- HiRISE -
Coupling SPHERE and CRIRES+ to characterise young giant exoplanets

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HiRISE team
G. Otten, E. Muslimov, K. Dohlen, Y. Charles, M. Houllé, N. Tchoubaklian, M. Phillips, R. Pourcelot,
U. Seemann, J.-L. Beuzit, E. Choquet, R. Dorn, M. Kasper, D. Mouillet, I. Baraffe, A. Reiners

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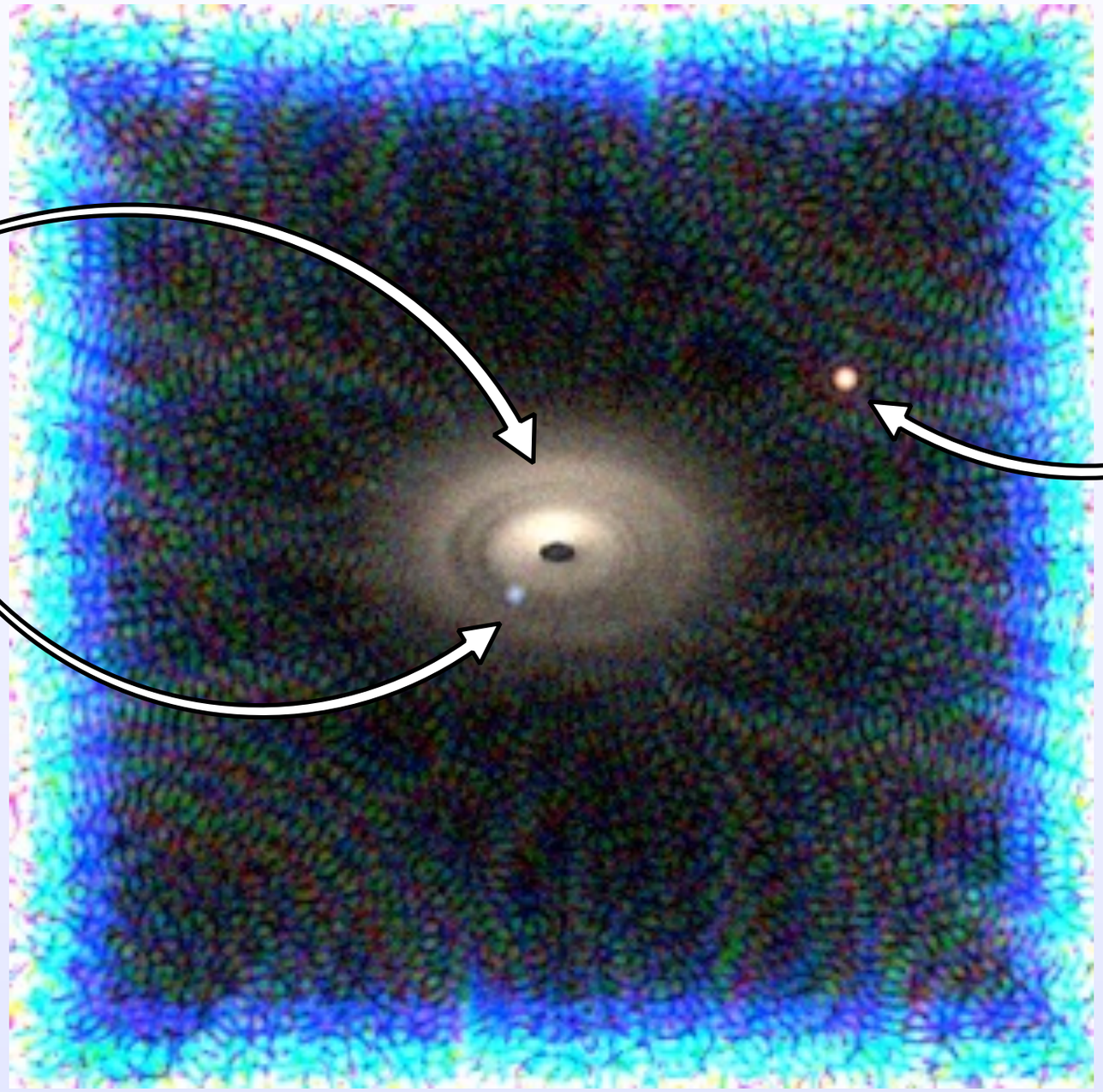
Direct imaging of exoplanets

