Characterization of directly-imaged exoplanets at high spectral resolution: Coupling SPHERE and CRIRES+

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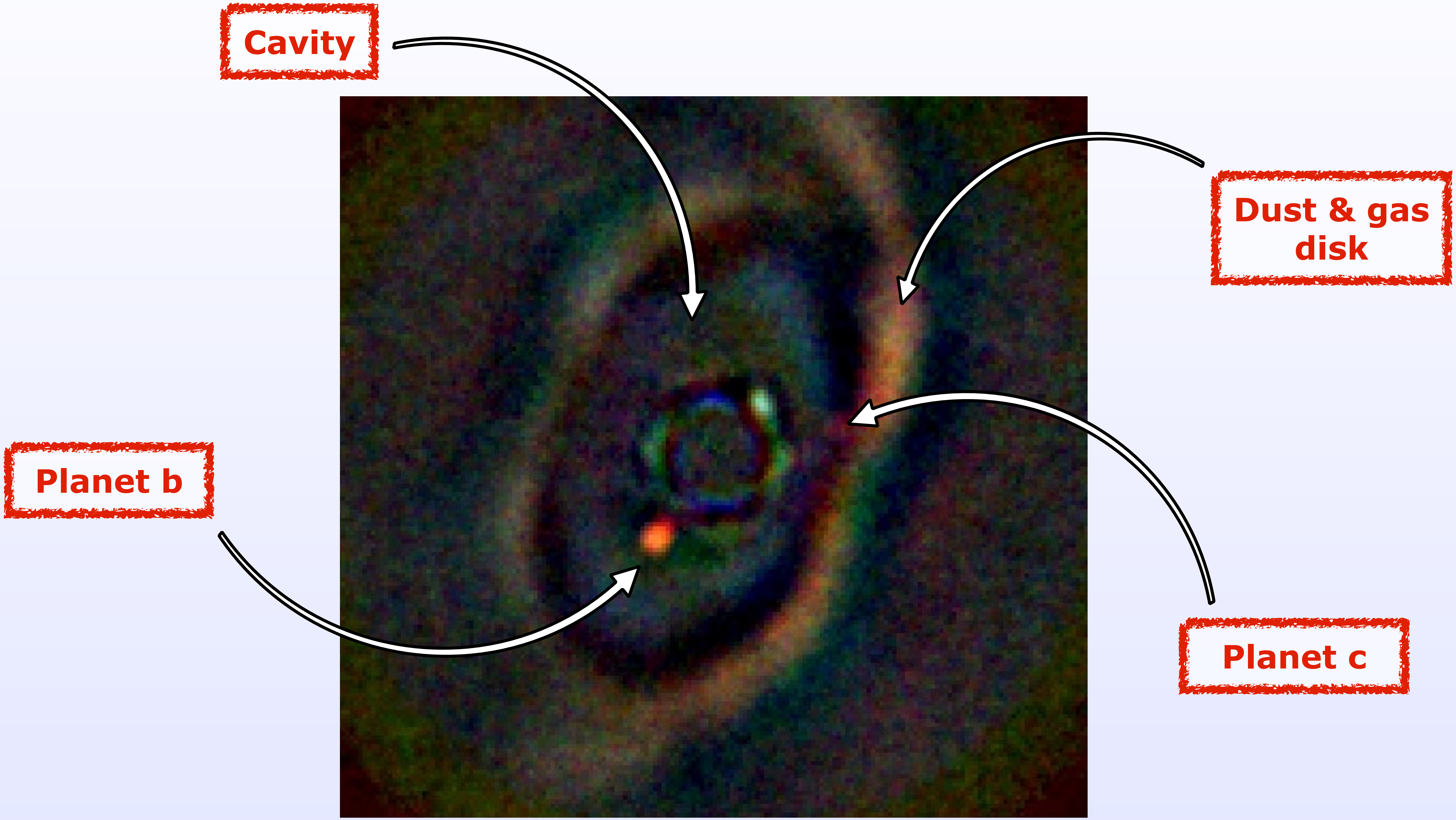
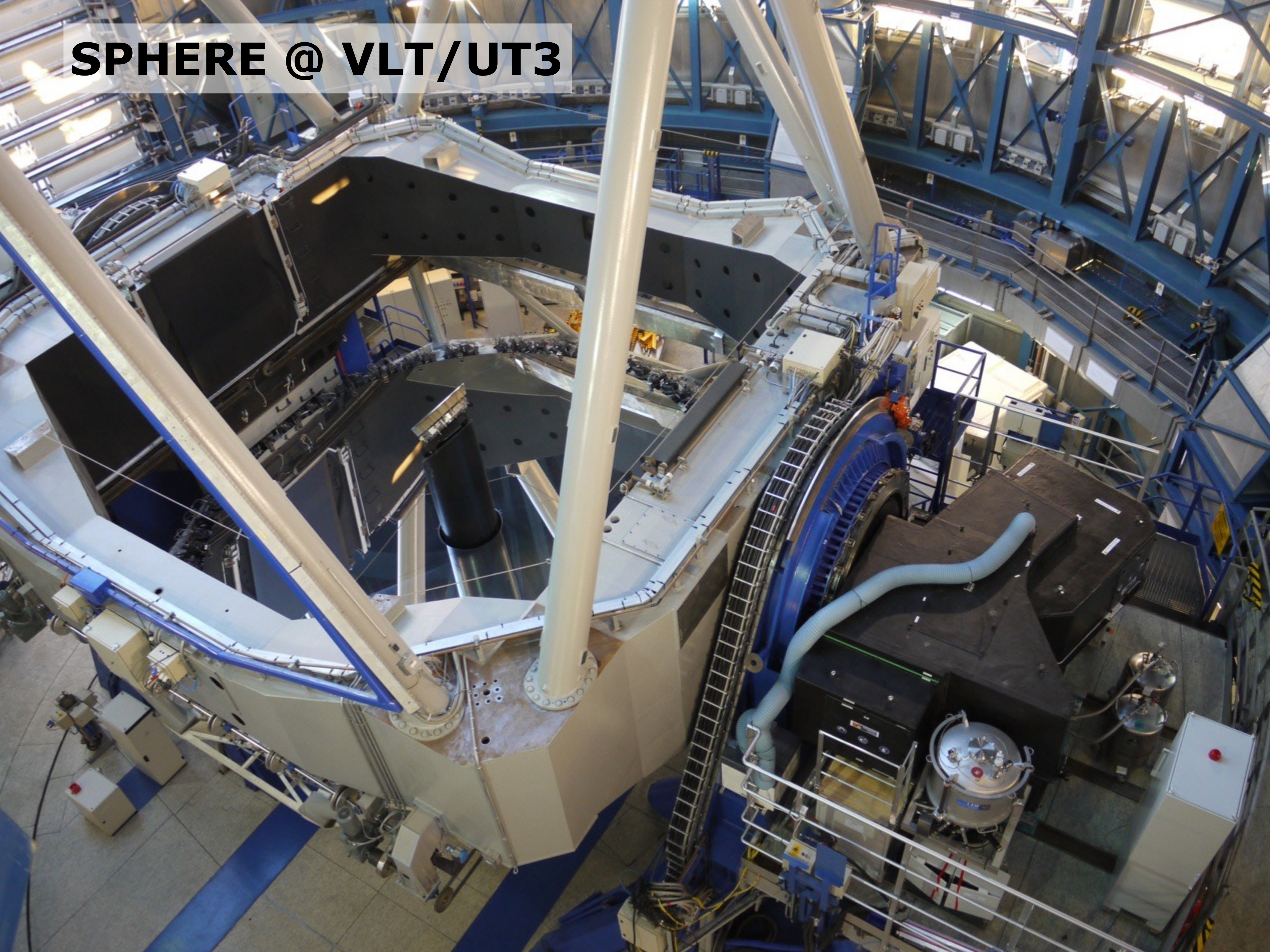
+ ESO Paranal support: A. Smette, L. Pallanca, L. Blanco, et al.

Direct imaging of exoplanets

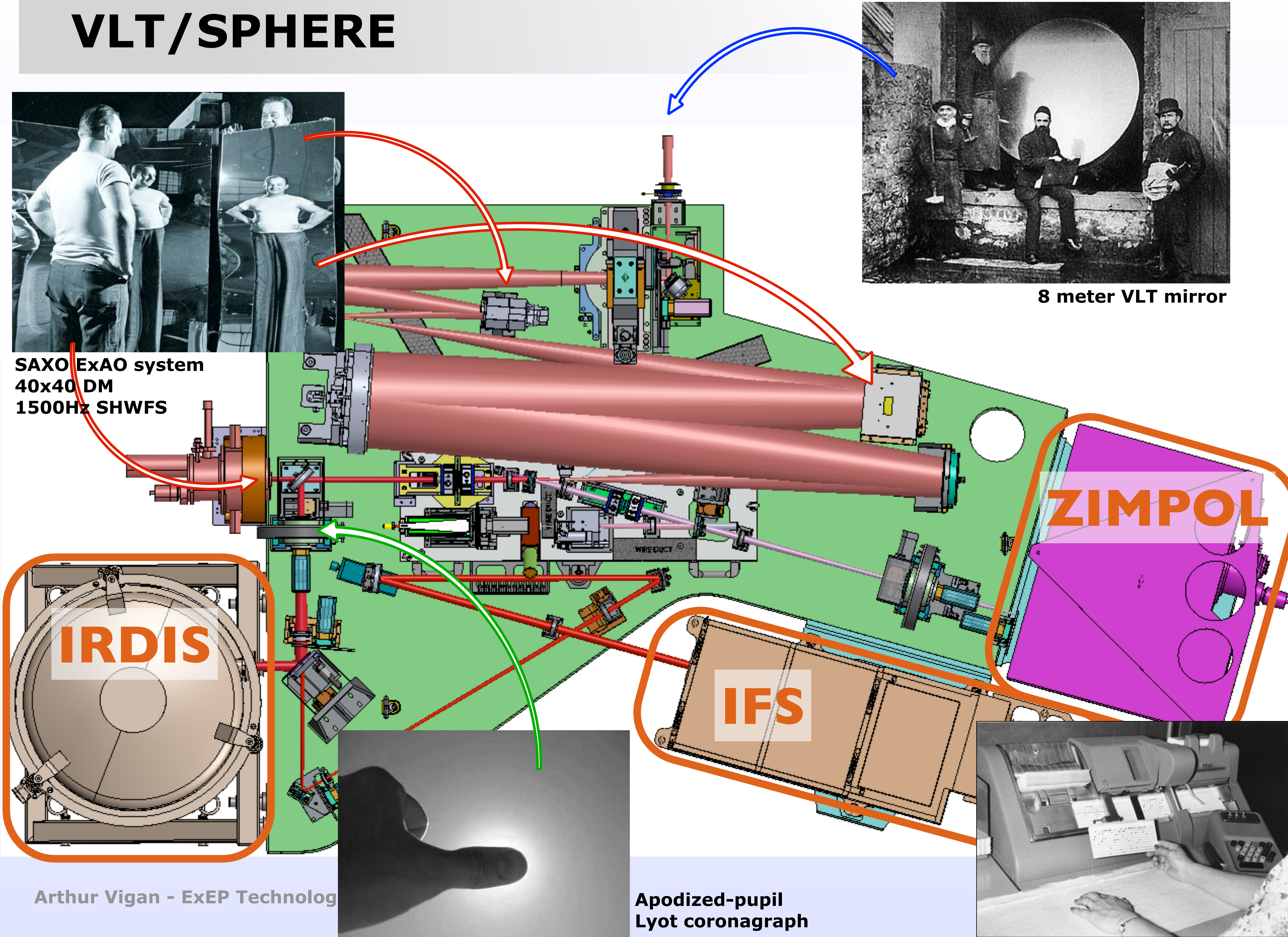


PDS 70 - Keppler et al. (2018)

SPHERE @ VLT/UT3



VLT/SPHERE


8 meter VLT mirror
SAXO ExAO system
40x40 DM
1500Hz SHWFS
ZIMPOL
IRDIS
IFS
WIRE DUCT
Apodized-pupil
Lyot coronagraph

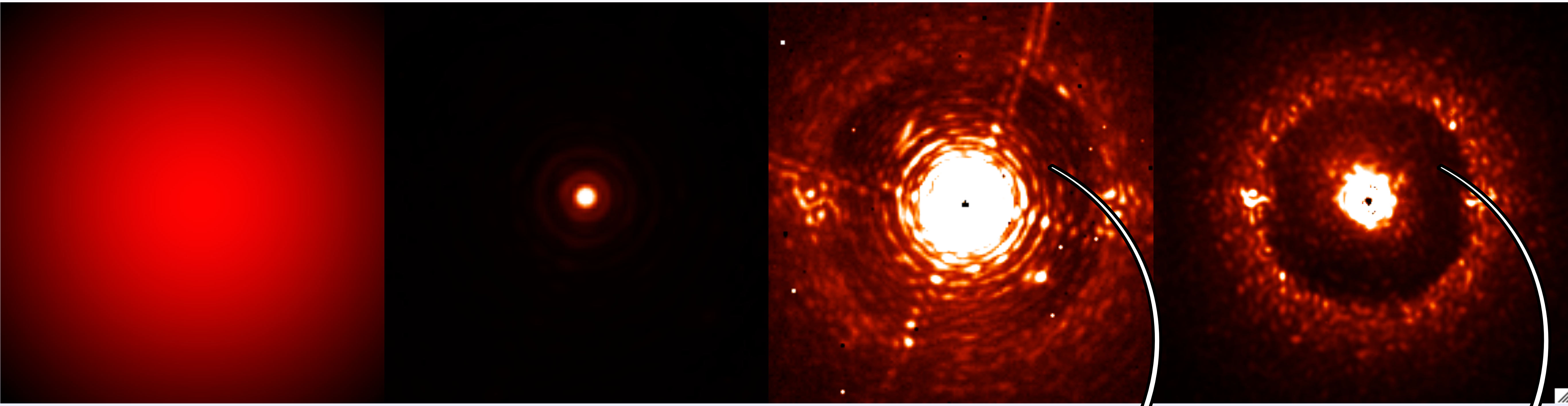
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

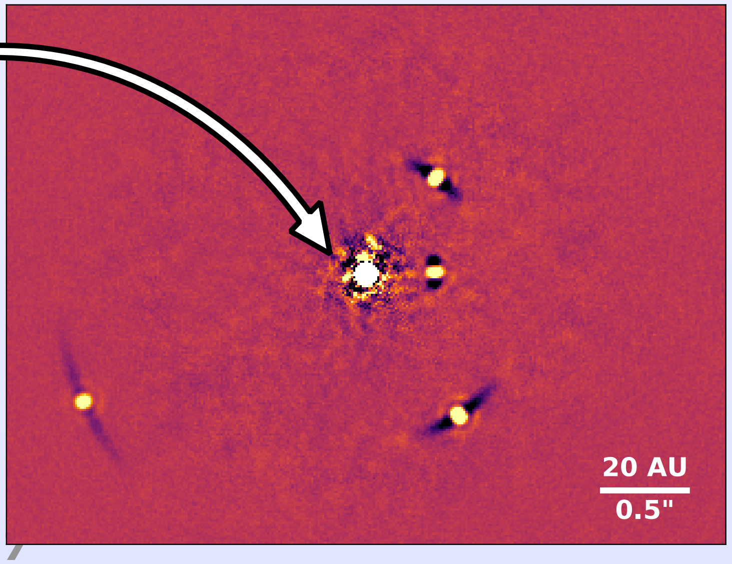
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



Diffraction limited within 20 λ/D

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

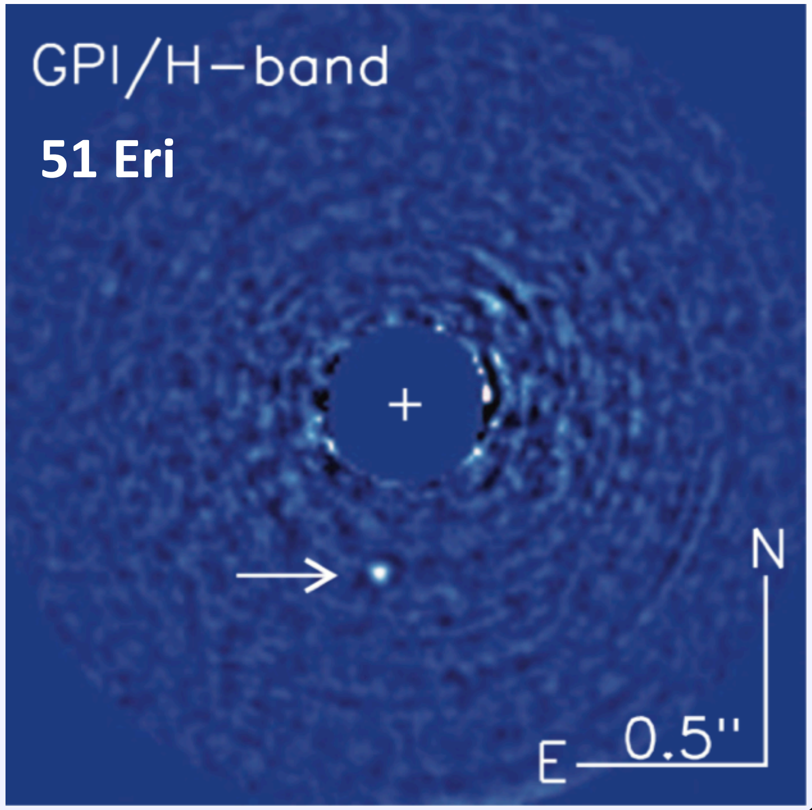
post-processing



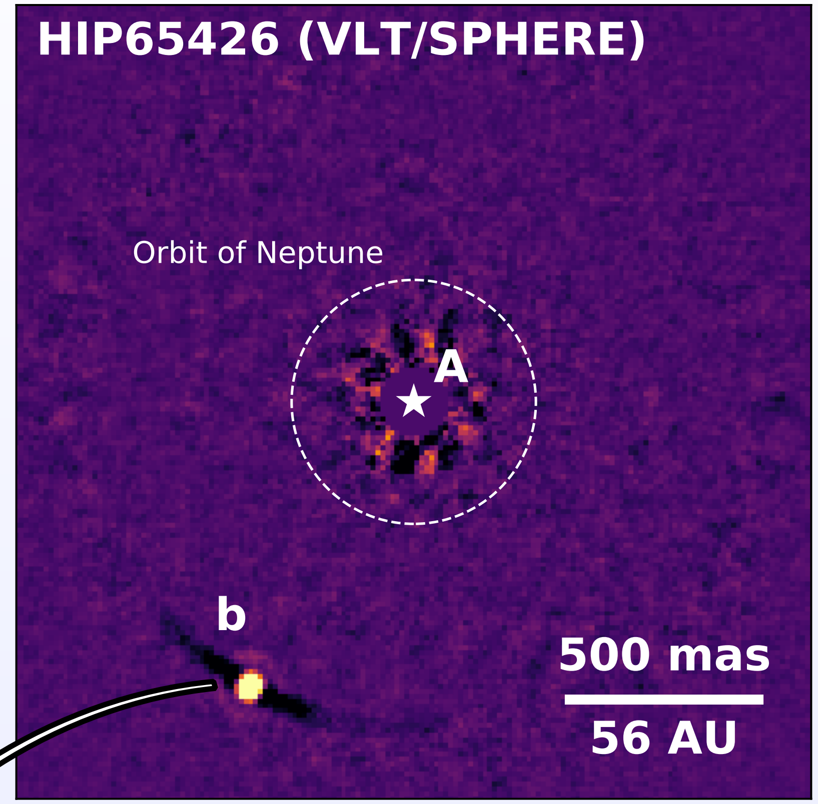
~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

