Direct characterization of young giant exoplanets at high spectral resolution

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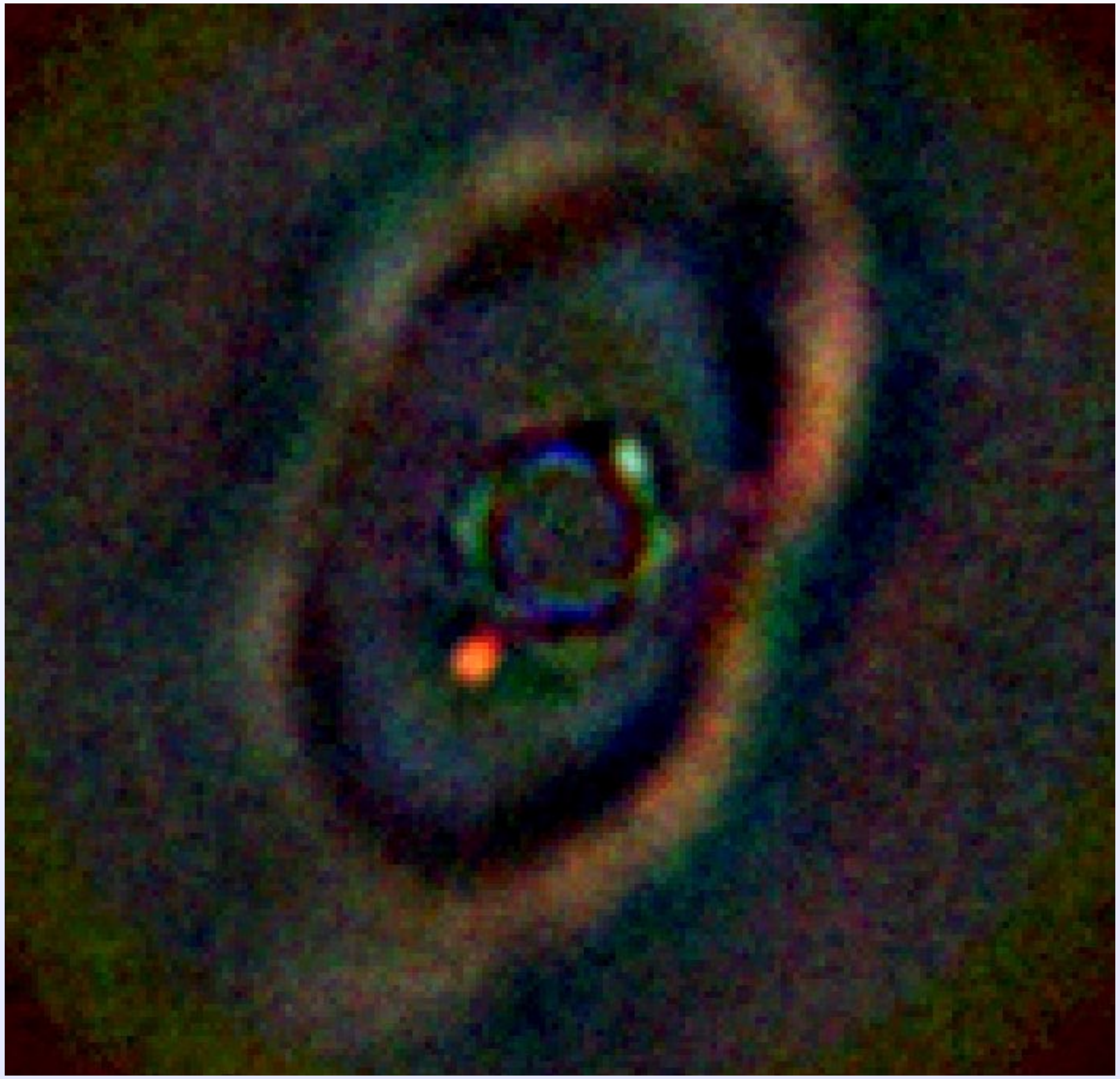
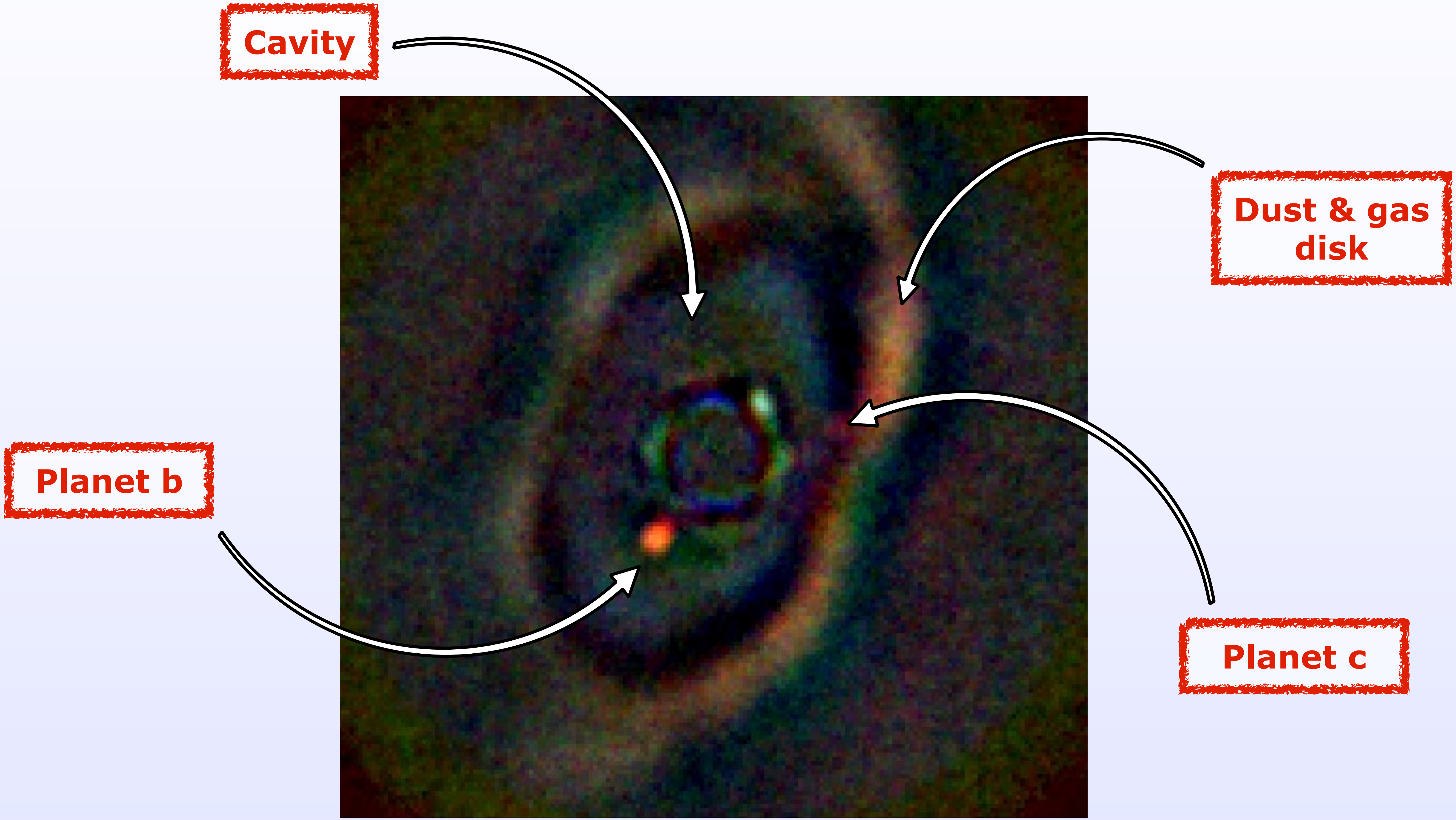
Direct imaging of exoplanetary systems



PDS 70 - Keppler et al. (2018)

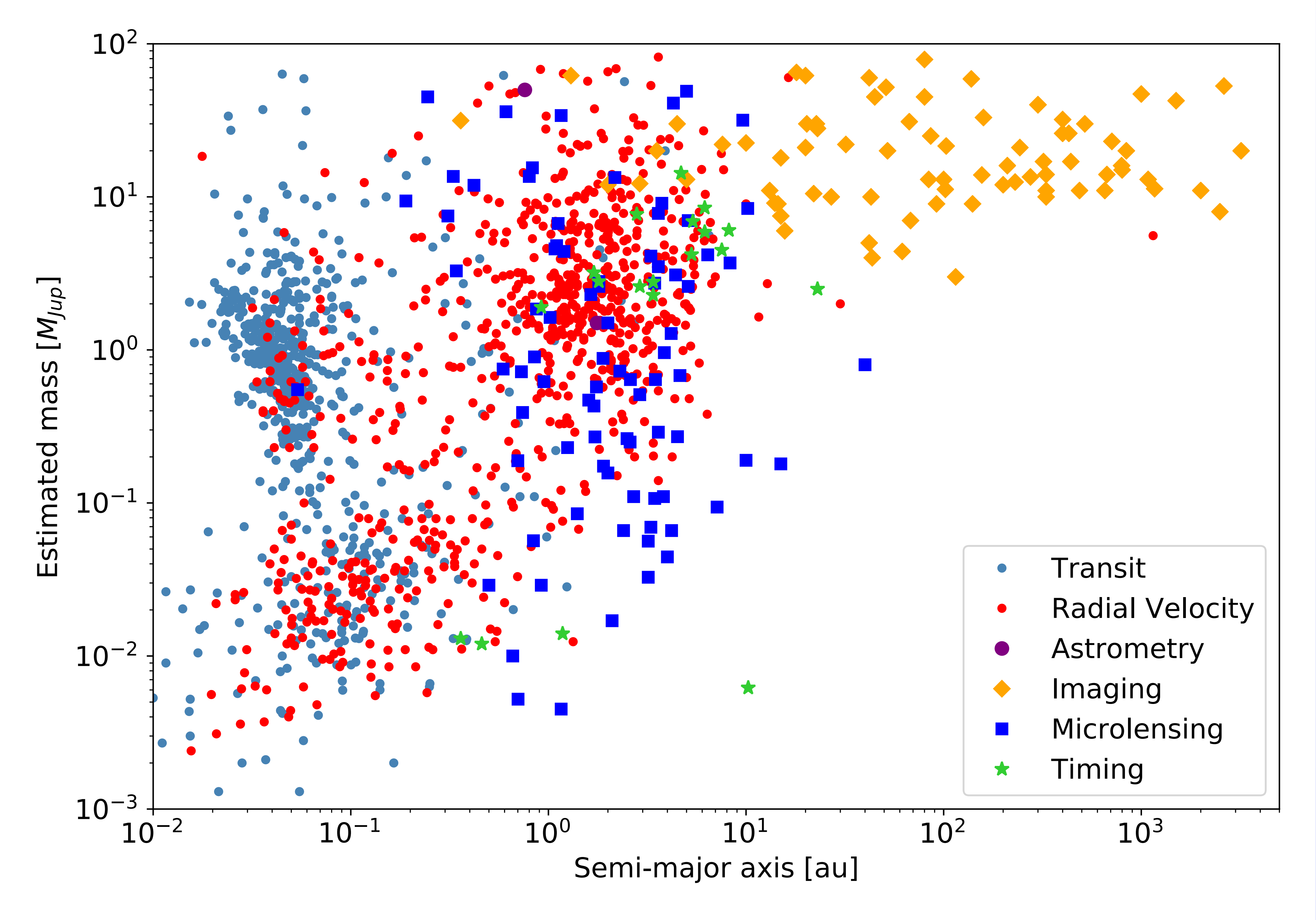
Direct imaging of exoplanetary systems



PDS 70 - Keppler et al. (2018)

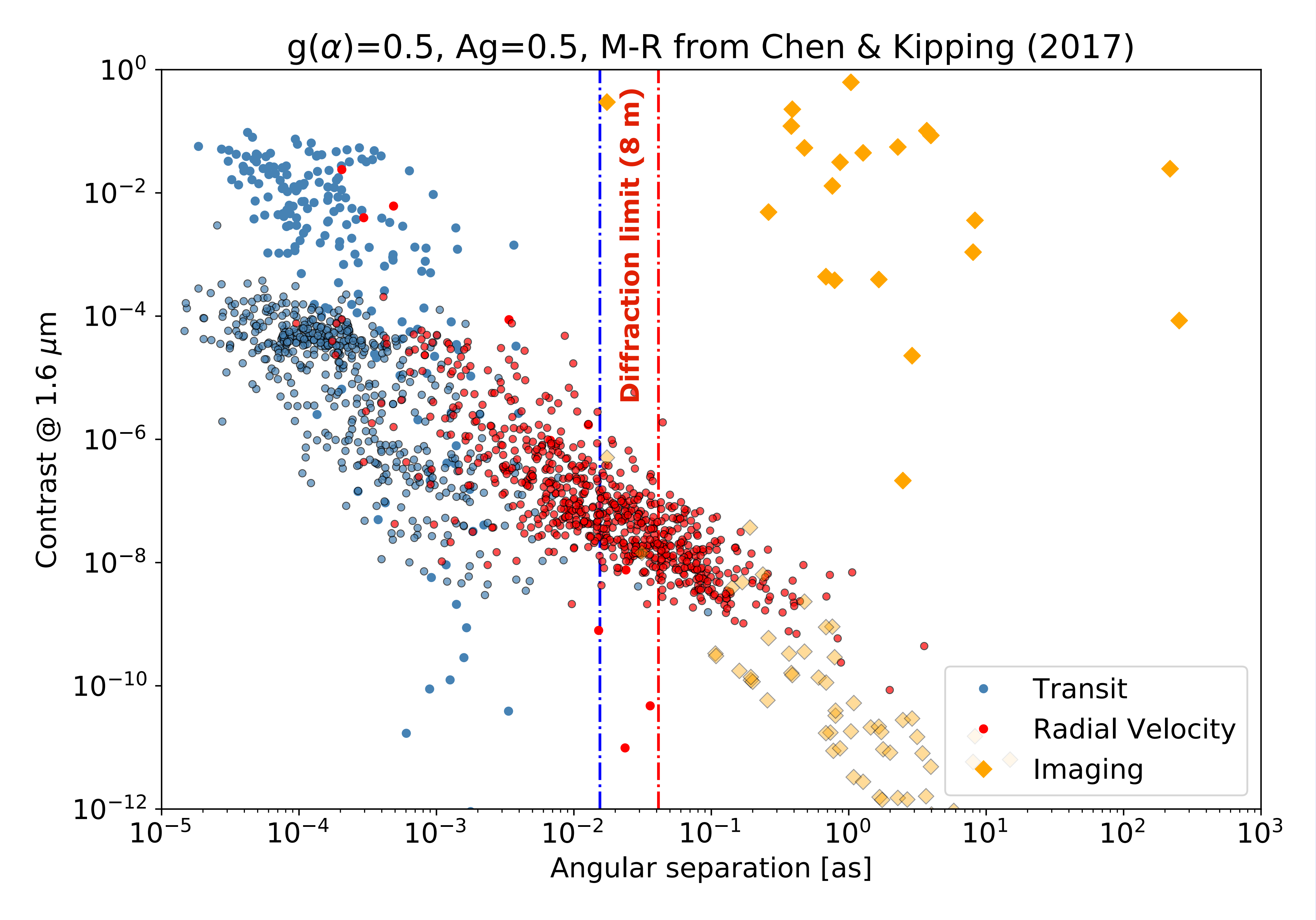
Direct imaging: the challenge

Physical units



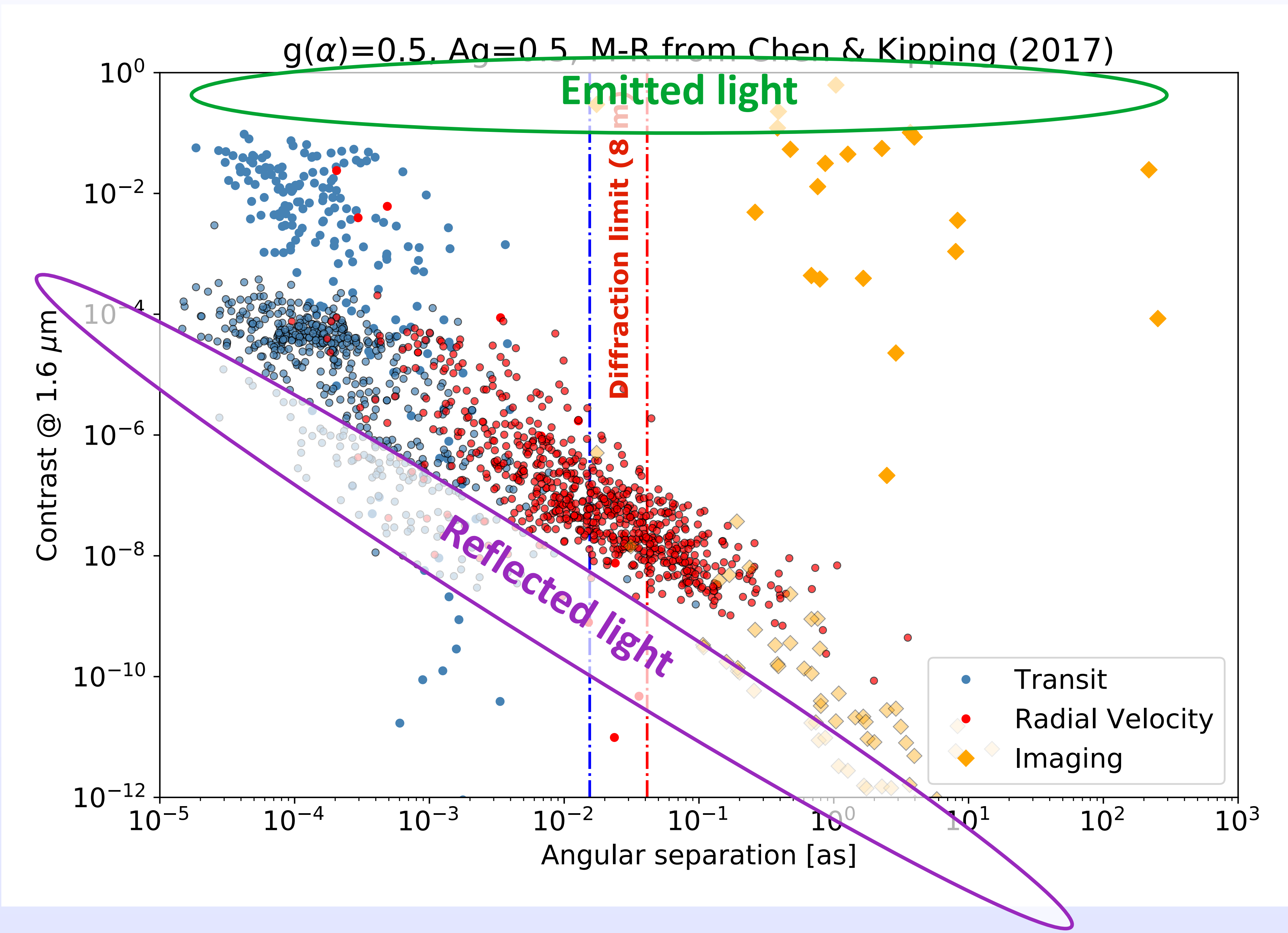
Direct imaging: the challenge

Observables

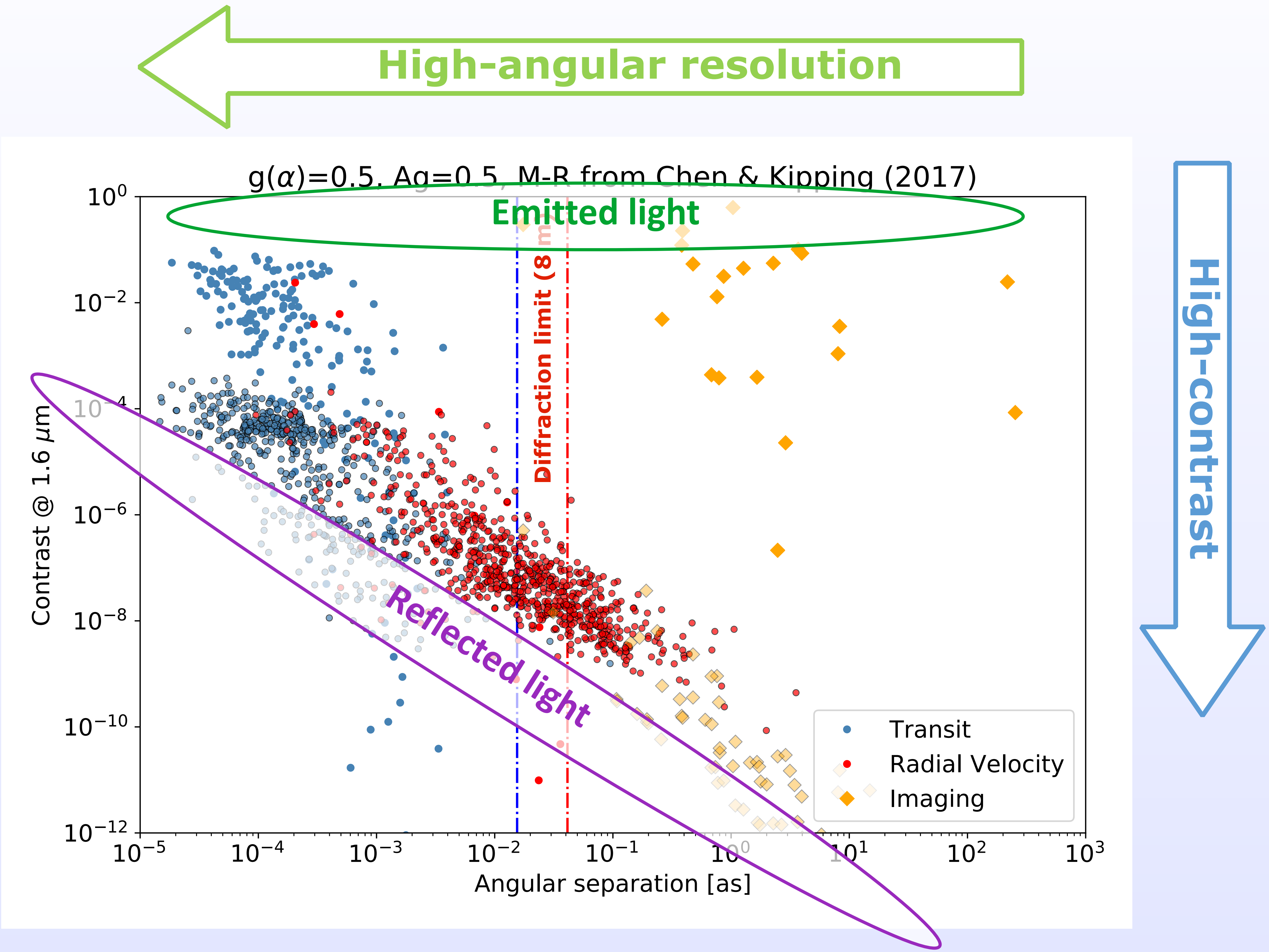


Direct imaging: the challenge

Observables



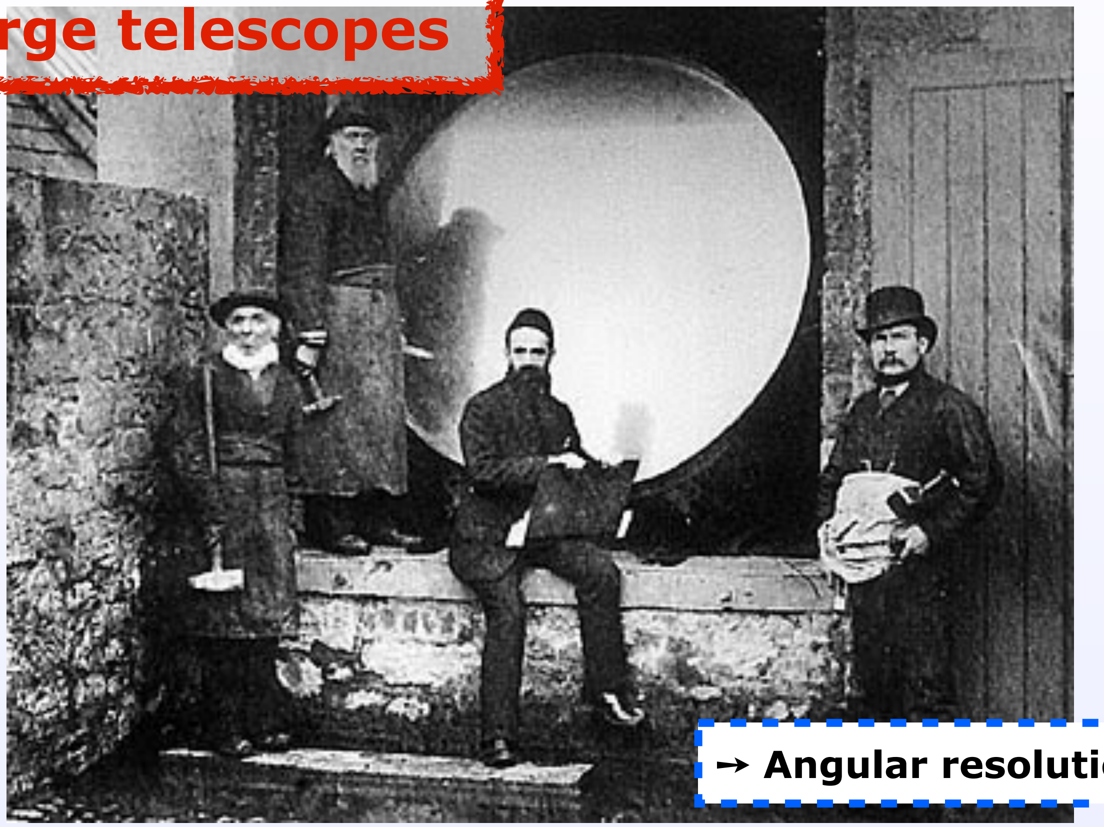
Direct imaging: the challenge



Direct imaging recipe

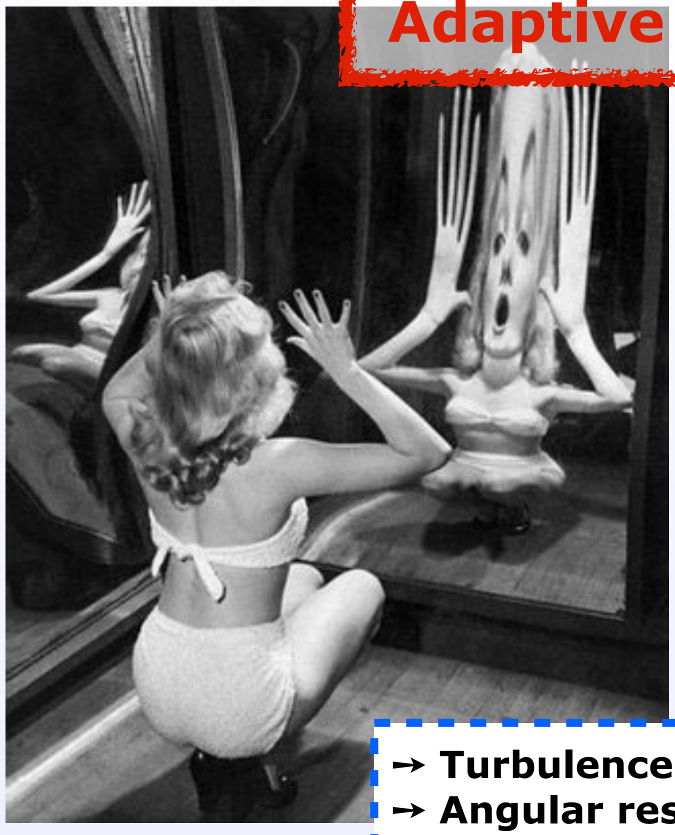
Direct imaging recipe

Large telescopes

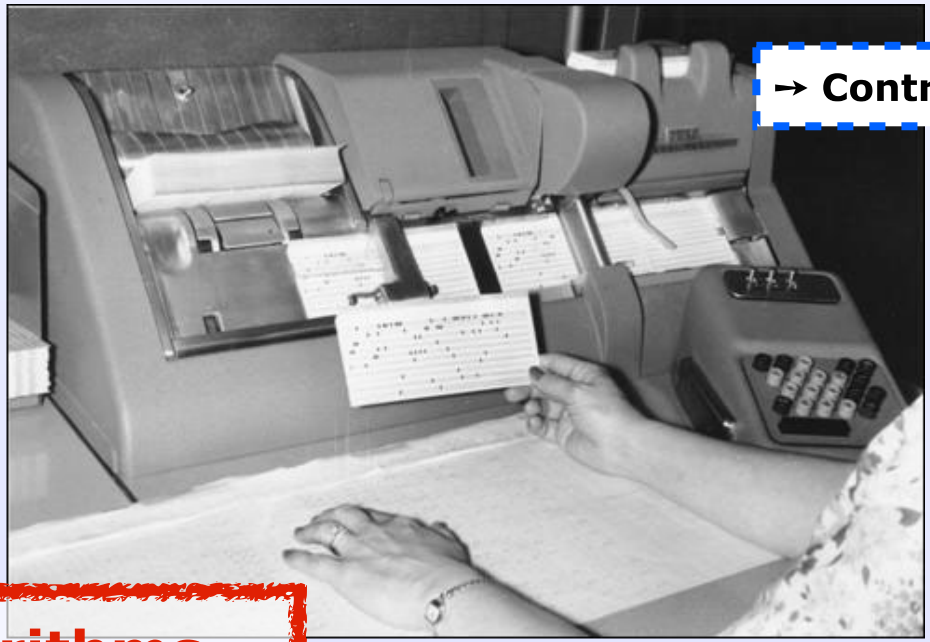


→ Angular resolution

Adaptive optics

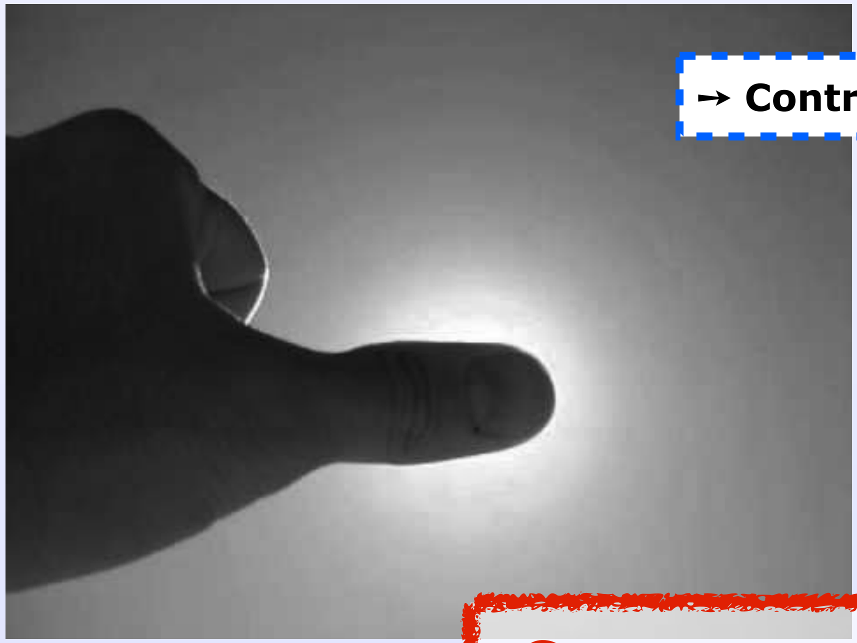


→ Turbulence correction
→ Angular resolution



→ Contrast

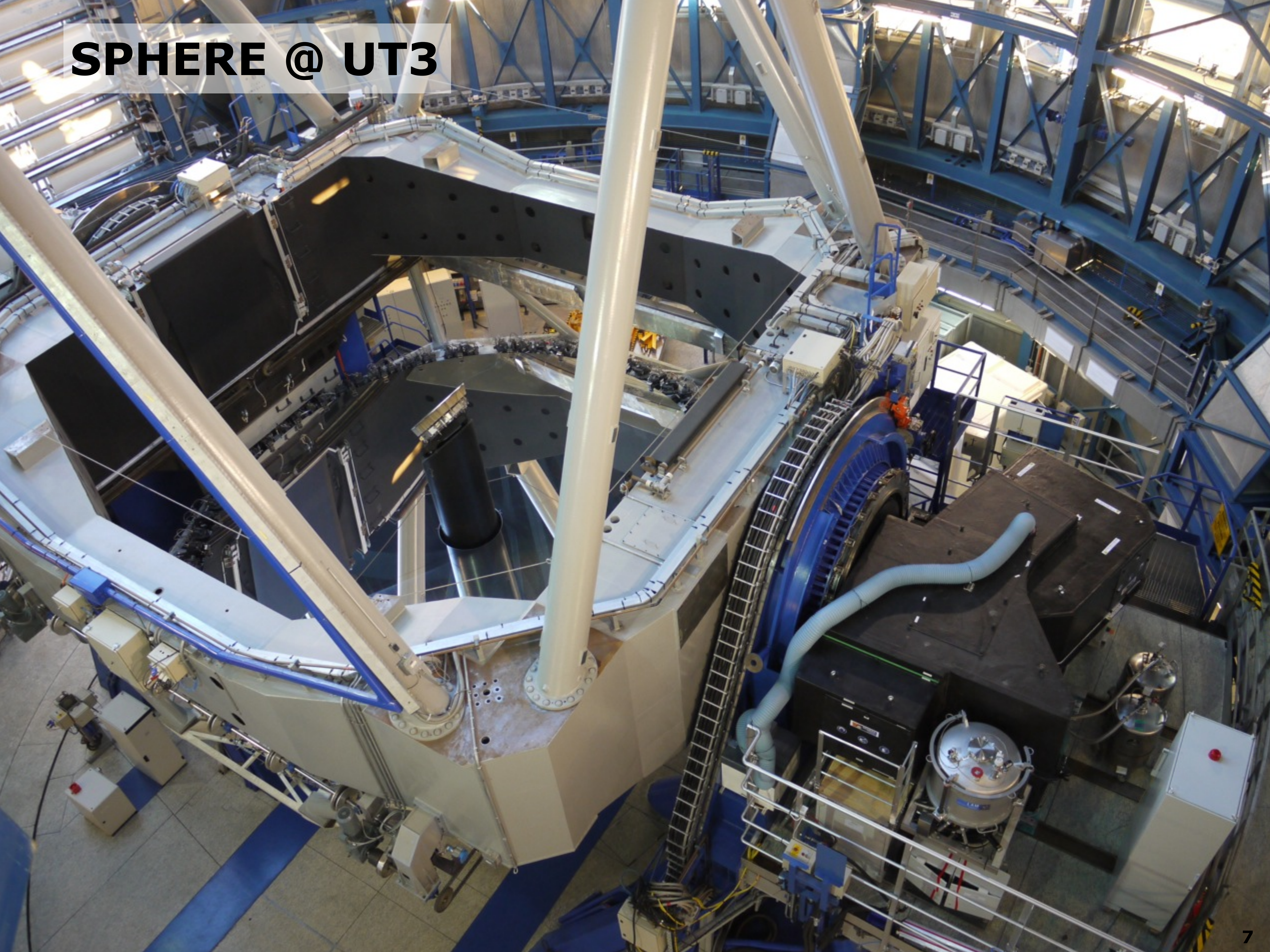
Algorithms



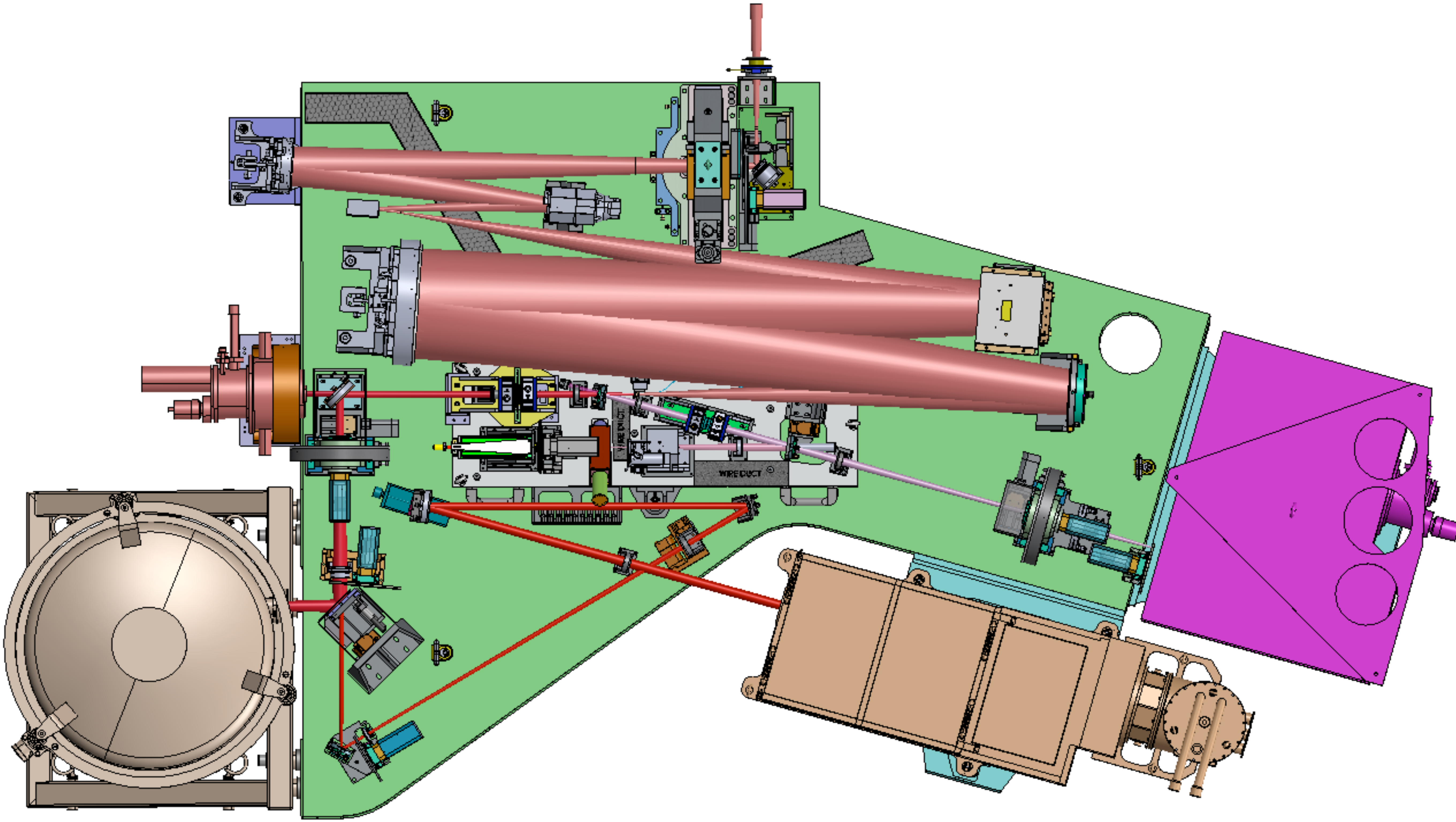
→ Contrast

Coronagraphs

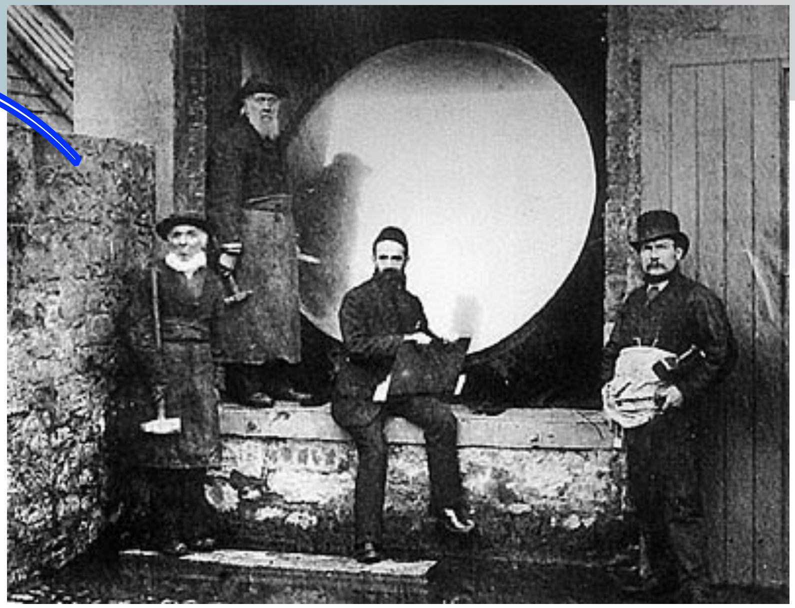
SPHERE @ UT3

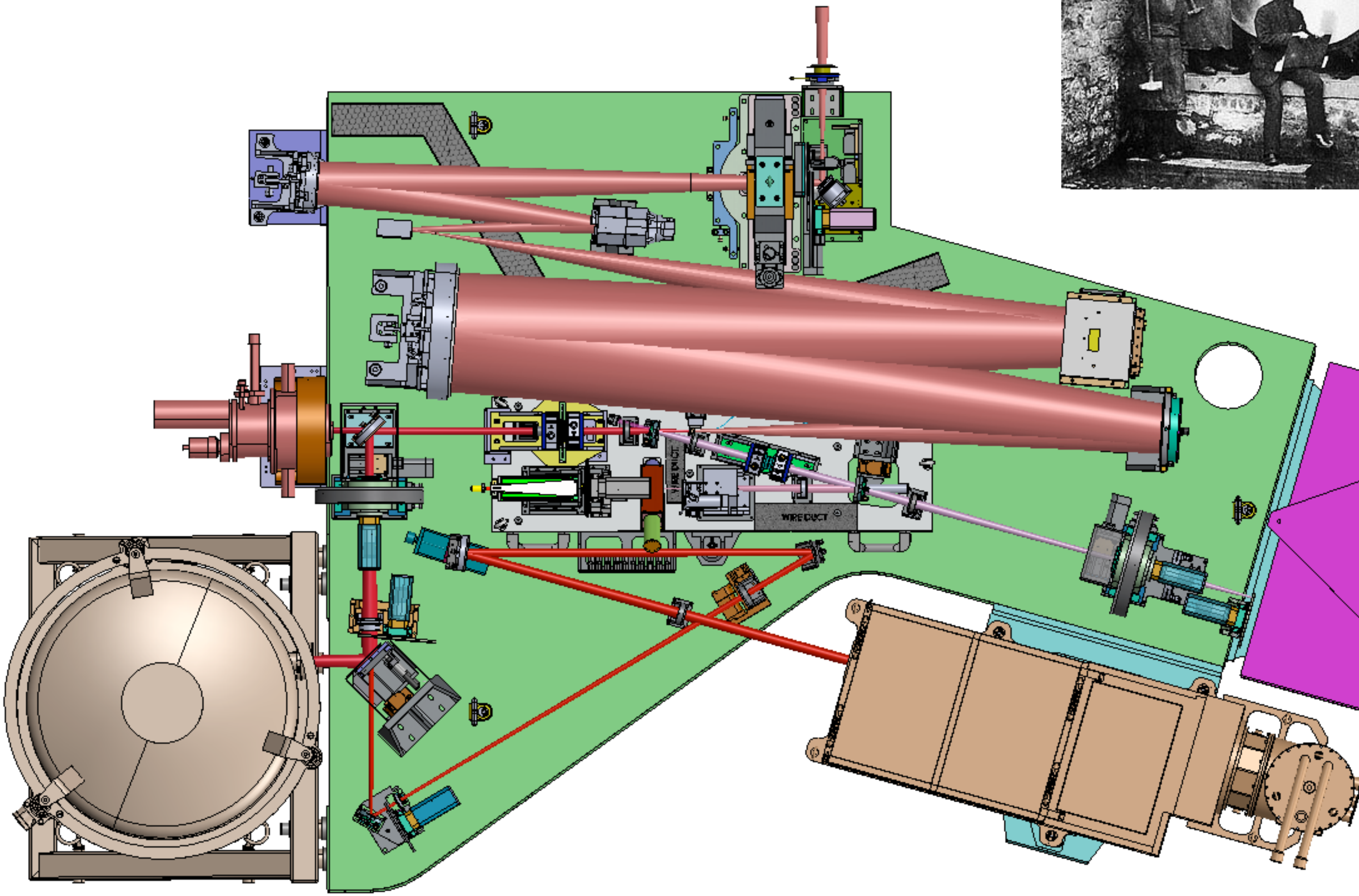


VLT/SPHERE

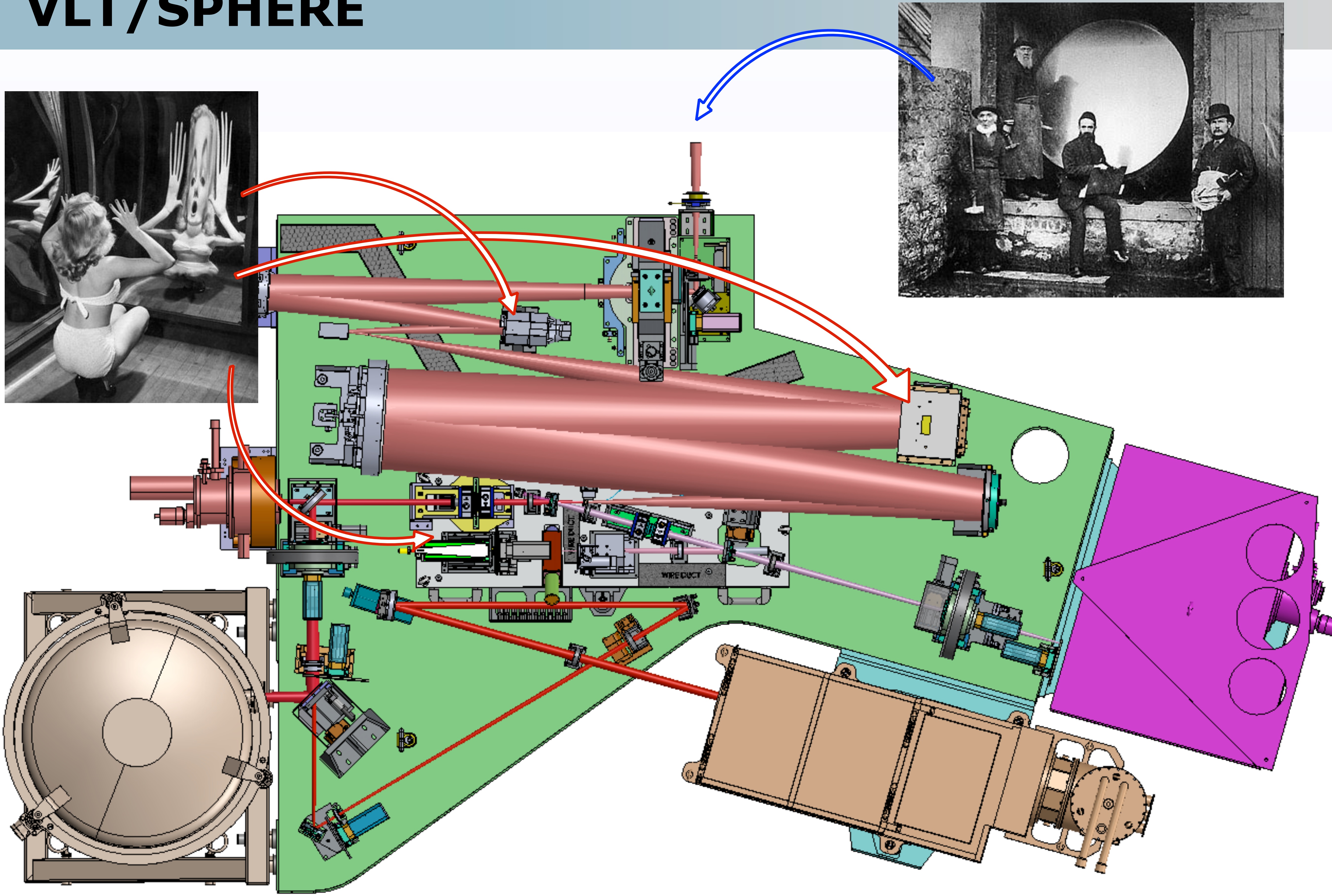


VLT/SPHERE

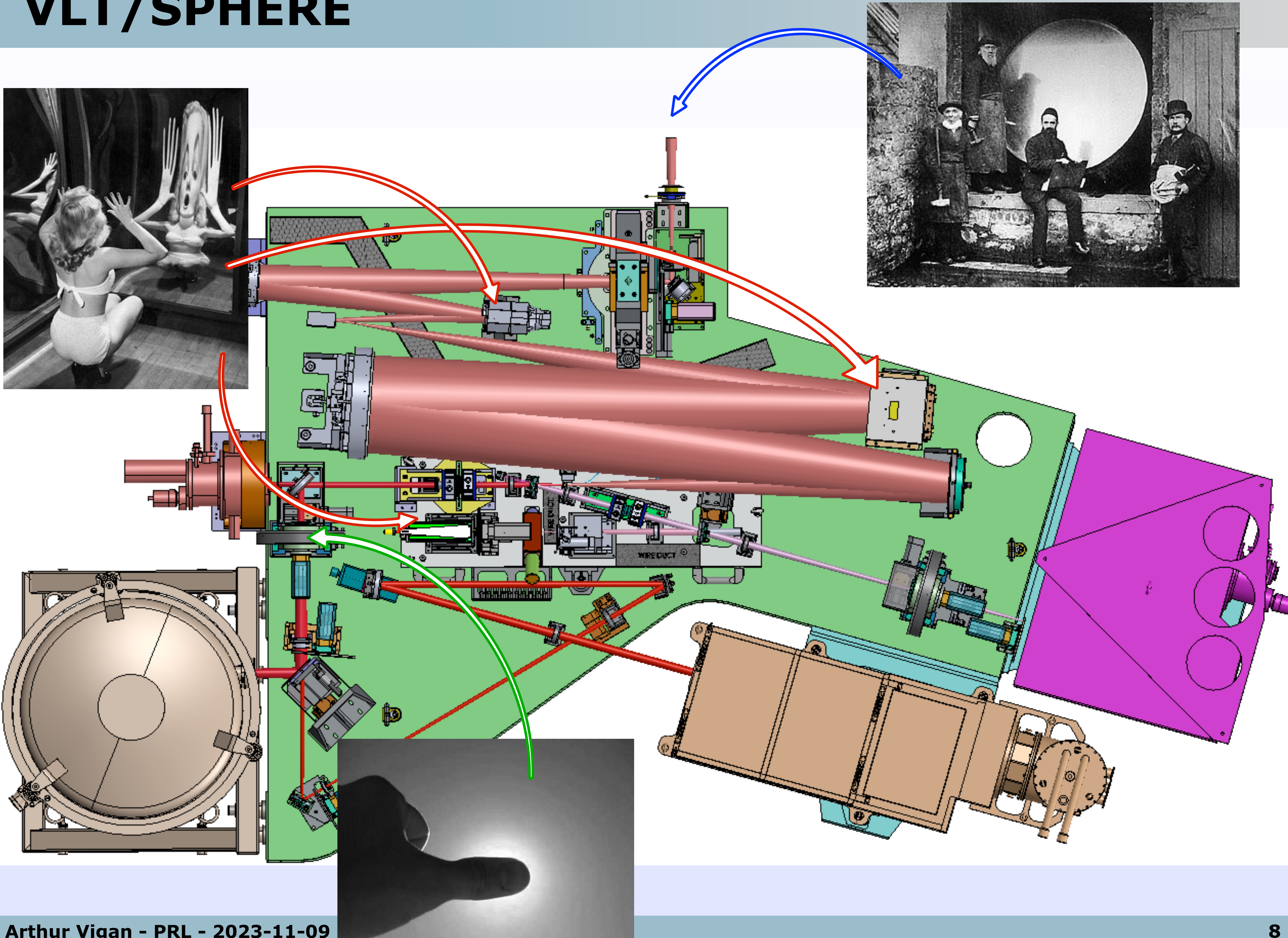




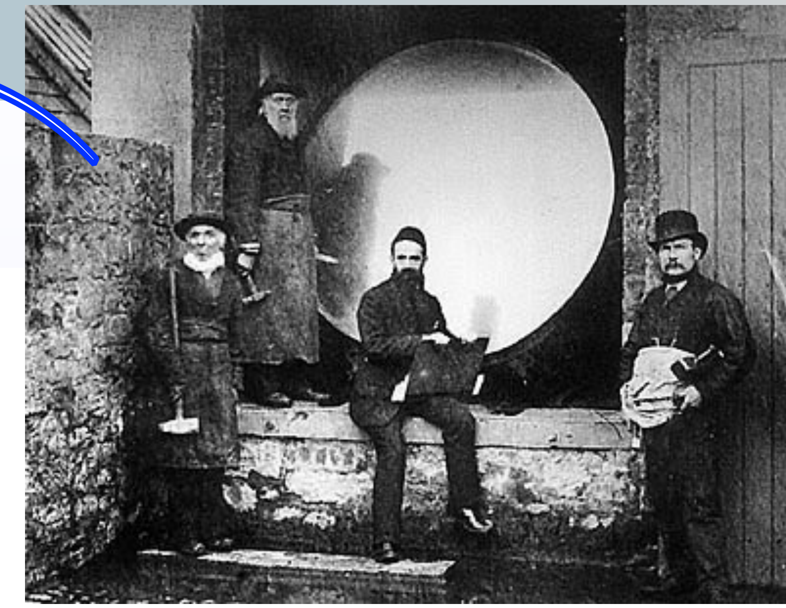
VLT/SPHERE

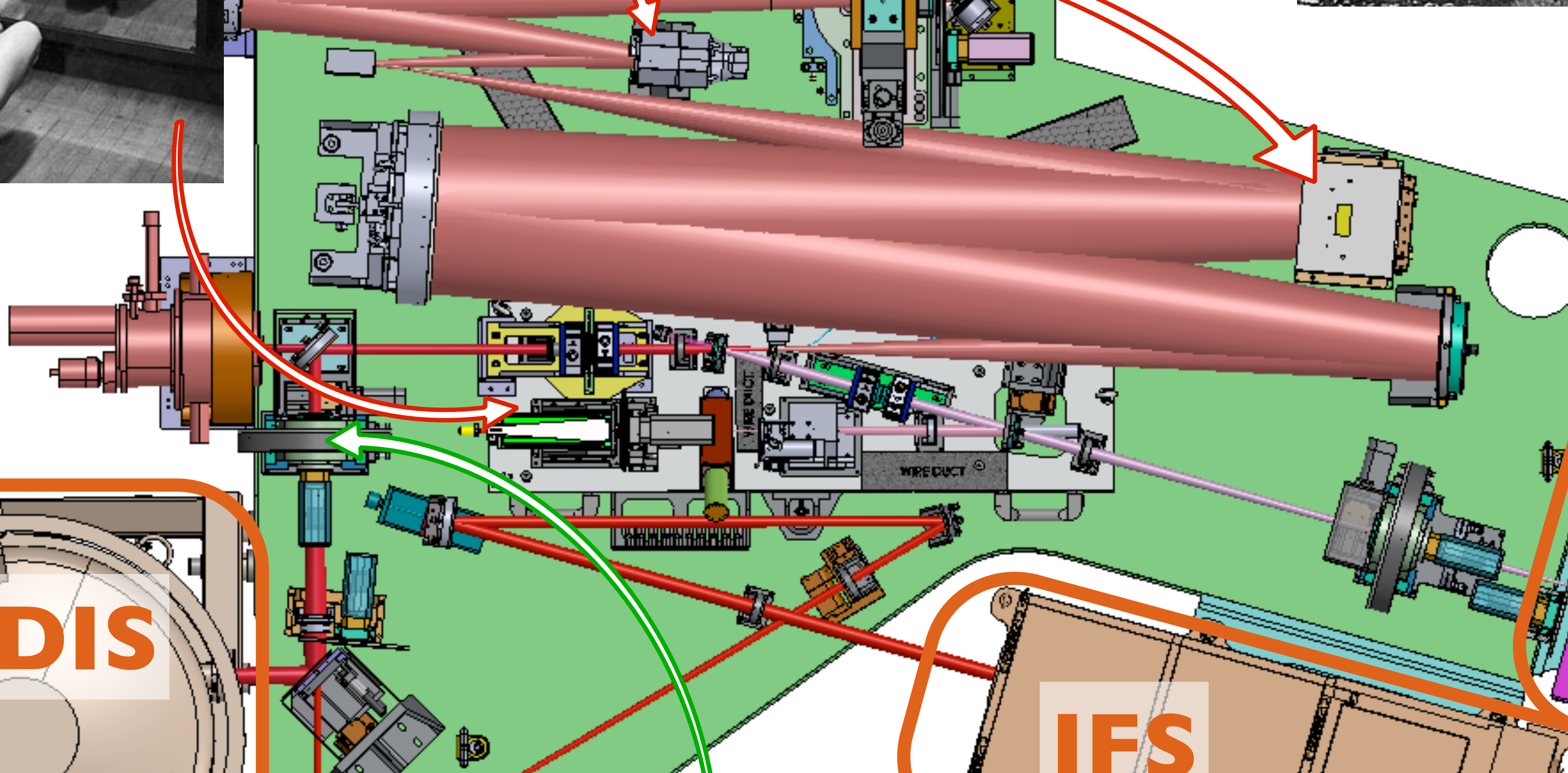


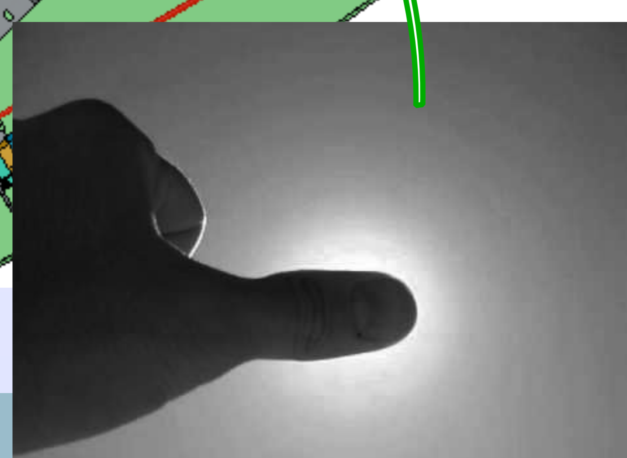
VLT/SPHERE

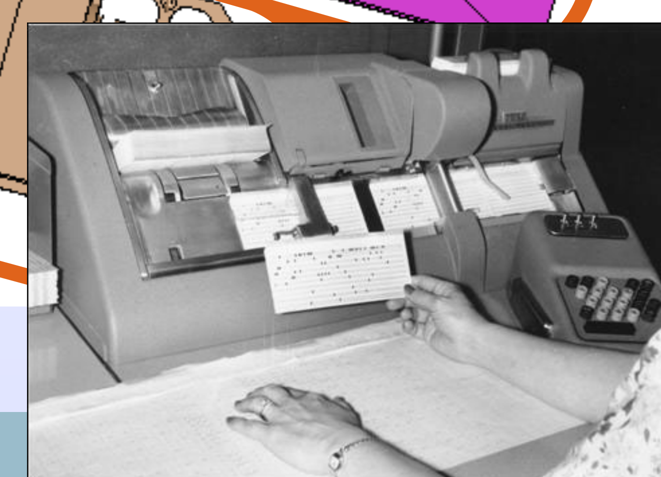


VLT/SPHERE



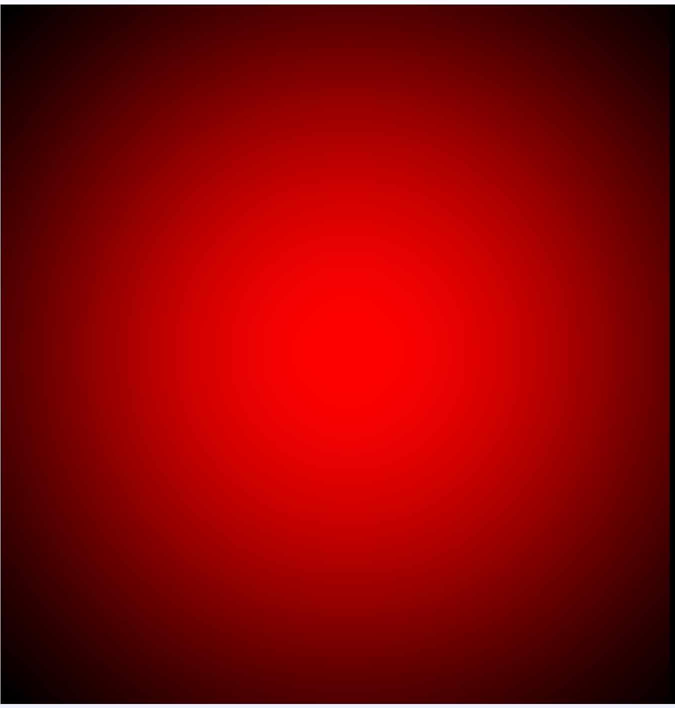




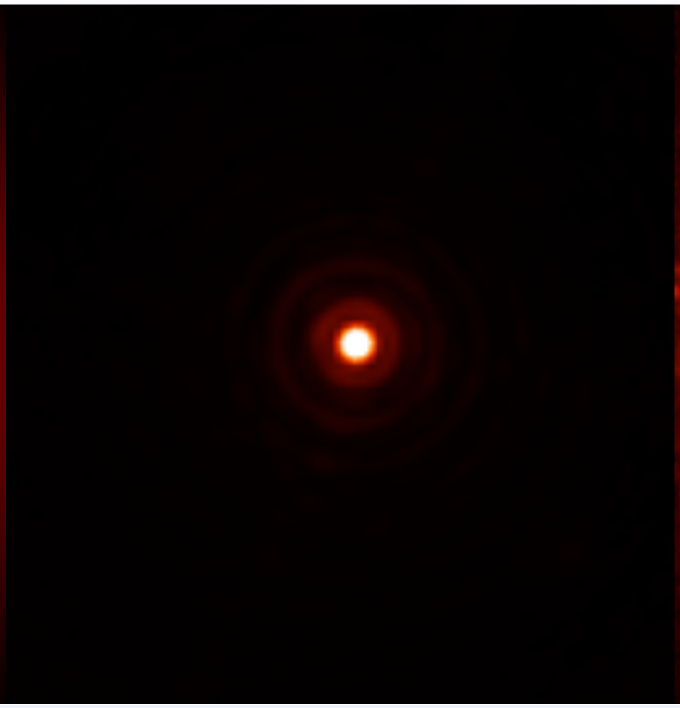


Direct imaging recipe

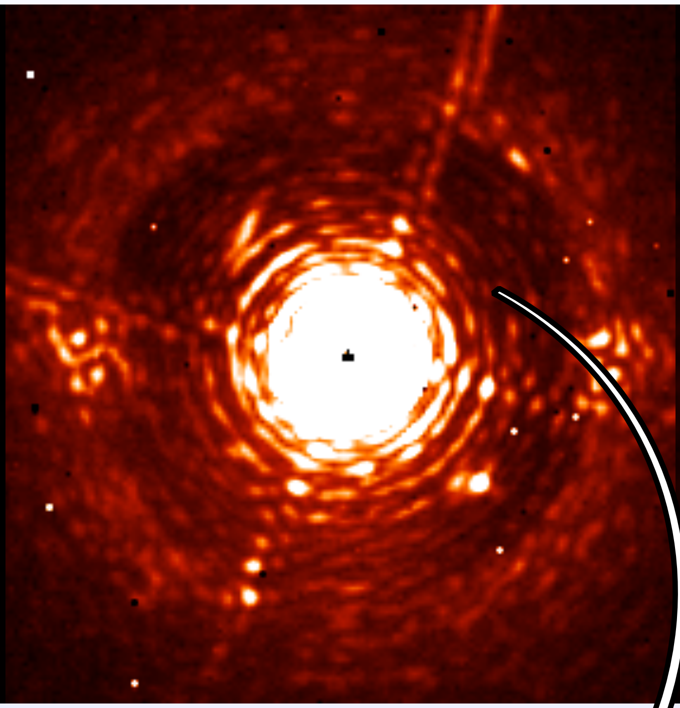
Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph



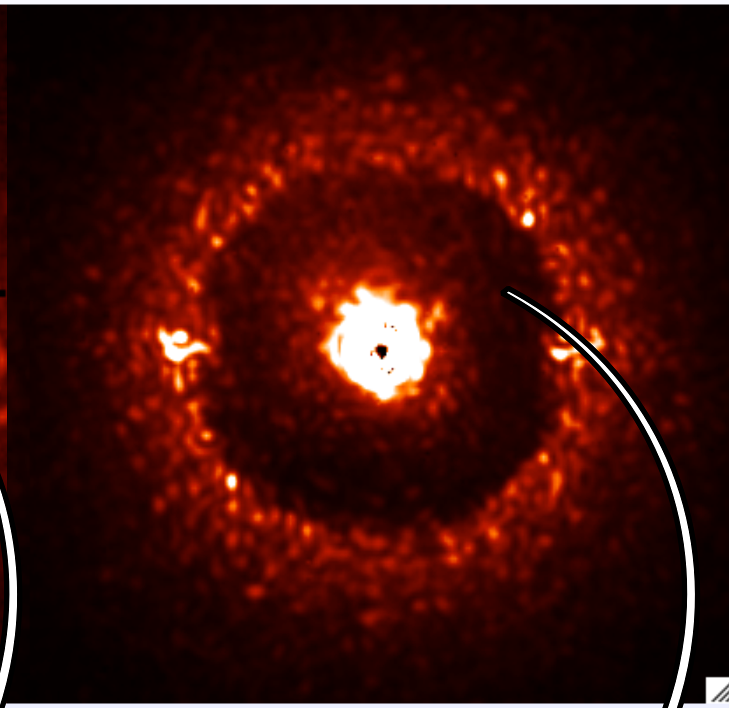
Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph



Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph



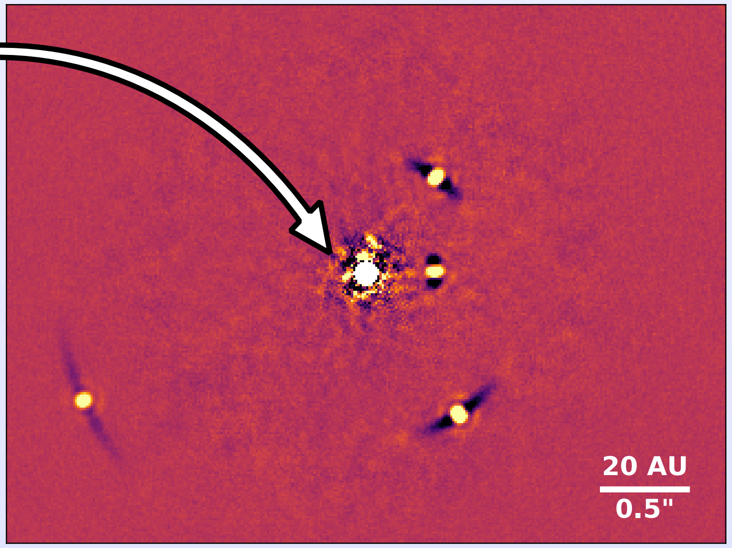
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



Diffraction limited within 20 λ/D

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

post-processing

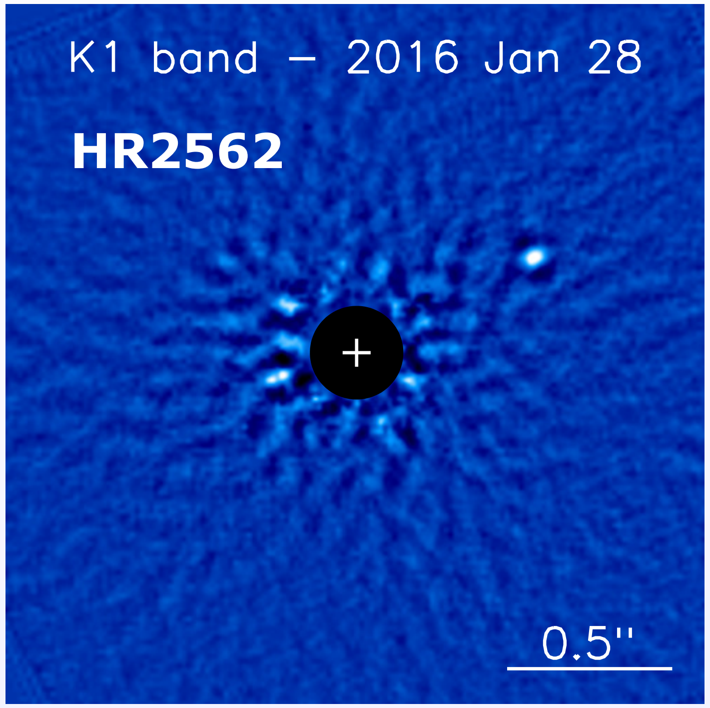


~10^{-5}-10^{-6} contrast down to 0.2"

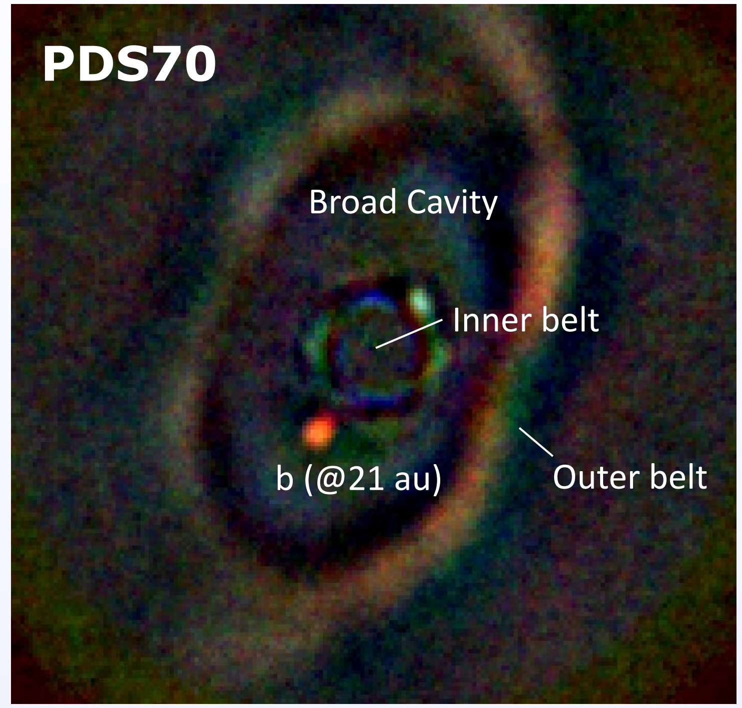
Enough to detect young giant exoplanets of a few Jupiter masses

Populations analysis

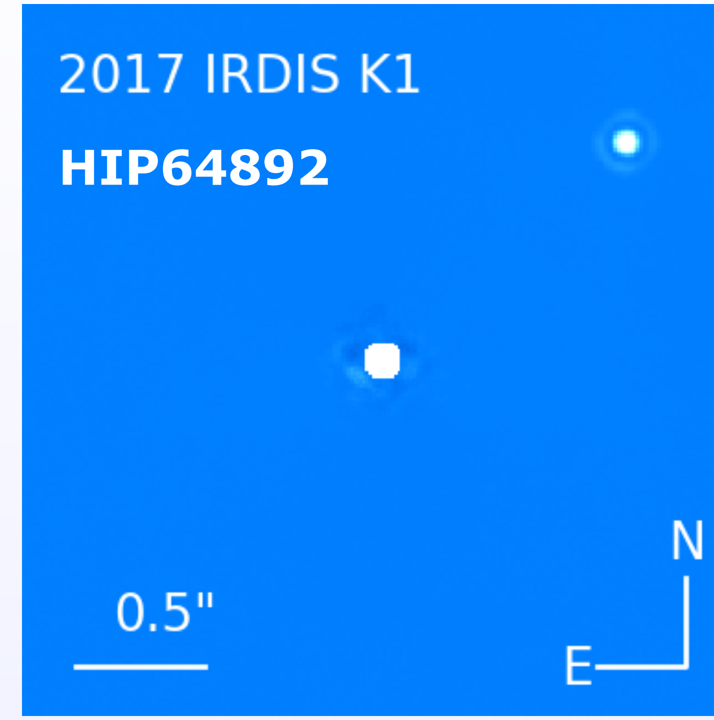
Nielsen et al. (2019)
Vigan et al. (2021)



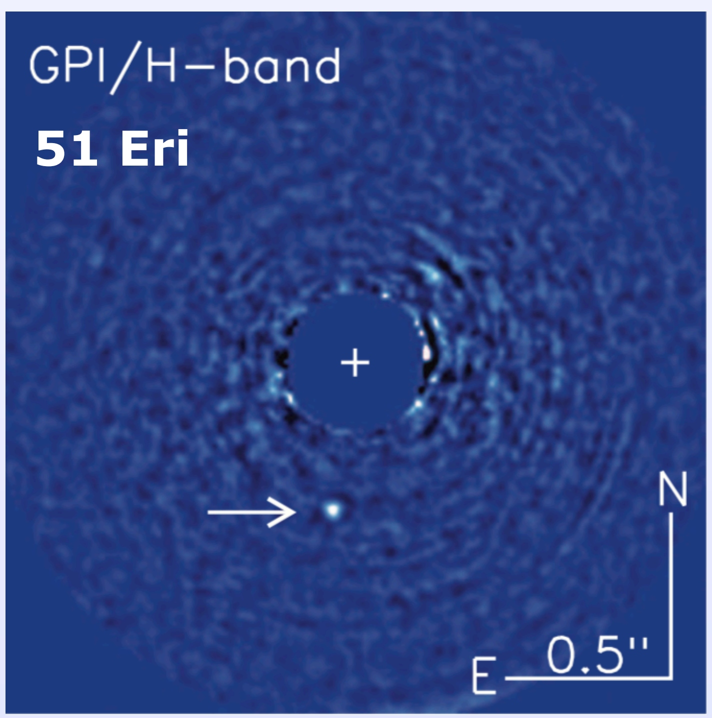
Konopacky et al. 2016



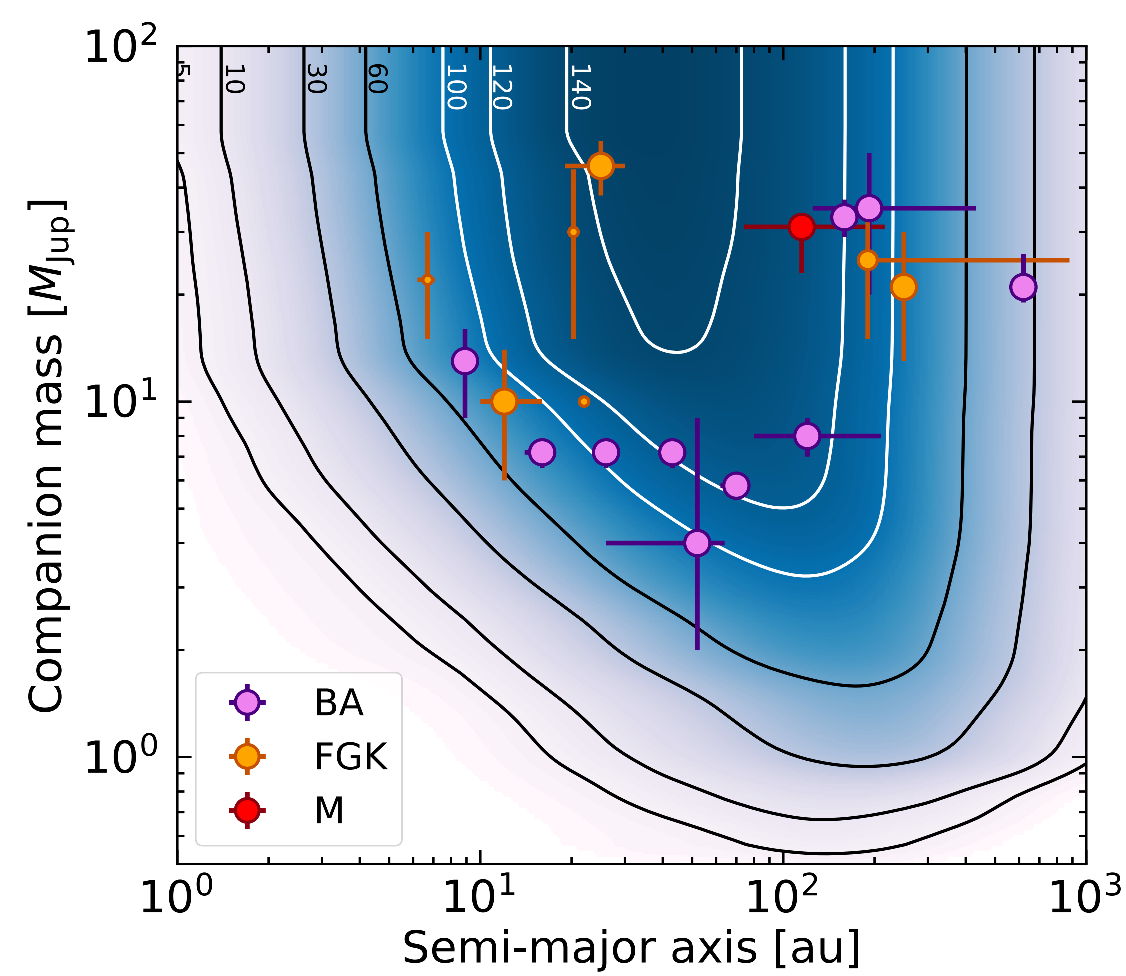
Keppler et al. 2018

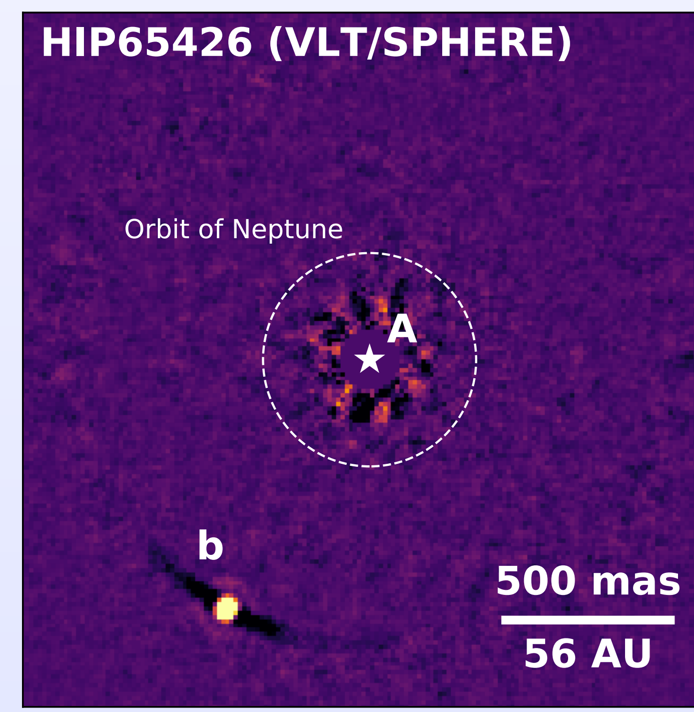


Cheetham et al. 2018



Macintosh et al. 2015

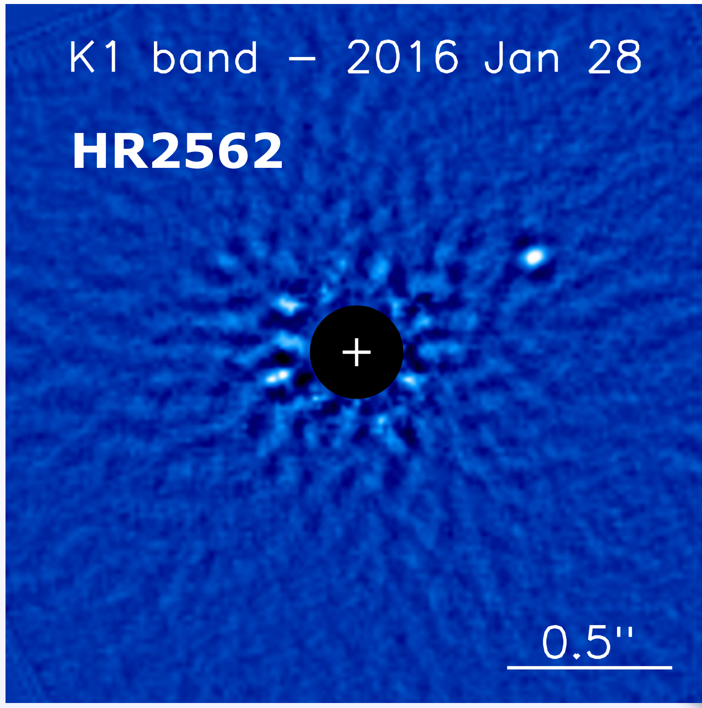




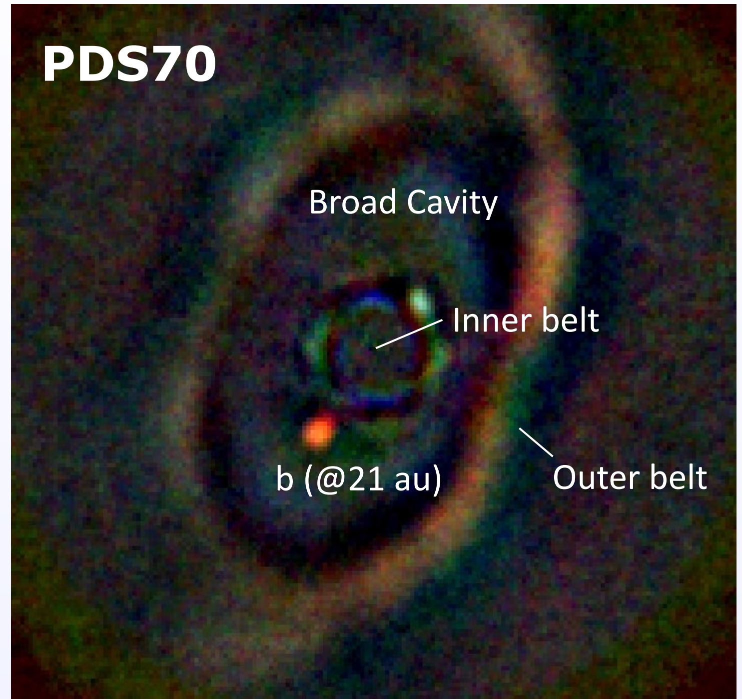
Chauvin et al. 2017

Populations analysis

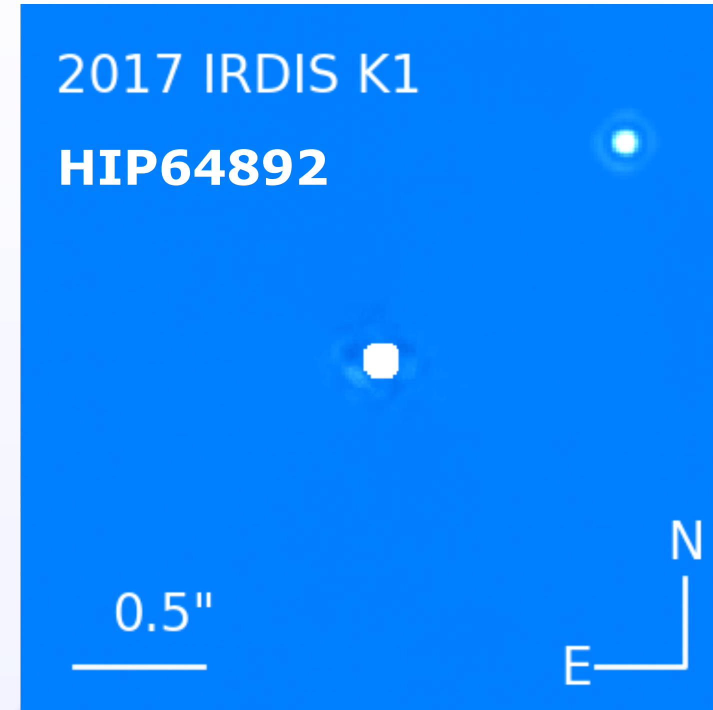
Nielsen et al. (2019)
Vigan et al. (2021)



