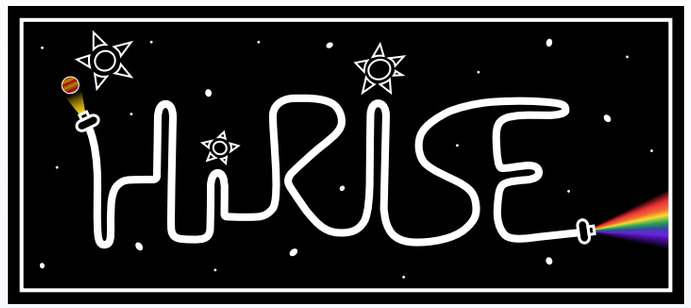
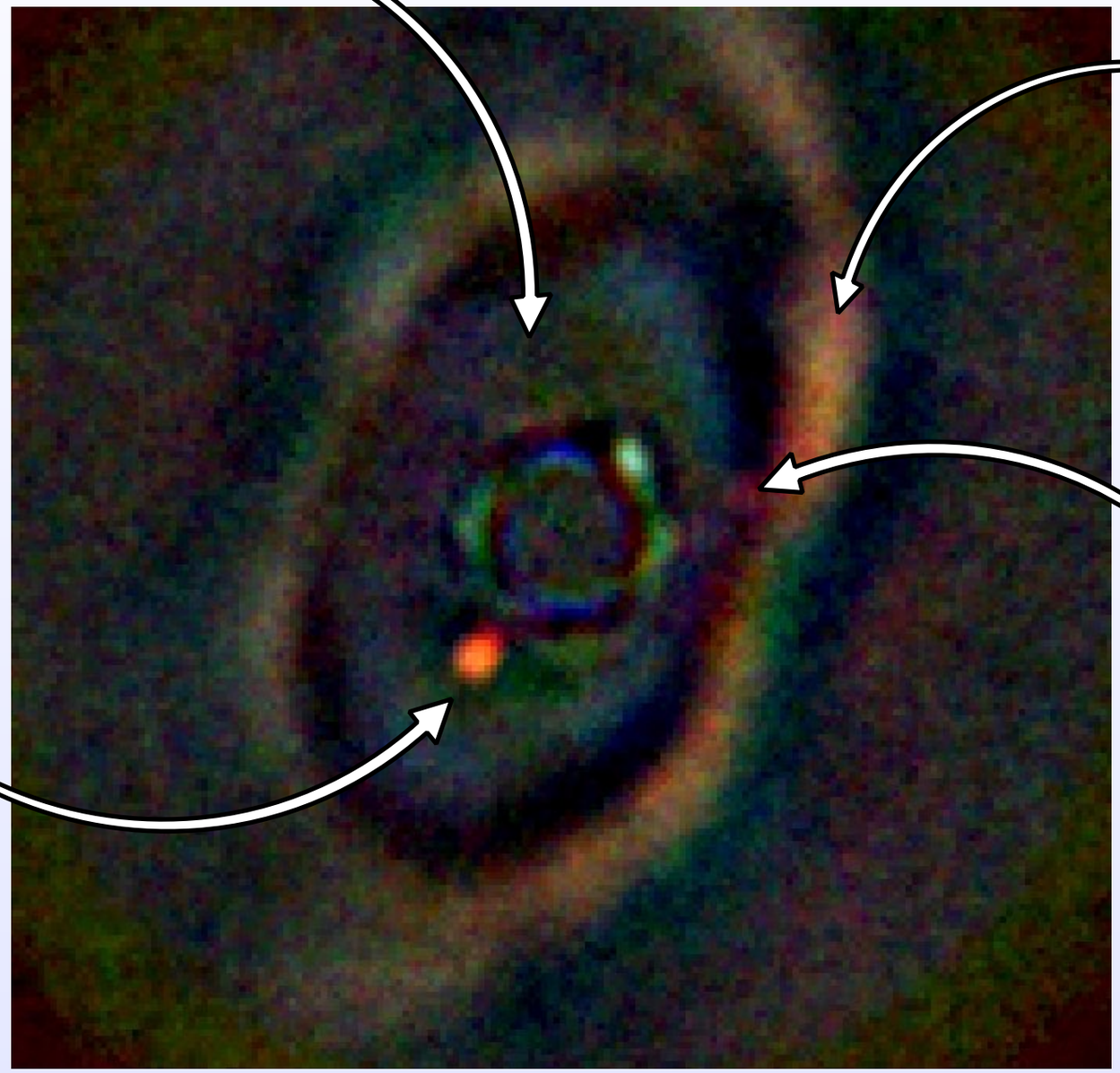


Characterization of directly-imaged exoplanets at high spectral resolution: Coupling SPHERE and CRIRES+

Arthur Vigan
Laboratoire d'Astrophysique de Marseille (LAM)
Centre National de la Recherche Scientifique (CNRS)

LAM: A. Vigan, G. Otten, E. Muslimov, M. El Morsy, M. Lopez, A. Viret, A. Costille, K. Dohlen, J.-L. Beuzit, M. Houllé, E. Choquet, J.-F. Sauvage, N. Tchoubaklian, Y. Charles / **University of Göttingen:** A. Reiners, H. Anwand / **ESO:** U. Seemann, M. Kasper, R. Dorn, G. Zins, J. Paufique / **University of Exeter:** M. Phillips, I. Baraffe / **IPAG:** D. Mouillet, A. Carlotti / **Laboratoire Lagrange:** M. N'Diaye, R. Pourcelot, D. Mary / **LESIA:** A. Boccaletti, B. Charnay
+ ESO Paranal support: A. Smette, L. Pallanca, et al.

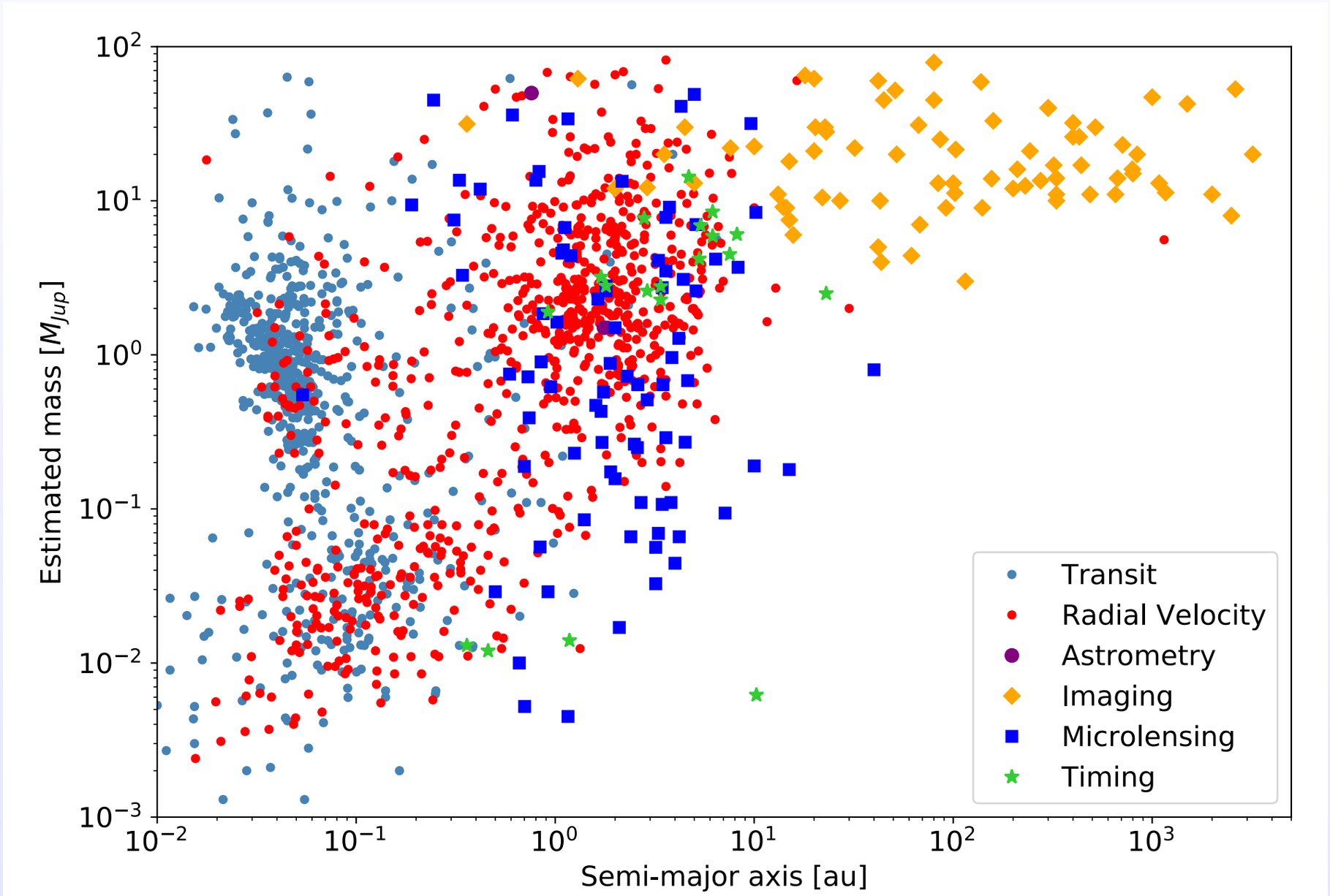
Direct imaging of exoplanets



PDS 70 - Keppler et al. (2018)

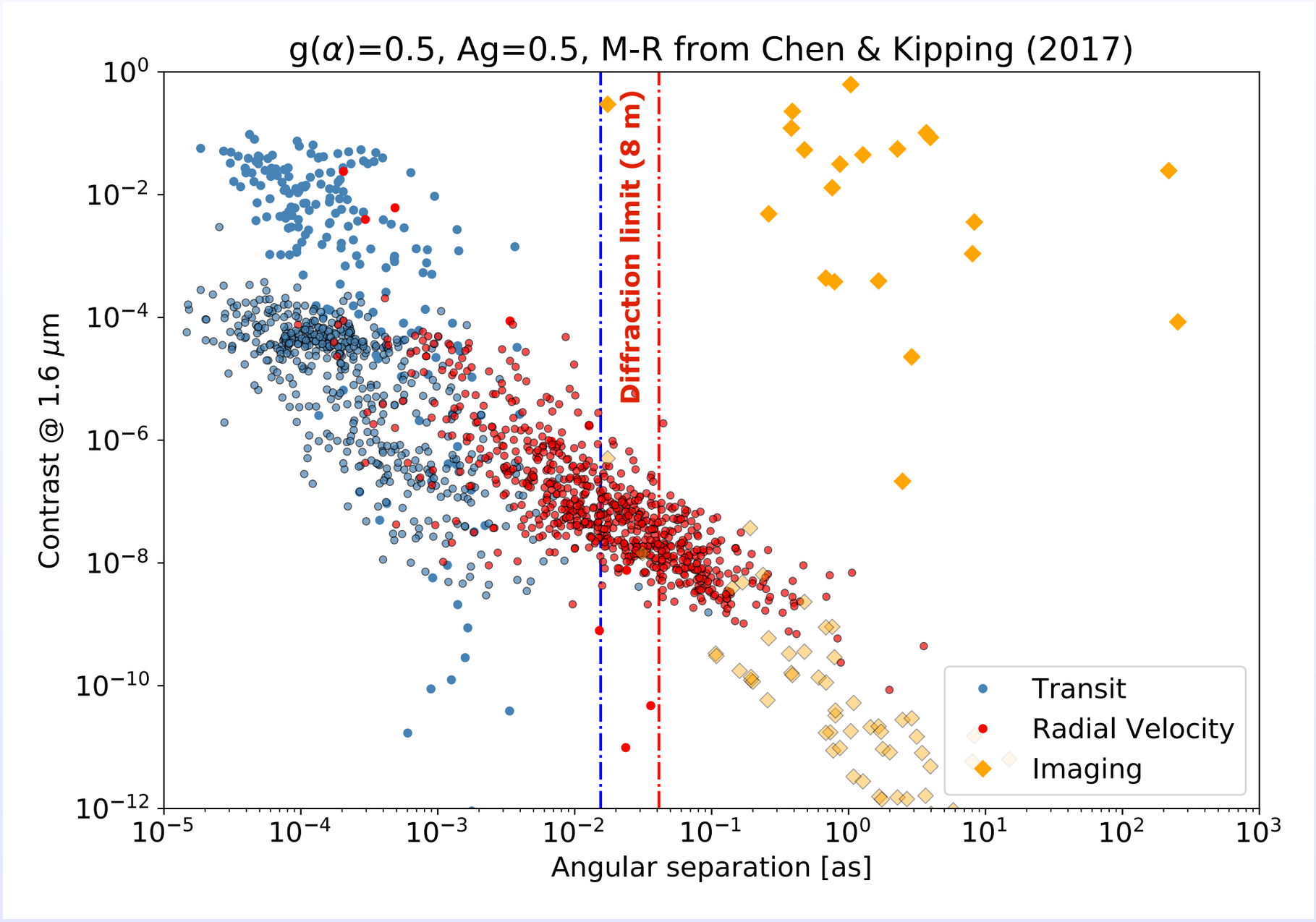
Direct imaging of exoplanets

Physical units



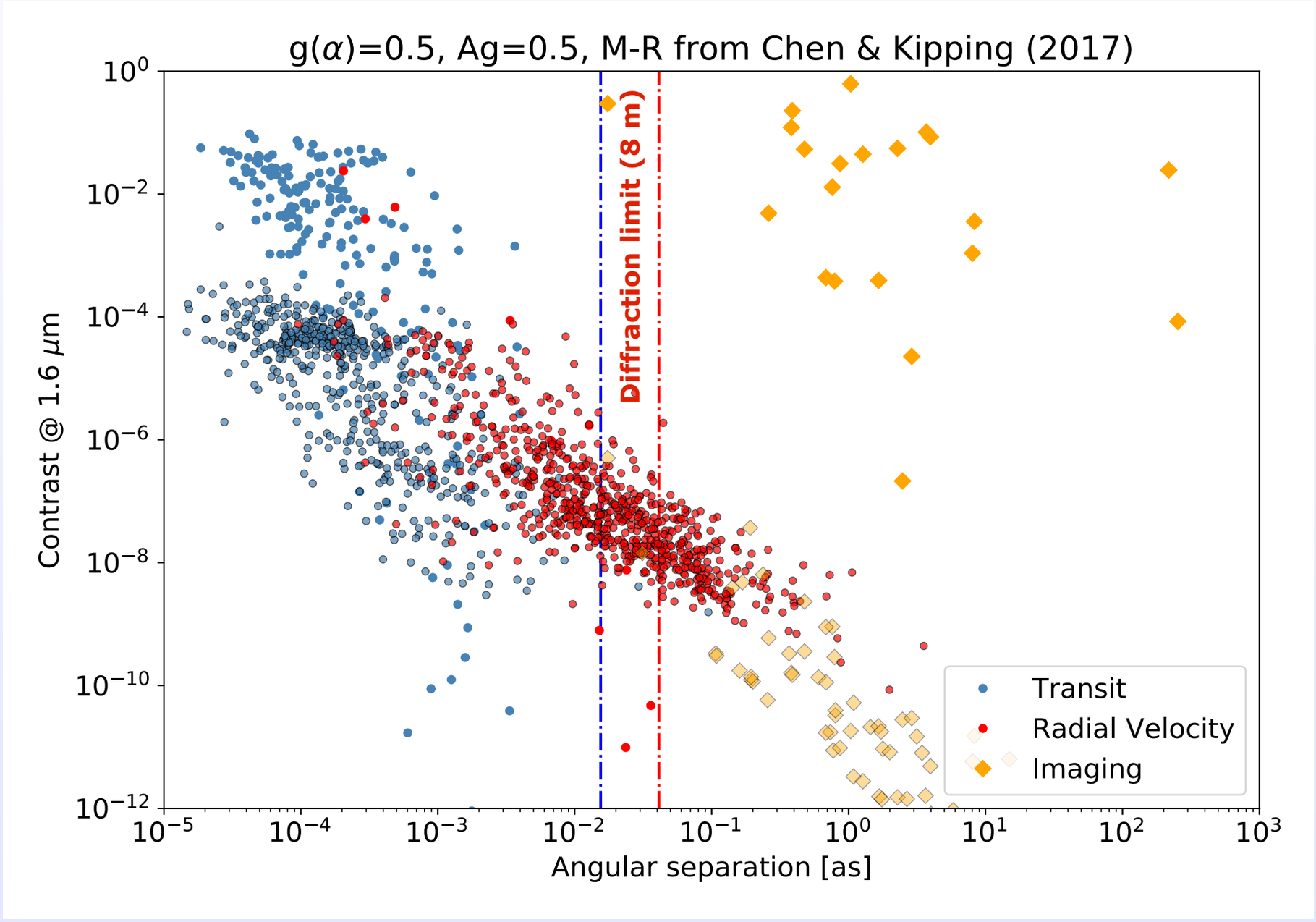
Direct imaging of exoplanets

Observables



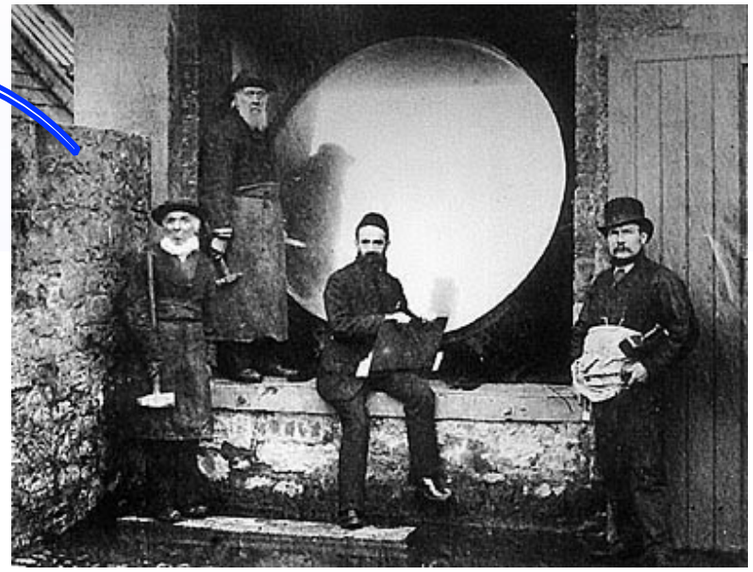
Direct imaging of exoplanets

High-angular resolution



High-contrast

VLT/SPHERE



IRDIS

IFS

ZIMPOL

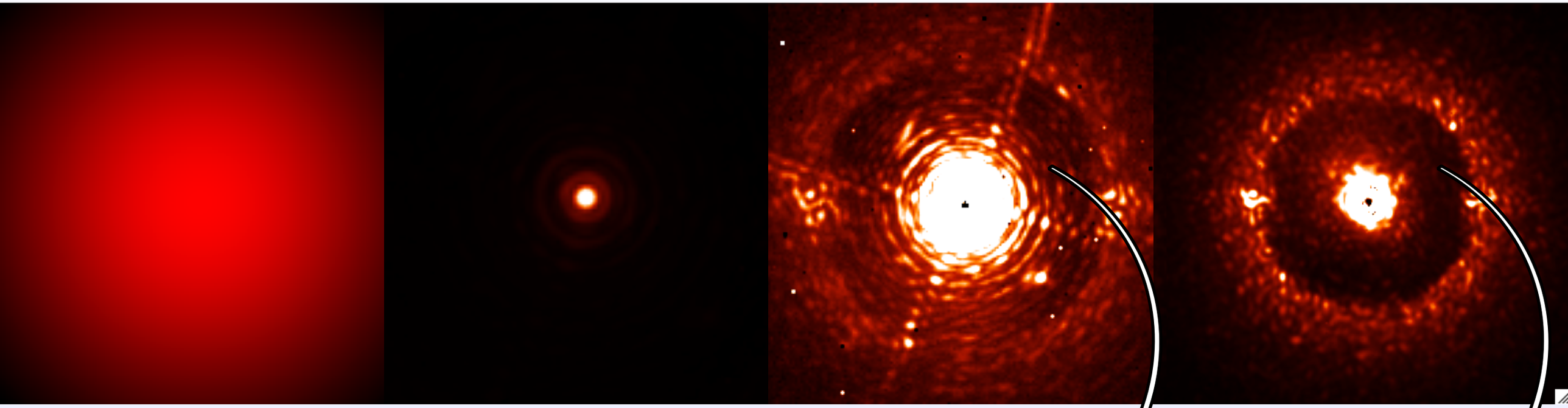
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