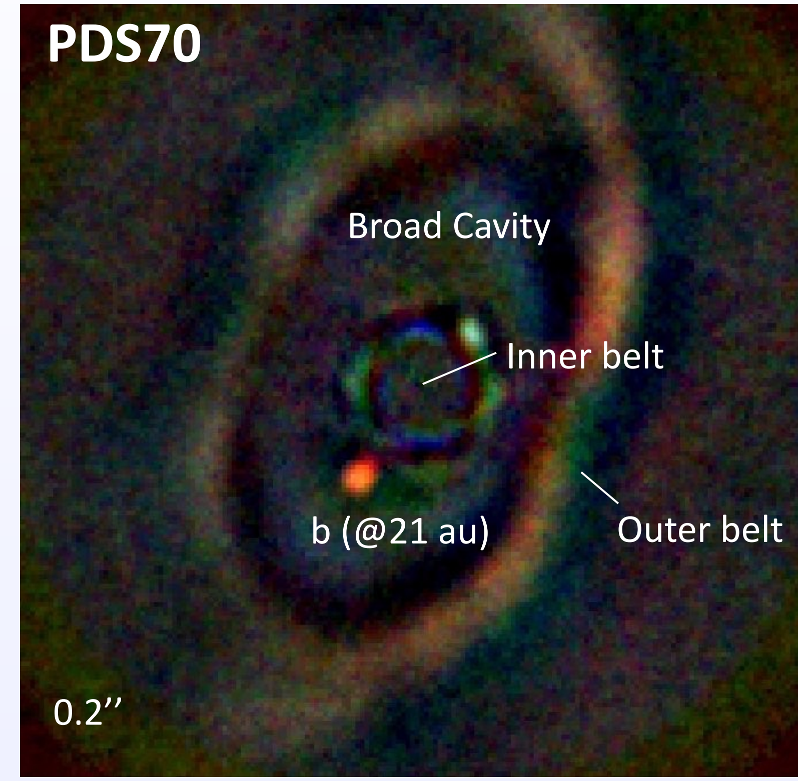
SPHERE and GPI detections



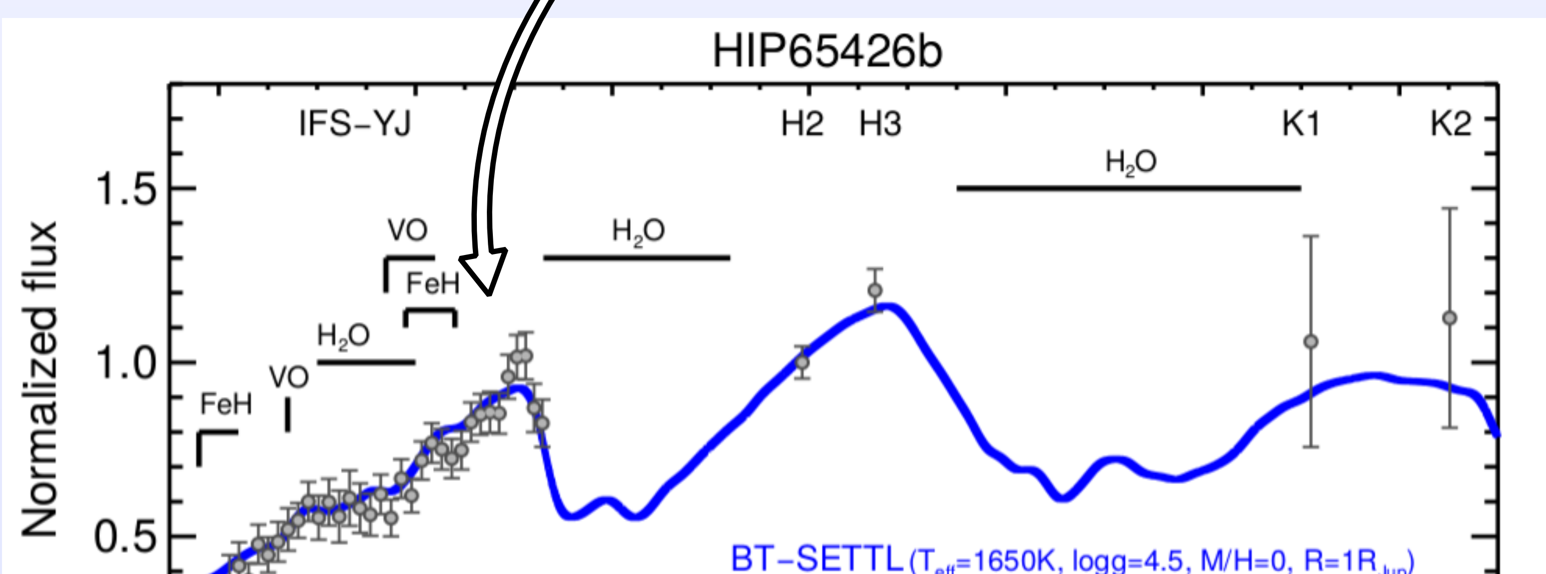
Macintosh et al. 2015



Chauvin et al. 2017



Keppler et al. 2018

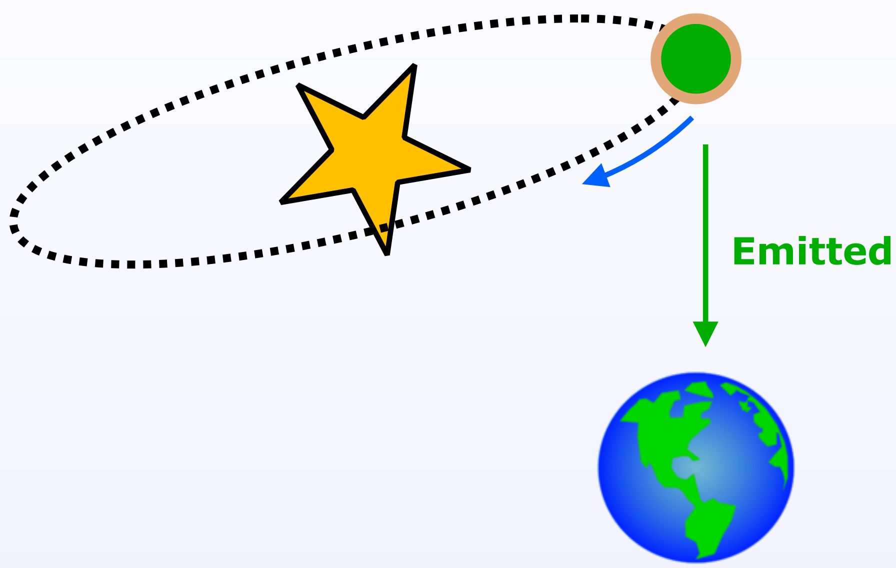


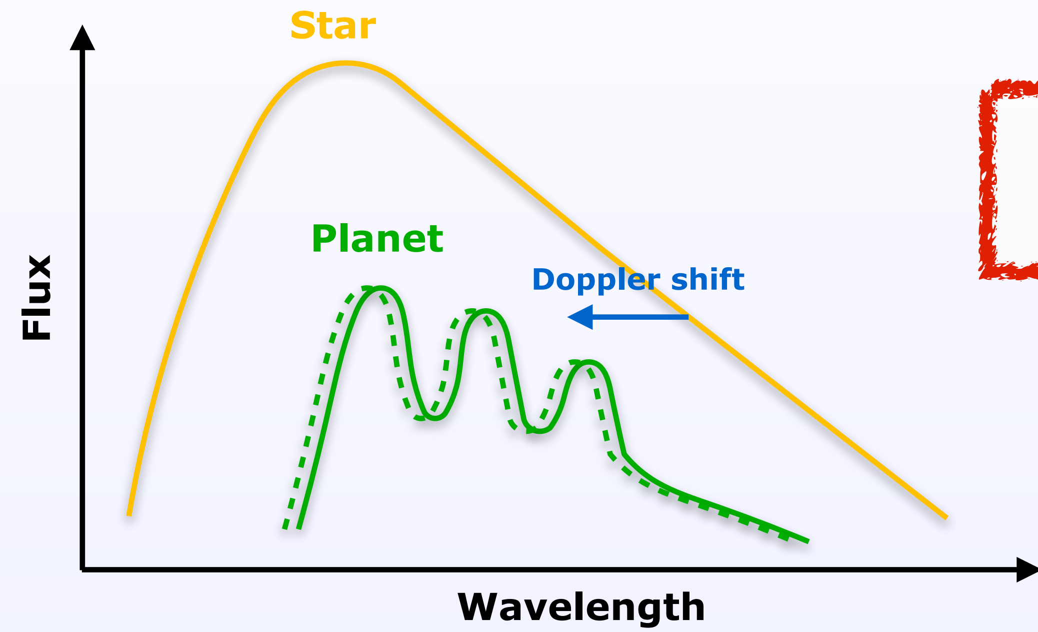
Very low resolution spectroscopy!

→ First order characterisation

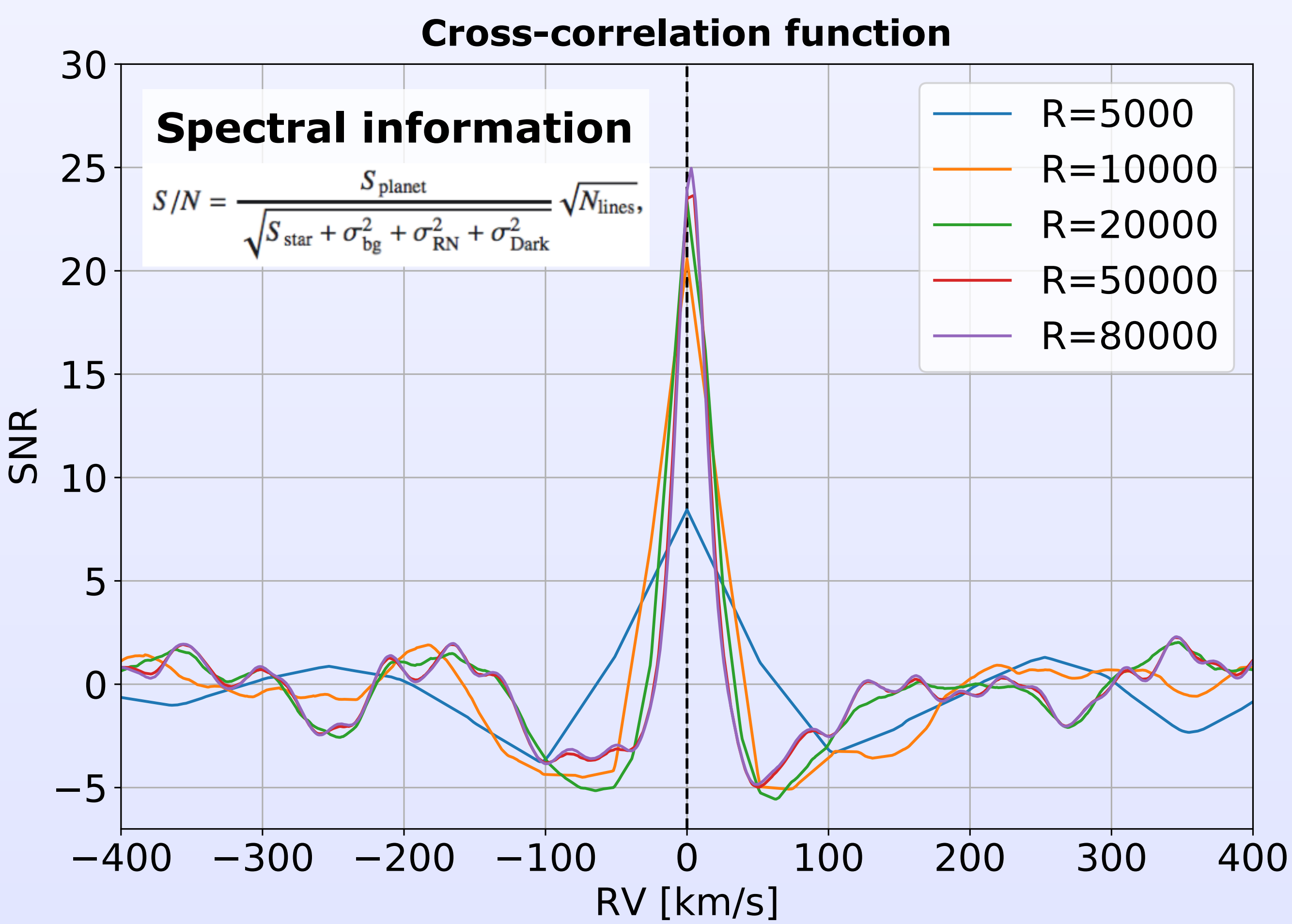
Go for high spectral resolution!

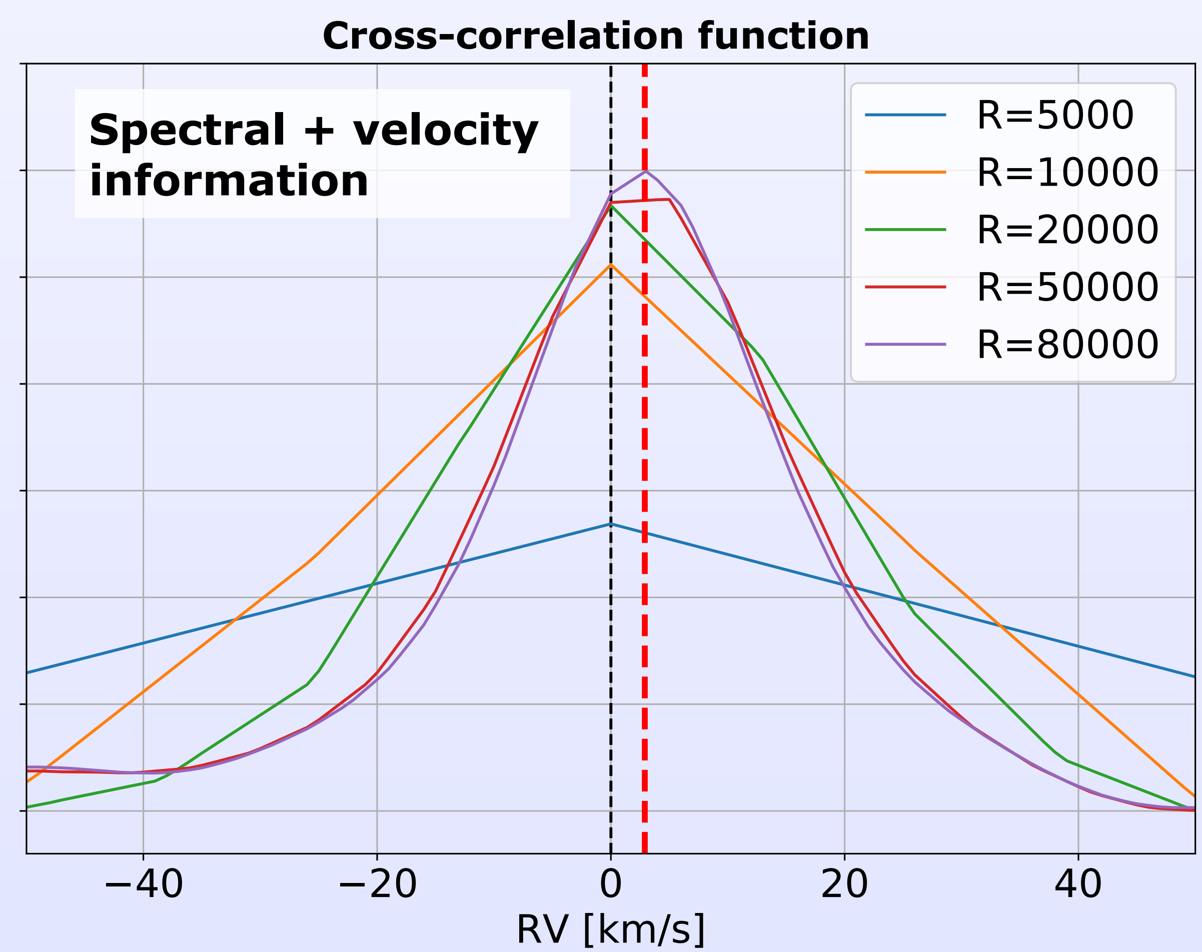
Detection boost at high-spectral resolution