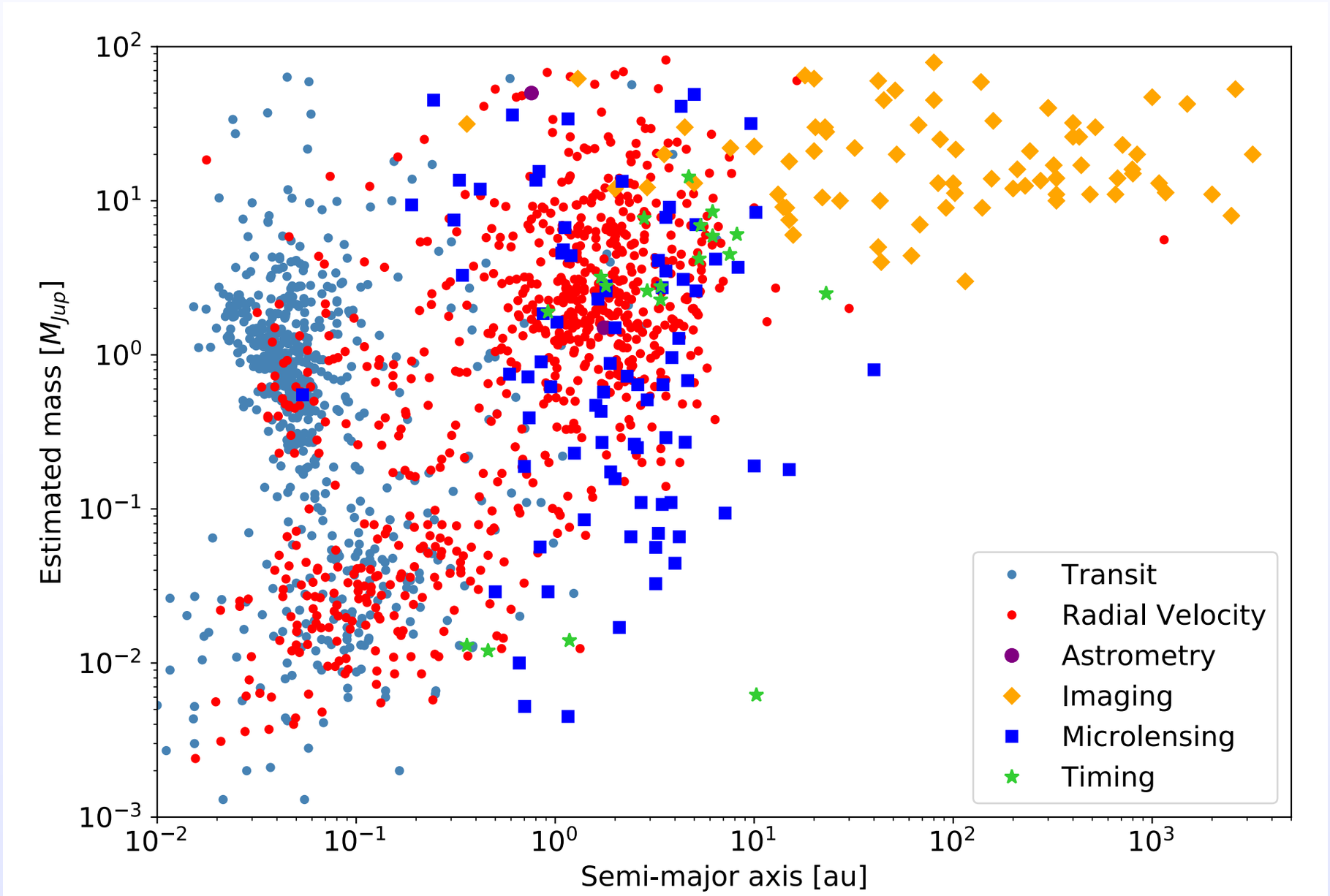


System architecture

Planets composition

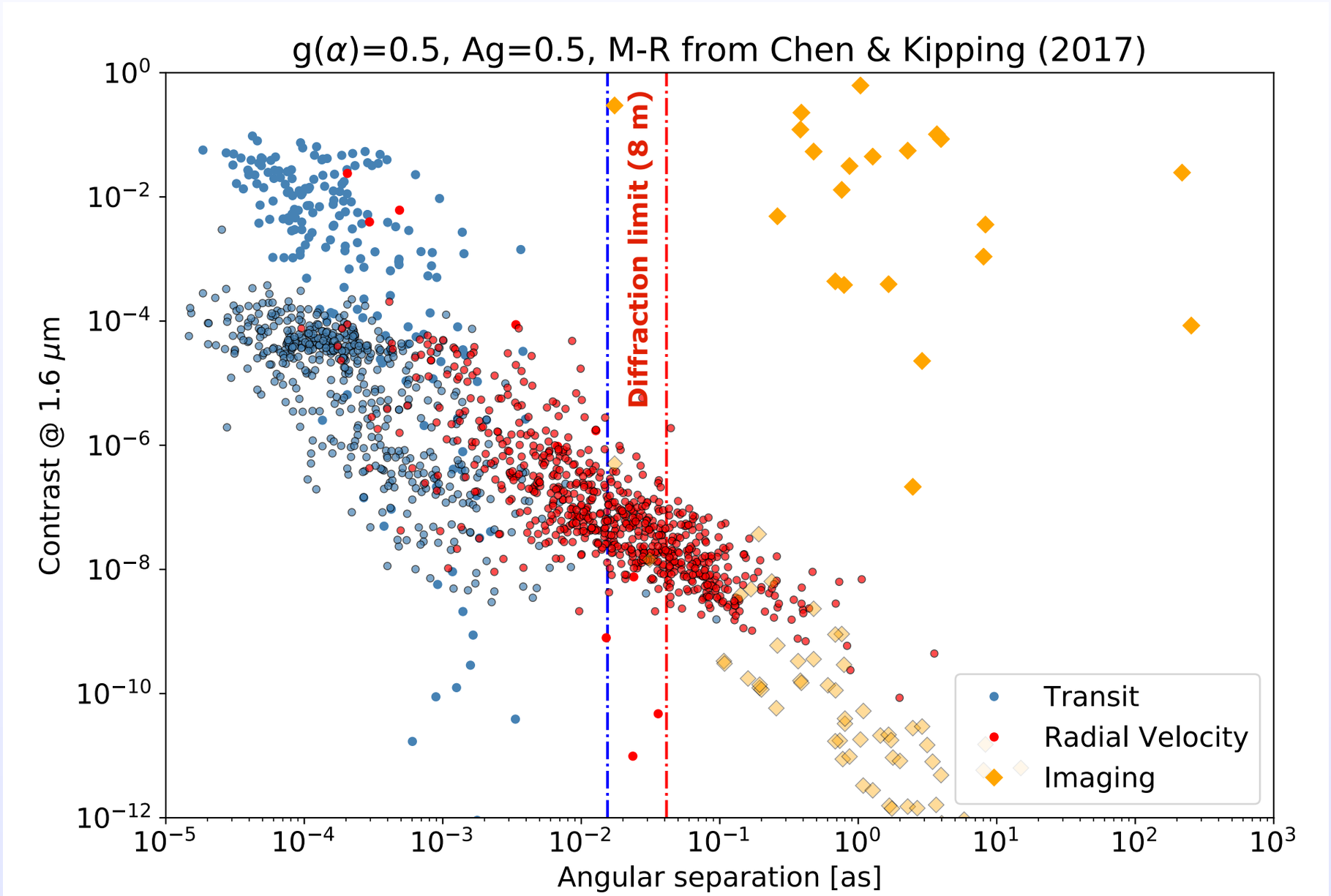
Direct imaging of exoplanets

Physical units



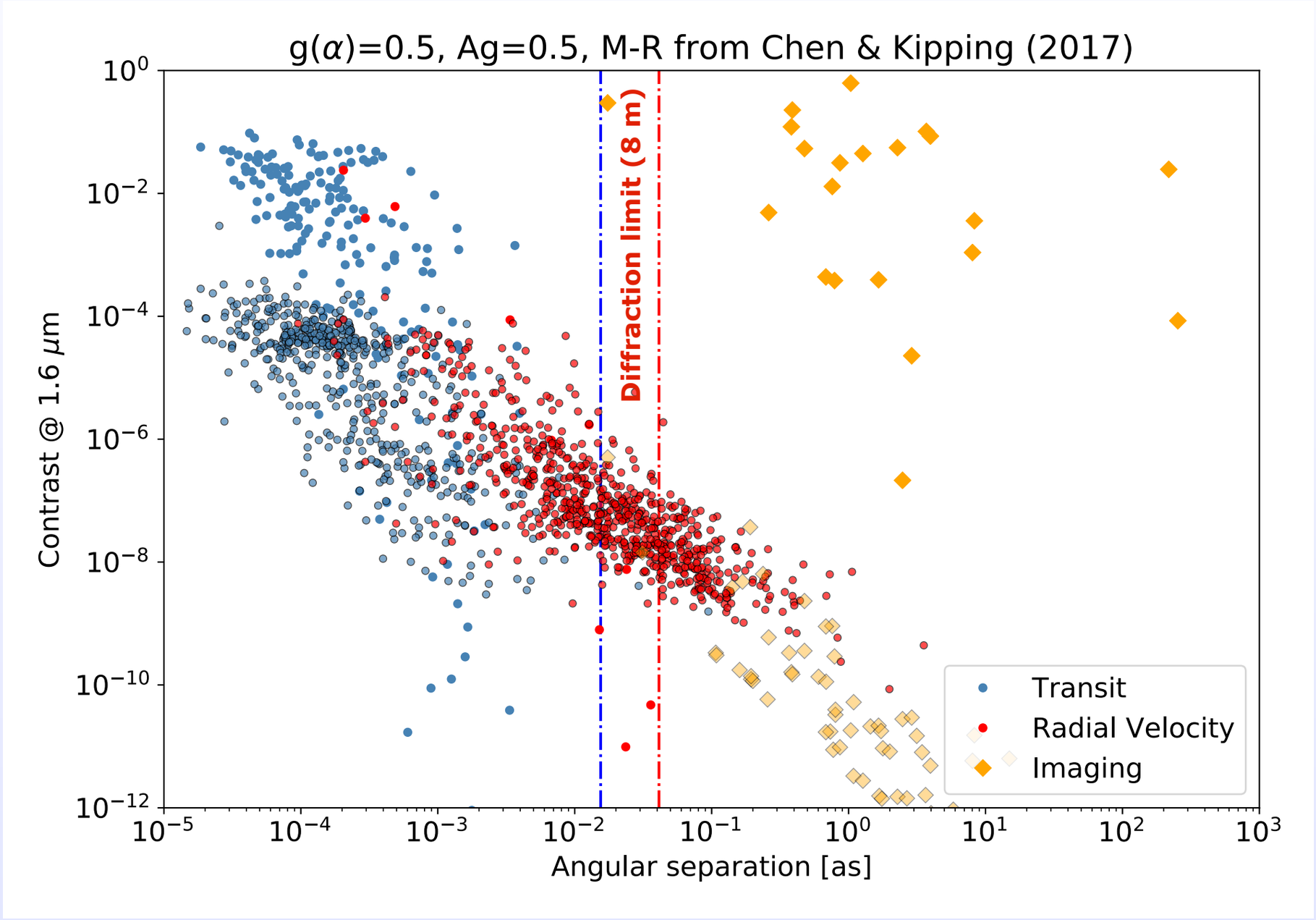
Direct imaging of exoplanets

Observables



Direct imaging of exoplanets

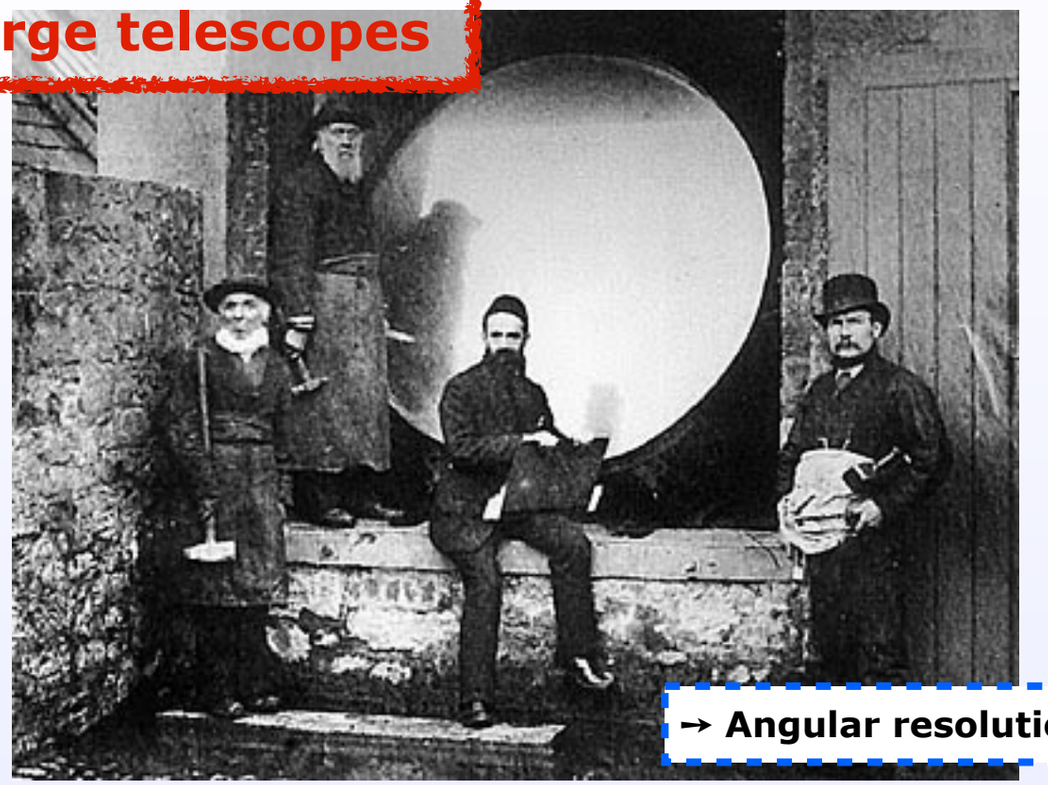
High-angular resolution



High-contrast

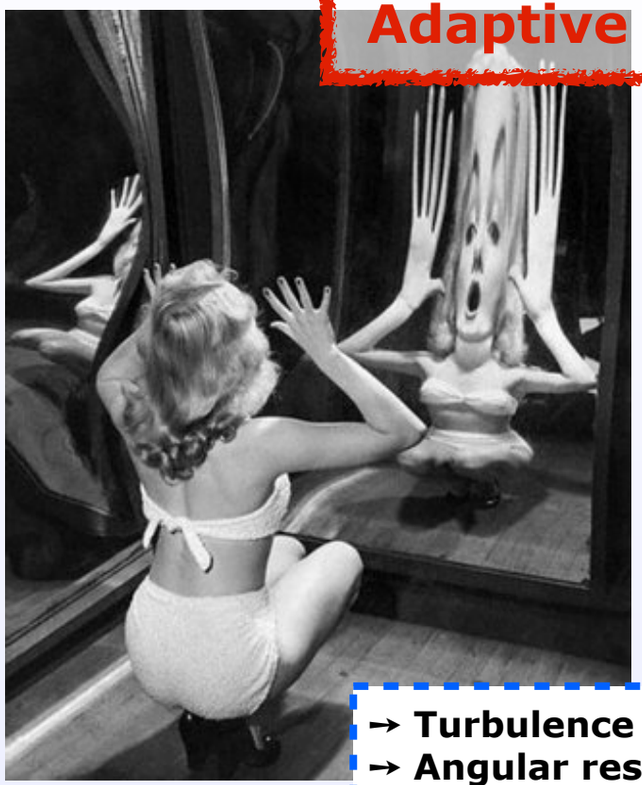
Direct imaging recipe

Large telescopes



→ Angular resolution

Adaptive optics



→ Turbulence correction
→ Angular resolution

→ Contrast

Algorithms

→ Contrast

Coronagraphs

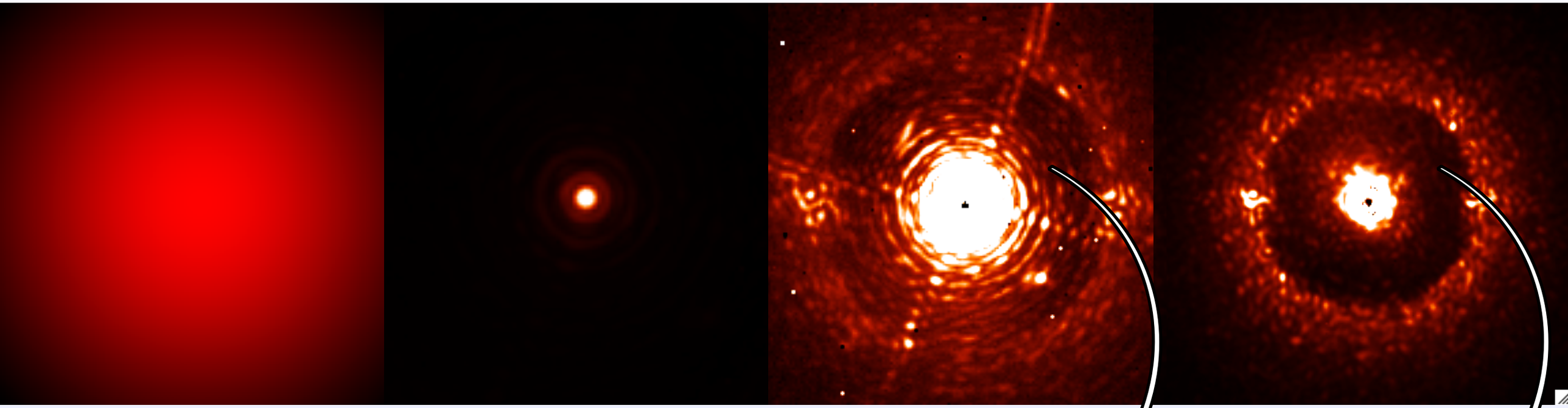
Direct imaging recipe

Seeing-limited PSF
✘ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

Diffraction-limited PSF
✔ Adaptive optics
✘ Coronagraph

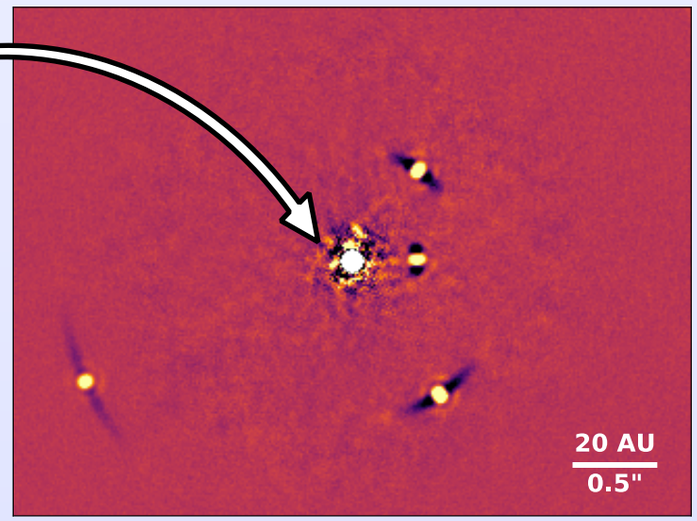
Coronagraphic image
✔ Adaptive optics
✔ Coronagraph