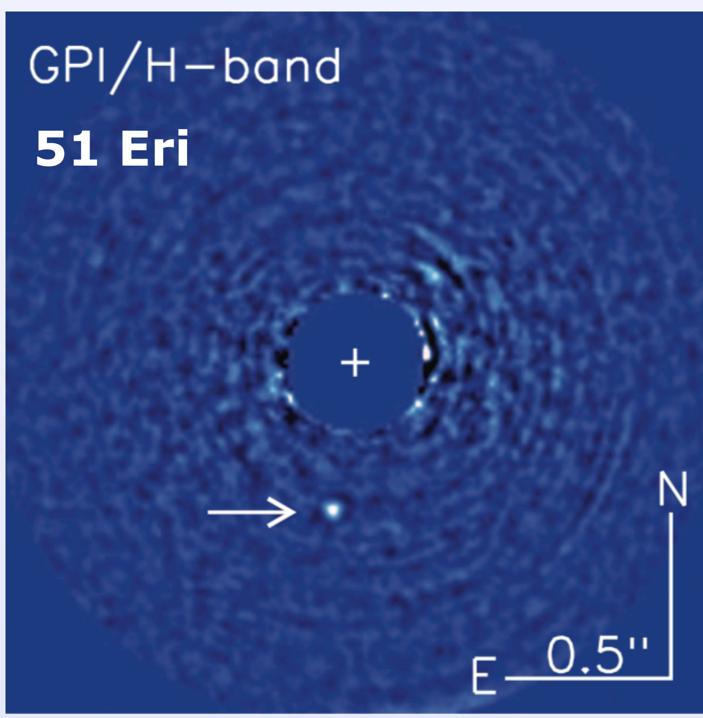
Konopacky et al. 2016



Keppler et al. 2018



Cheetham et al. 2018



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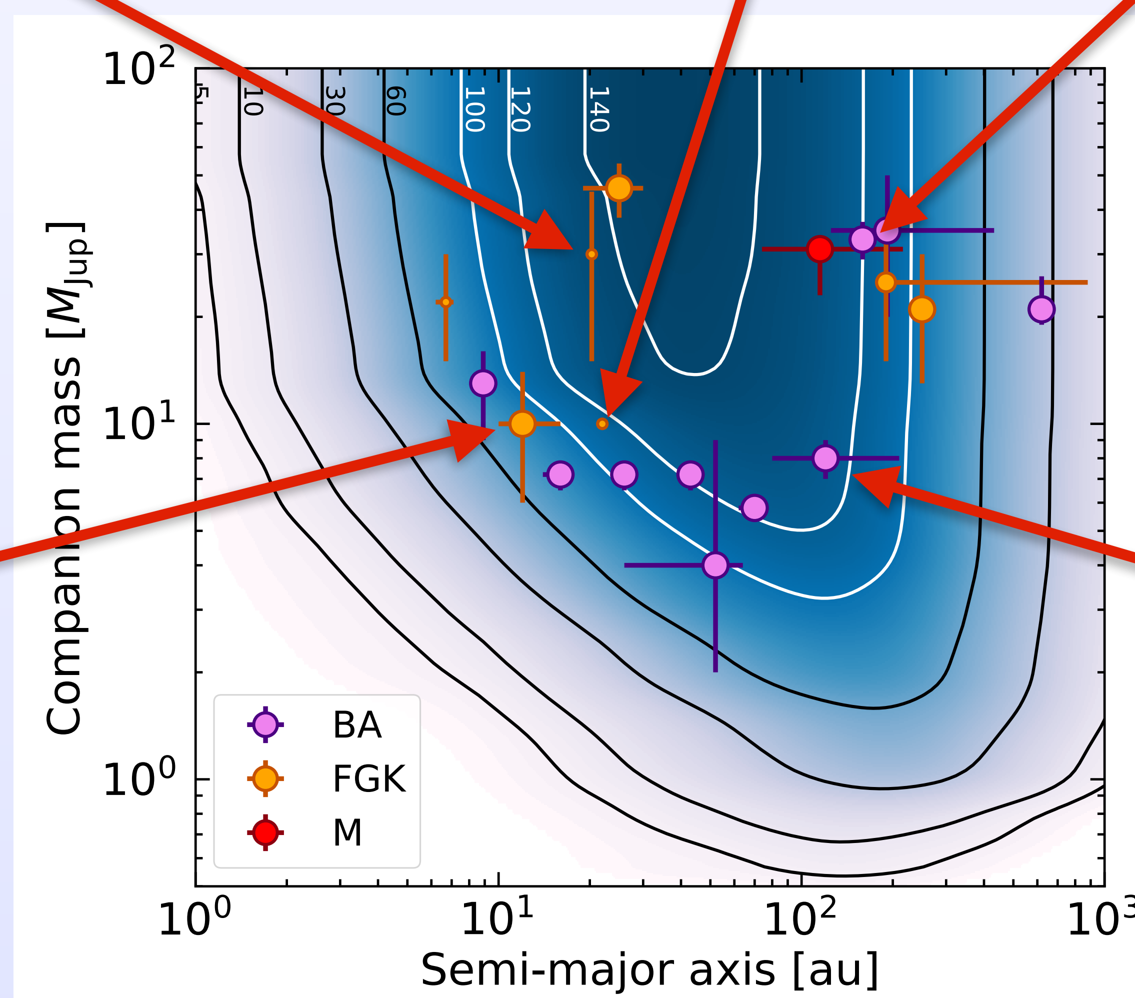

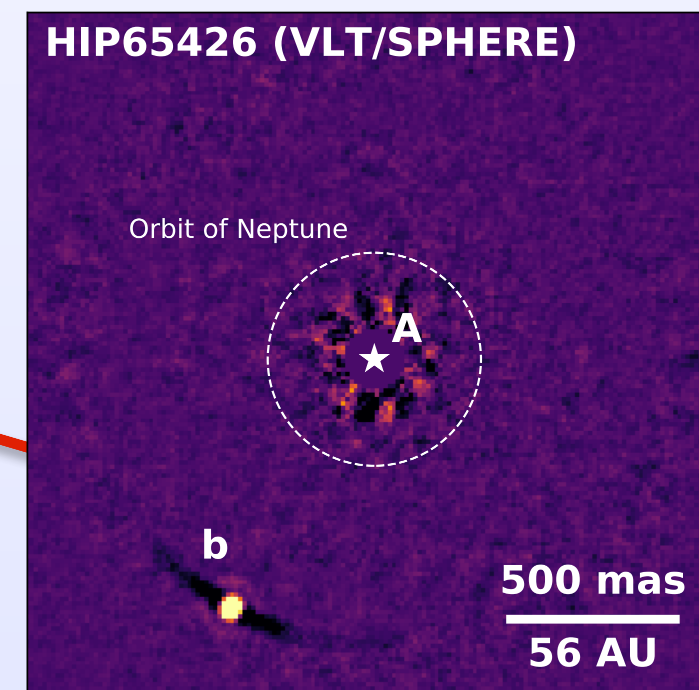

Chauvin et al. 2017

Populations analysis

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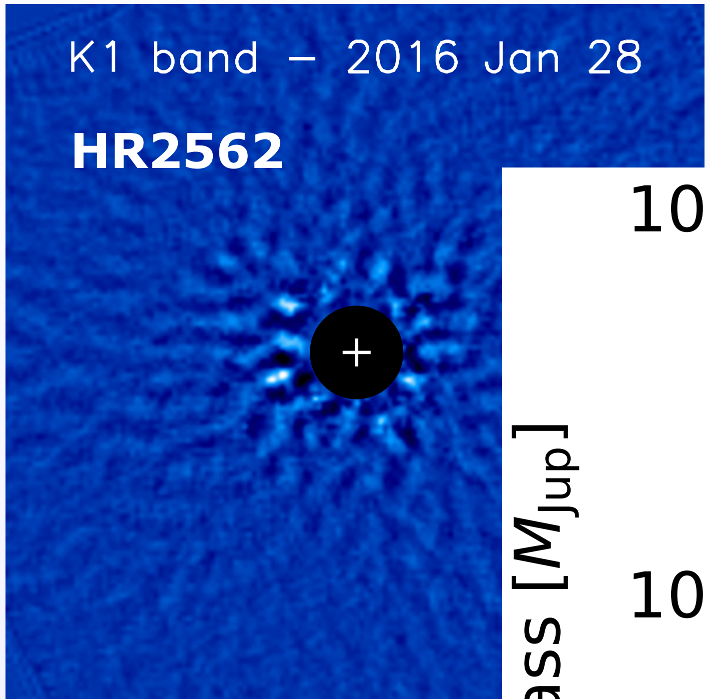
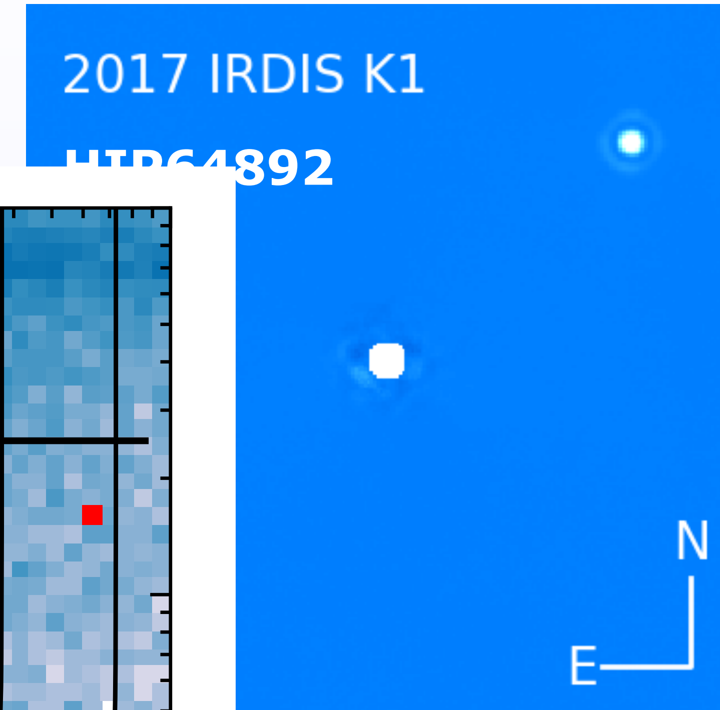
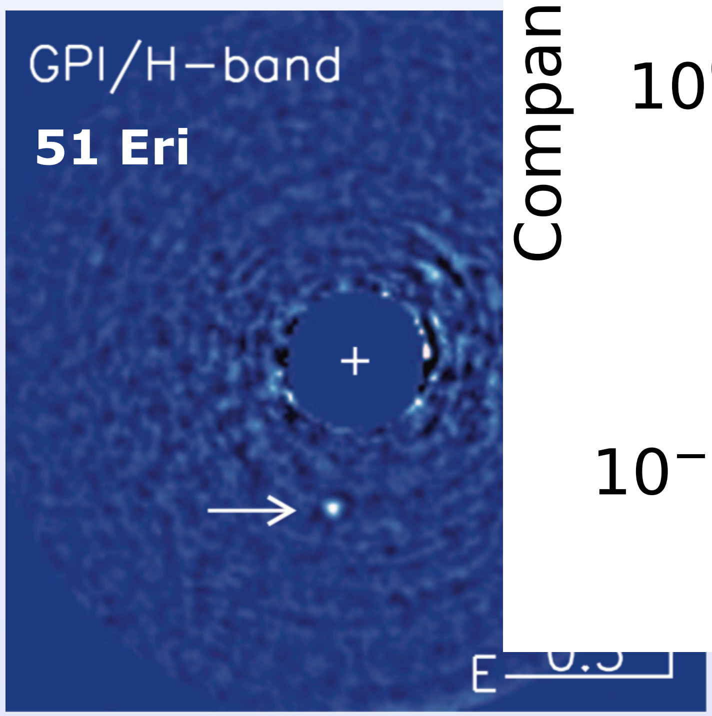
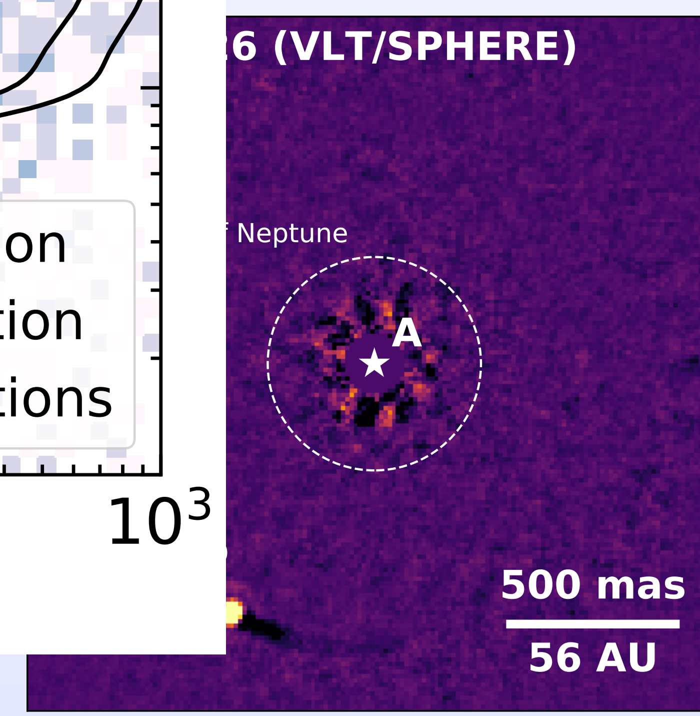


Konopacky et al. 2016

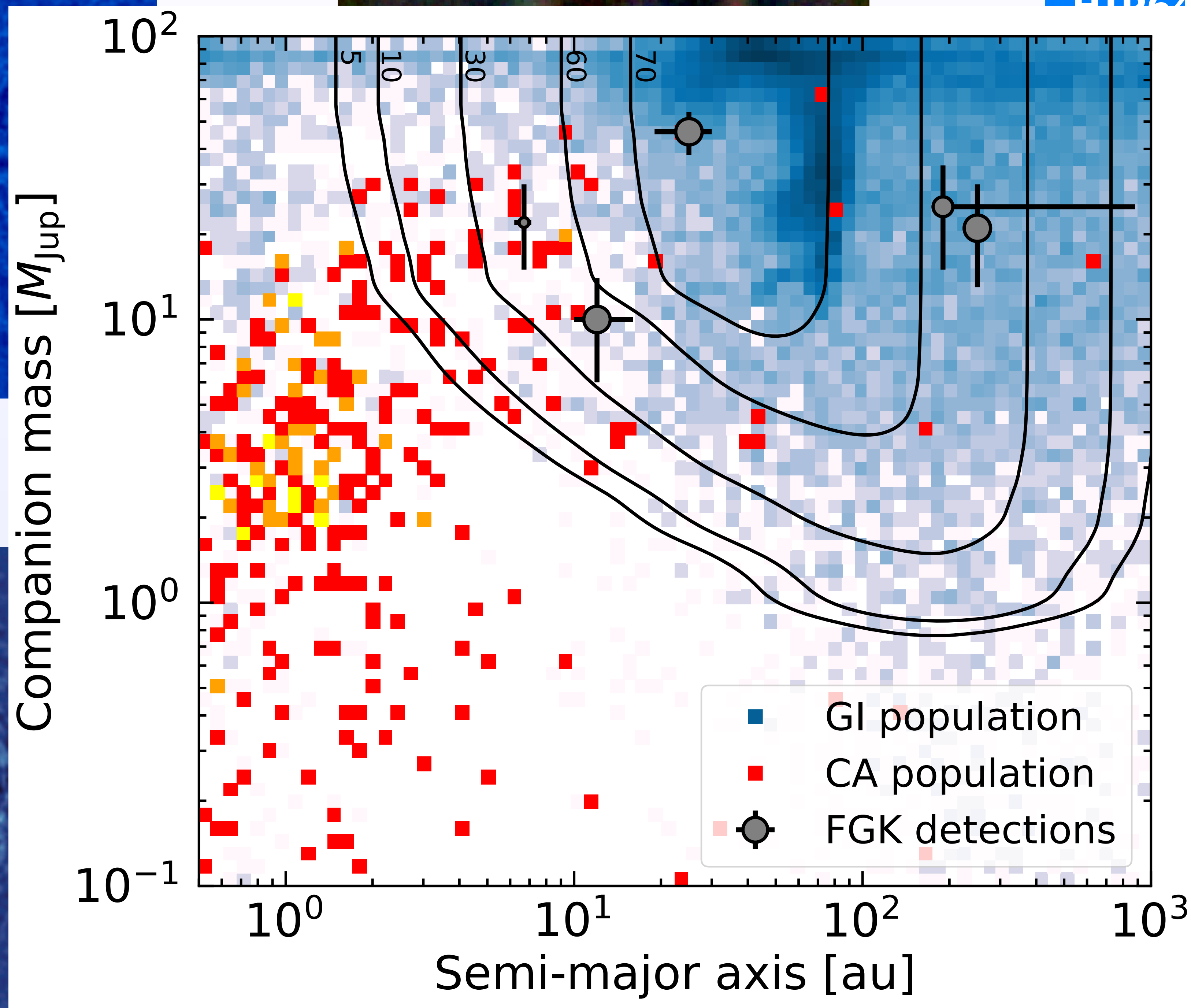


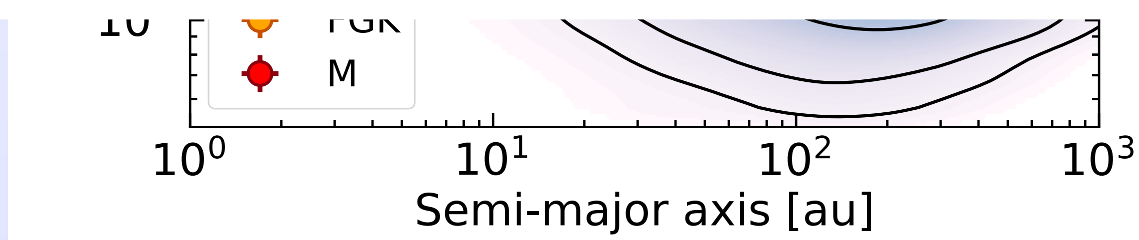


Macintosh et al. 2015

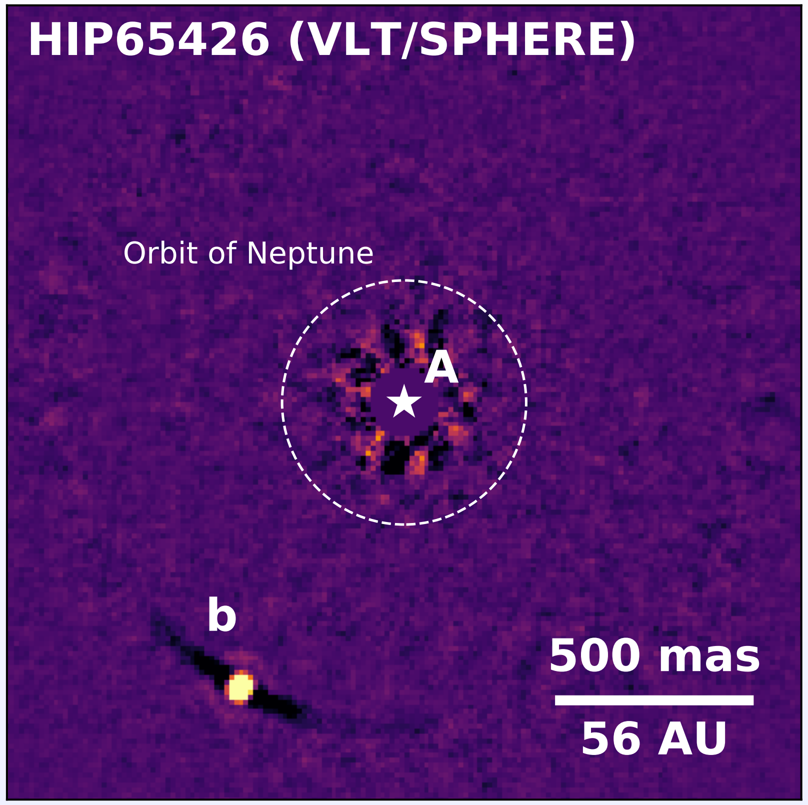


Chauvin et al. 2017



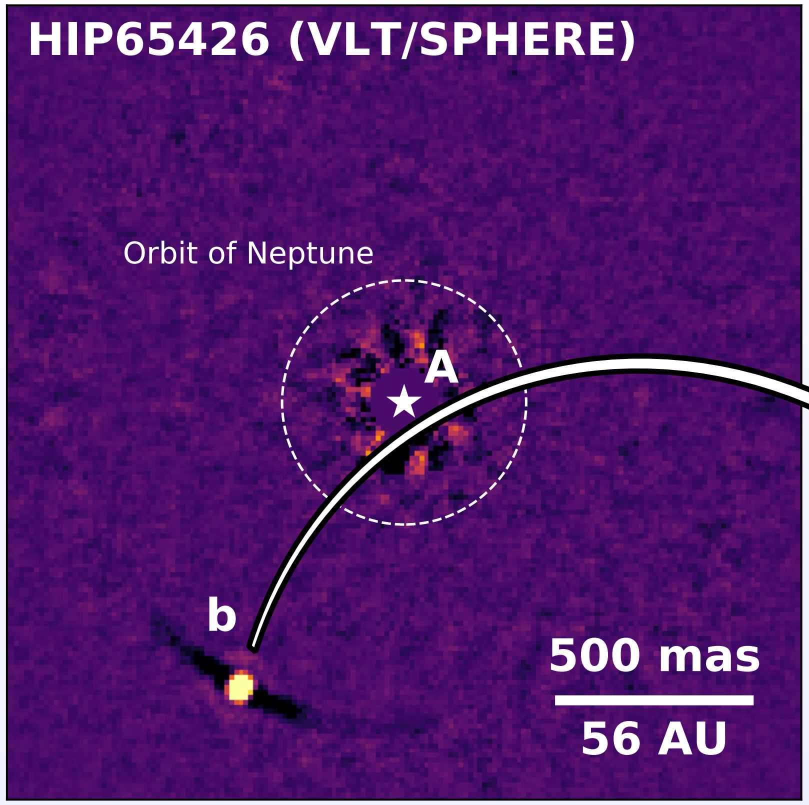


Detections with high-contrast instruments

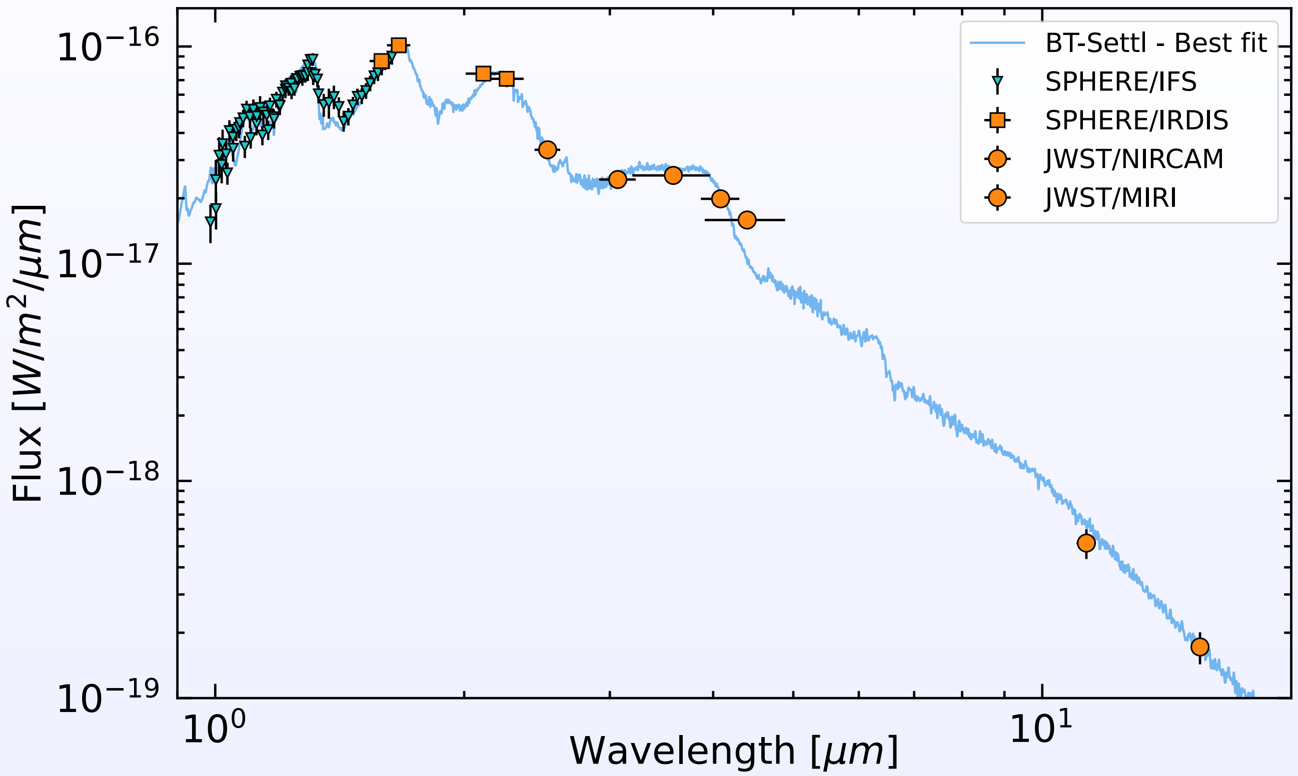


Chauvin et al. 2017

Detections with high-contrast instruments

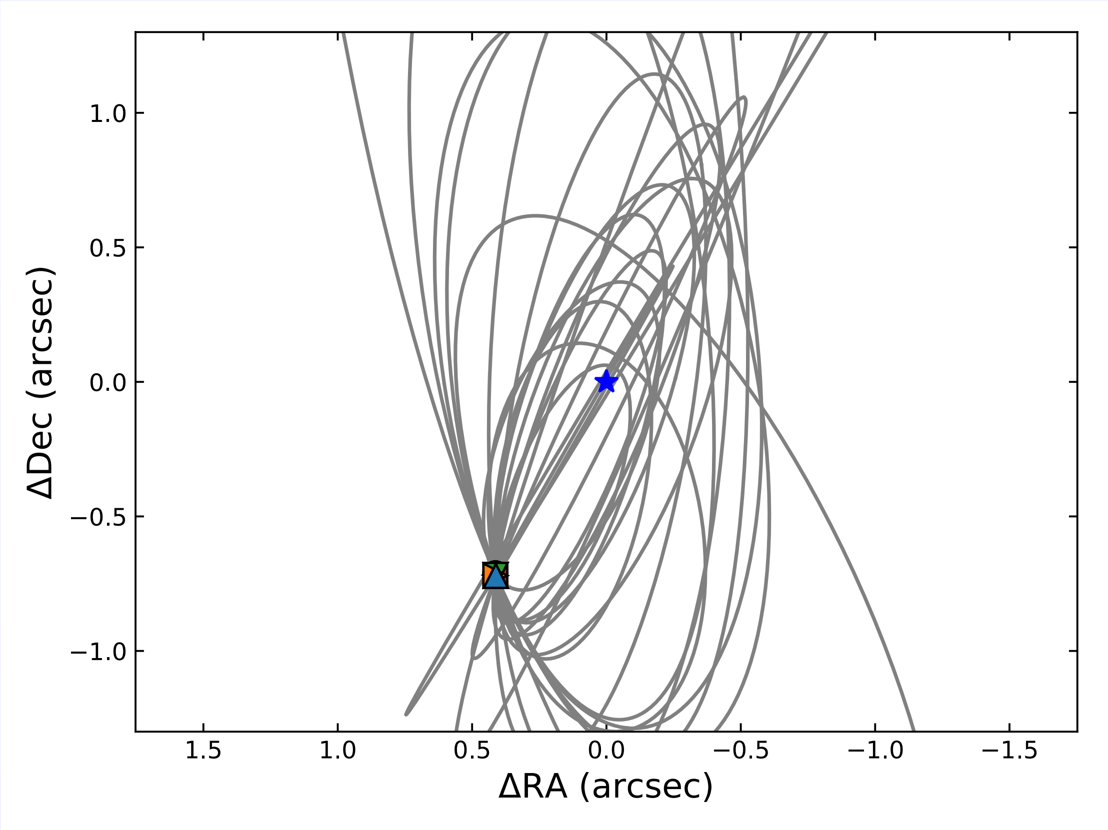


Chauvin et al. 2017

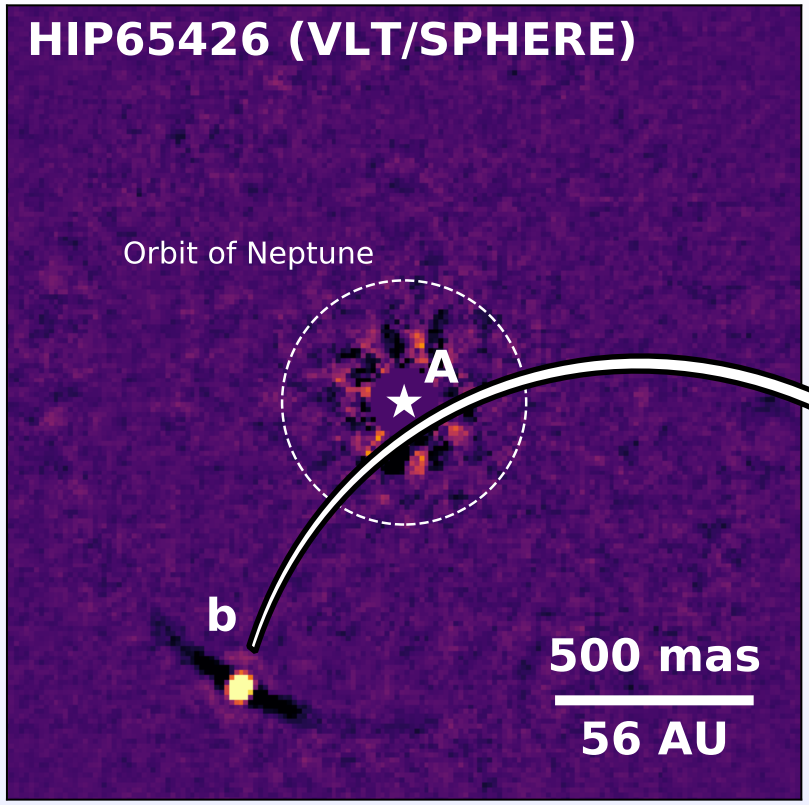


Very low resolution

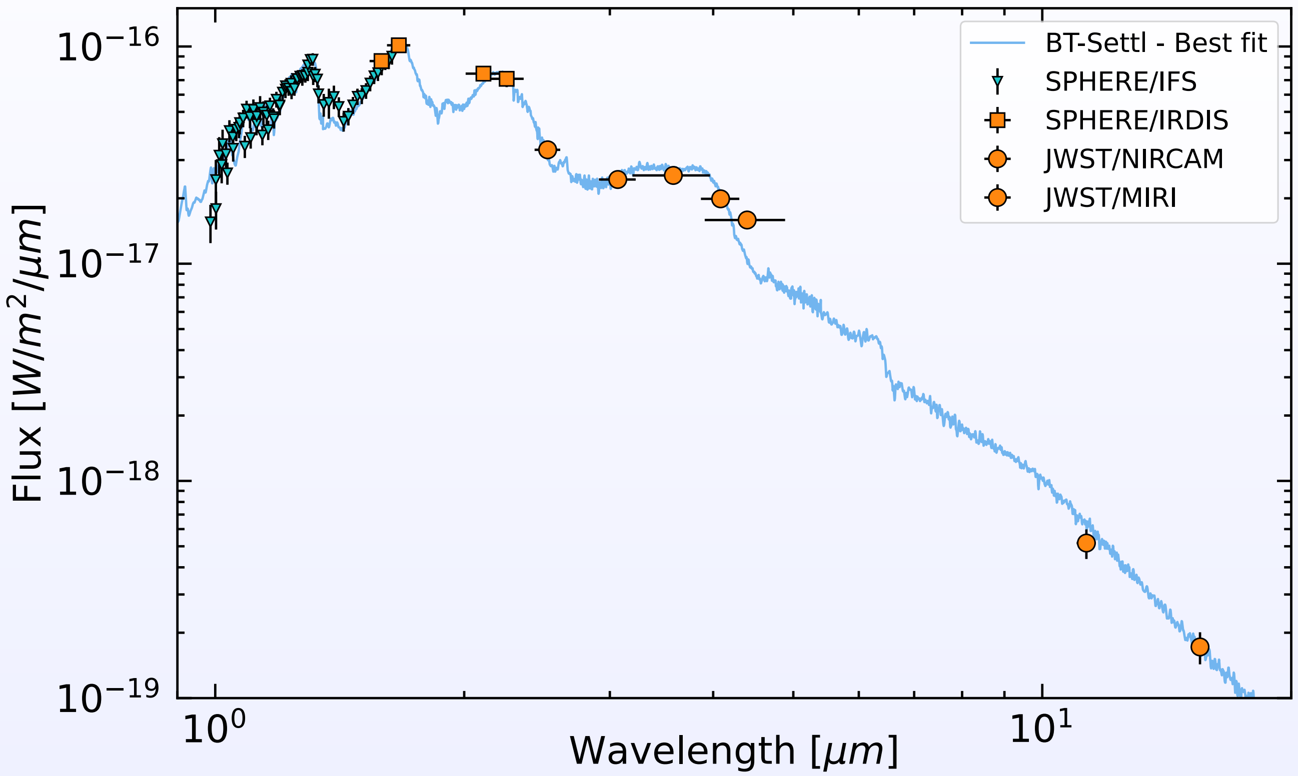
Just enough for first order characterisation!

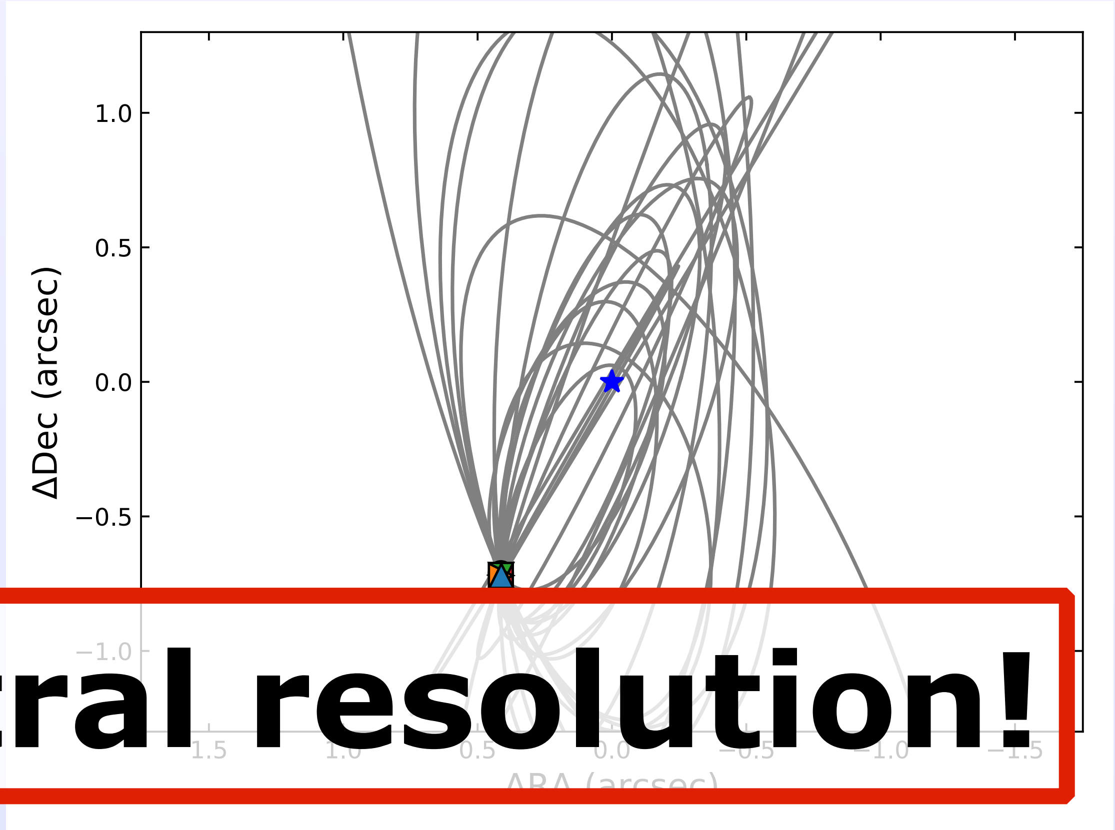


Detections with high-contrast instruments



Chauvin et al. 2017



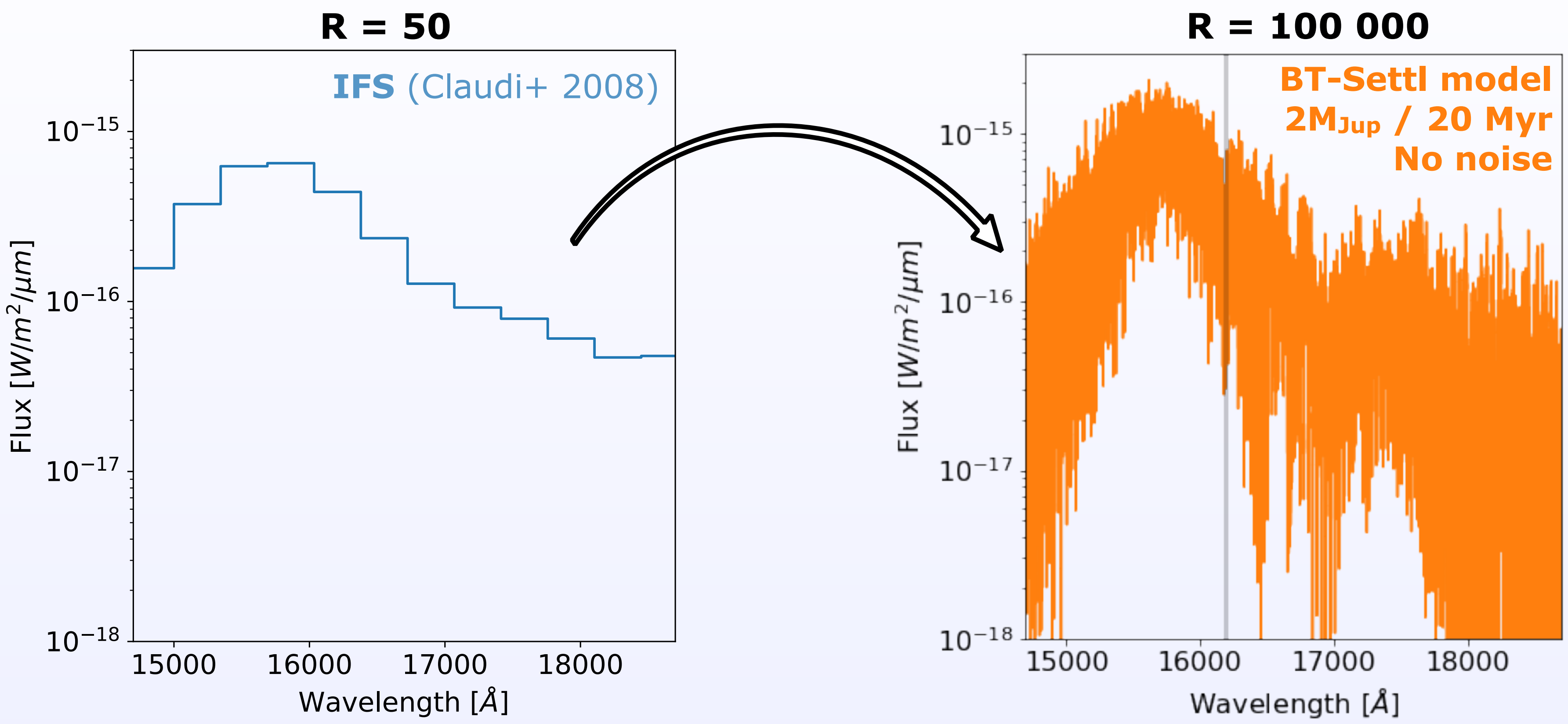


Very low resolution

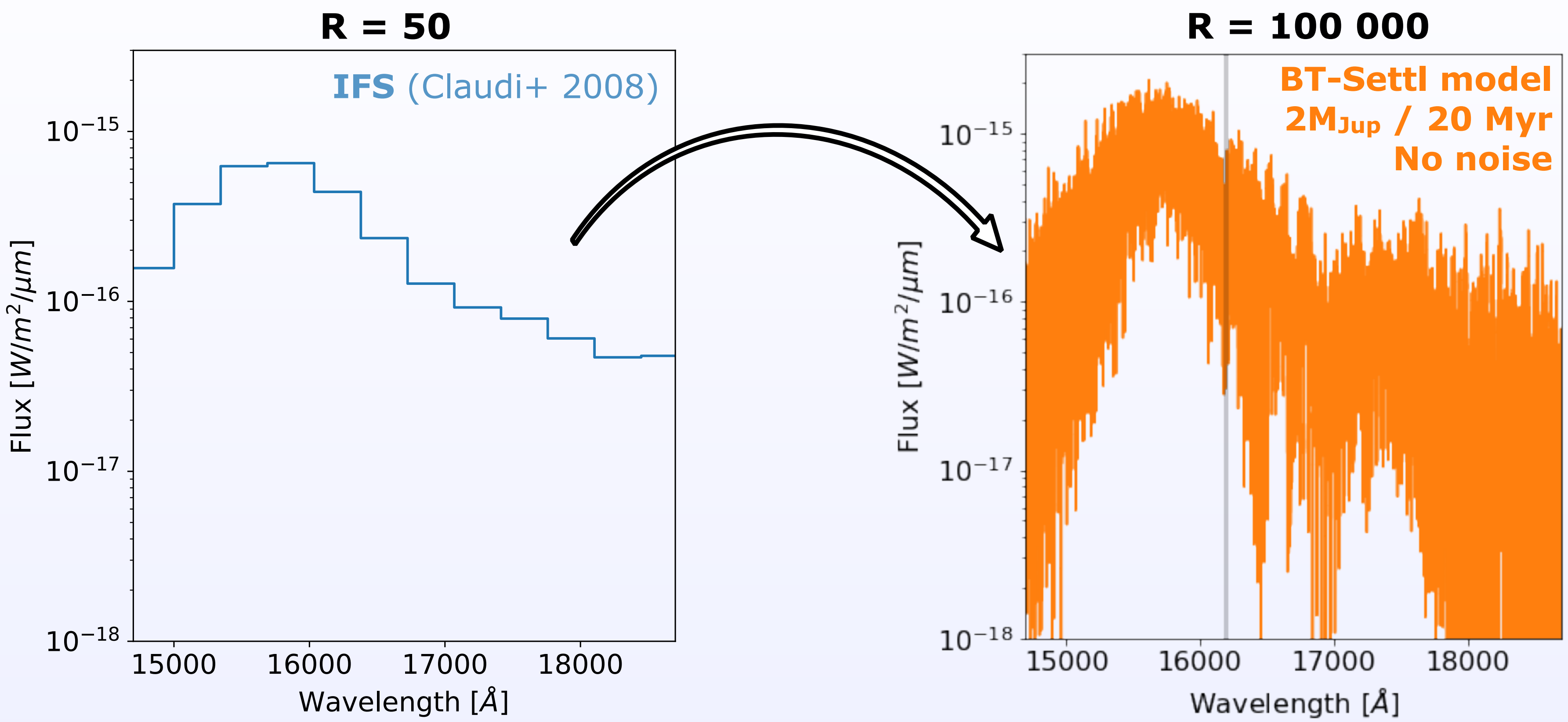
Just enough for first order characterisation!

Need for high spectral resolution!

Spectral content

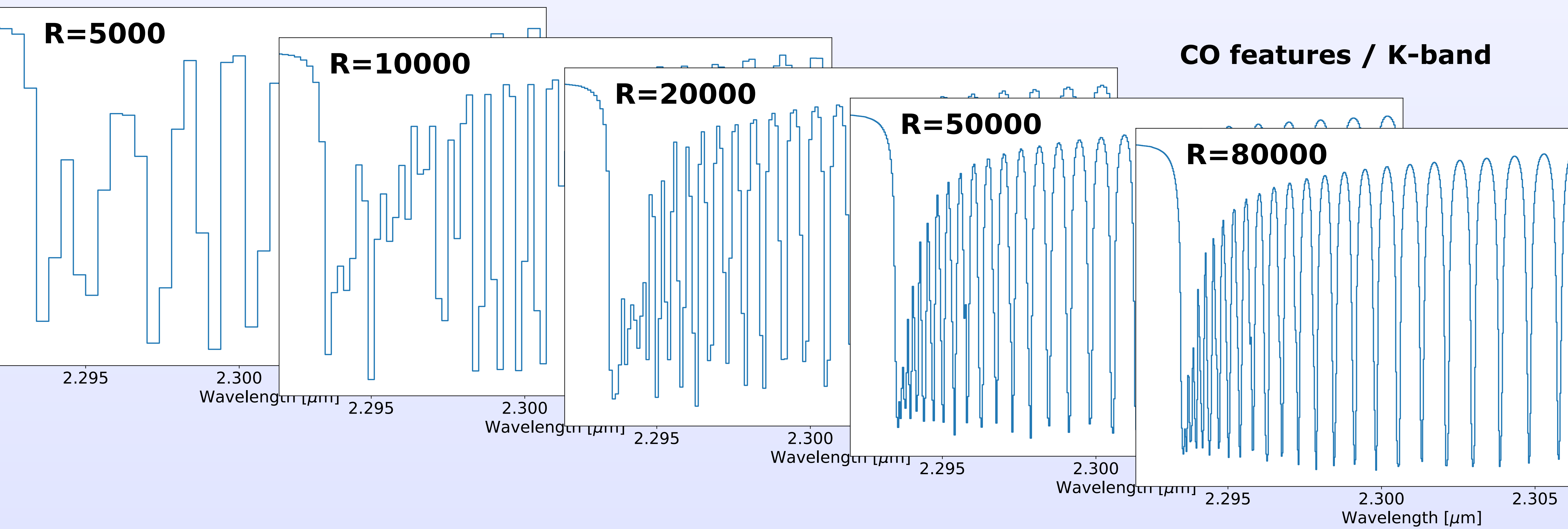


Spectral content

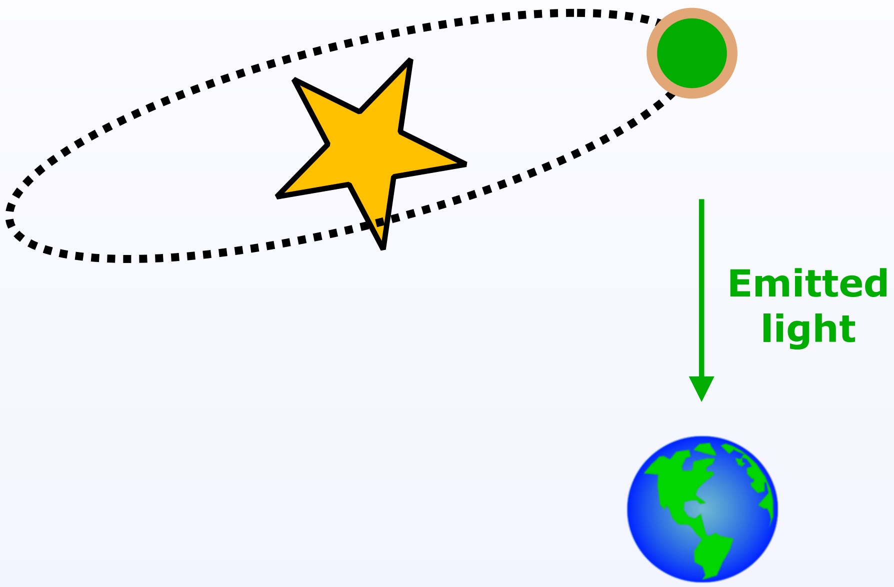


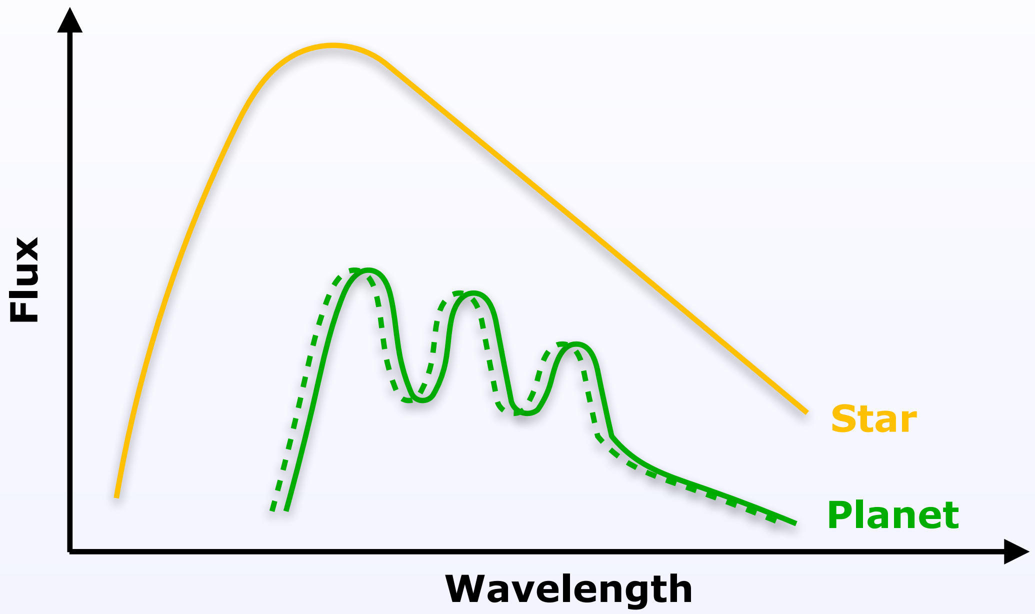
Requires
R ≫ 10 000

CO features / K-band

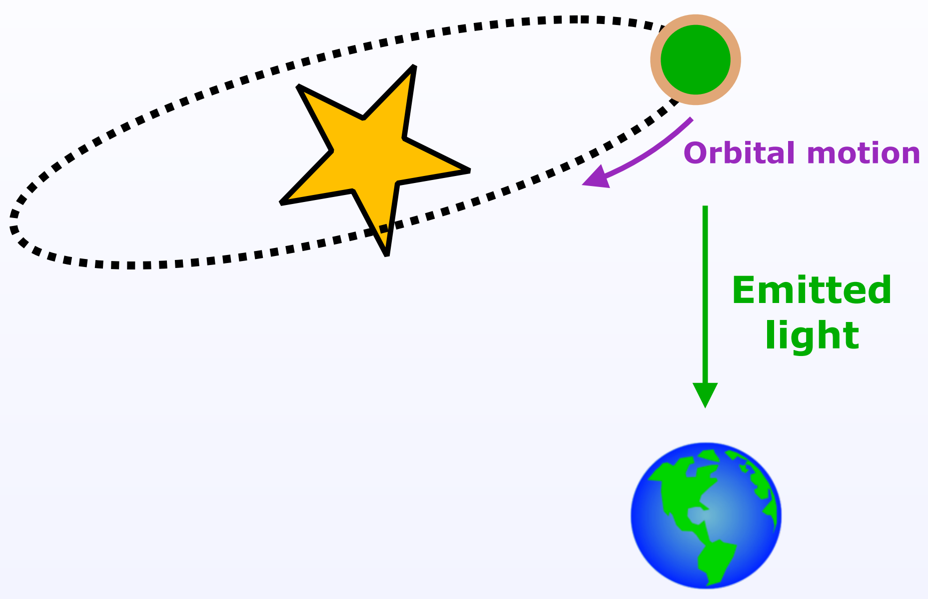


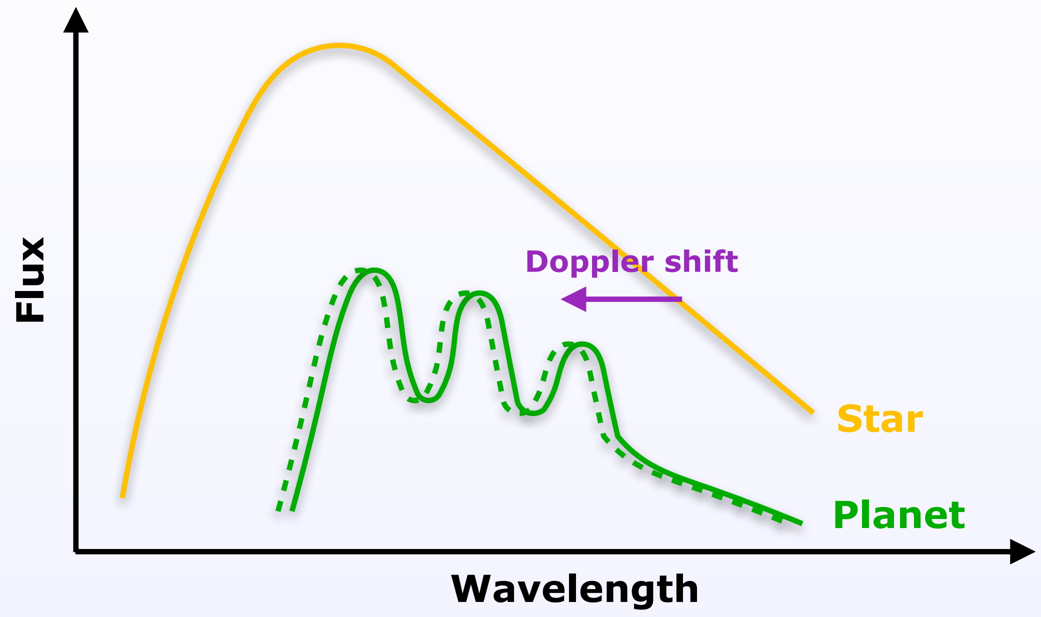
Orbital and rotational information



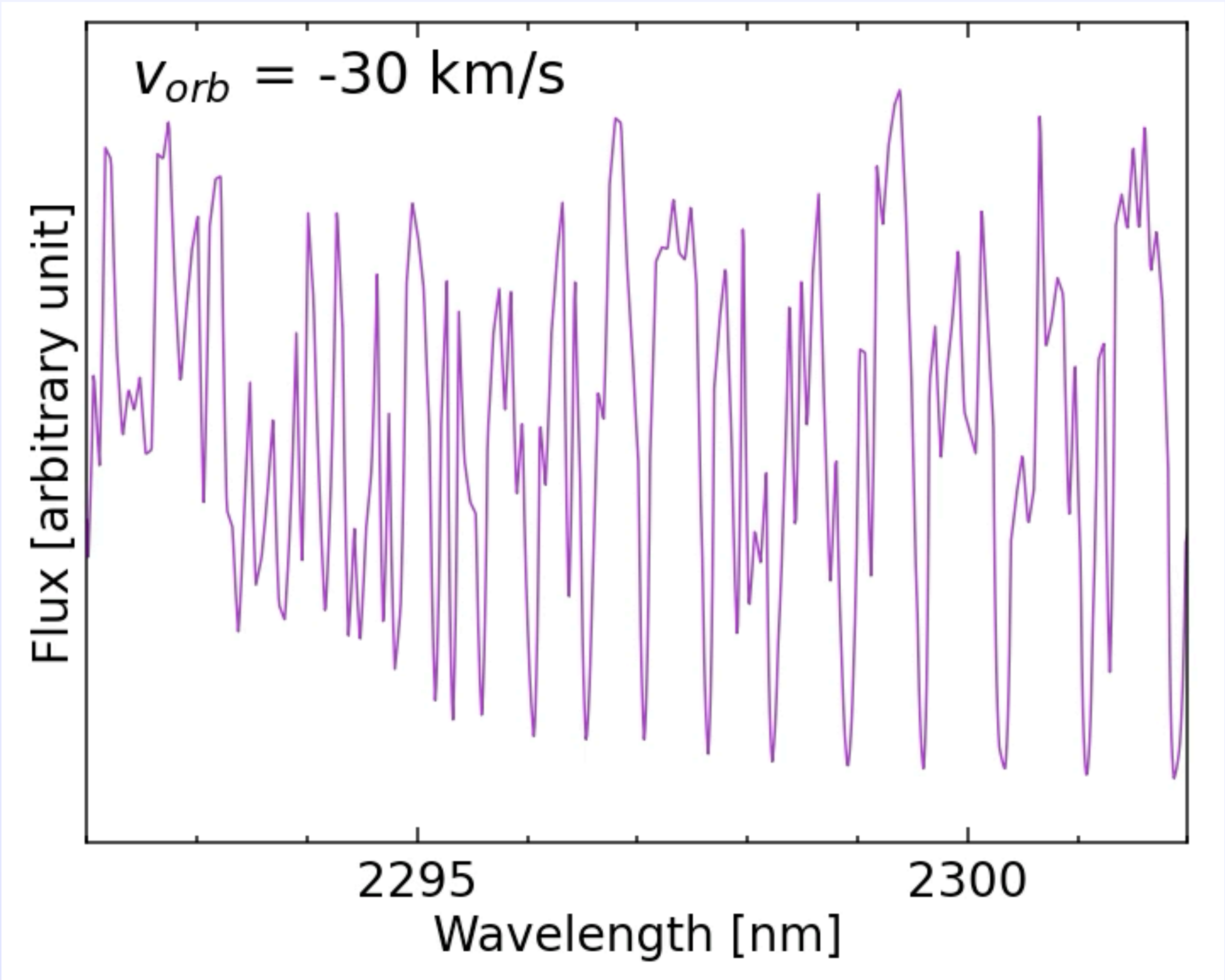


Orbital and rotational information

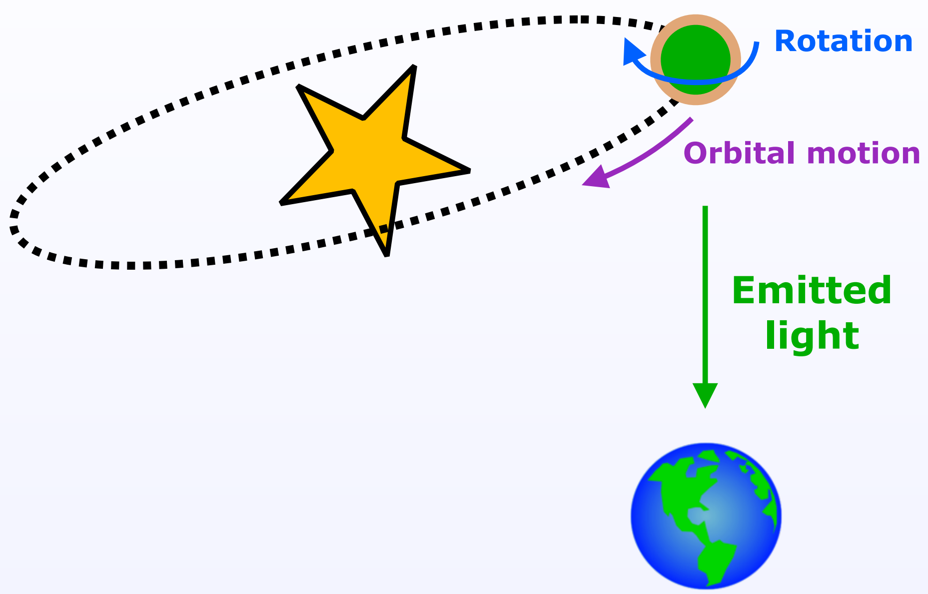


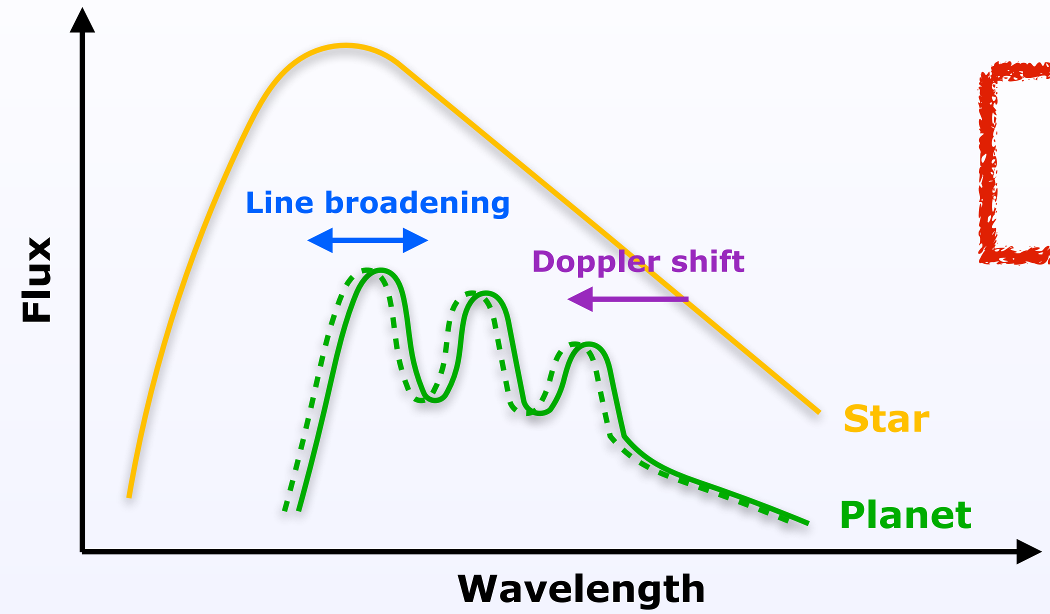


Effect of orbital motion



Orbital and rotational information

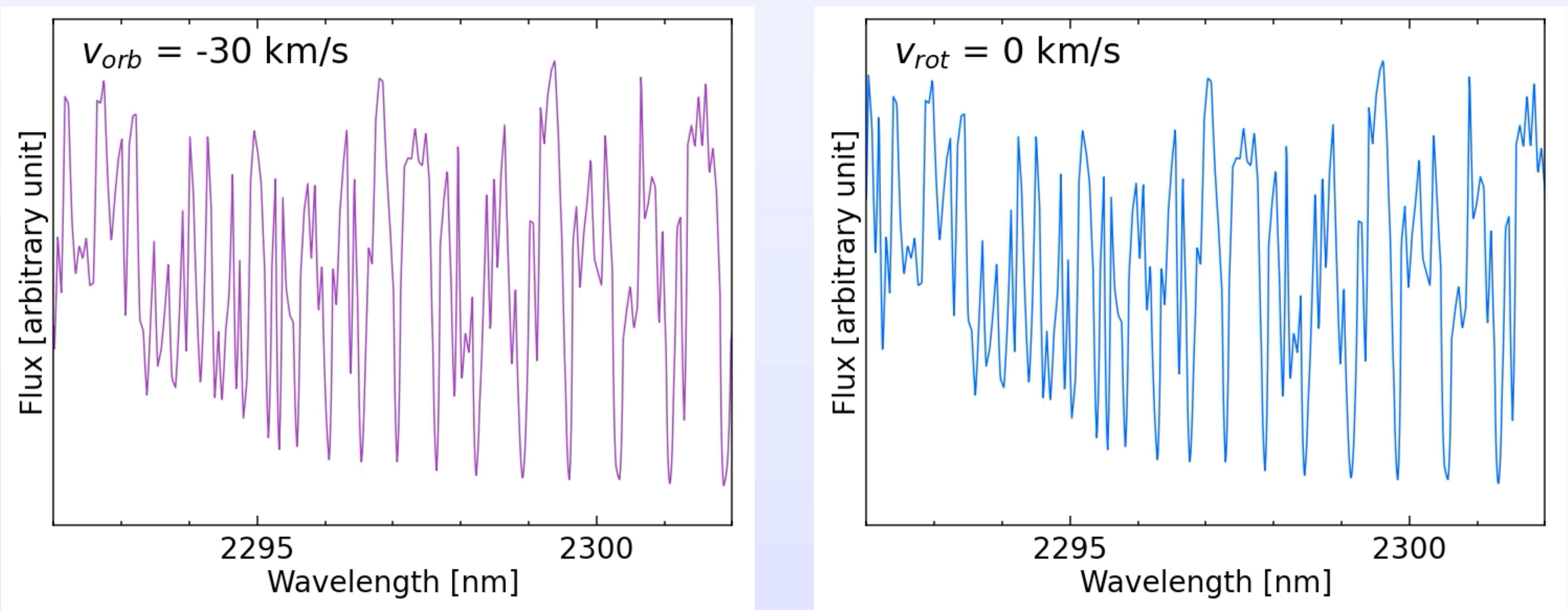




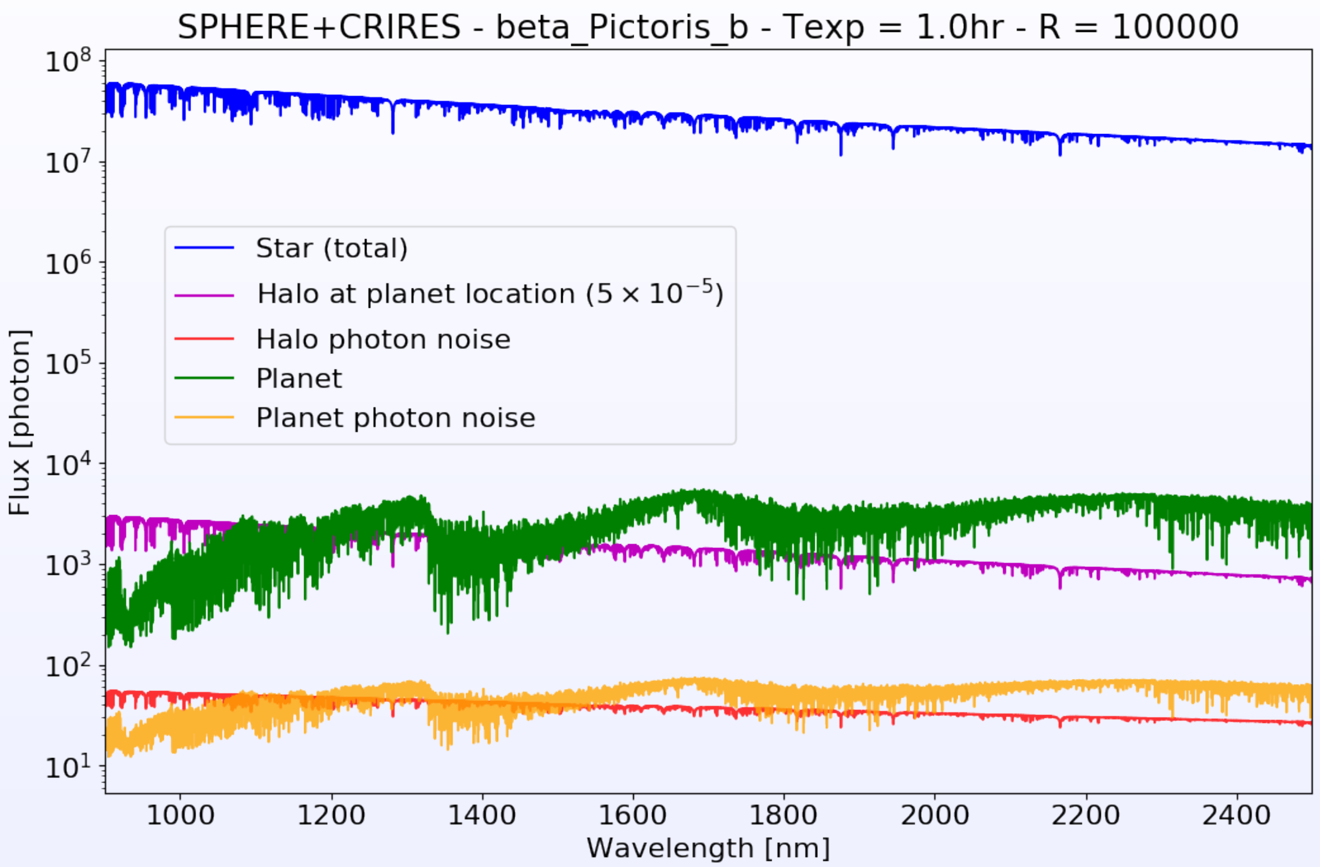
Requires R ≫ 30 000

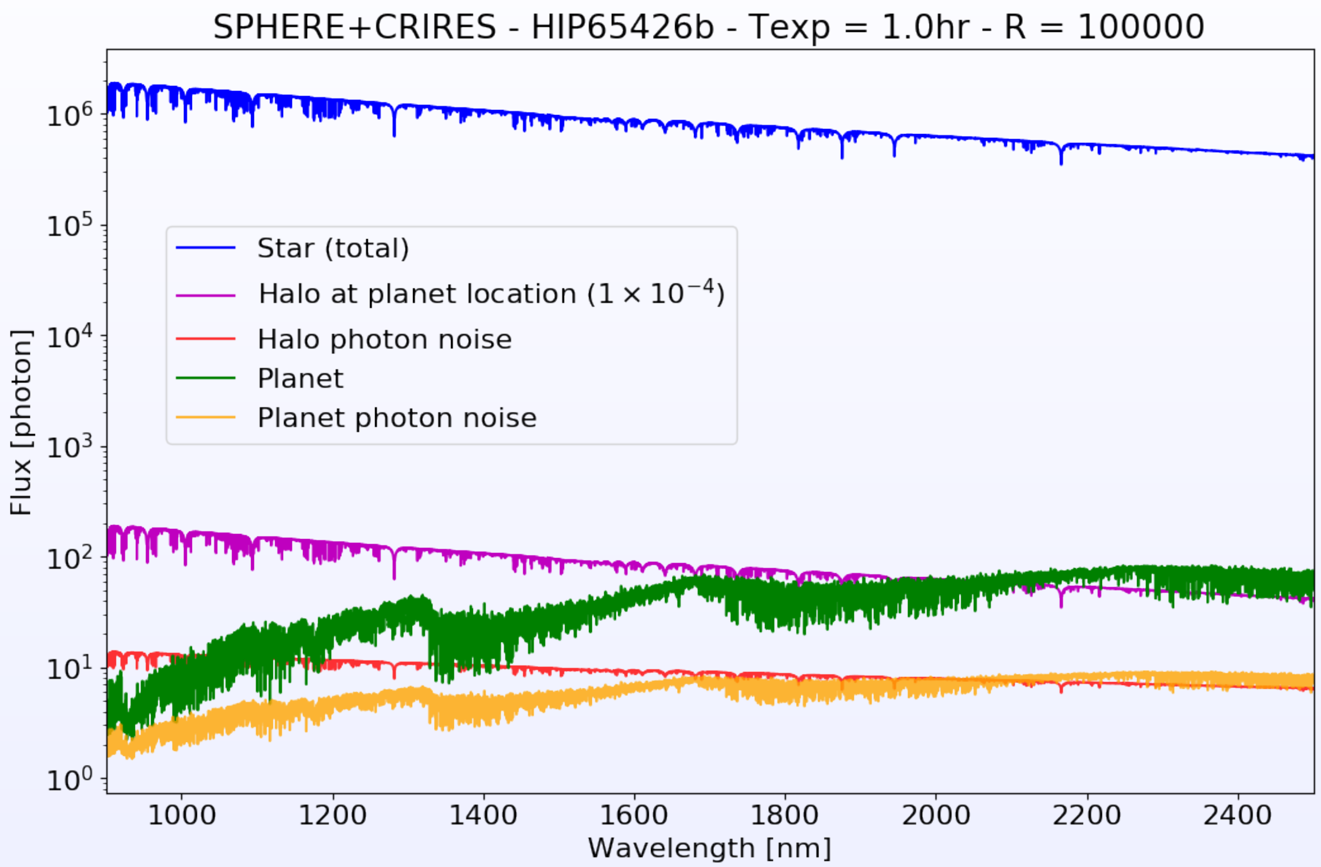
Effect of orbital motion

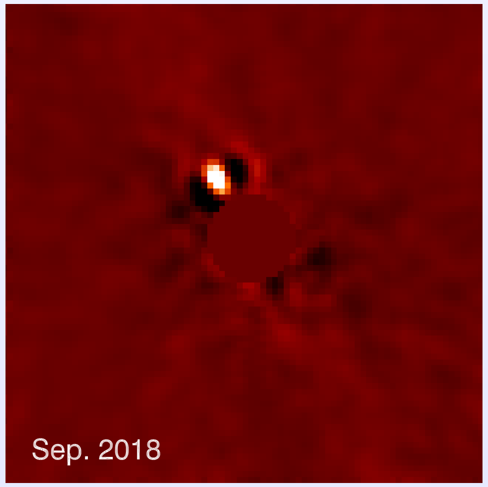
Effect of rotation



A few numbers...

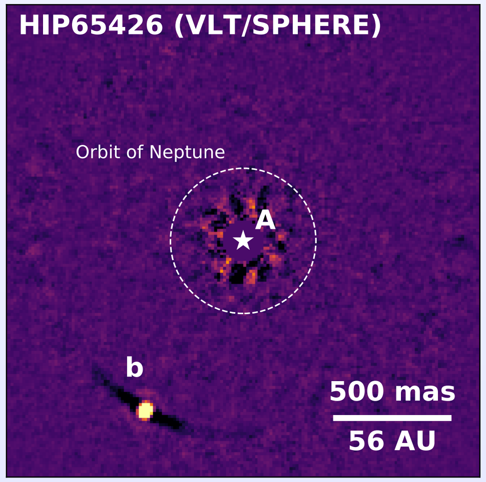






>1000 photon/channel

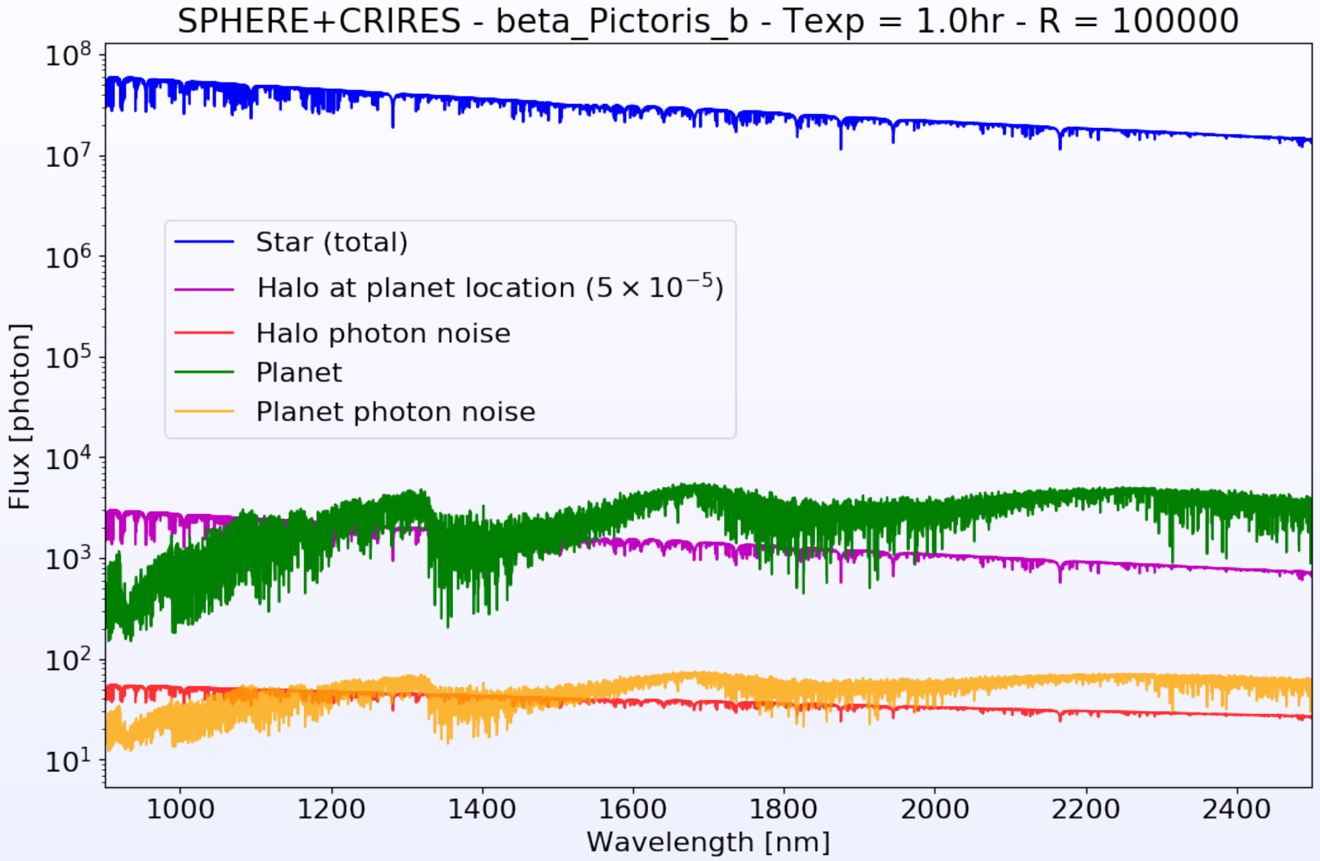
SNR > 100

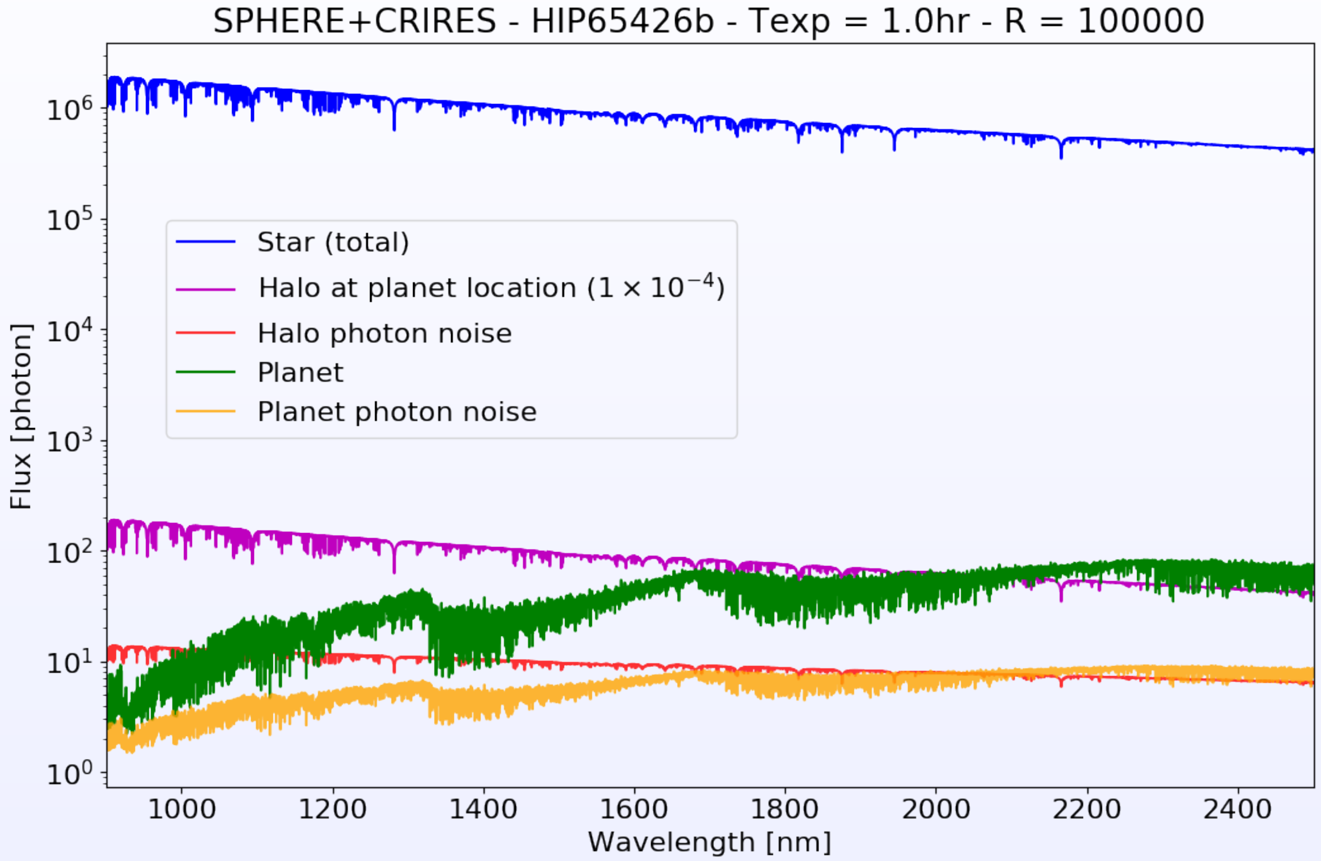


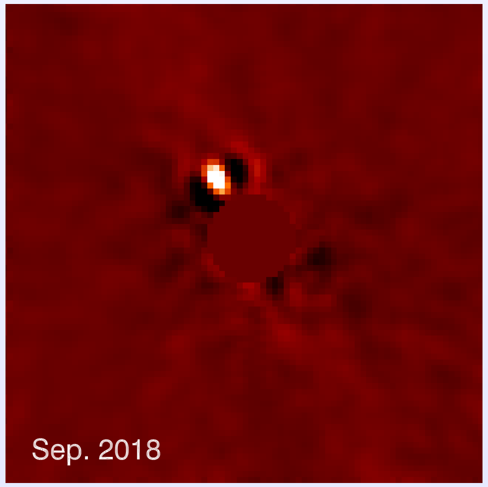
>10 photon/channel

SNR > 10

A few numbers...

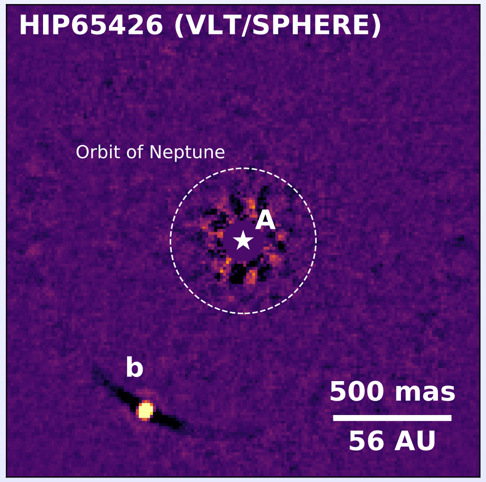






>1000 photon/channel

SNR > 100



>10 photon/channel

SNR > 10

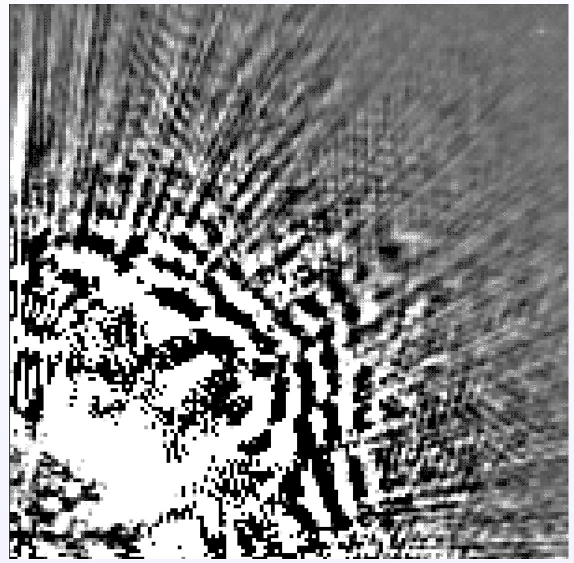
It's hard!!