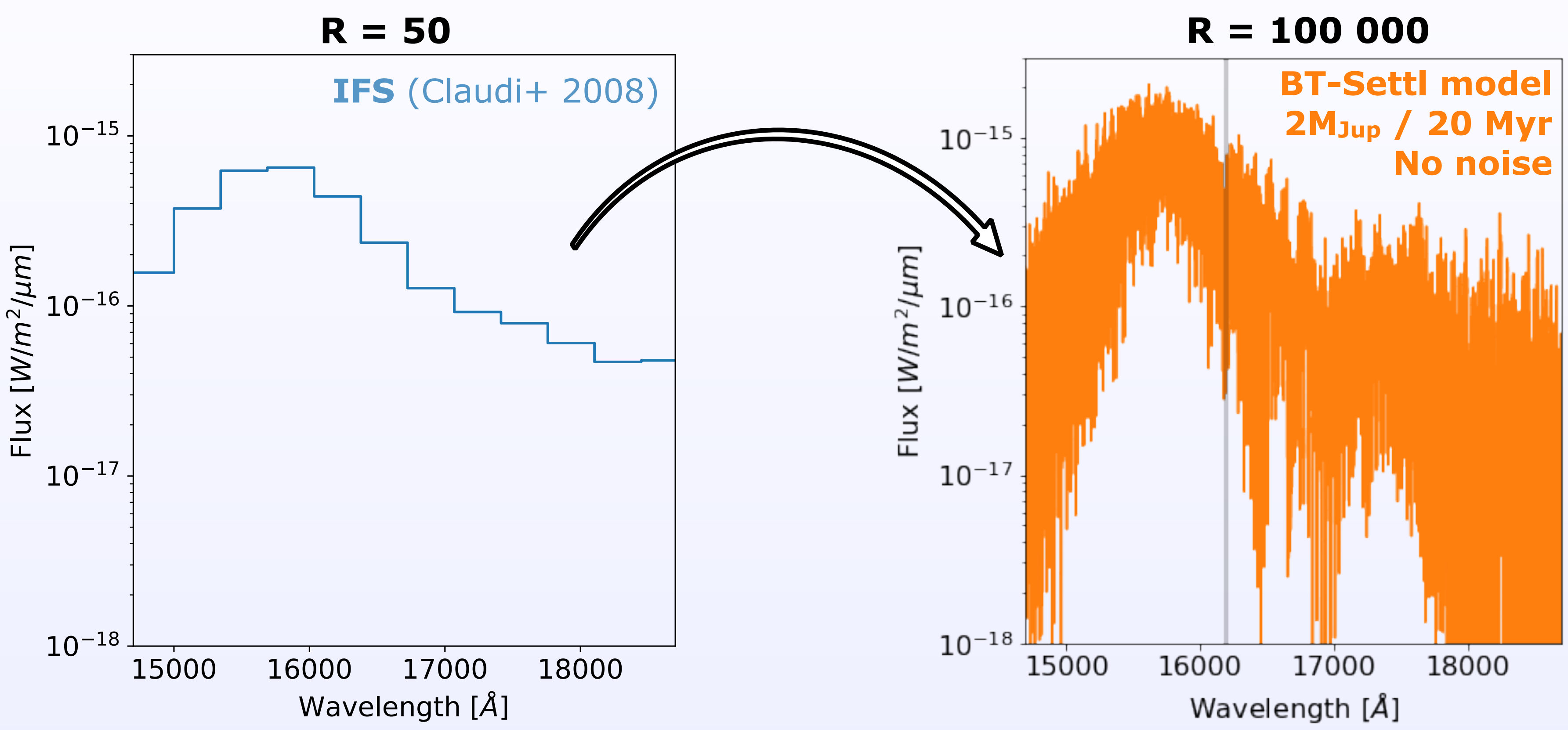


Requires
R ≫ 10 000

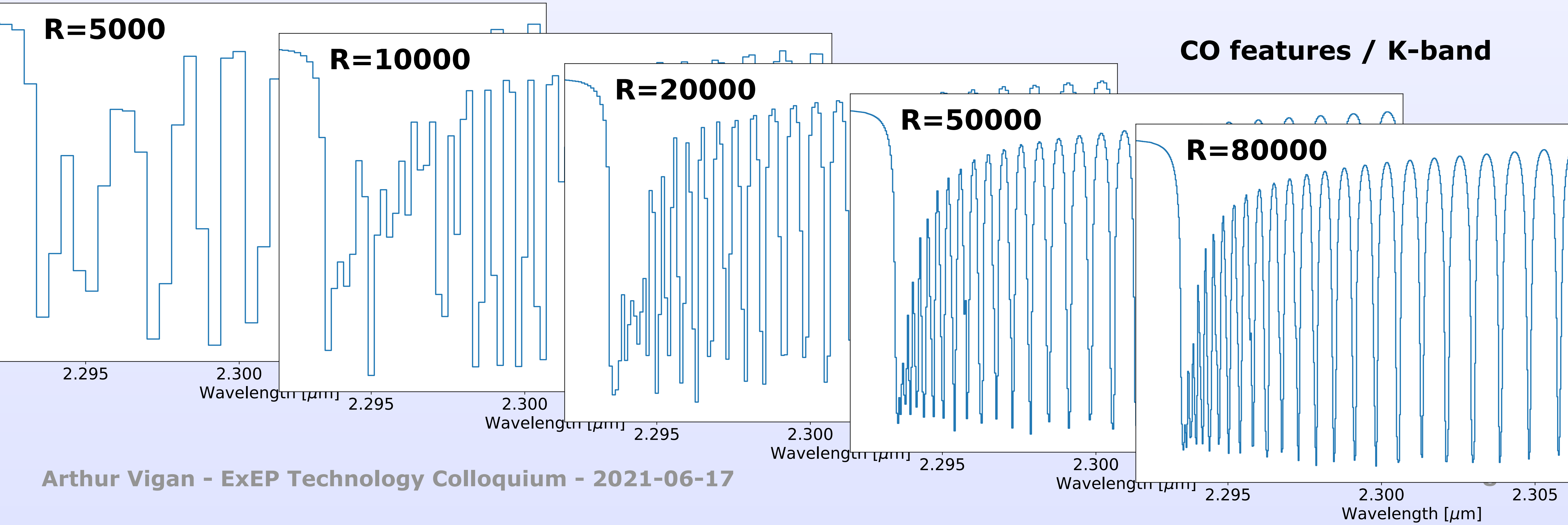




Characterisation at high-spectral resolution

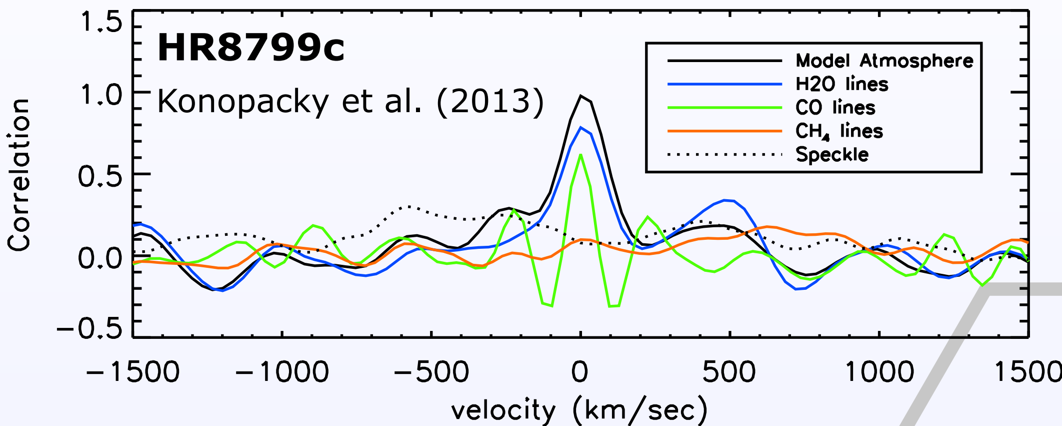


Requires
R ≫ 10 000

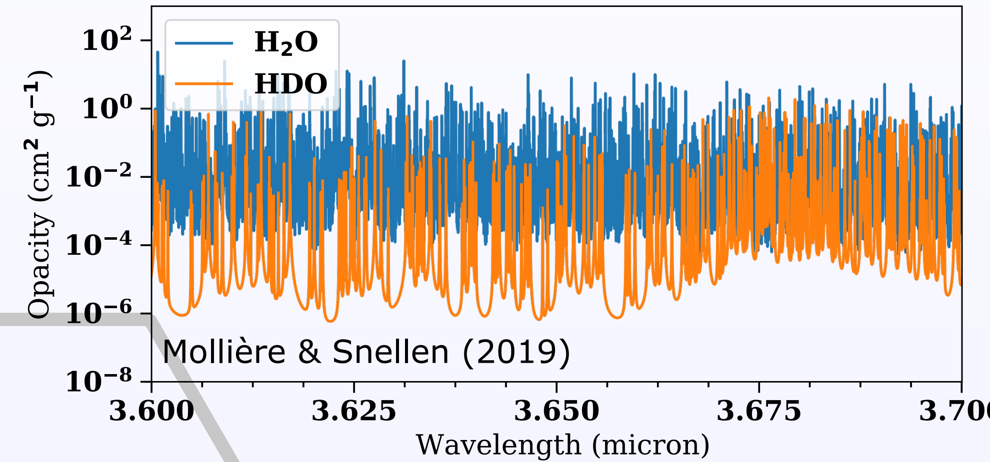


Exoplanet science at high resolution

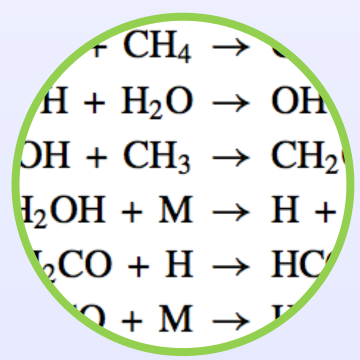
Molecules detection



Isotopologues detection

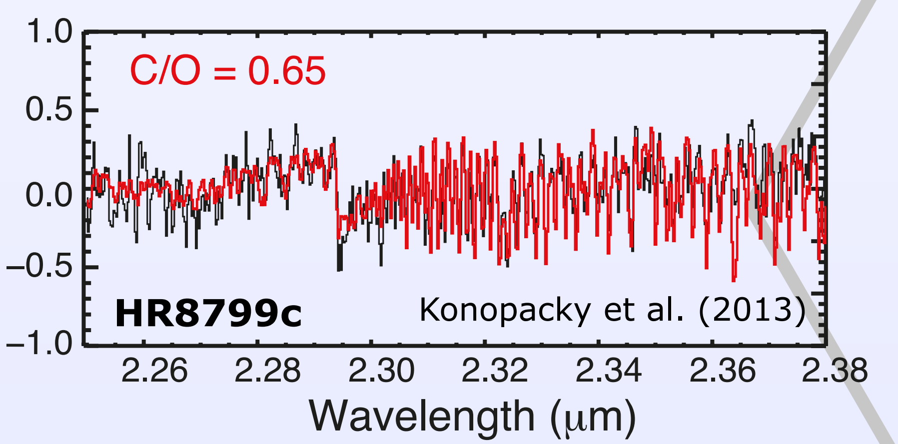


Formation, migration & evolution

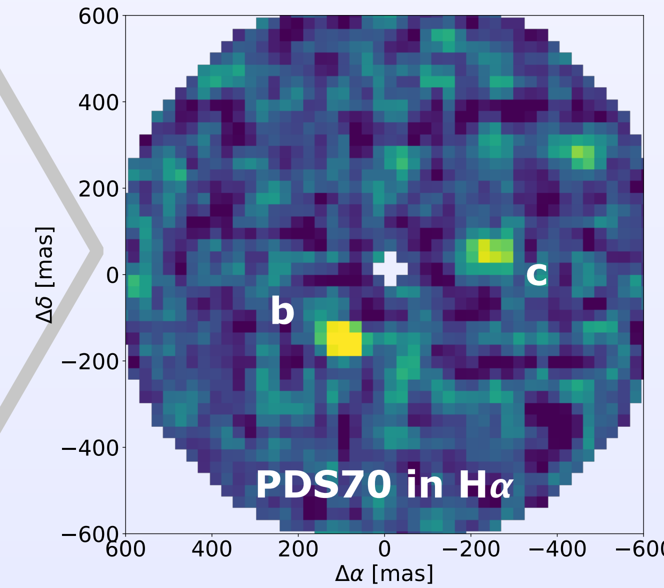


Atmospheric chemistry & dynamics

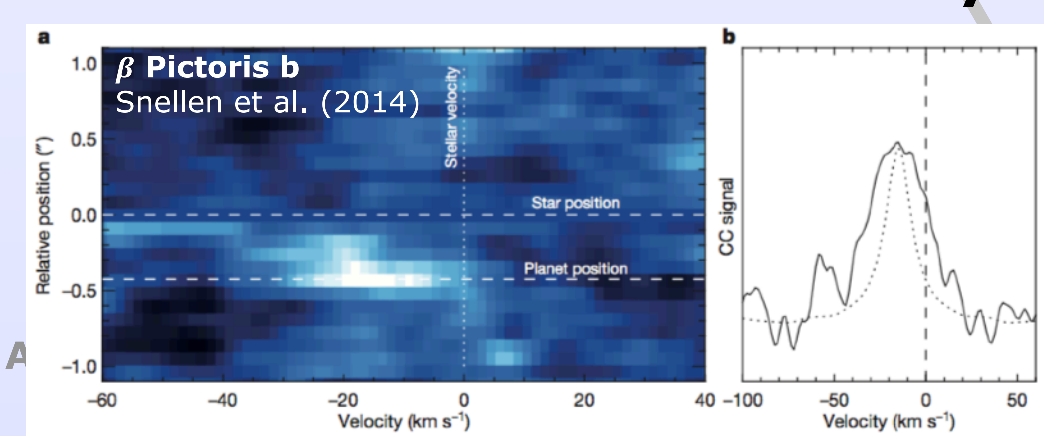
Abundances determination



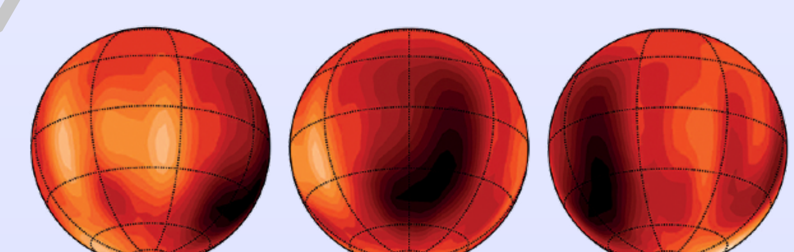
Accretion lines



Orbital and rotational velocity

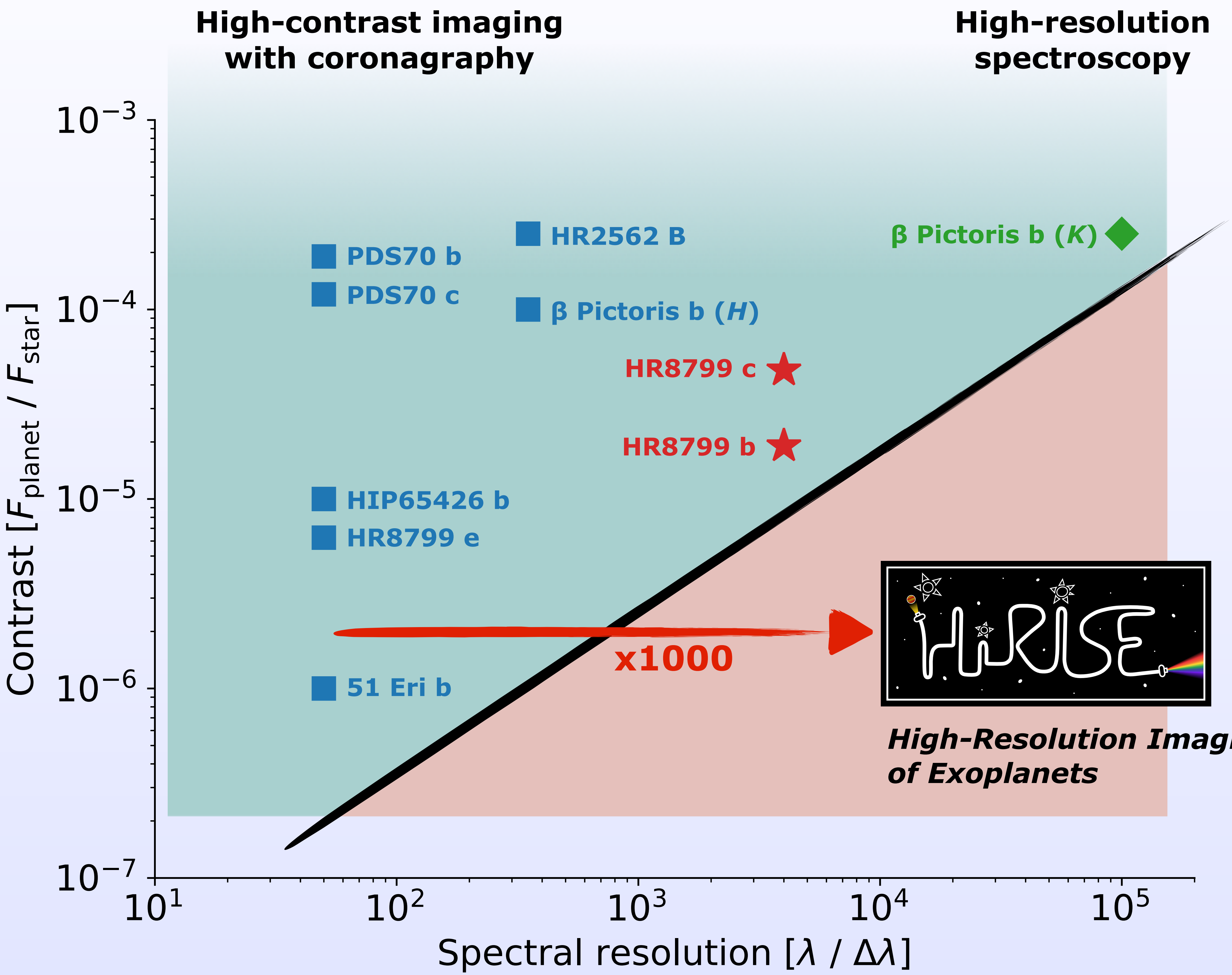


Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR



High-Resolution Imaging and Spectroscopy of Exoplanets

Characterisation

10-15 companions already known at

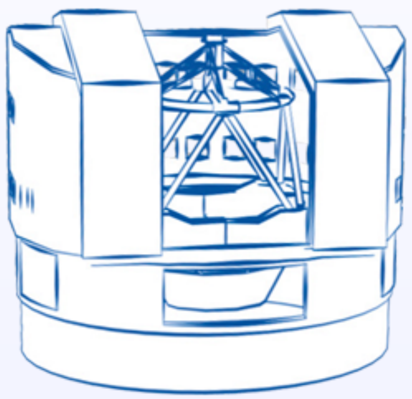
- **separation < 1"**
- **contrast < 10^{-4}**

Companions detected by other means

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

A unique window of opportunity

VLT/UT3

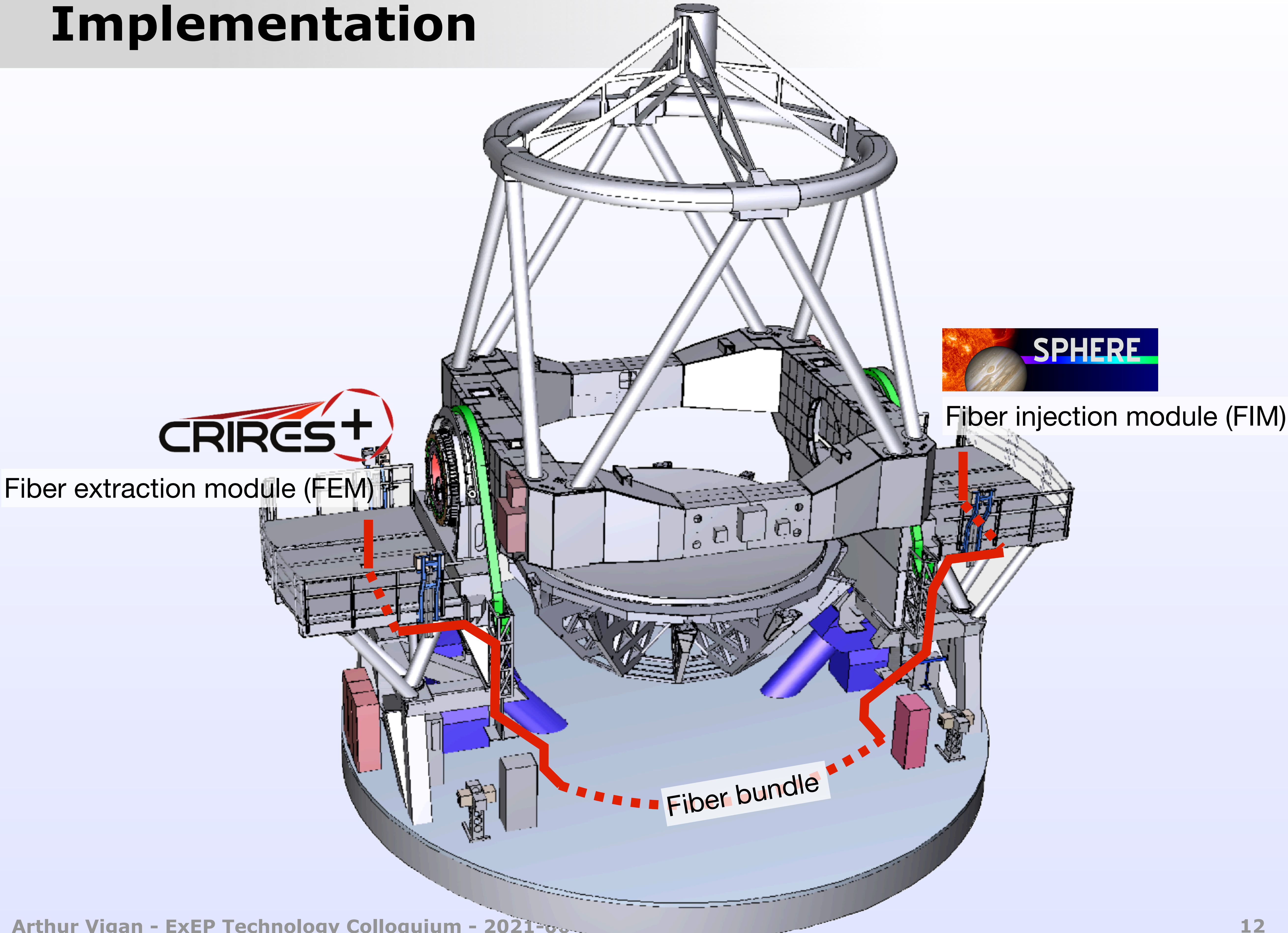


High-contrast exoplanet imager		High-resolution spectrograph
SPHERE		CRIRES+
✔	Extreme adaptive optics	✘
✔	Coronagraphy	✘
Y J H K	Spectral coverage	Y J H K L M
50 - 350	Spectral resolution	50 000 - 100 000

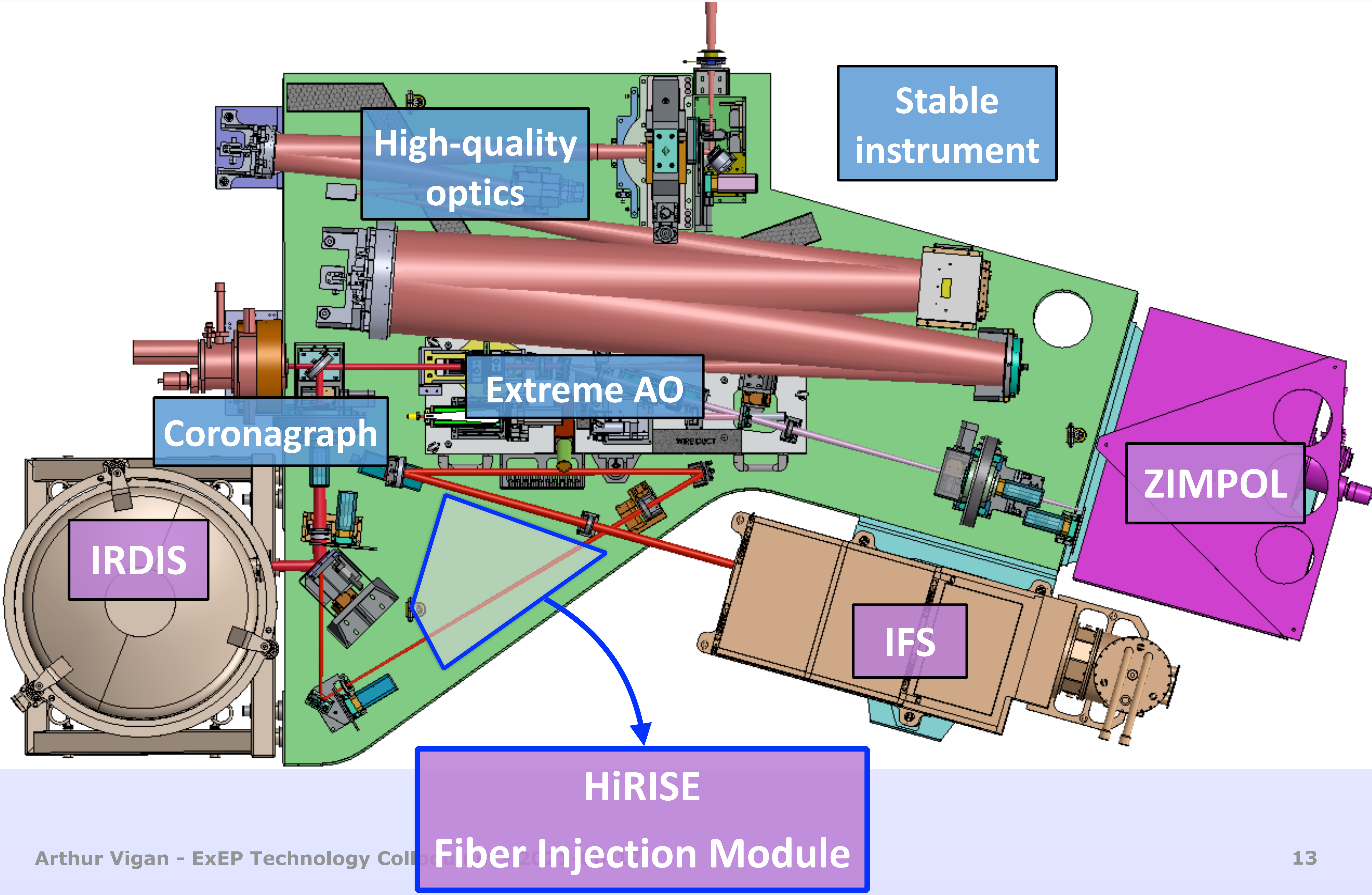
Fiber coupling

HiRISE

Implementation

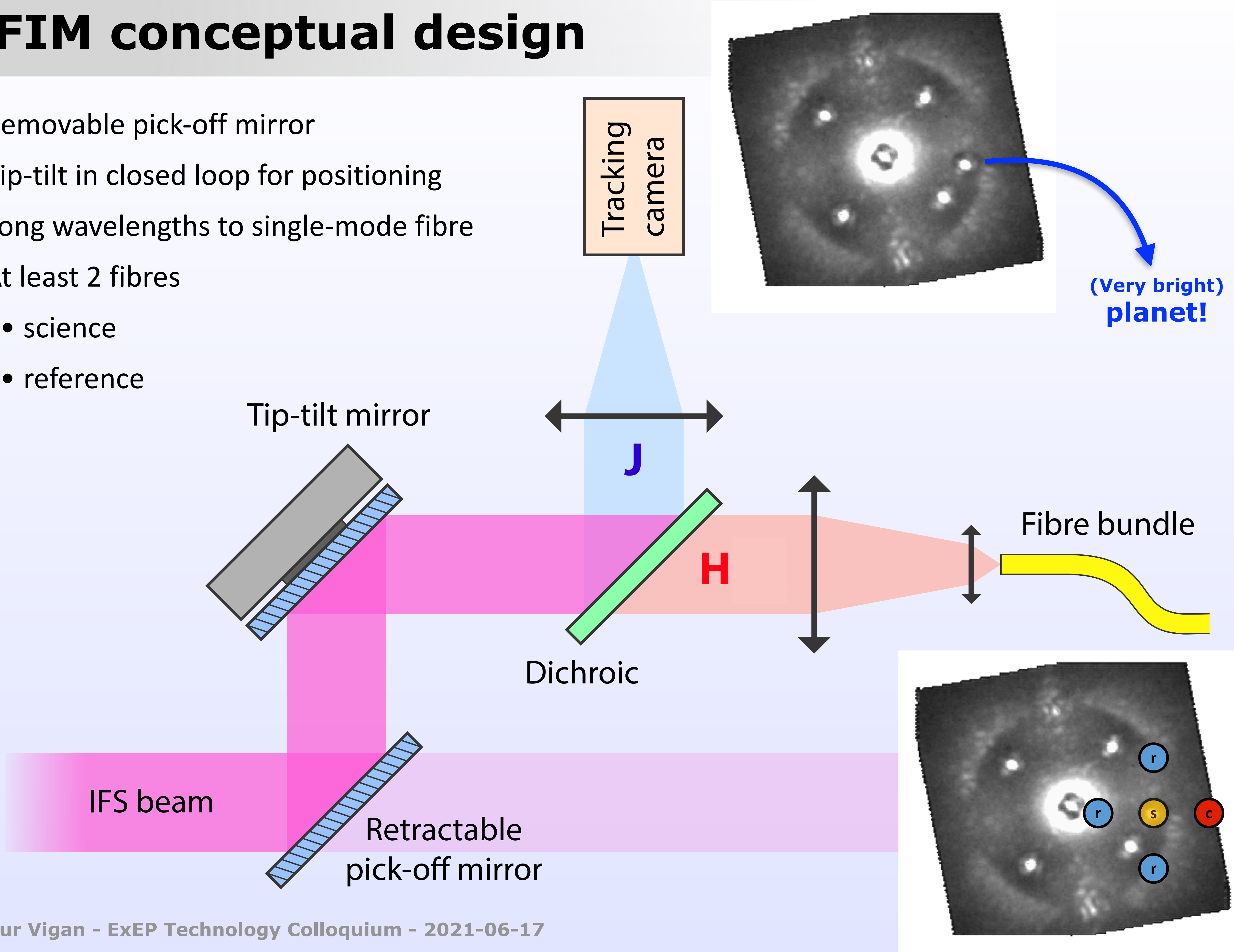


Fiber injection module in SPHERE



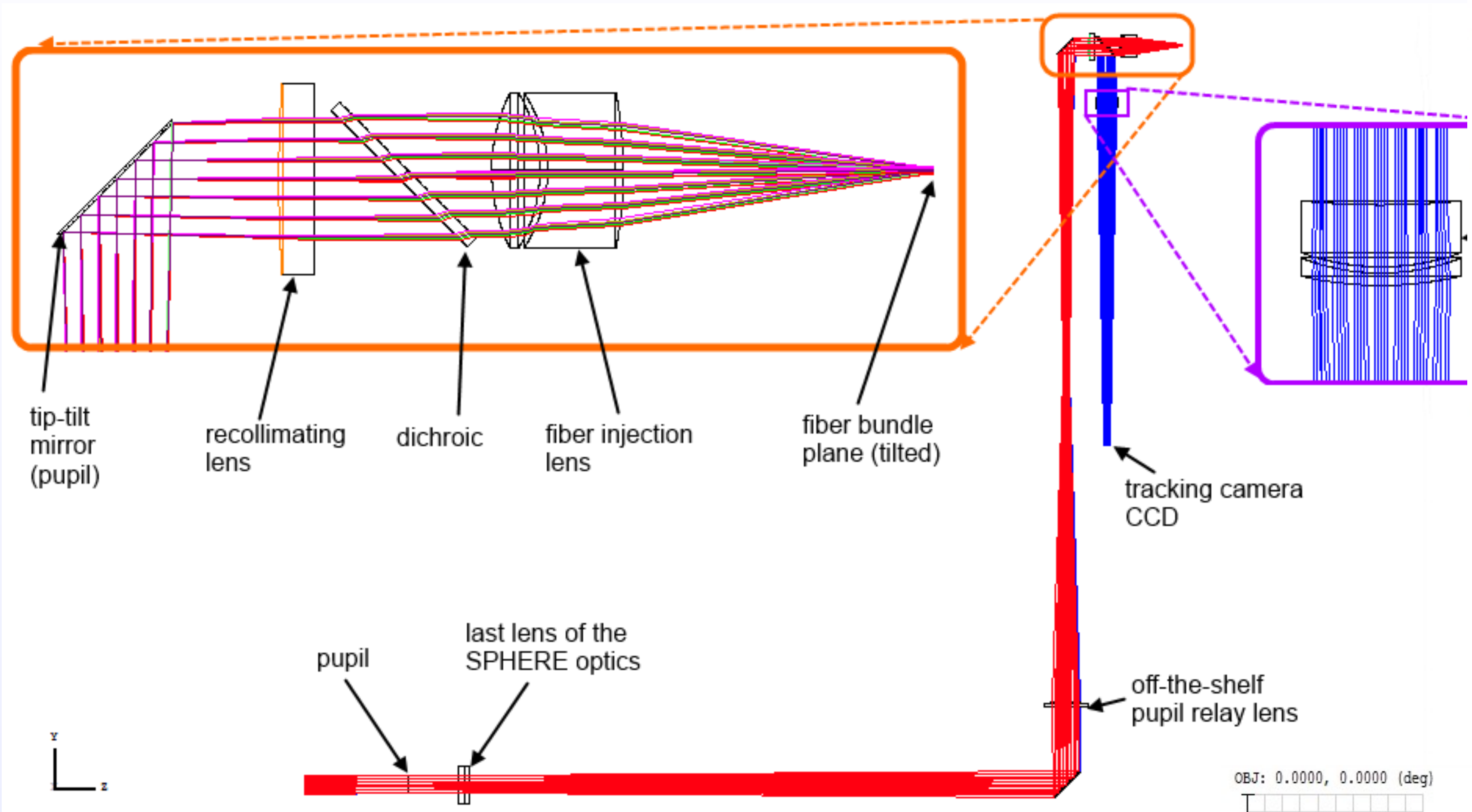
FIM conceptual design

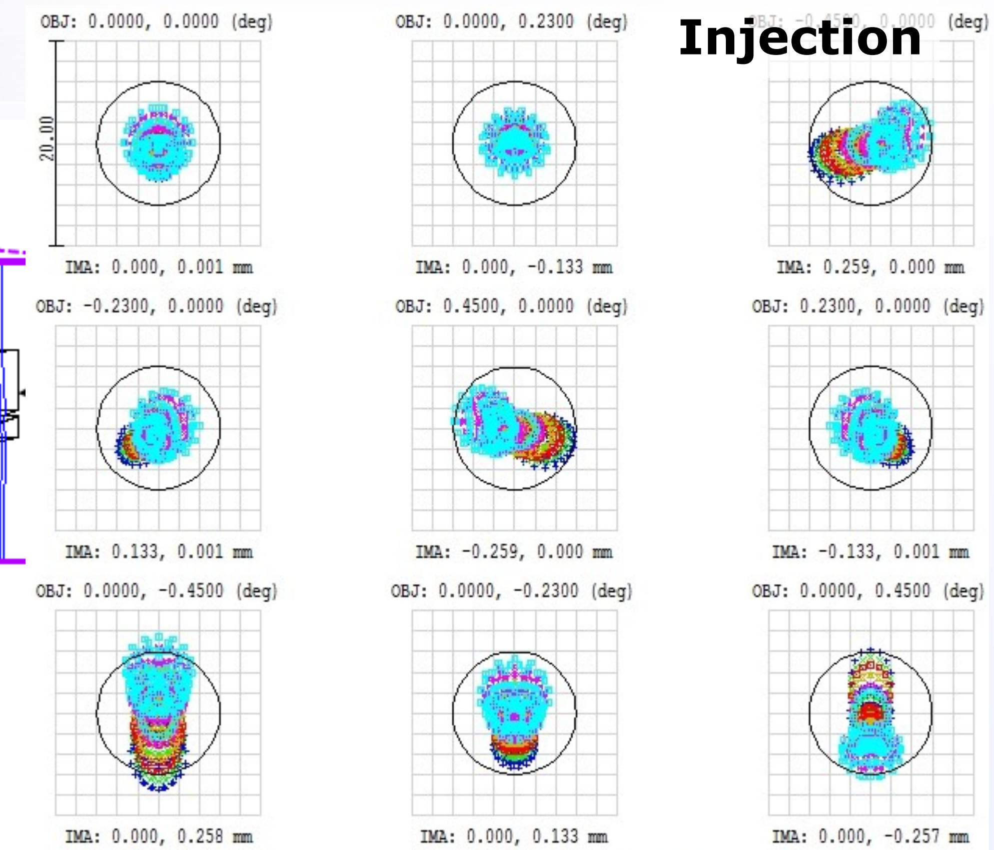
- Removable pick-off mirror
- Tip-tilt in closed loop for positioning
- Long wavelengths to single-mode fibre
- At least 2 fibres
    - science
    - reference



