Direct characterization of young giant exoplanets at high spectral resolution

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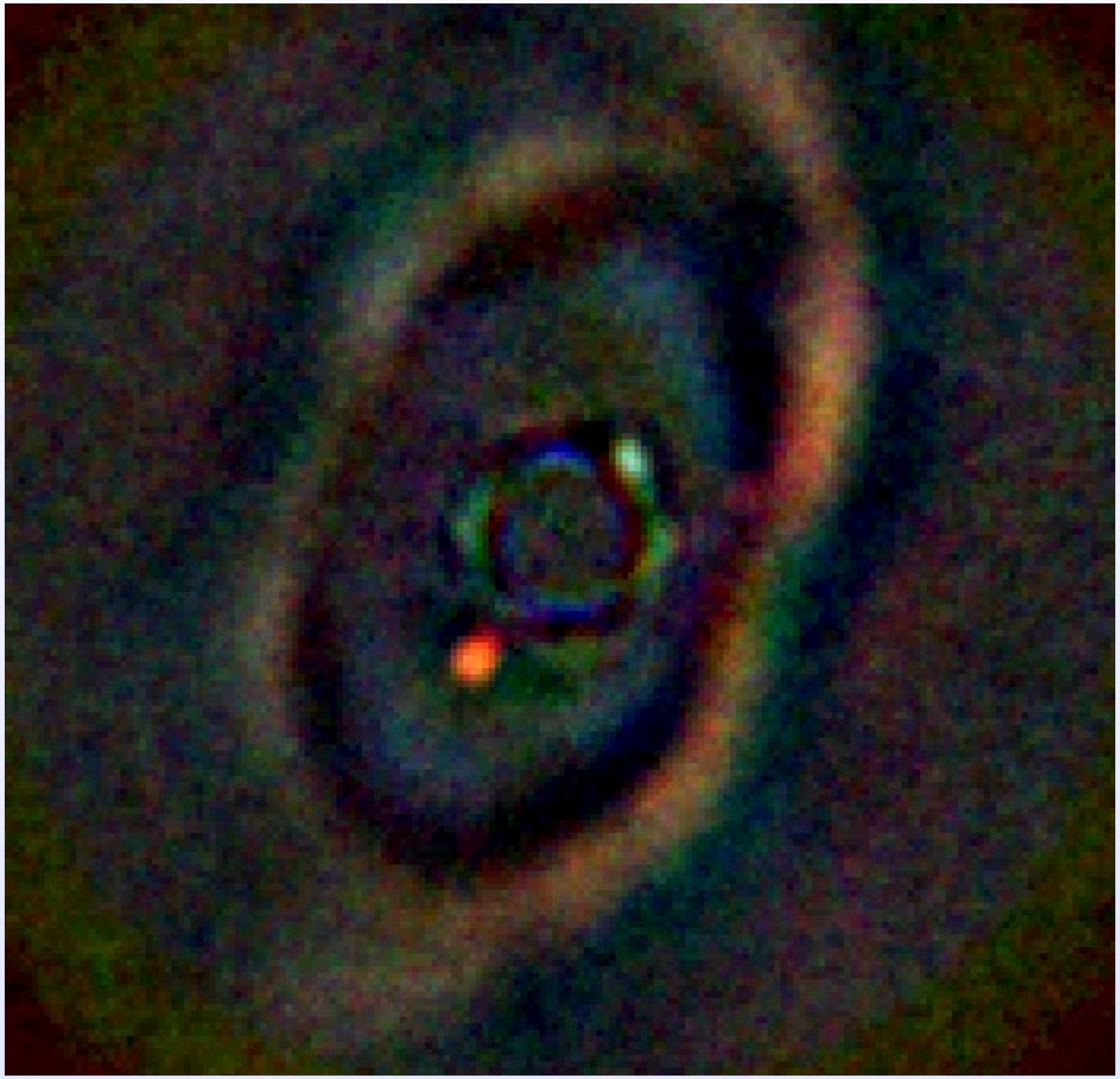
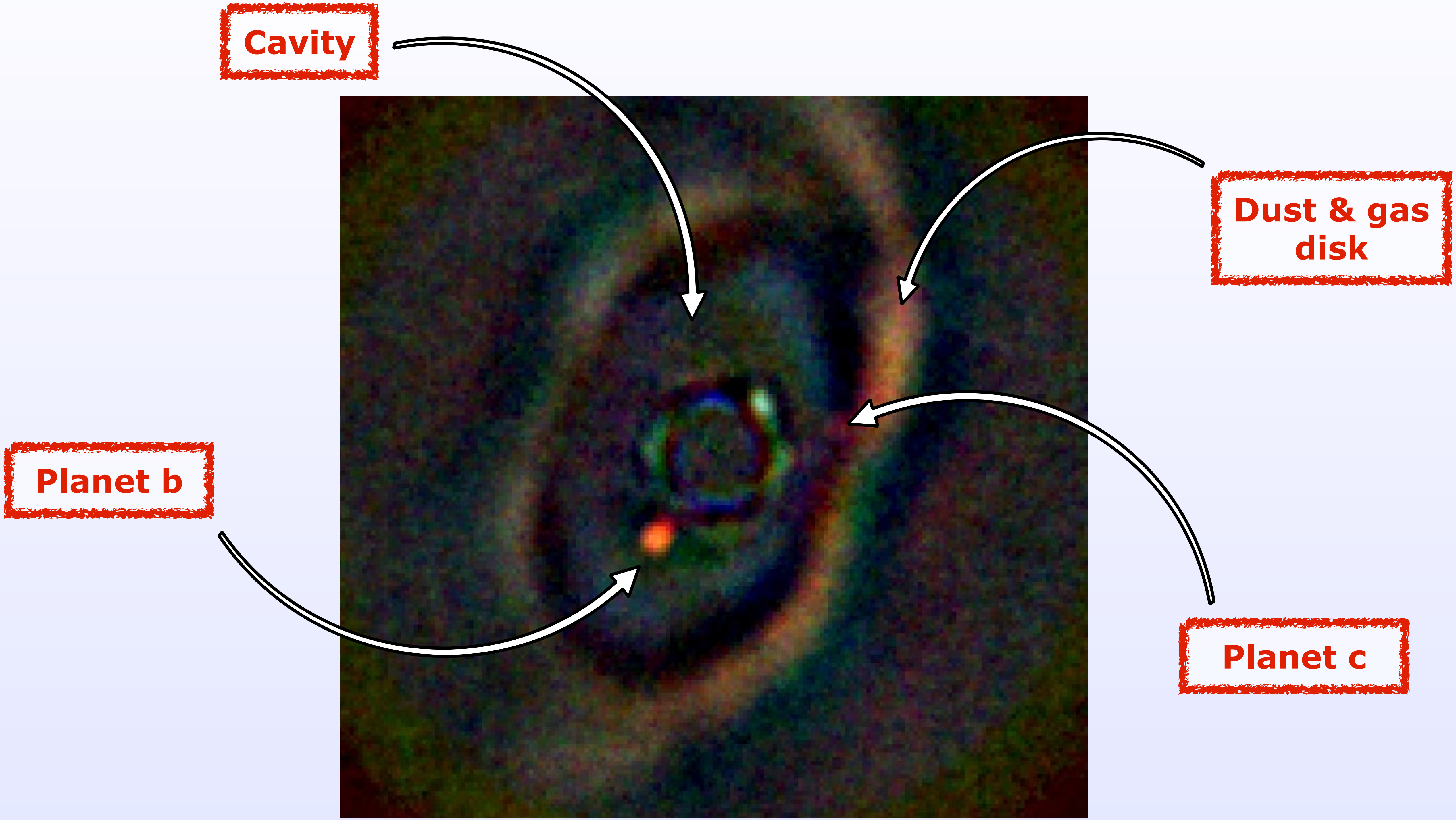
Direct imaging of exoplanetary systems



PDS 70 - Keppler et al. (2018)

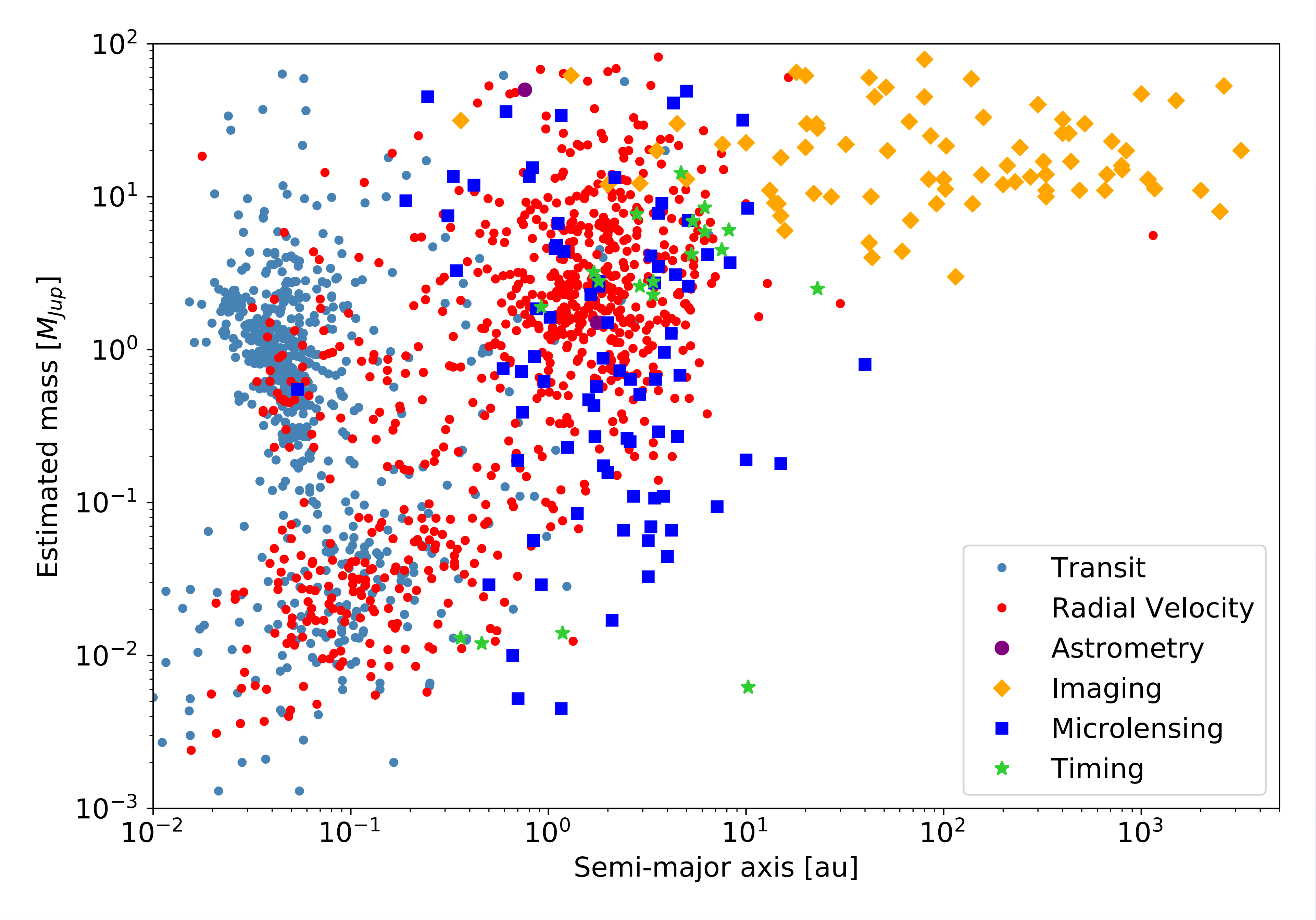
Direct imaging of exoplanetary systems



PDS 70 - Keppler et al. (2018)

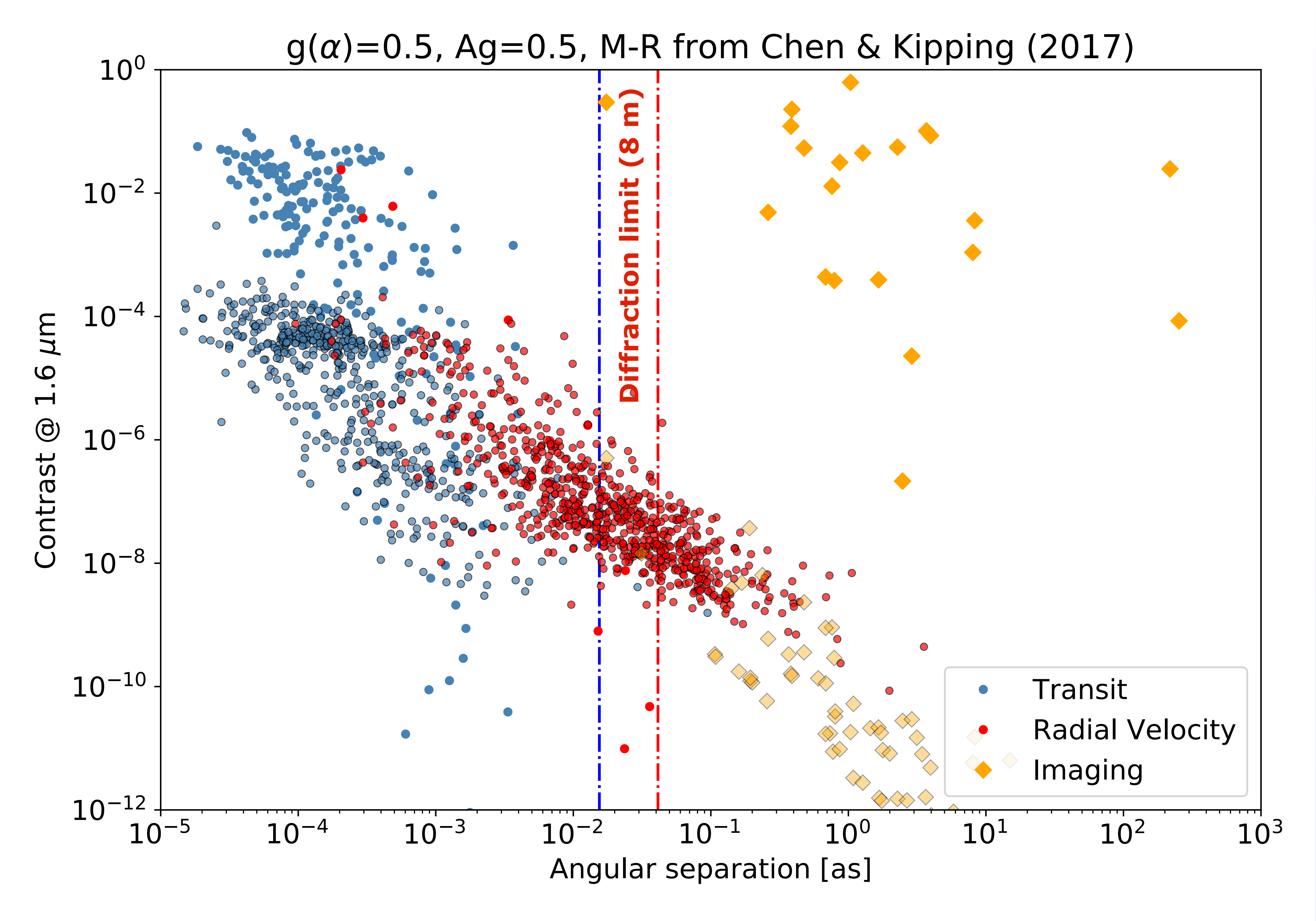
Direct imaging: the challenge

Physical units



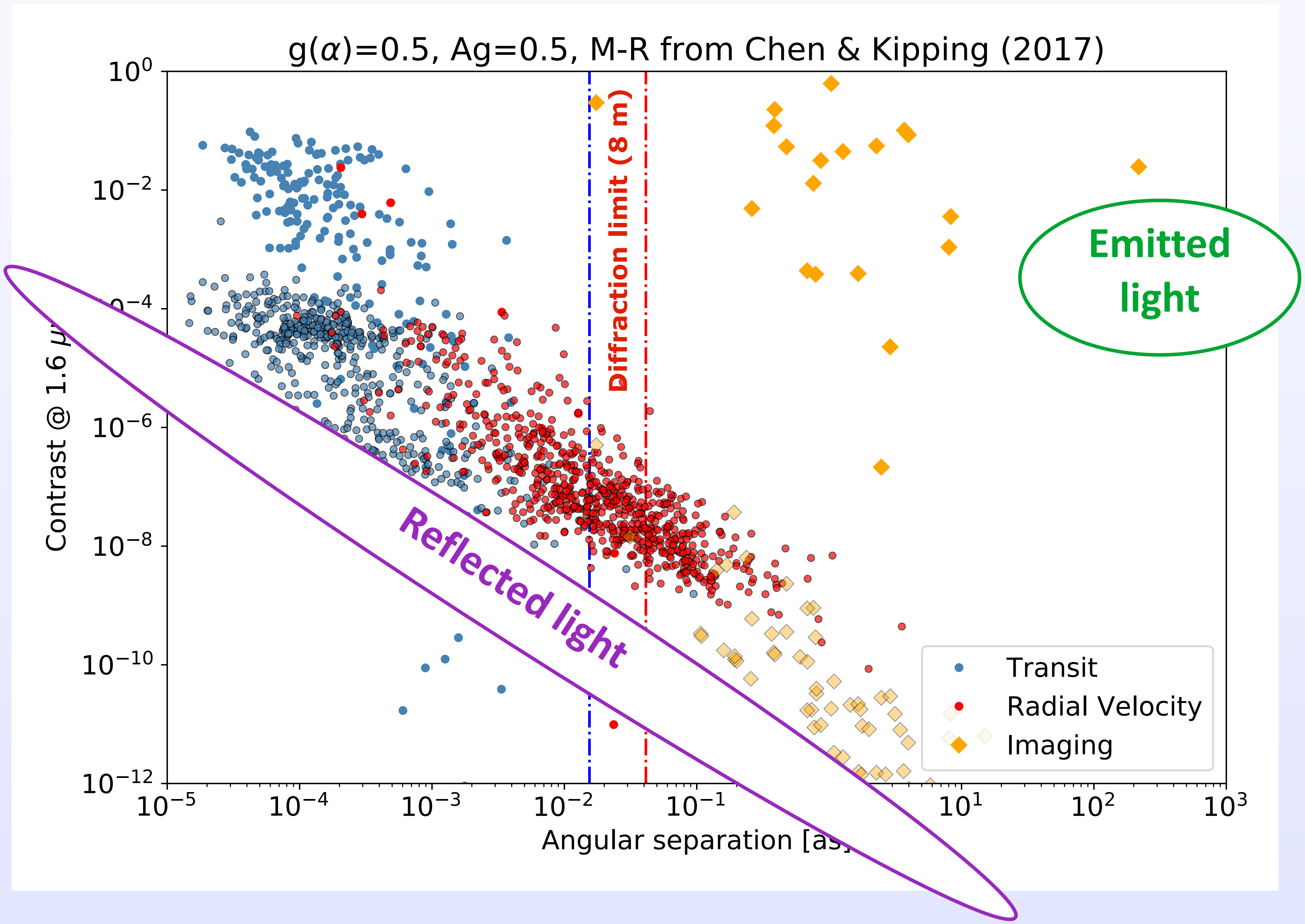
Direct imaging: the challenge

Observables

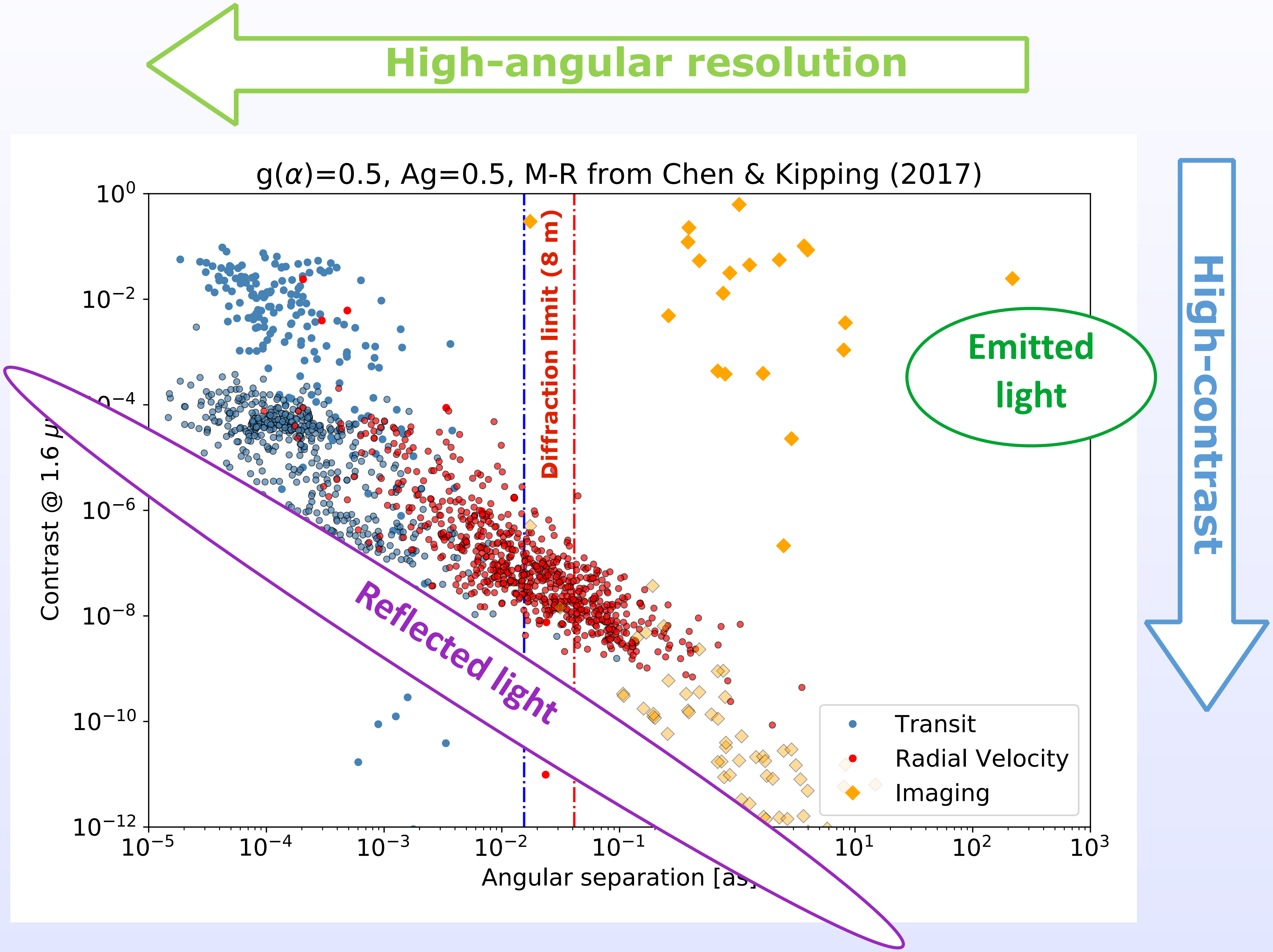


Direct imaging: the challenge

Observables



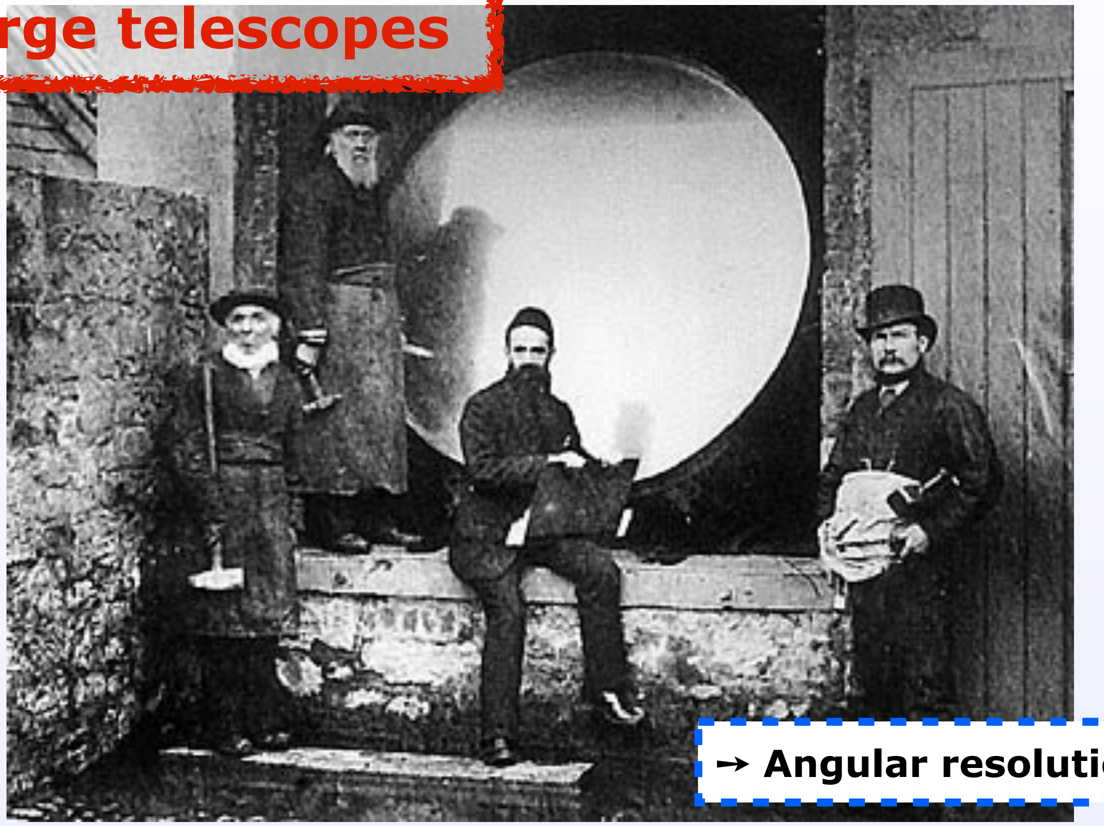
Direct imaging: the challenge



Direct imaging recipe

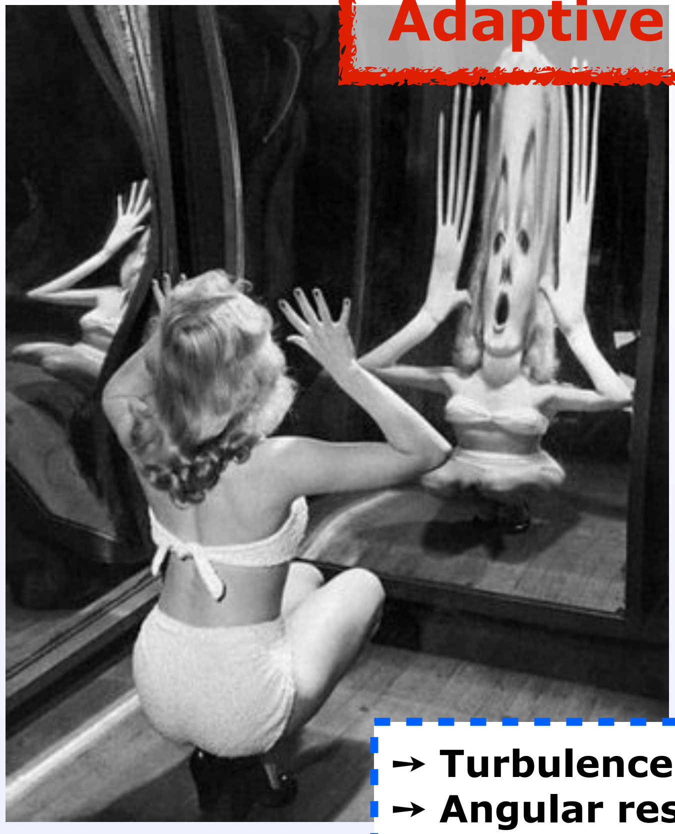
Direct imaging recipe

Large telescopes

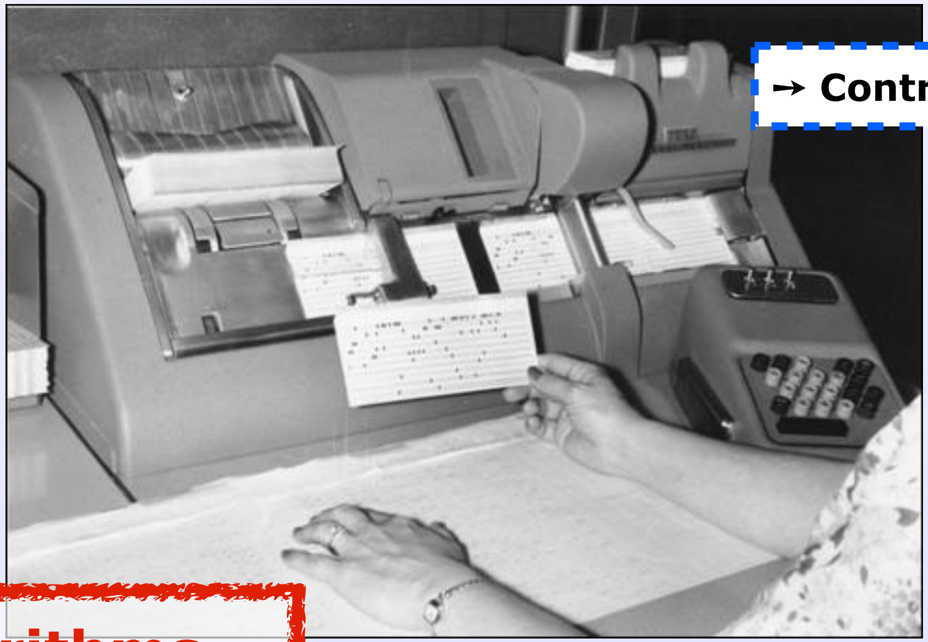


→ Angular resolution

Adaptive optics

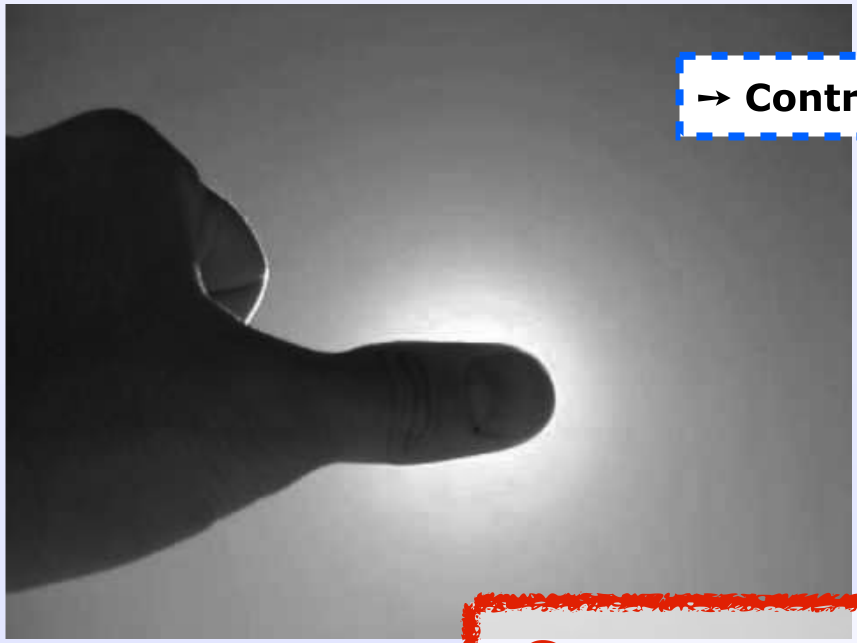


→ Turbulence correction
→ Angular resolution



→ Contrast

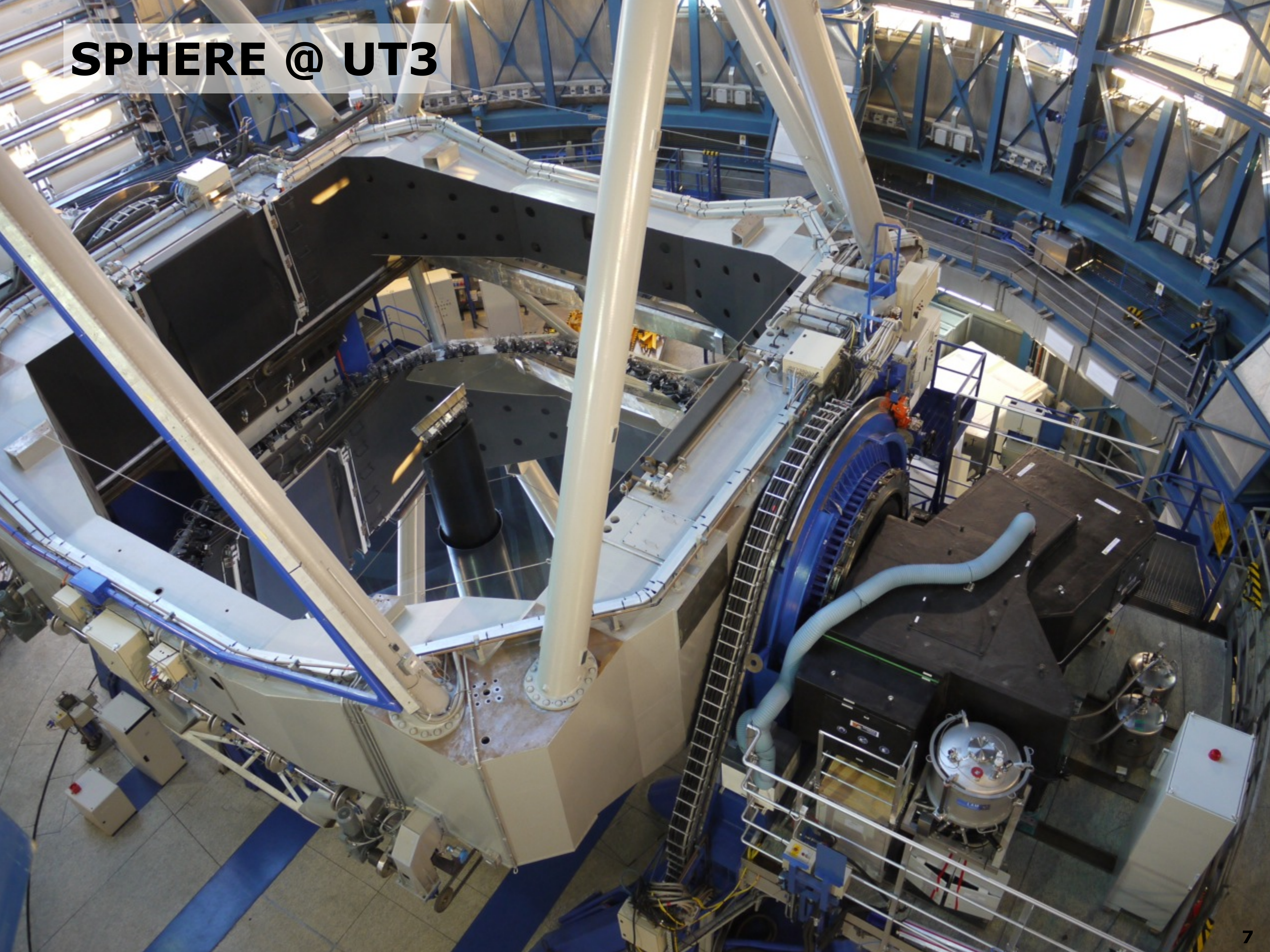
Algorithms



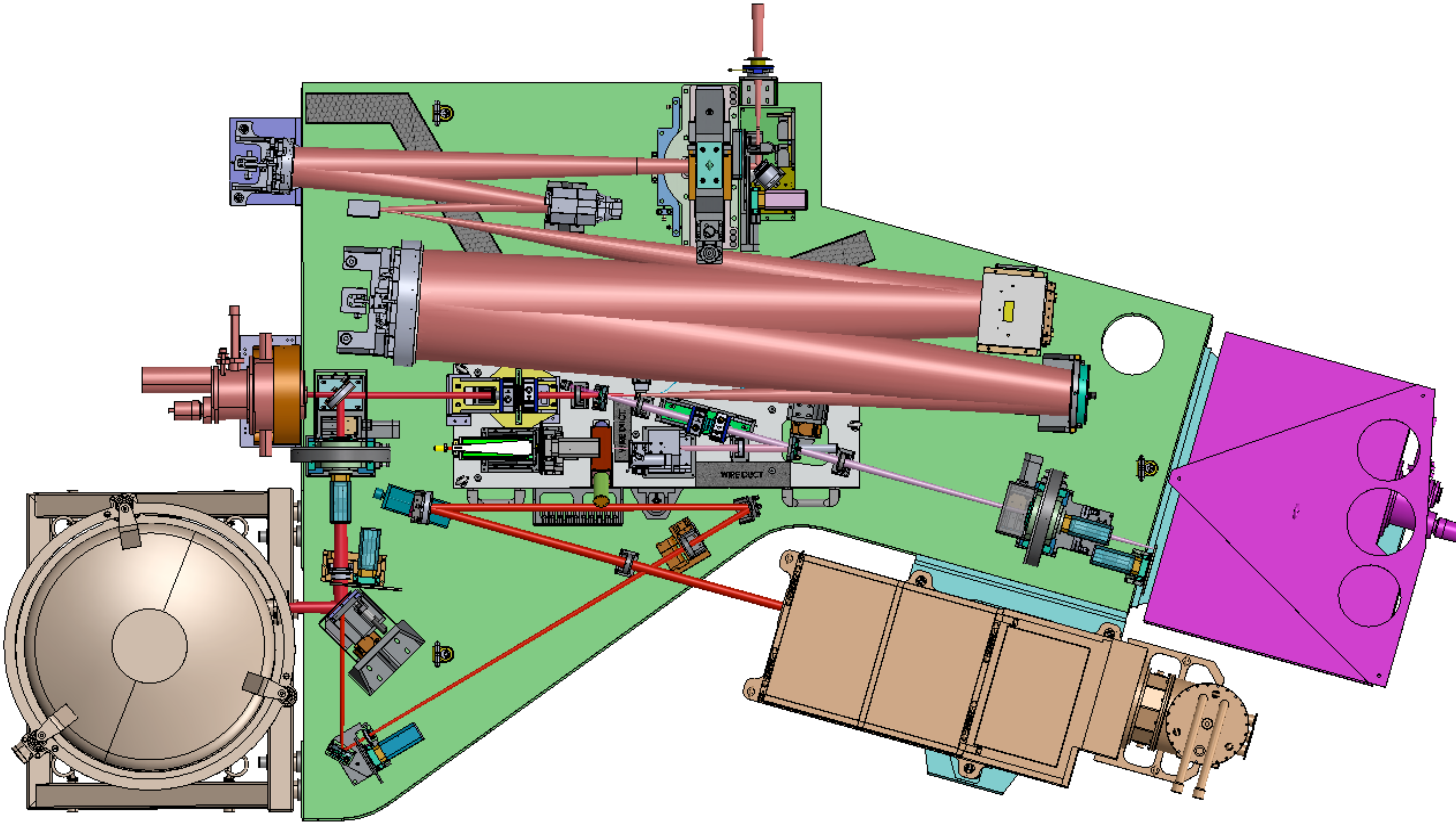
→ Contrast

Coronagraphs

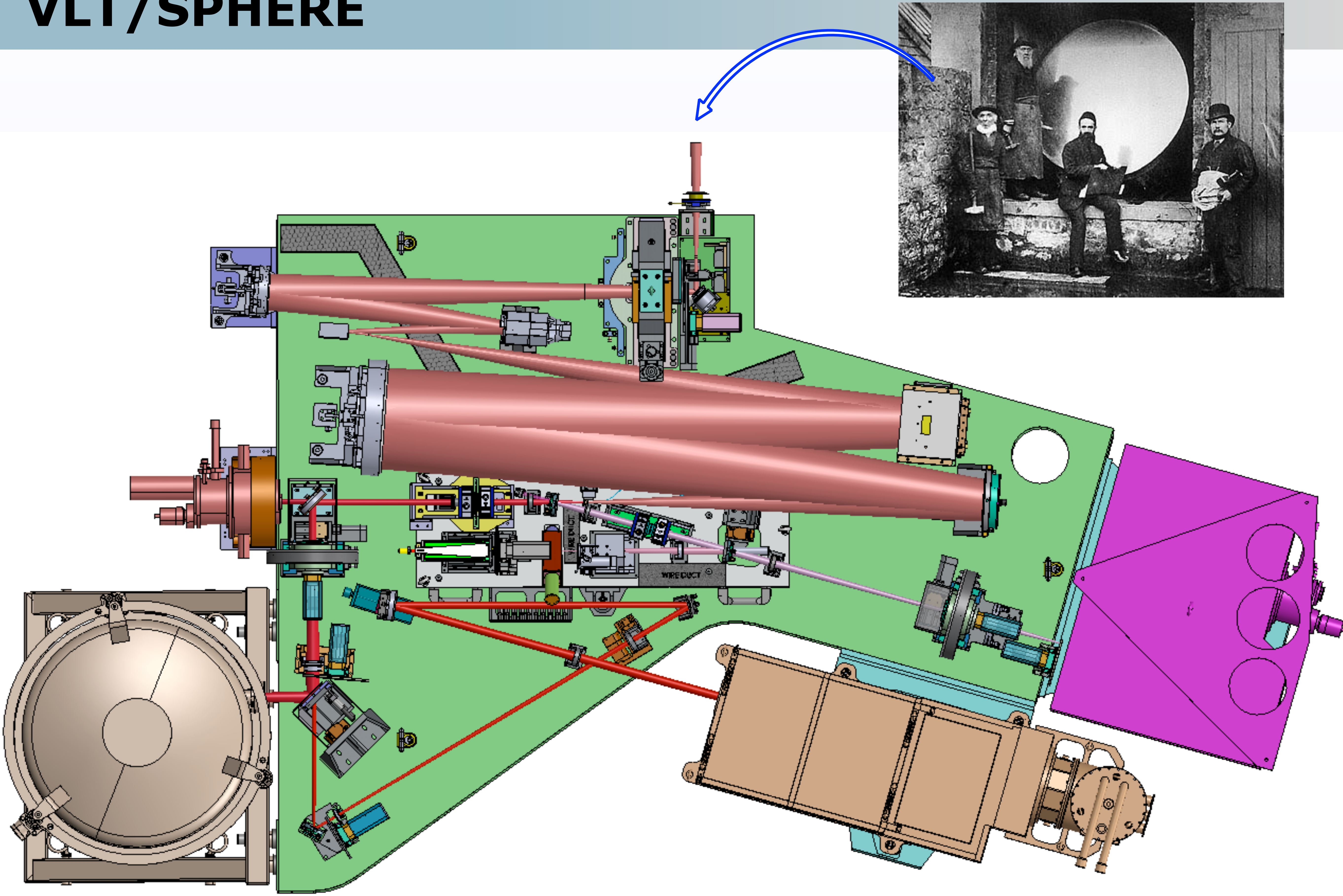
SPHERE @ UT3



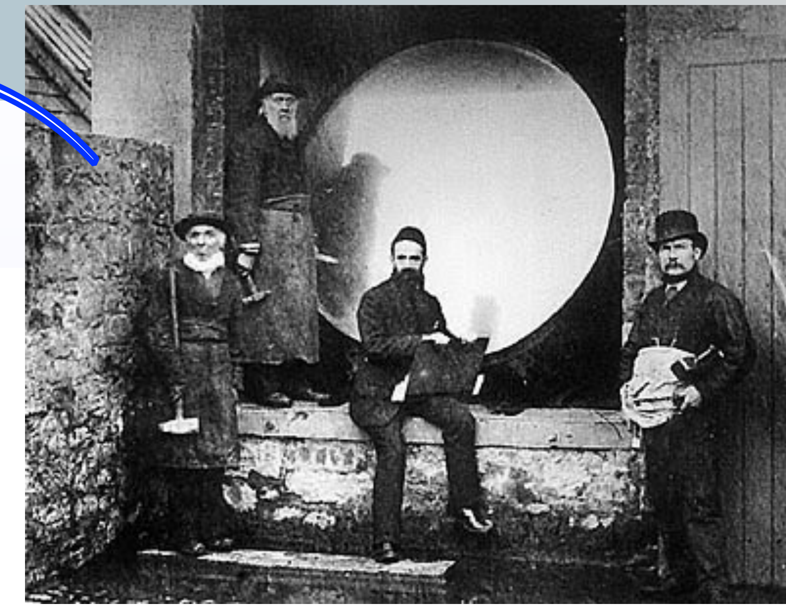
VLT/SPHERE

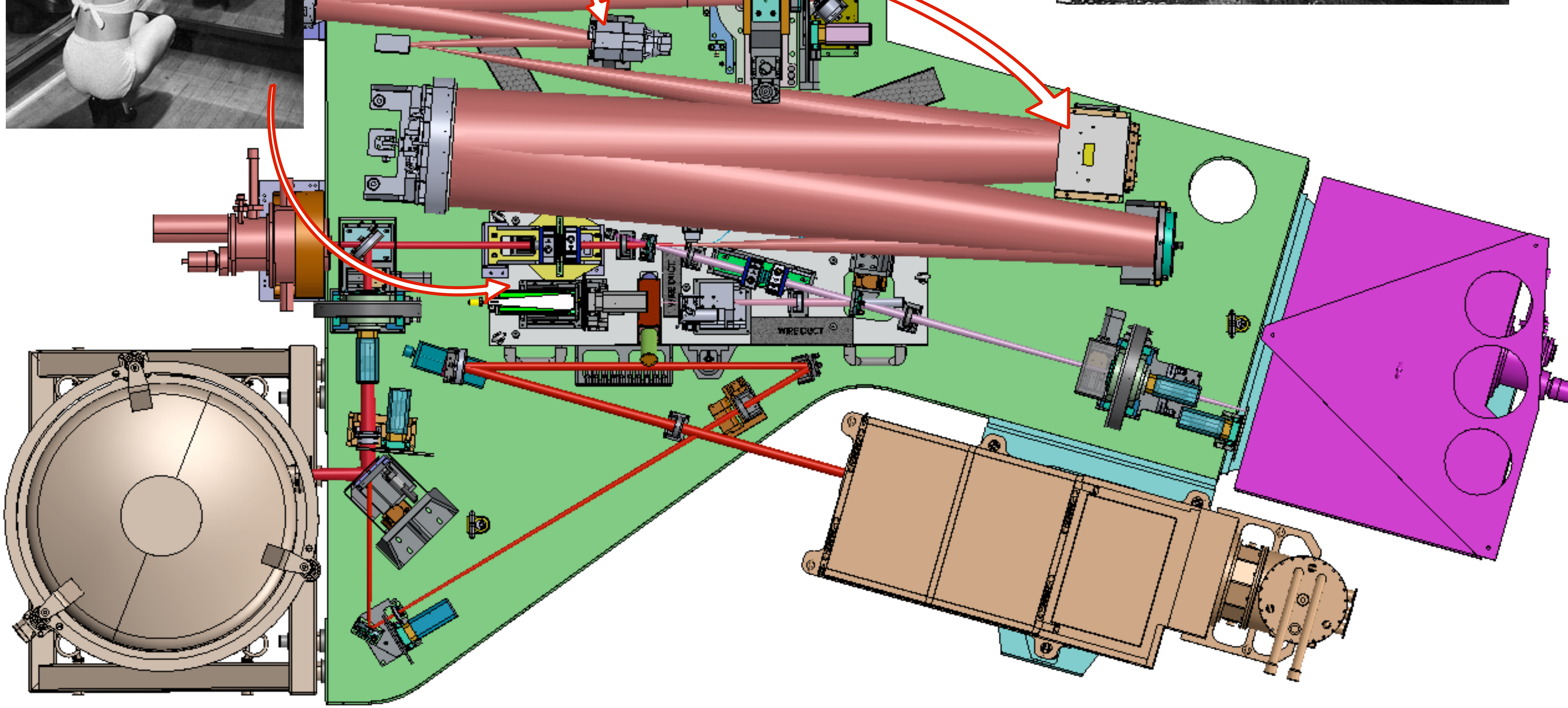


VLT/SPHERE

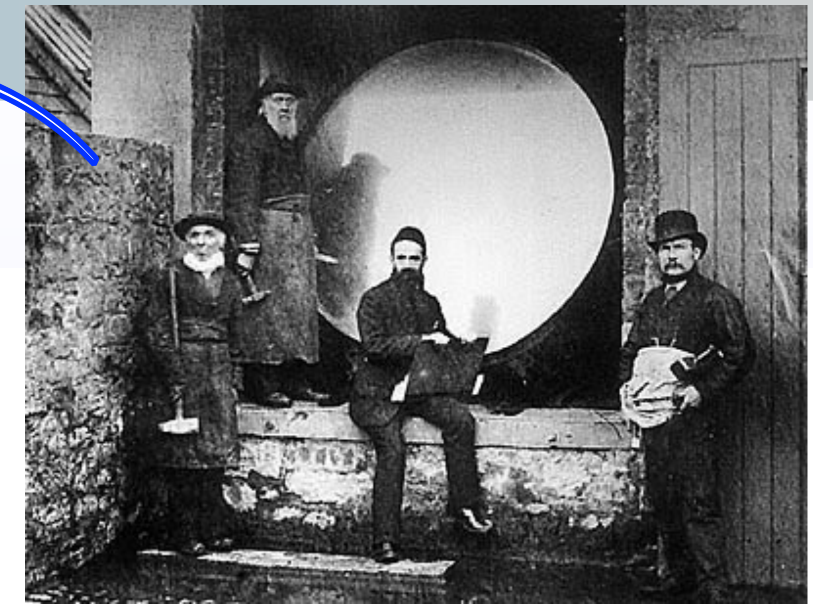


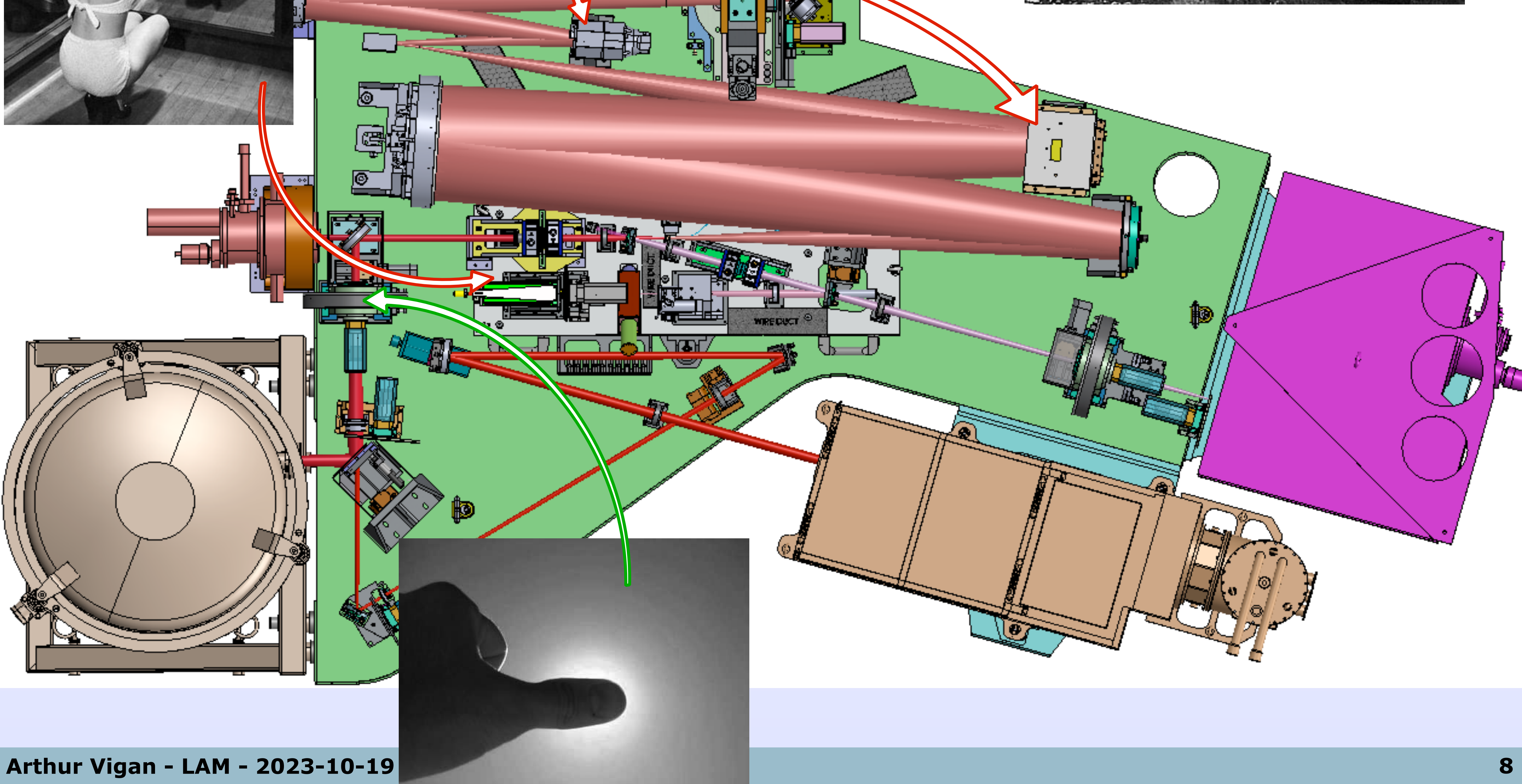
VLT/SPHERE



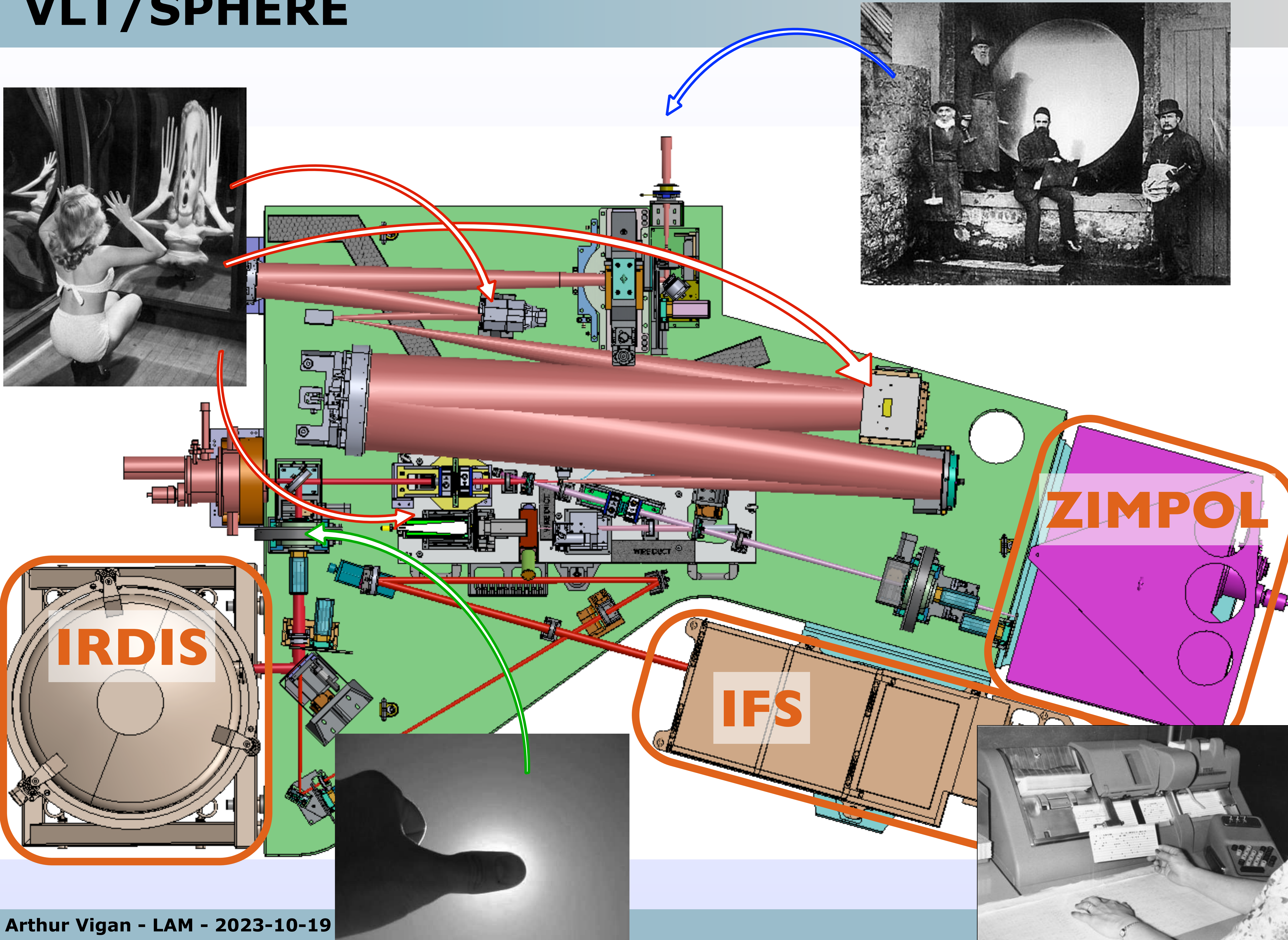


VLT/SPHERE

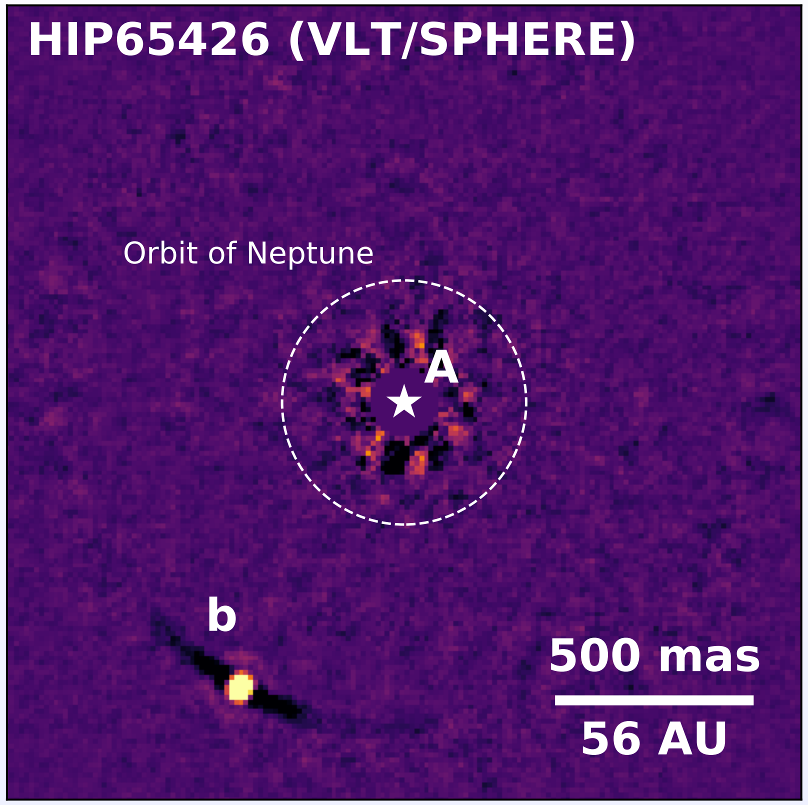




VLT/SPHERE

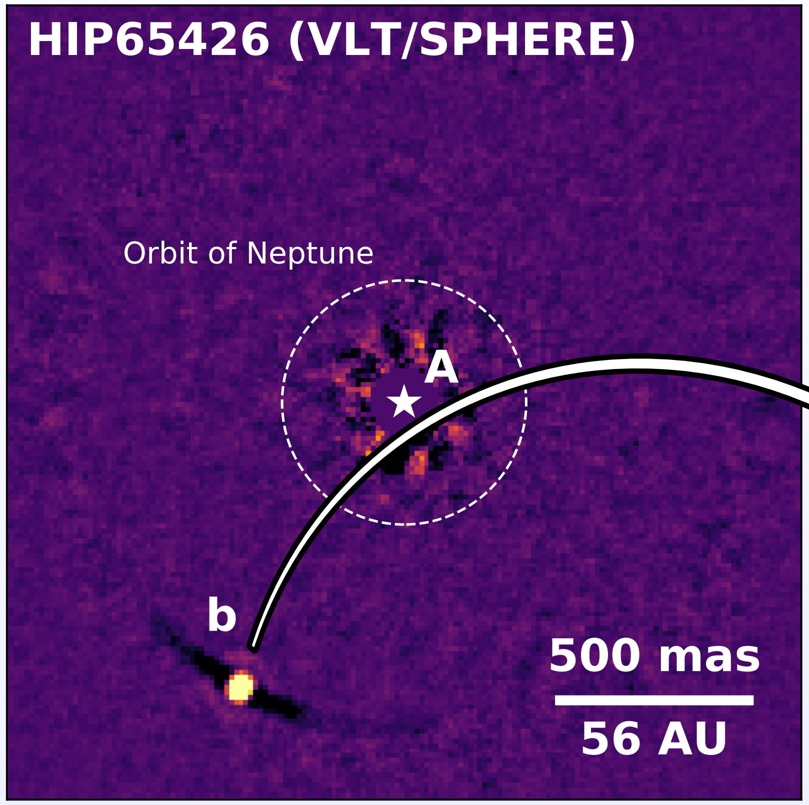


Detections with high-contrast instruments

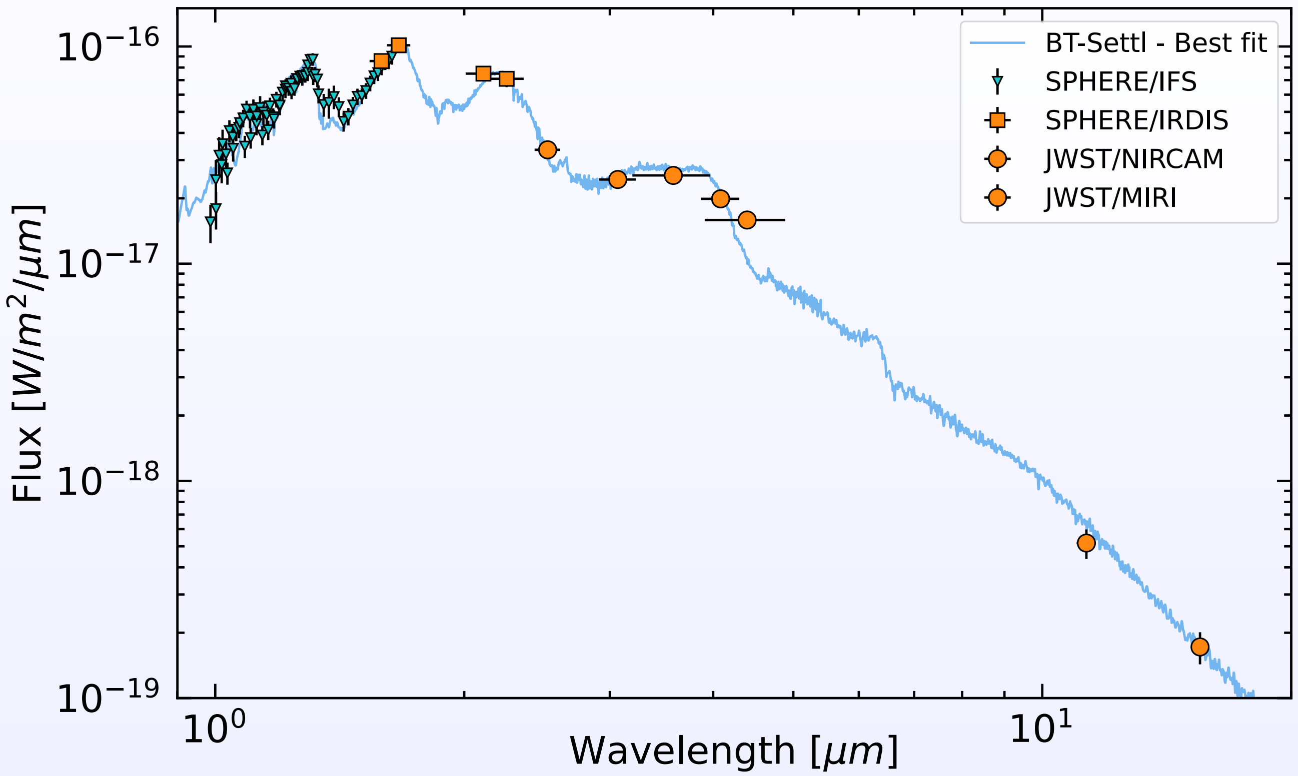


Chauvin et al. 2017

Detections with high-contrast instruments

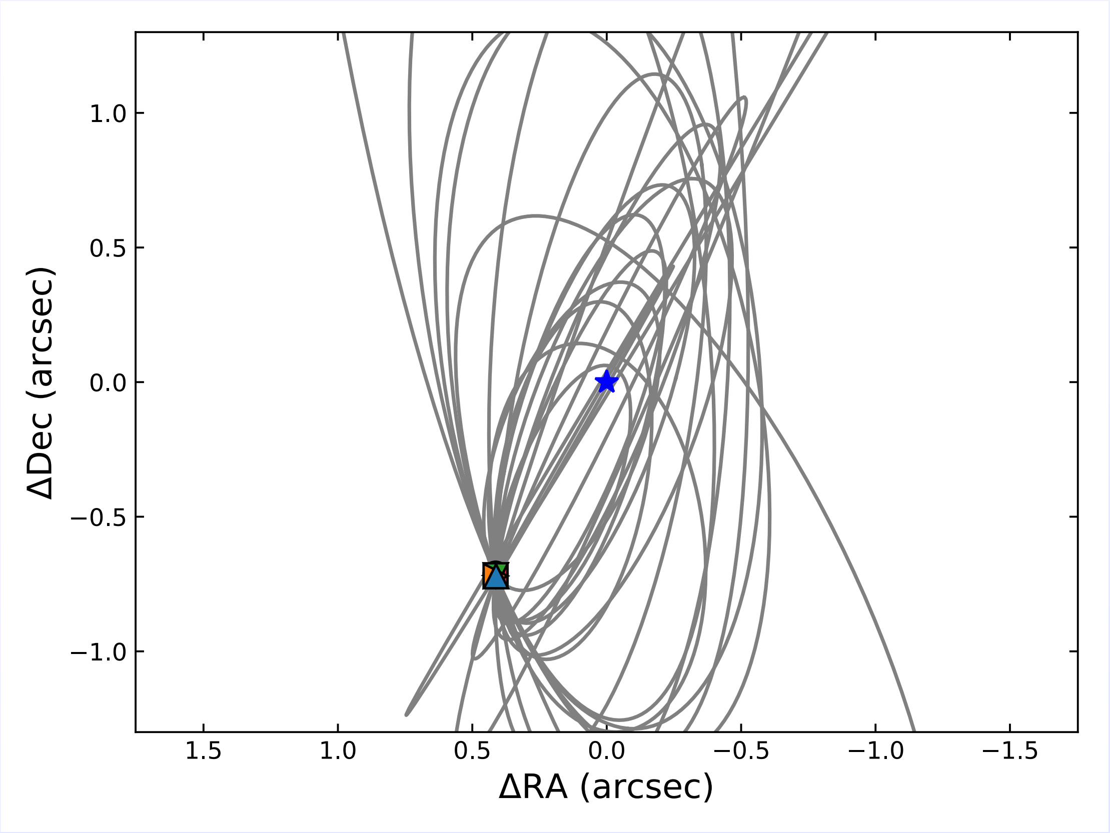


Chauvin et al. 2017

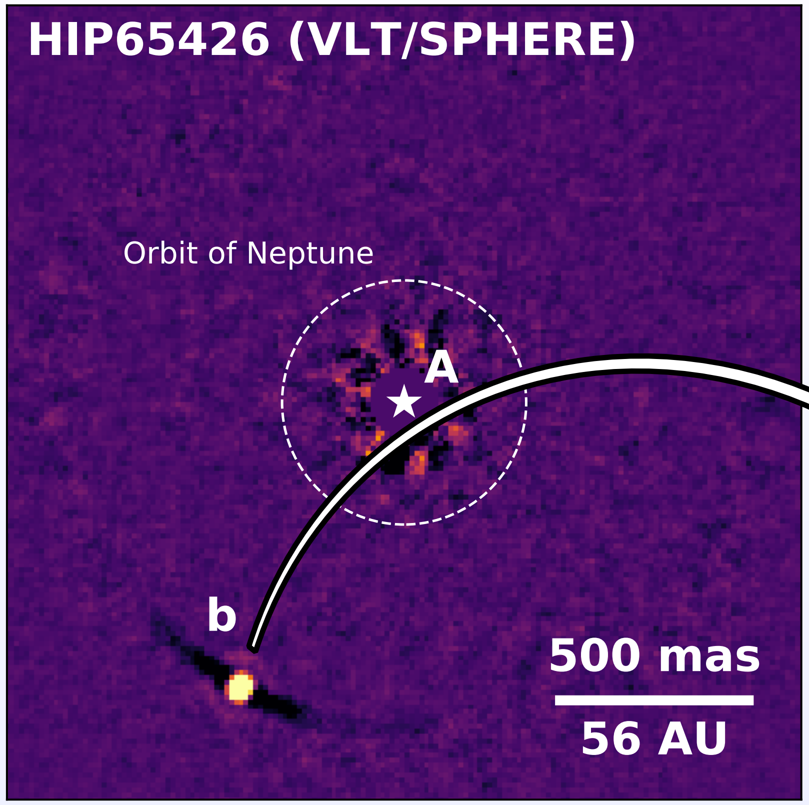


Very low resolution

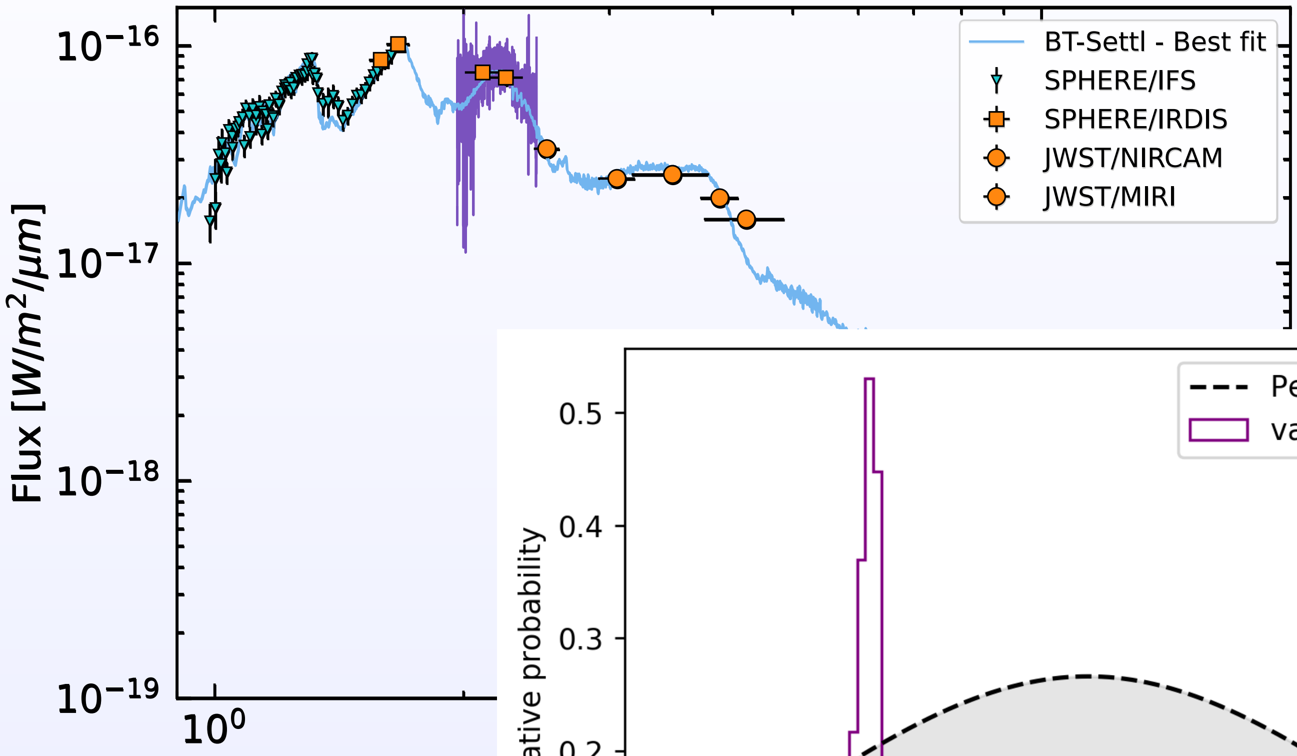
Just enough for first order characterisation!