Diffraction limited within 20 λ/D

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

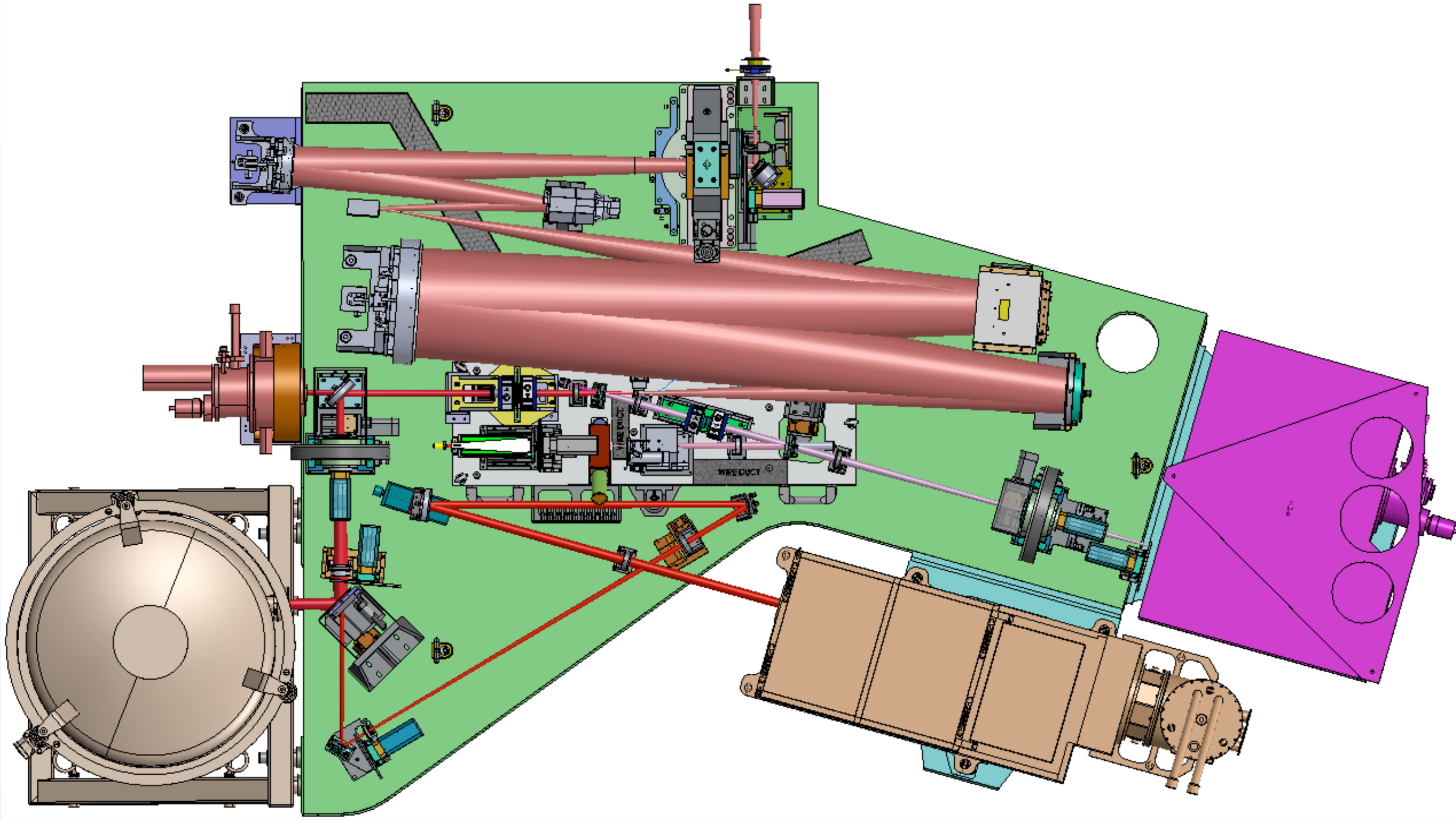
post-processing



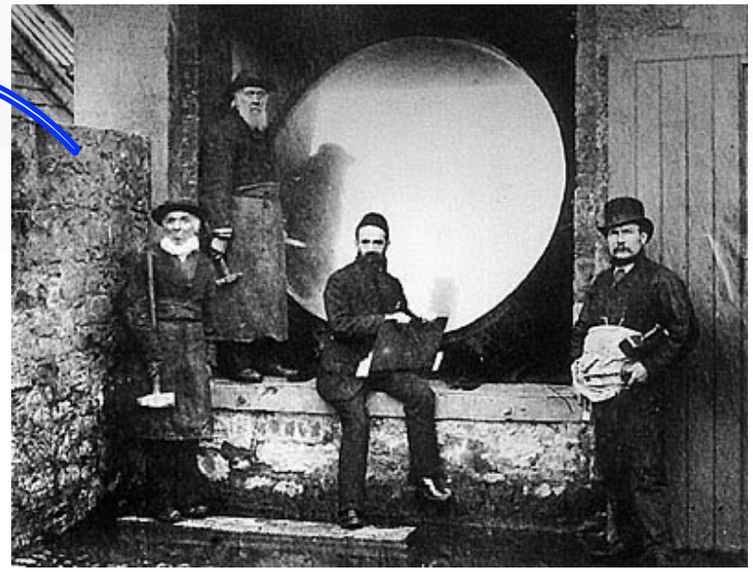
~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

VLT/SPHERE



VLT/SPHERE



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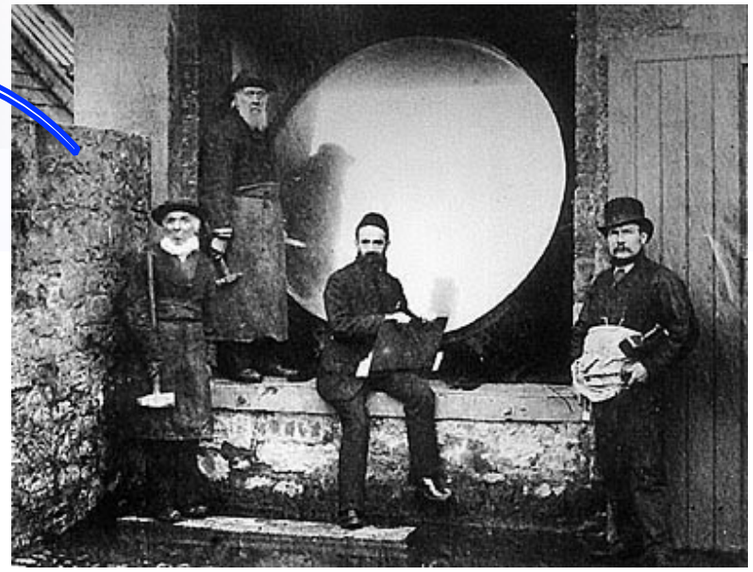
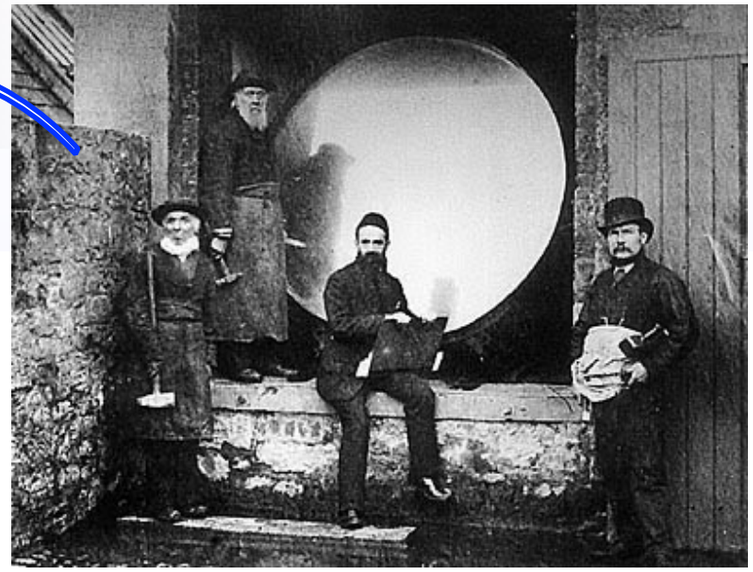
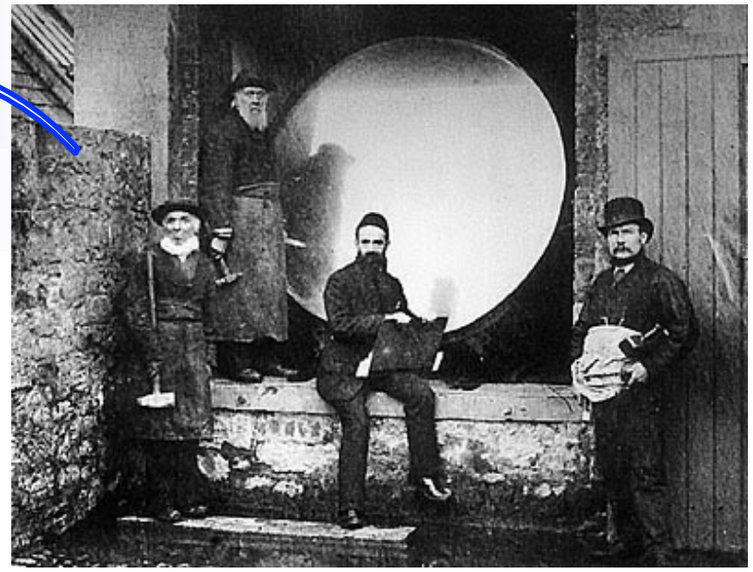