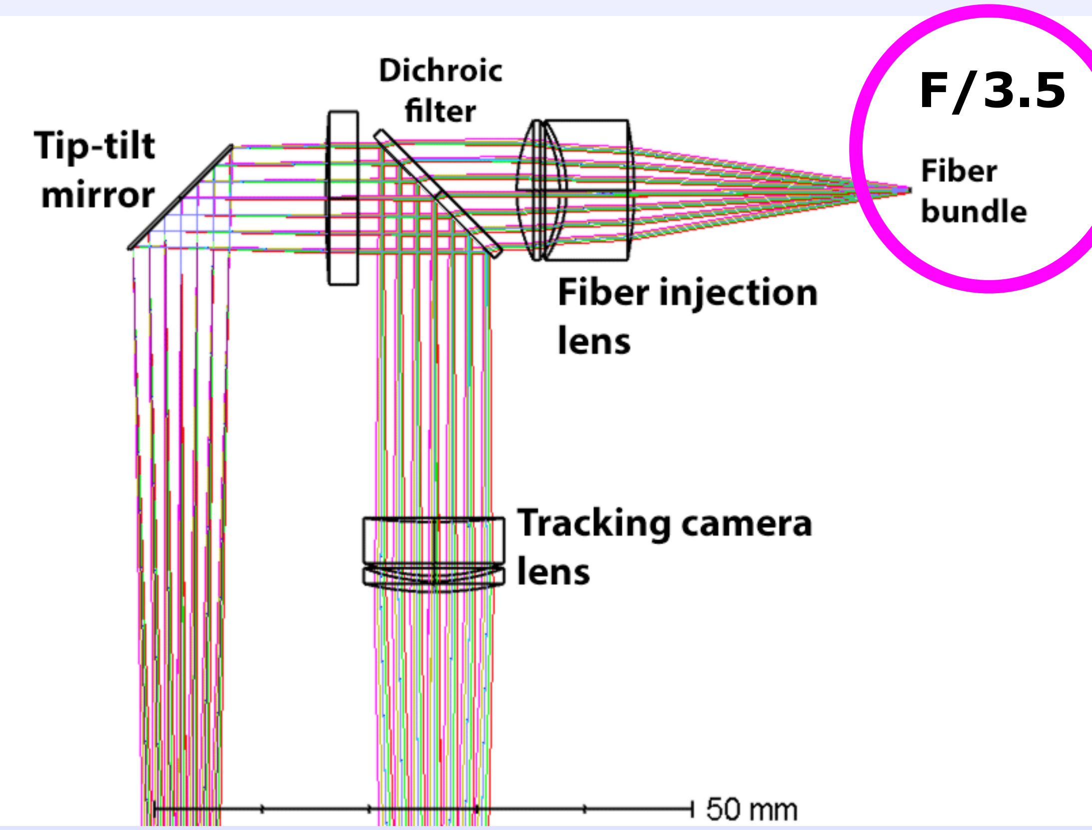
Optical design

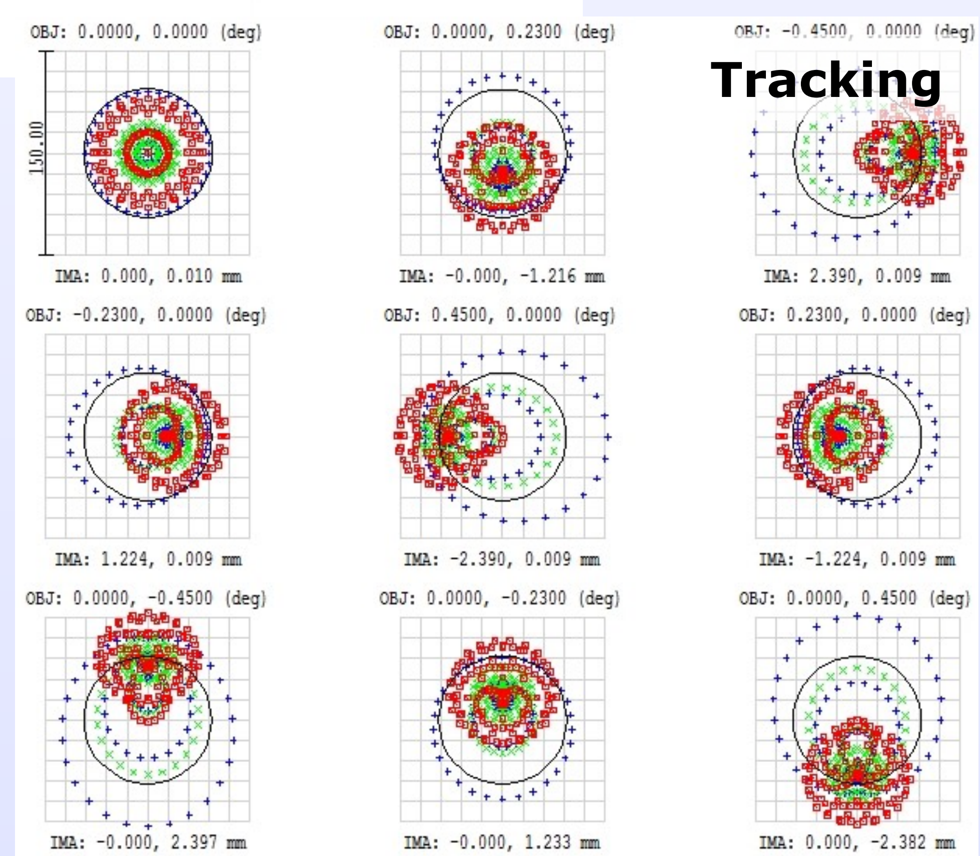
Optical design: E. Muslimov





~30 nm rms on axis



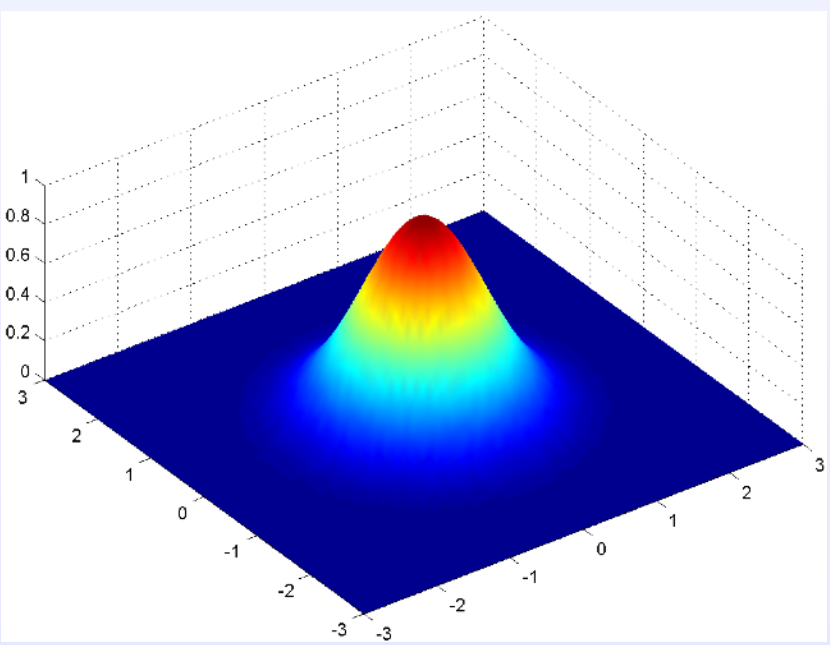


~60 nm rms on axis

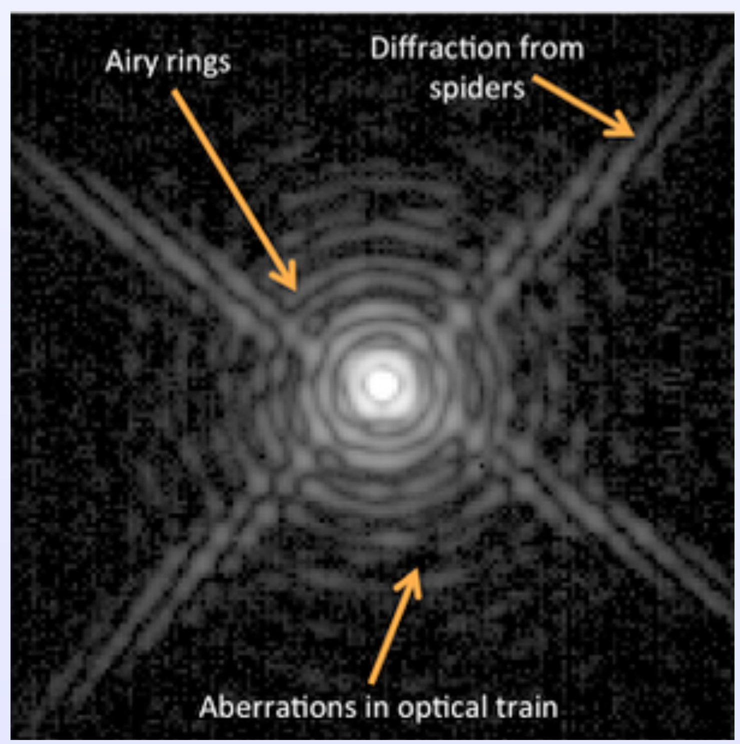
HiRISE injection efficiency

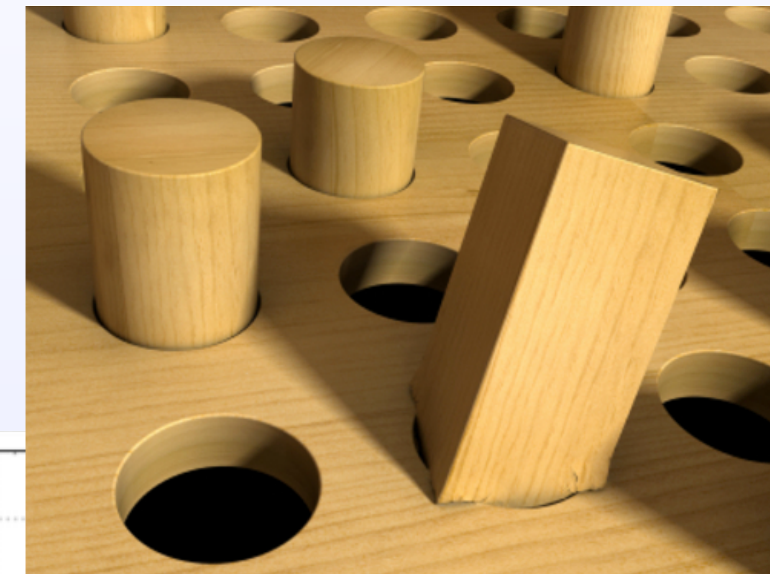
How much stellar/planetary light can you inject into an SMF?

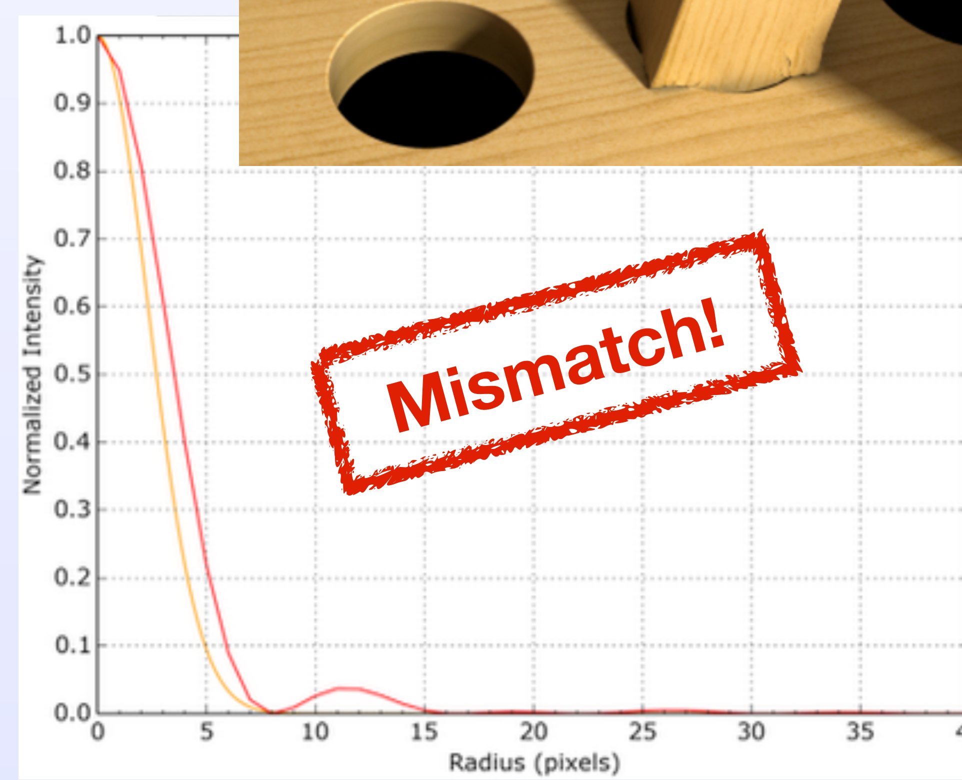
- Single-mode fiber:
  - EM_{00} mode is quasi-Gaussian



- Telescope PSF:
  - Obstructed pupil + spiders
  - Complicated pattern

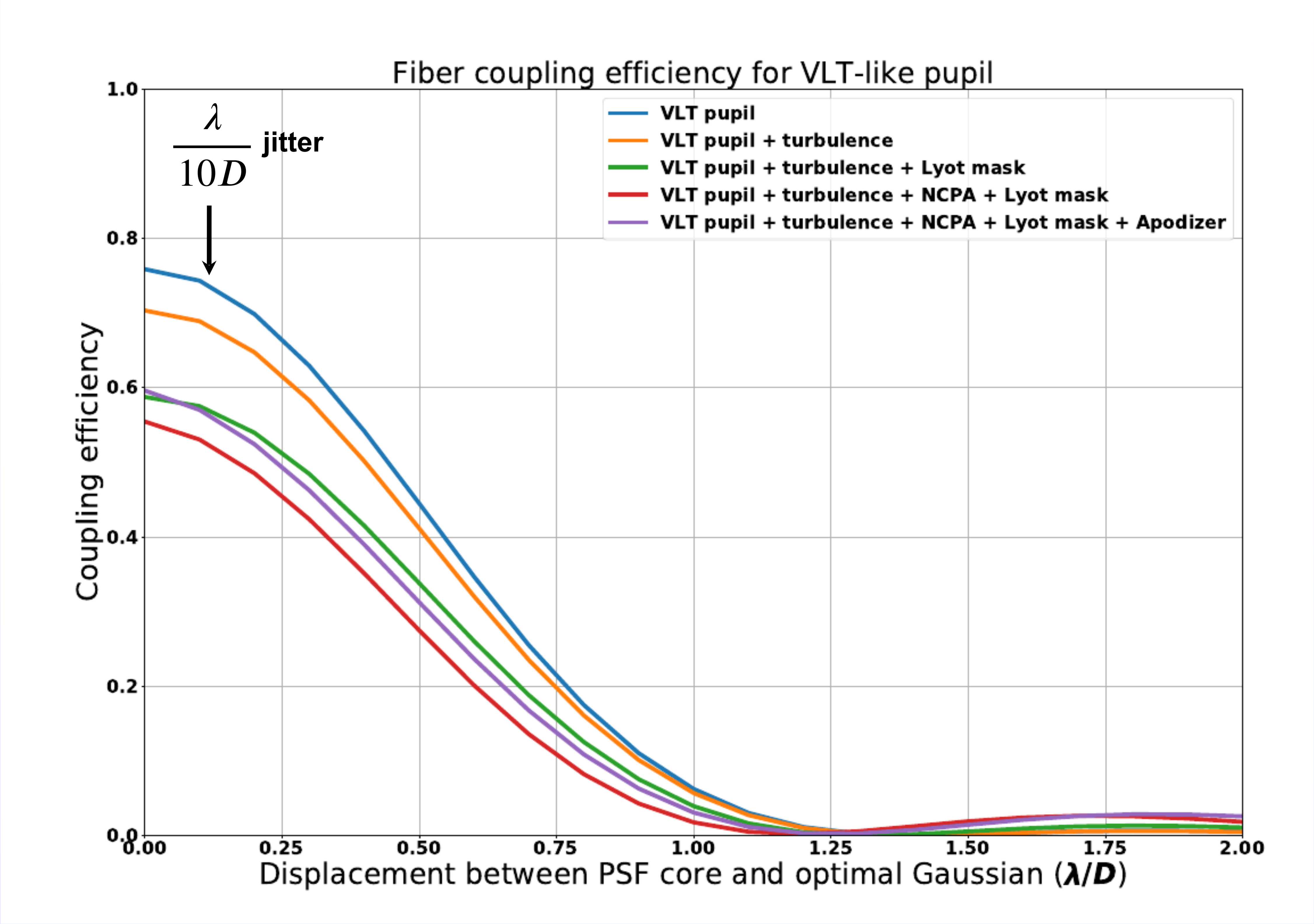




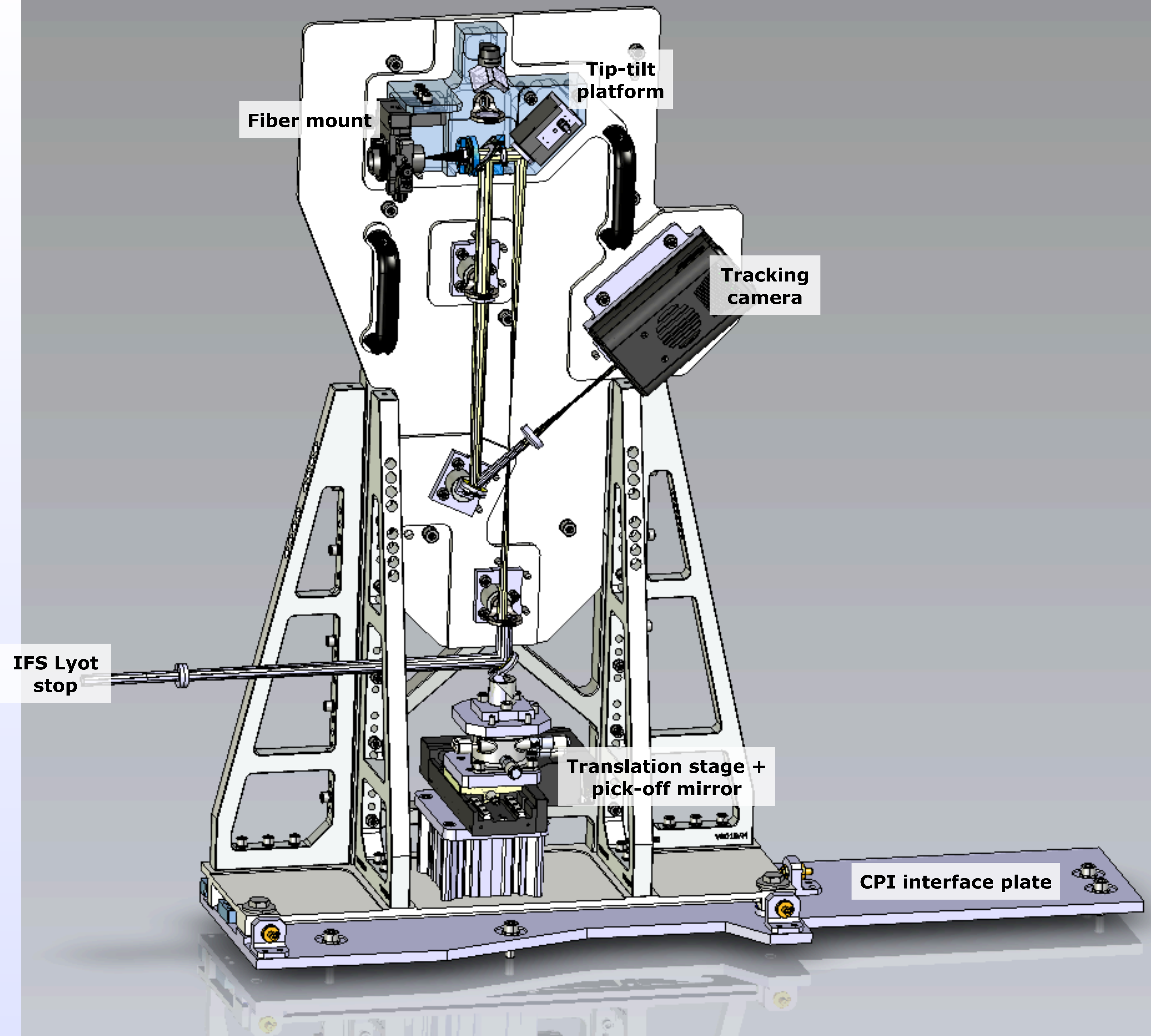


Jovanovic et al. (2017)