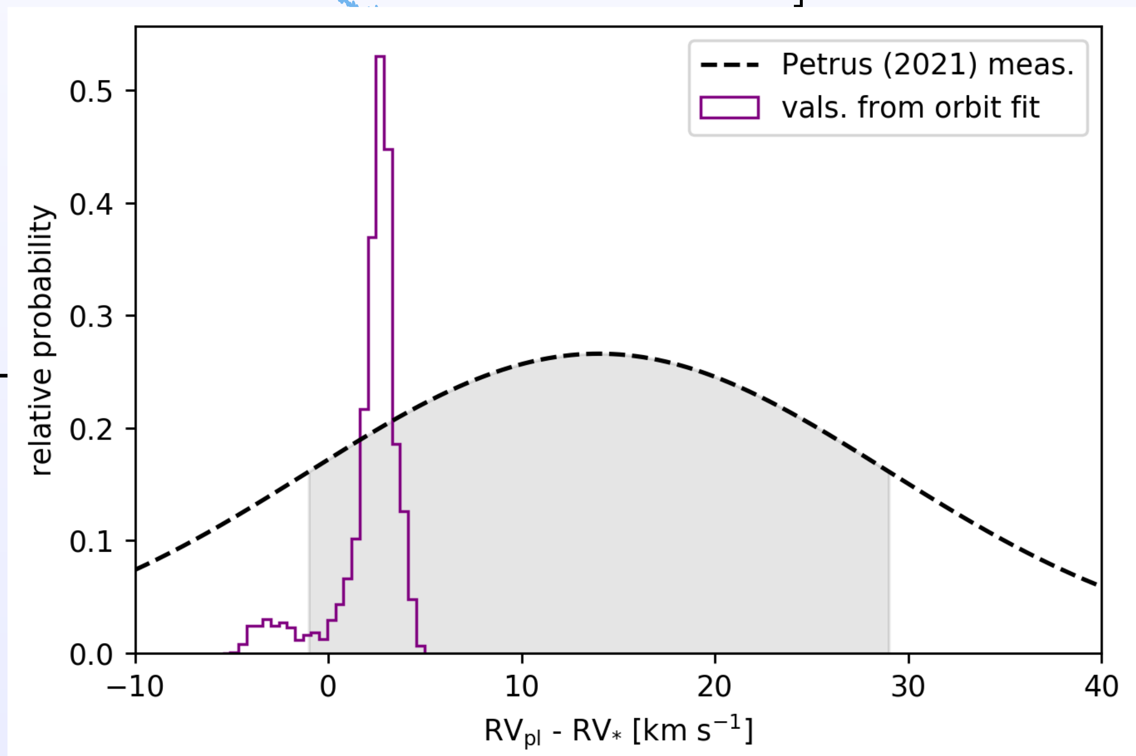


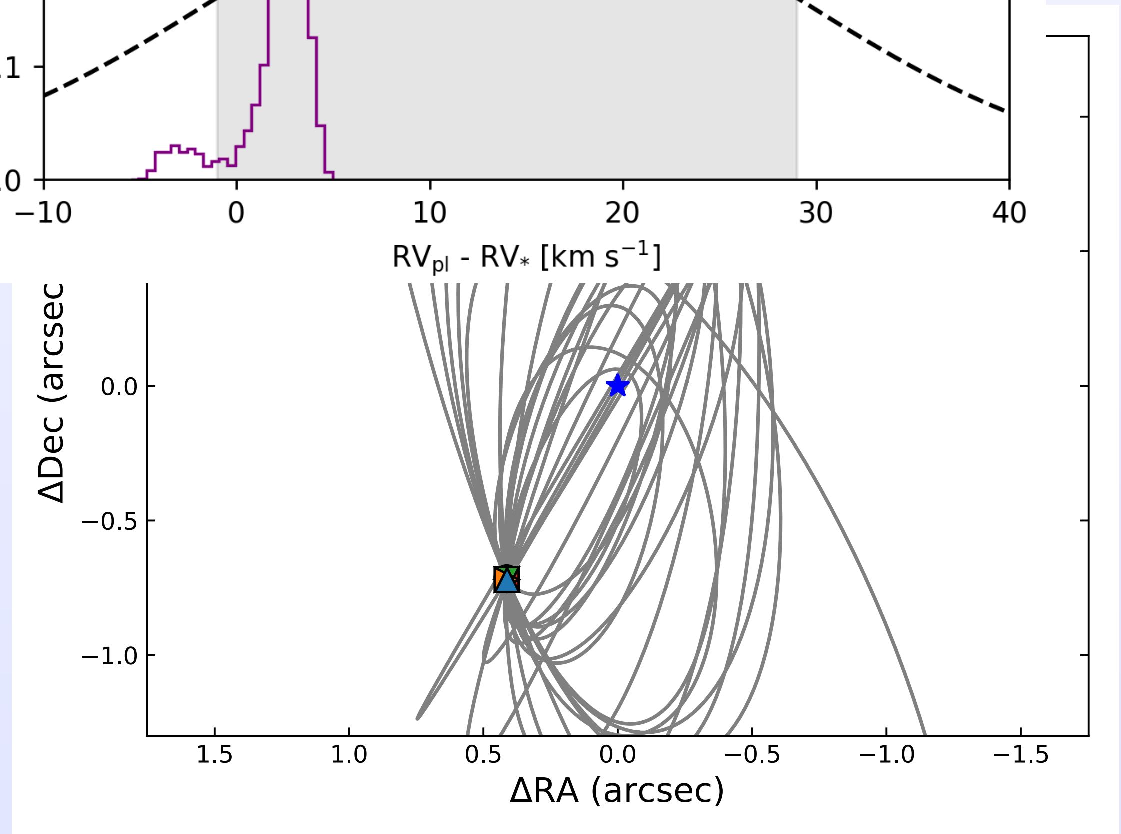
Detections with high-contrast instruments



Chauvin et al. 2017







Very low resolution

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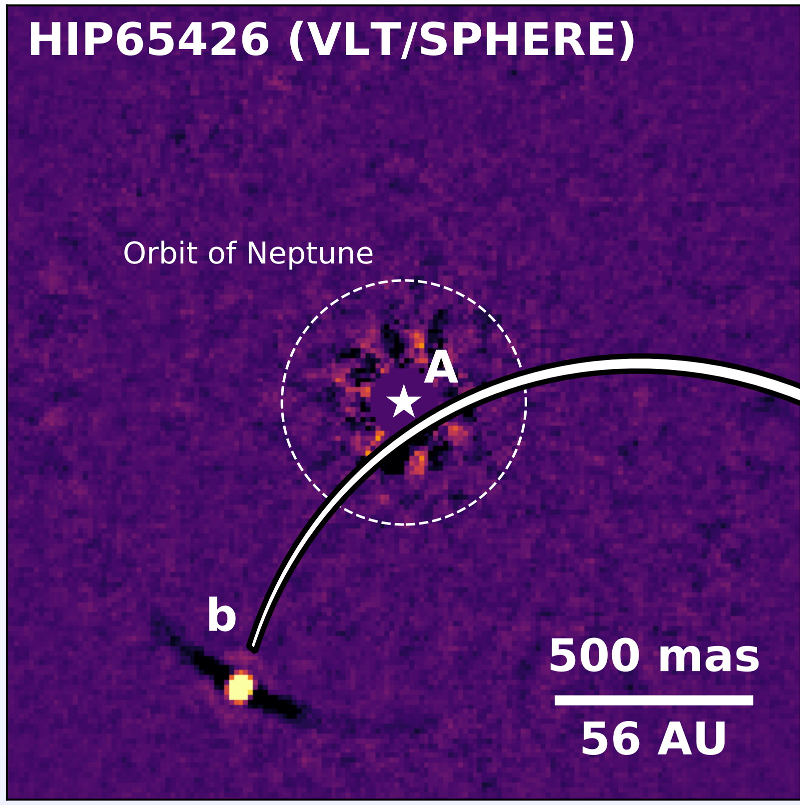
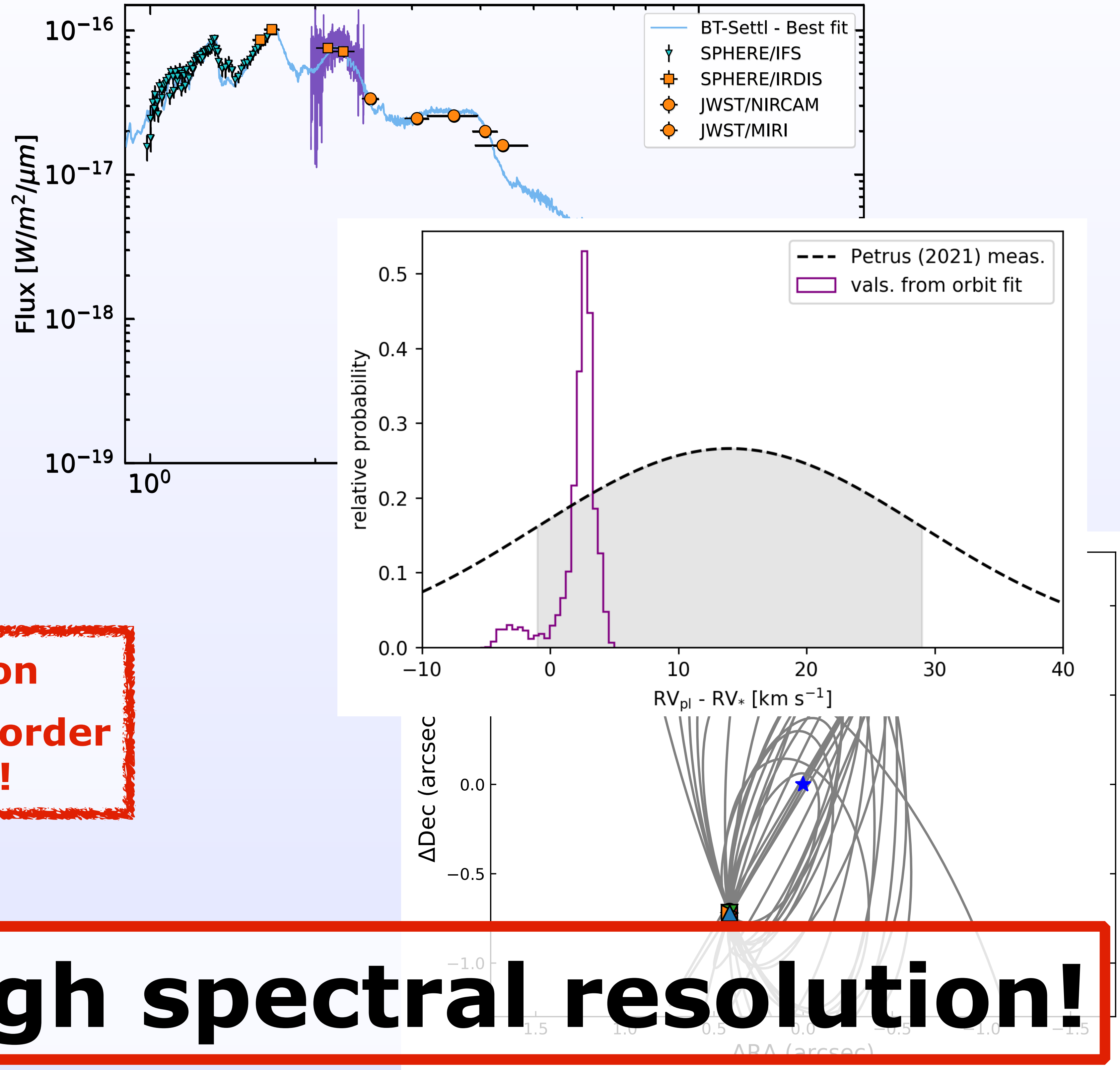
Detections with high-contrast instruments



Chauvin et al. 2017

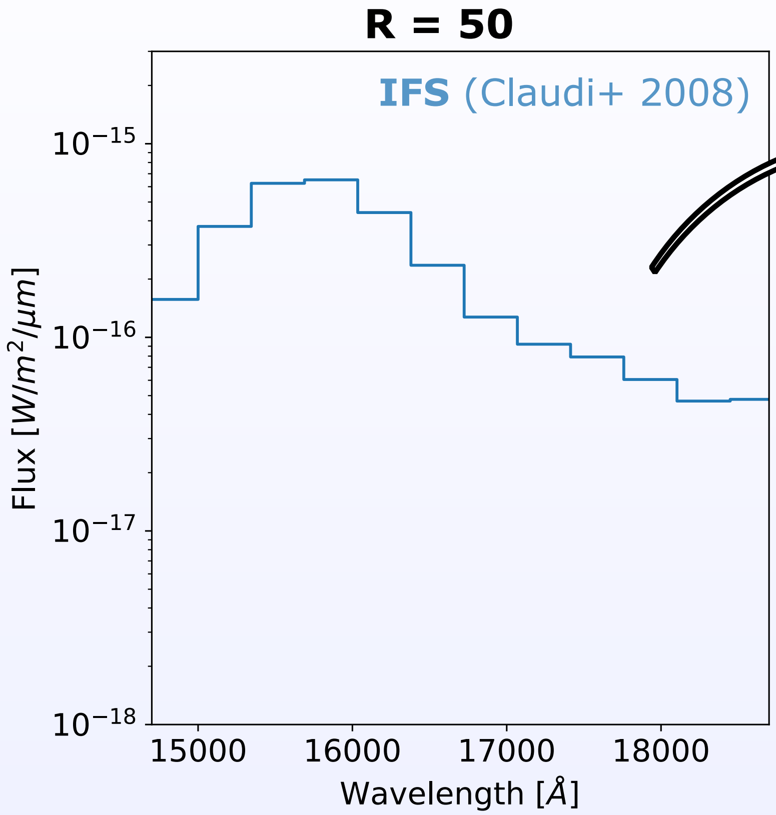


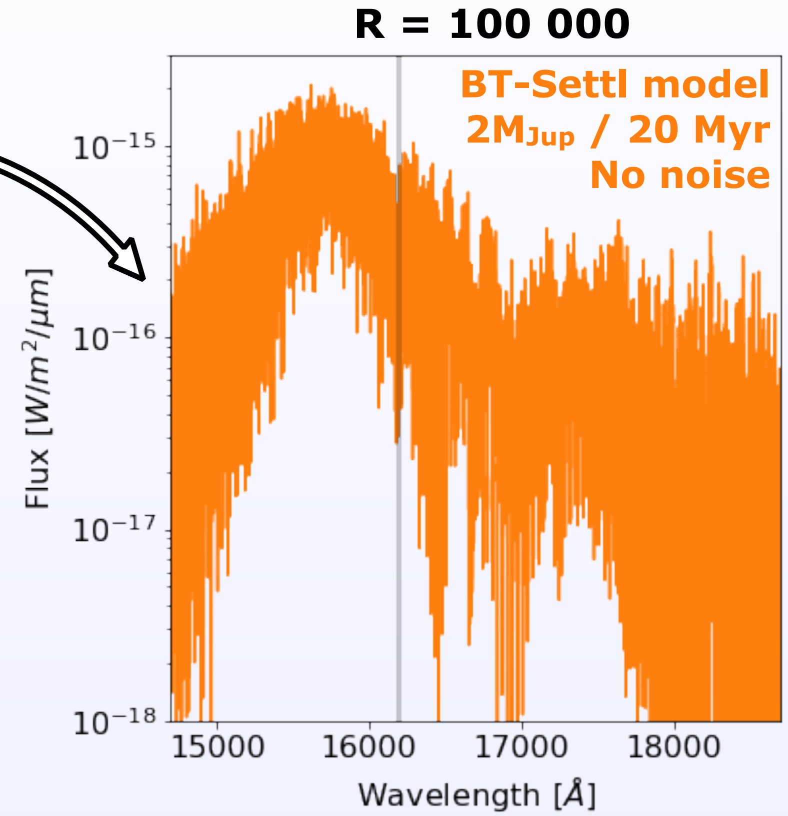
Very low resolution

Just enough for first order characterisation!

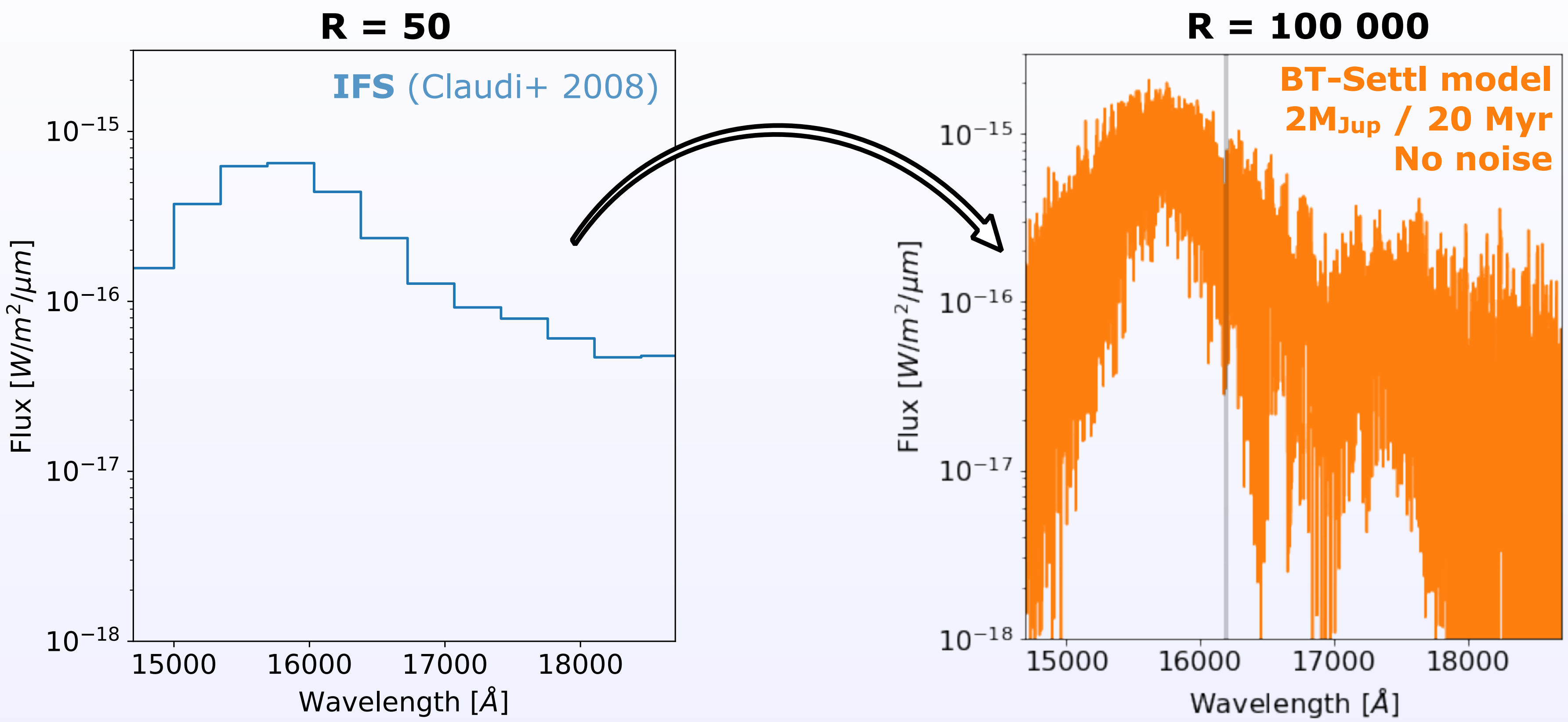
Need for high spectral resolution!

Spectral content



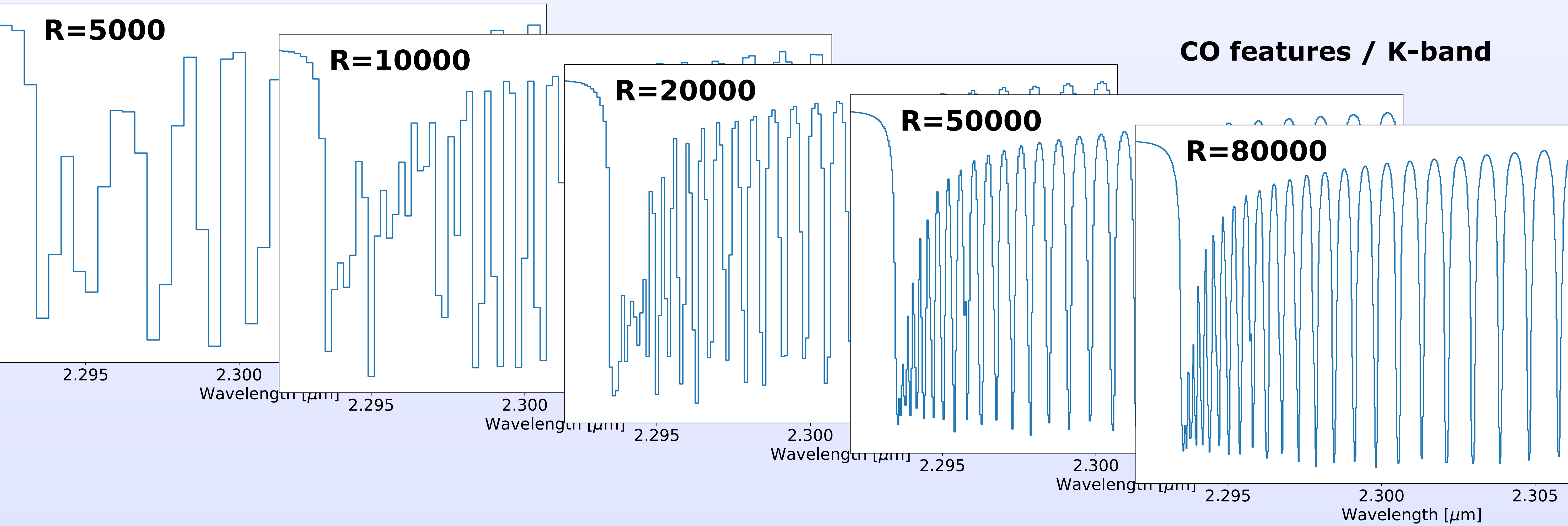


Spectral content

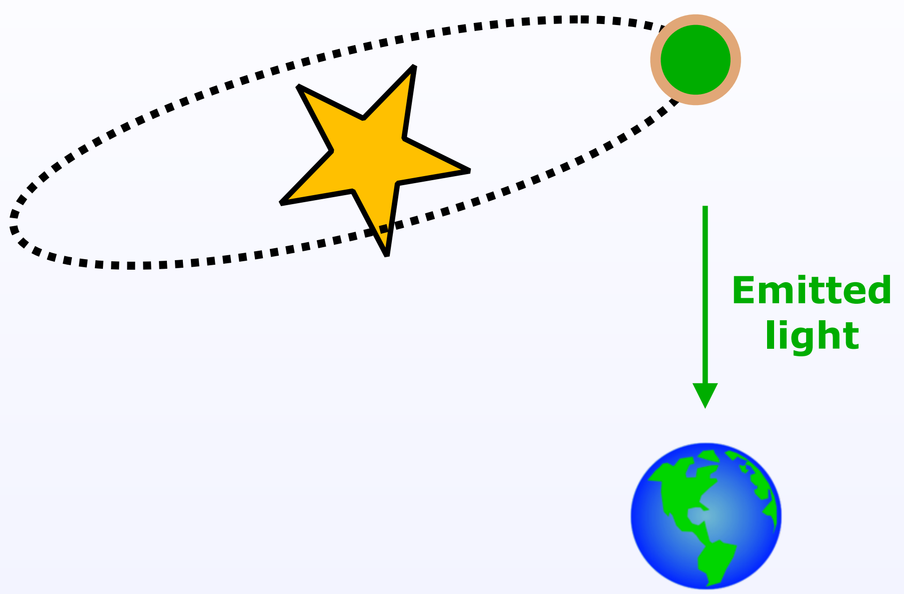


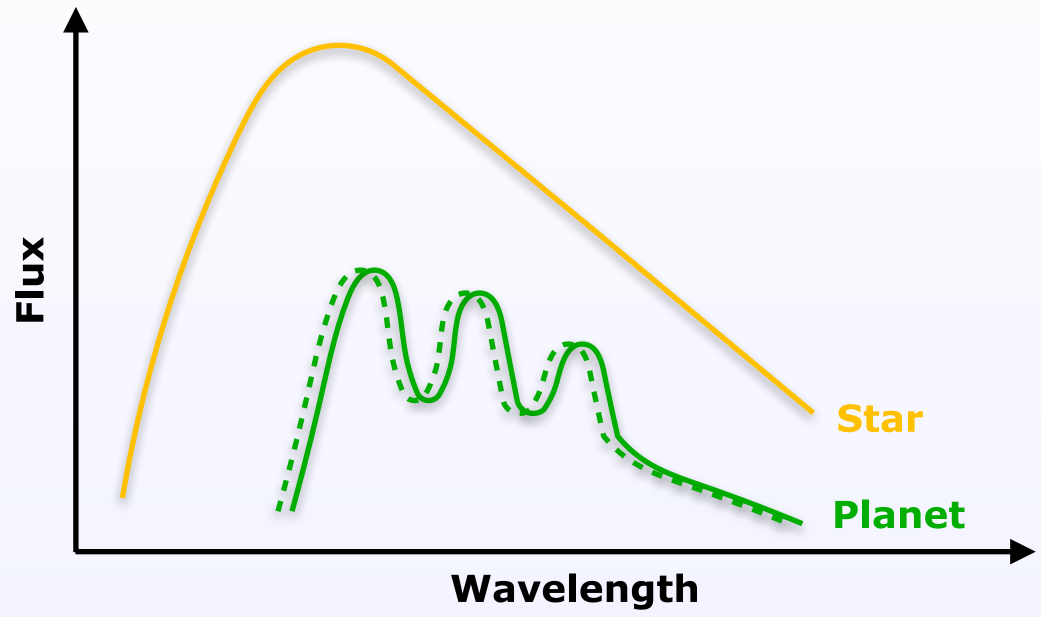
Requires
R ≫ 10 000

CO features / K-band

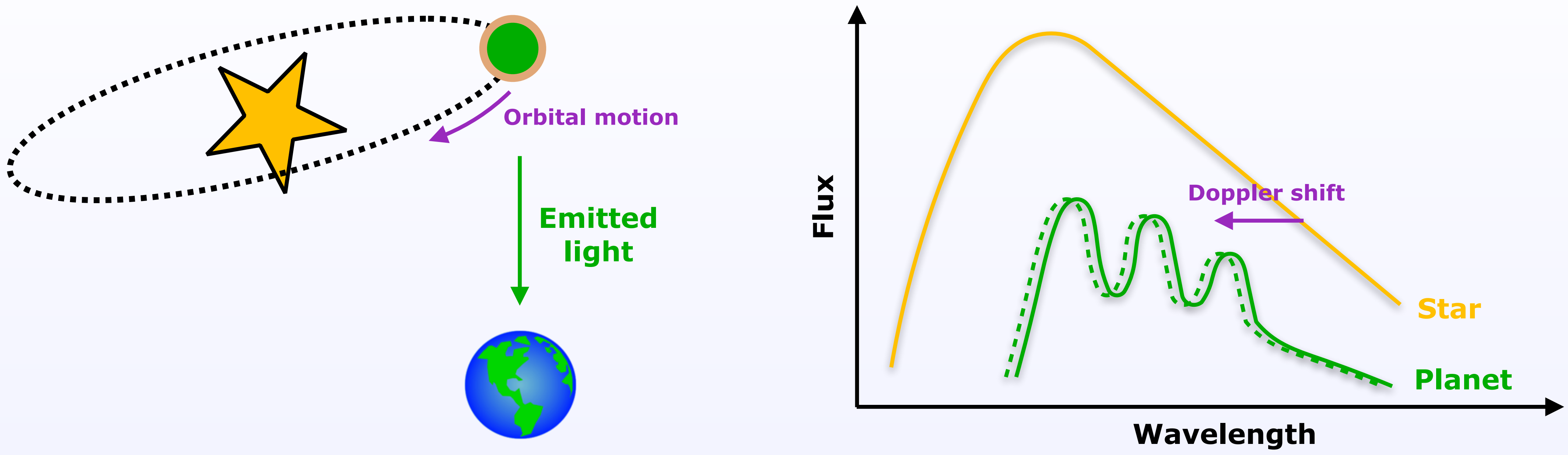


Orbital and rotational information

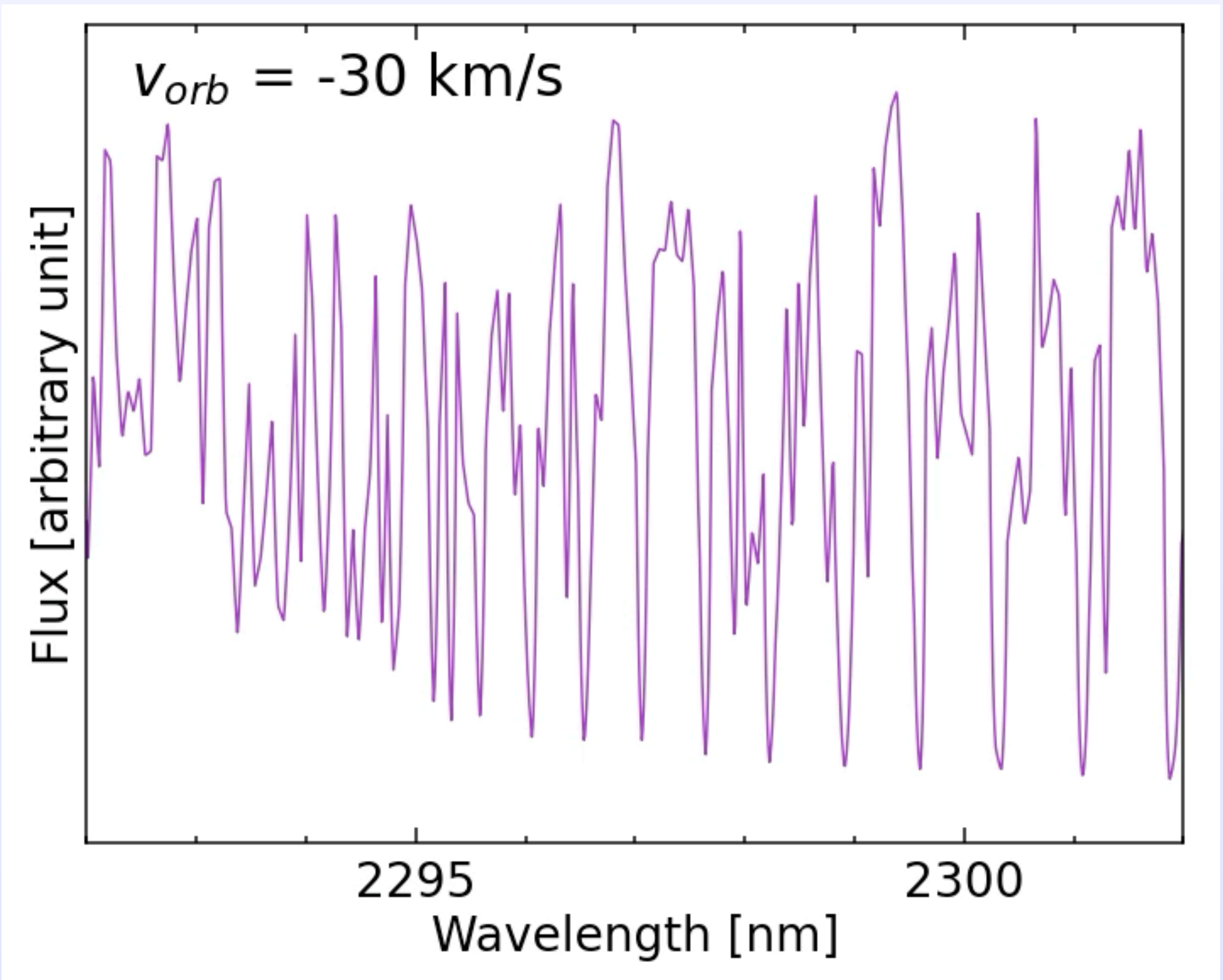




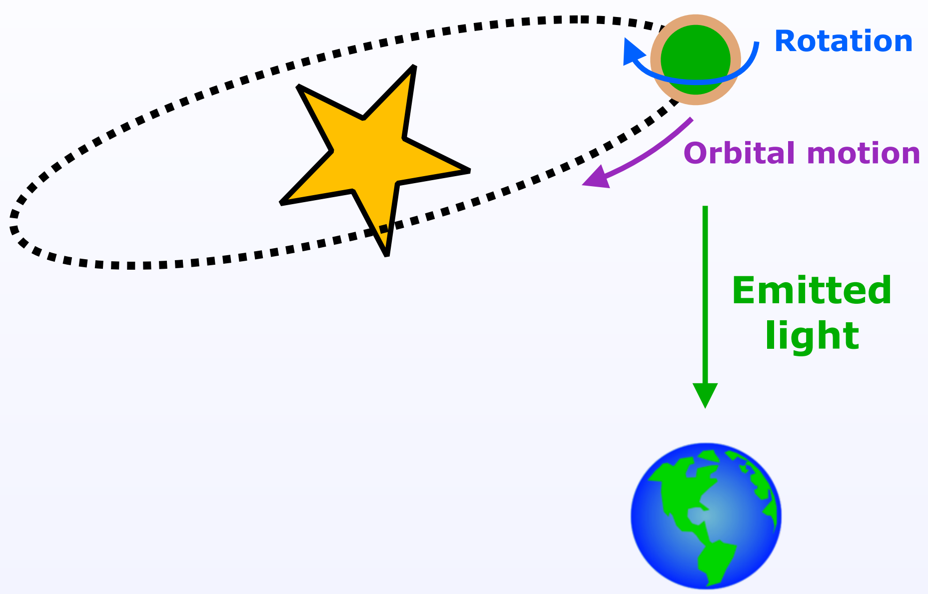
Orbital and rotational information

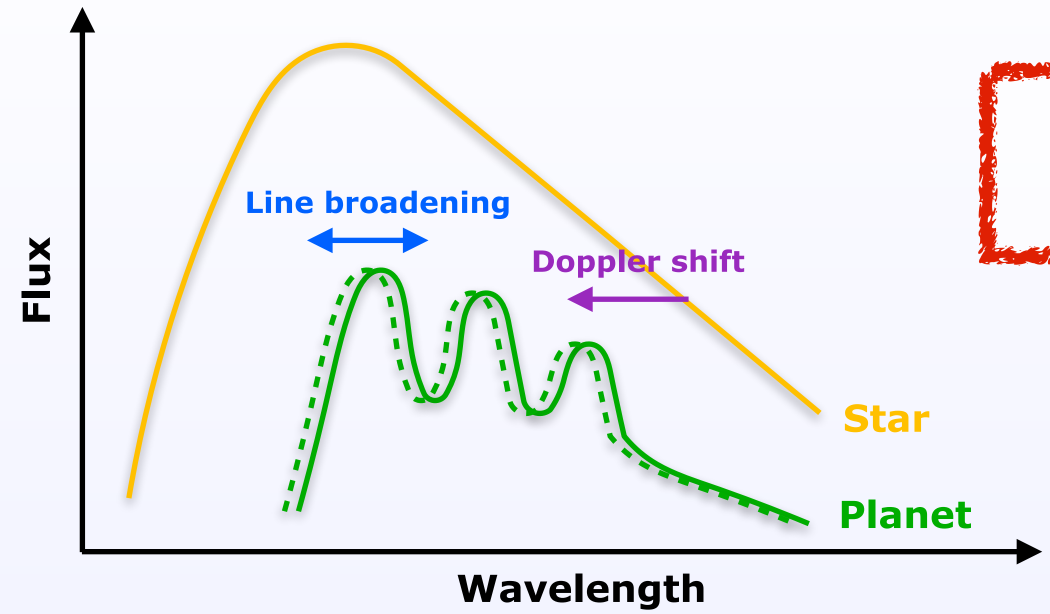


Effect of orbital motion

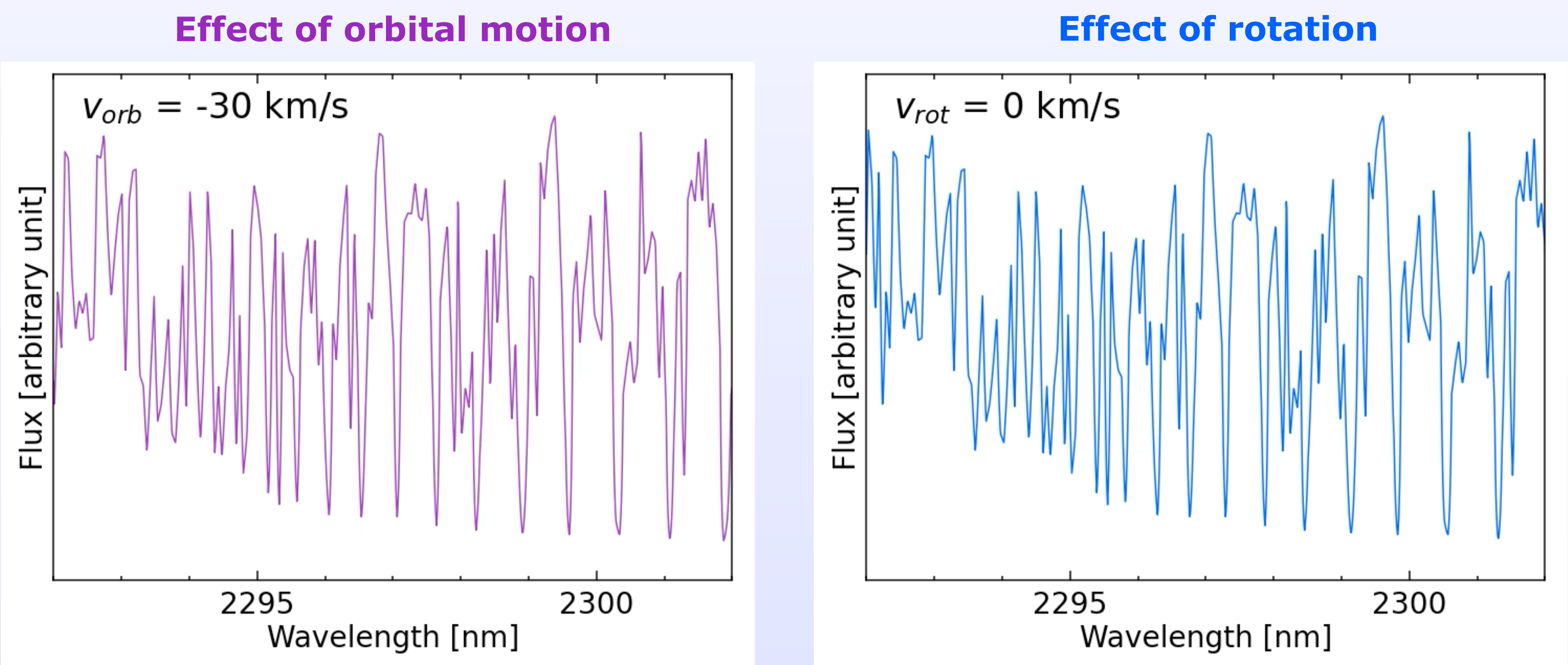


Orbital and rotational information

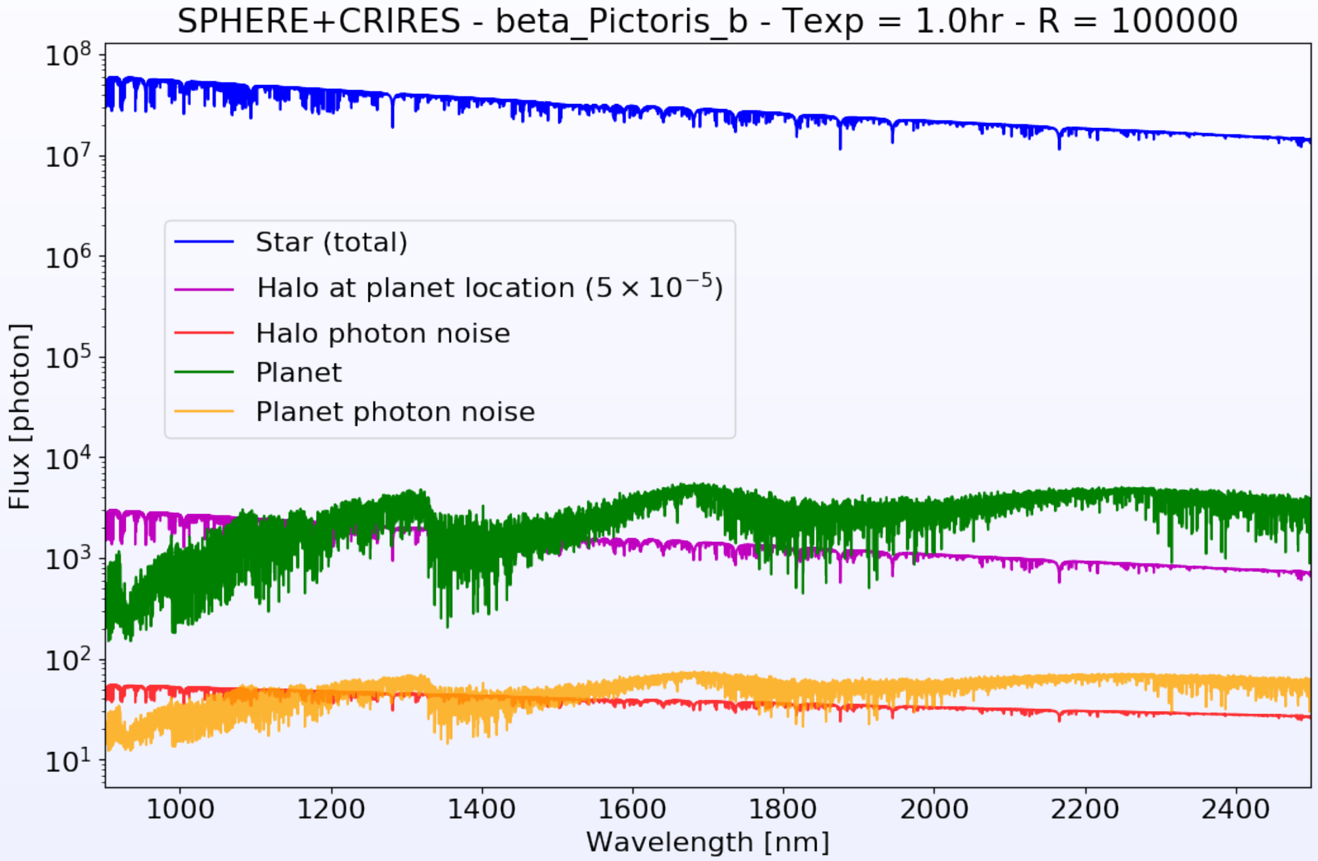


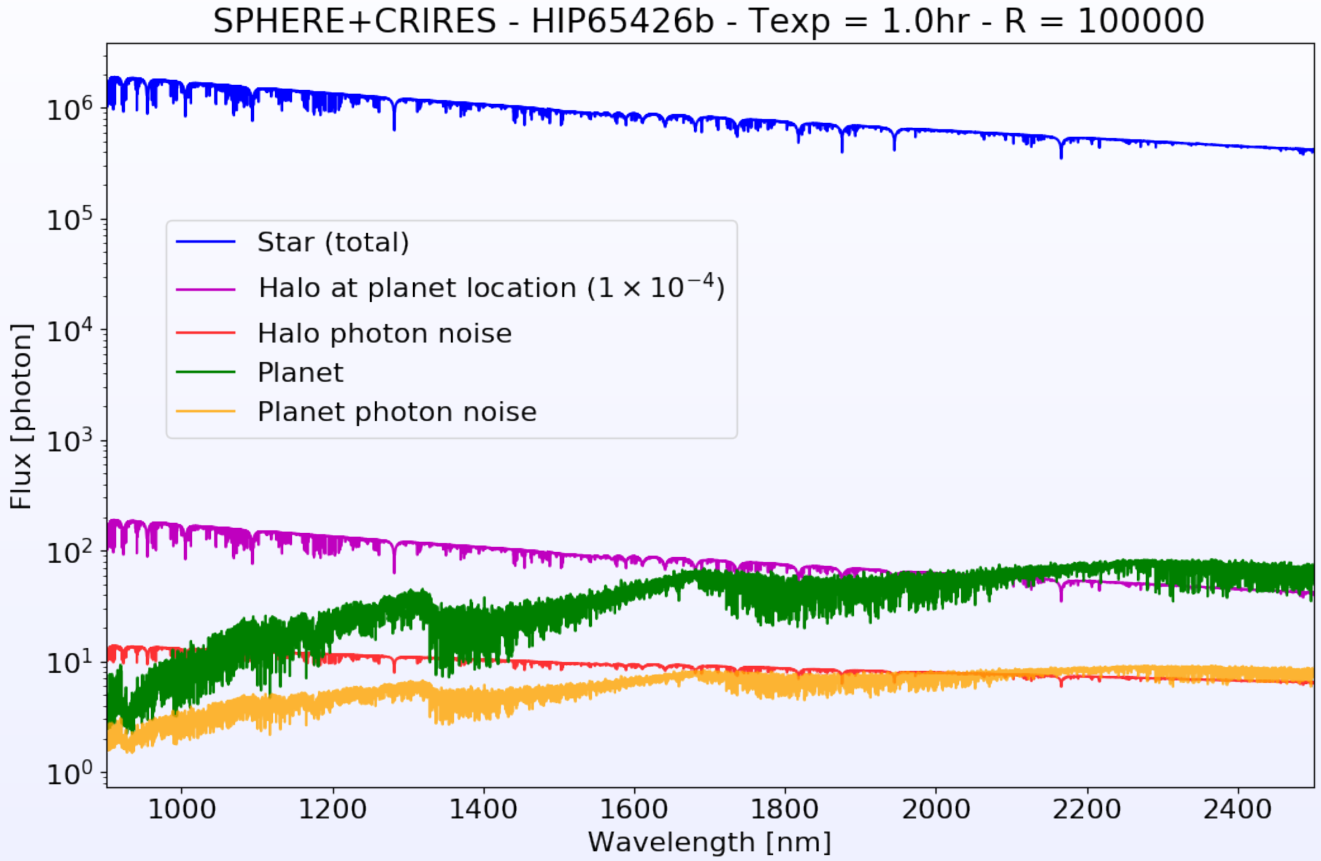


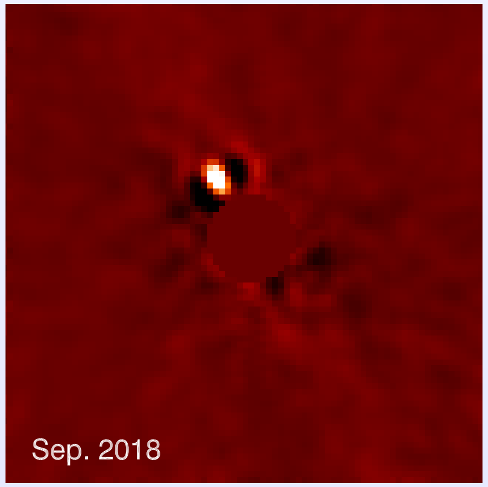
Requires R ≫ 30 000



A few numbers...

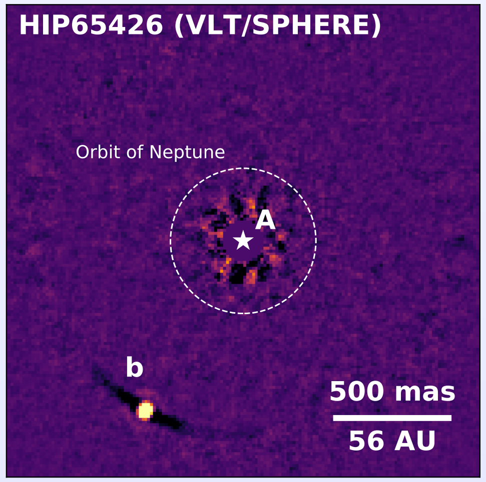






>1000 photon/channel

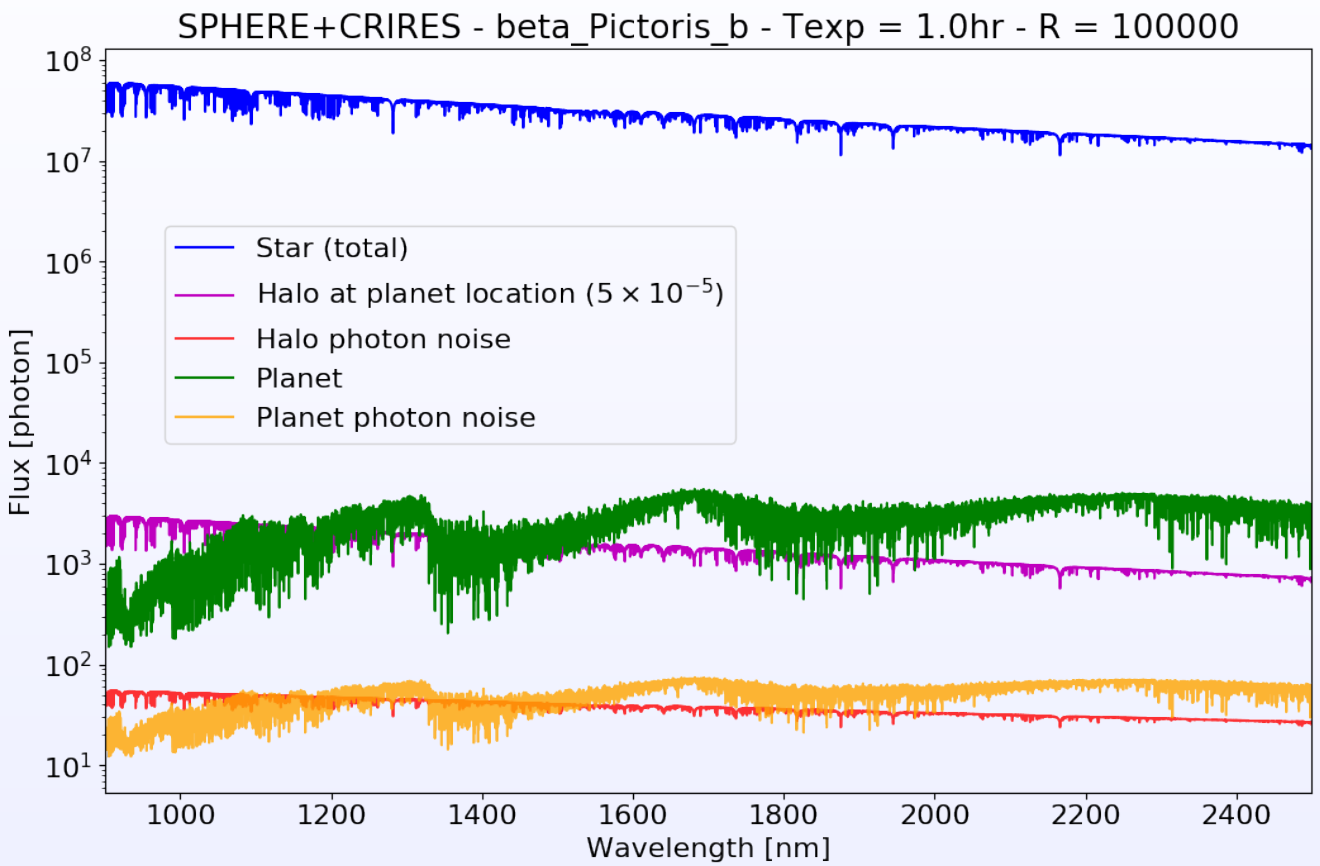
SNR > 100

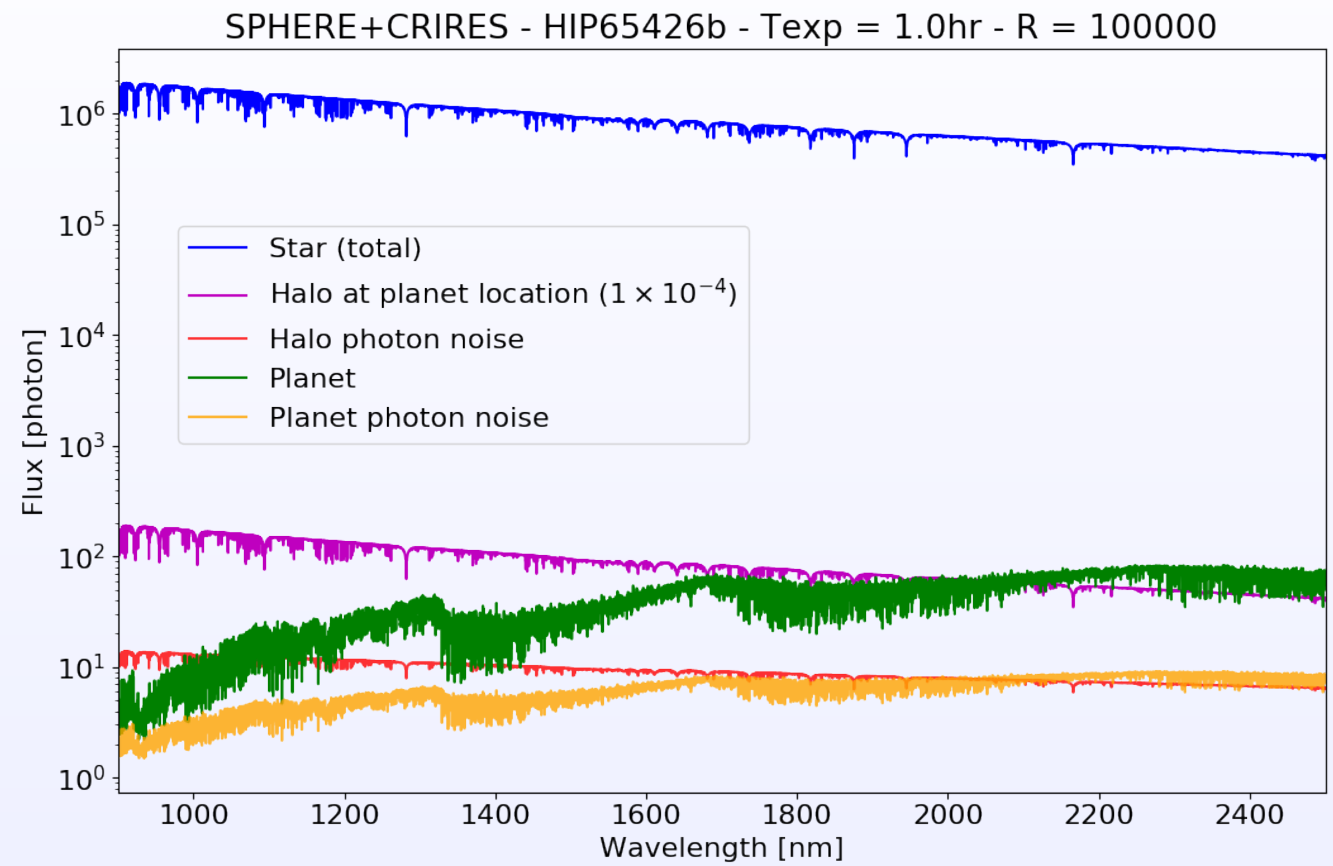


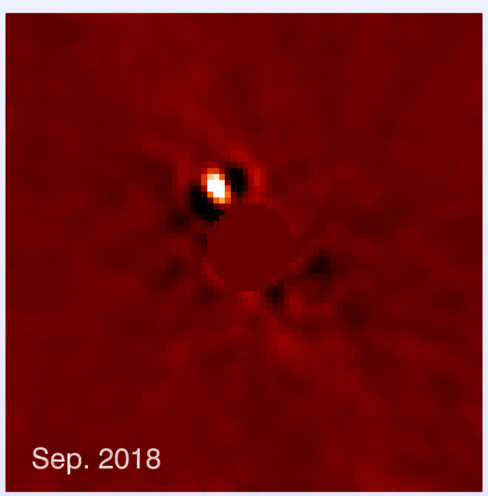
>10 photon/channel

SNR > 10

A few numbers...

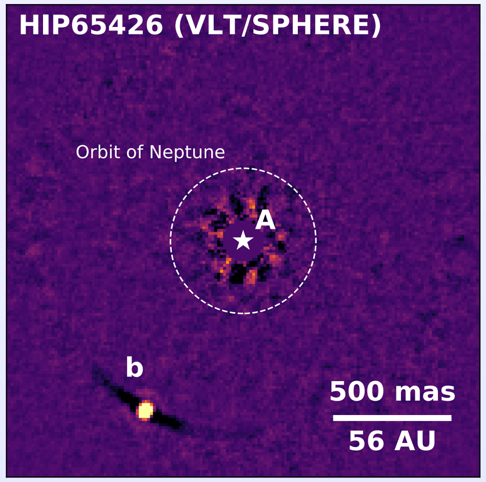






>1000 photon/channel

SNR > 100



>10 photon/channel

SNR > 10

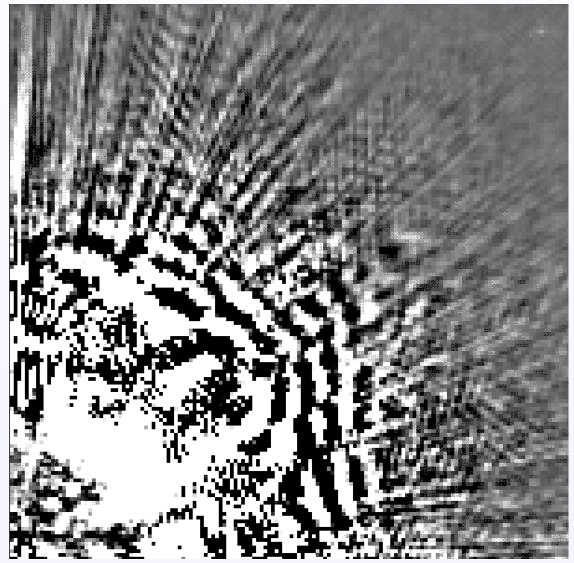
It's hard!!

Boost in detection

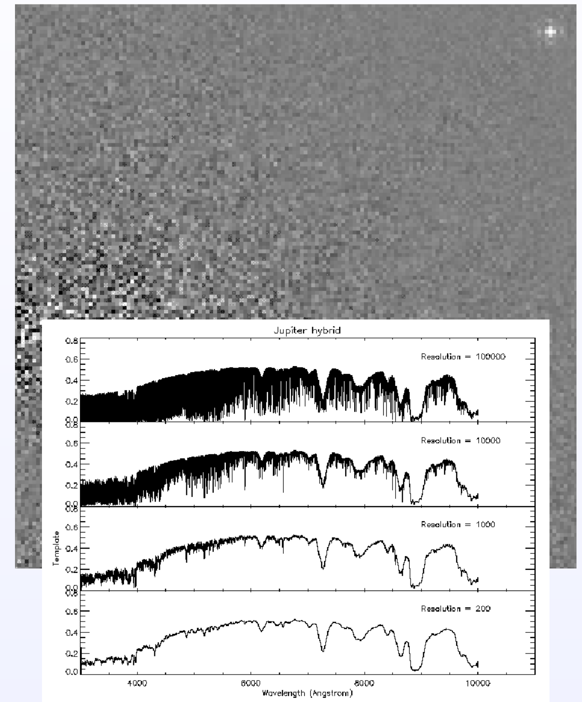
HST/ACS simulation

Sparks & Ford (2002)

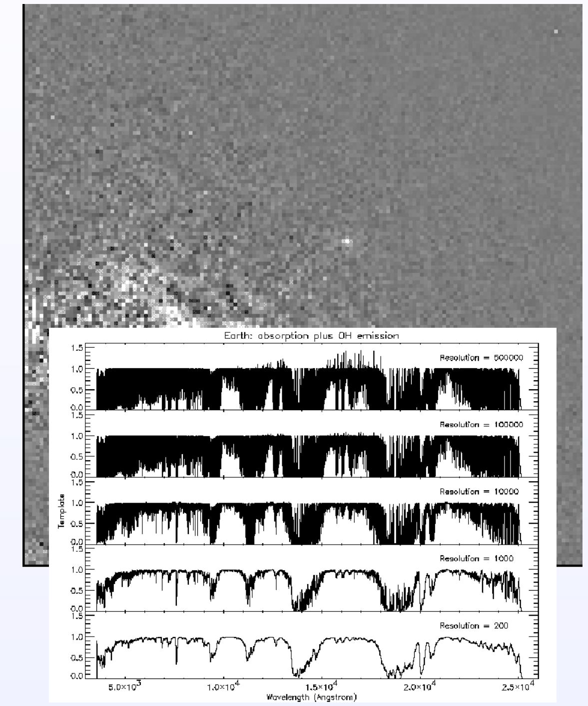
Roll-subtraction (=ADI)

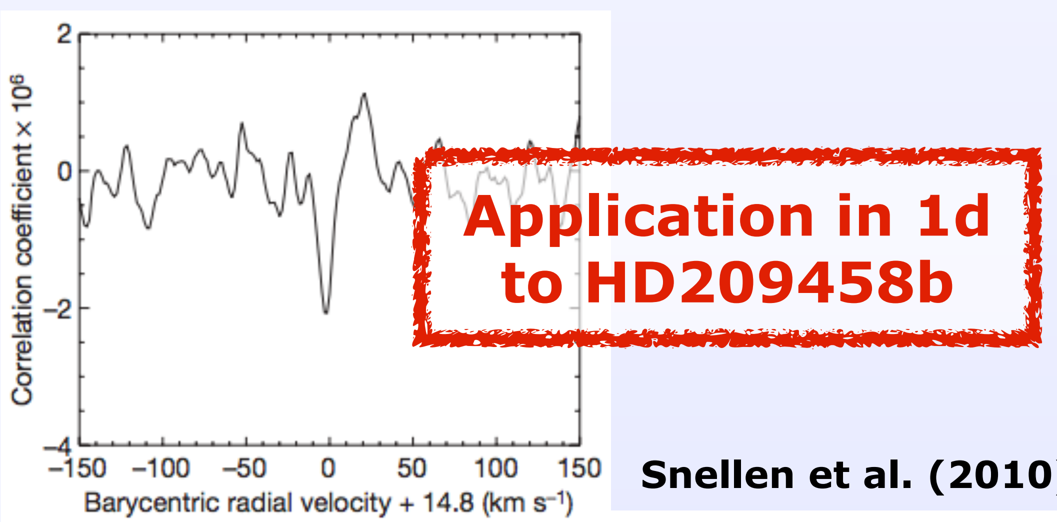


Jupiter template CCF

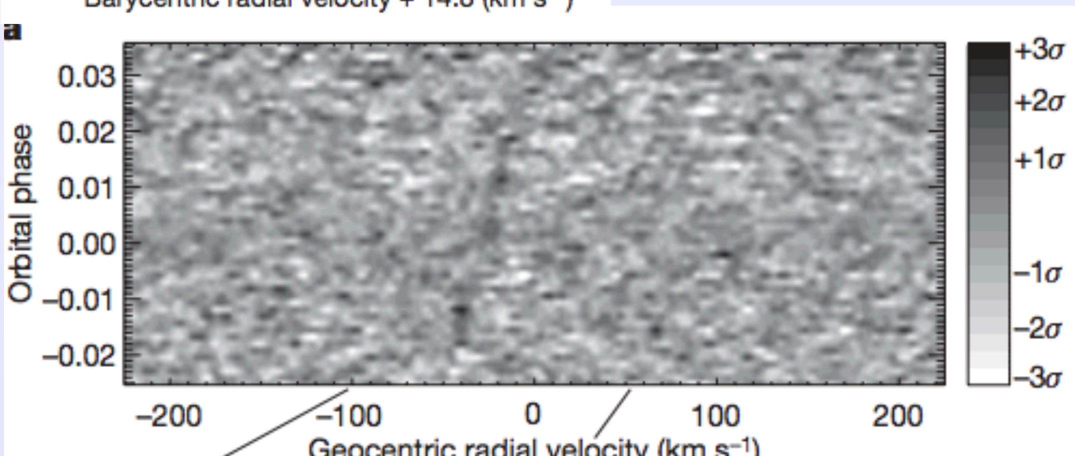


Bright Earth template CCF

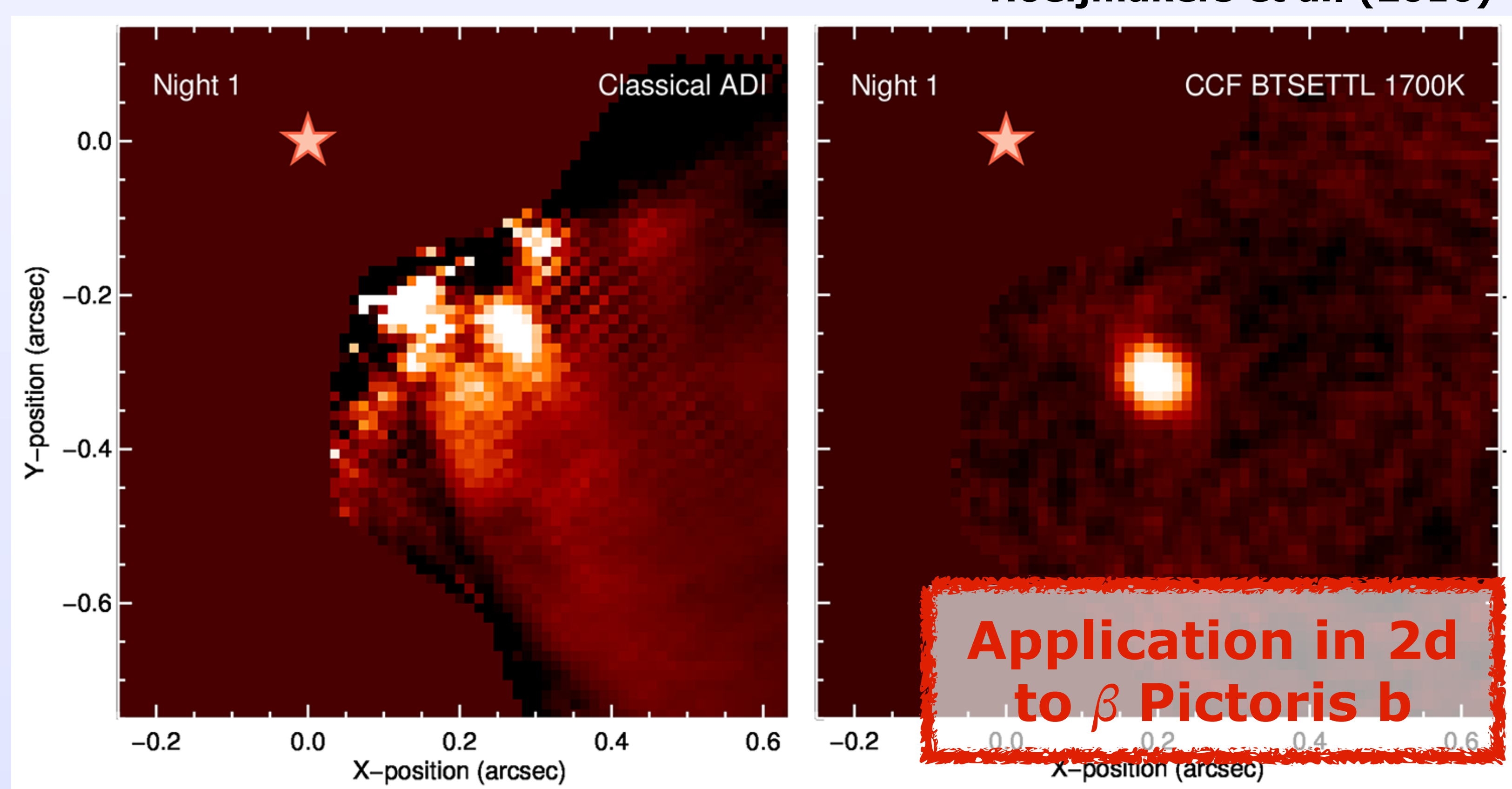




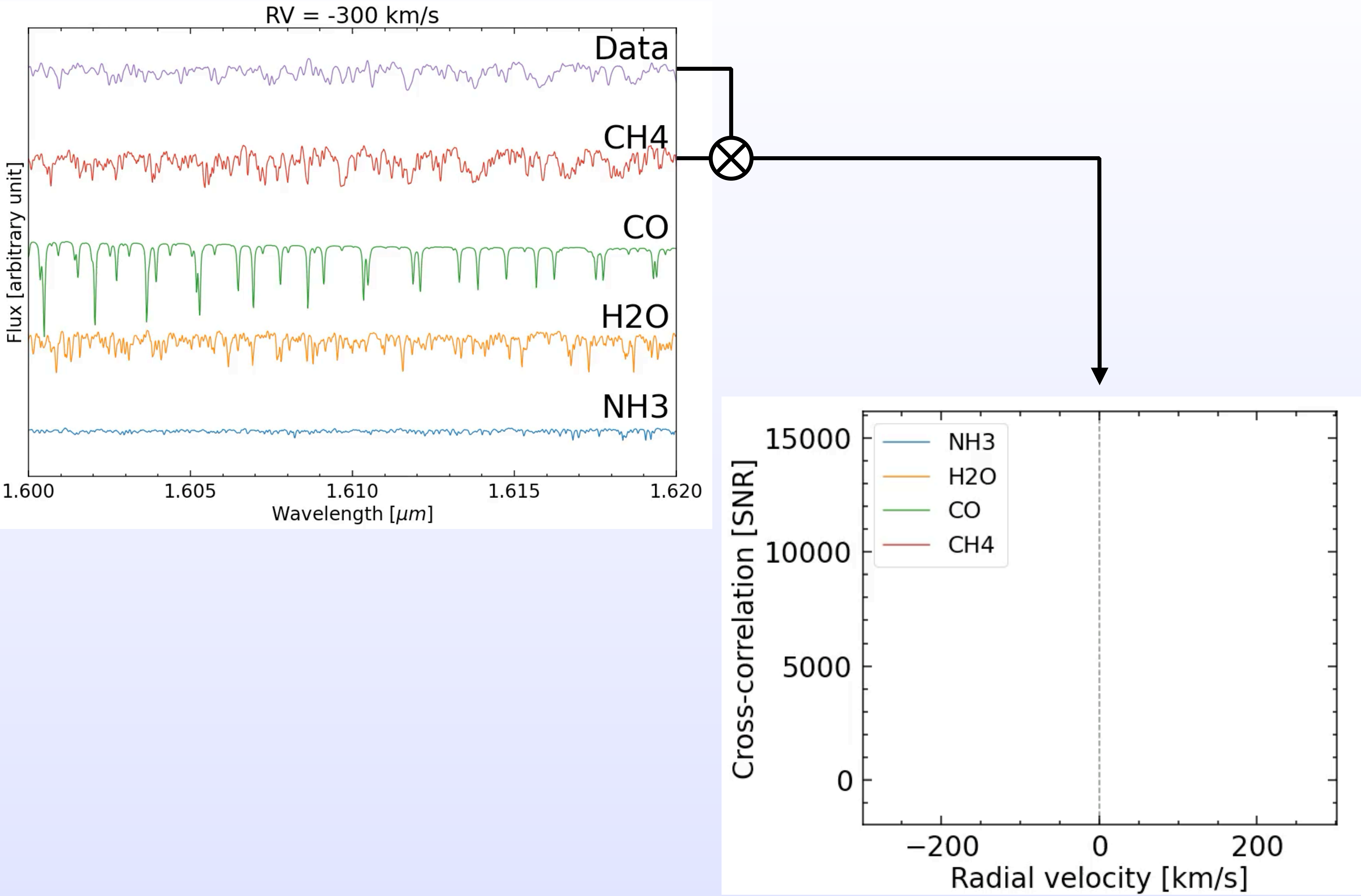
Snellen et al. (2010)



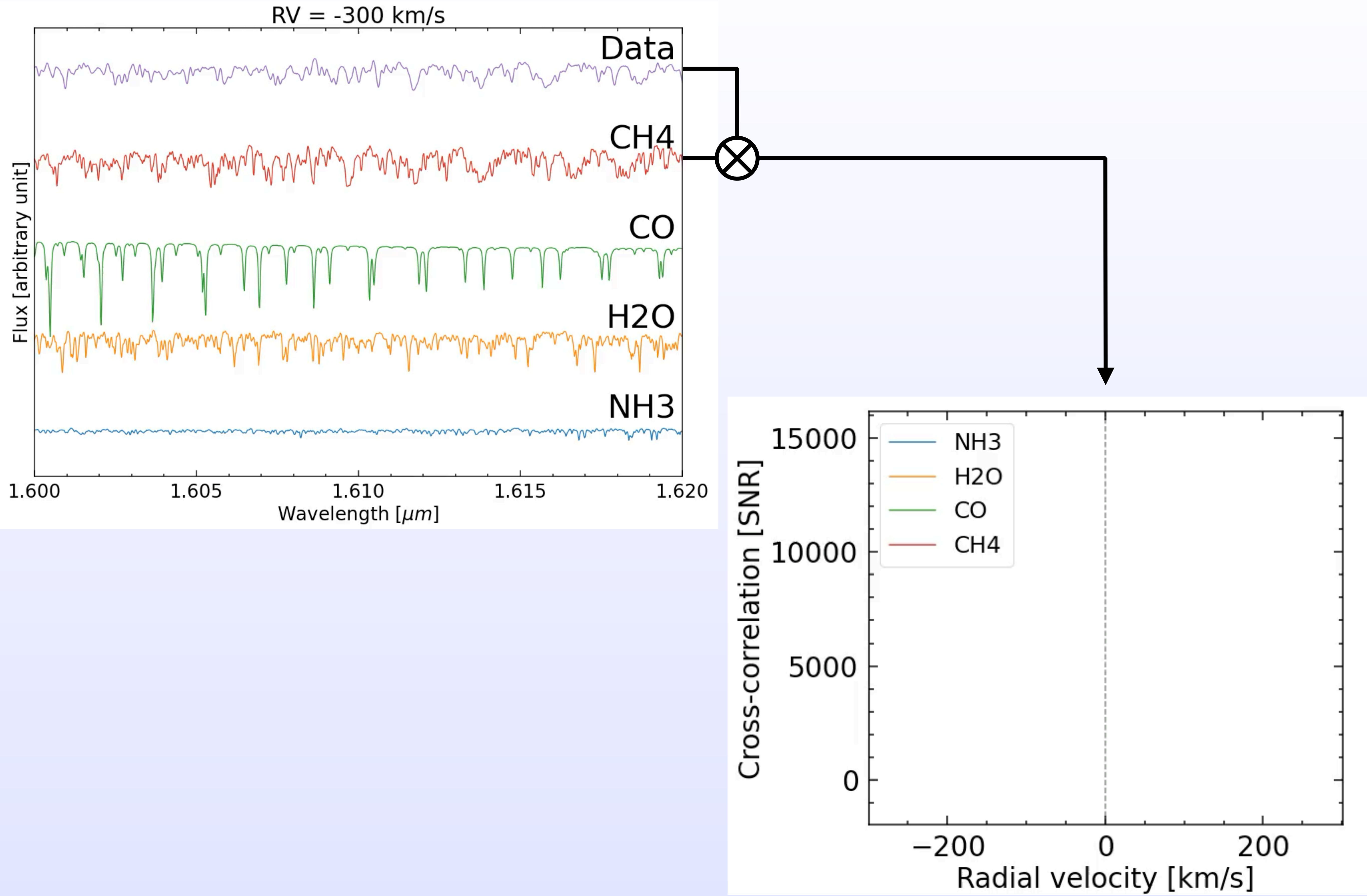
Hoeijmakers et al. (2016)



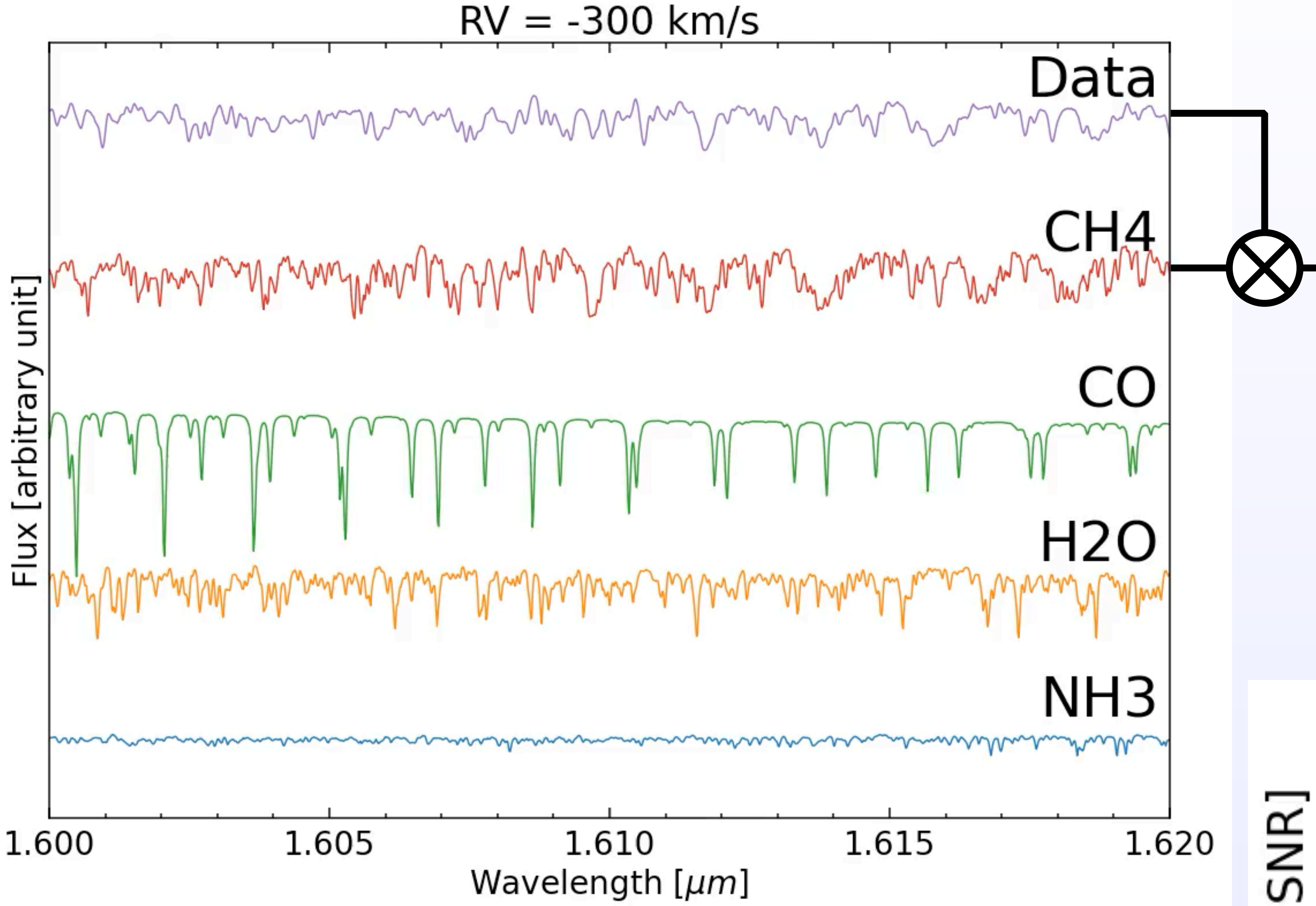
Boost in detection

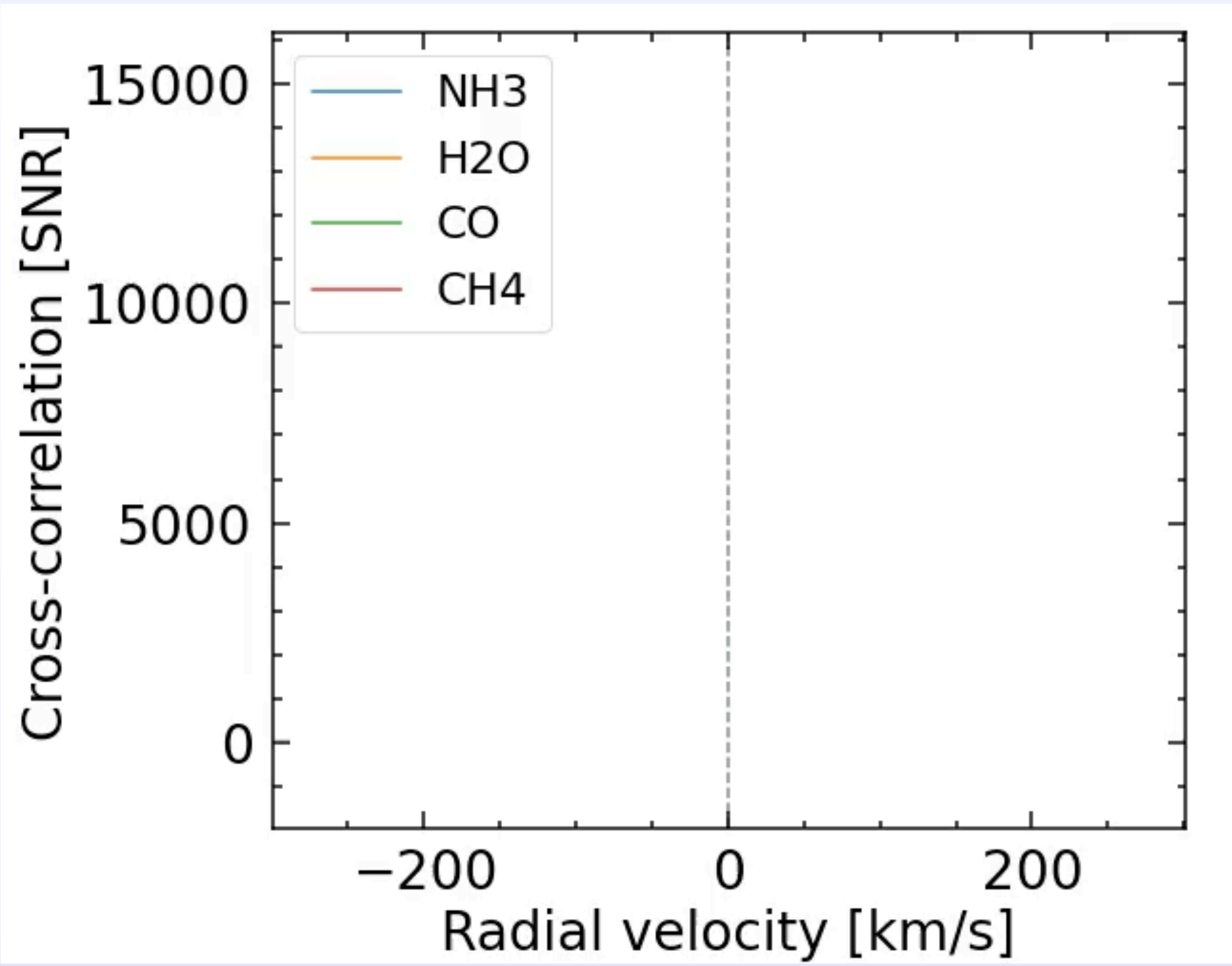


Boost in detection

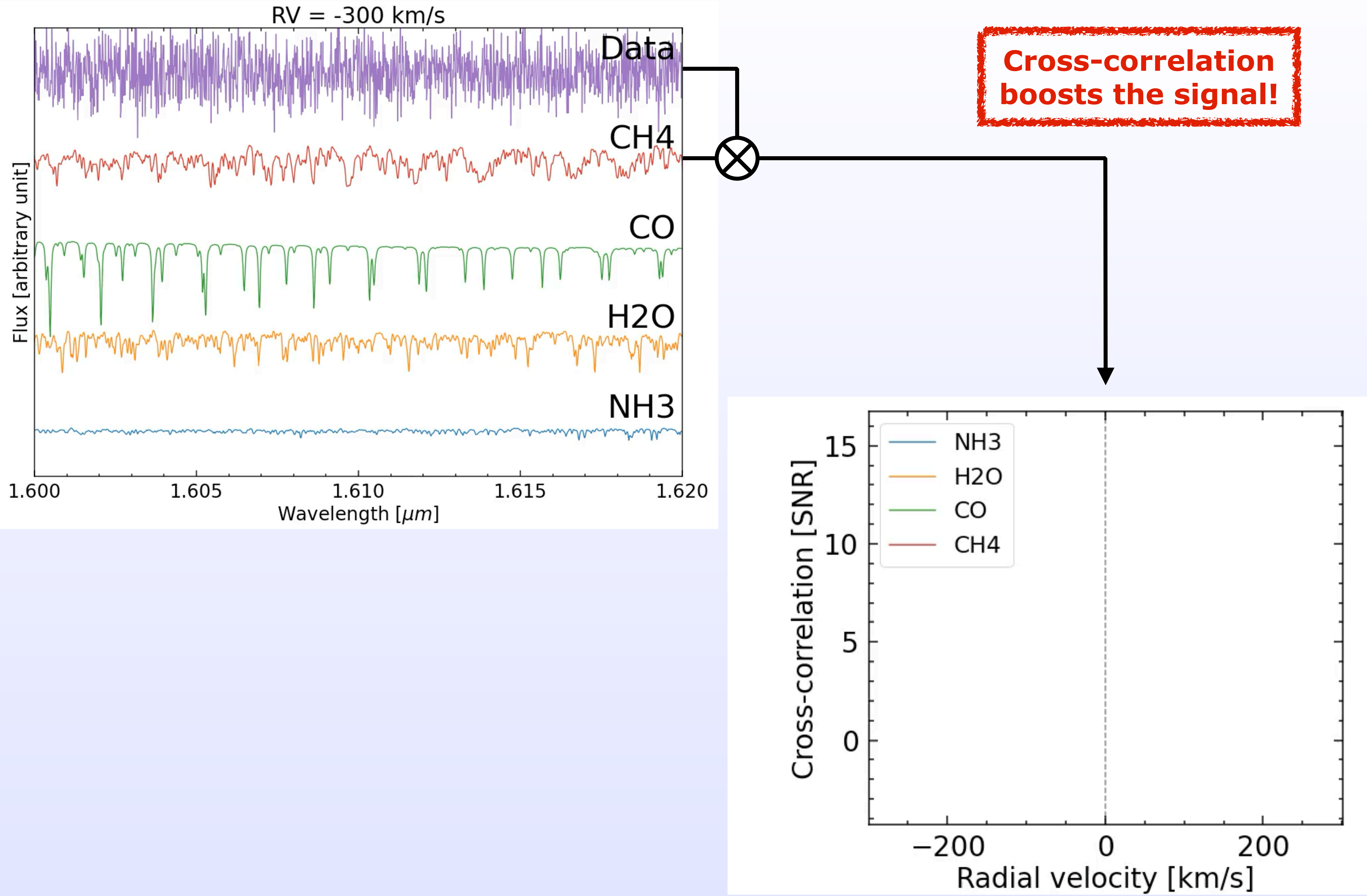


Boost in detection



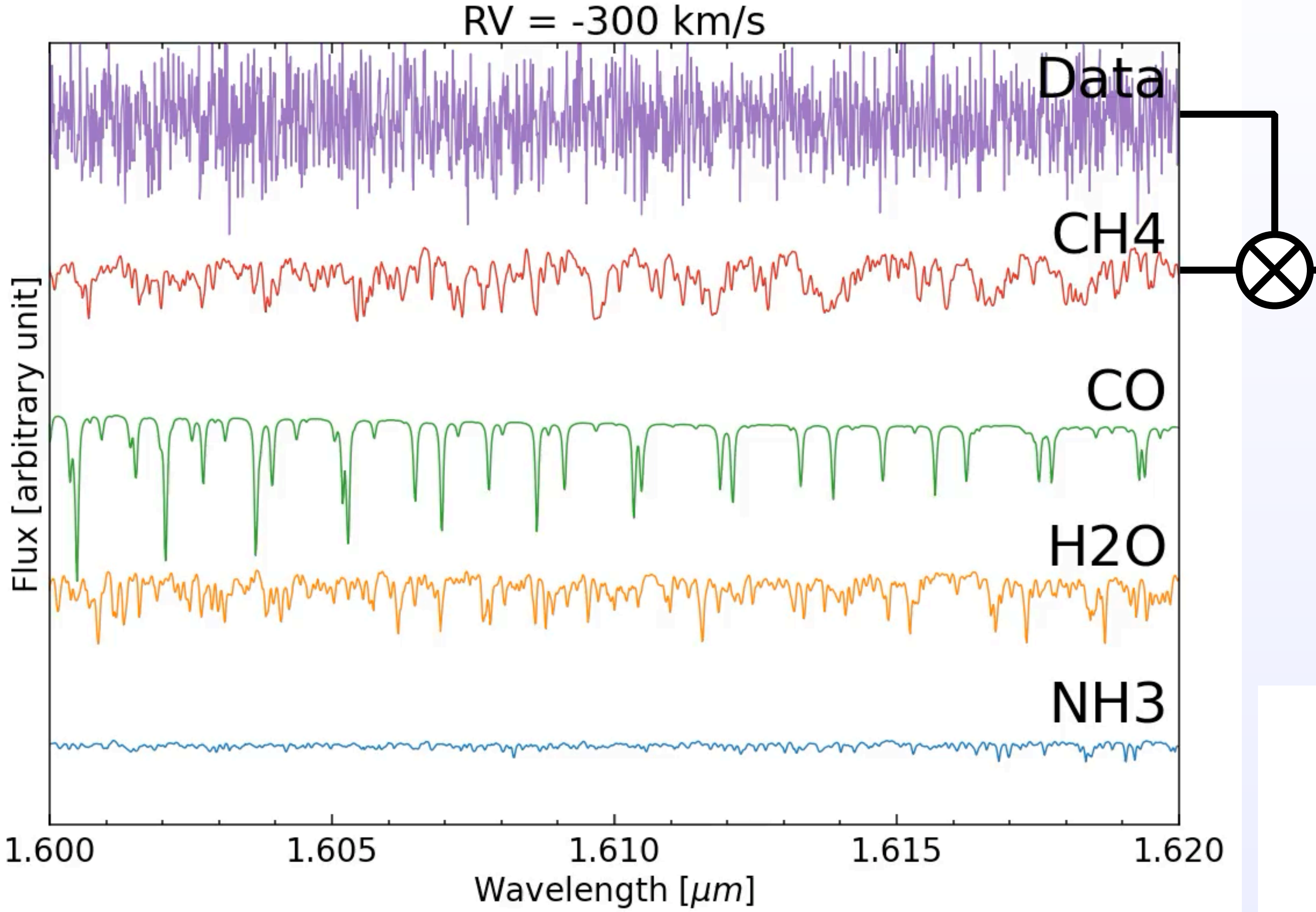


Boost in detection



Cross-correlation boosts the signal!