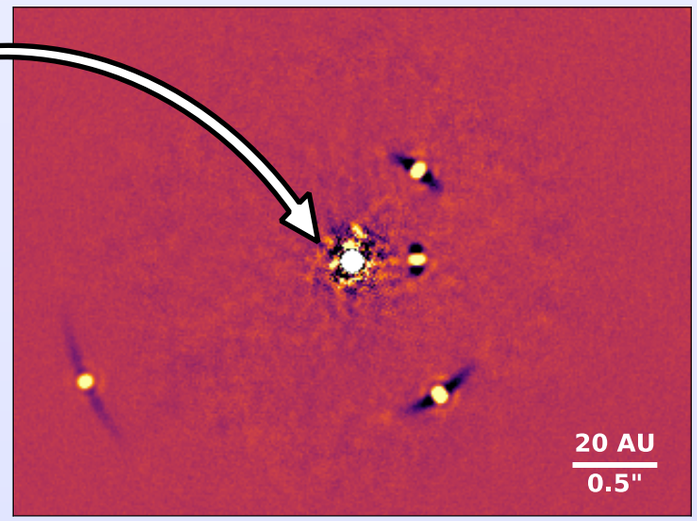
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



Diffraction limited within 20 λ/D

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

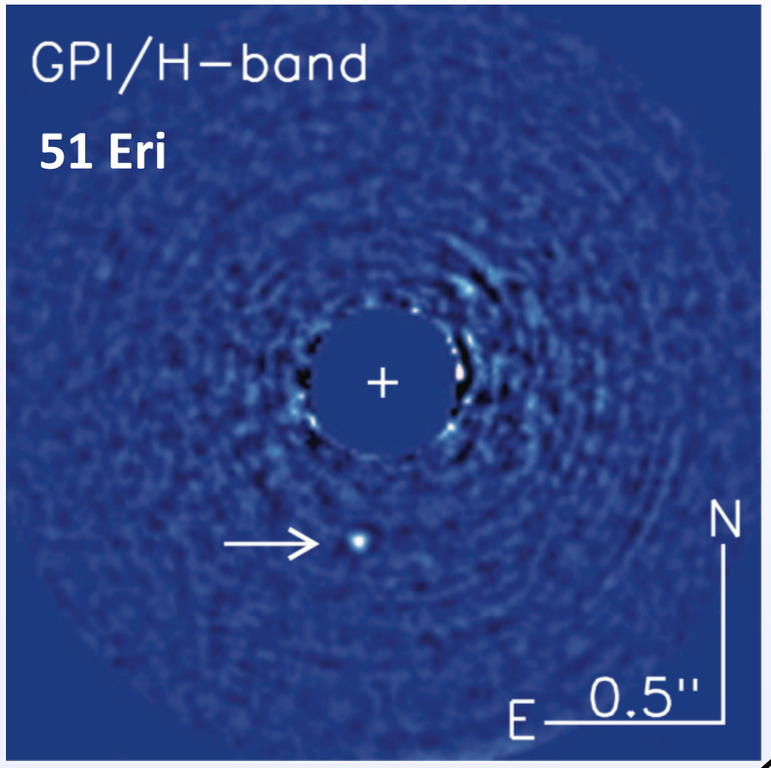
post-processing



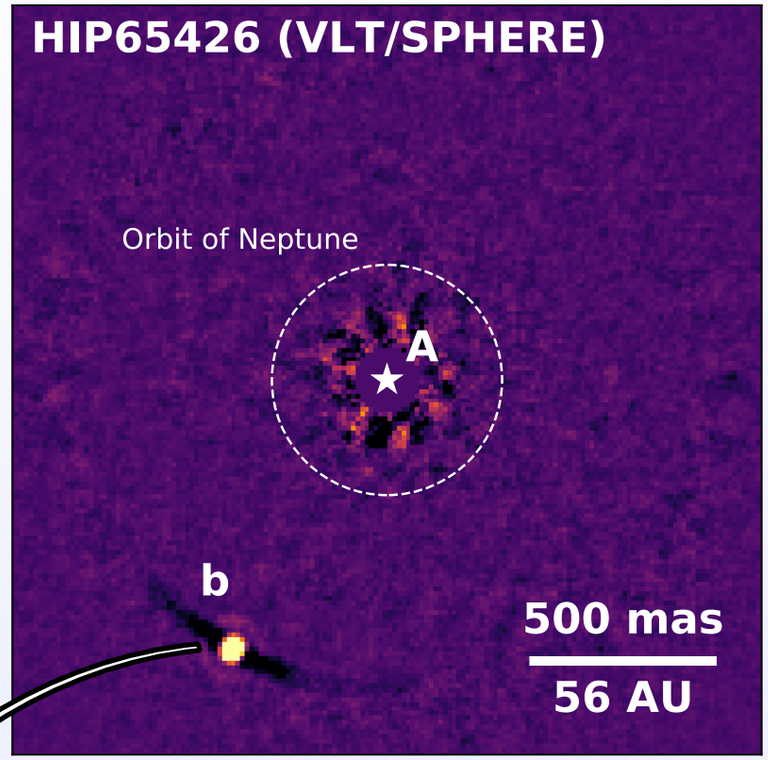
~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

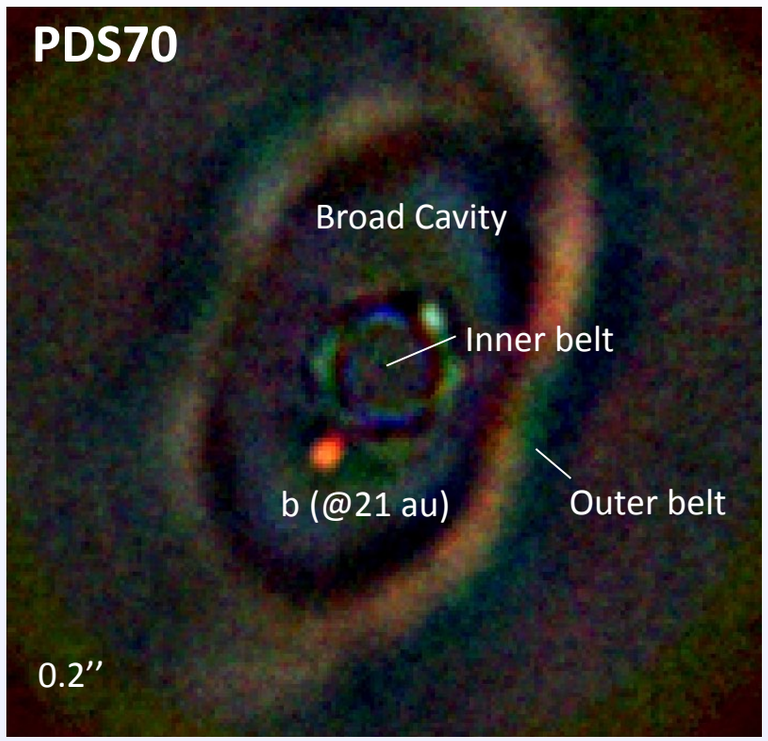
SPHERE and GPI detections



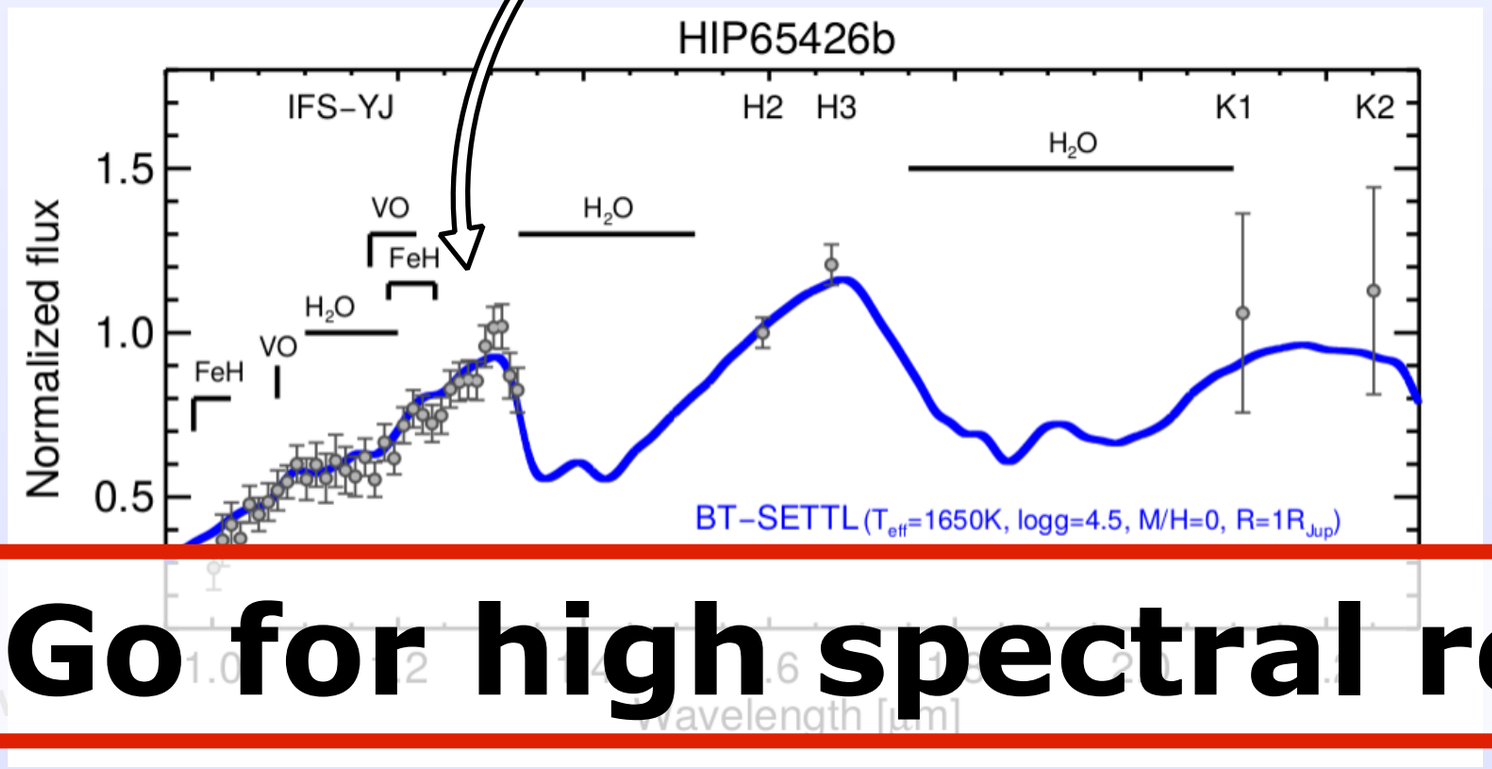
Macintosh et al. 2015



Chauvin et al. 2017



Keppler et al. 2018

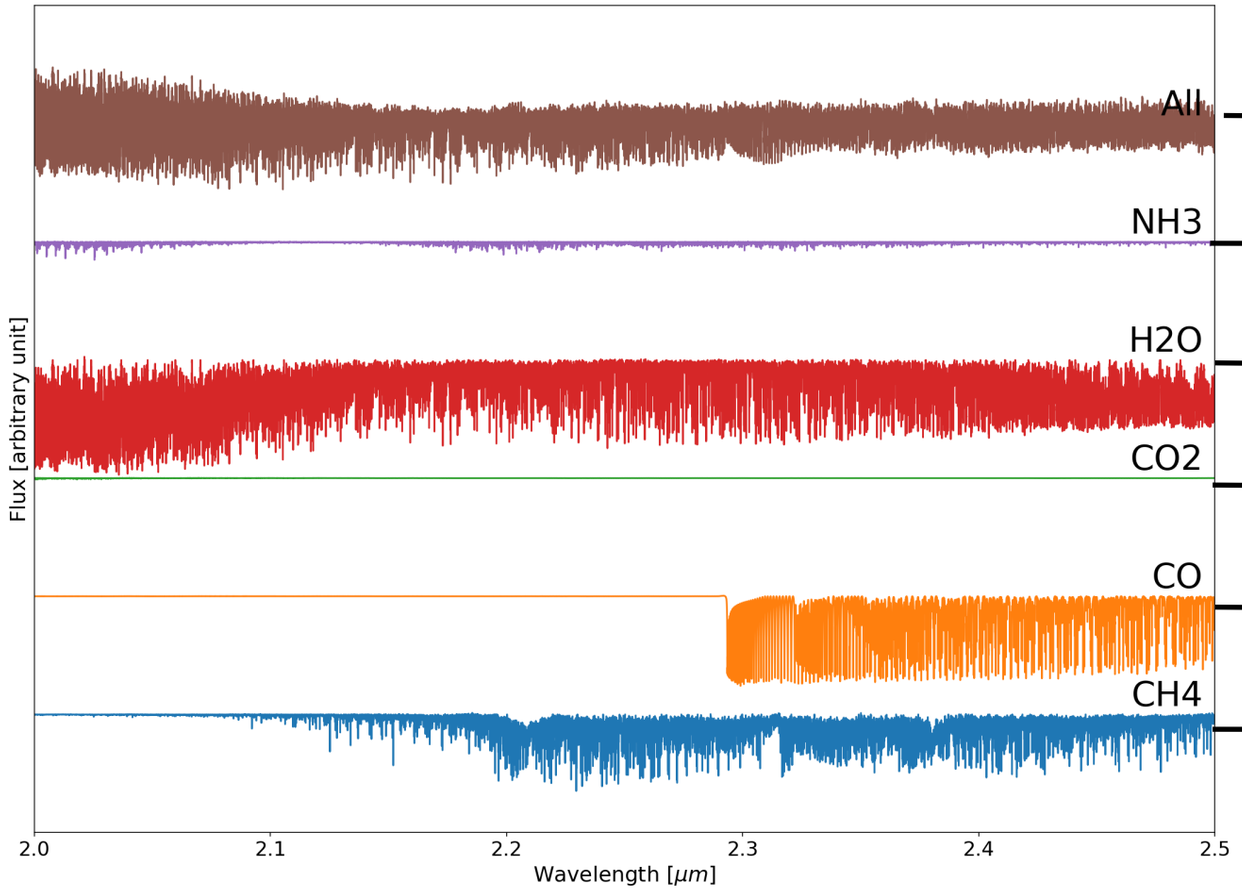


Very low resolution spectroscopy!

→ First order characterisation

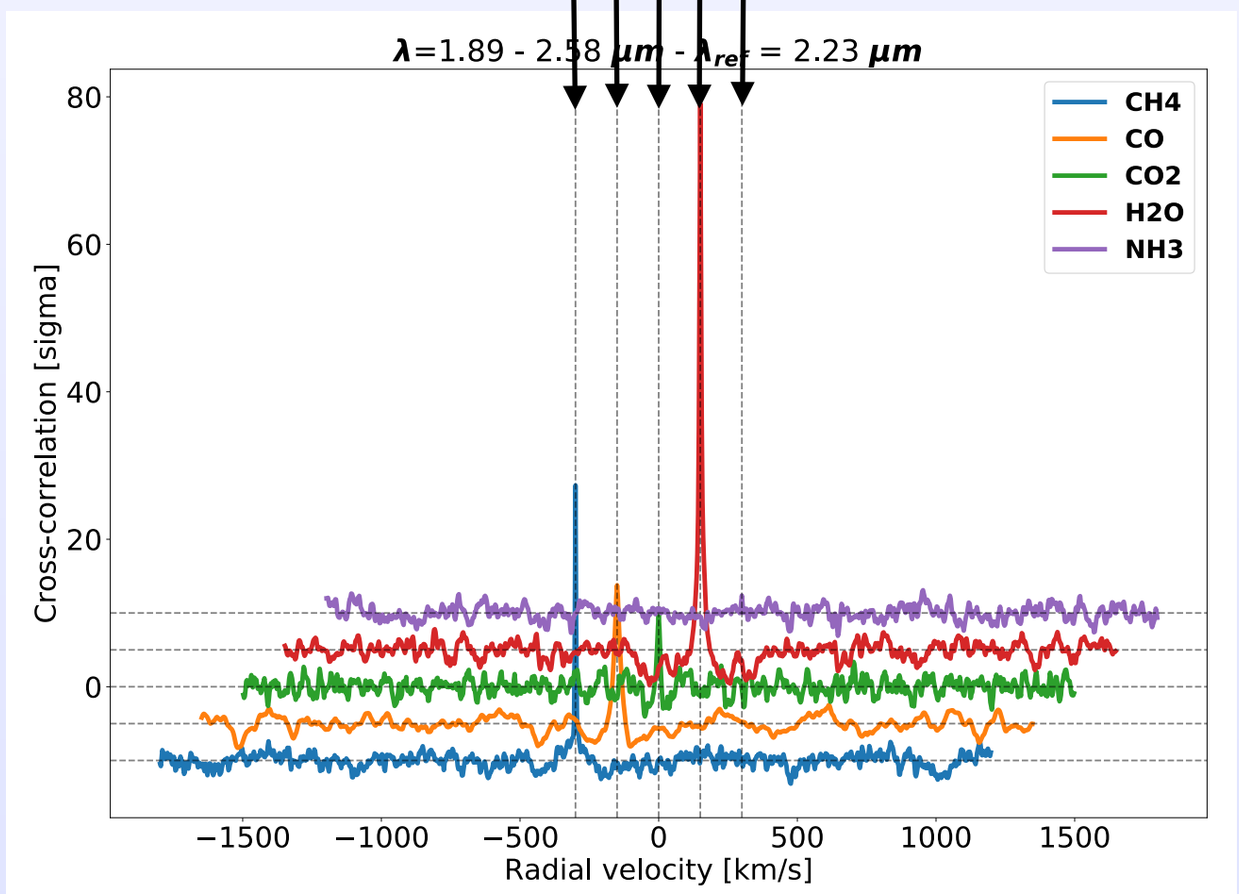
Go for high spectral resolution!