VLT/SPHERE



VLT/SPHERE

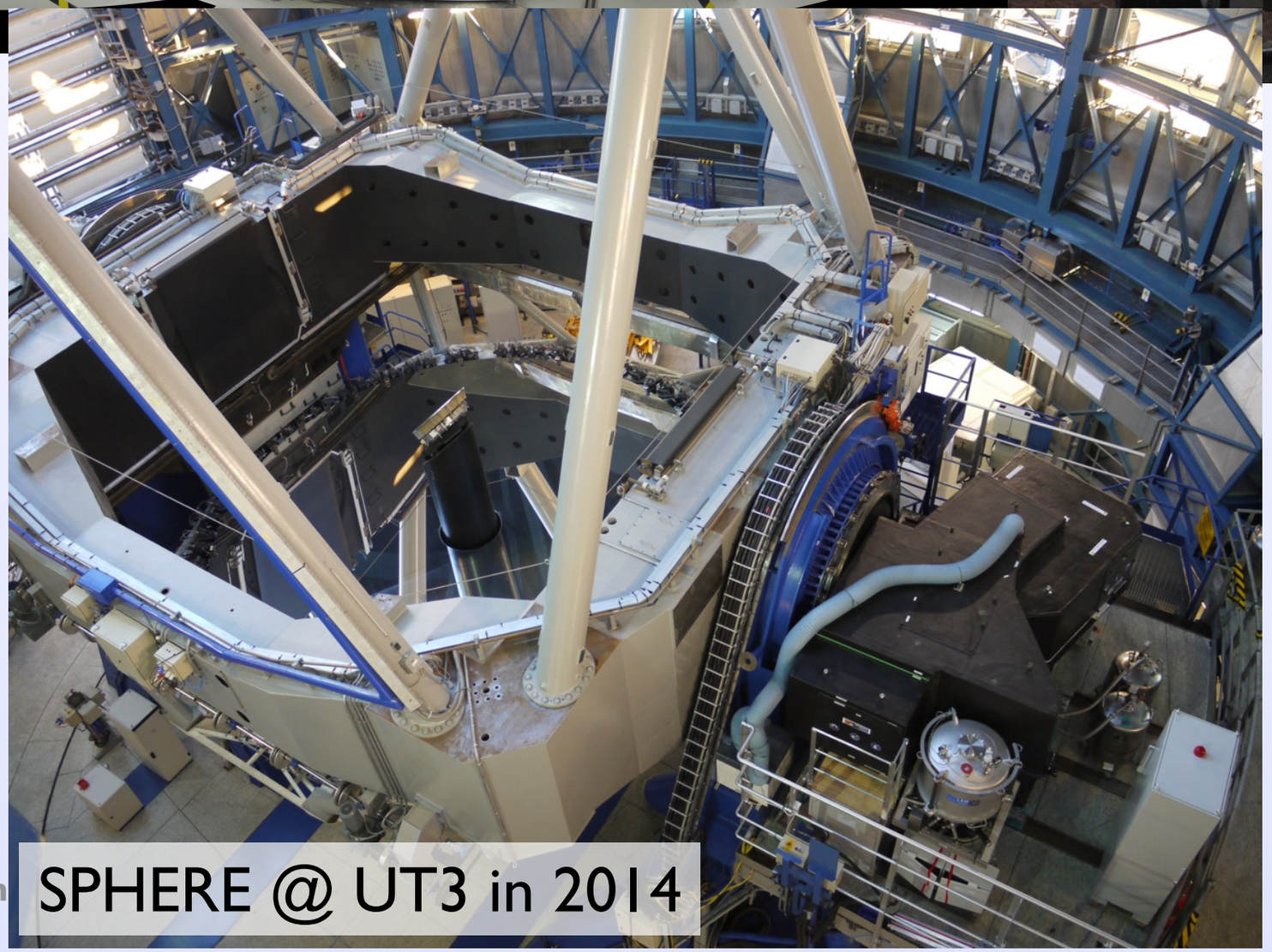


IRDIS

IFS

ZIMPOL

SPHERE @ IPAG in 2013



SPHERE @ UT3 in 2014

SPHERE offered to the community since April 2015

Maire+ 2016

Stolker+ 2016

Ginski+ 2016

Lagrange+ 2016

Maire+ 2017

Keppler+ 2018

Feldt+ 2017

Van Boekel+ 2017

Peretti+ 2018

Sissa+ 2018

Samland+ 2017

Mesa+ 2016

Boccaletti+ 2015

Bonavita+ 2017

Sissa+ 2018

Müller+ 2018

Avenhaus+ 2017

Lazzoni+ 2018

Benisty+ 207

Pohl+ 2017

Mesa+ 2016

Rodet+ 2018

Garufi+ 2016

Milli+ 2017

de Boer+ 2016

Delorme+ 201

Mesa+ 2018

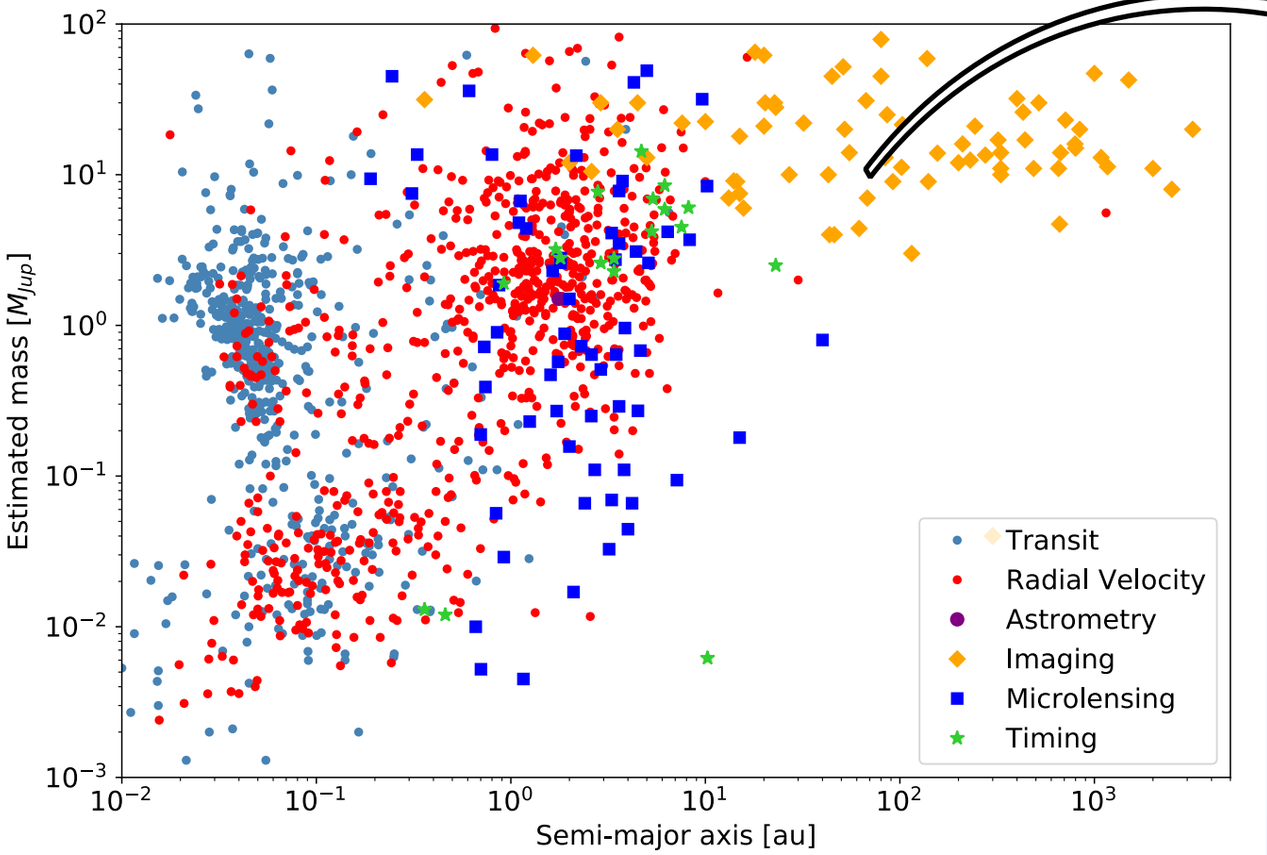
Cheetham+ 2018

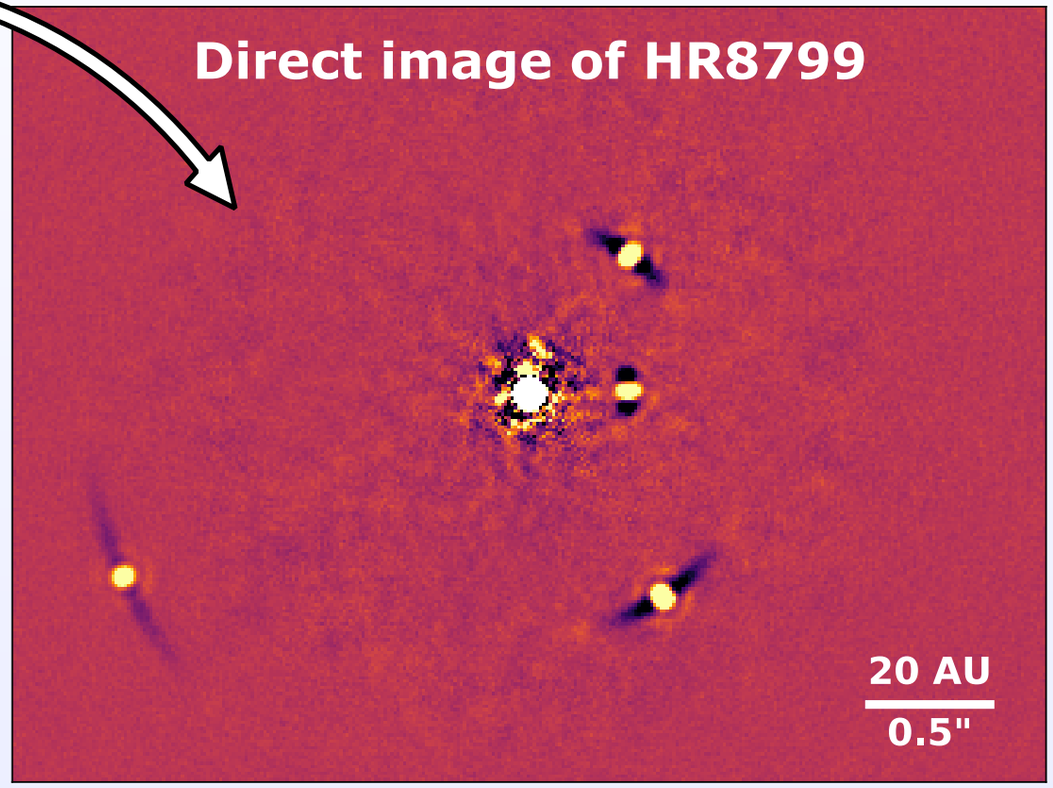
Thalmann+ 2016

Olofsson+

Atmospheric composition of exoplanets

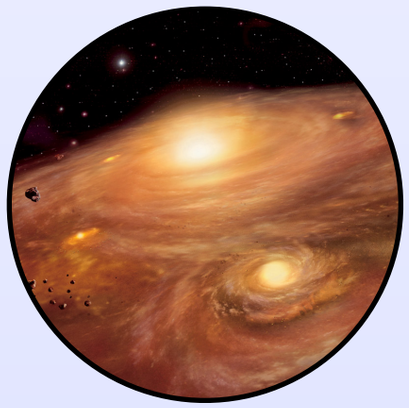
Distant young giant exoplanets



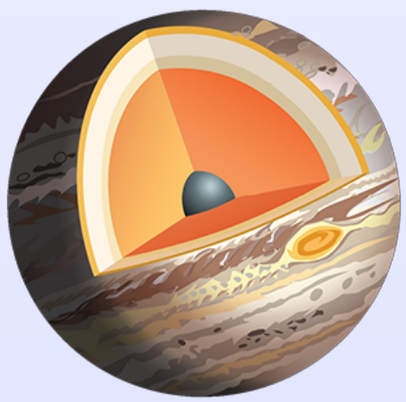


Zurlo, **Vigan** et al. (2016)

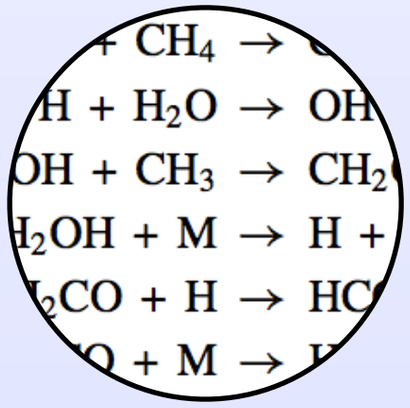
Formation & migration ?



Internal structure ?