Boost in detection



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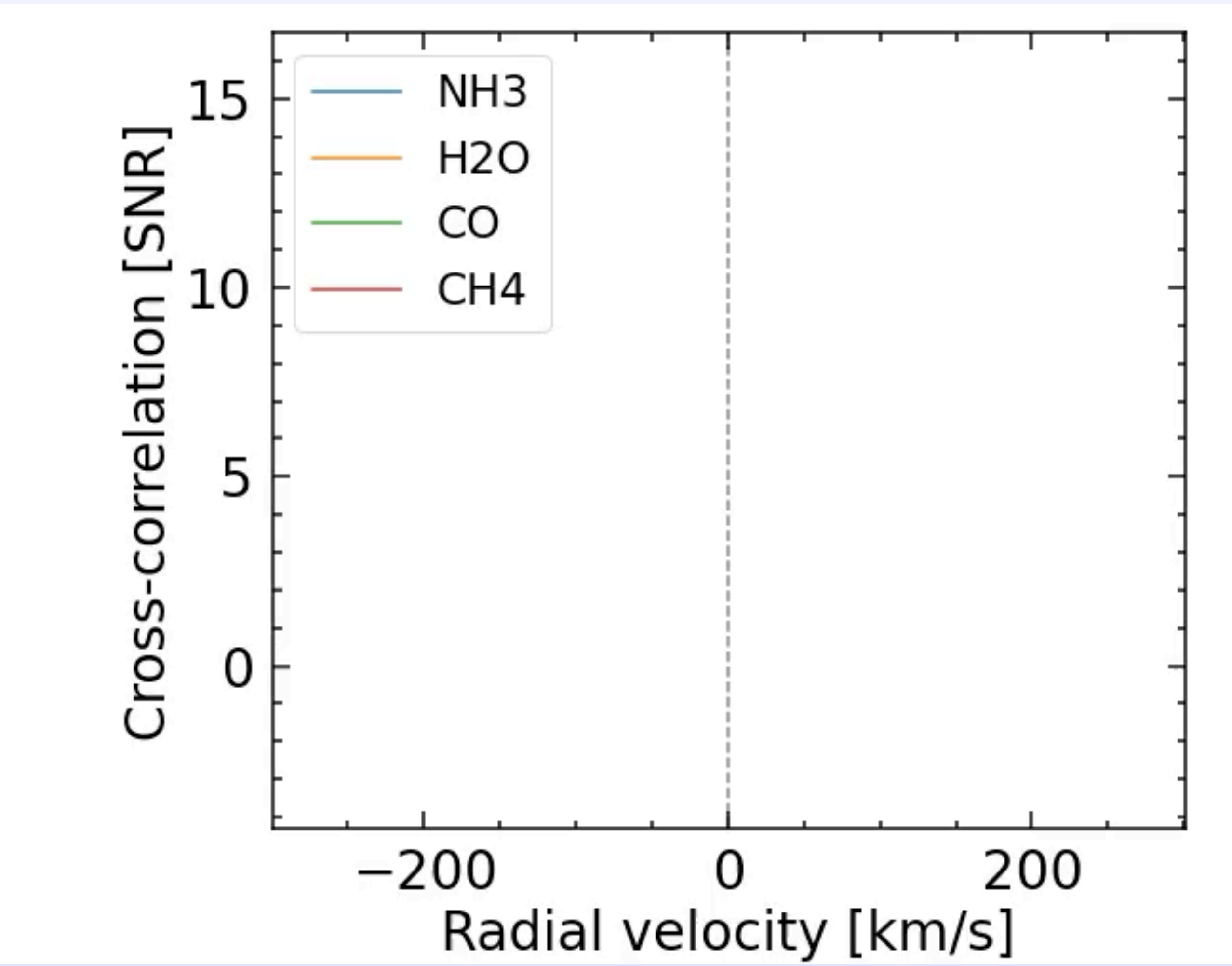
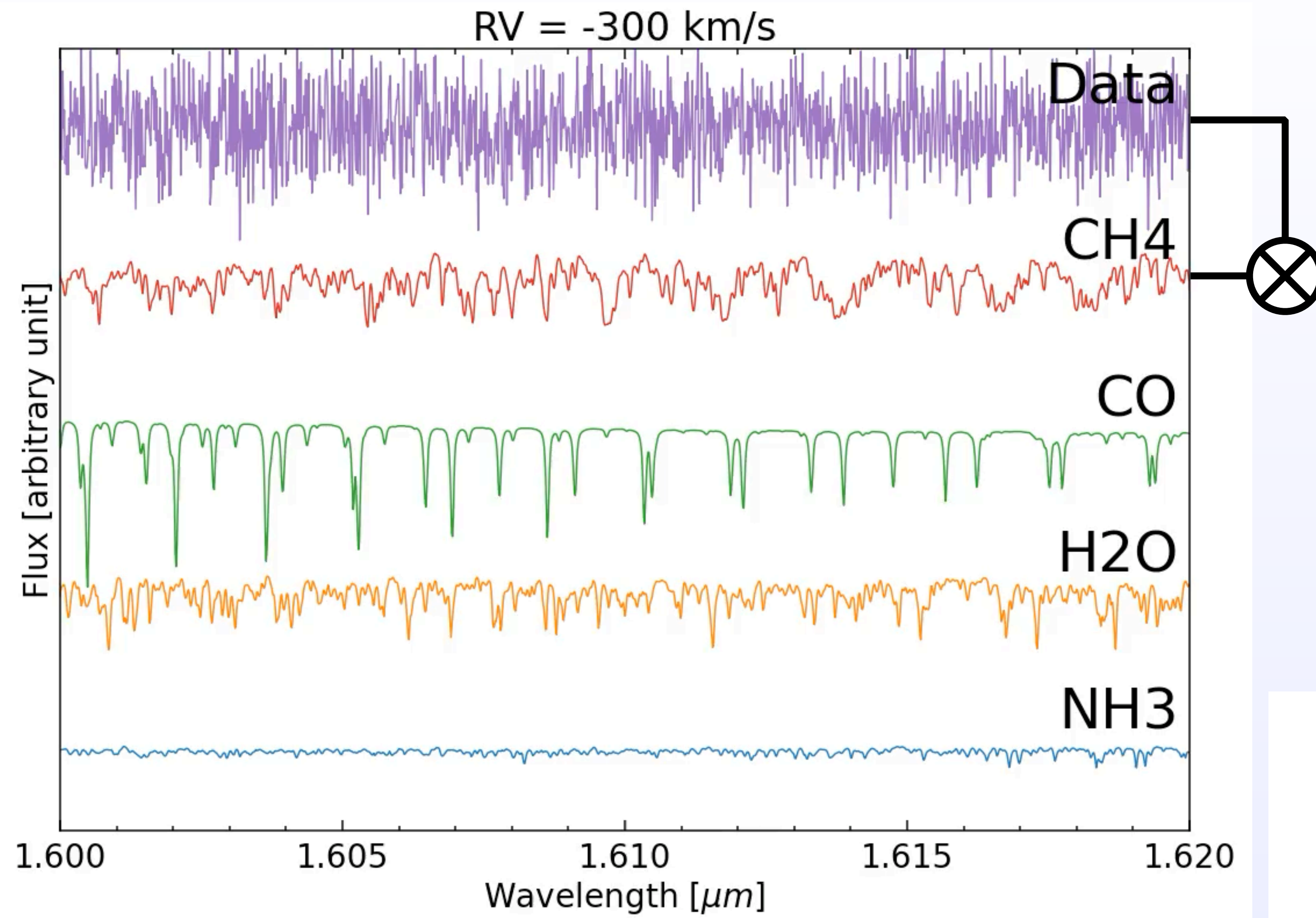


Boost in detection



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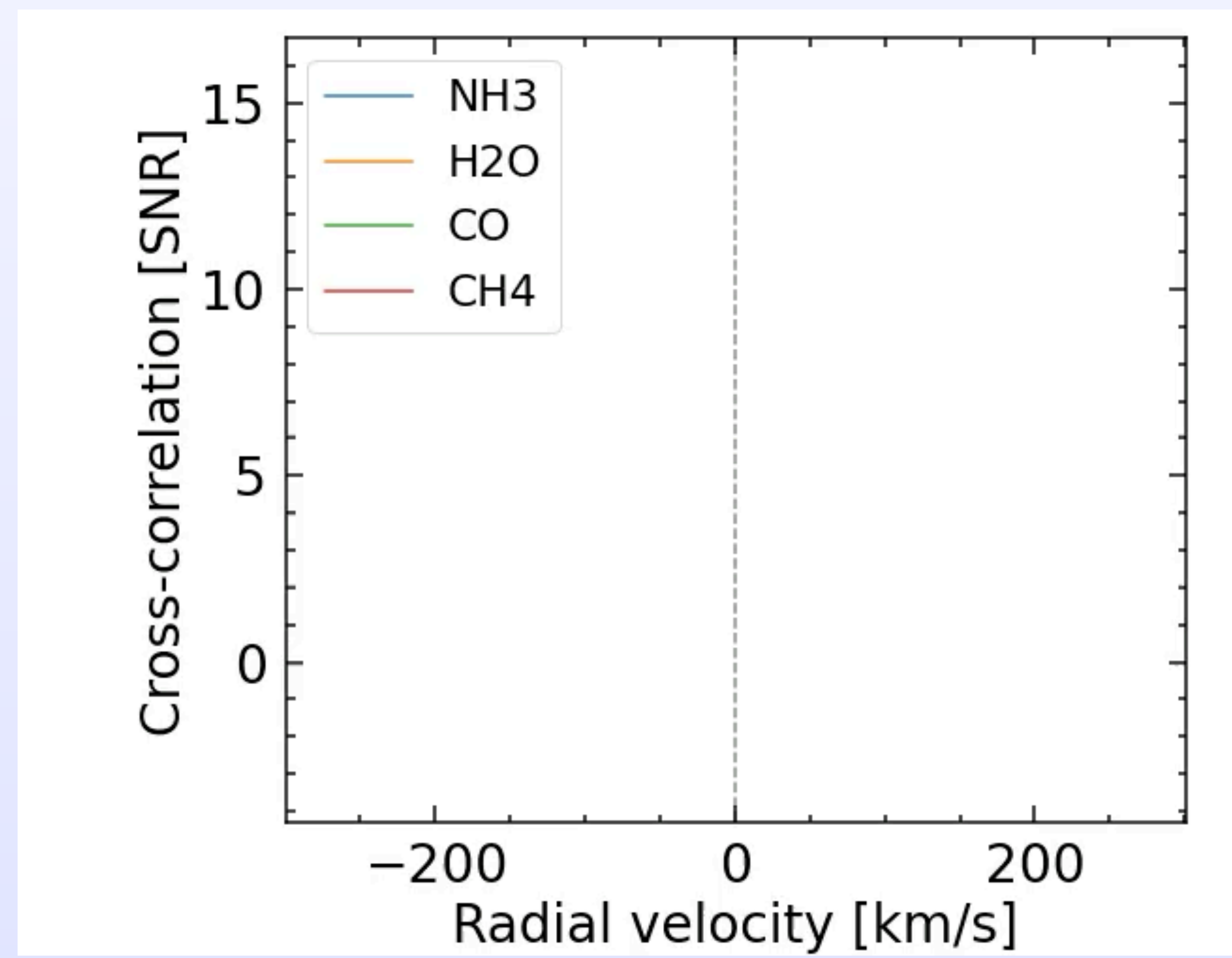
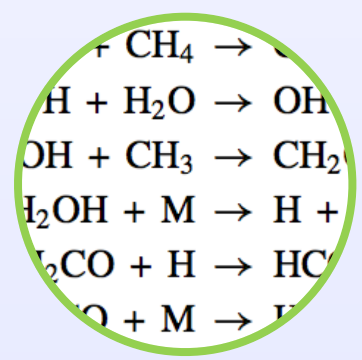


$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}} + \sigma^2_{\text{bg}} + \sigma^2_{\text{RN}} + \sigma^2_{\text{dark}}}} \sqrt{N_{\text{lines}}}$$

Snellen et al. (2015)

Exoplanet science at high resolution

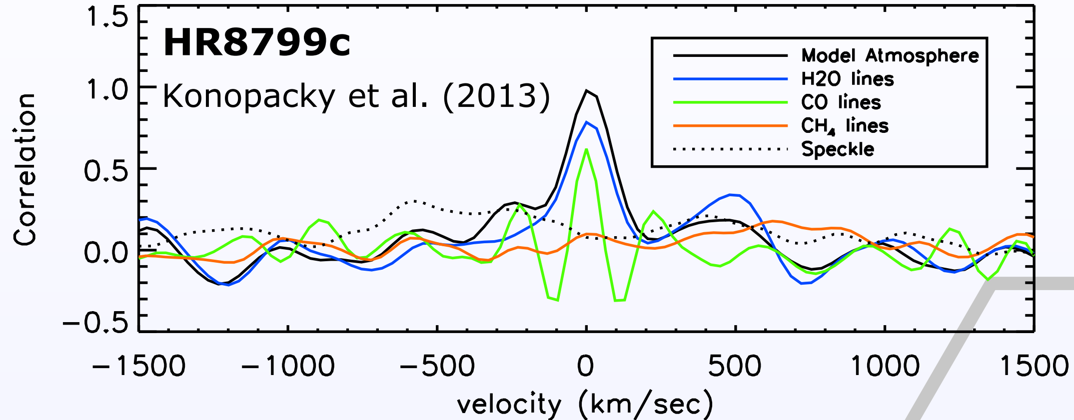
Formation,
migration & evolution



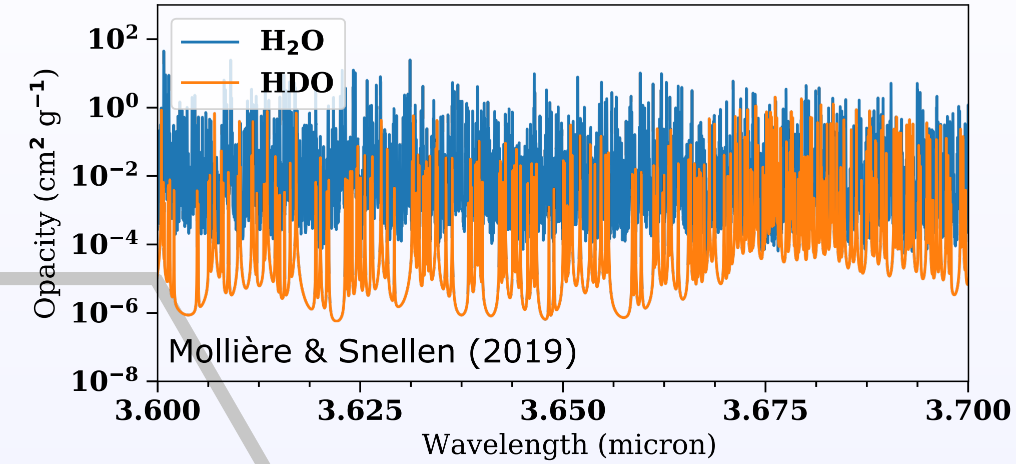
Atmospheric
chemistry & dynamics

Exoplanet science at high resolution

Molecules detection

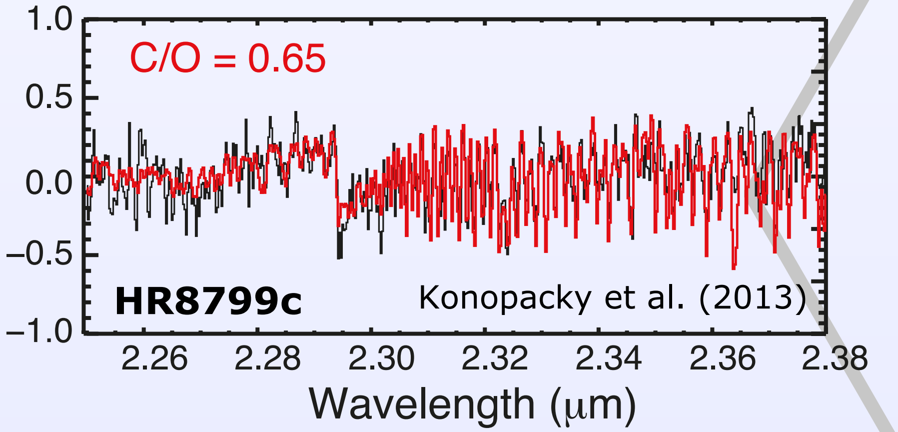


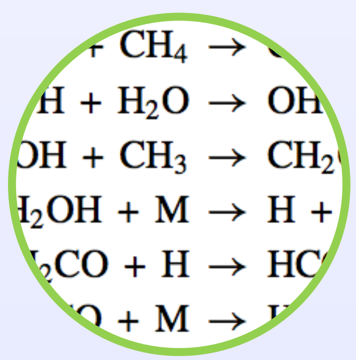
Isotopologues detection



Formation, migration & evolution

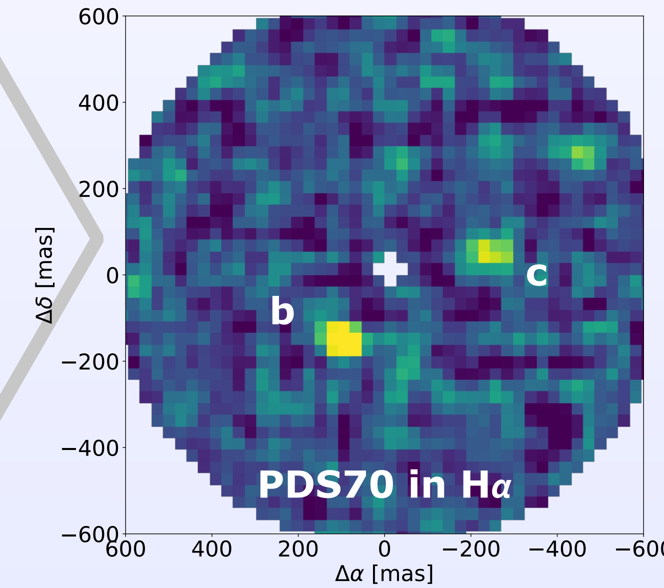
Abundances determination



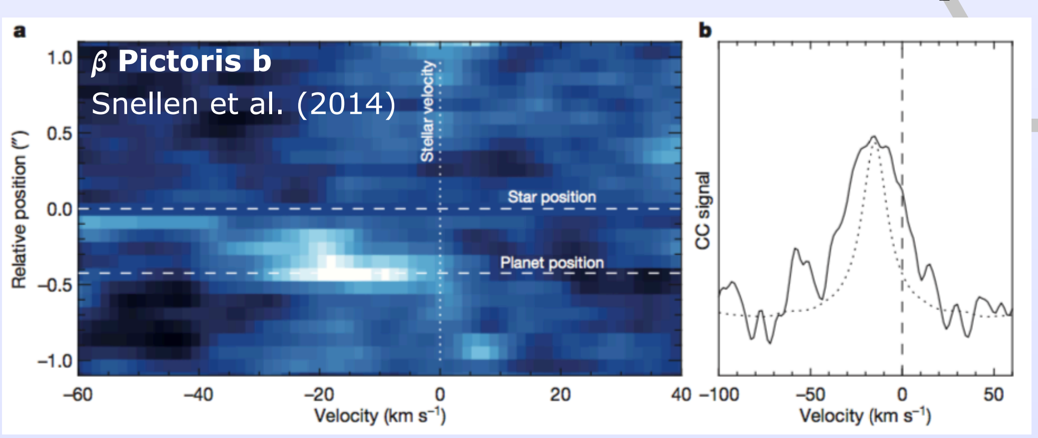


Atmospheric chemistry & dynamics

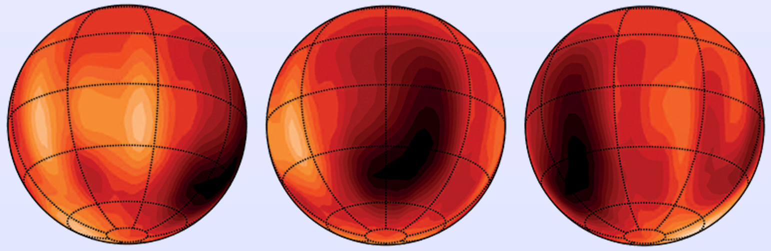
Accretion lines



Orbital and rotational velocity

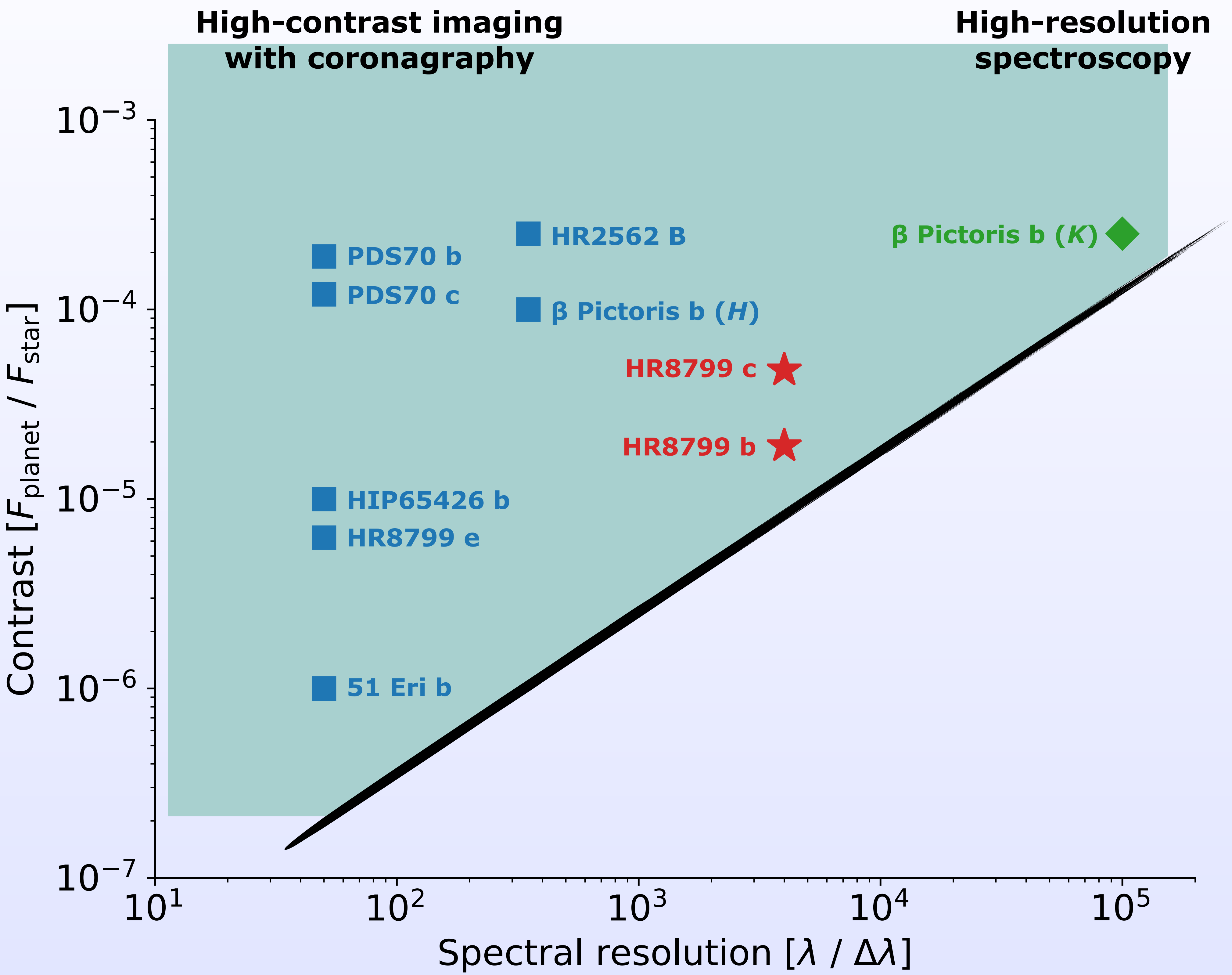


Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR



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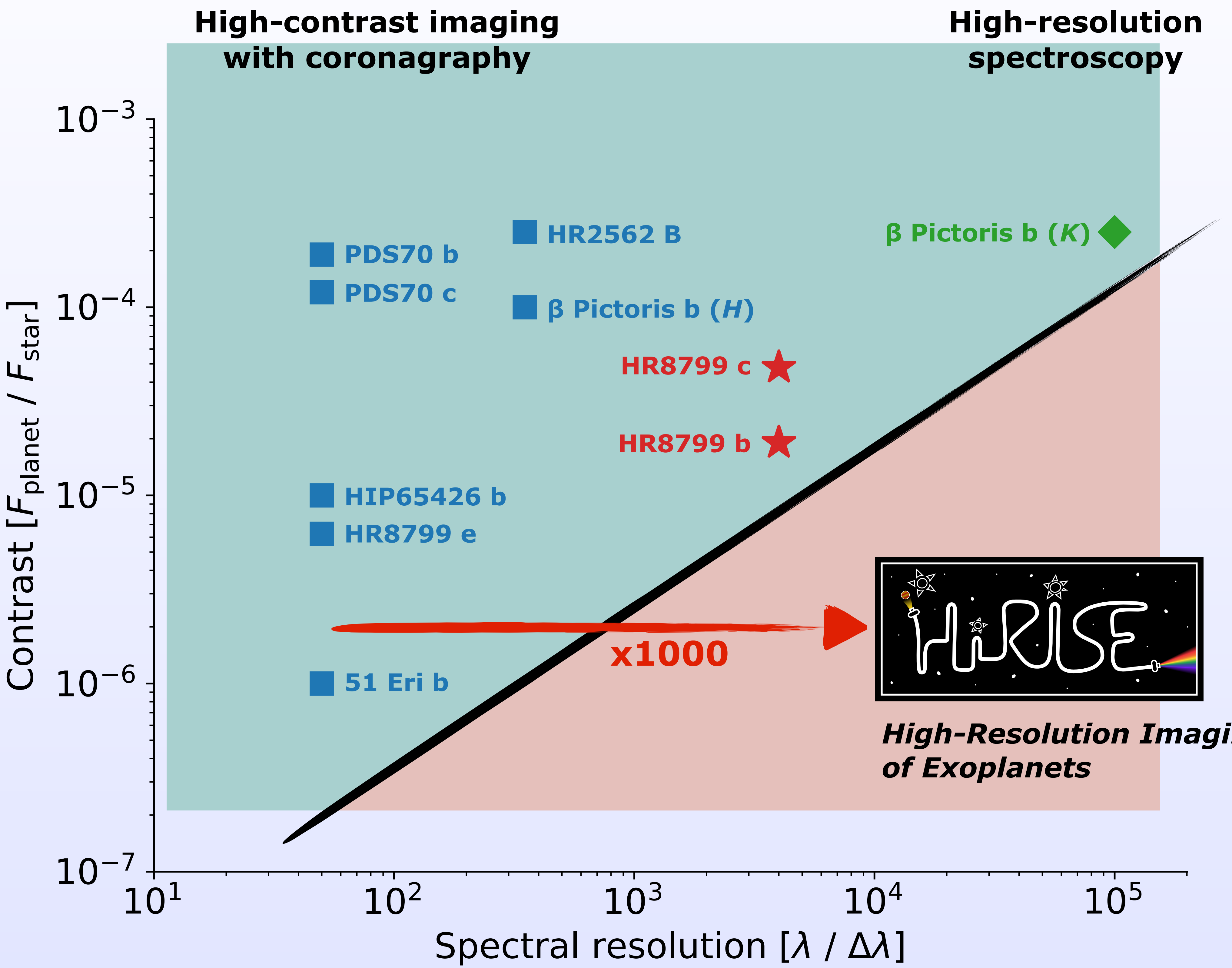
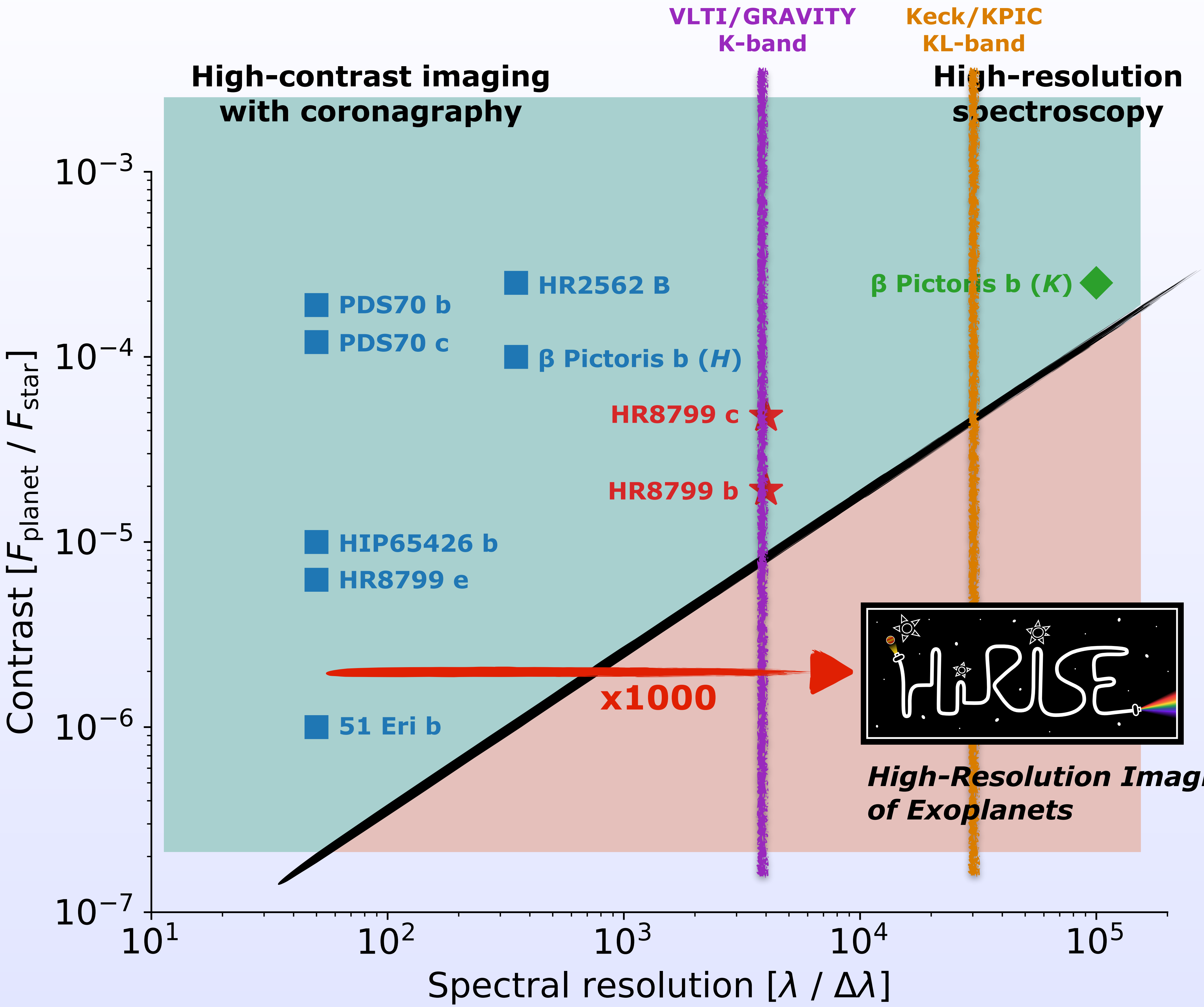


High-Resolution Imaging and Spectroscopy of Exoplanets

Young exoplanets characterisation in near-IR



Characterisation

15-20 companions already known at

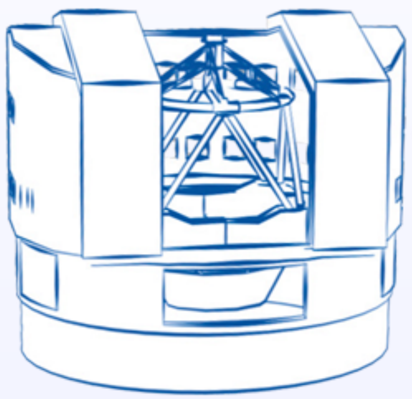
- **separation < 1"**
- **contrast < 10^{-4}**

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

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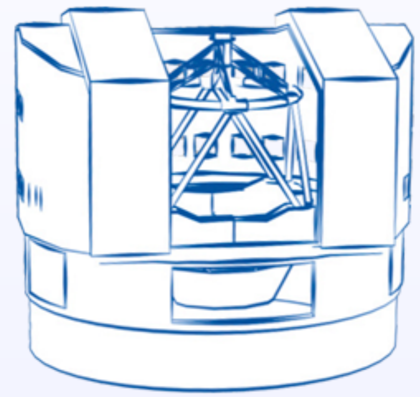

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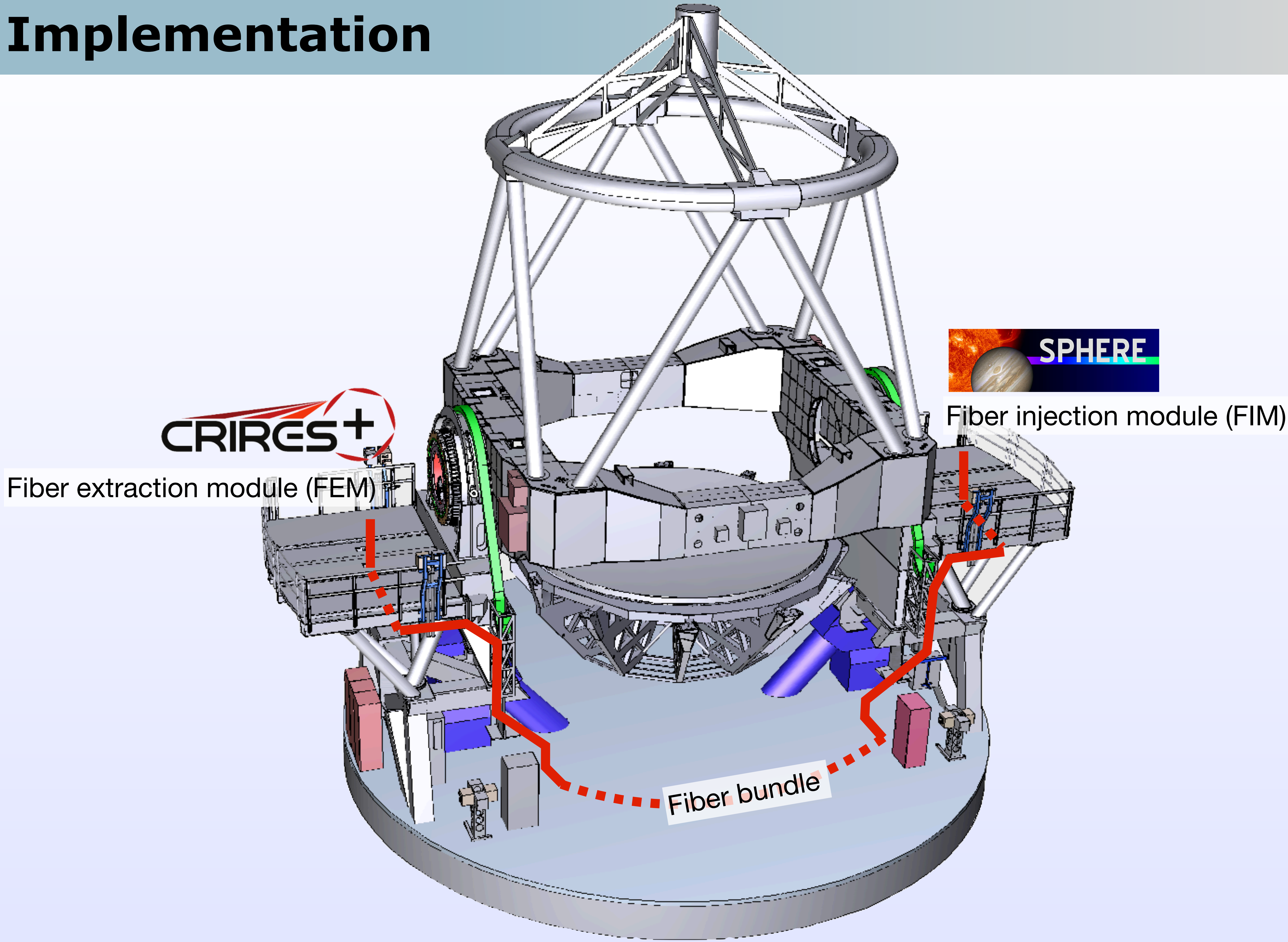
Fiber coupling

HiRISE

Implementation



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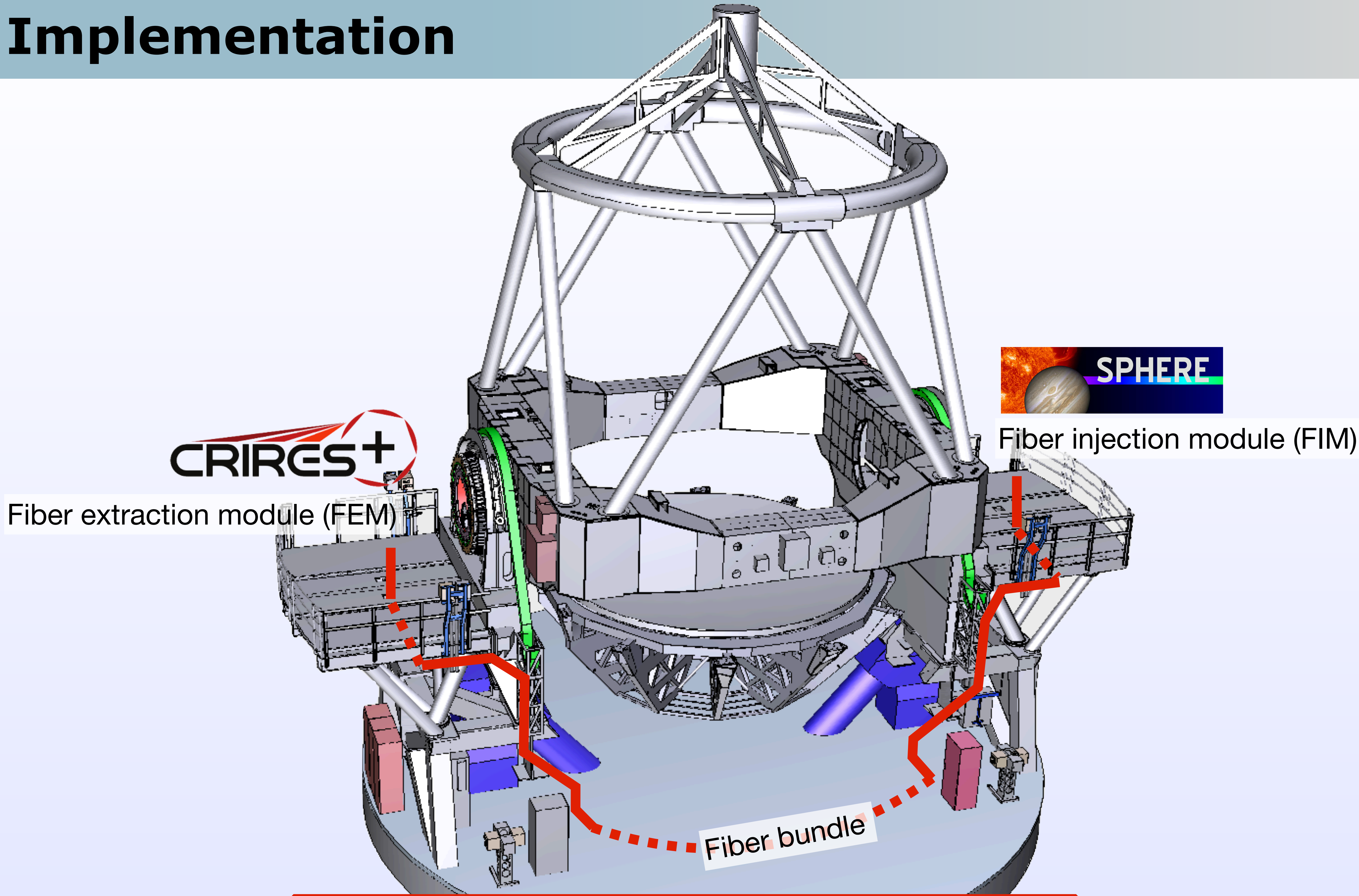


Is it really worth it?

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

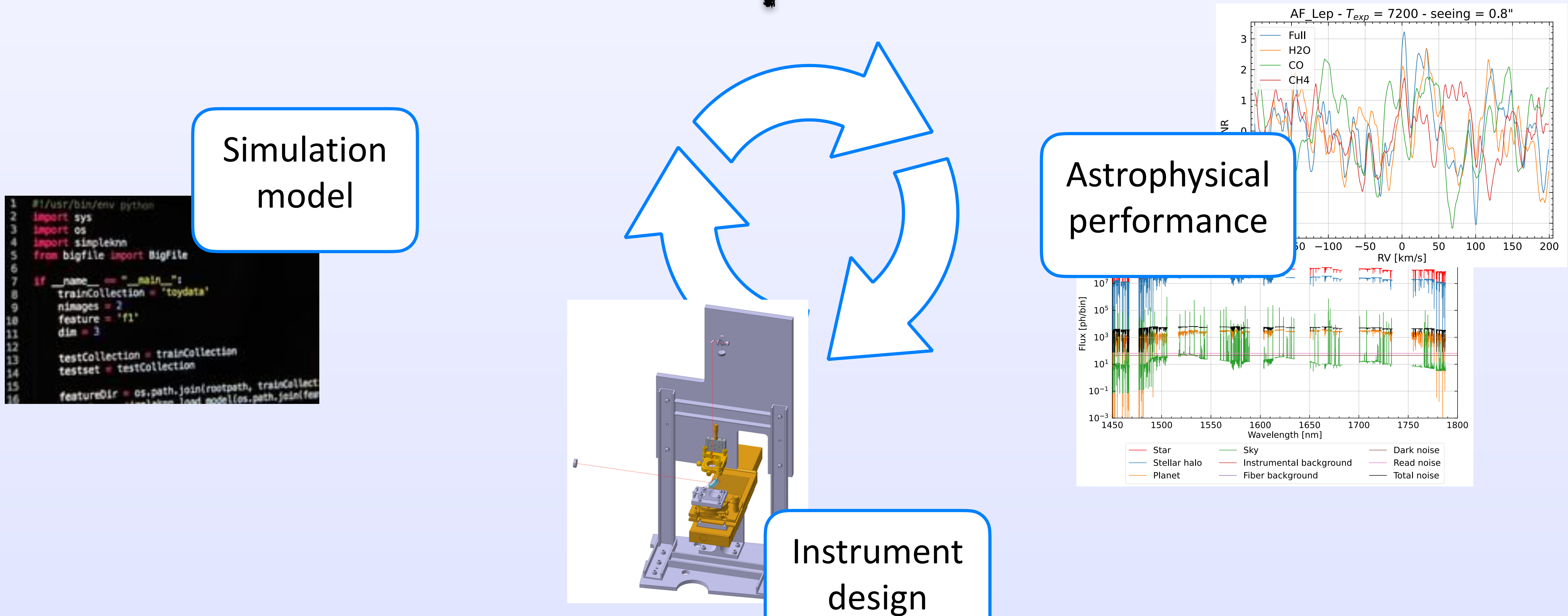
Technical requirements

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



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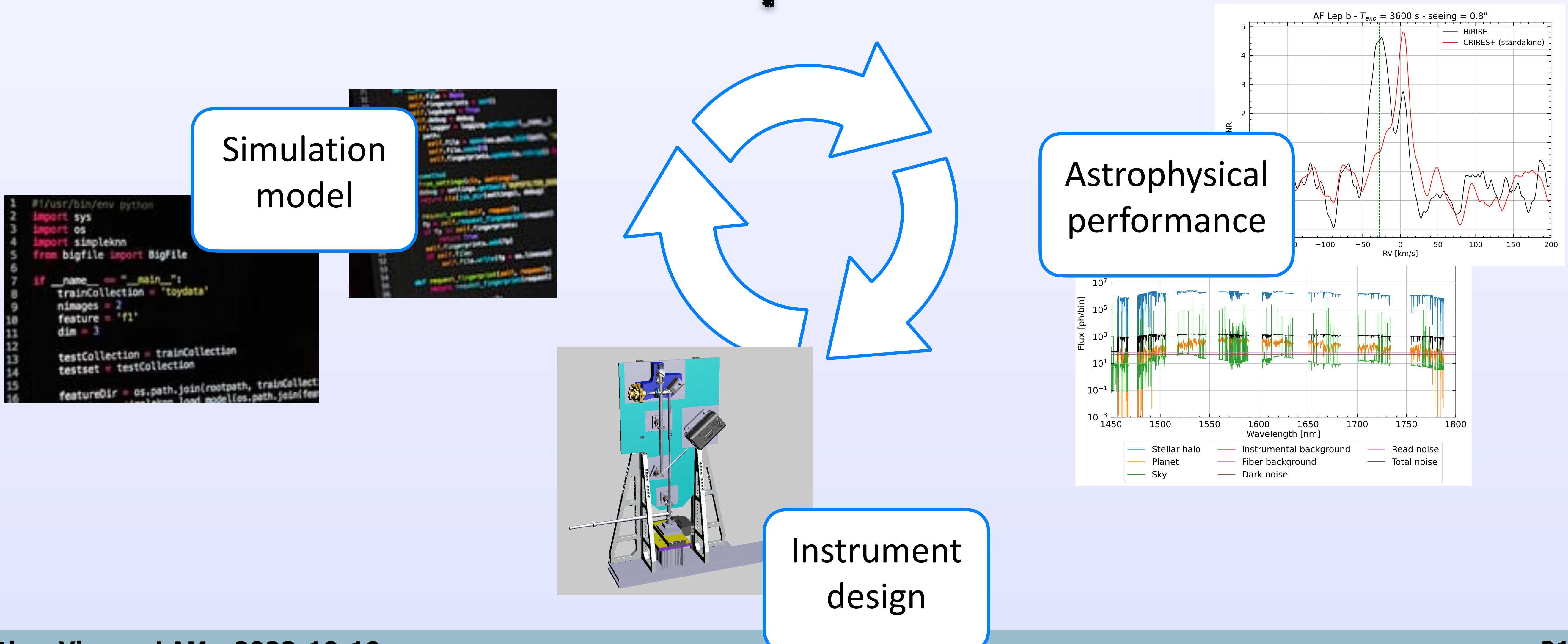

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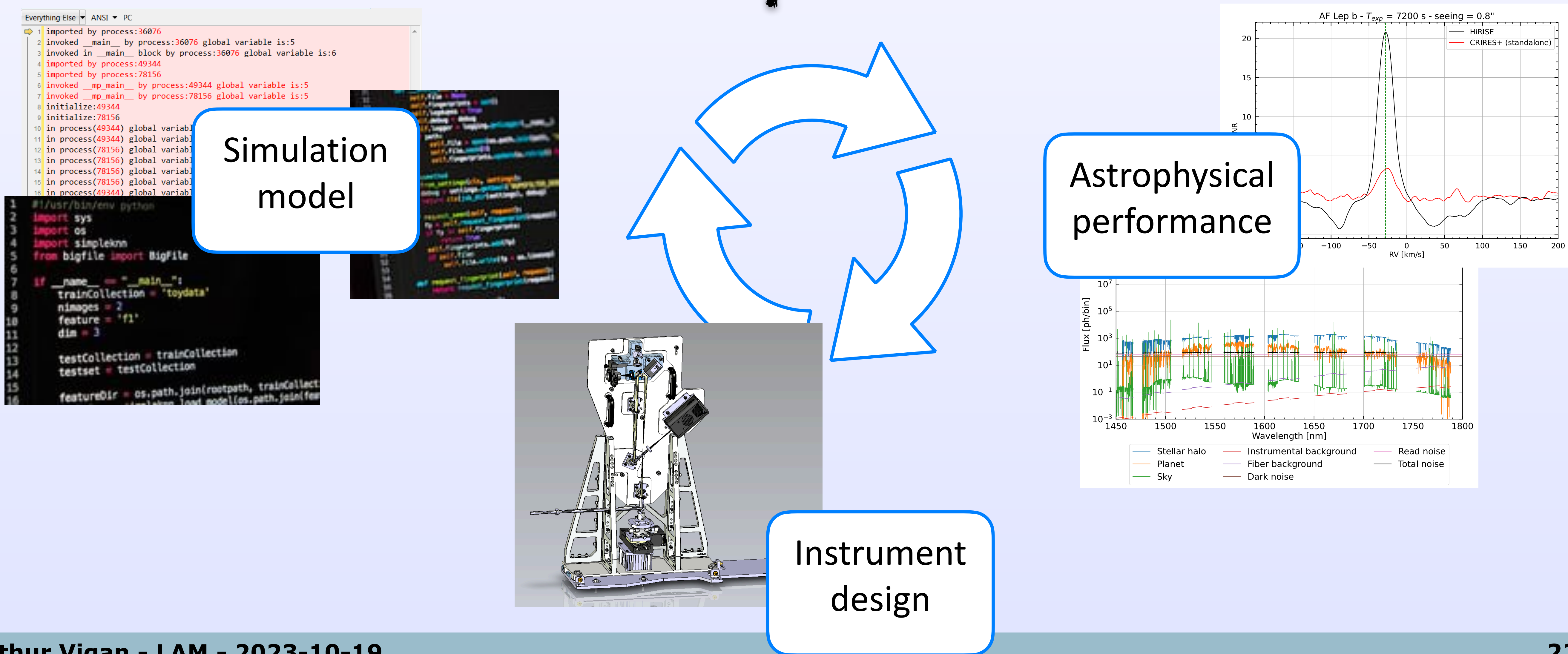
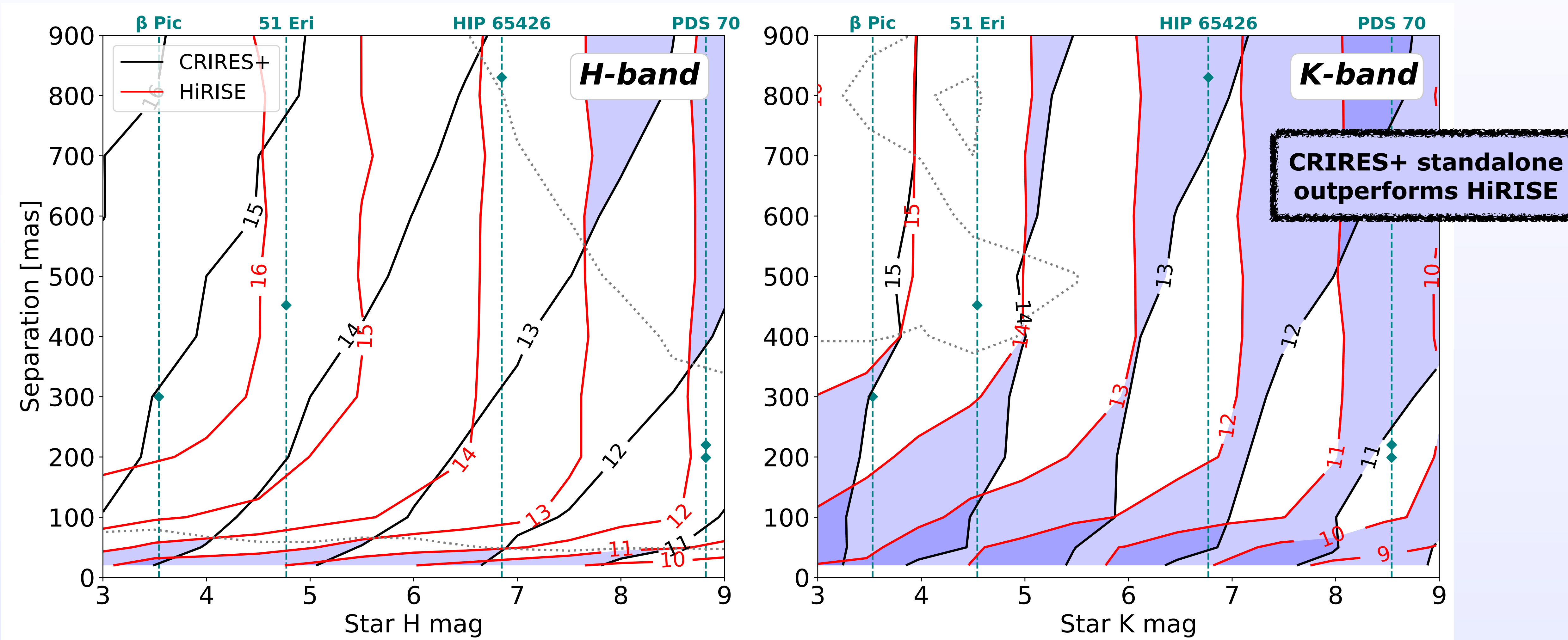
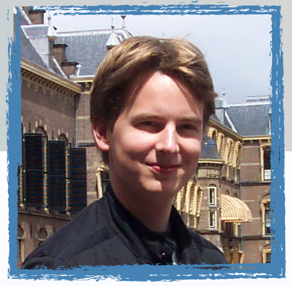


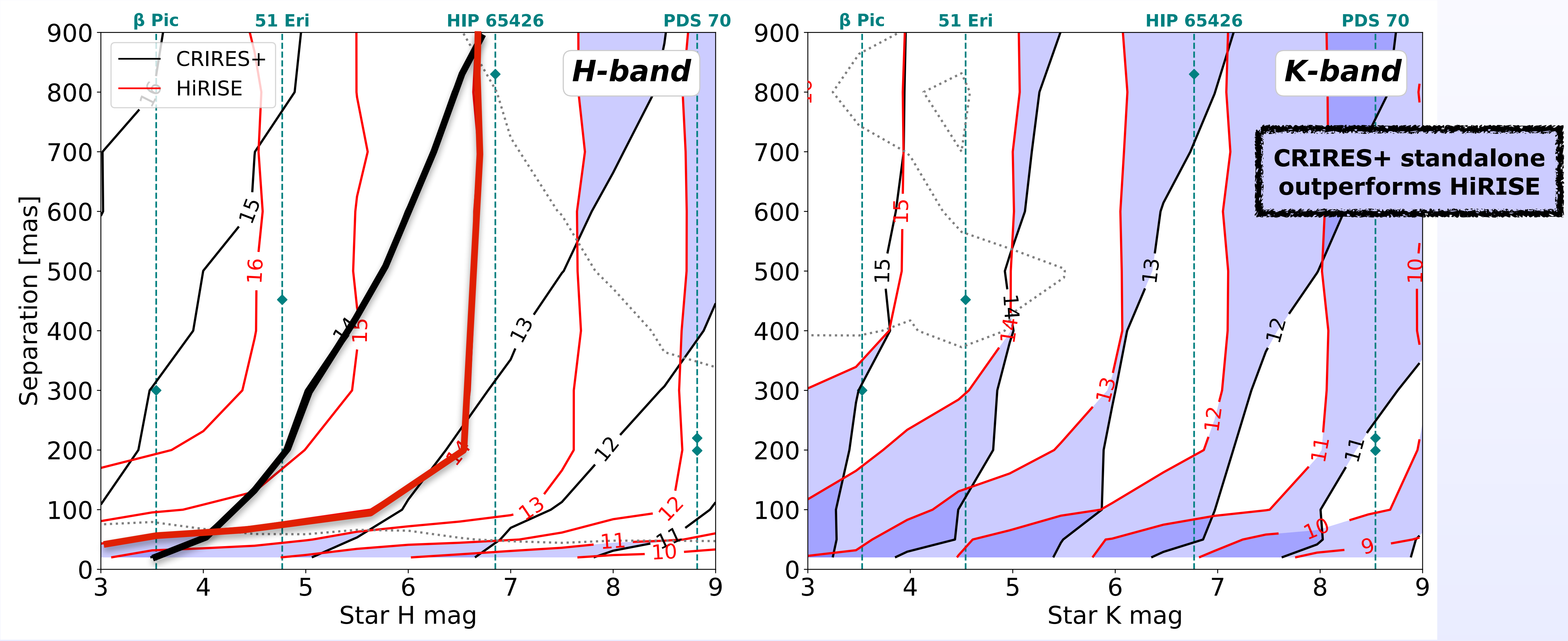
Performance analysis



Otten et al. (2021)

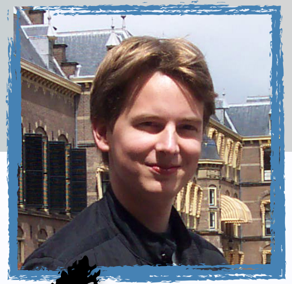
Performance analysis

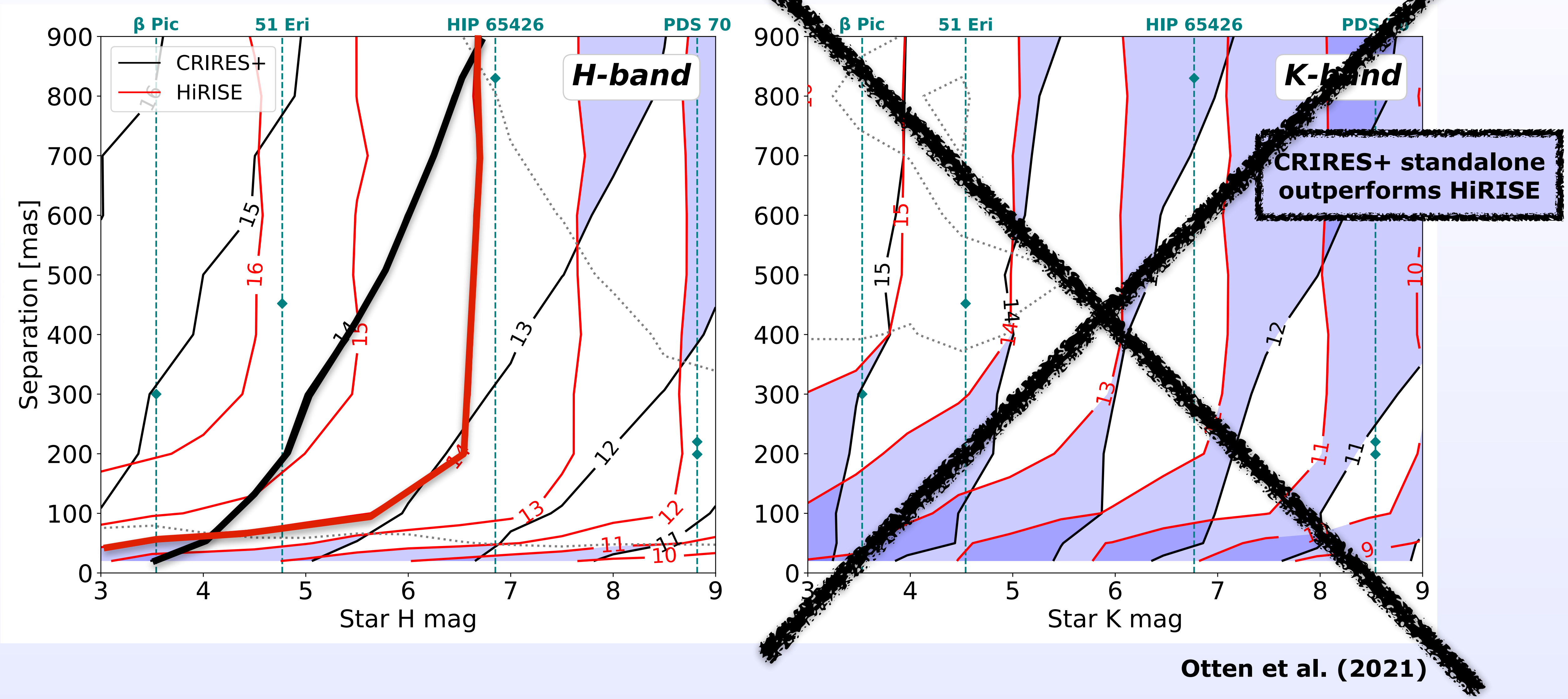




Otten et al. (2021)

Performance analysis

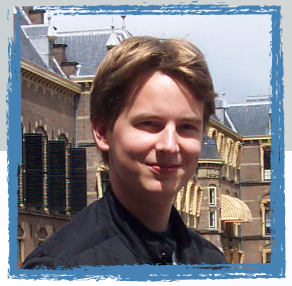


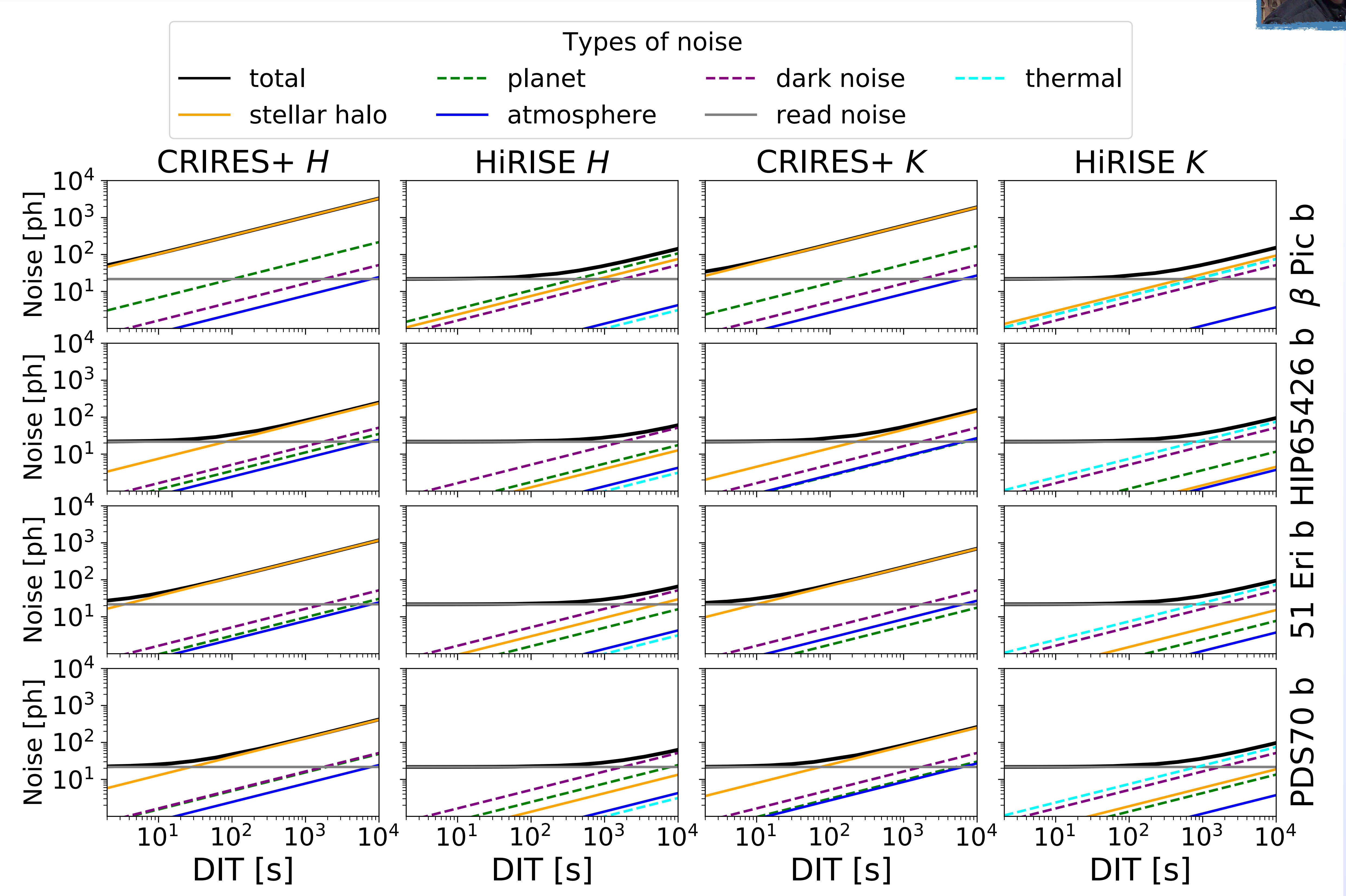


Otten et al. (2021)

It is worth it in the H band!