Detection boost at high-spectral resolution

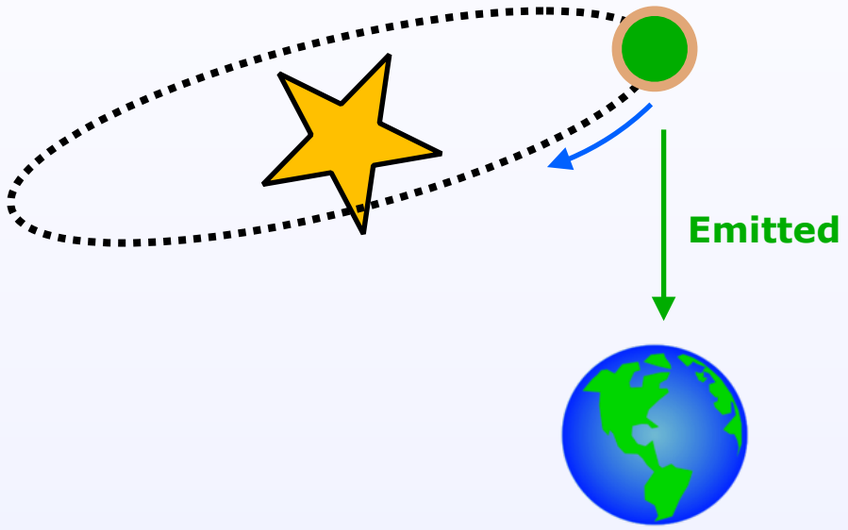


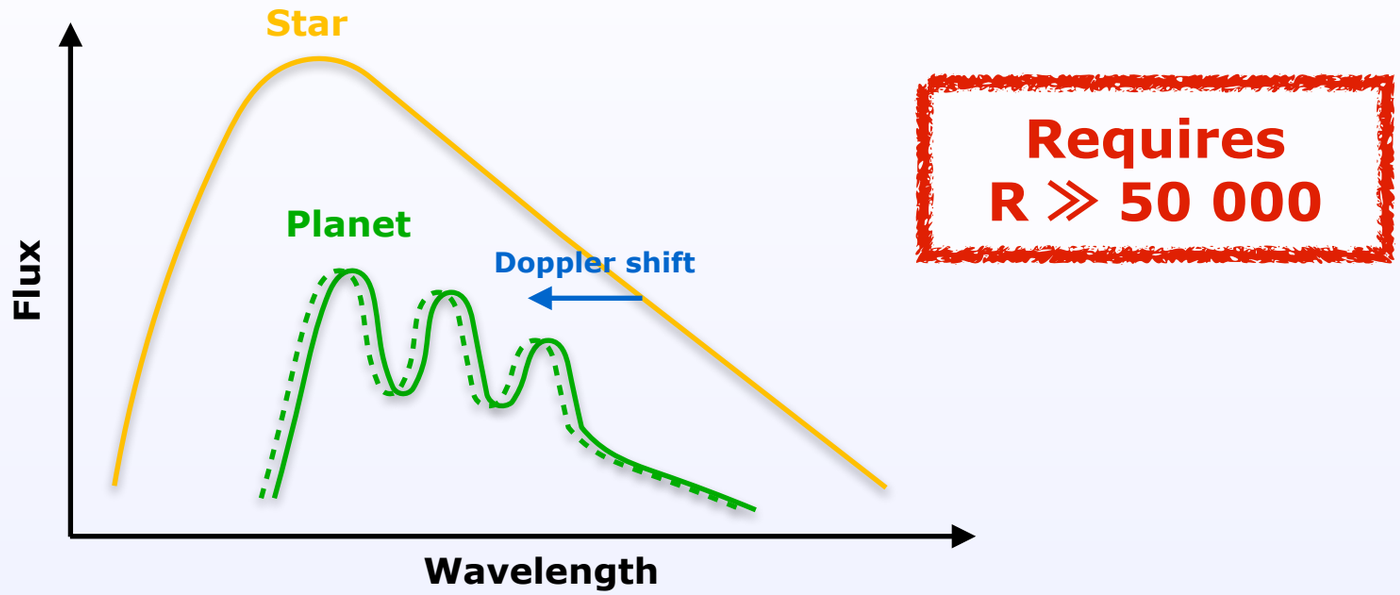
ATMO models
Tremblin et al. (2015)
Philipps et al. (2020)

Standard CCF approach



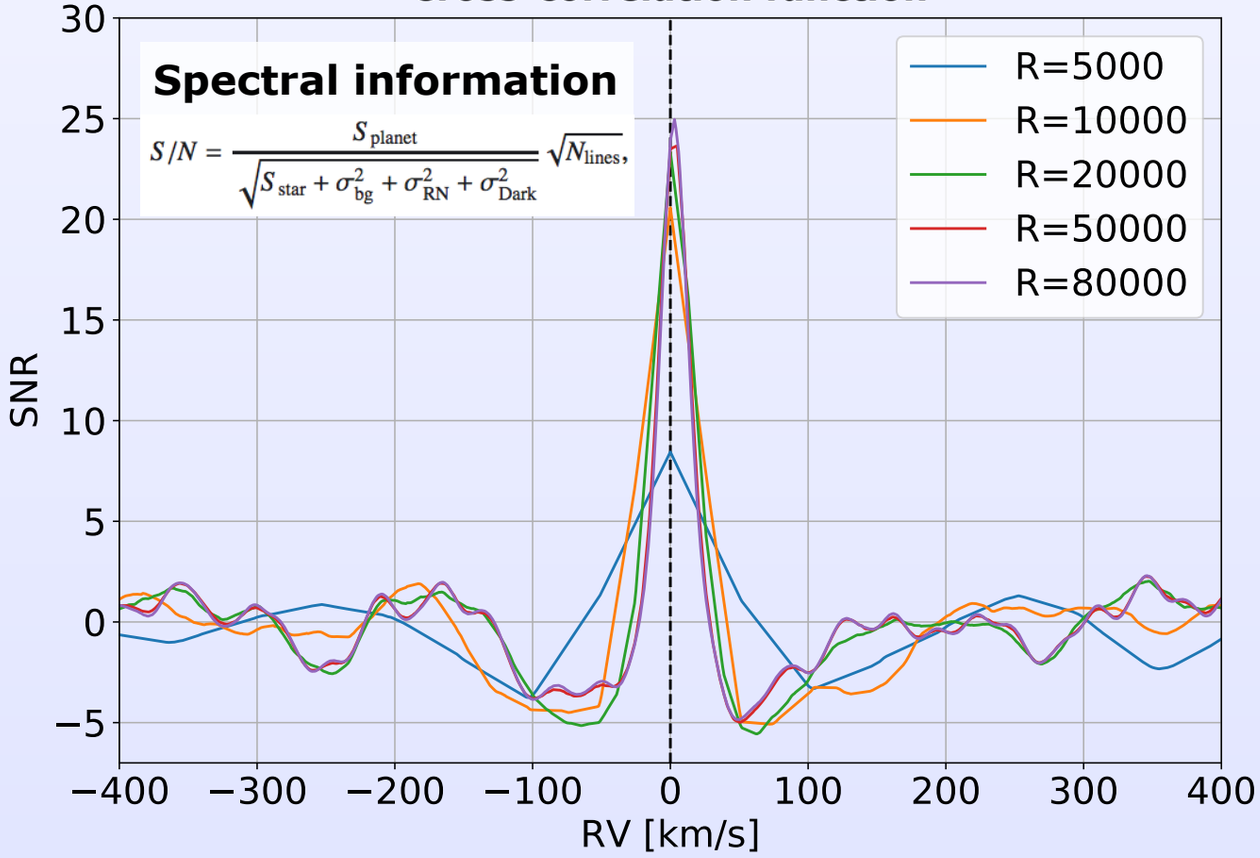
Detection boost at high-spectral resolution



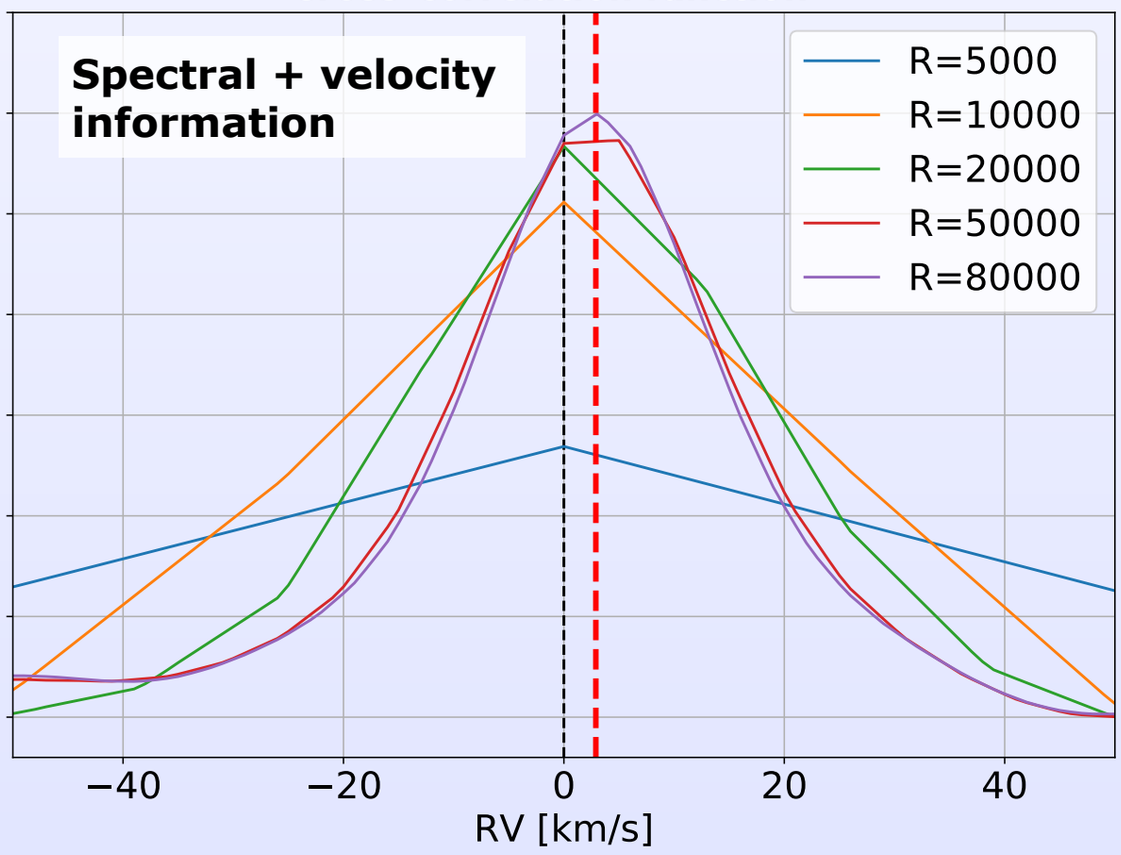


Requires
$R \gg 50\,000$

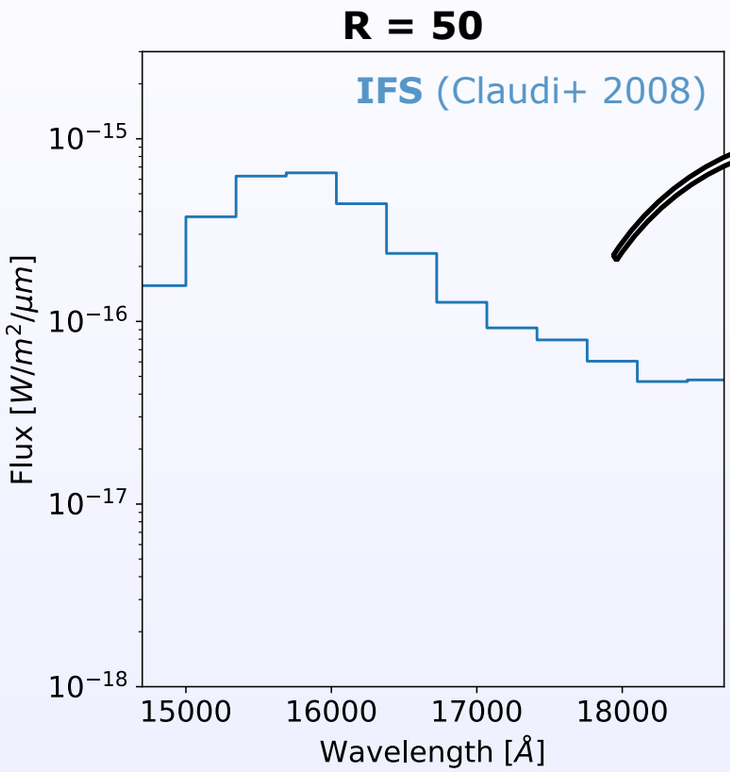
Cross-correlation function

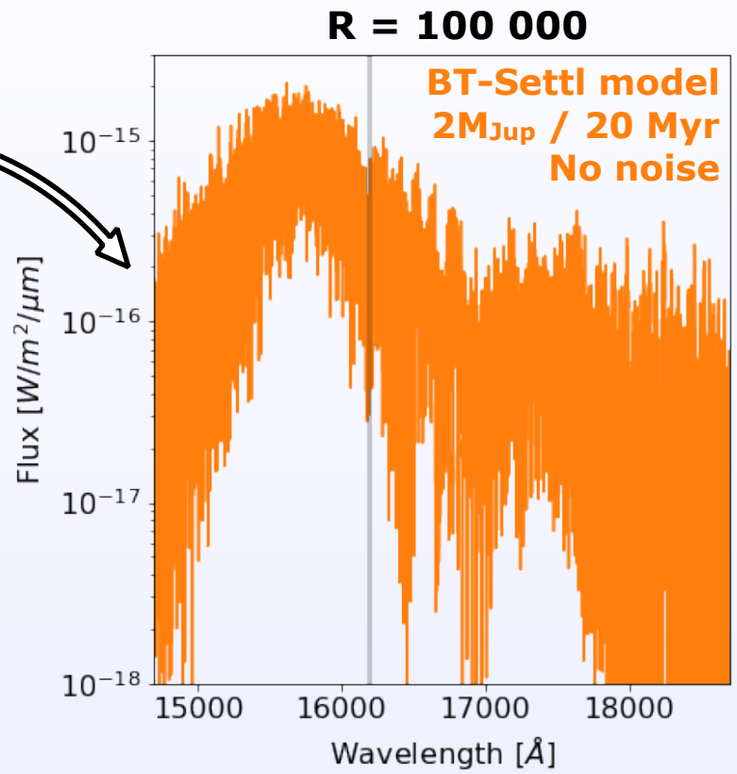


Cross-correlation function



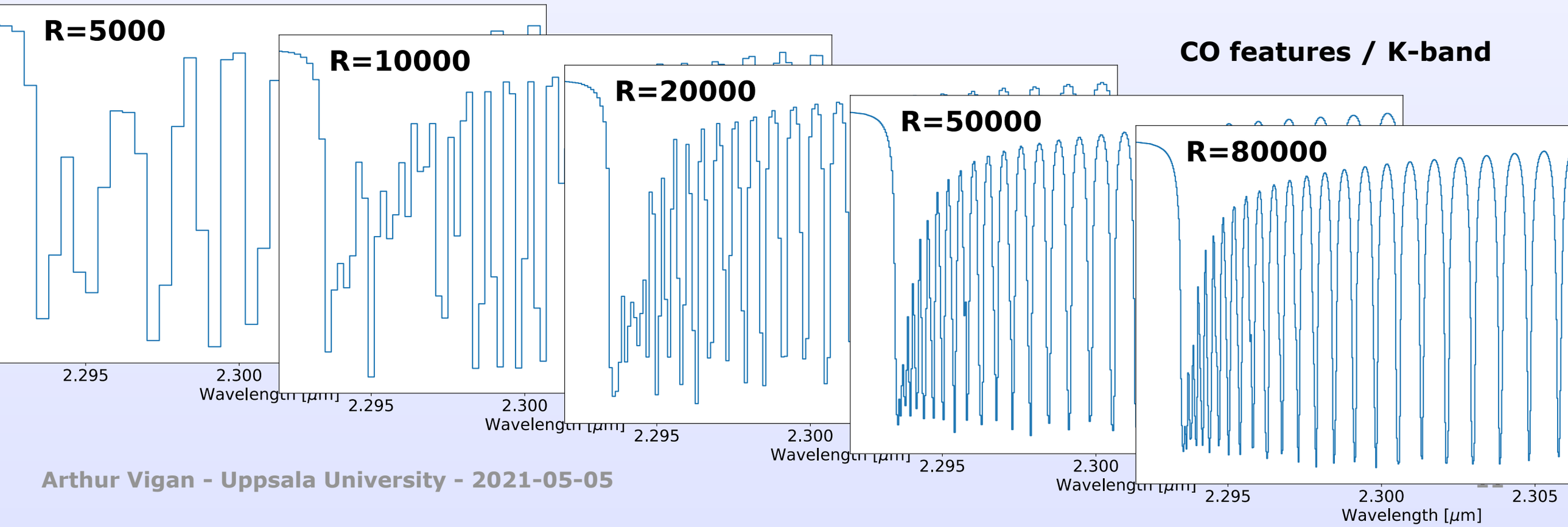
Characterisation at high-spectral resolution