Boost in detection

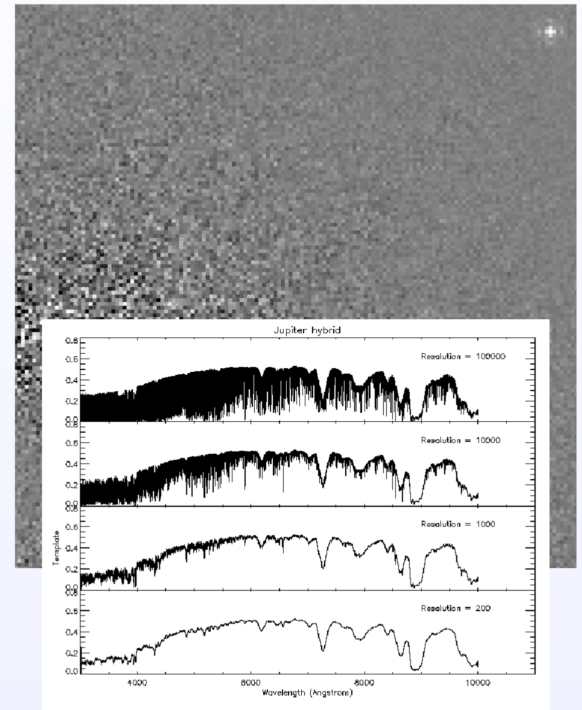
HST/ACS simulation

Sparks & Ford (2002)

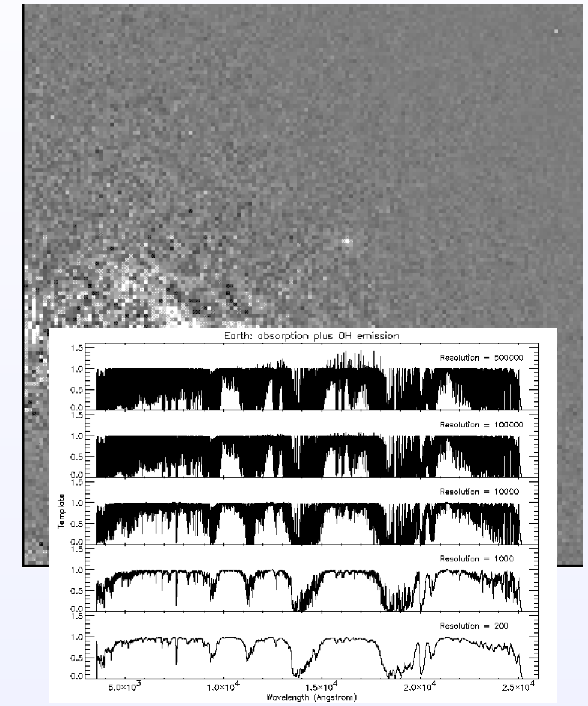
Roll-subtraction (=ADI)

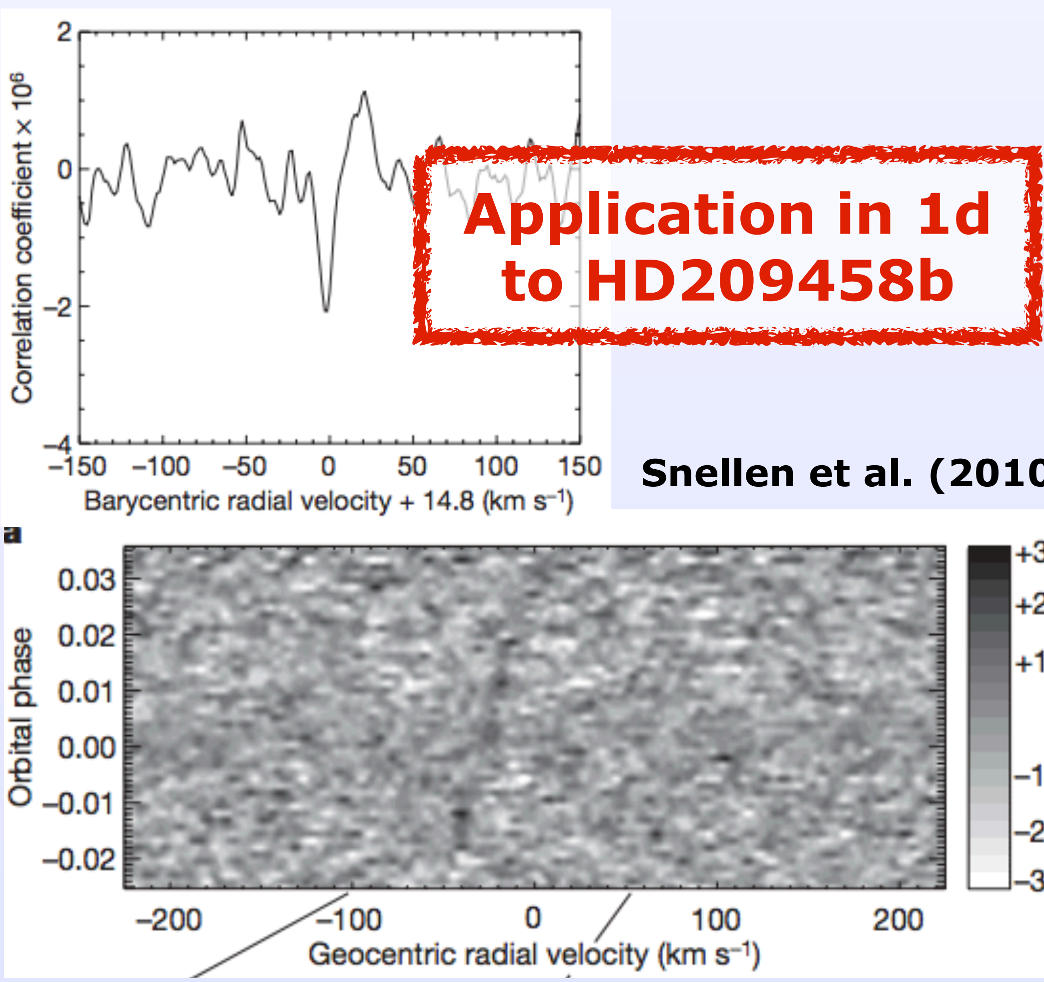


Jupiter template CCF



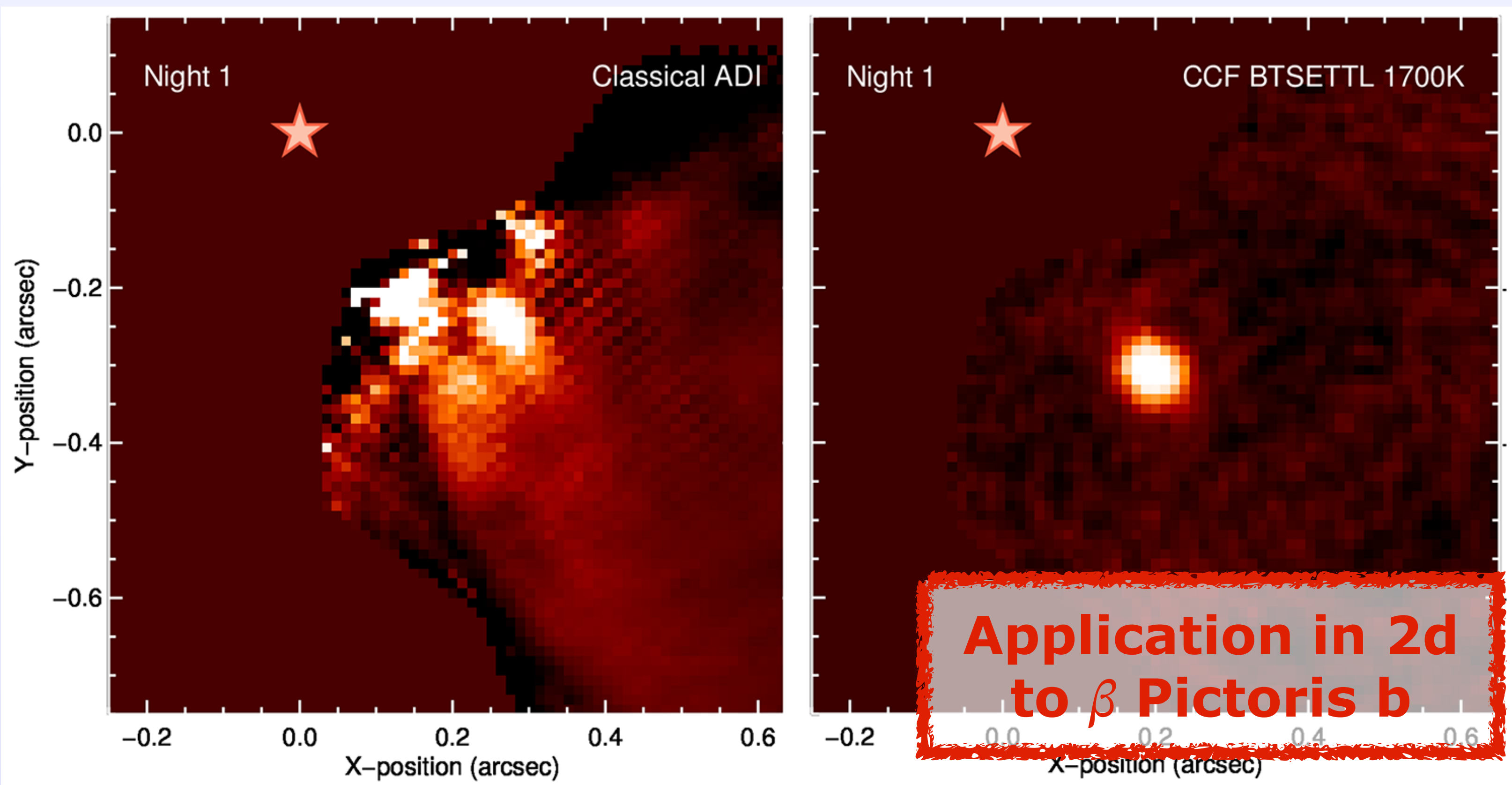
Bright Earth template CCF





Snellen et al. (2010)

Hoeijmakers et al. (2016)



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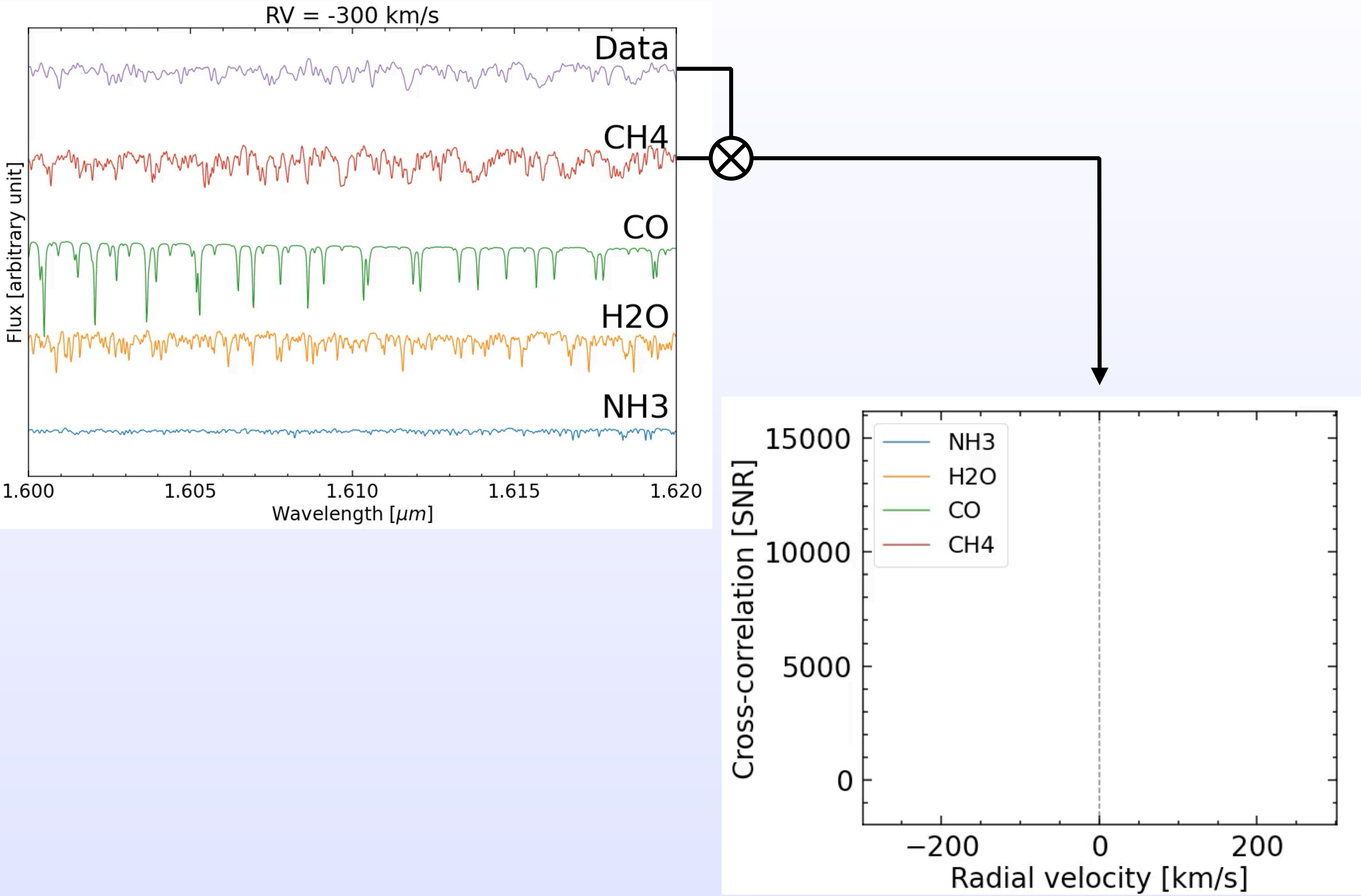
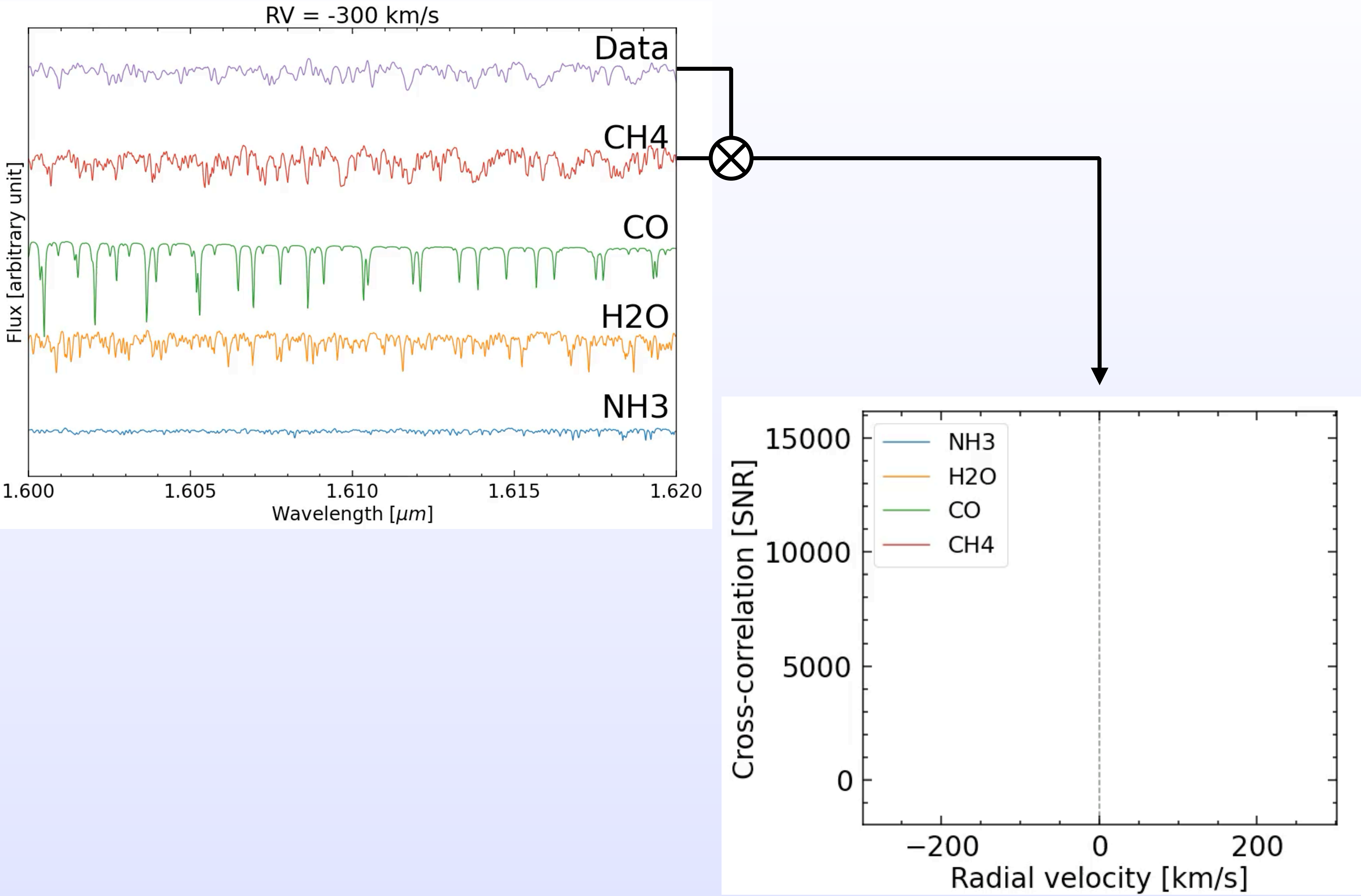
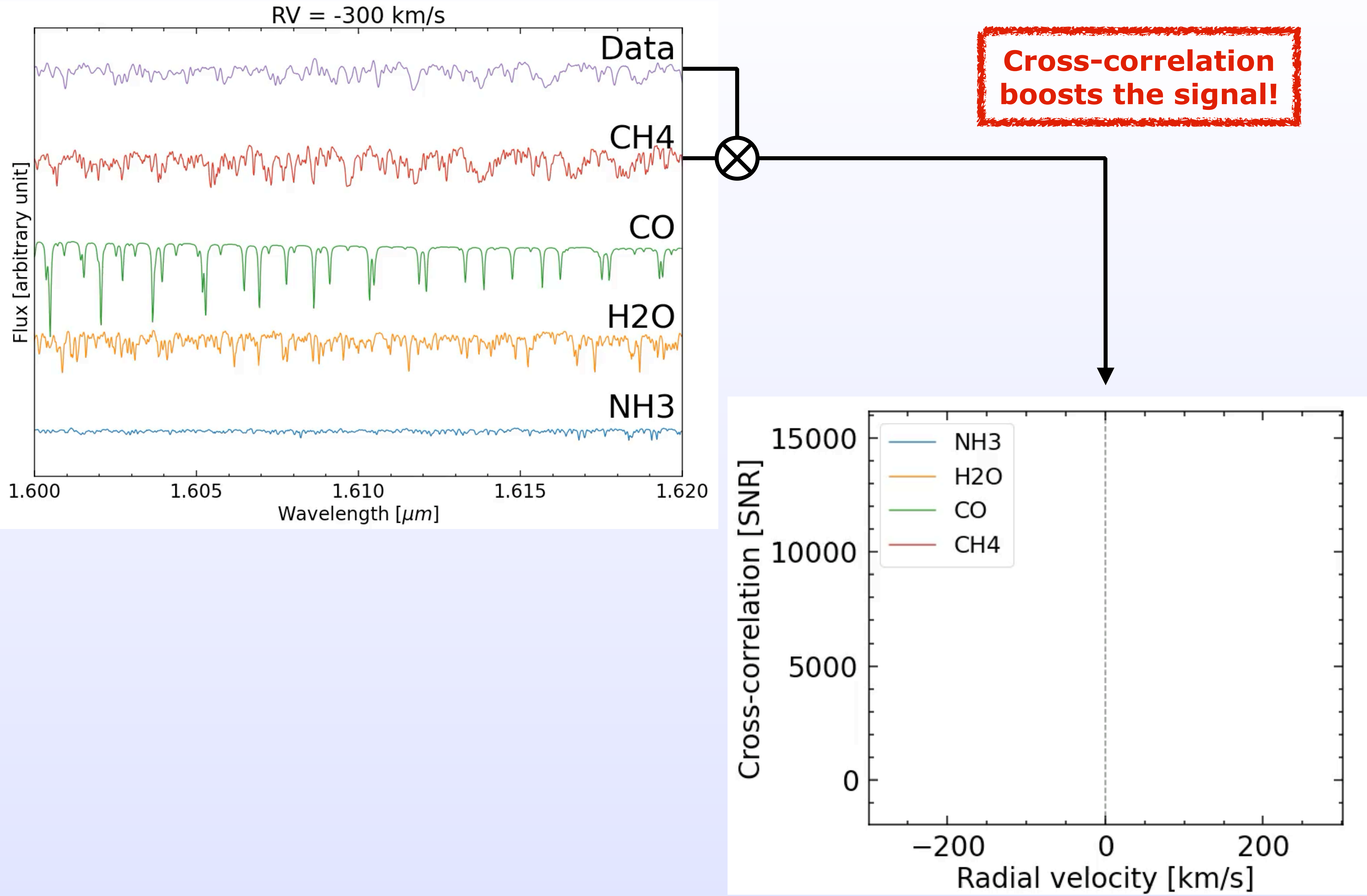


Boost in detection

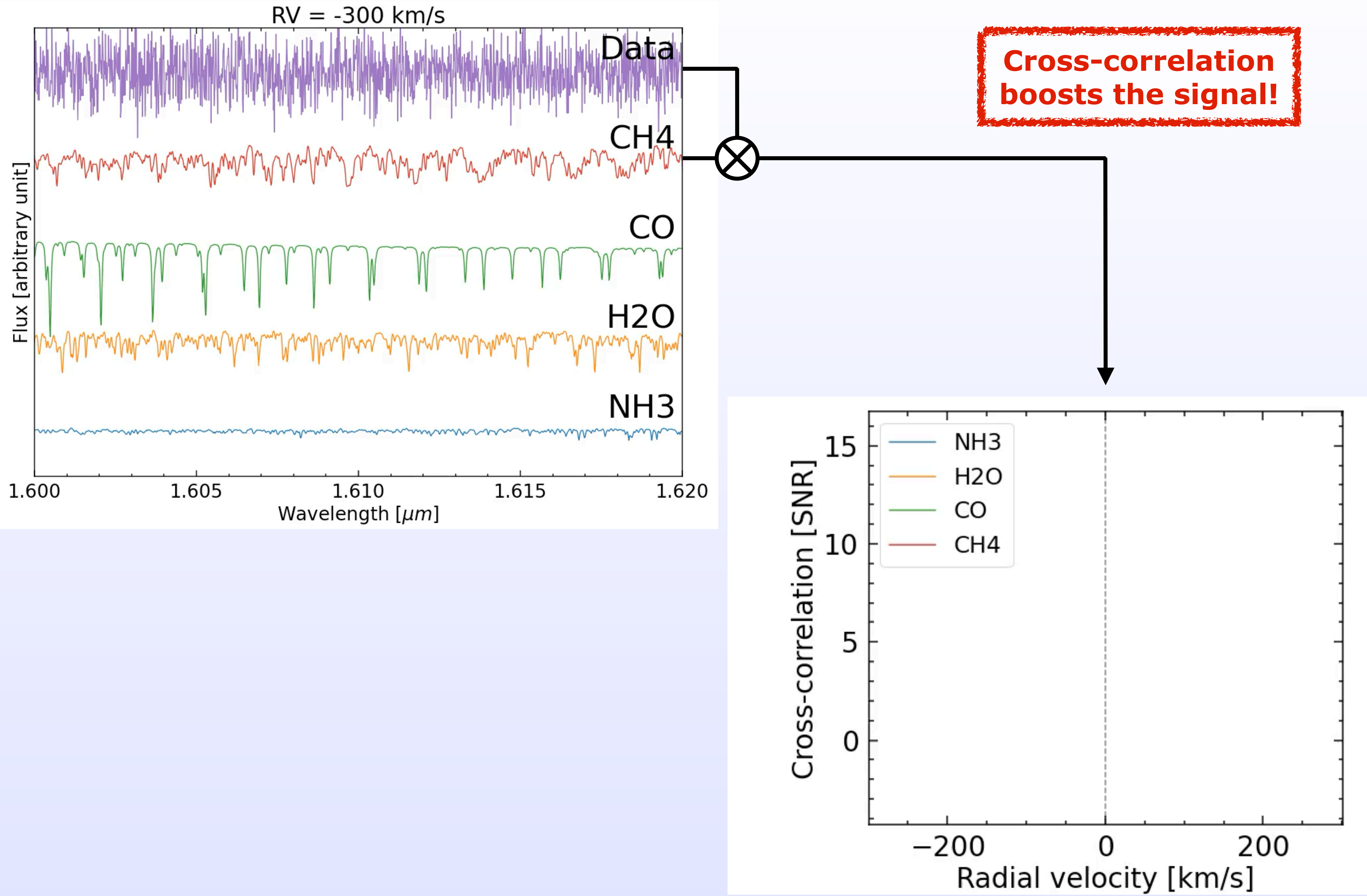


Boost in detection



Cross-correlation boosts the signal!

Boost in detection



Cross-correlation boosts the signal!

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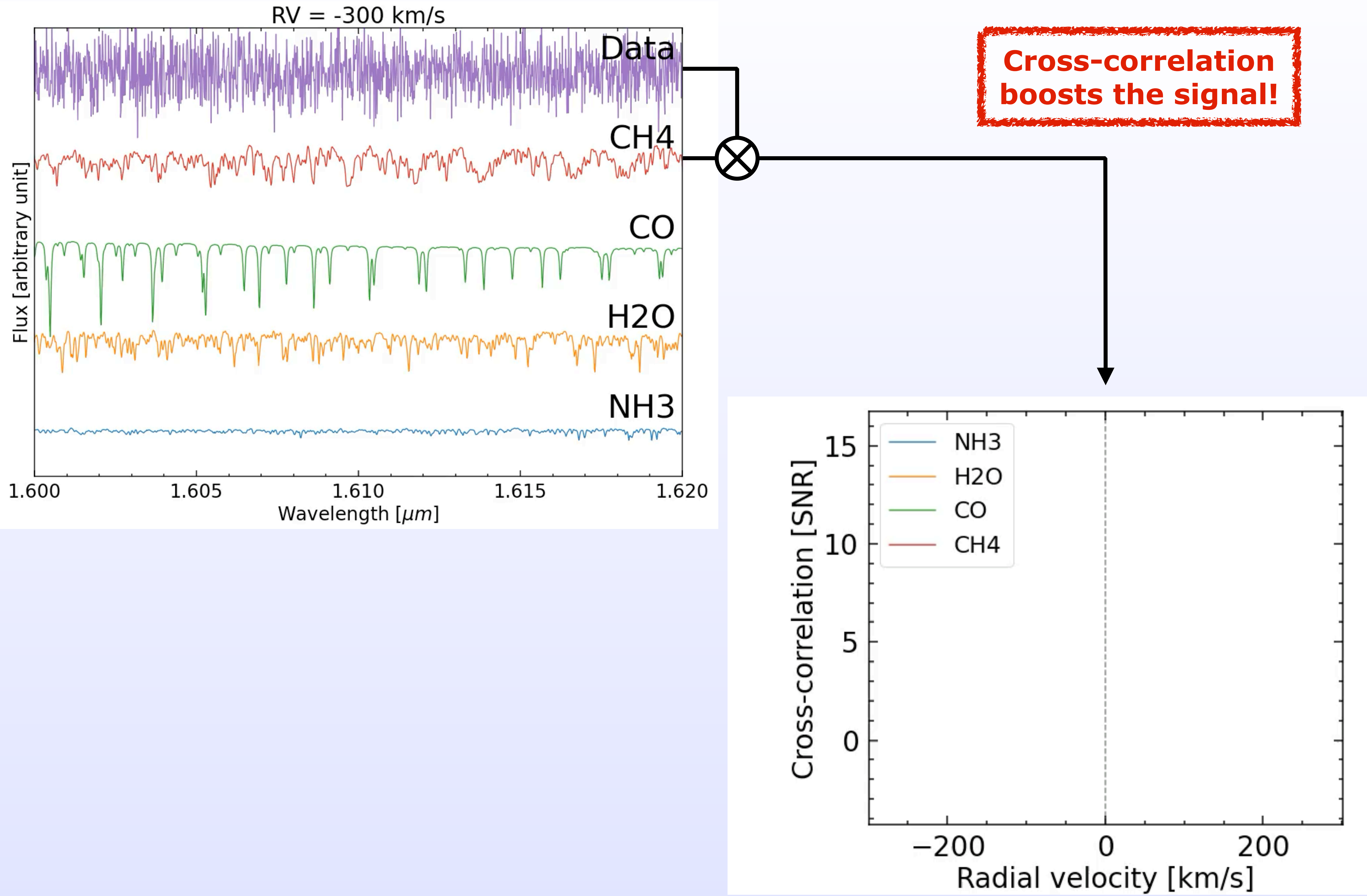
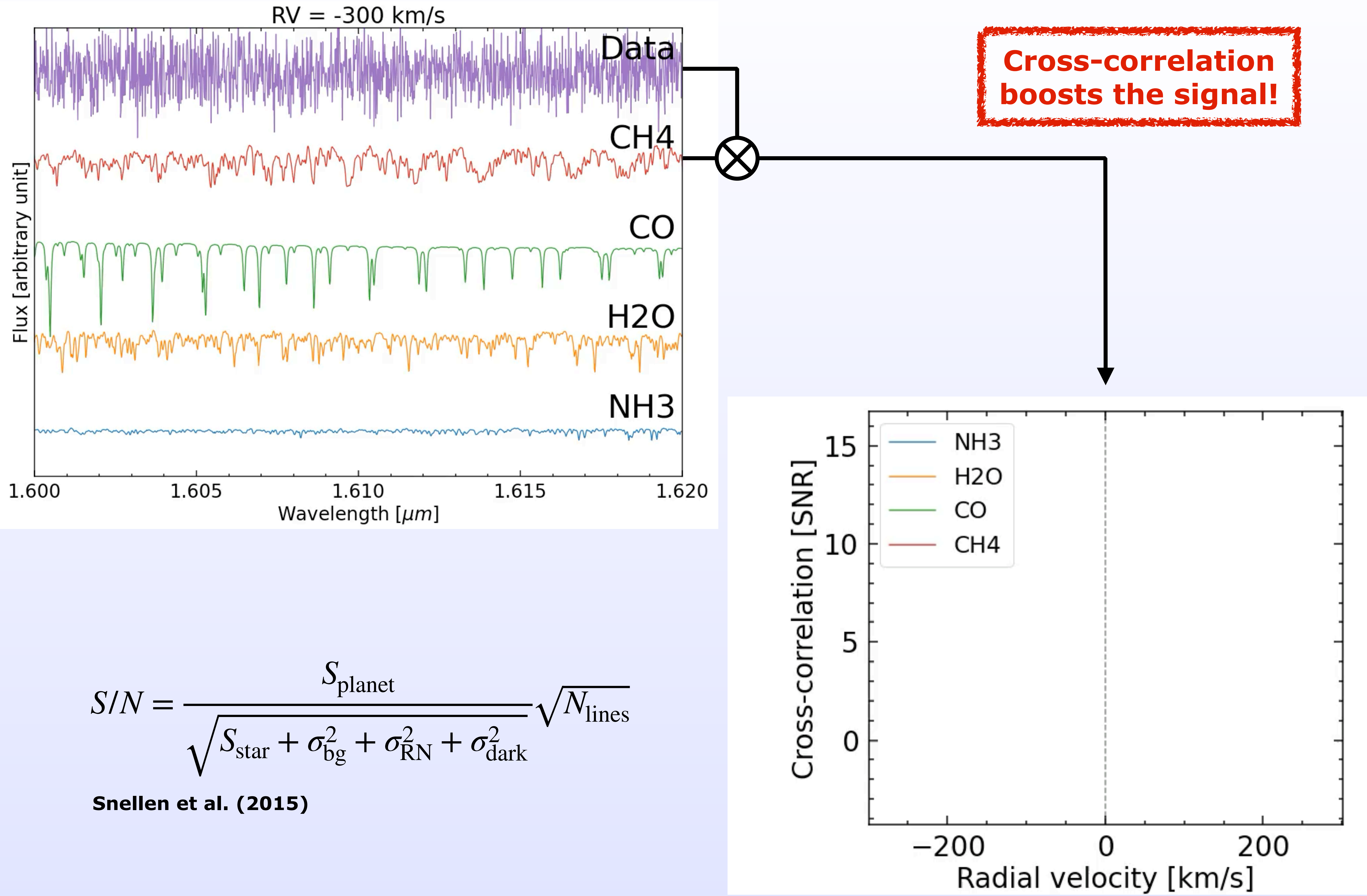


Boost in detection



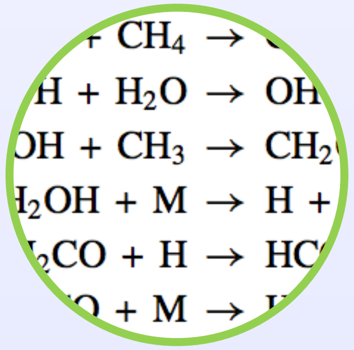
Cross-correlation boosts the signal!

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

Snellen et al. (2015)

Exoplanet science at high resolution

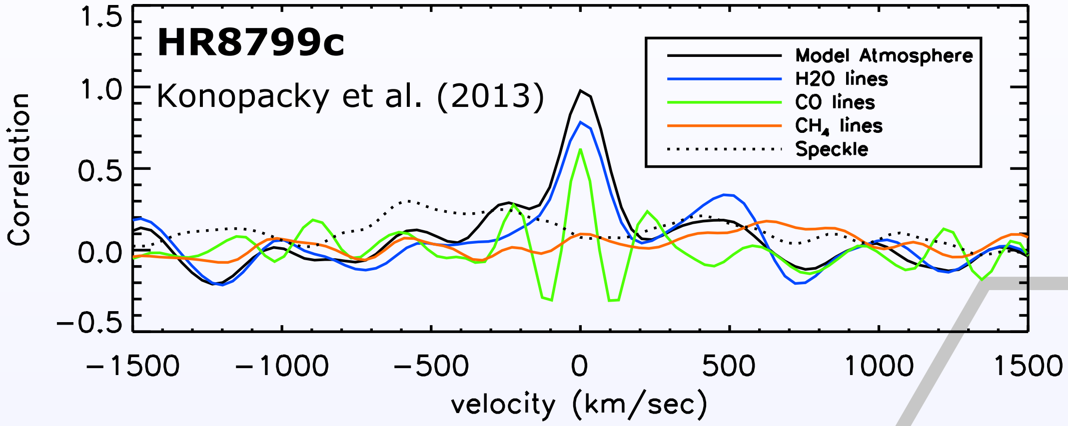
Formation,
migration & evolution



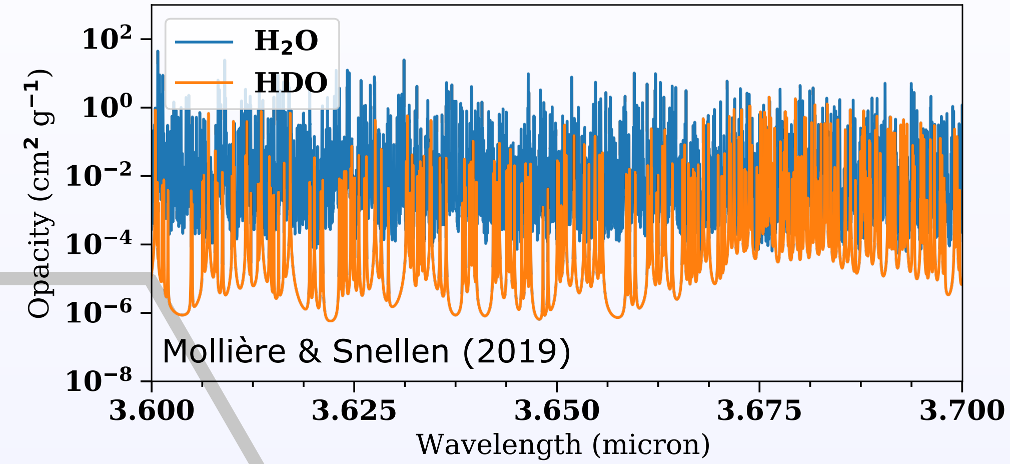
Atmospheric
chemistry & dynamics

Exoplanet science at high resolution

Molecules detection

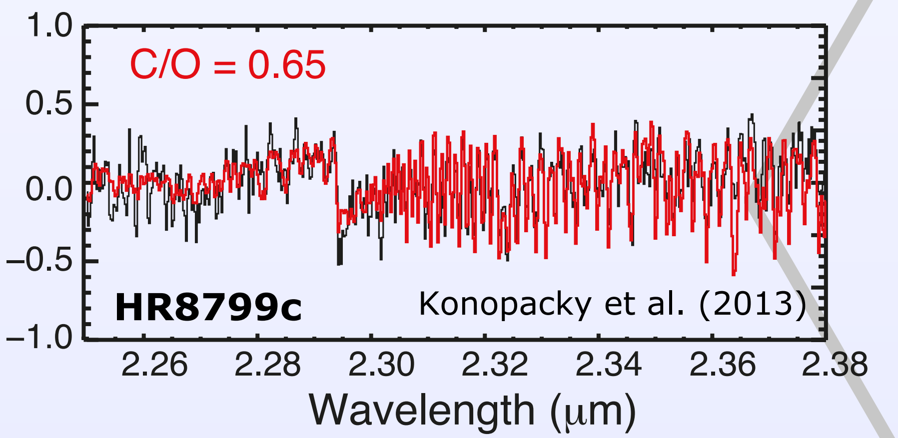


Isotopologues detection

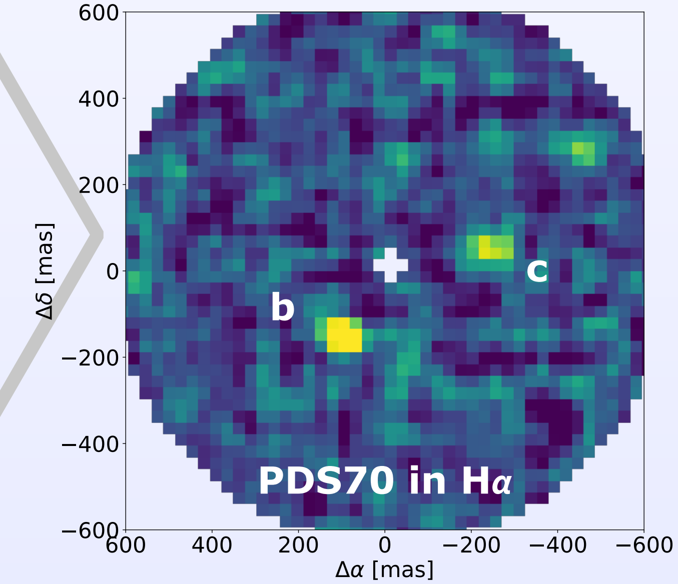


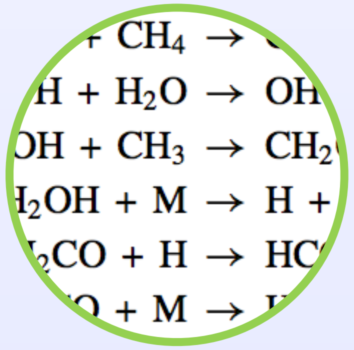
Formation, migration & evolution

Abundances determination



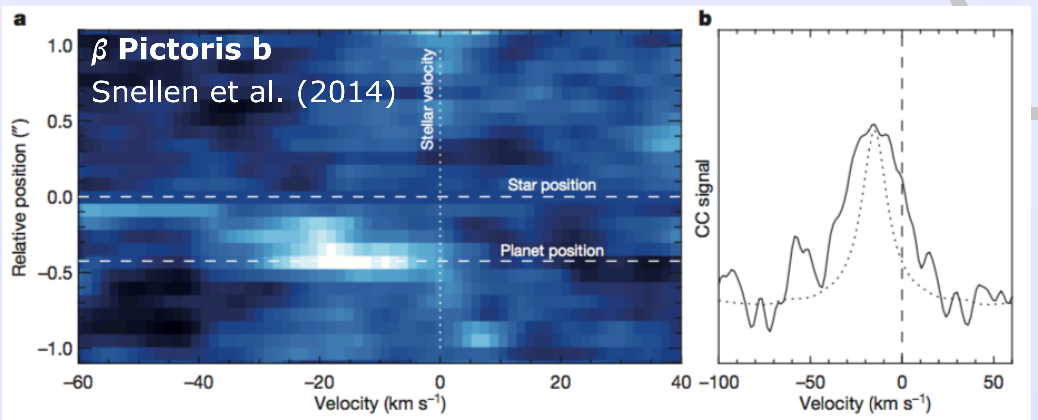
Accretion lines



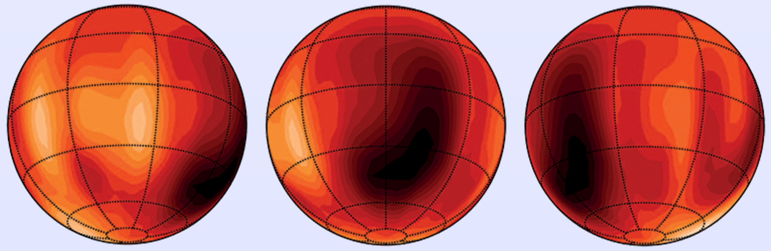


Atmospheric chemistry & dynamics

Orbital and rotational velocity

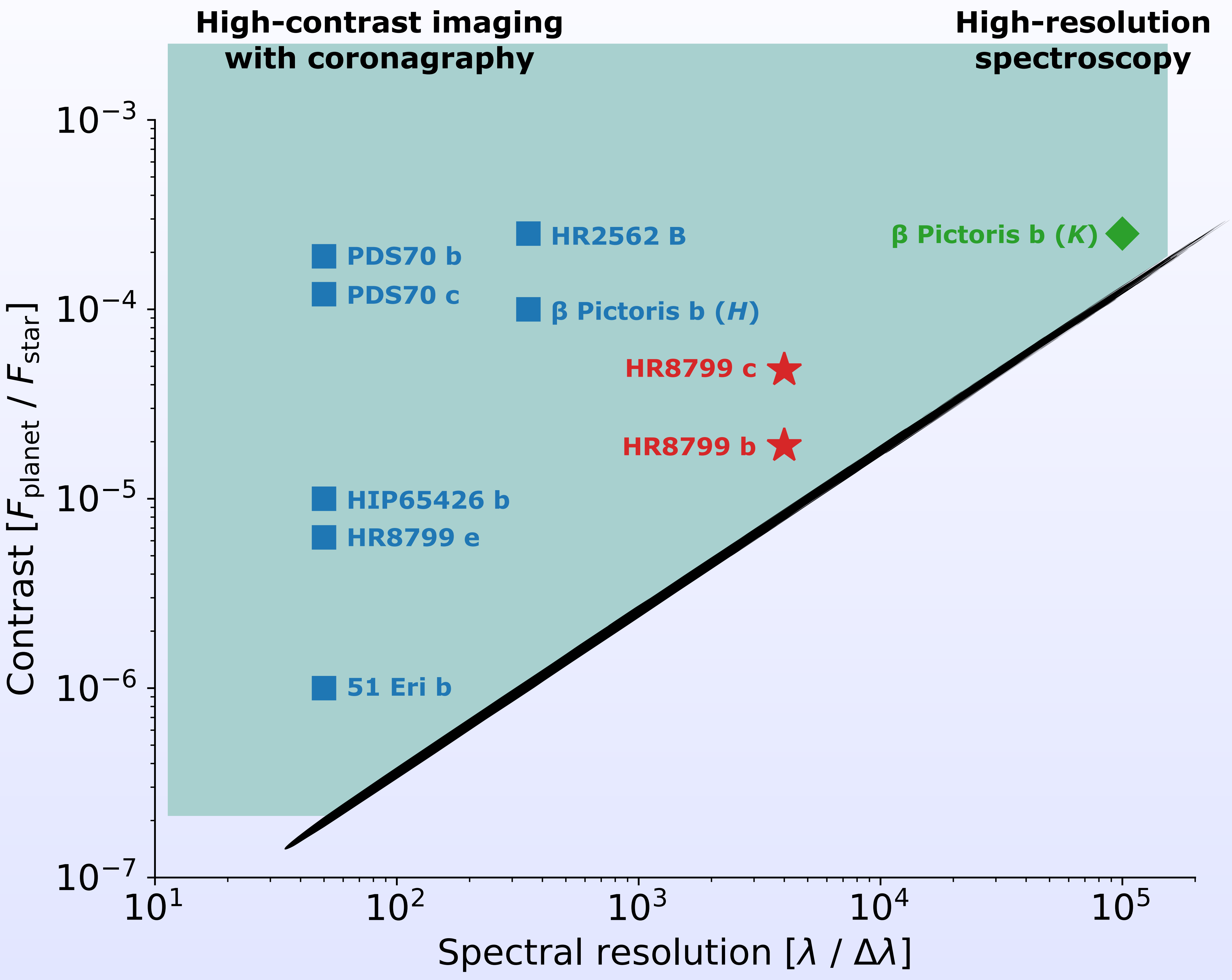


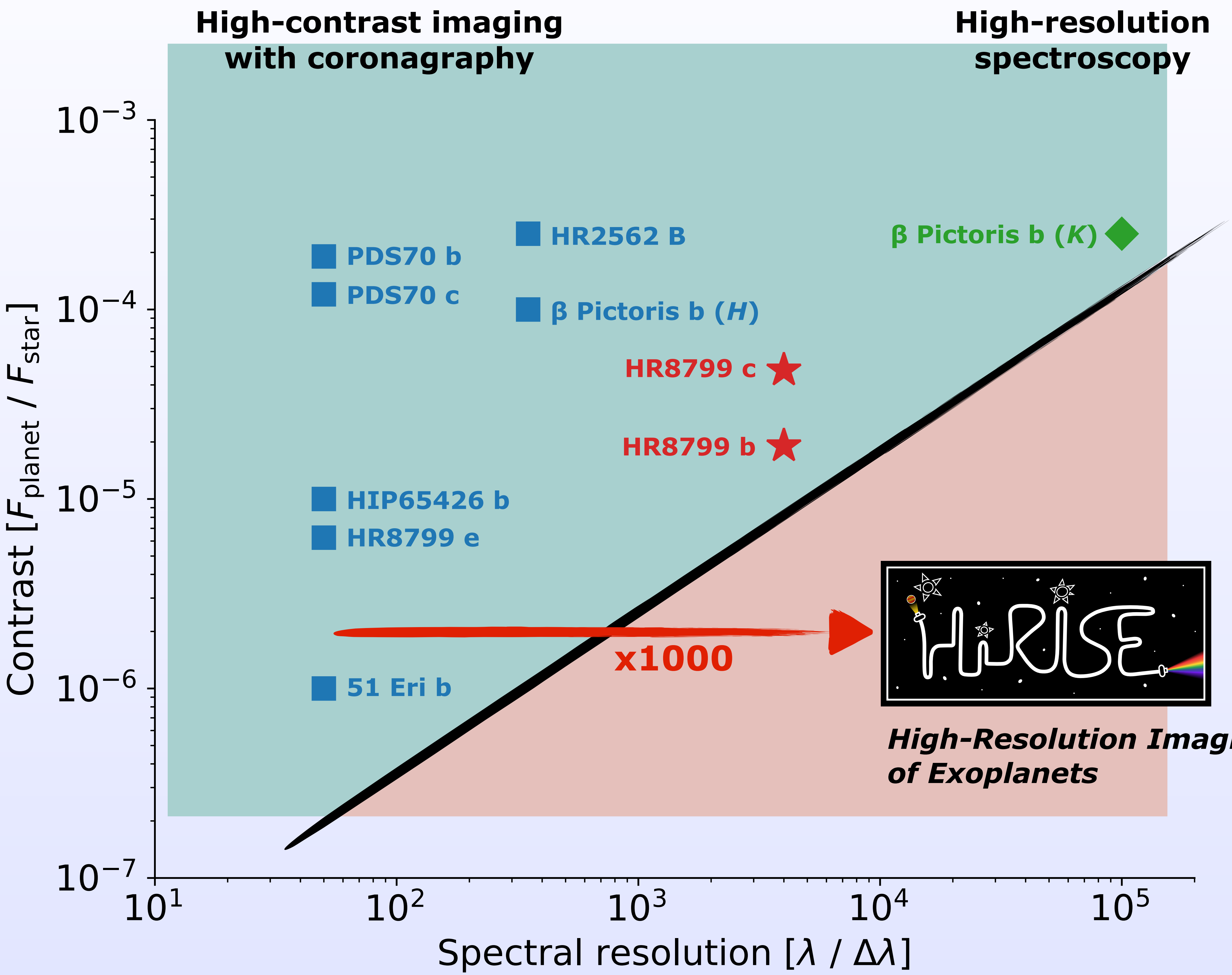
Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR





High-Resolution Imaging and Spectroscopy of Exoplanets

Characterisation

15-20 companions already known at

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

Companions detected by other means

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

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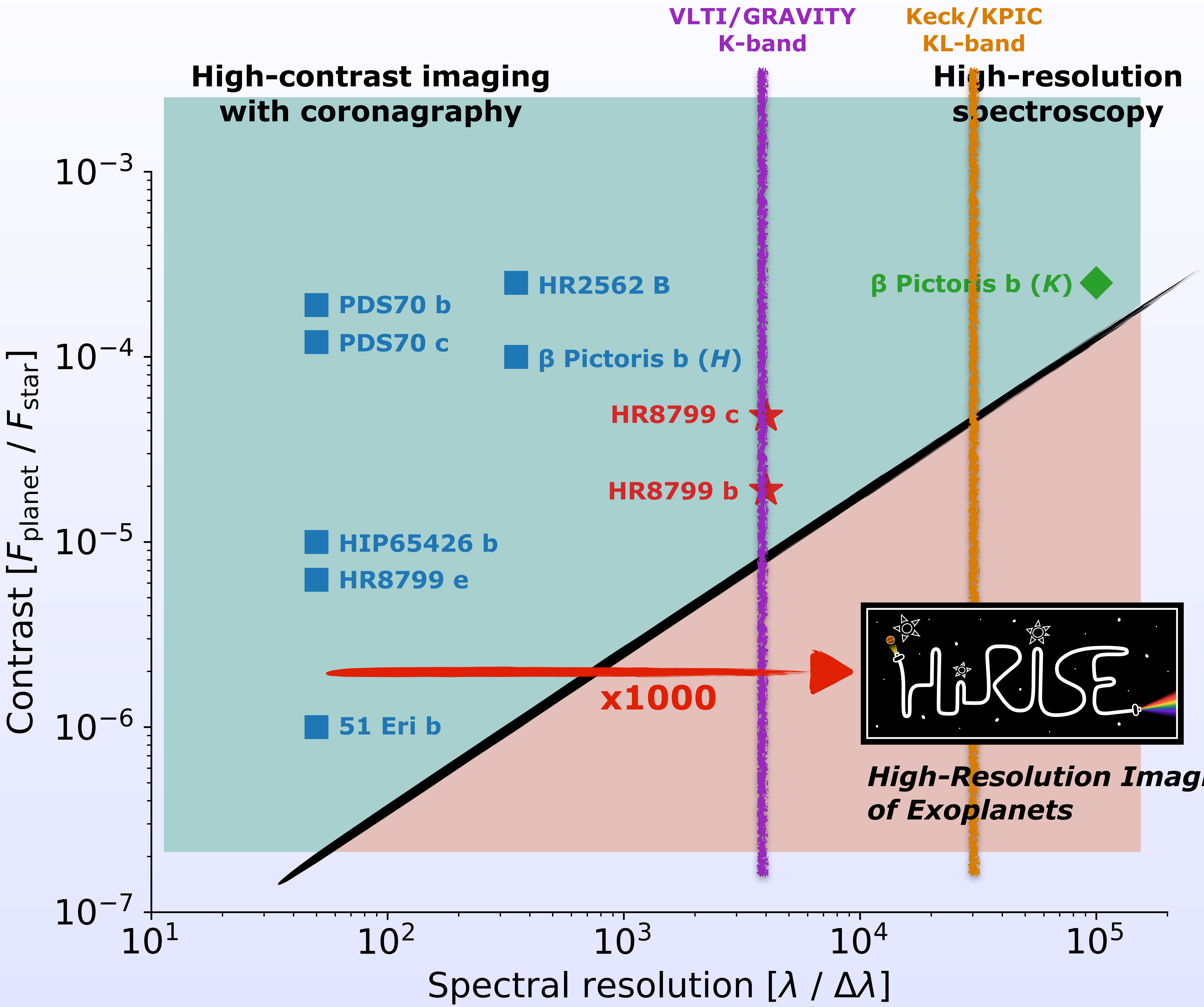

High-Resolution Imaging and Spectroscopy of Exoplanets

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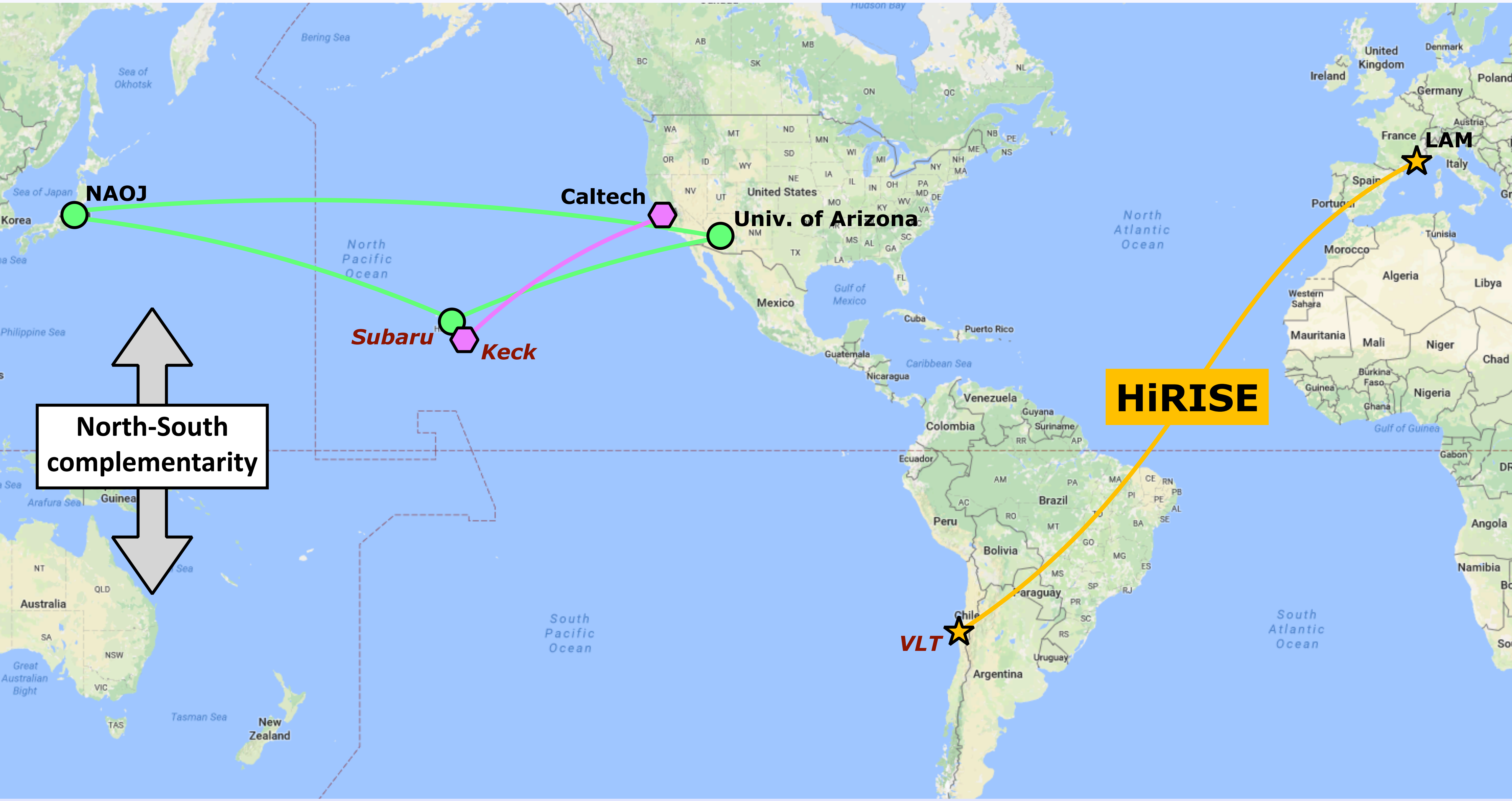
A European opportunity in the South

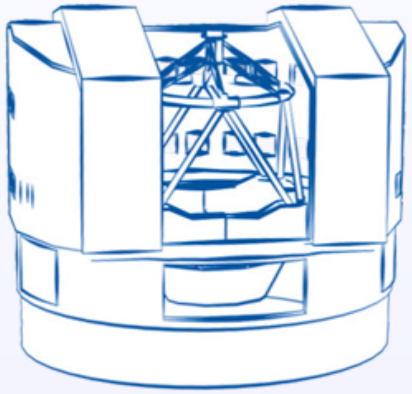
Existing instruments on 8-10 m telescopes with ExAO:

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



A unique window of opportunity

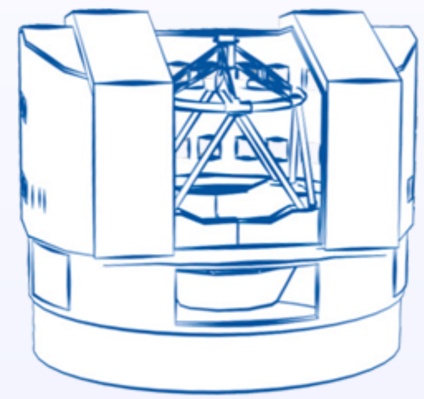
VLT/UT3



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

A unique window of opportunity

VLT/UT3



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SPHERE		CRIRES+
✔	Extreme adaptive optics	✘
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Y J H K	Spectral coverage	Y J H K L M
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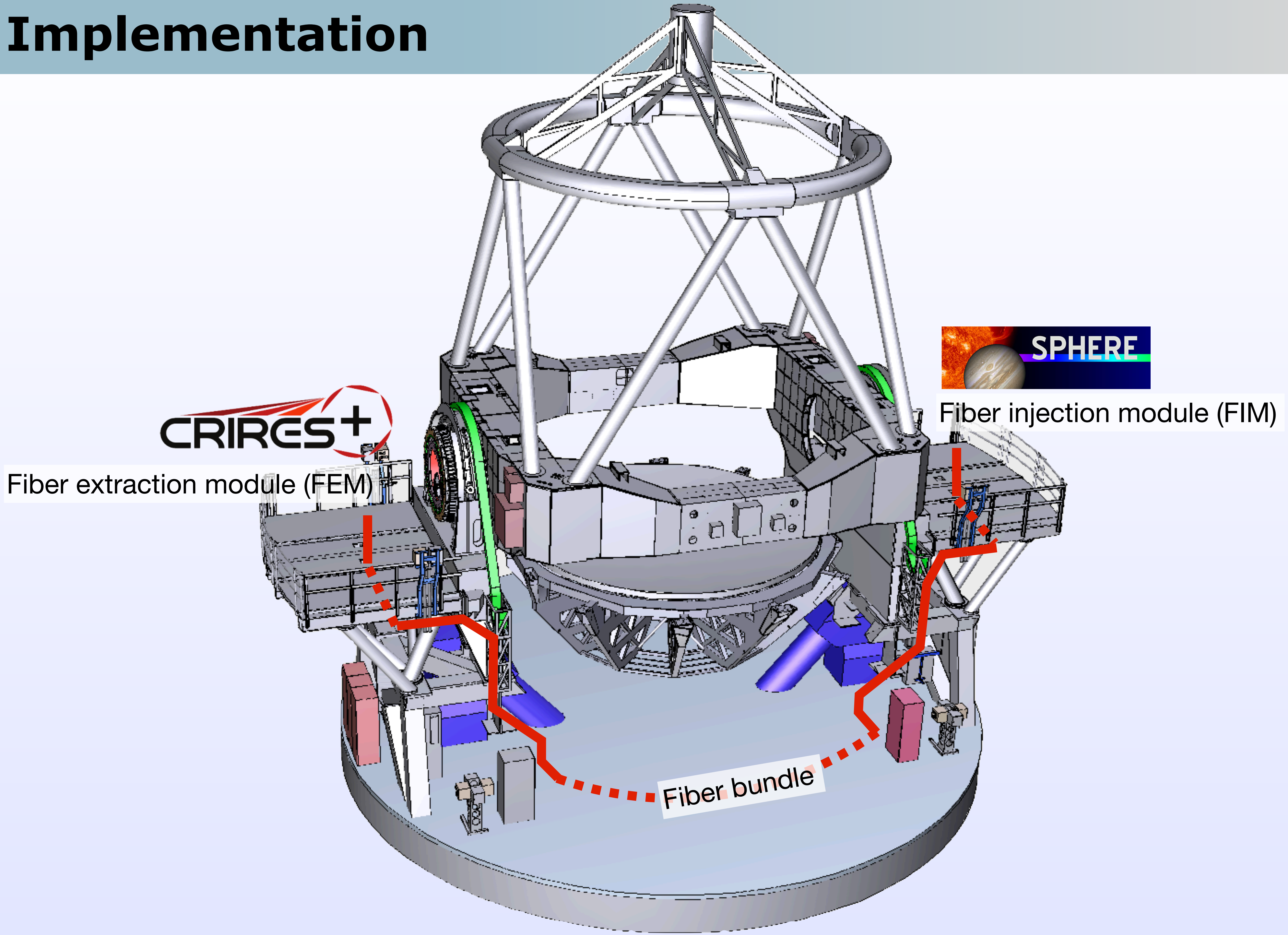
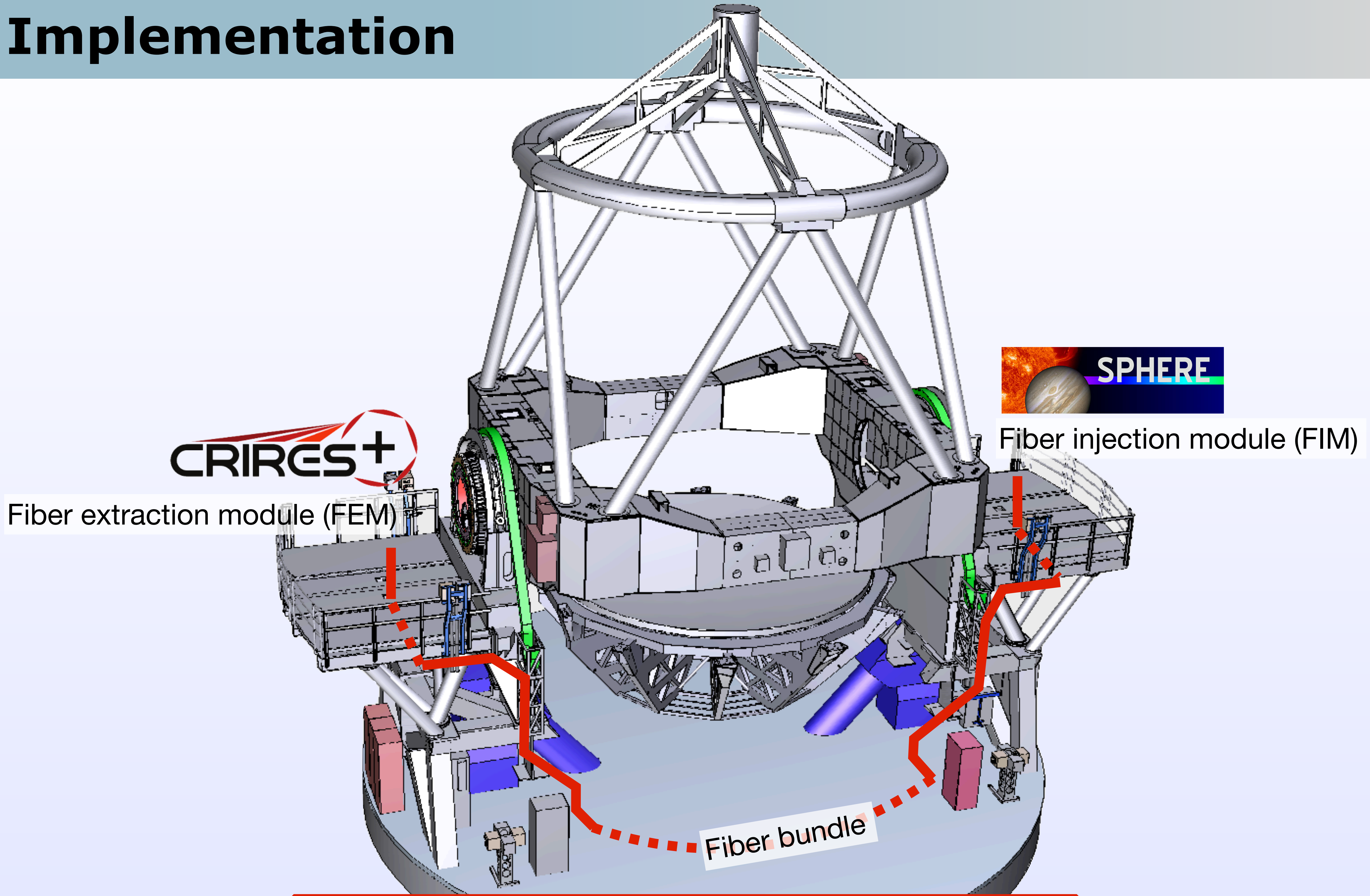
Fiber coupling

HiRISE

Implementation



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

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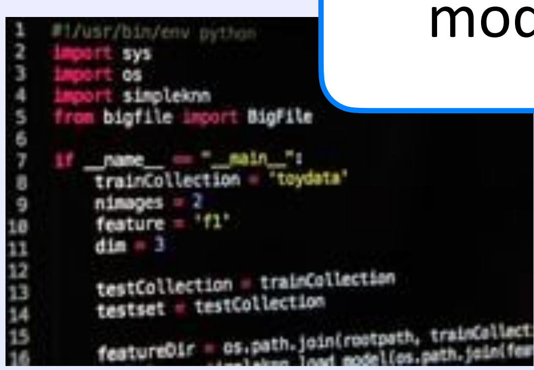
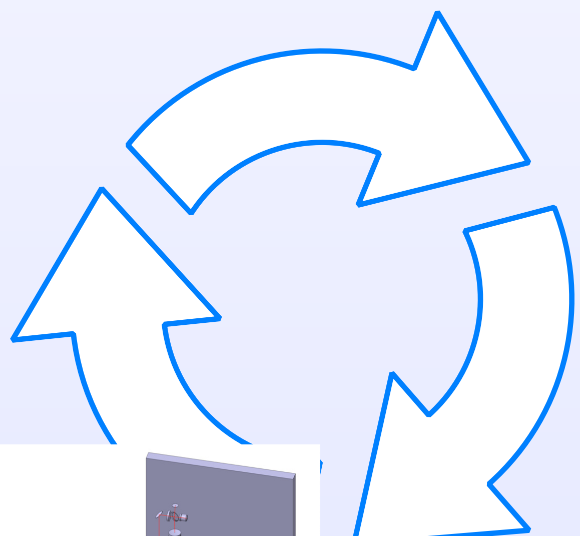
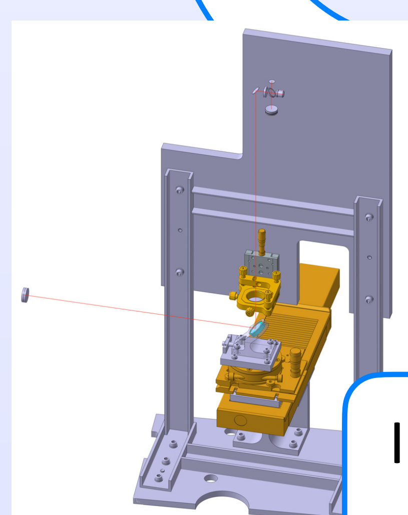


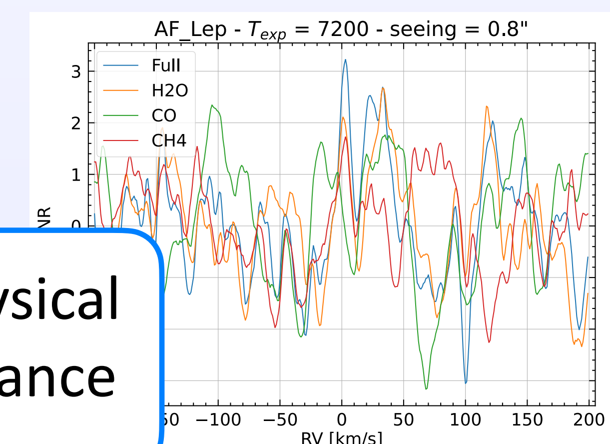
Simulation model

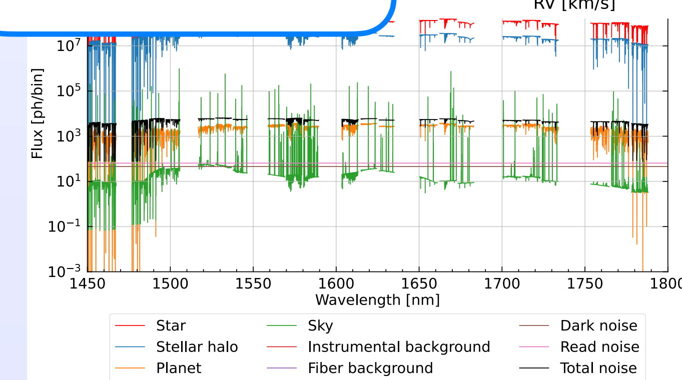




Instrument design

Astrophysical performance





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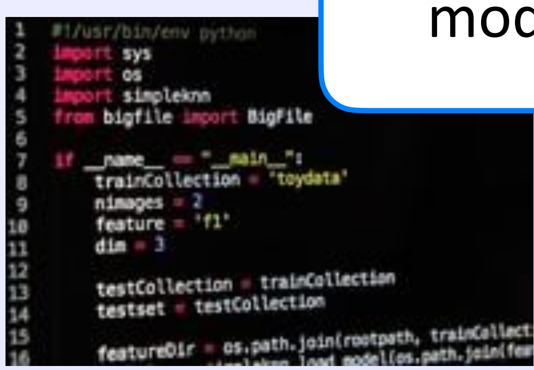


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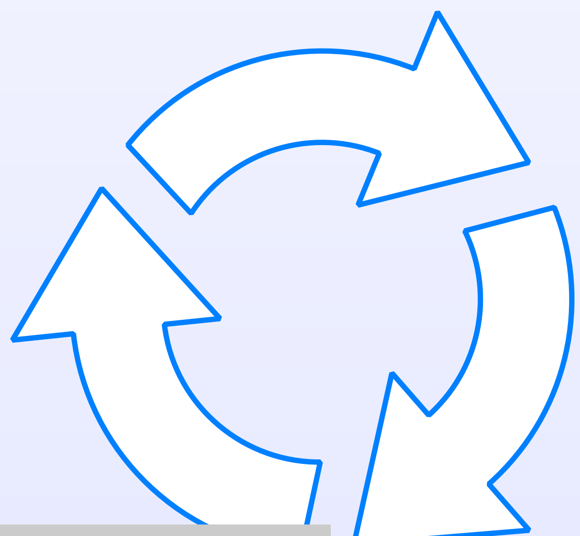

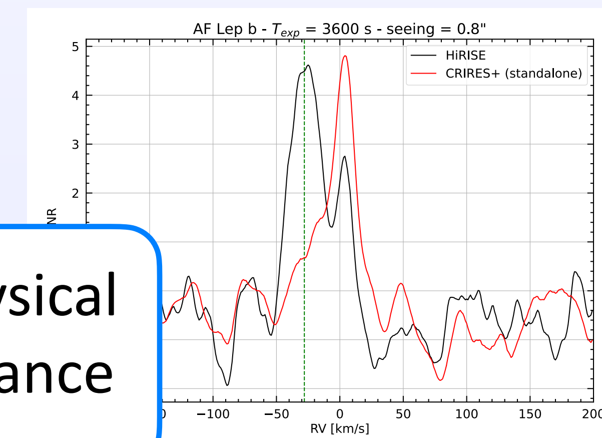

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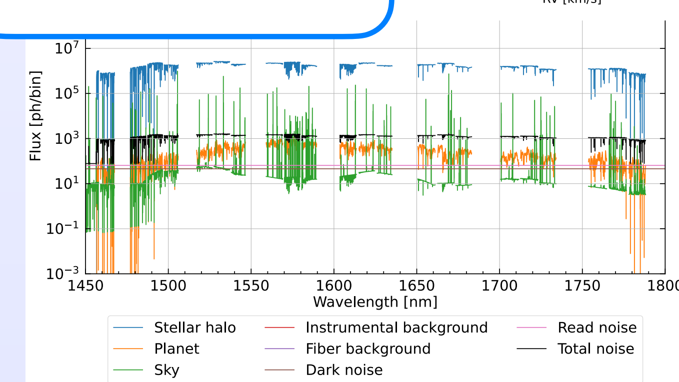

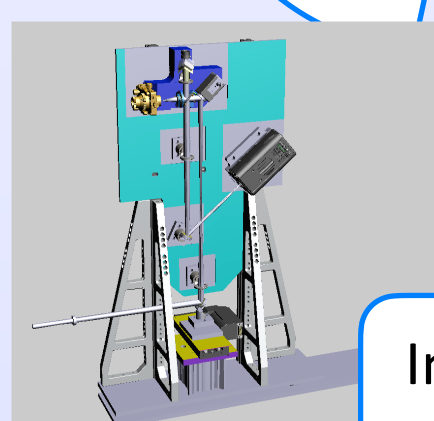

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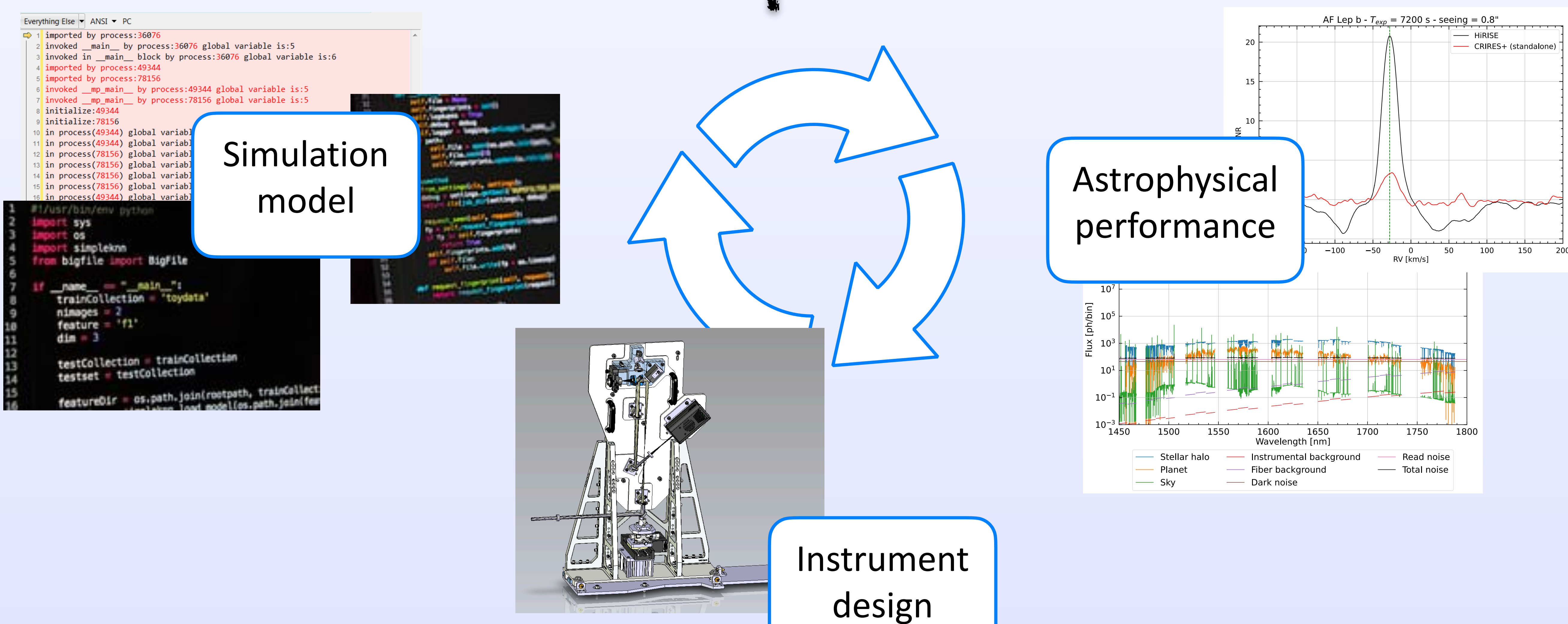
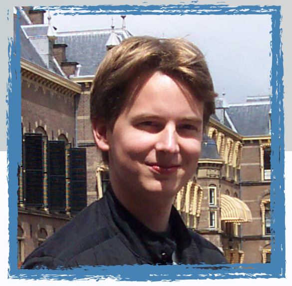
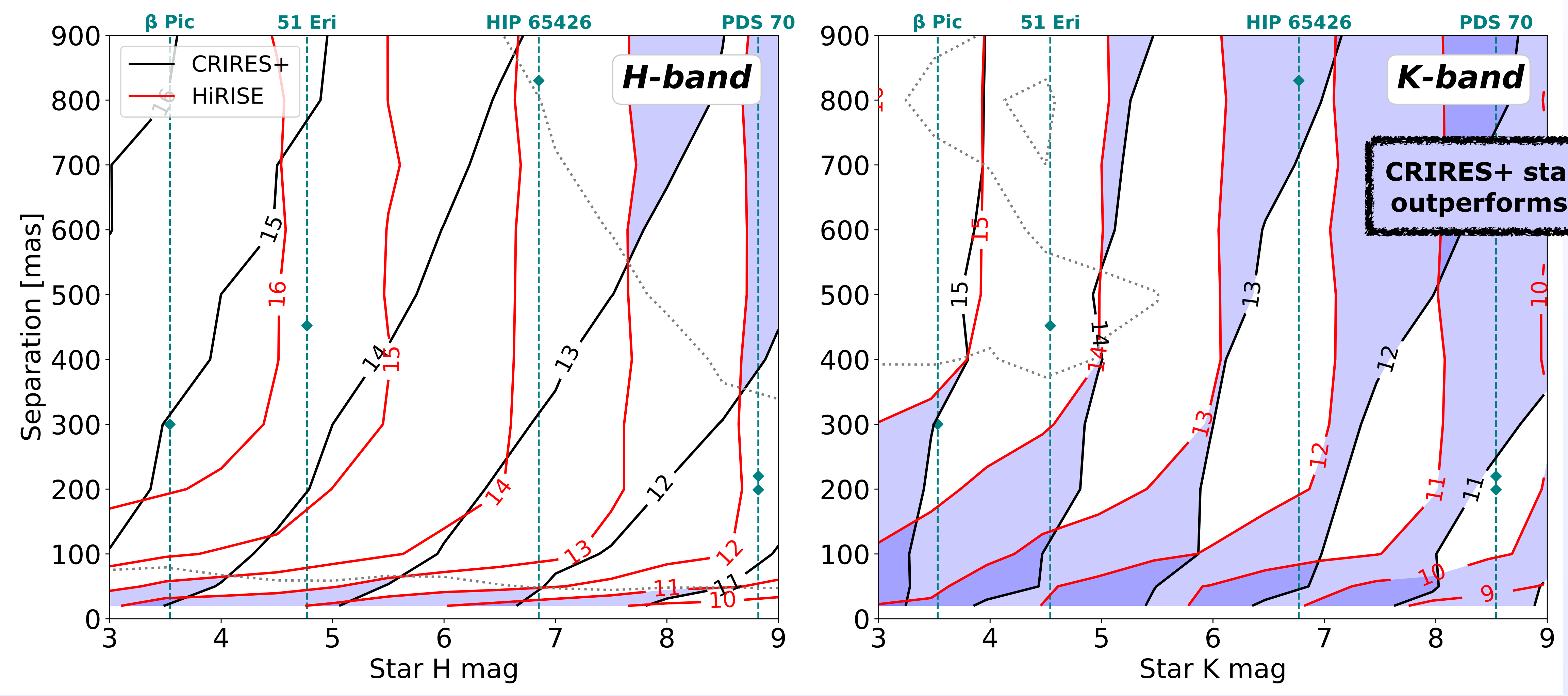


Performance analysis

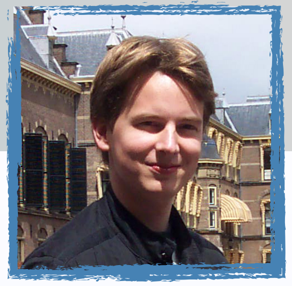


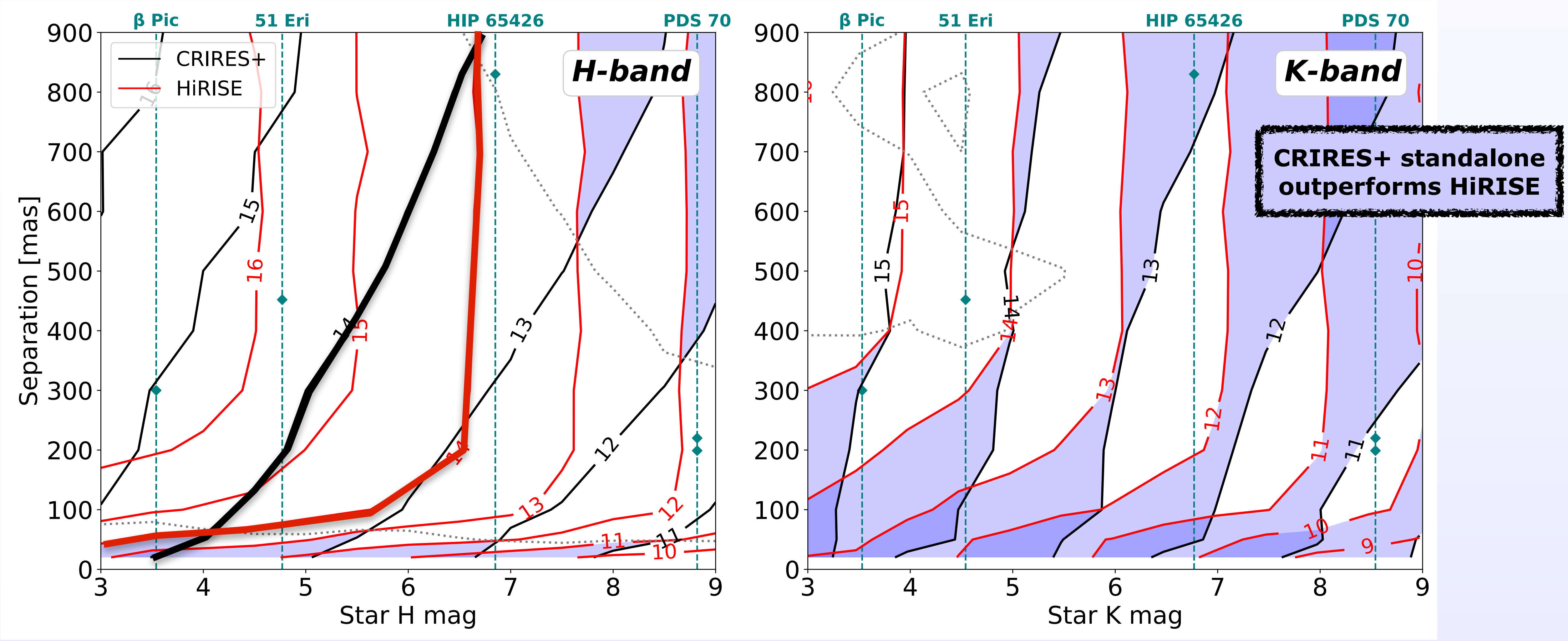


CRIRES+ standalone outperforms HiRISE

Otten et al. (2021)

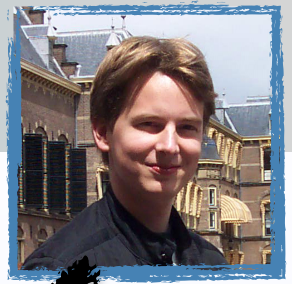
Performance analysis

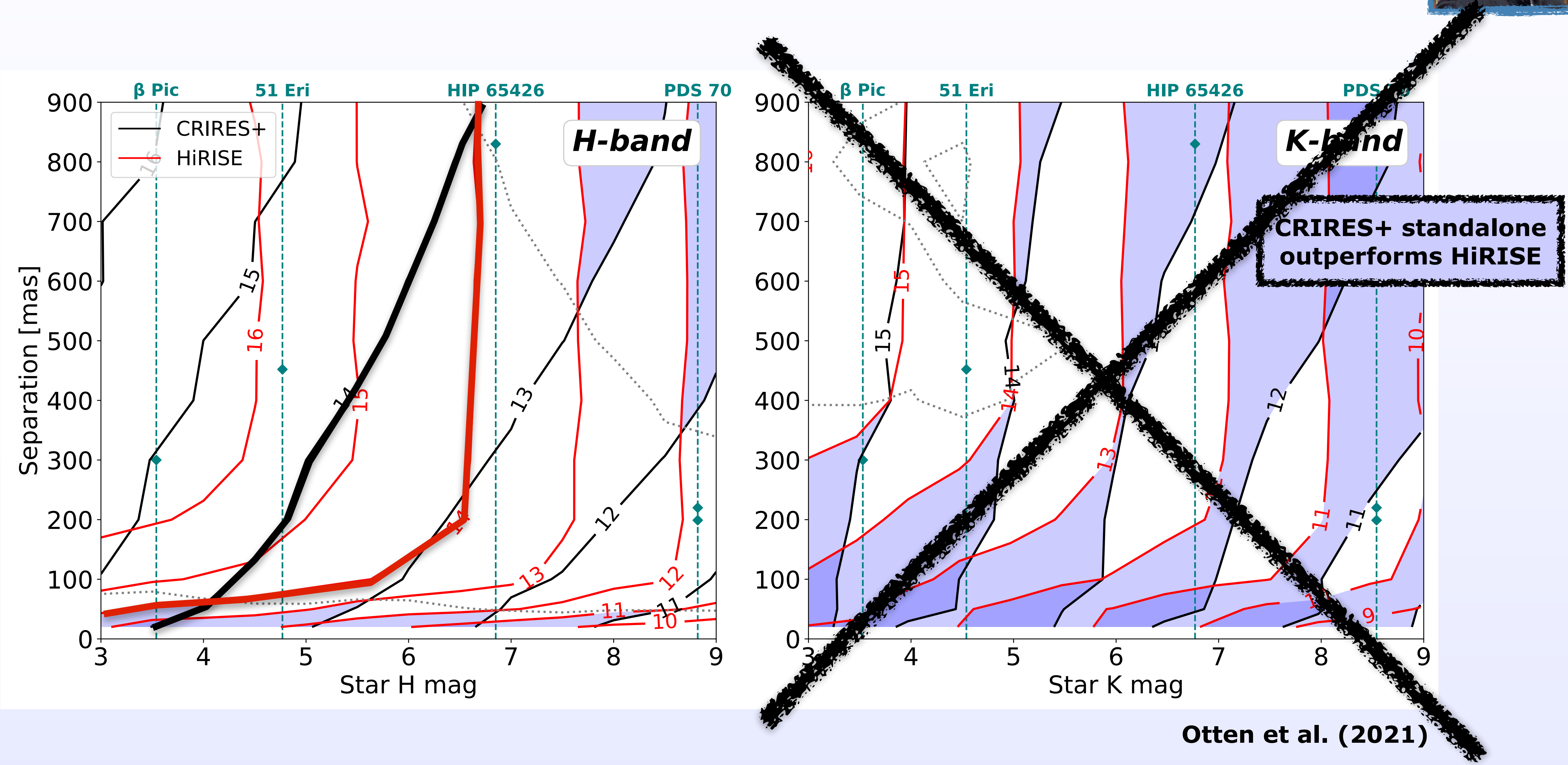




Otten et al. (2021)

Performance analysis

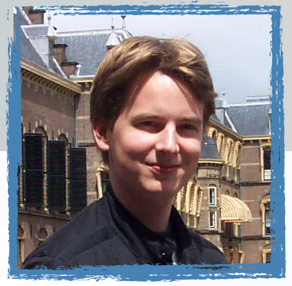


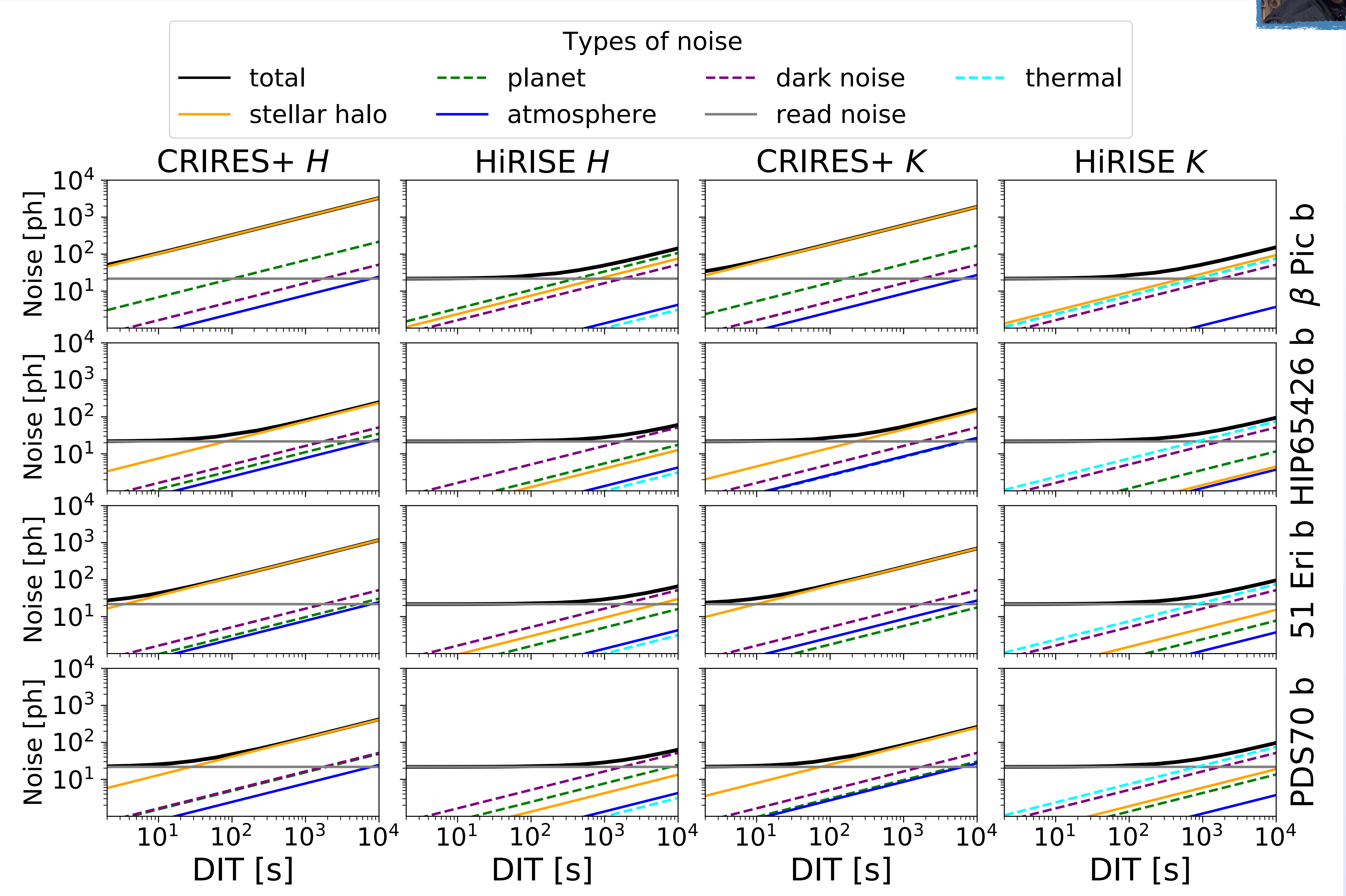


Otten et al. (2021)

It is worth it in the H band!