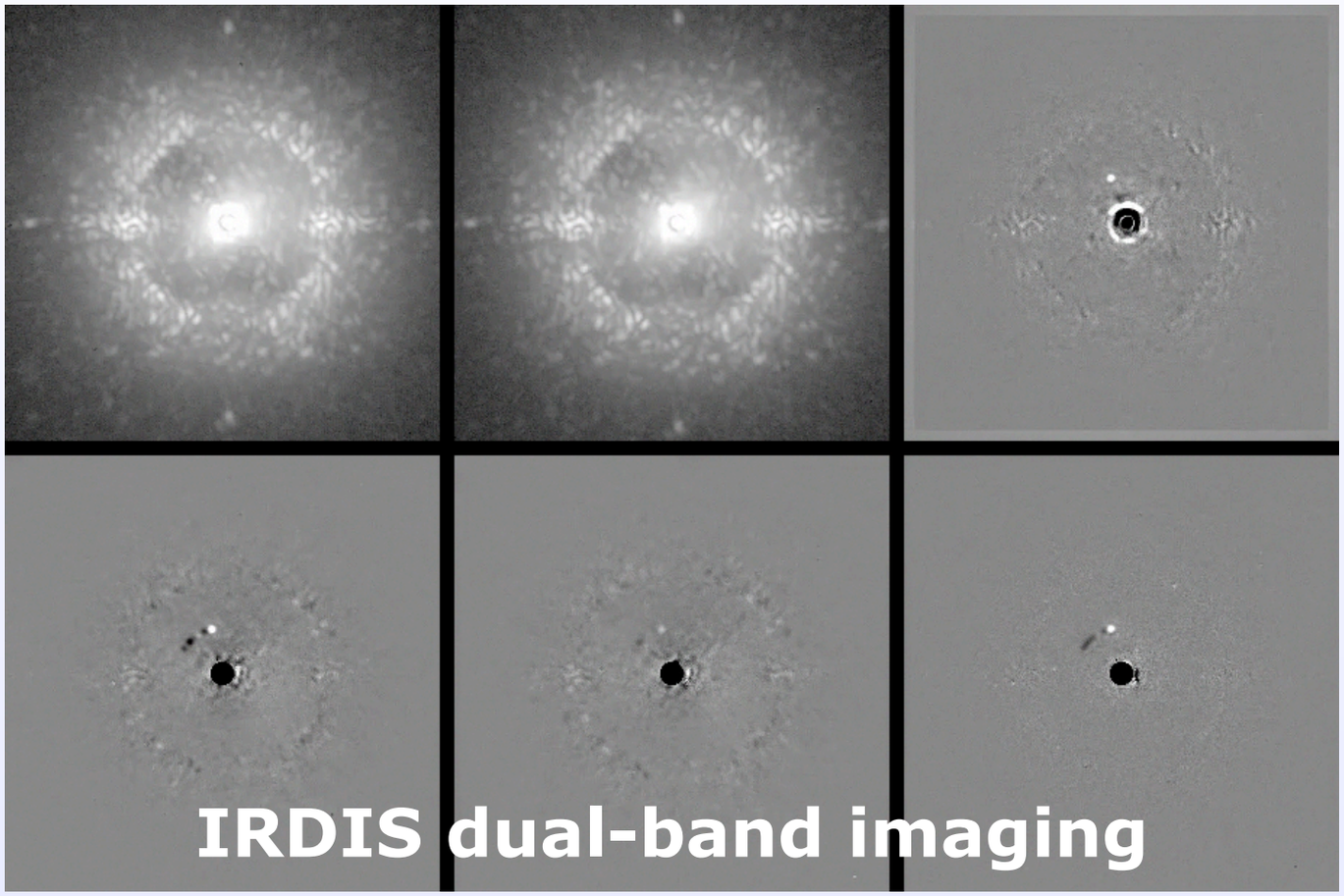


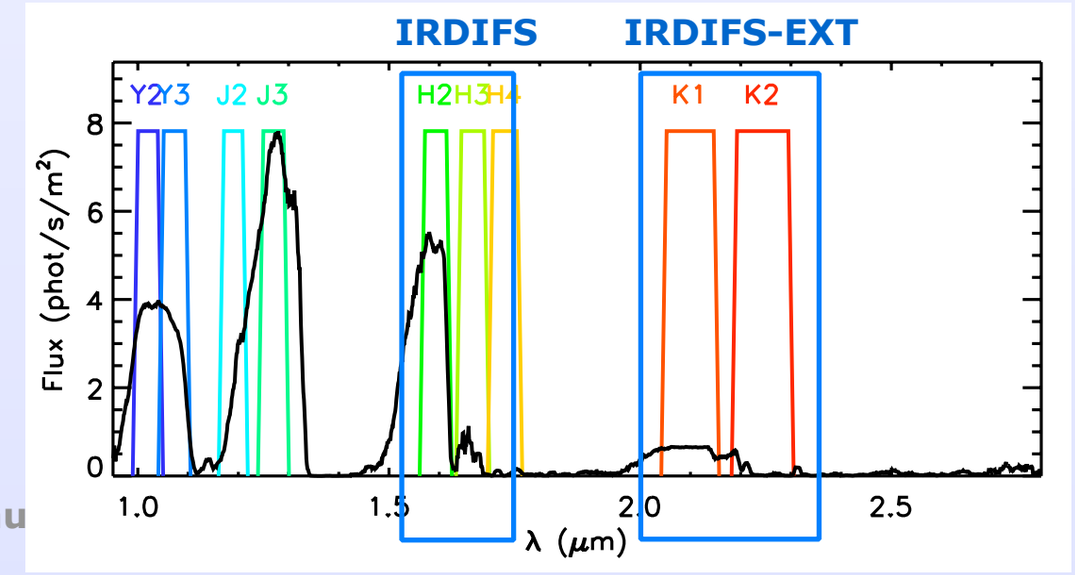
Atmosphere chemistry & dynamics ?

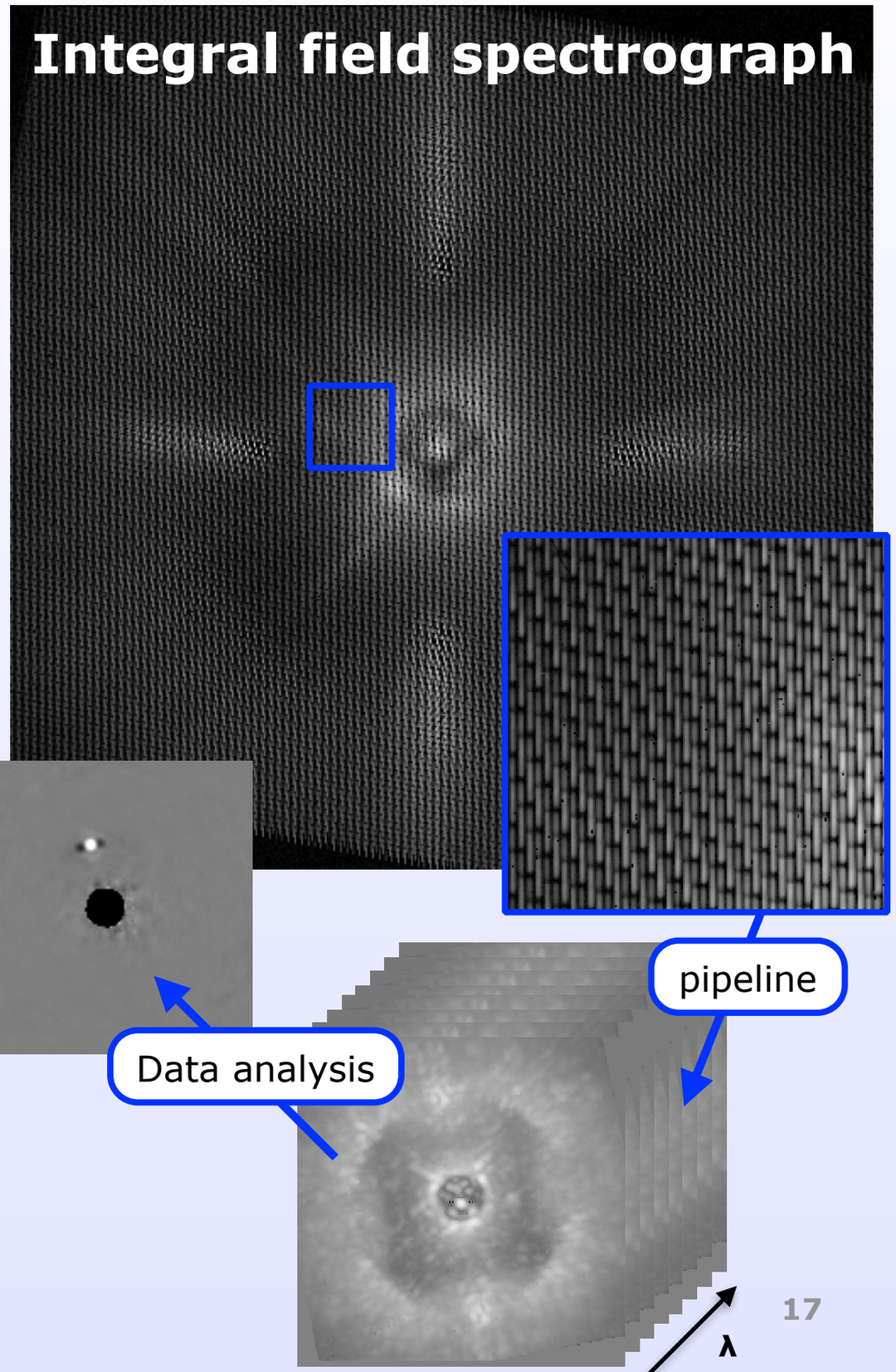


IRDIFS: the exoplanet hunting mode

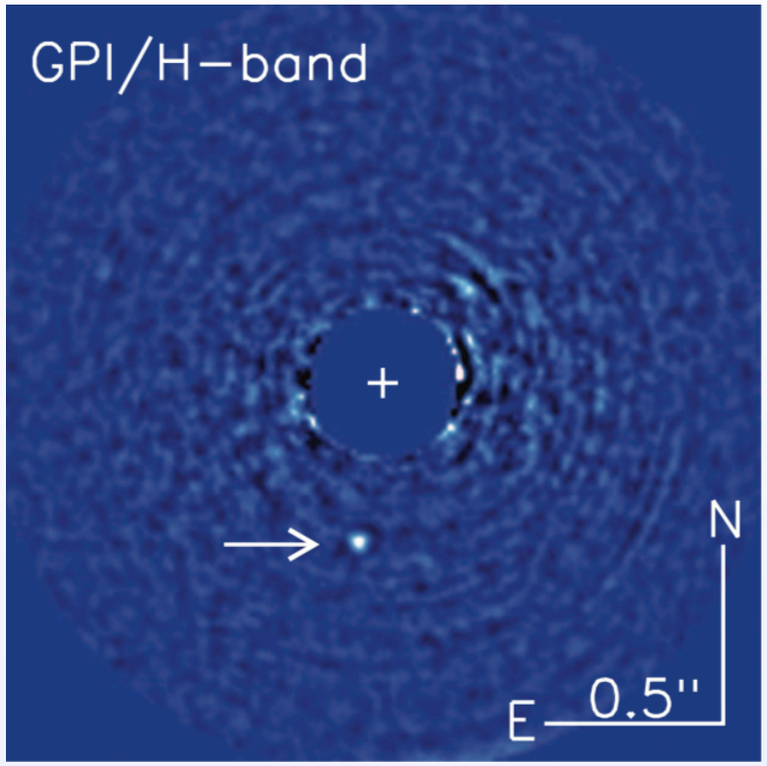
SPHERE designed as a <u>survey instrument</u>