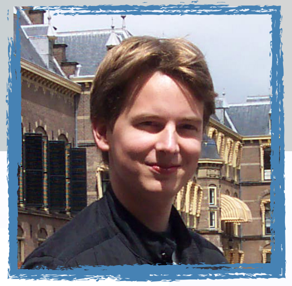
Performance analysis

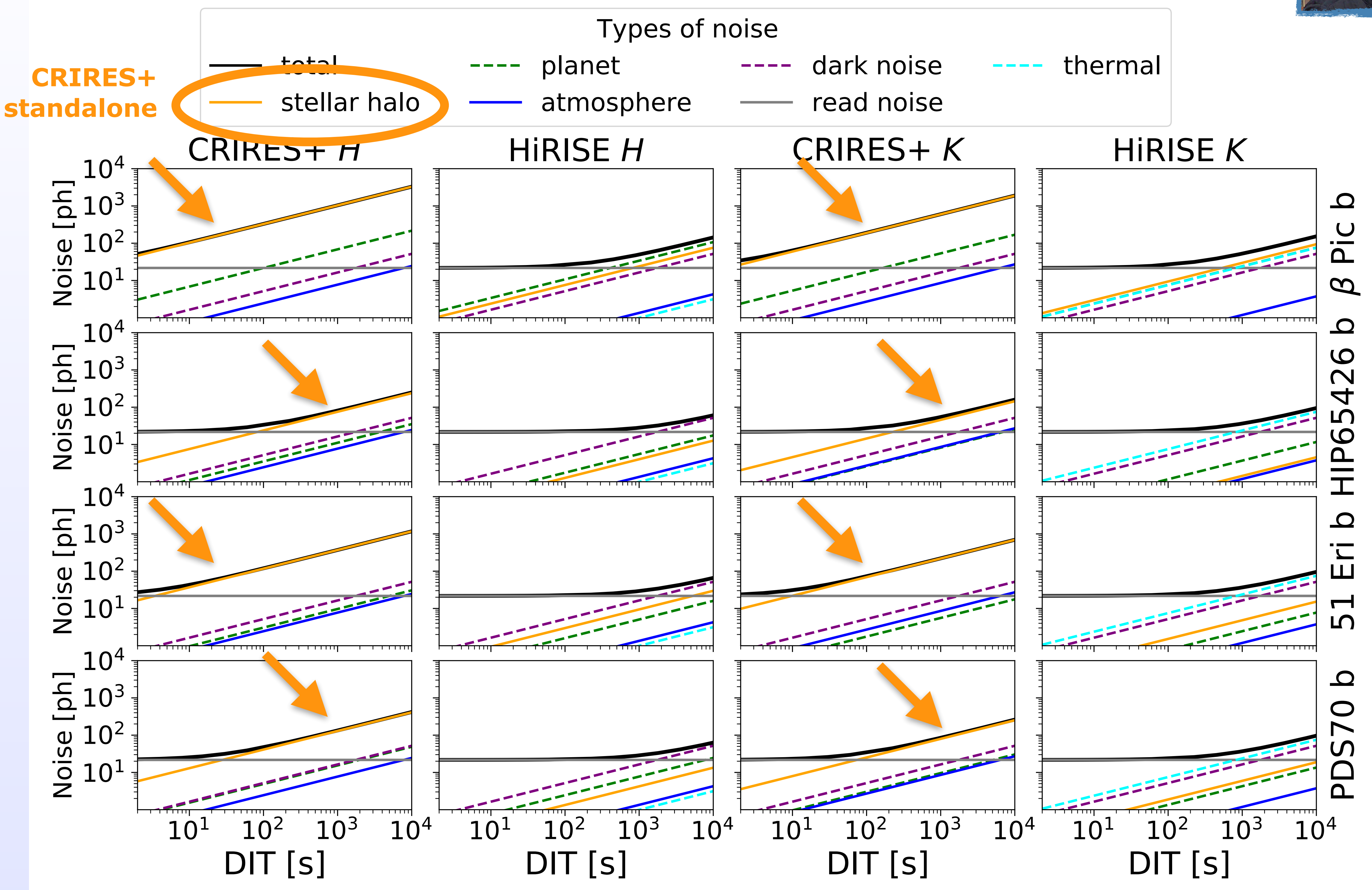




Otten et al. (2021)

Performance analysis





Otten et al. (2021)

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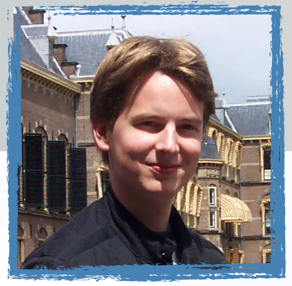
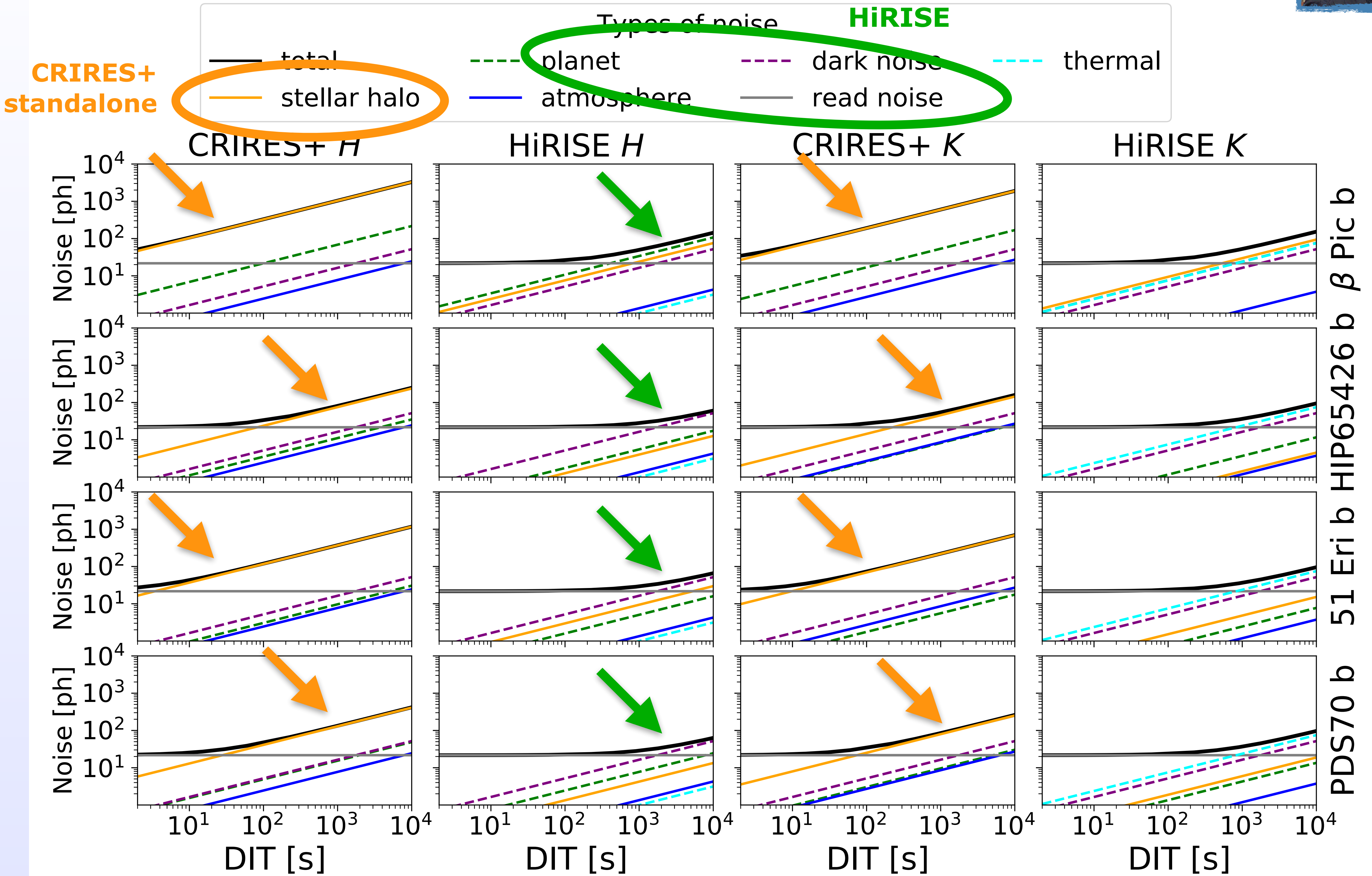
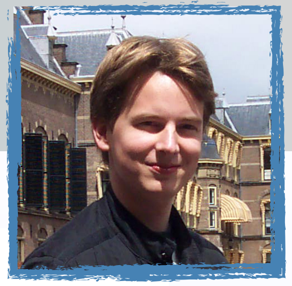
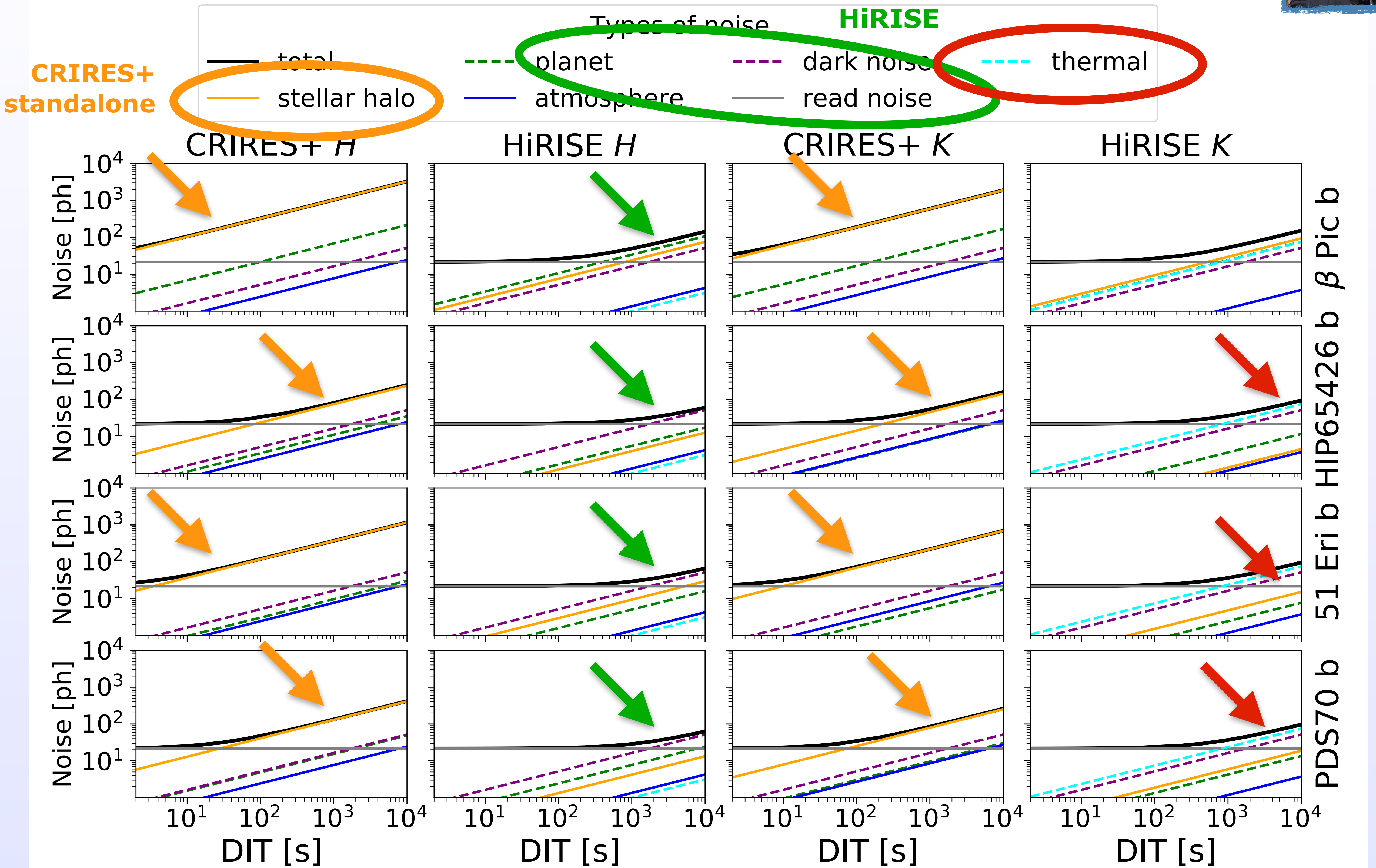




Otten et al. (2021)

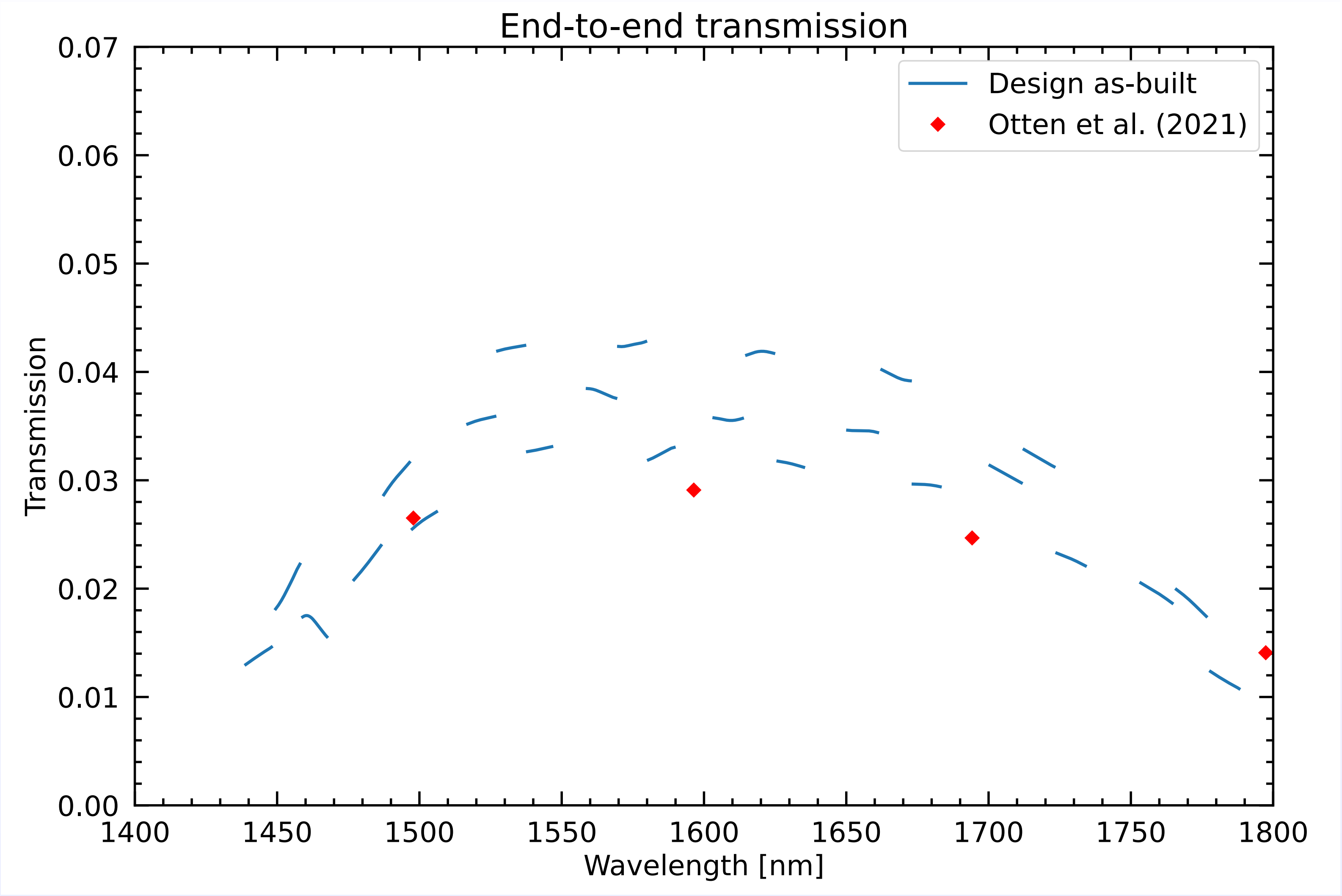
Performance analysis





Otten et al. (2021)

Transmission budget



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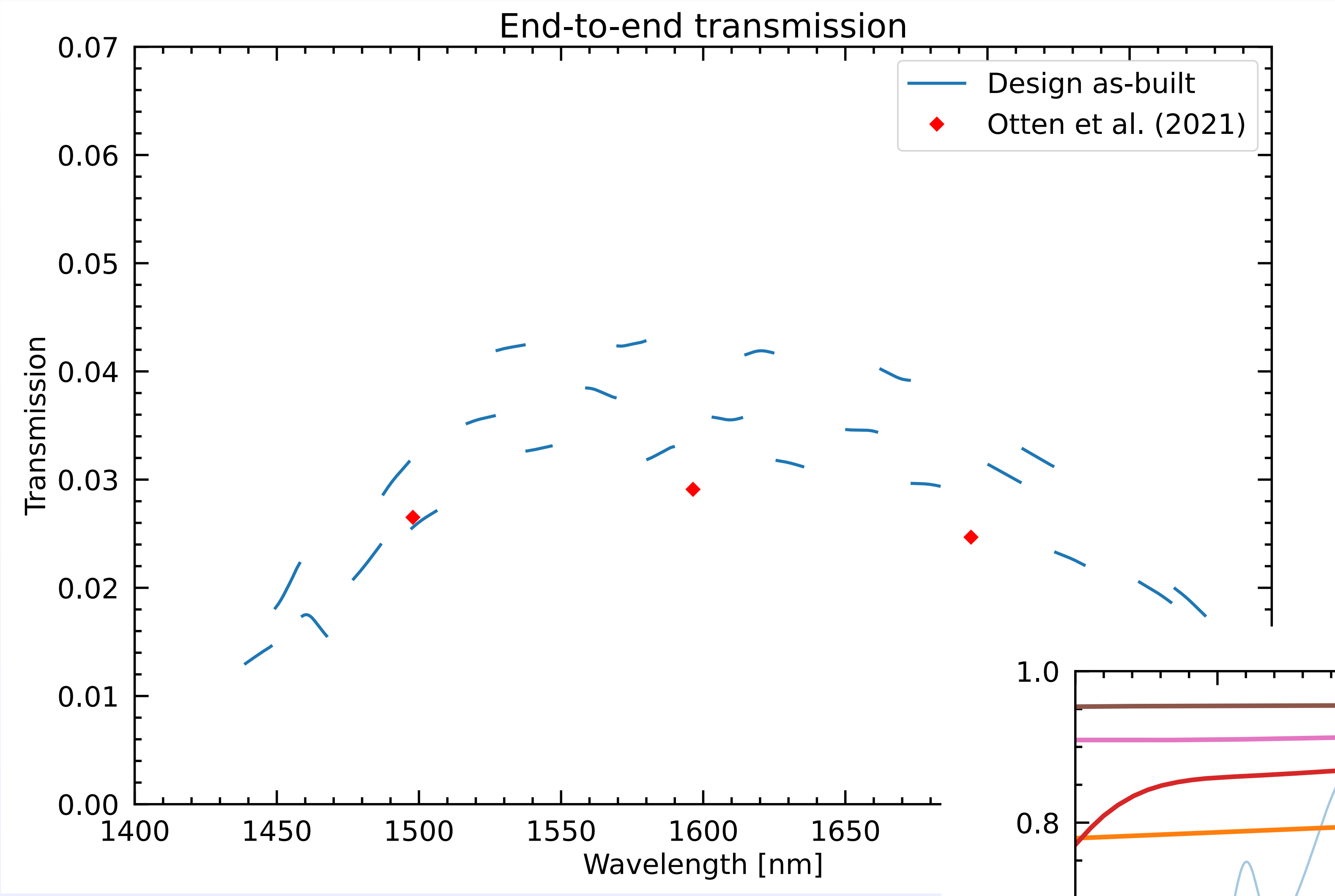

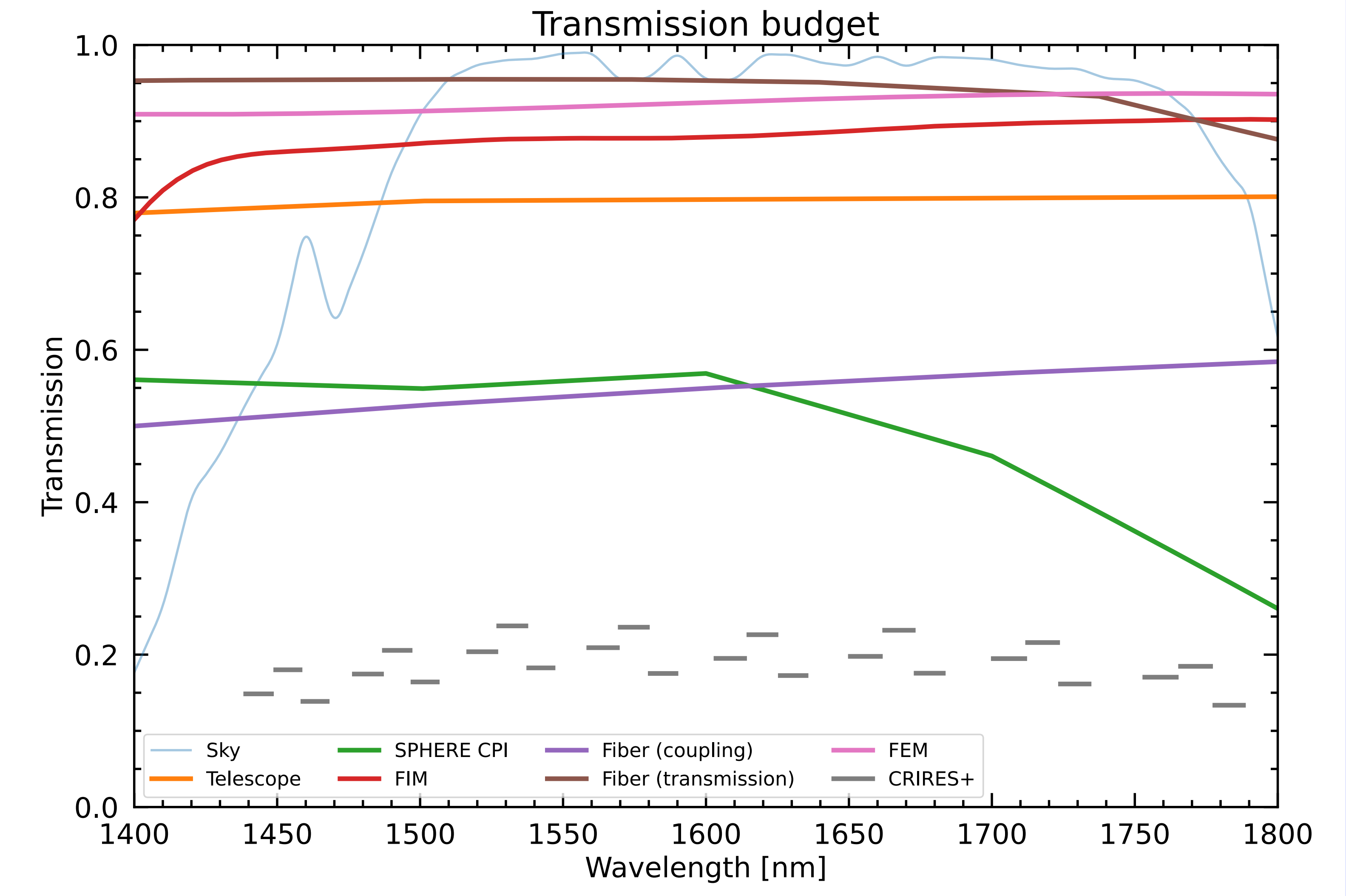

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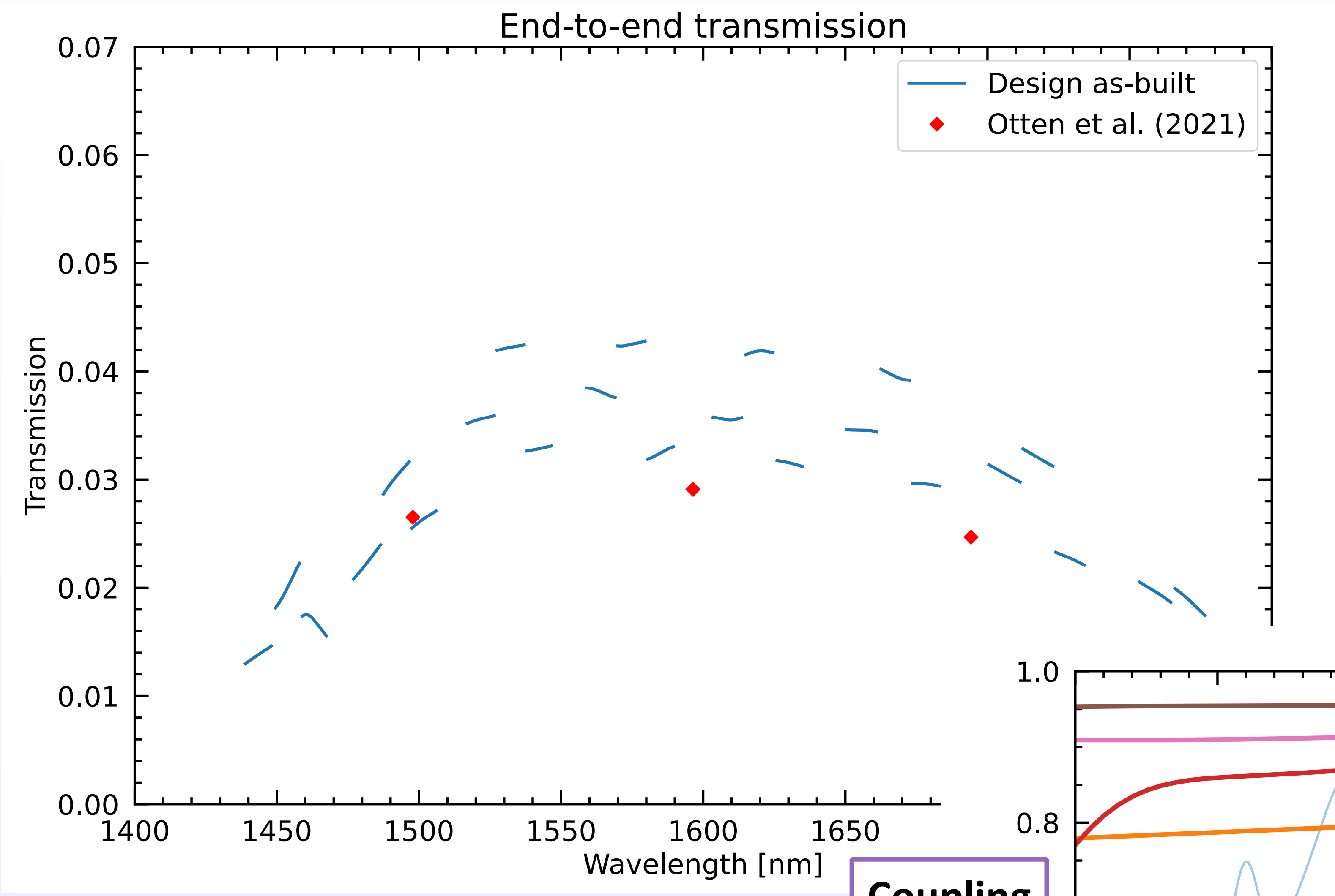
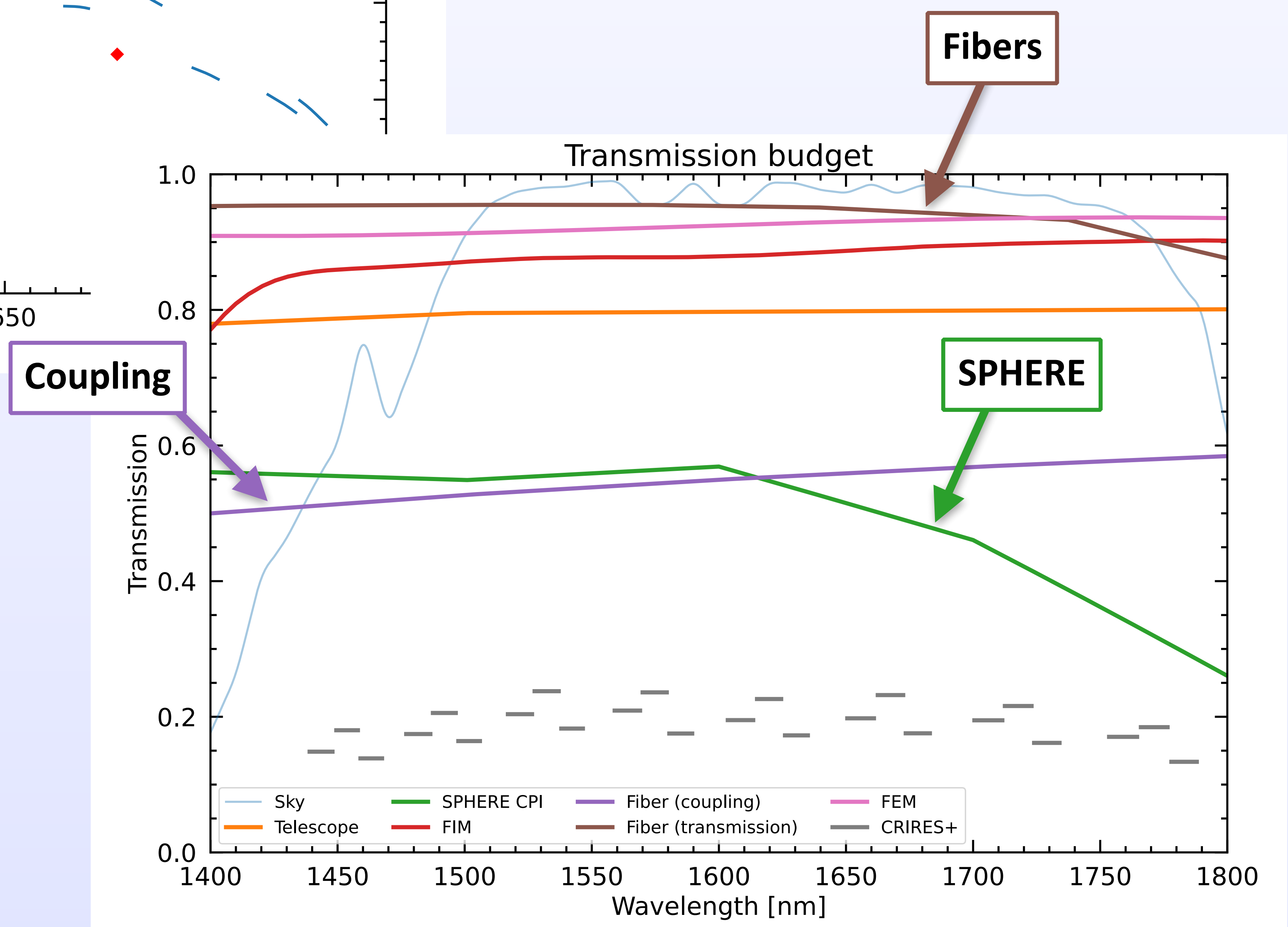
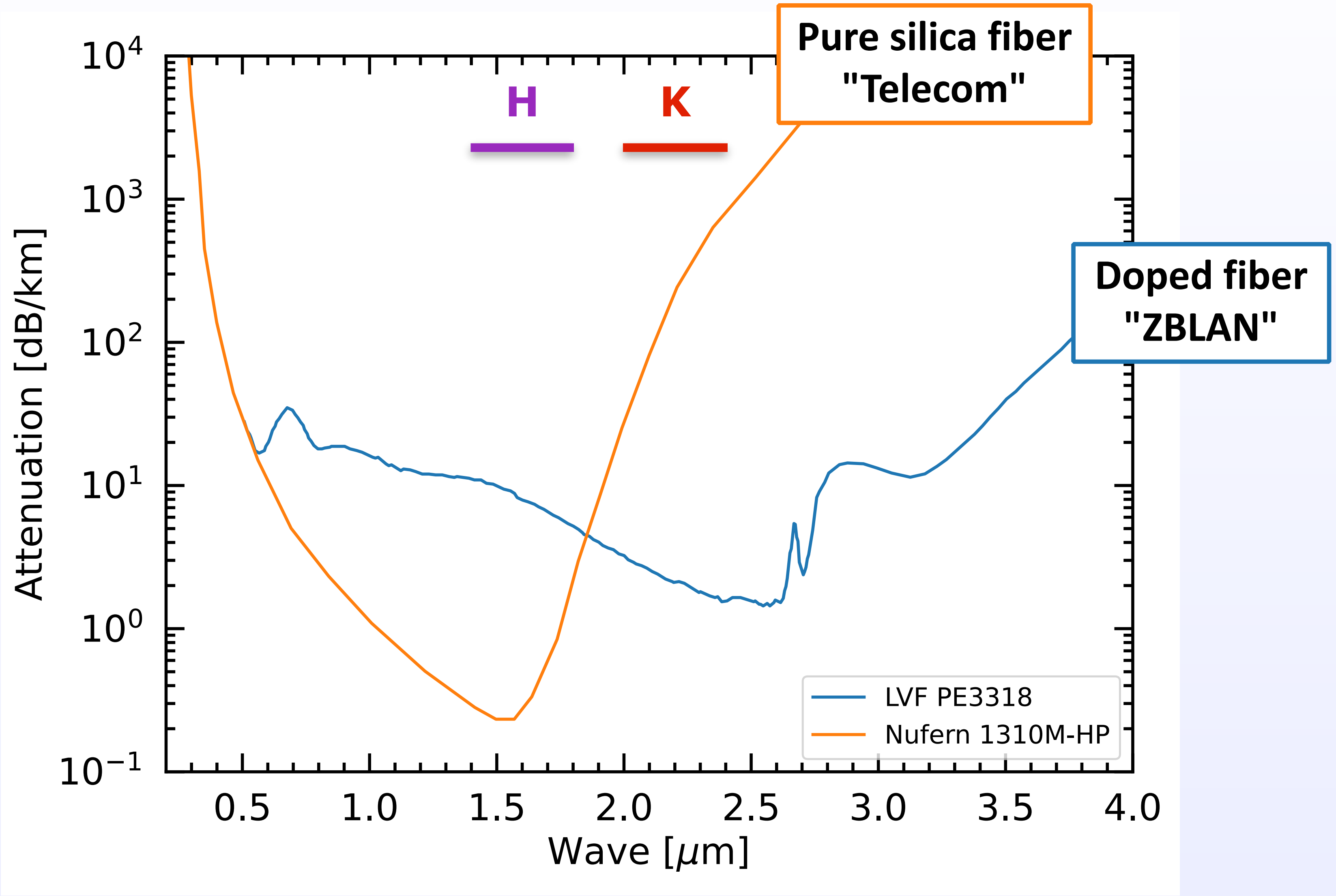




Choice of optical fiber



	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

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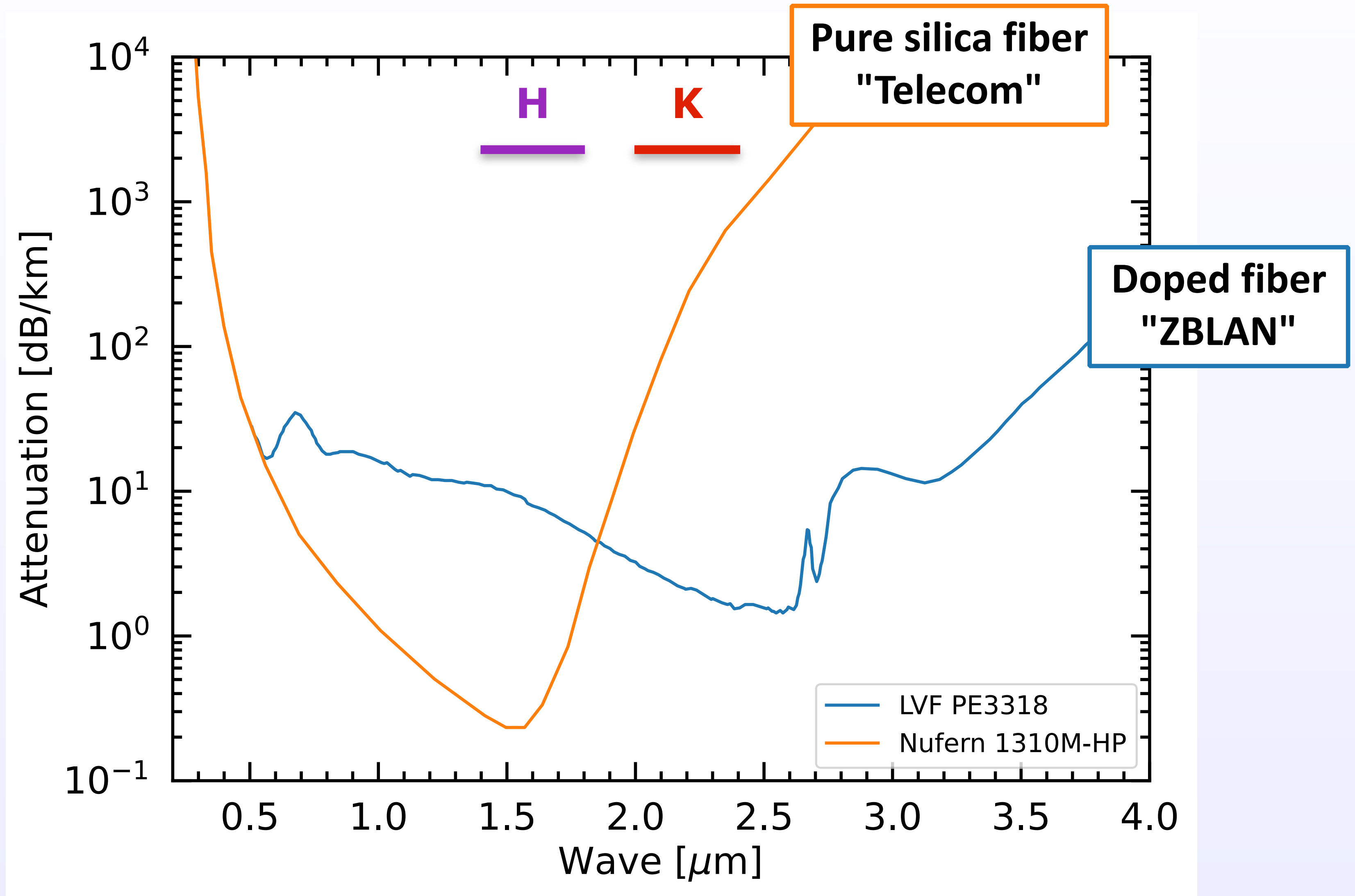

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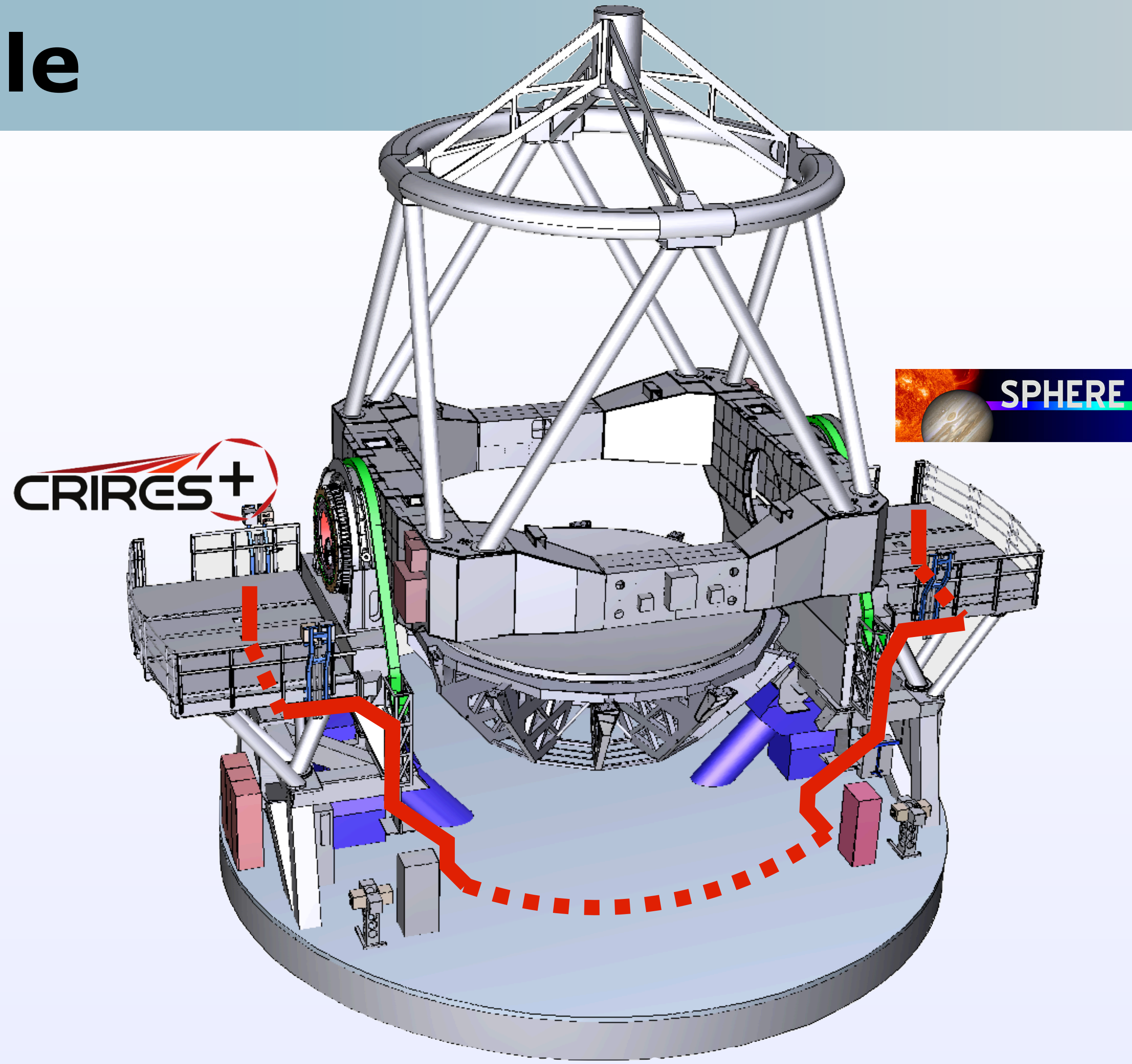
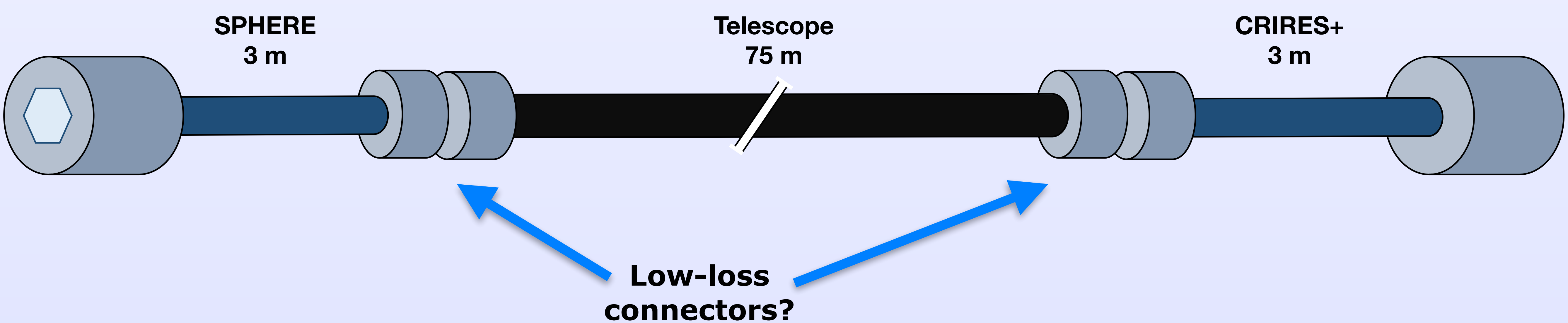
Final choice: Telecom fiber

Fiber bundle

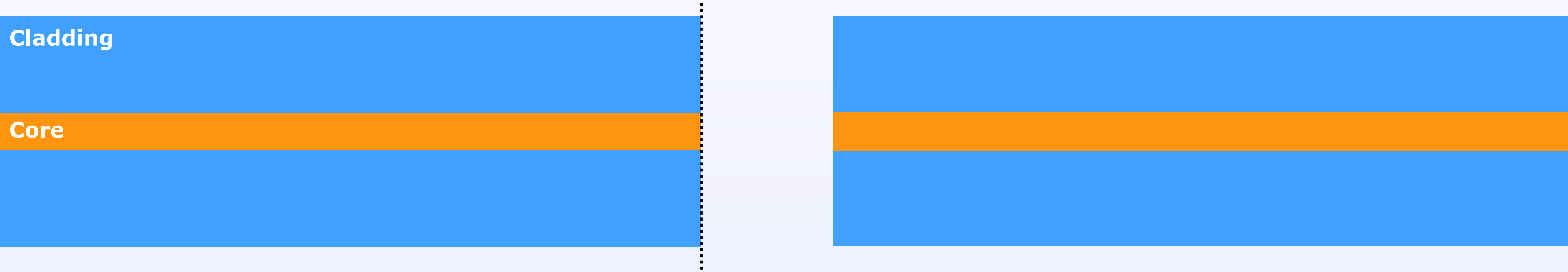




Low-loss connectors

Fibers

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



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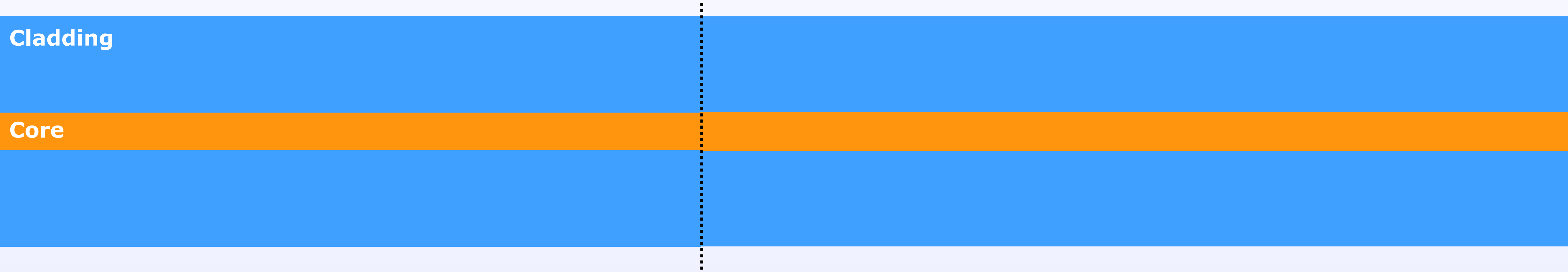

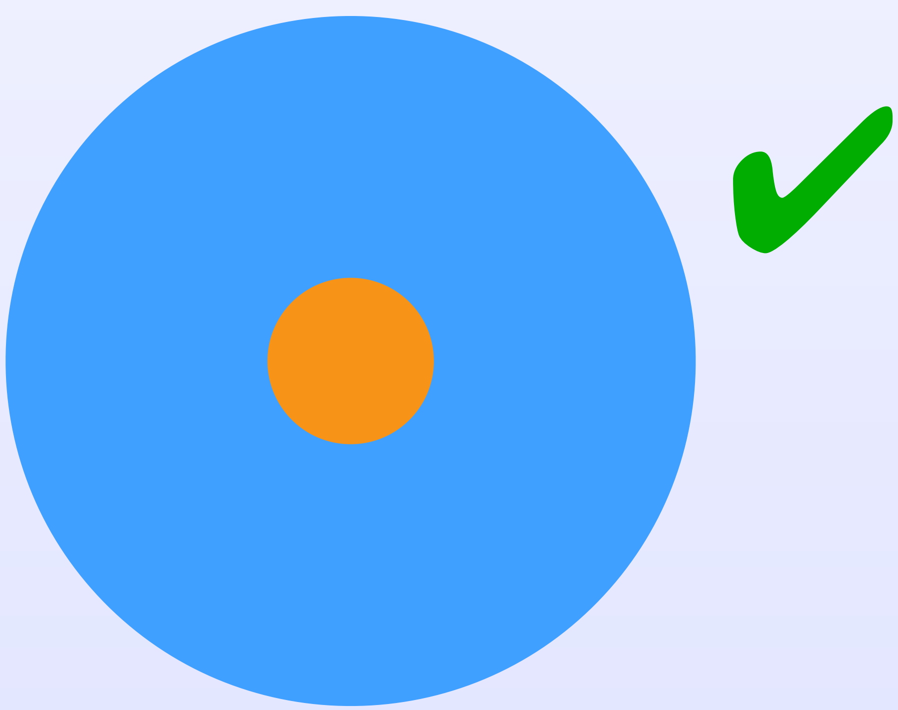

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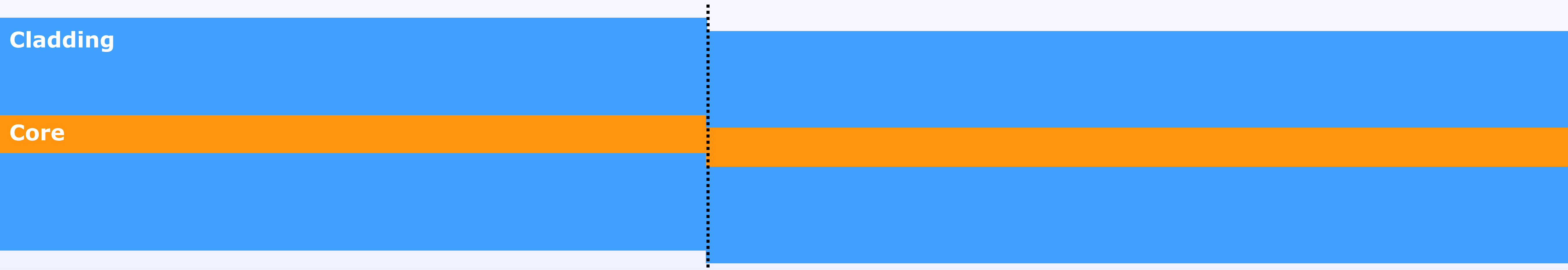

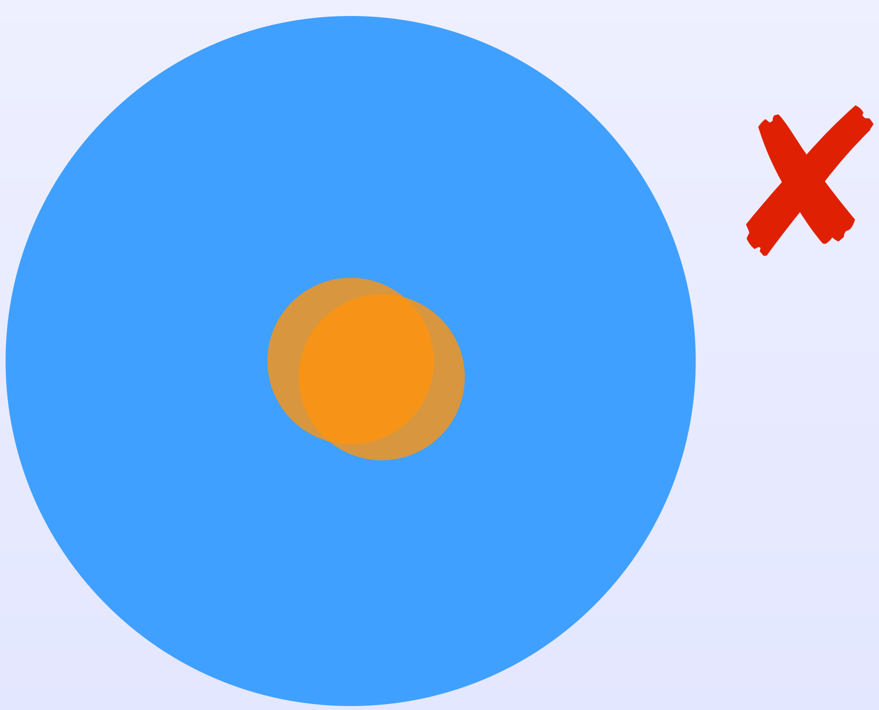

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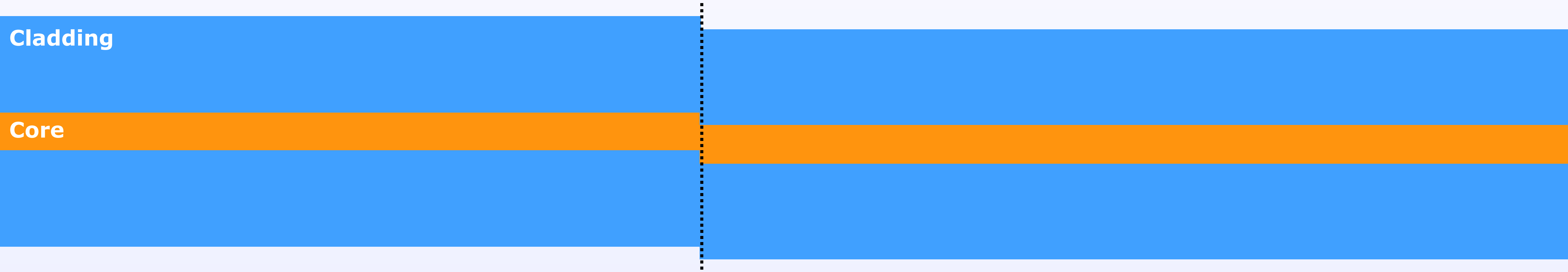
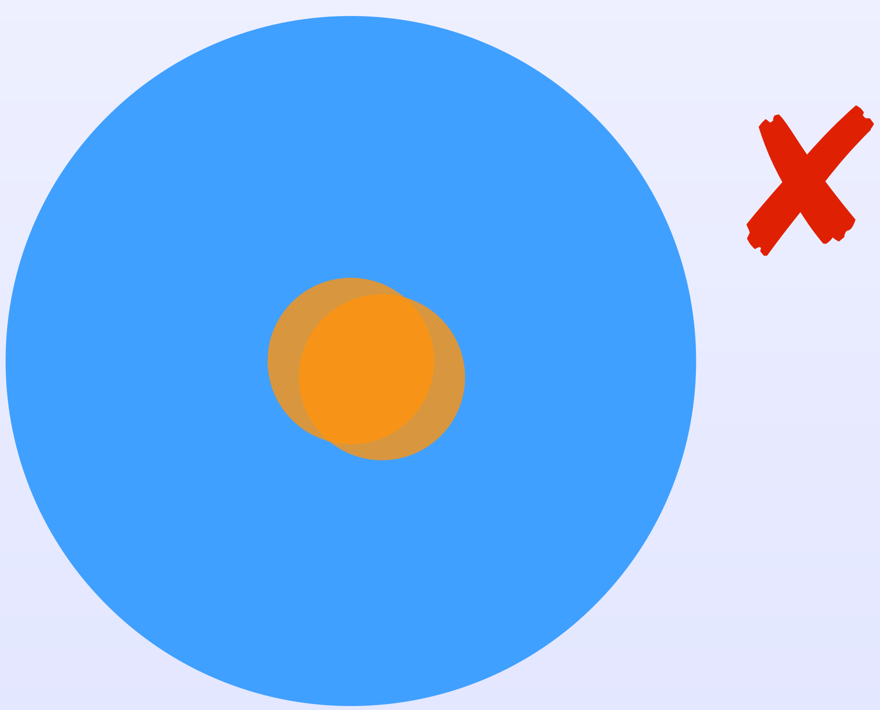
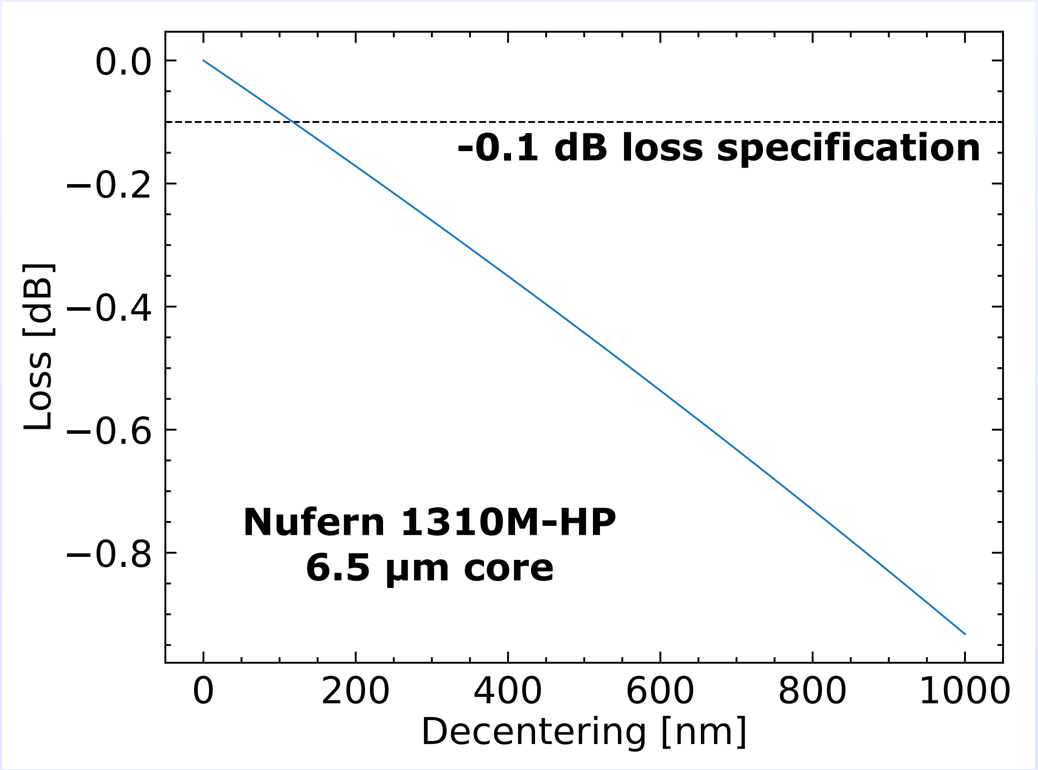


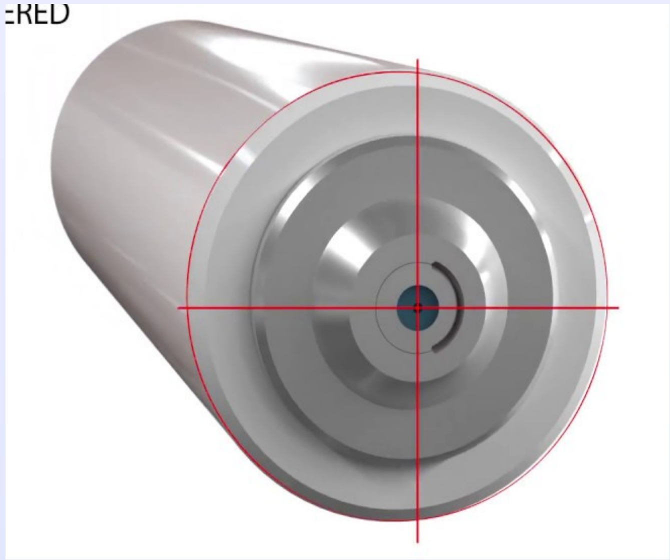




Low-loss connectors

- 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



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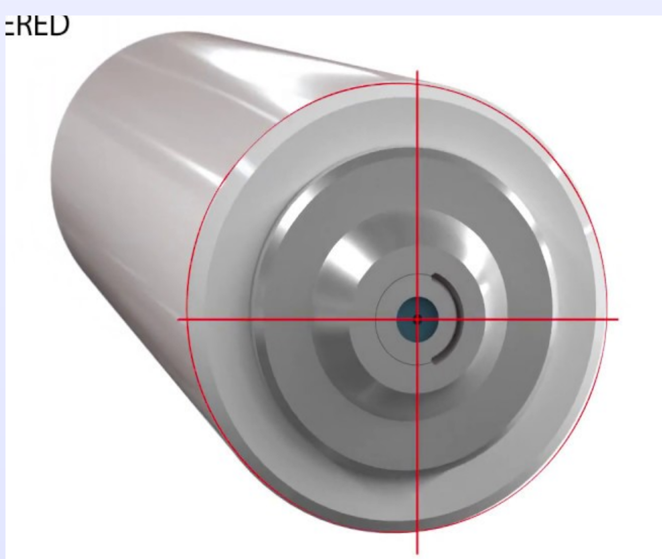
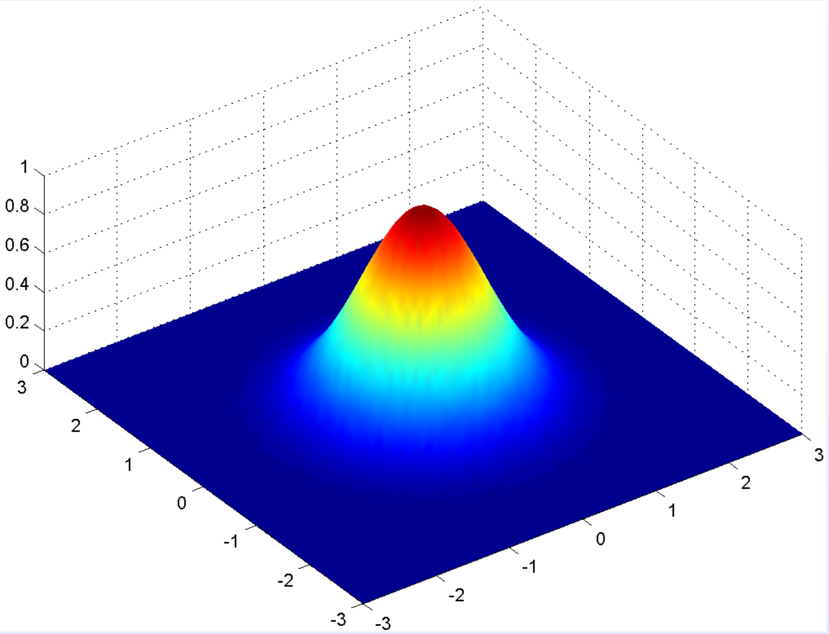


Final choice:
No connectors

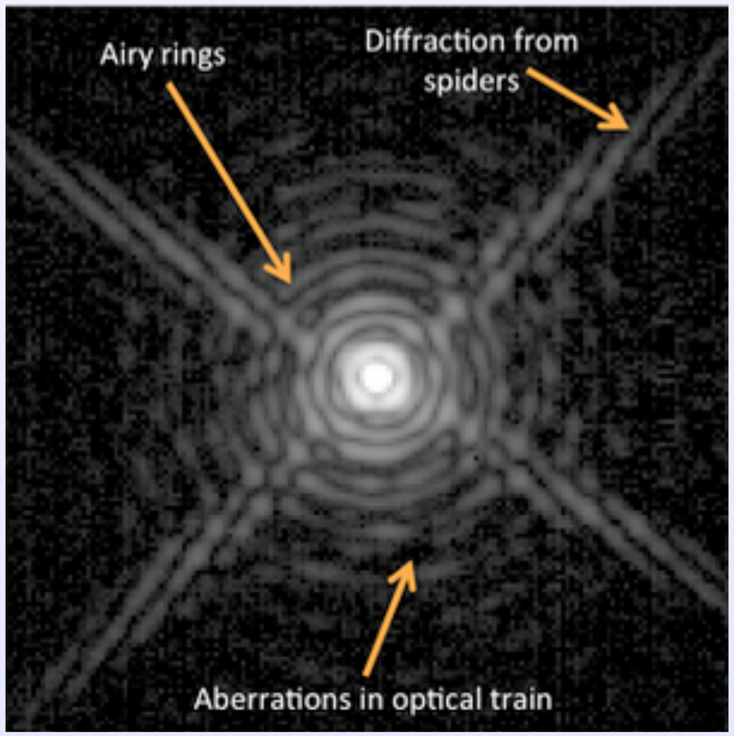
Single-mode fiber coupling

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



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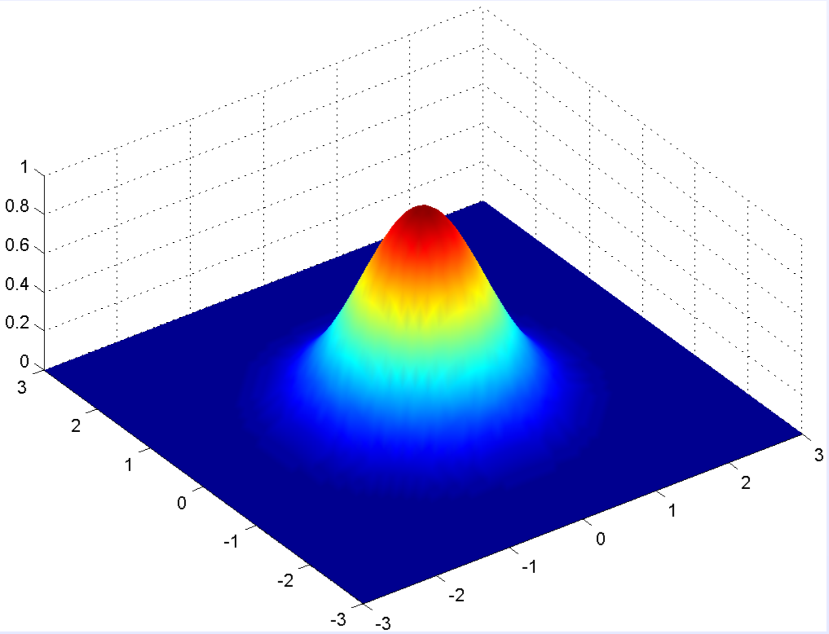

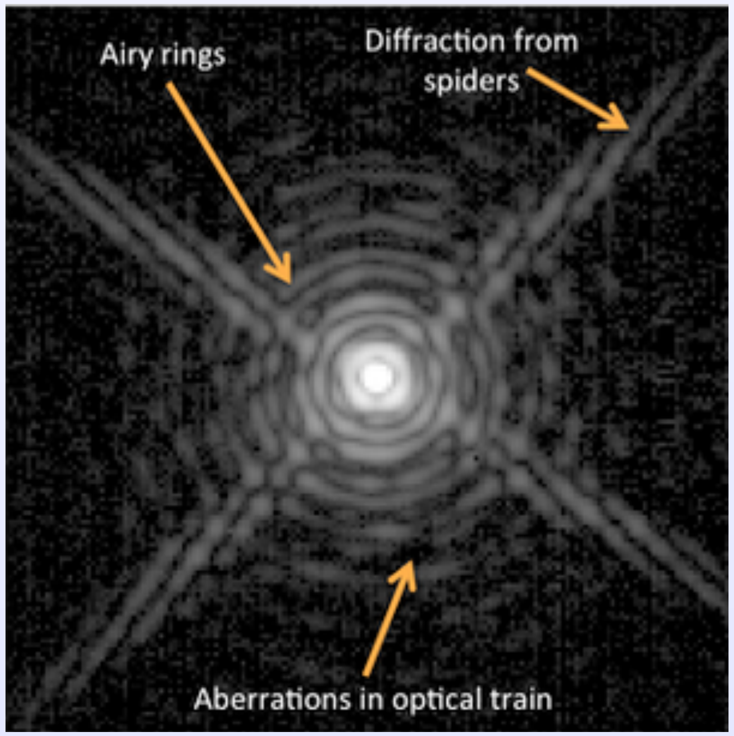

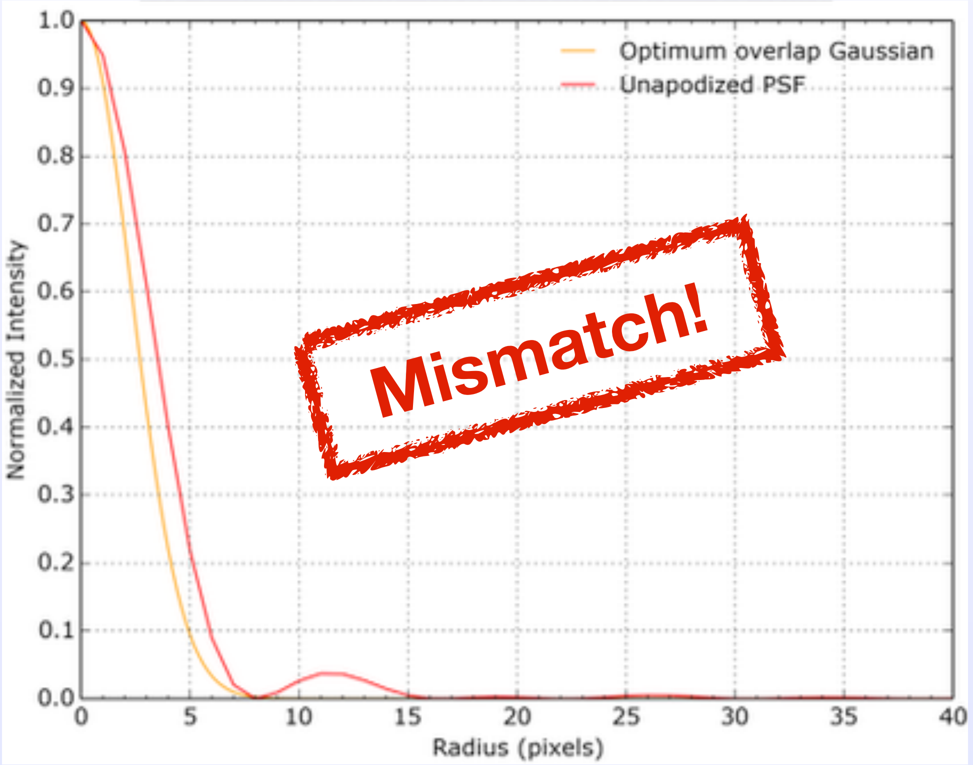

Jovanovic et al. (2017)

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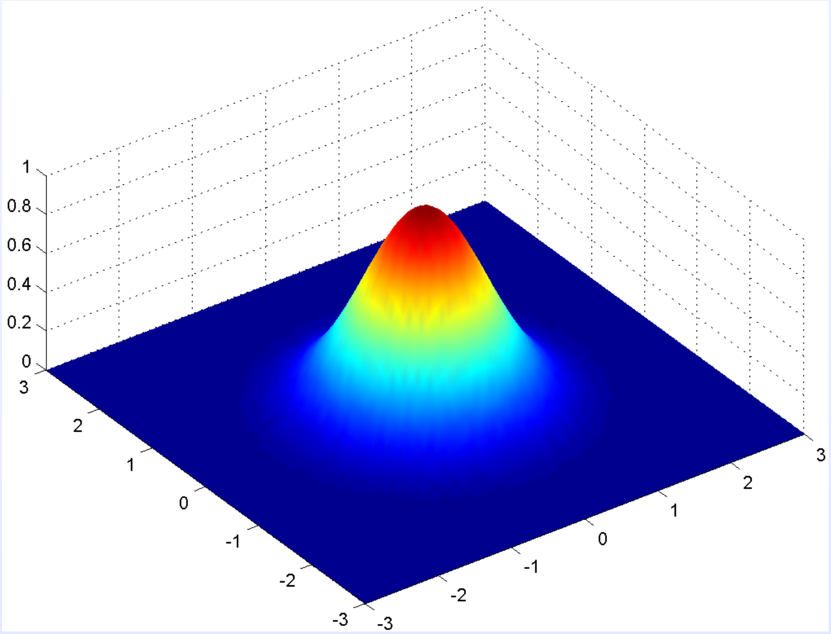
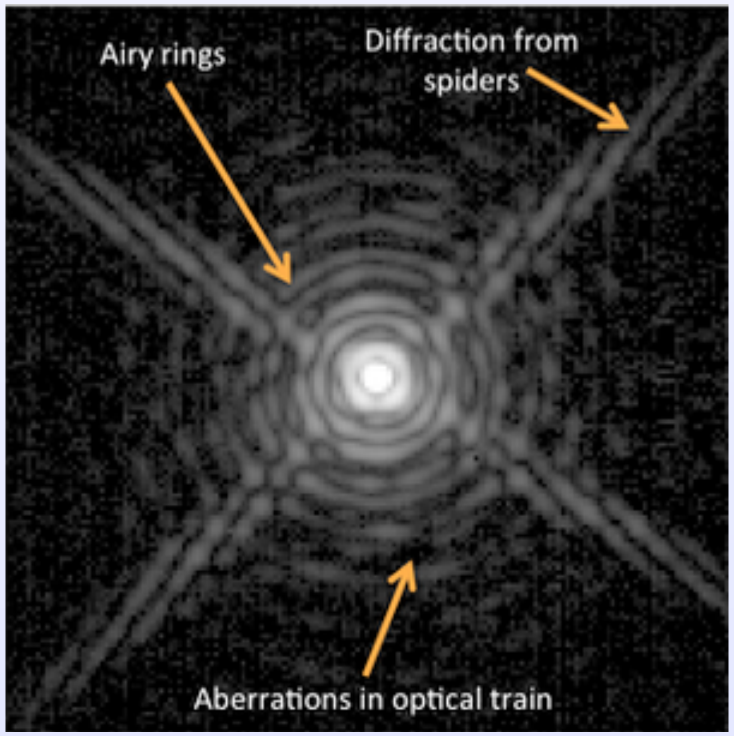
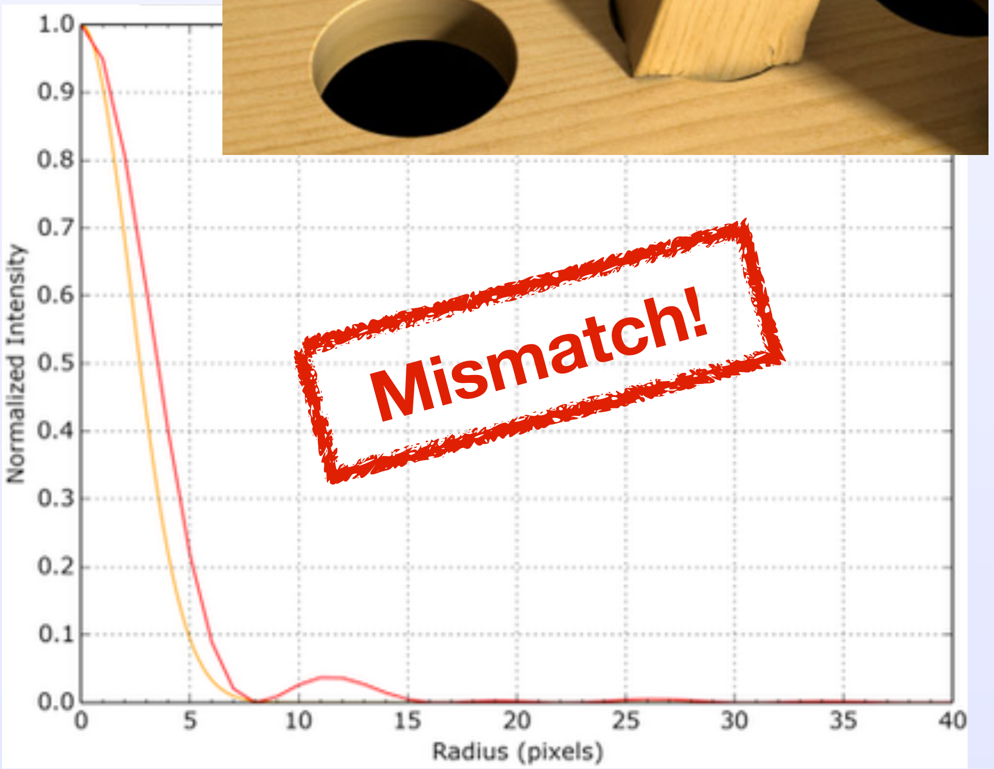
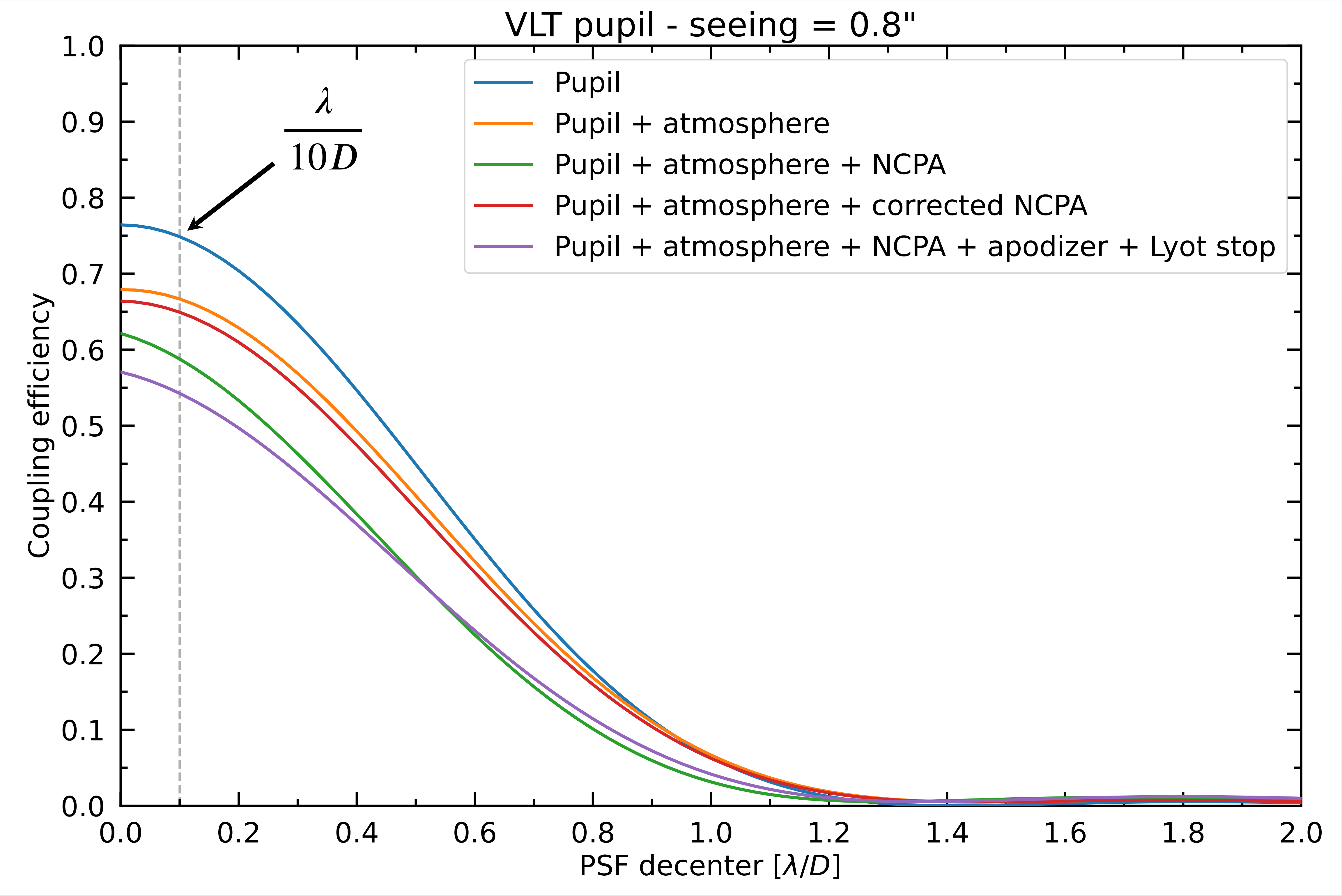






Jovanovic et al. (2017)

Coupling vs. PSF centering



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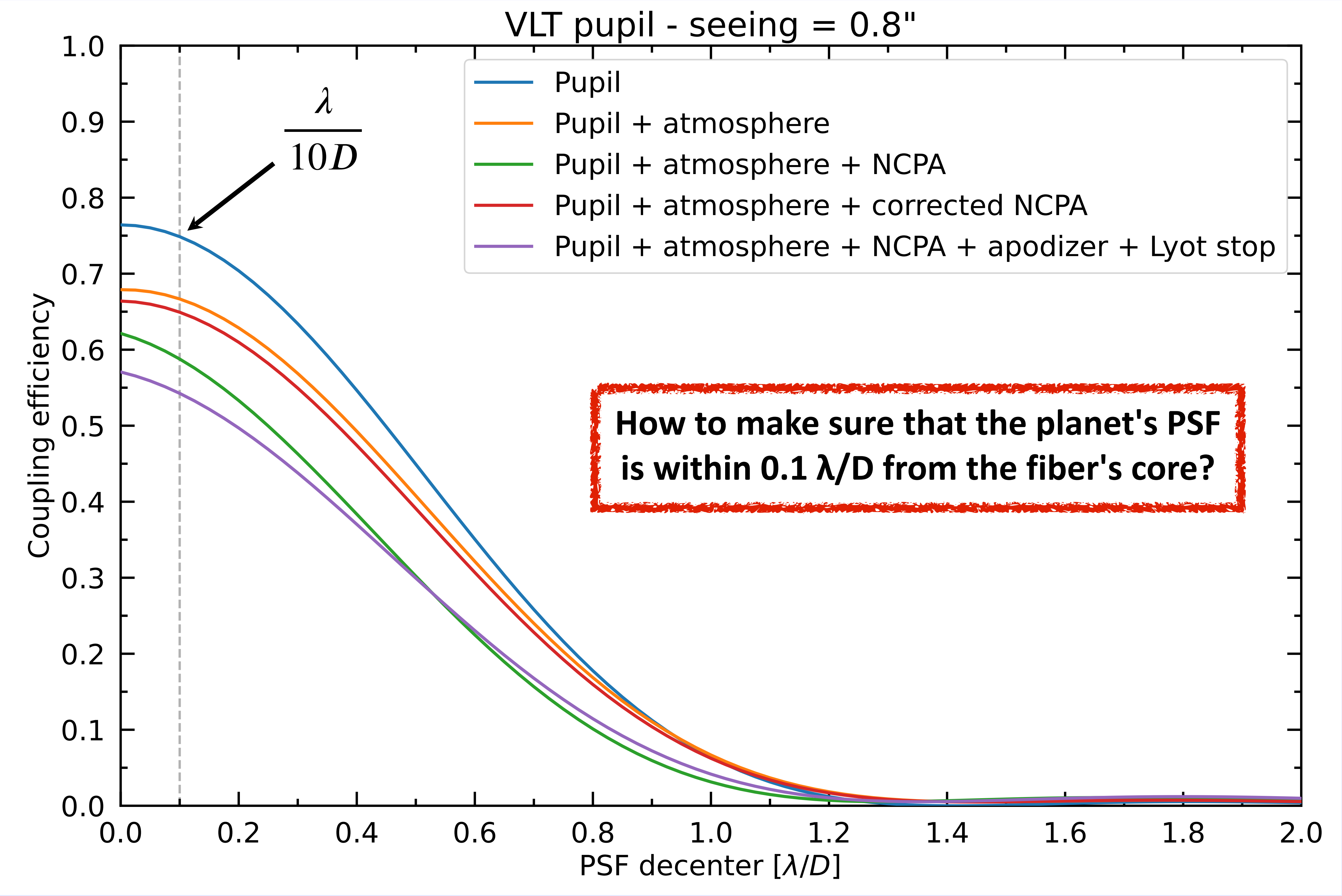
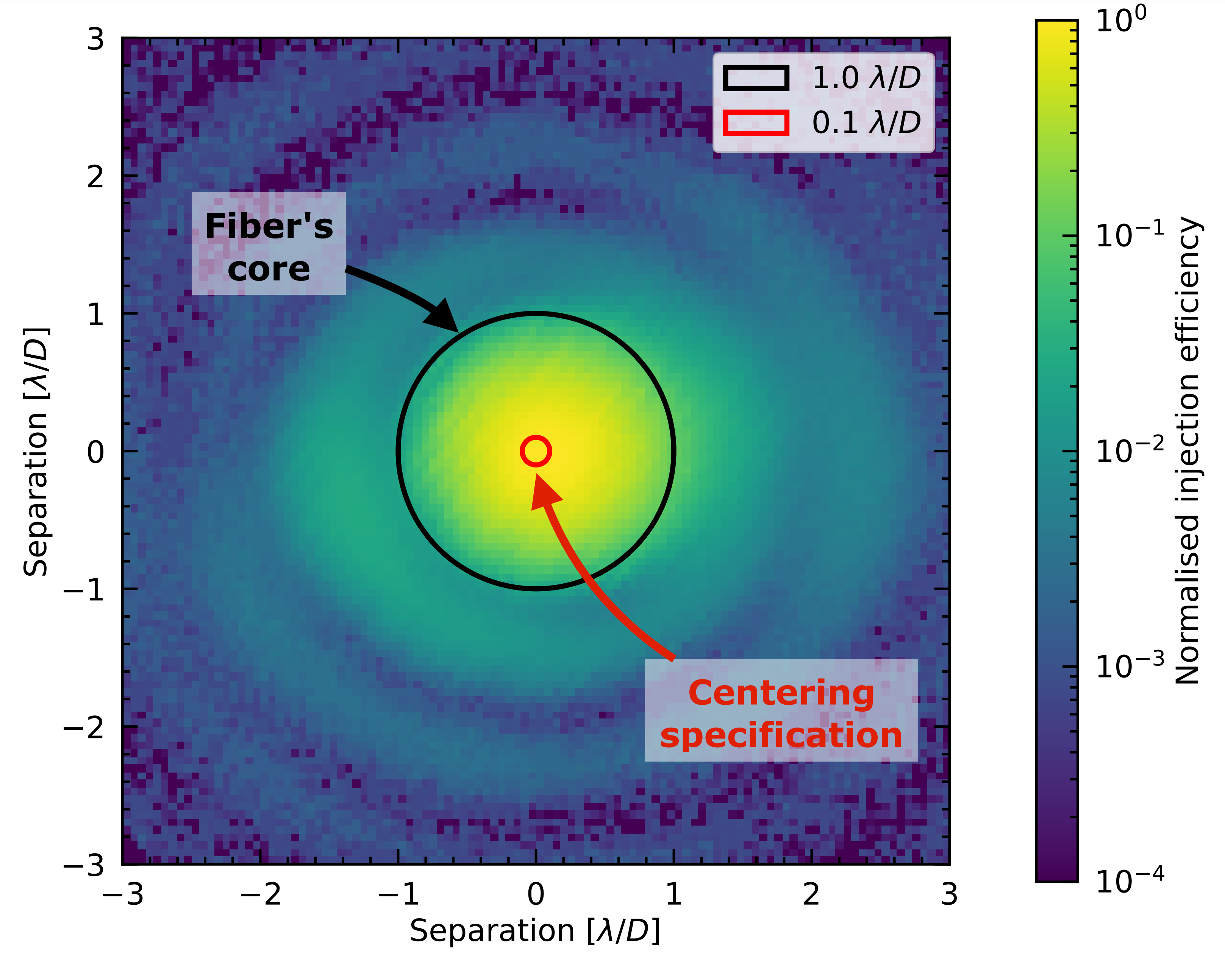


How to make sure that the planet's PSF is within 0.1 λ/D from the fiber's core?