Performance analysis





Otten et al. (2021)

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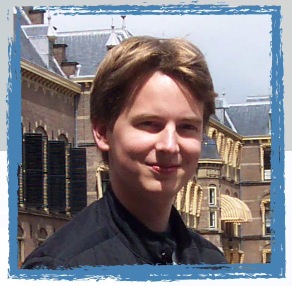

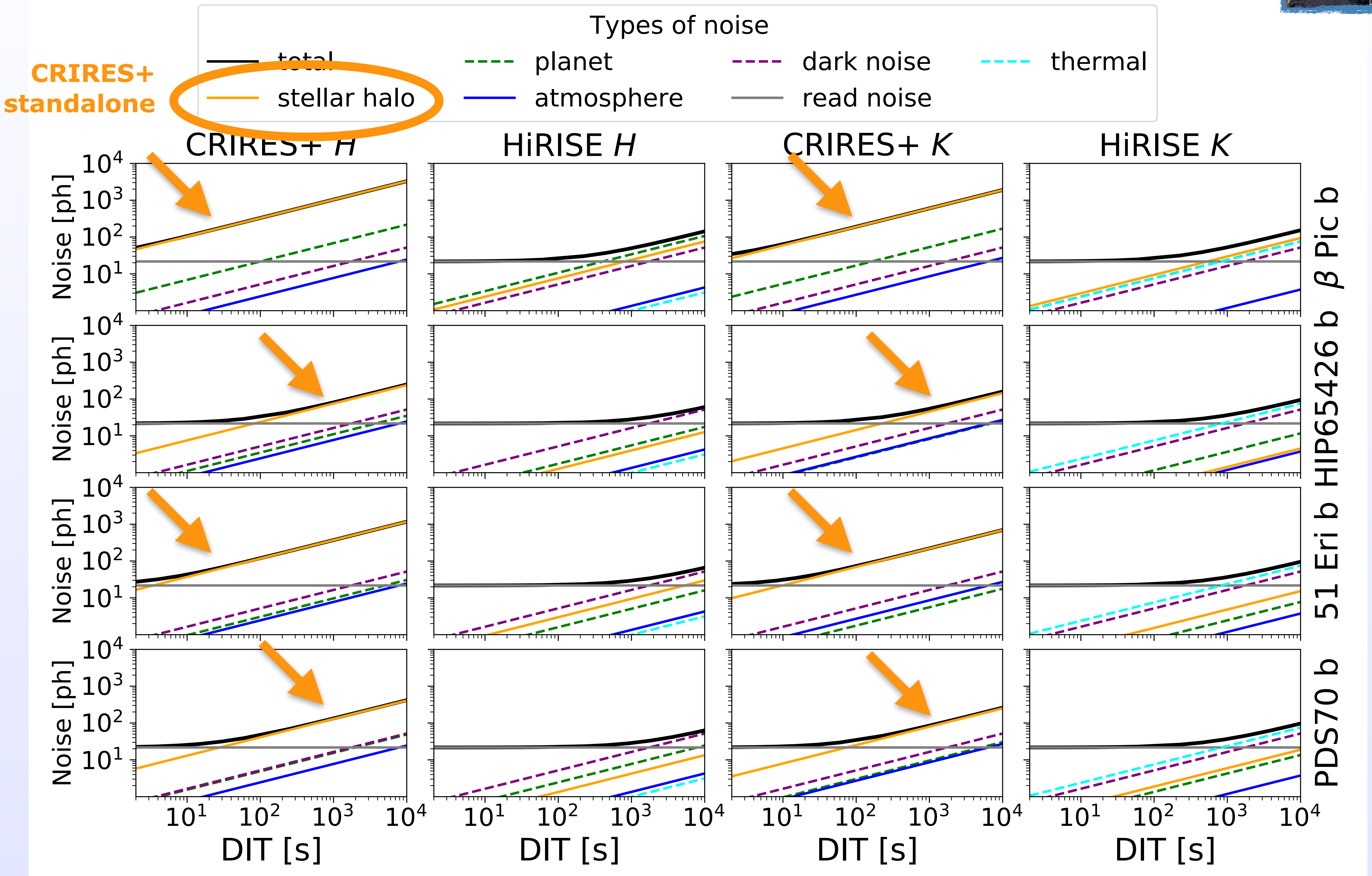

Otten et al. (2021)

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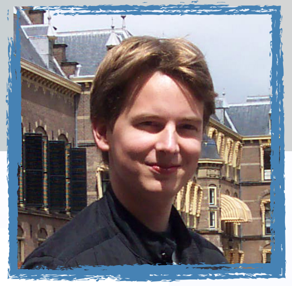

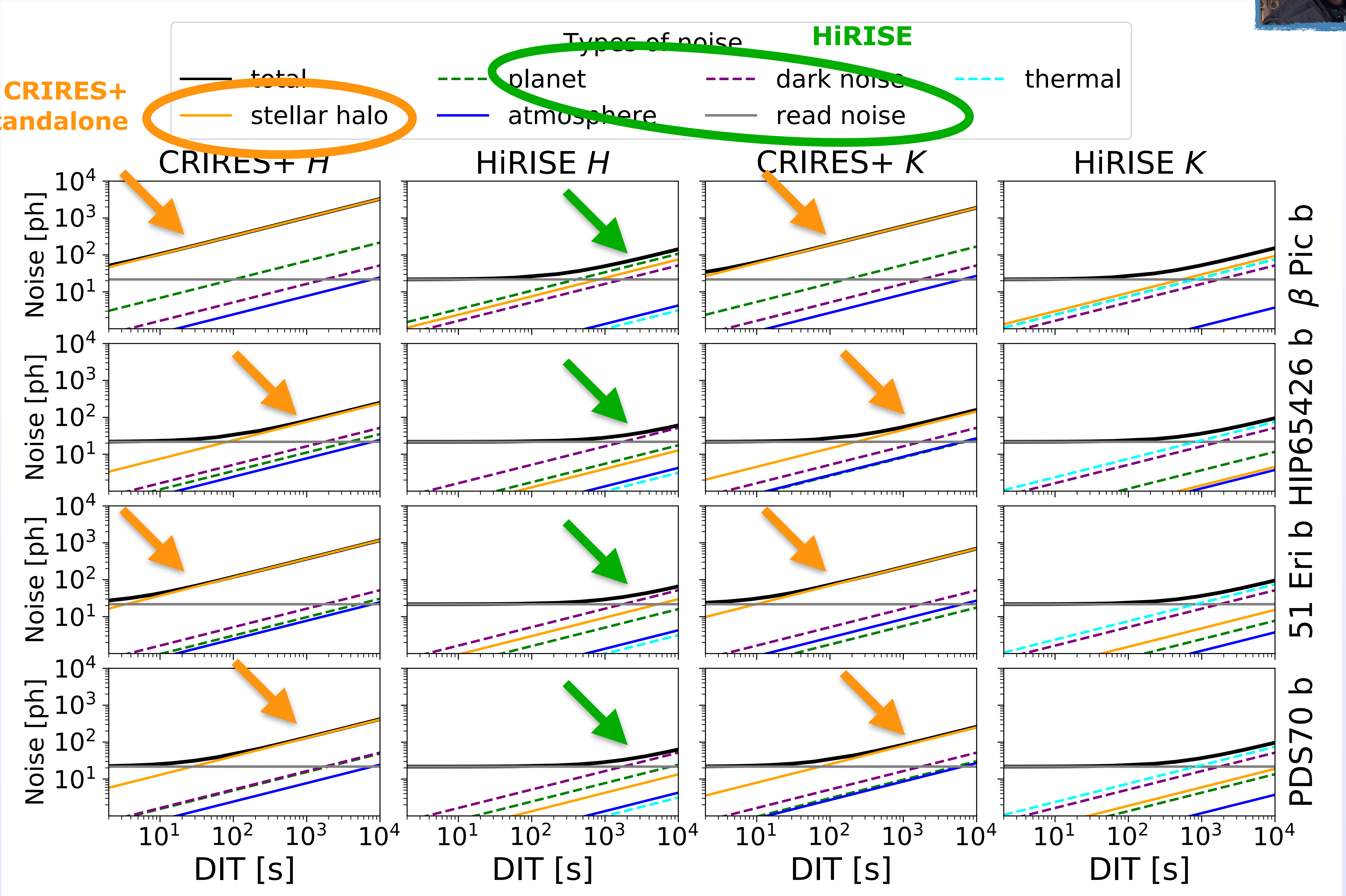

Otten et al. (2021)

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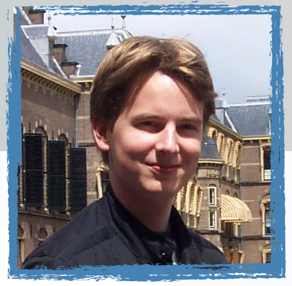
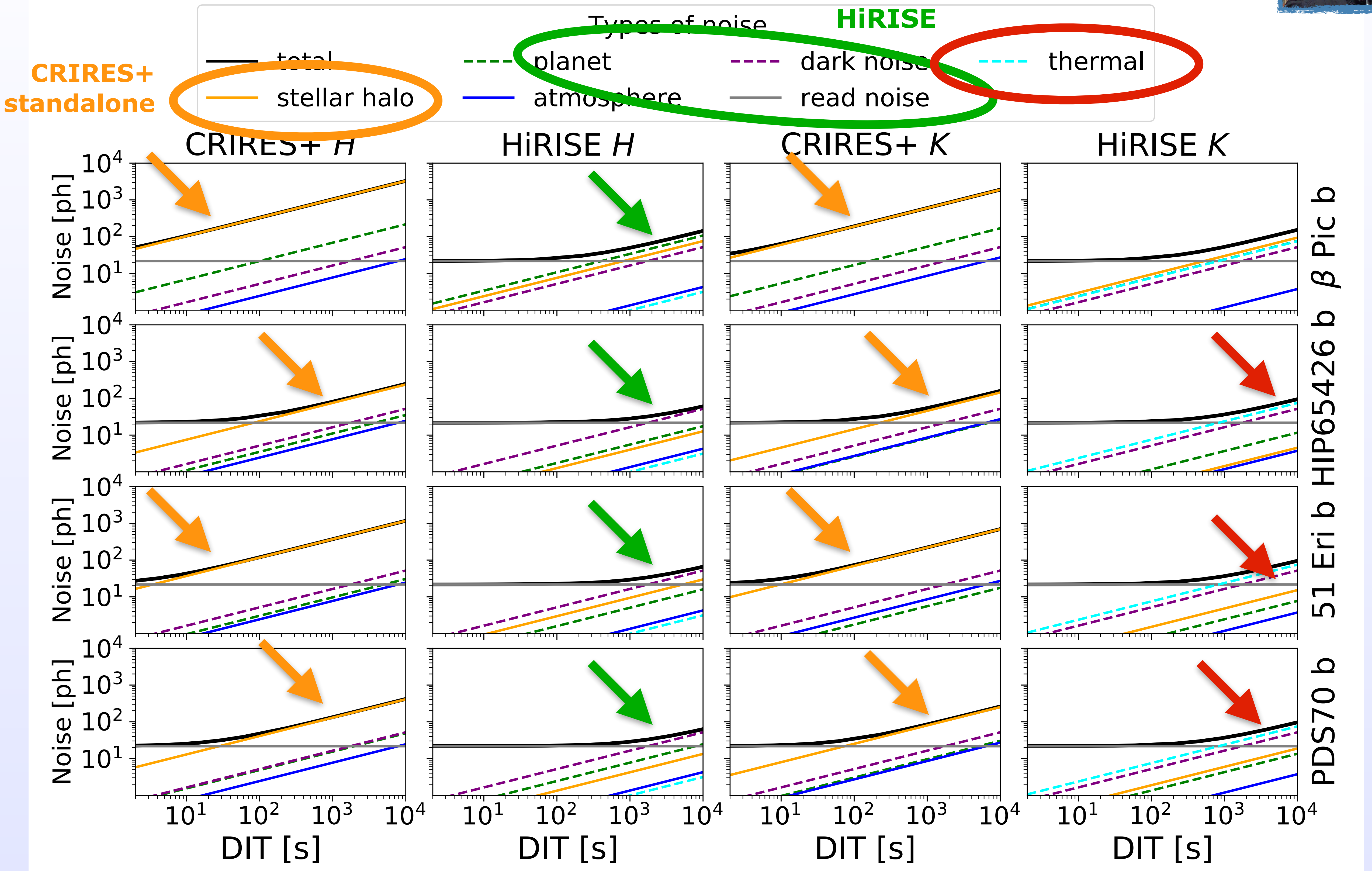
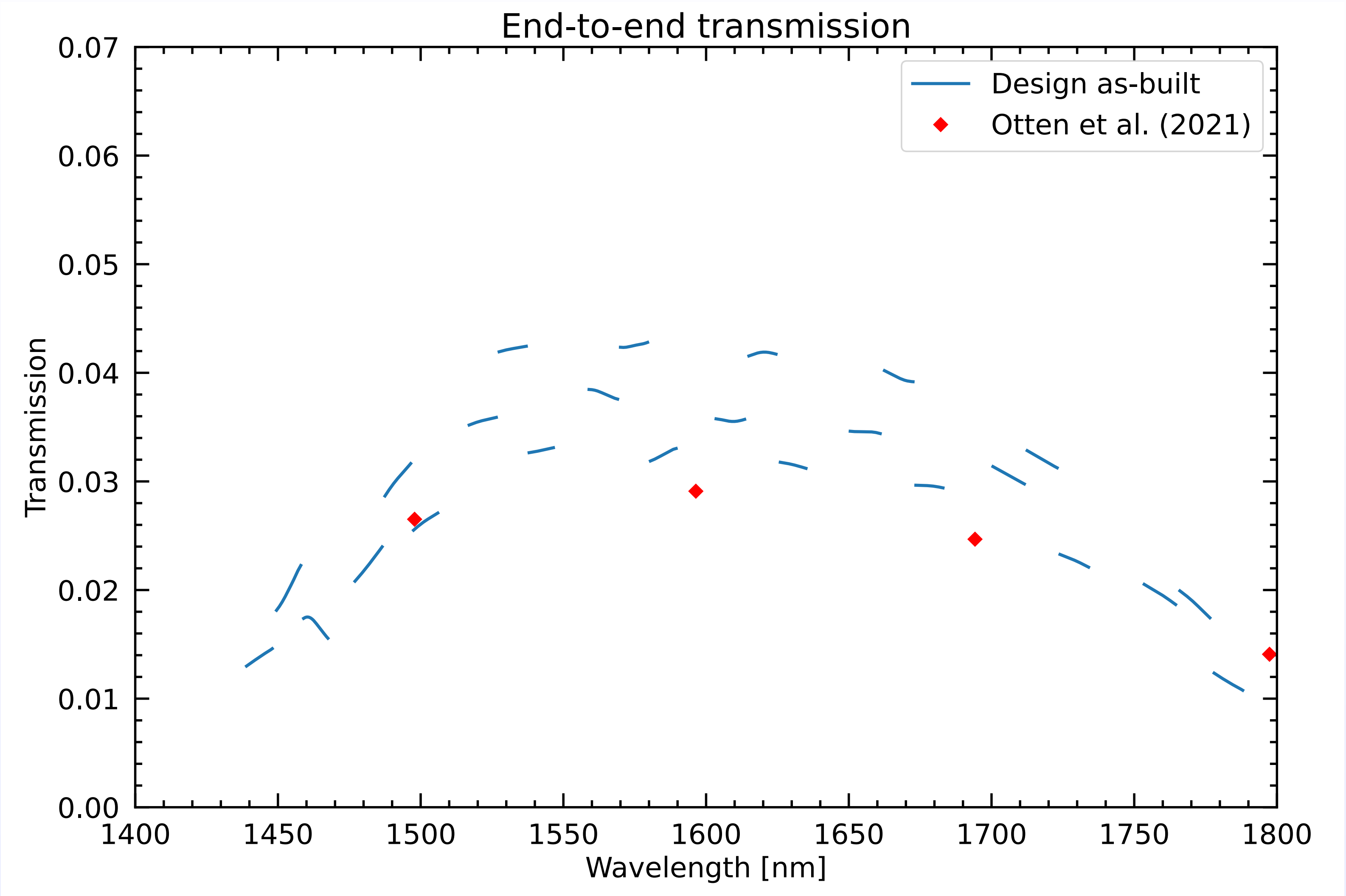




Otten et al. (2021)

Transmission budget



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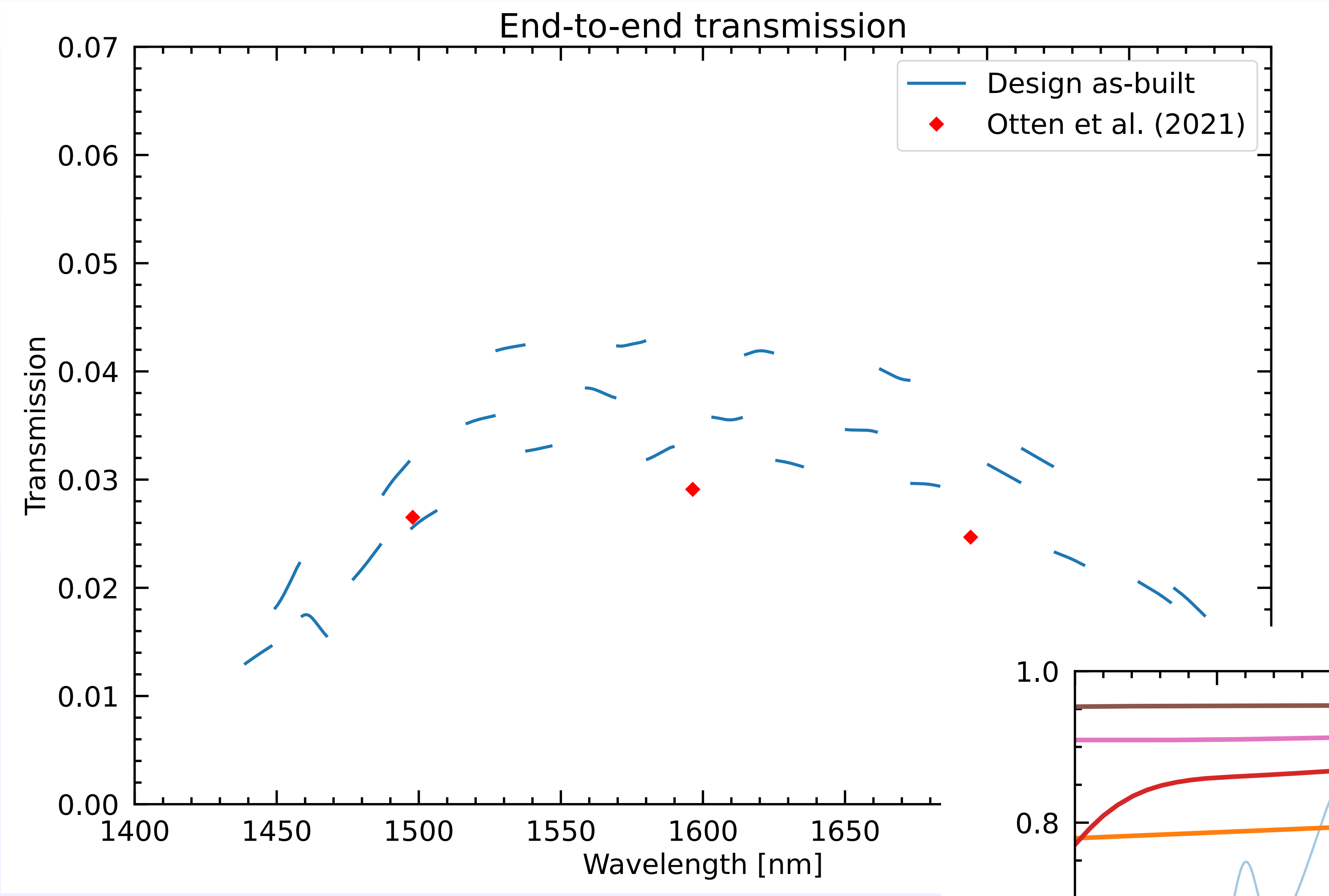

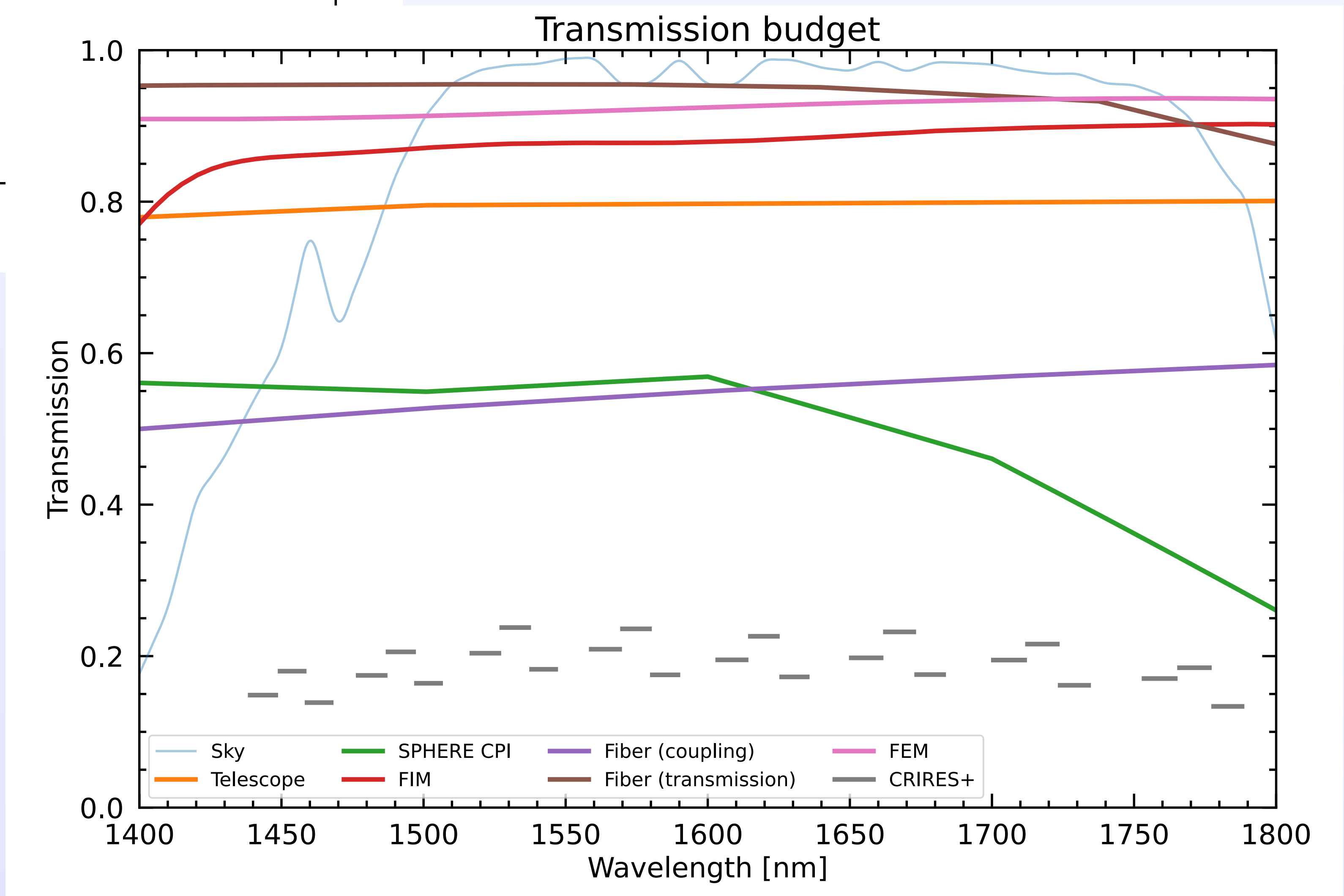

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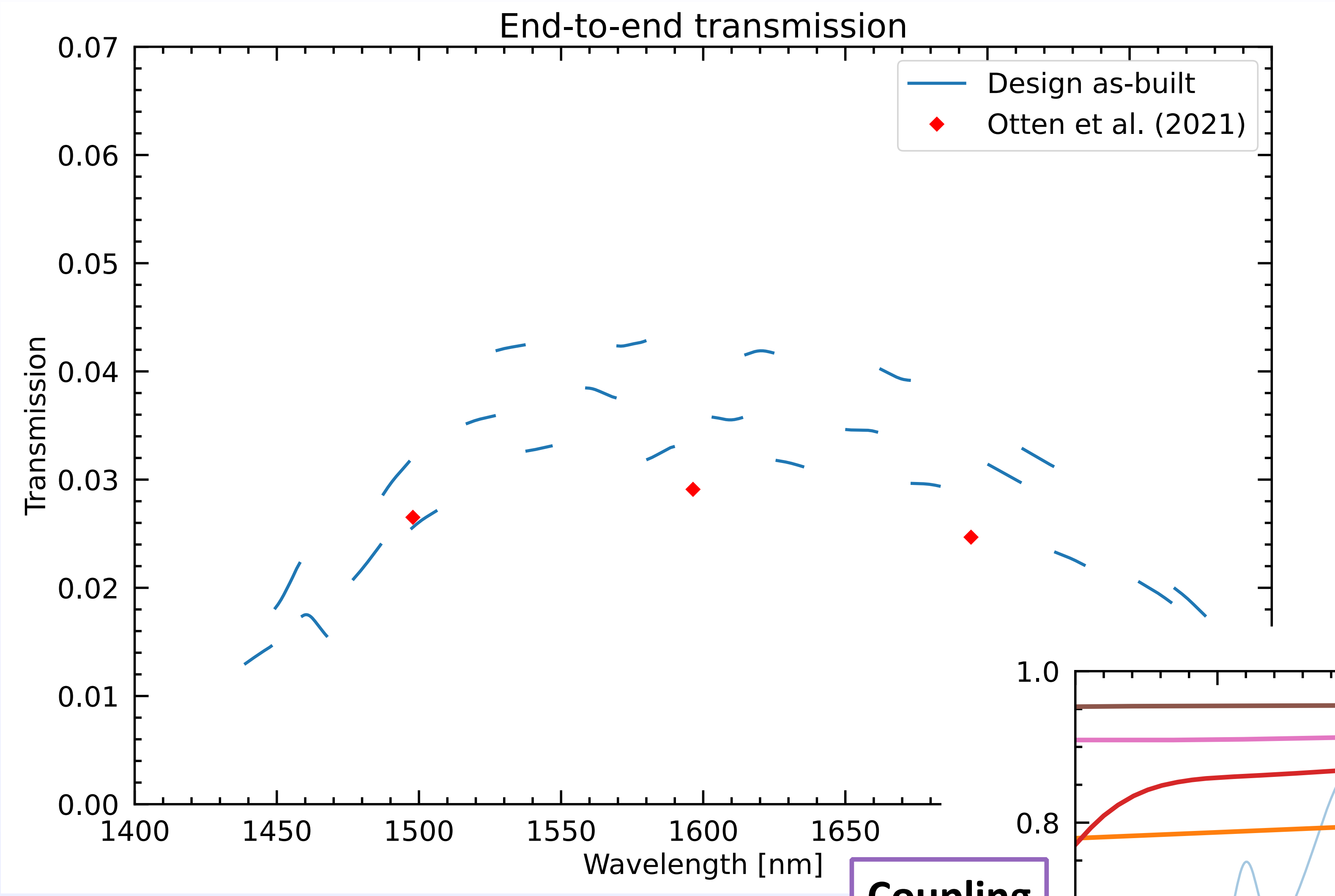
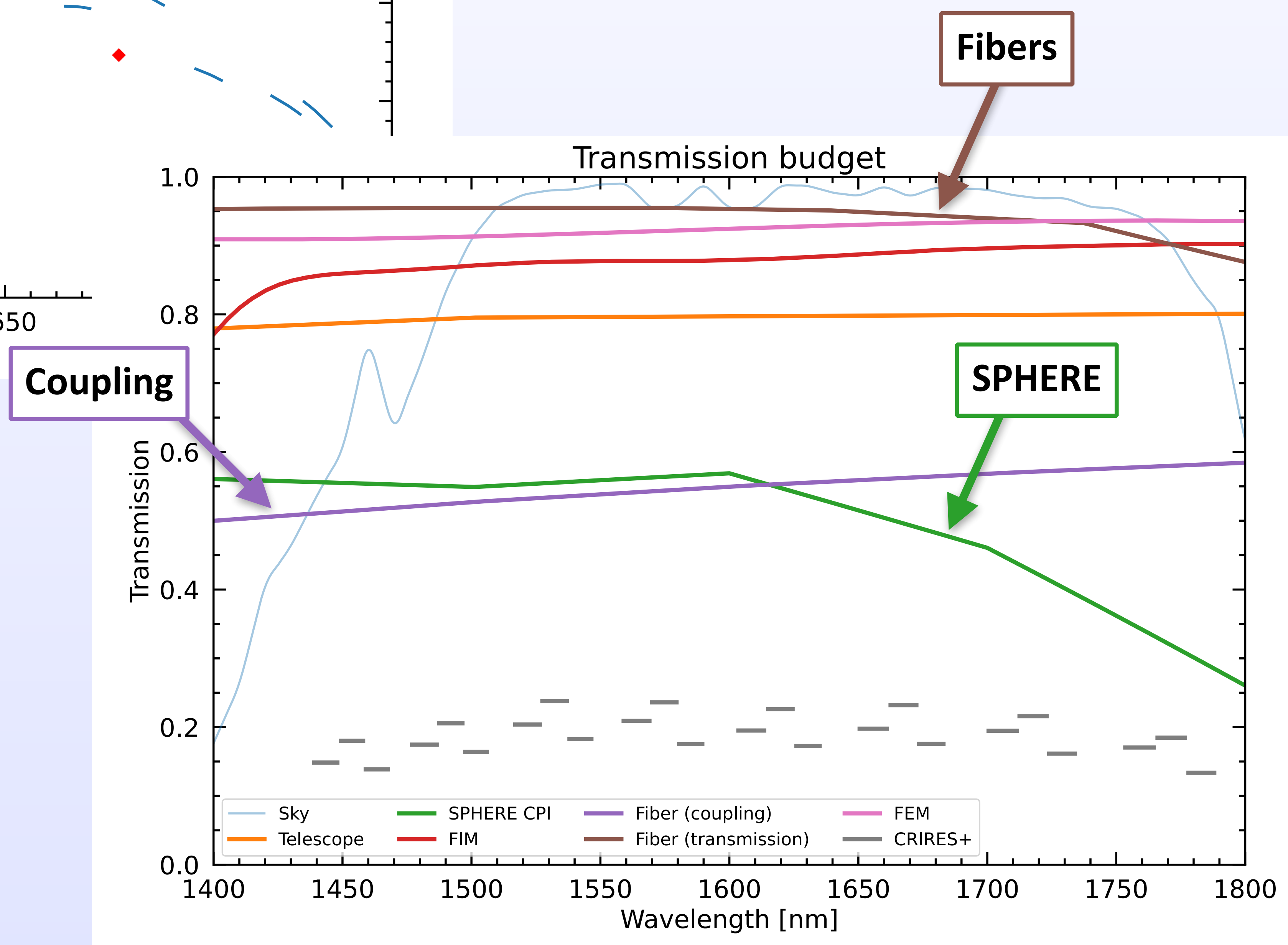
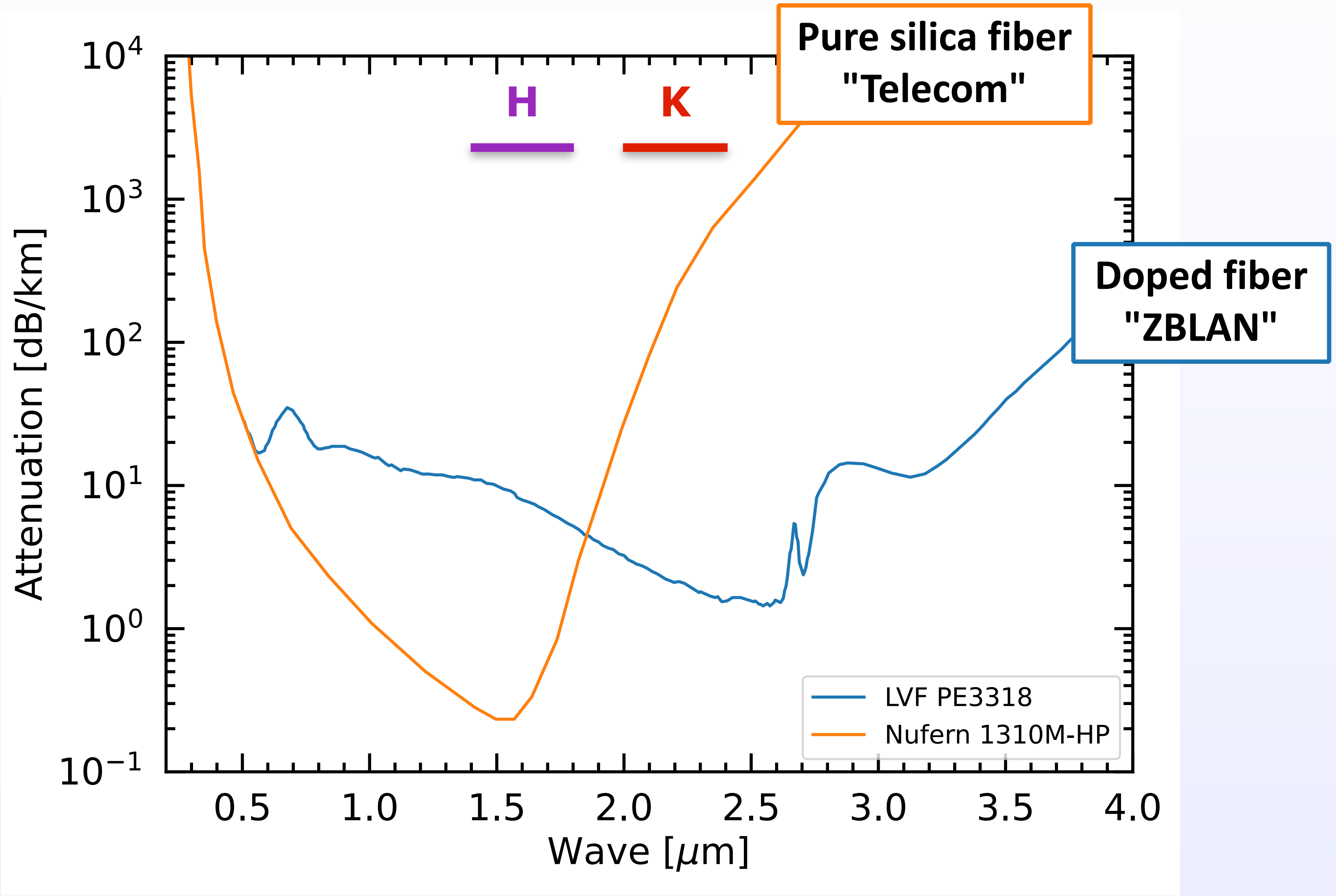


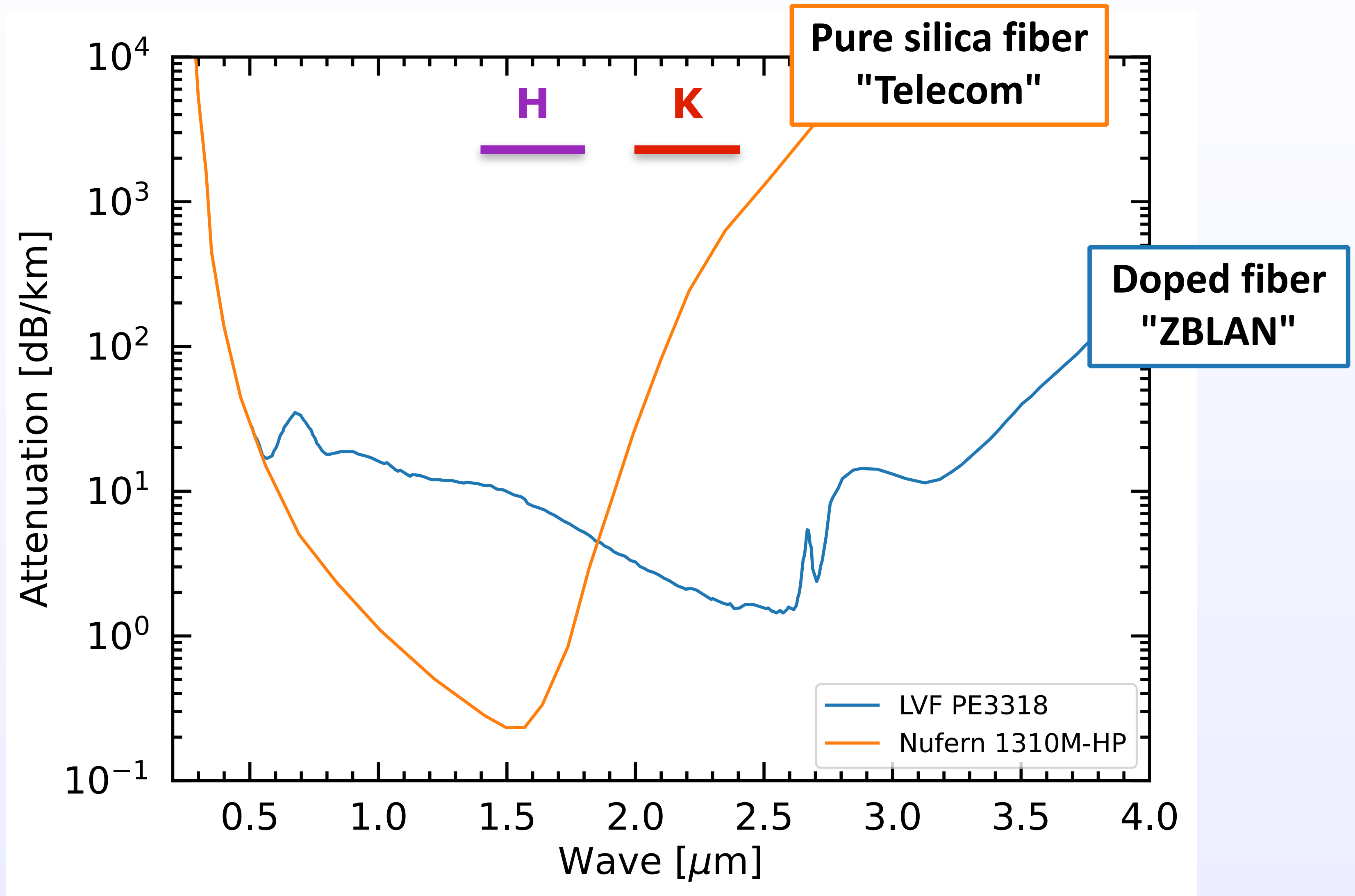


Choice of optical fiber



	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

Choice of optical fiber

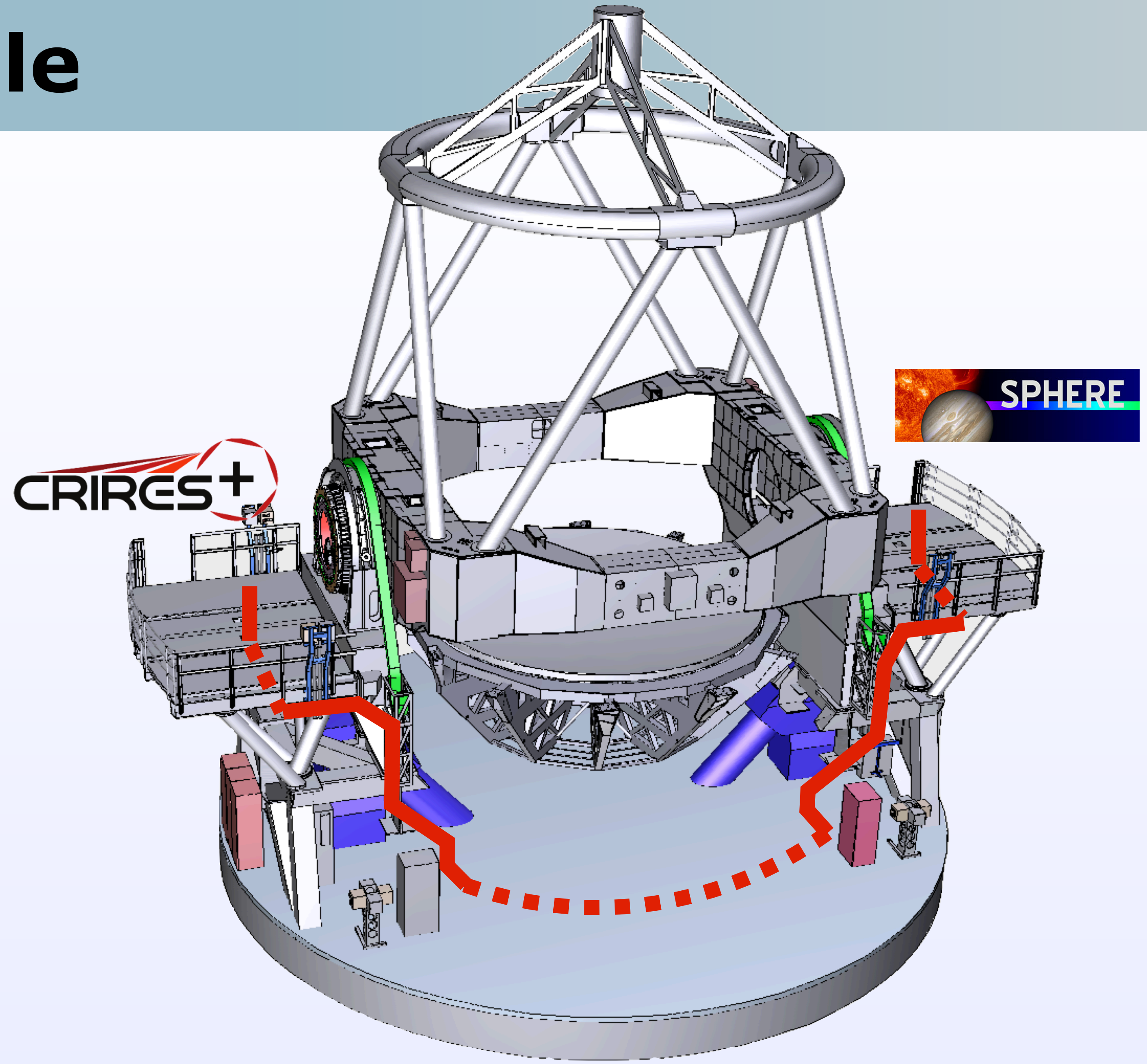


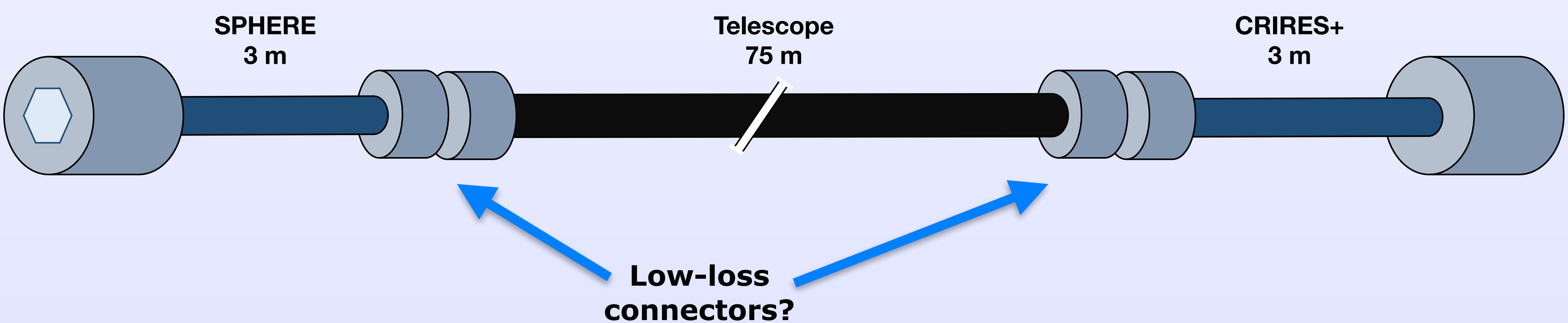
	Advantages	Drawbacks
ZBLAN	Transmission in K band	(Supposedly) fragile Very expensive (~100 €/m) Transmission in H ba…
Telecom	Transmission in H band Extremely cheap (~1 €/m)	Transmission in …

Final choice: Telecom fiber

Fiber bundle

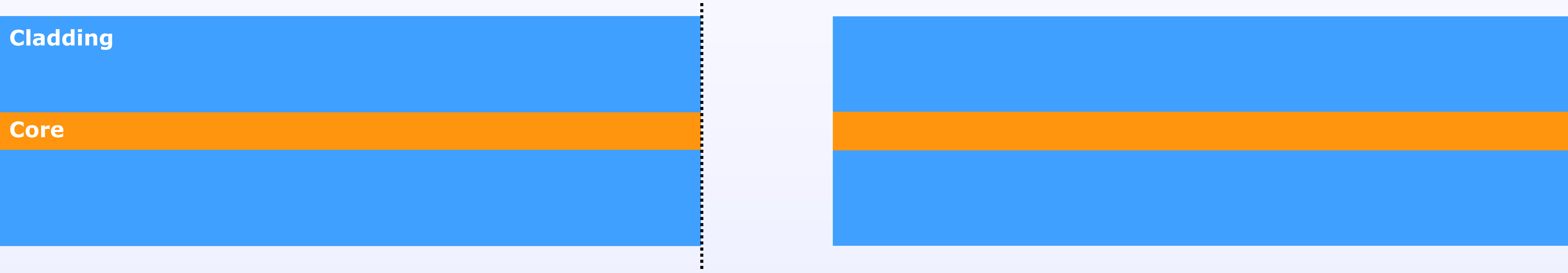
Fibers





Low-loss connectors

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



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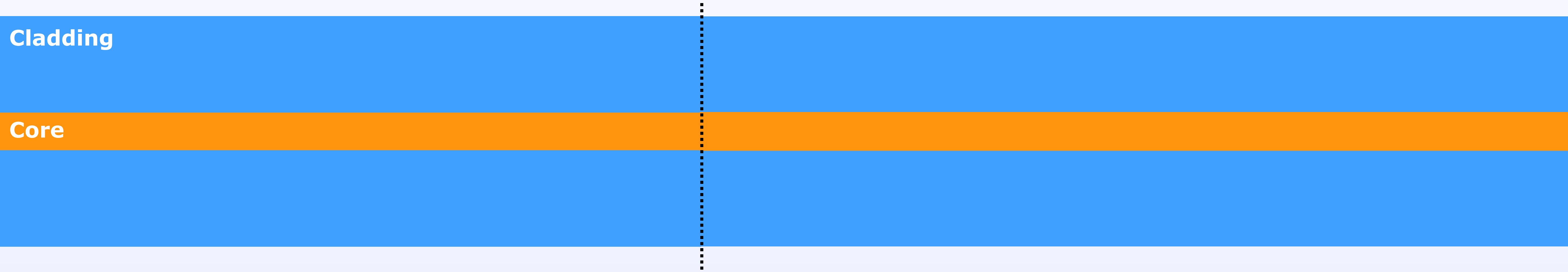

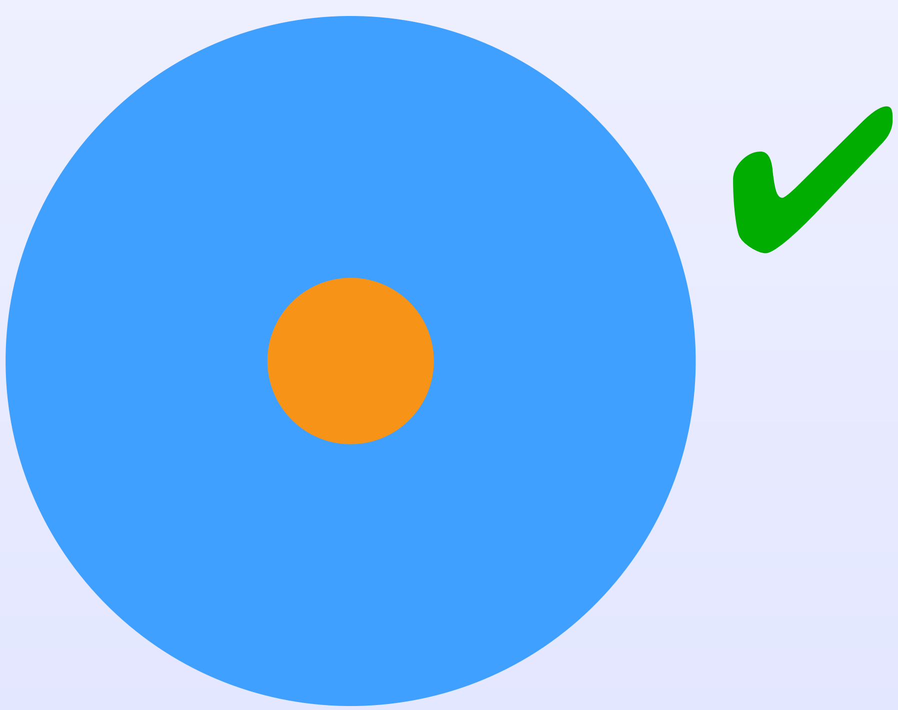

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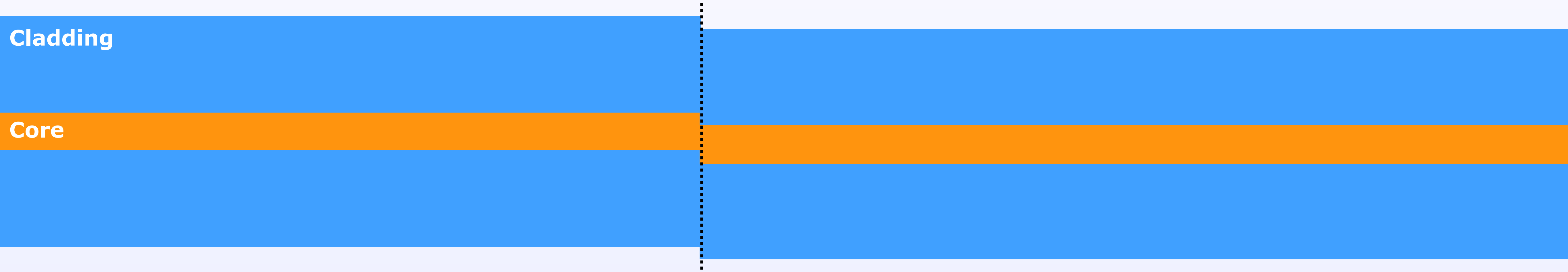

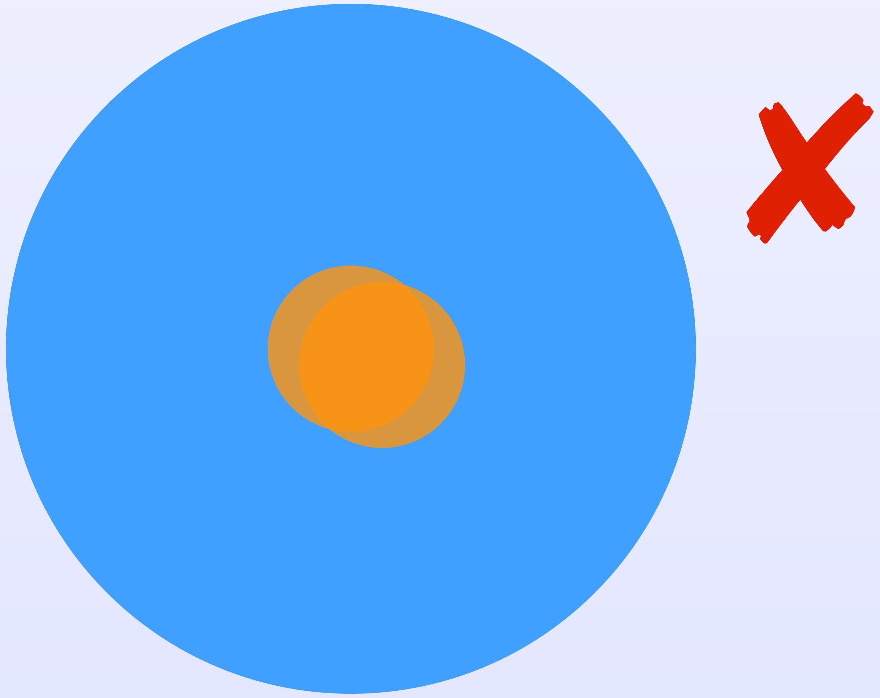

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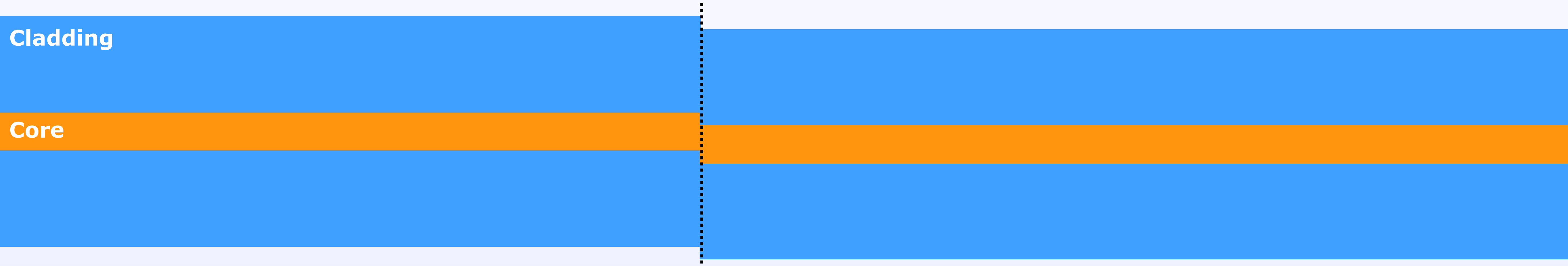
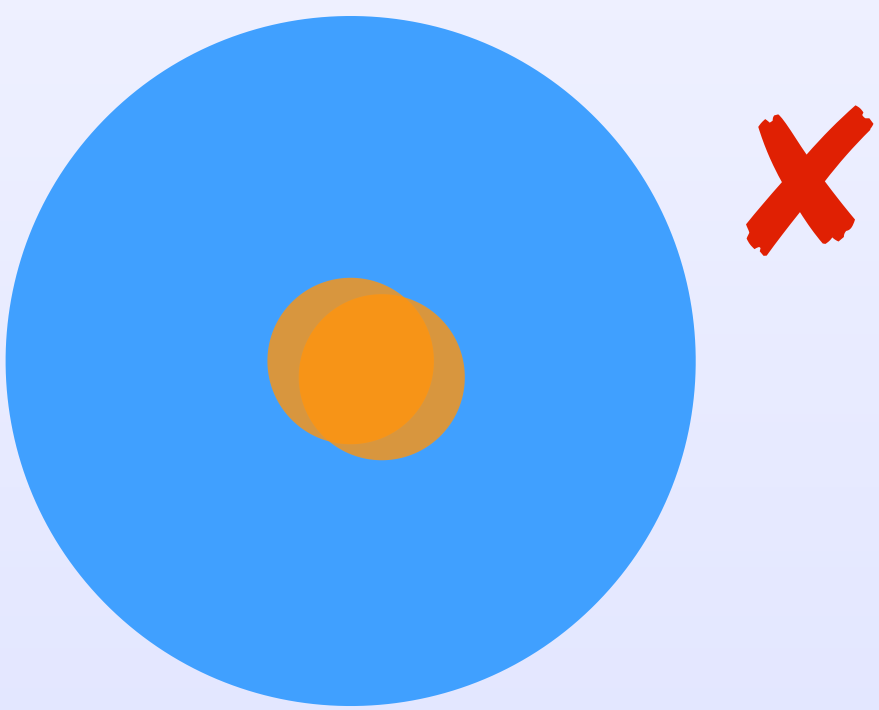
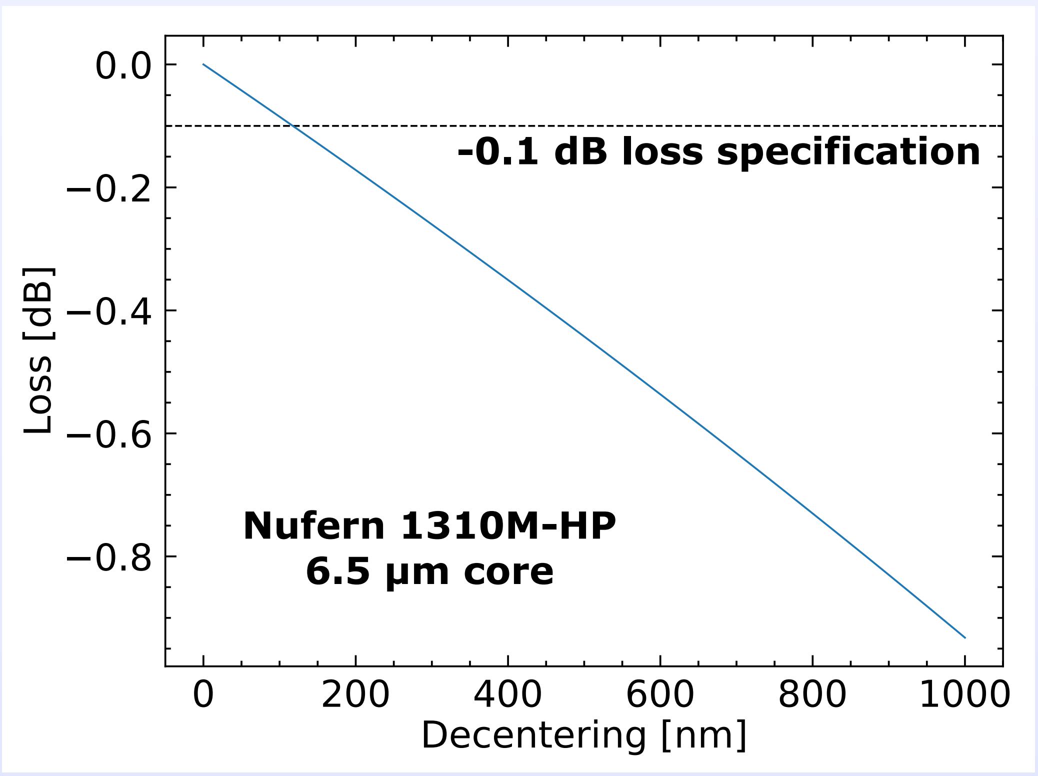


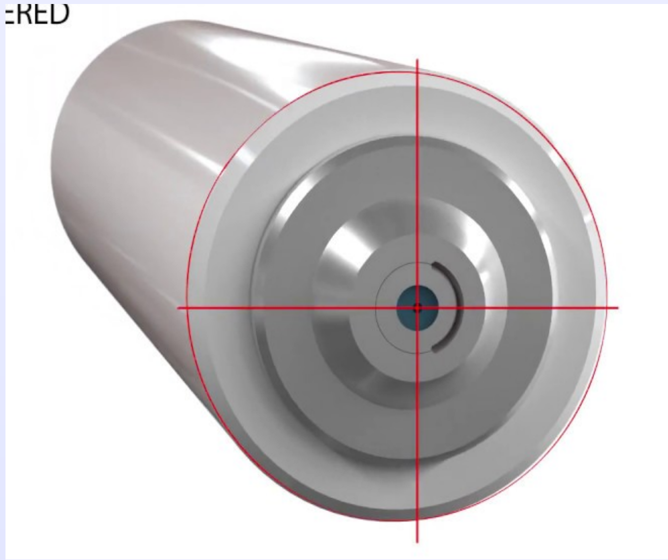




Low-loss connectors

- 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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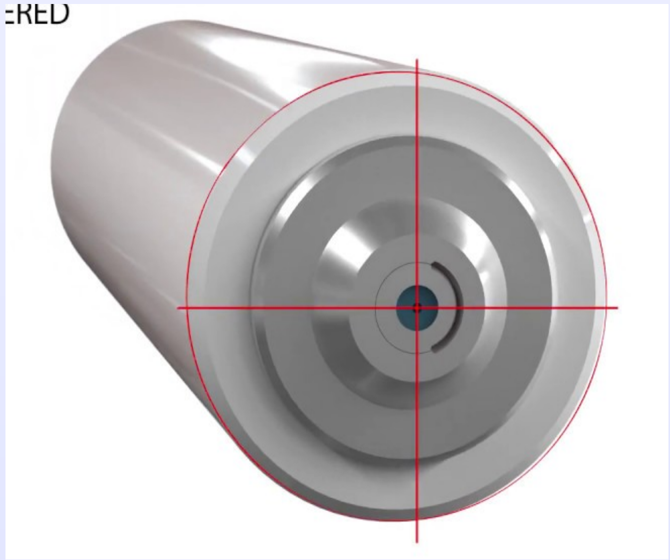
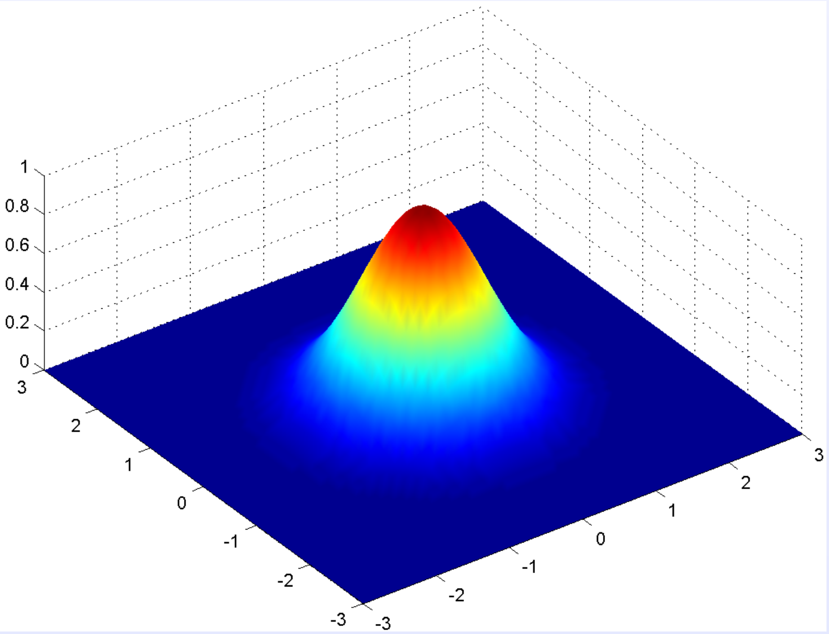


Final choice:
No connectors

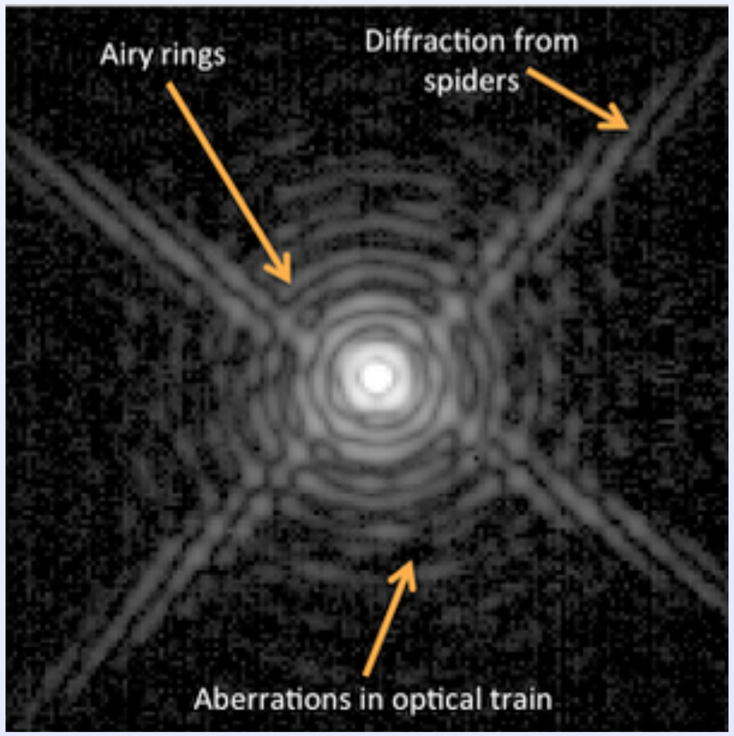
Single-mode fiber coupling

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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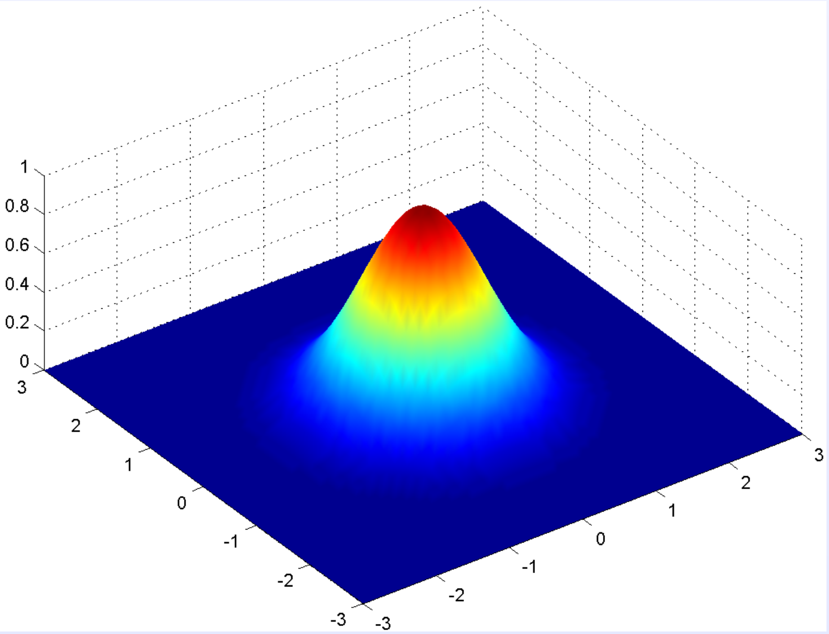

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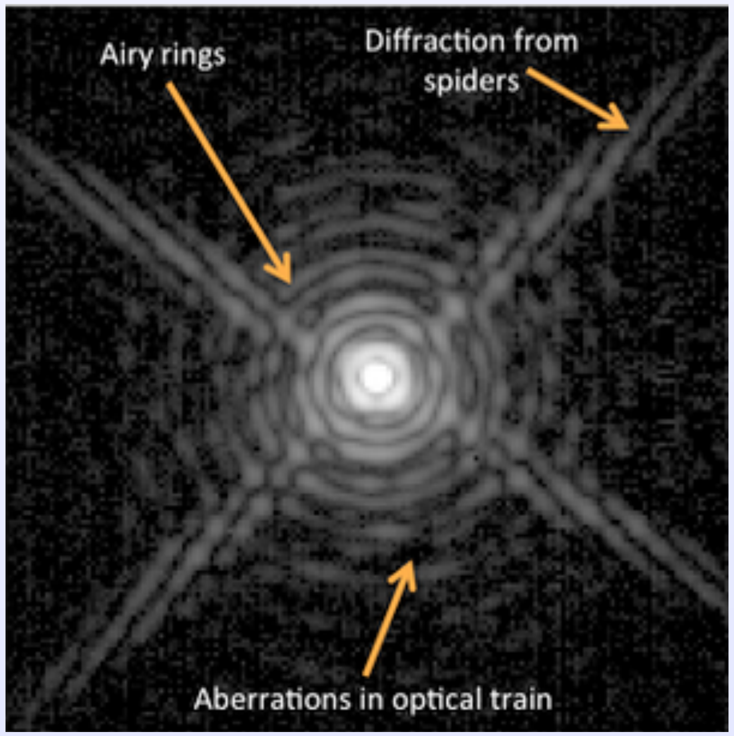

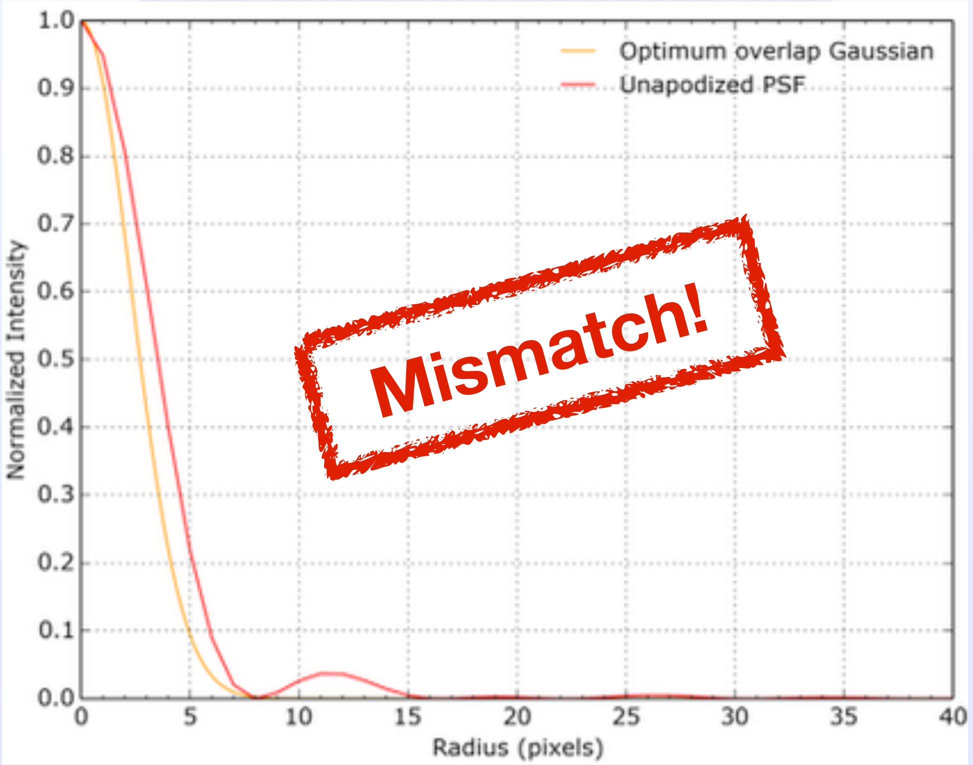

Jovanovic et al. (2017)

Single-mode fiber coupling

Coupling

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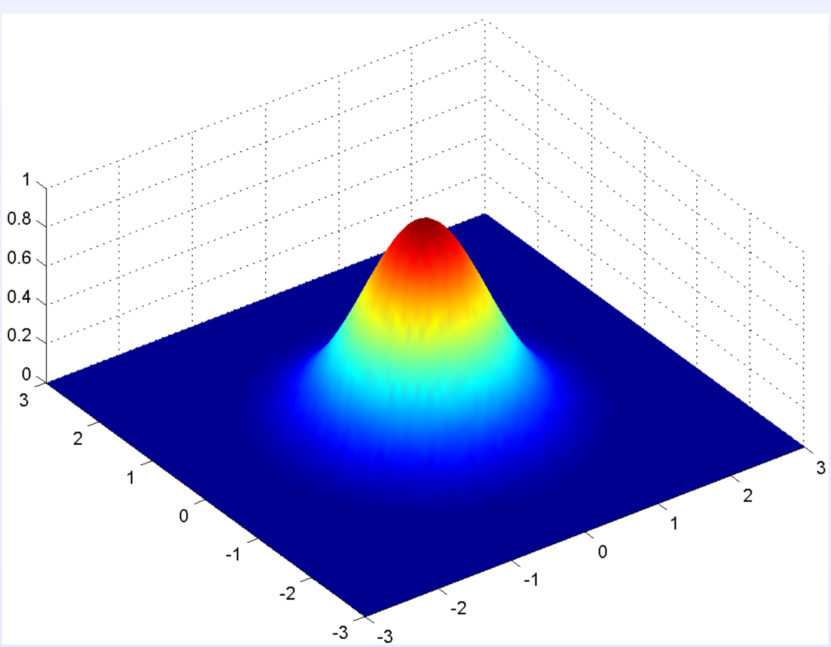
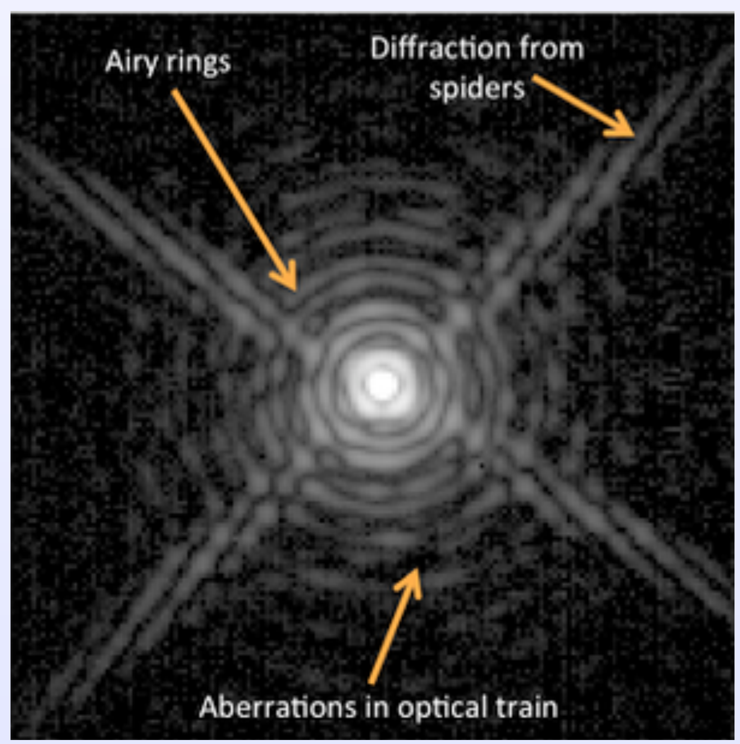
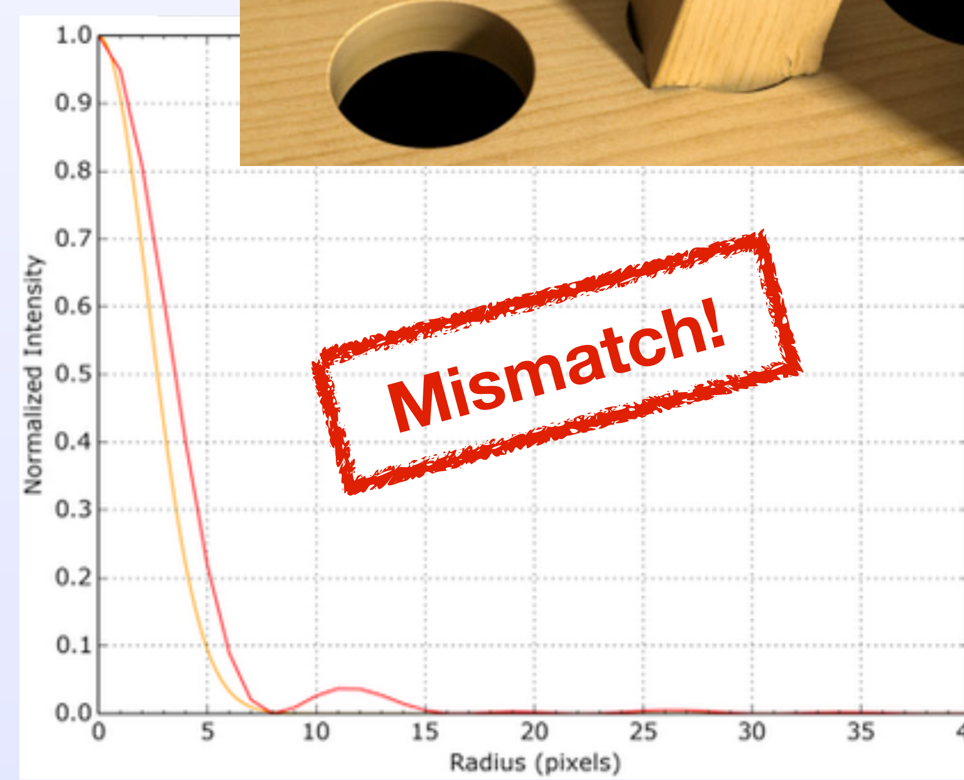


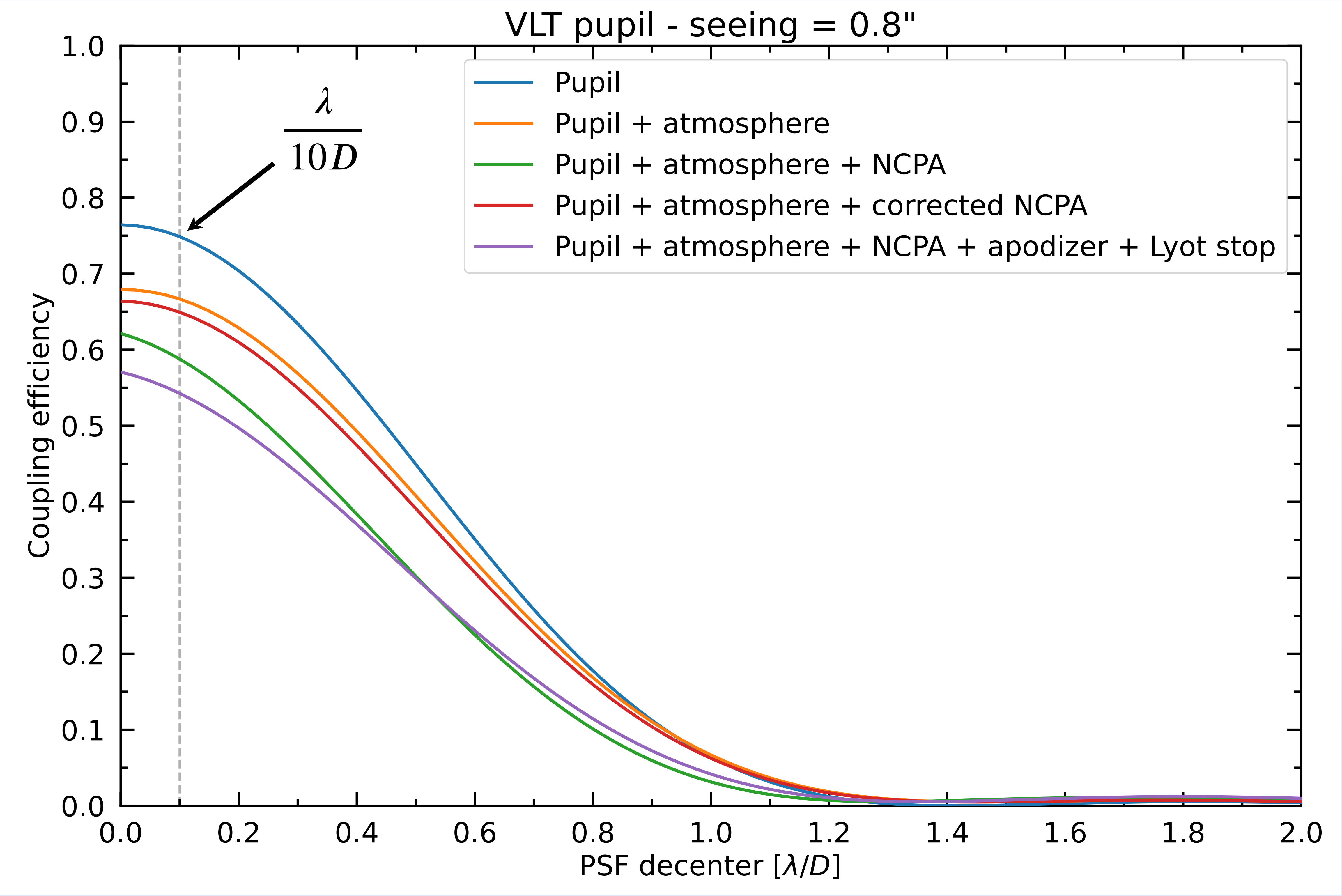




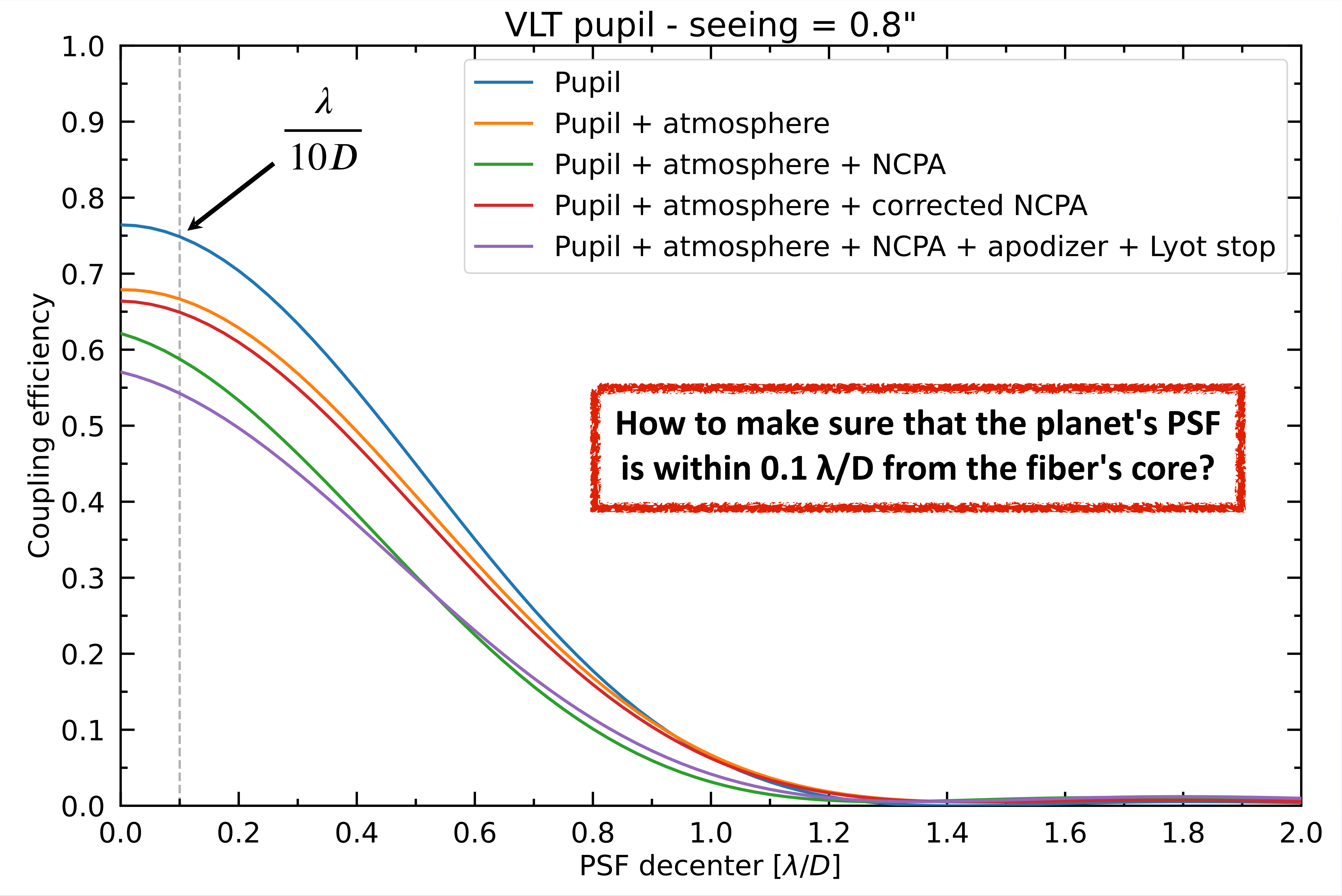
Jovanovic et al. (2017)