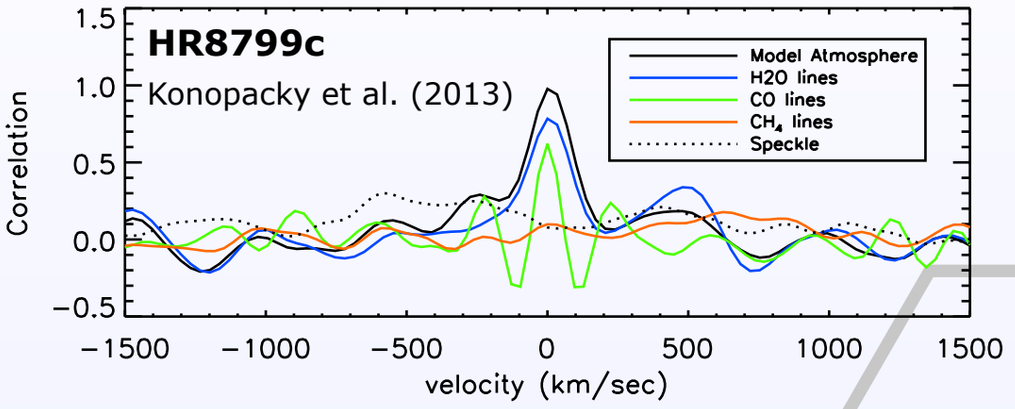
Requires
R ≫ 10 000

CO features / K-band

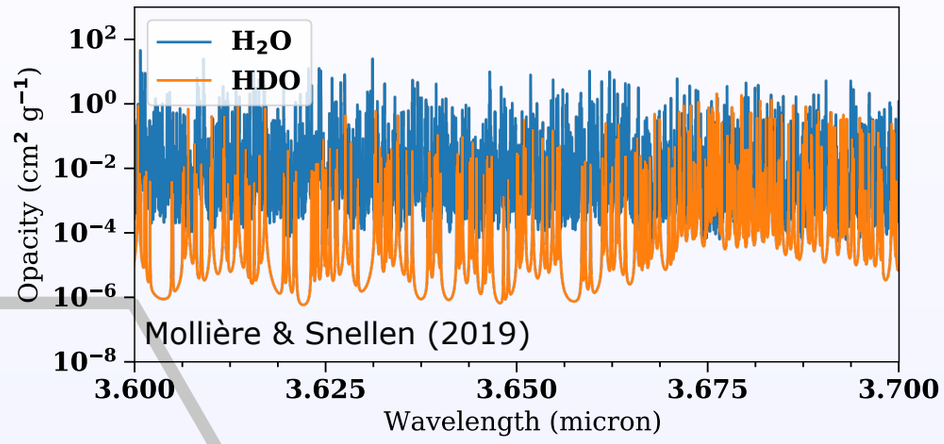


Exoplanet science at high resolution

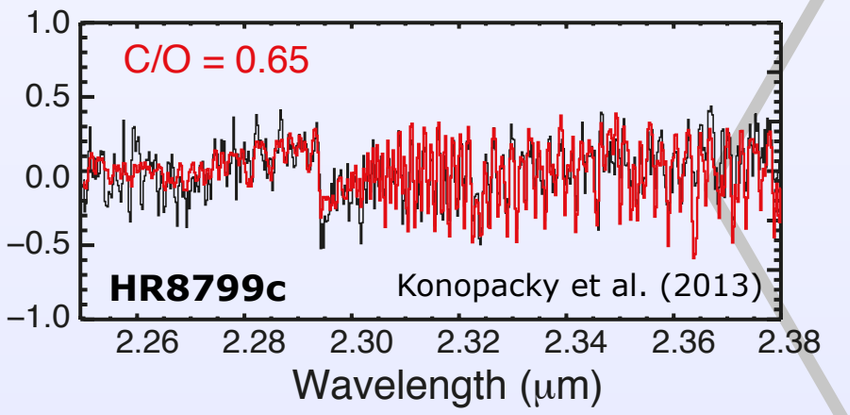
Molecules detection



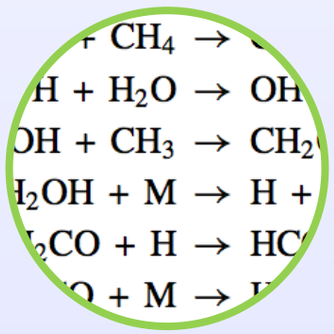
Isotopologues detection



Abundances determination

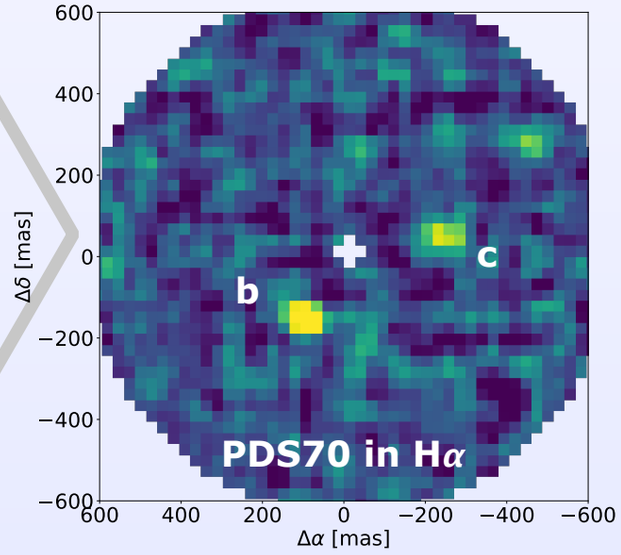


Formation, migration & evolution

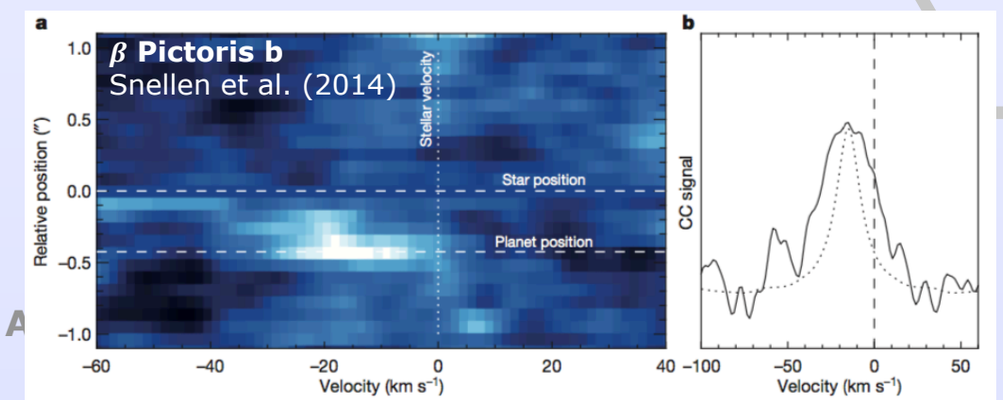


Atmospheric chemistry & dynamics

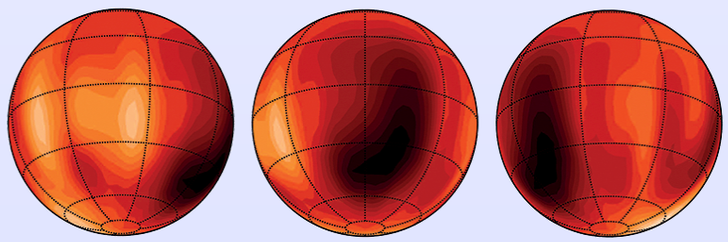
Accretion lines



Orbital and rotational velocity

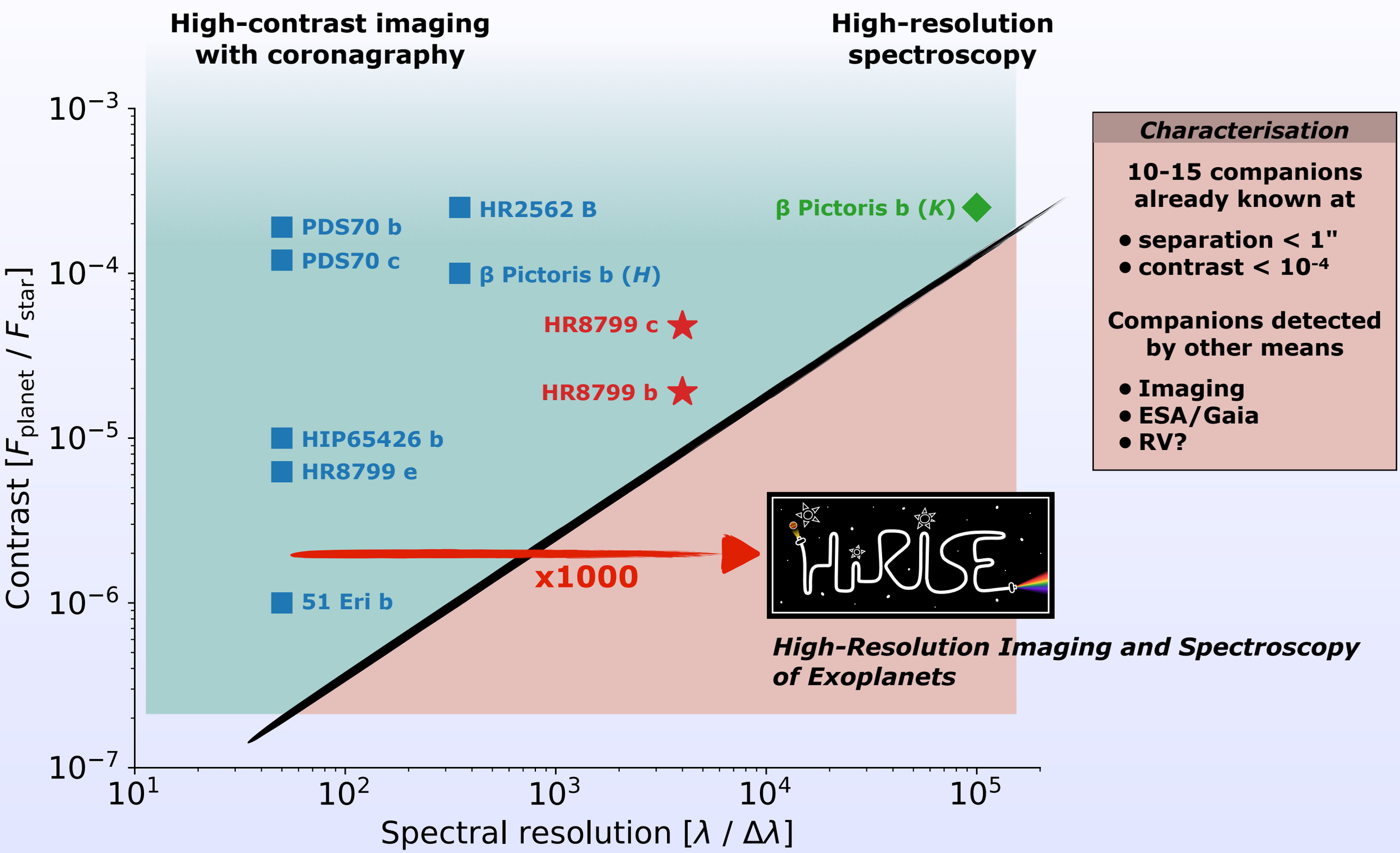


Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

Young exoplanets characterisation in near-IR



Characterisation

10-15 companions already known at

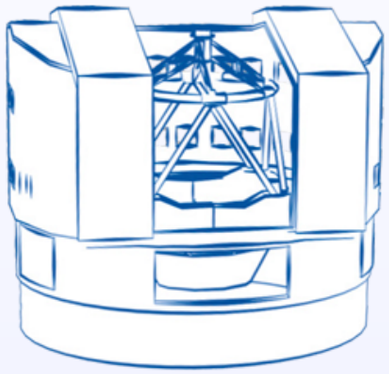
- **separation < 1"**
- **contrast < 10^{-4}**

Companions detected by other means

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

A unique window of opportunity

VLT/UT3



High-contrast exoplanet imager

SPHERE

High-resolution spectrograph

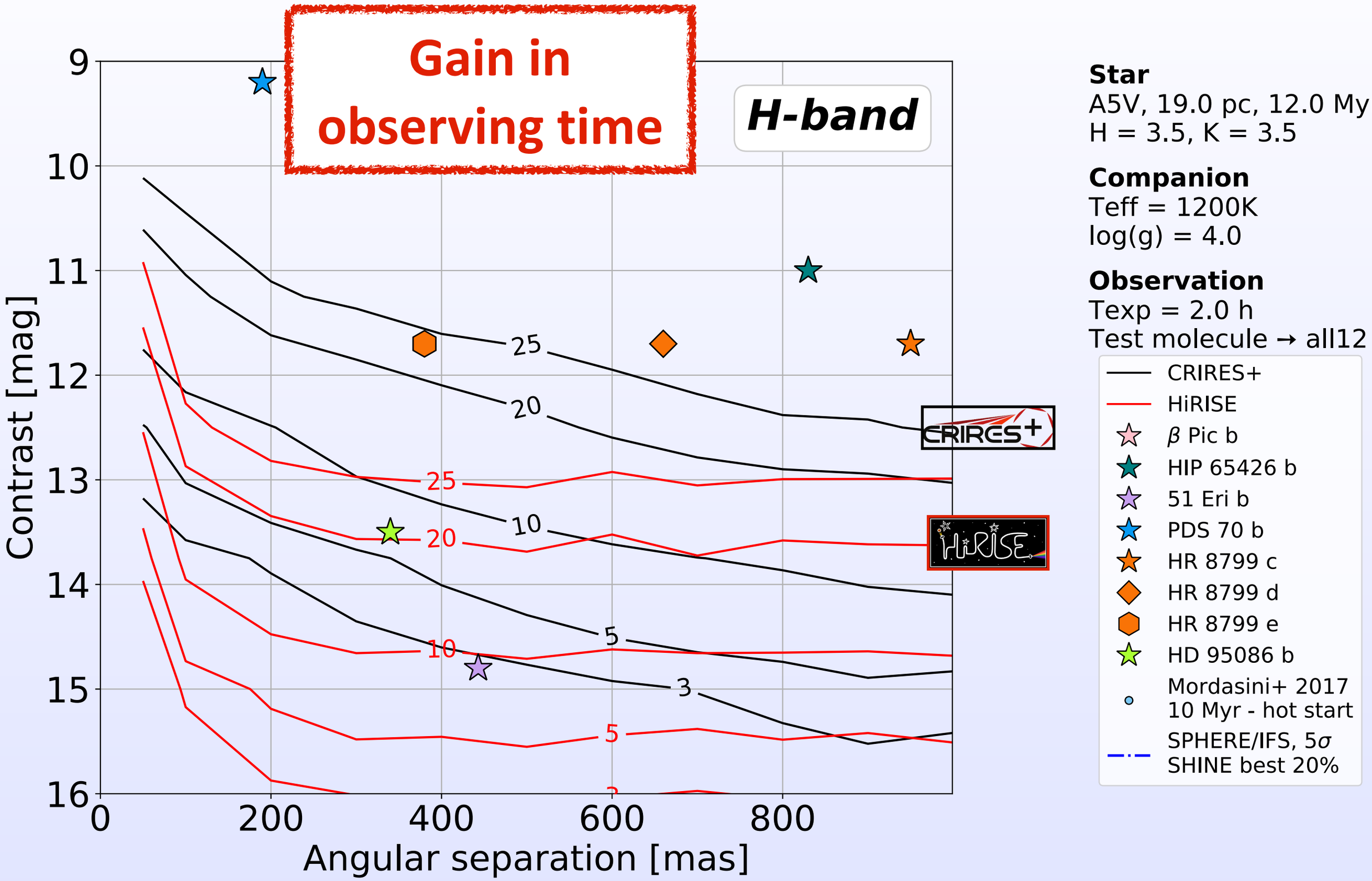
CRIRES+

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

Fiber coupling

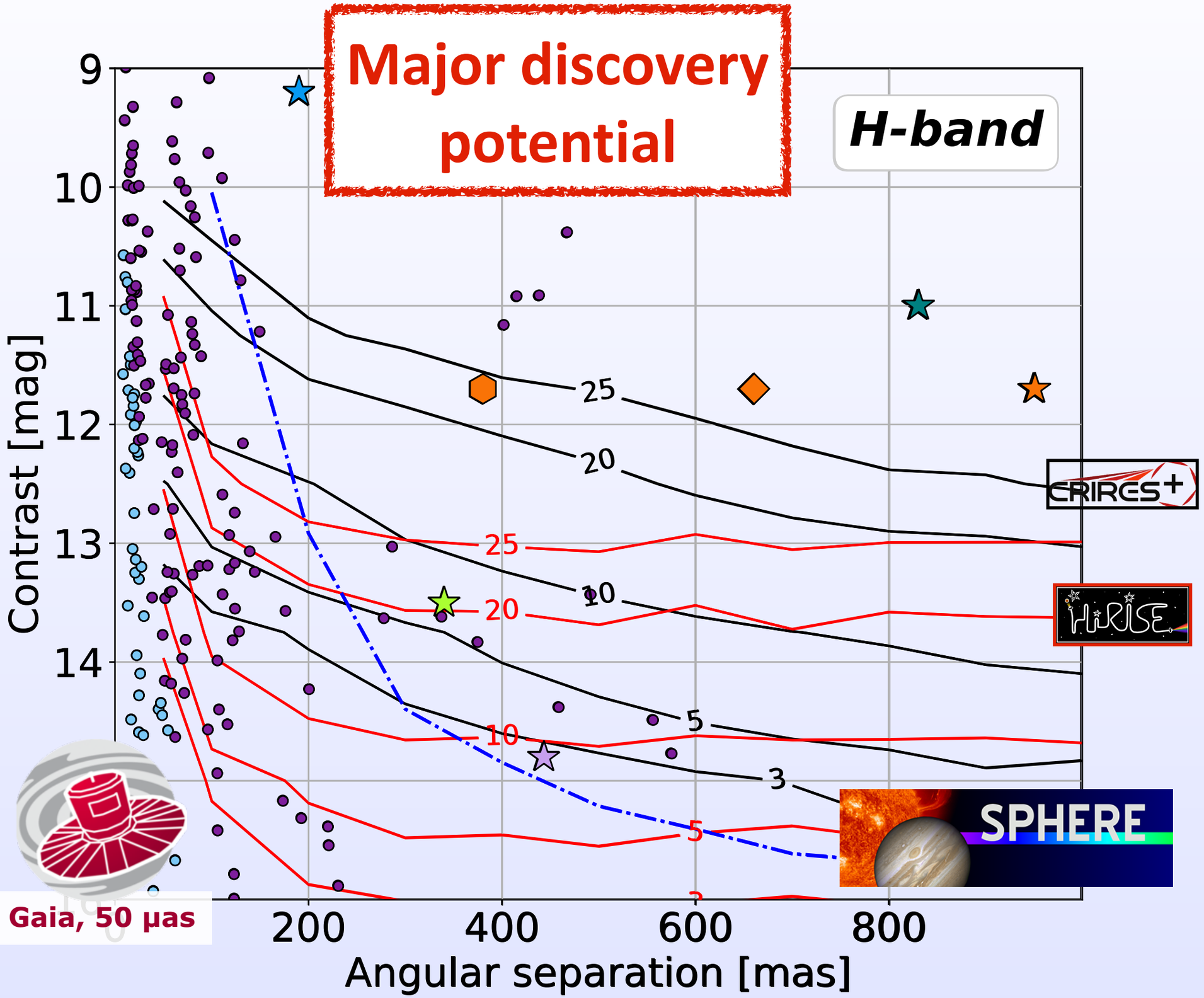
HiRISE

Expected performance



Otten, Vigan et al. (2021)