HiRISE injection efficiency

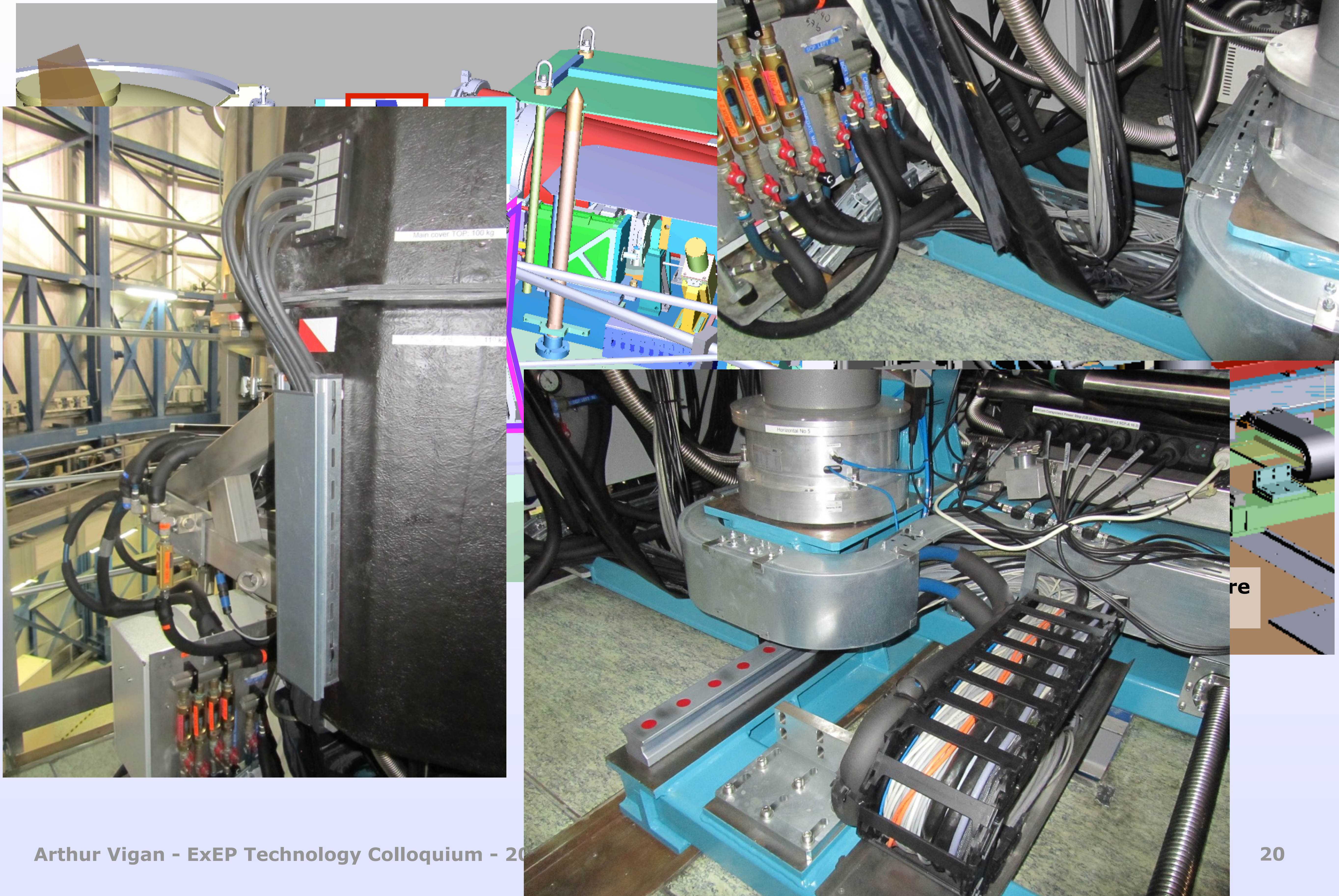


Fiber injection module in SPHERE

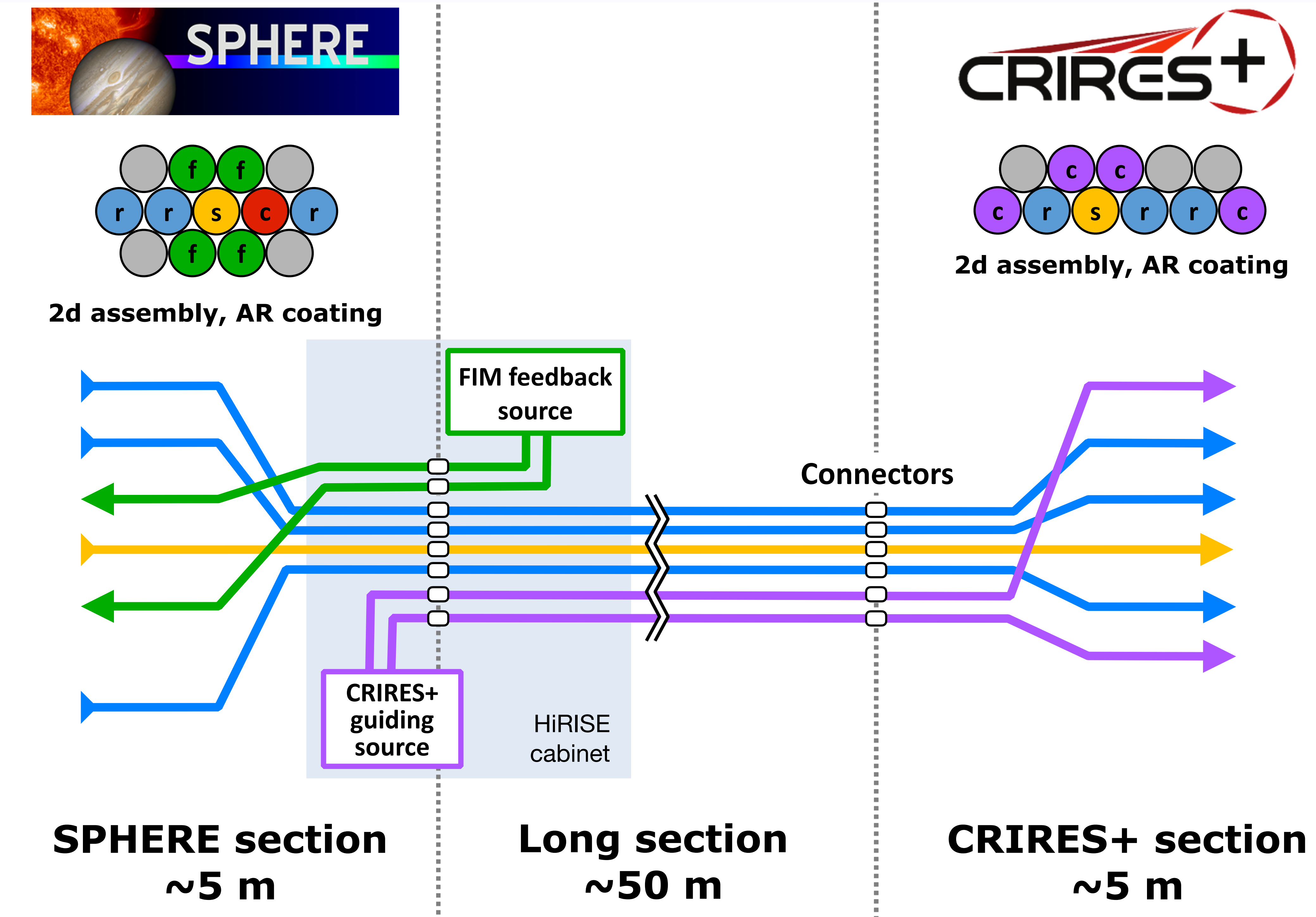


Tip-tilt platform
Fiber mount
Tracking camera
IFS Lyot stop
Translation stage + pick-off mirror
CPI interface plate

Fiber injection module ir



Fiber bundle



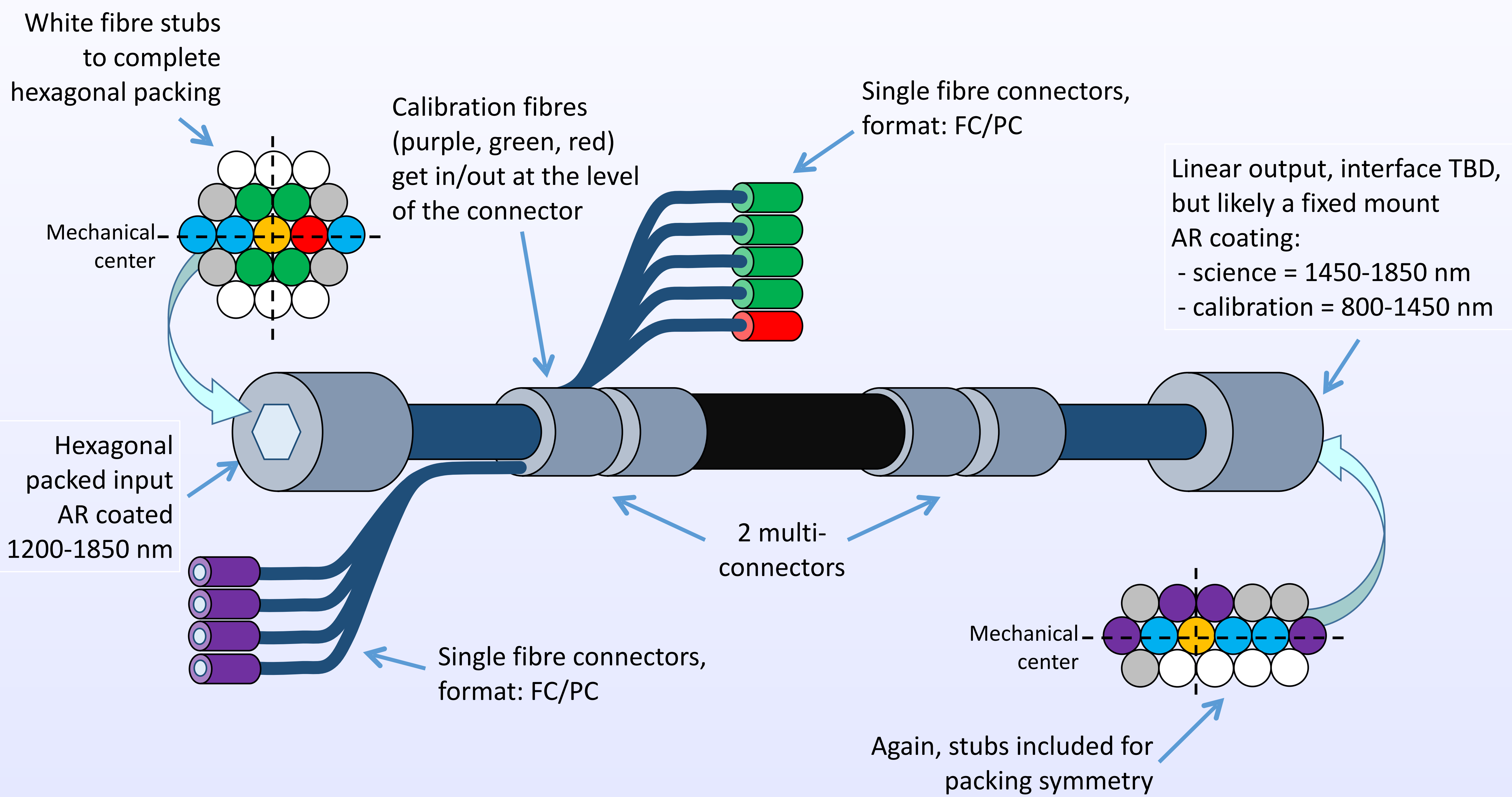
Science fibers (Nufern 1310M-HP)

- s — Science fiber, planet, 1.4-1.8 µm
- r — Reference fiber, star, 1.4-1.8 µm

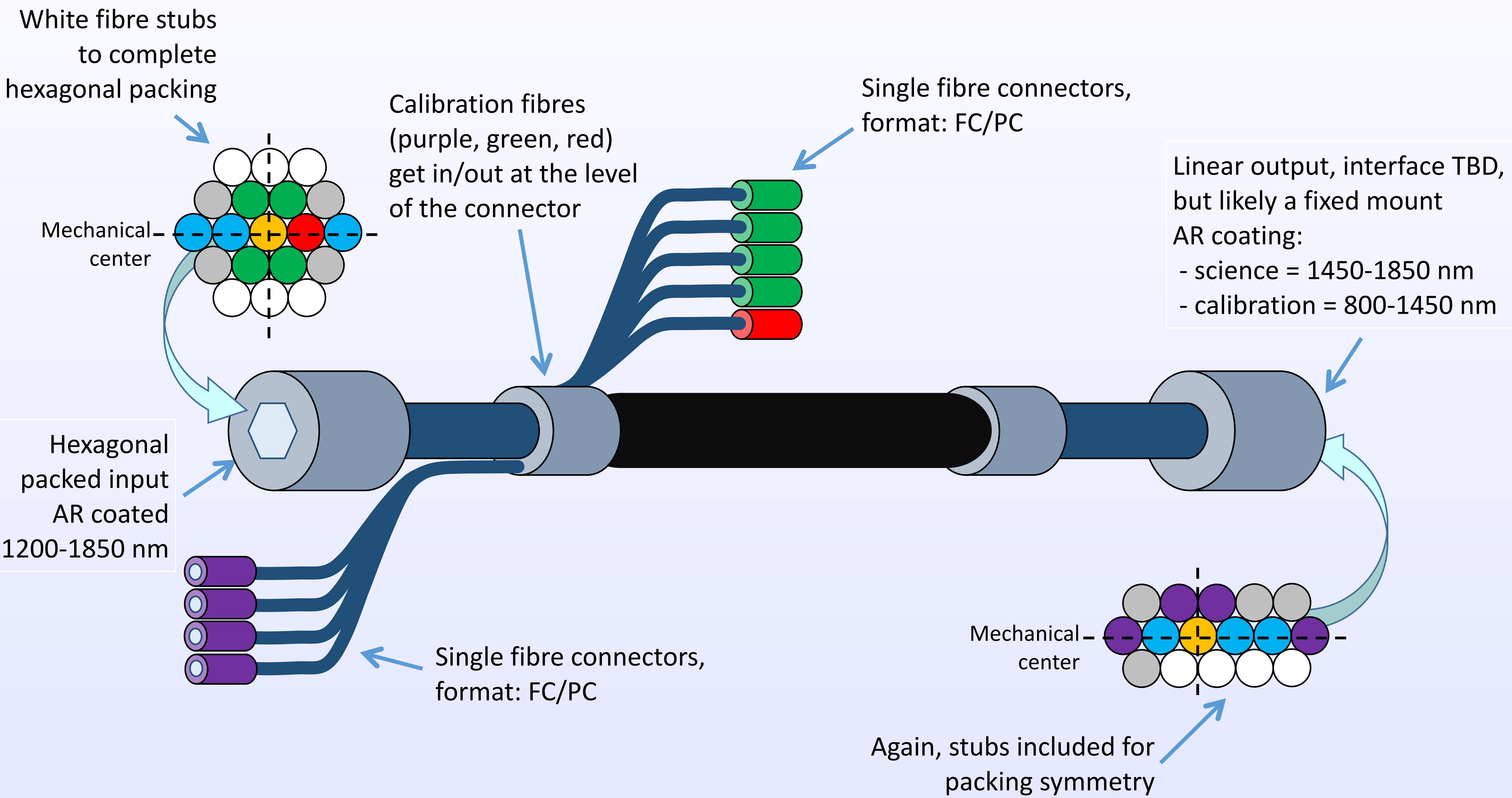
Calibration fibers (Nufern 1310M-HP)

- f — SPHERE feedback fiber, max 1.4 µm
- c — CRIRES+ calib fibers, 0.8-1.6 µm

Fiber bundle with connectors

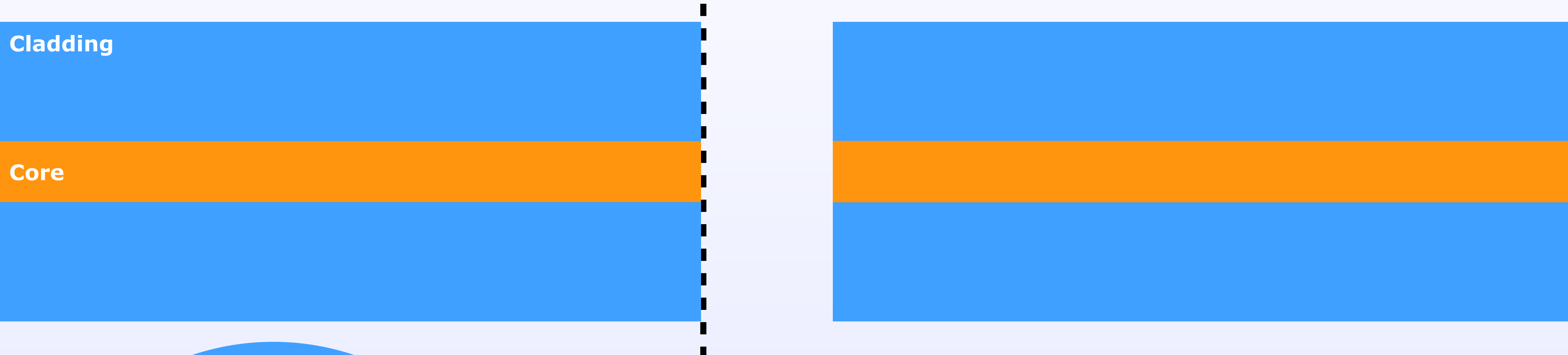


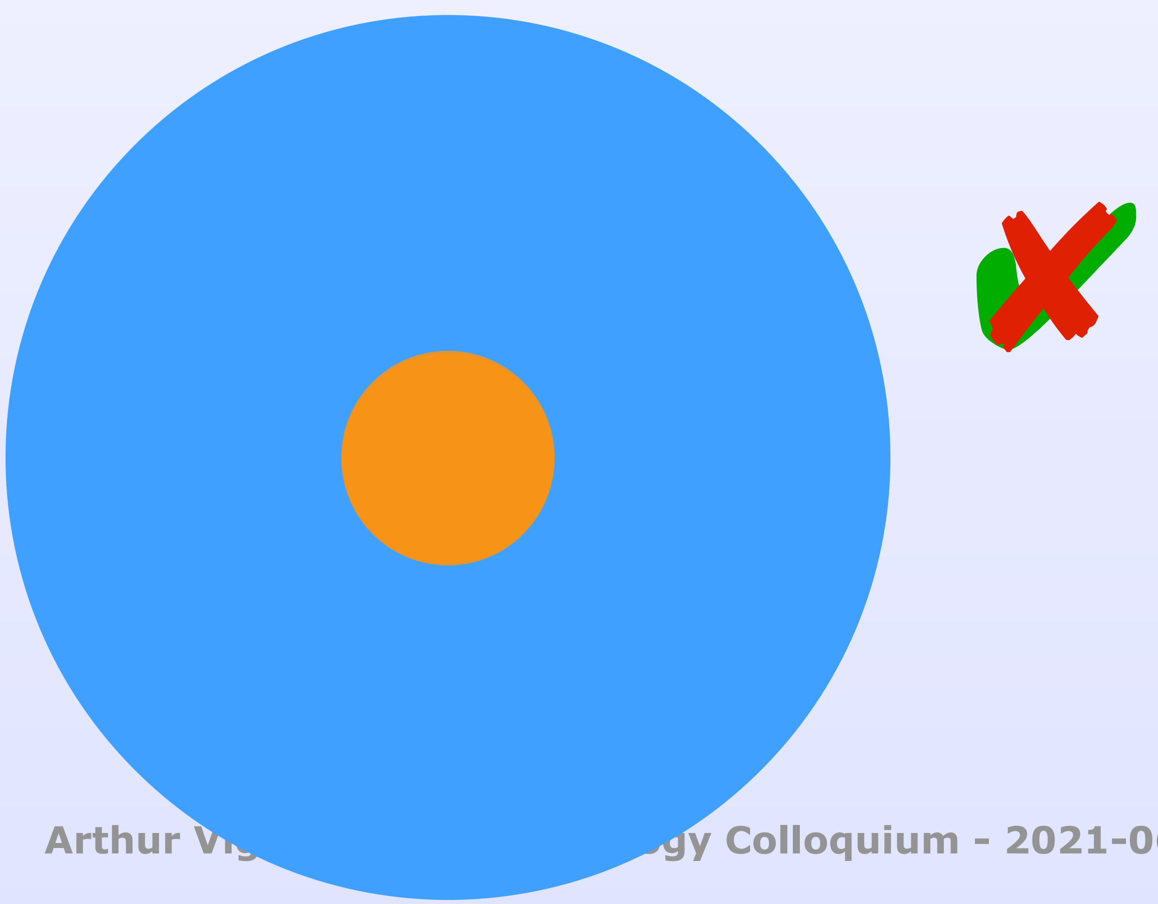
Fiber bundle without connectors

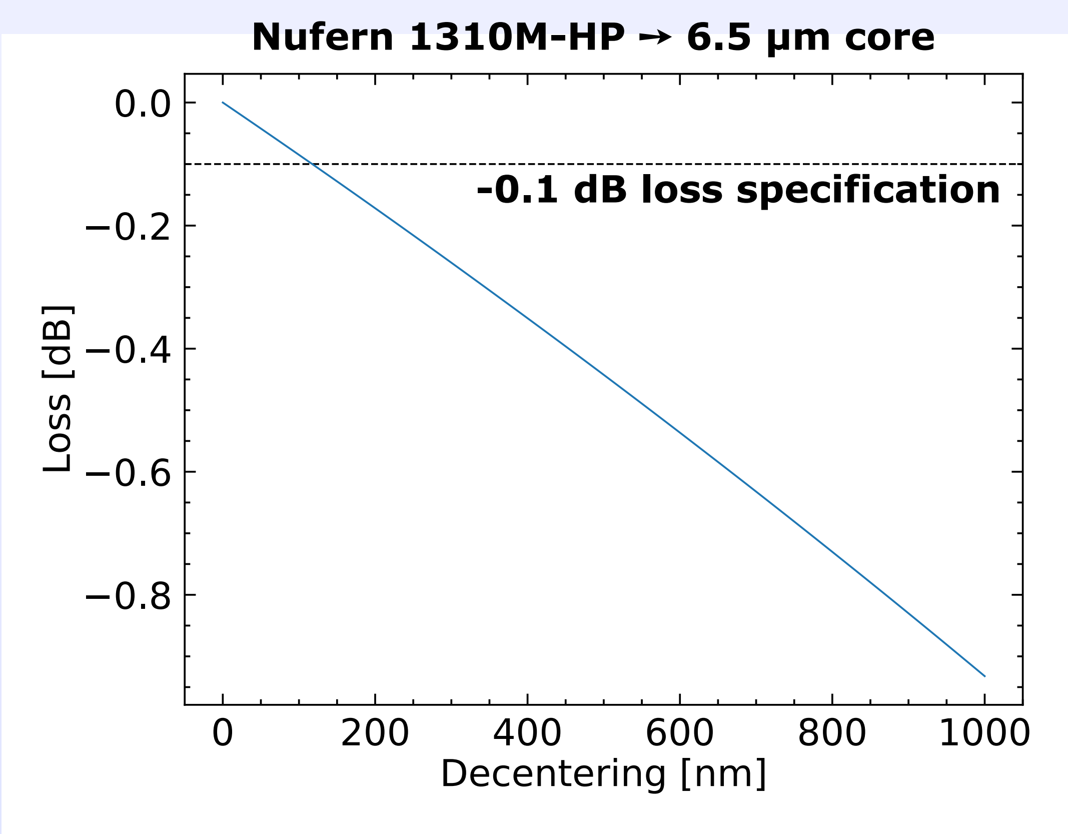


Low-loss connectors

- Throughput is a key driver of the performance
- Problem: single-mode fibres have very small cores! Typically **4-8 µm**



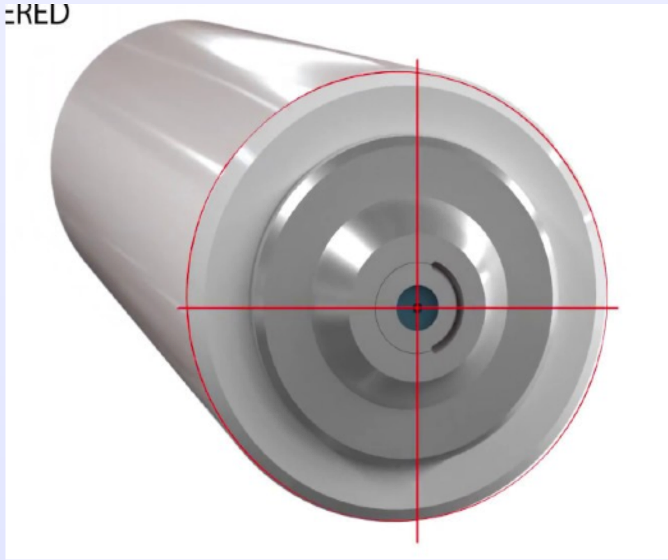




Low-loss connectors

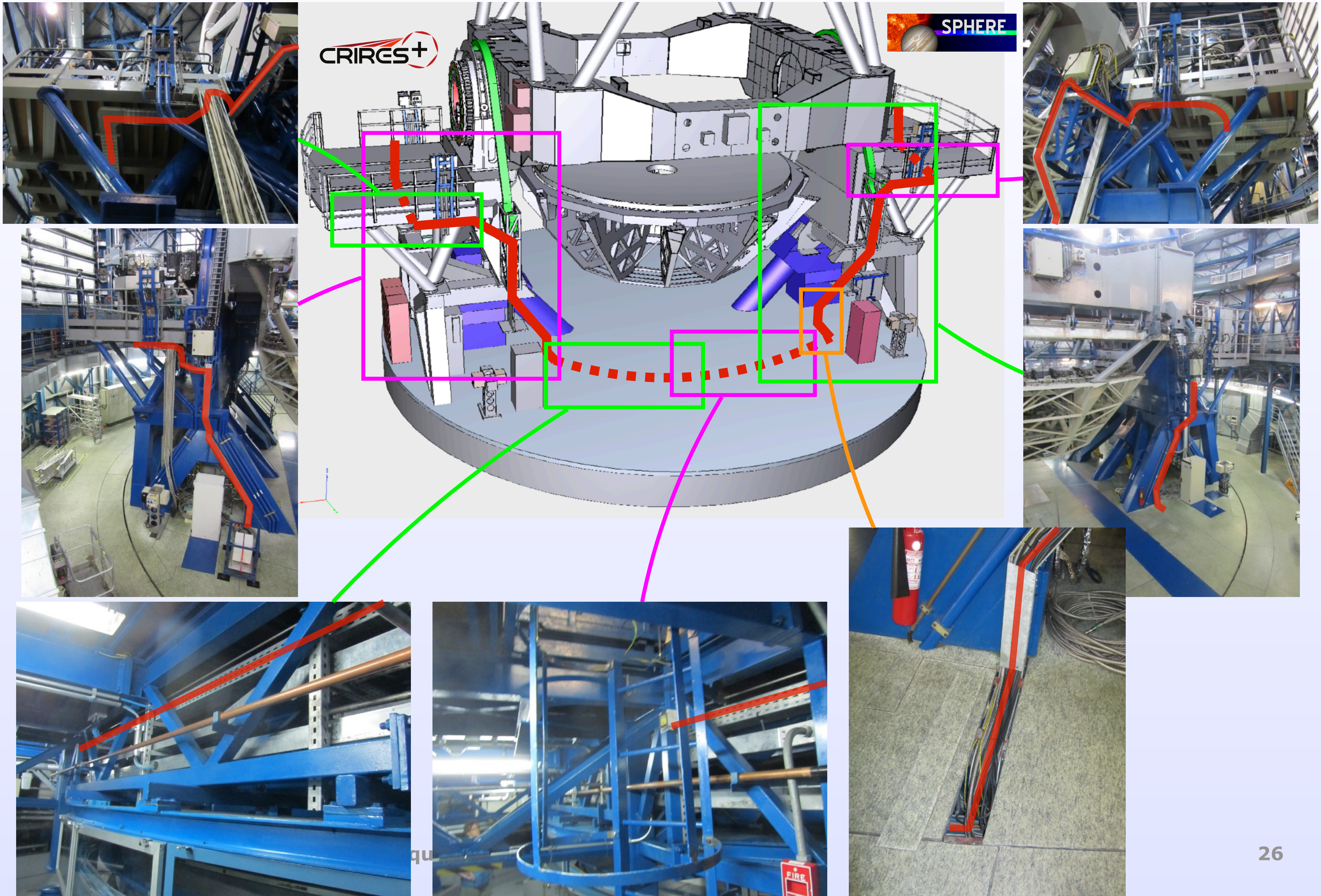
- Rugged connectors with repeatable connection exist...