Coupling vs. PSF centering

Coupling

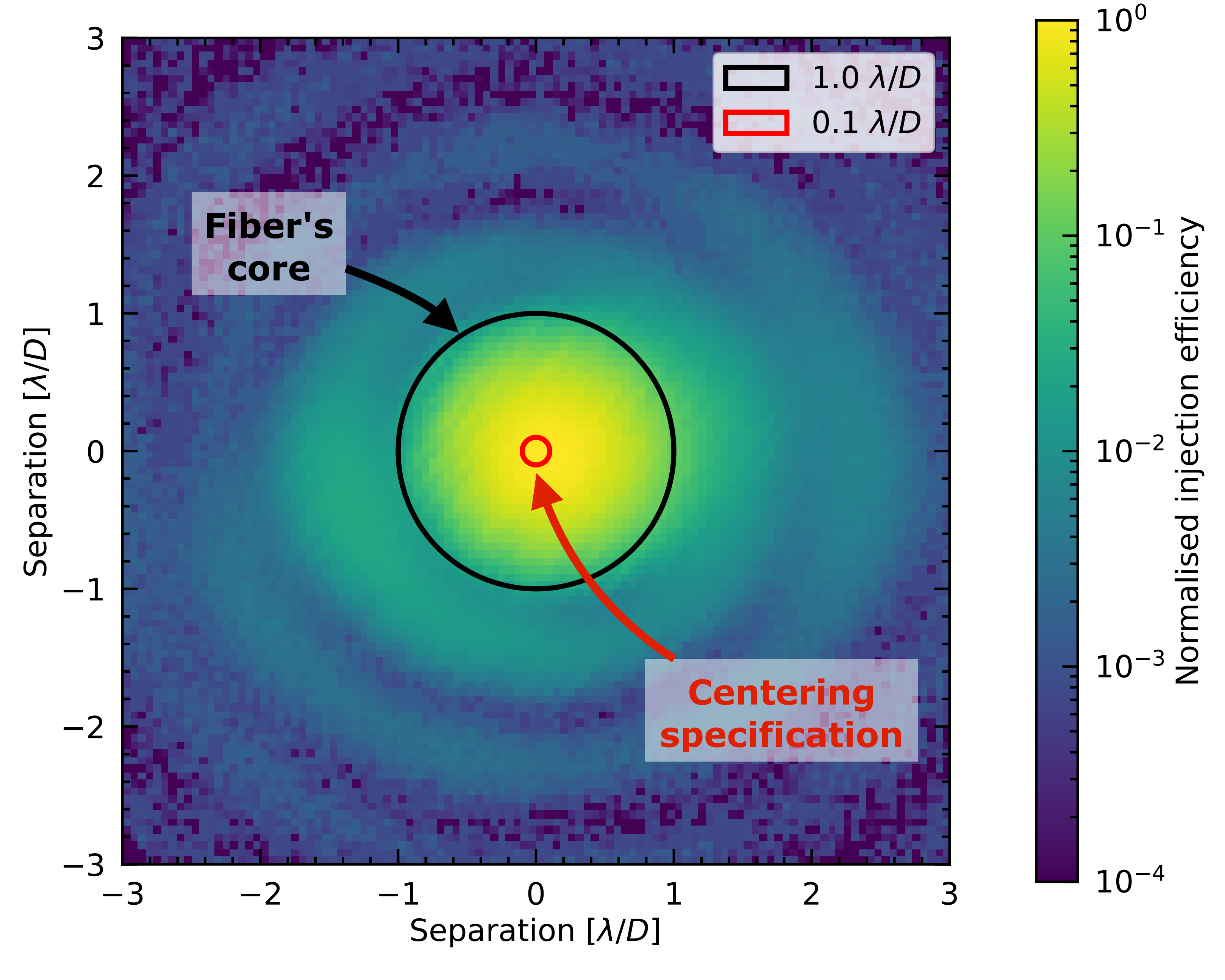


Coupling vs. PSF centering



PSF centering: an operational challenge

Coupling



PSF centering: an operational challenge

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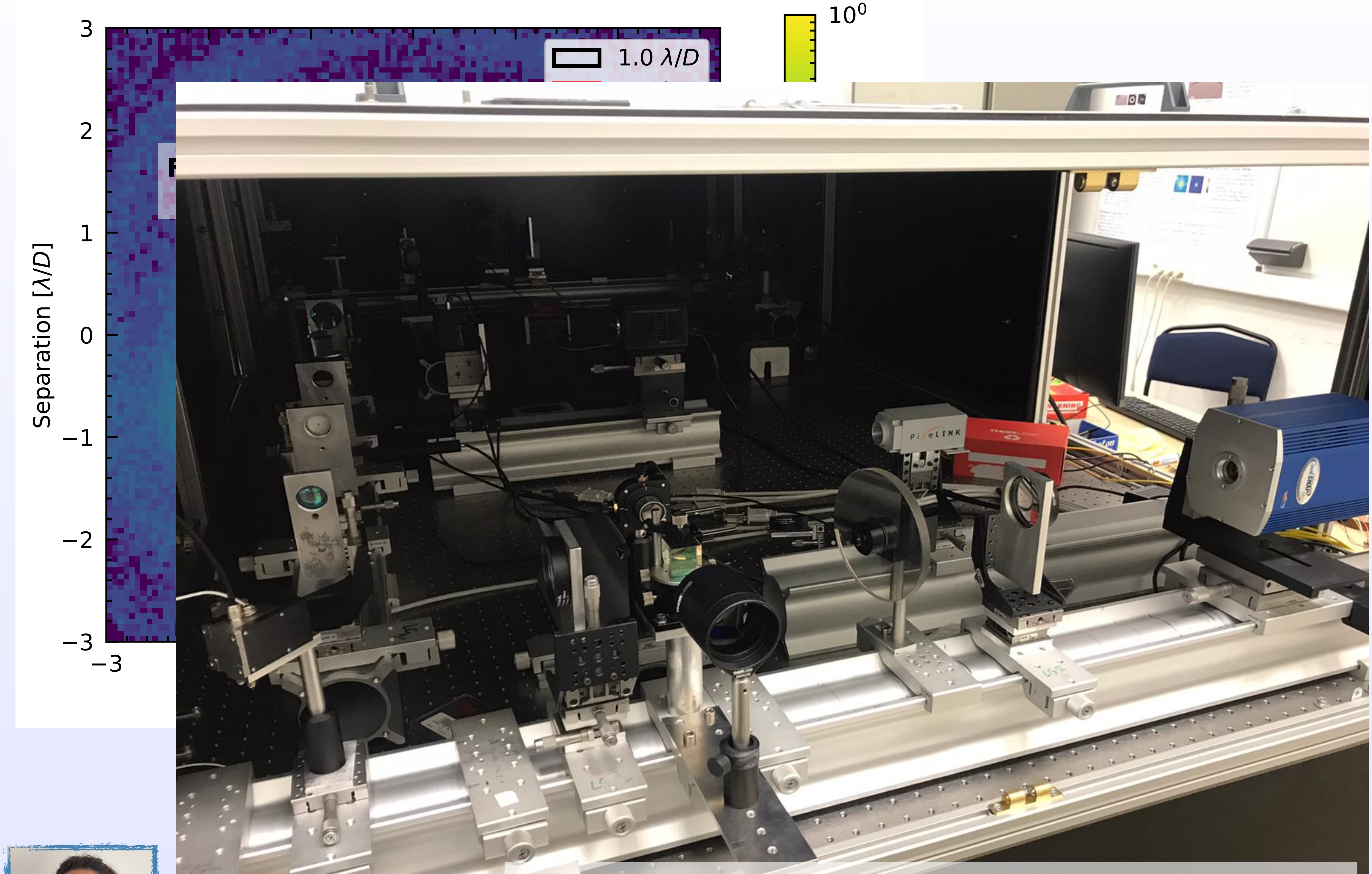
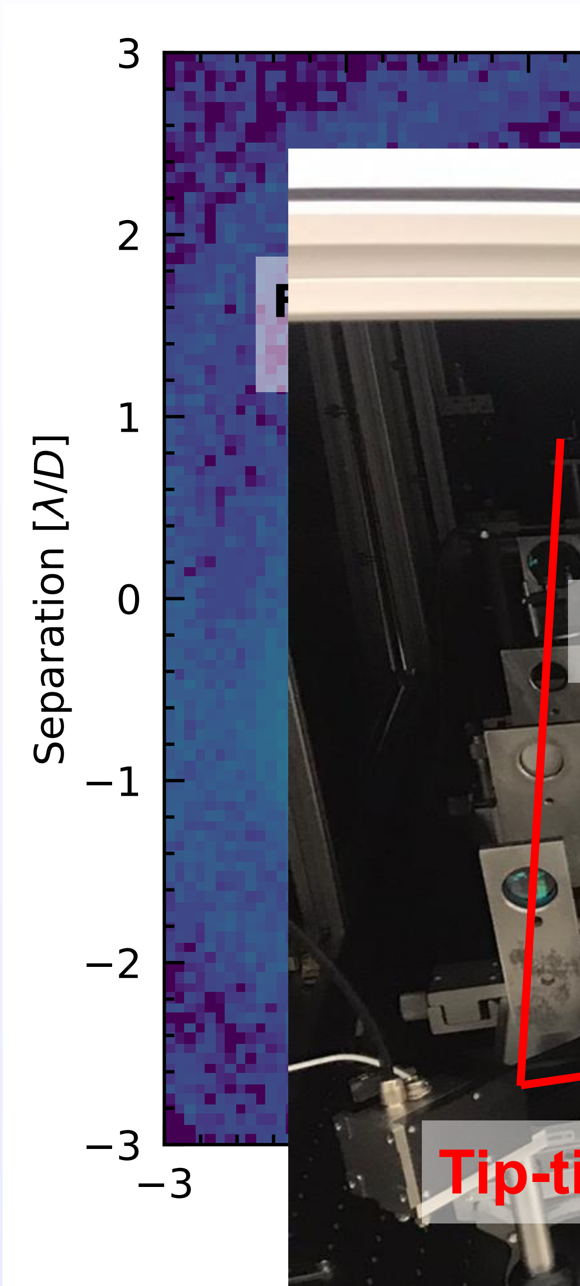
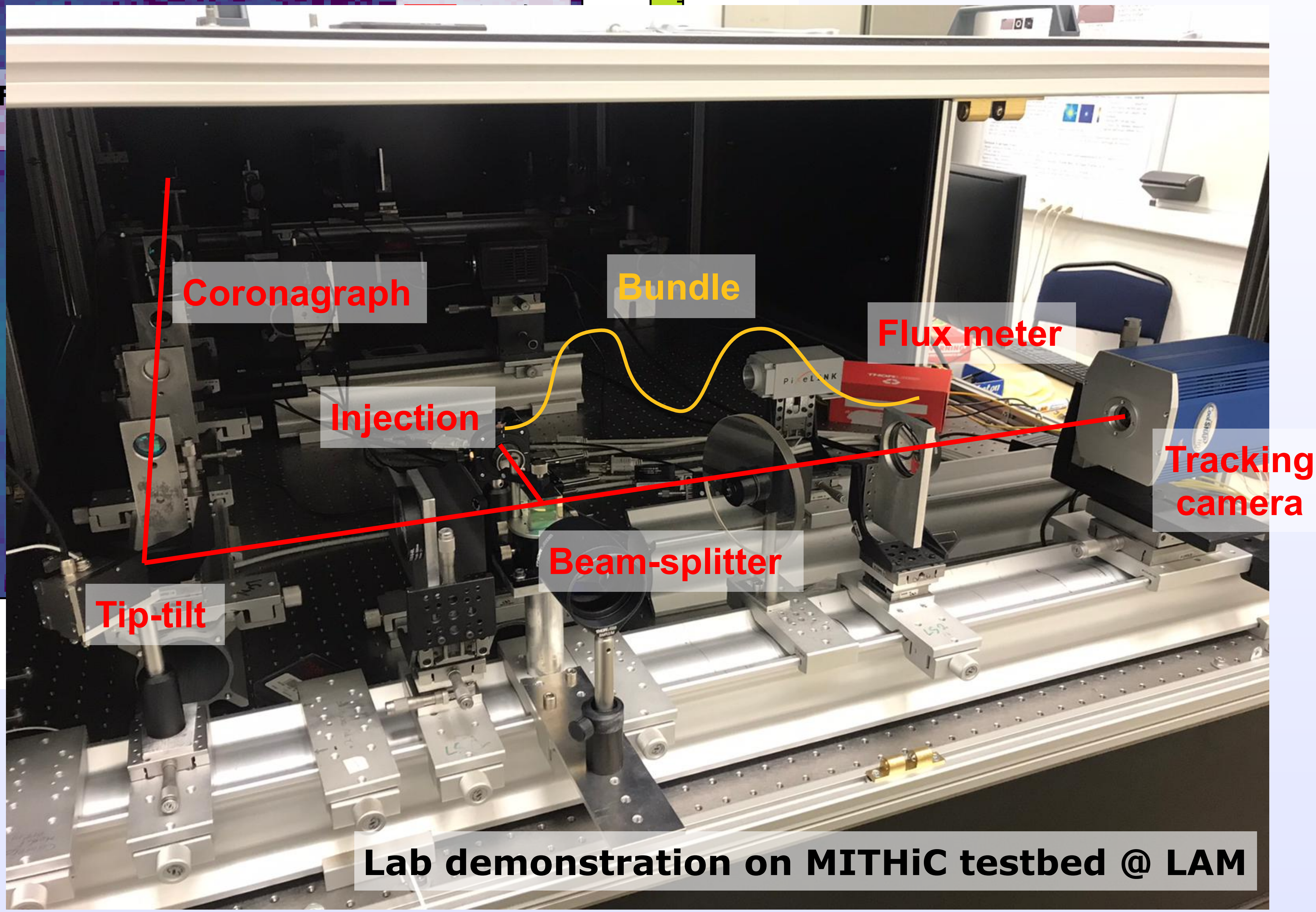


Lab demonstration on MITHiC testbed @ LAM

PSF centering: an operational challenge

Coupling





PSF centering: an operational challenge

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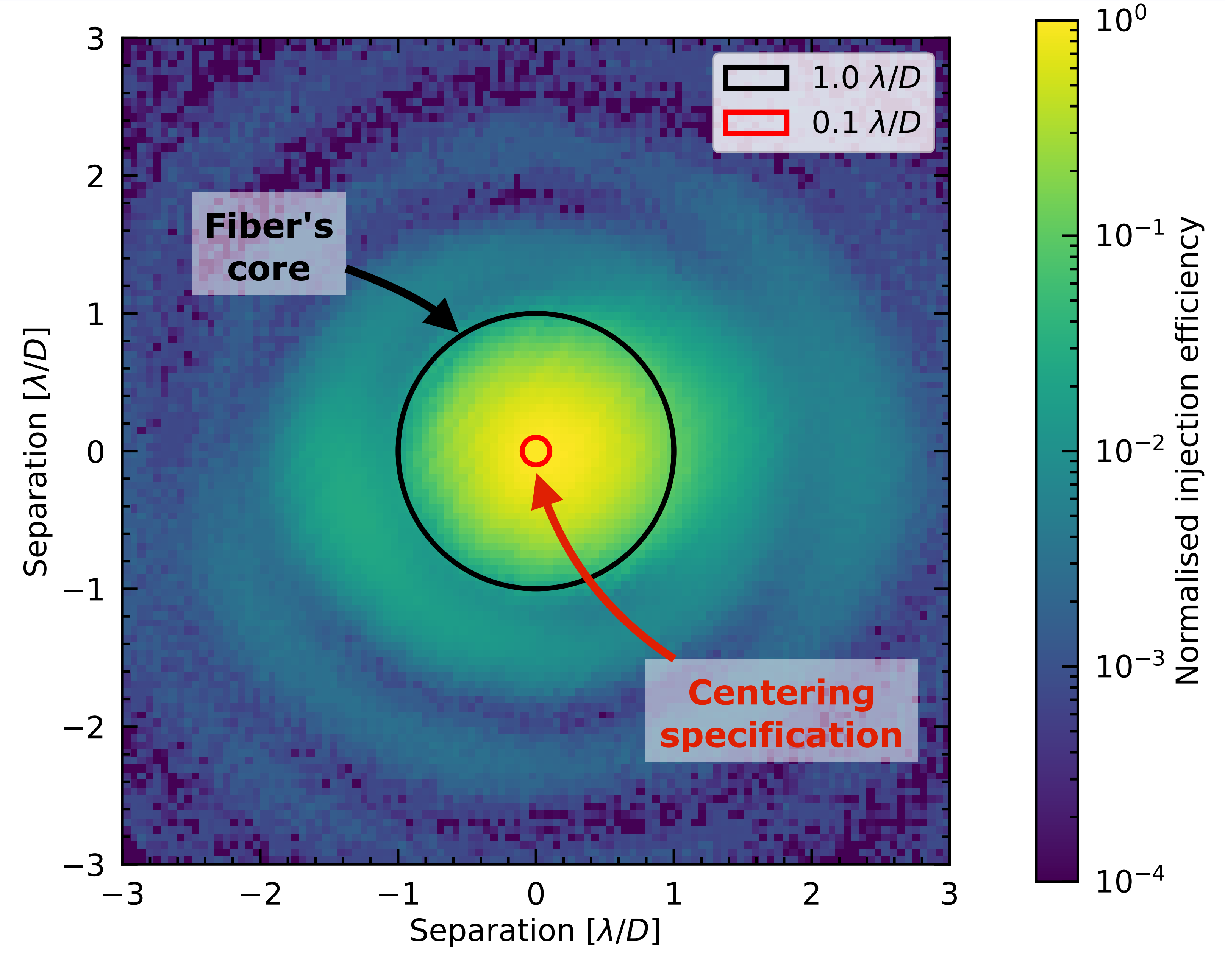
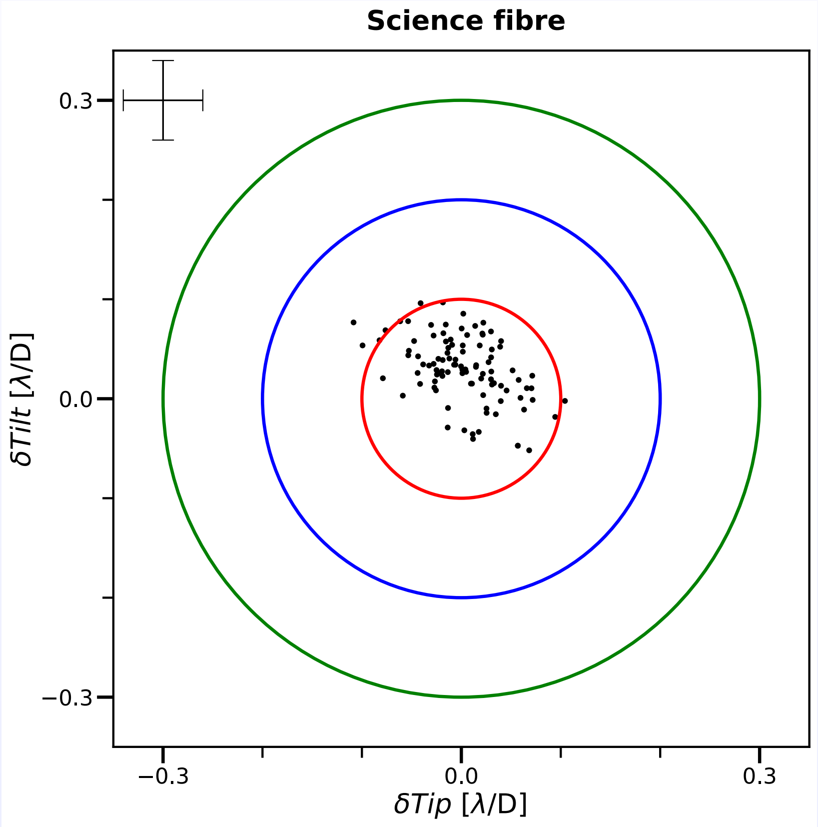


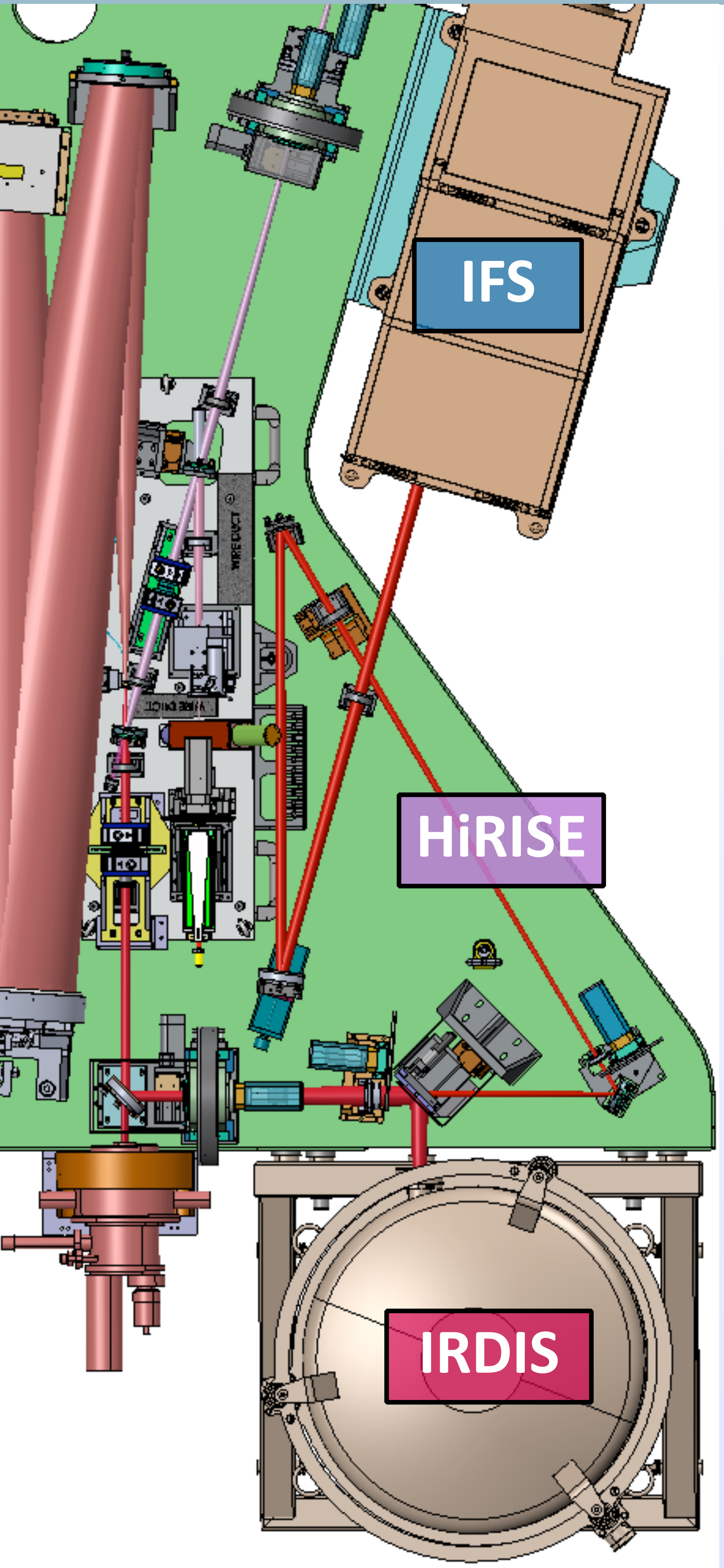


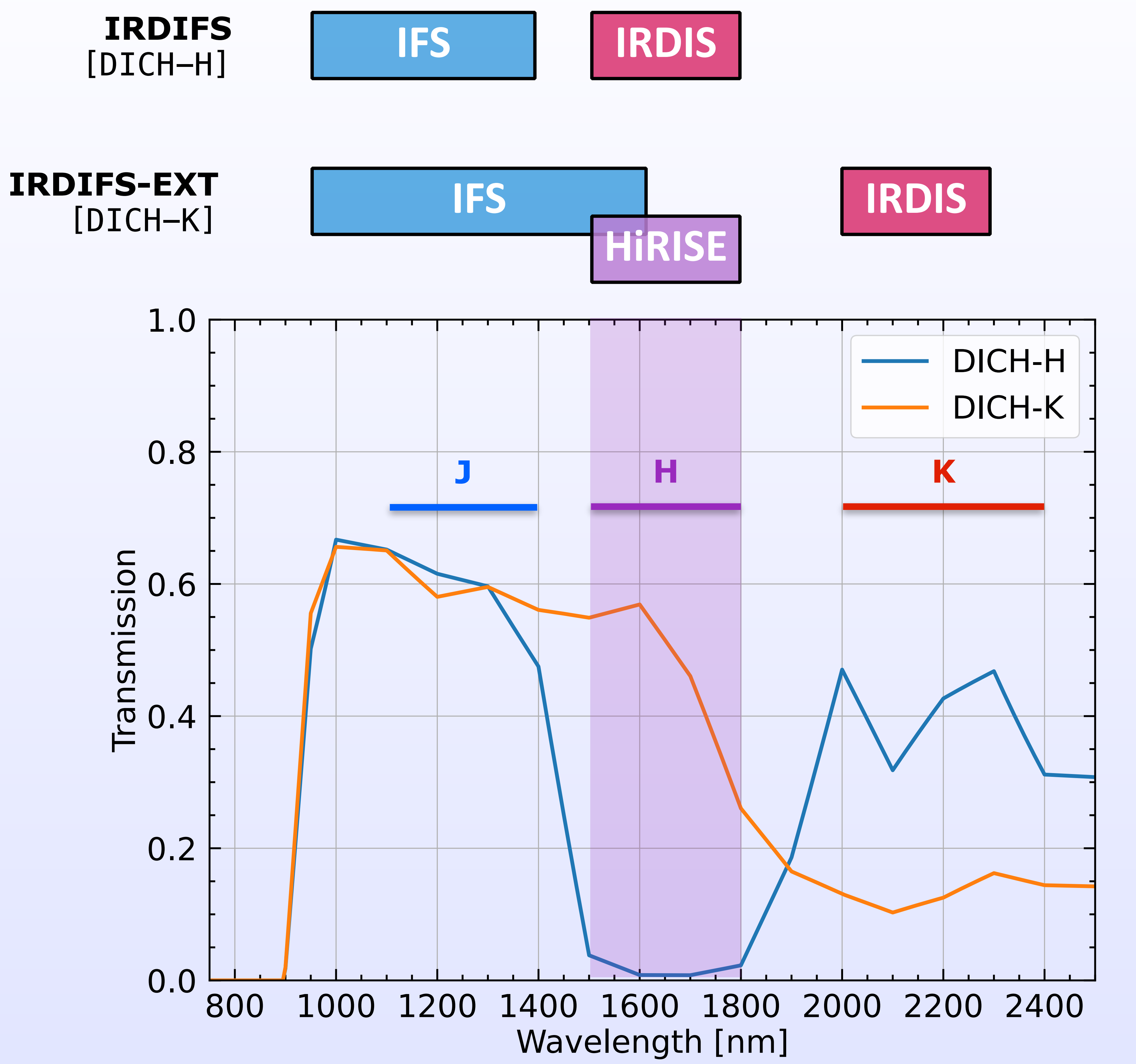
El Morsy et al. (2022)

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

Photon sharing in SPHERE

SPHERE





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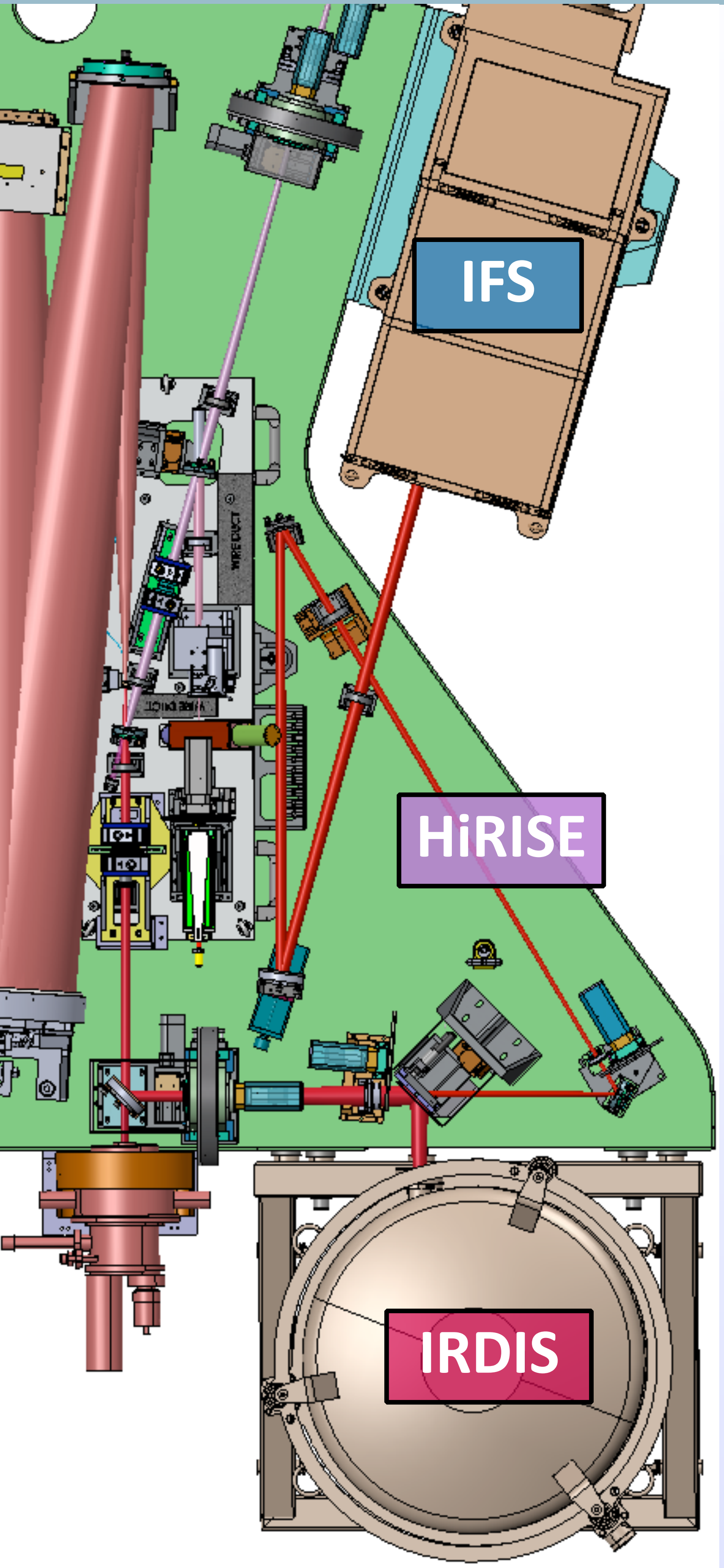
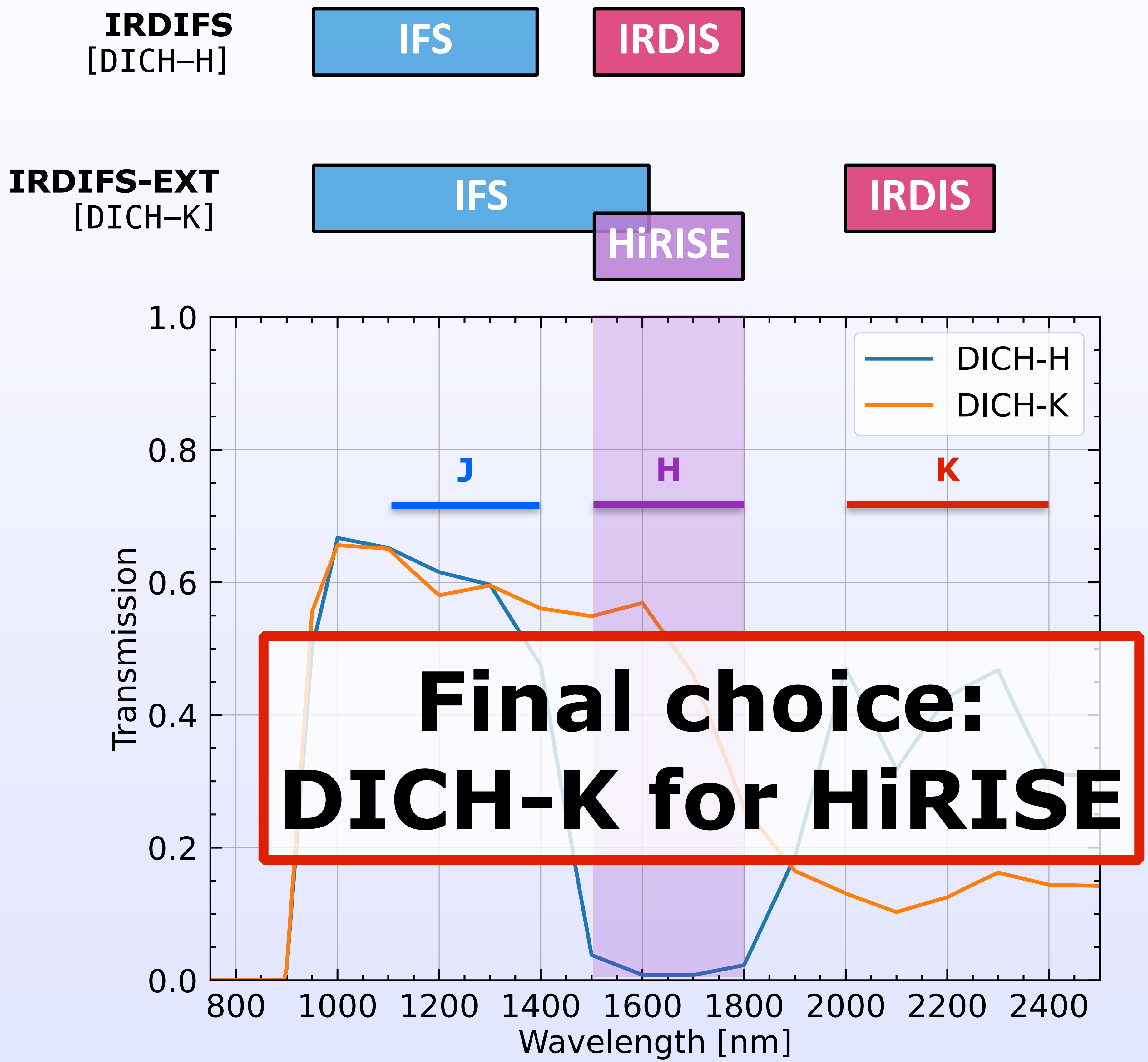


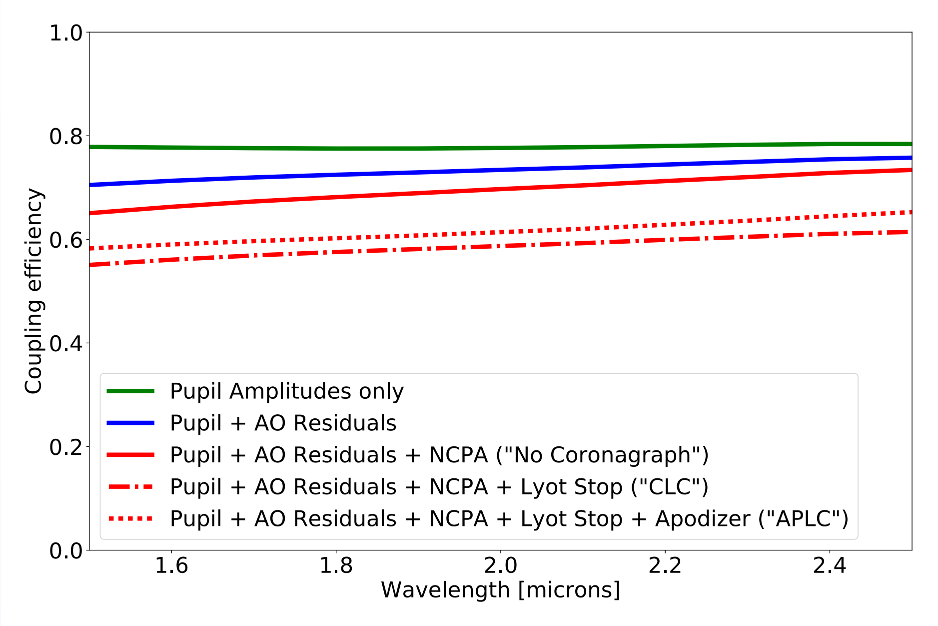


Final choice: DICH-K for HiRISE

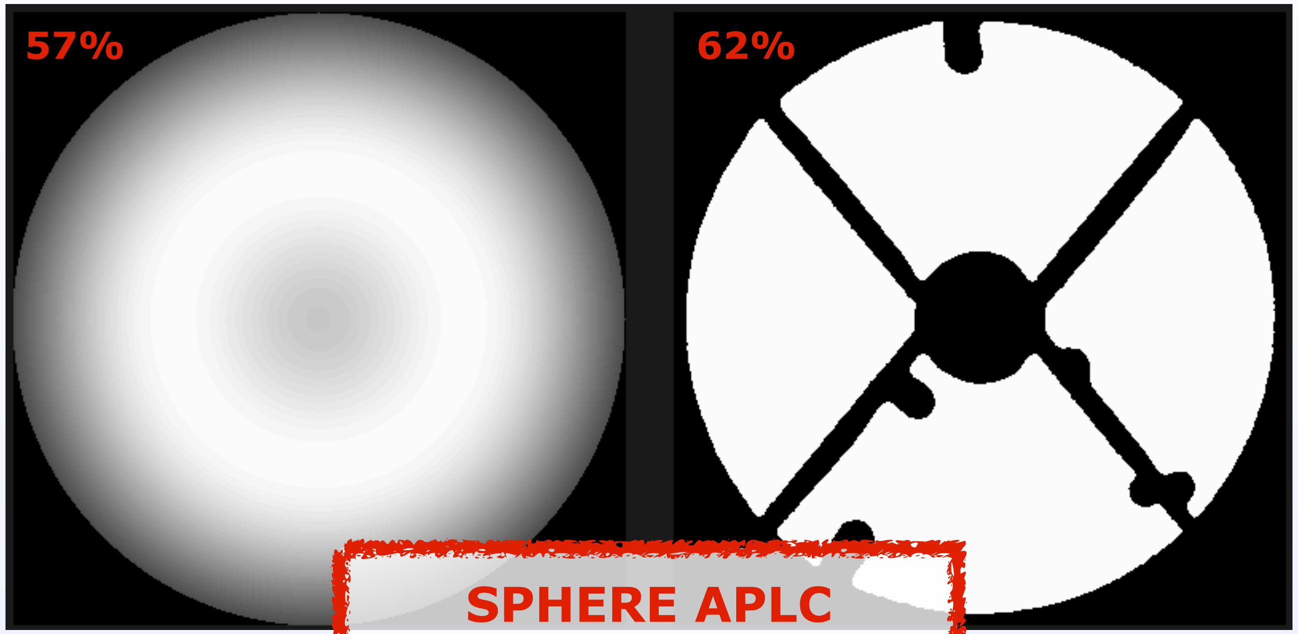
To have or not to have [a coronagraph]?

SPHERE

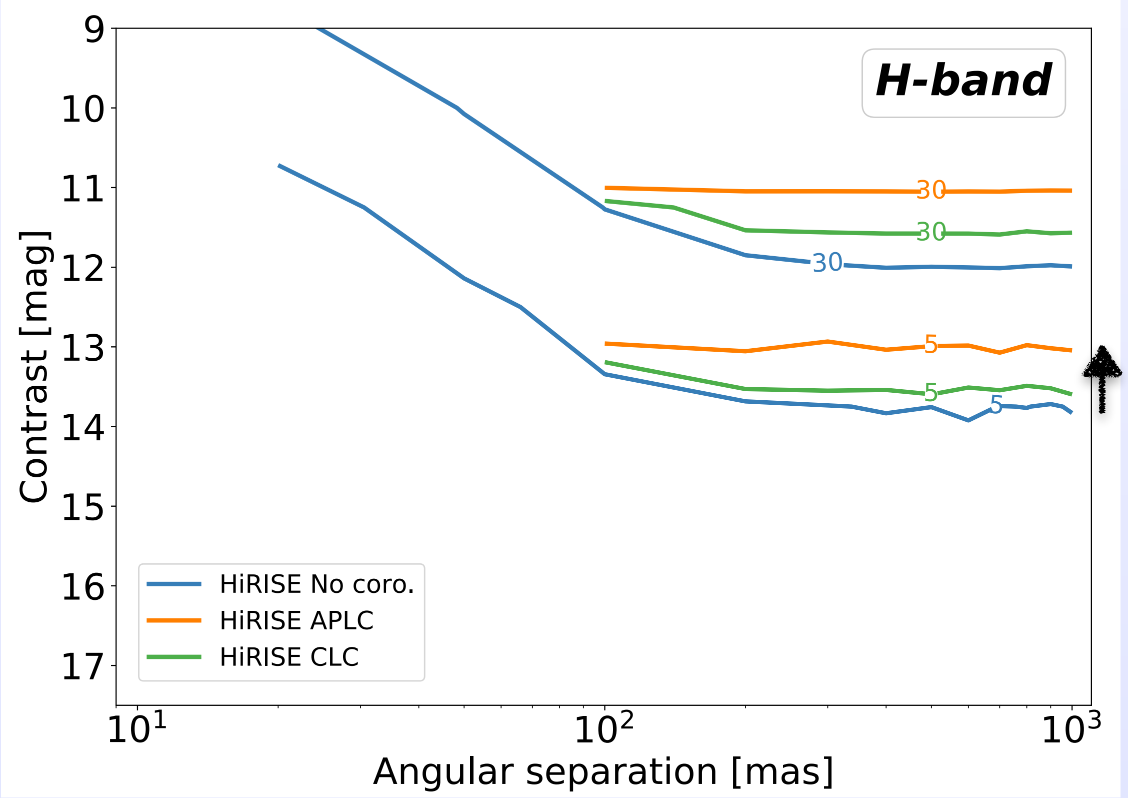
Coupling efficiency



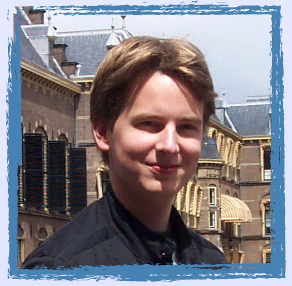
Transmission



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



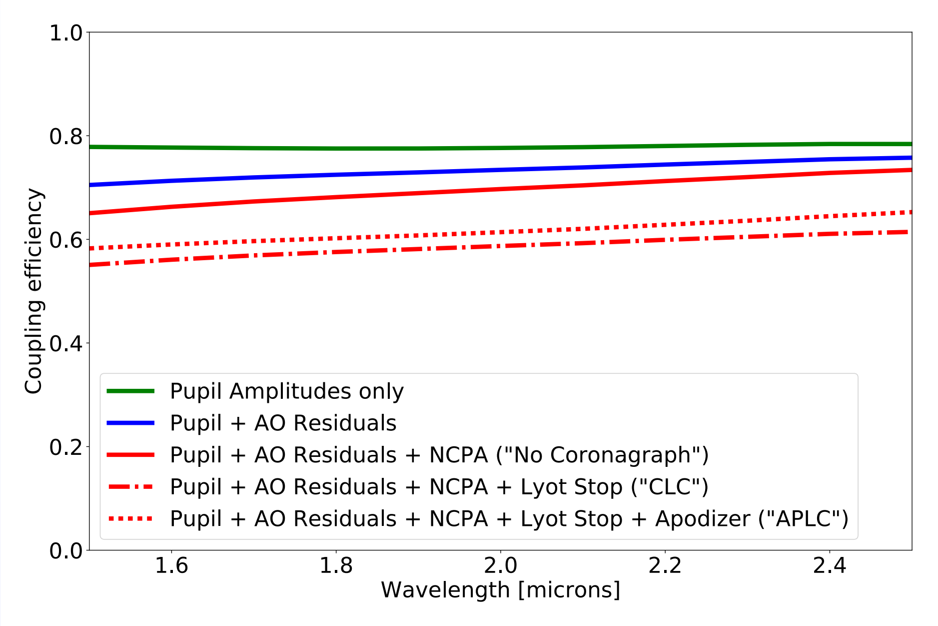
1 mag loss



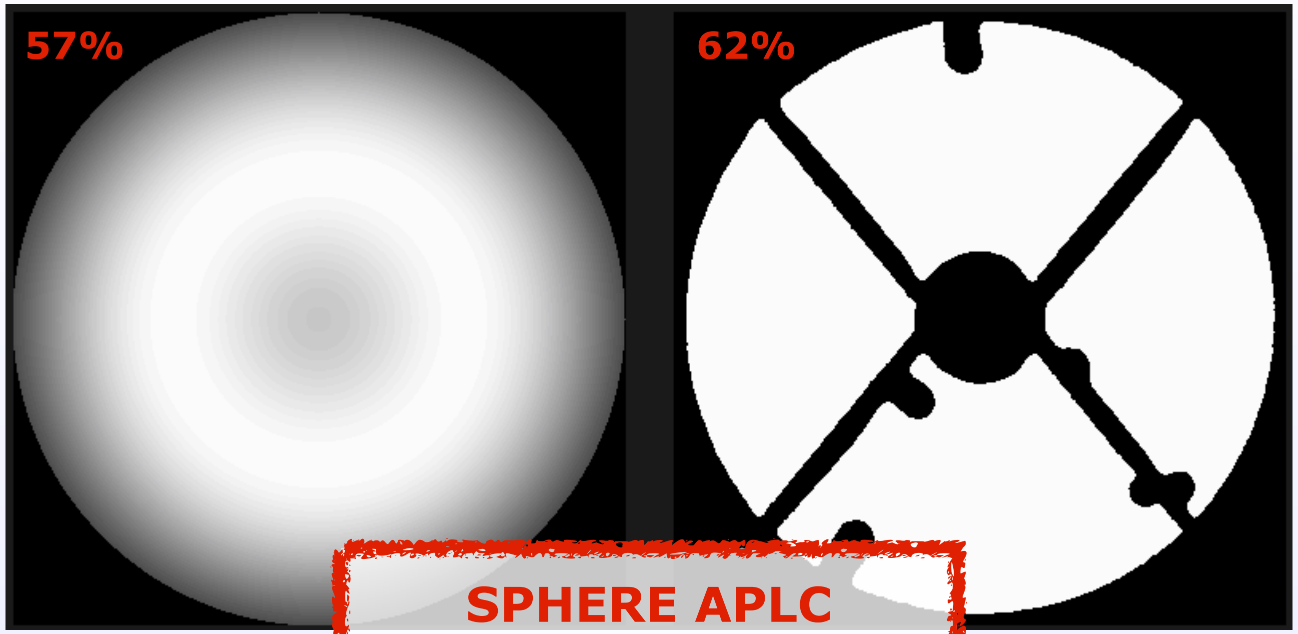
To have or not to have [a coronagraph]?

SPHERE

Coupling efficiency



Transmission



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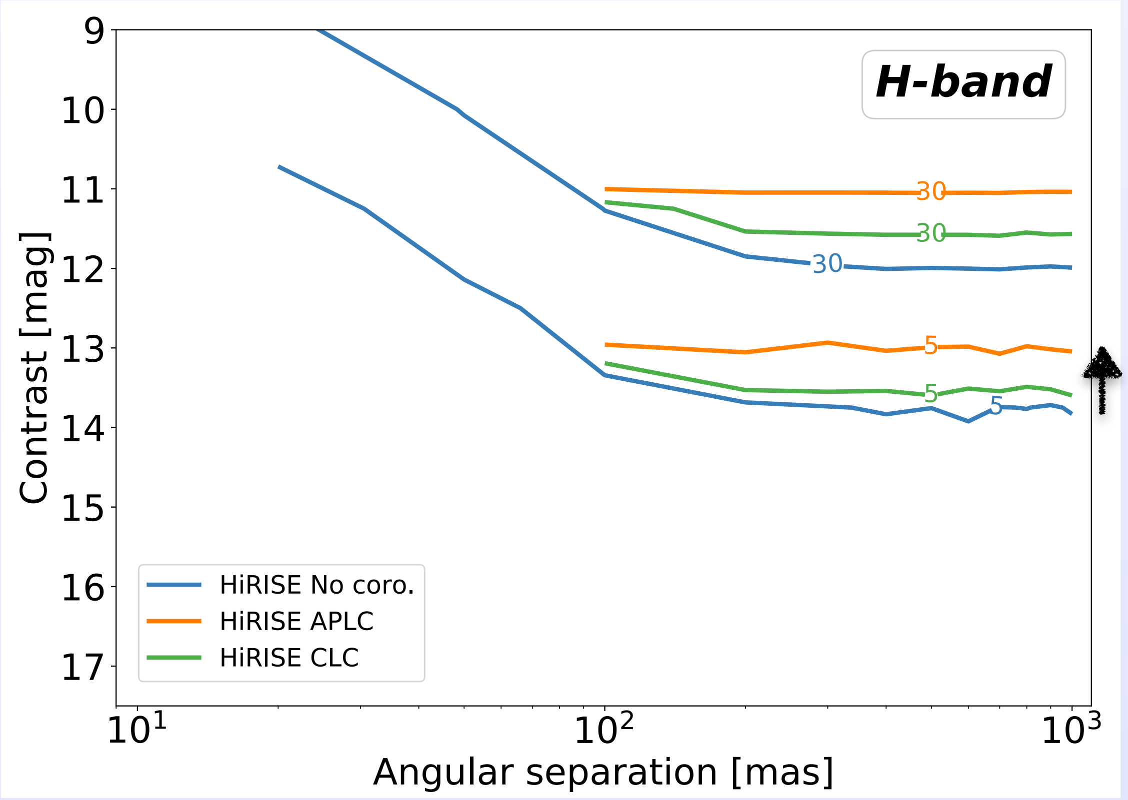
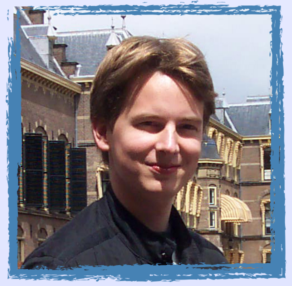
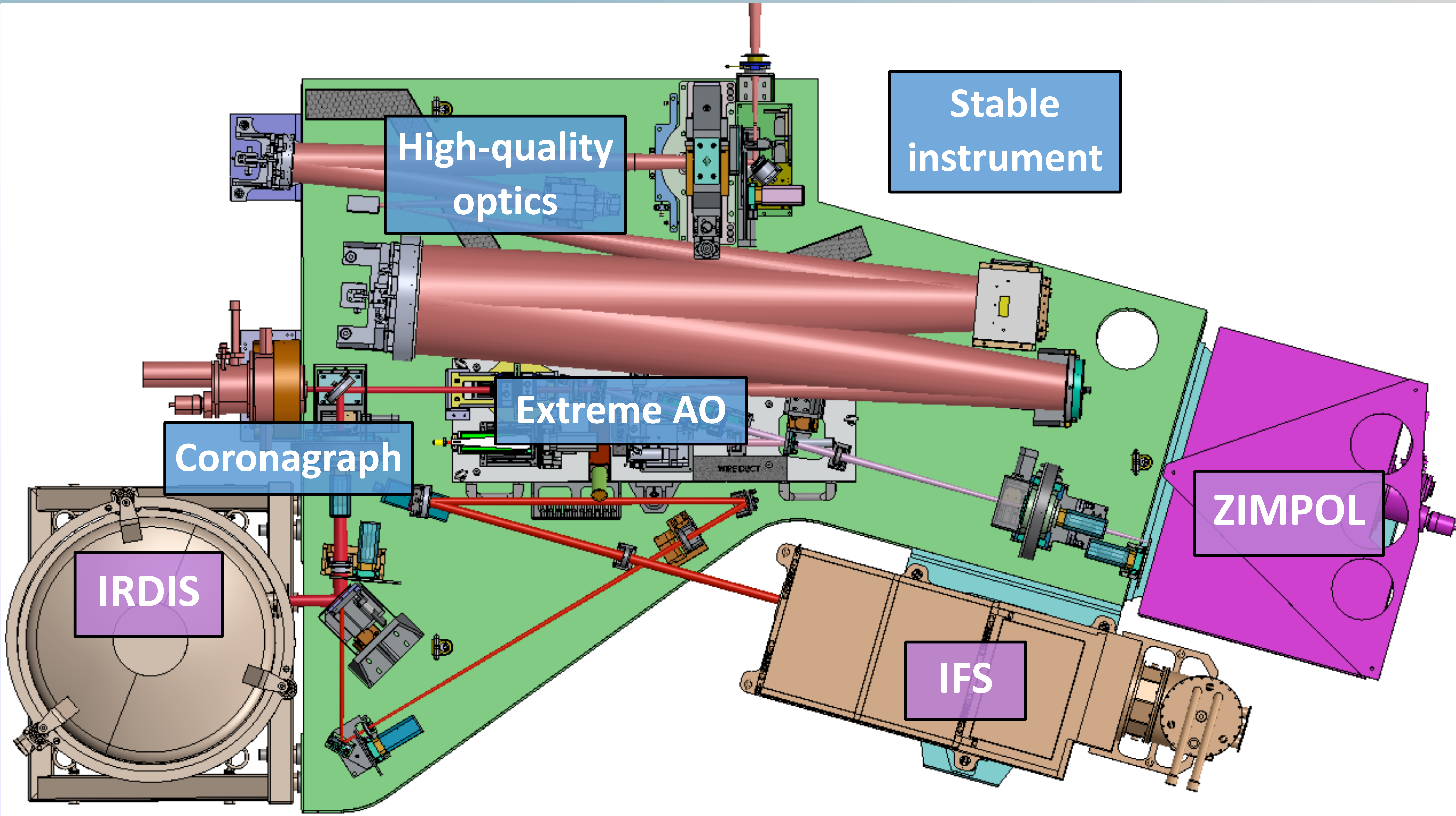


Final choice: No coronagraph



Fiber injection module



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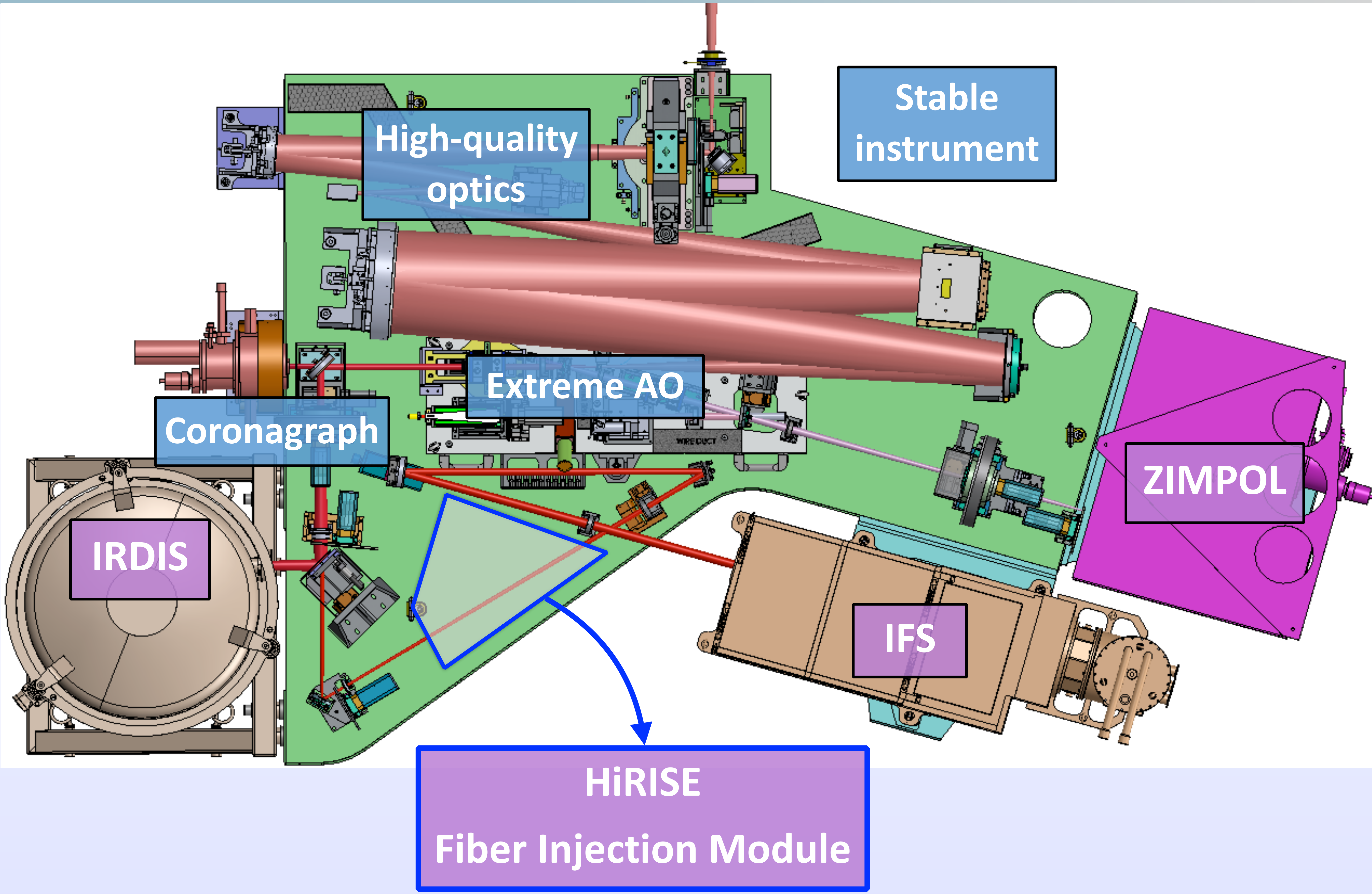

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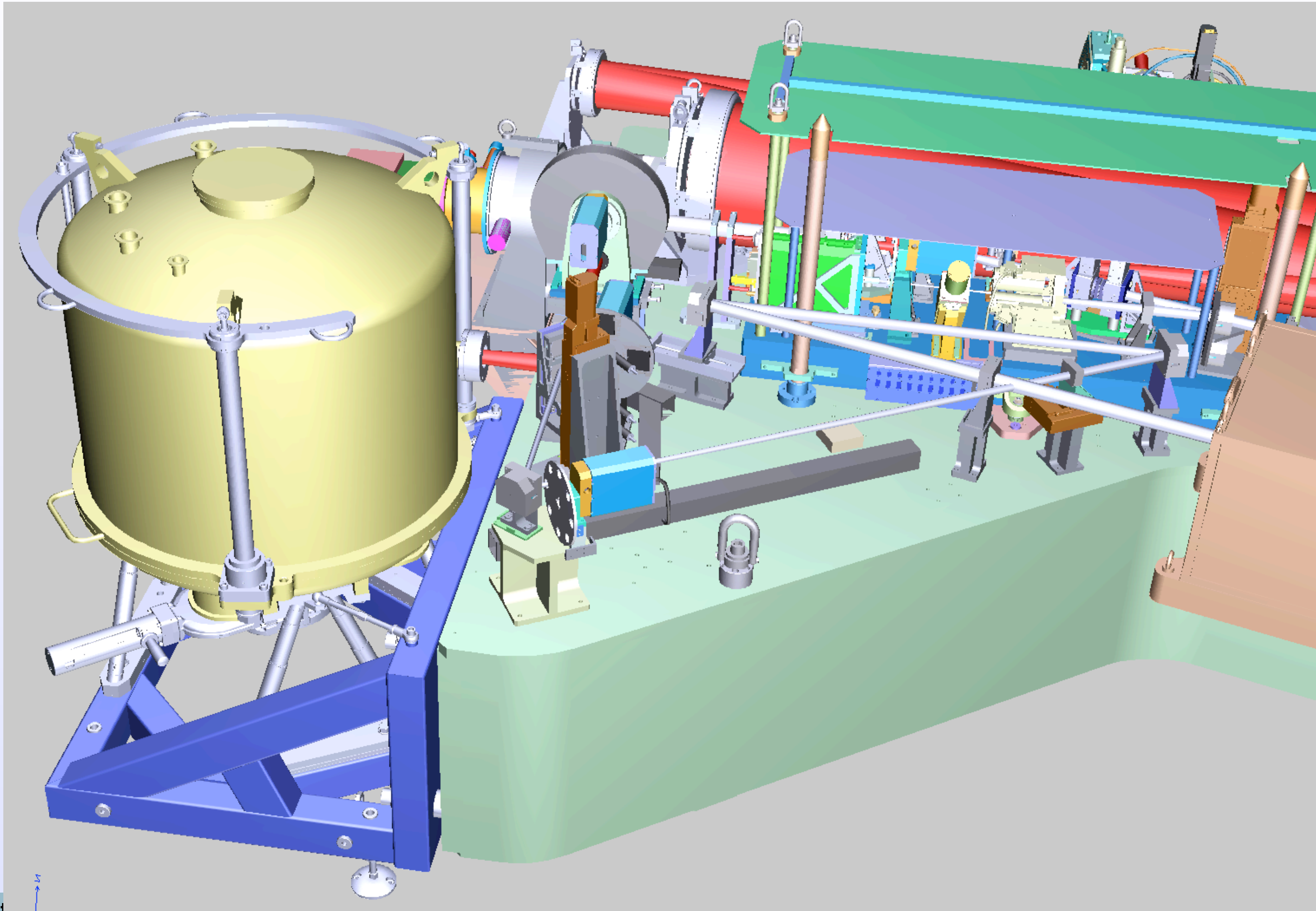

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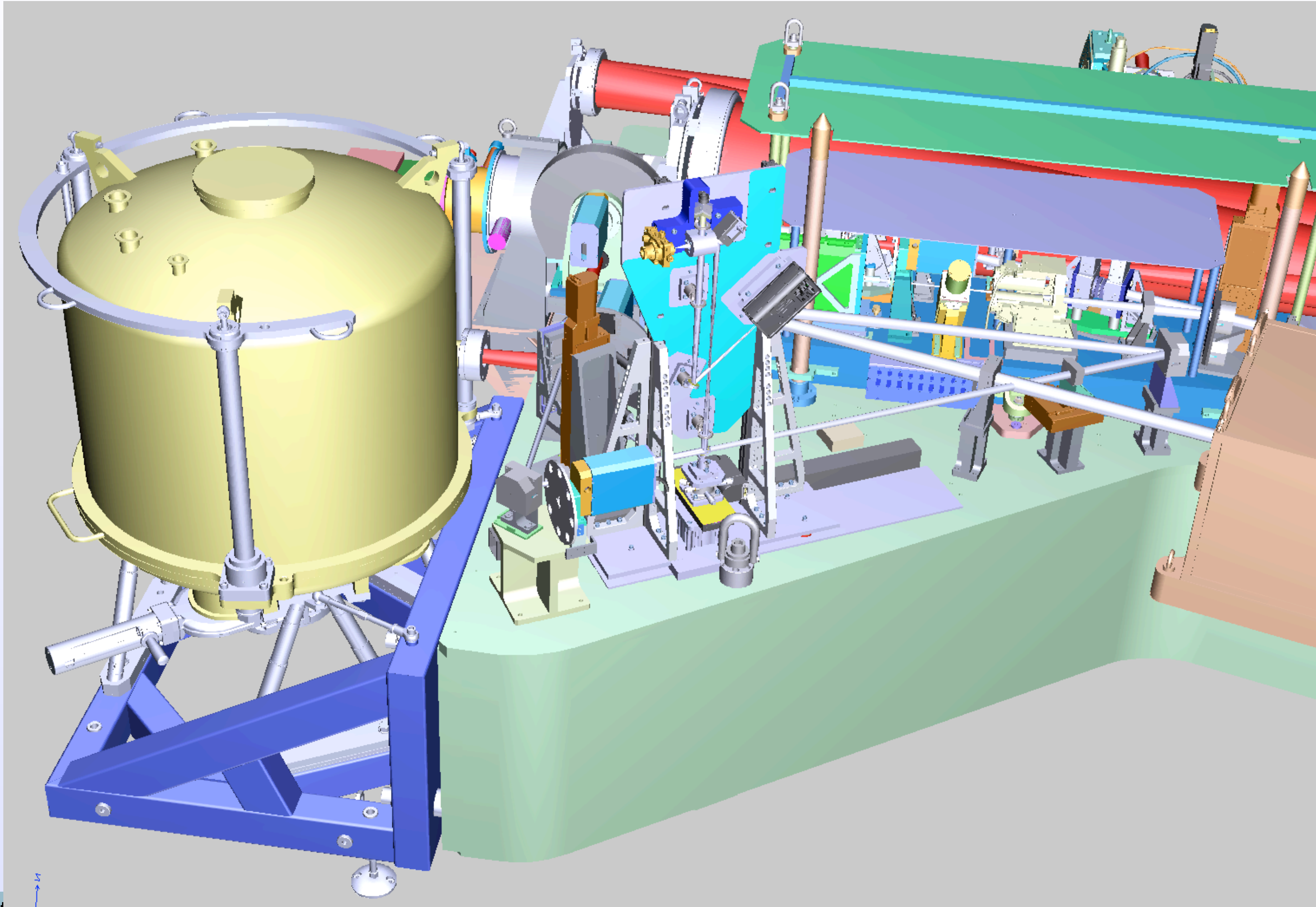
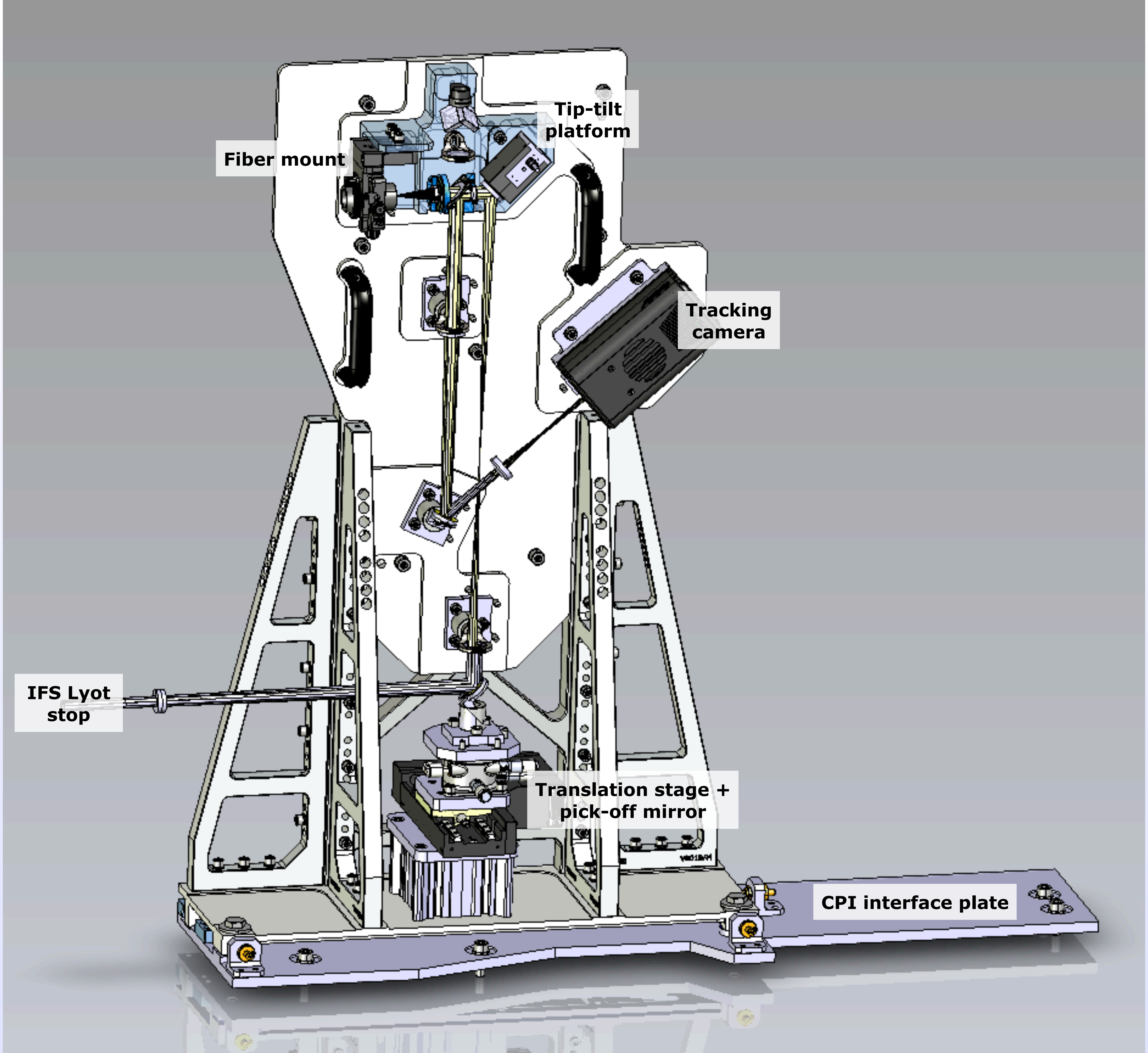
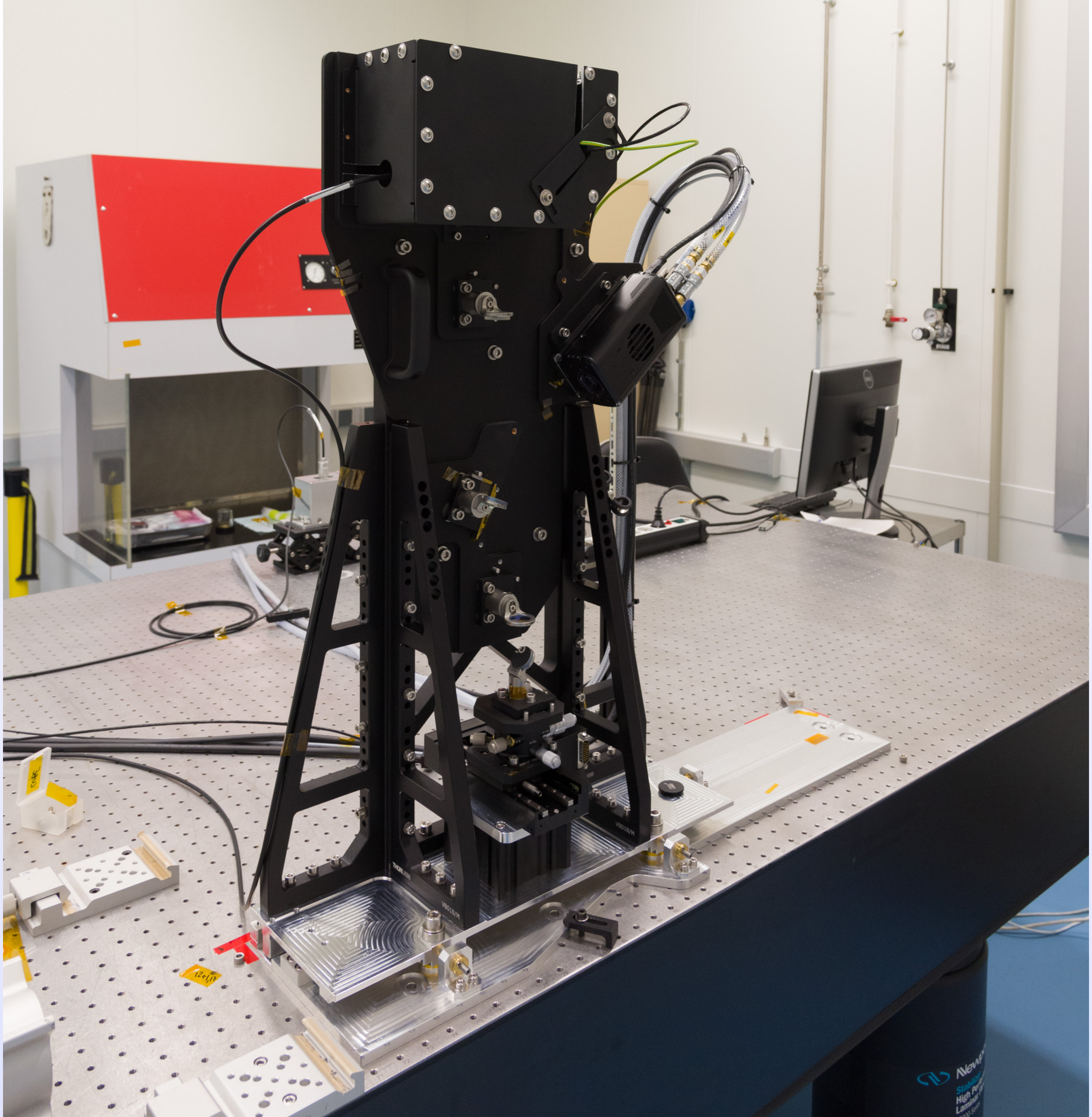



Tip-tilt platform
Fiber mount
Tracking camera
IFS Lyot stop
Translation stage + pick-off mirror
CPI interface plate



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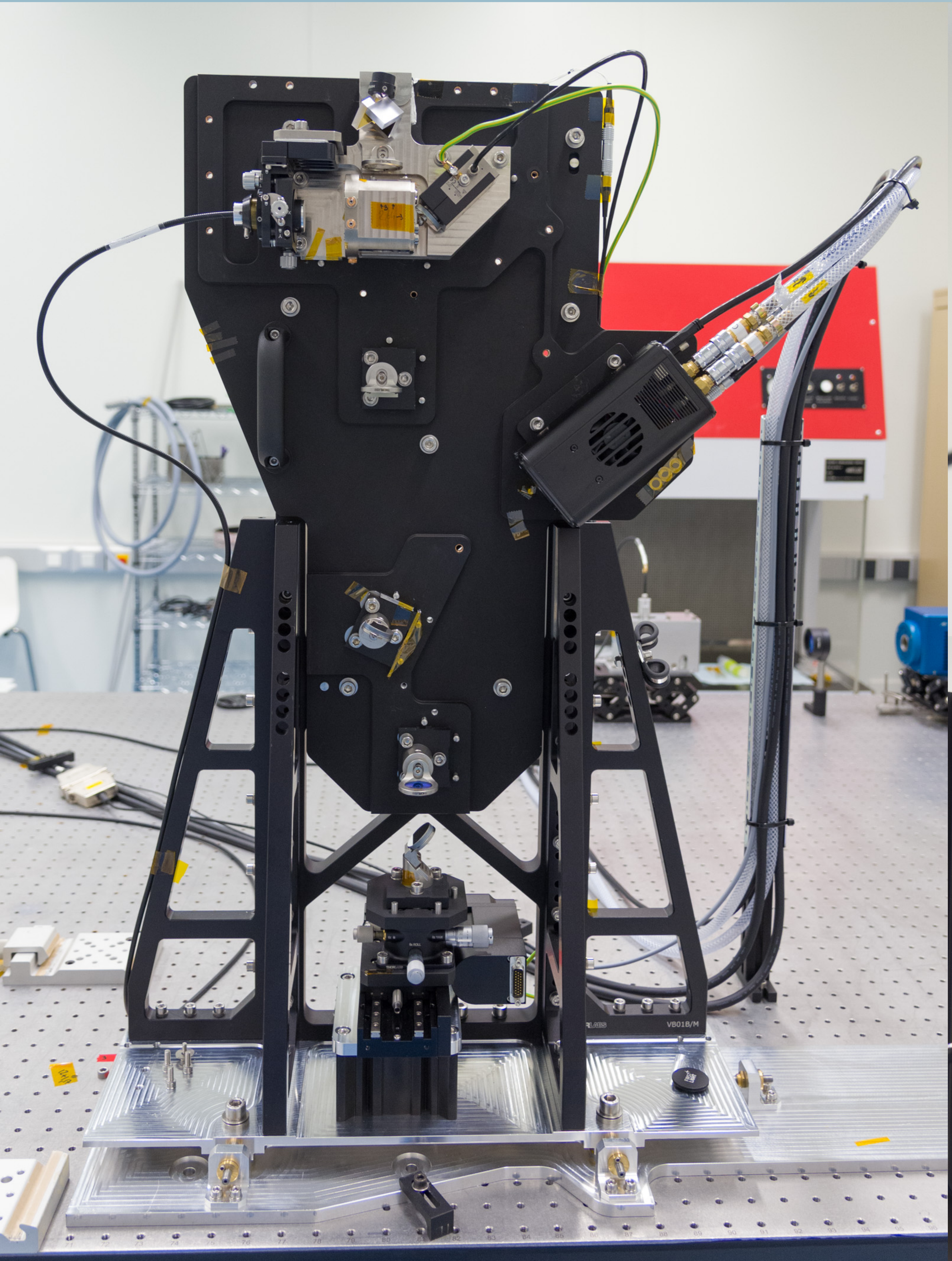
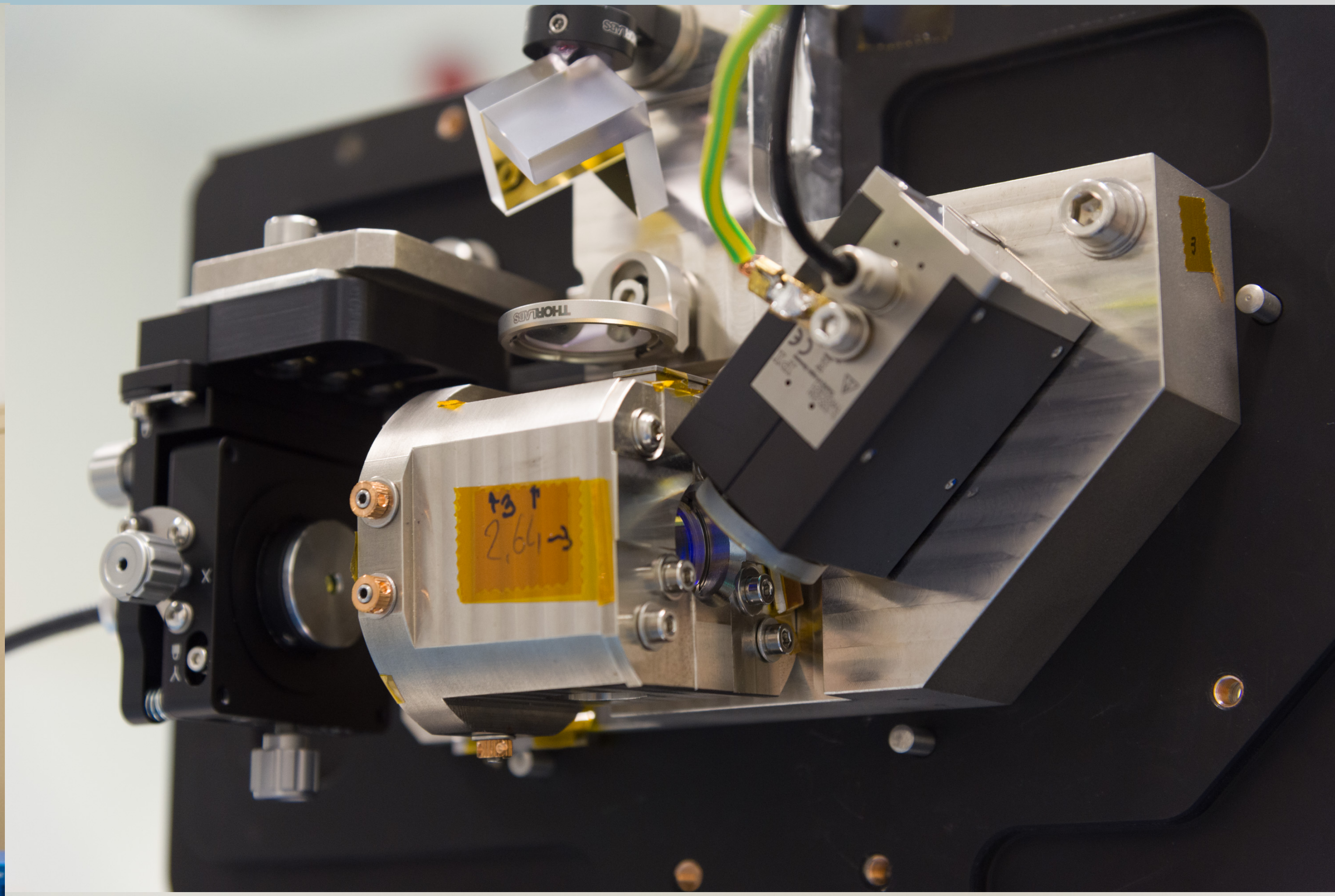
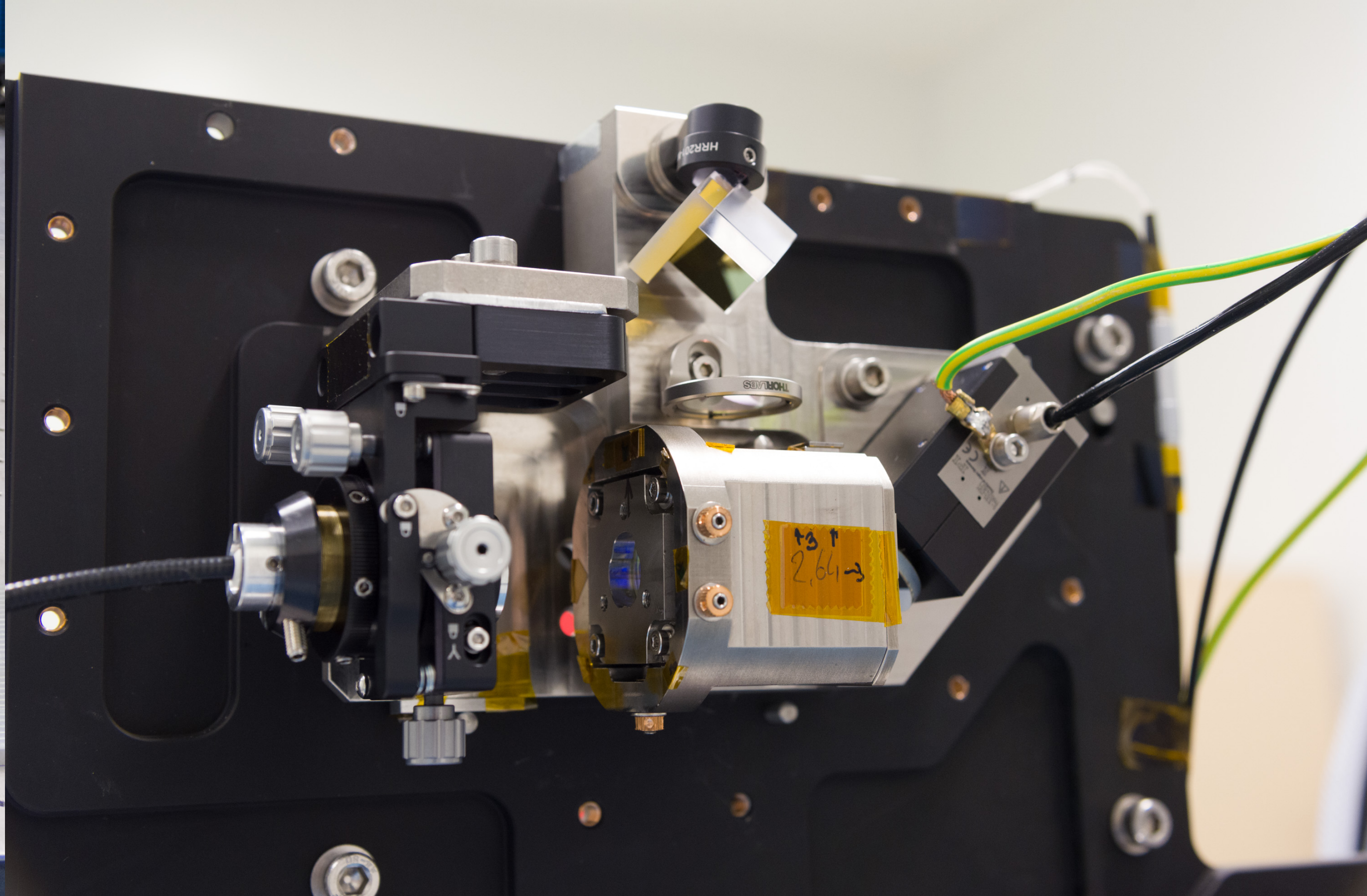
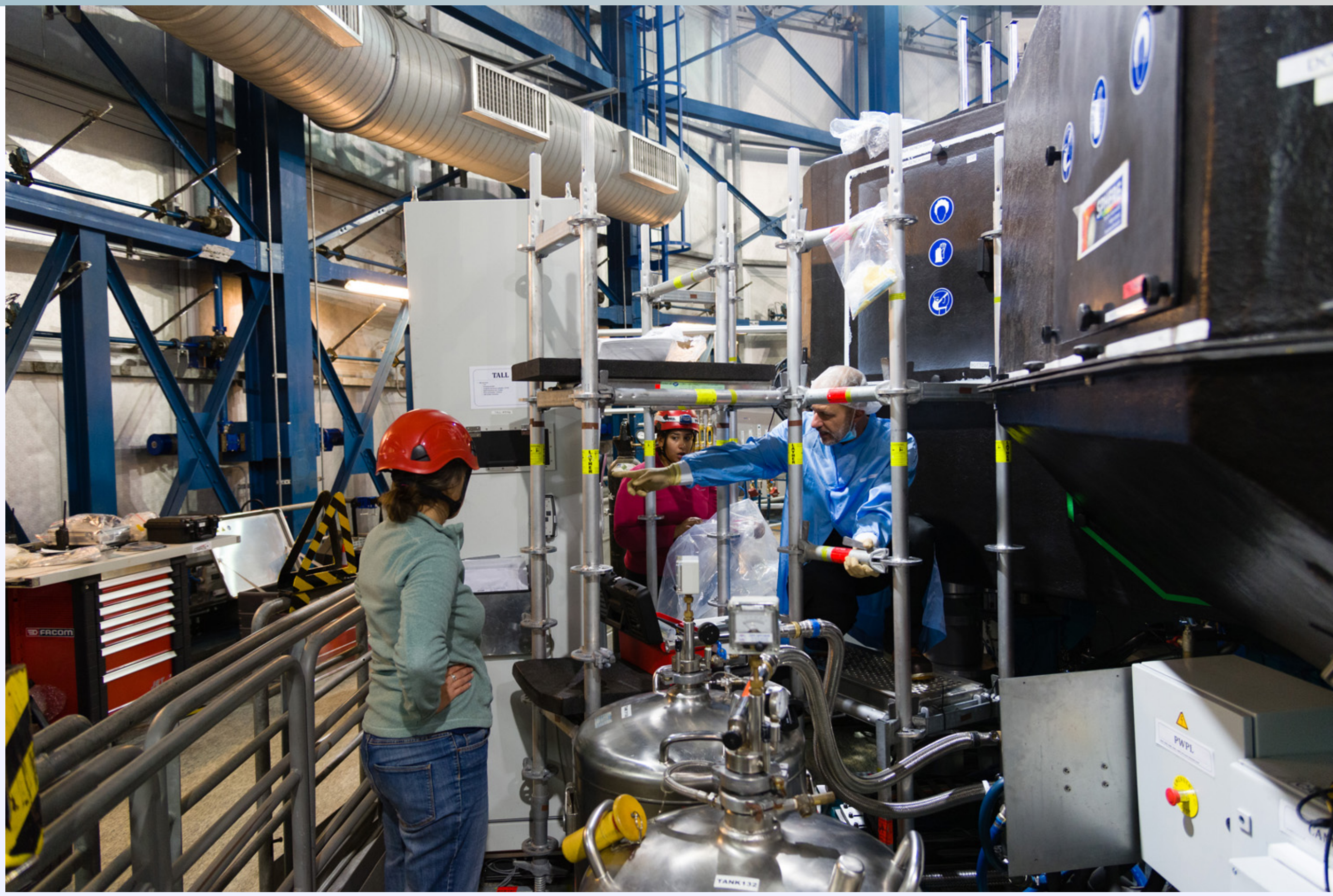