PSF centering: an operational challenge

Coupling



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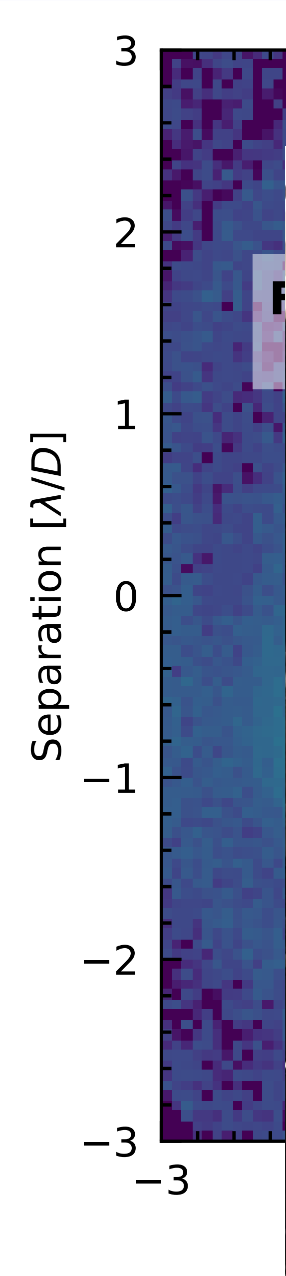
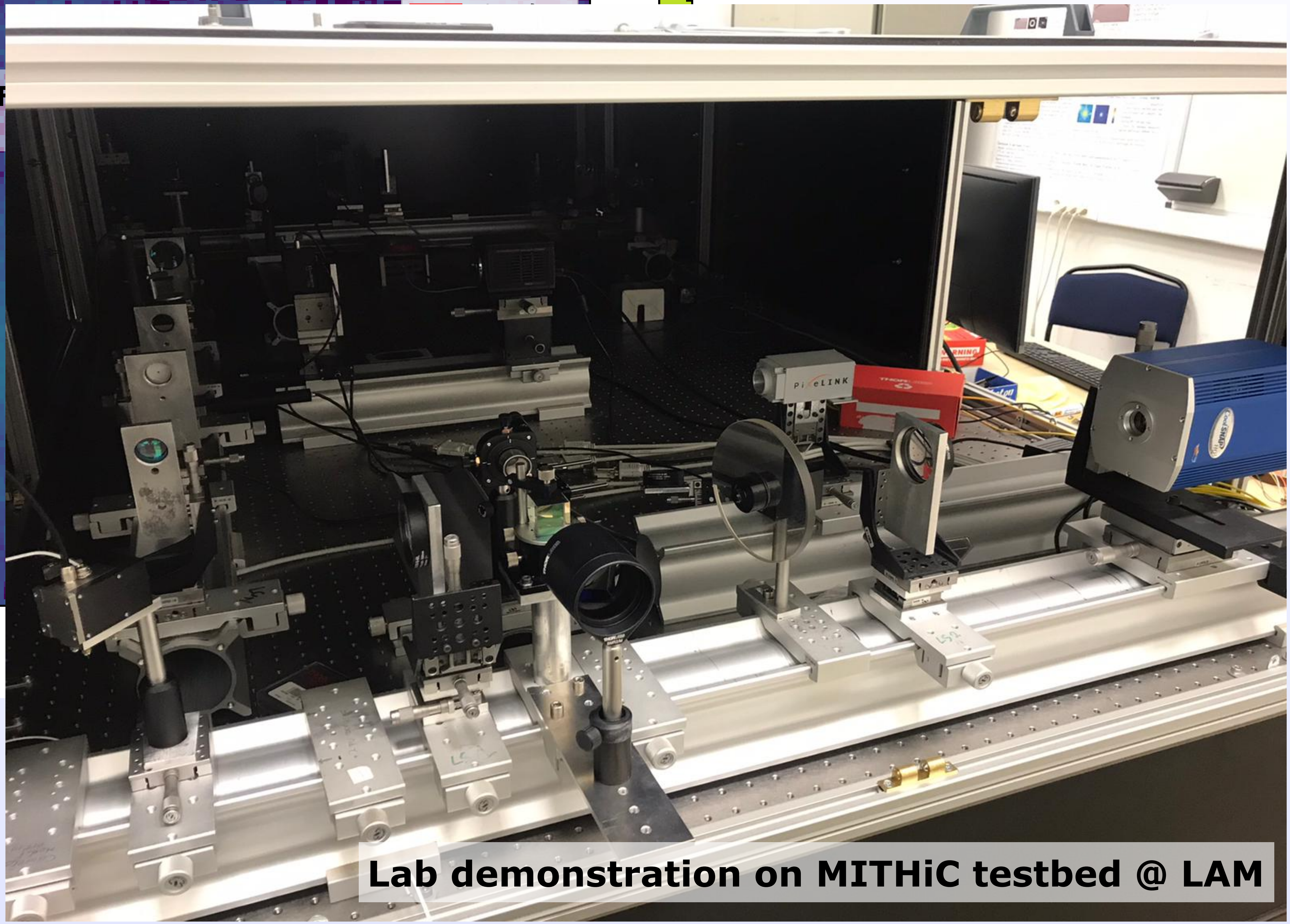
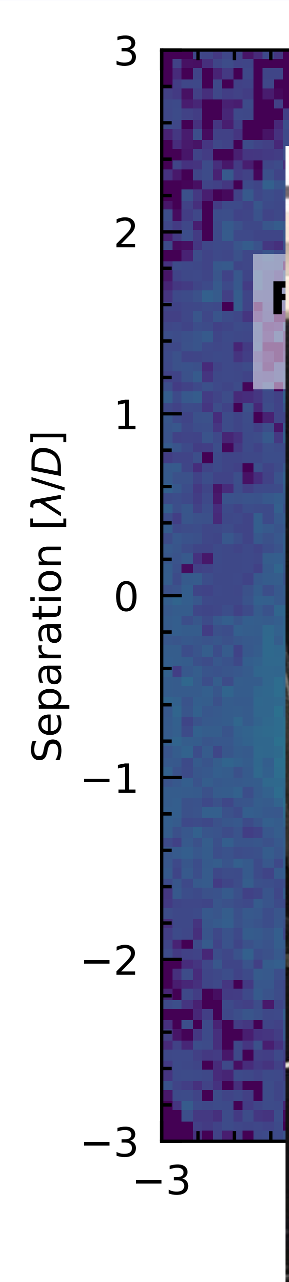


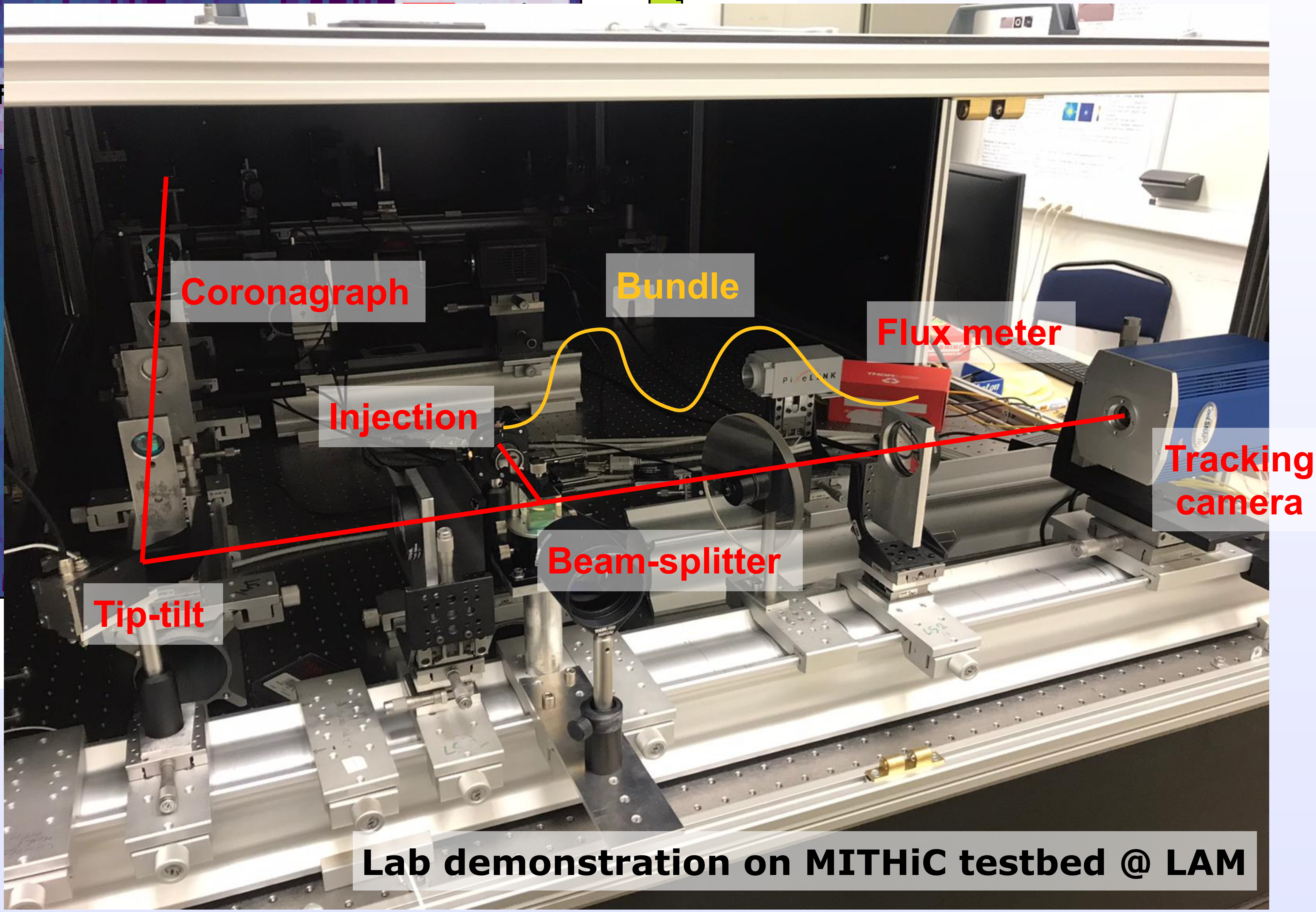


Lab demonstration on MITHiC testbed @ LAM

PSF centering: an operational challenge

Coupling





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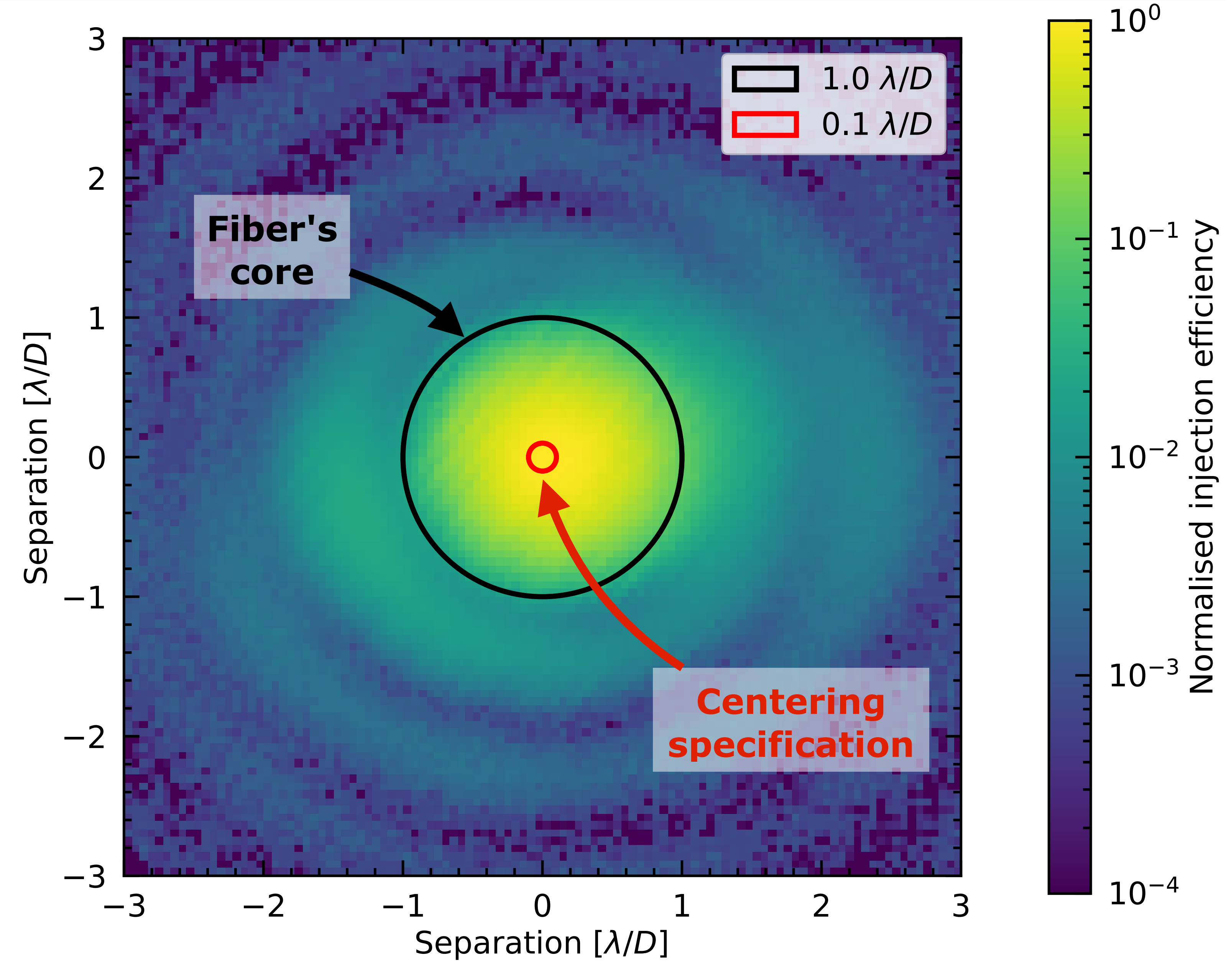
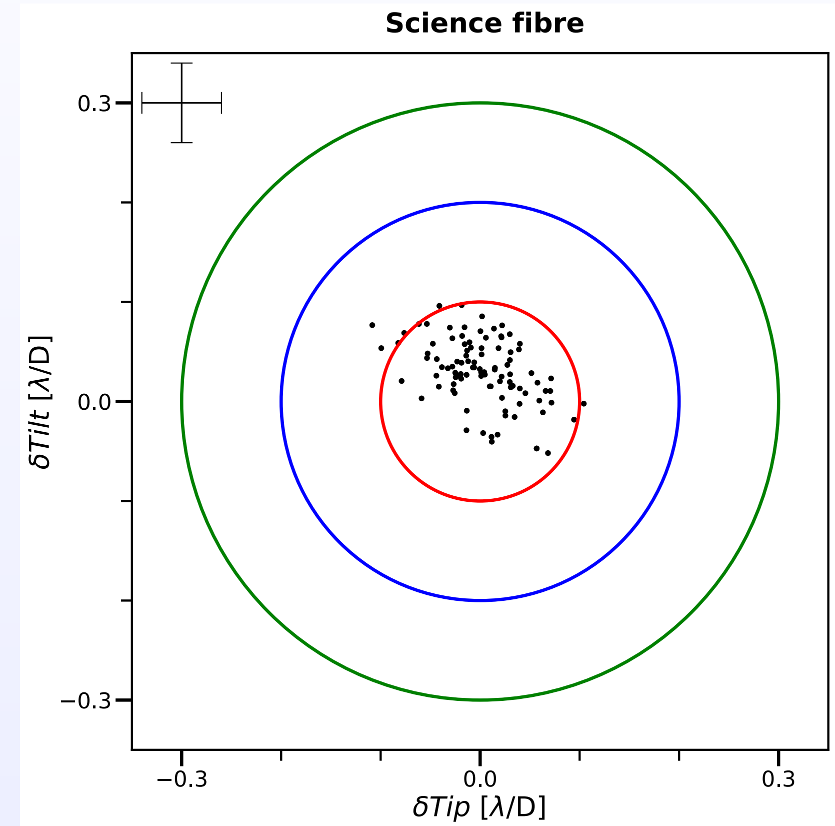
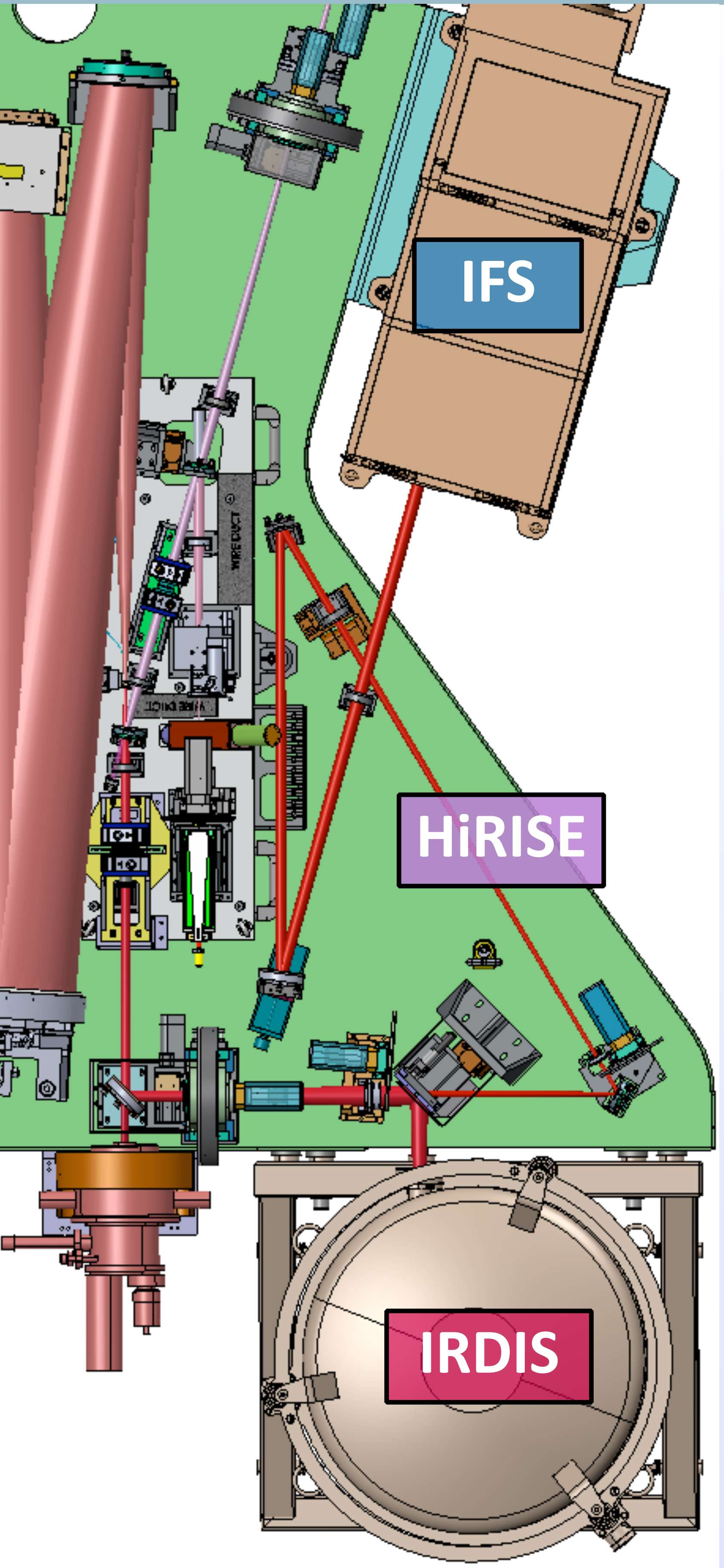


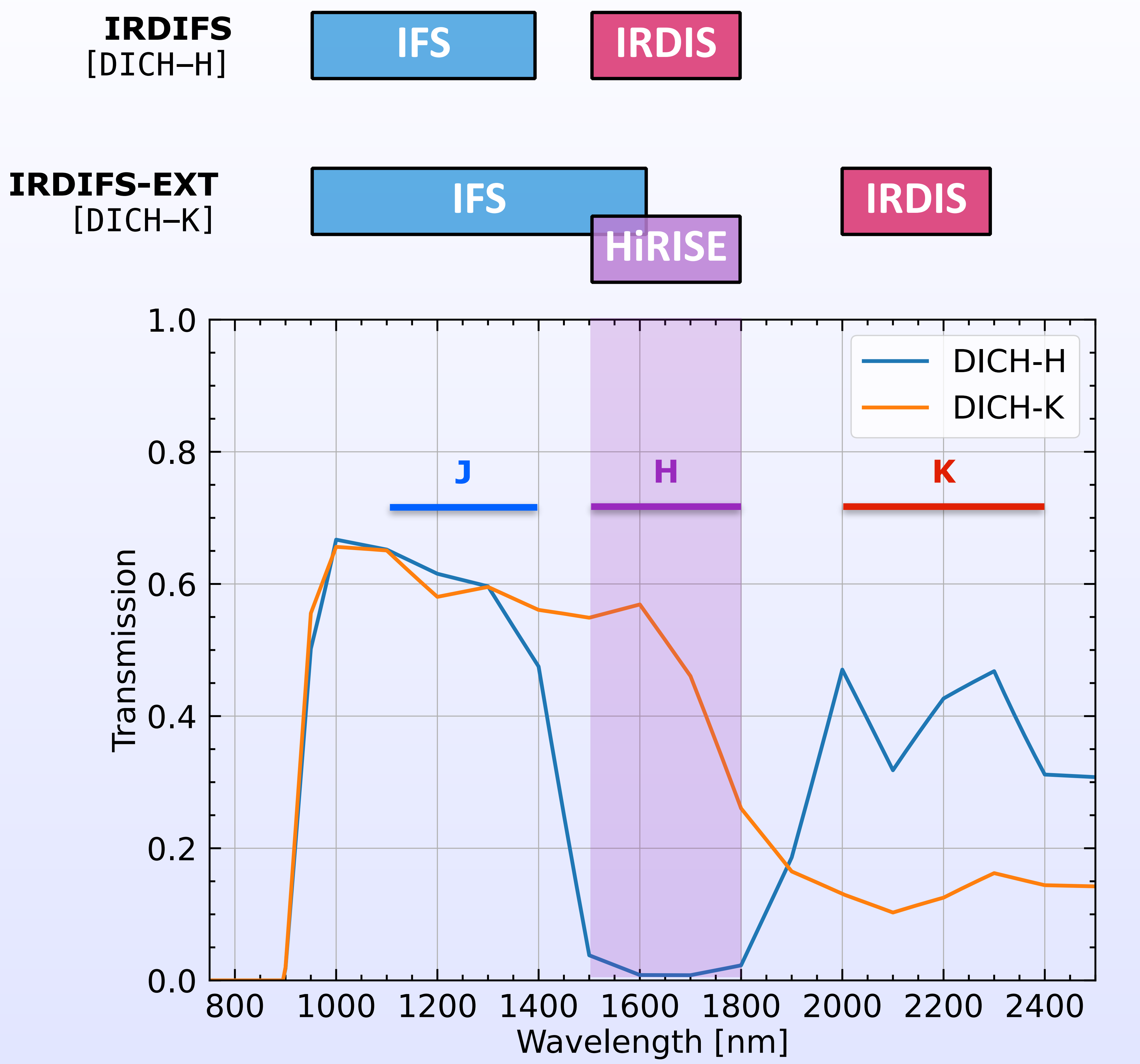


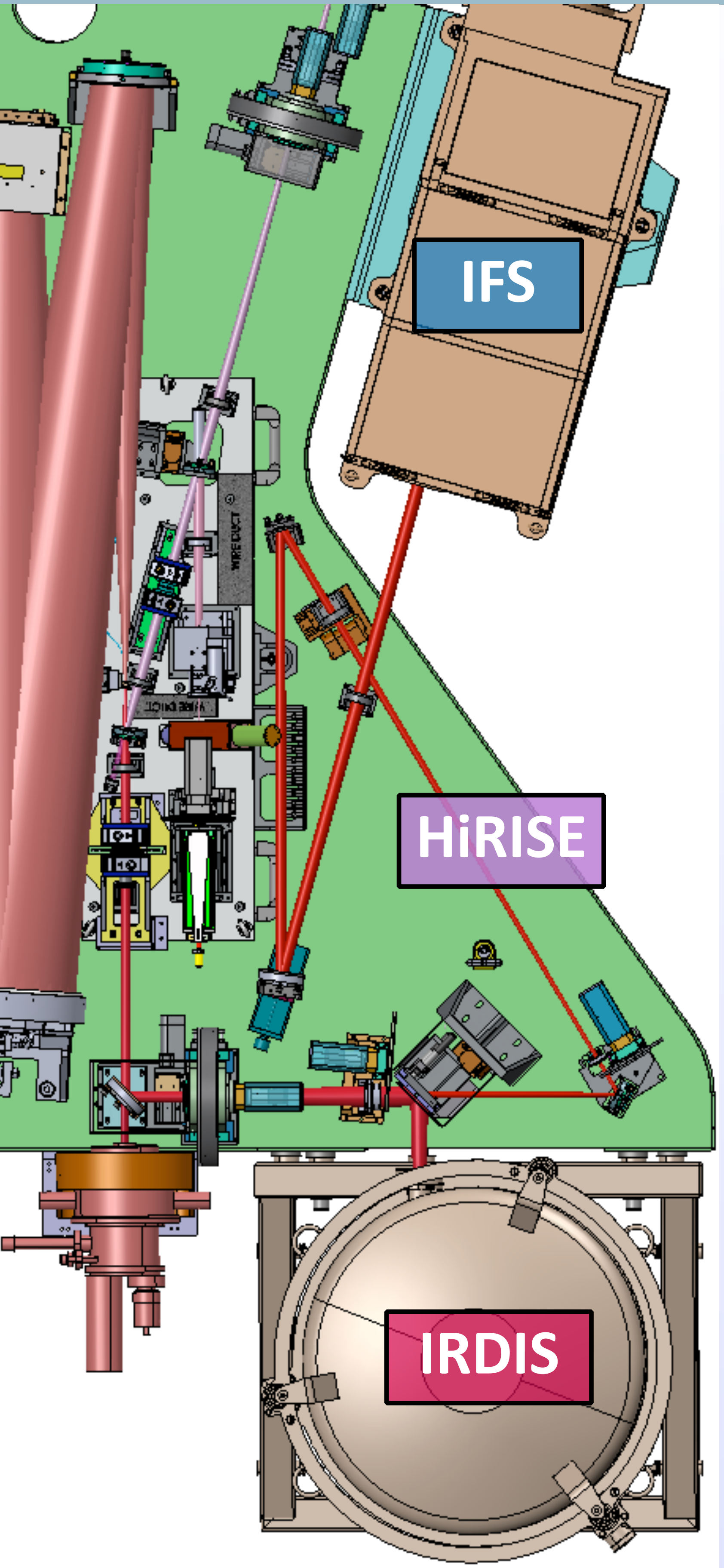
El Morsy et al. (2022)

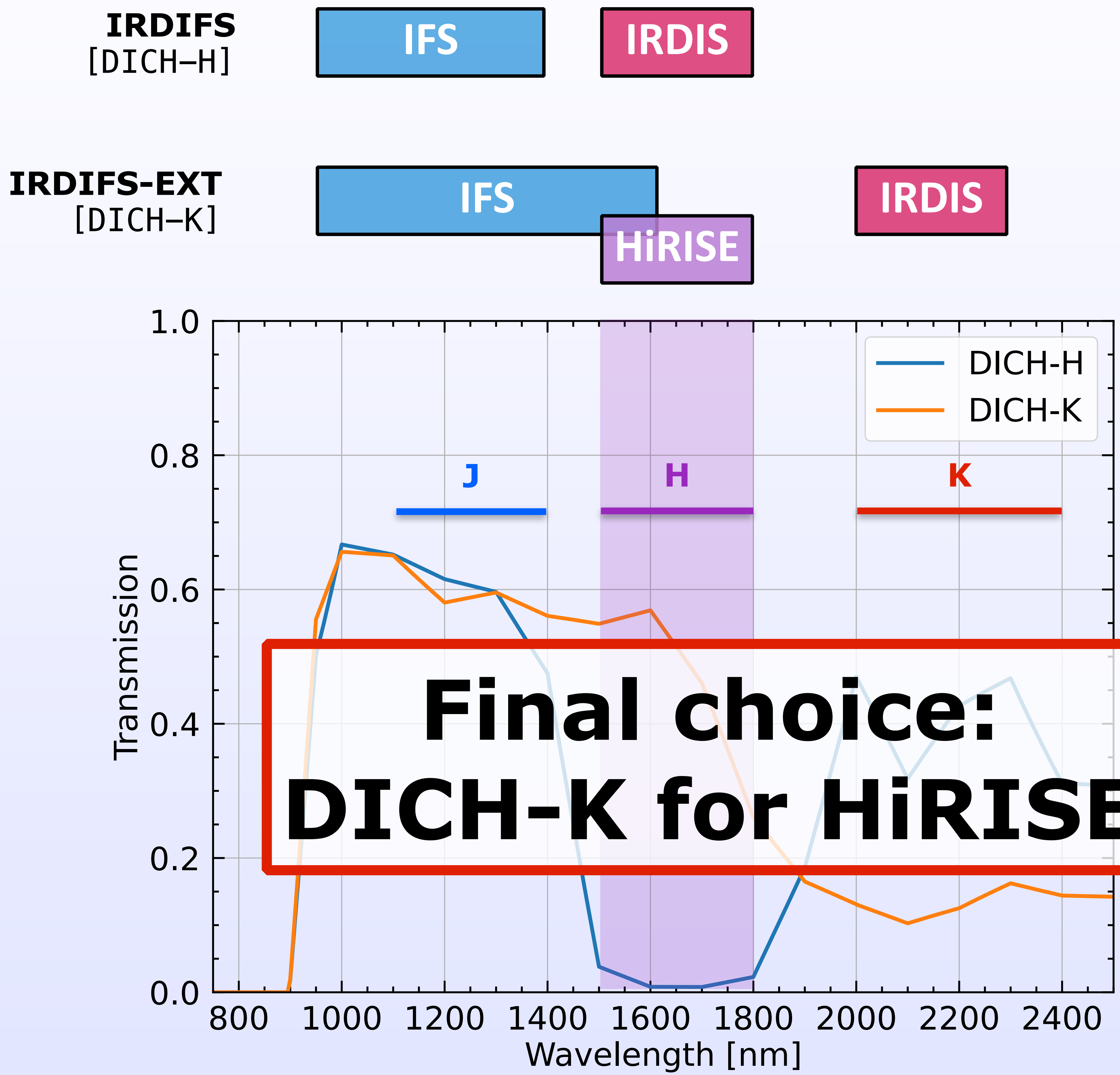
For the planet:
- **0.1 λ/D feasible, but challenging!**
- **0.2 λ/D is a good baseline**

Photon sharing in SPHERE







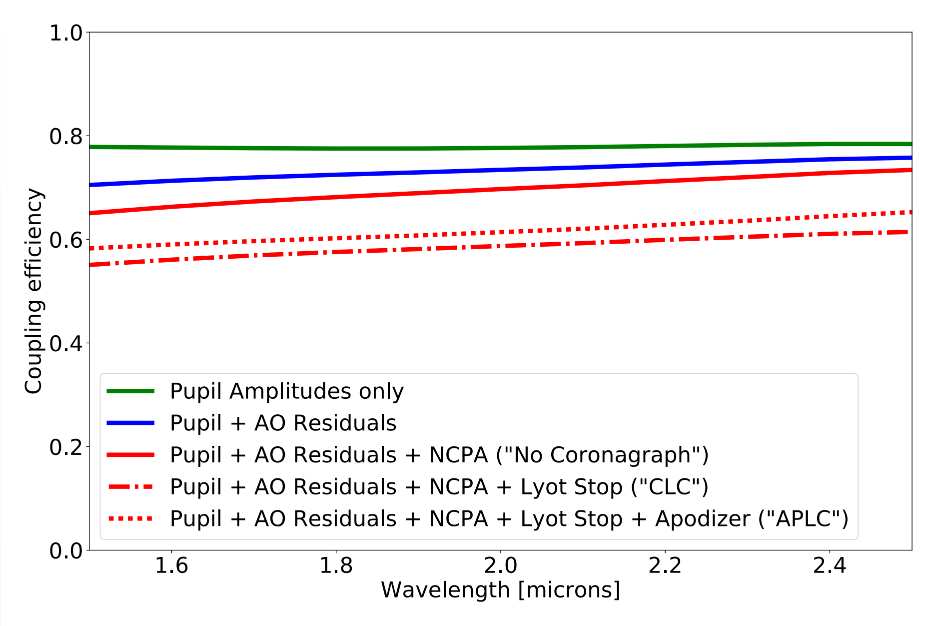


Final choice: DICH-K for HiRISE

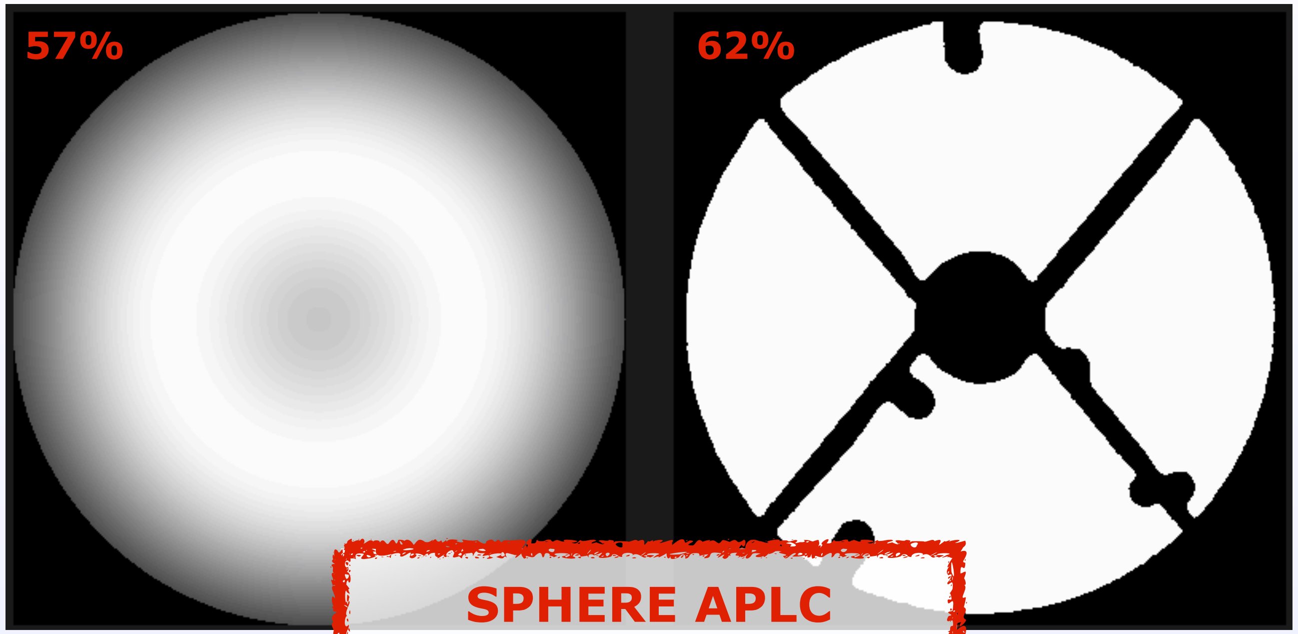
To have or not to have [a coronagraph]?

SPHERE

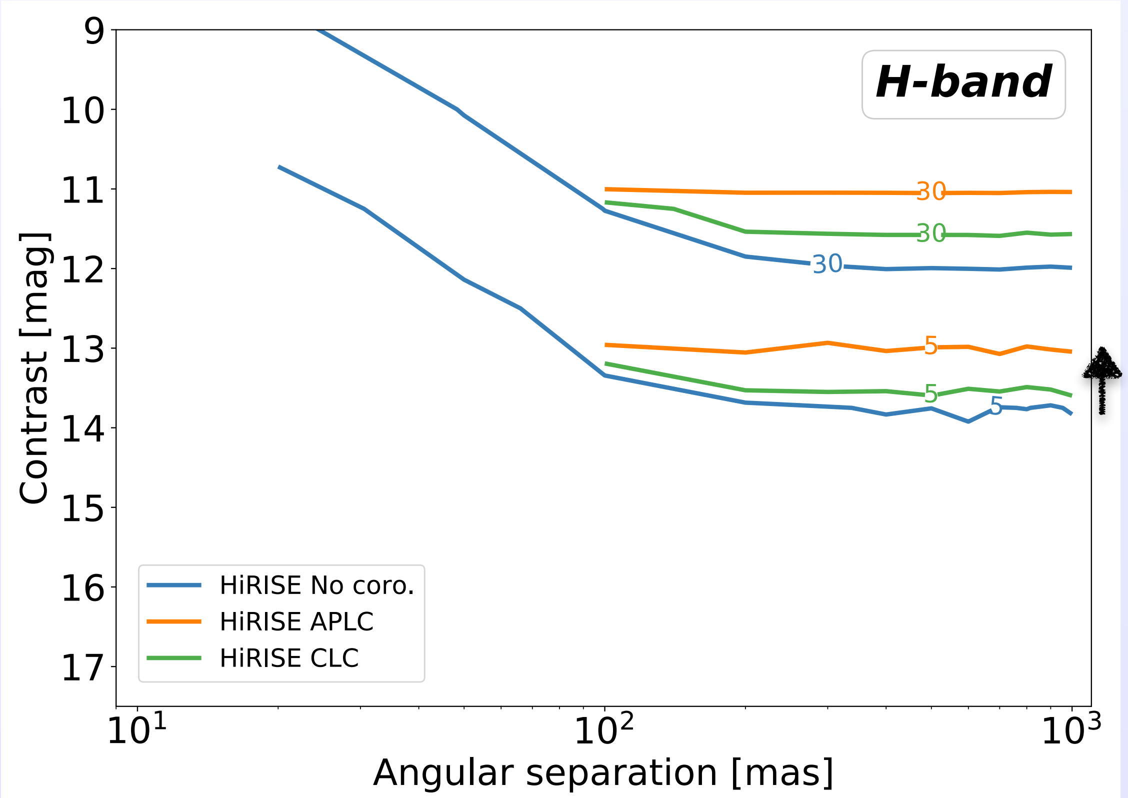
Coupling efficiency



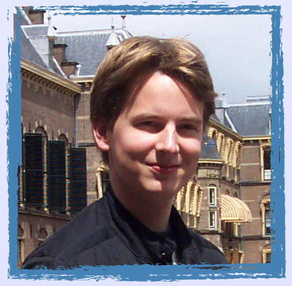
Transmission



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

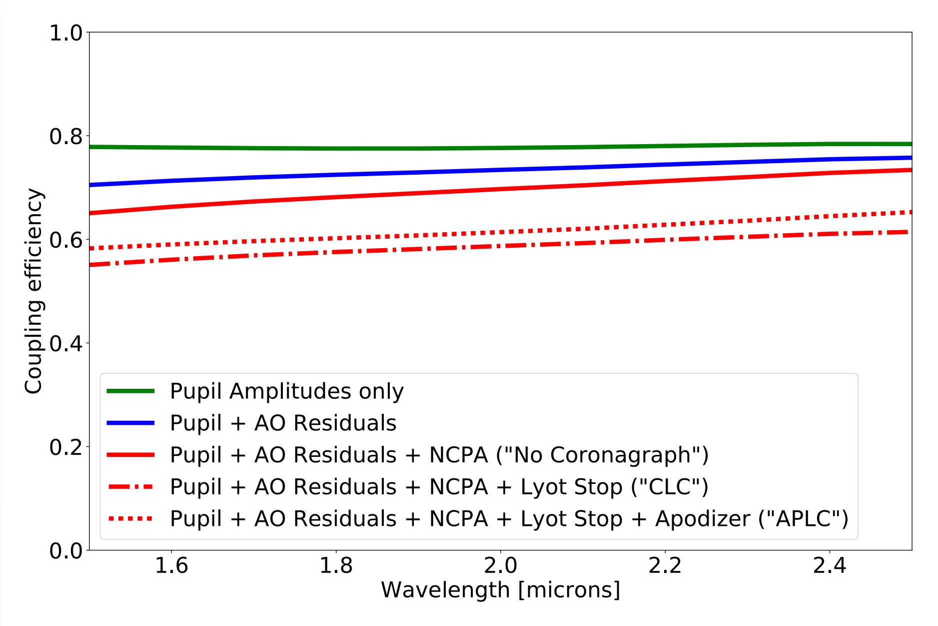


1 mag loss

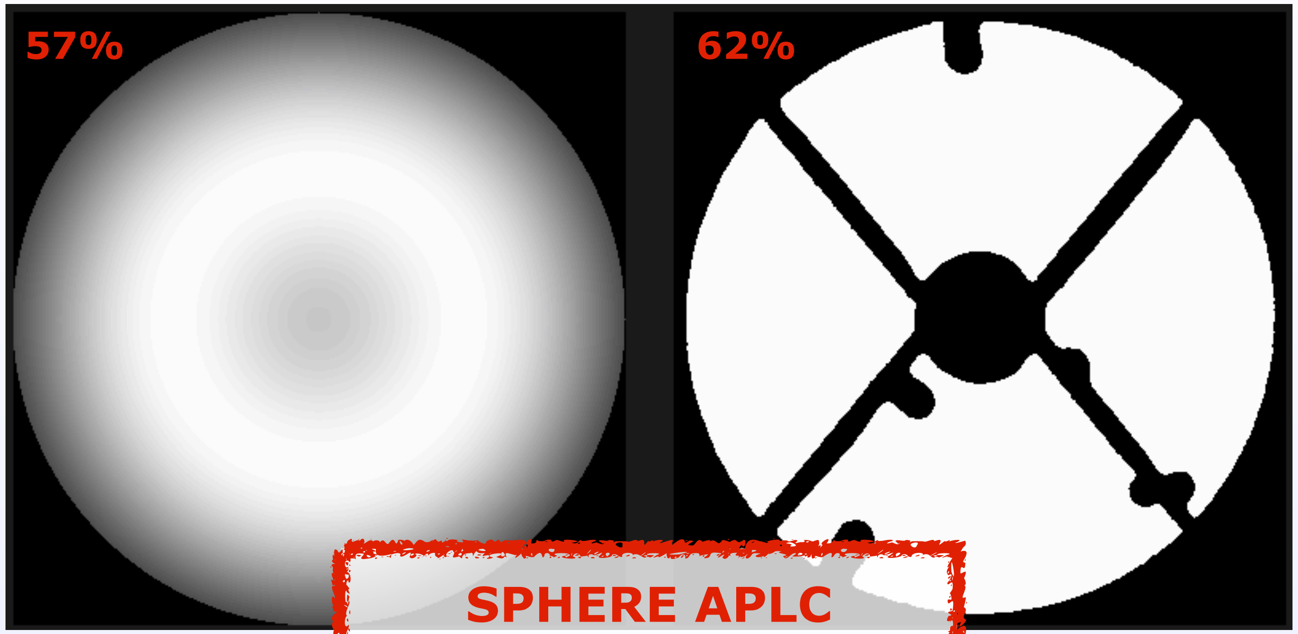


To have or not to have [a coronagraph]?

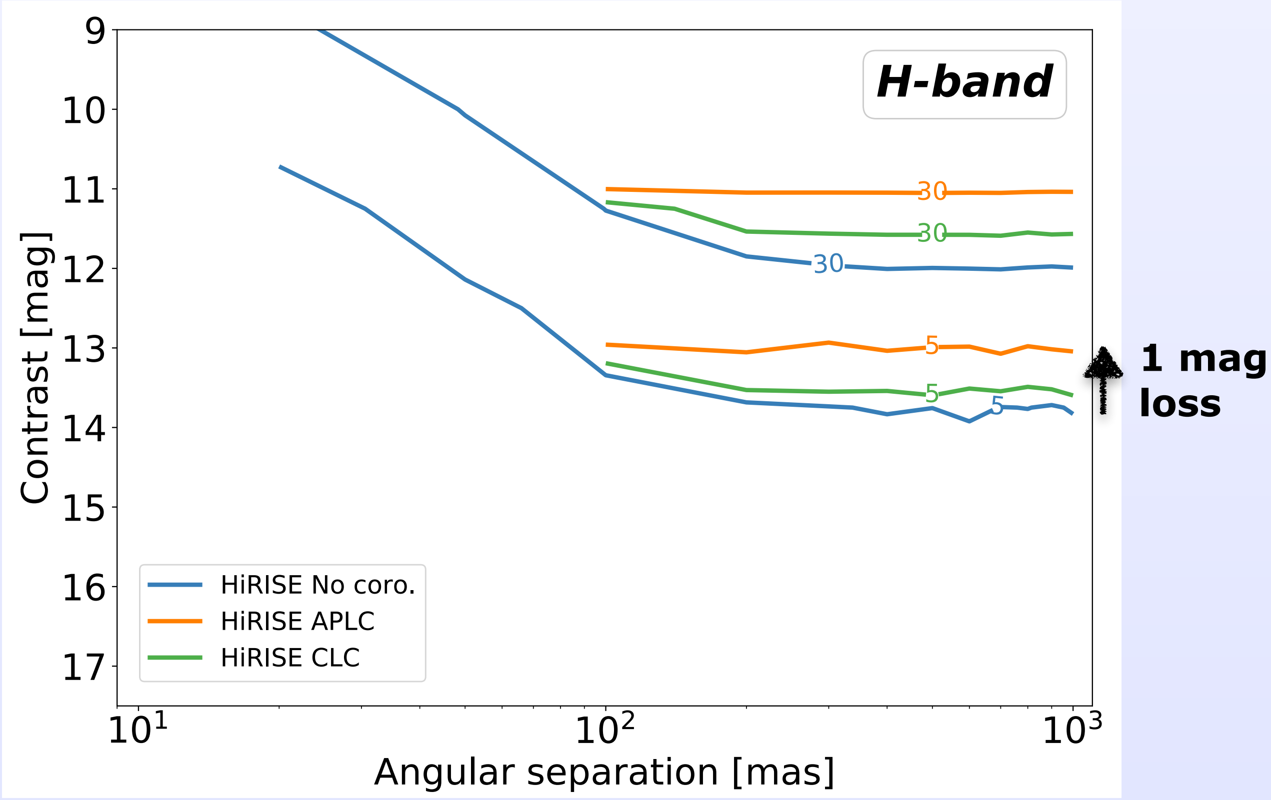
Coupling efficiency



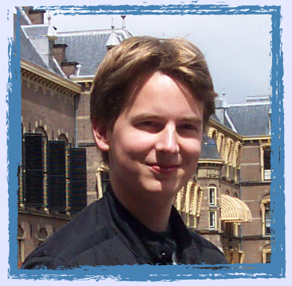
Transmission



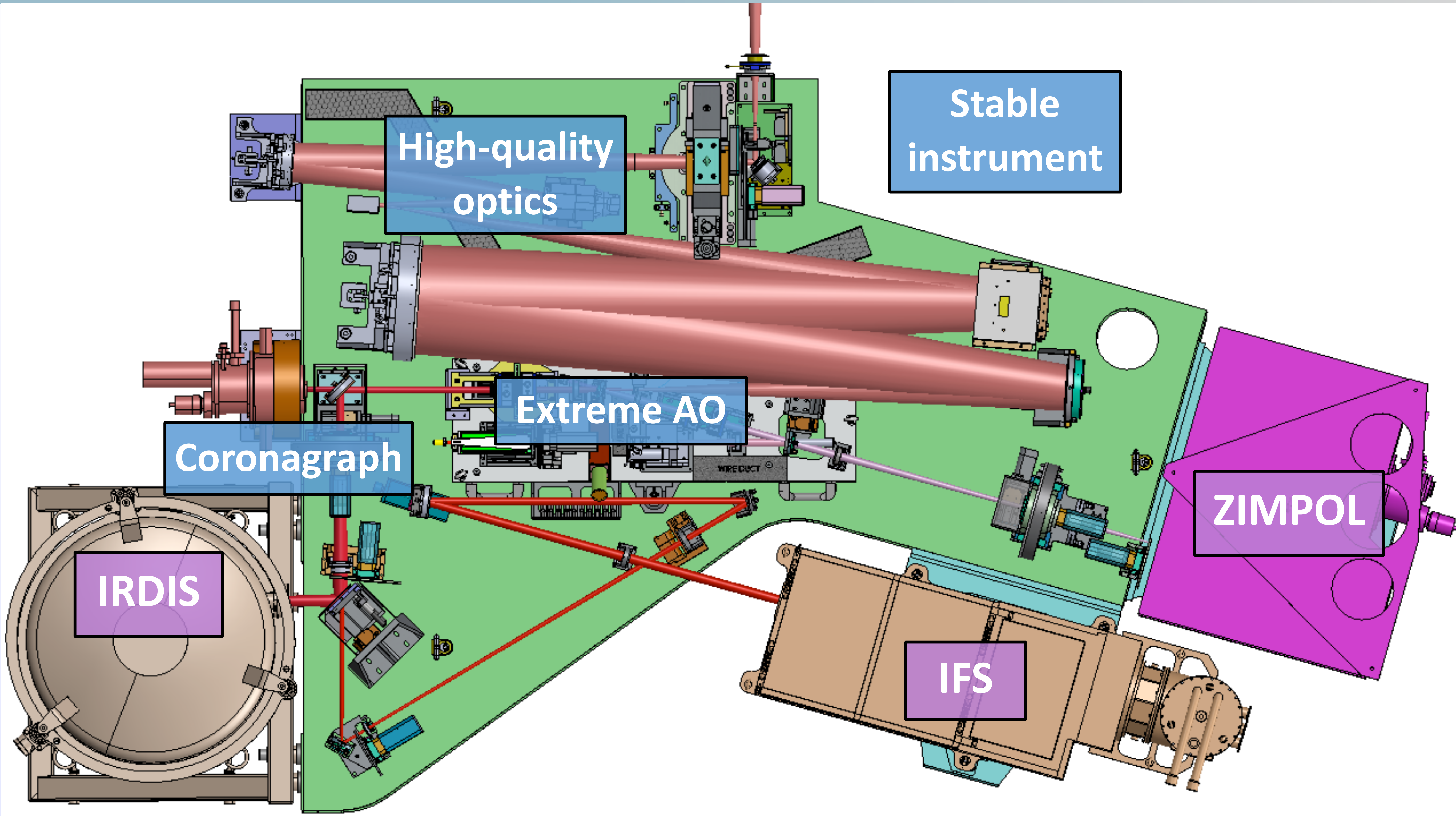
SPHERE APLC
<40% of the total flux is transmitted!!



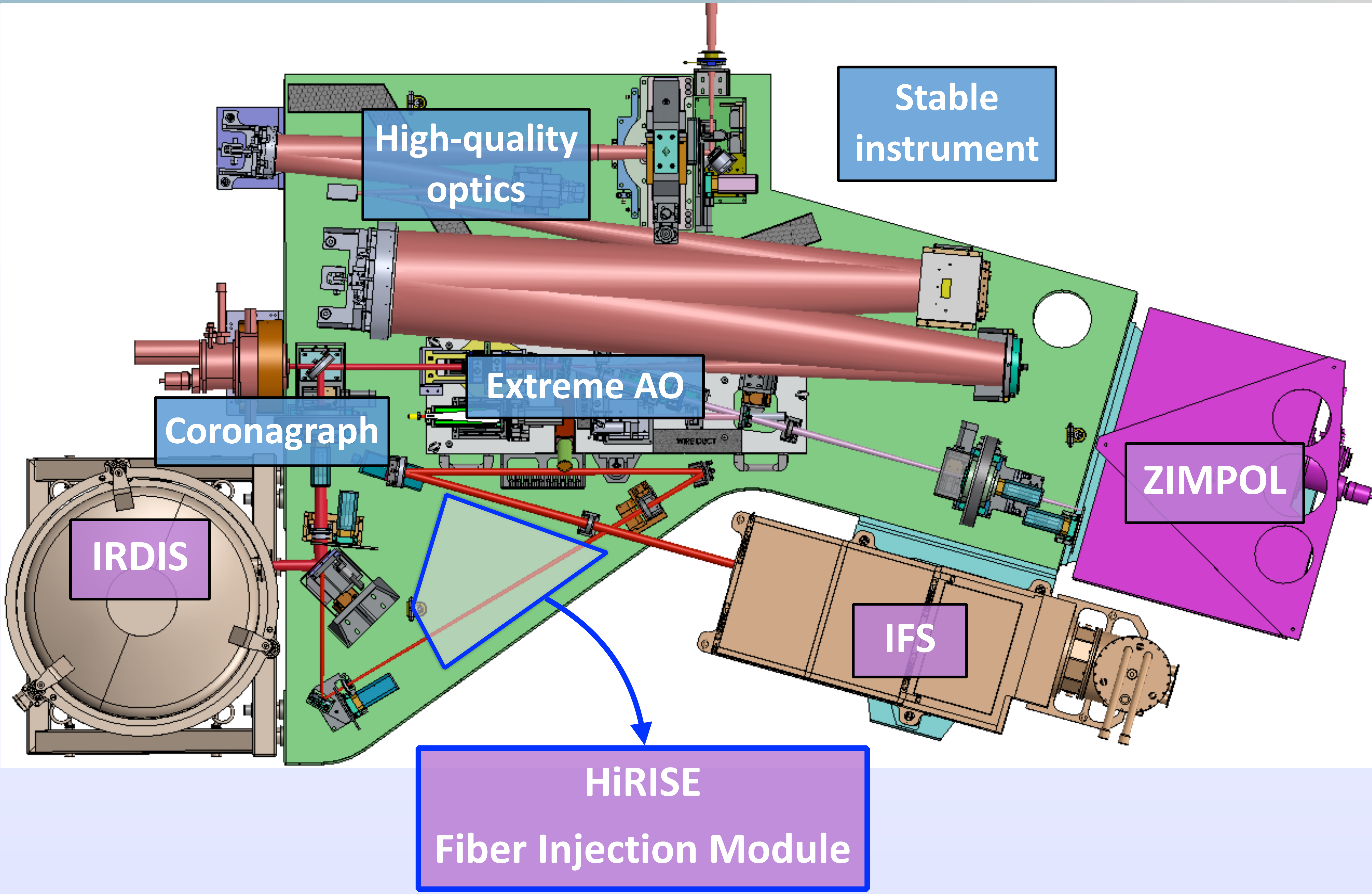
Final choice: No coronagraph



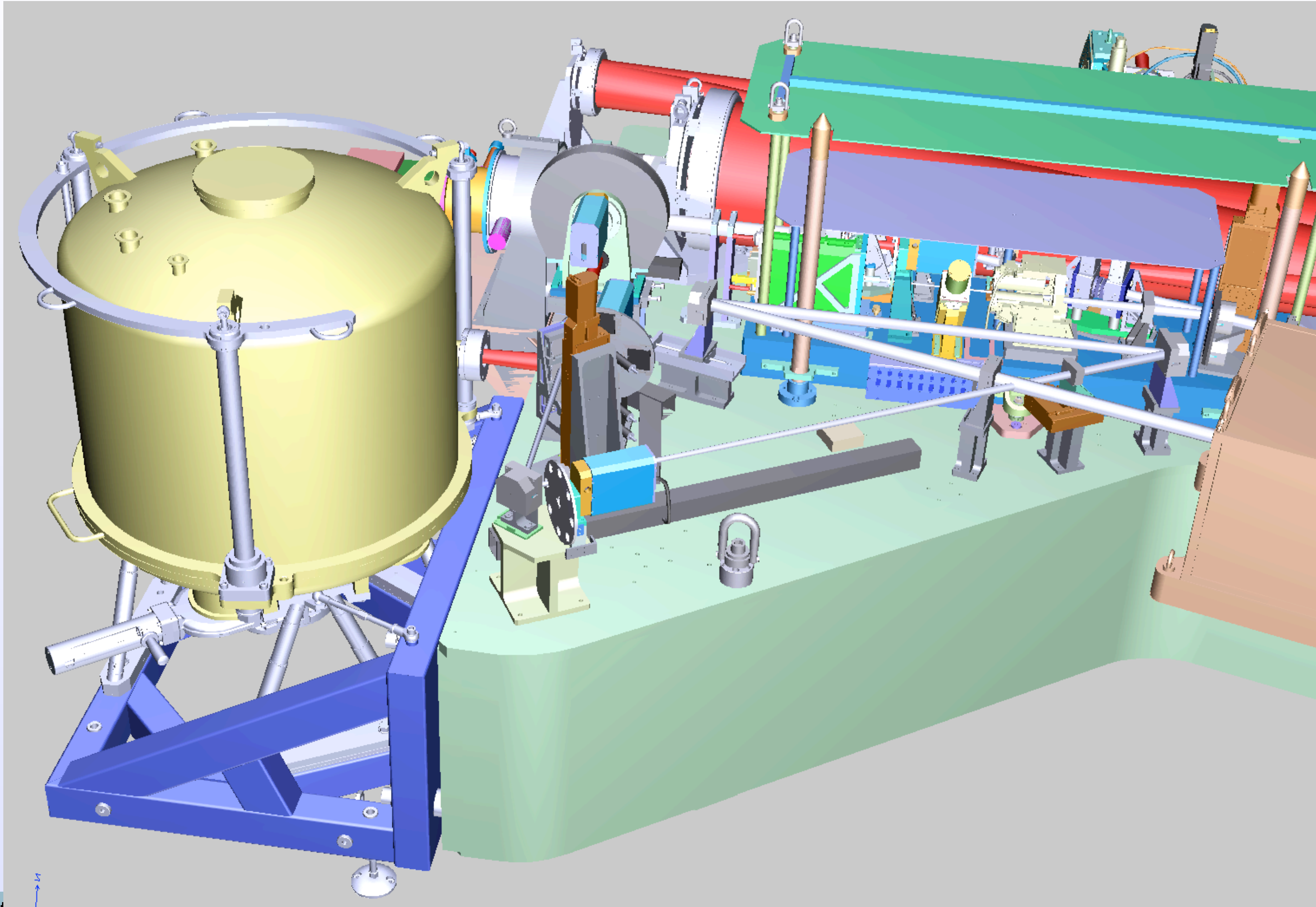
Fiber injection module



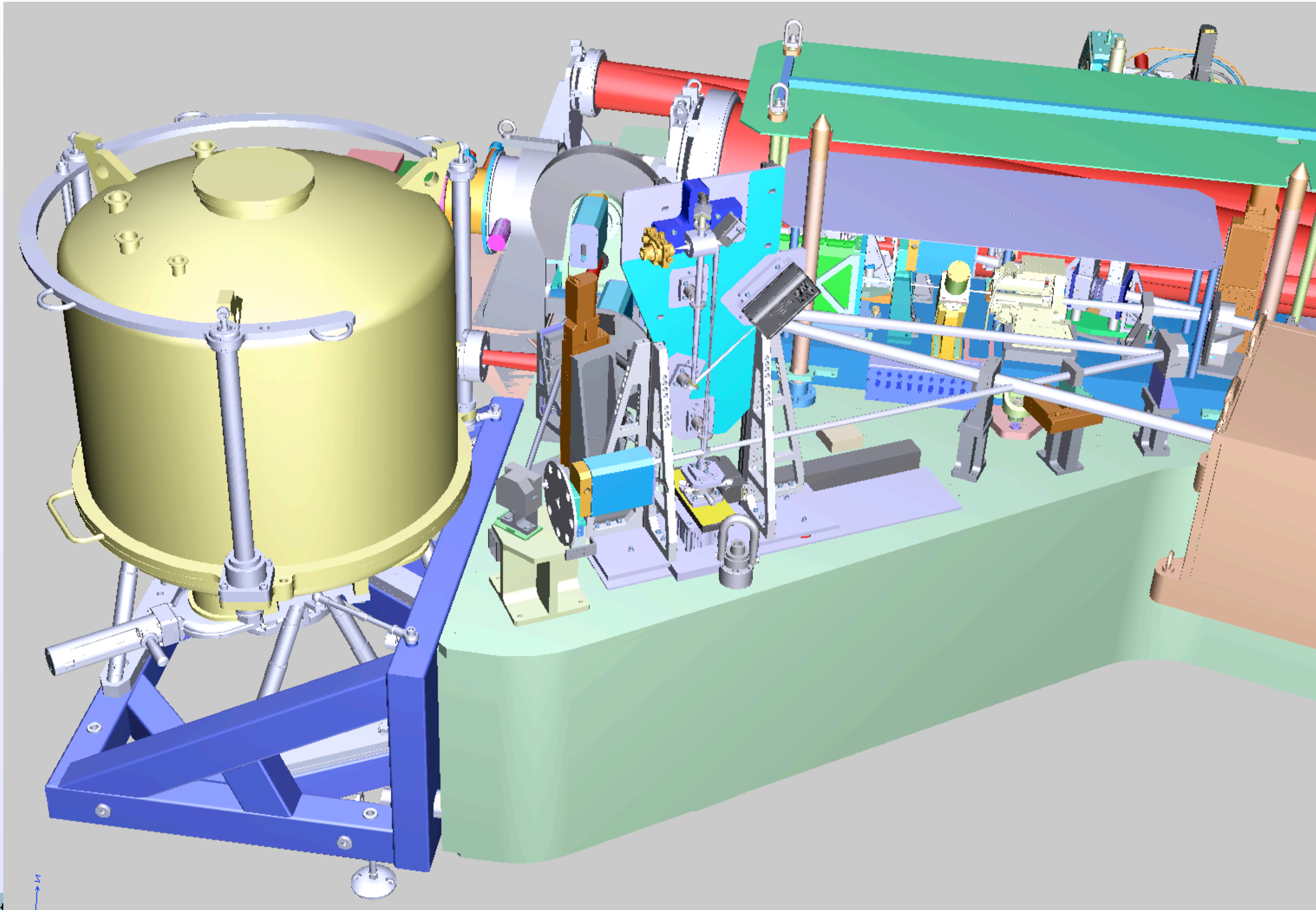
Fiber injection module

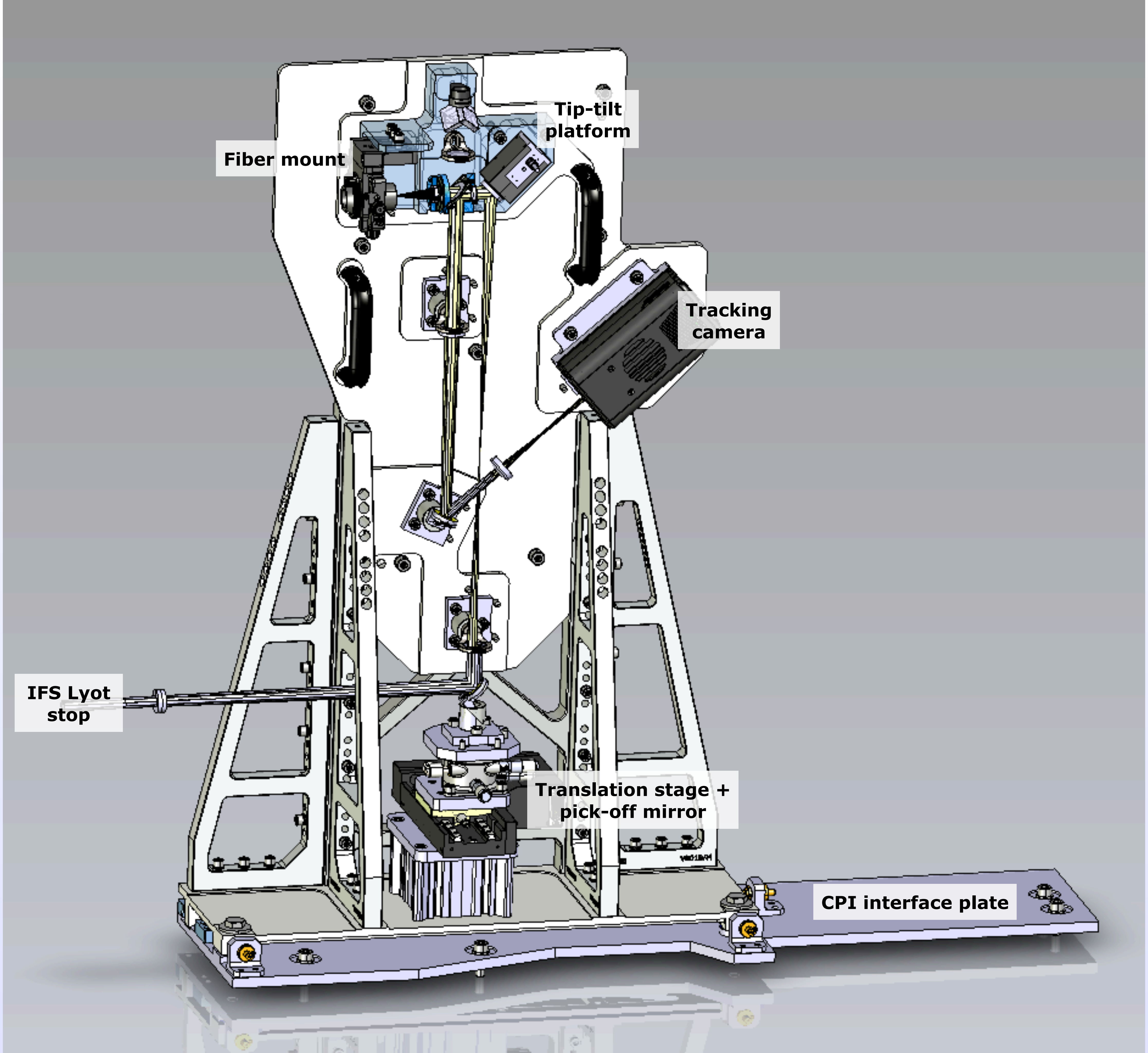


Fiber injection module

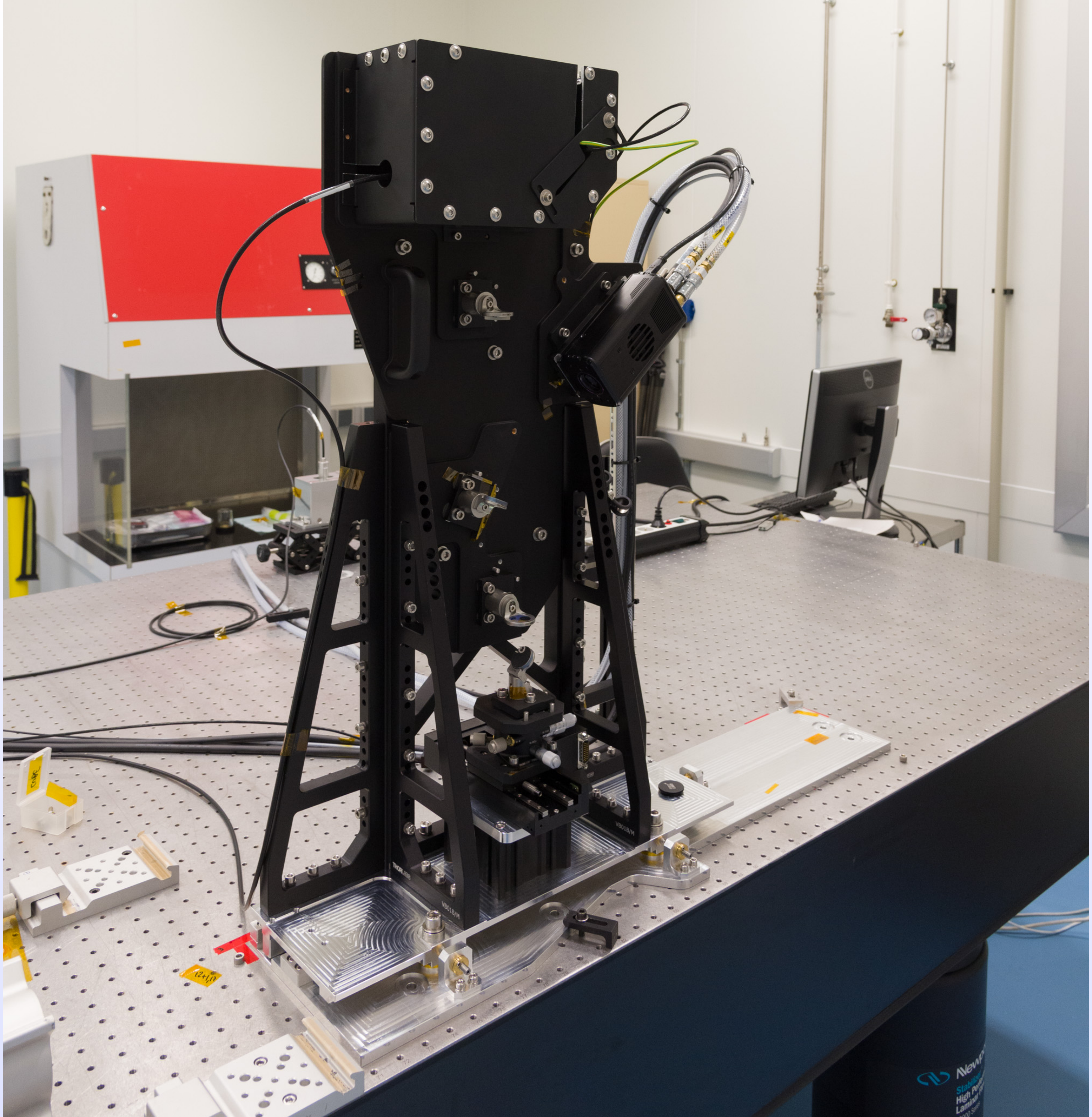


Fiber injection module

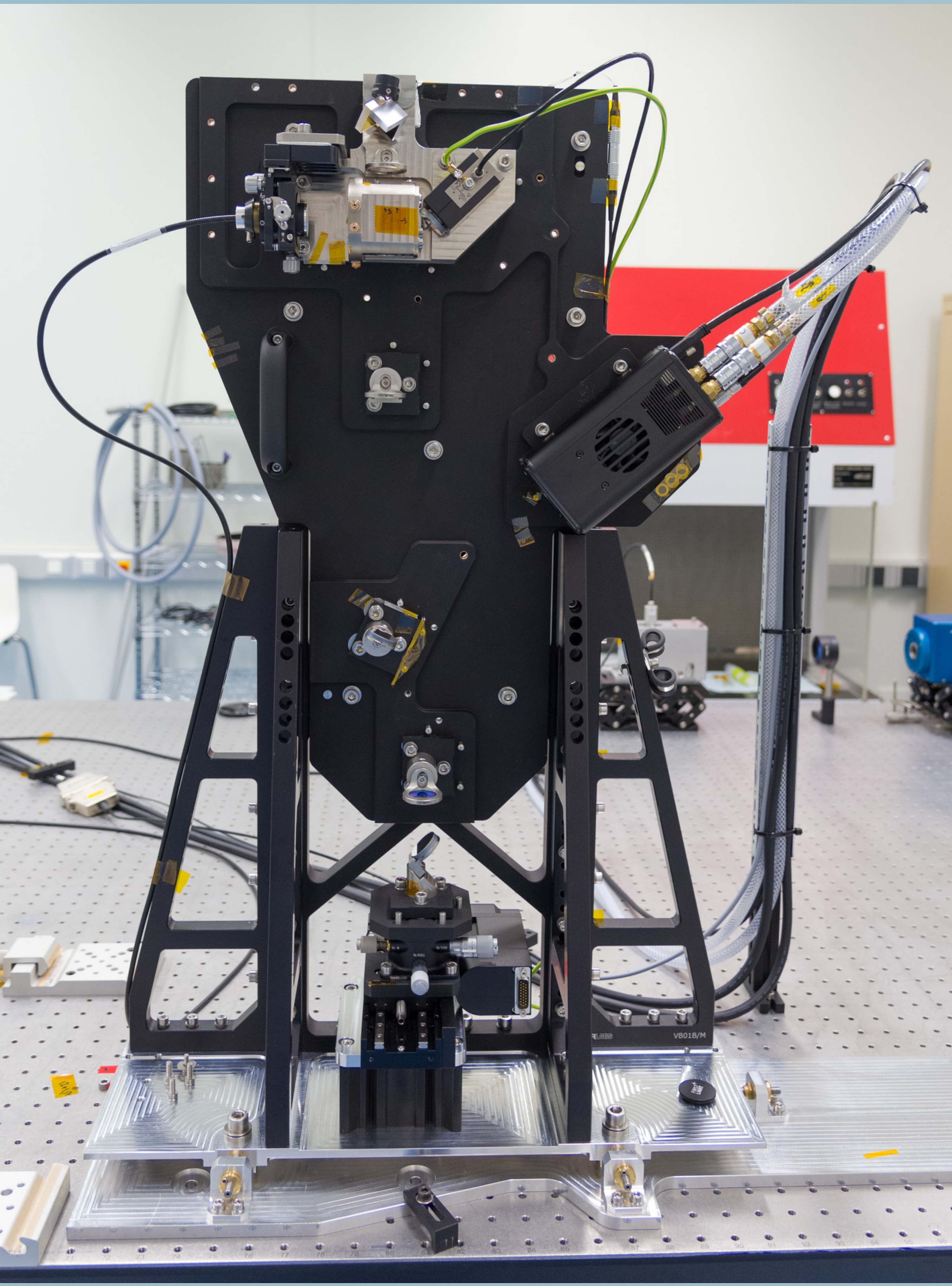


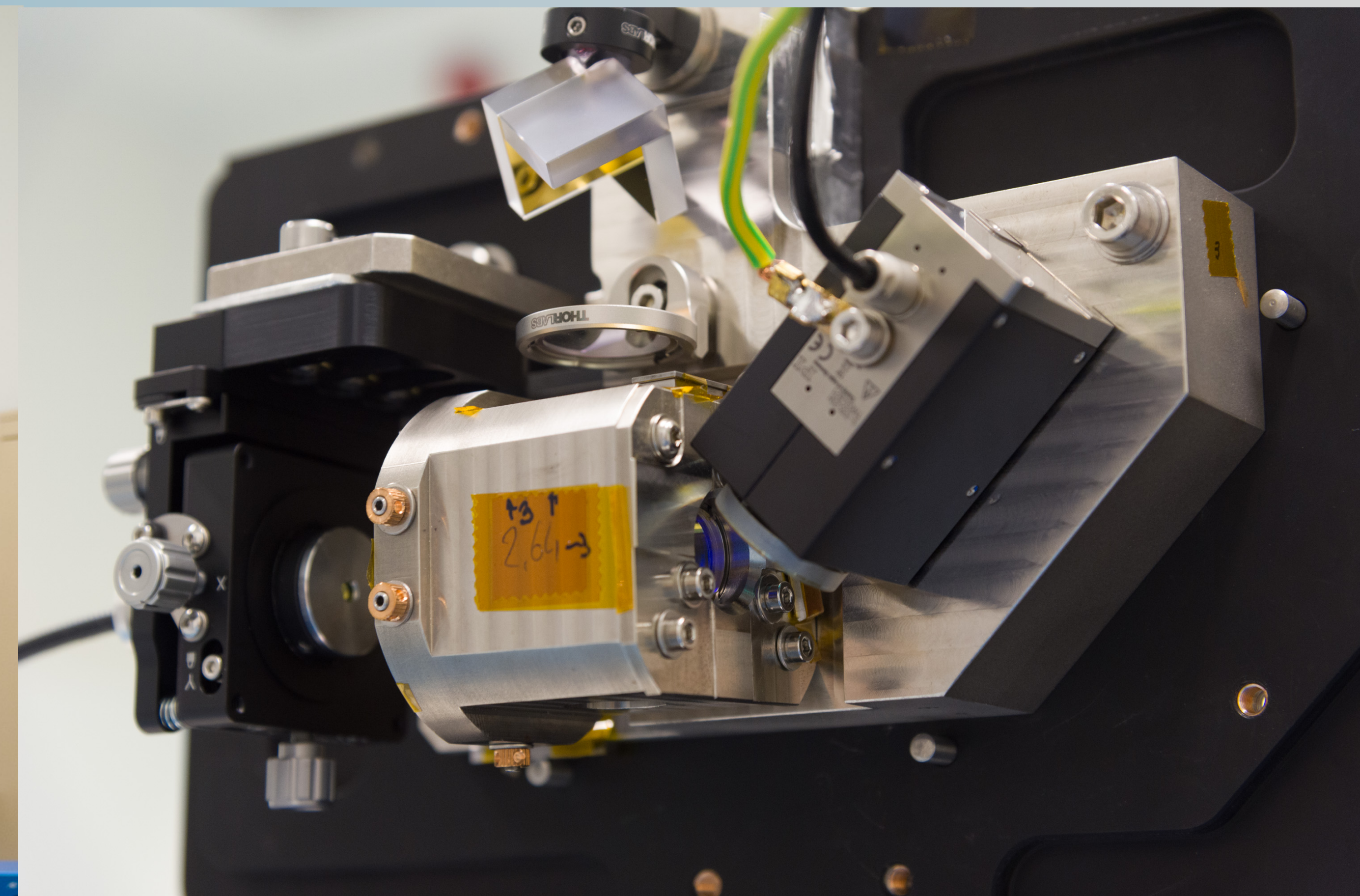


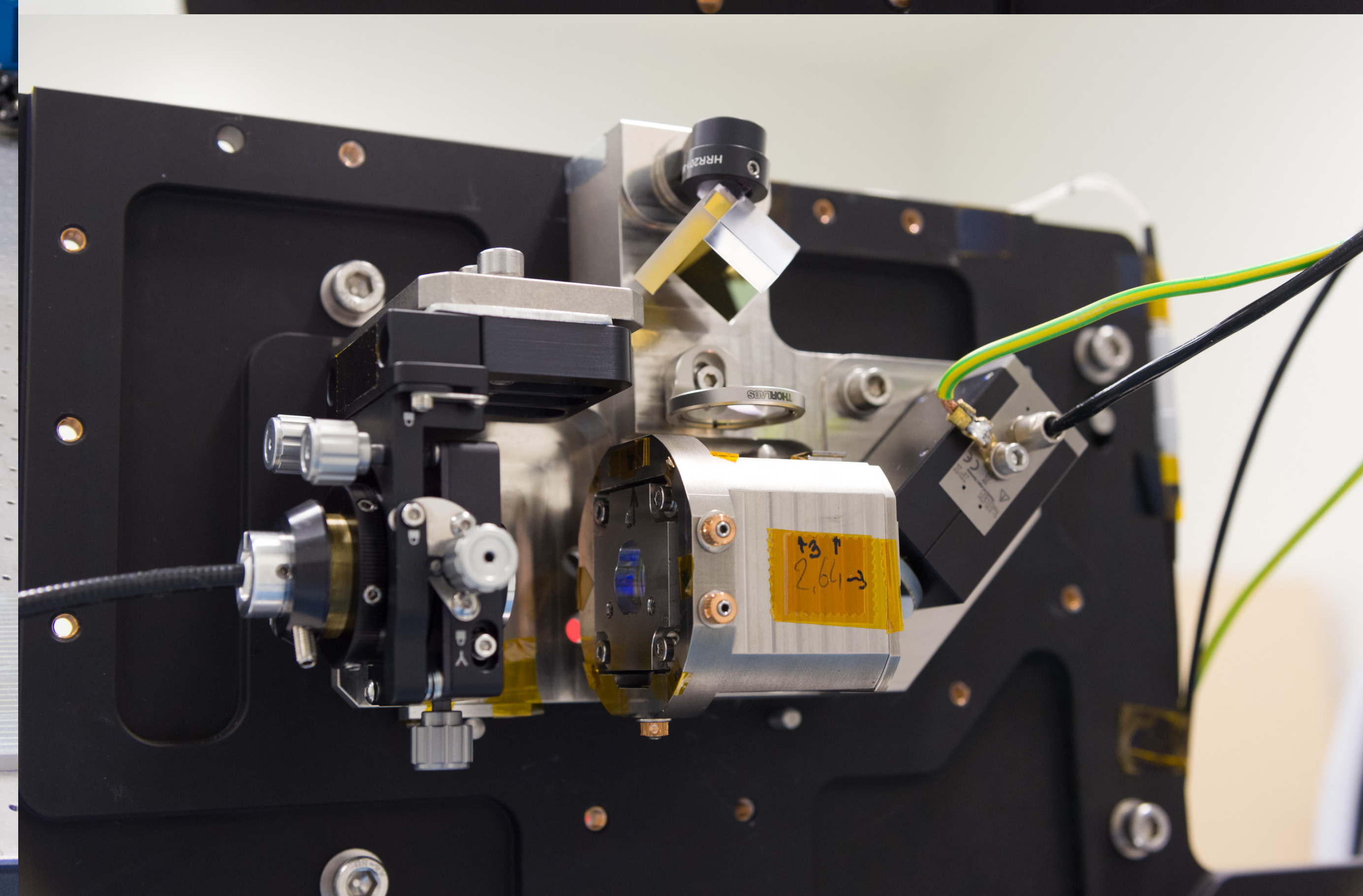
Tip-tilt platform
Fiber mount
Tracking camera
IFS Lyot stop
Translation stage + pick-off mirror
CPI interface plate