Expected performance



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

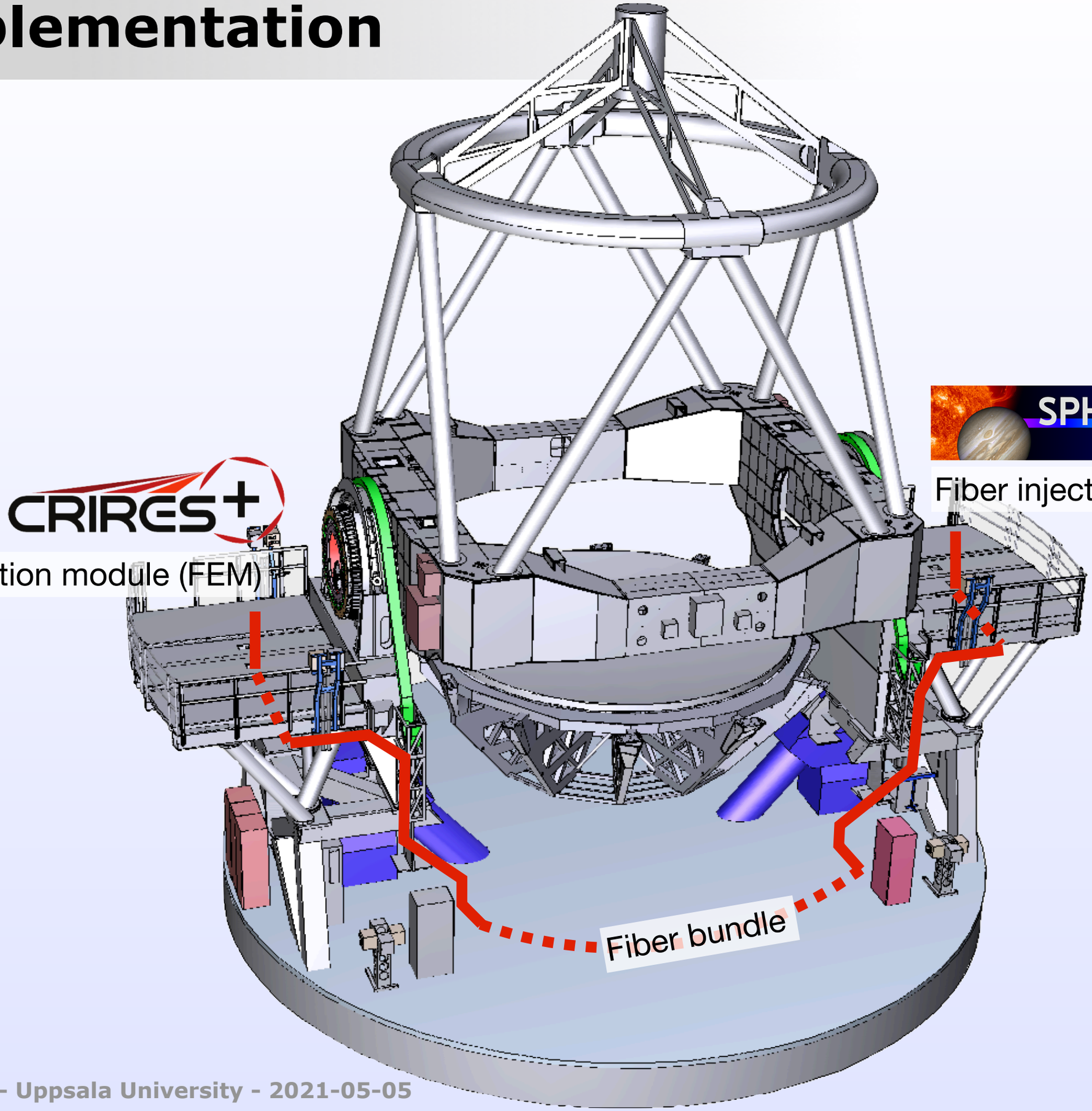
Companion
Teff = 1200K
log(g) = 4.0

Observation
Texp = 2.0 h
Test molecule → all12

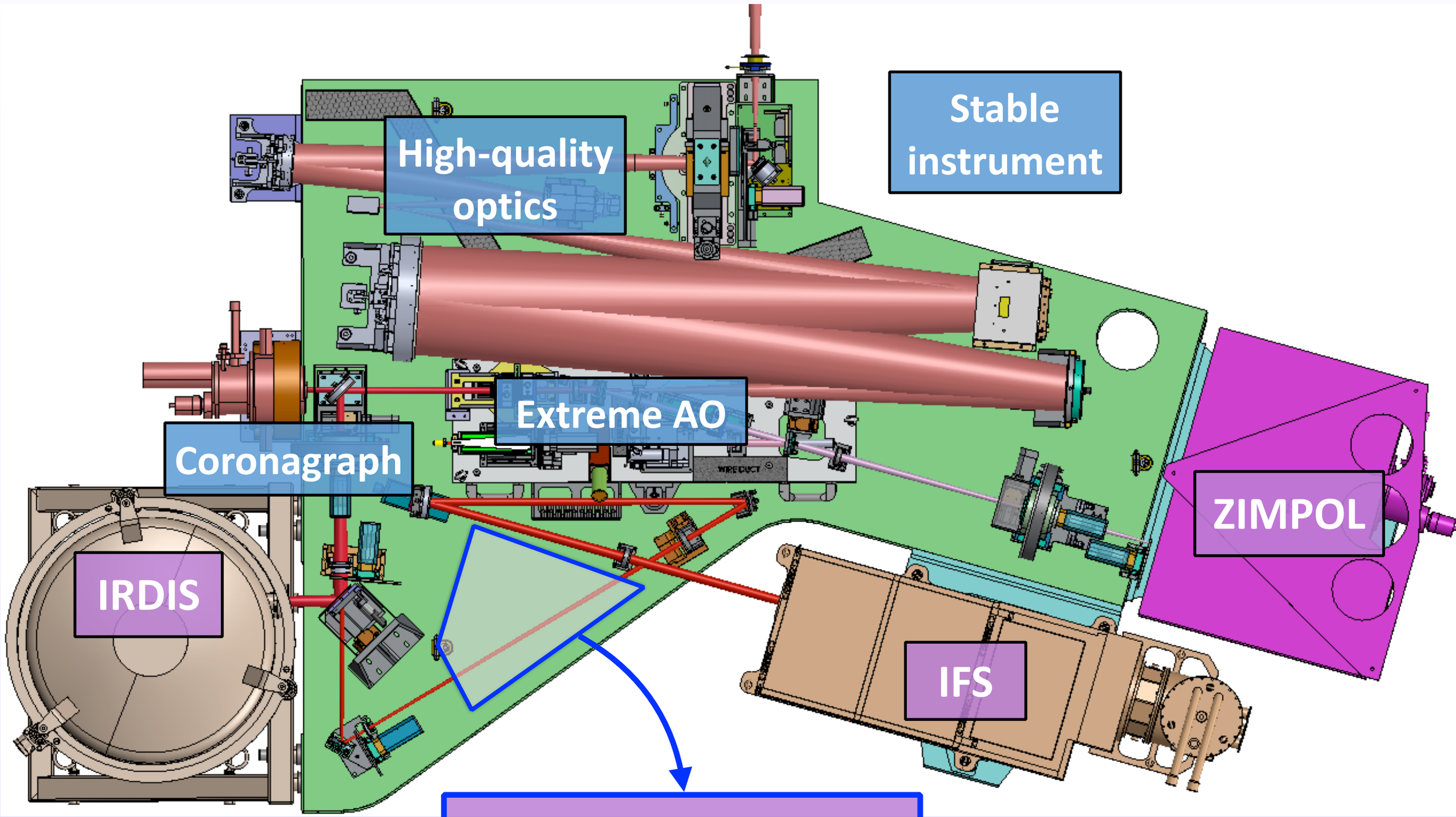
- CRIRES+
- HiRISE
- β Pic b
- HIP 65426 b
- 51 Eri b
- PDS 70 b
- HR 8799 c
- HR 8799 d
- HR 8799 e
- HD 95086 b
- Mordasini+ 2017 10 Myr - hot start
- SPHERE/IFS, 5σ SHINE best 20%

Otten, Vigan et al. (2021)

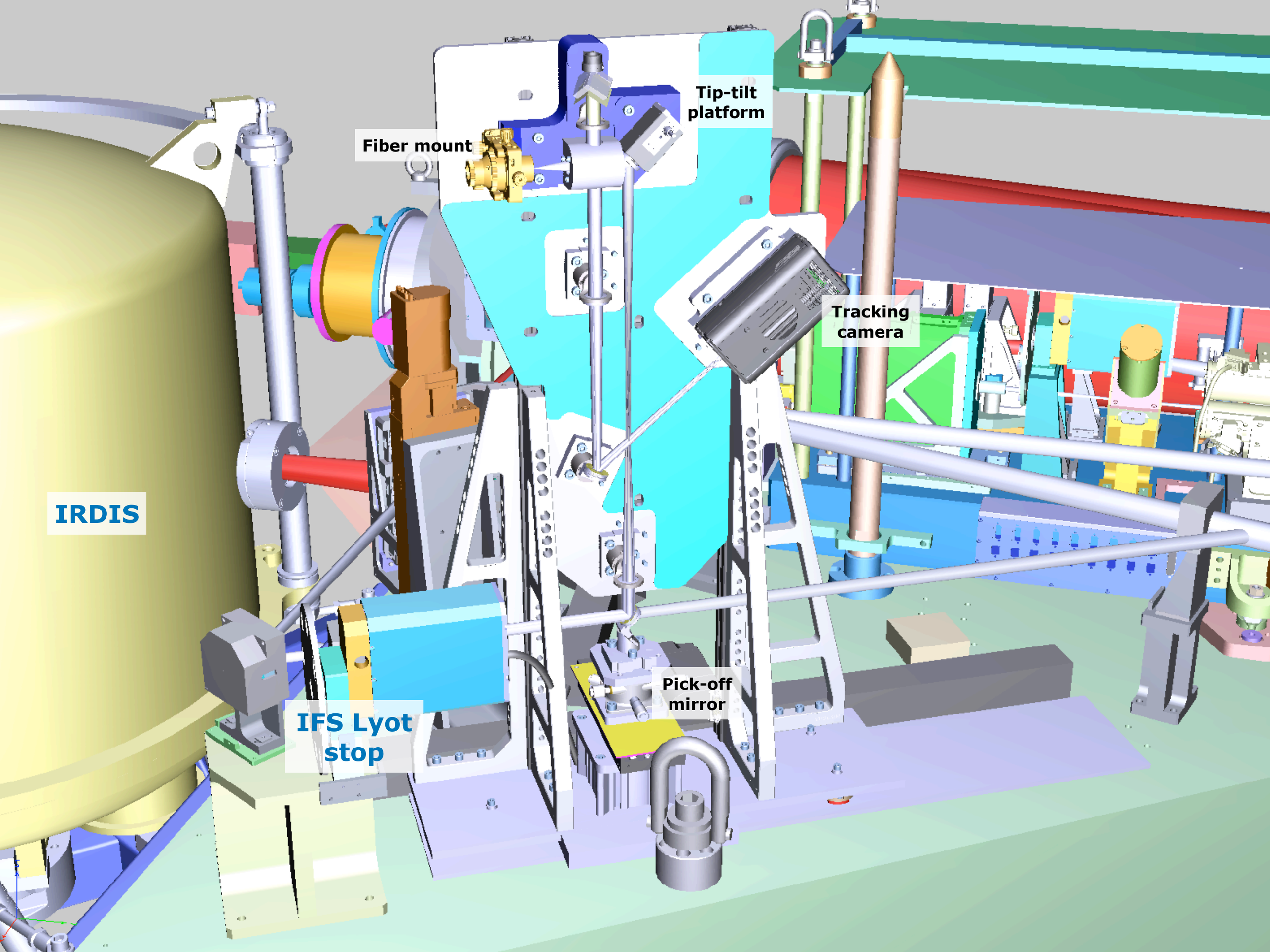
Implementation



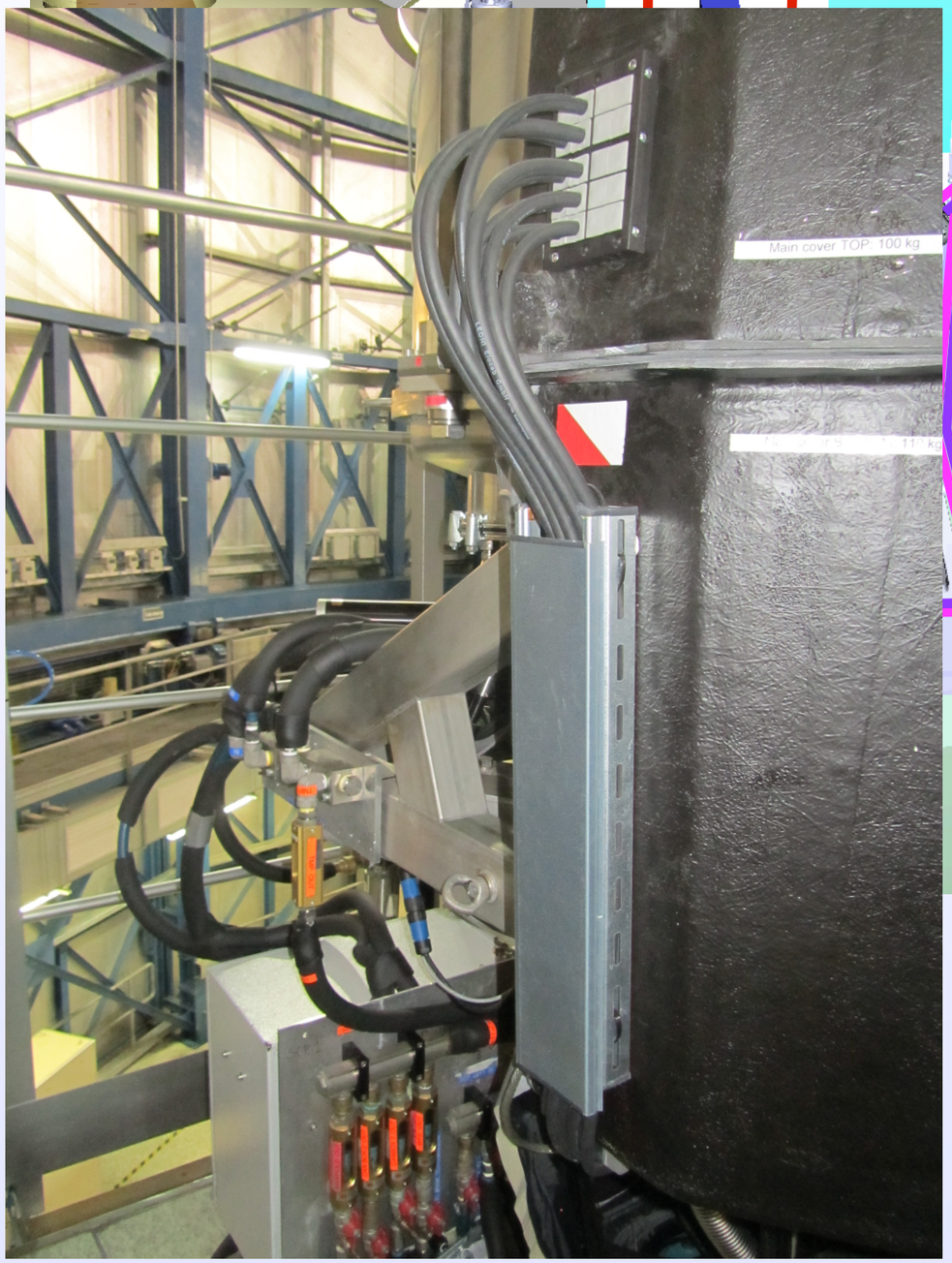
Fiber injection module in SPHERE

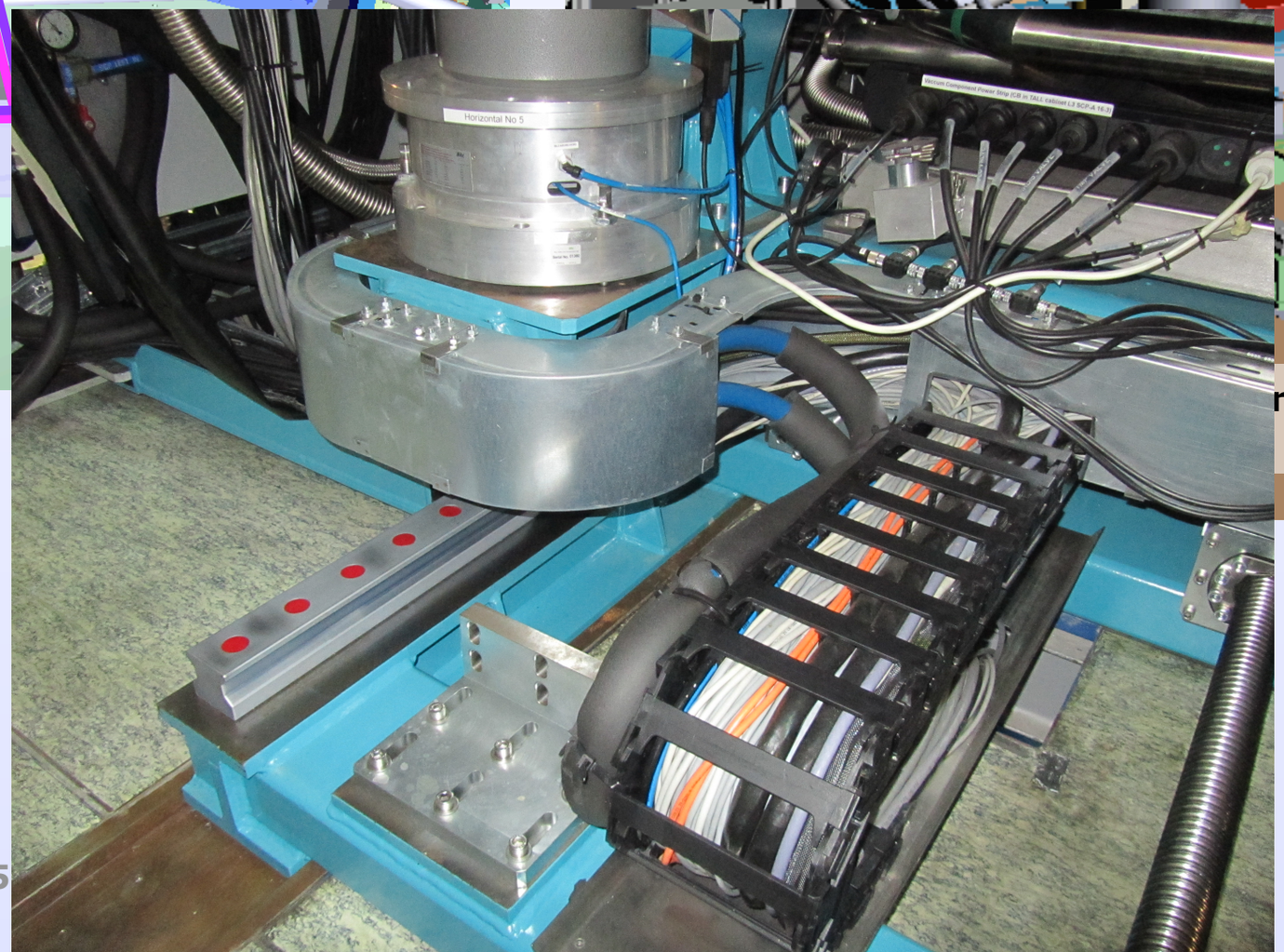


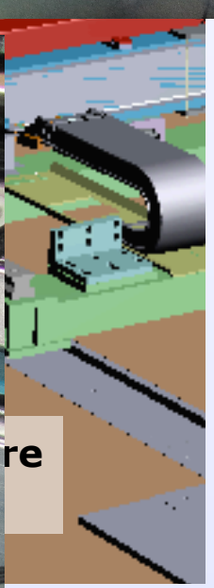
Fiber injection module in SPHERE


Tip-tilt platform
Fiber mount
Tracking camera
IRDIS
IFS Lyot stop
Pick-off mirror

Fiber injection module in

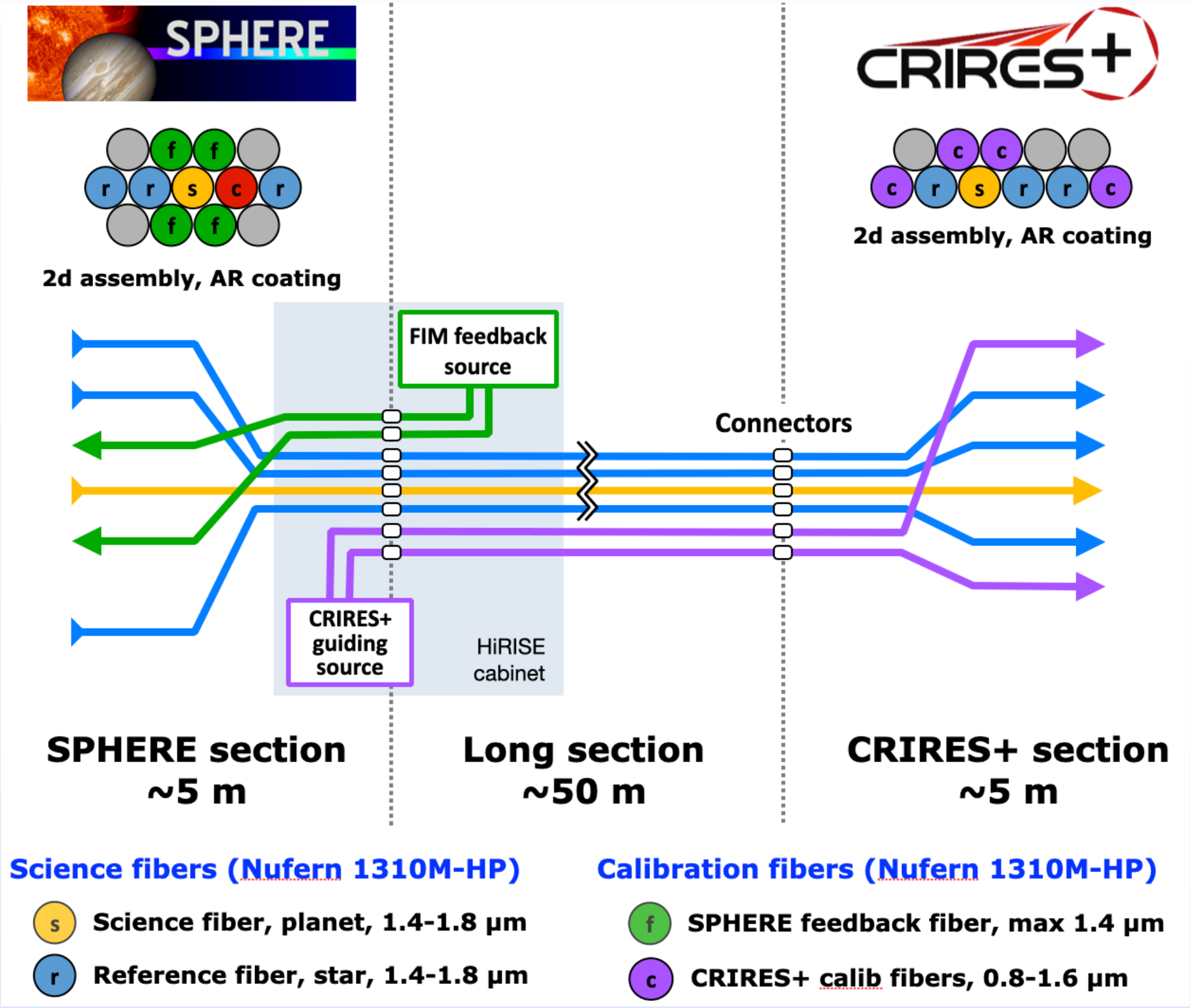






re

Fiber bundle



Fiber bundle

White fibre stubs
to complete
hexagonal packing

Mechanical
center

Calibration fibres
(purple, green, red)
get in/out at the level
of the connector

Single fibre connectors,
format: FC/PC

Linear output, interface TBD,
but likely a fixed mount
AR coating:
- science = 1450-1850 nm
- calibration = 800-1450 nm