Fiber injection module



Fiber injection module

Fiber injection module

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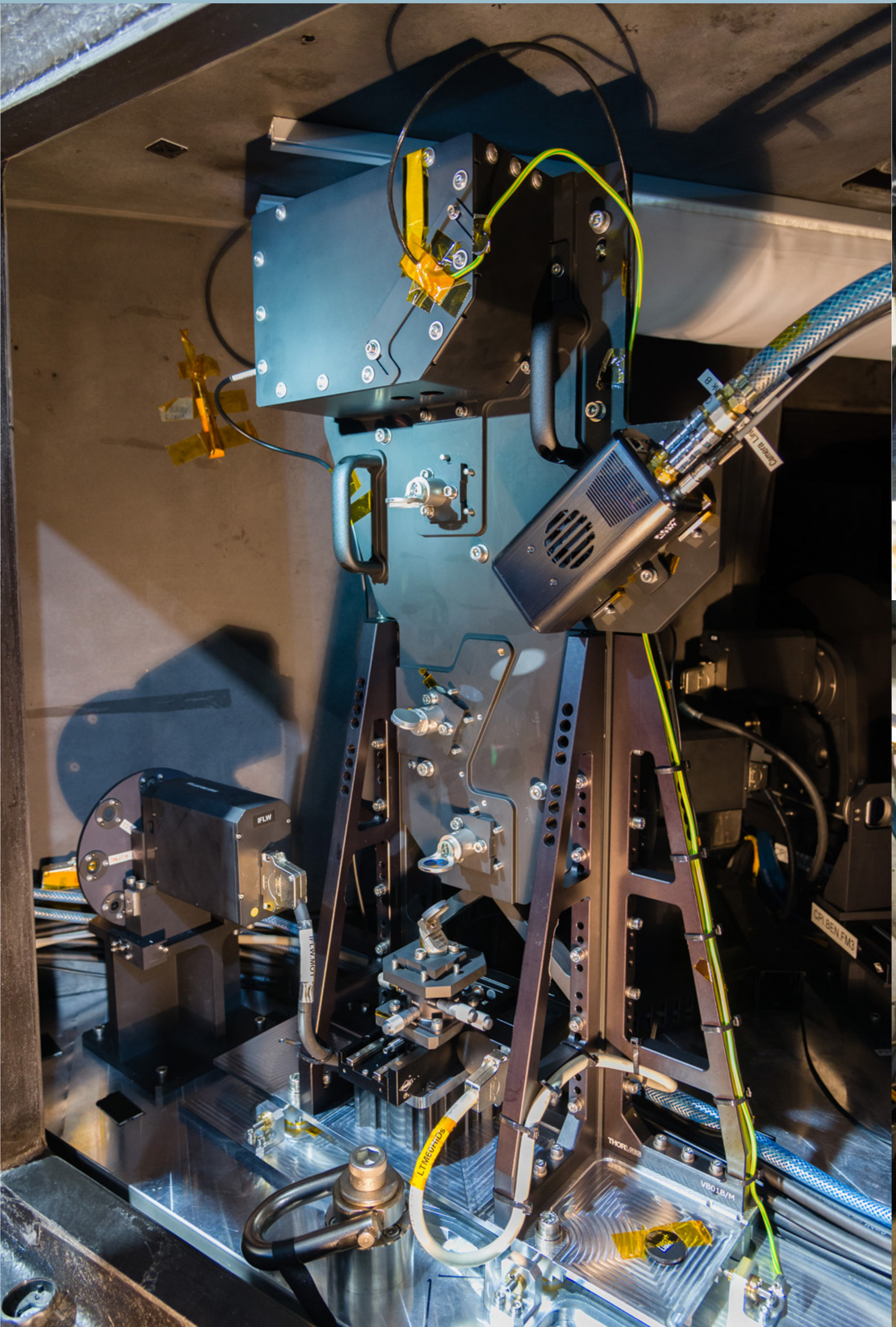
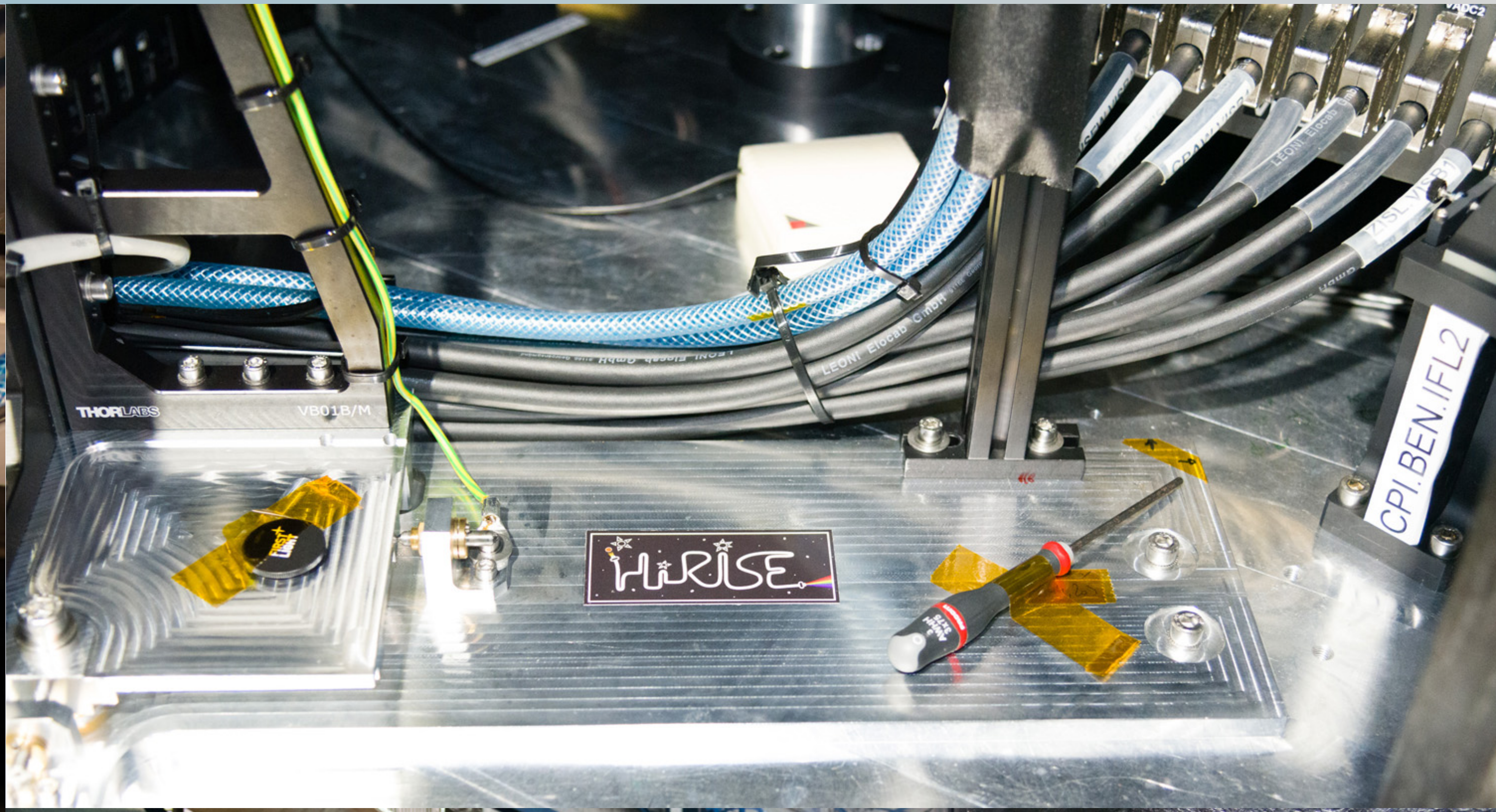
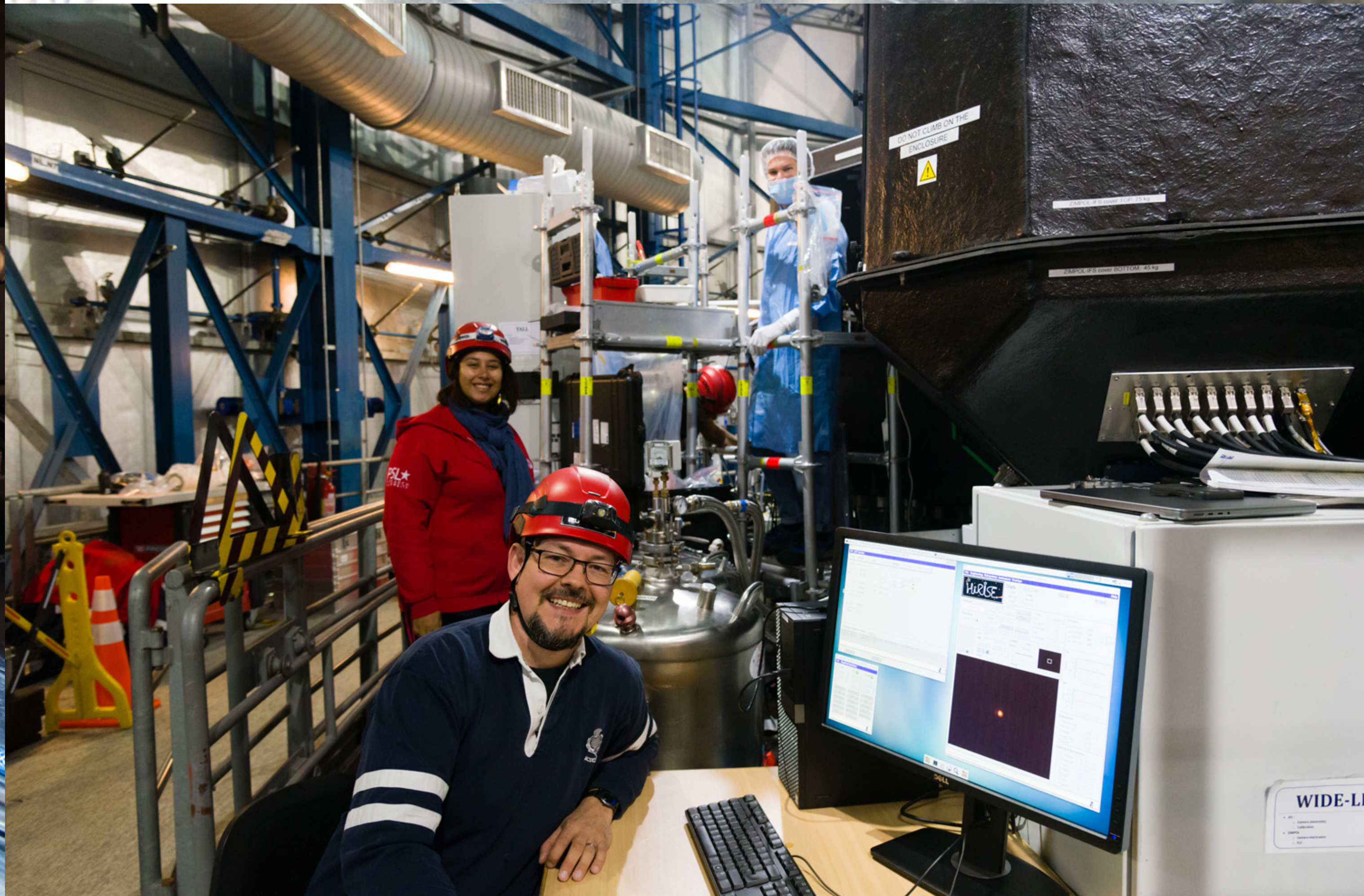
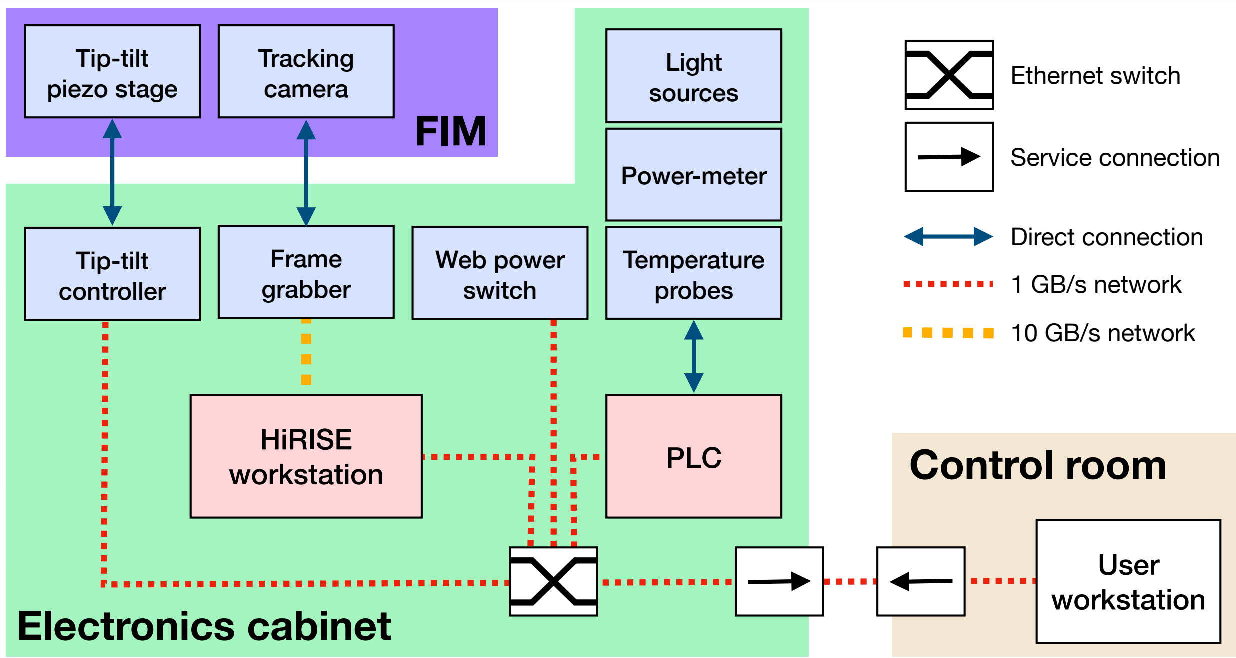
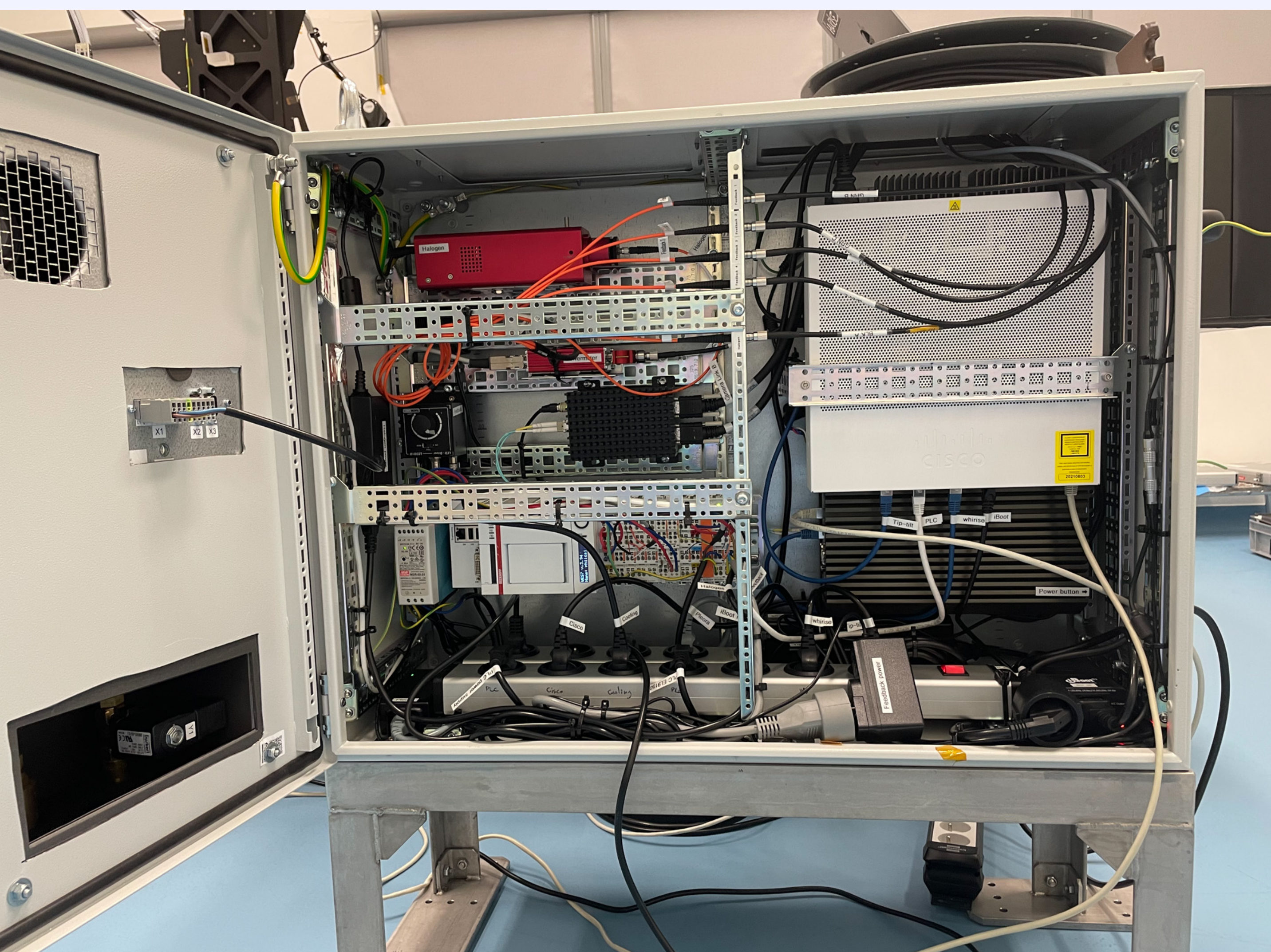




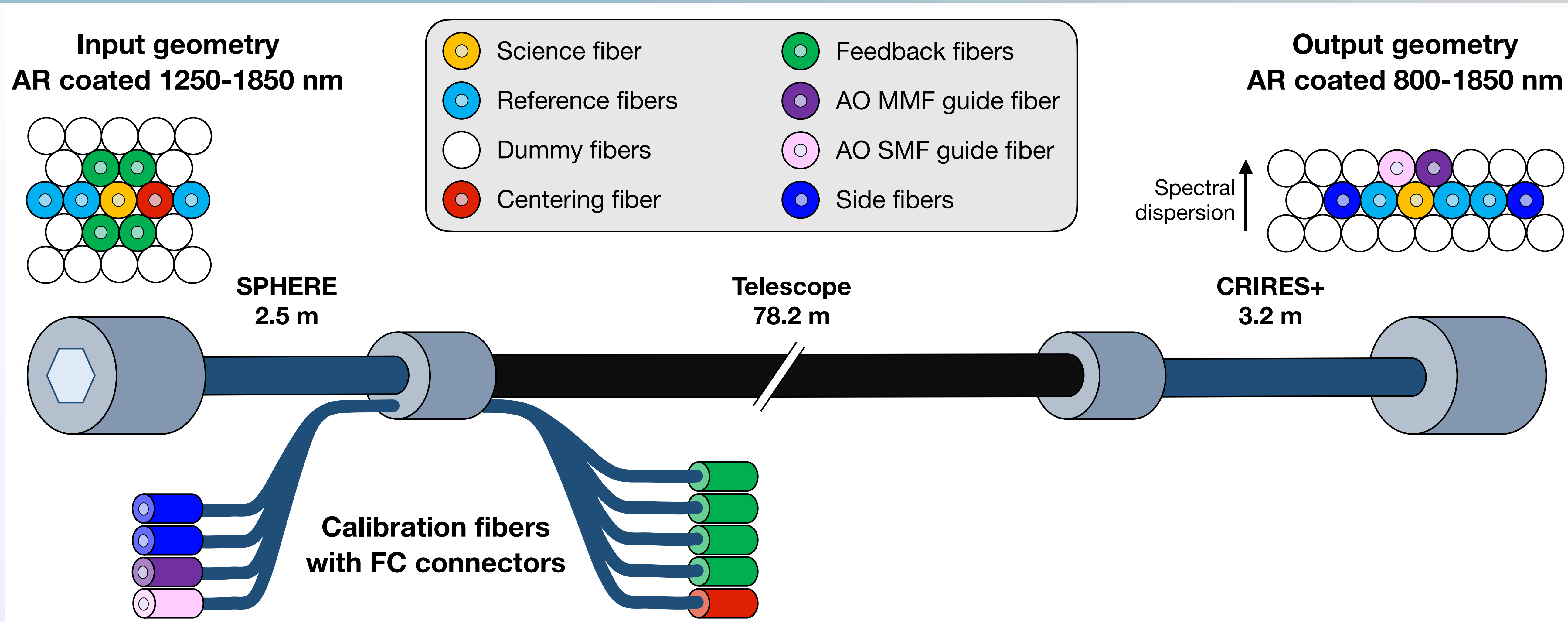


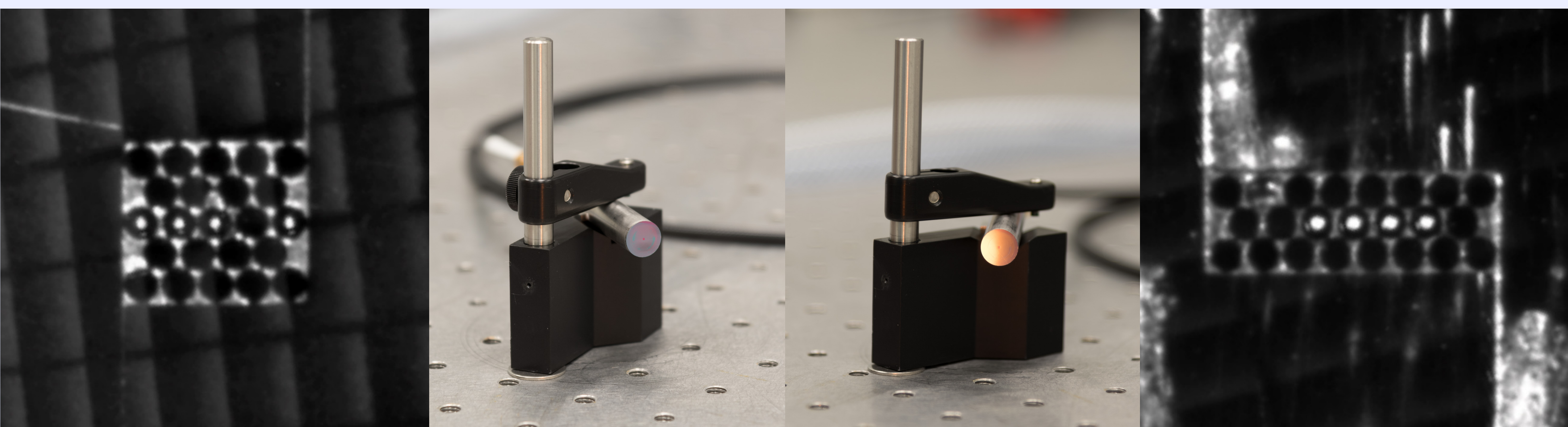
Electronics cabinet





A complex fiber bundle





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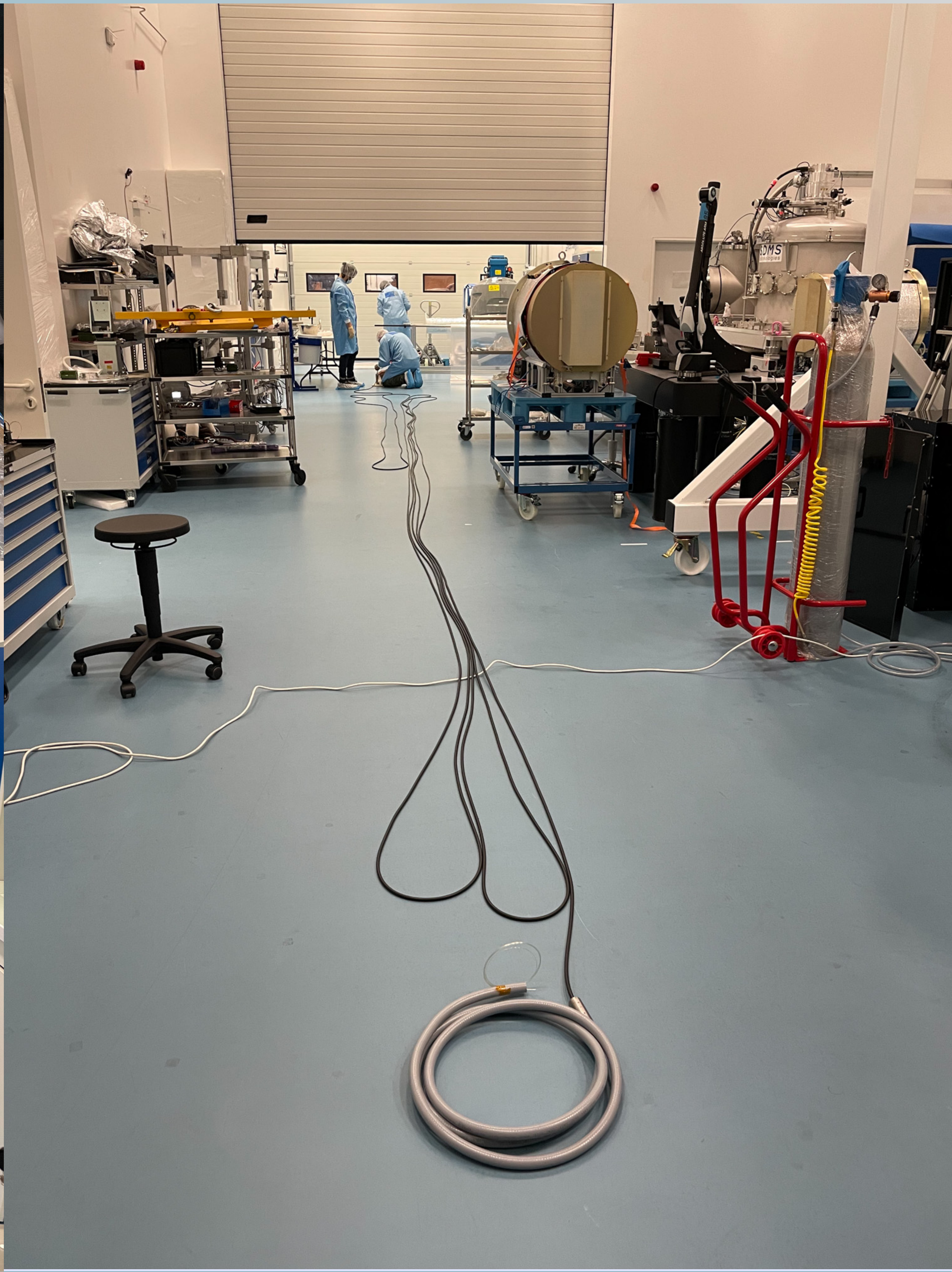

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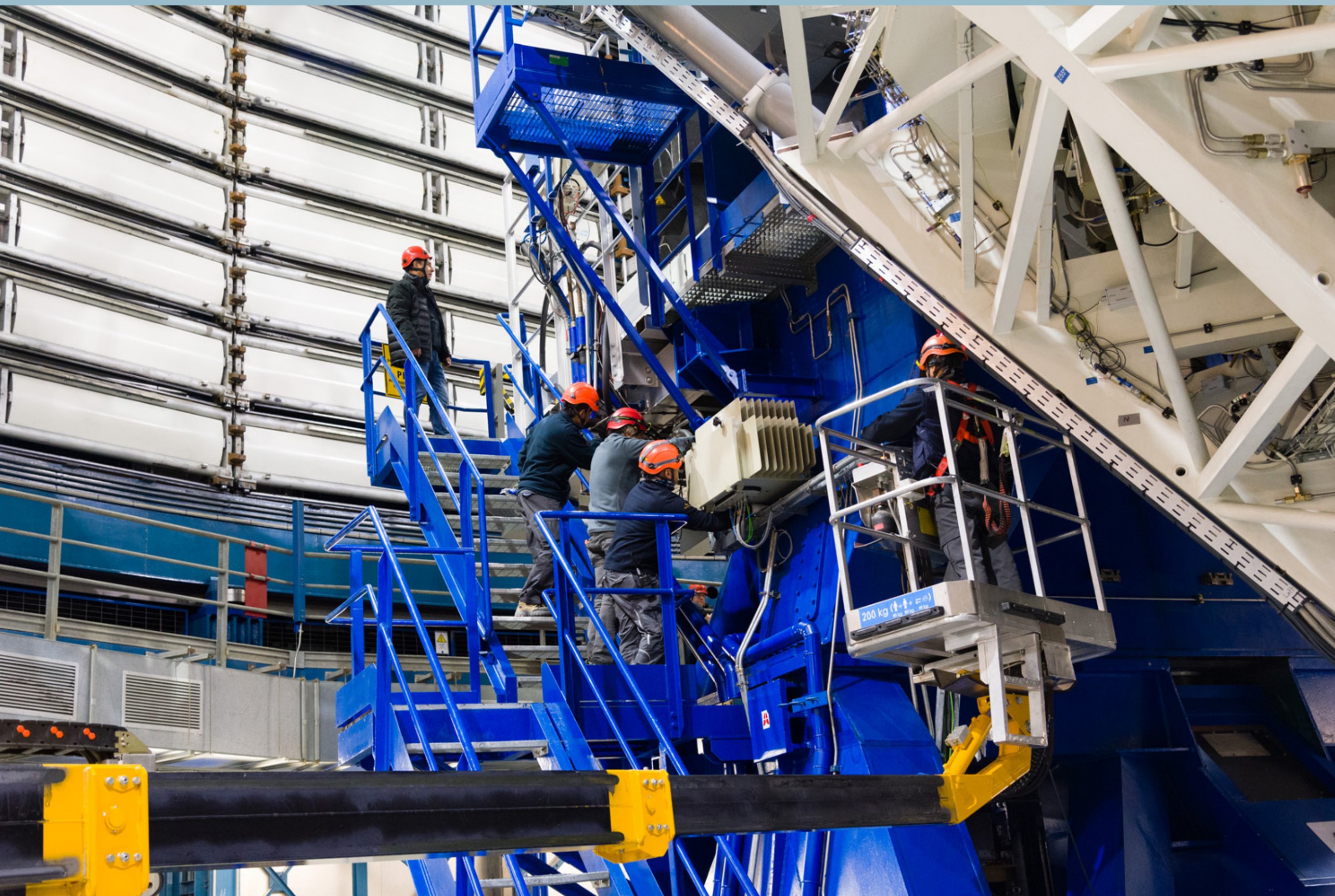

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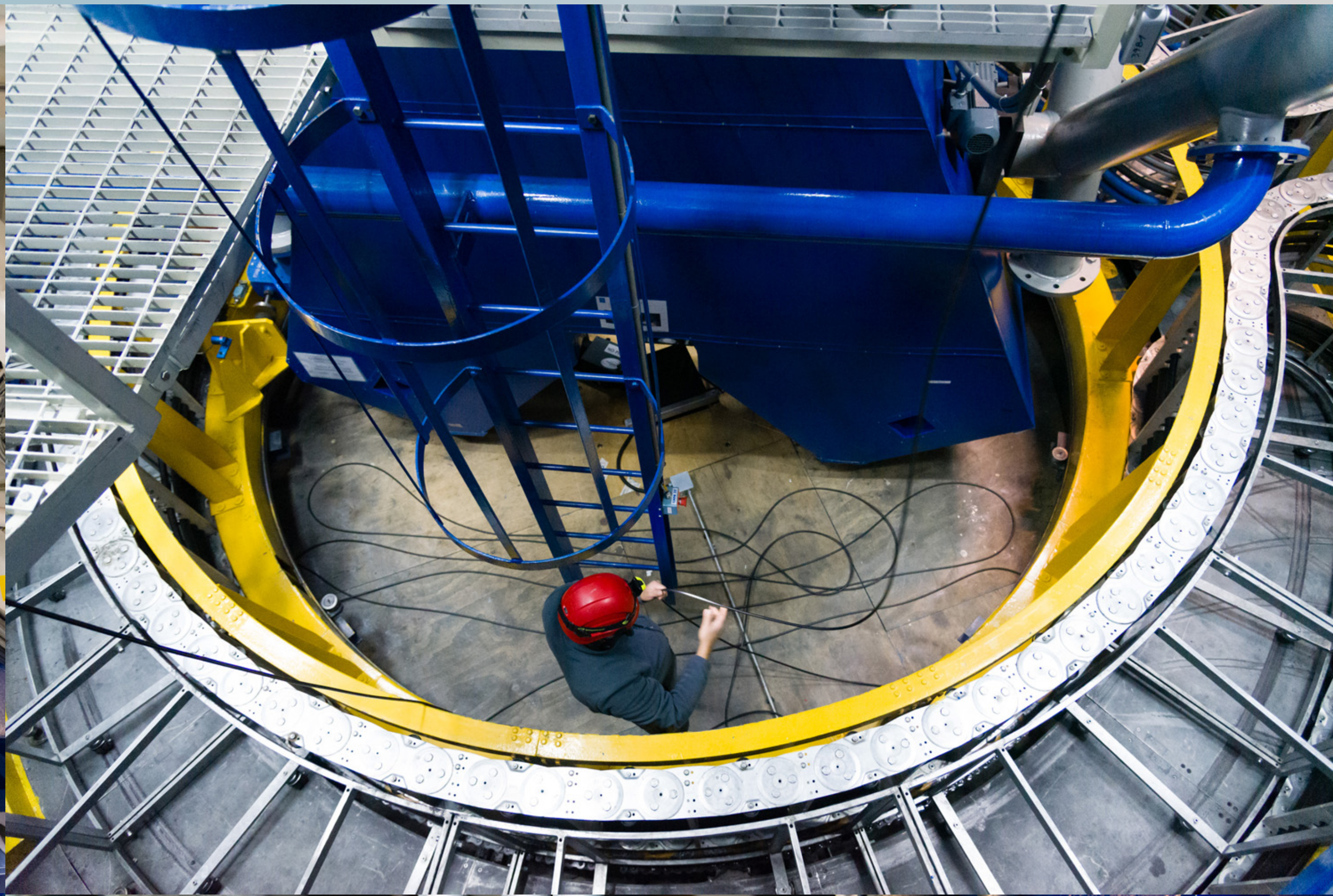
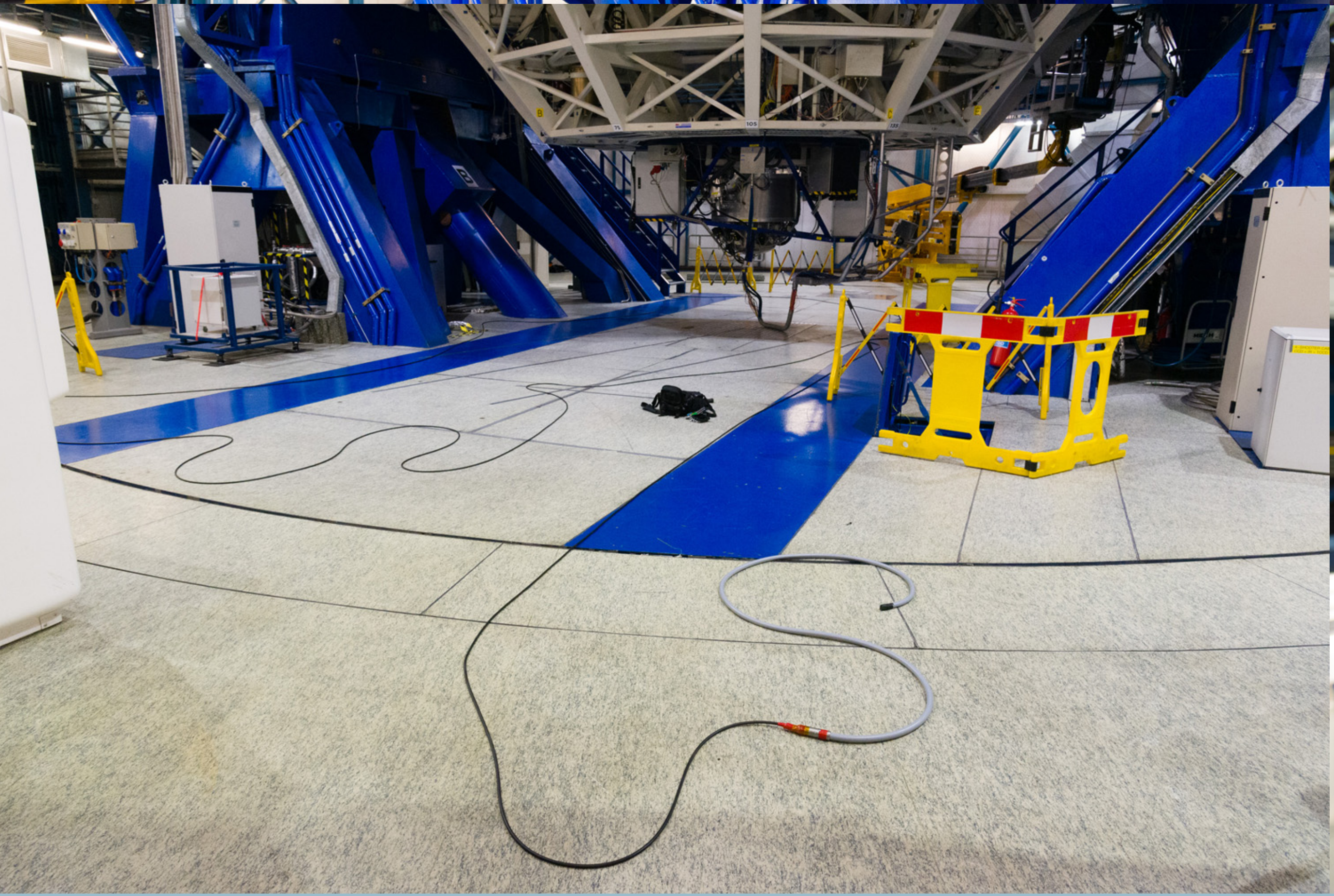
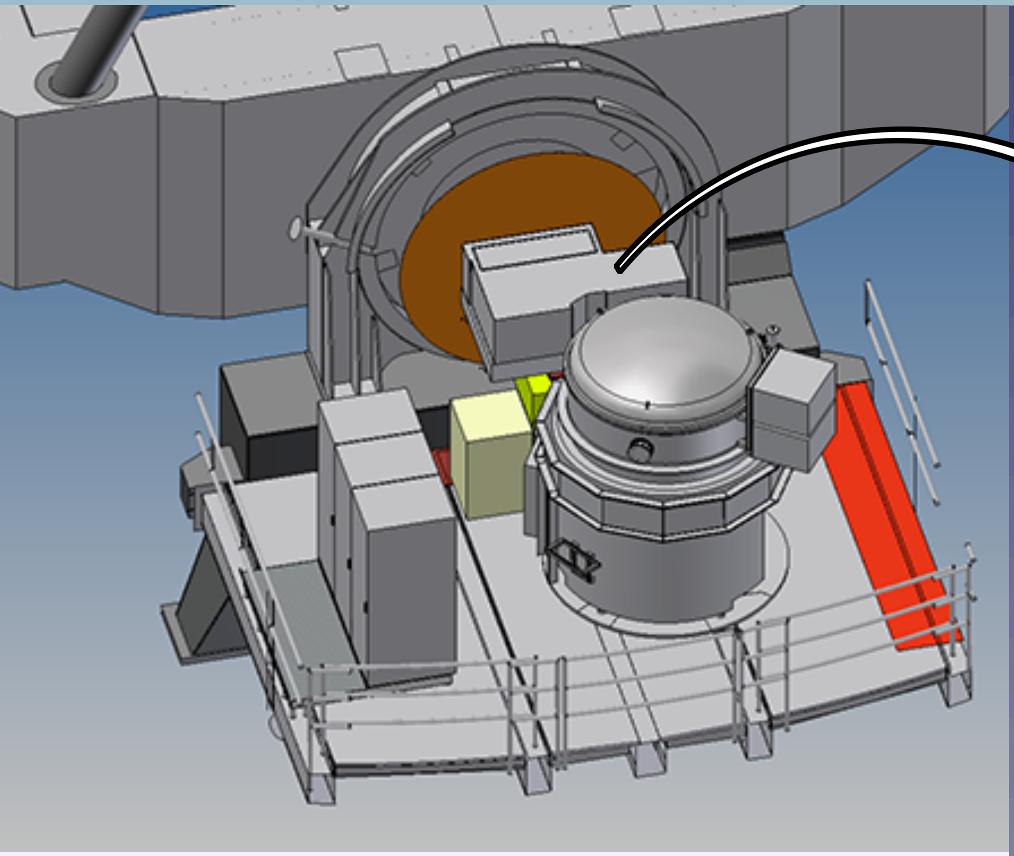
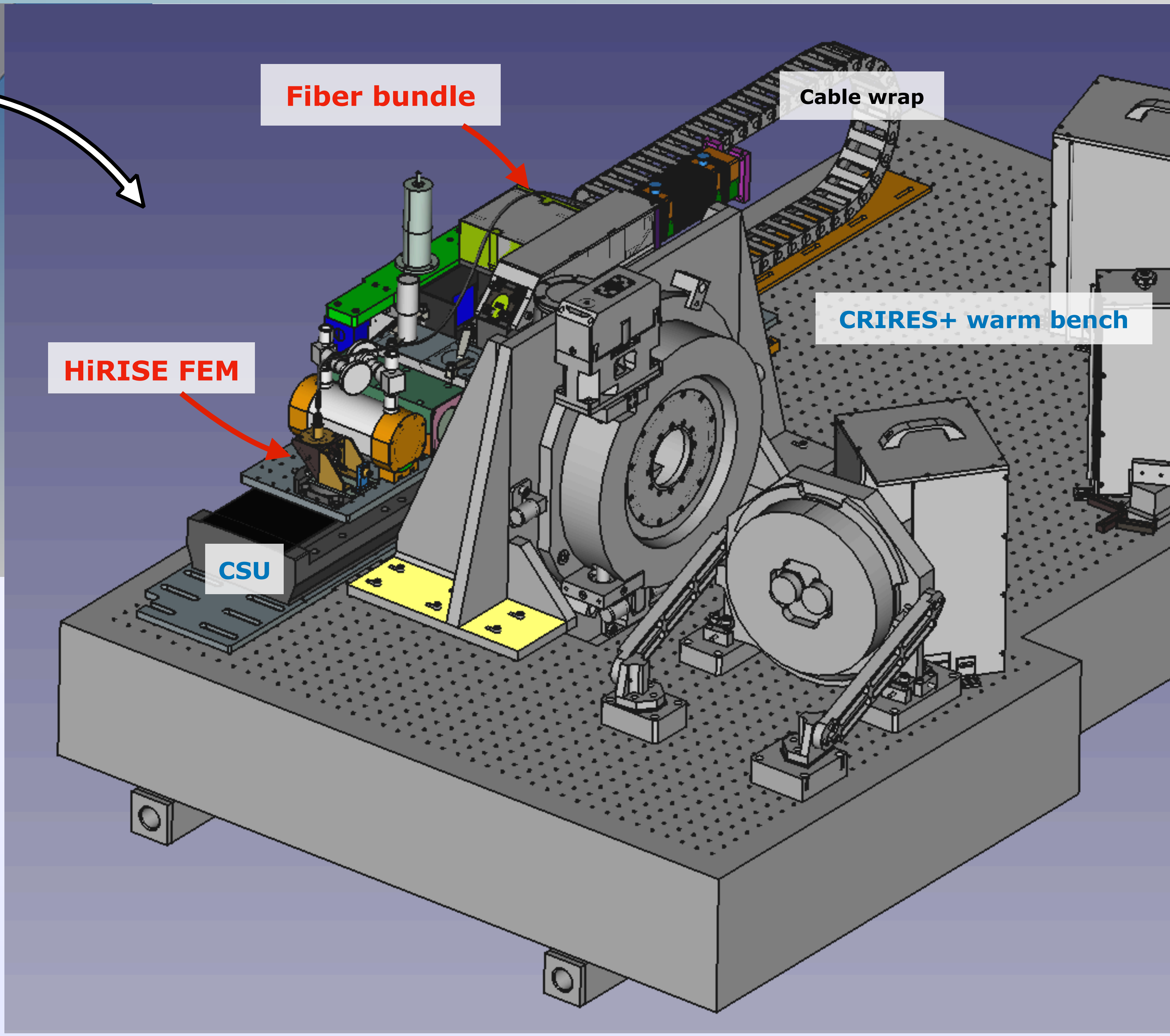