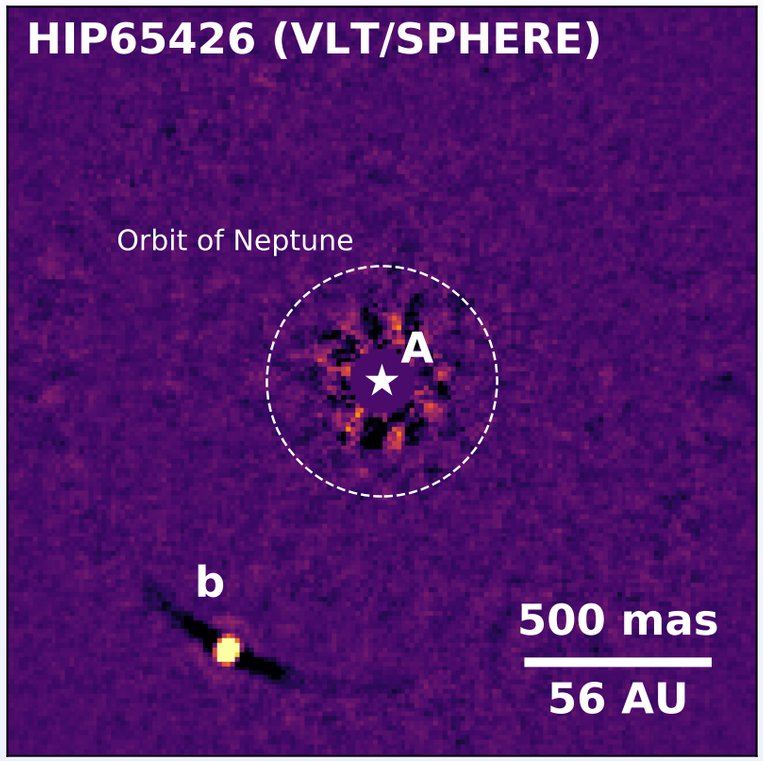




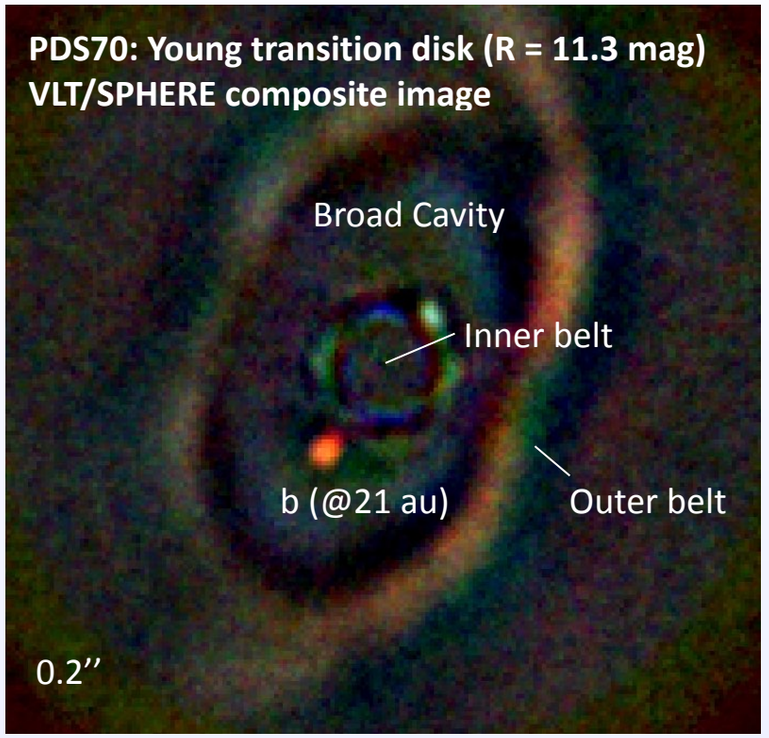
Recent direct imaging detections



Macintosh et al. 2015

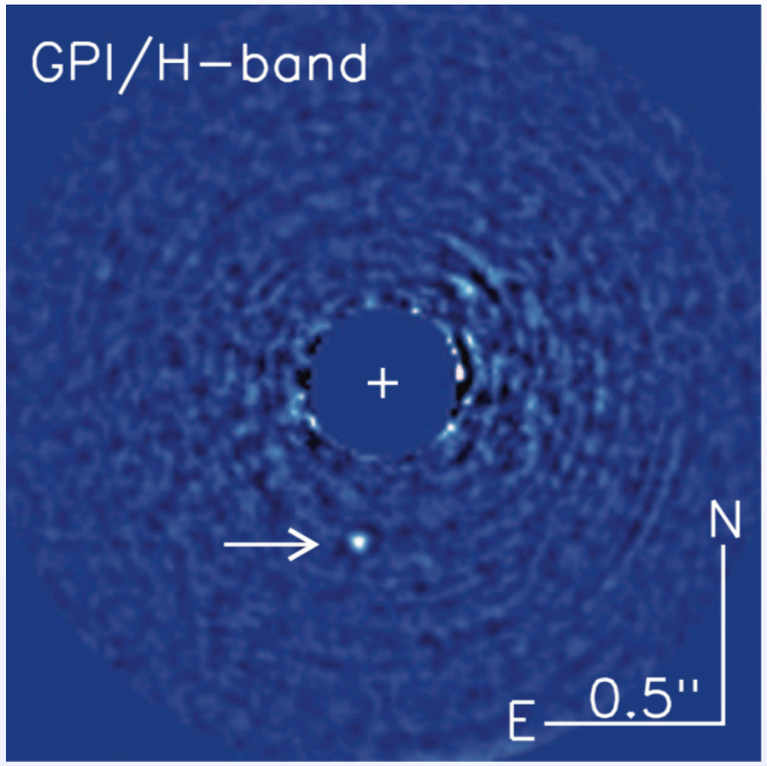


Chauvin et al. 2017

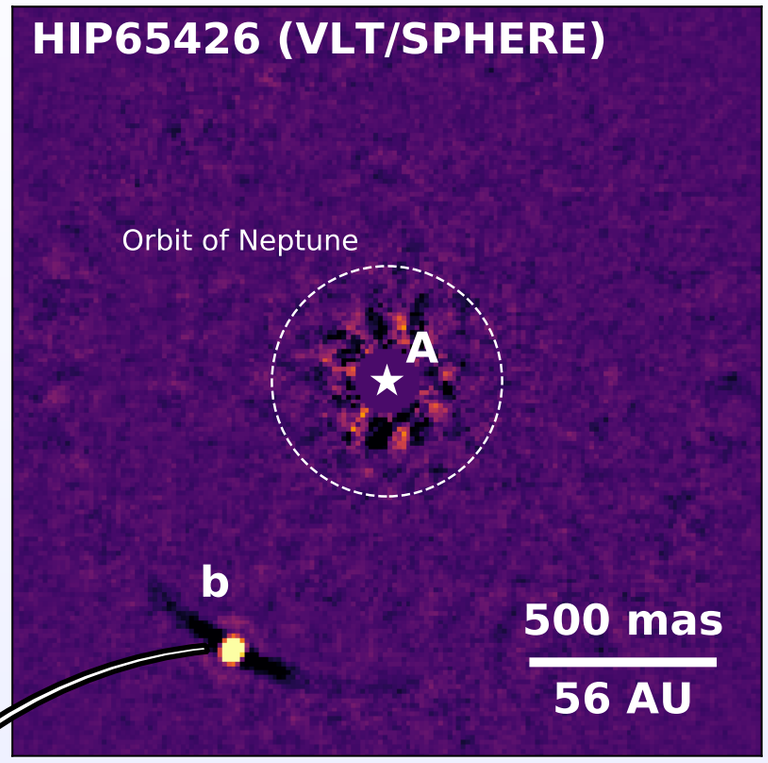


Keppler et al. 2018

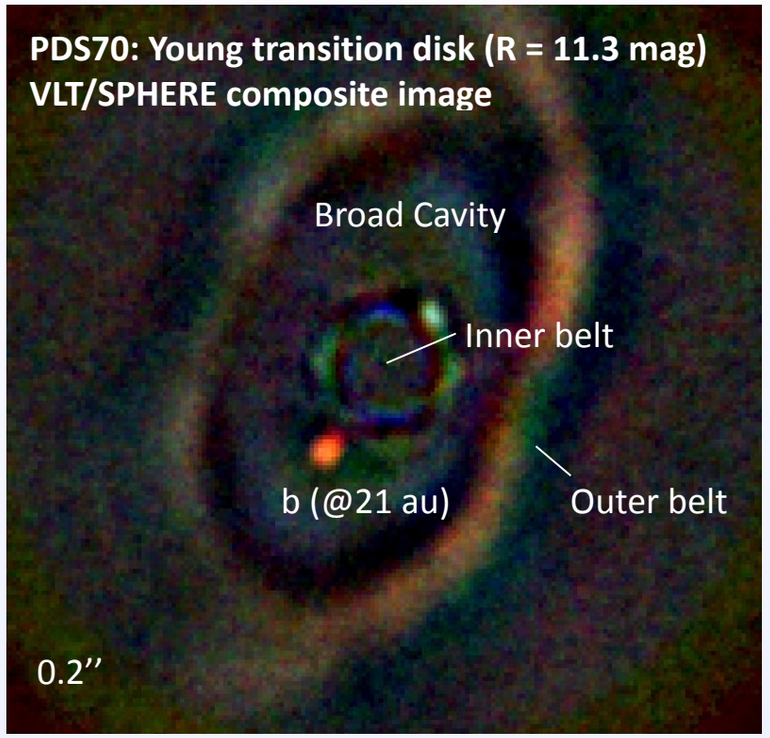
Recent direct imaging detections



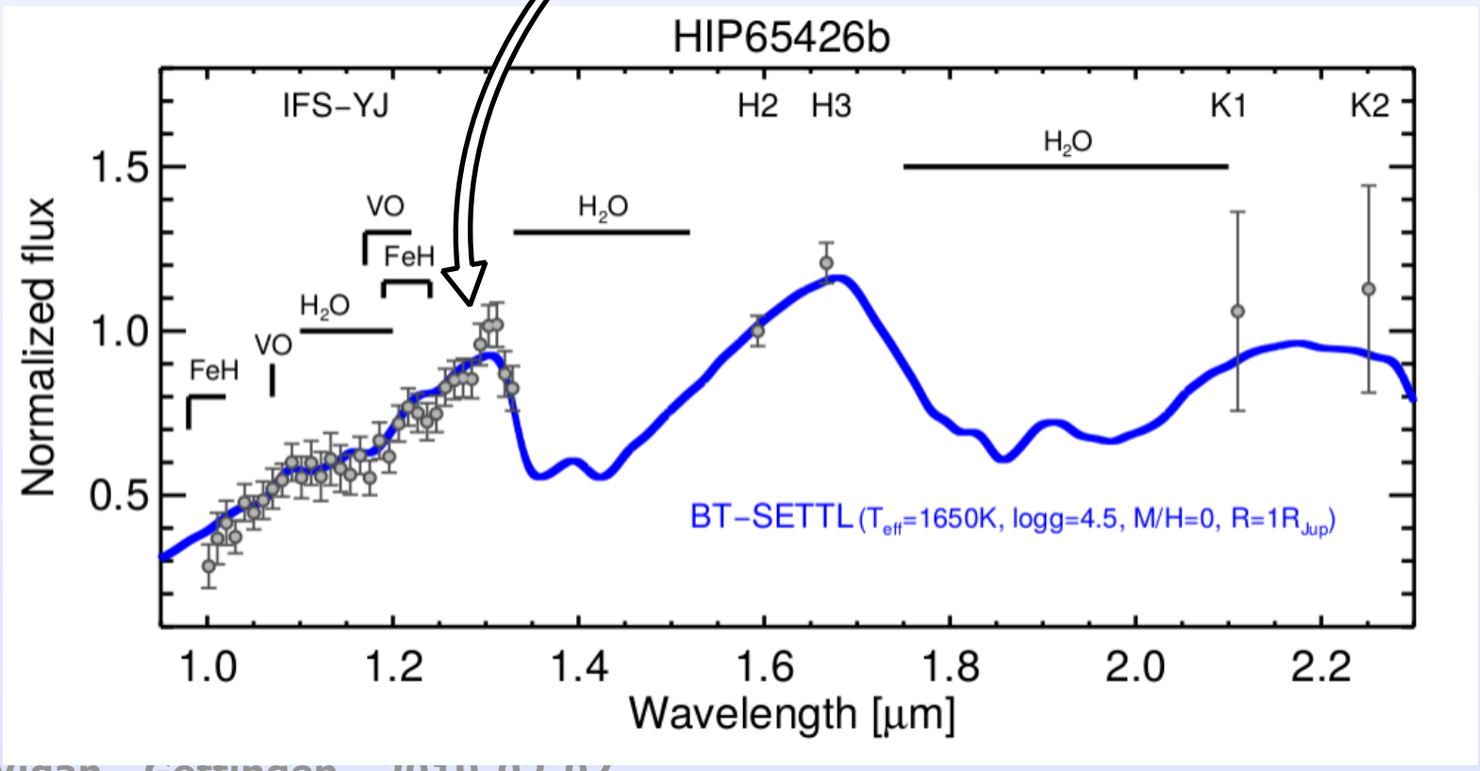
Macintosh et al. 2015



Chauvin et al. 2017



Keppler et al. 2018



Very low resolution spectroscopy!