Hexagonal
packed input
AR coated
1200-1850 nm

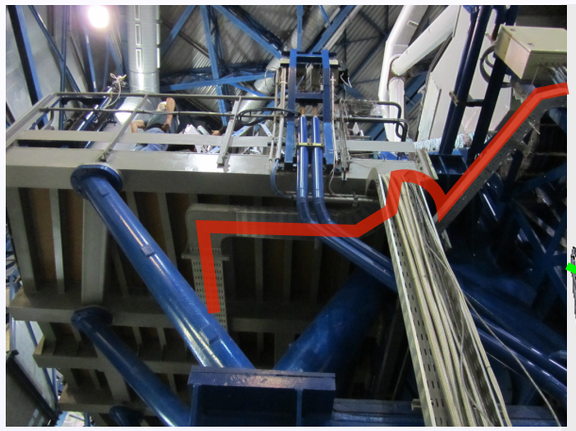
2 multi-
connectors

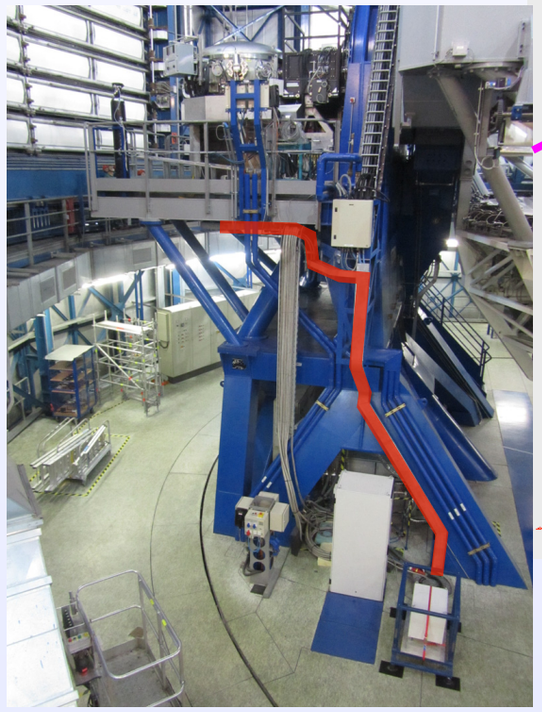
Single fibre connectors,
format: FC/PC

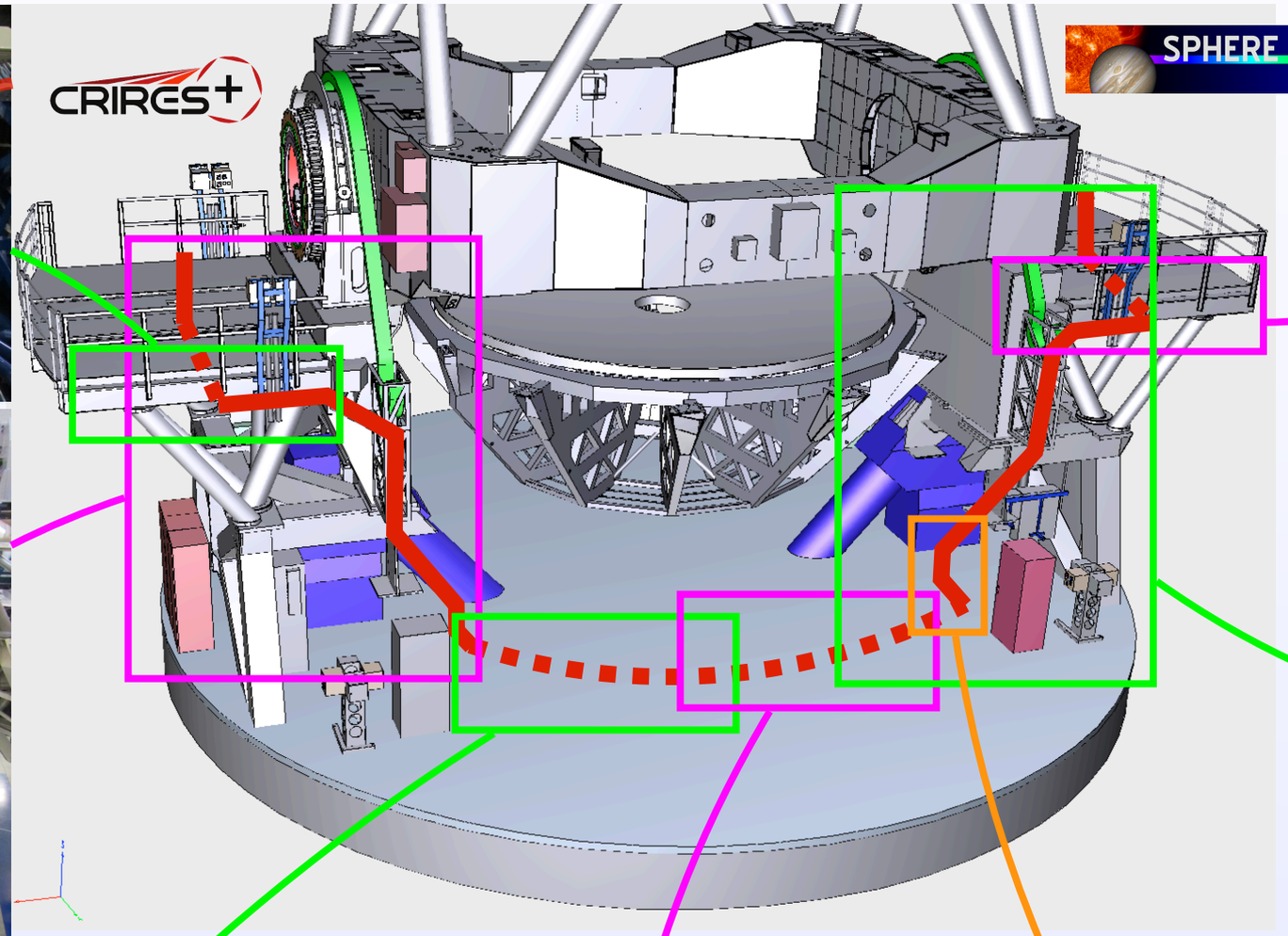
Mechanical
center

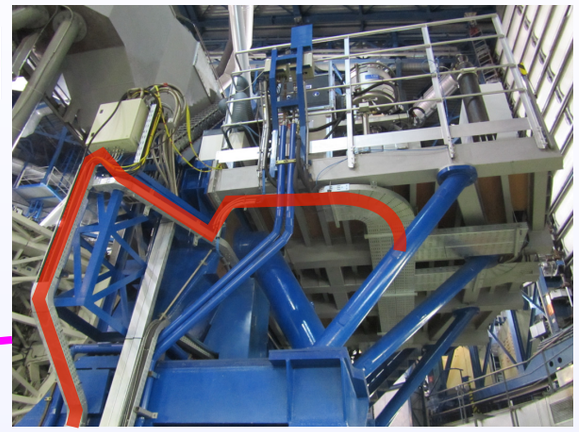
Again, stubs included for
packing symmetry