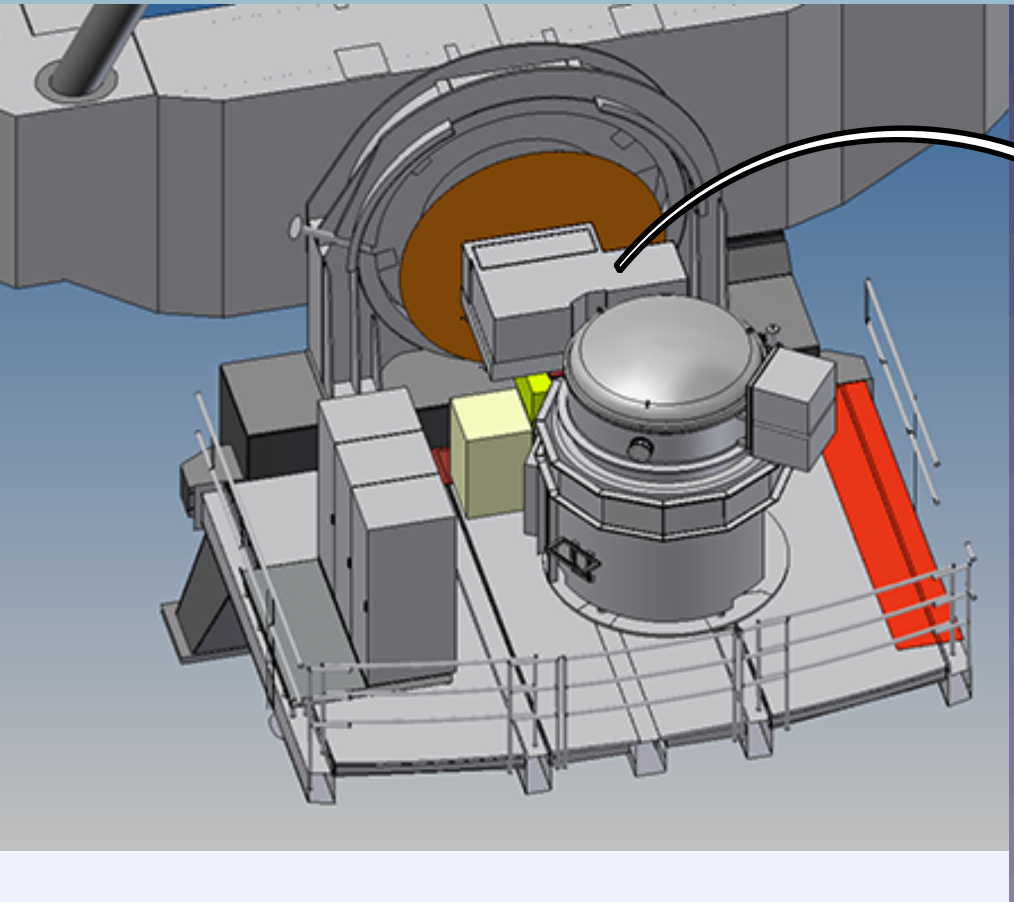


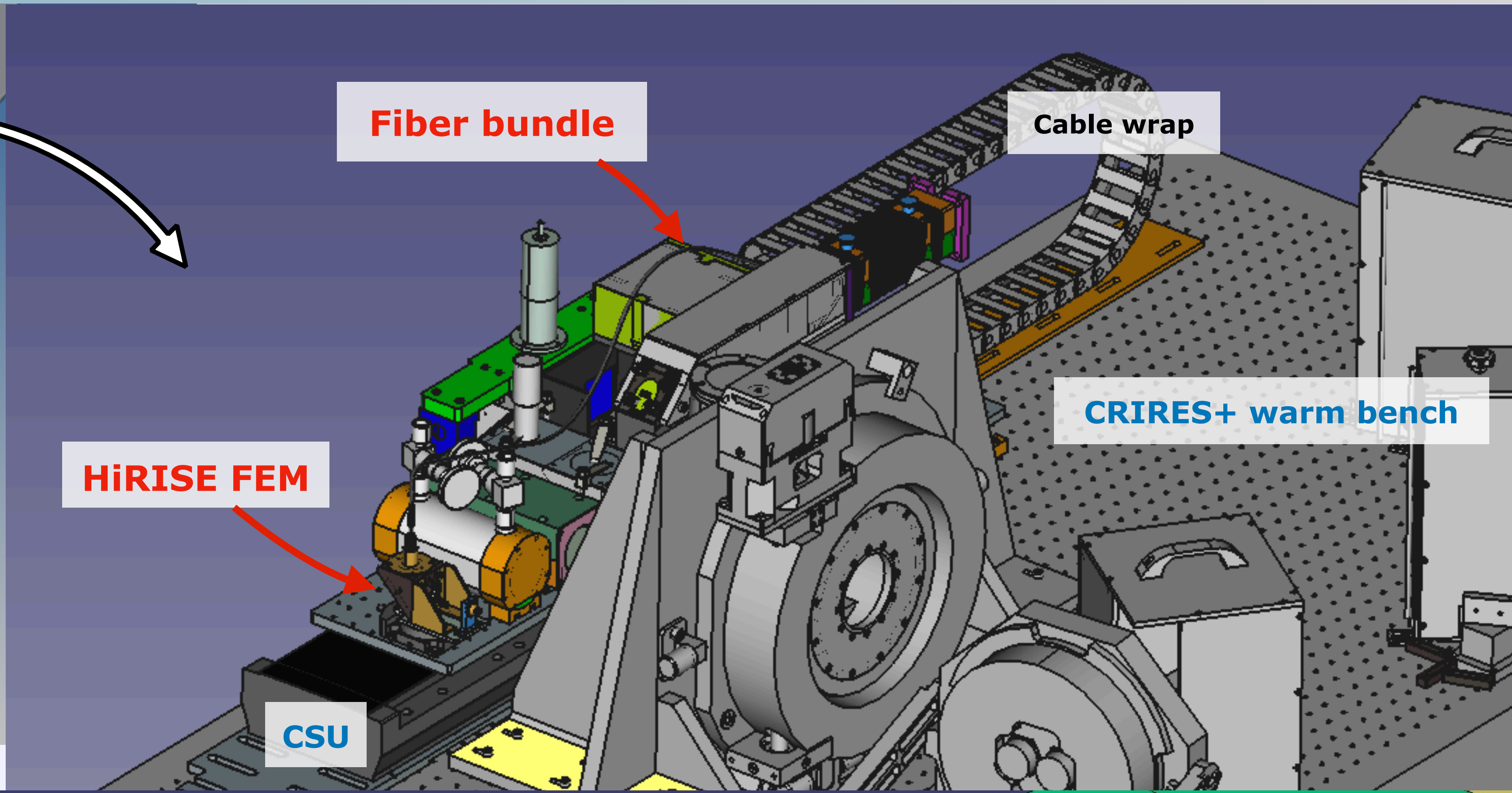
Fiber extraction module

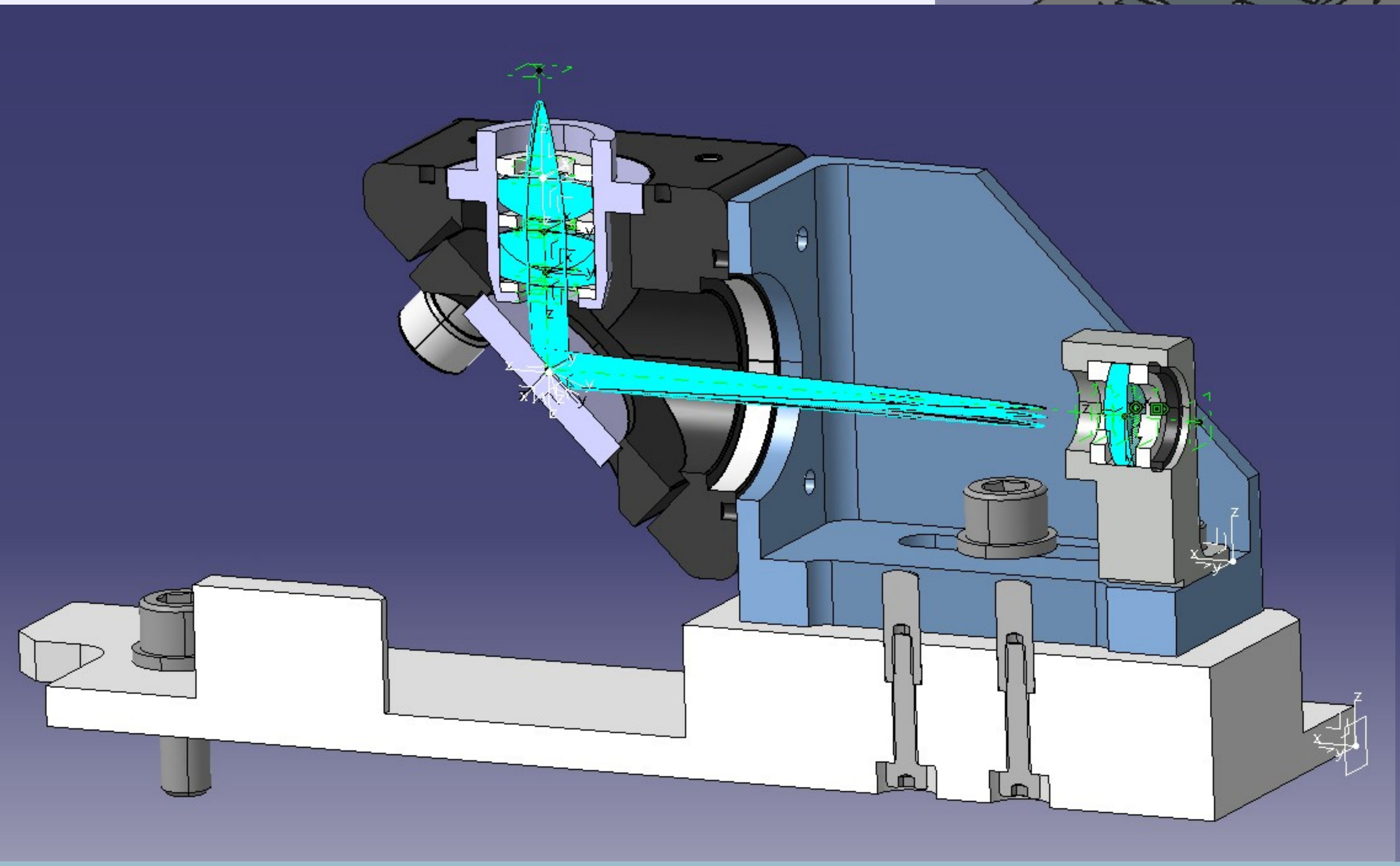


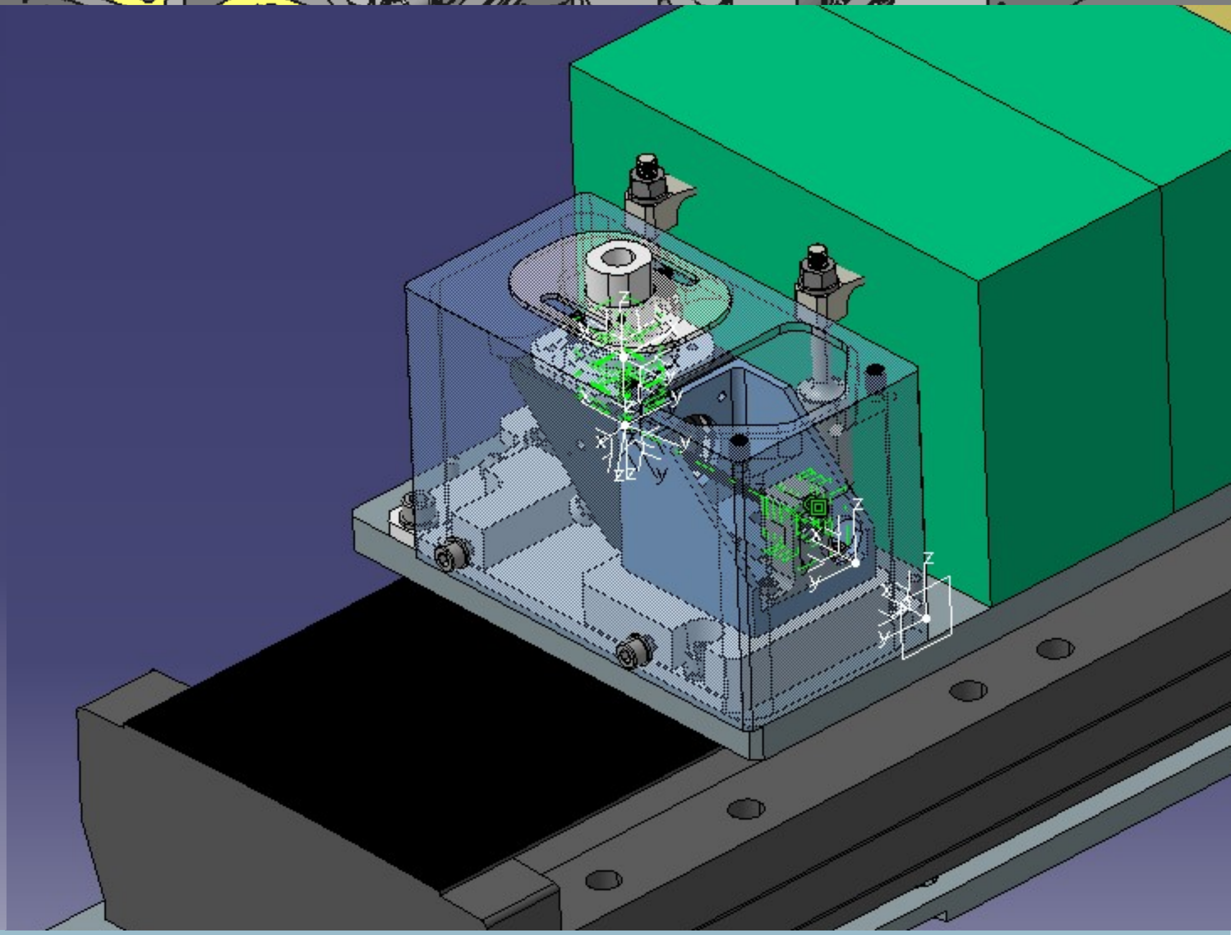


Fiber extraction module

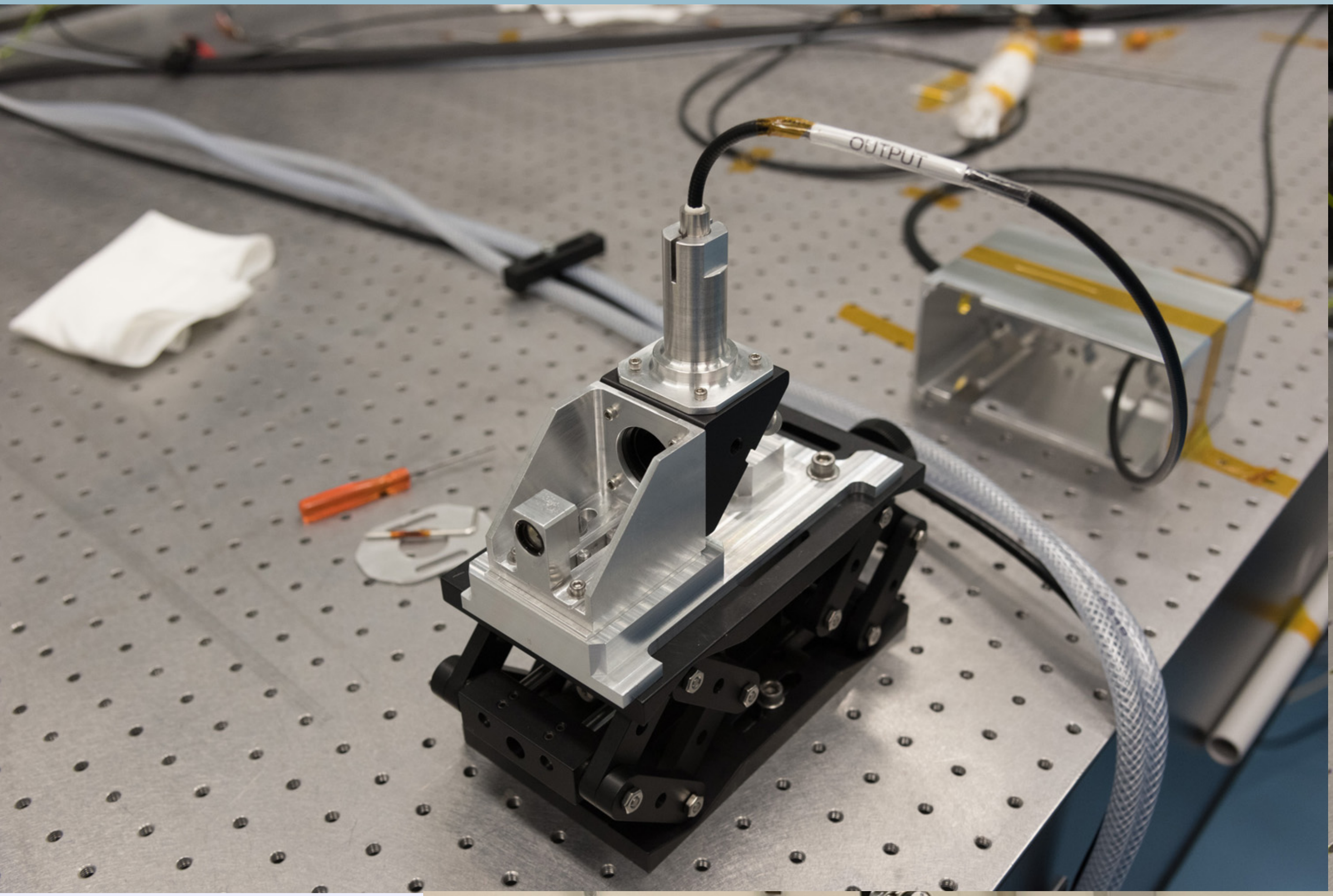


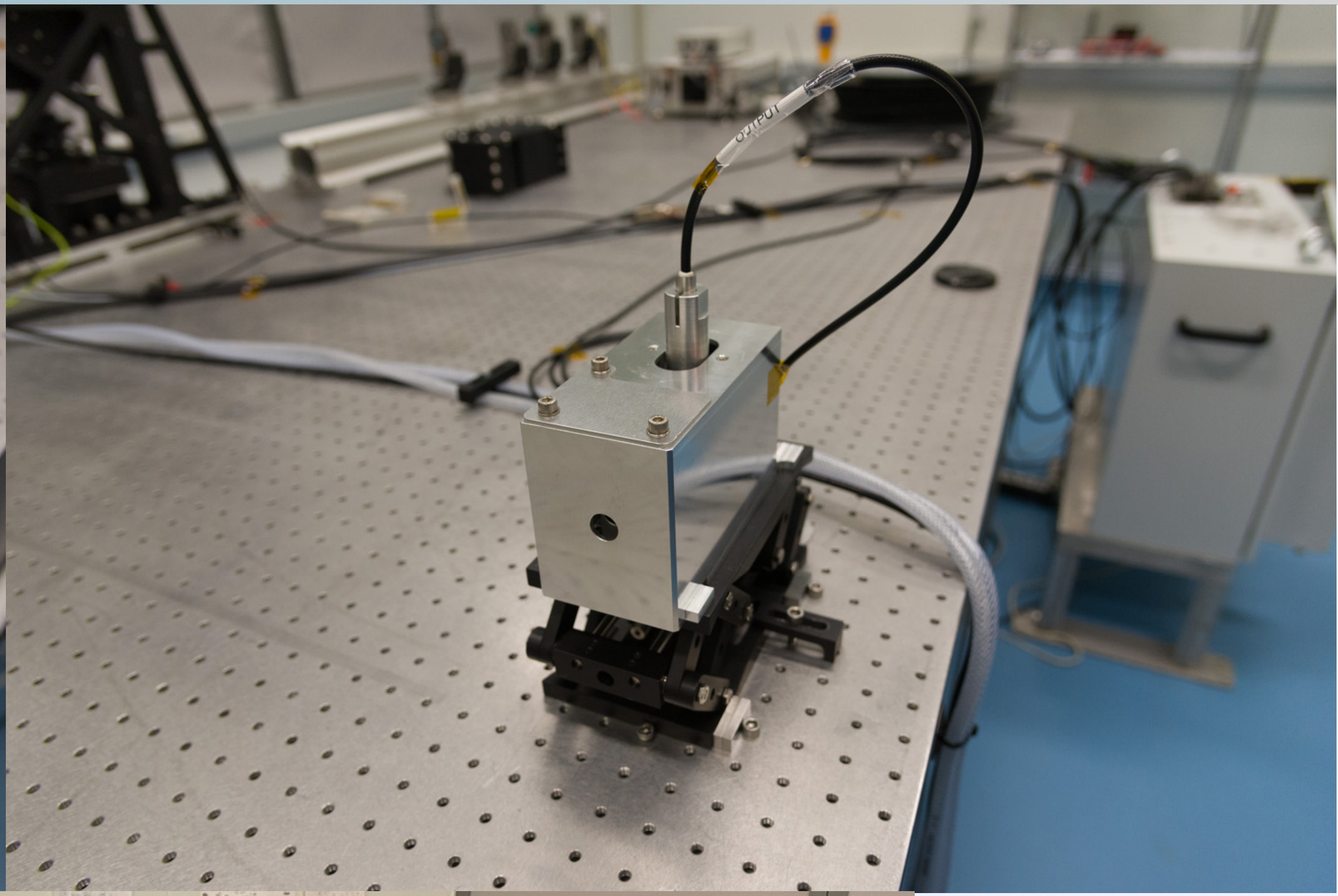


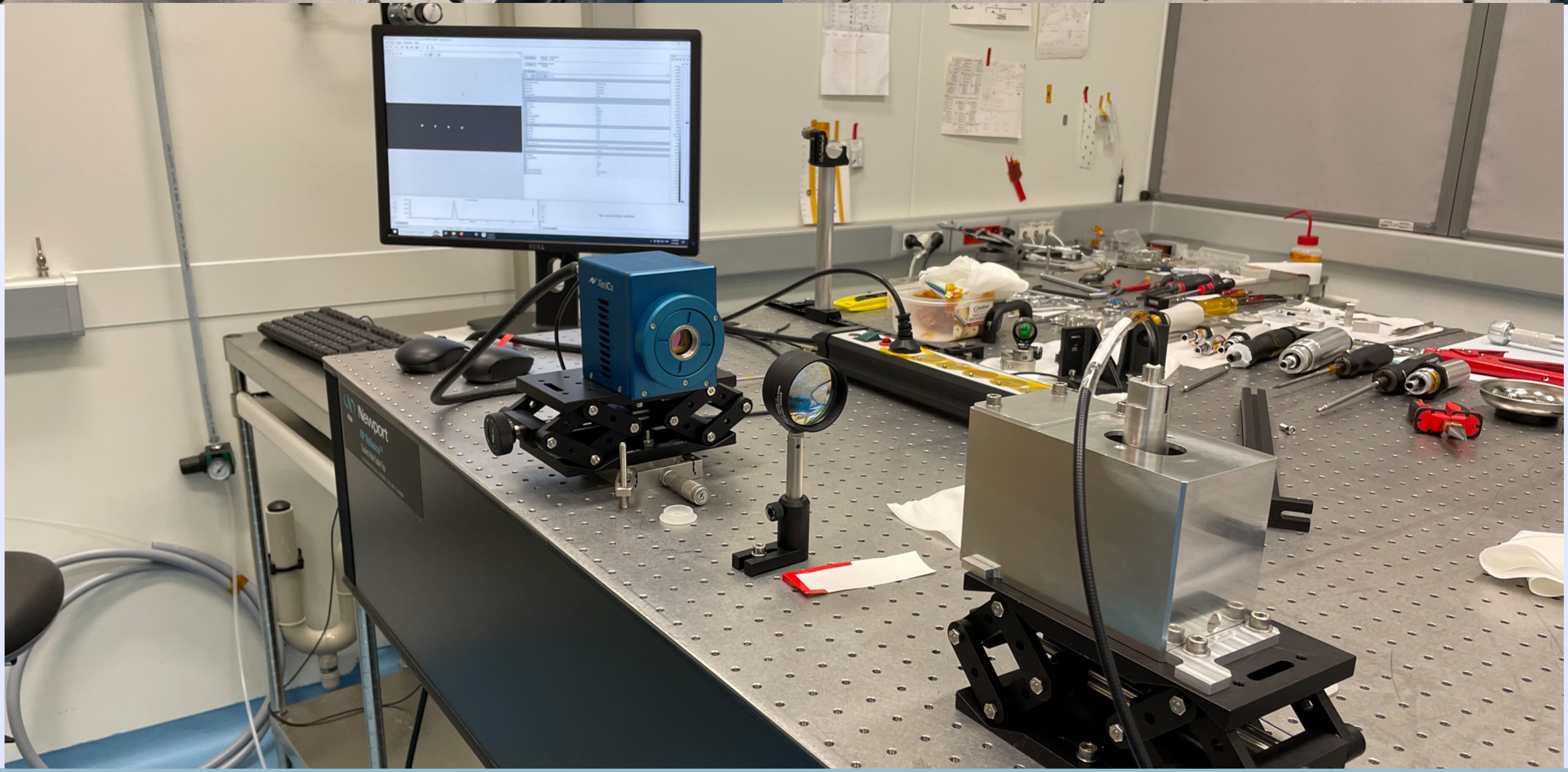




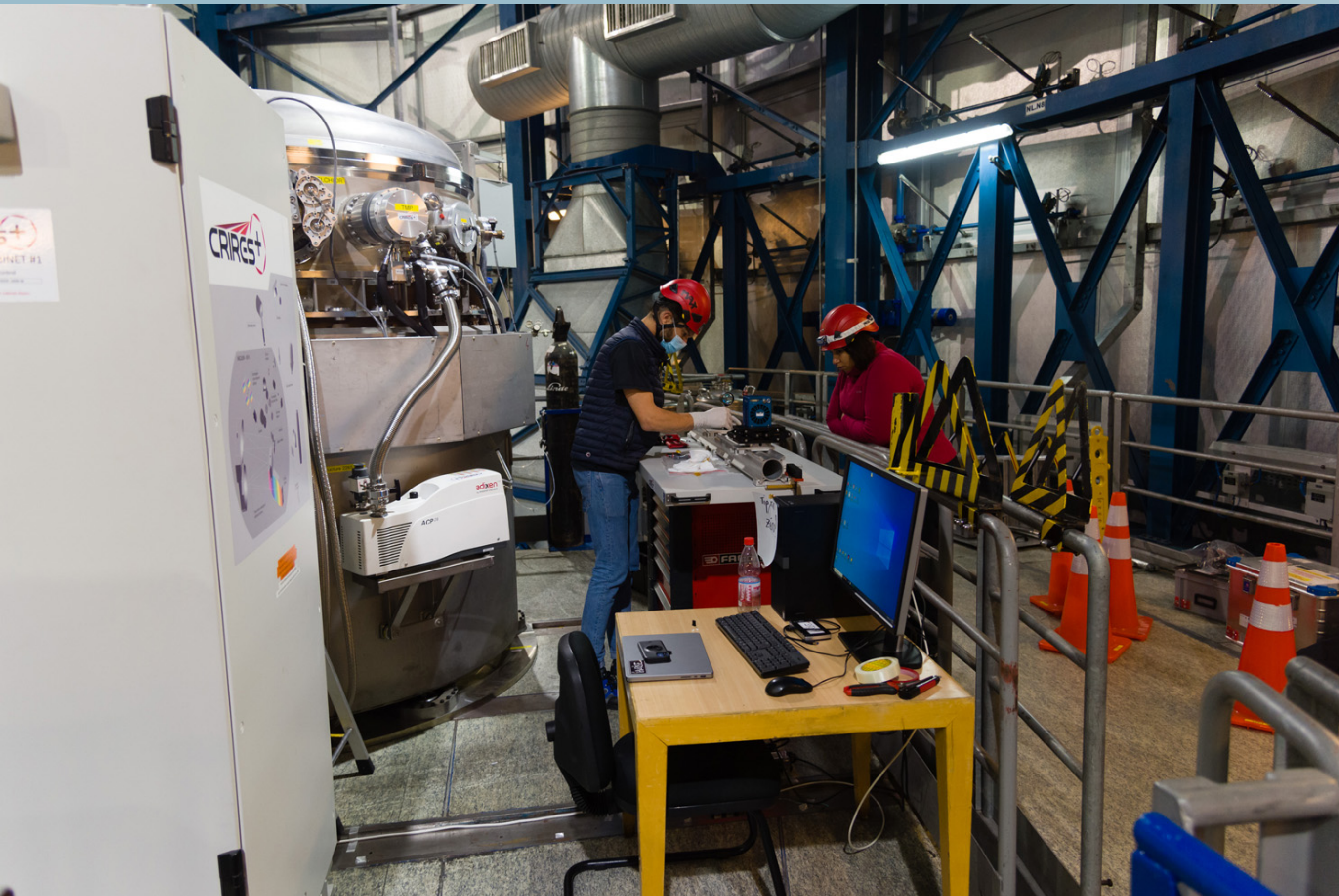
Fiber extraction module

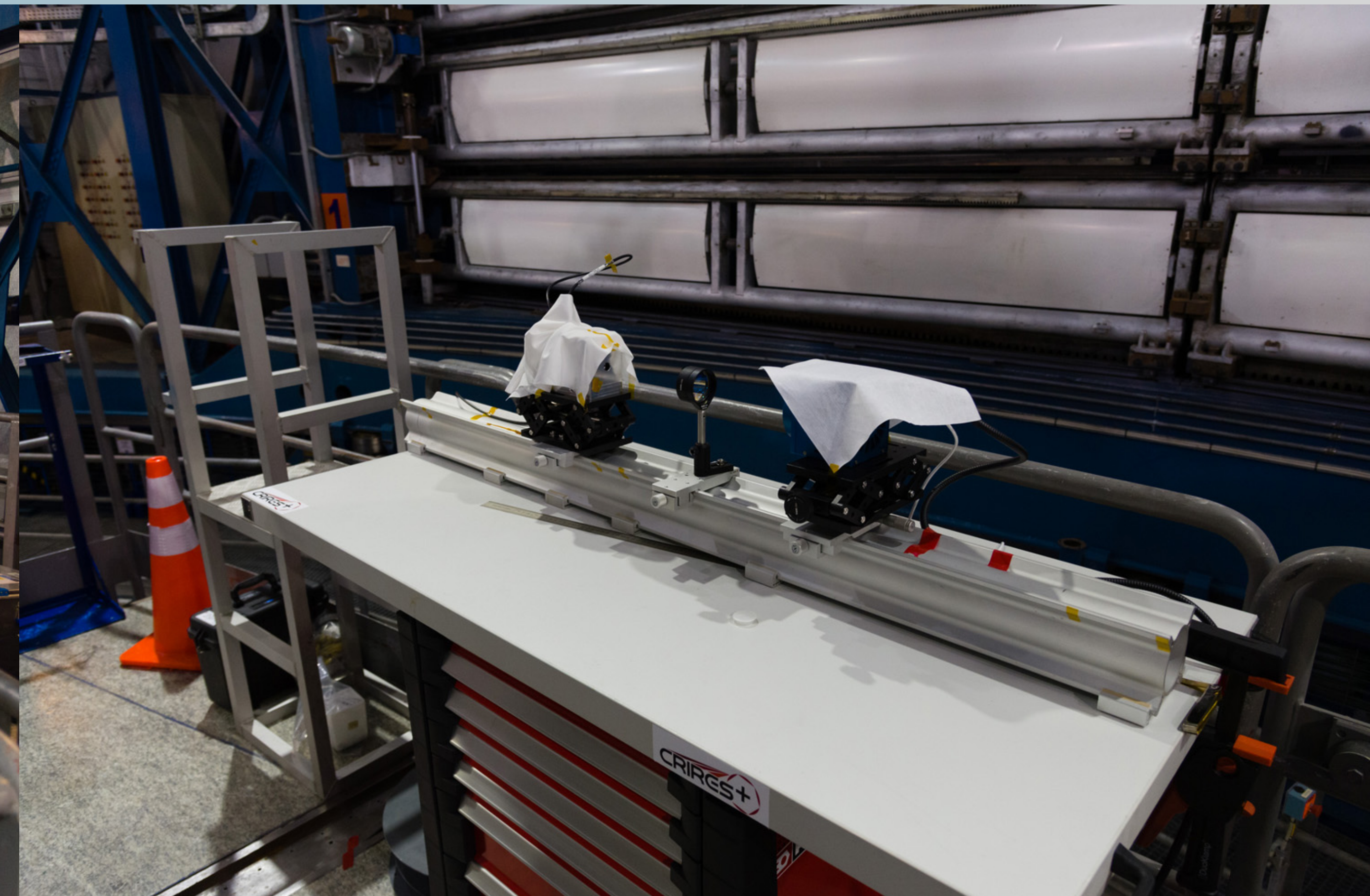




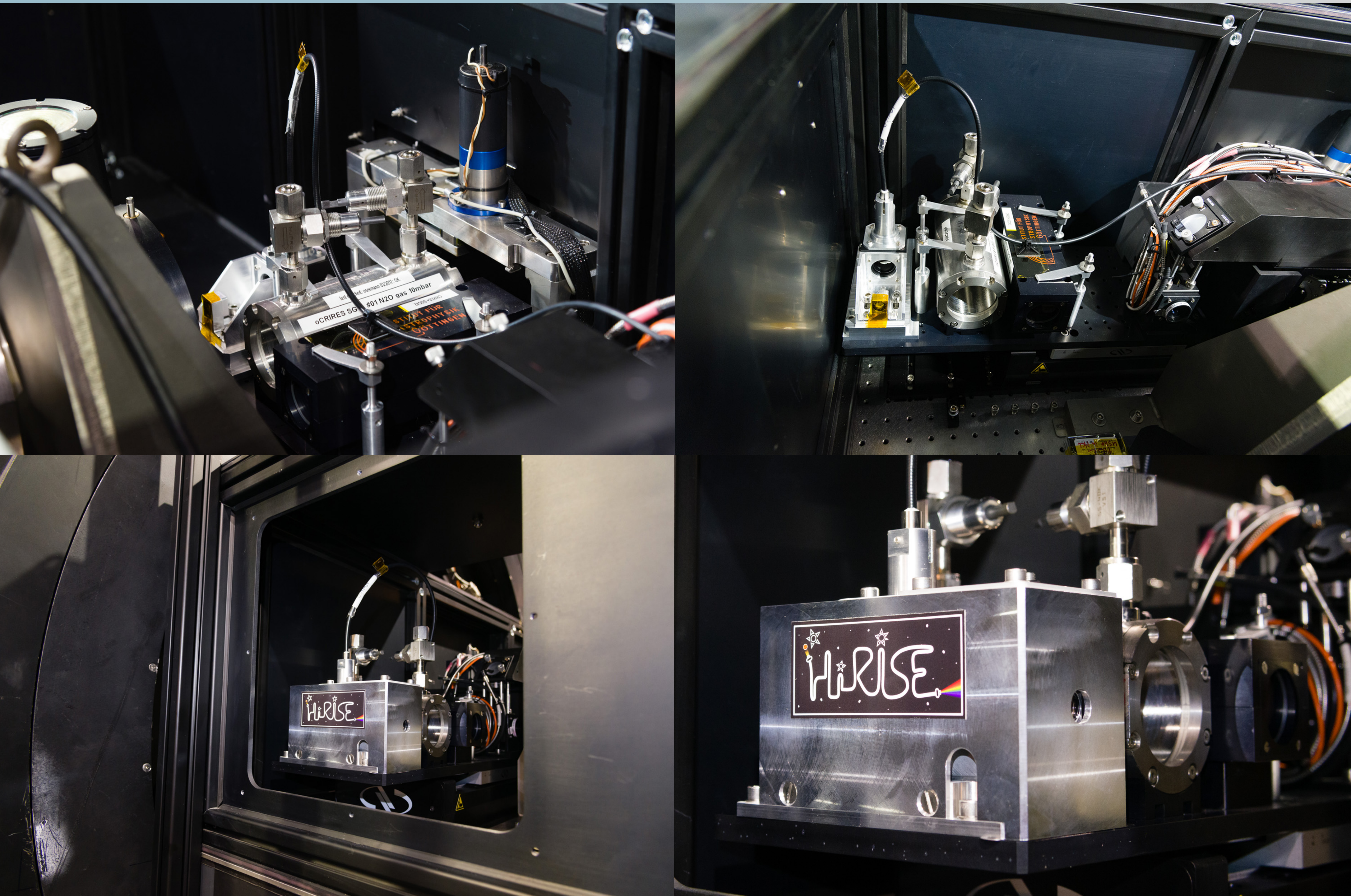


Fiber extraction module

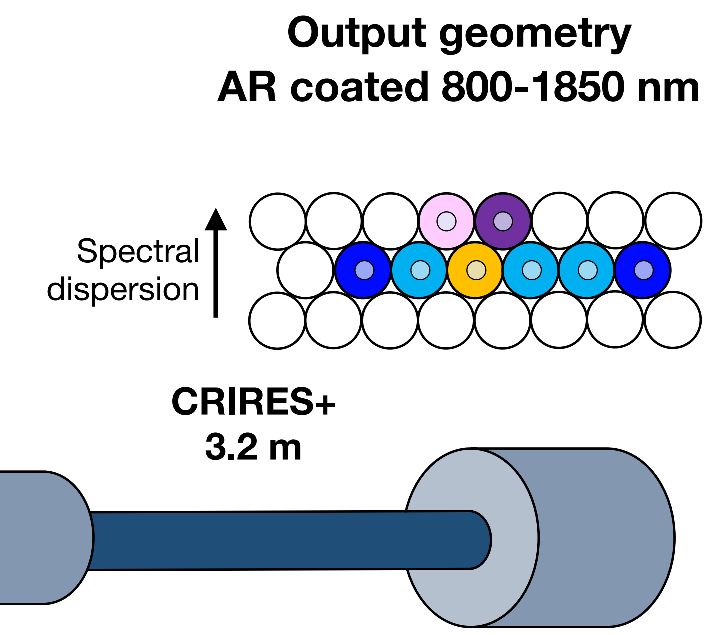


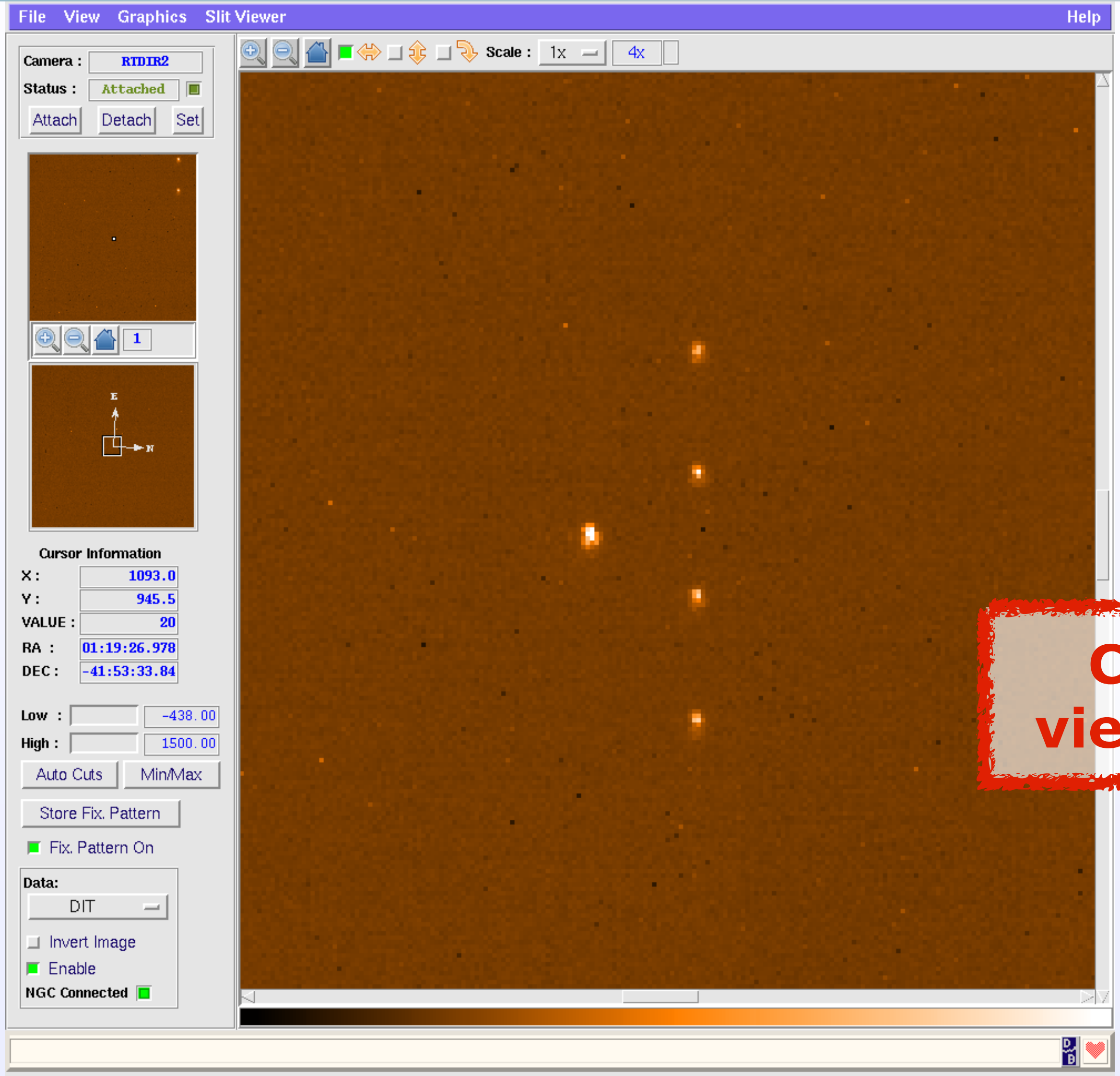


Fiber extraction module



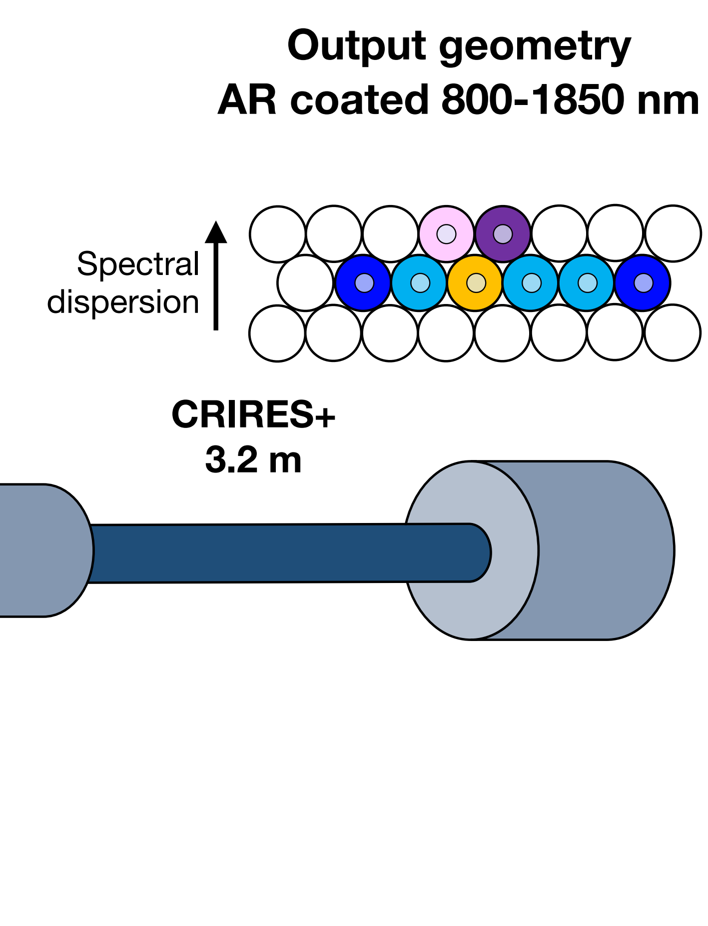
Light into the CRIRES spectrograph

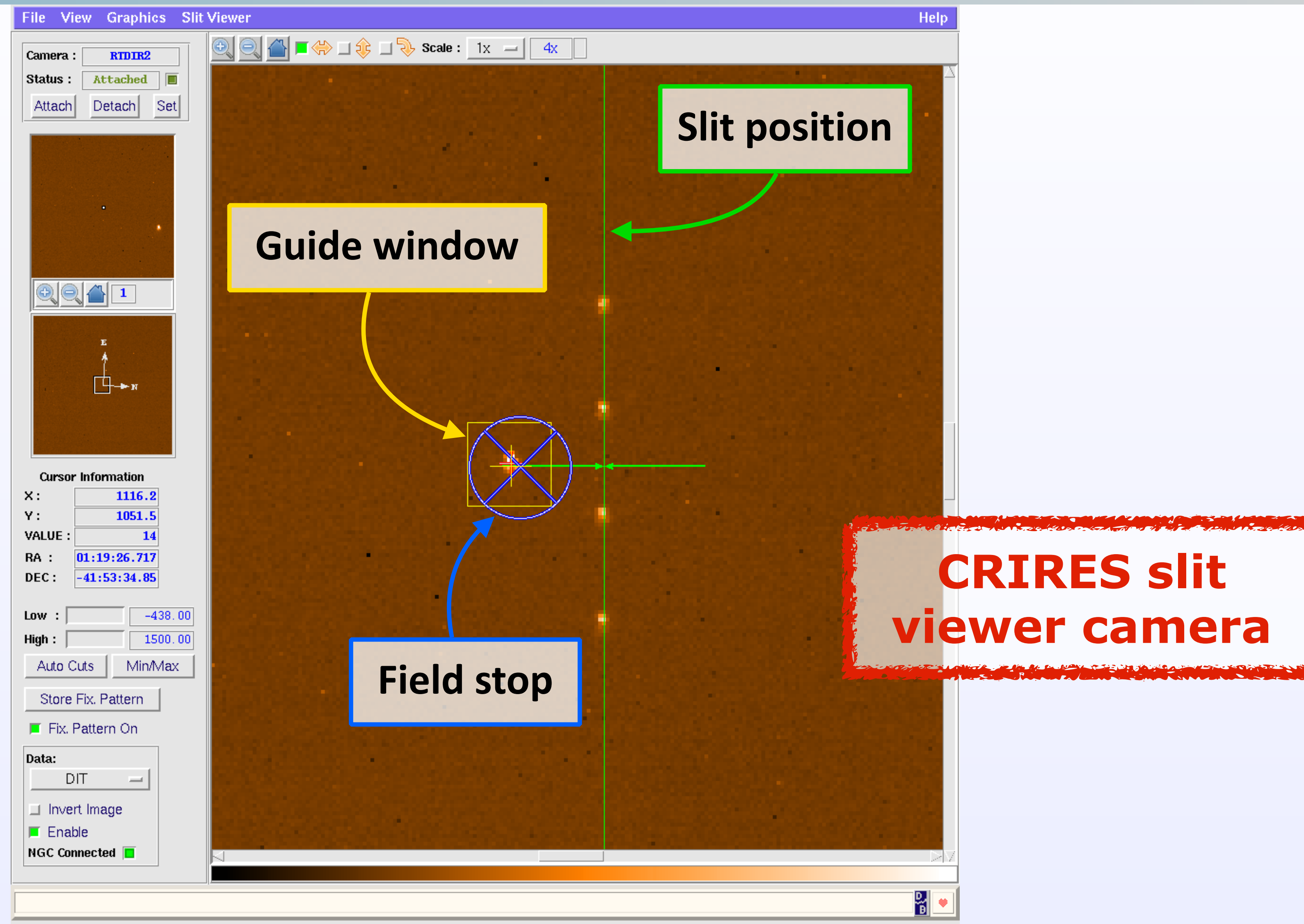




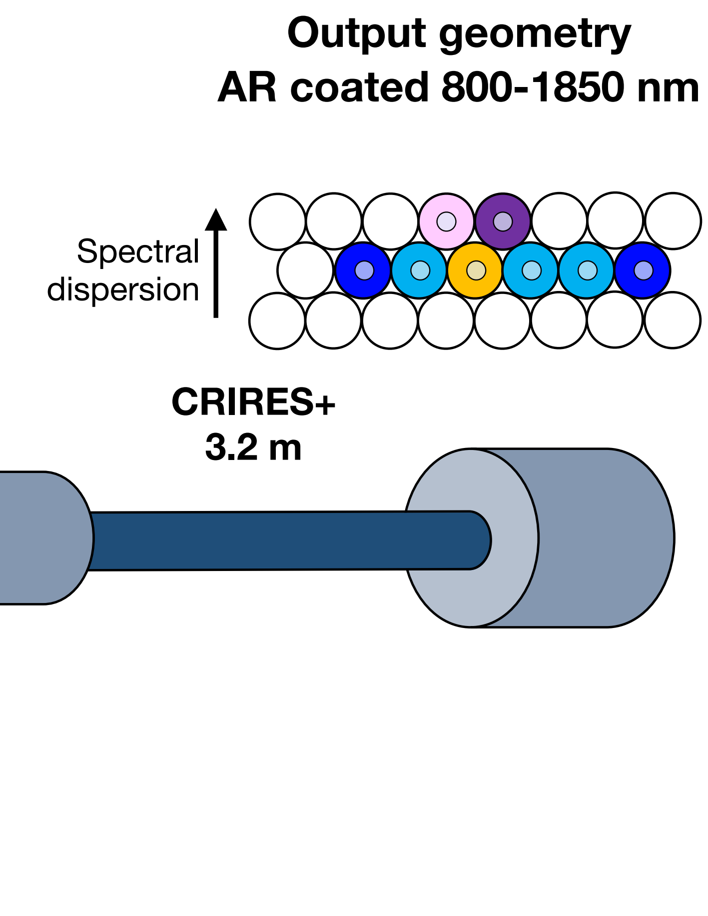
CRIRES slit viewer camera

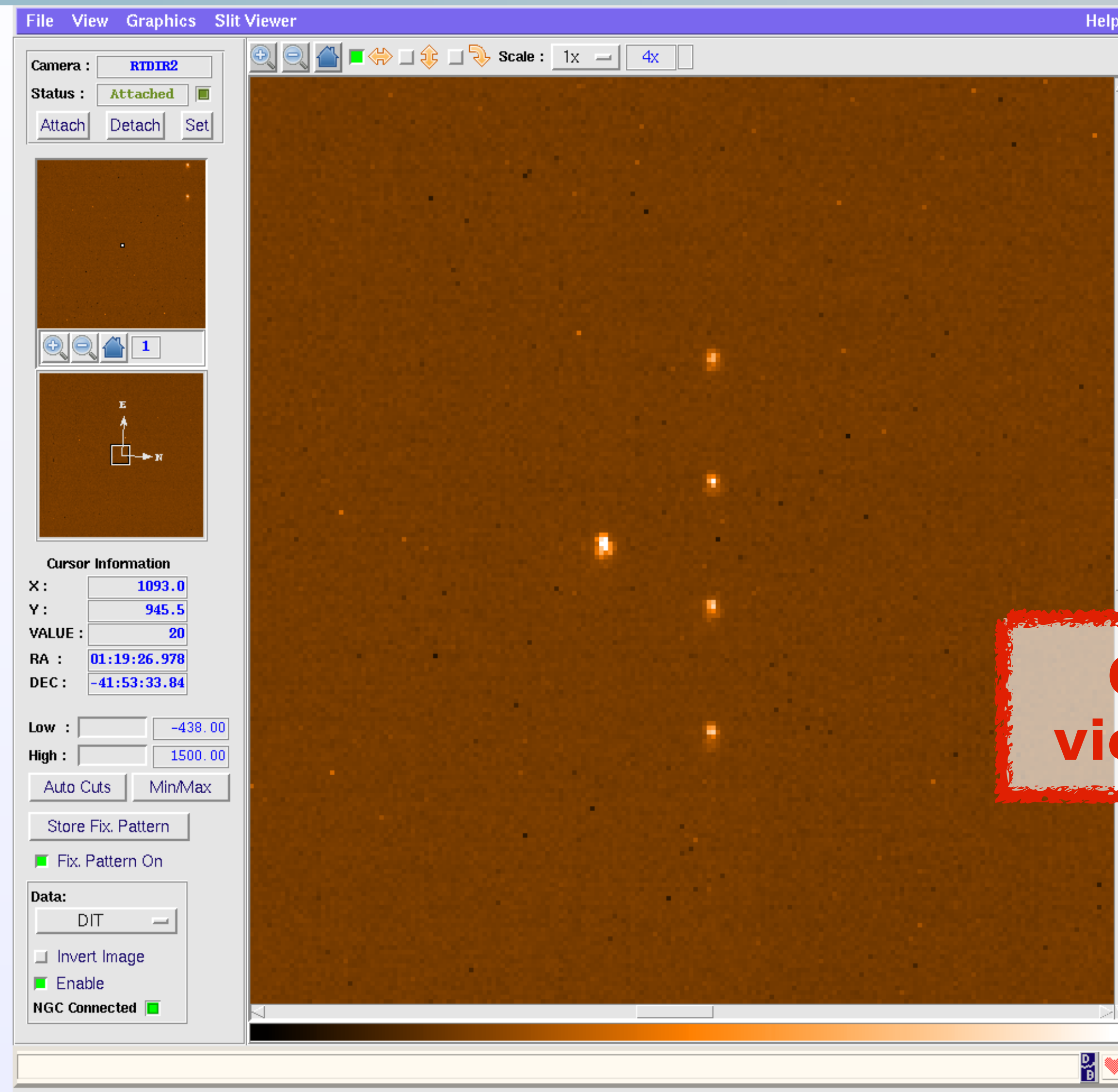
Light into the CRIRES spectrograph





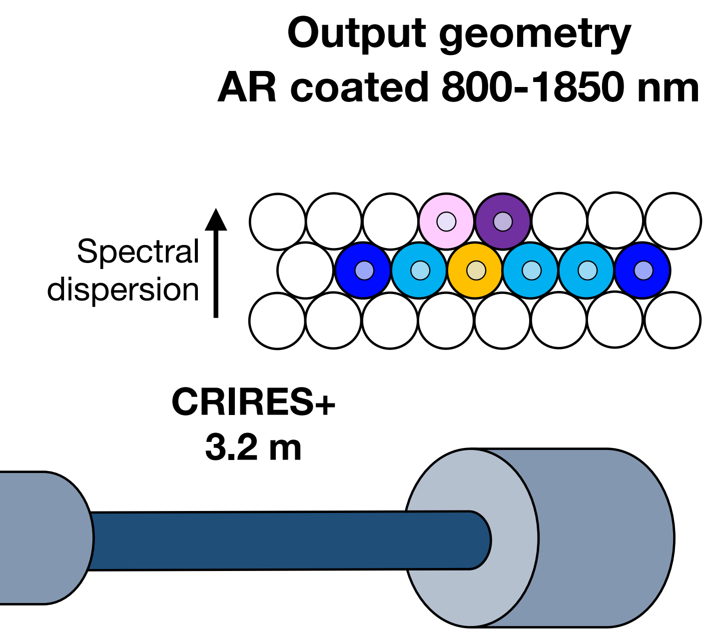
Light into the CRIRES spectrograph

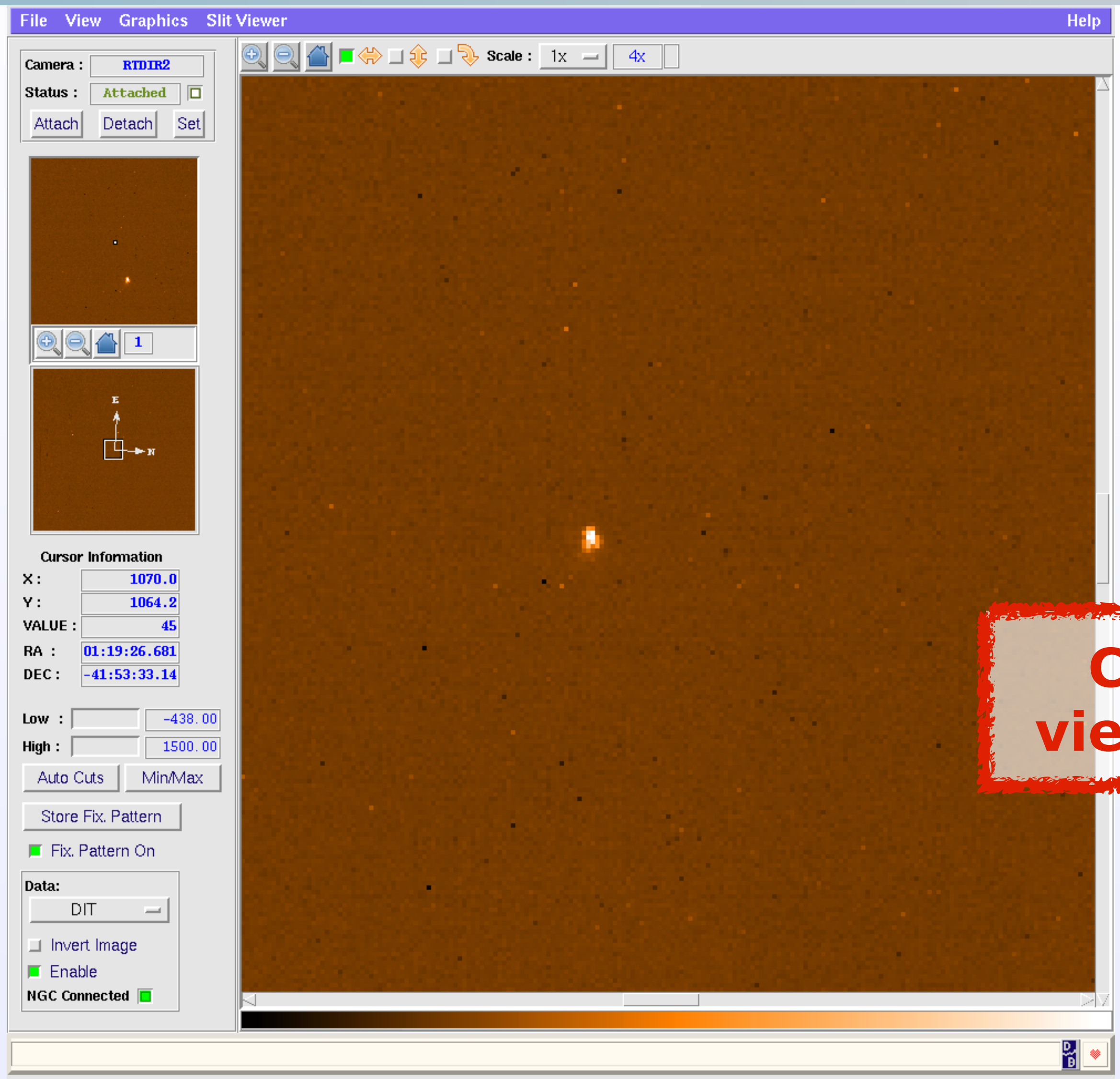




CRIRES slit viewer camera

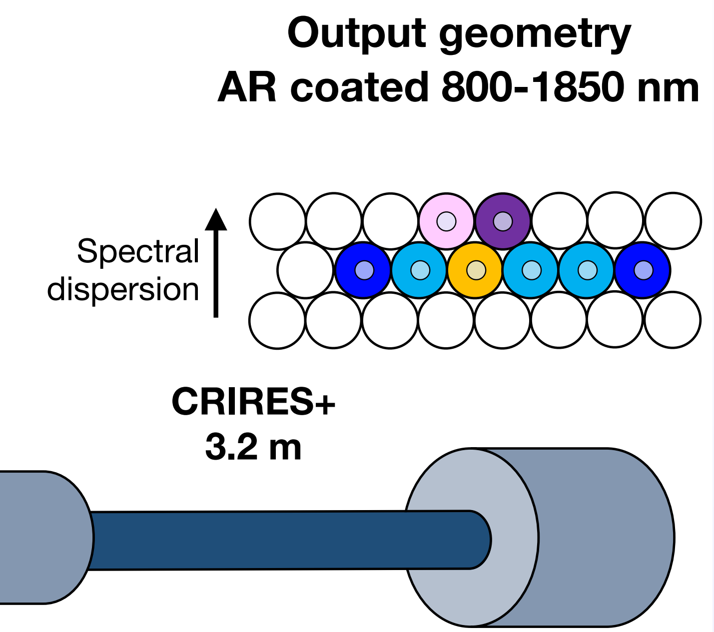
Light into the CRIRES spectrograph

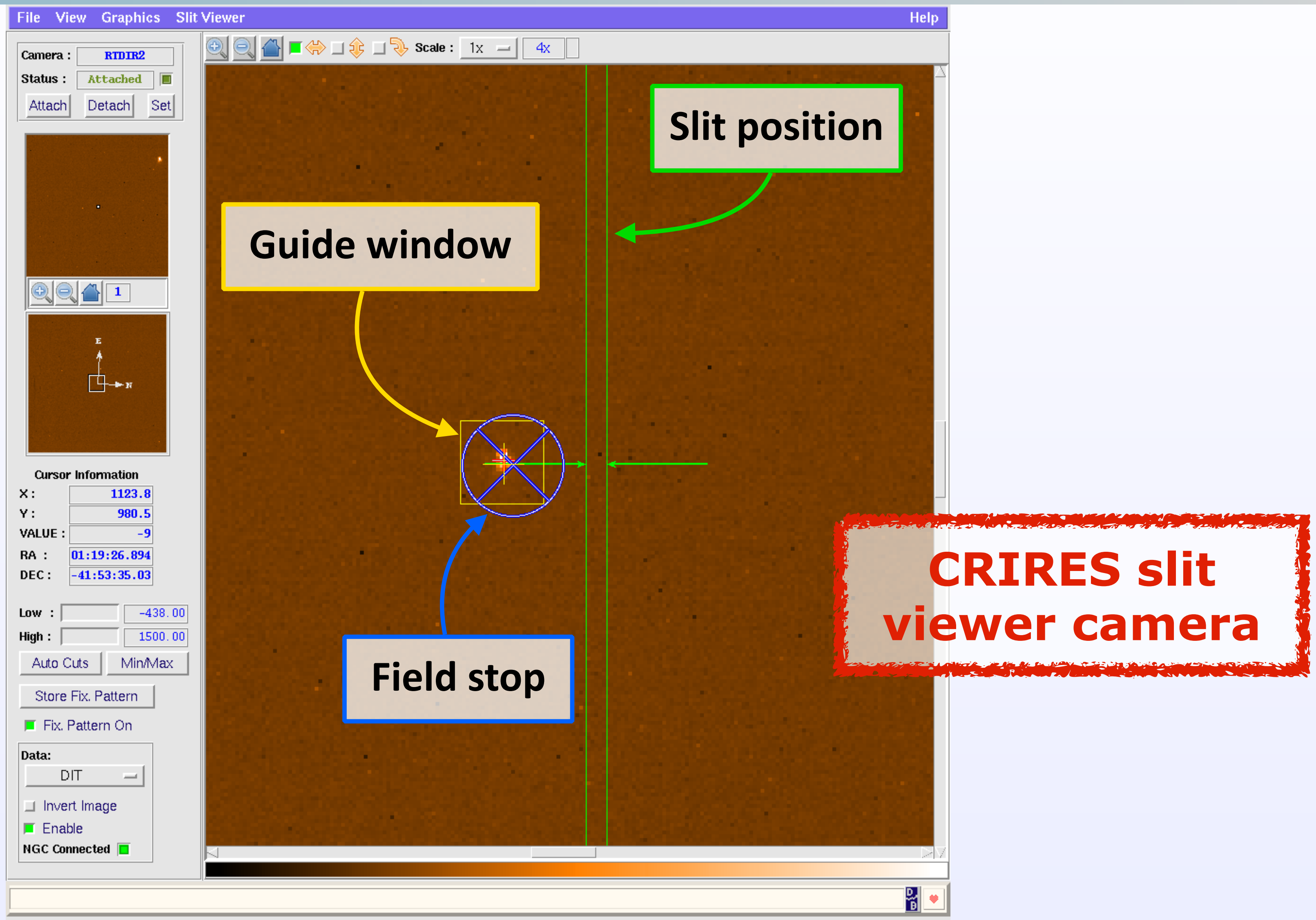




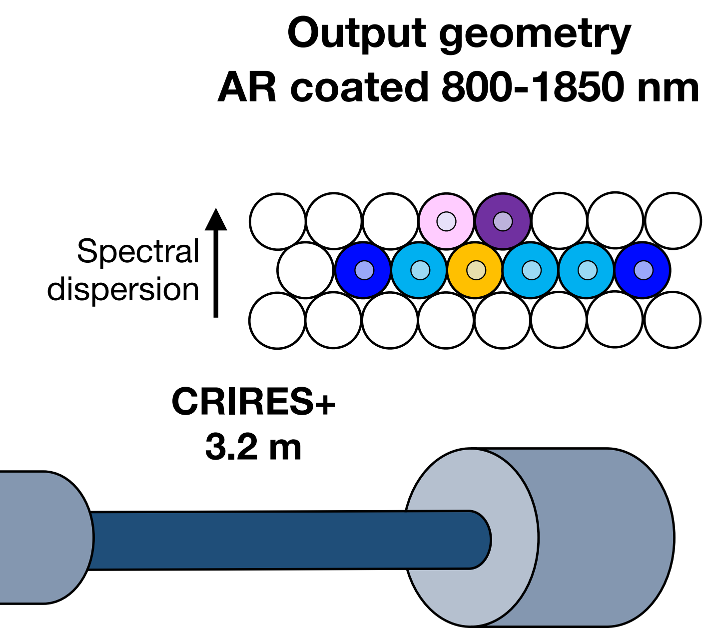
CRIRES slit viewer camera

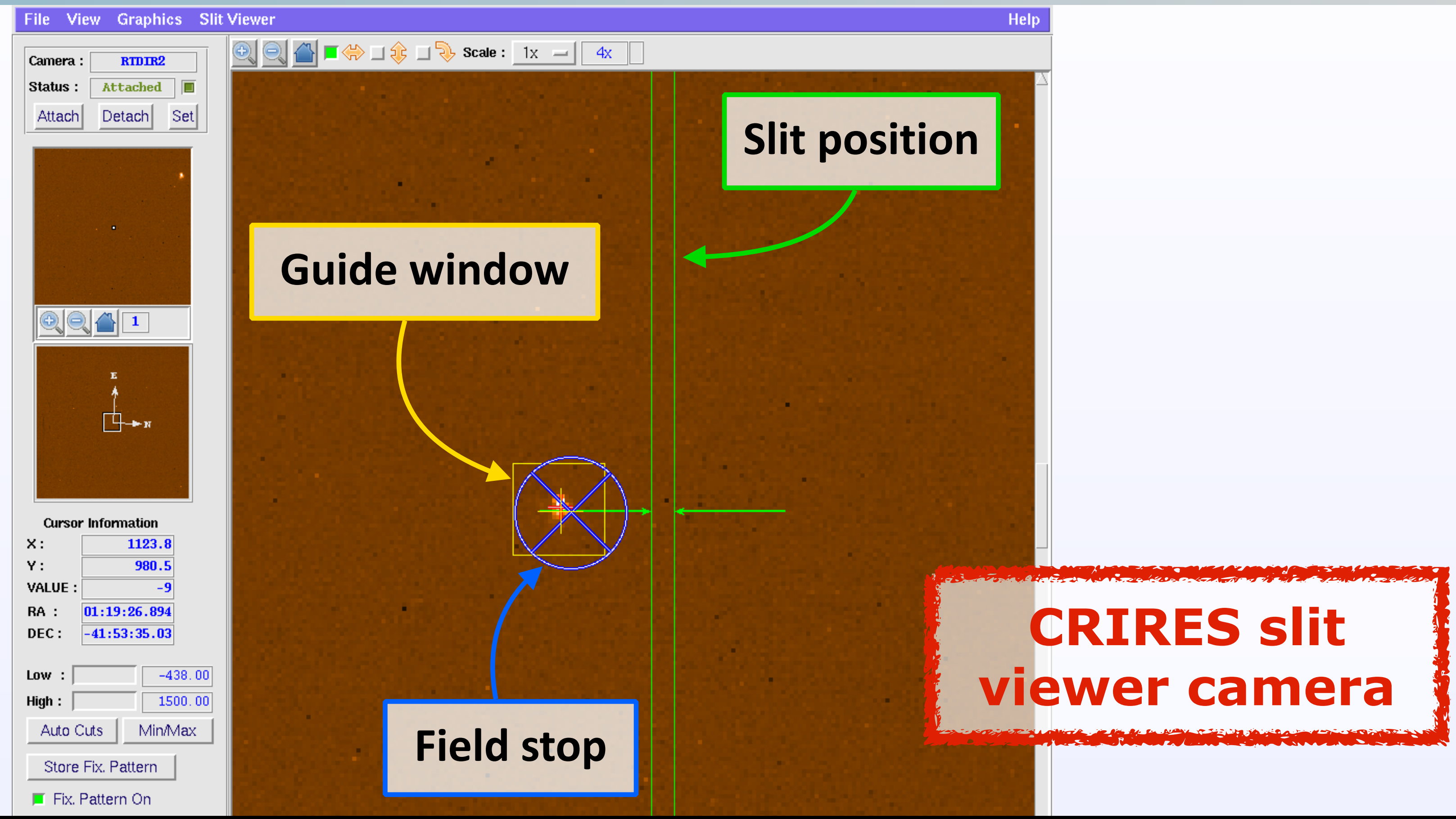
Light into the CRIRES spectrograph

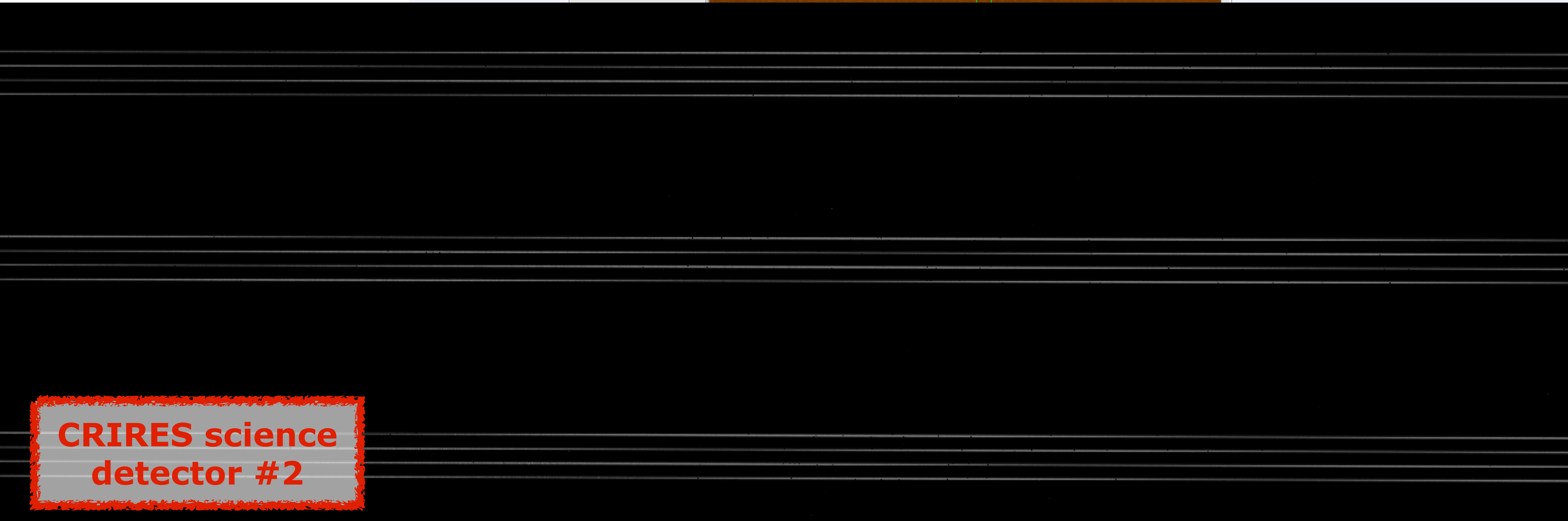




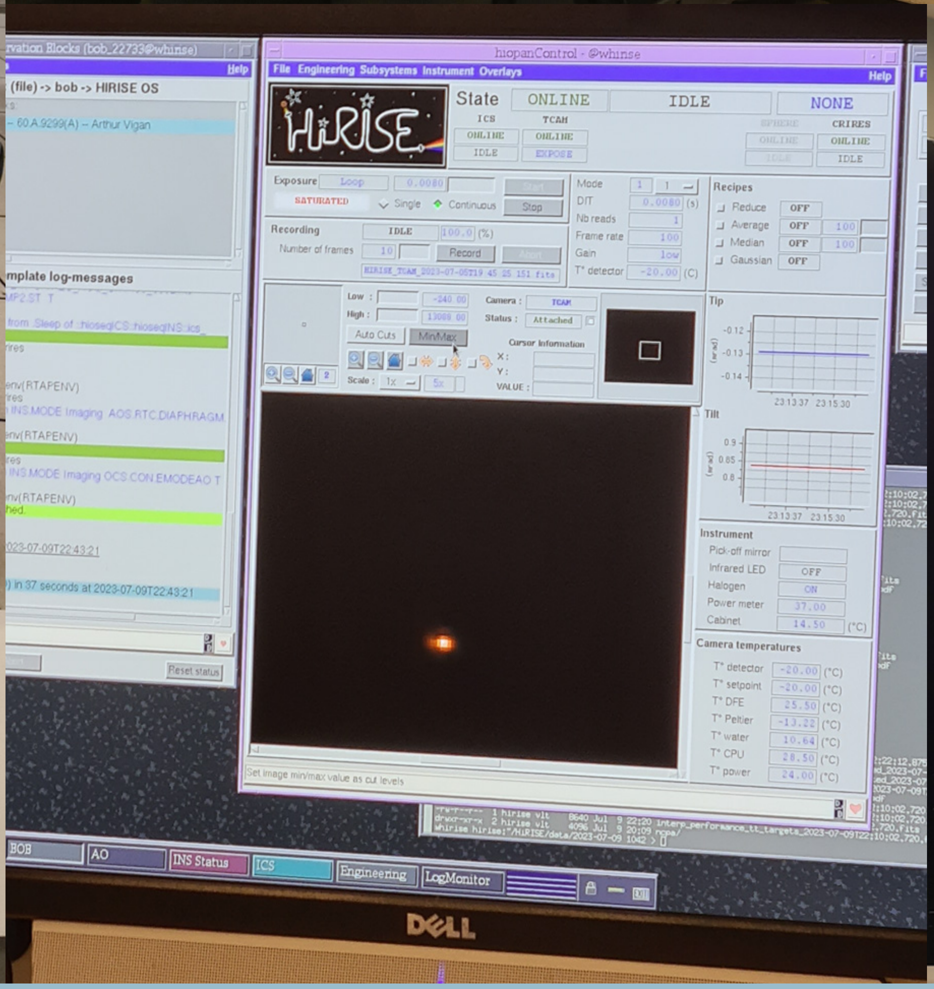
Light into the CRIRES spectrograph

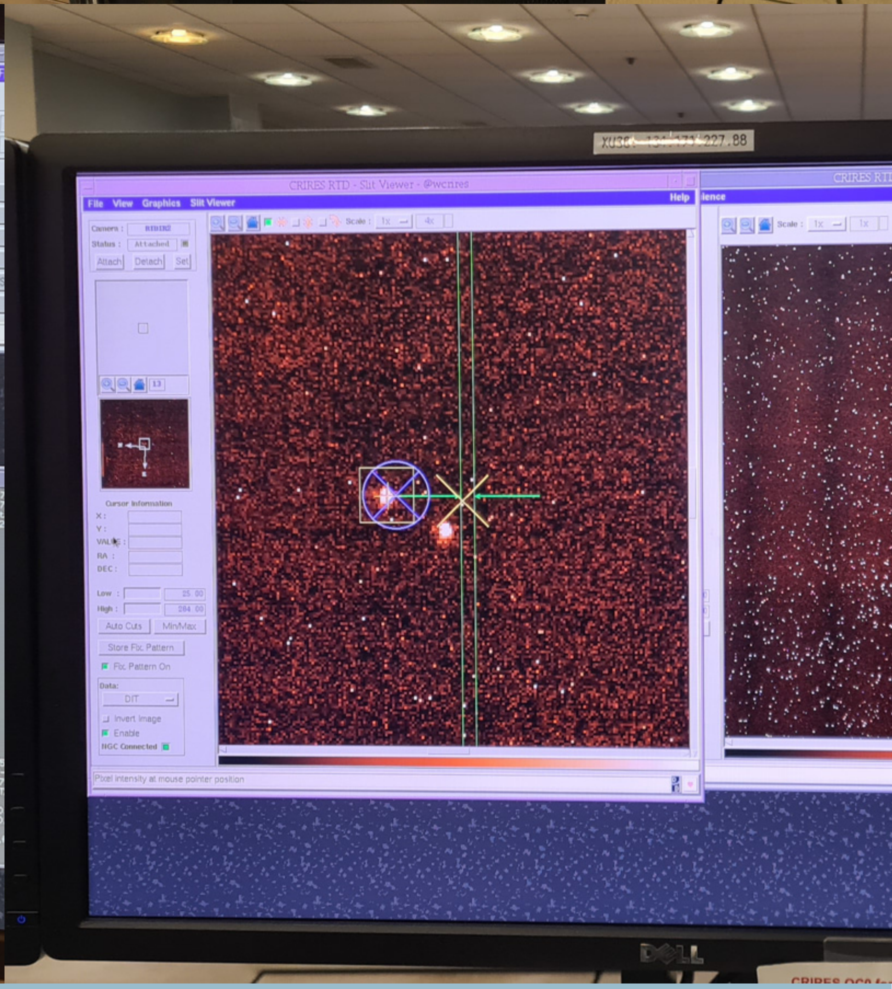






First light!





First light!

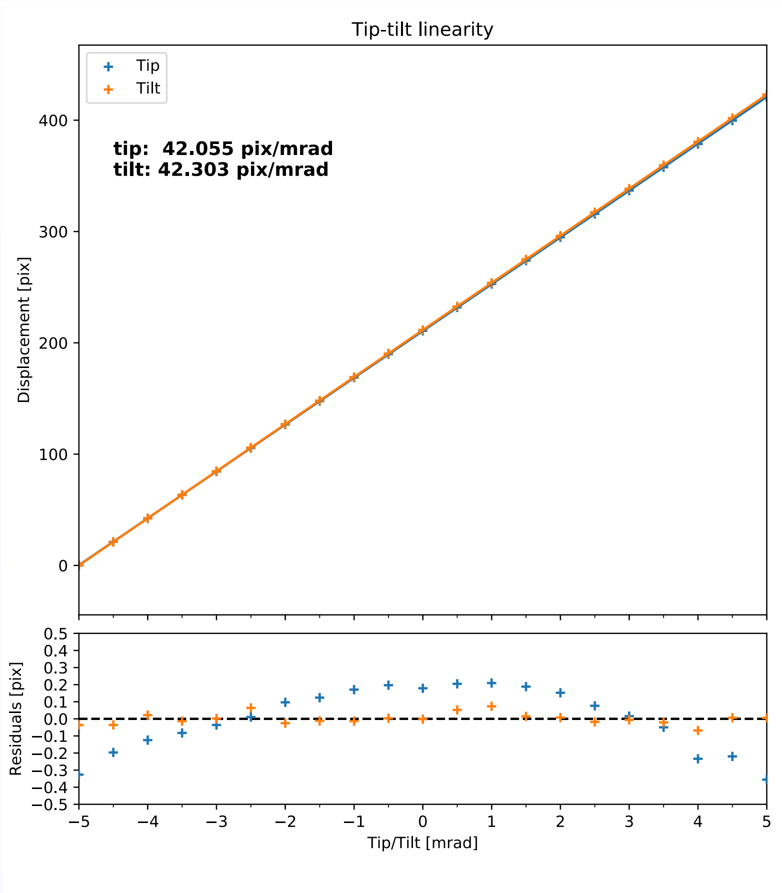
Operations: daytime calibrations

Daytime

Operations: daytime calibrations

Daytime

Tip-tilt mirror linearity

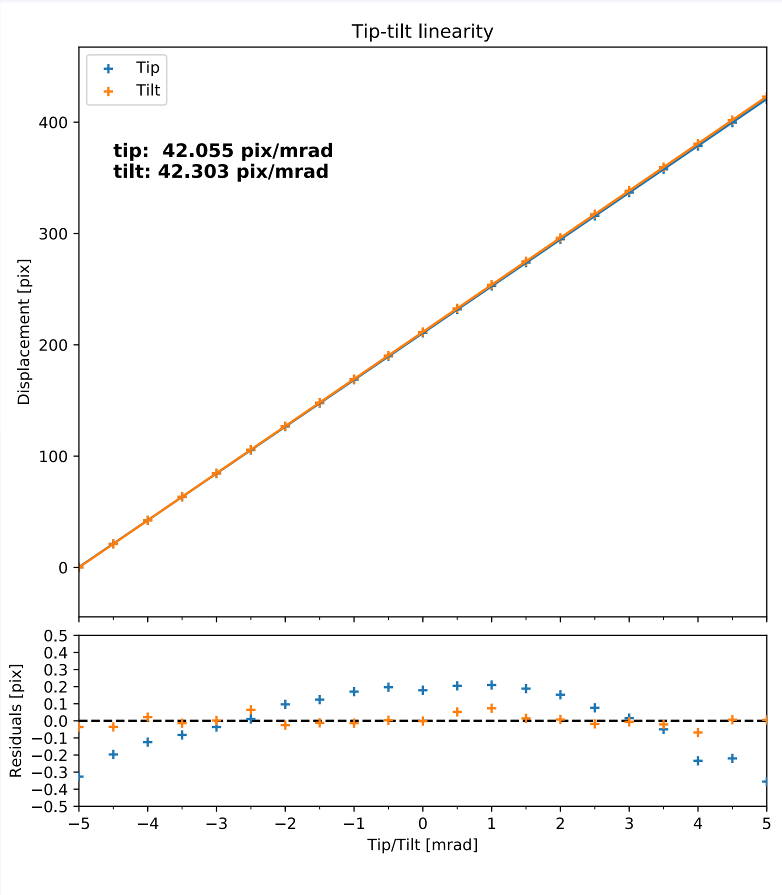


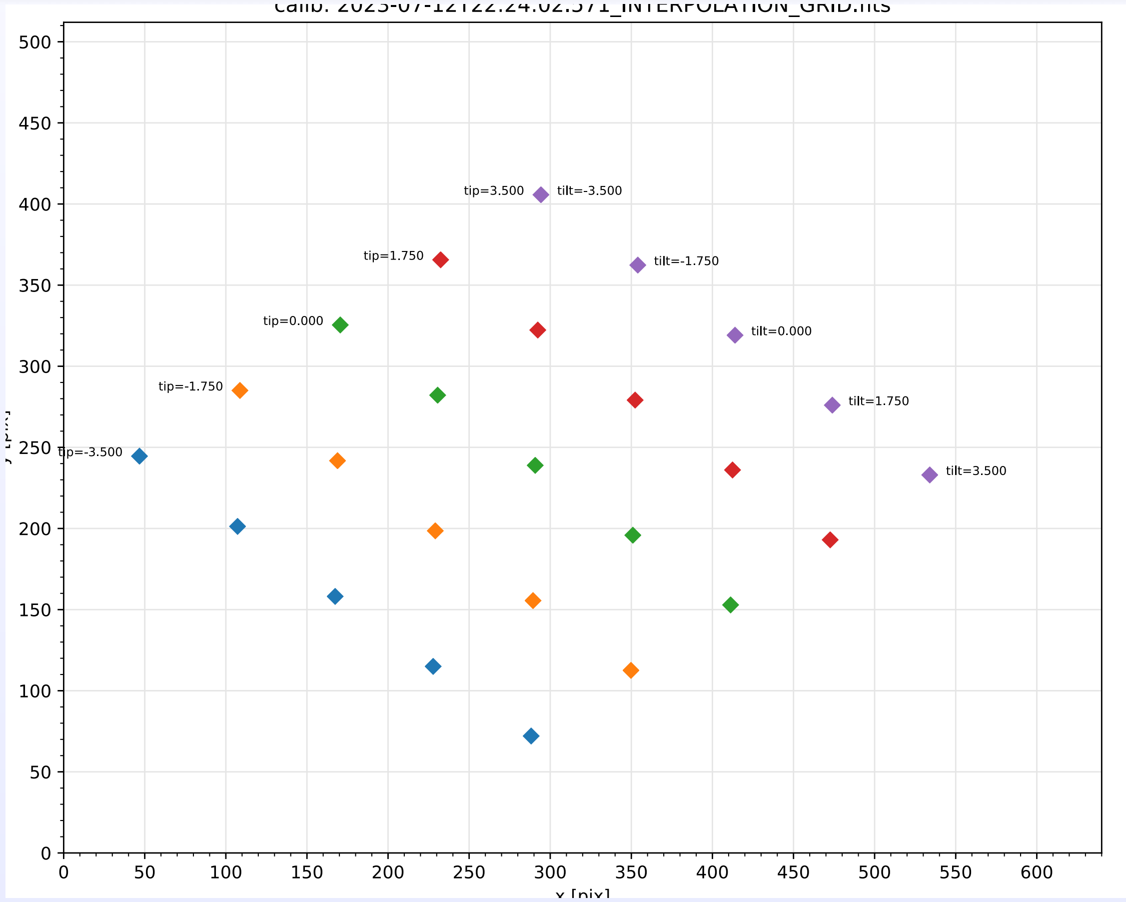
Operations: daytime calibrations

Daytime

Tip-tilt mirror linearity

Tip-tilt mirror interpolation matrix





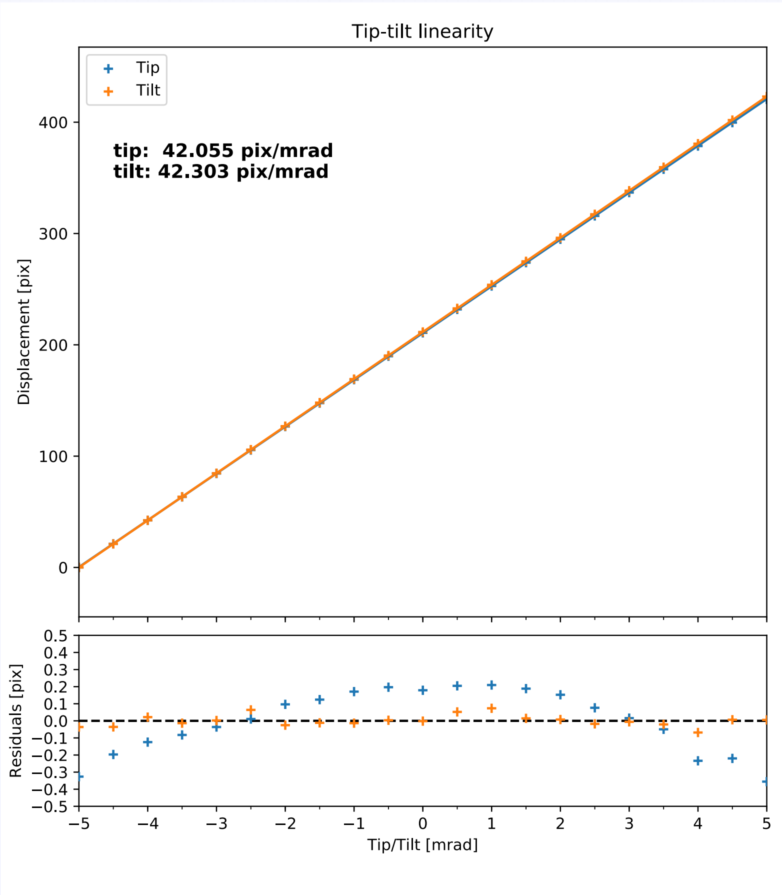
Operations: daytime calibrations

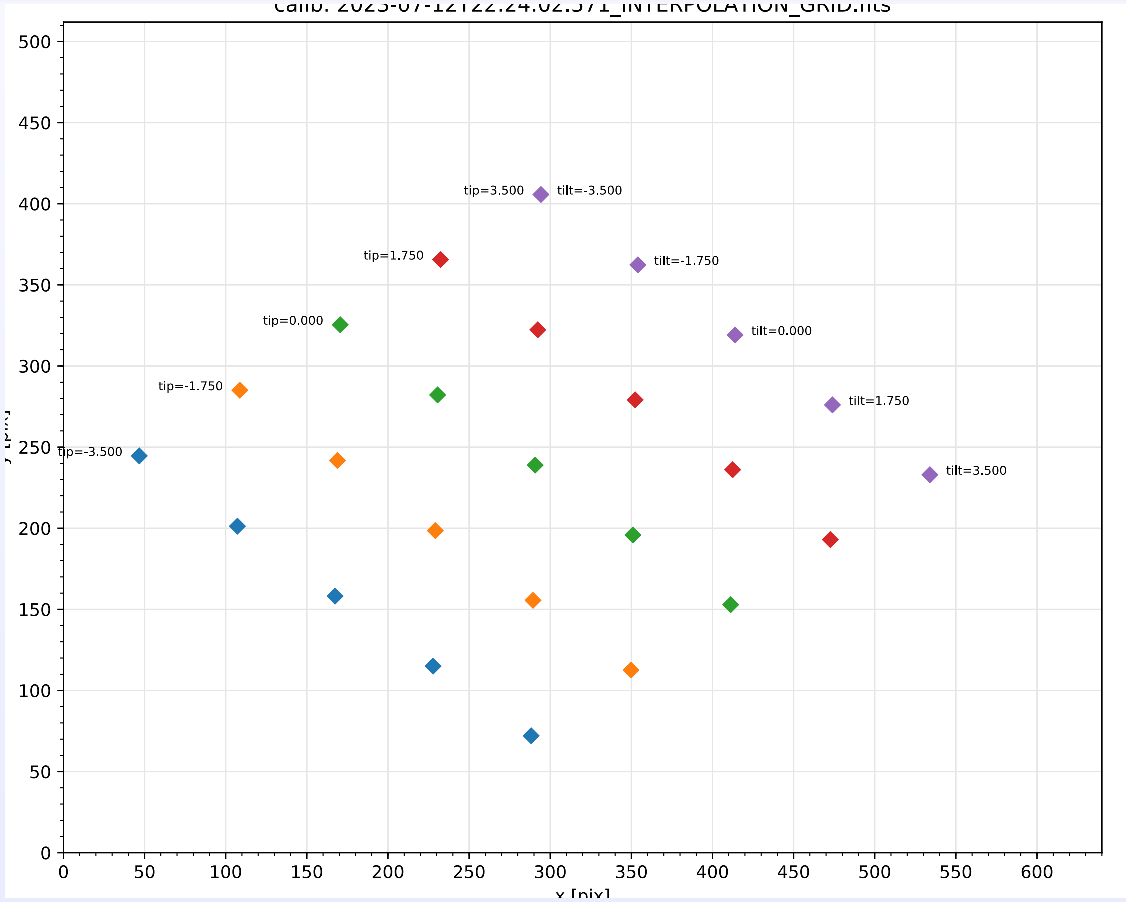
Daytime

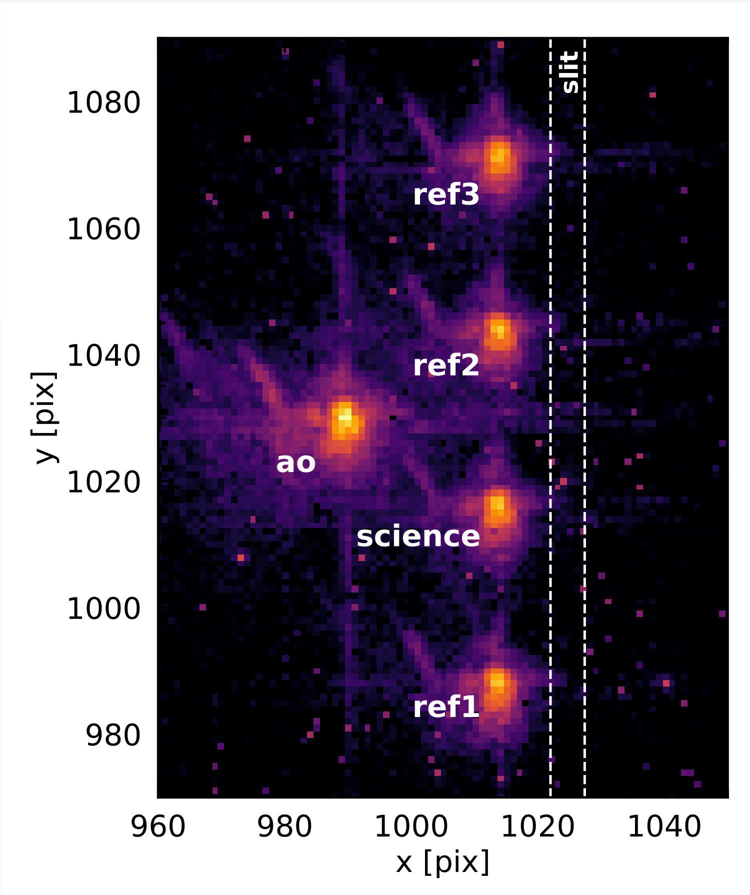
Tip-tilt mirror linearity

Tip-tilt mirror interpolation matrix

Fibers location on slit viewer







Operations: daytime calibrations

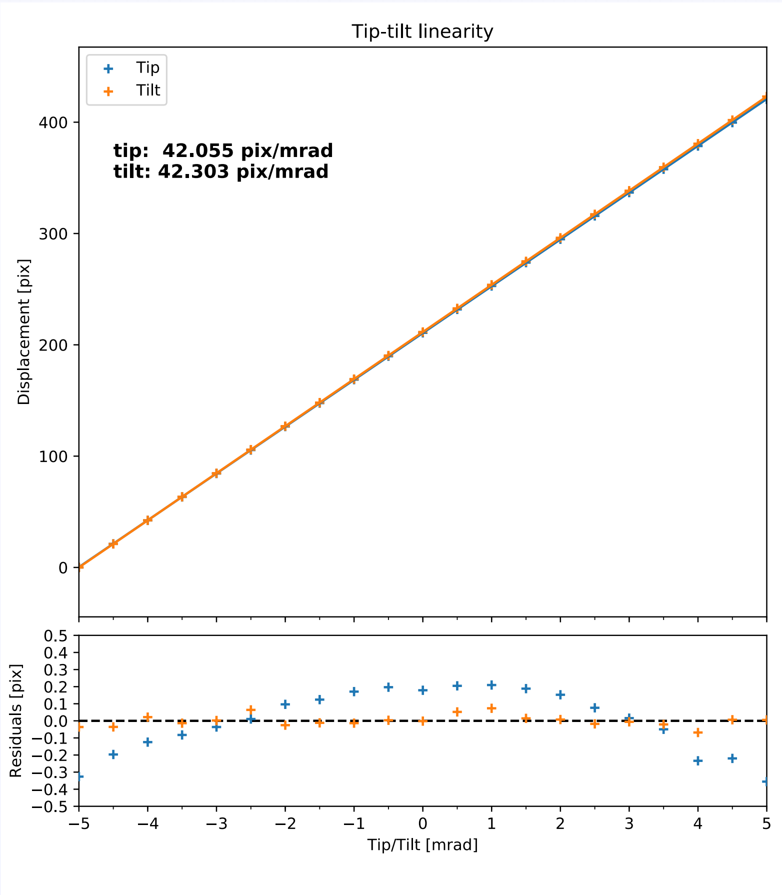
Daytime

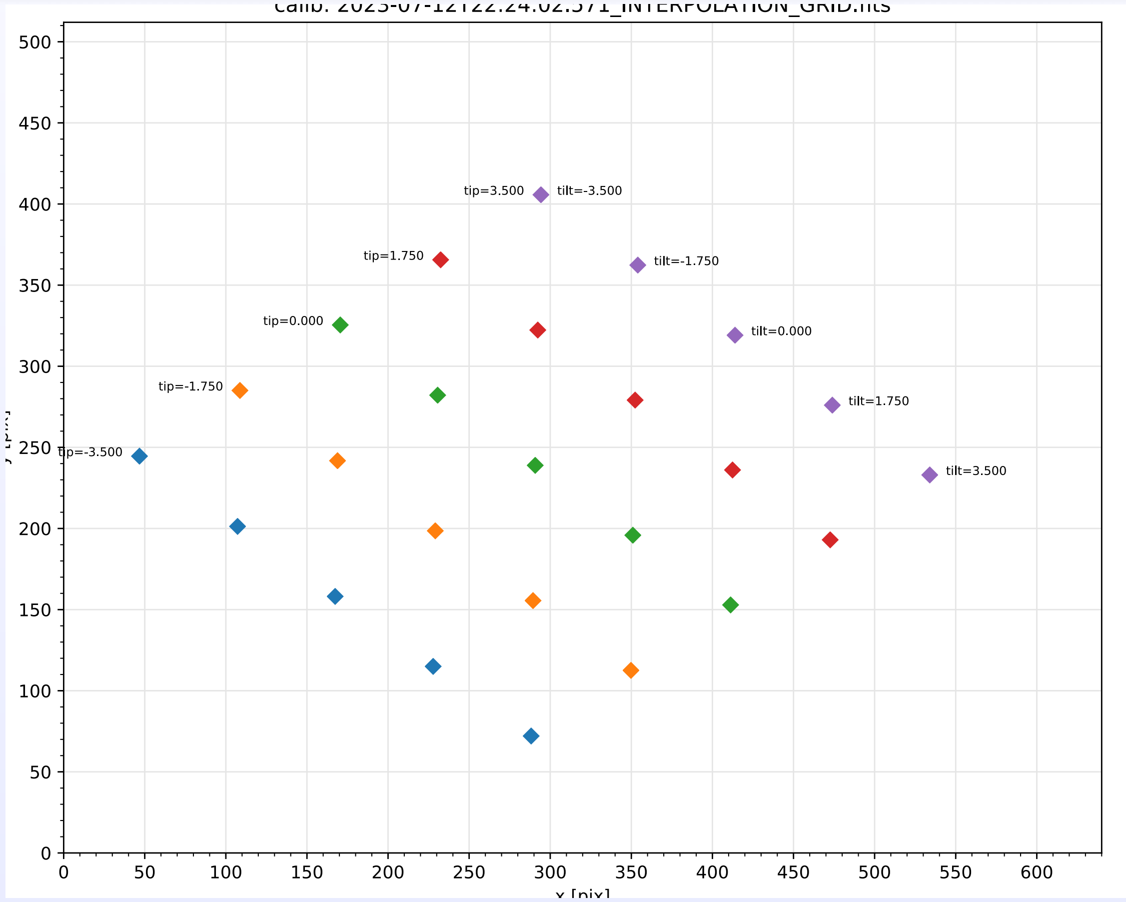
Tip-tilt mirror linearity

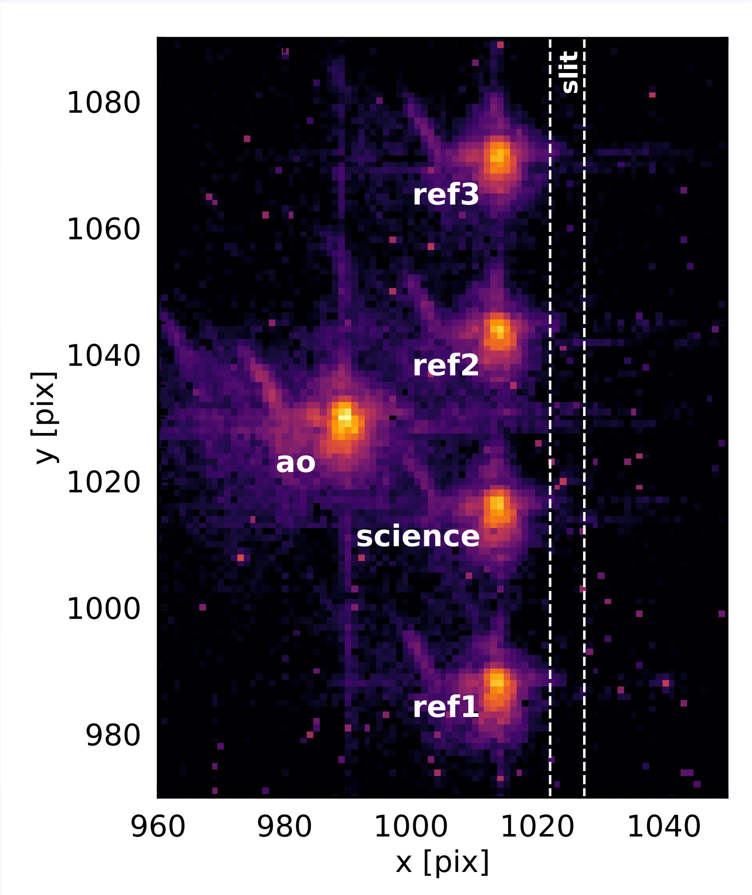
Tip-tilt mirror interpolation matrix

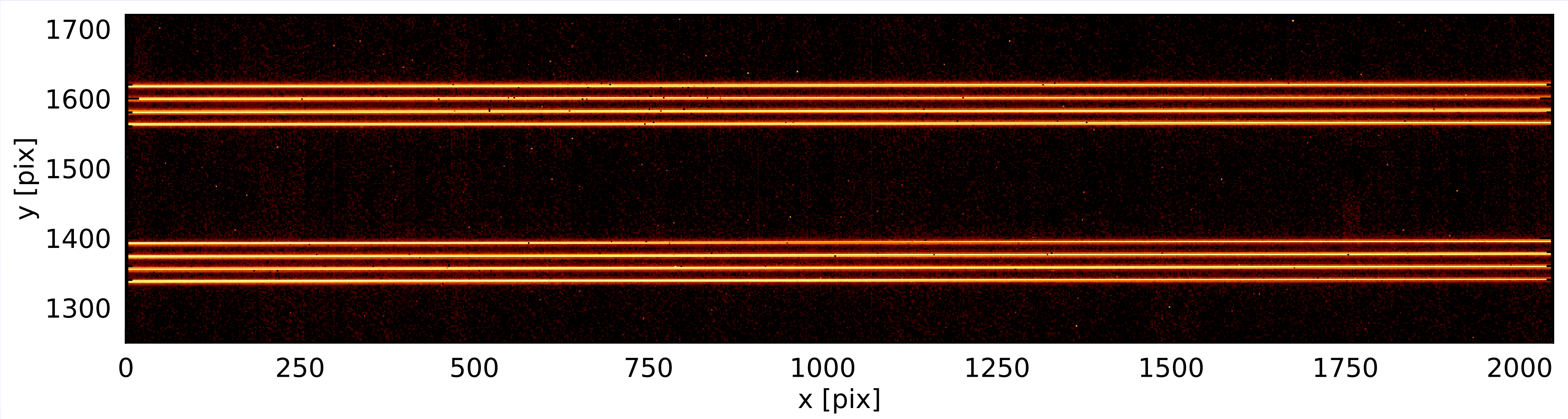
Fibers location on slit viewer

Fibers trace on science detector

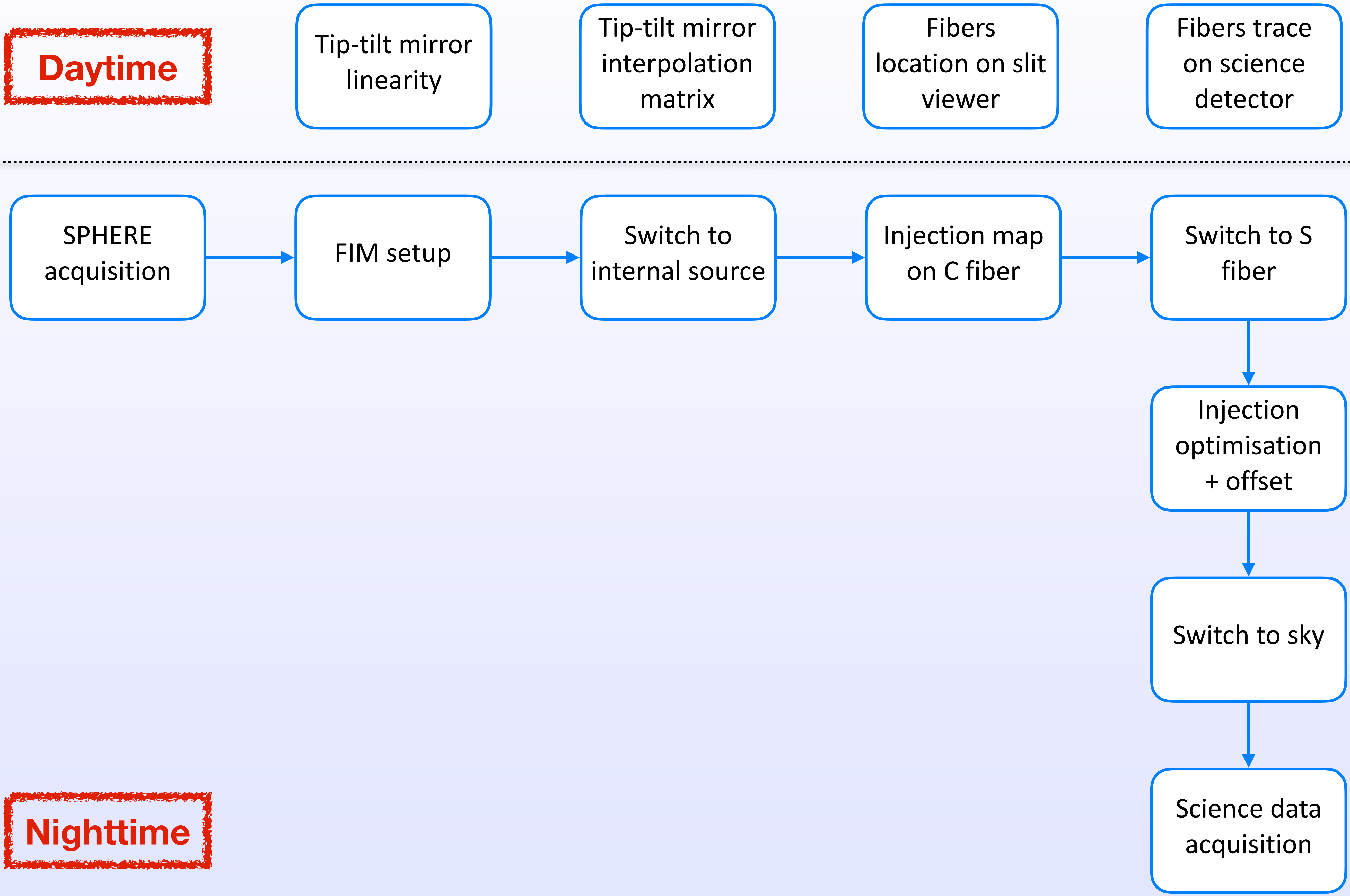








Operations: target acquisition



Operations: target acquisition

Daytime

Tip-tilt mirror linearity

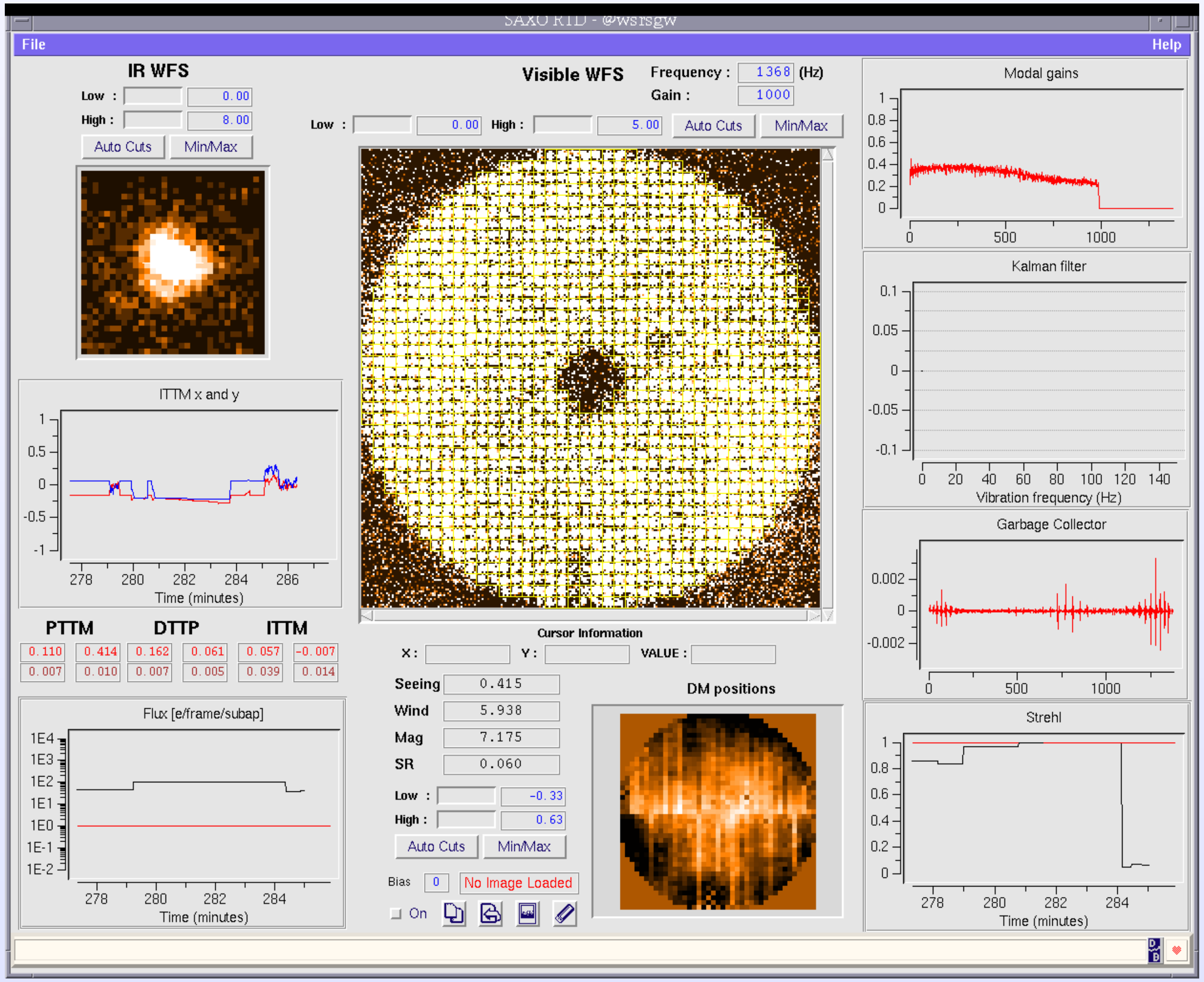
Tip-tilt mirror interpolation matrix

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

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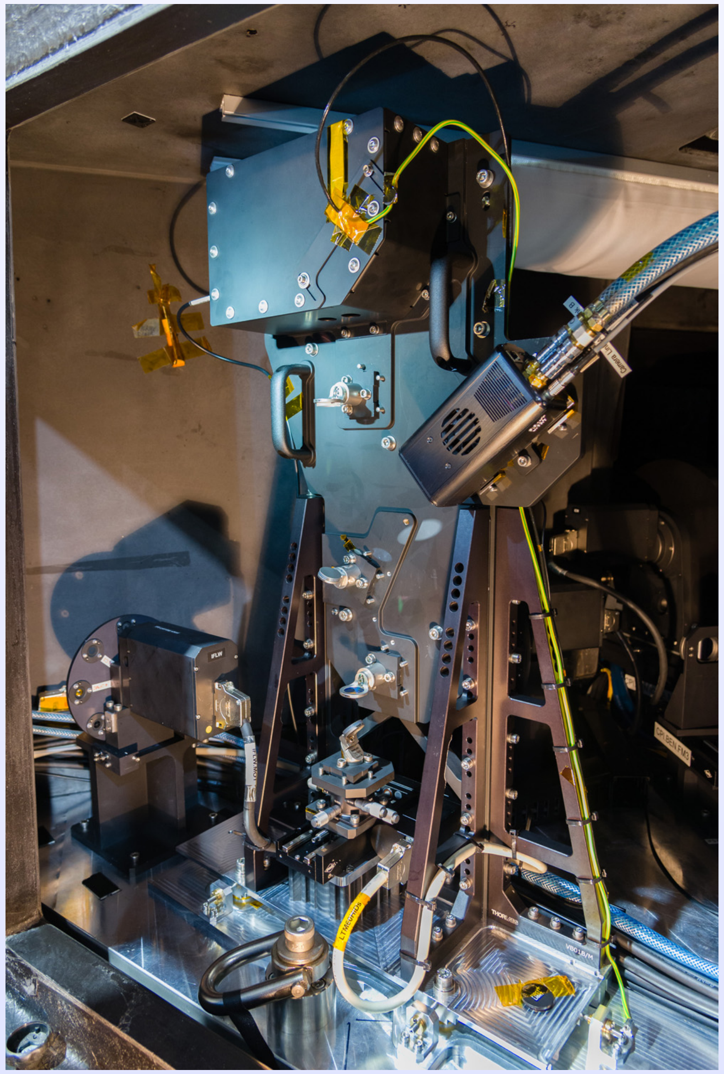

Nighttime

Operations: target acquisition

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Tip-tilt mirror linearity

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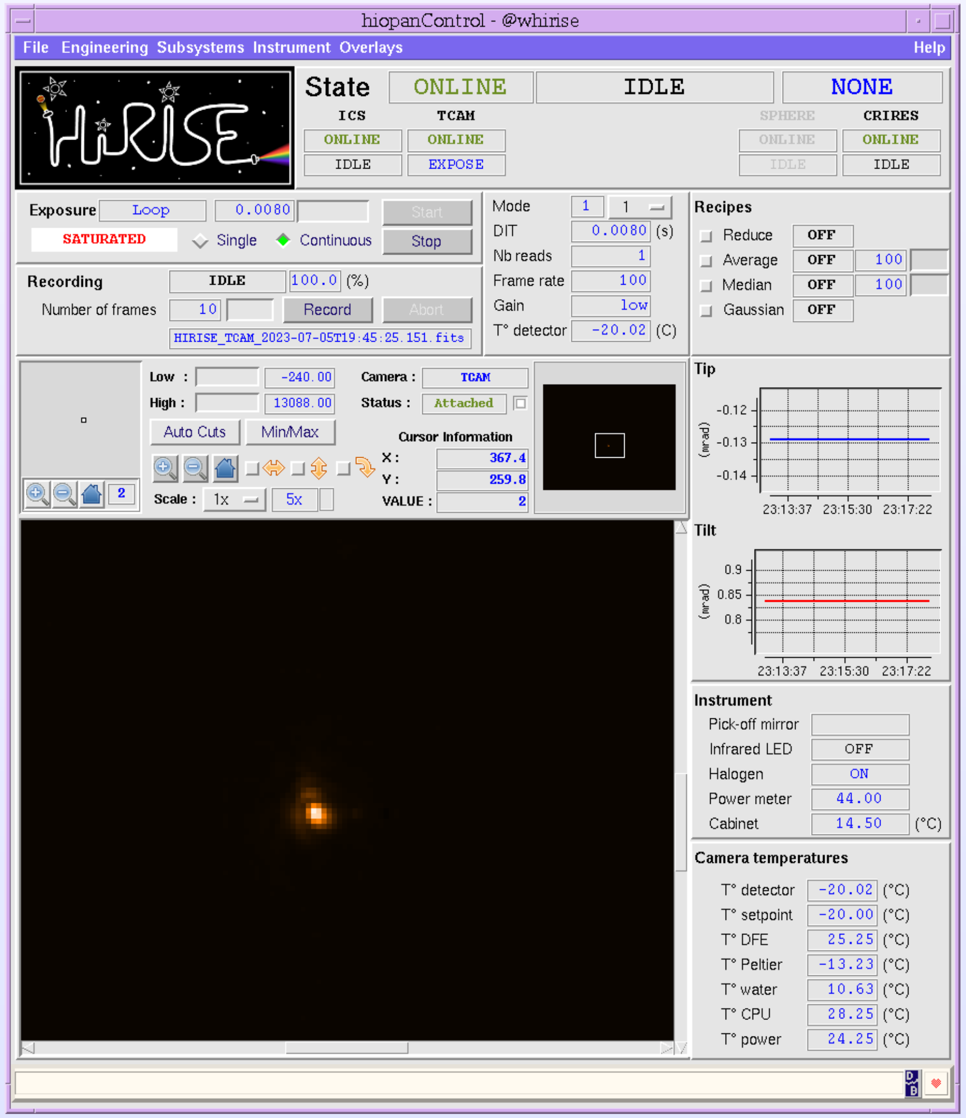


Nighttime

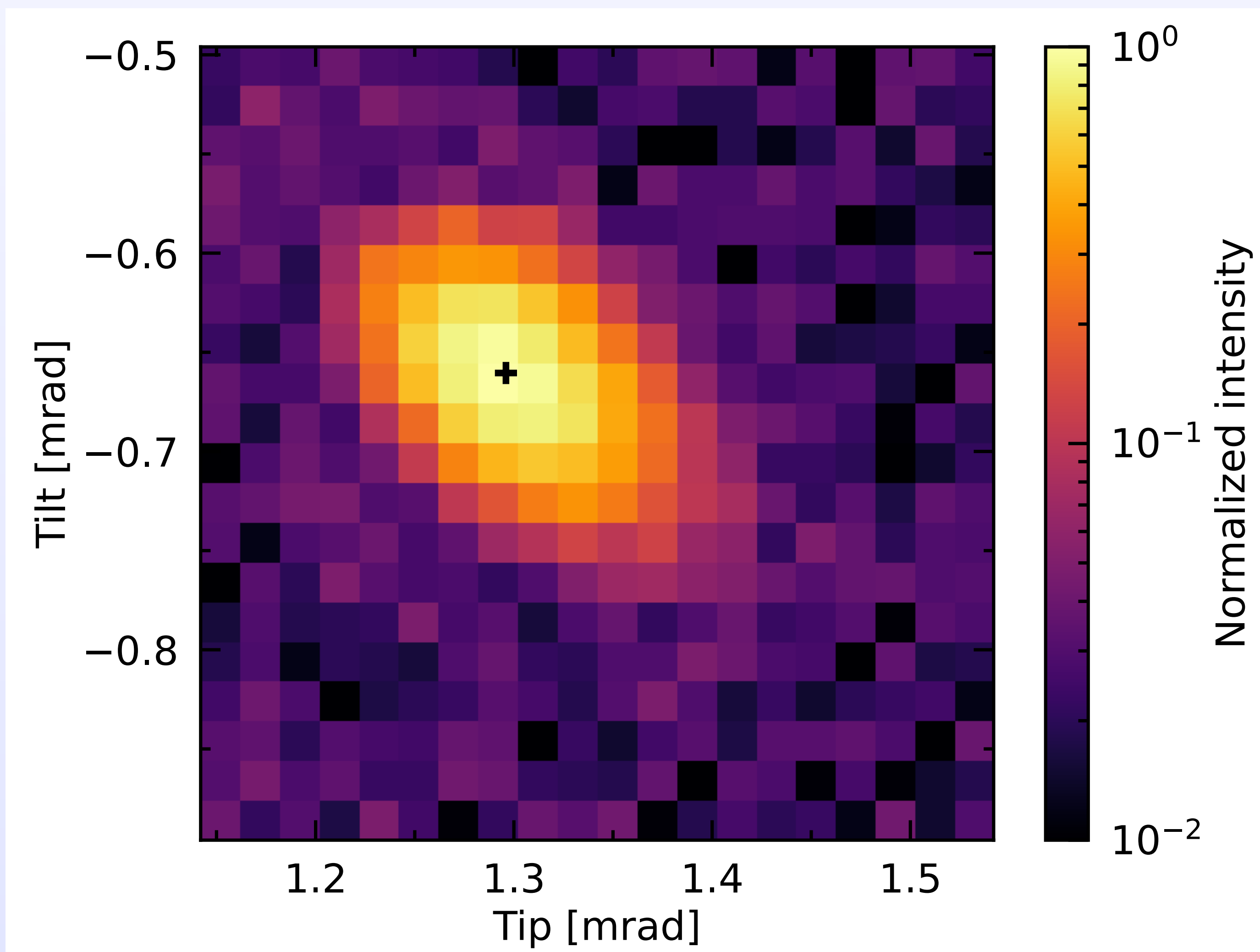
Operations: target acquisition

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

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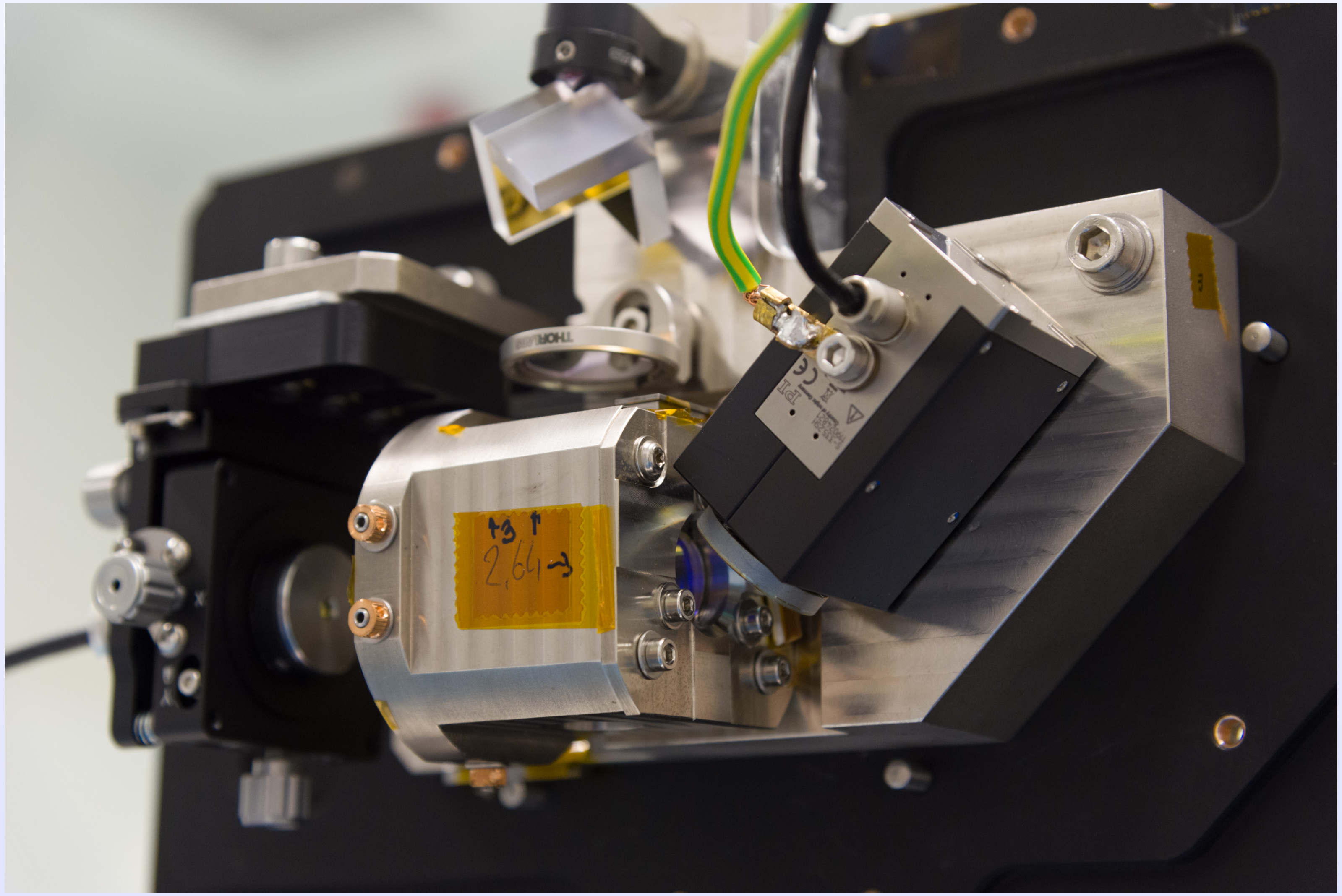