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

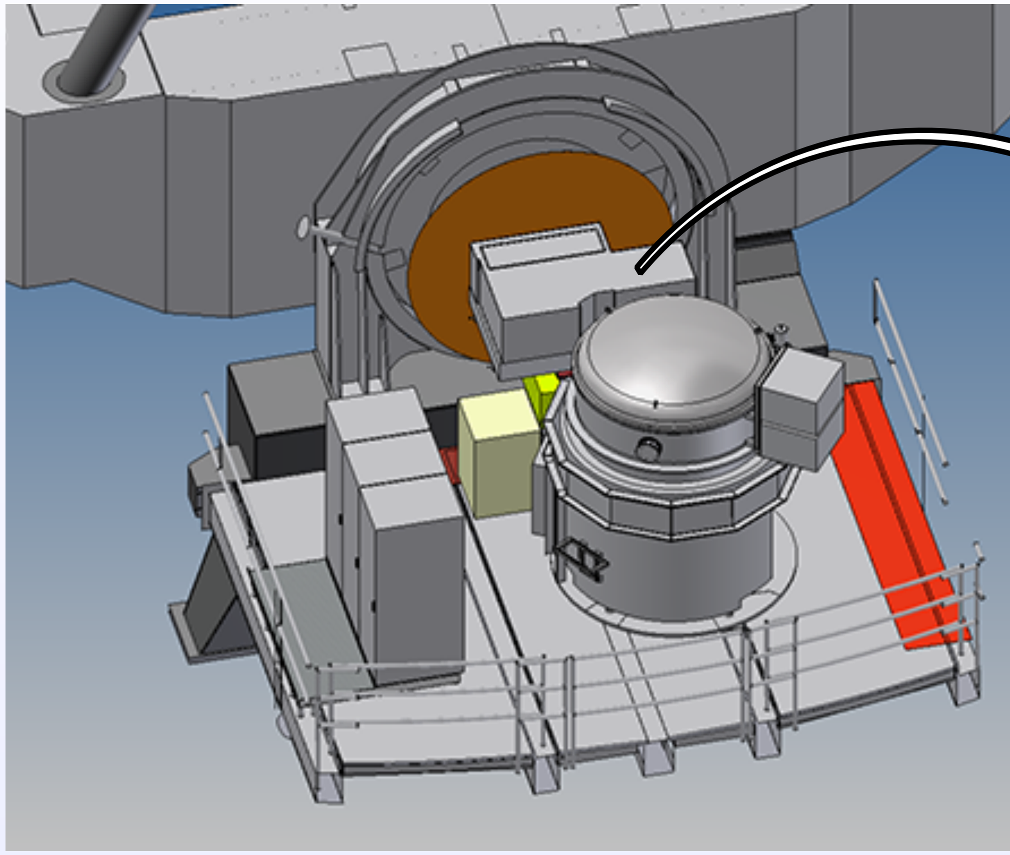


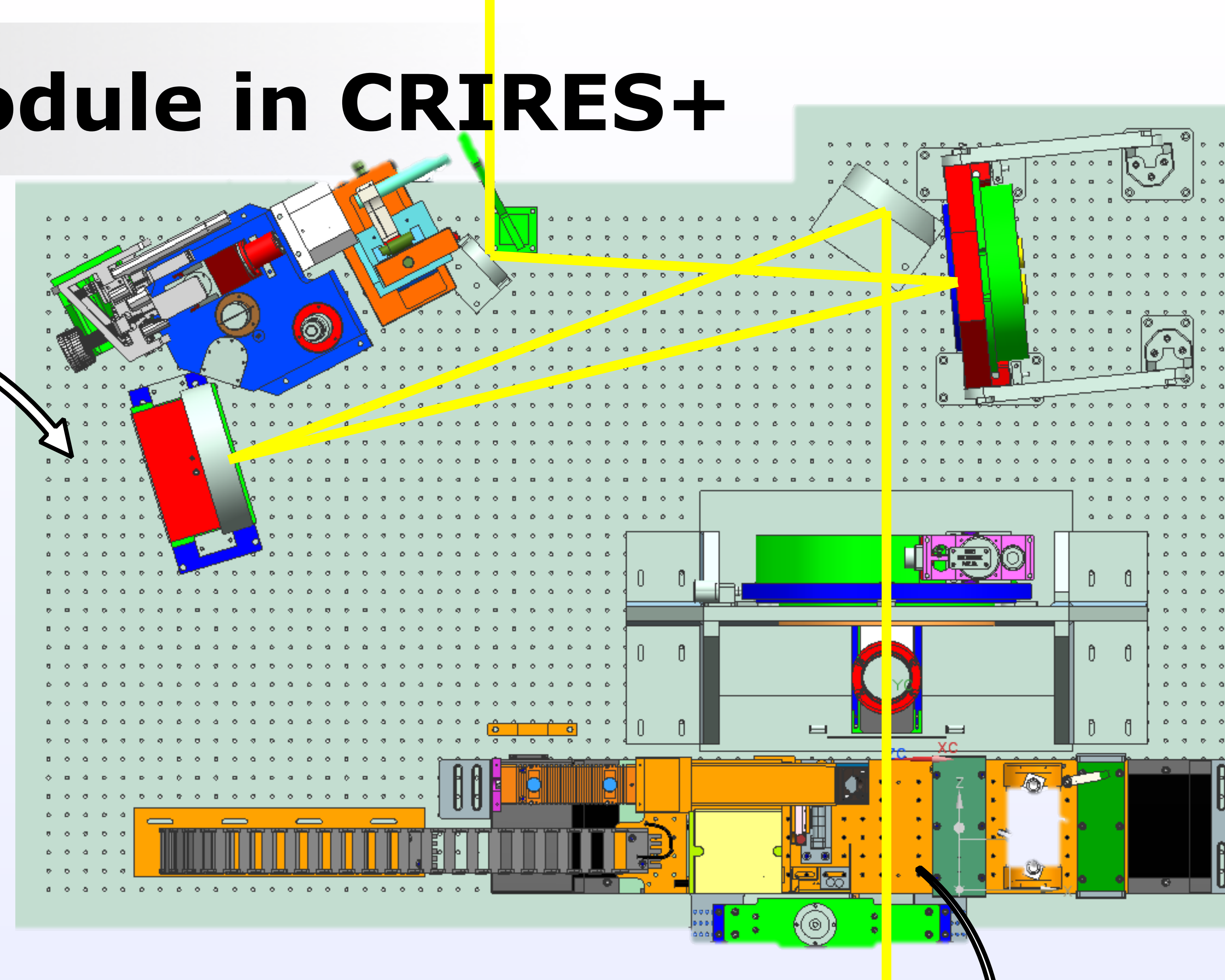
https://www.diamond-fo.com/technologies/technology/active-core-alignment-aca/

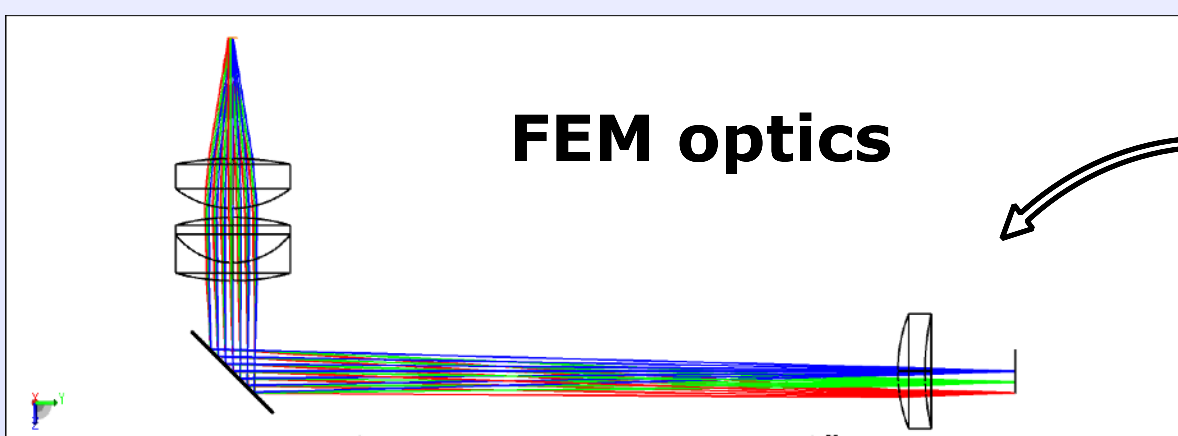
Fiber bundle around UT3

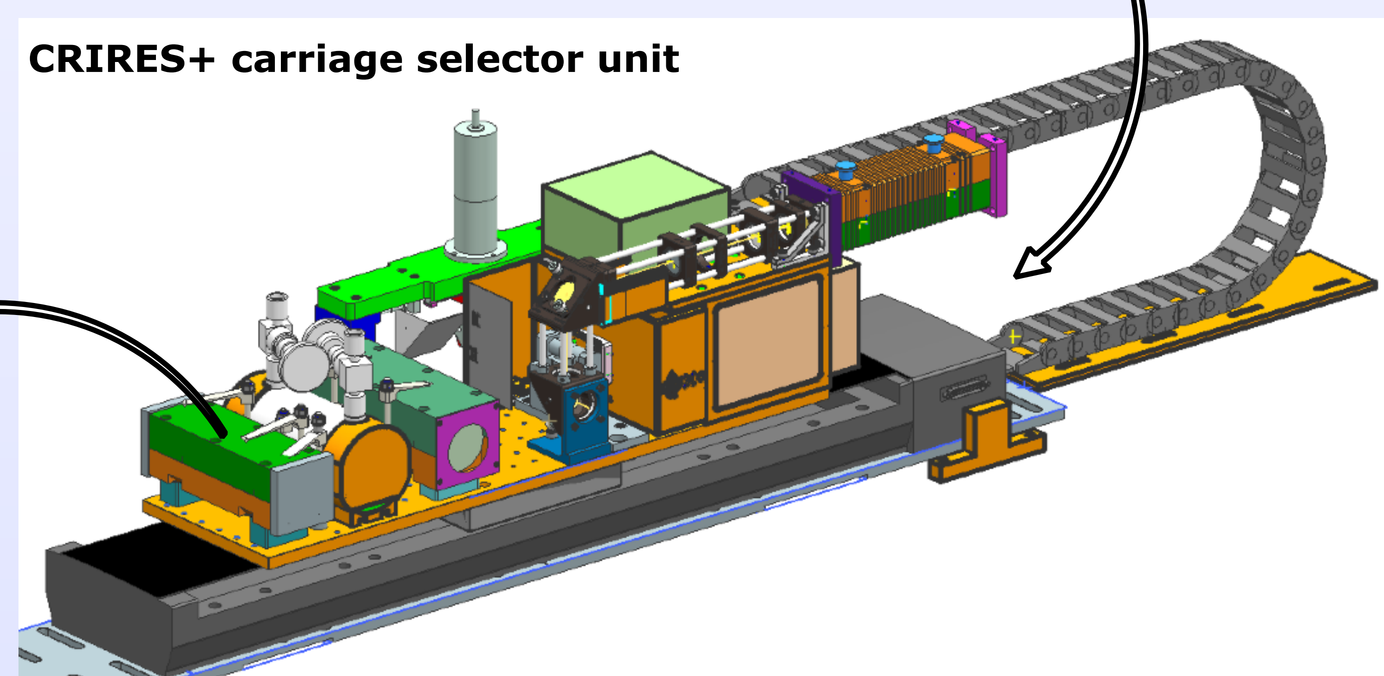


Fiber extraction module in CRIRES+

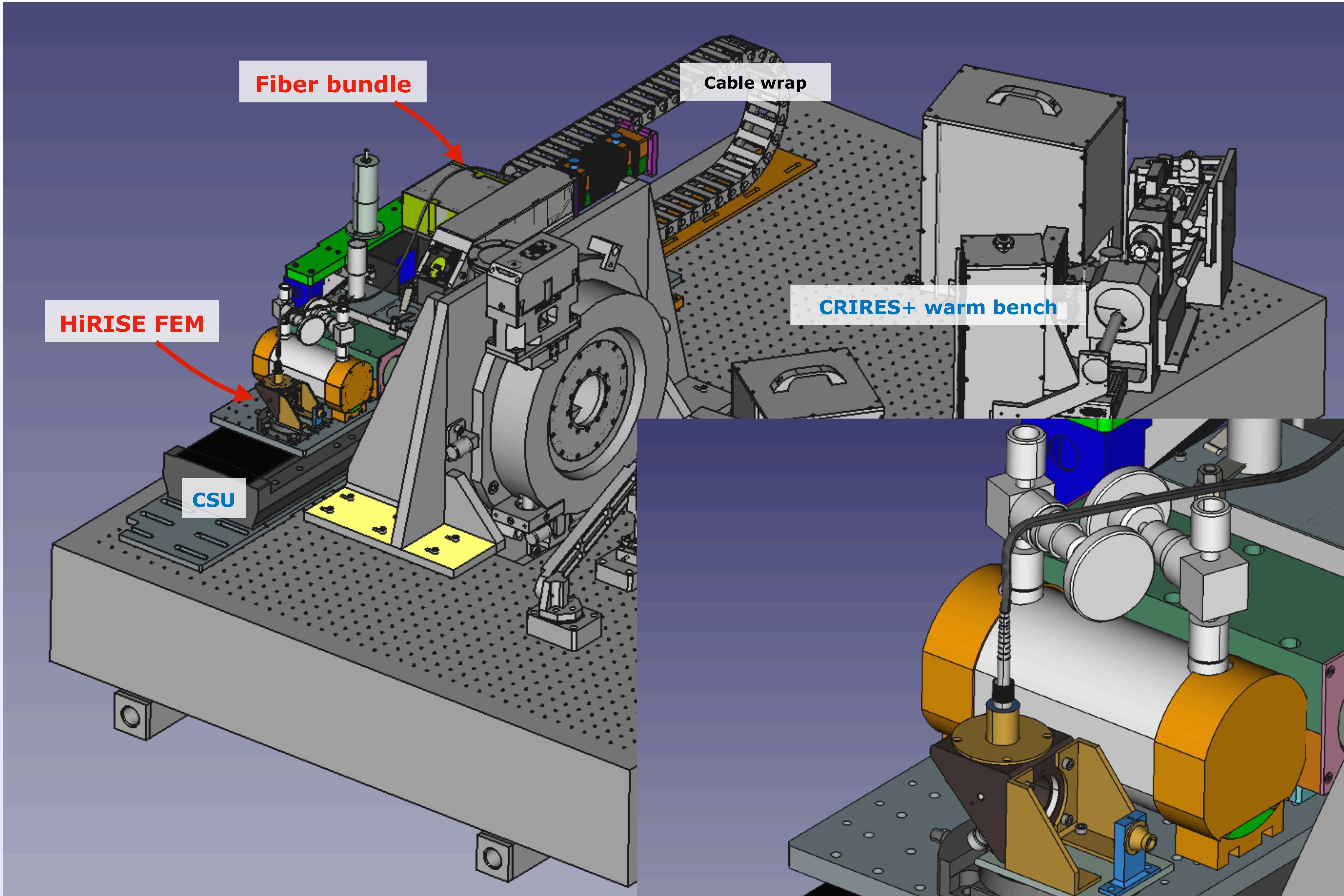






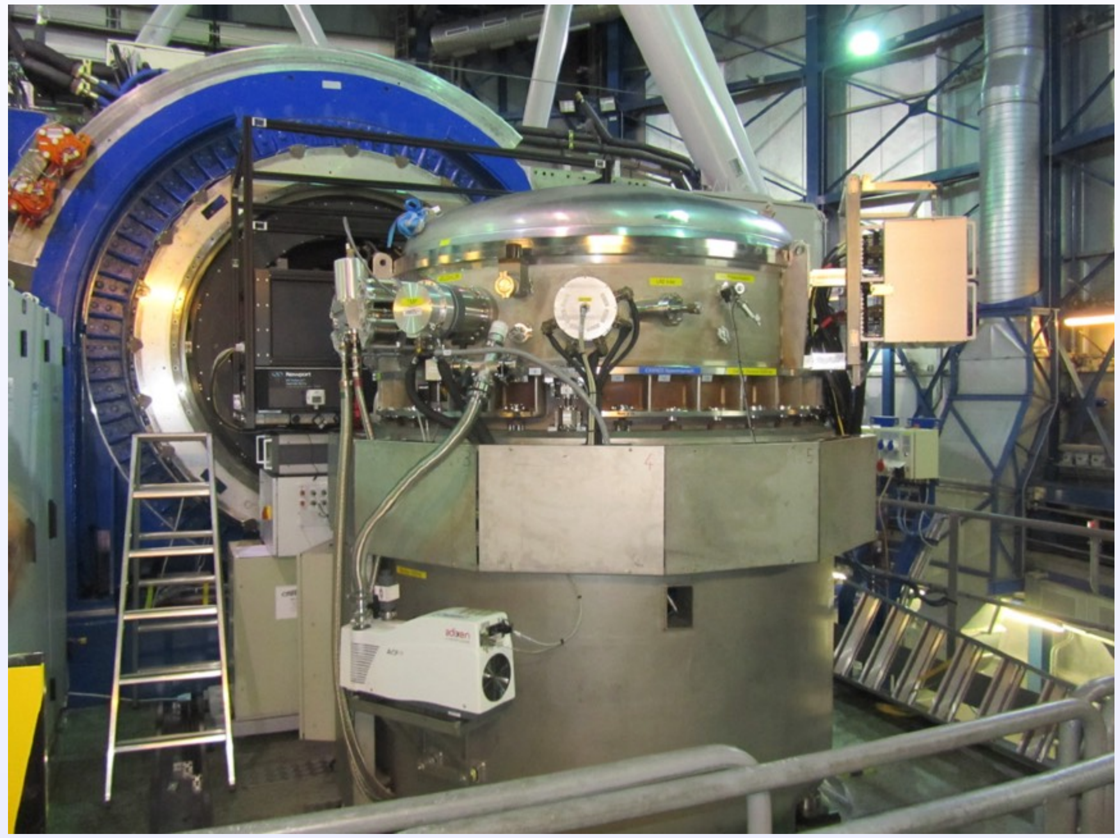


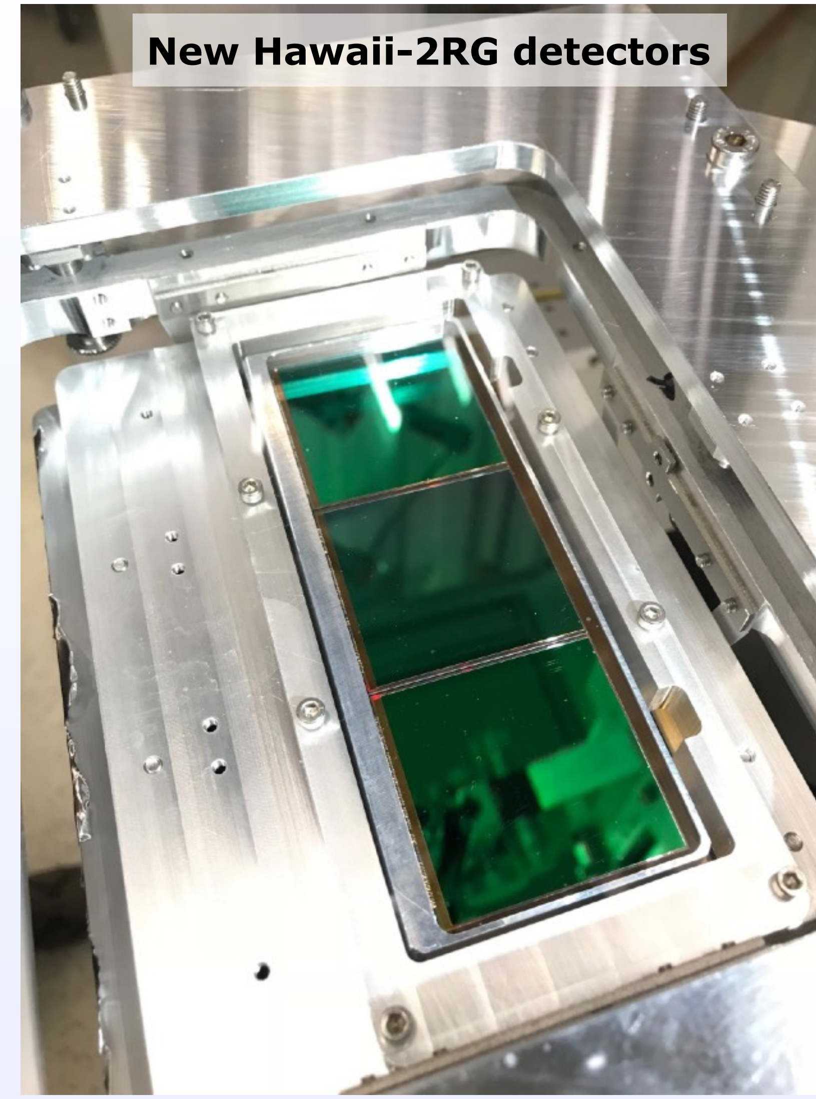
Fiber extraction module in CRIRES+

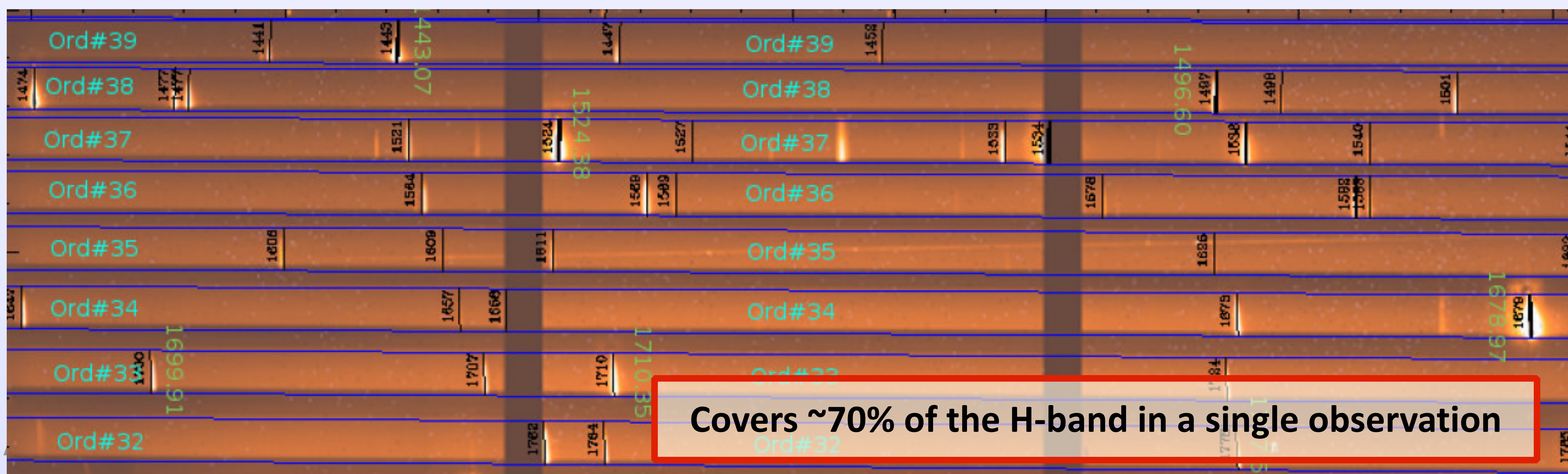


CRIRES+: improving CRIRES

- NIR infrared echelle spectrograph
- New cross-dispersion gratings stage
- New Hawaii-2RG detectors
- Improved polarimetric unit