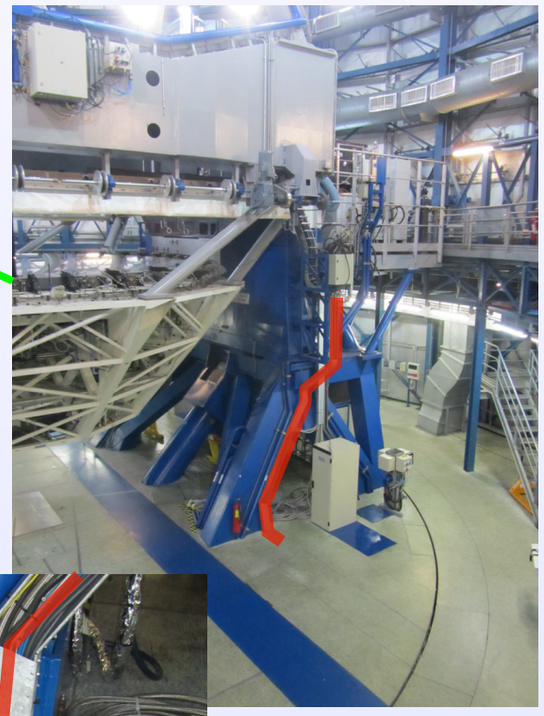
Fiber bundle around UT3

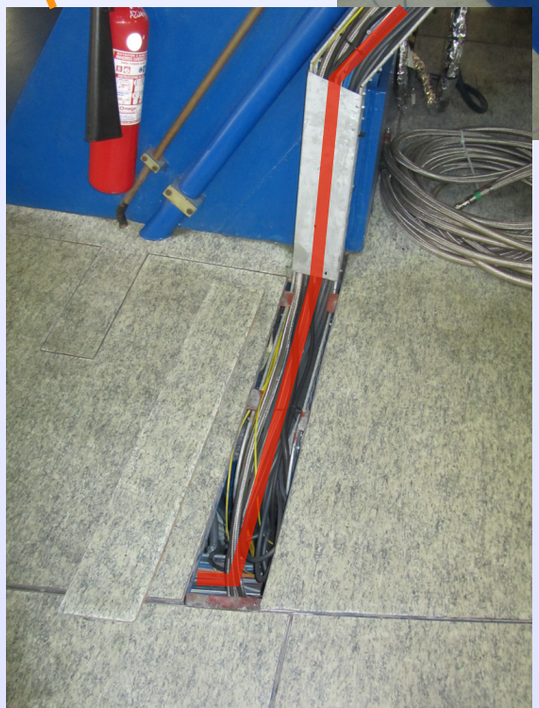




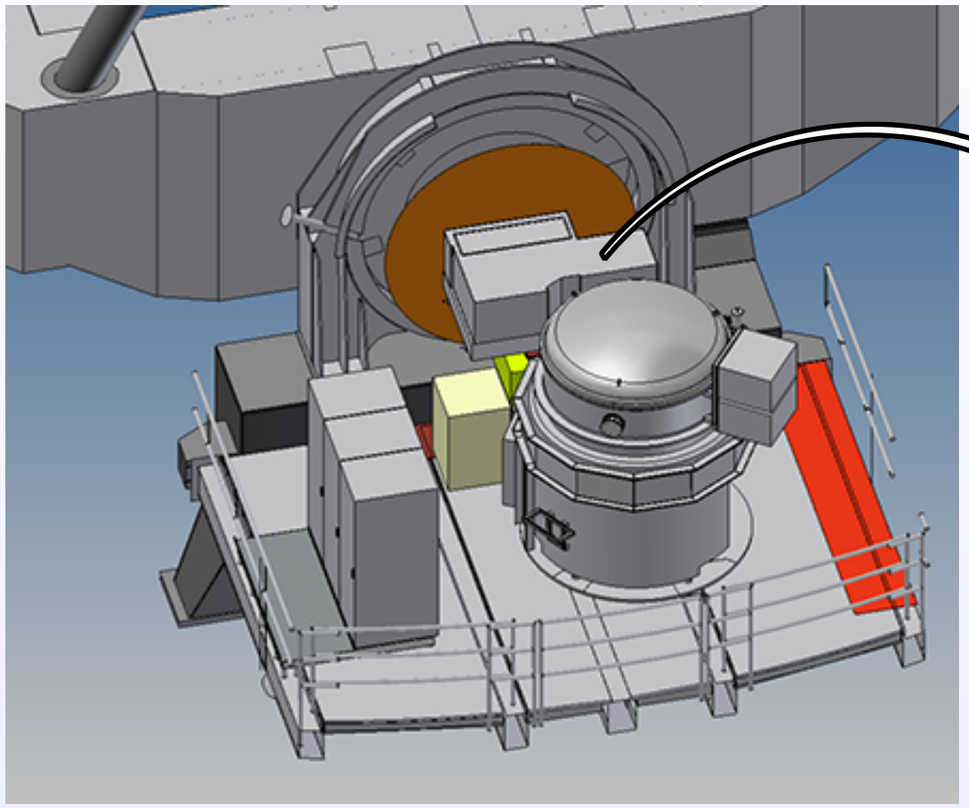


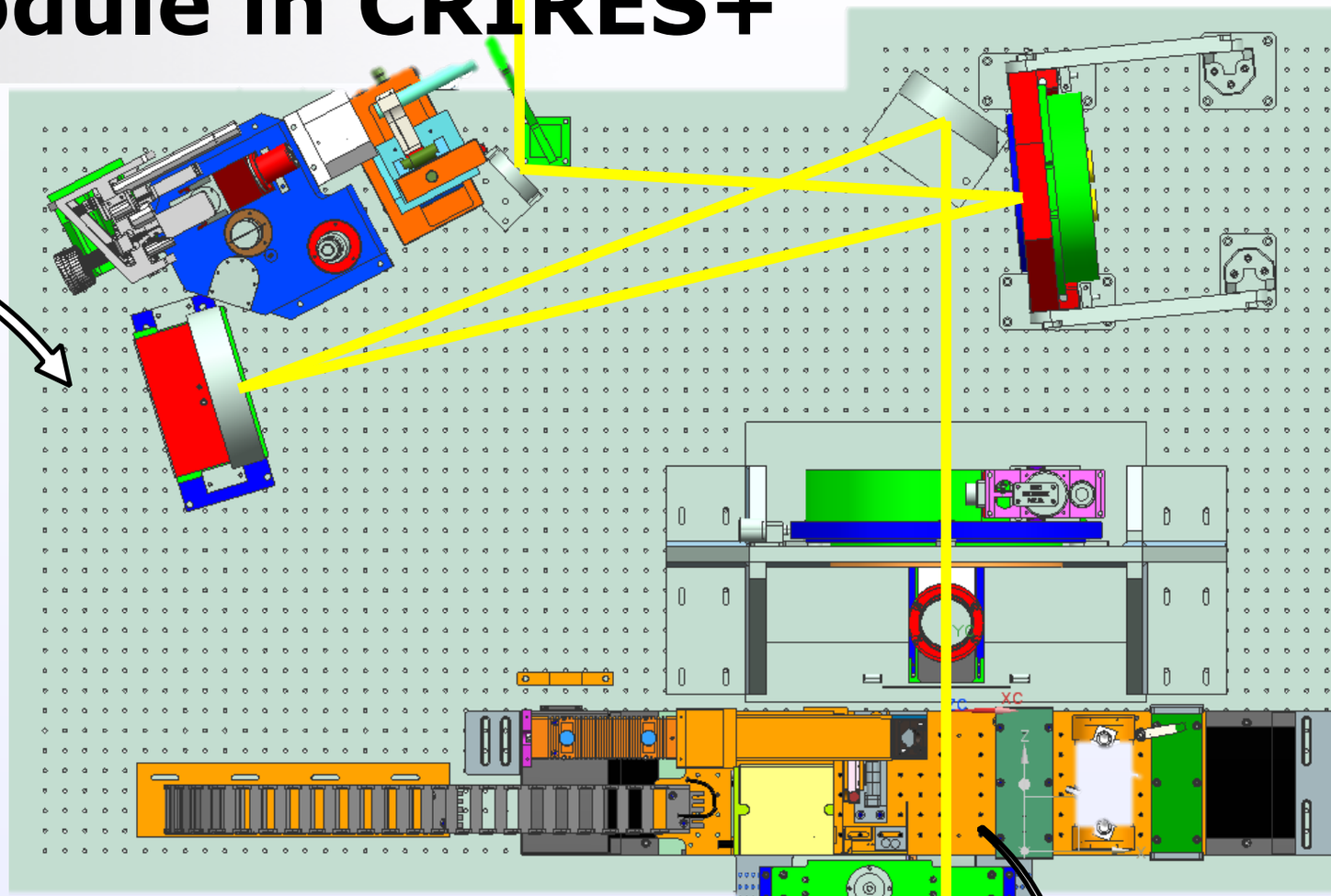


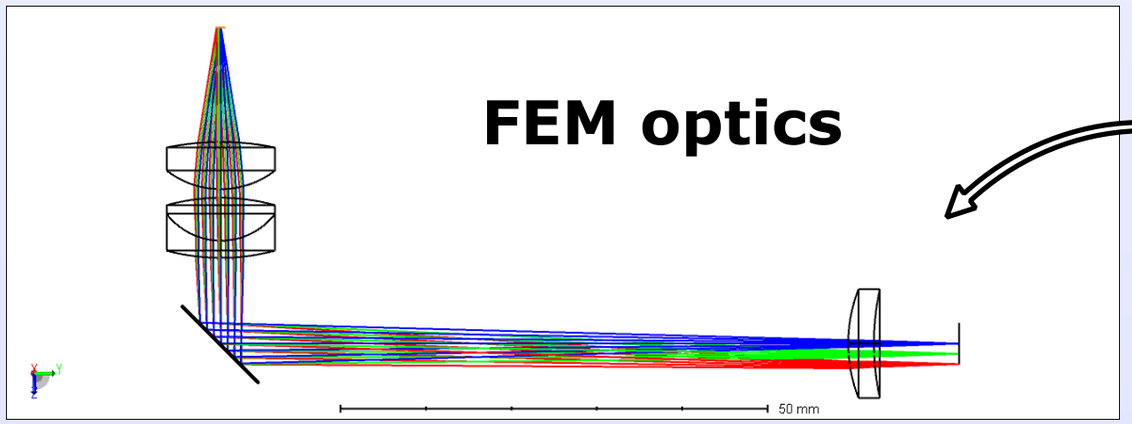




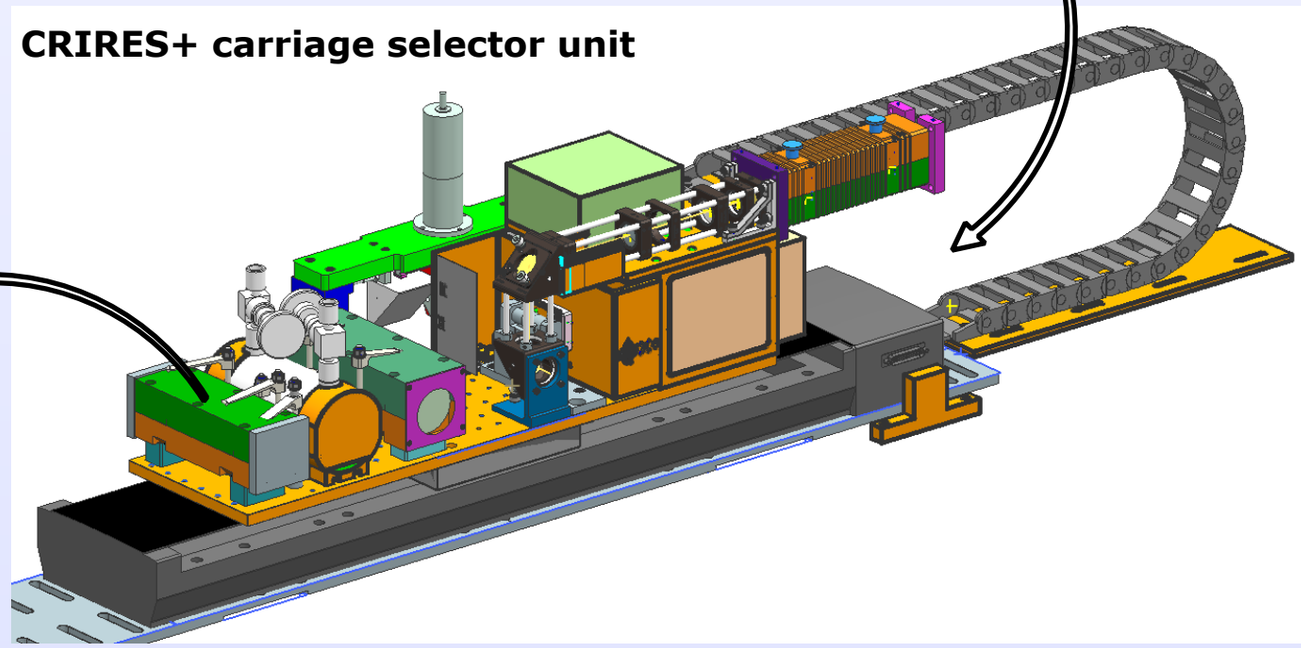
Fiber extraction module in CRIRES+



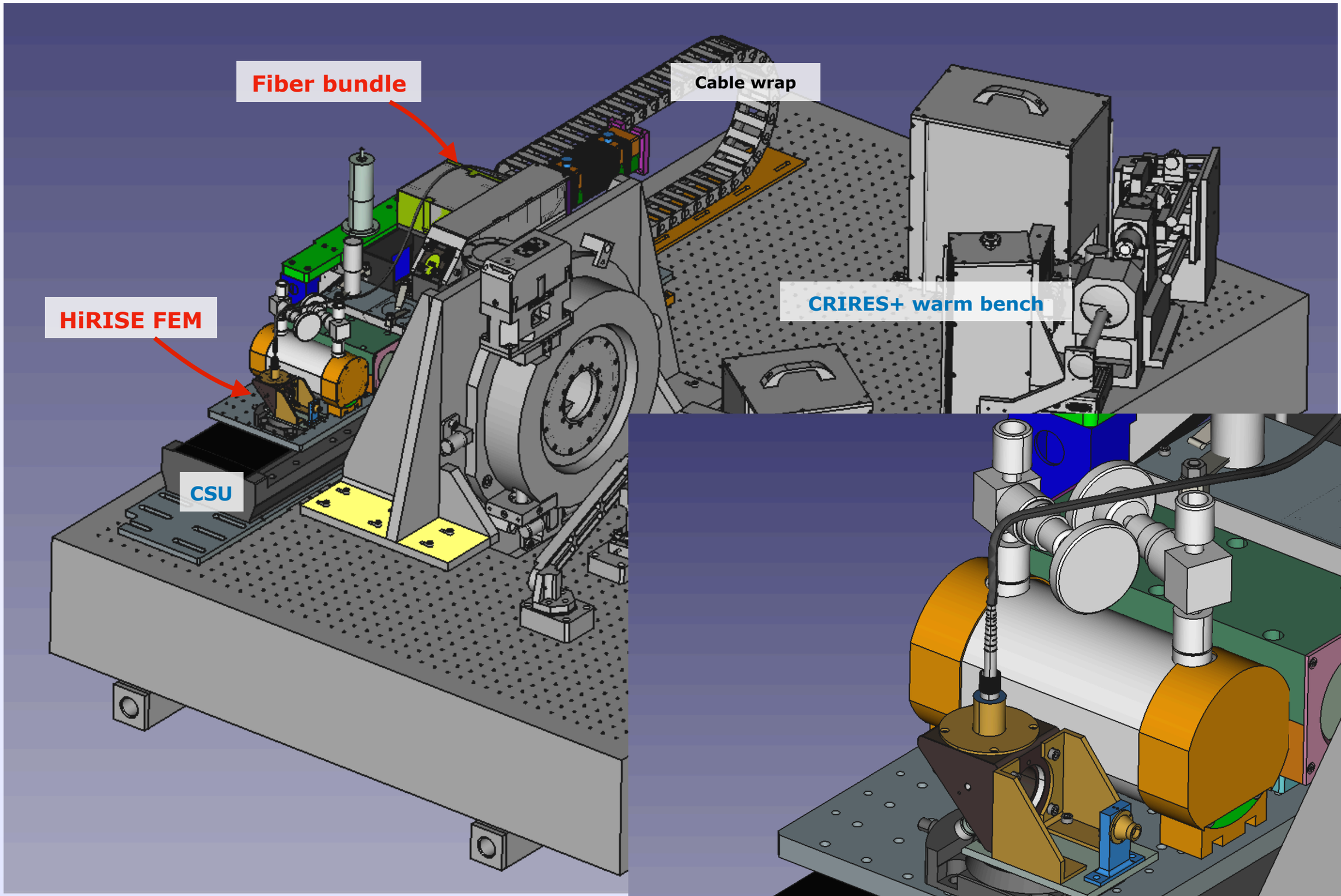




CRIRES+ carriage selector unit

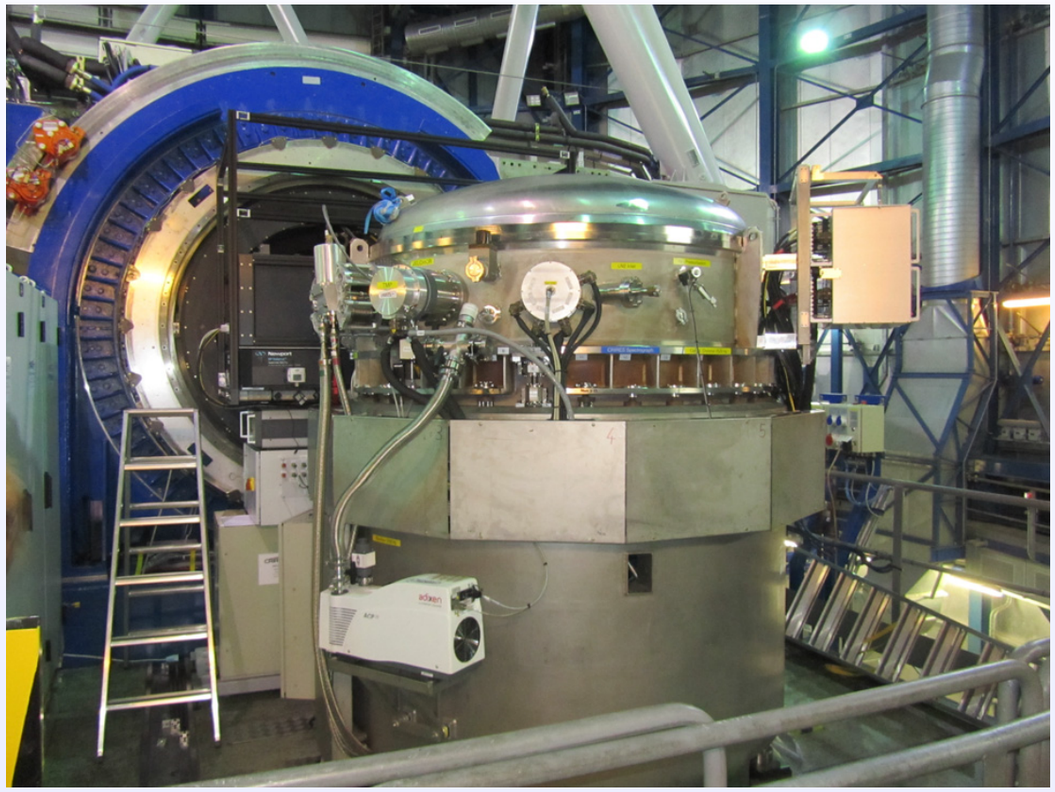


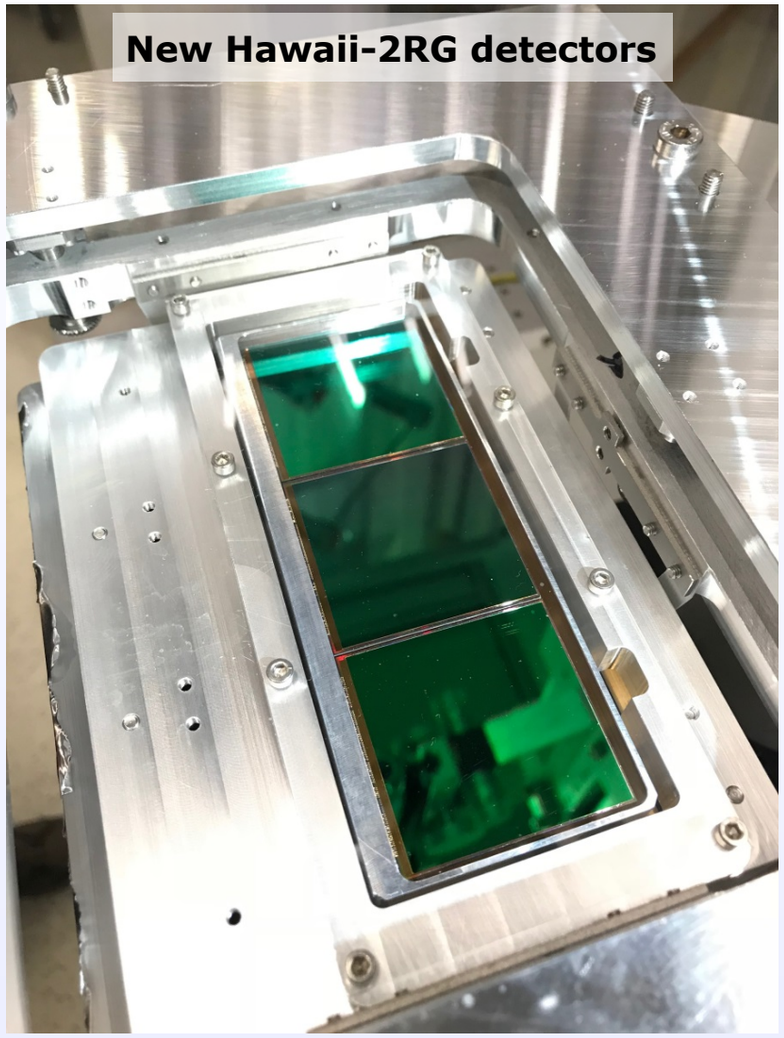
Fiber extraction module in CRIRES+

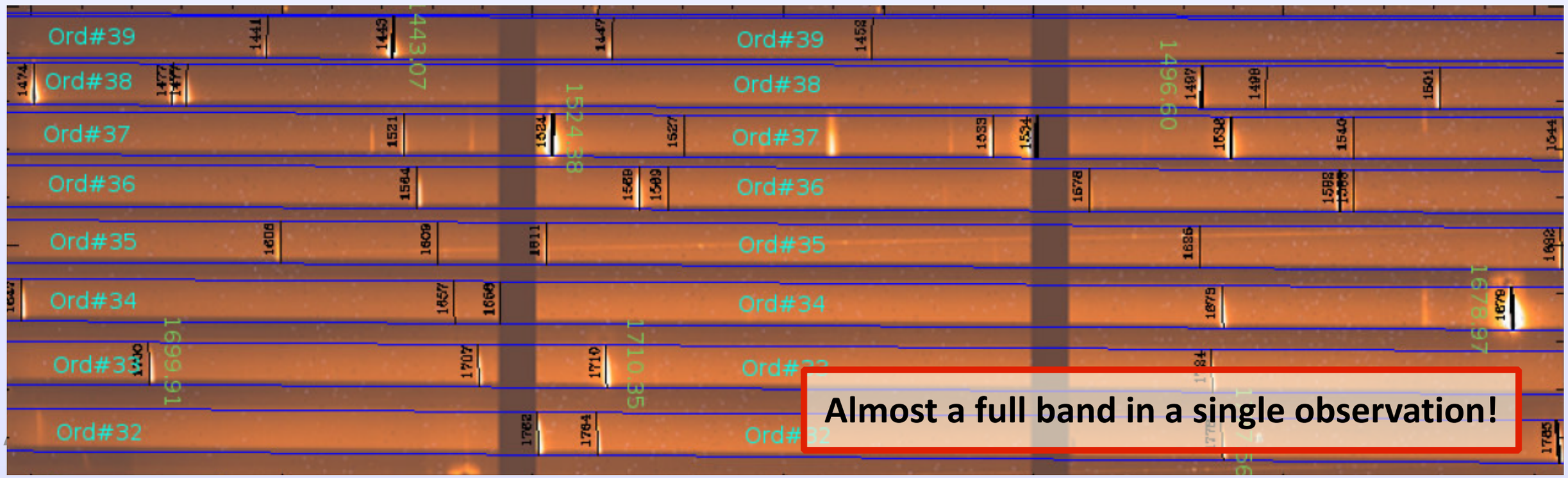


CRIRES+: improving CRIRES

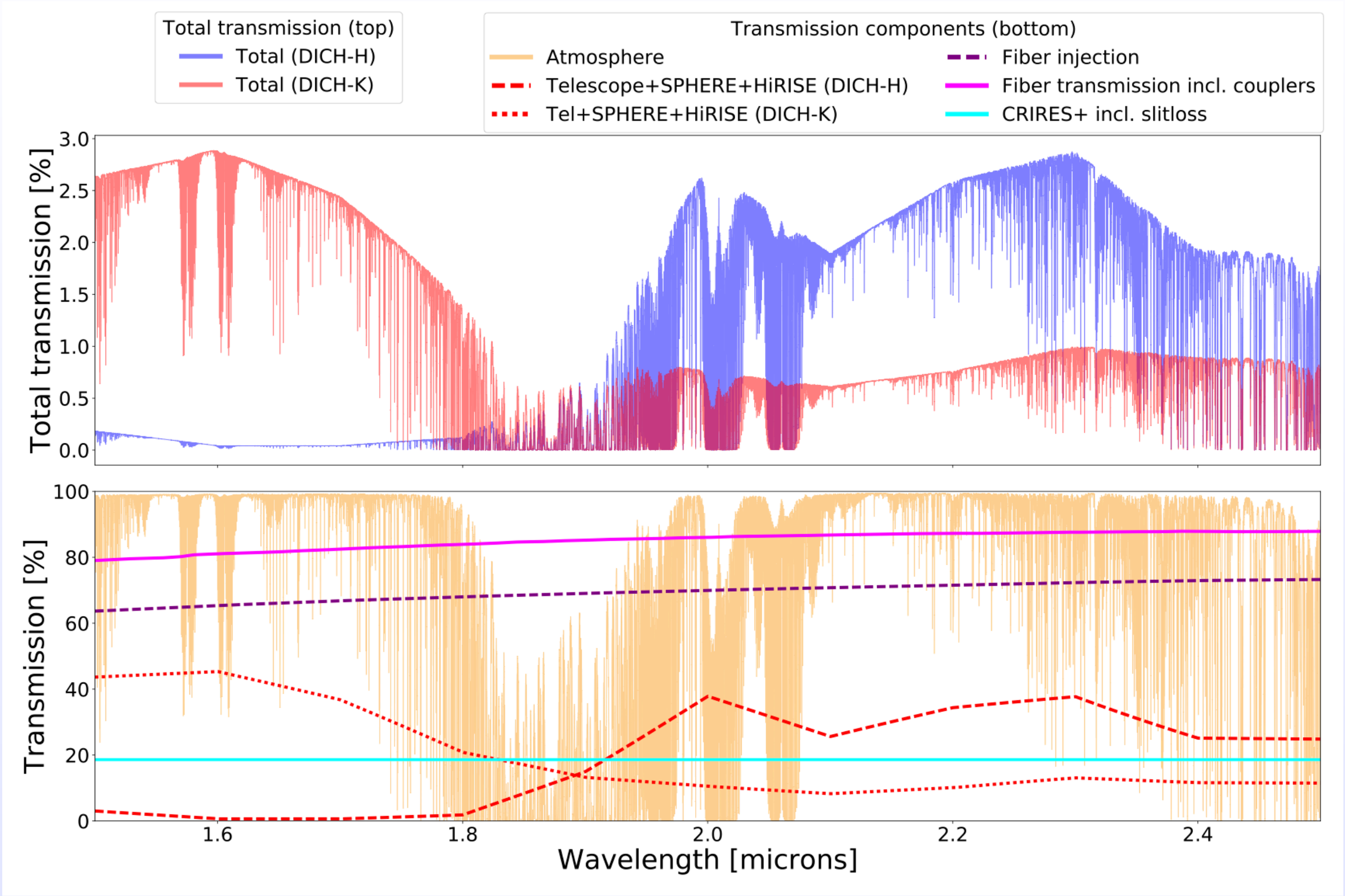
- NIR infrared echelle spectrograph
- New cross-dispersion gratings stage
- New Hawaii-2RG detectors