Nighttime

Operations: target acquisition

Daytime

Tip-tilt mirror linearity

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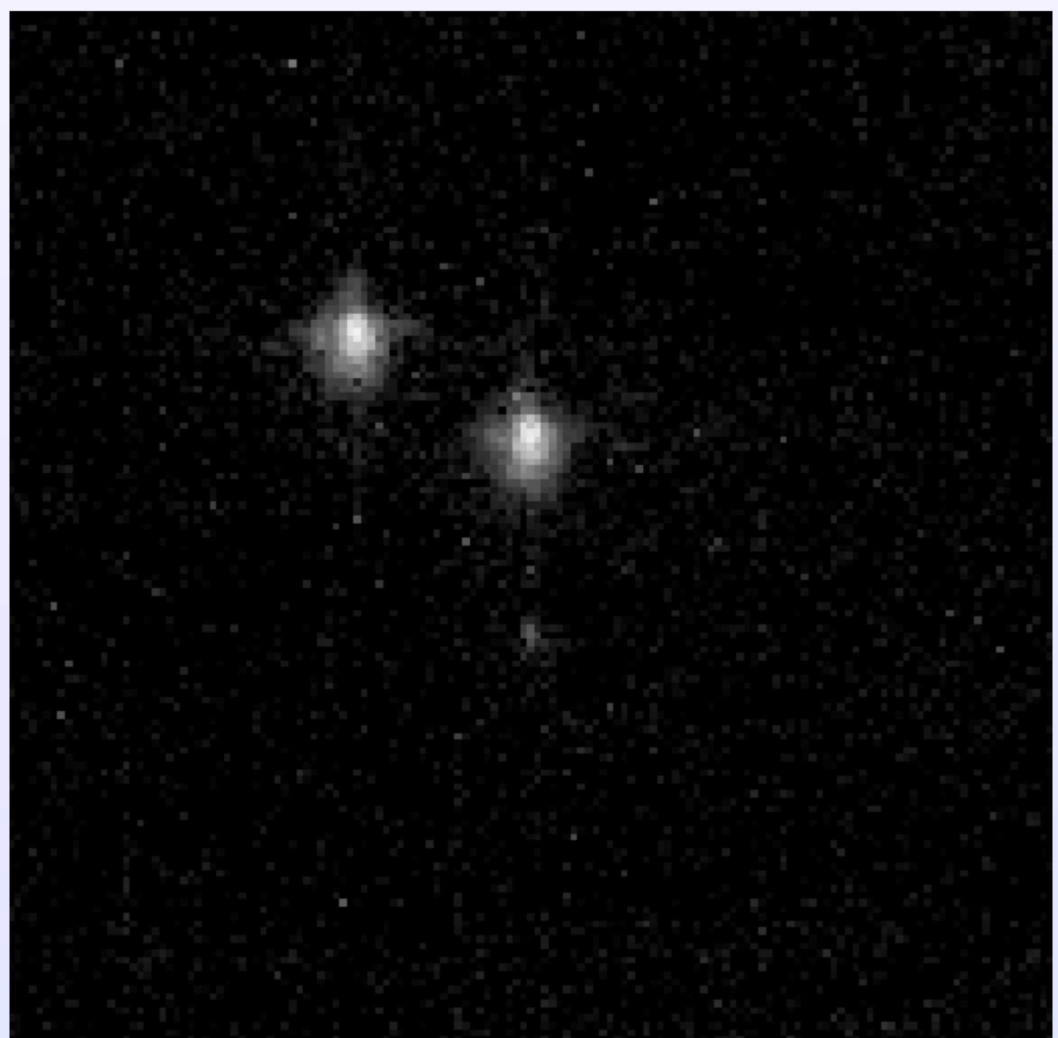
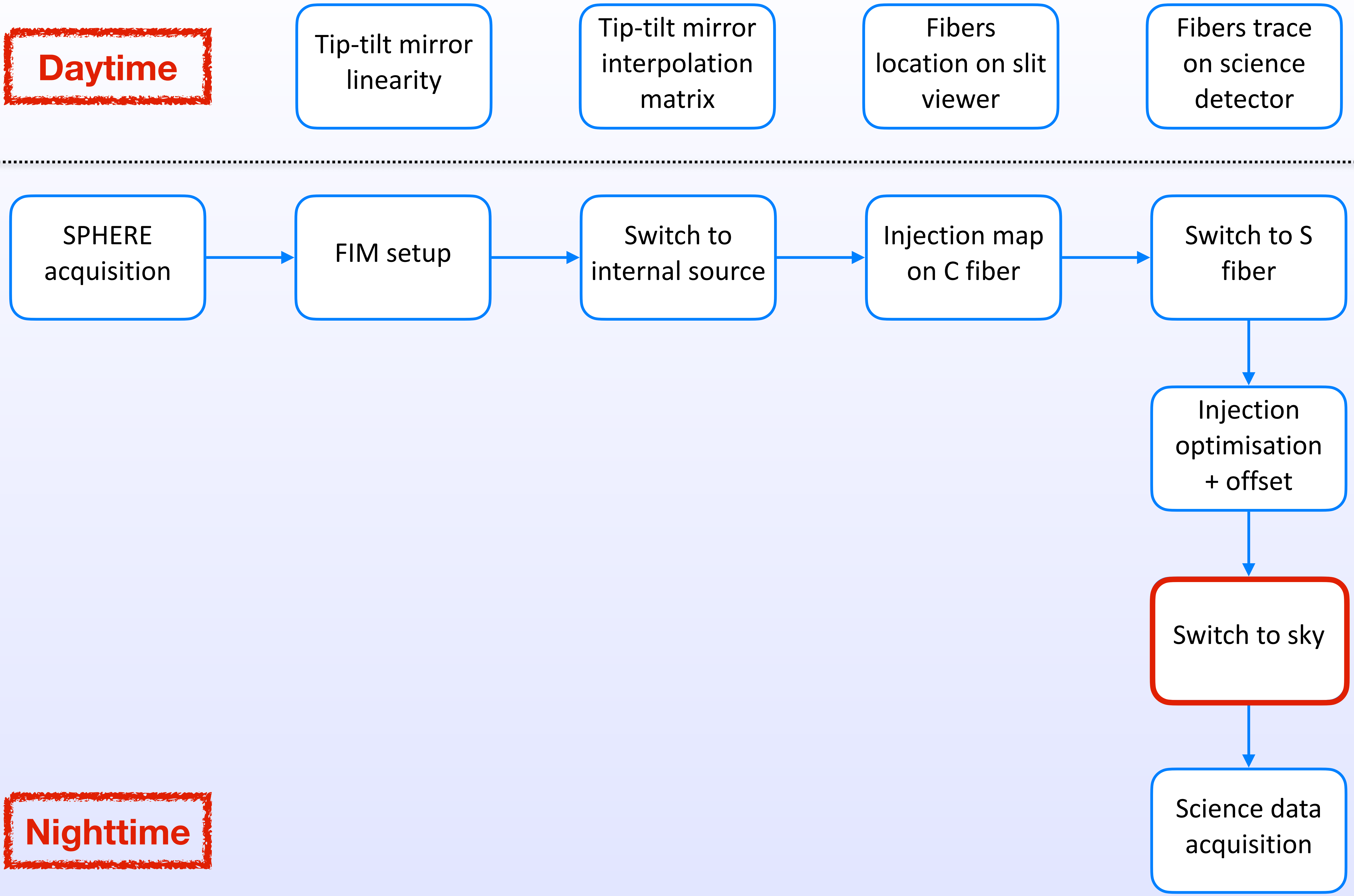
SPHERE acquisition → FIM setup → Switch to internal source → Injection map on C fiber → Switch to S fiber → Injection optimisation + offset → Switch to sky → Science data acquisition



Operations: target acquisition



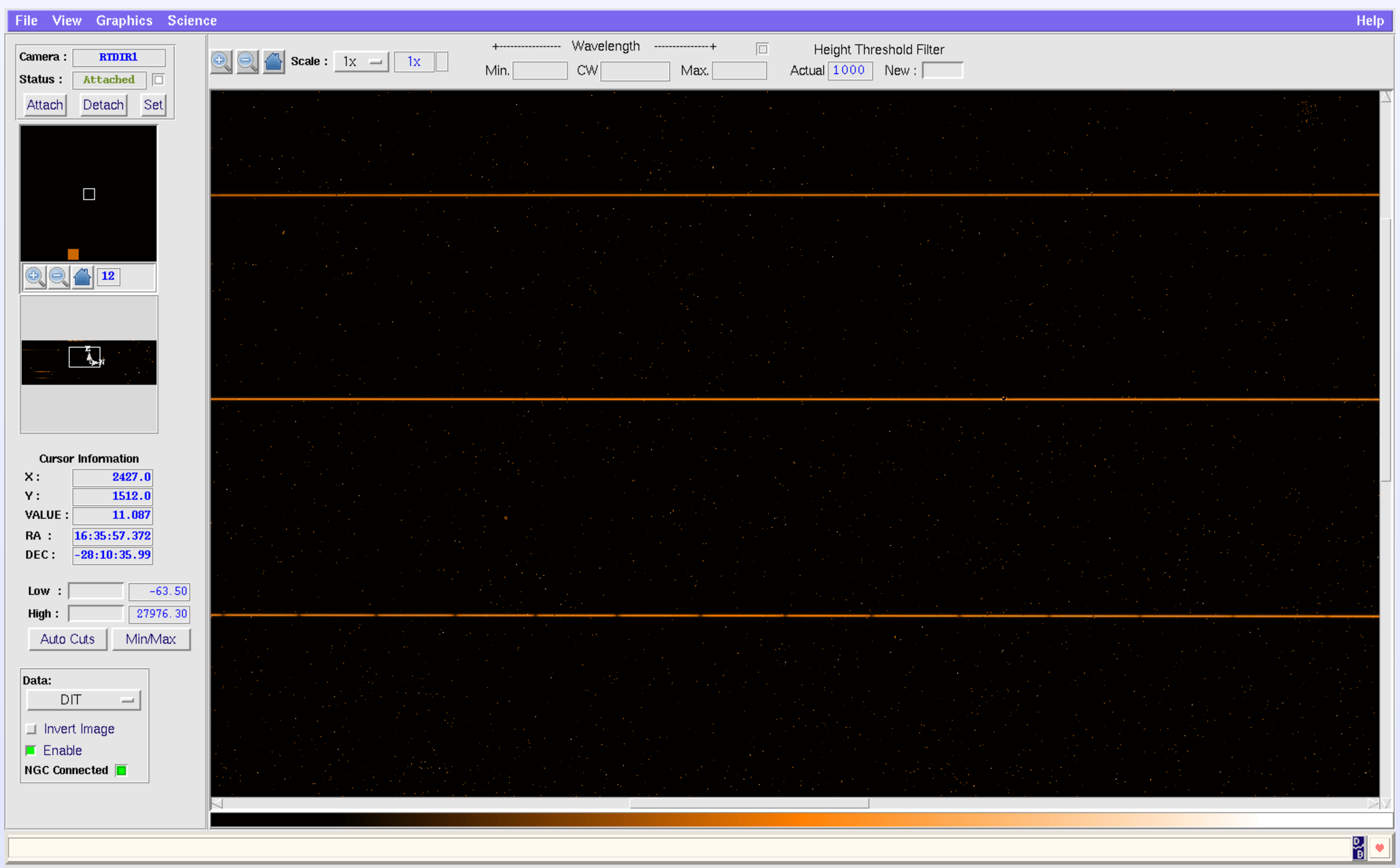
Operations: target acquisition

Daytime

- Tip-tilt mirror linearity
- Tip-tilt mirror interpolation matrix
- Fibers location on slit viewer
- Fibers trace on science detector

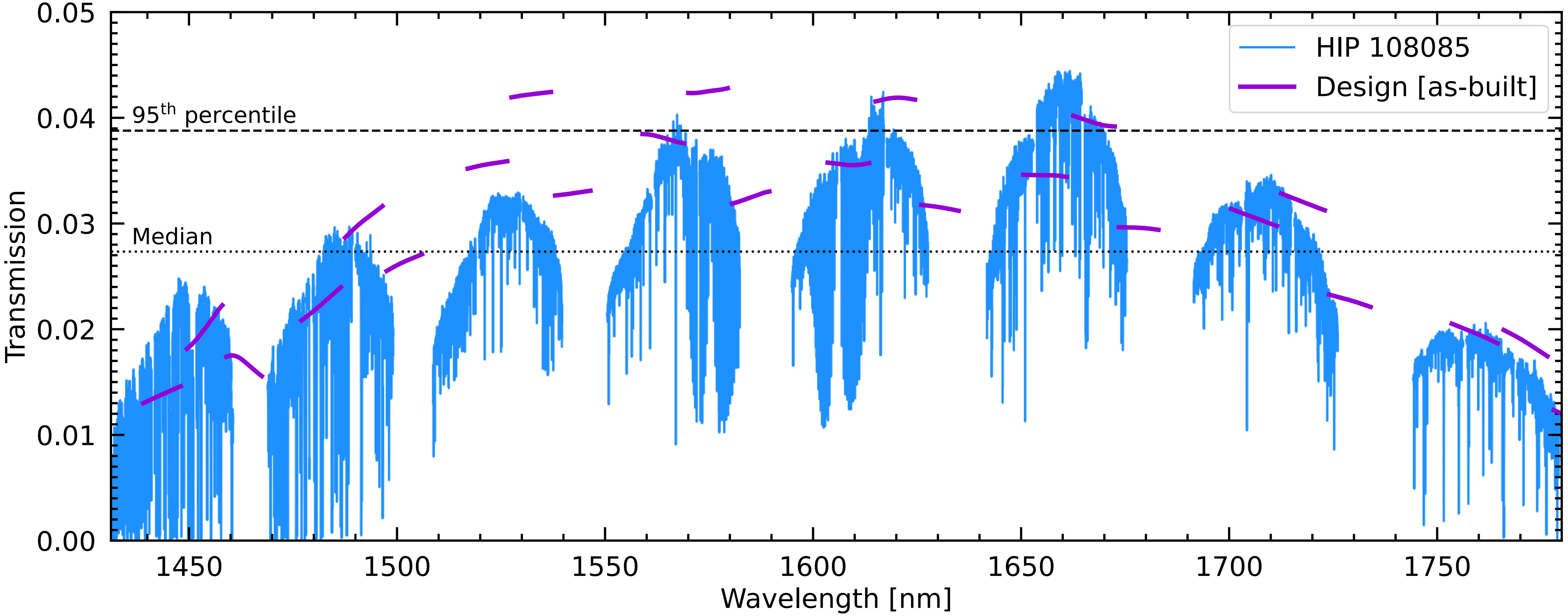
Nighttime

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



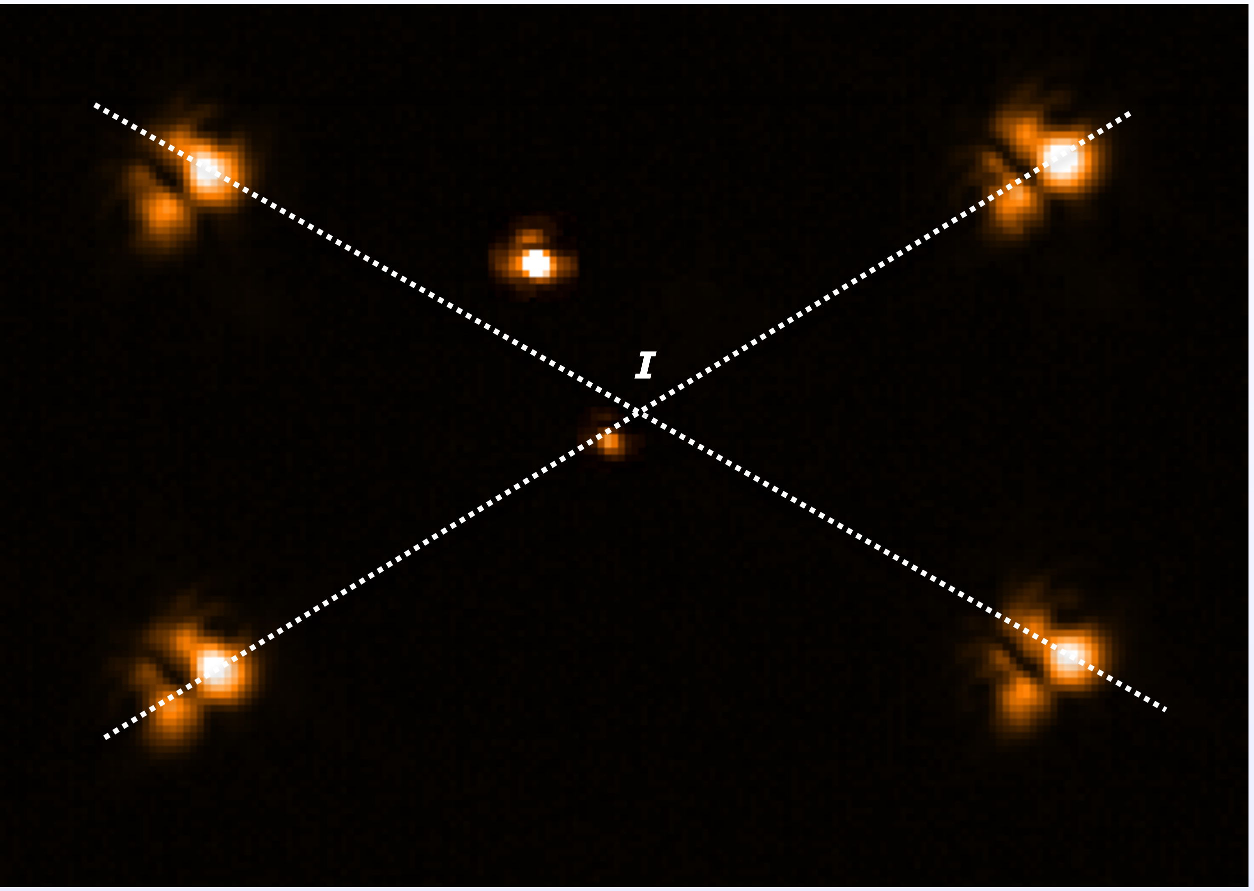
Commissioning results: transmission

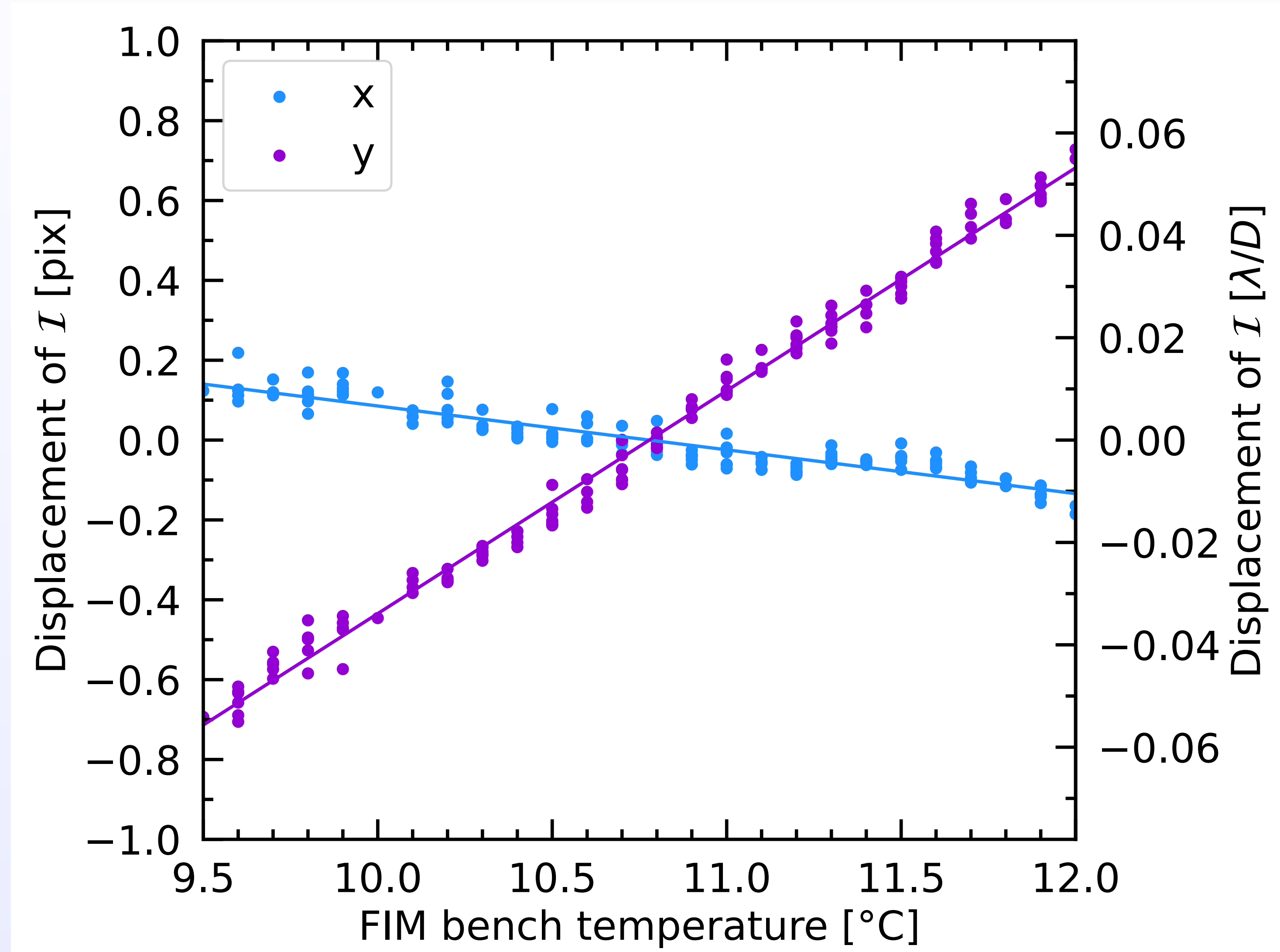
Median conditions
Bright star



End-to-end transmission exactly within specifications

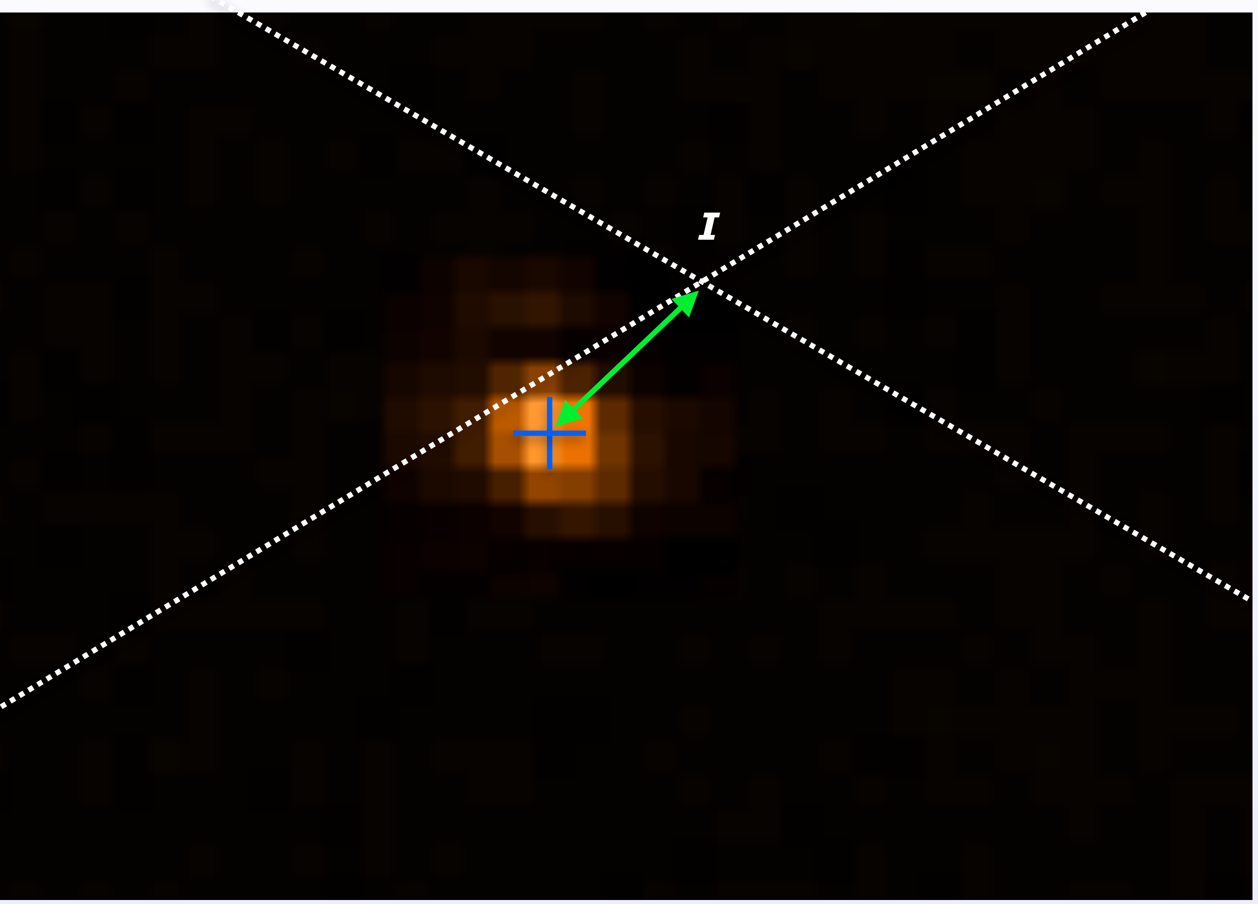
Commissioning: stability

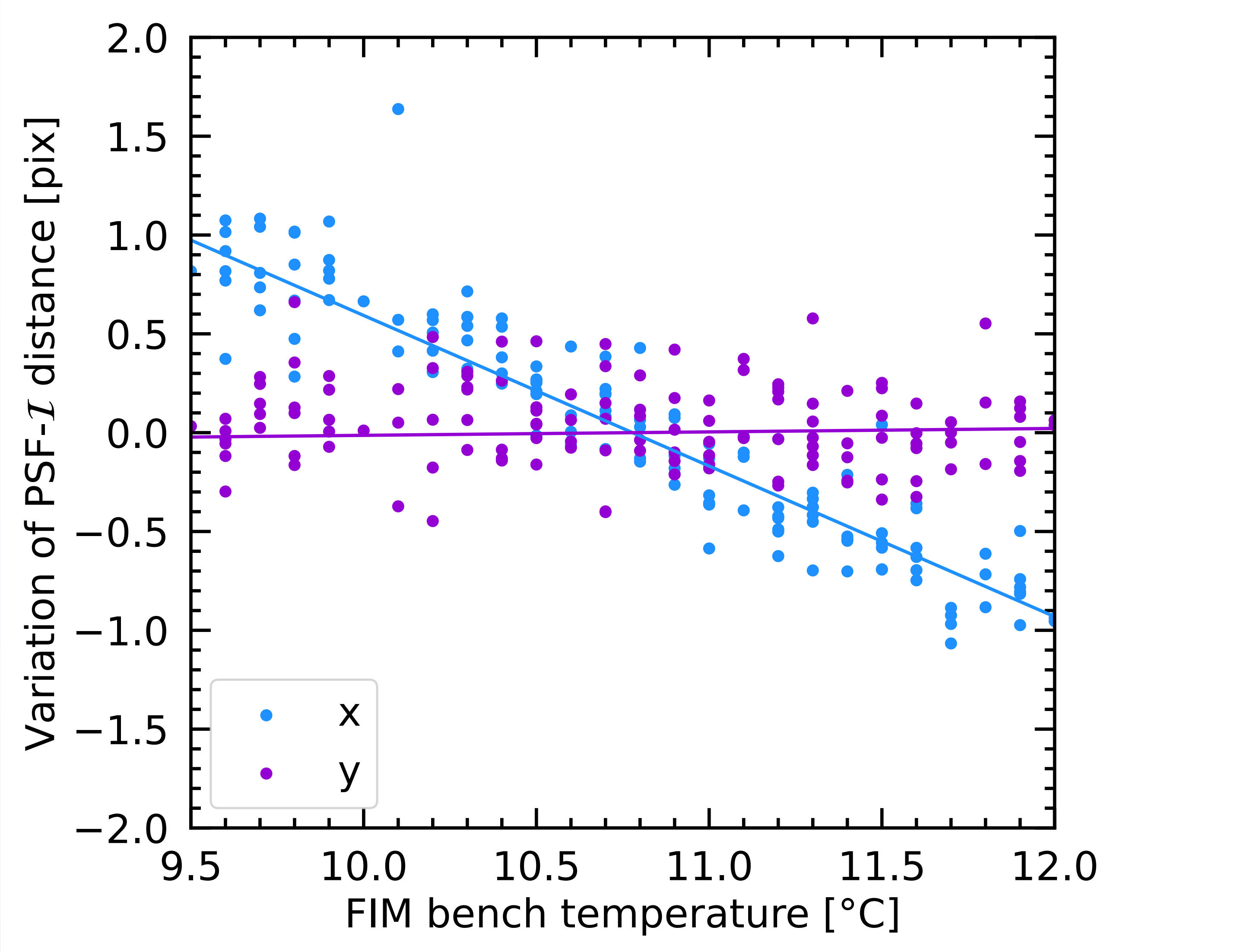




The science PSF moves a lot with temperature

Commissioning: stability

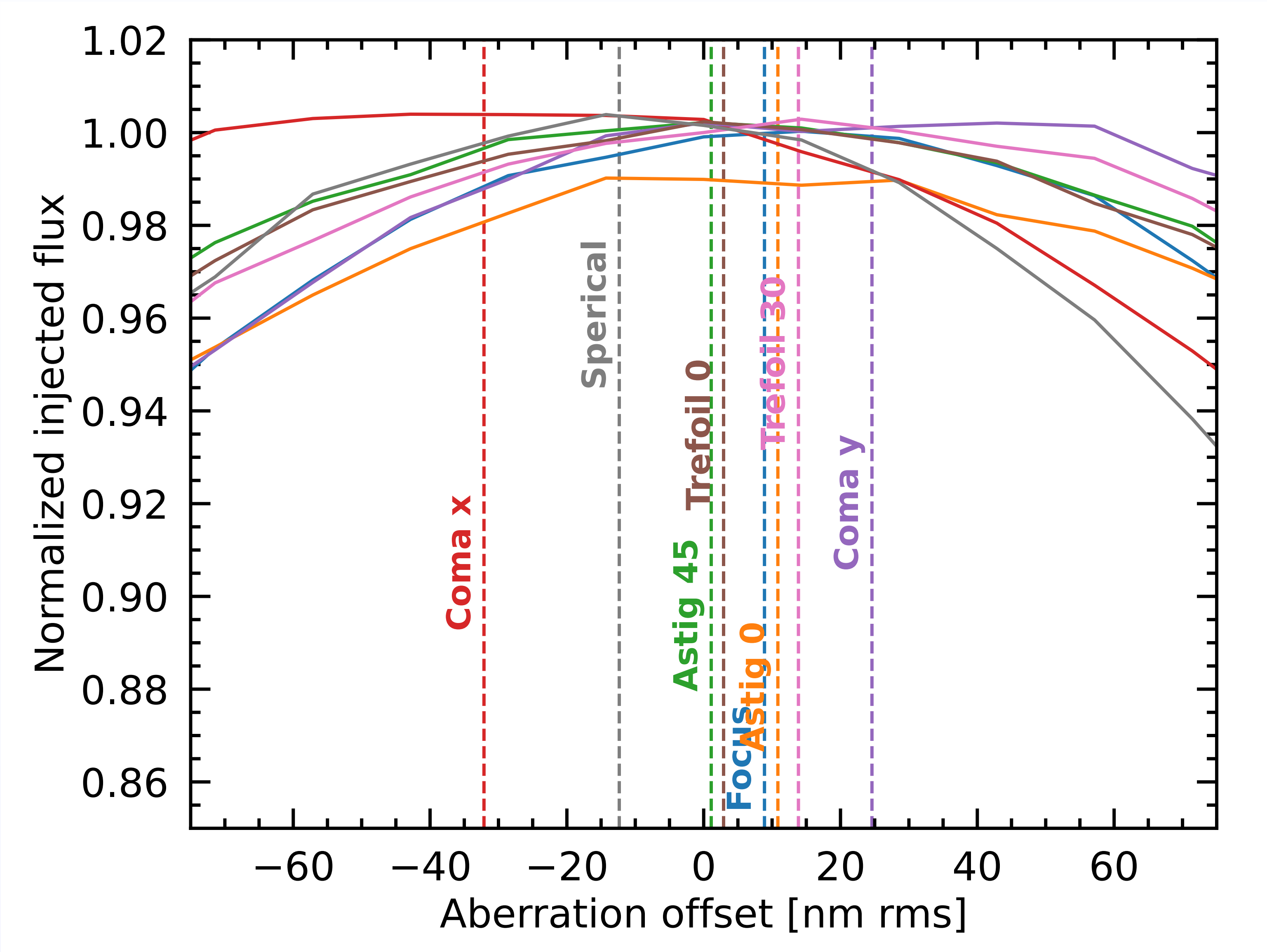




The science PSF moves a lot with temperature

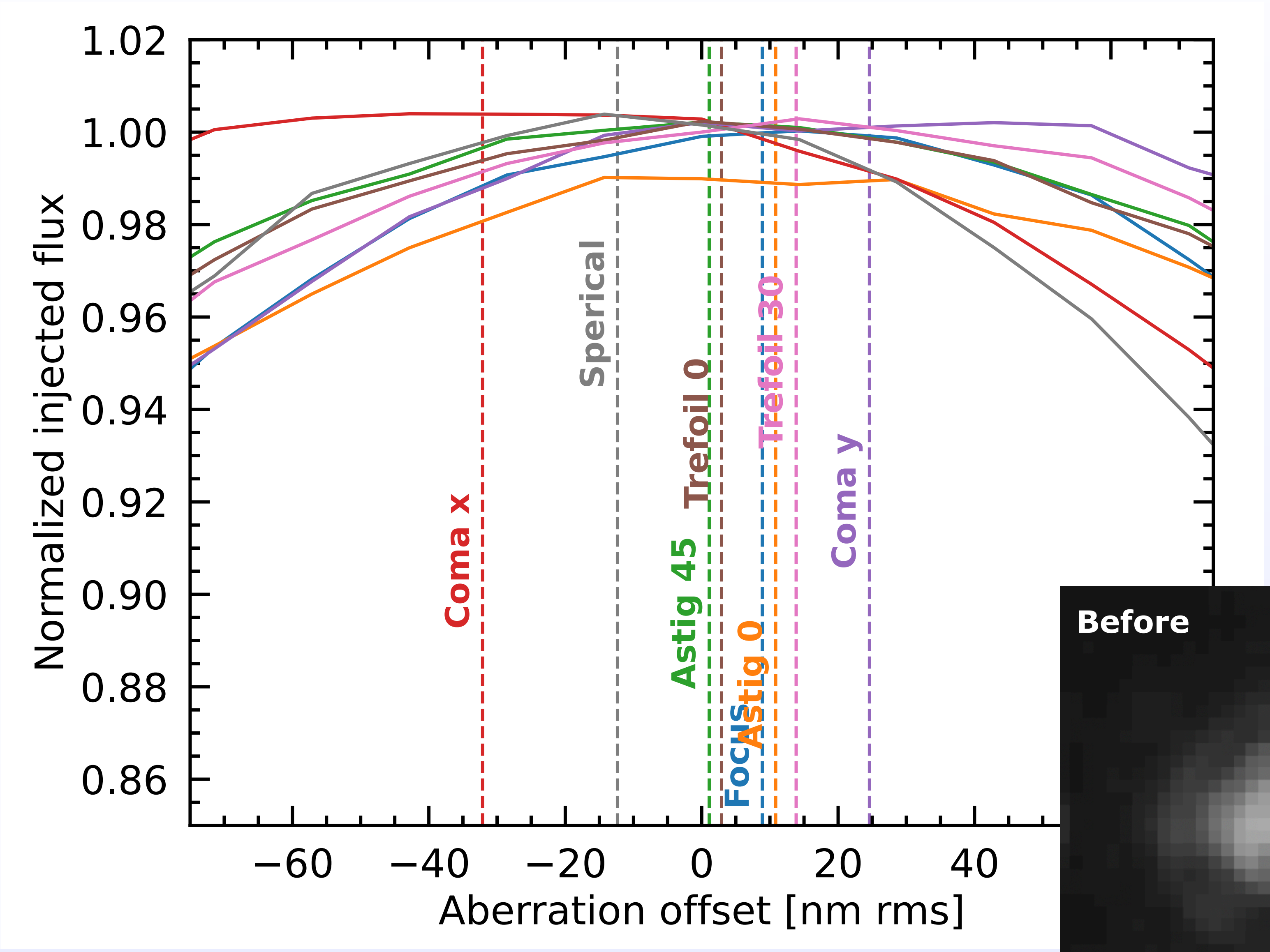
Motion compensation is NOT straightforward

Commissioning: NCPA

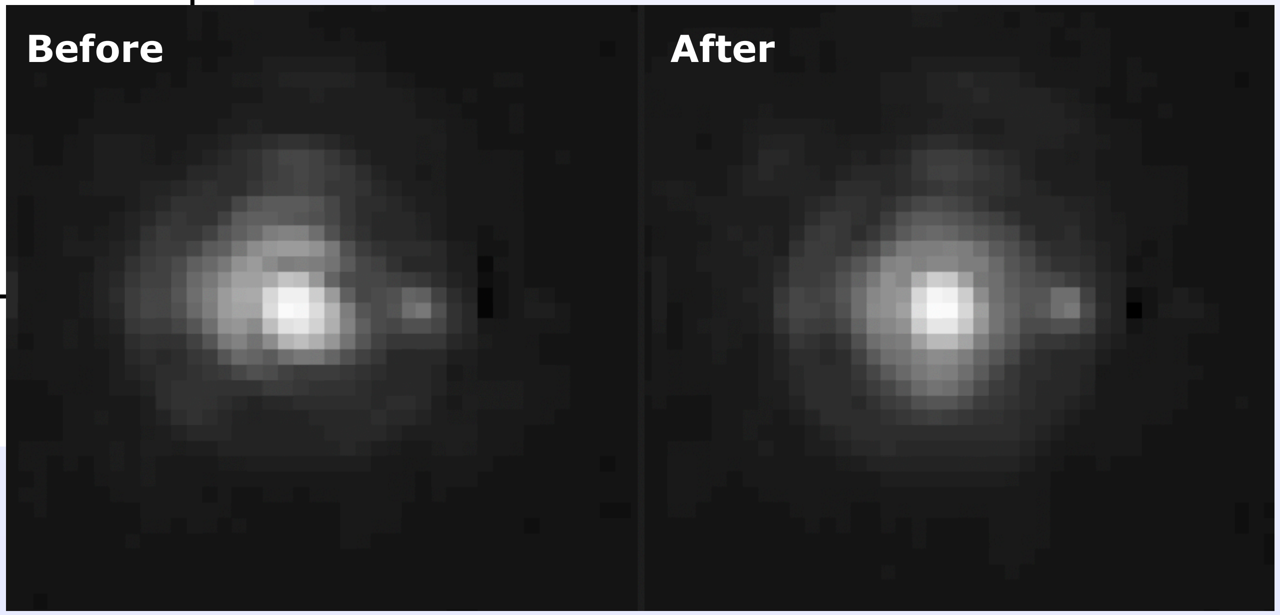


Level of NCPA is acceptable and no major gain expected from compensation

Commissioning: NCPA

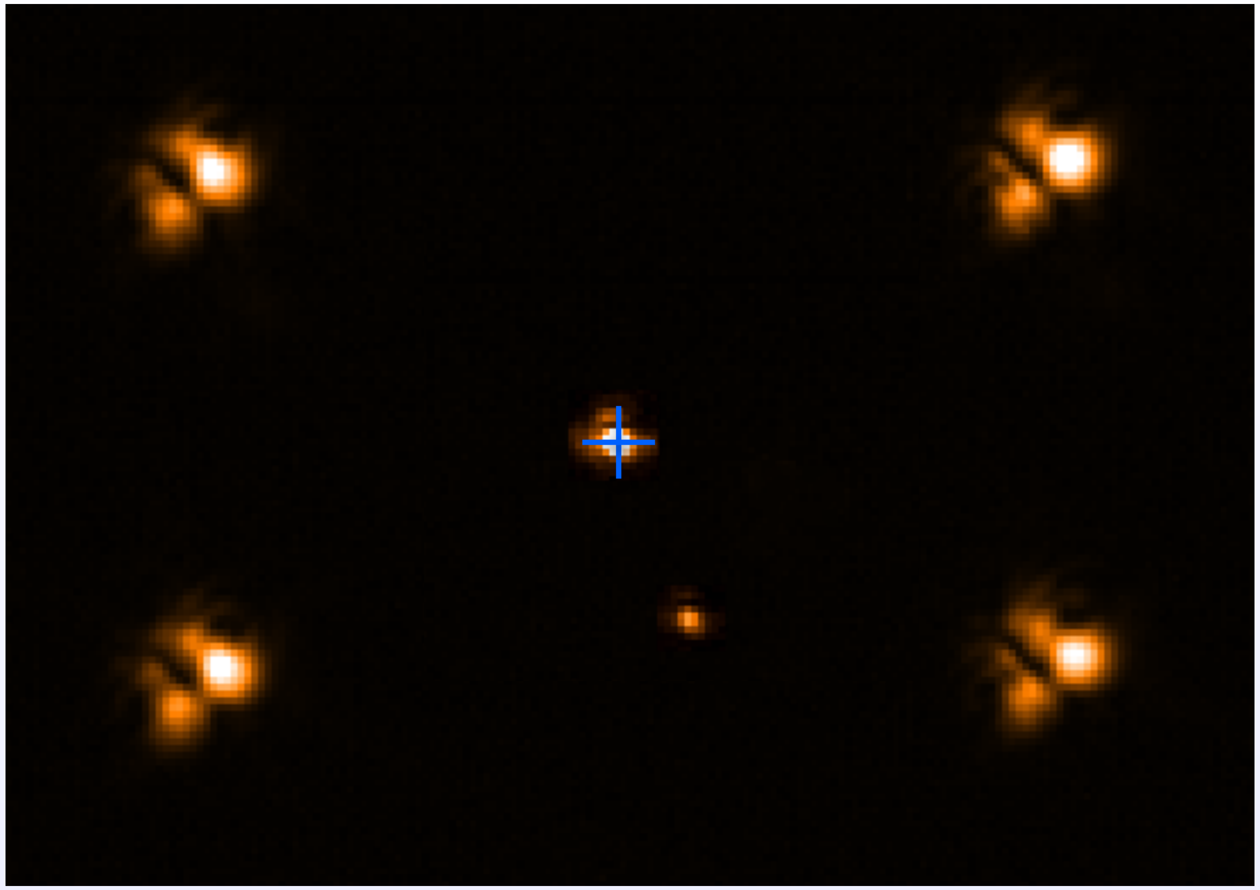


Optimisation on FIM camera

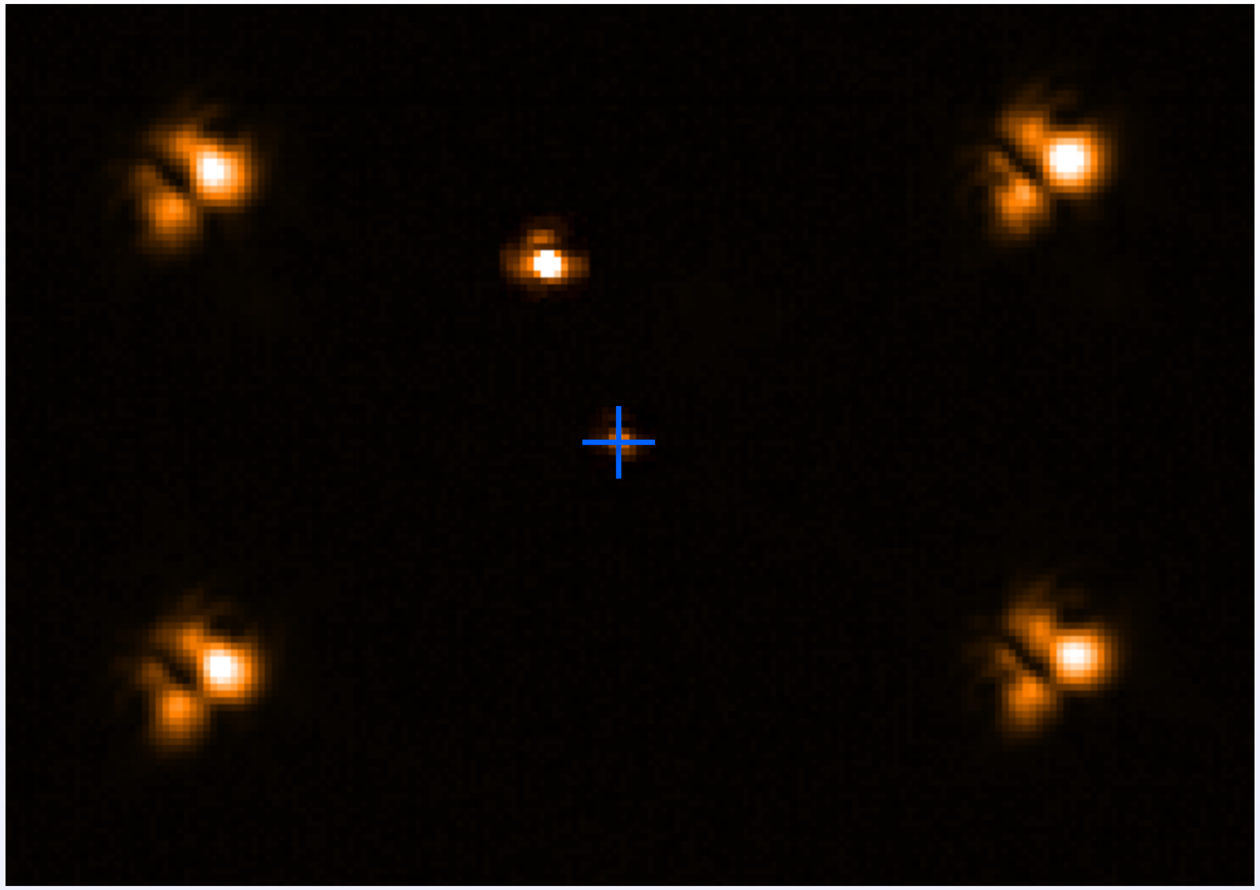


Level of NCPA is acceptable and no major gain expected from compensation

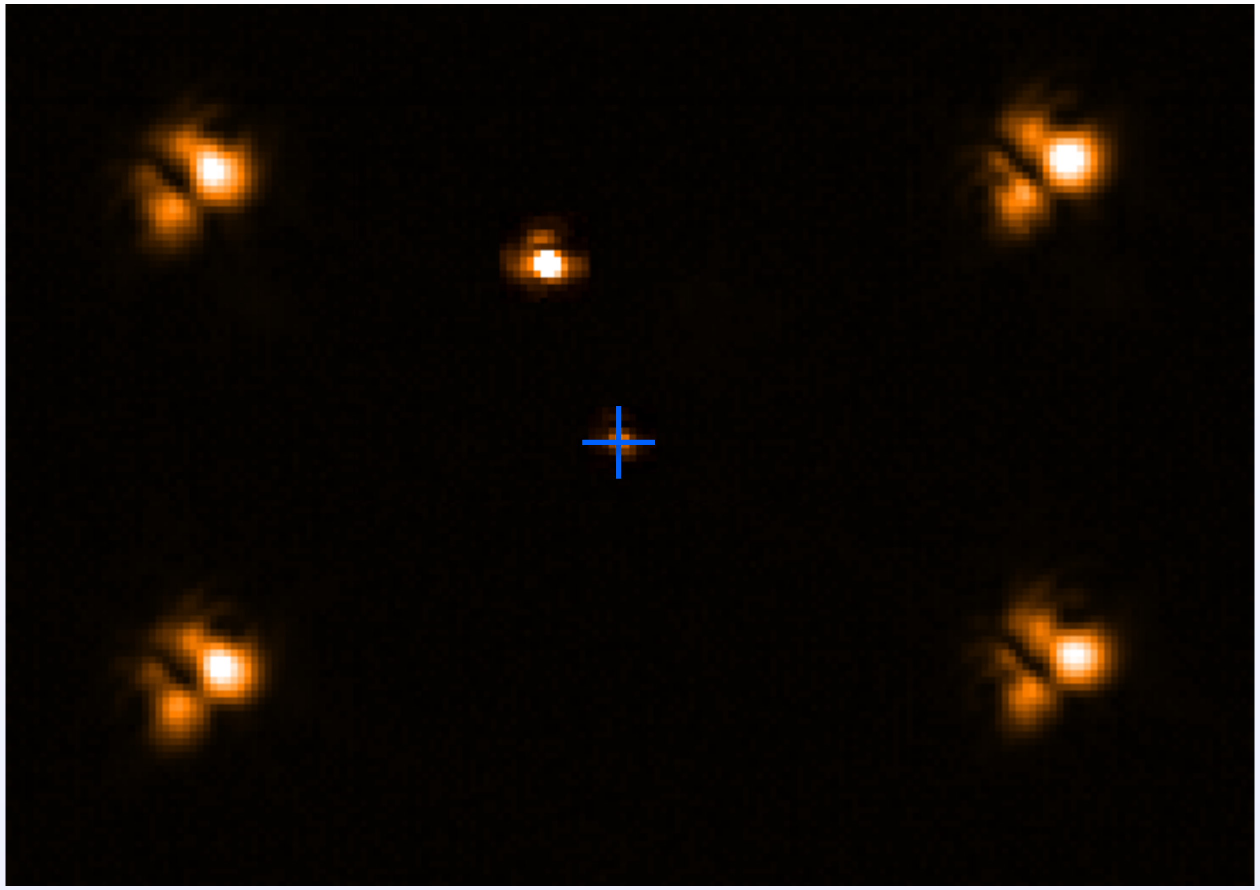
Commissioning: astrometry

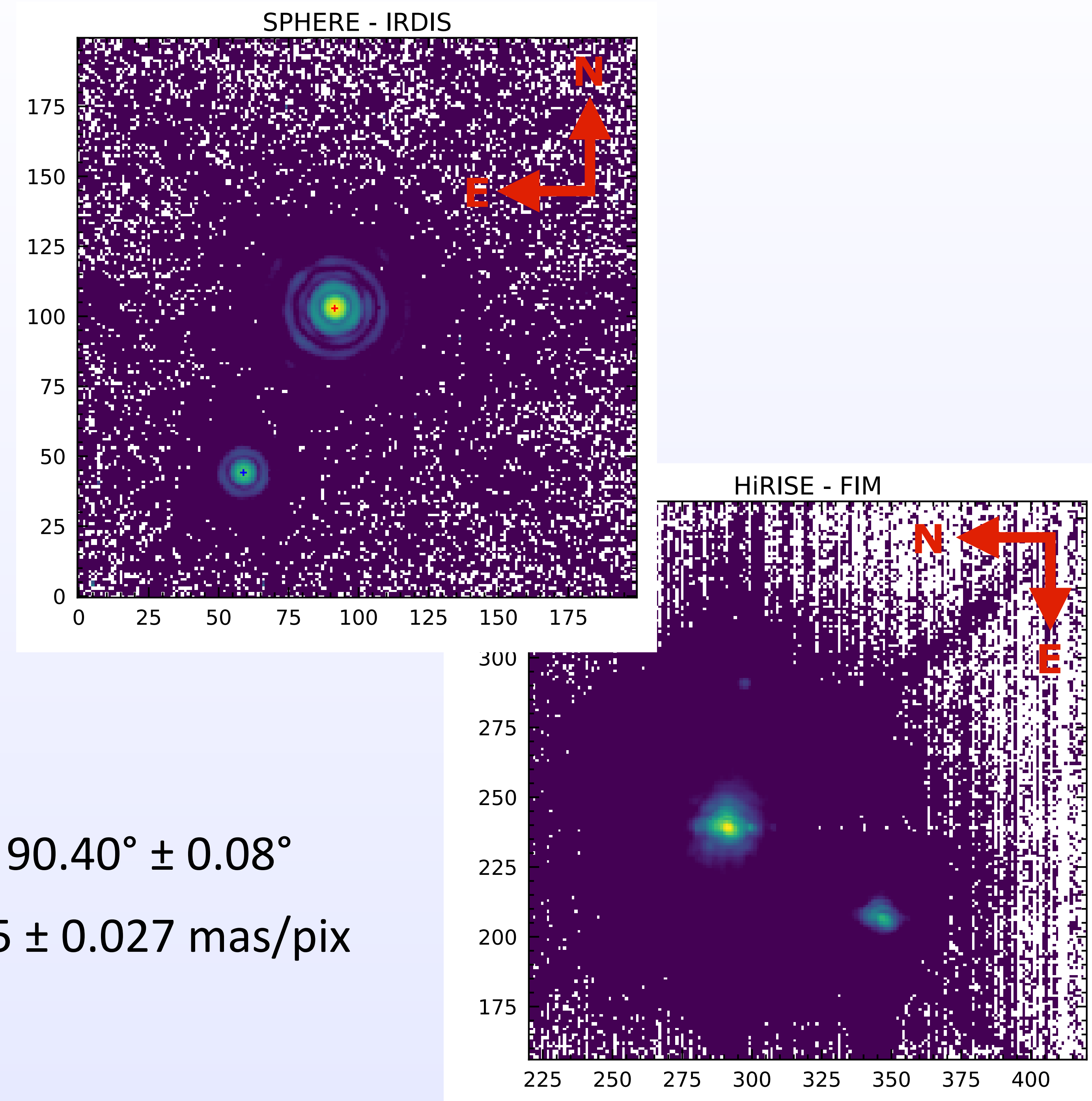


Commissioning: astrometry



Commissioning: astrometry

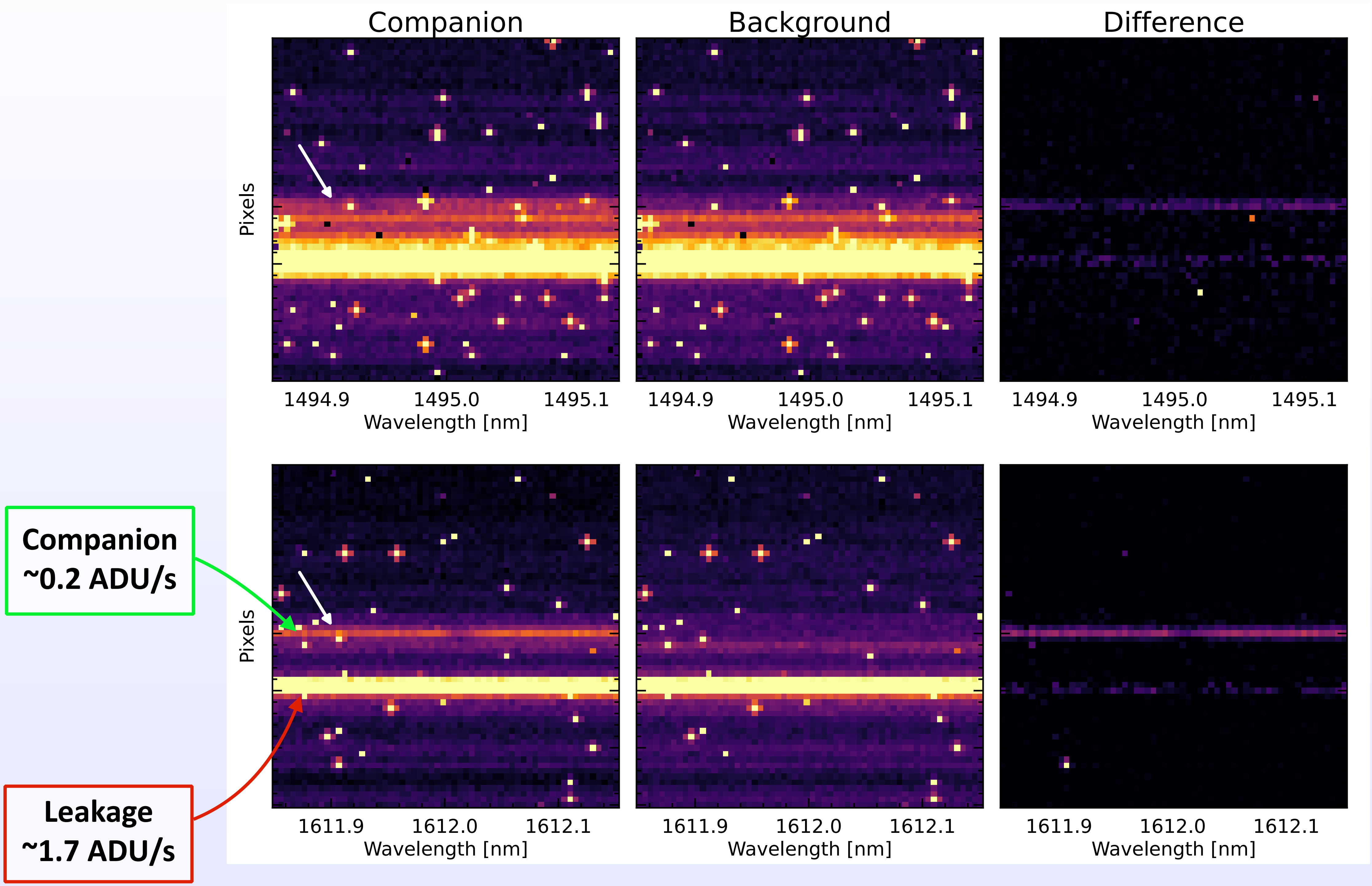




- North correction = 90.40° ± 0.08°
- Pixel scale = 12.805 ± 0.027 mas/pix

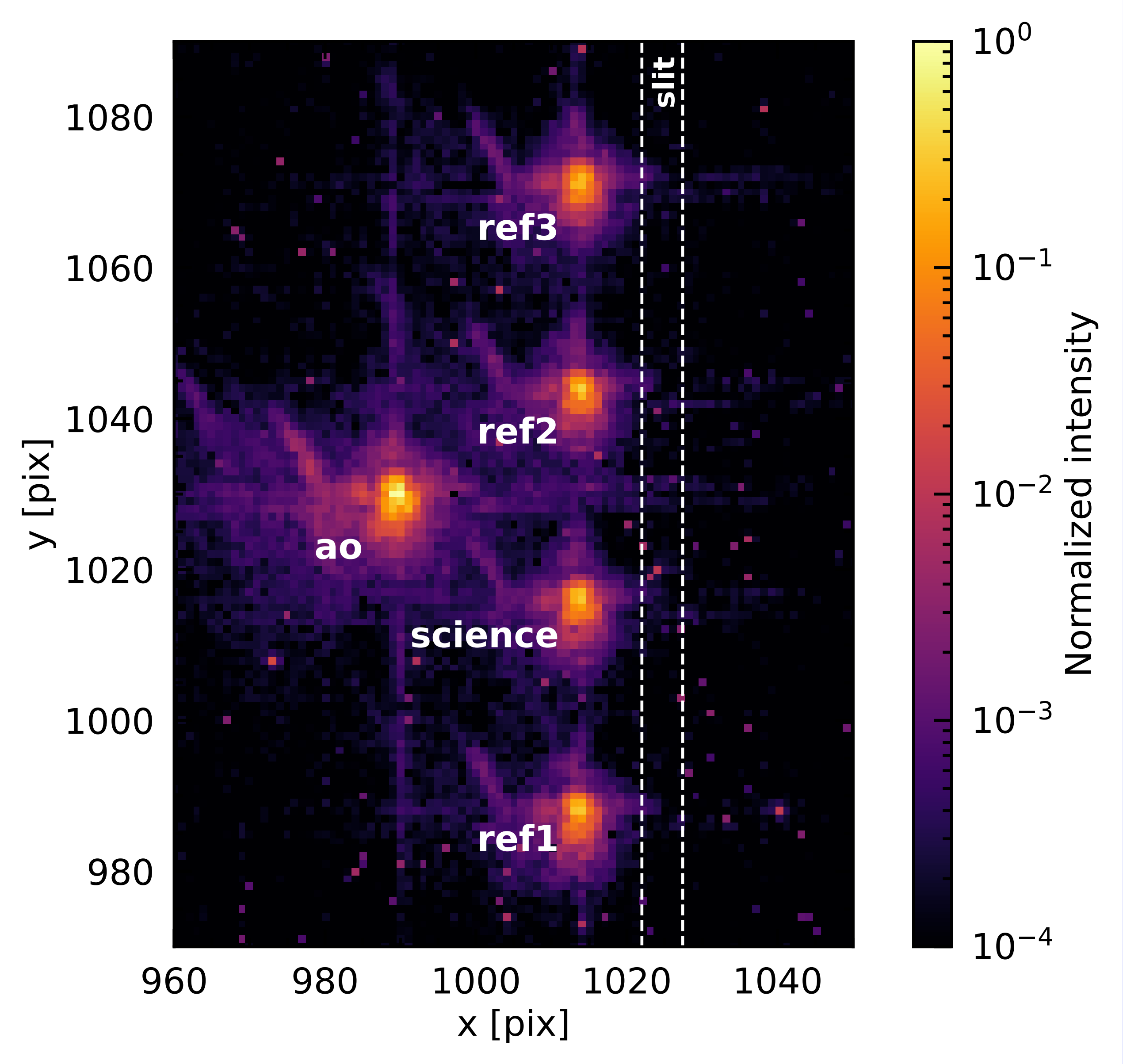
Cross-calibration strategy with SPHERE/IRDIS

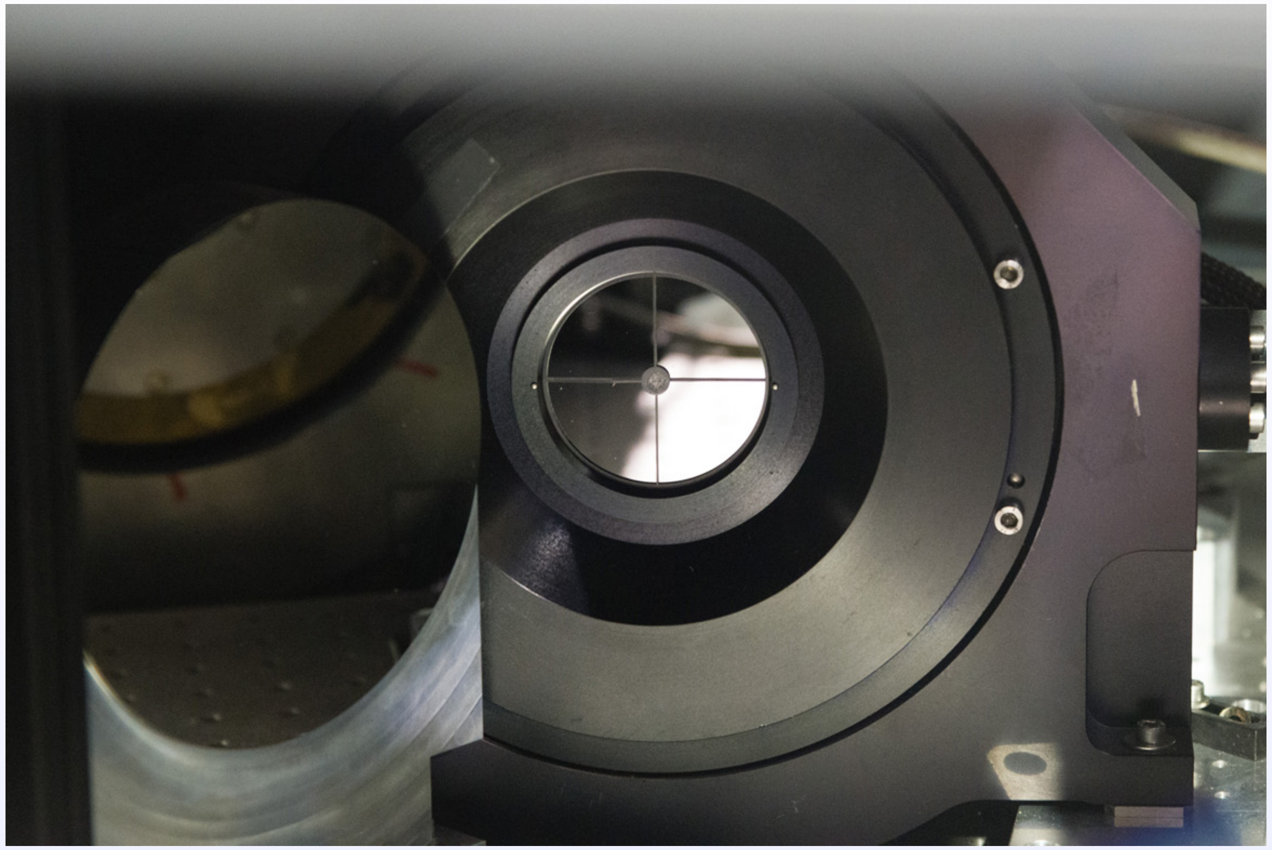
Commissioning: AO guide fiber leakage

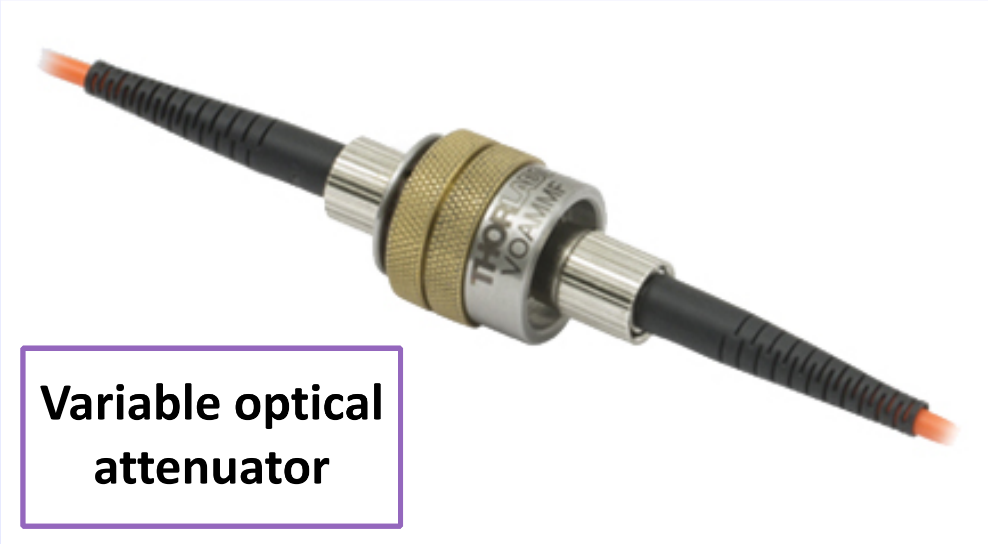


MACAO guide fiber leaks inside the slit

Commissioning: AO guide fiber leakage





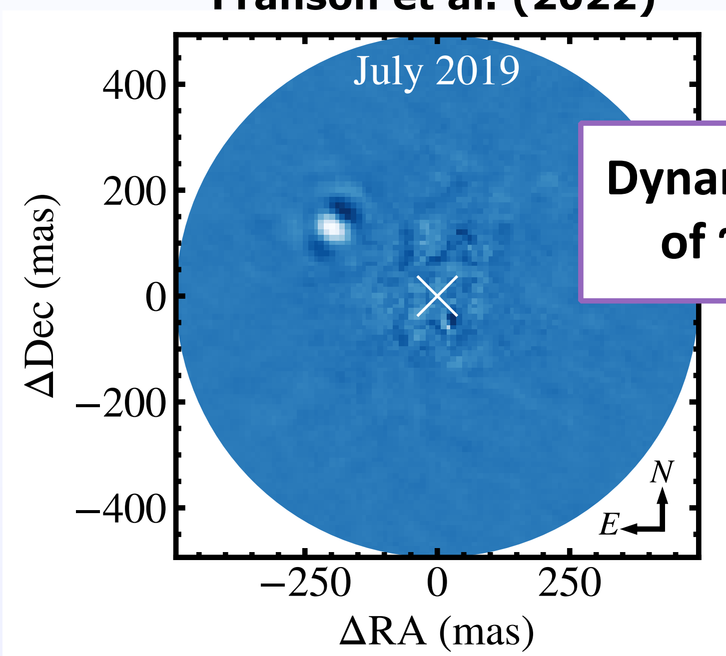


Mitigation strategy already foreseen

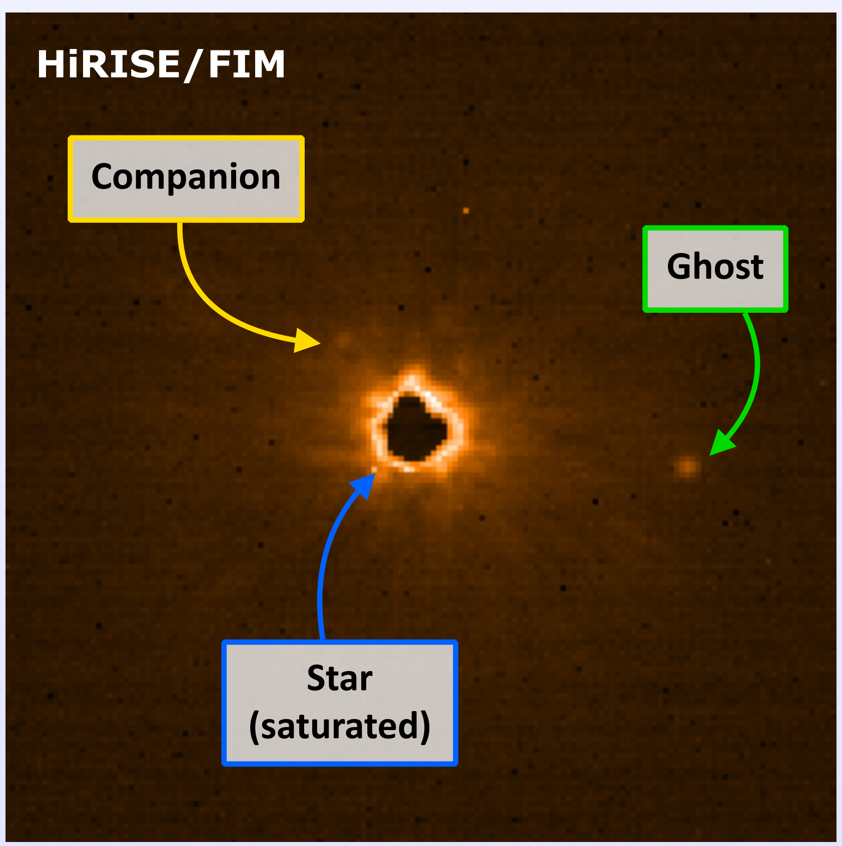
Commissioning: a first detection of HD984 B

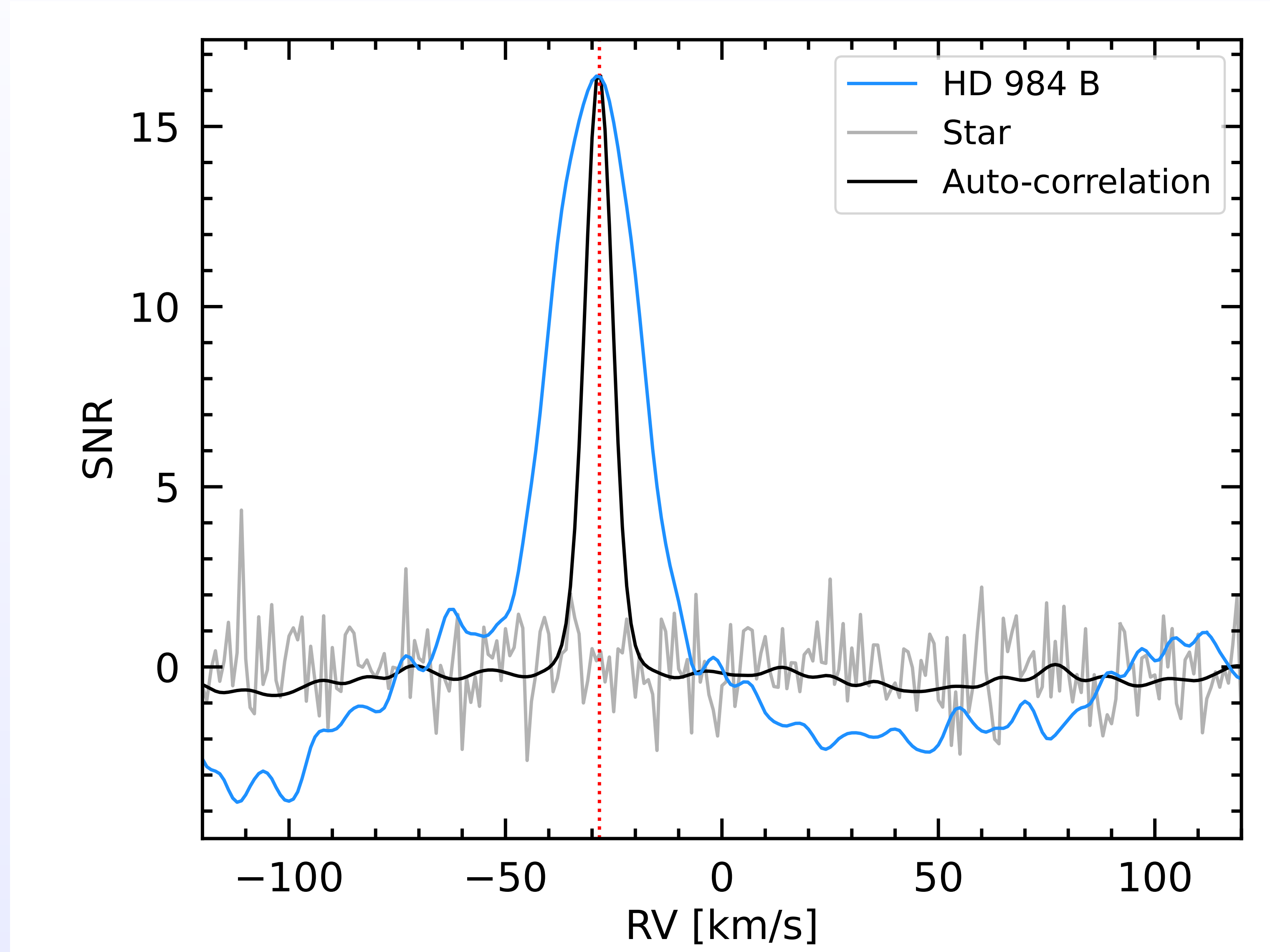
Discovery: **Meshkat et al. (2015)**

Franson et al. (2022)



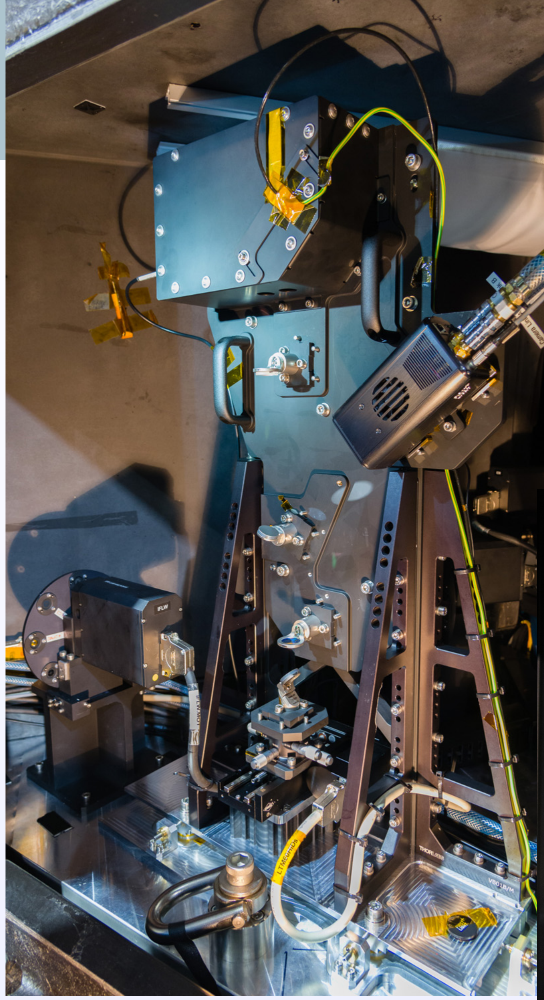
Dynamical mass of ~60 M_{Jup}

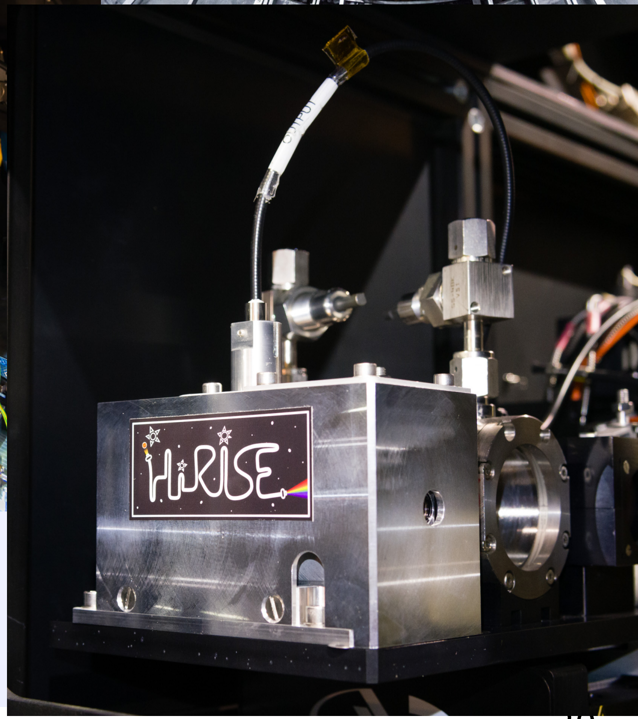




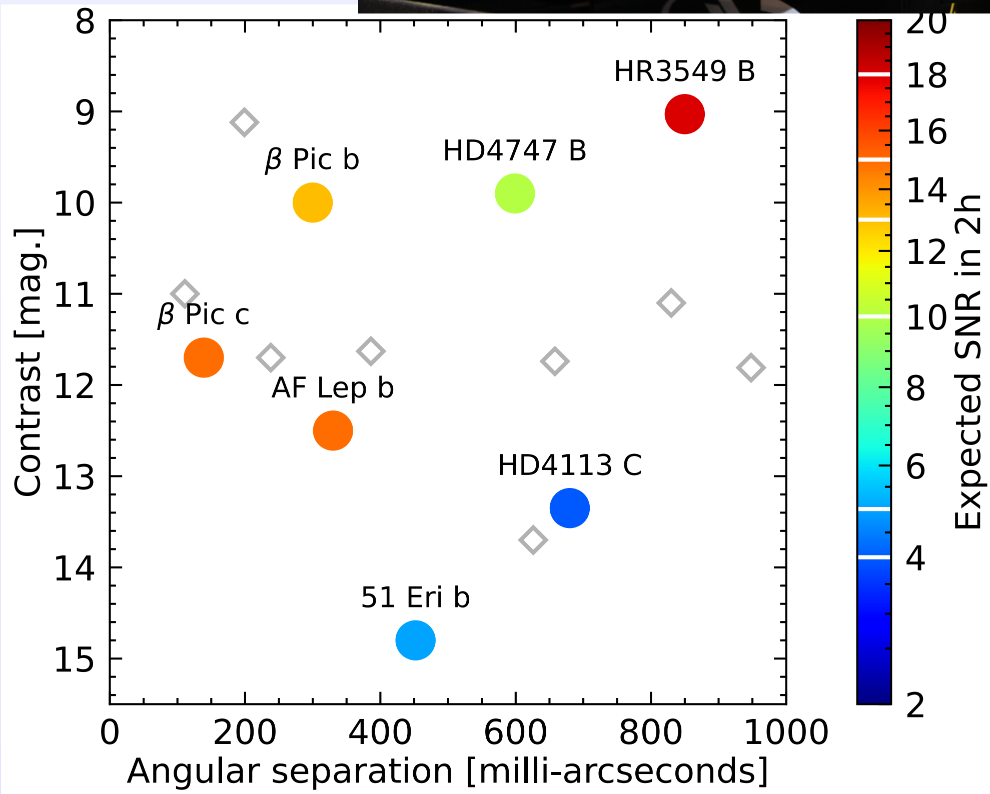
- Least-square CCF analysis
- BT-Settl model at T_{eff} = 2700K
- v_{orb} sin i = -31 km/s, v_{rot} sin i = 13 km/s
- Value in agreement wit KPIC data (Costes et al. in prep.)

Conclusions & prospects

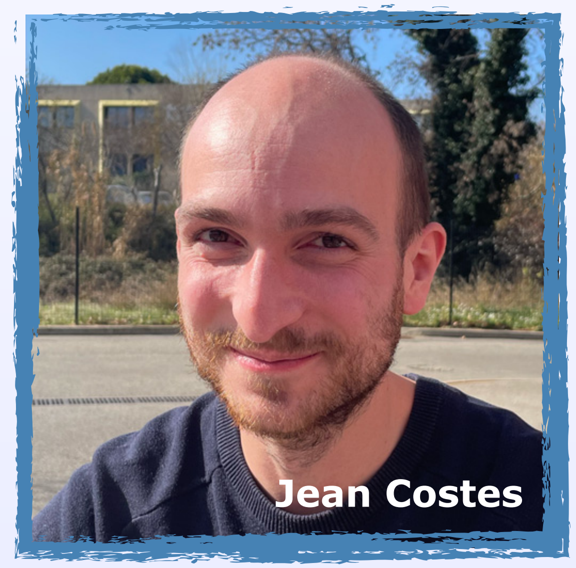


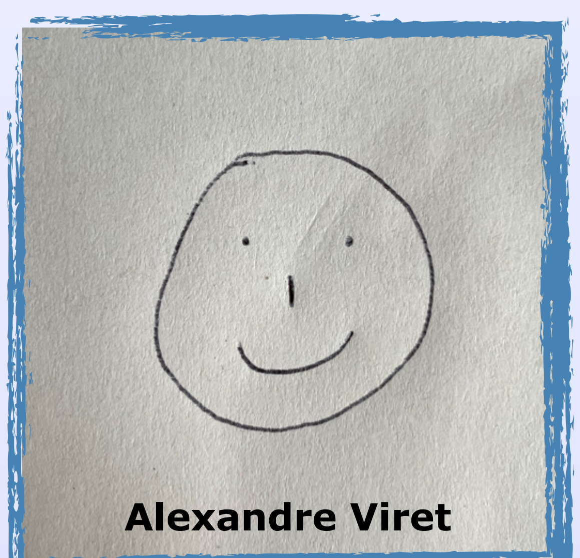


1. **High-spectral resolution of directly-imaged exoplanets**
   - Unique opportunity on VLT/UT3!
   - Coupling between SPHERE and CRIRES+ in H band
   - Visitor instrument on the VLT
   - First light in July 2023
2. **HiRISE survey**
   - New opportunities for understanding of exoplanets
   - 3 nights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