Fiber injection module

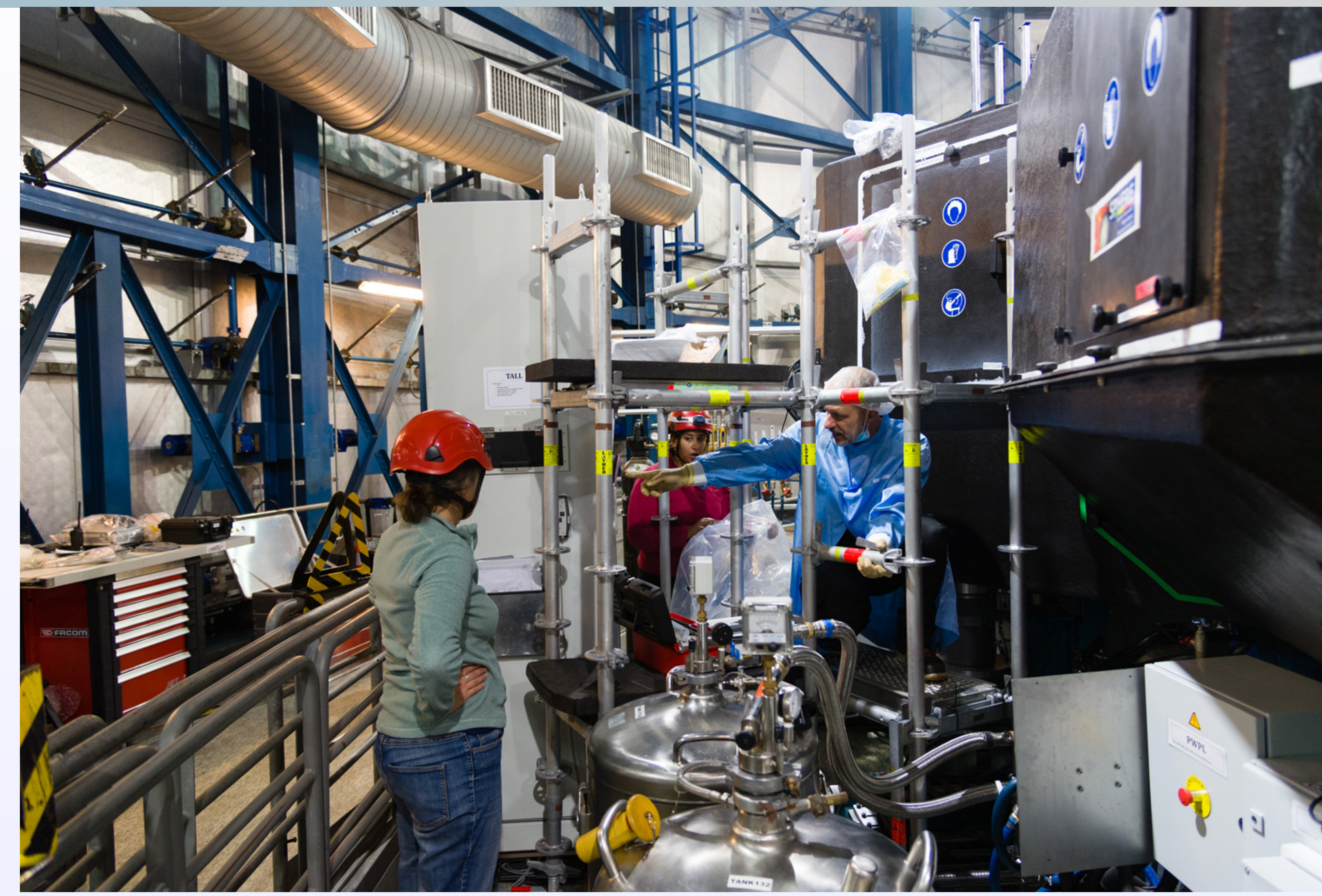






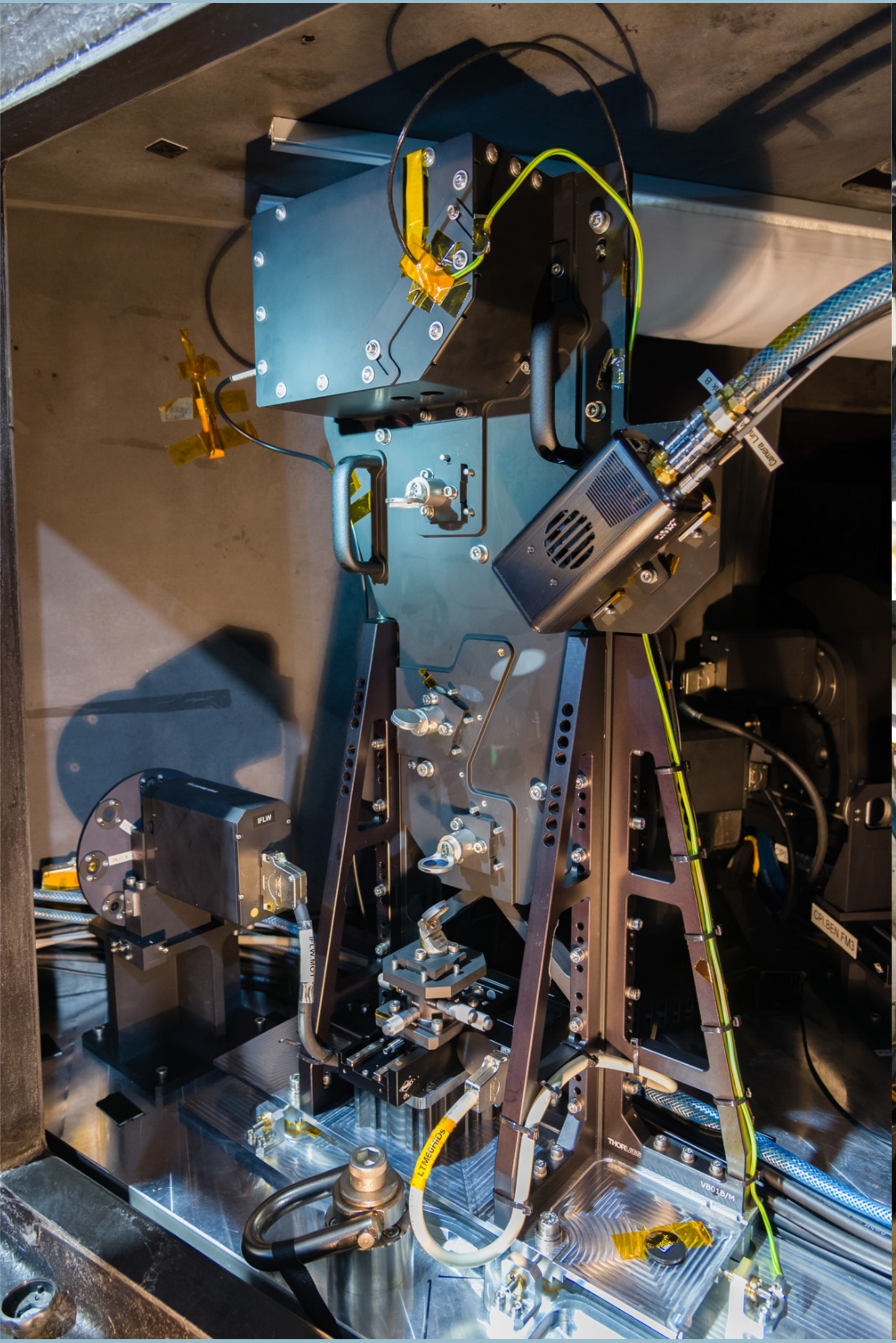
Fiber injection module

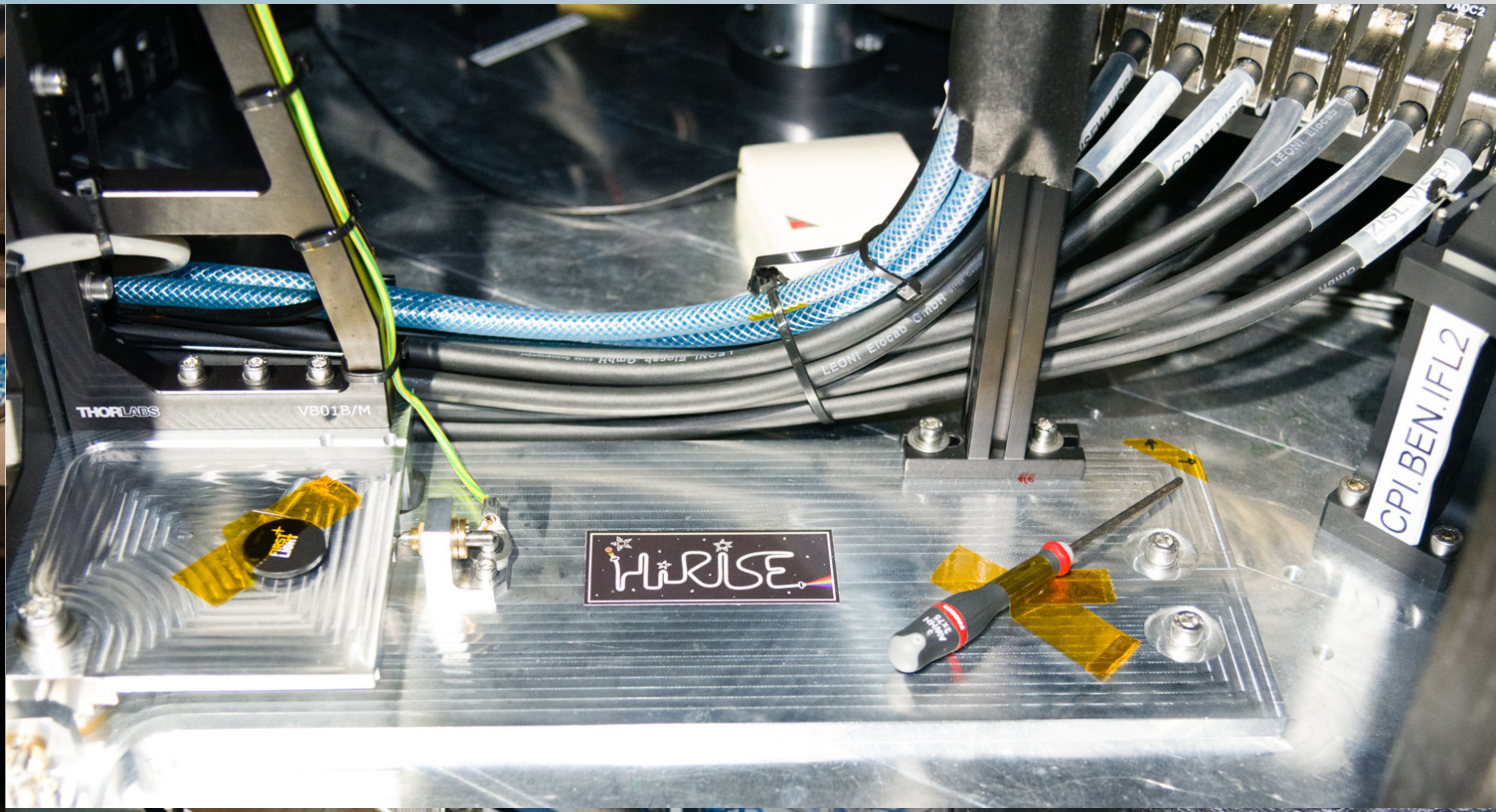
Fiber injection module

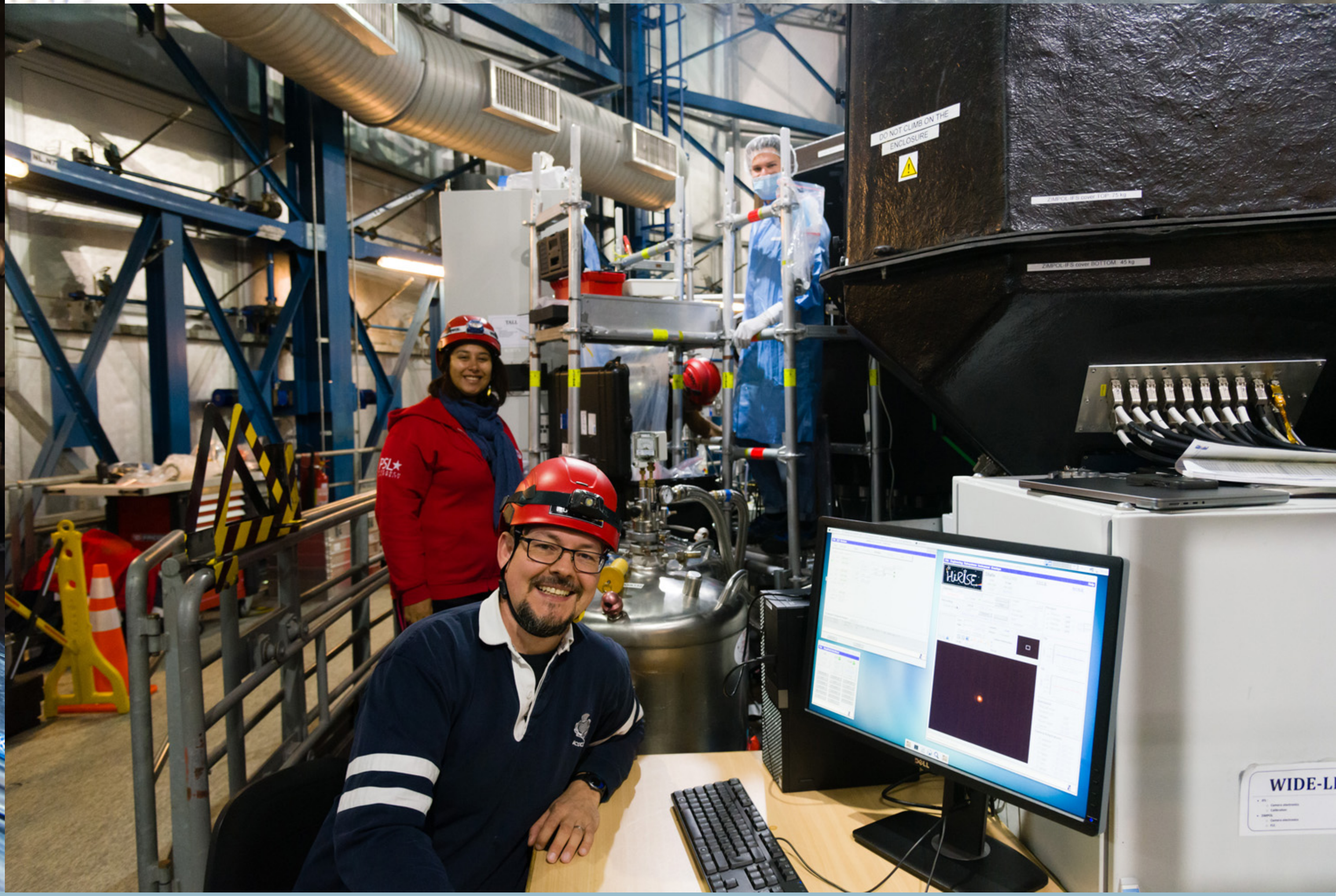


Fiber injection module

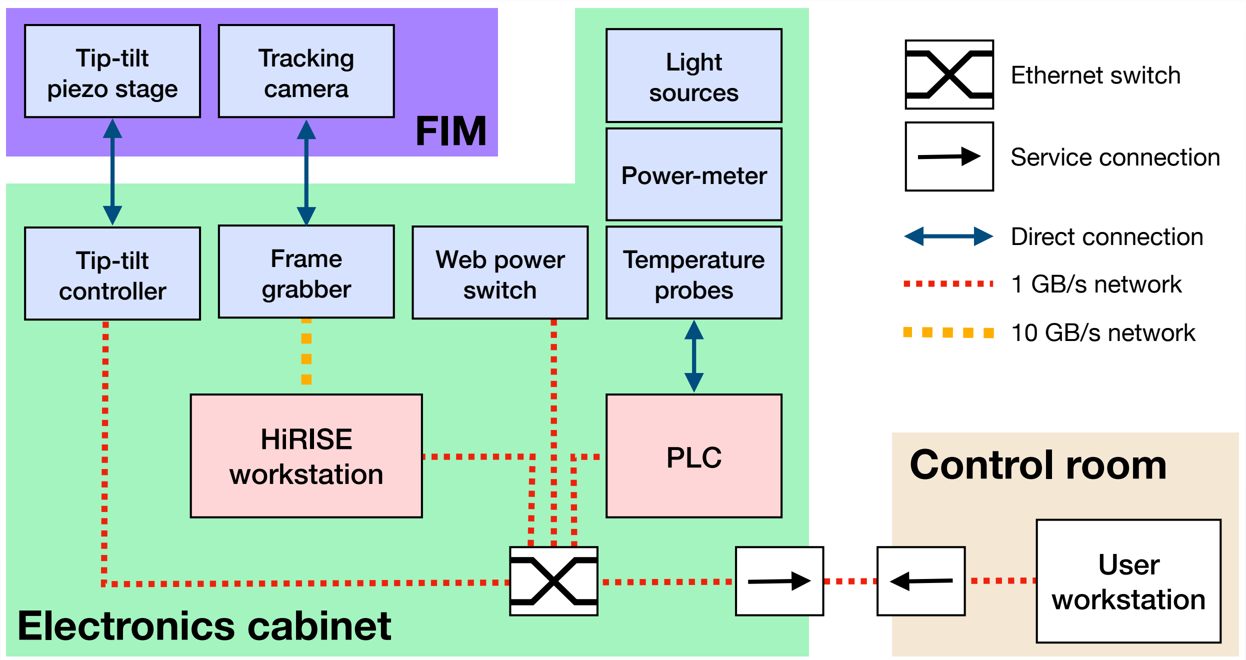
Fiber injection module



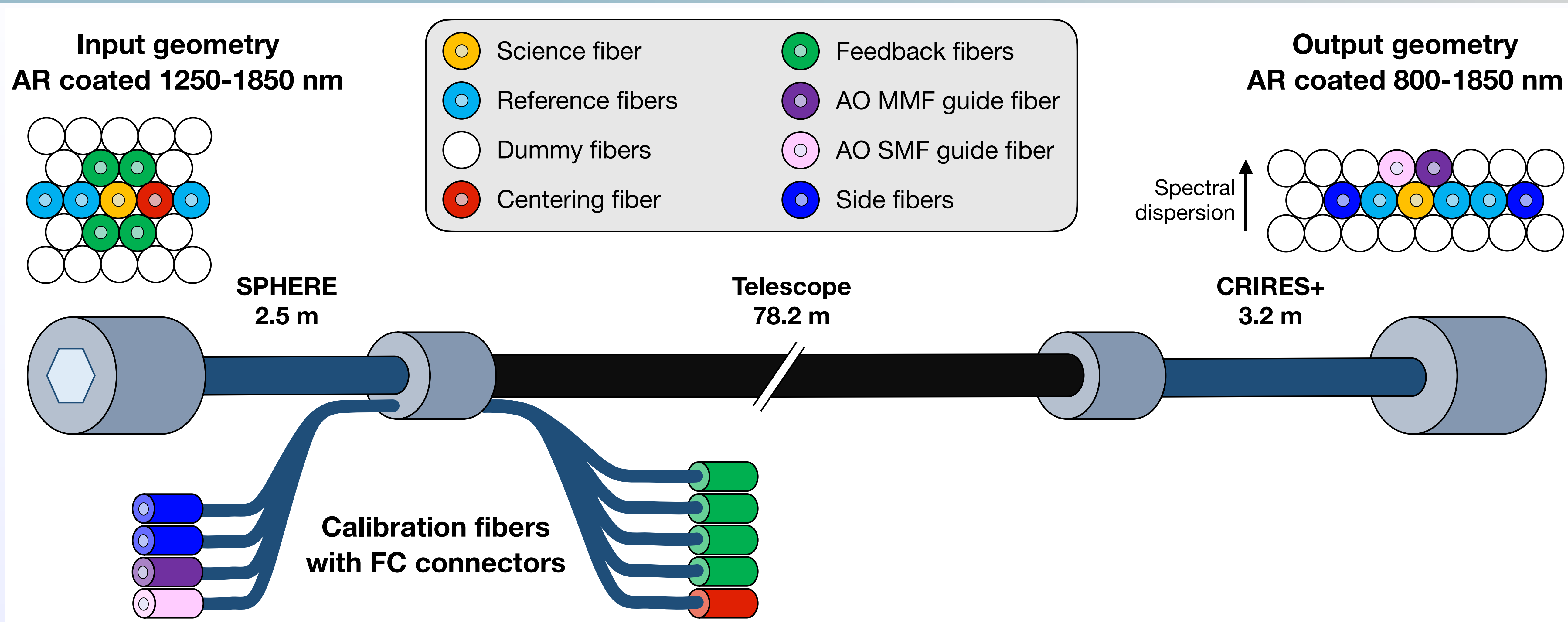


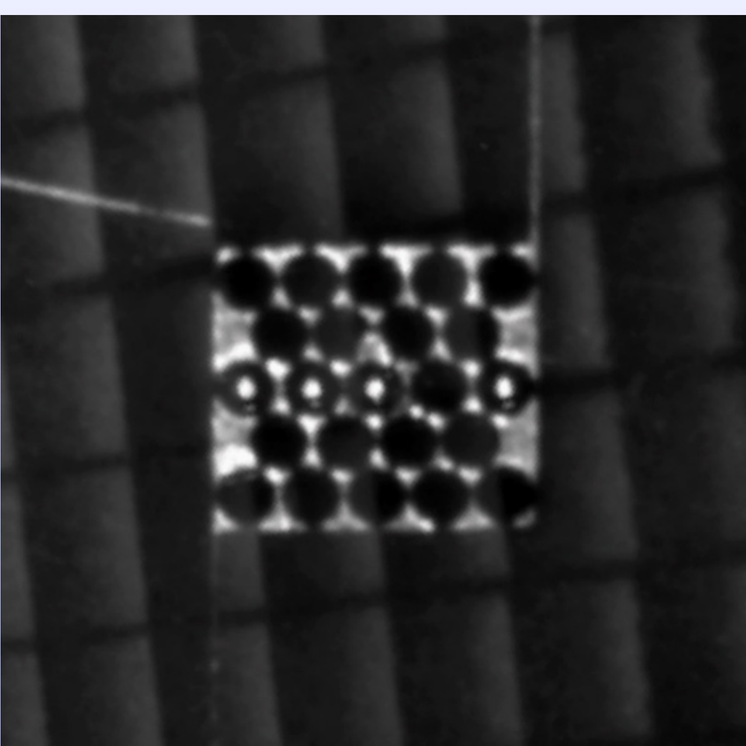


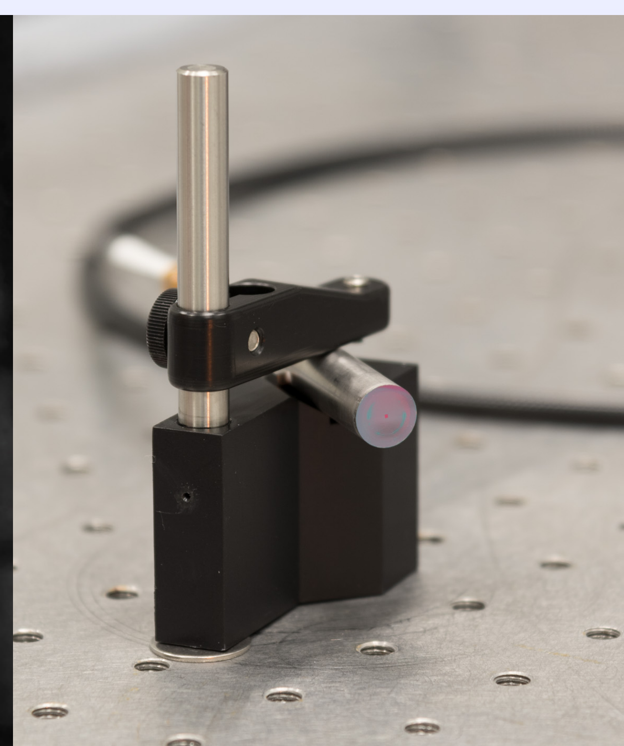
Electronics cabinet

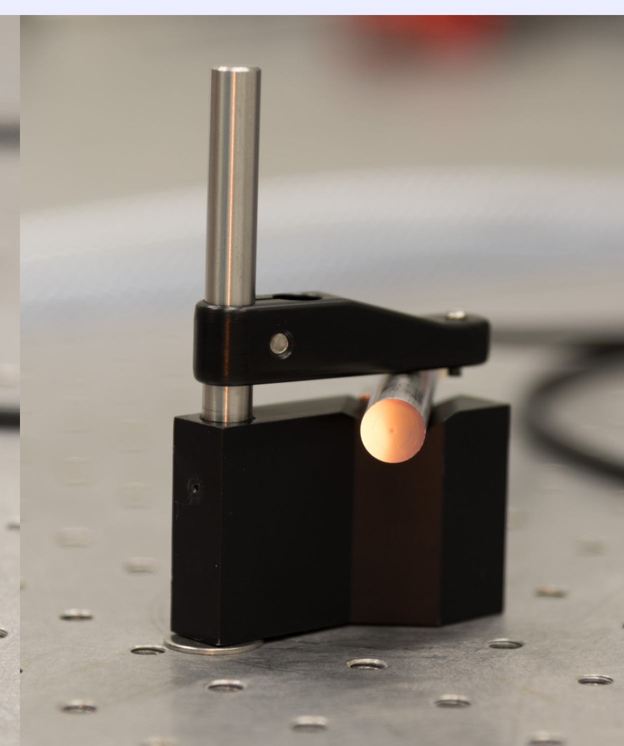


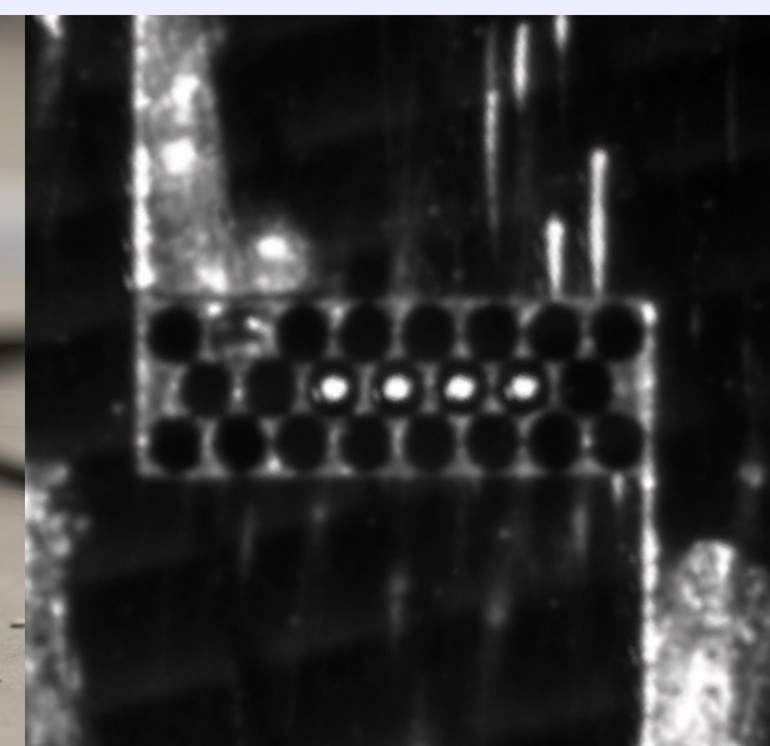
A complex fiber bundle



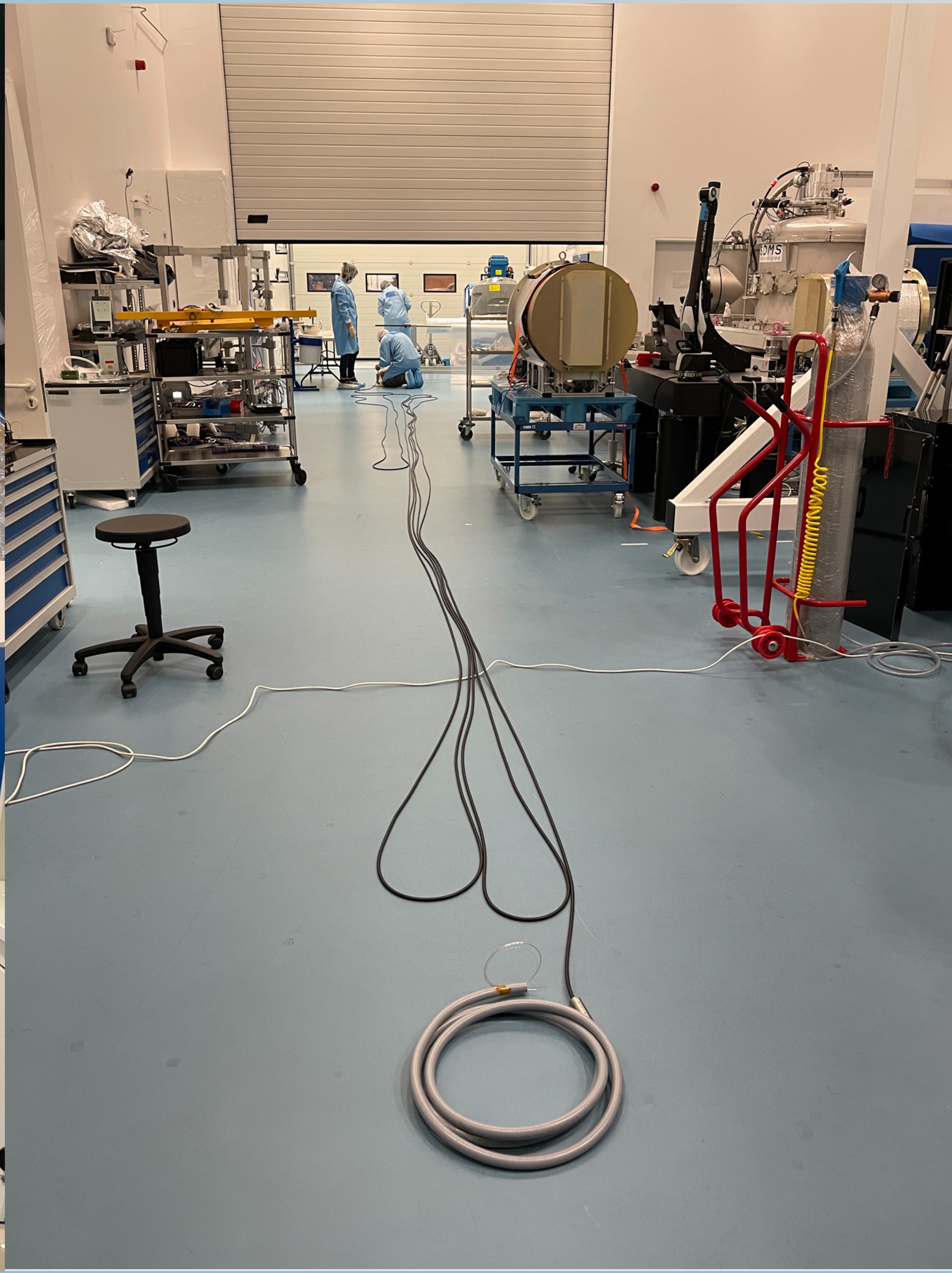




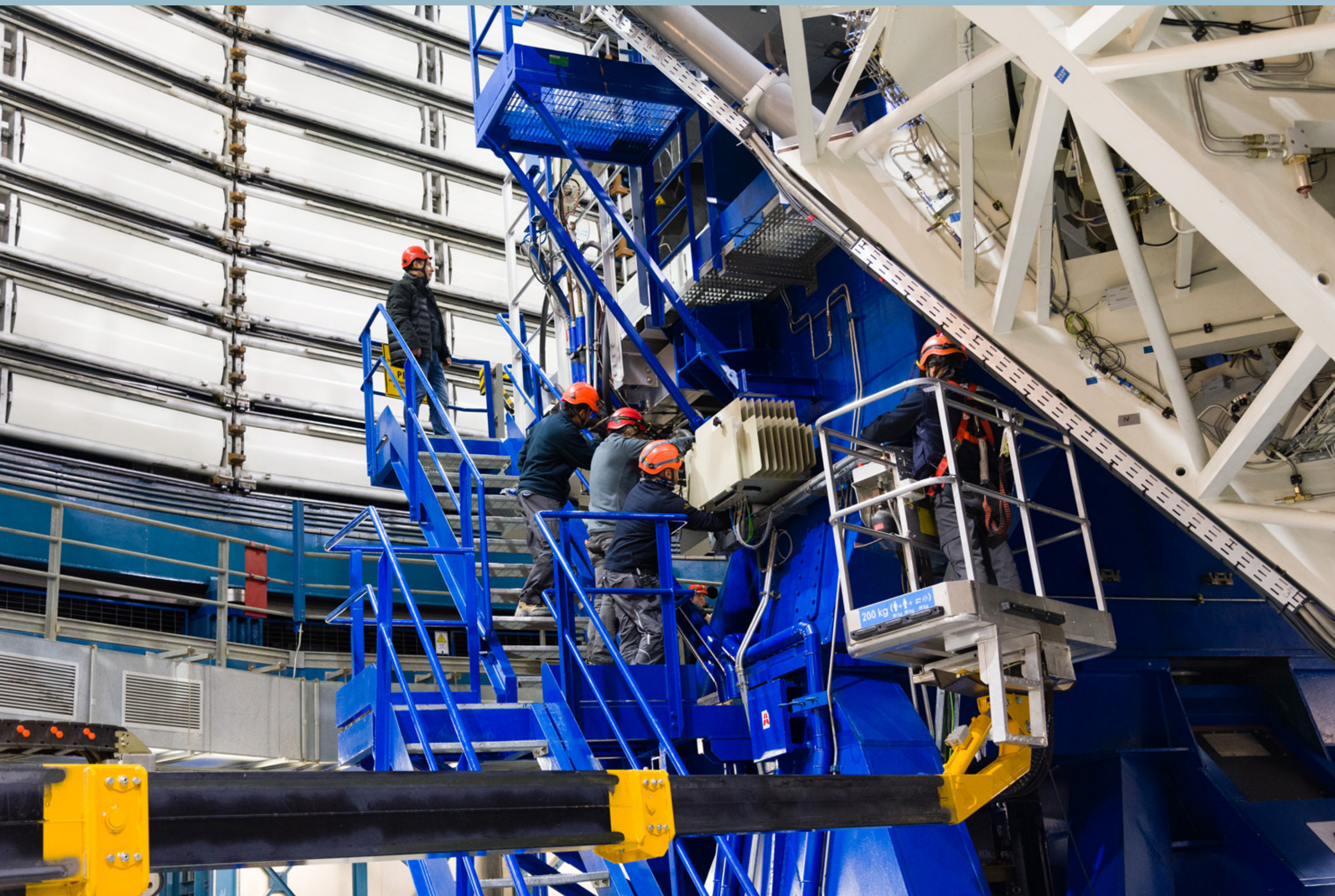




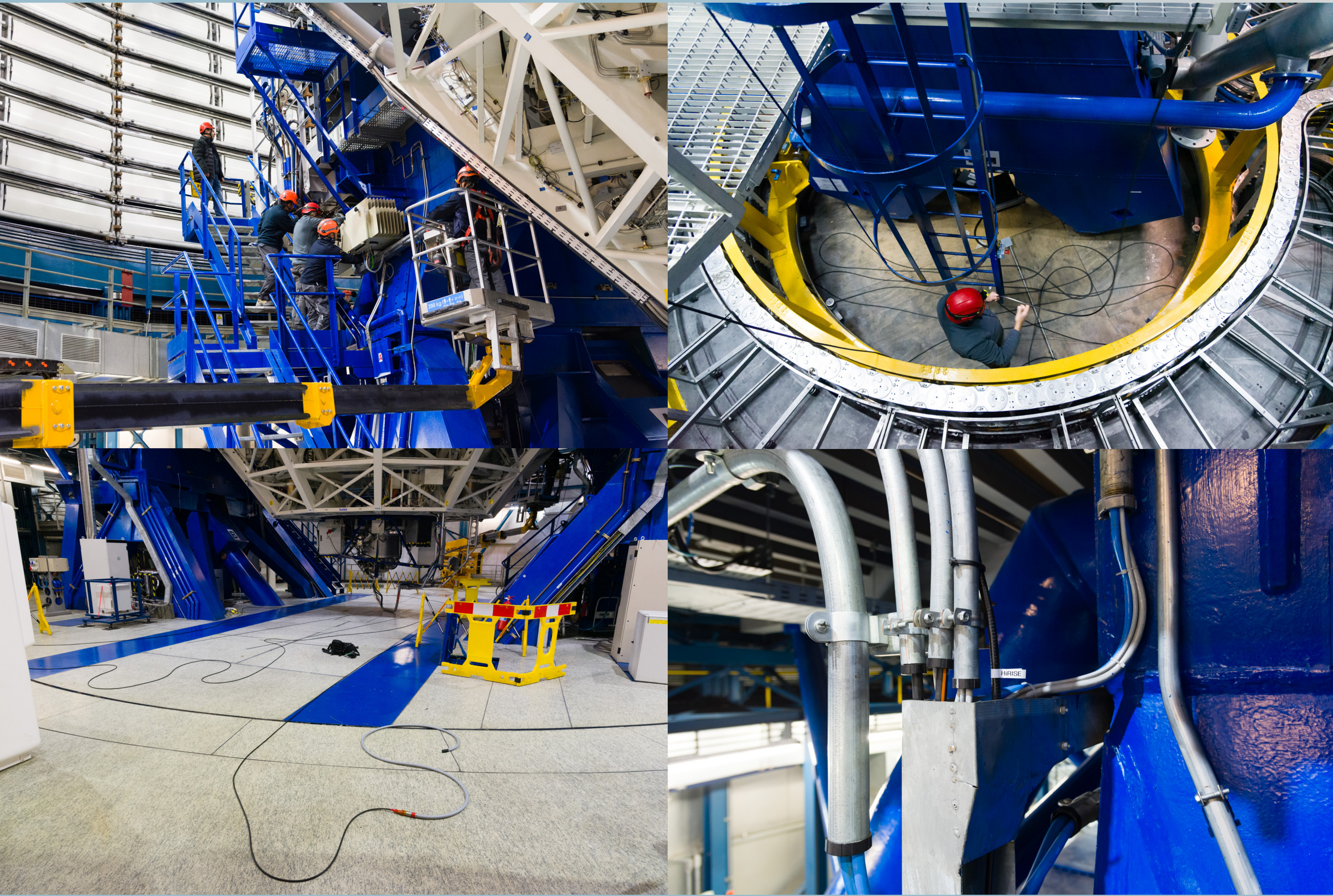
A complex fiber bundle



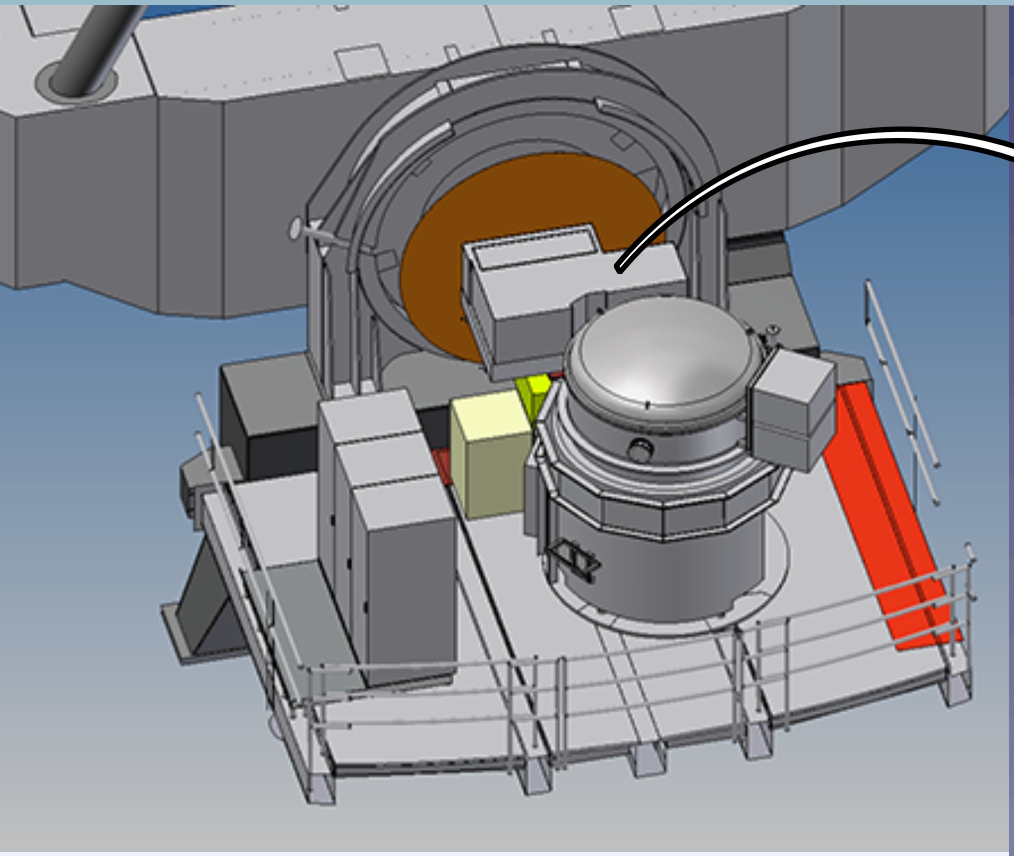
A complex fiber bundle

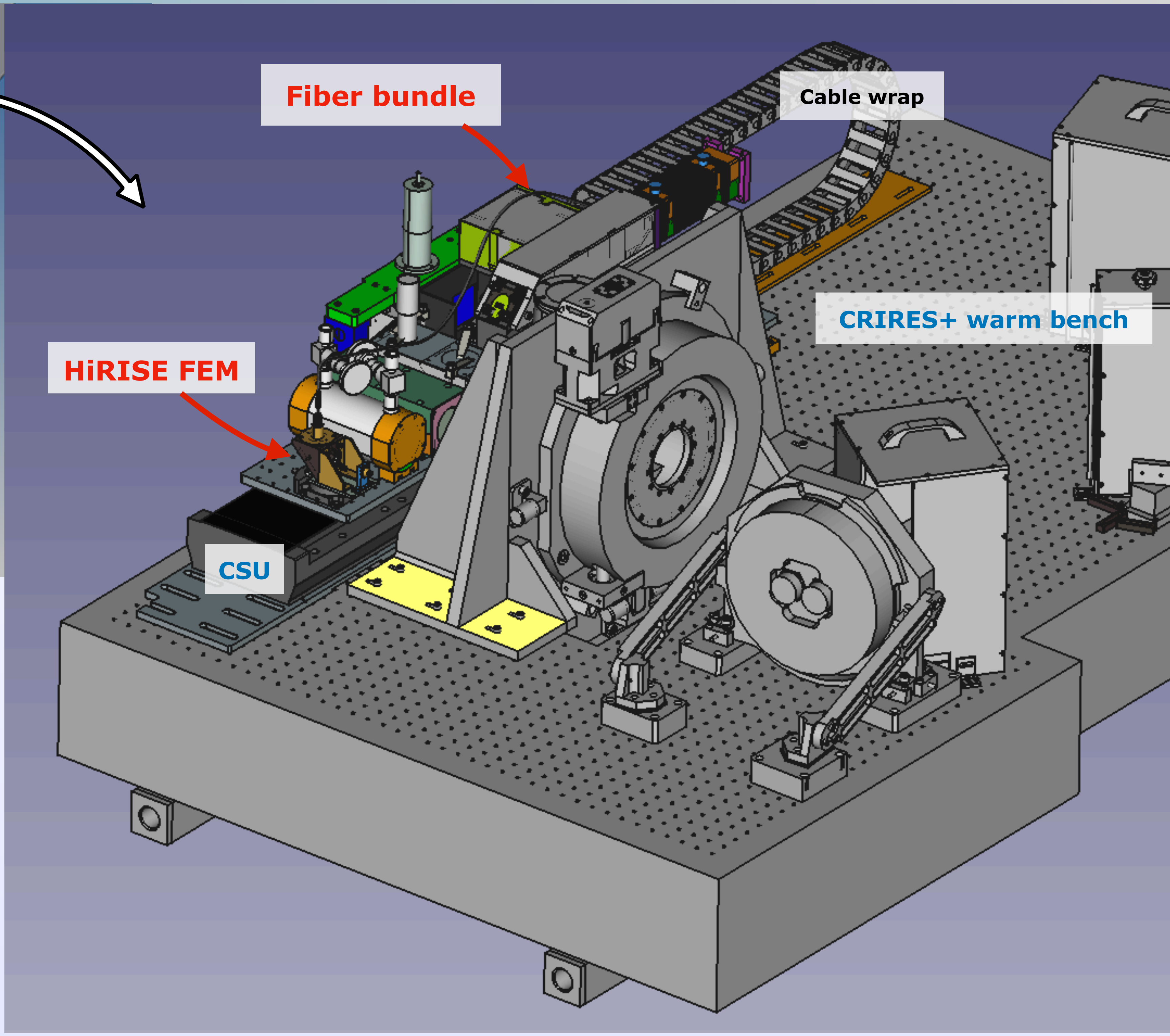


A complex fiber bundle

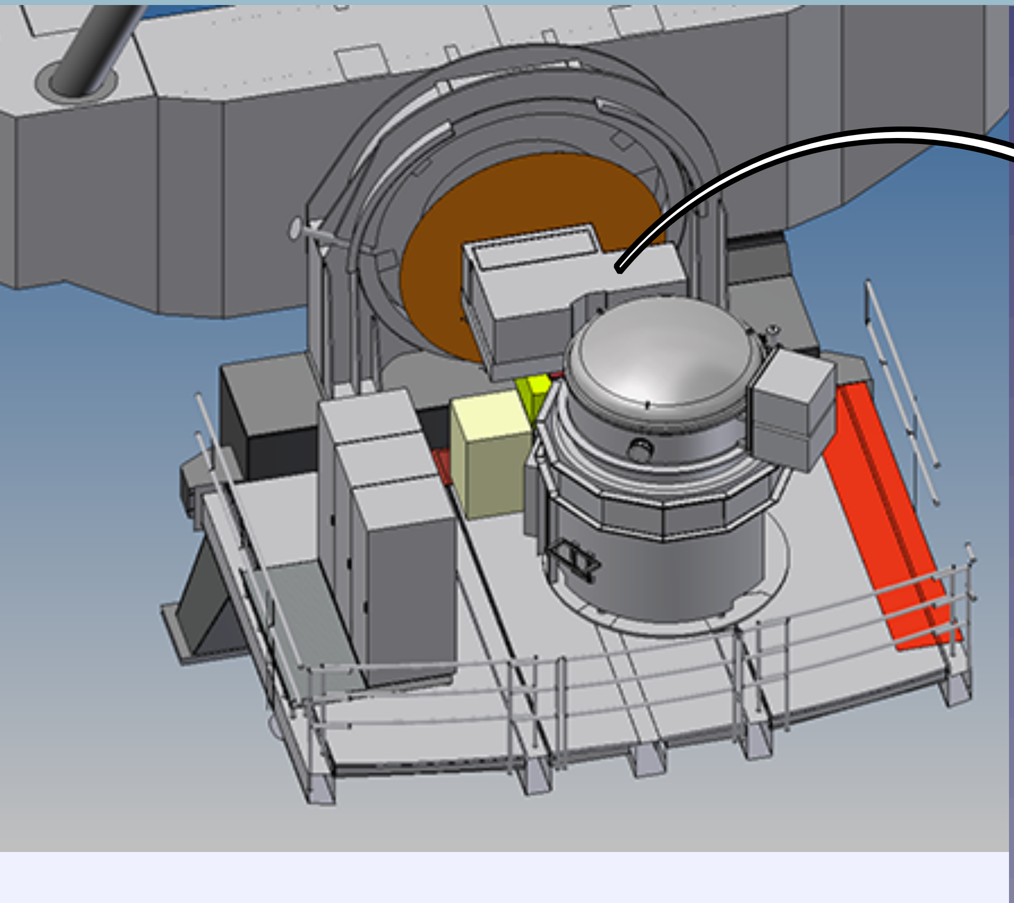


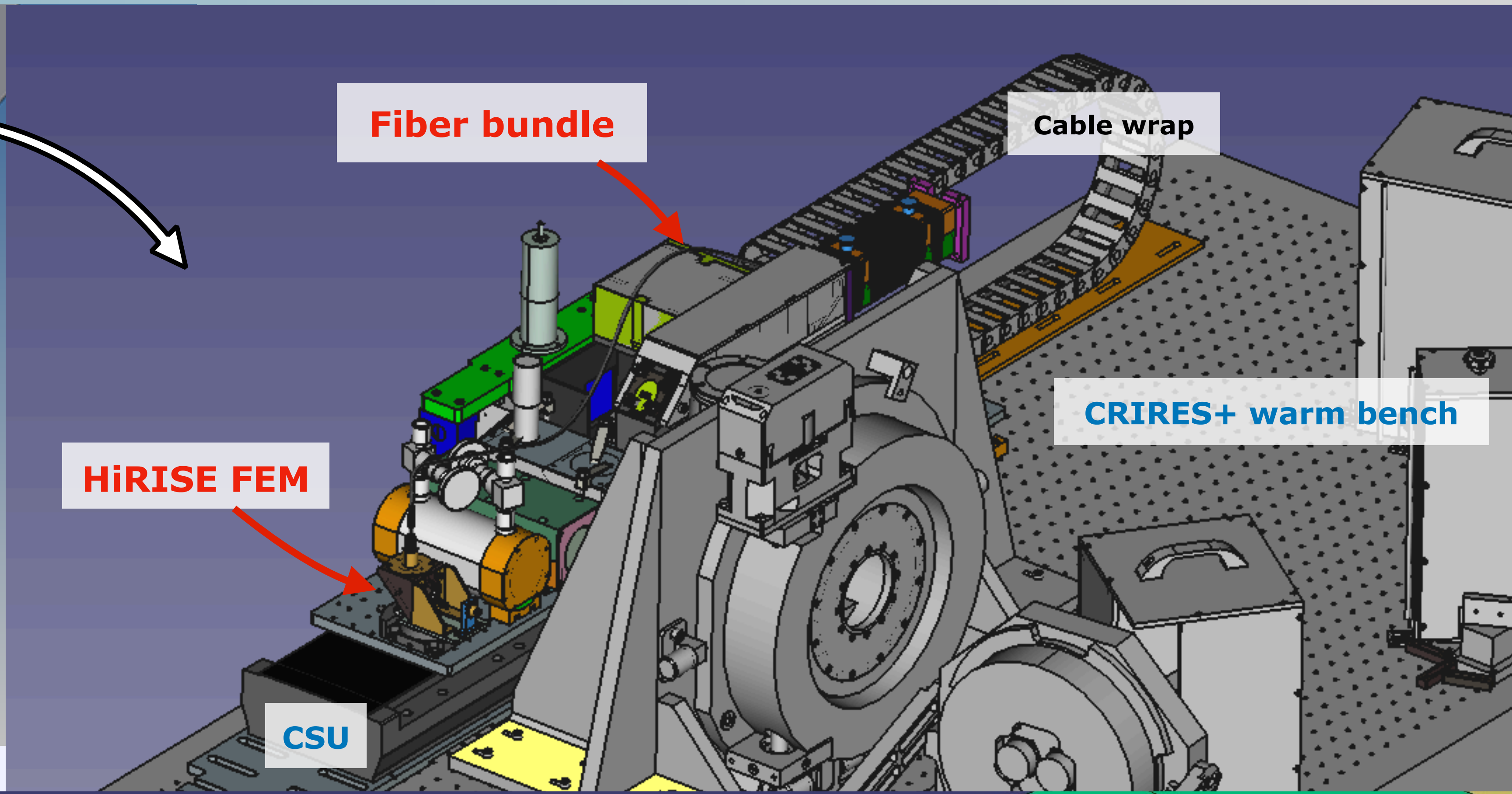
Fiber extraction module

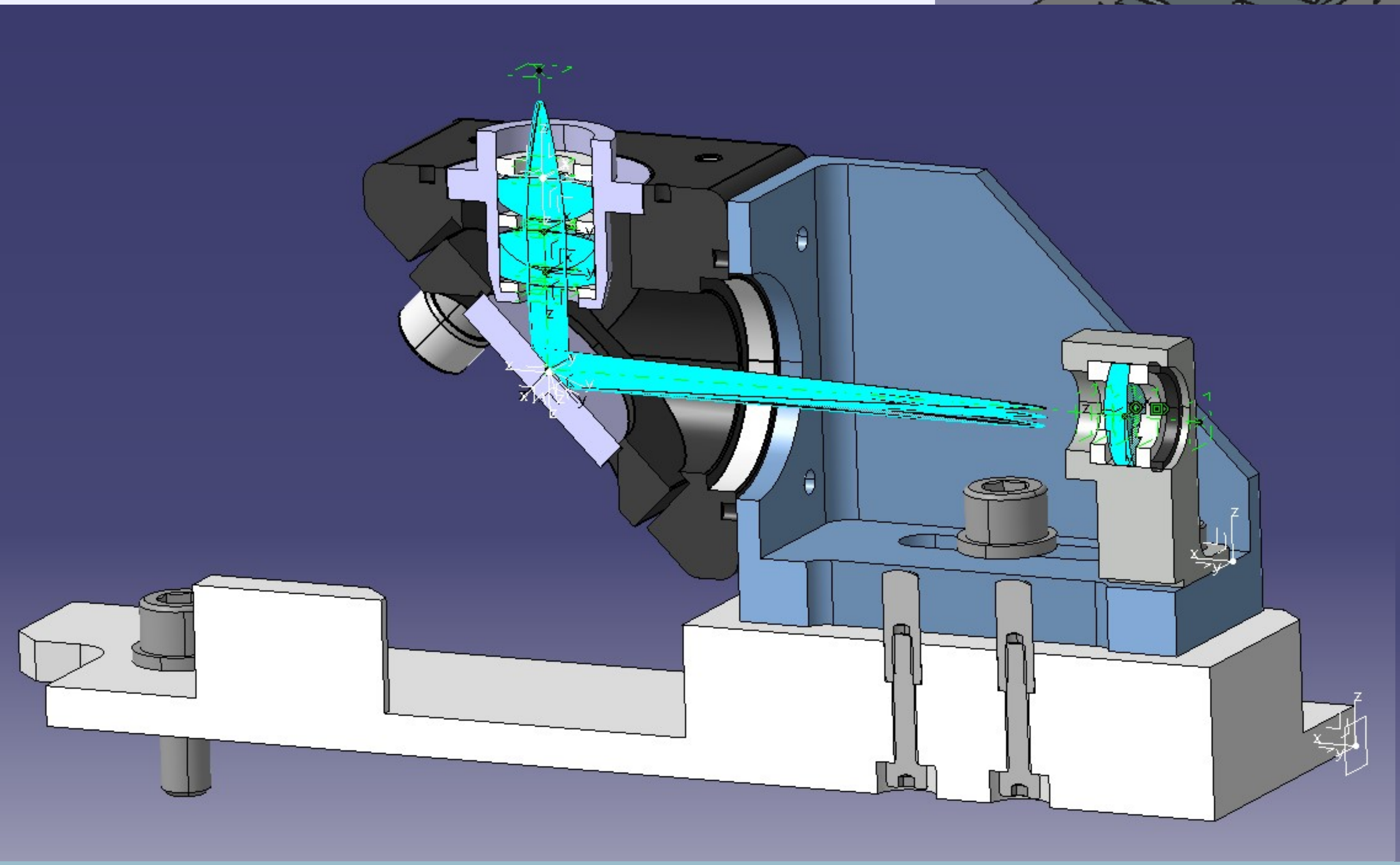


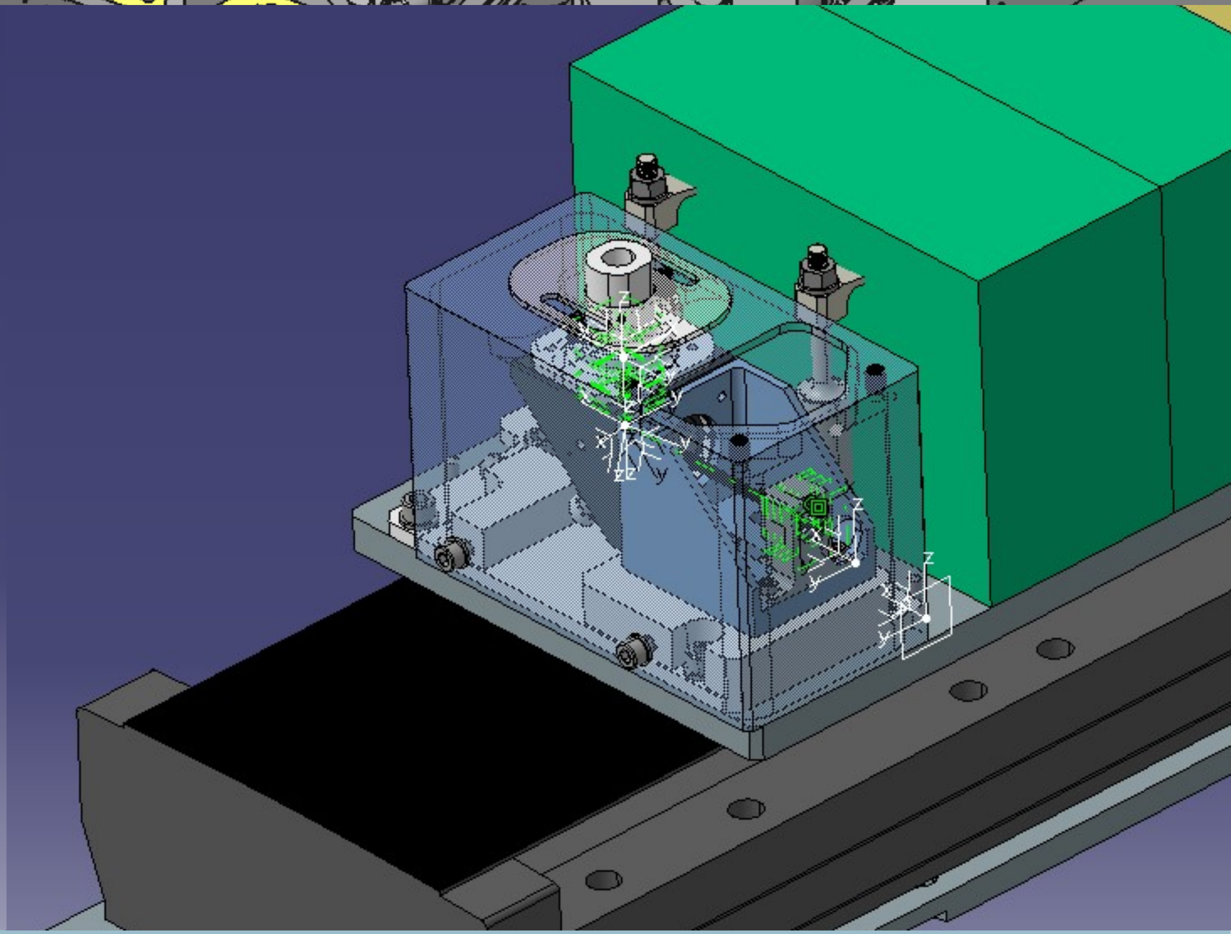


Fiber extraction module

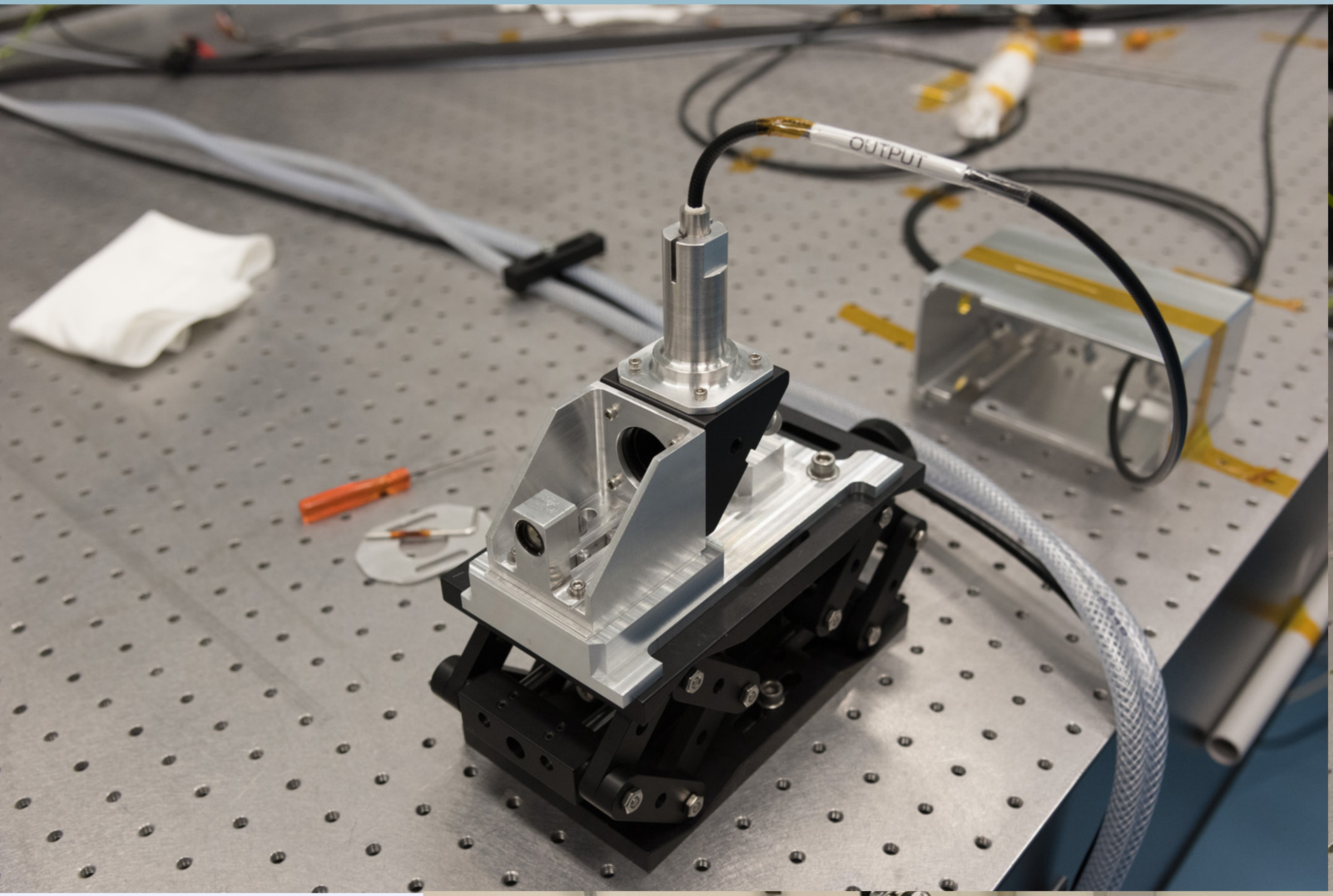


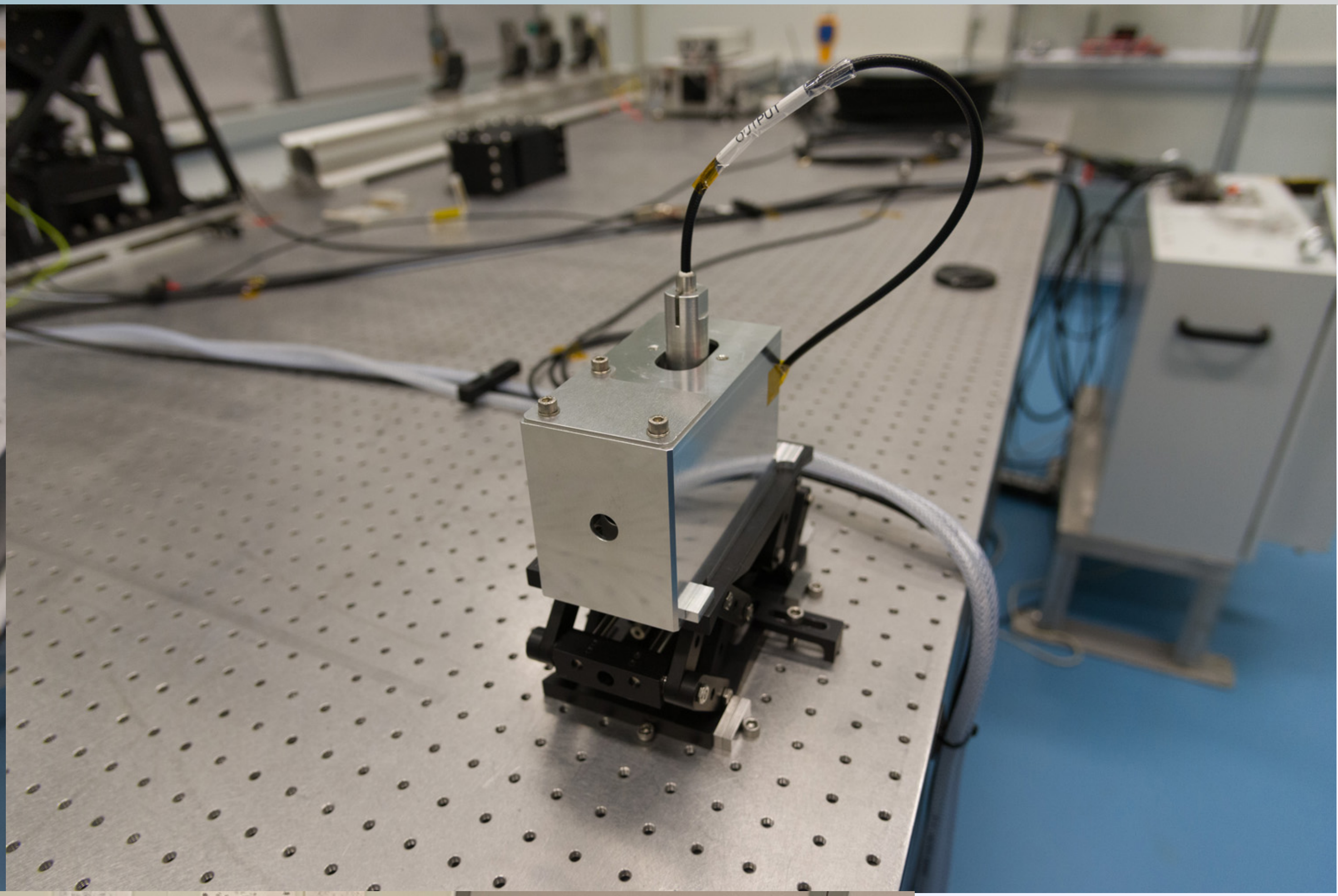


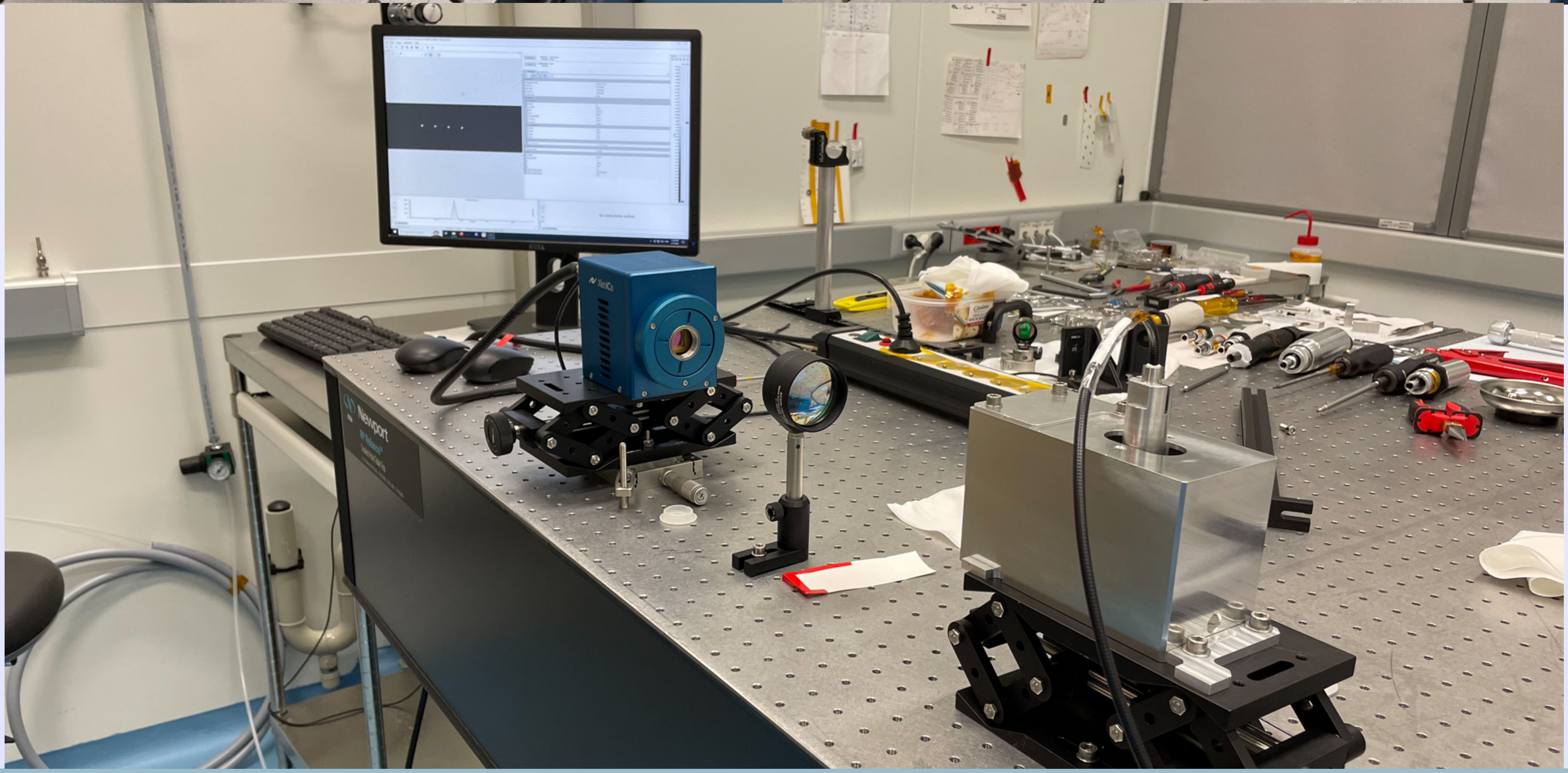




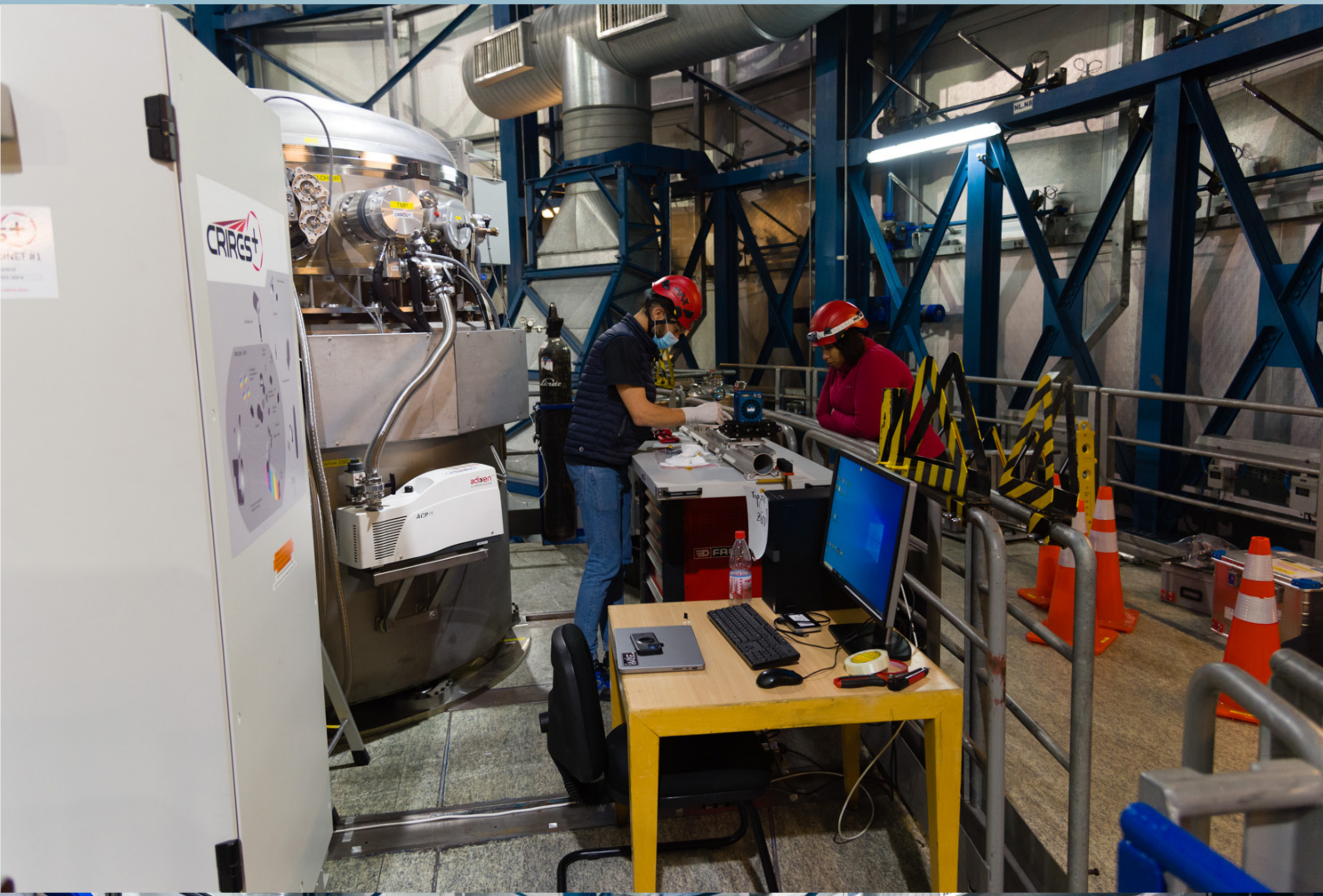
Fiber extraction module

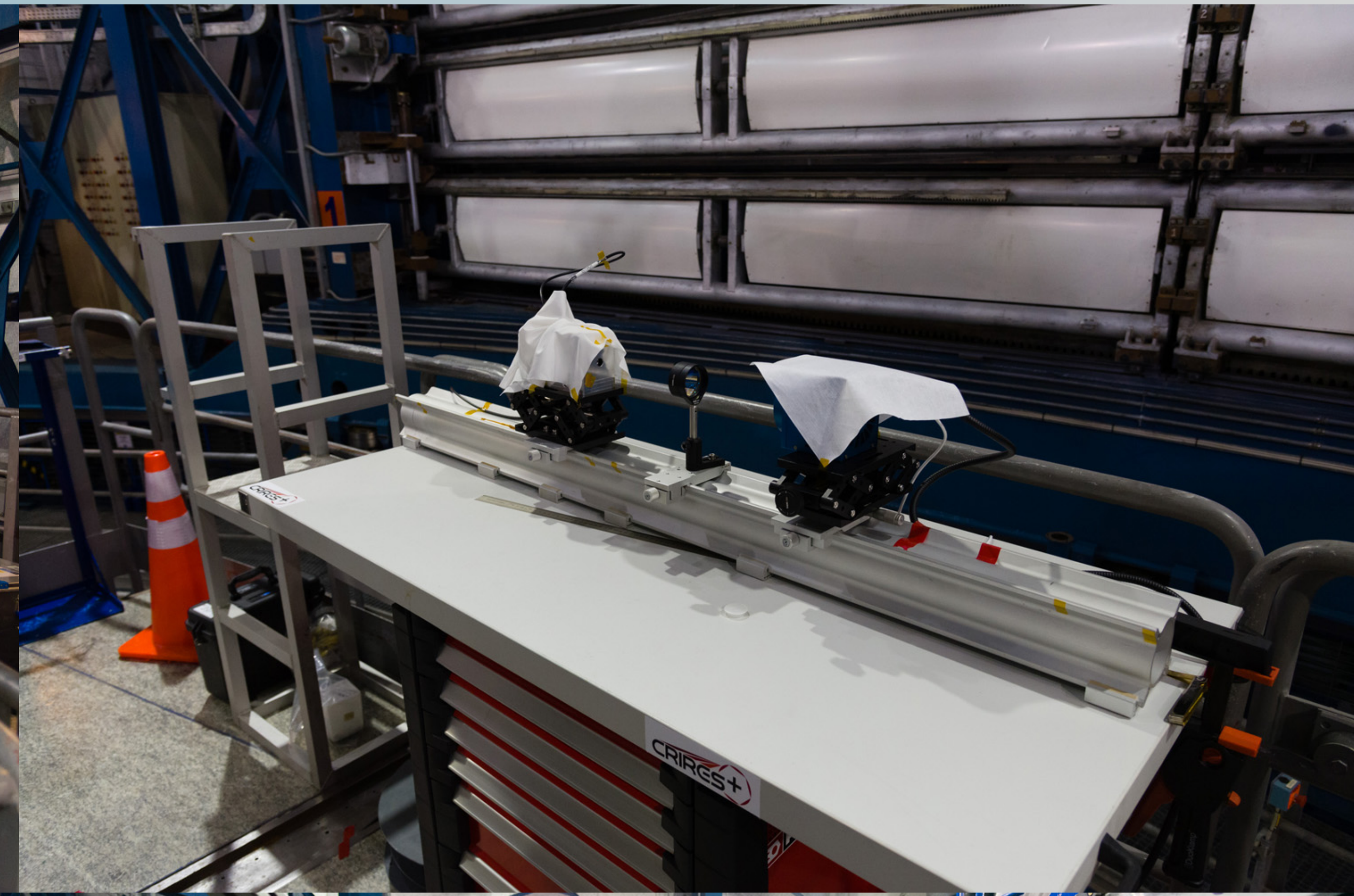




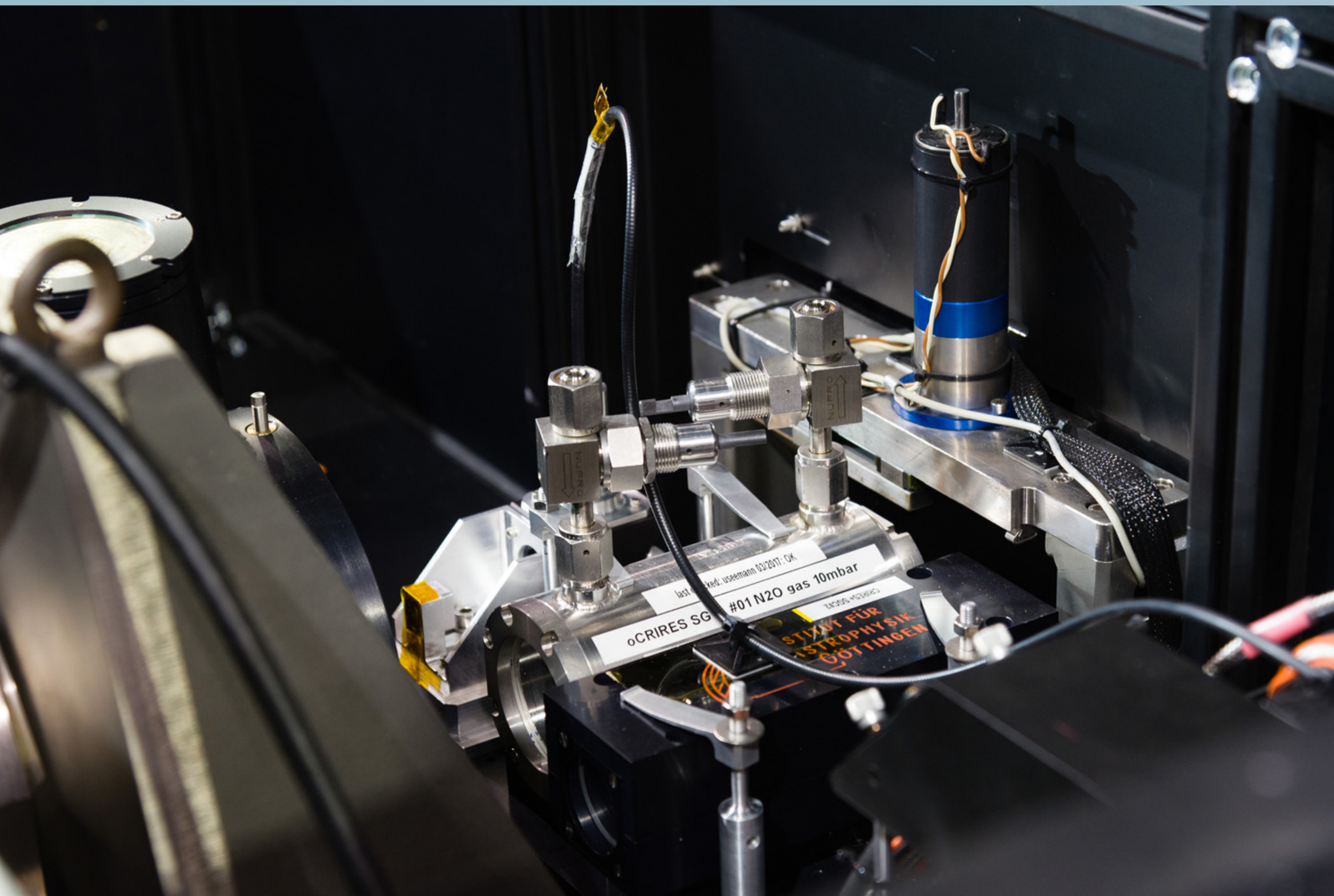


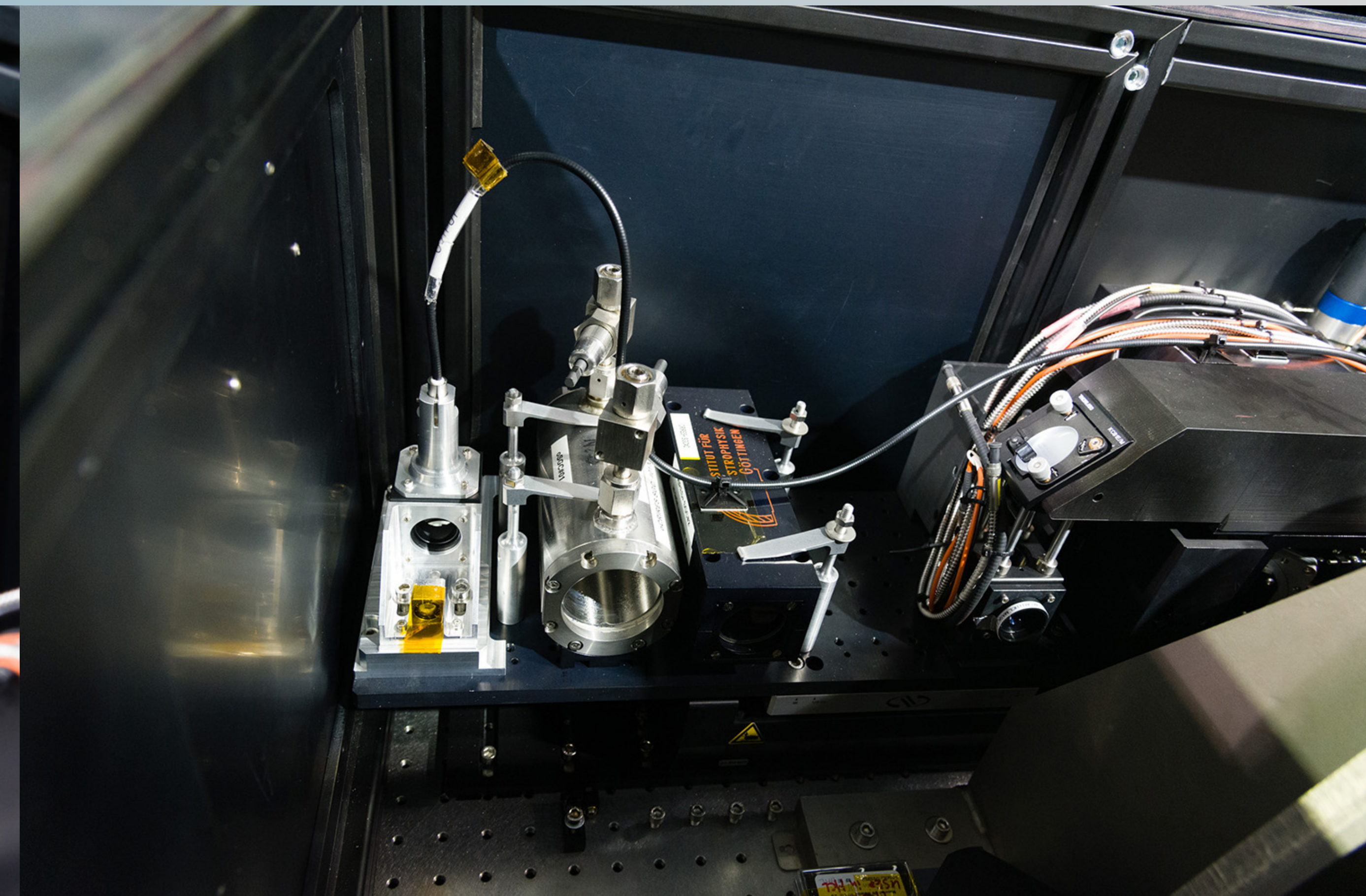
Fiber extraction module

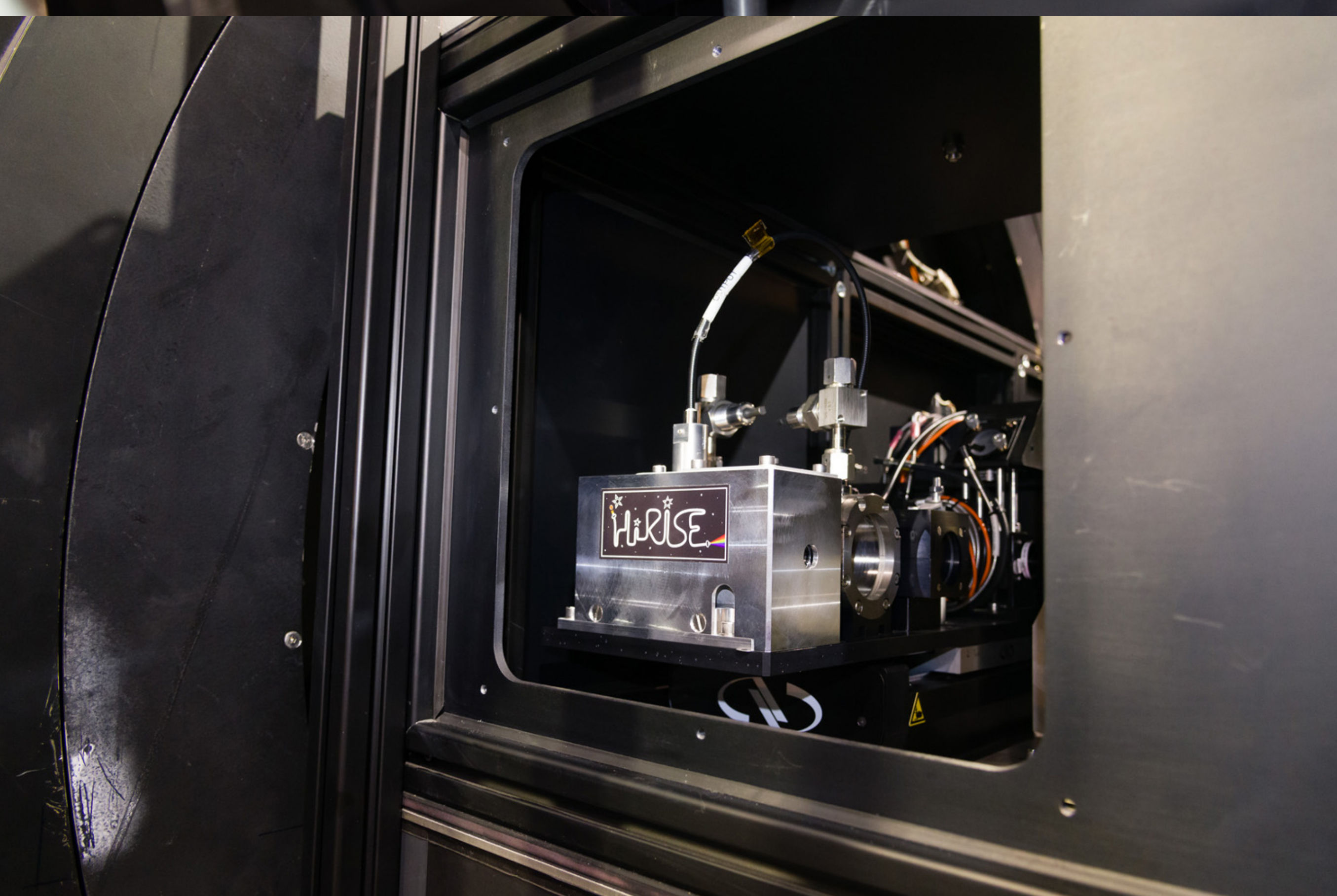


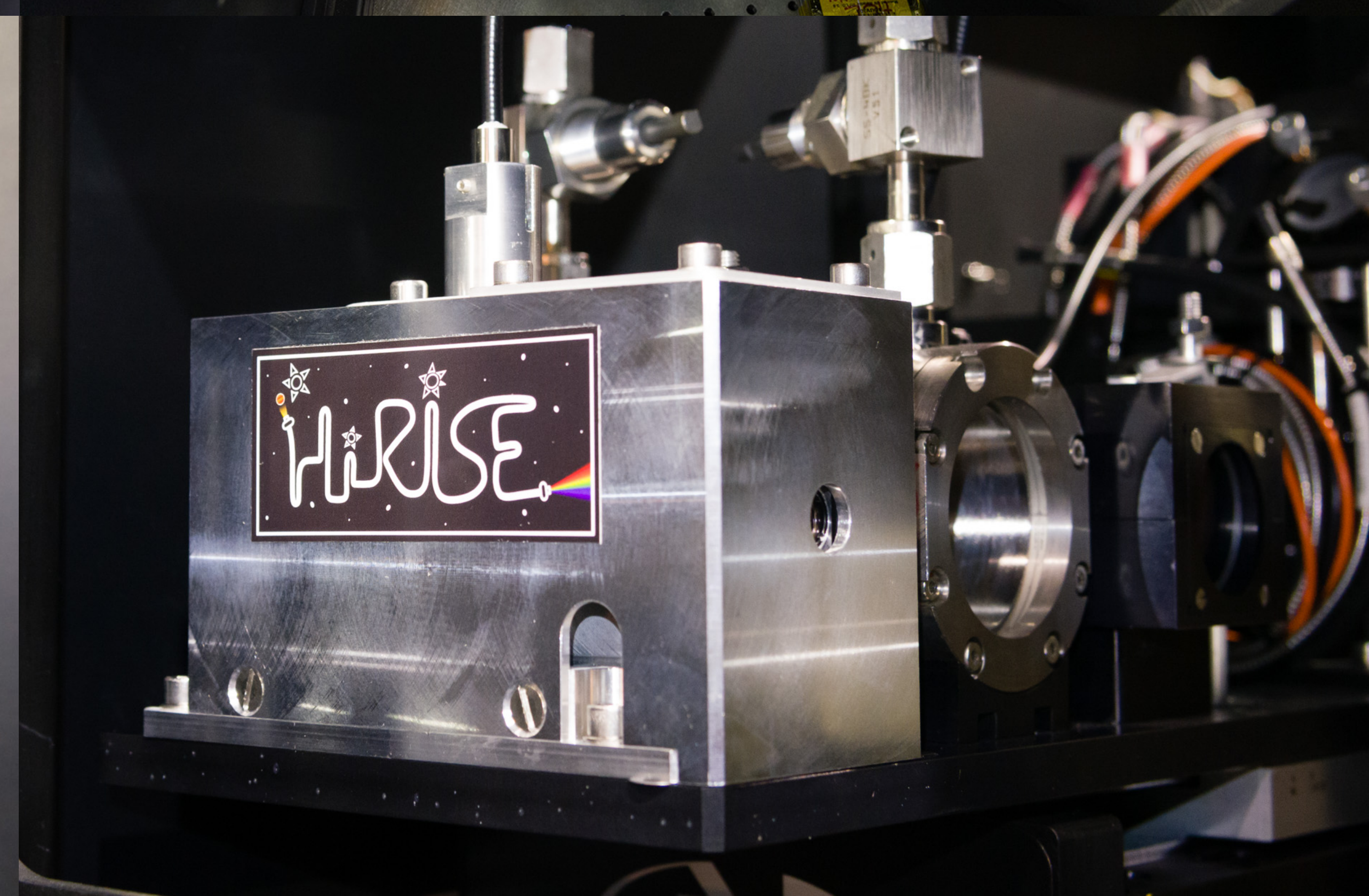


Fiber extraction module

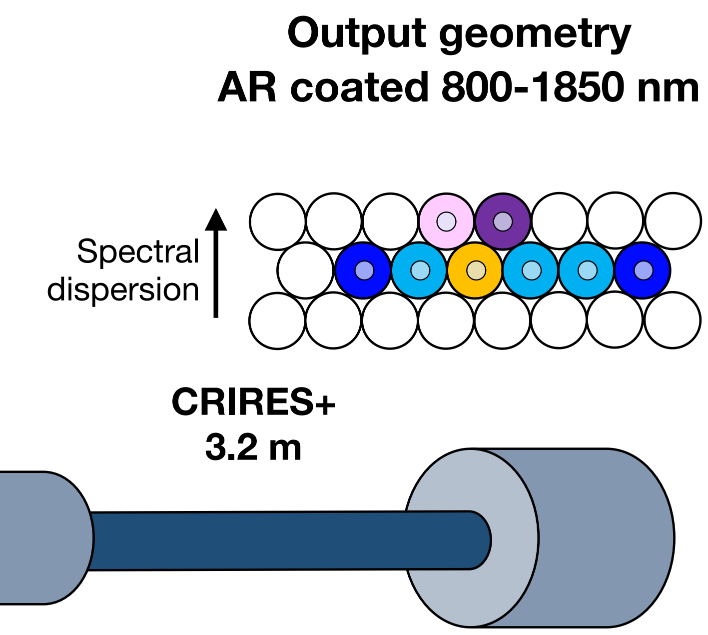


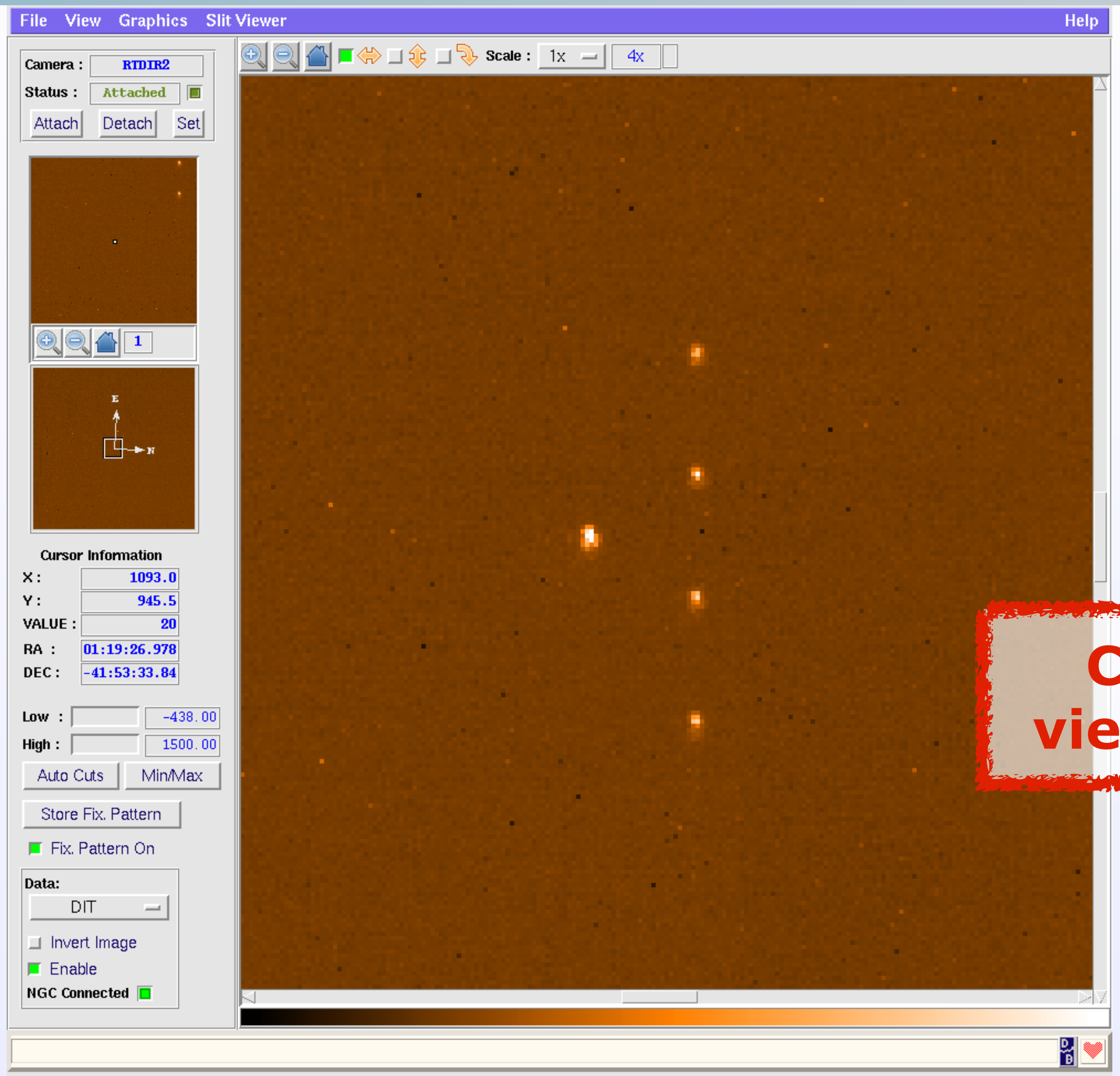






Light into the CRIRES spectrograph

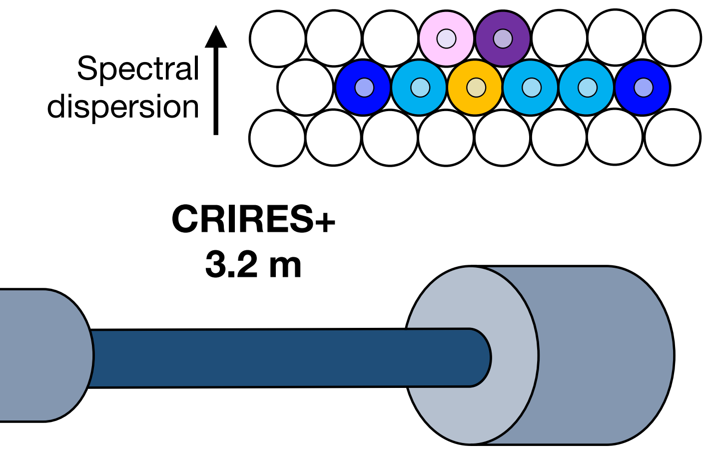


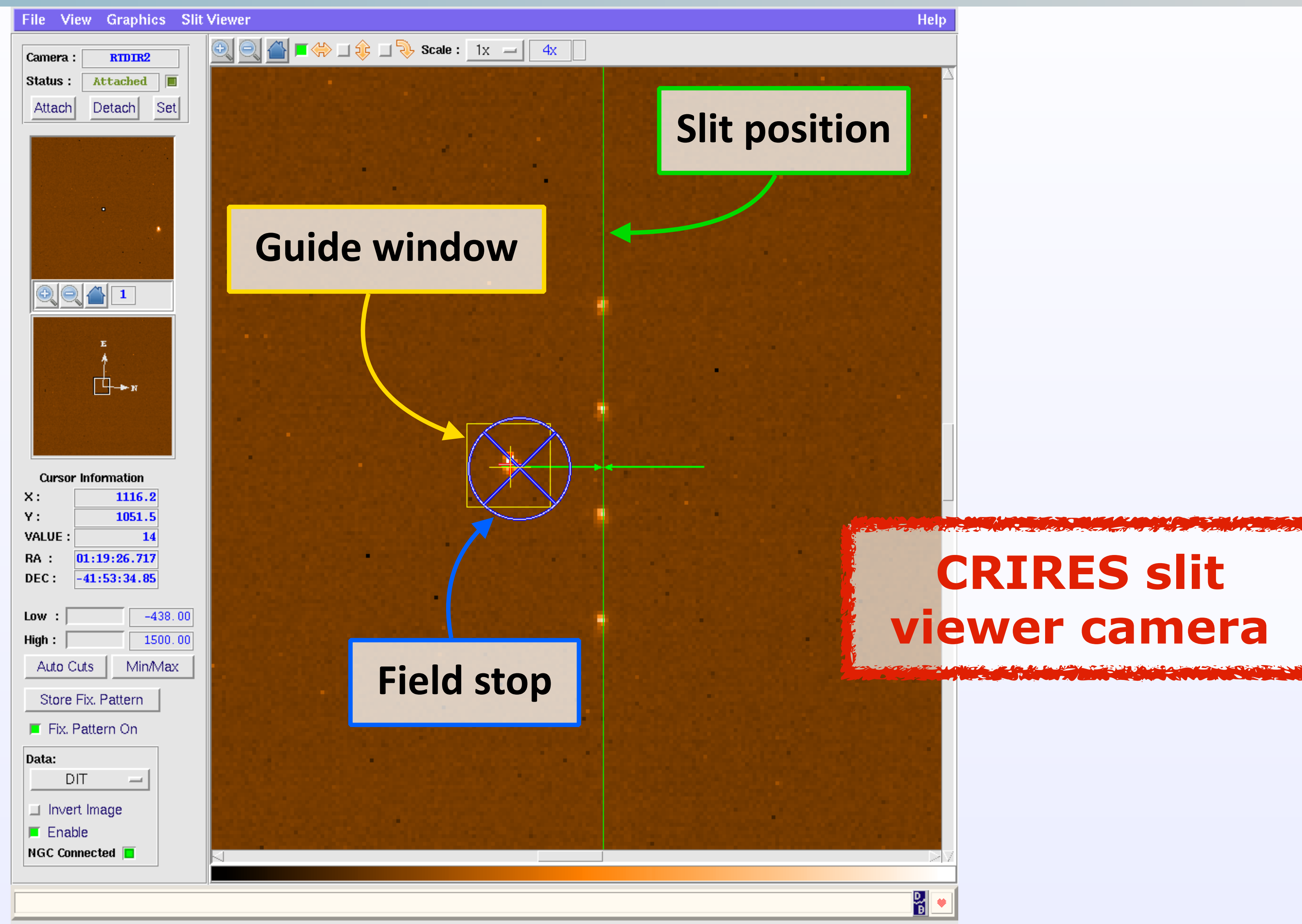


CRIRES slit viewer camera

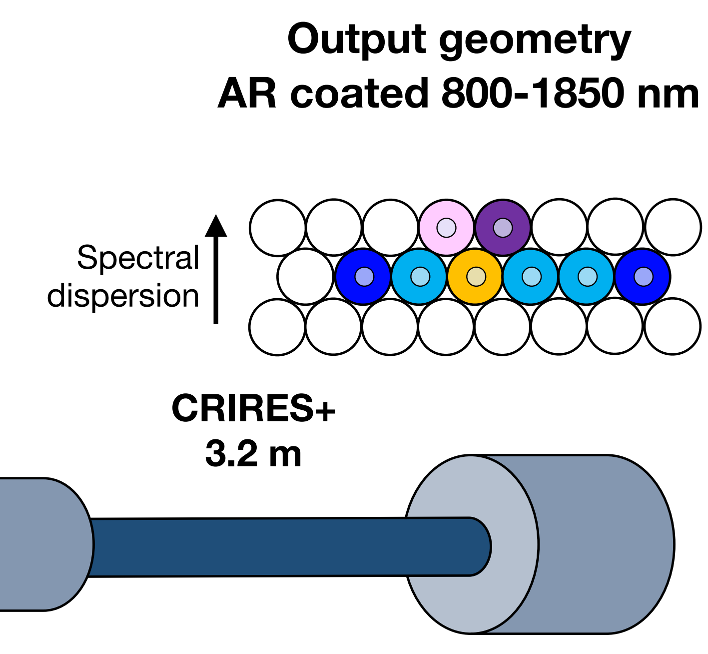
Light into the CRIRES spectrograph

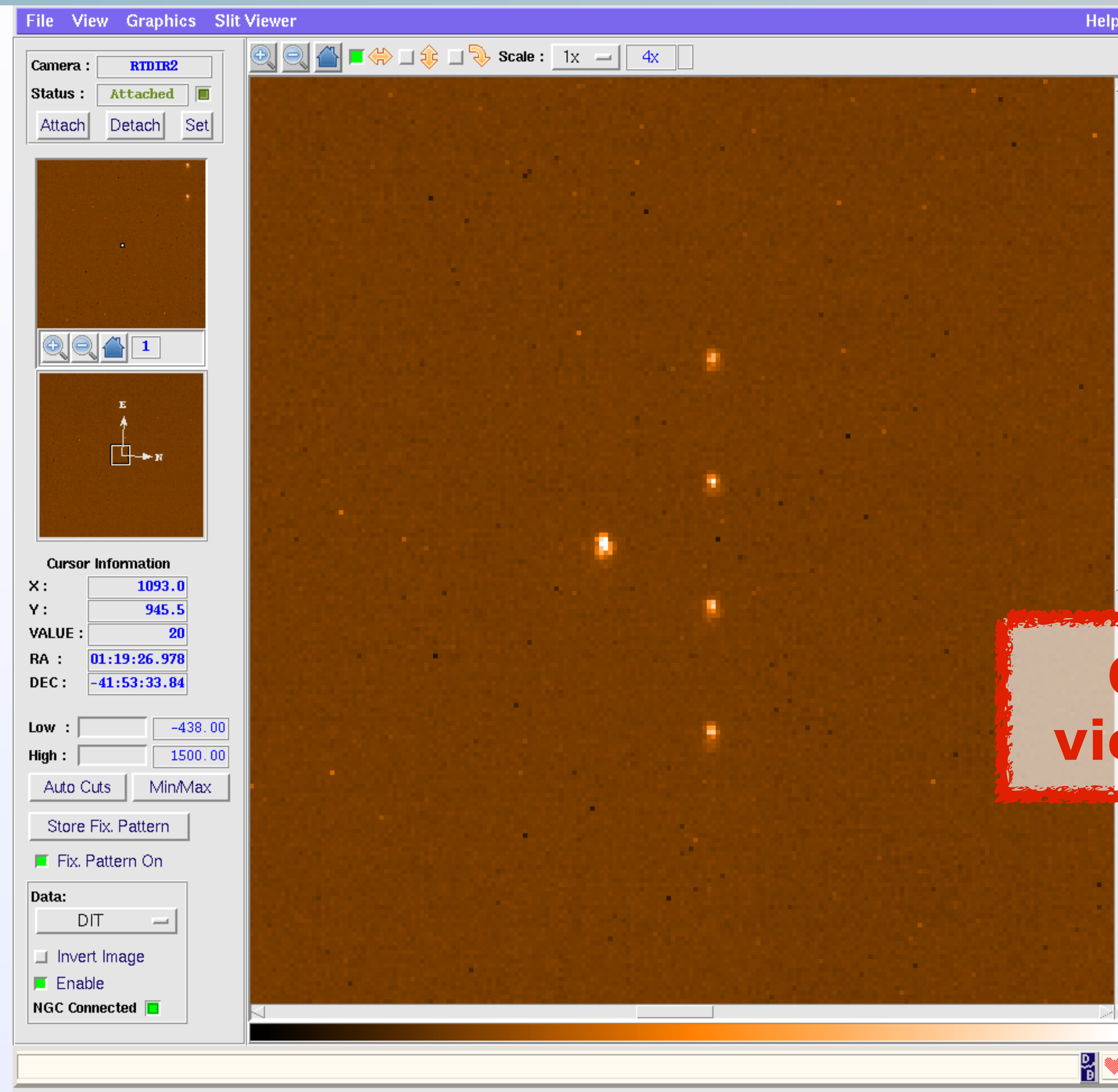
Output geometry
AR coated 800-1850 nm





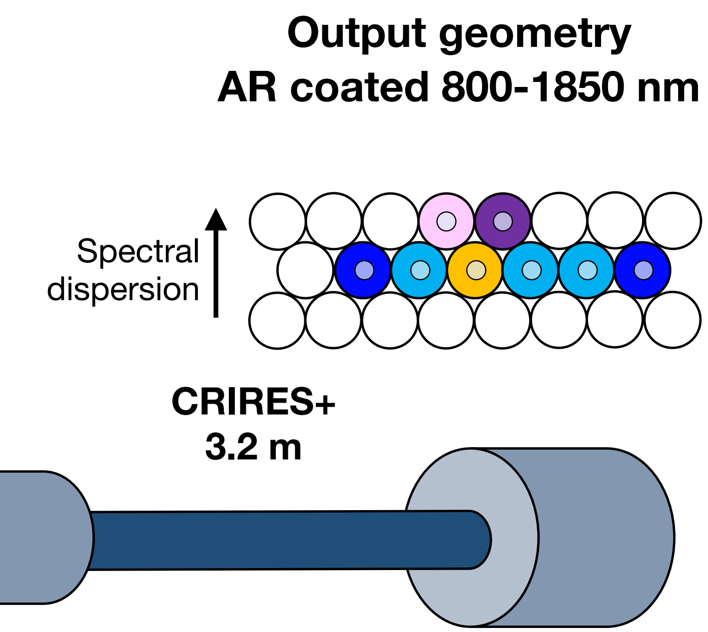
Light into the CRIRES spectrograph

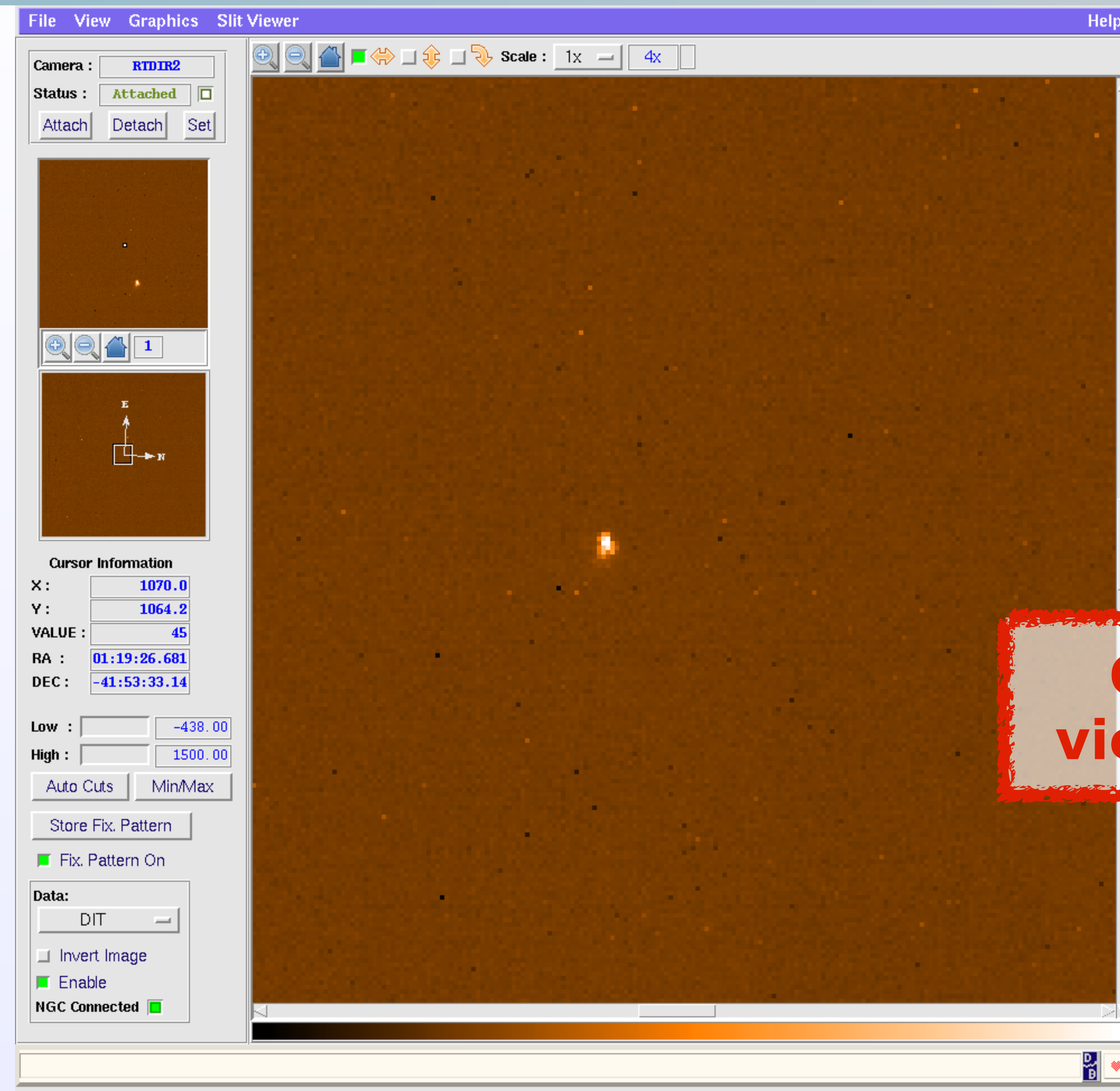




CRIRES slit viewer camera

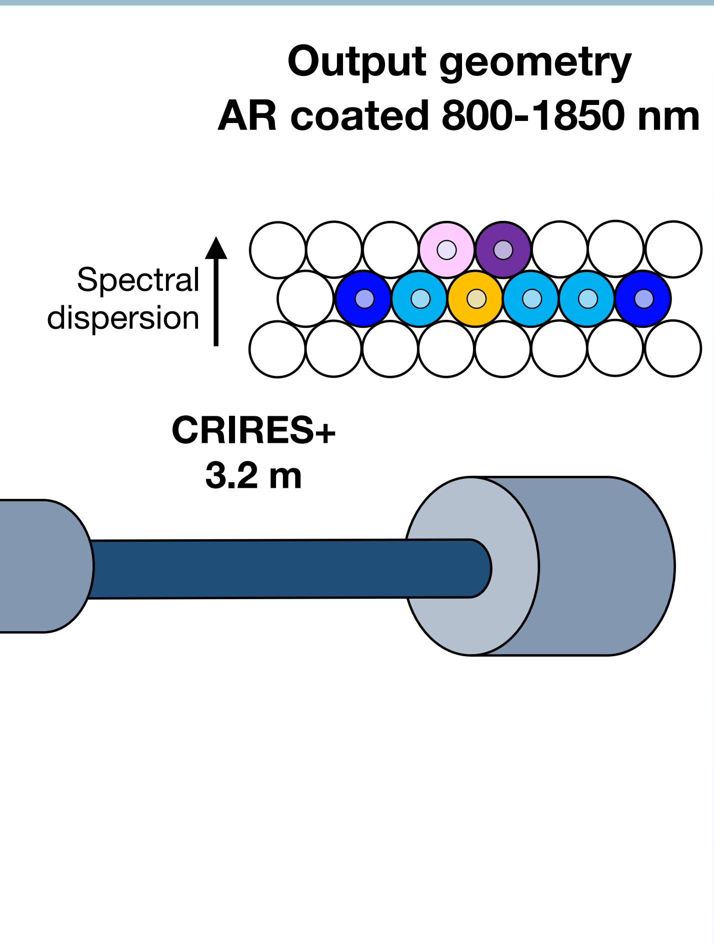
Light into the CRIRES spectrograph