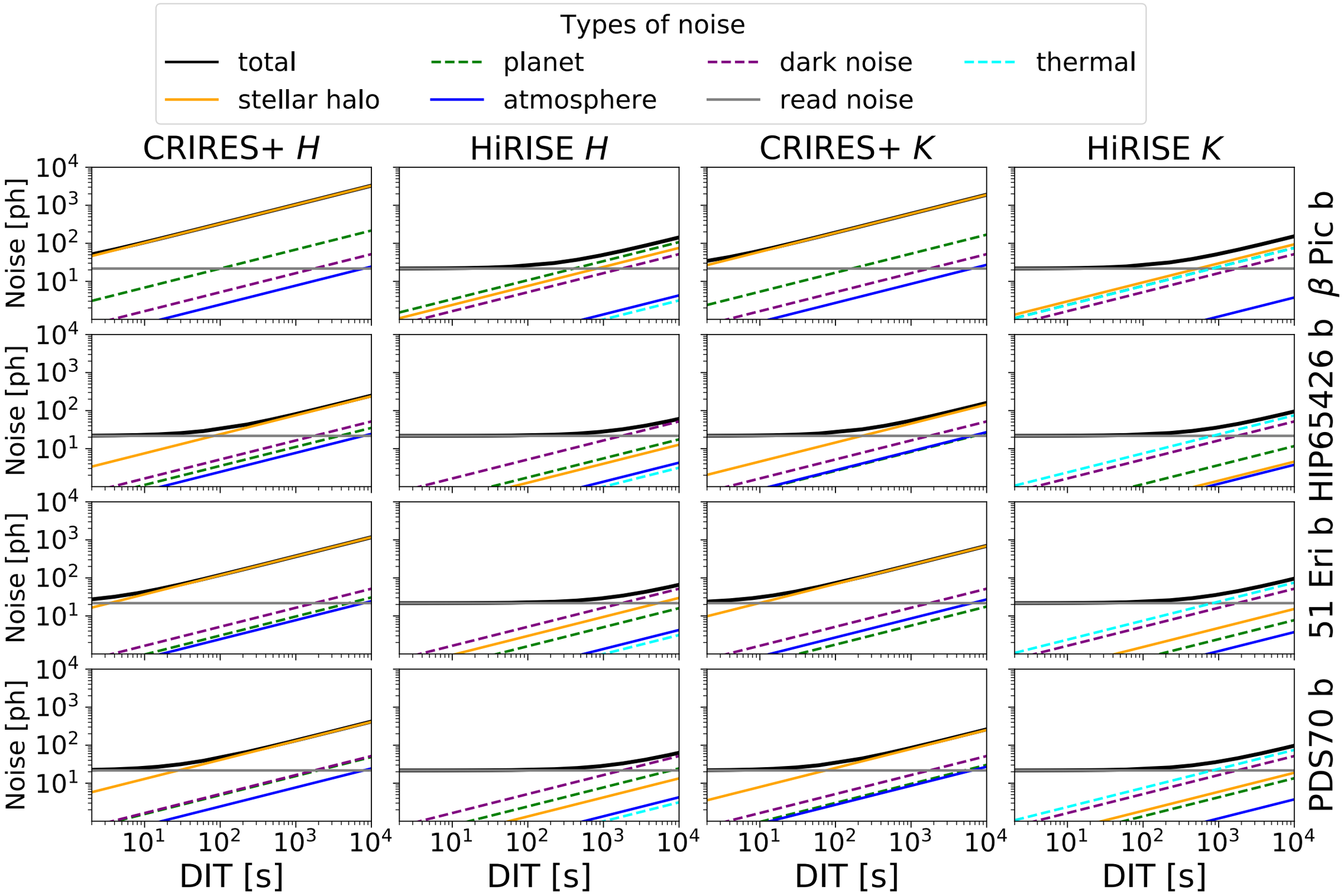


Performance estimation

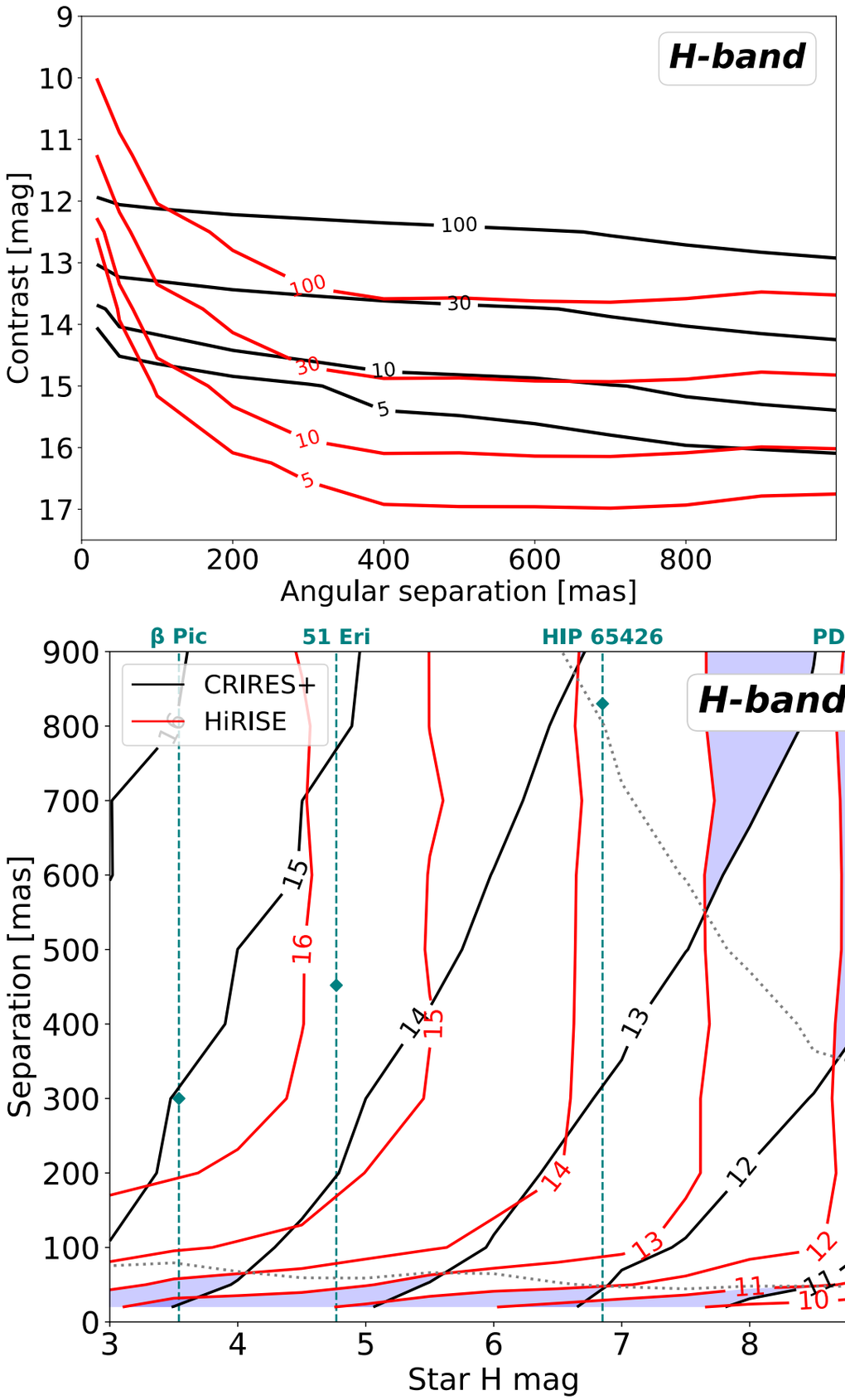


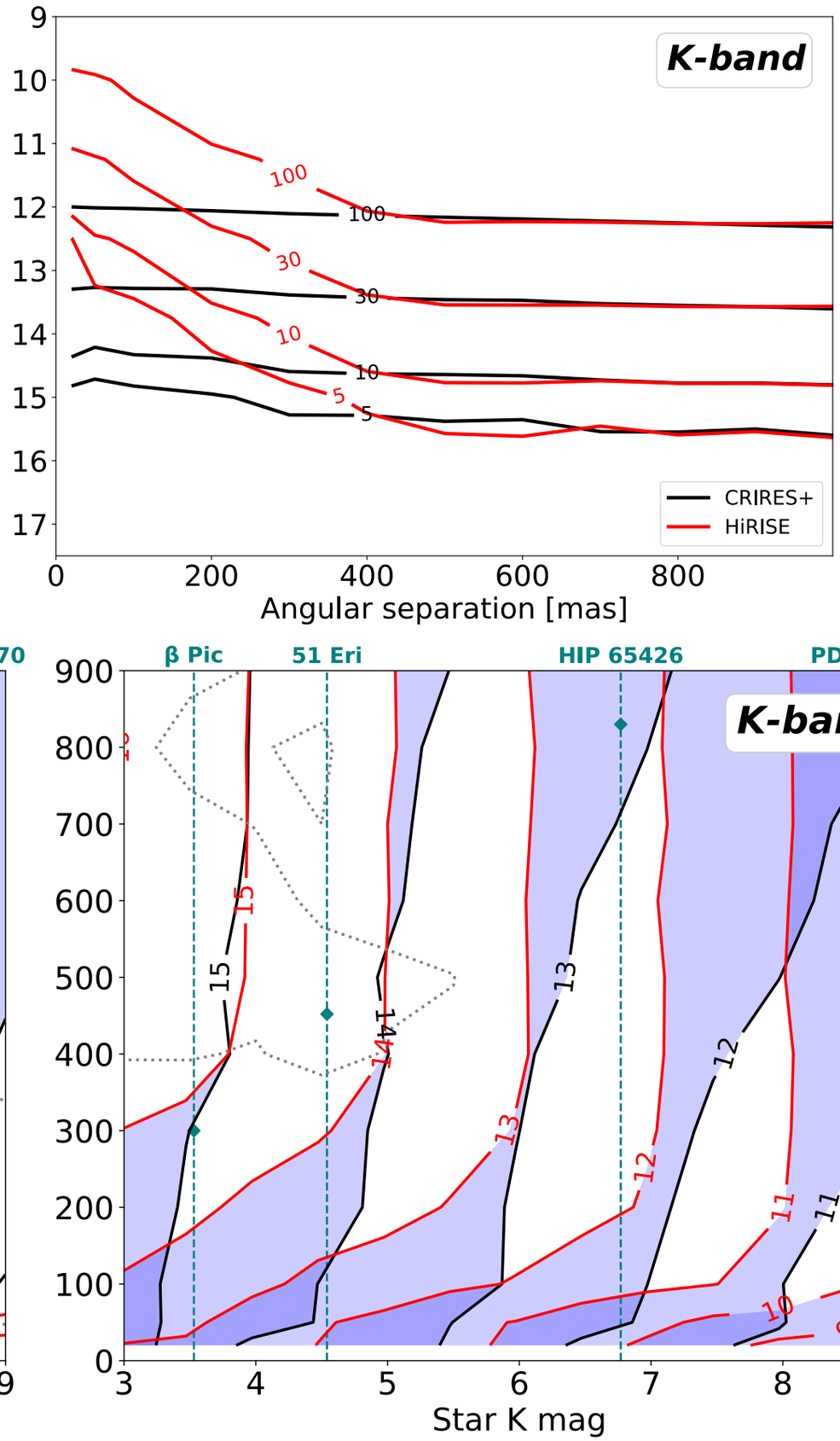
End-to-end model from Otten et al. (2021)

Performance estimation



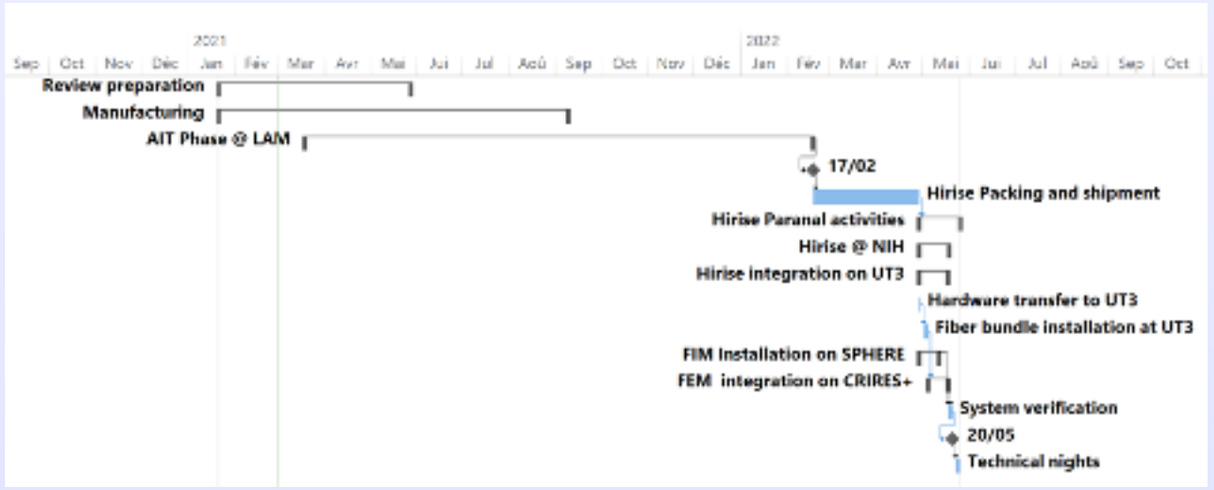
Performance estimation



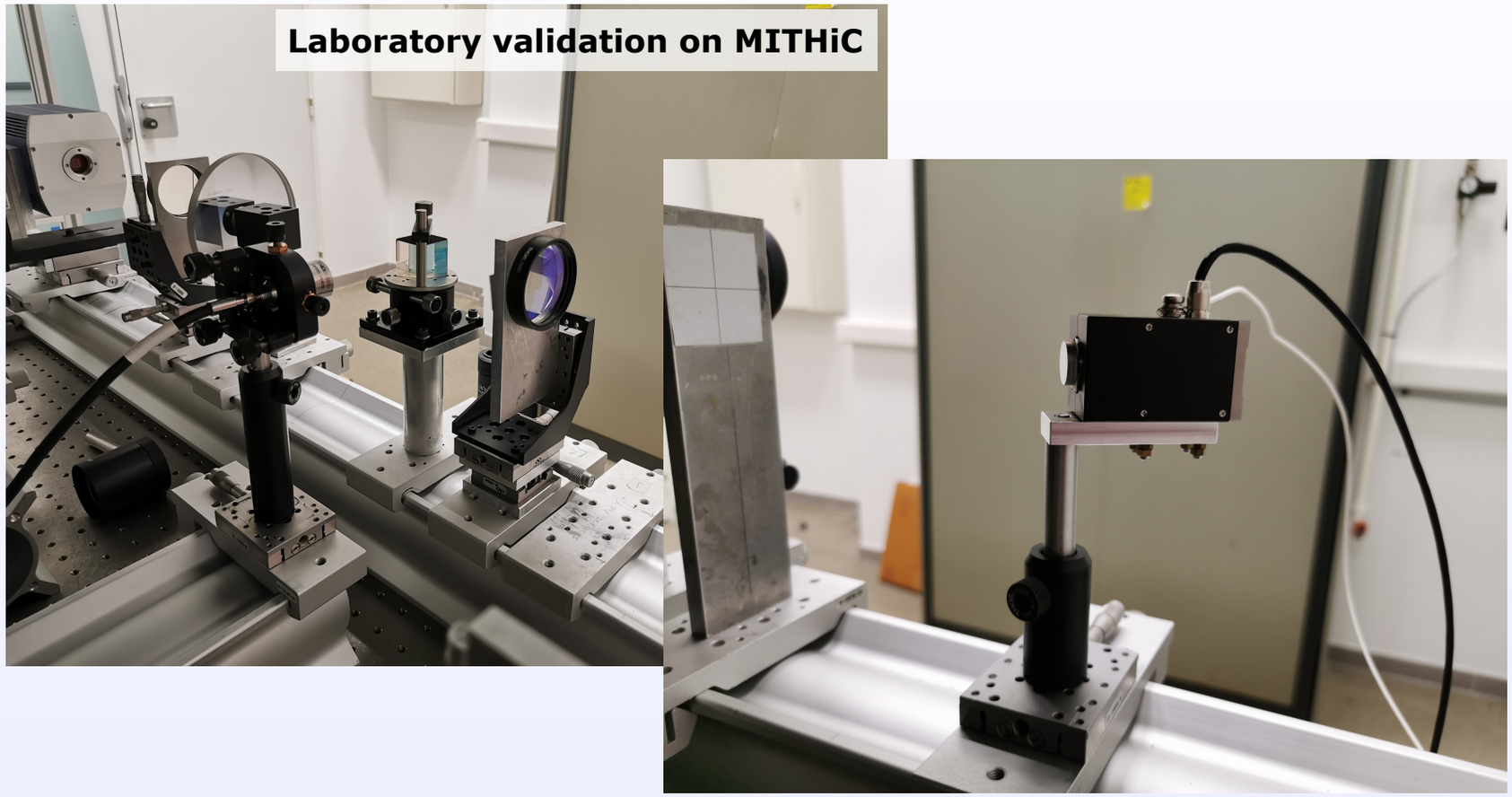


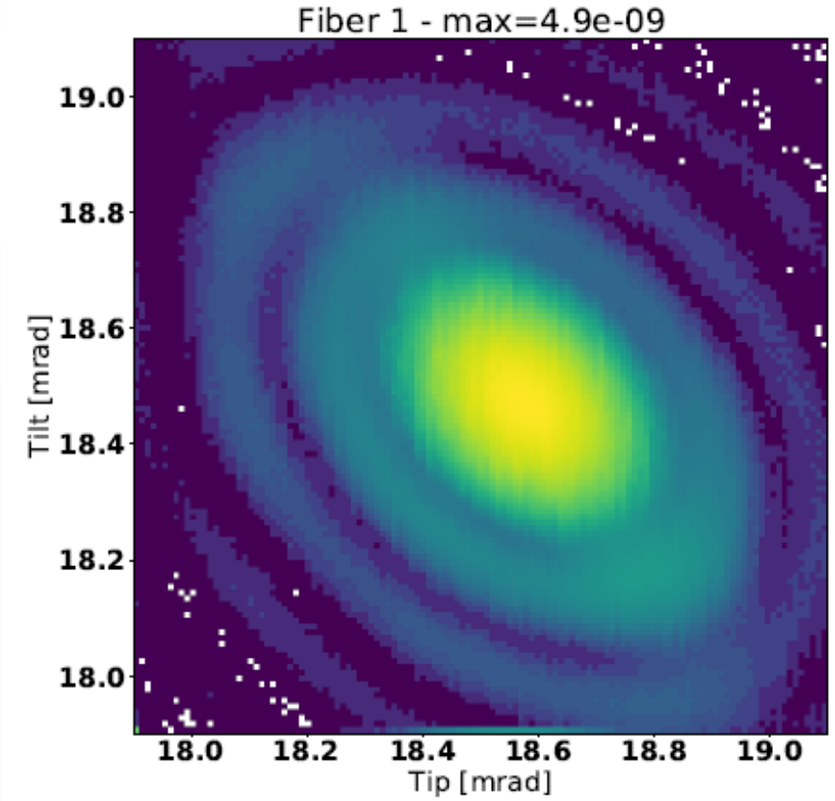
Status of HiRISE

- 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 Paranal
- Schedule:

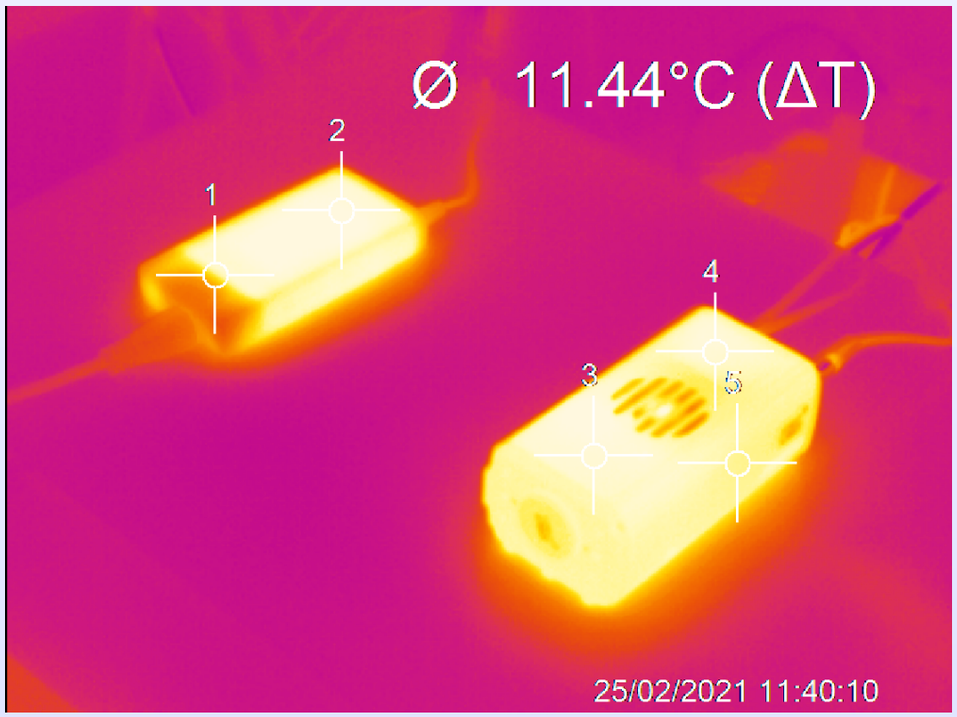


Technical activities





Fiber injection map



FIM tracking camera testing

Conclusions

HiRISE postdoc!

Preparation and analysis of the first on-sky data

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