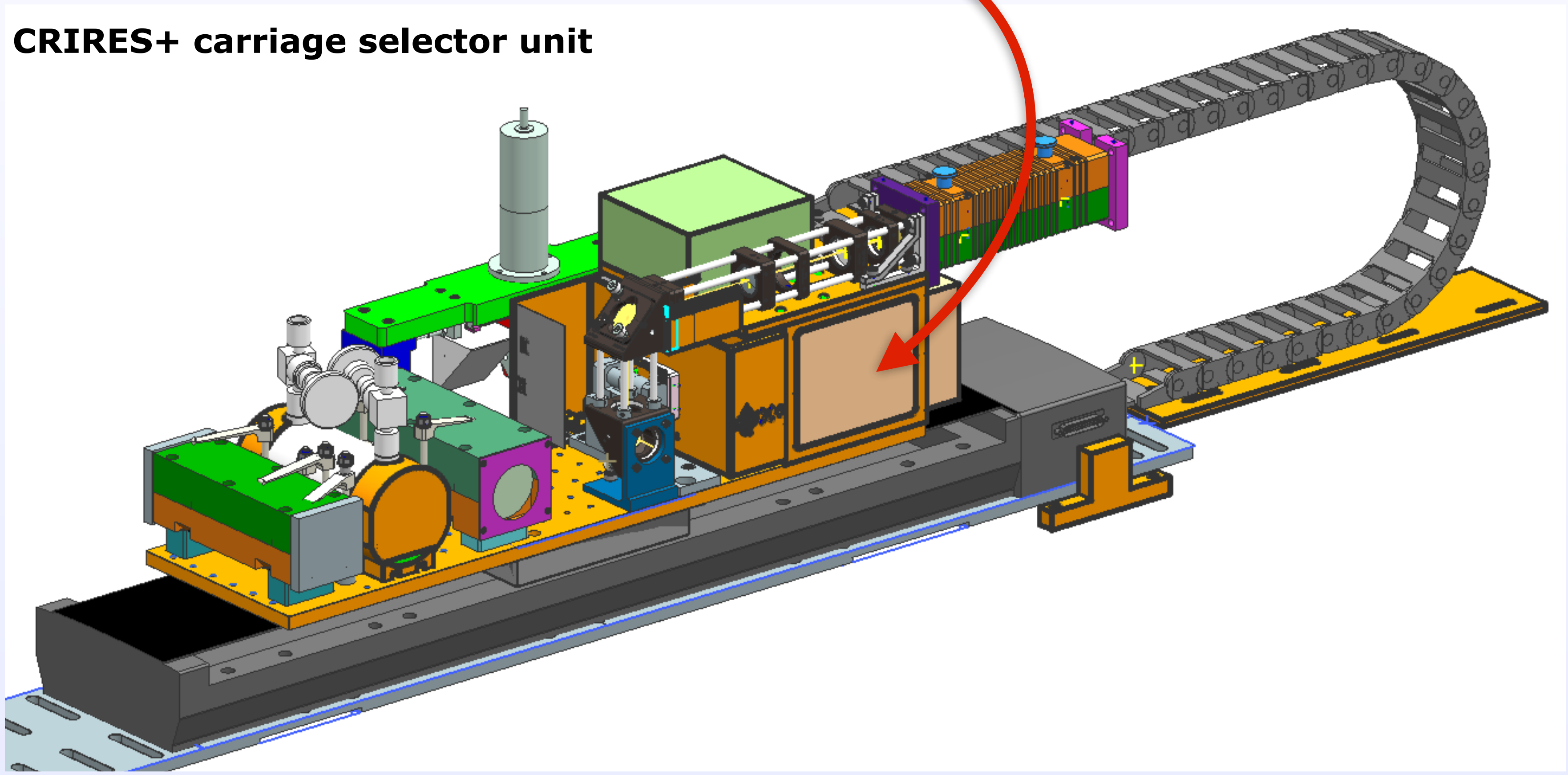






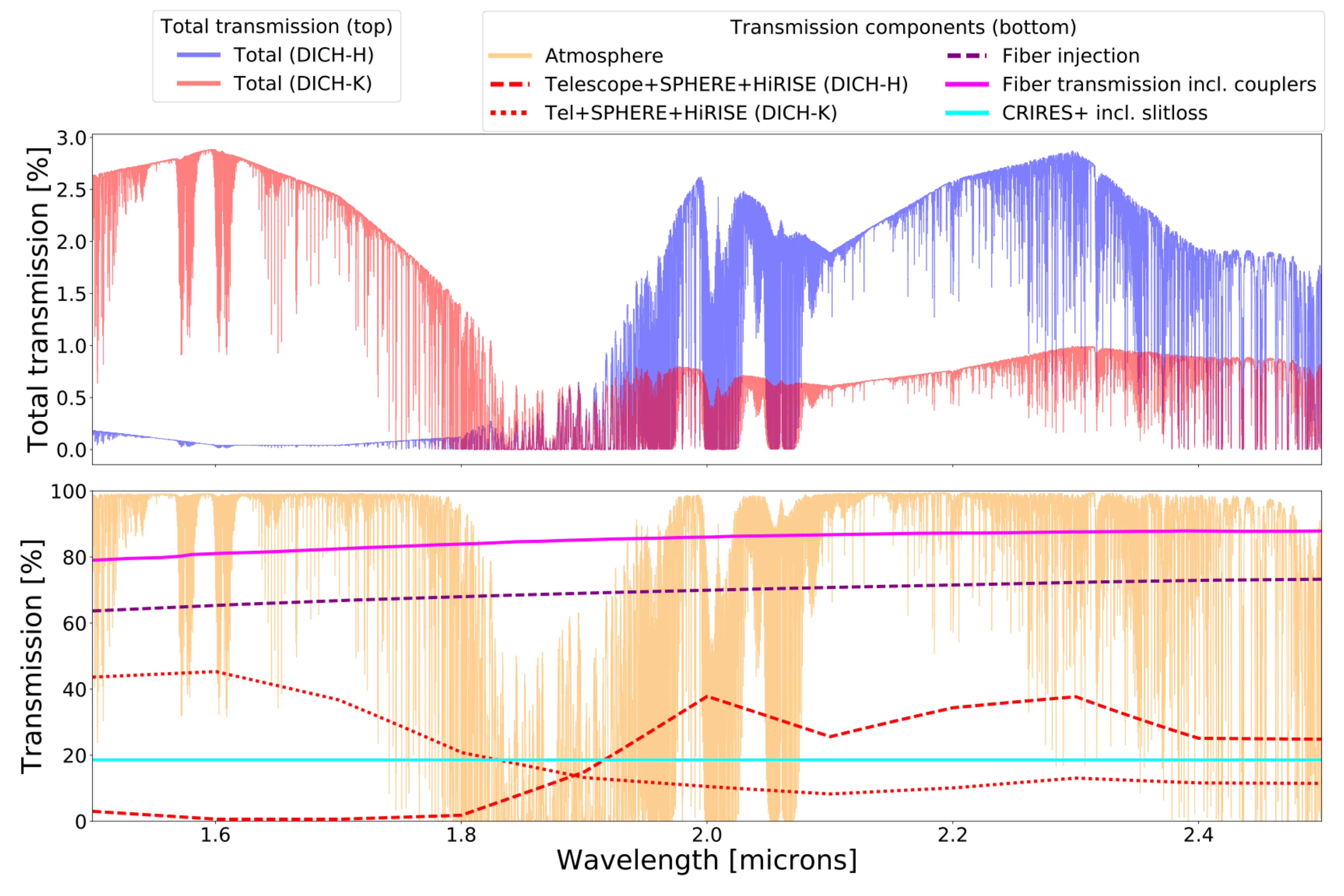
Spectropolarimetry with HiRISE?

- **Not possible!**
- Spectropolarimetric unit located inside the CSU



- Already photon-starved regime... **<u>every</u> <u>single</u> <u>photon</u> <u>counts</u>**!

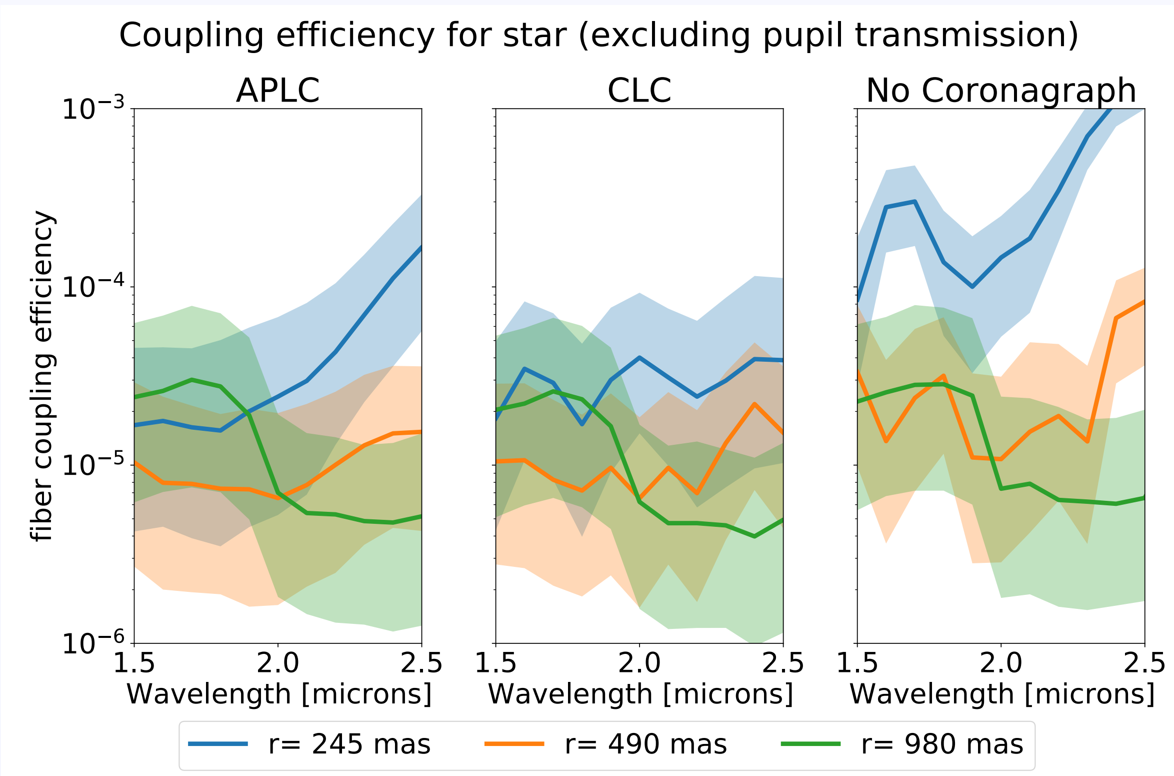
Transmission budget

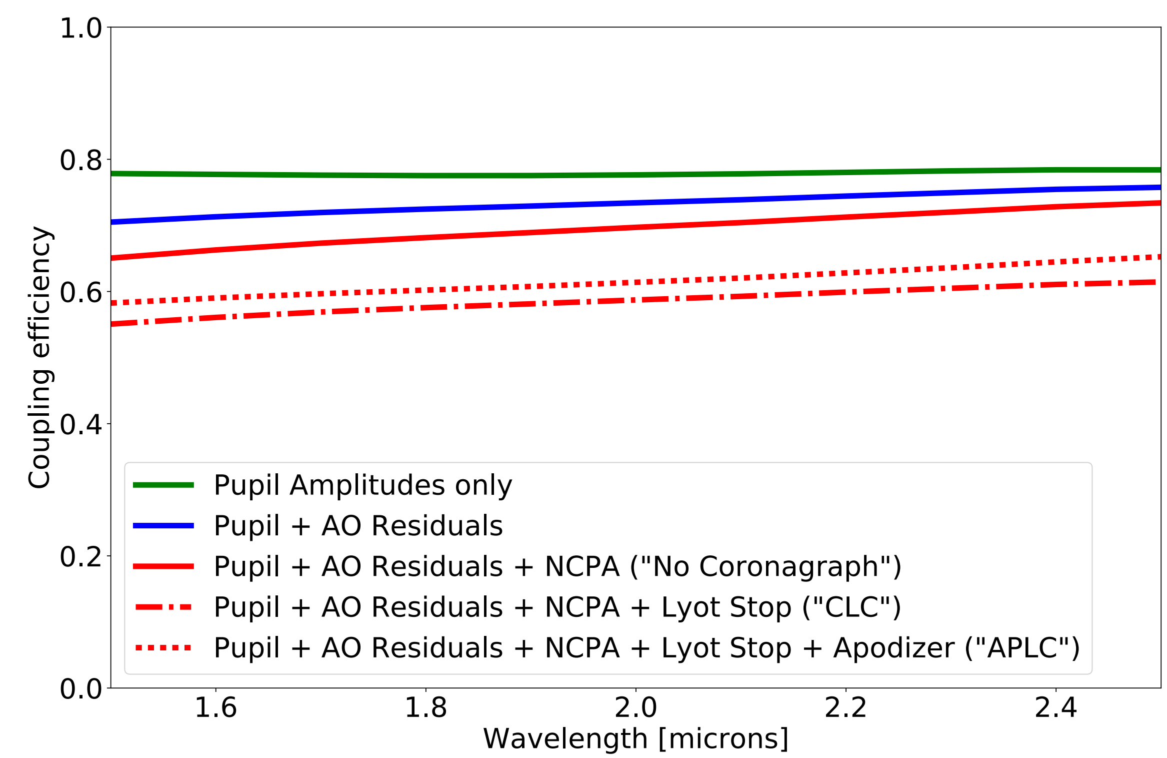


End-to-end model from Otten et al. (2021)

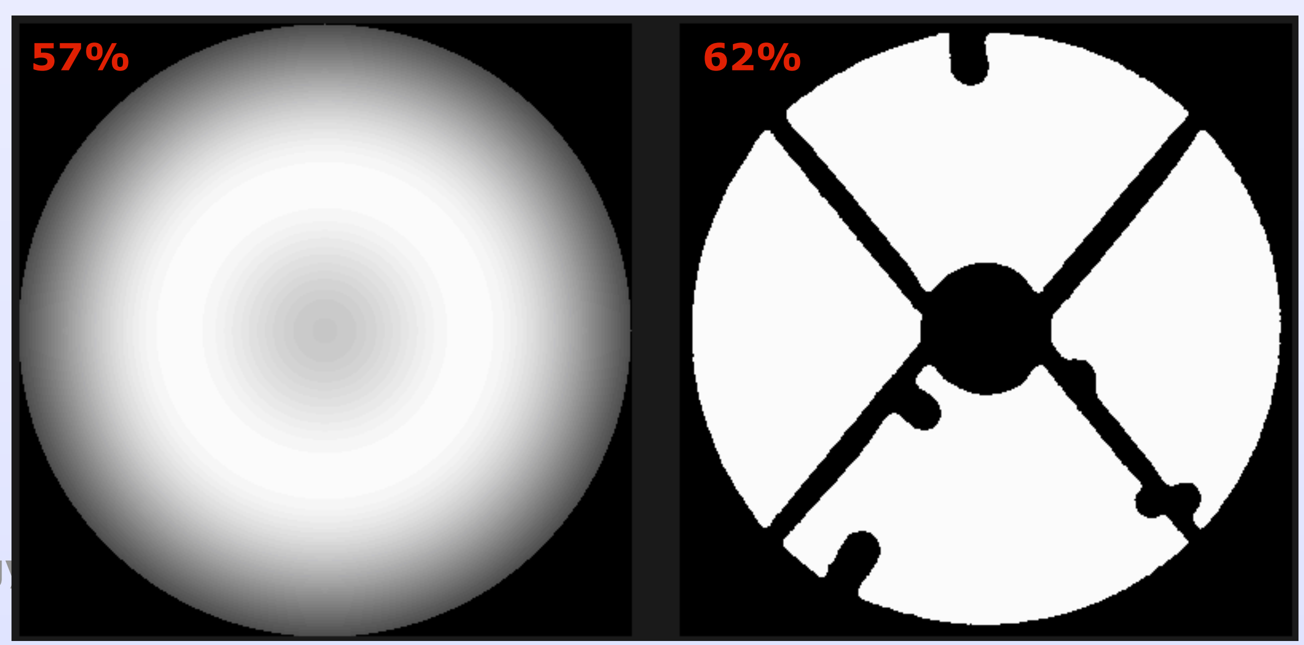
Do we really want a coronagraph?

- Baseline in SPHERE ➙ apodized pupil Lyot coronagraph
- YES, from the injection efficiency point-of-view...



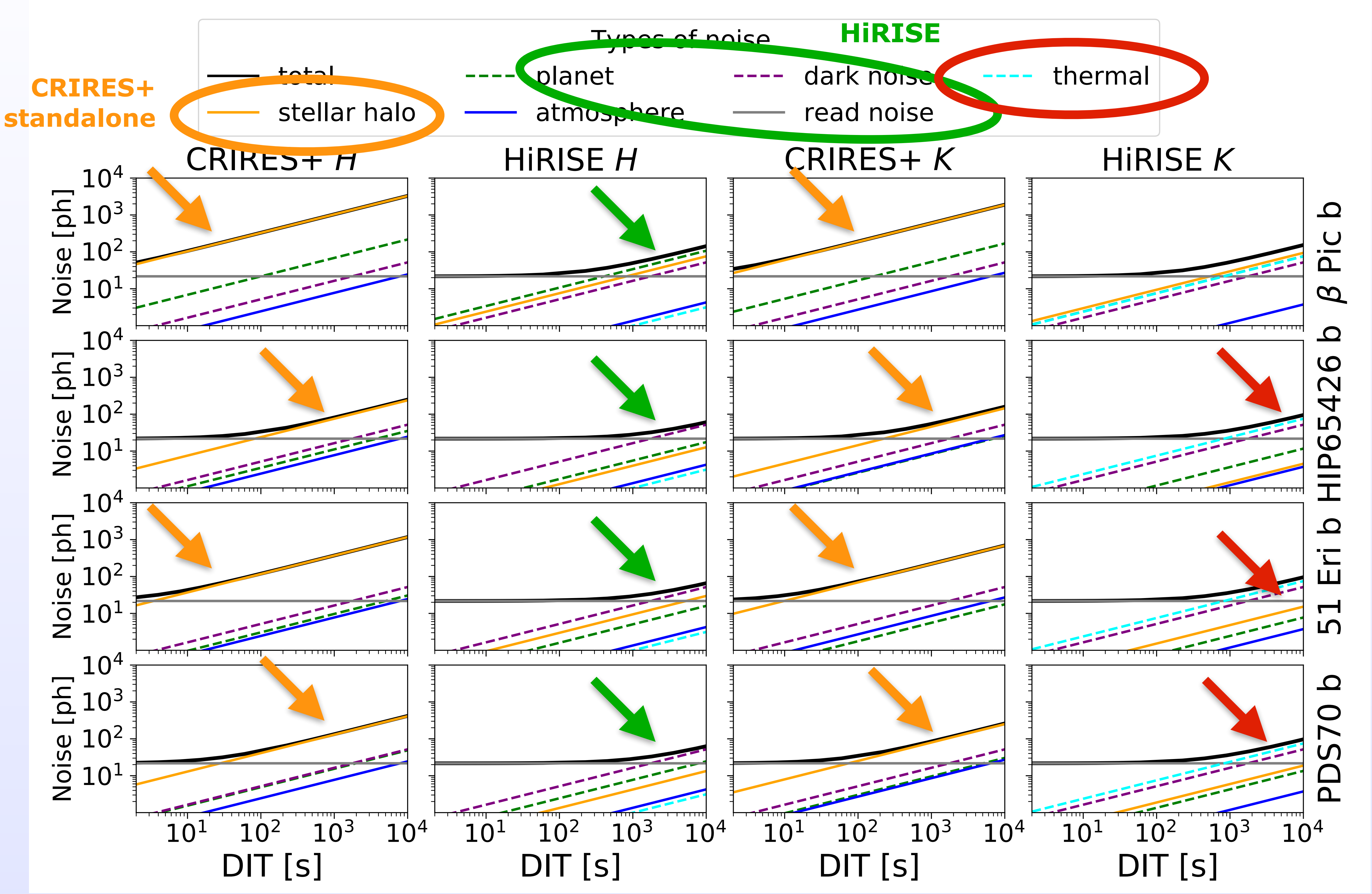


- ... but certainly not from the throughput point-of-view!