R<100

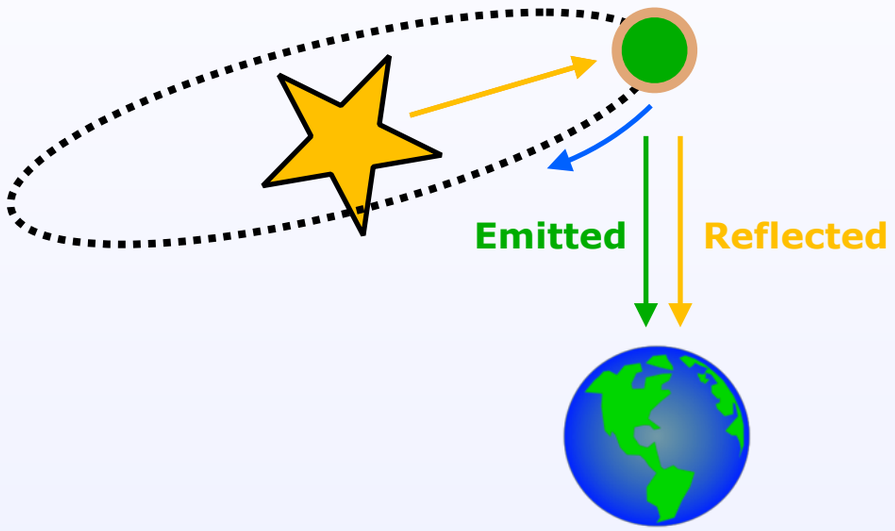
Going to higher spectral resolution

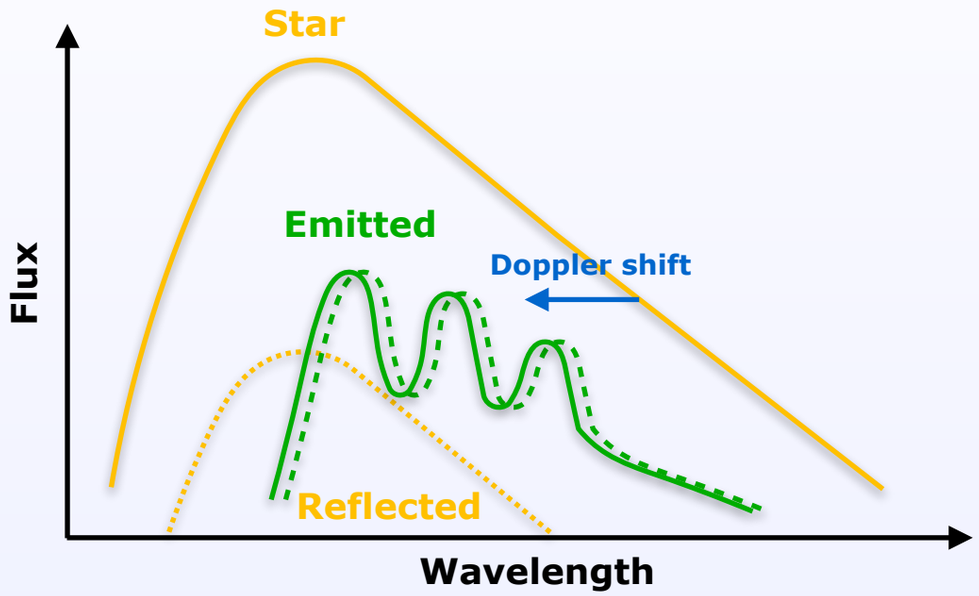
Detection

Characterization

Going to higher spectral resolution

Detection

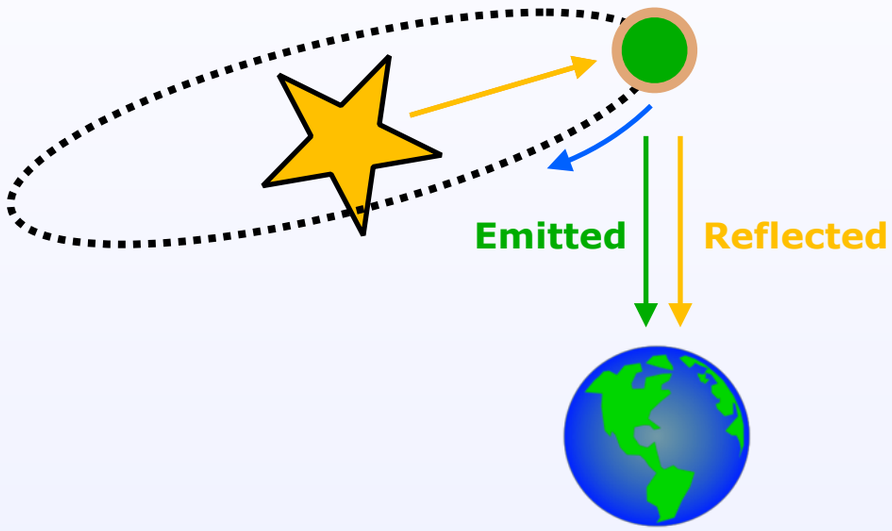


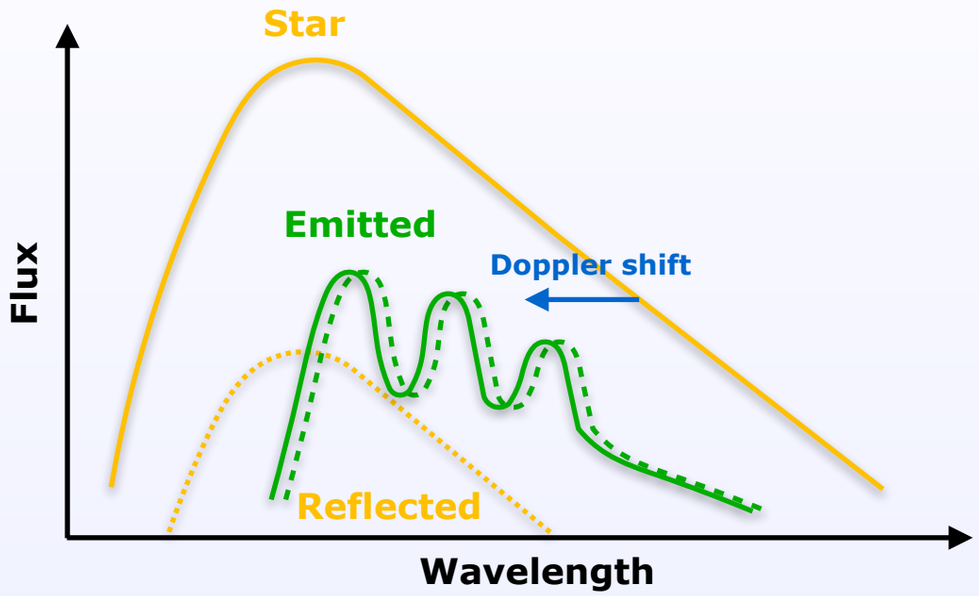


Characterization

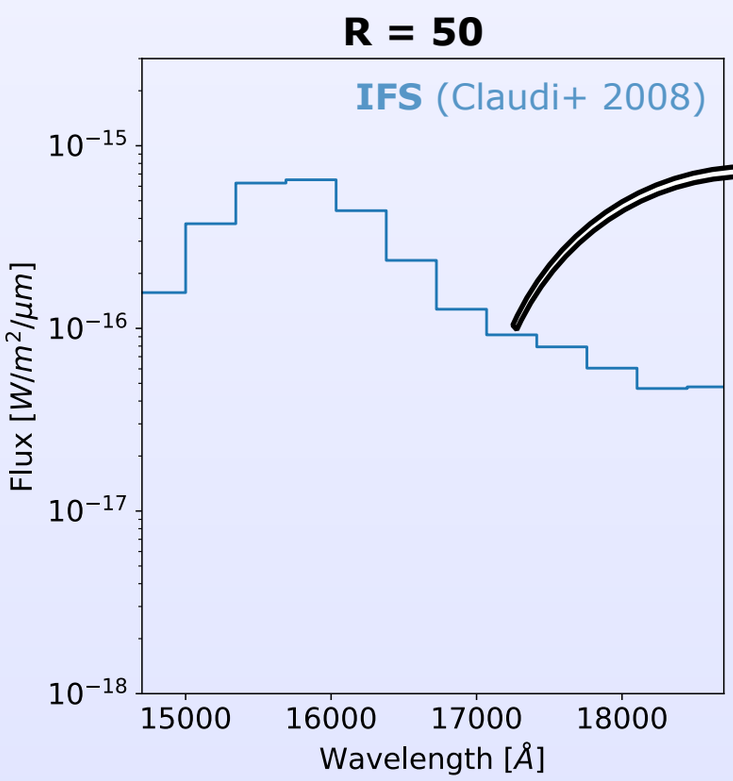
Going to higher spectral resolution

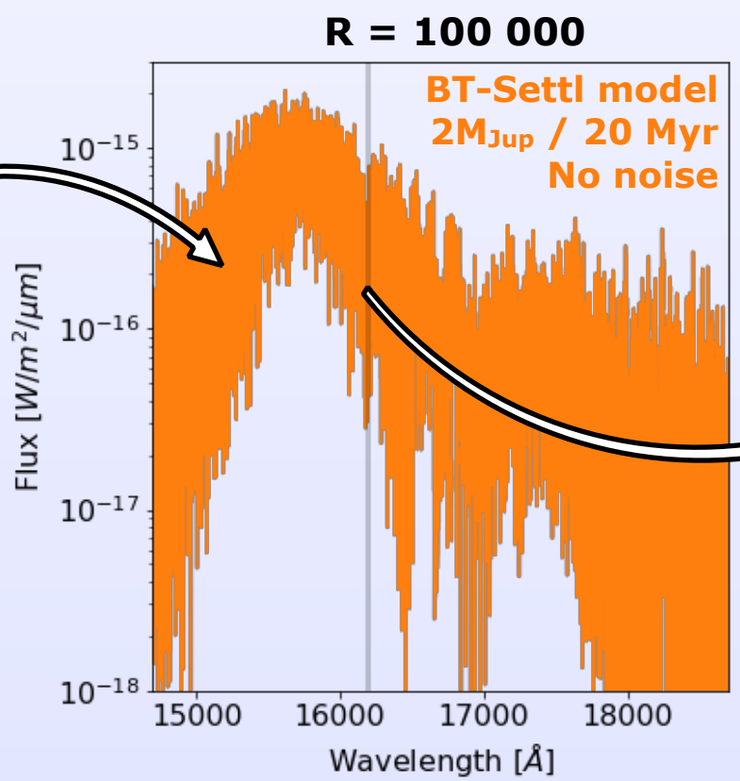
Detection

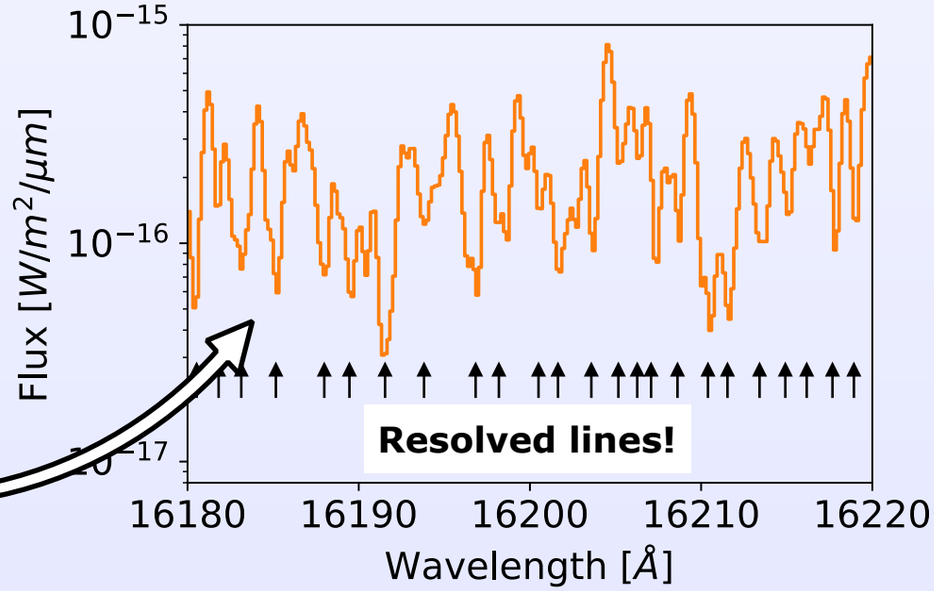




Characterization



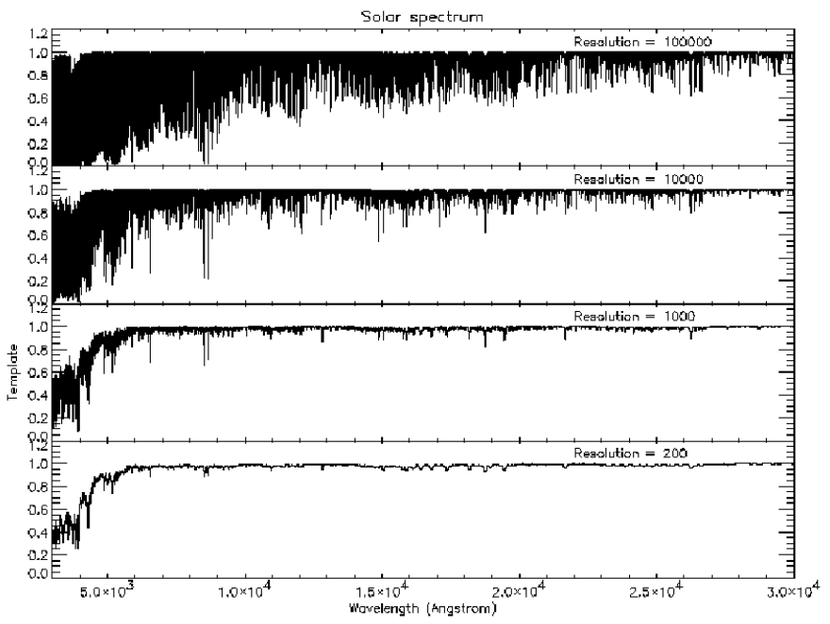




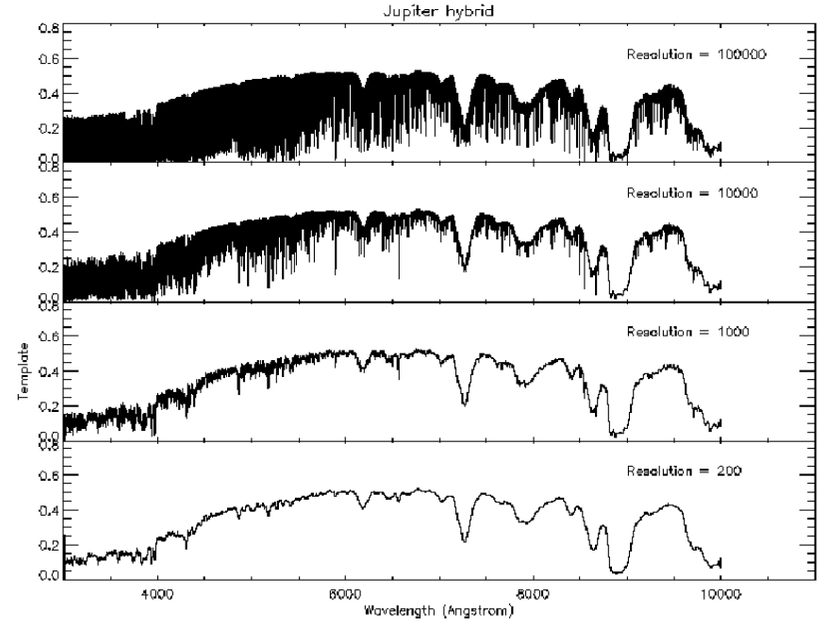