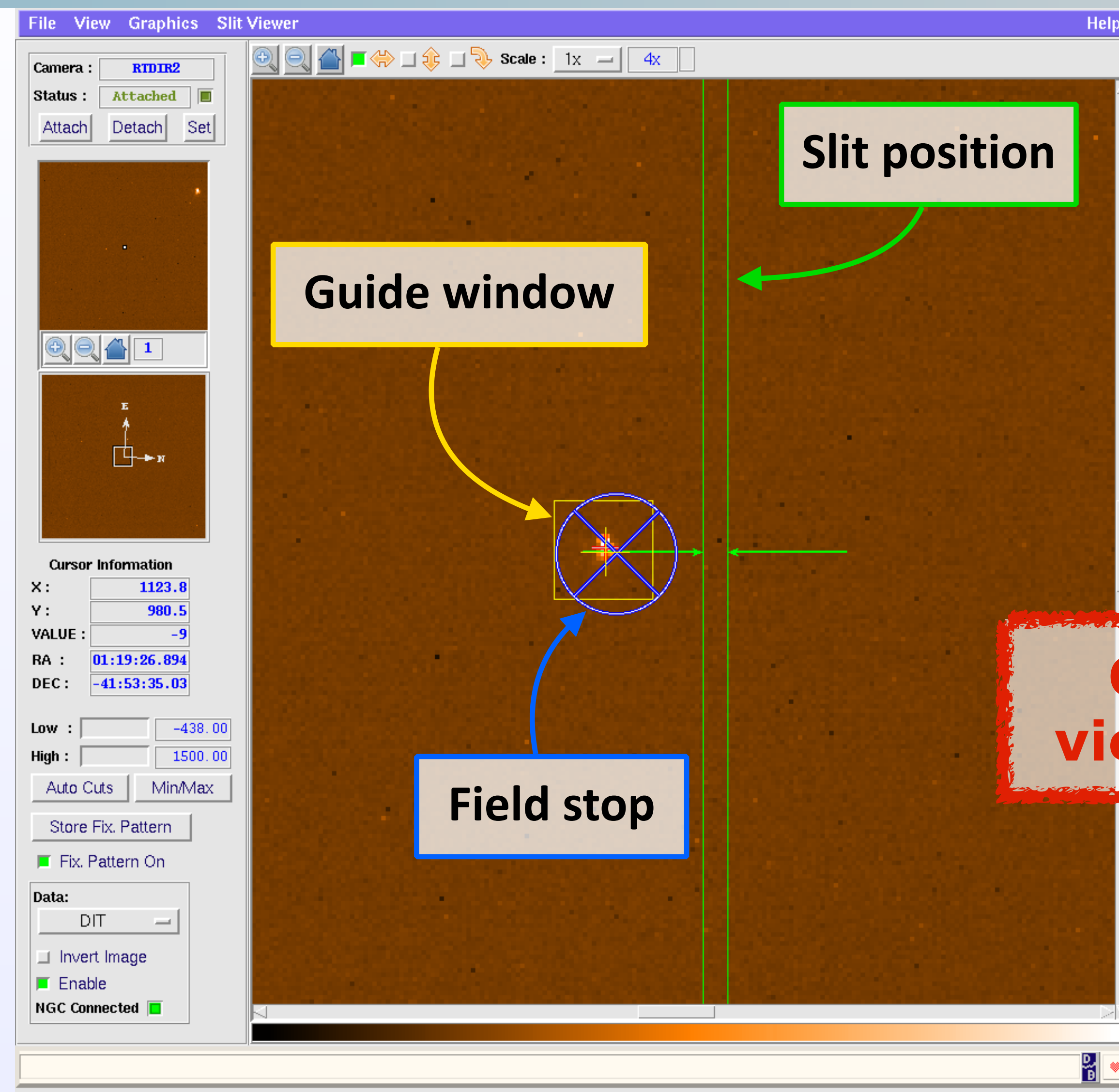




CRIRES slit viewer camera

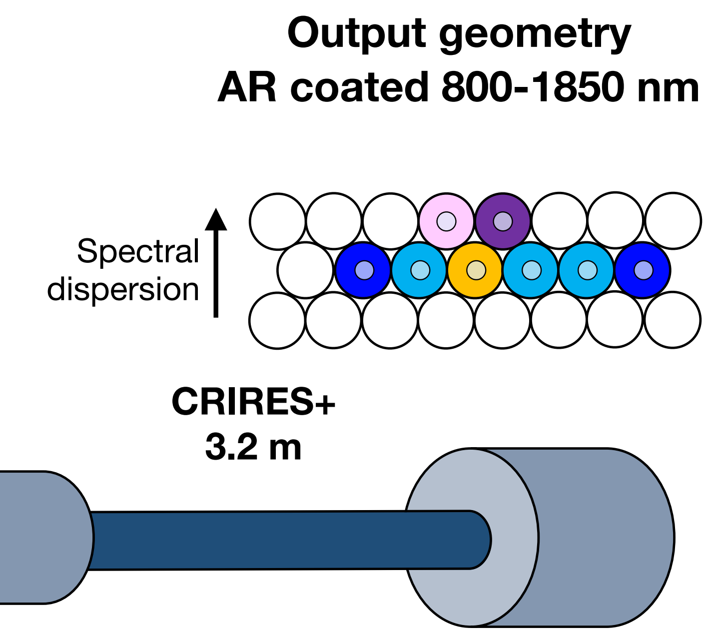
Light into the CRIRES spectrograph

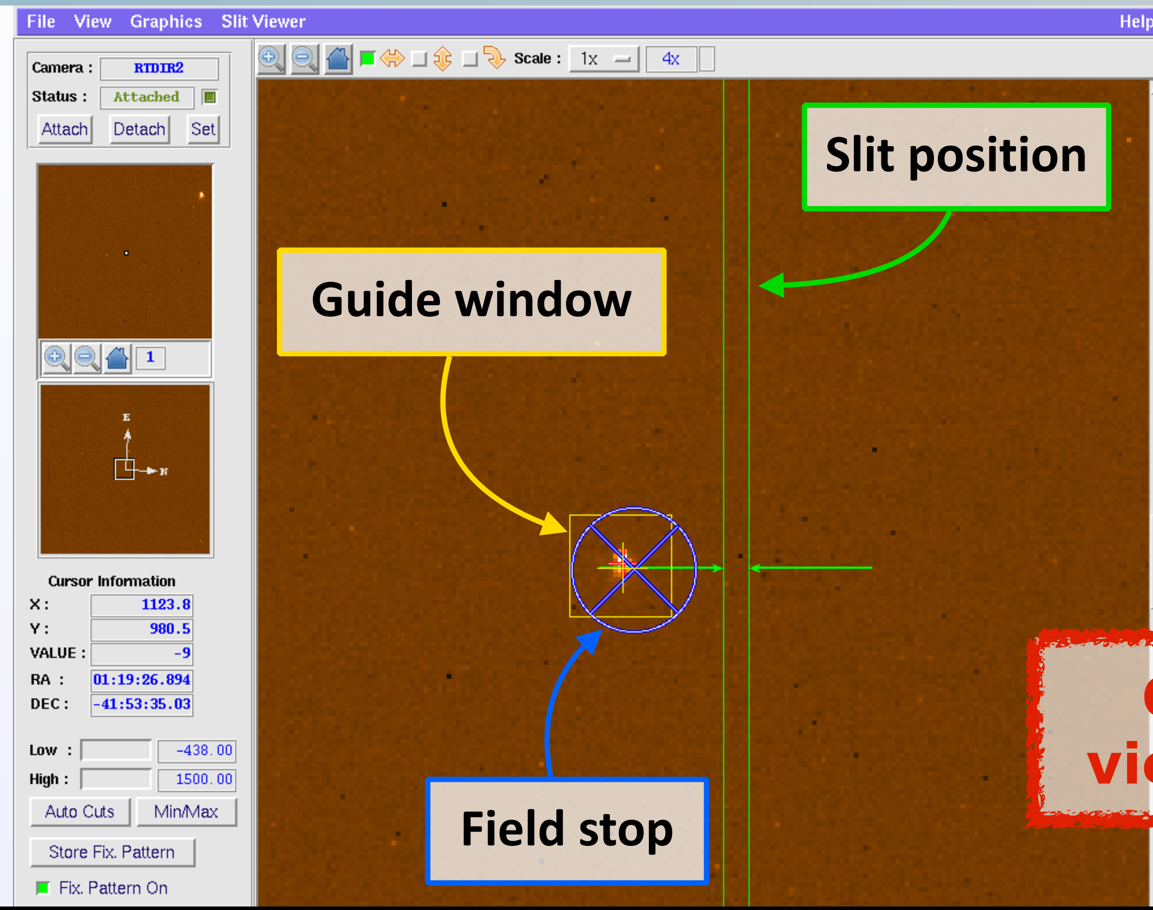


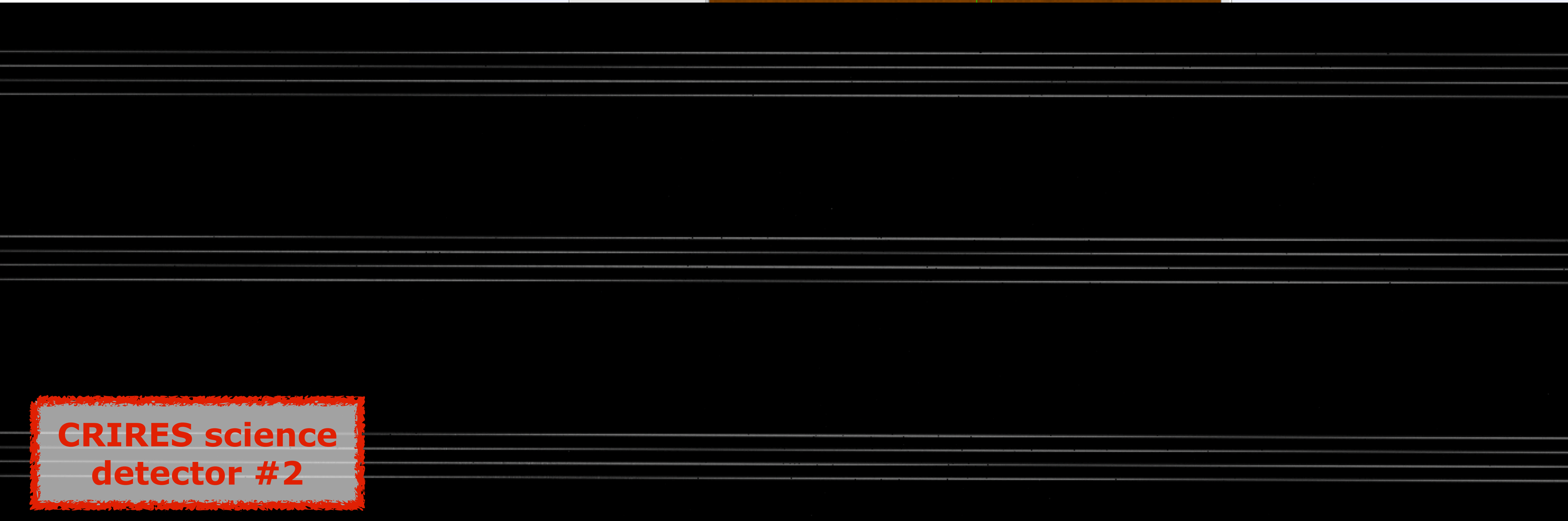


CRIRES slit viewer camera

Light into the CRIRES spectrograph

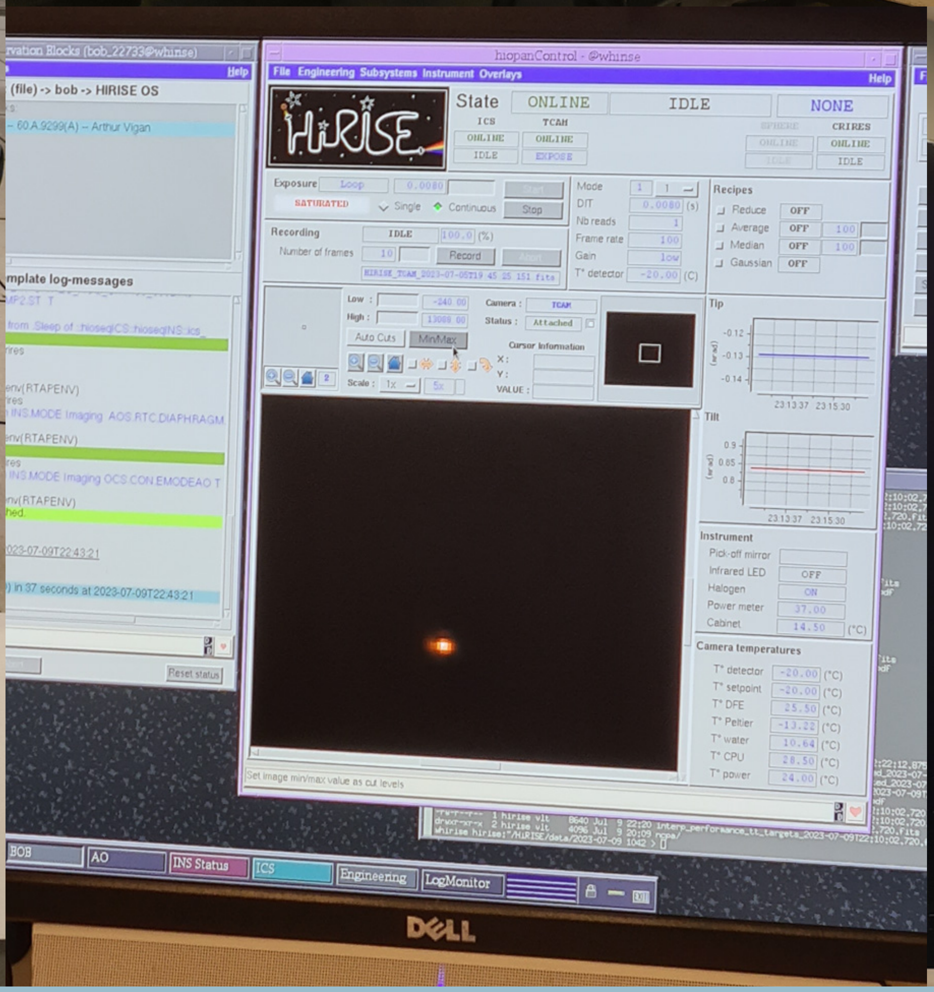


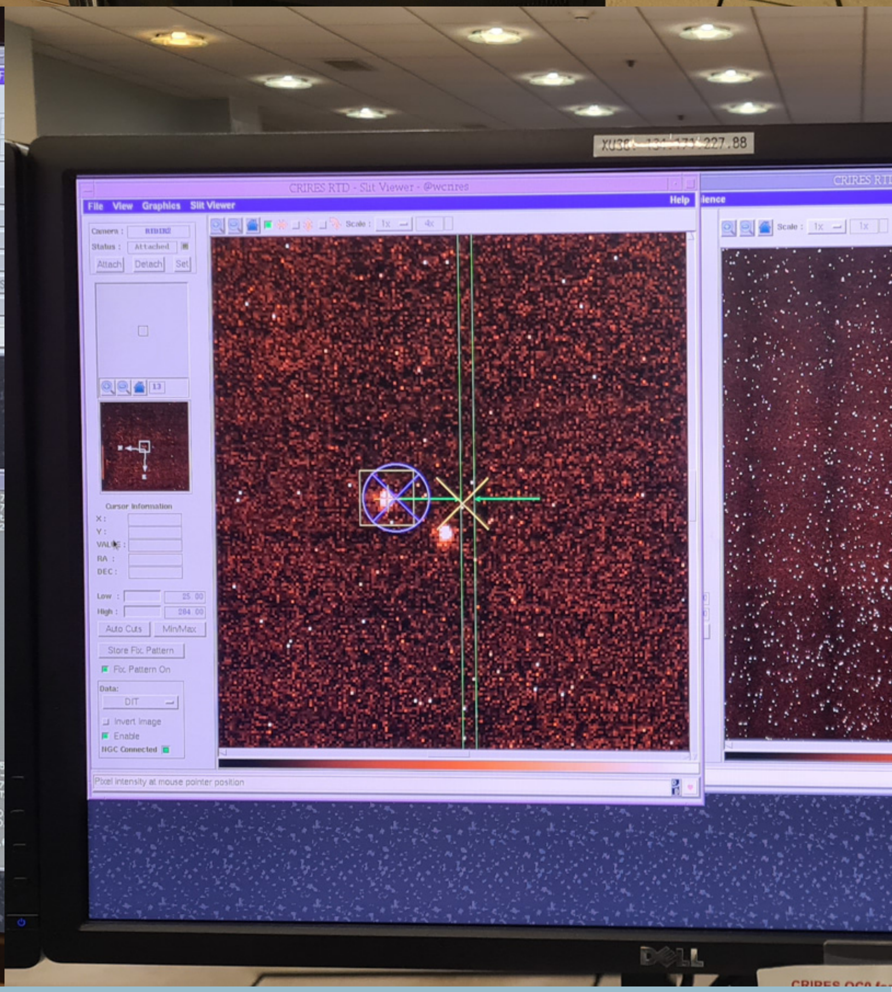




First light!


Put M2tc
STANDBY
IT Control Room

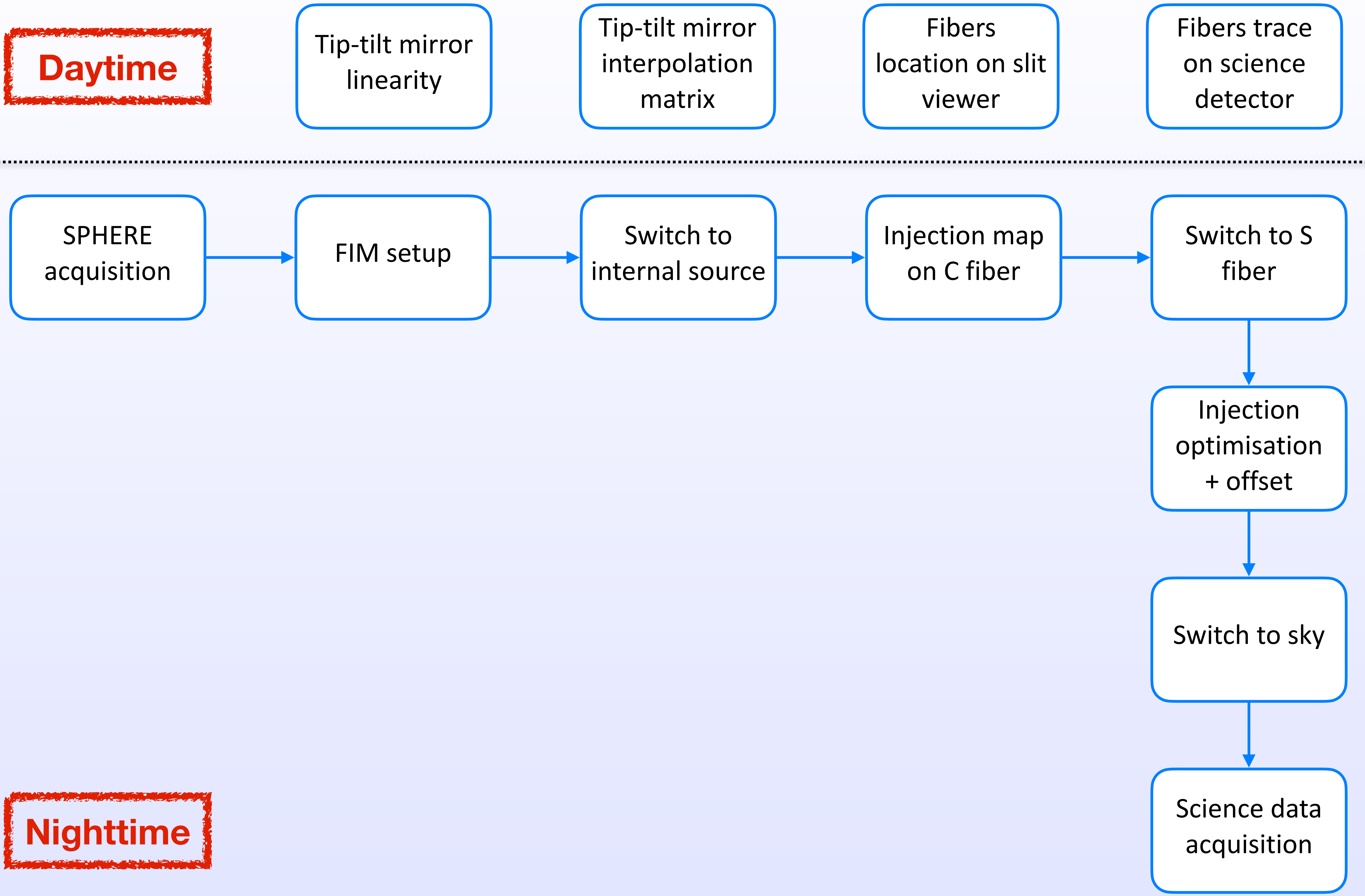

HiRISE
State
ONLINE
IDLE
NONE
Exposure
Recording
Recipes
Instrument
Camera temperatures
BOB
AO
INS Status
ICS
Engineering
LogMonitor
DELL


DELL

First light!

CRIRES
Instrument modes:
DAY = Standby
CALIB = Online for daytime calibs
NIGHT = Online for on-sky observations
Bright magnitude limits:
SV guide star with AO: H = 0
SV guide star in NoAO: H = -2
AO NGS: R = 0.2
Detector Saturation Px Scale minDIT
Science 37,000 ADU 0.059"/px 1.427s
Slit Viewer 20,000 ADU 0.037"/px 0.08 s
• AO: Humidity limit 50%
• AO: not allowed in THK
• If PWV ≤ 2.5, give priority to LM band observations
• Any observation template can be started 15 minutes before the end of evening twilight
• Before centering the star, check the MACAO Tip/Tilt mount values (!!! ≠0 !!!)
Wavelength settings (INS WLEN CWLEN)
DELL
CRIRES QC0 for AO:

Operations: target acquisition



Operations: target acquisition

Daytime

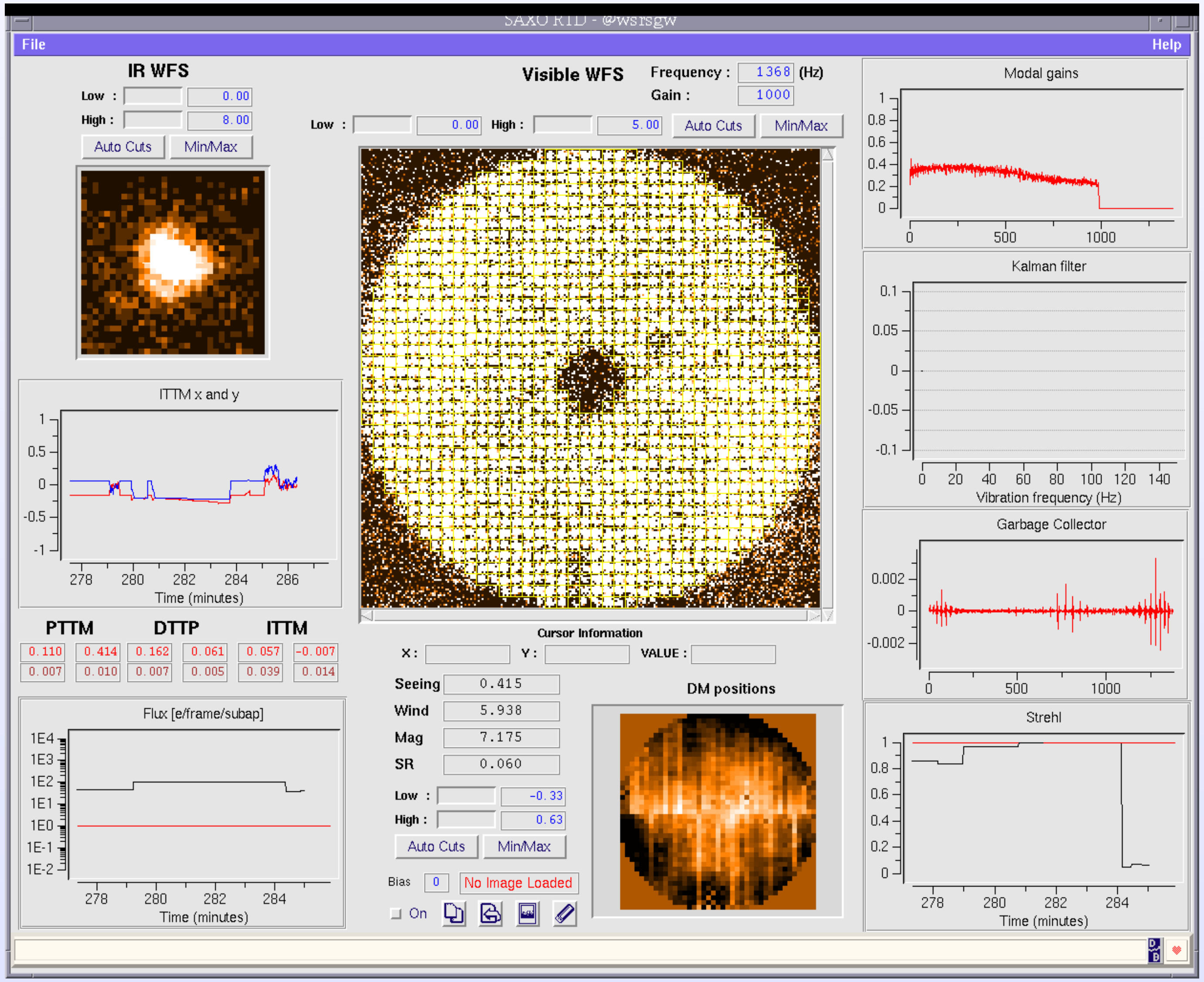
Tip-tilt mirror linearity

Tip-tilt mirror interpolation matrix

Fibers location on slit viewer

Fibers trace on science detector

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



Nighttime

Operations: target acquisition

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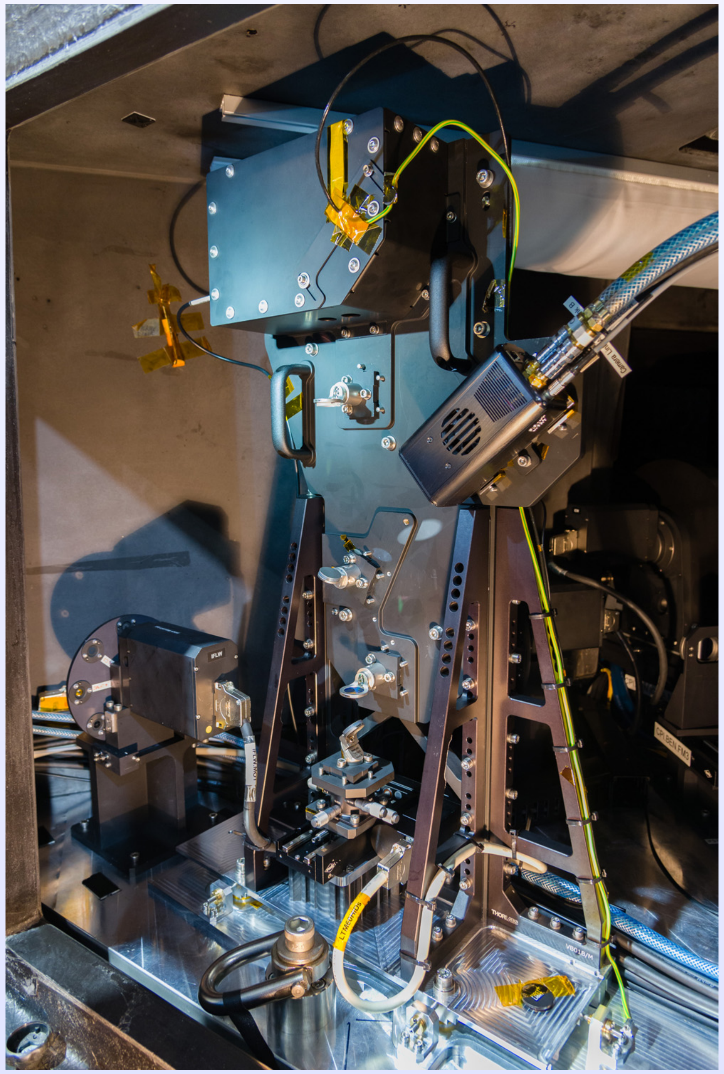


Nighttime

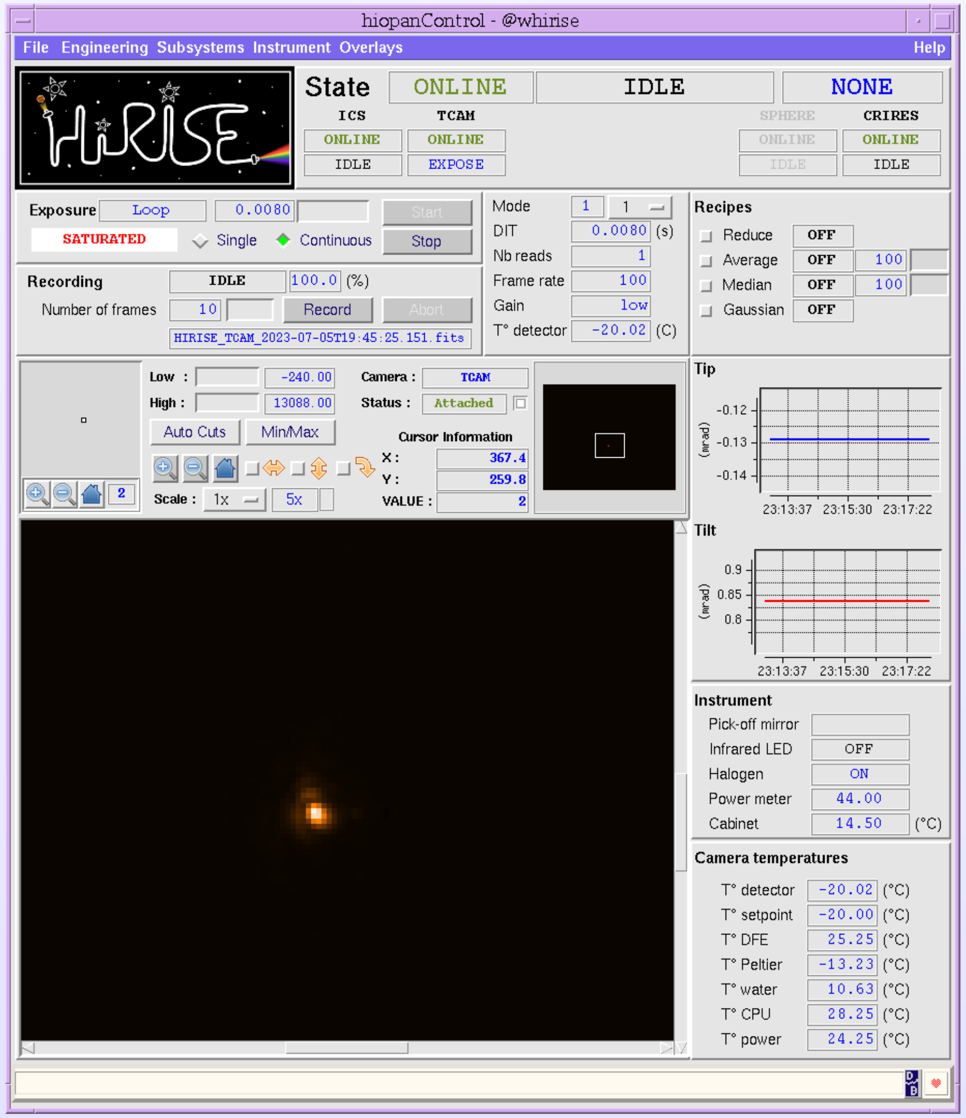
Operations: target acquisition

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



Operations: target acquisition

Daytime

Tip-tilt mirror linearity

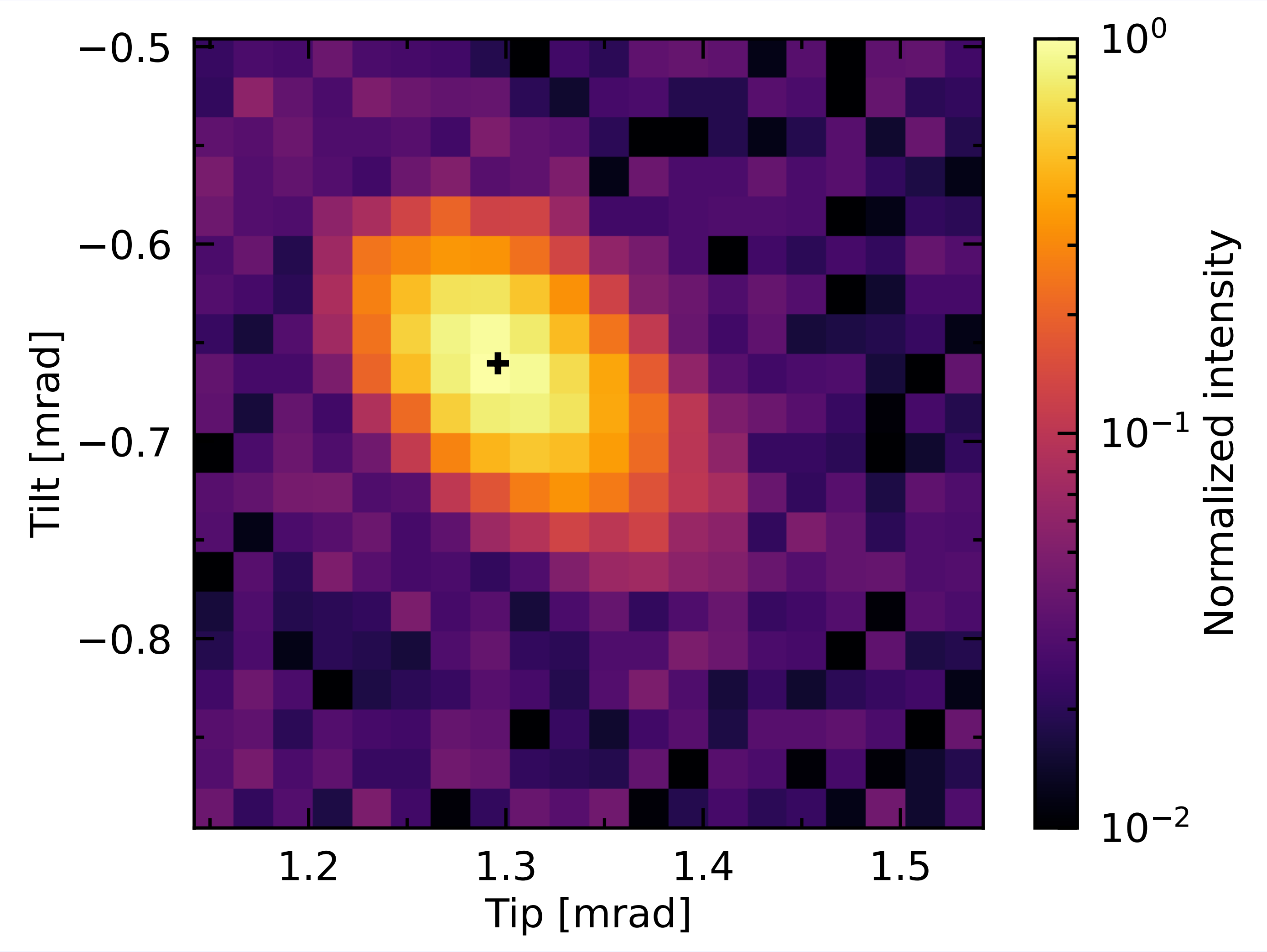
Tip-tilt mirror interpolation matrix

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



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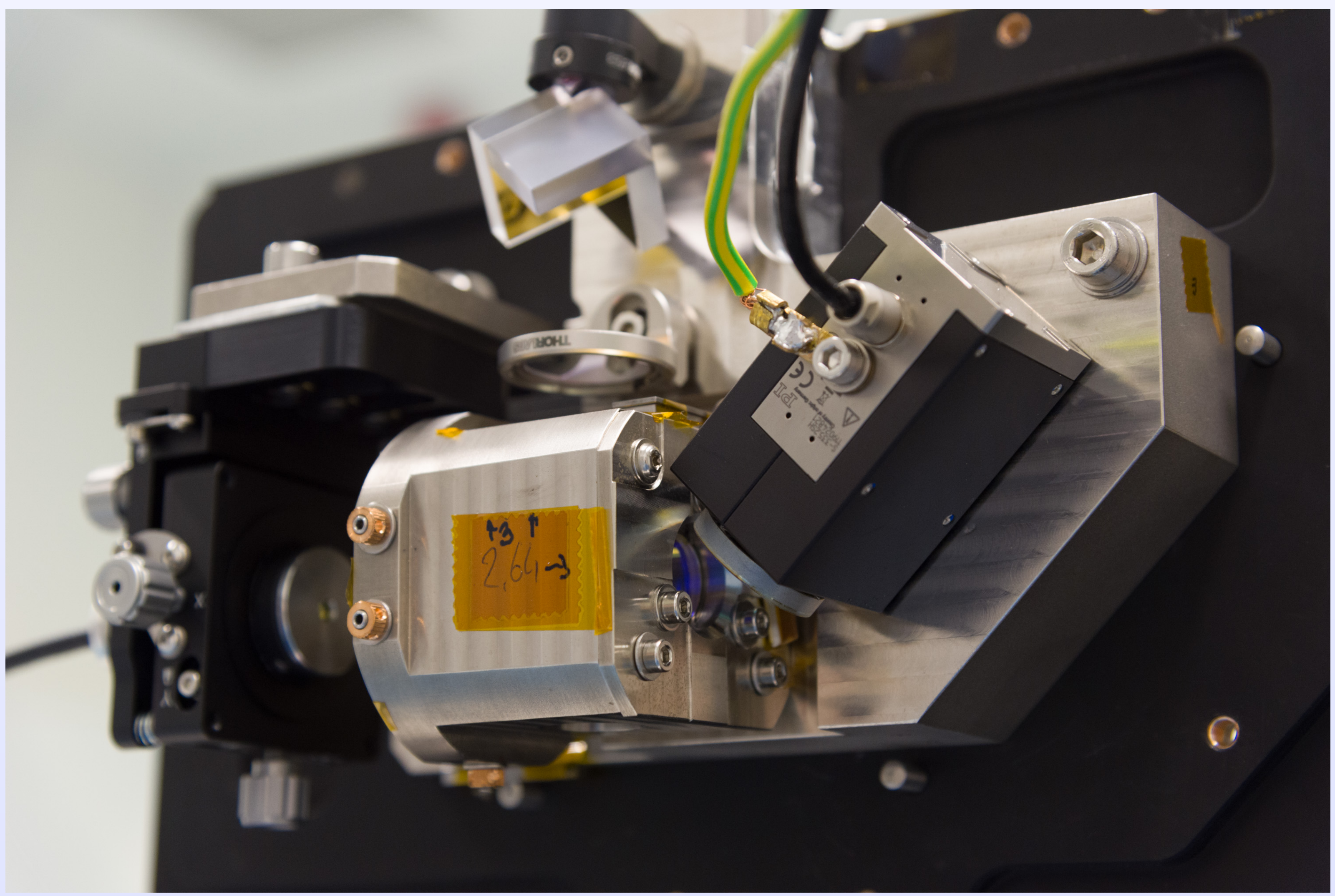