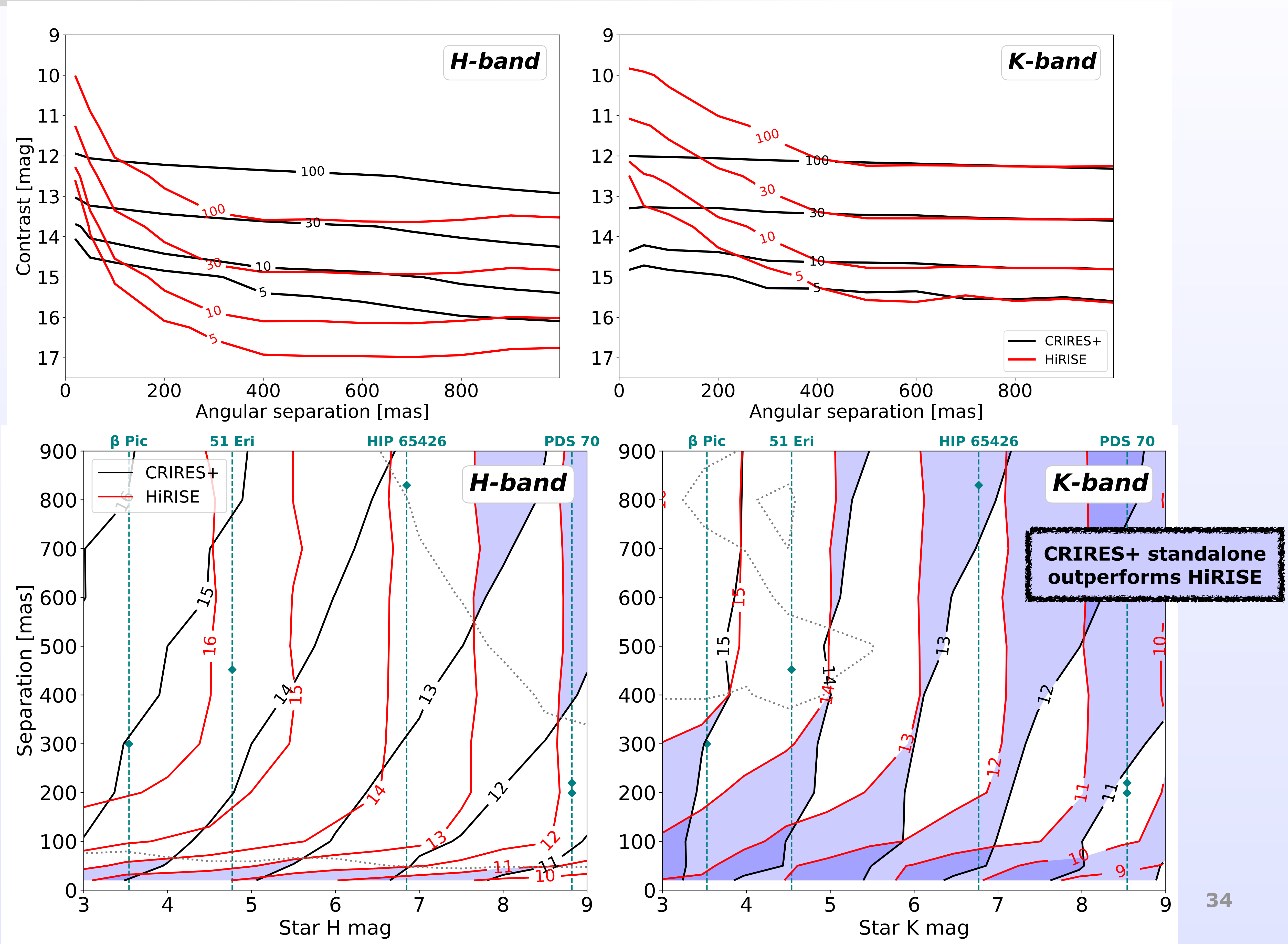
<40% of the total flux is transmitted!!

Performance estimation

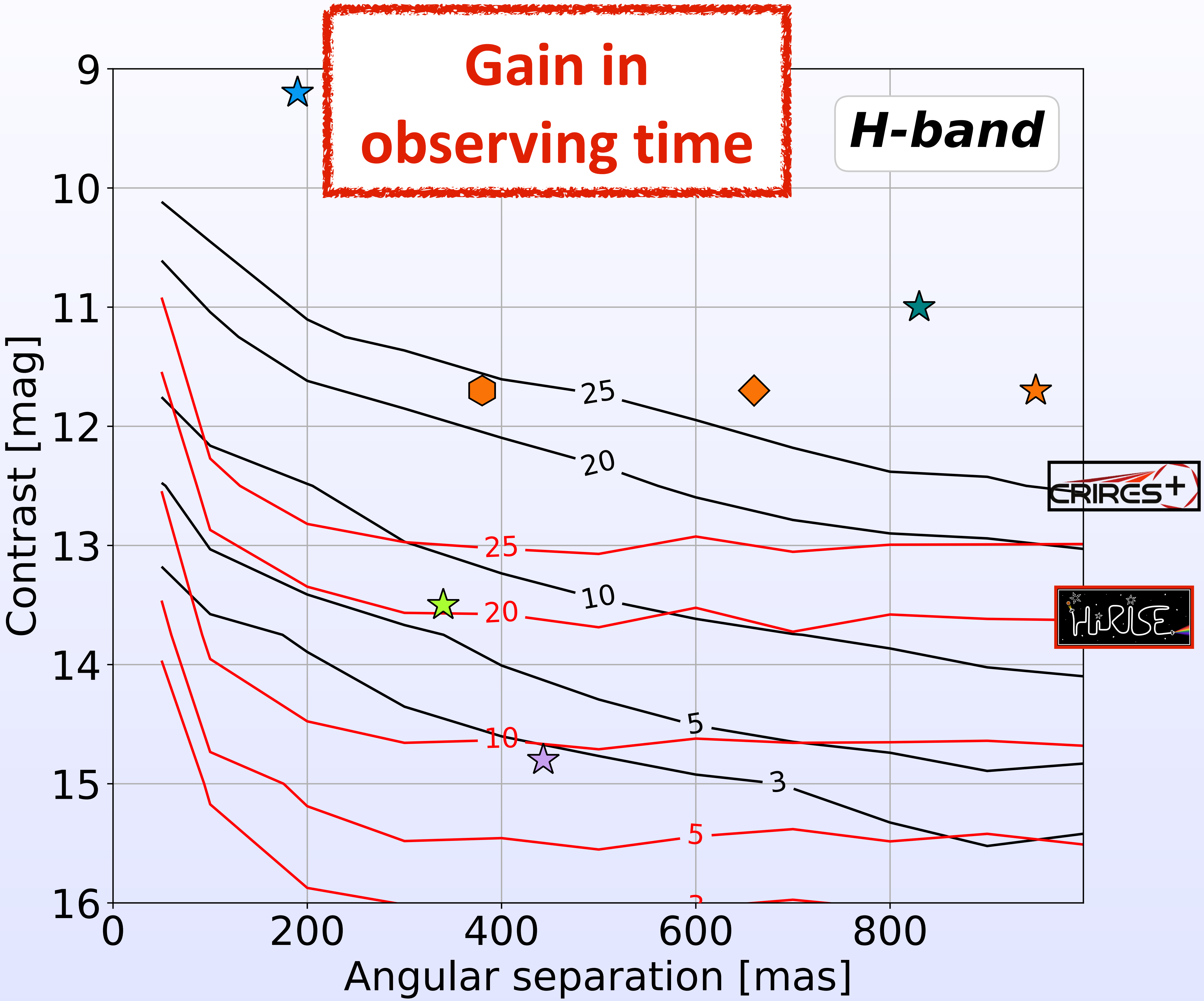


End-to-end model from Otten et al. (2021)

Performance estimation



Expected performance



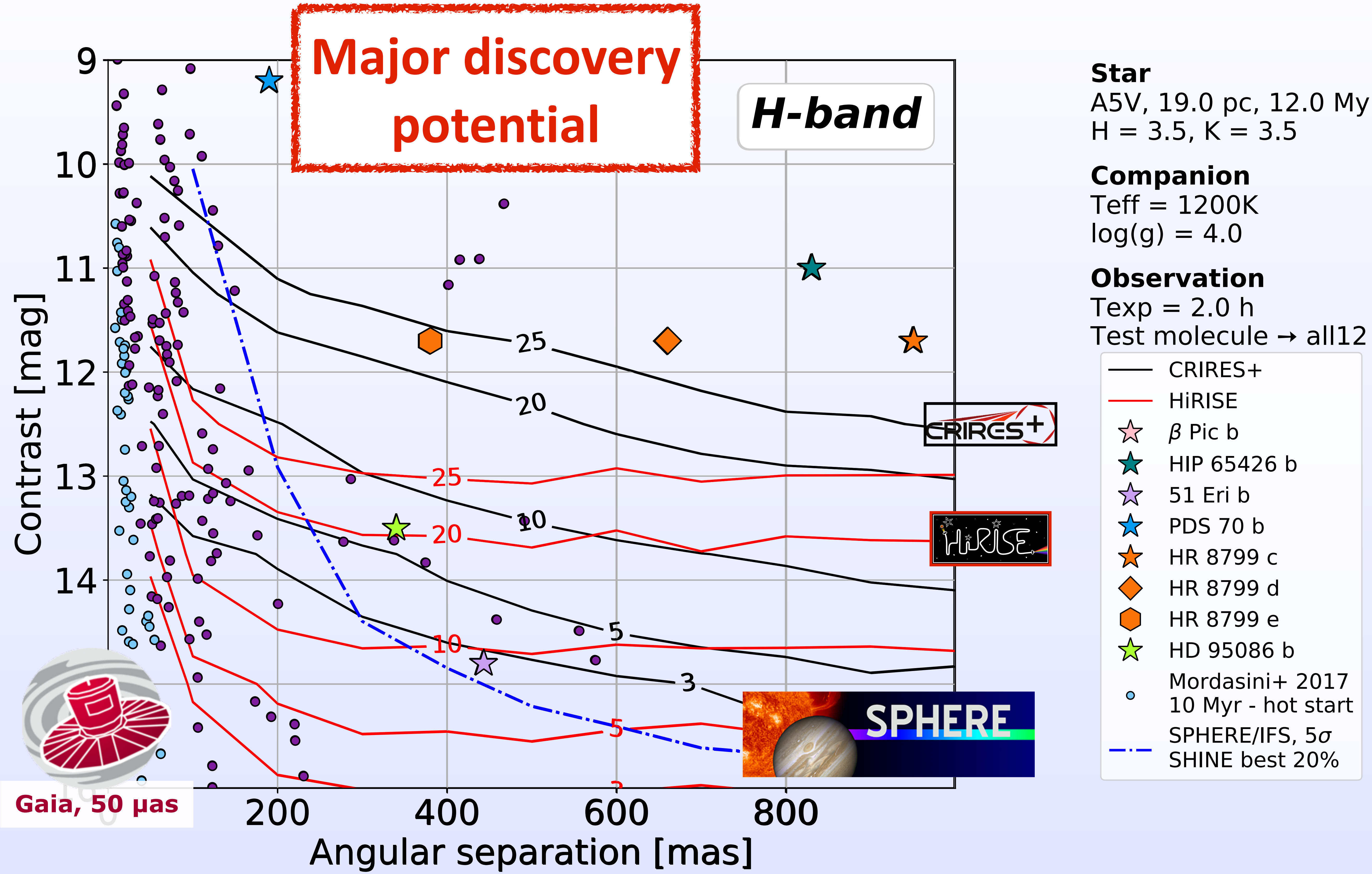
Star
A5V, 19.0 pc, 12.0 Myr
H = 3.5, K = 3.5

Companion
Teff = 1200K
log(g) = 4.0

Observation
Texp = 2.0 h
Test molecule → all12

Otten, Vigan et al. (2021)

Expected performance



Star
A5V, 19.0 pc, 12.0 Myr
H = 3.5, K = 3.5

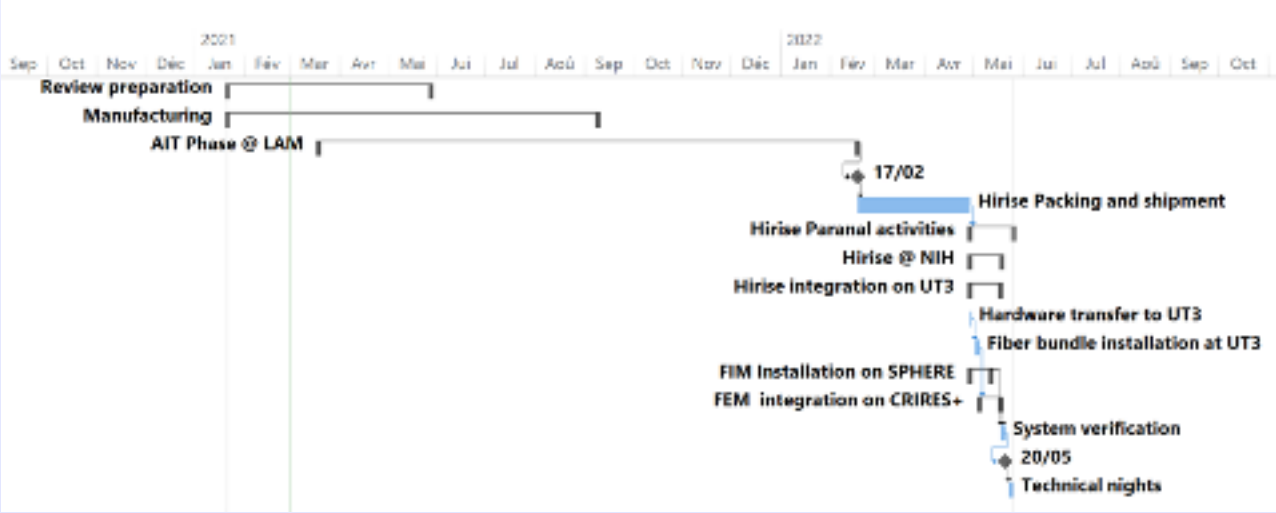
Companion
Teff = 1200K
log(g) = 4.0

Observation
Texp = 2.0 h
Test molecule → all12

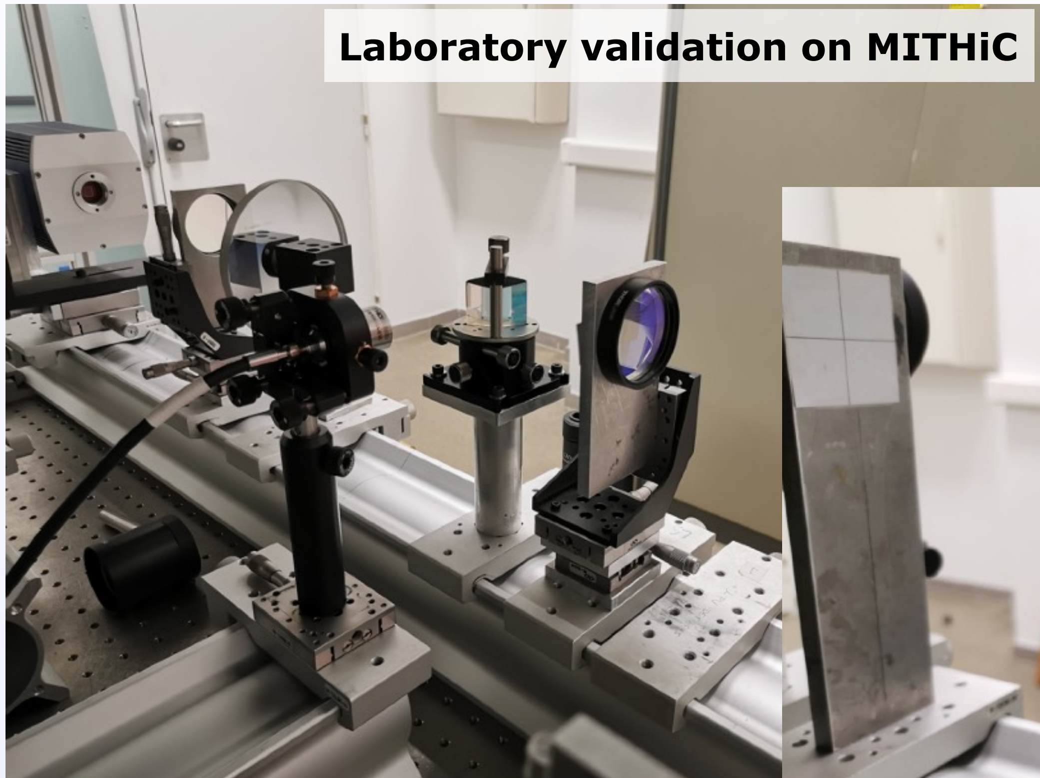
Otten, Vigan et al. (2021)

Status of HiRISE

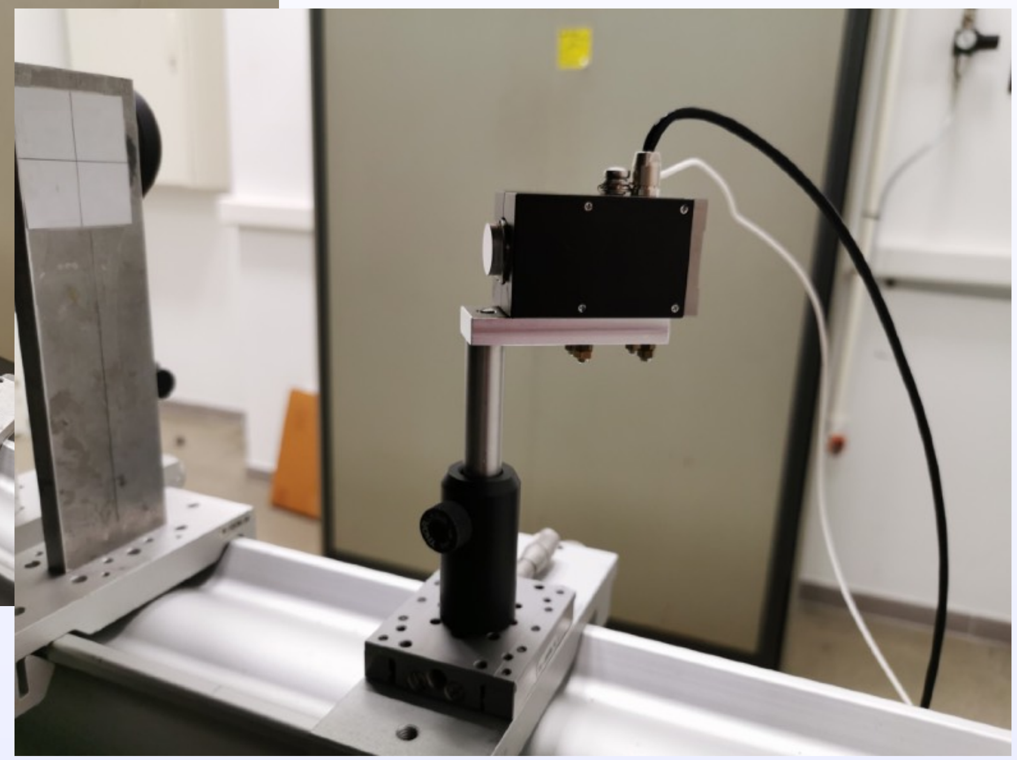
- Many discussions with ESO over the past 2 years
- Science case validated by the OPC: **strong support!**
- Technical proposal validated by STC and Council: **strong support!**
  - **HiRISE accepted as a visitor instrument by Paranal**
- Current activities:
  - Final design
  - Identification of manufacturers
  - Procurement of some hardware
  - Laboratory validations
  - Design review with ESO Paranal
- Schedule:

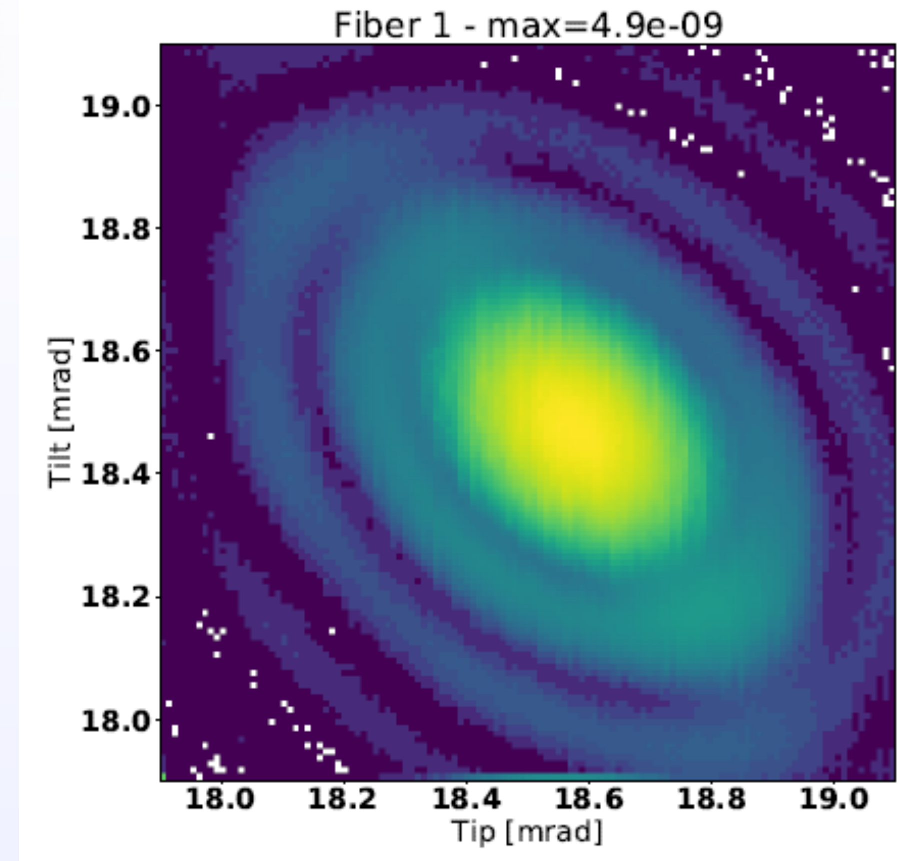


Technical activities

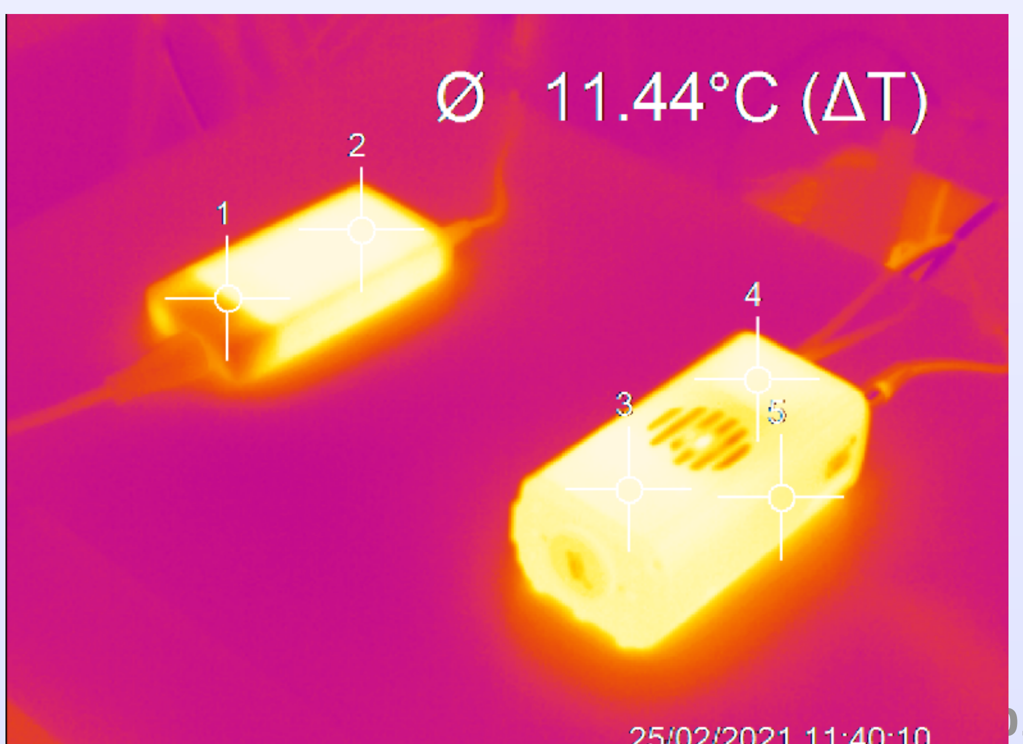


Laboratory validation on MITHiC





Fiber injection map



FIM tracking camera testing

Conclusions

HiRISE postdoc!

Preparation and analysis of the first on-sky data

https://astro.vigan.fr/hirise.html

1. High spectral resolution on exoplanets

- Improved characterization
- Detection boost
- Opens new opportunities for understanding of exoplanets

2. HiRISE: high-spectral resolution of directly-imaged exoplanets

- Unique opportunity on VLT/UT3!
- Couling between SPHERE and CRIRES+
- Final design on-going
- Accepted by ESO/Paranal as a visitor instrument
- On sky probably mid-2022
- Demonstrator for future instrumentation ELT/PCS or post-JWST exoplanet imagers