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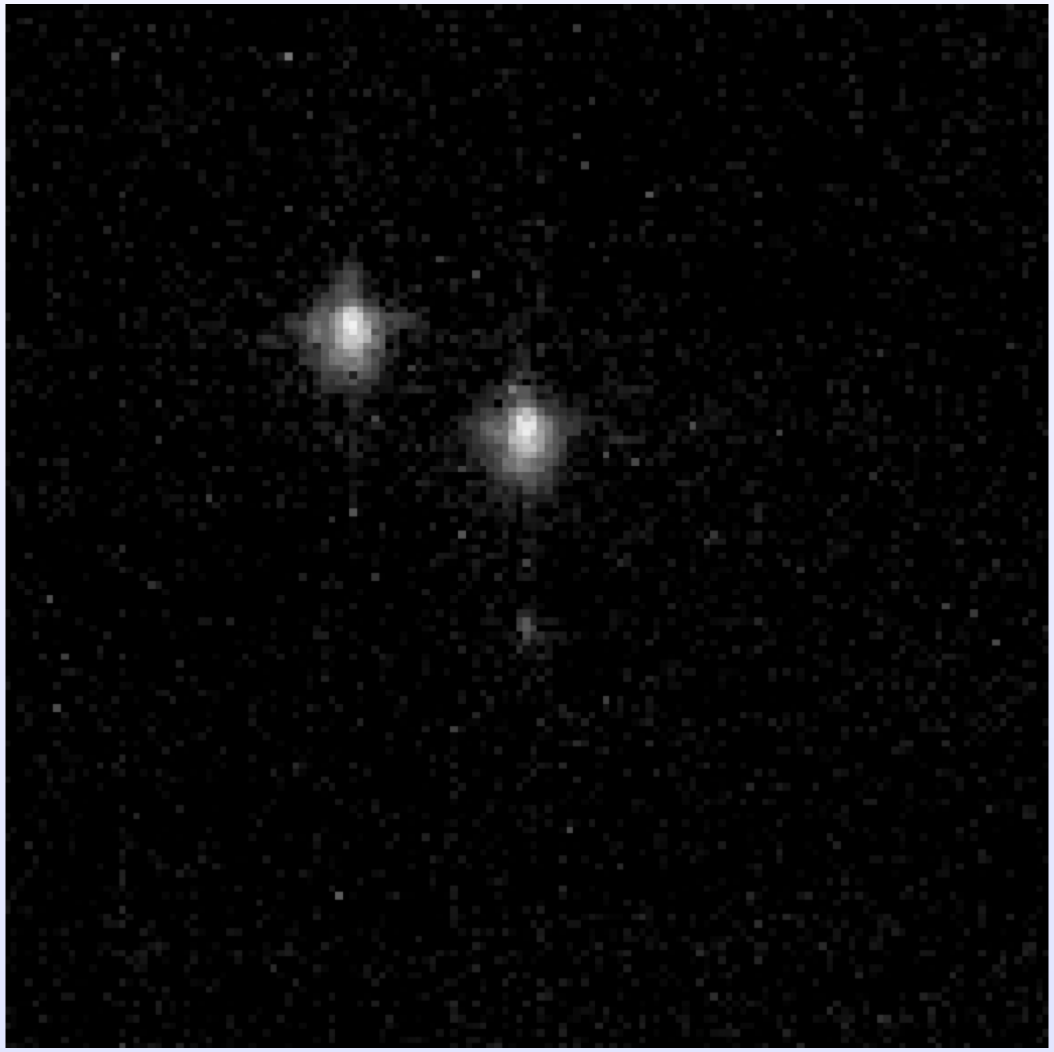
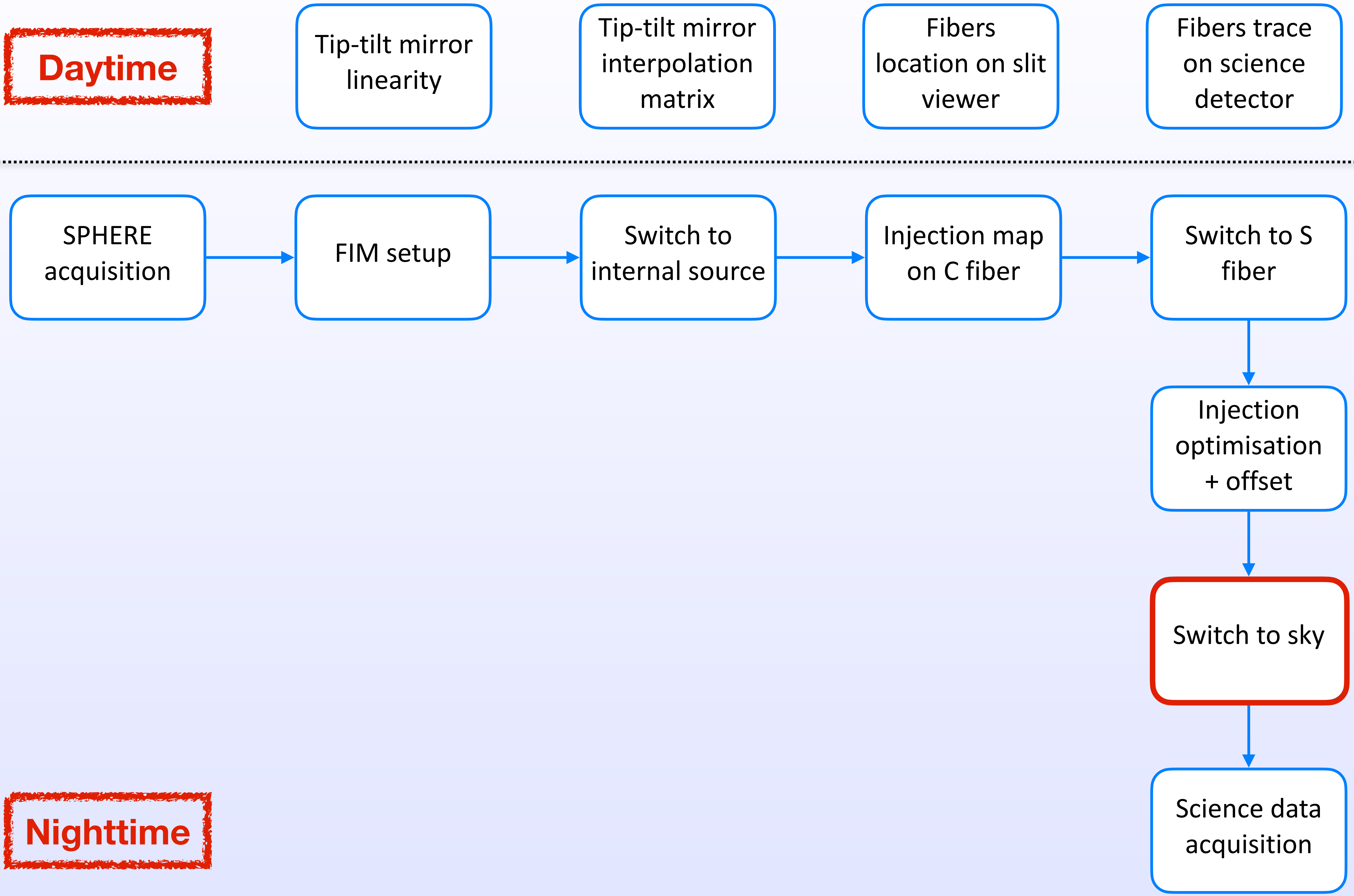


Nighttime

Operations: target acquisition



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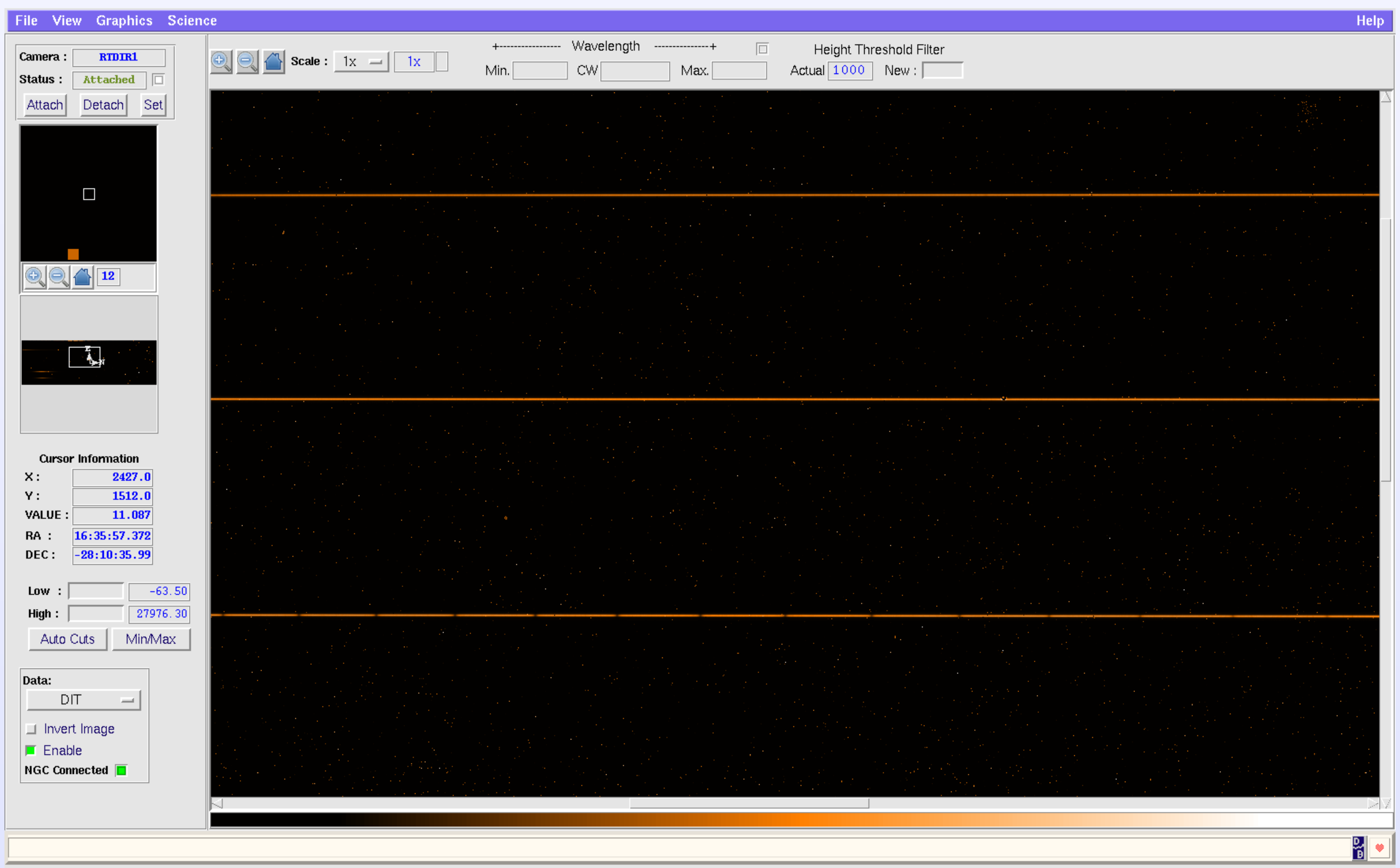
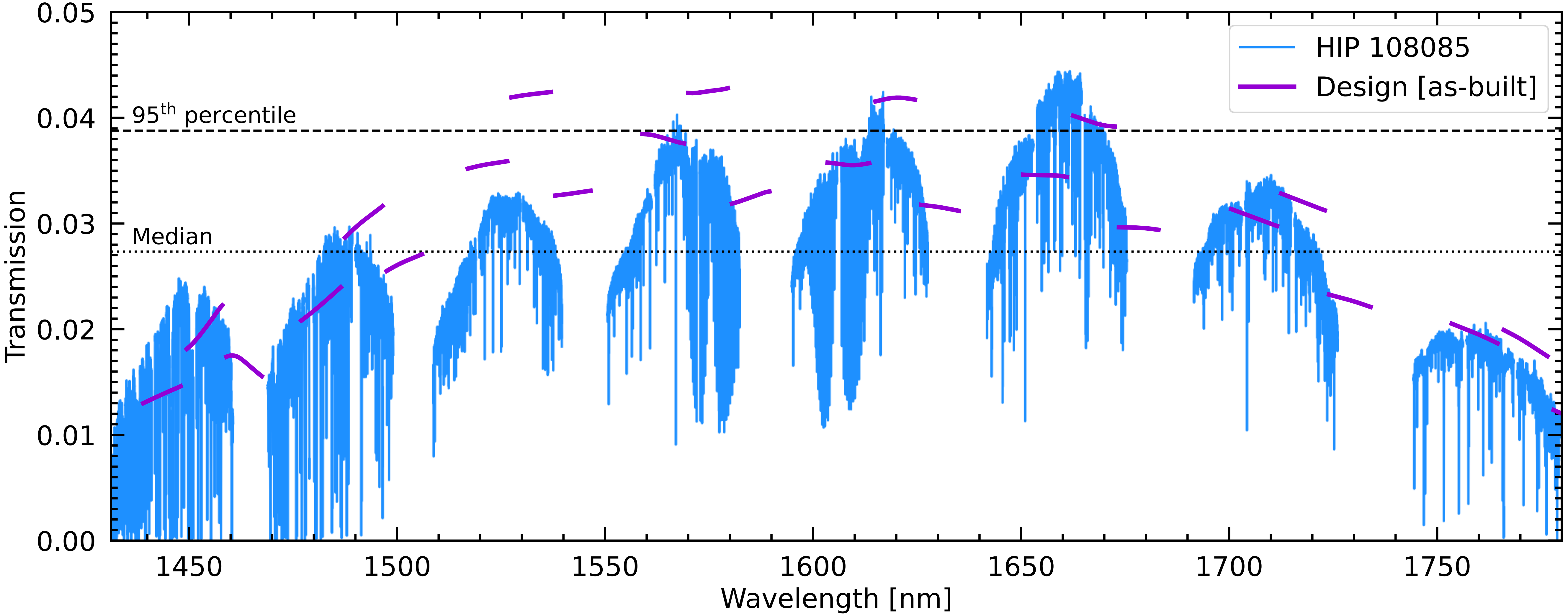


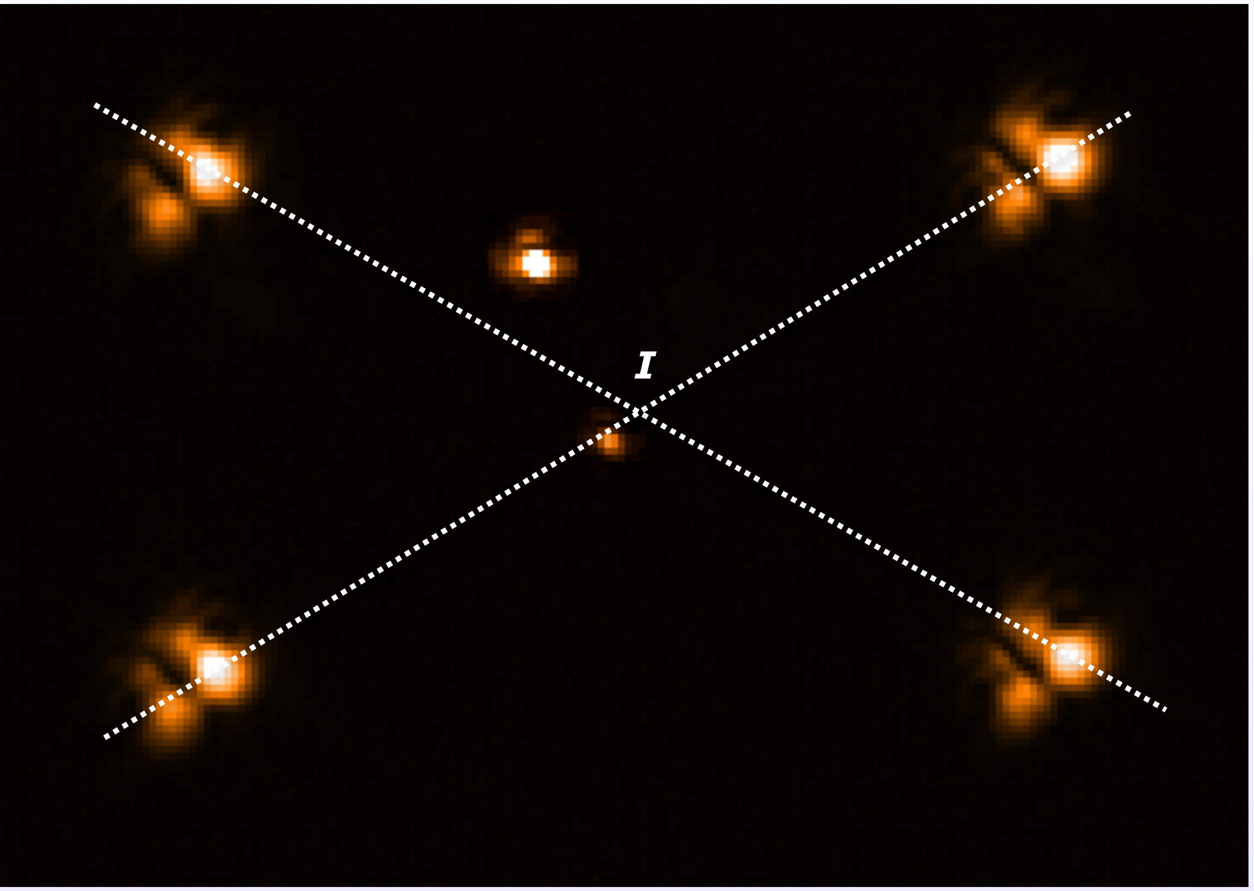
Commissioning results: transmission

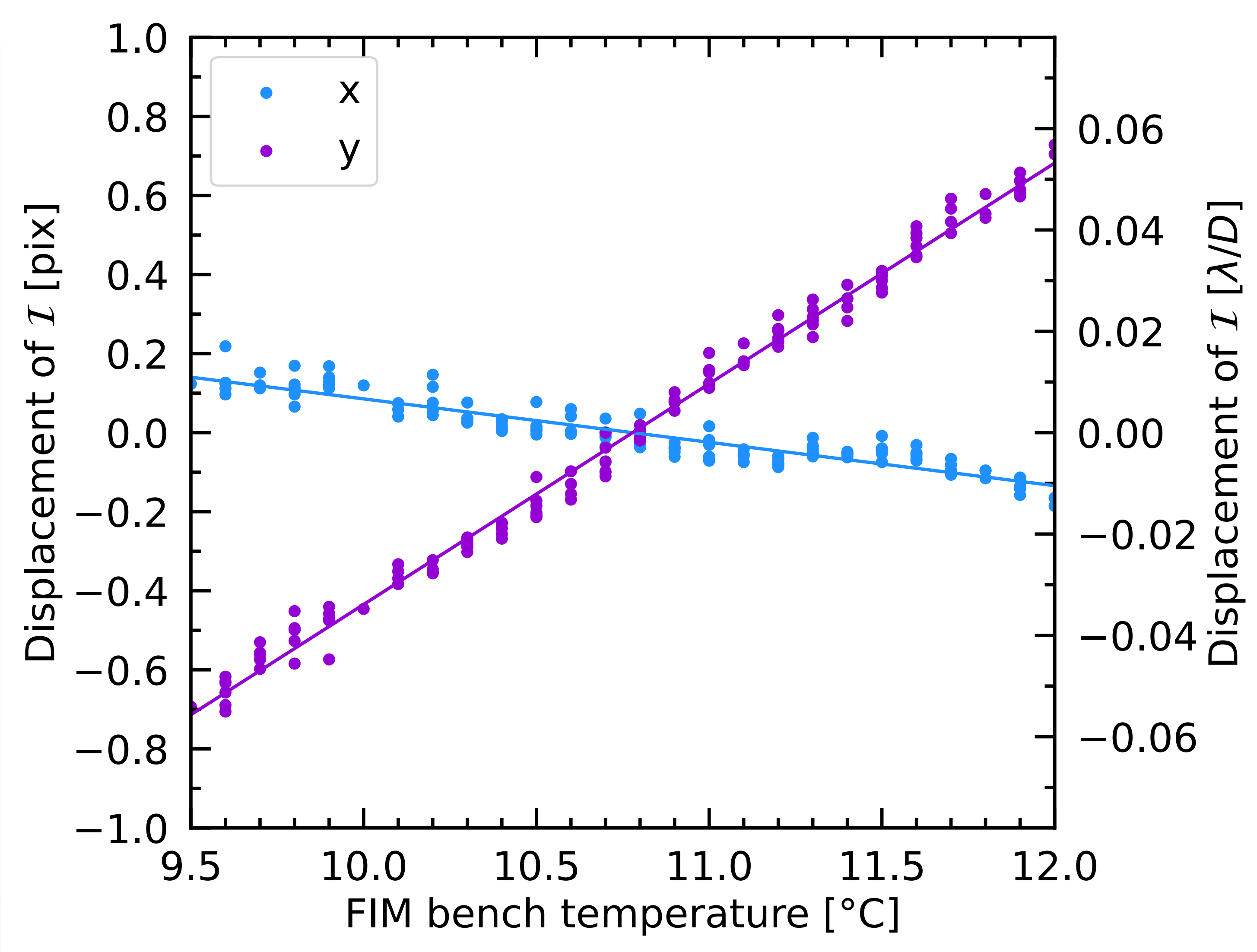
Median conditions
Bright star



End-to-end transmission exactly within specifications

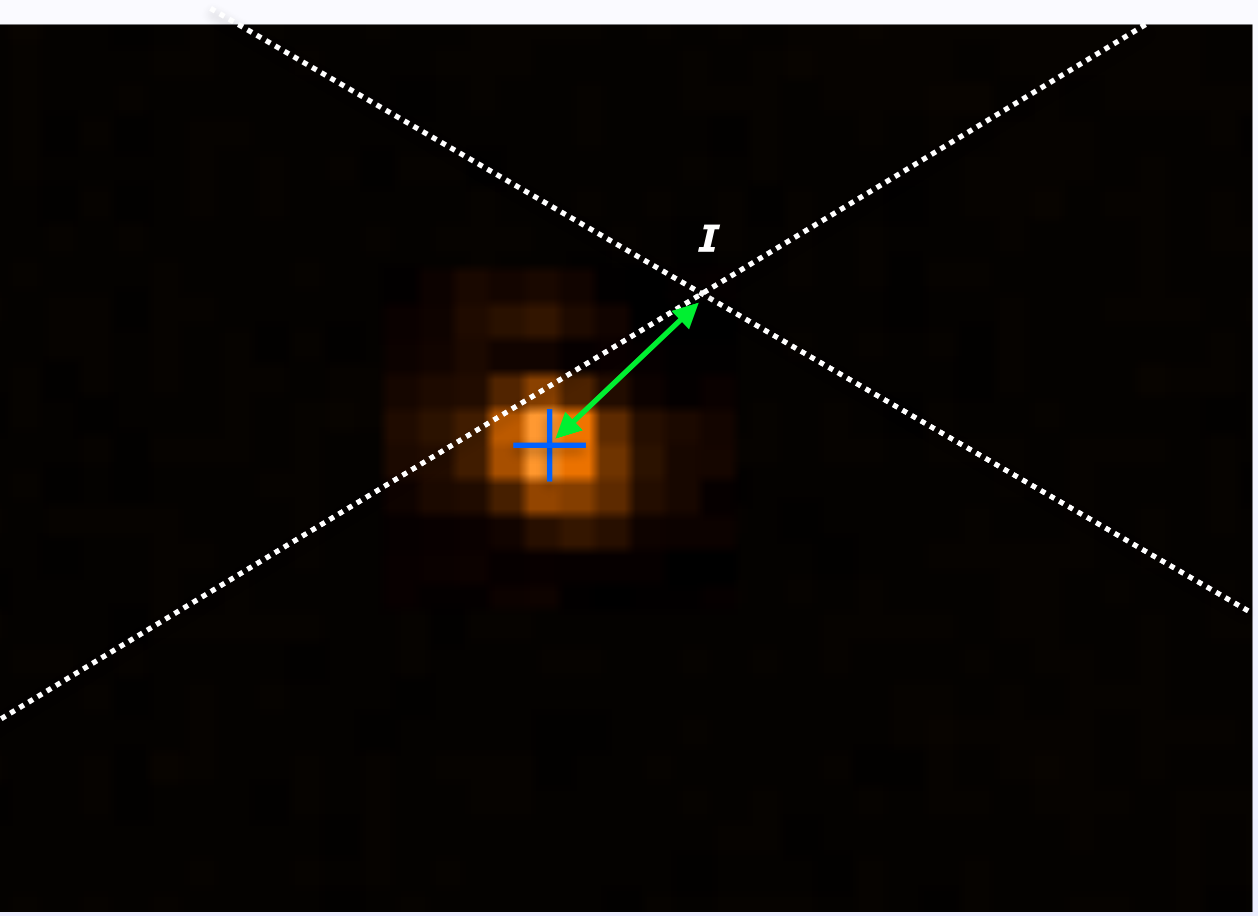
Commissioning: stability

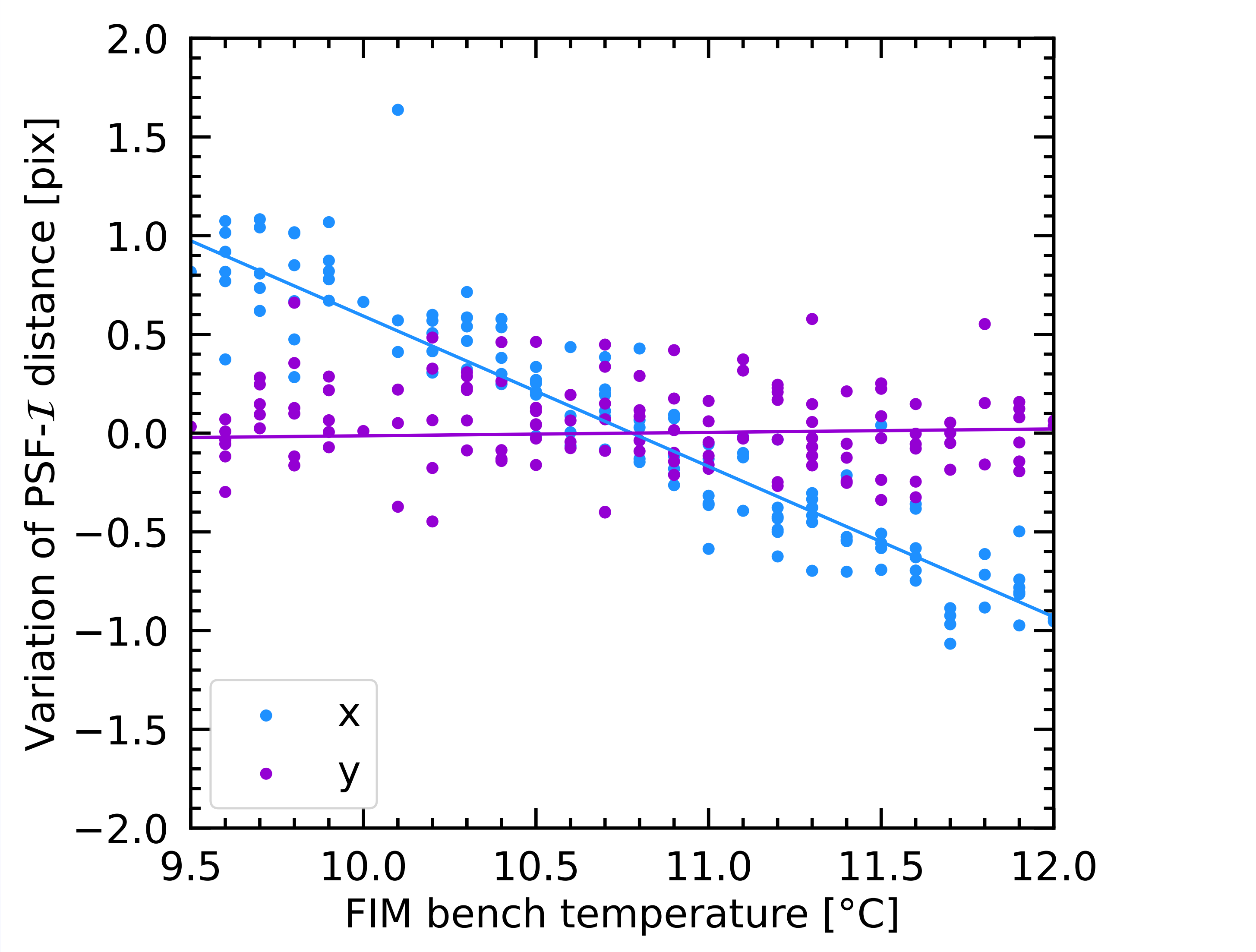




The science PSF moves a lot with temperature

Commissioning: stability

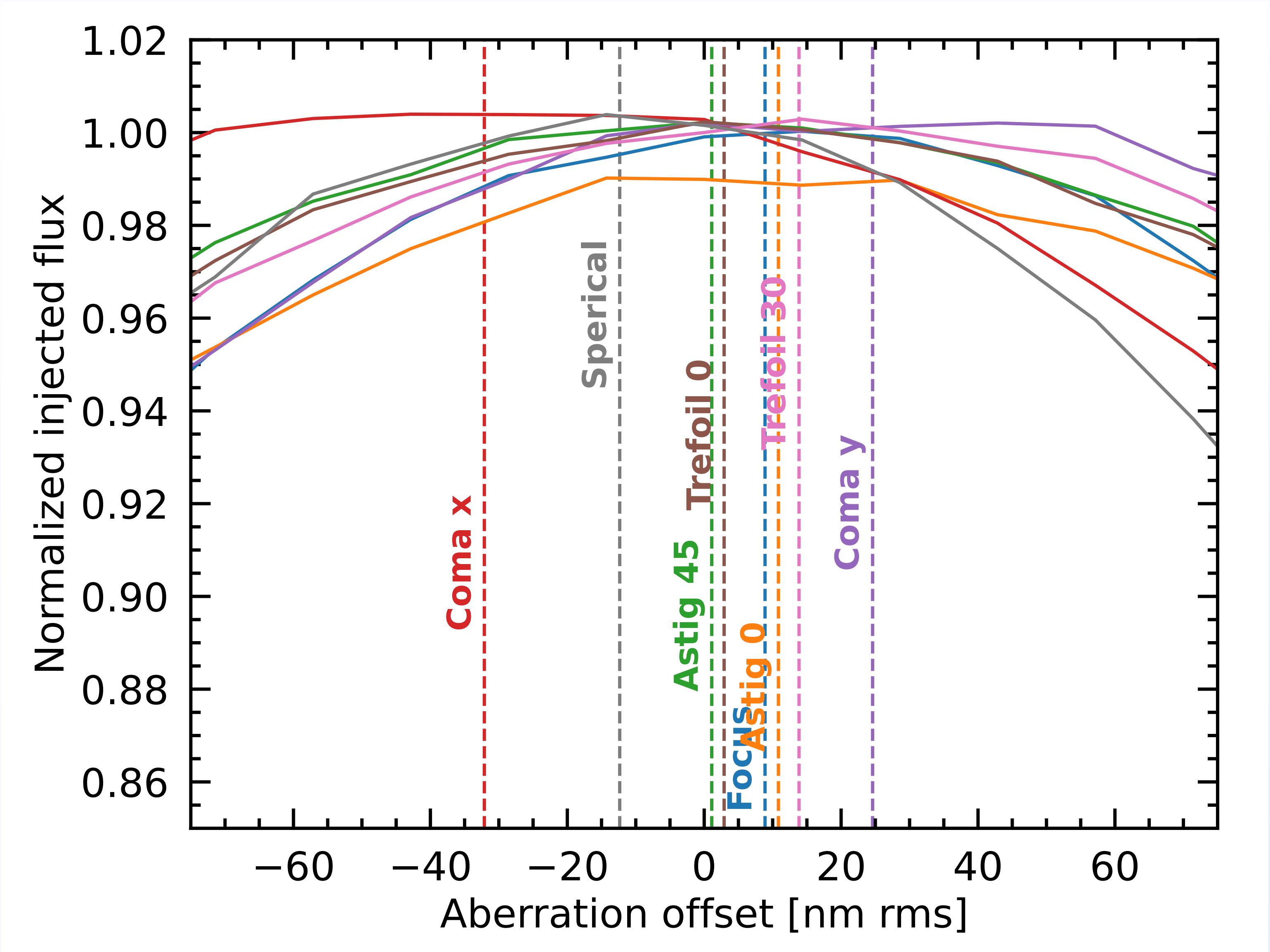




The science PSF moves a lot with temperature

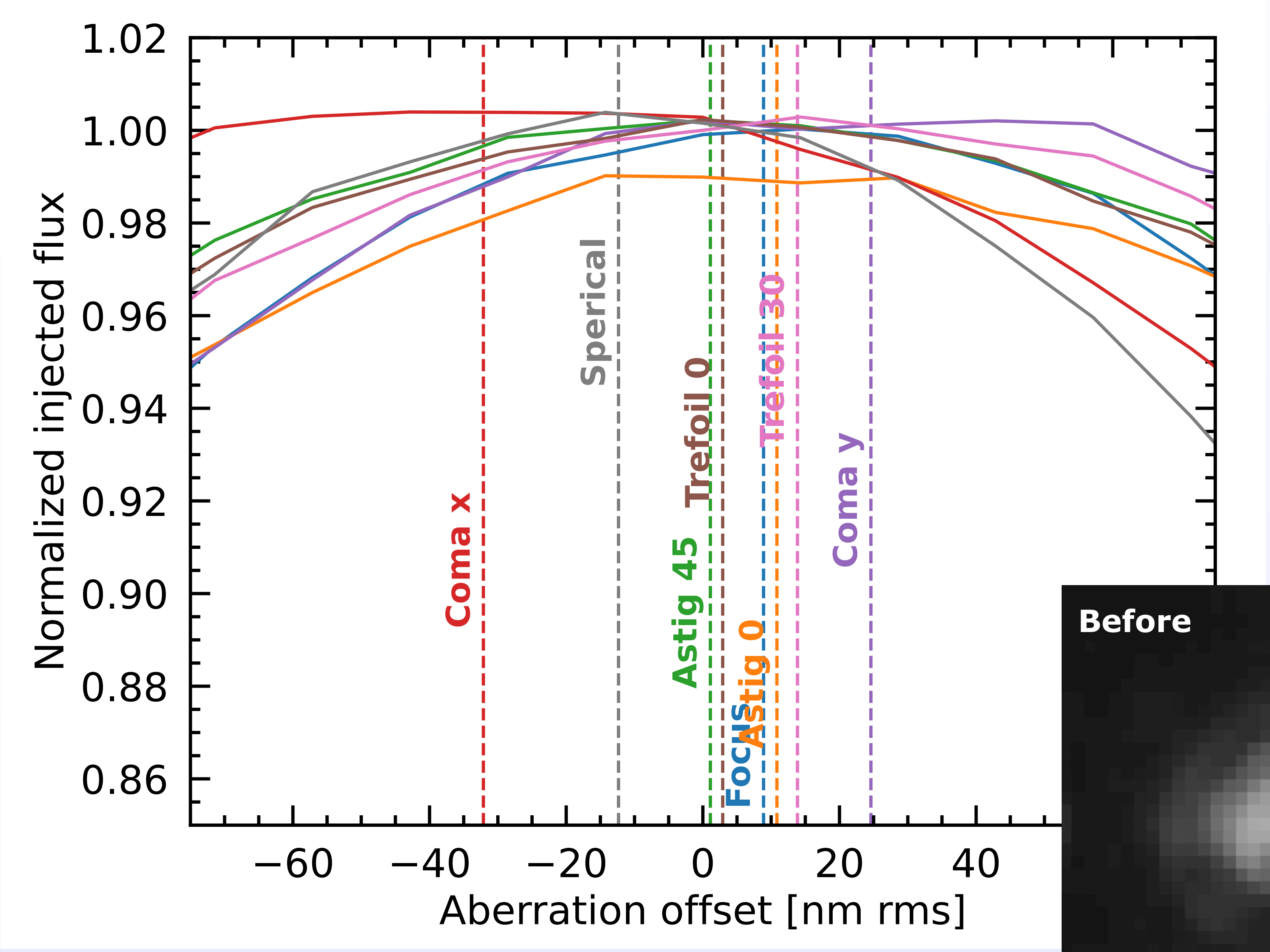
Motion compensation is NOT straightforward

Commissioning: NCPA

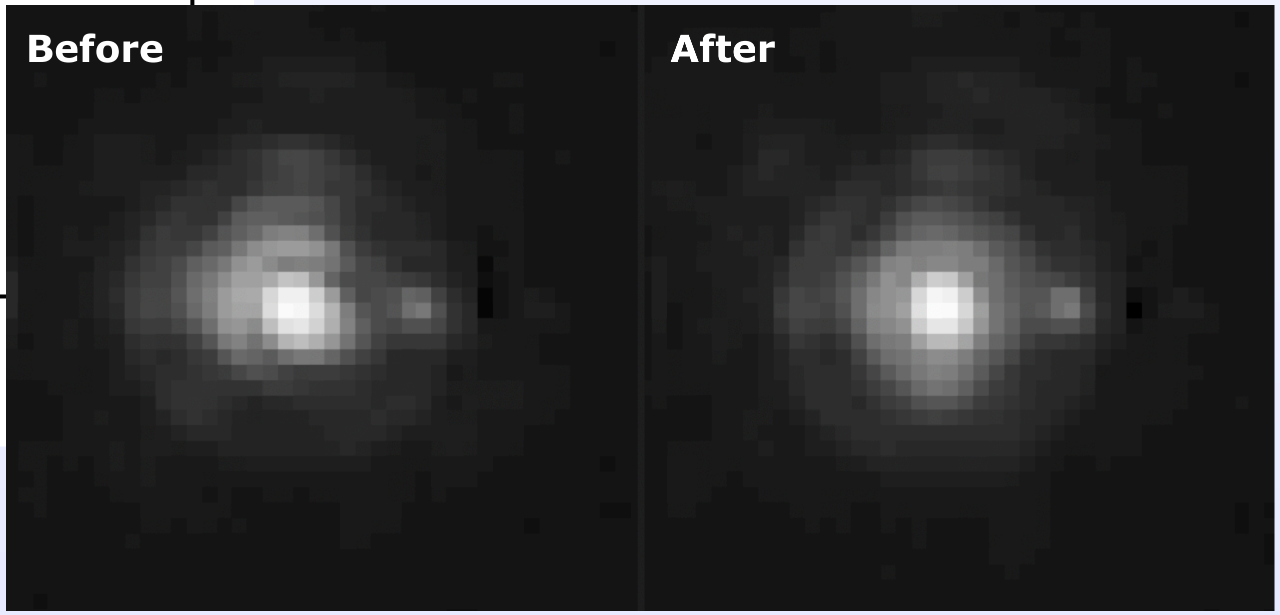


Level of NCPA is acceptable and no major gain expected from compensation

Commissioning: NCPA

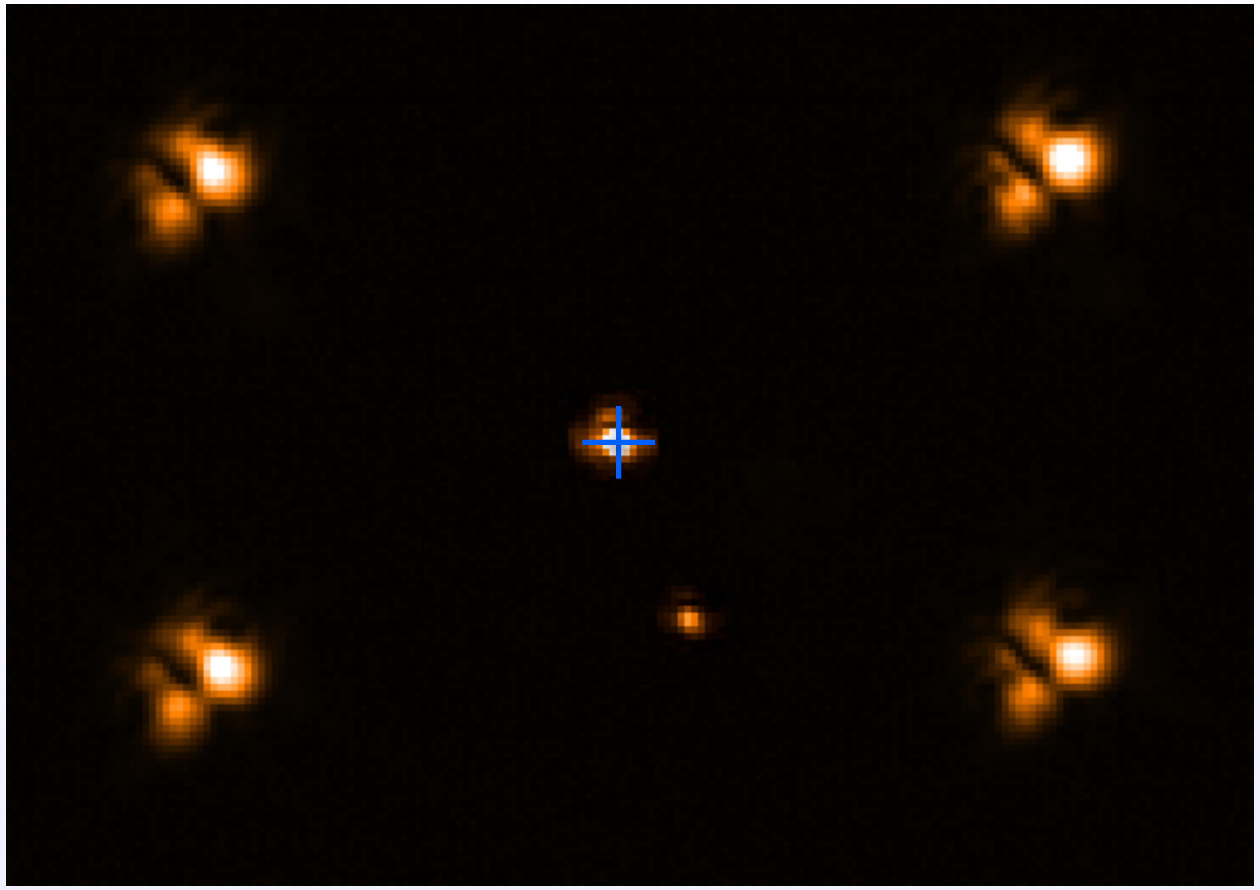


Optimisation on FIM camera

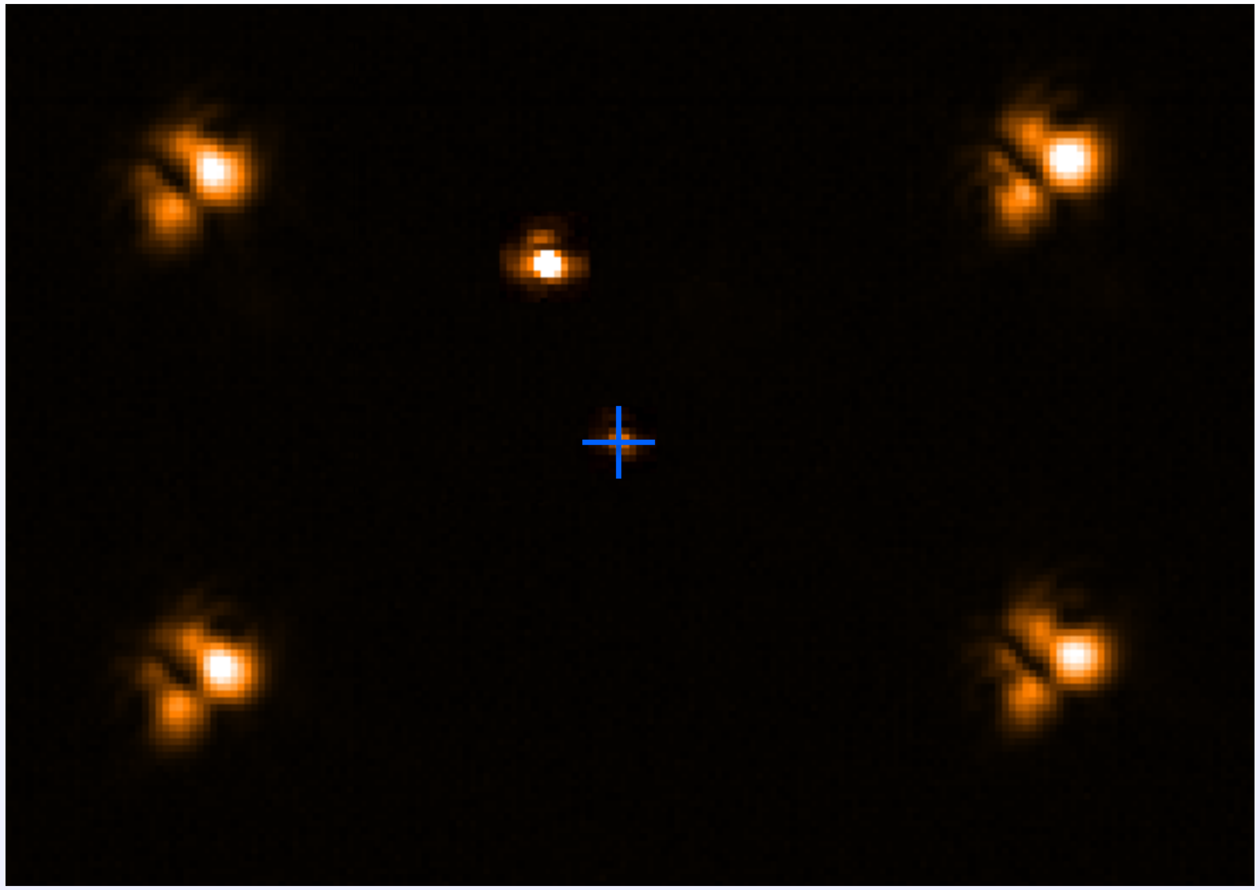


Level of NCPA is acceptable and no major gain expected from compensation

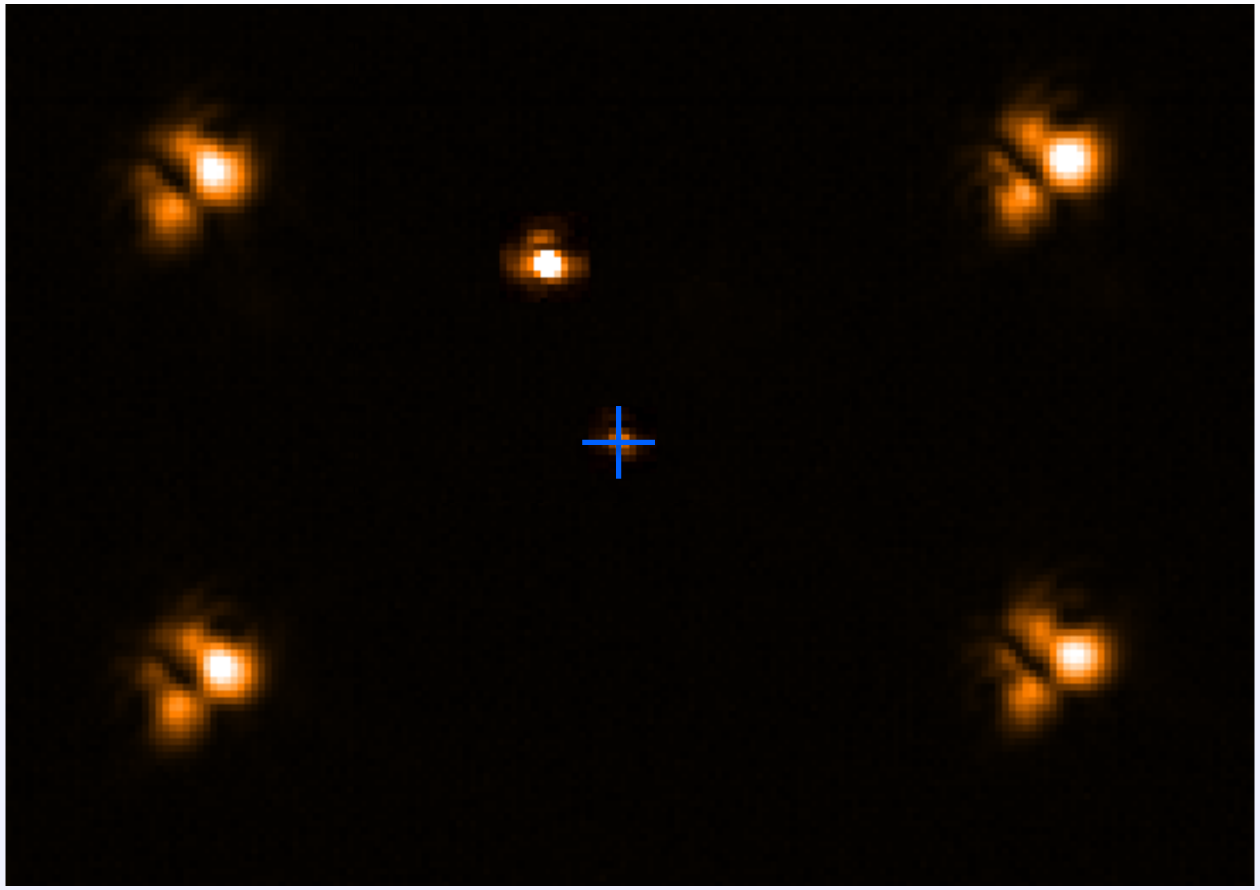
Commissioning: astrometry

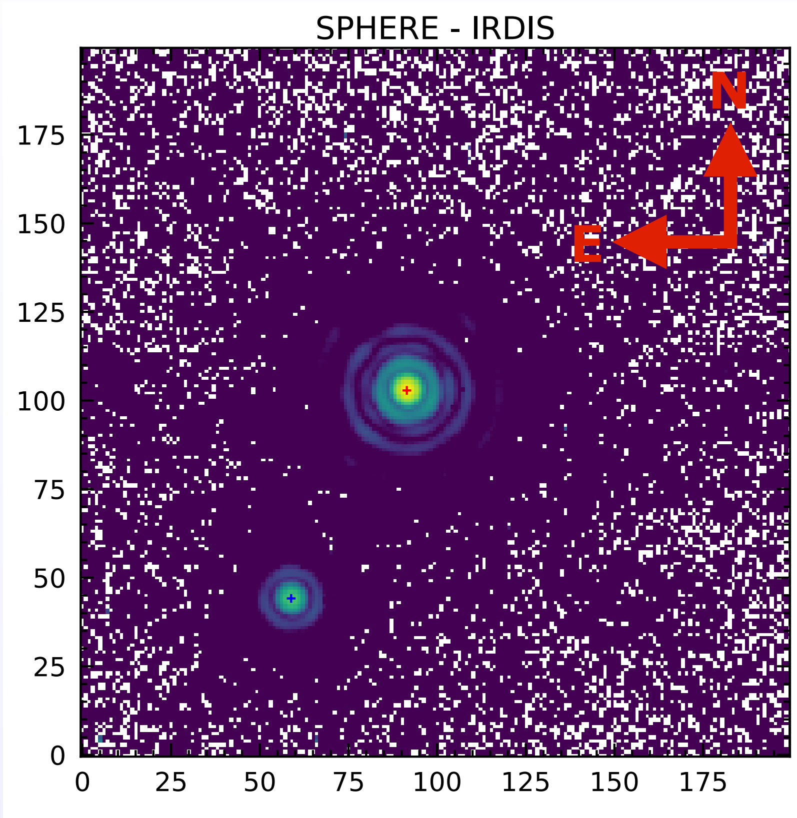


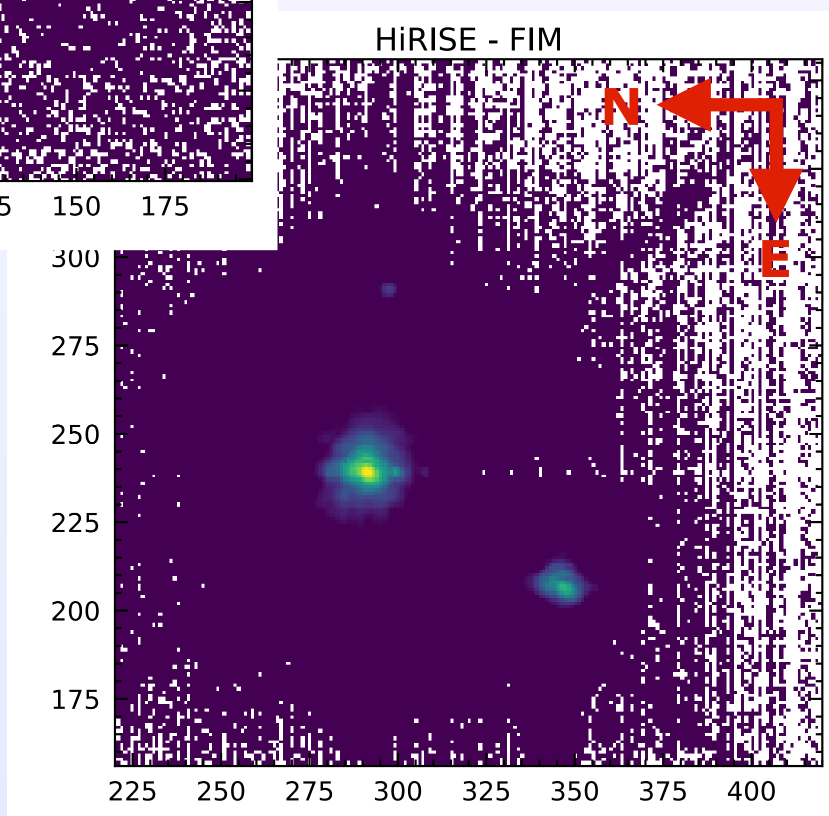
Commissioning: astrometry



Commissioning: astrometry



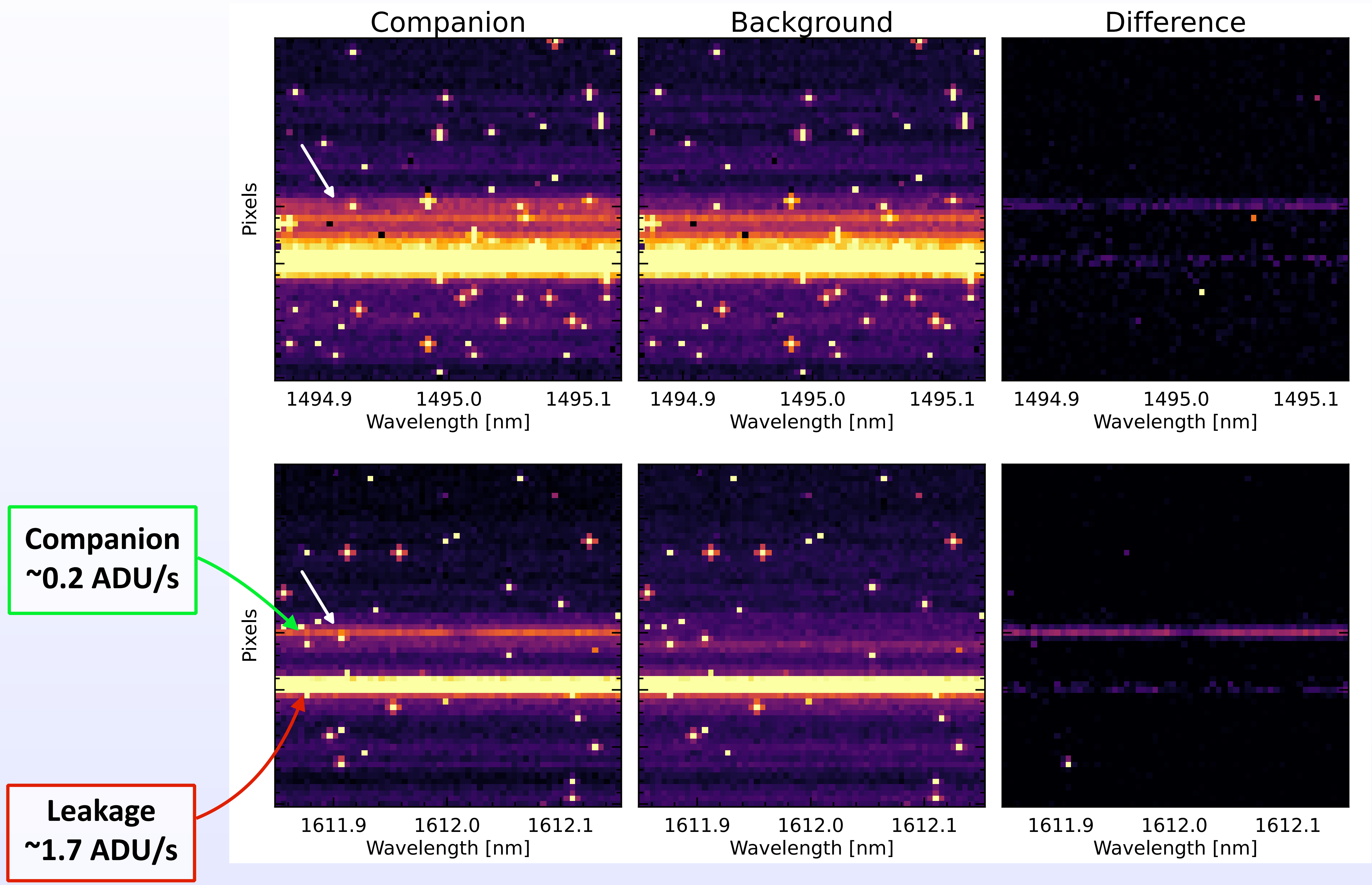




- North correction = 90.40° ± 0.08°
- Pixel scale = 12.805 ± 0.027 mas/pix

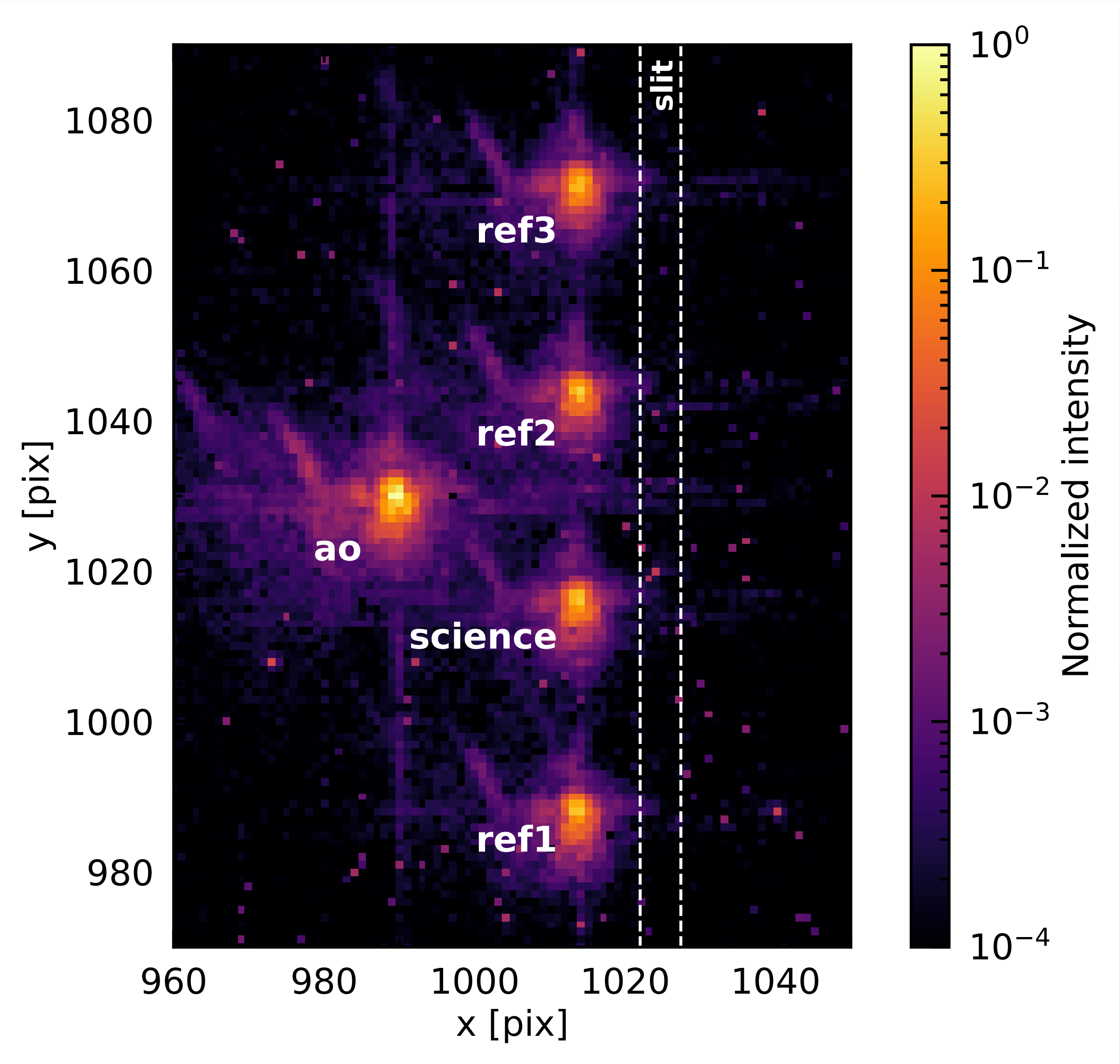
Cross-calibration strategy with SPHERE/IRDIS

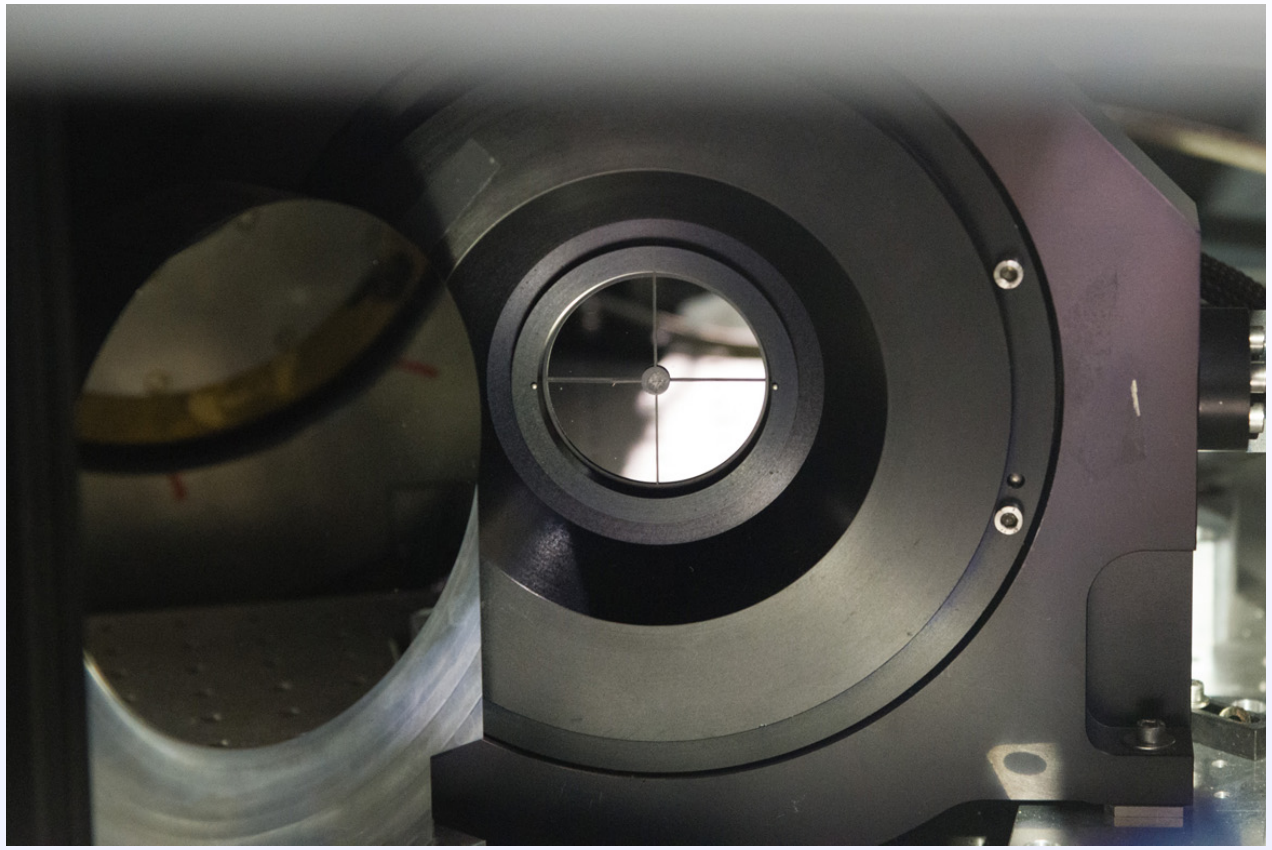
Commissioning: AO guide fiber leakage

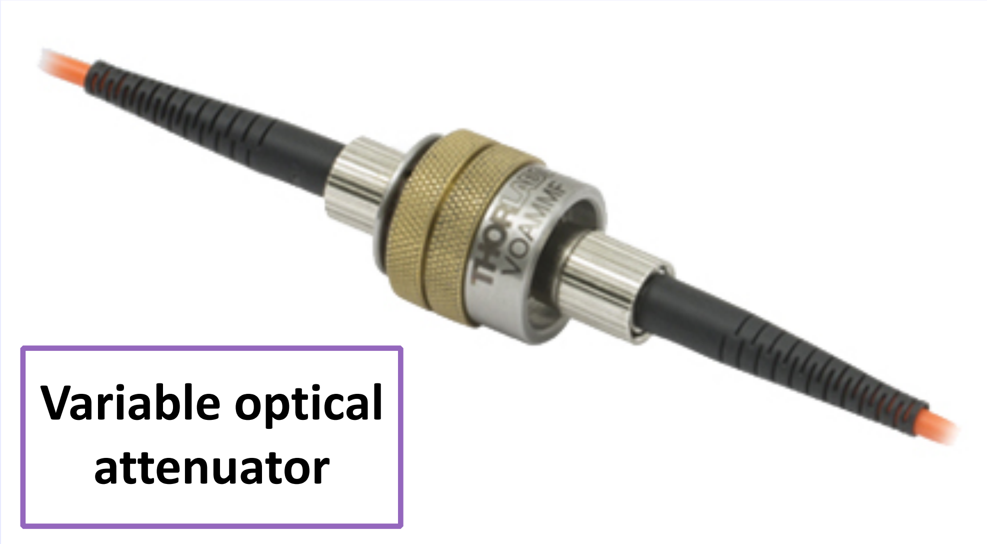


MACAO guide fiber leaks inside the slit

Commissioning: AO guide fiber leakage







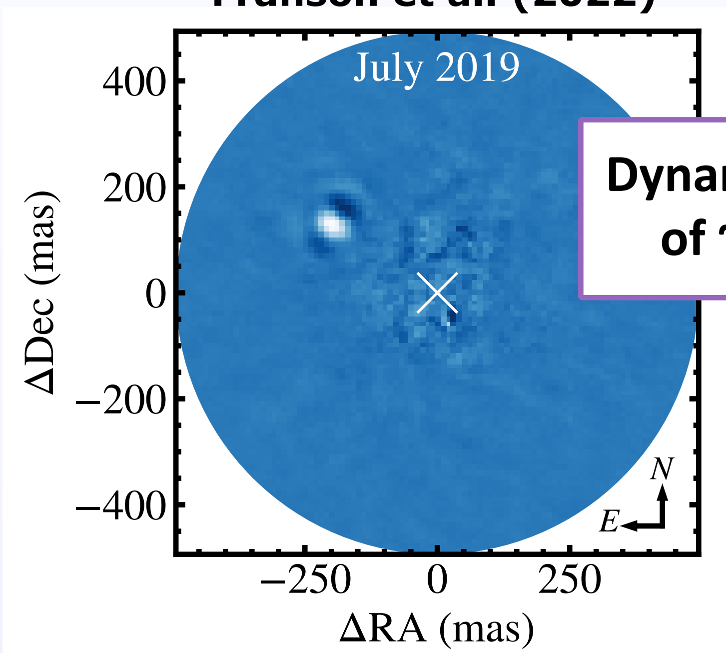
Variable optical attenuator

Mitigation strategy already foreseen

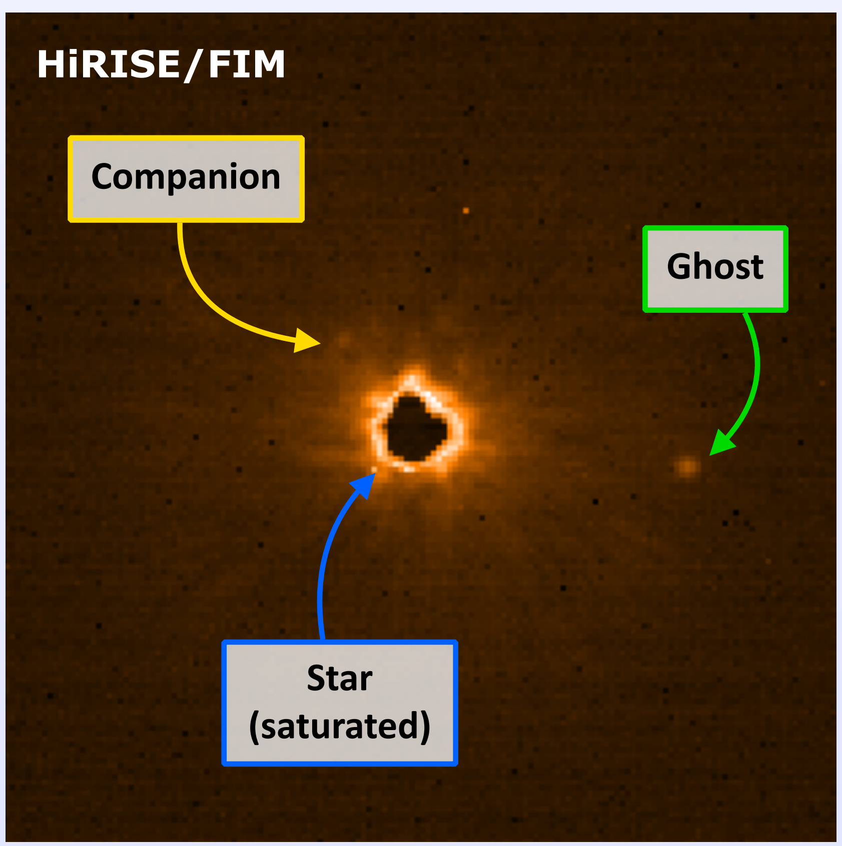
Commissioning: a first detection of HD984 B

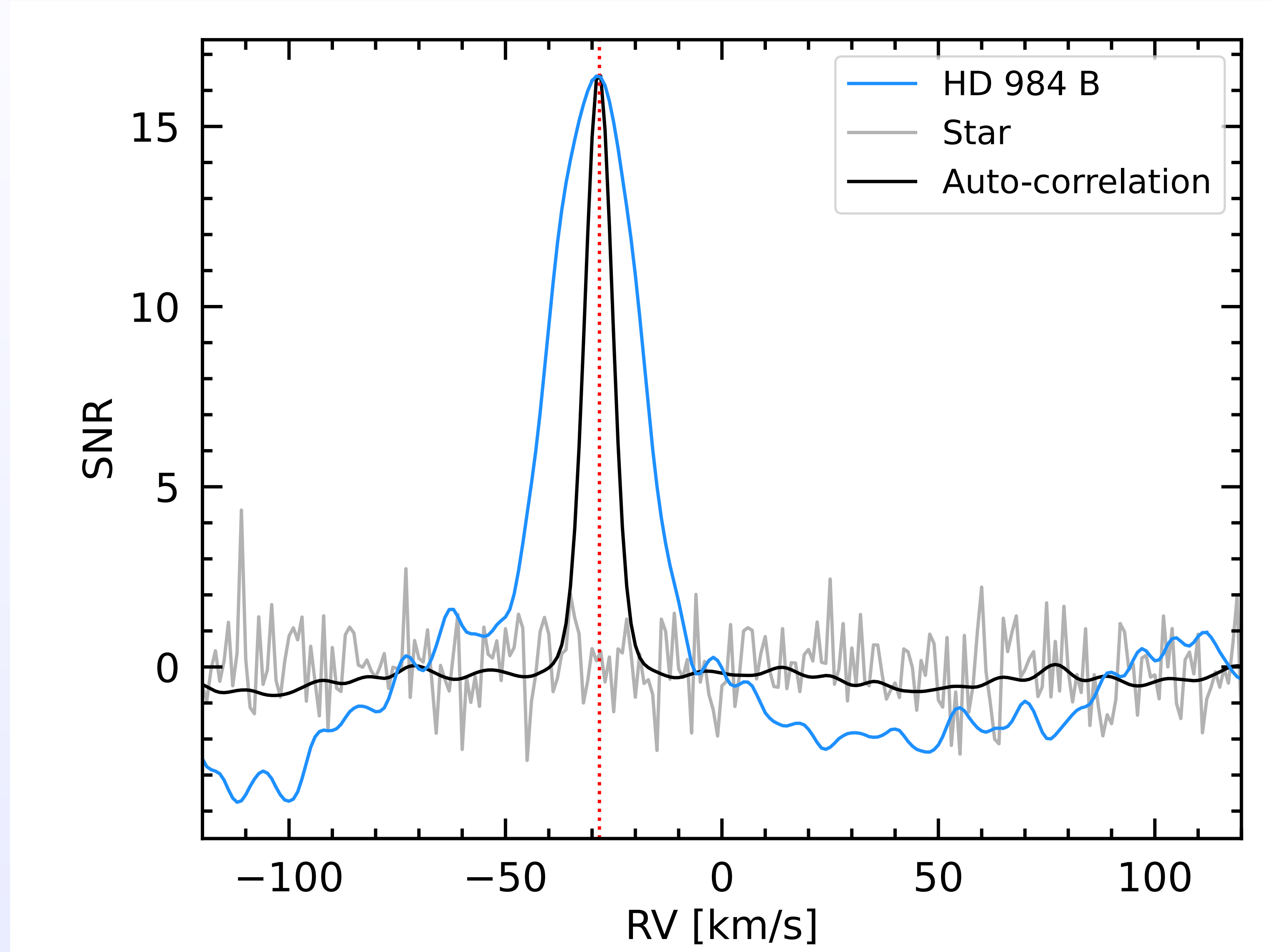
Discovery: **Meshkat et al. (2015)**

Franson et al. (2022)



Dynamical mass of ~60 M_{Jup}

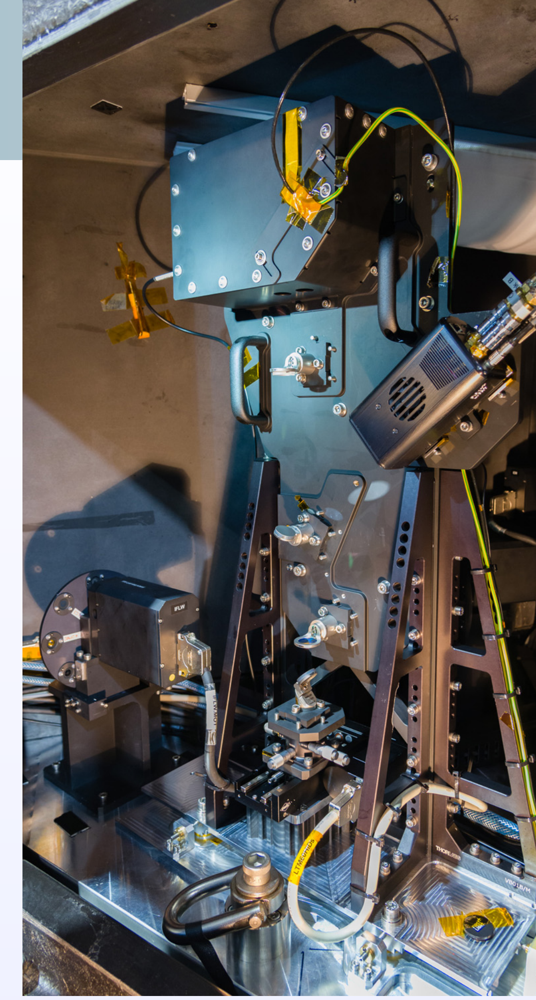


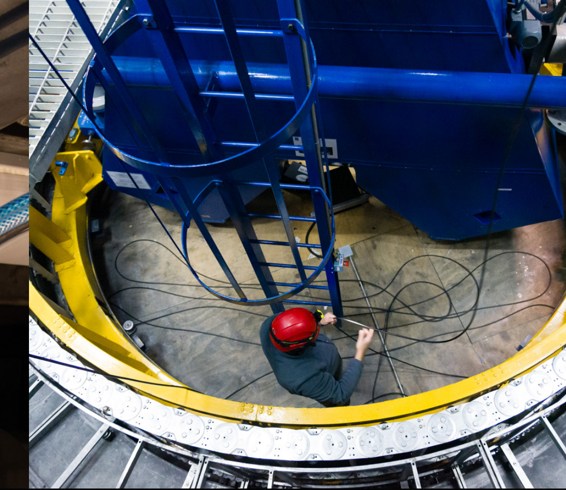


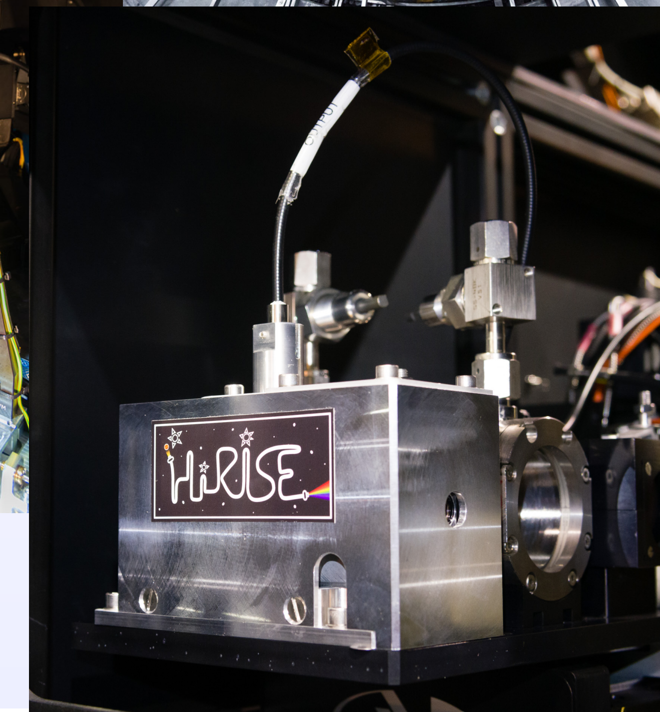
- Least-square CCF analysis
- BT-Settl model at $T_{\rm eff}$ = 2700K
- $v_{\rm orb}$ sin i = -31 km/s, $v_{\rm rot}$ sin i = 13 km/s
- Value in agreement wit KPIC data (Costes et al. in prep.)

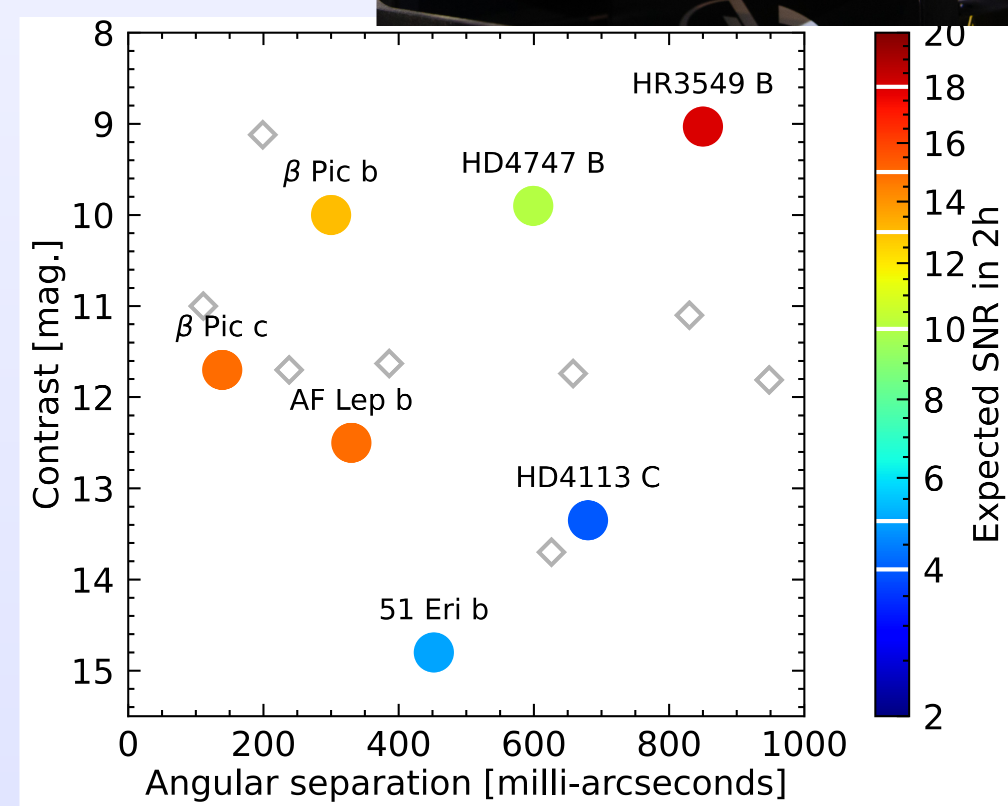
Conclusions & prospects

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
   - 3 nights in November 2023
   - Large programme to be submitted in P114









HiRISE core team

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


HiRISE
DELL