Exoplanets at high-resolution: theory

Sparks & Ford 2002

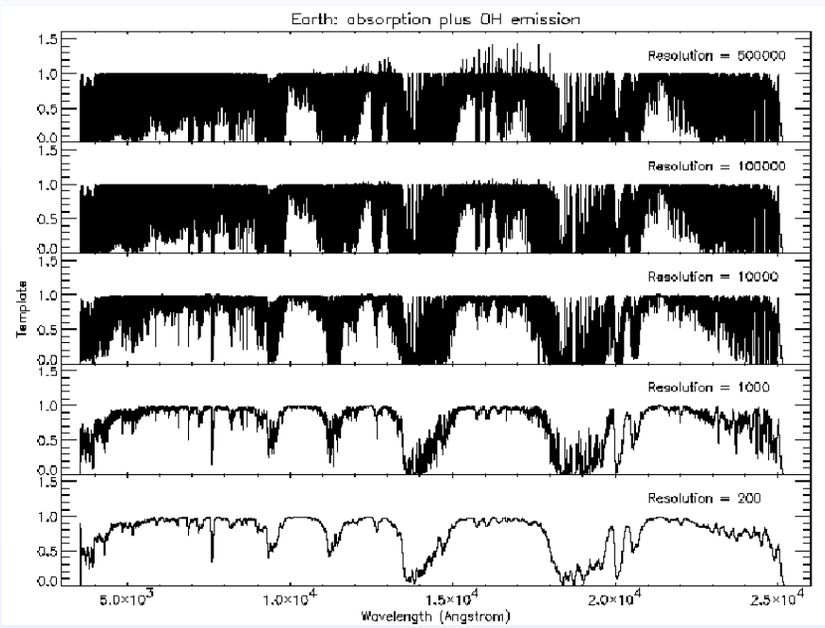
Sun template



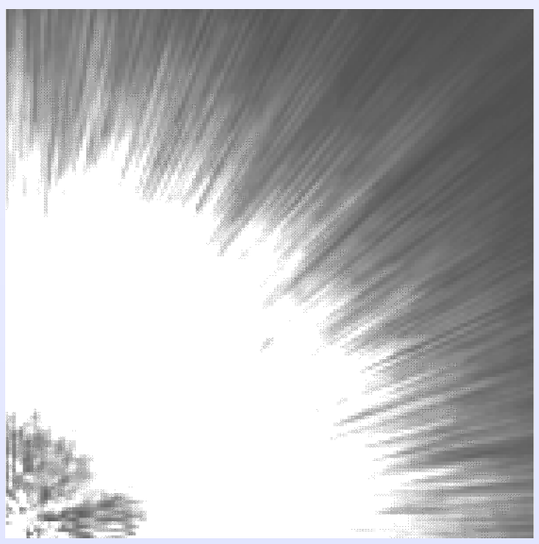
Jupiter template



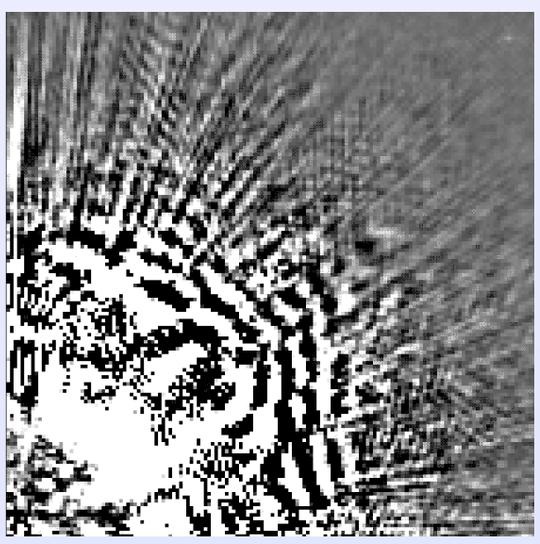
Earth template



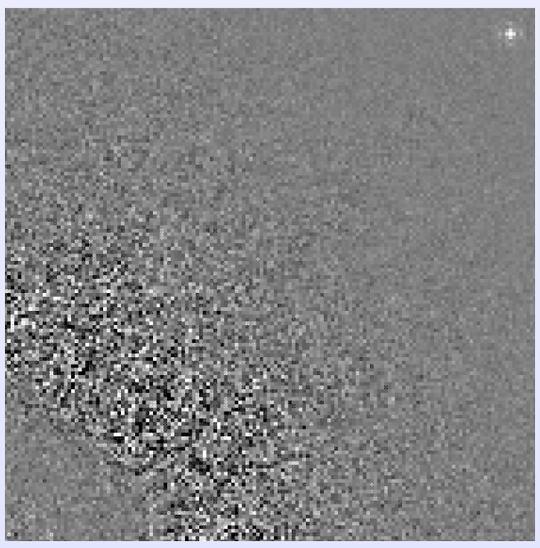
HST/ACS simulation



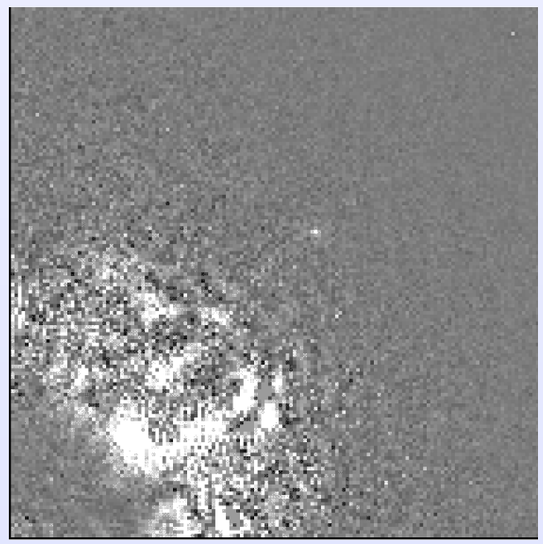
Roll-subtraction (=ADI)



Jupiter template CCF

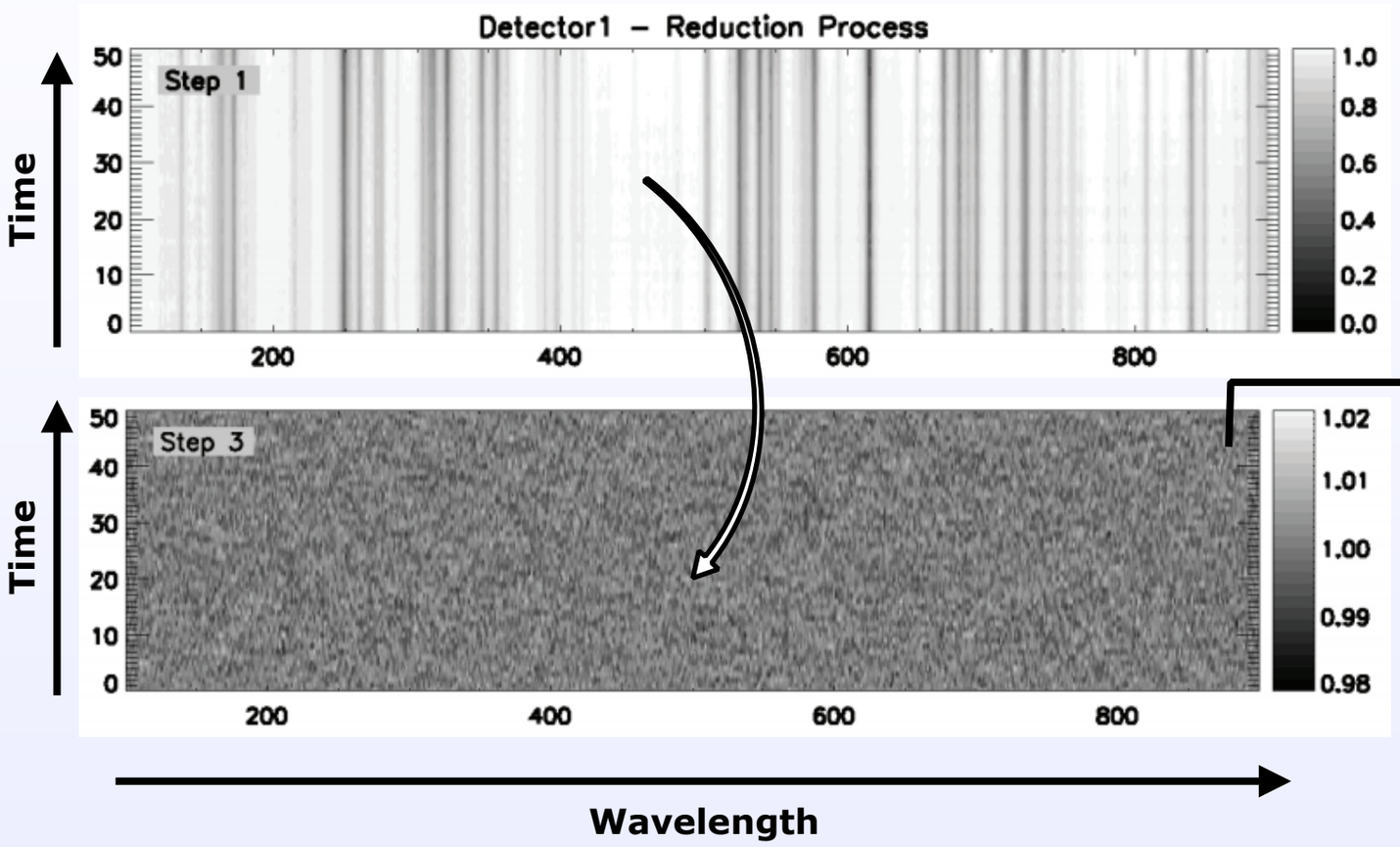


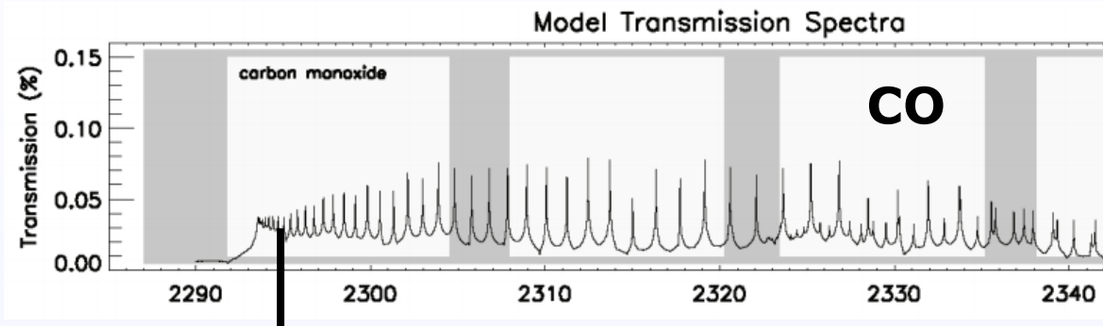
Bright Earth template CCF

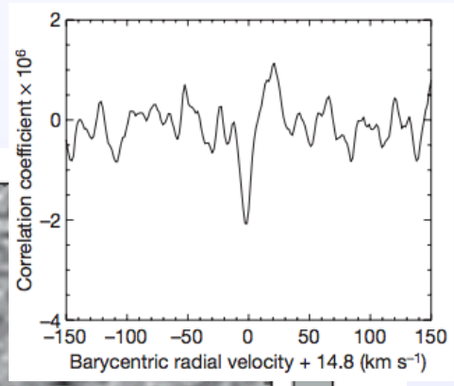


Exoplanets at high-resolution: practice

HD209458b - Snellen et al. 2010

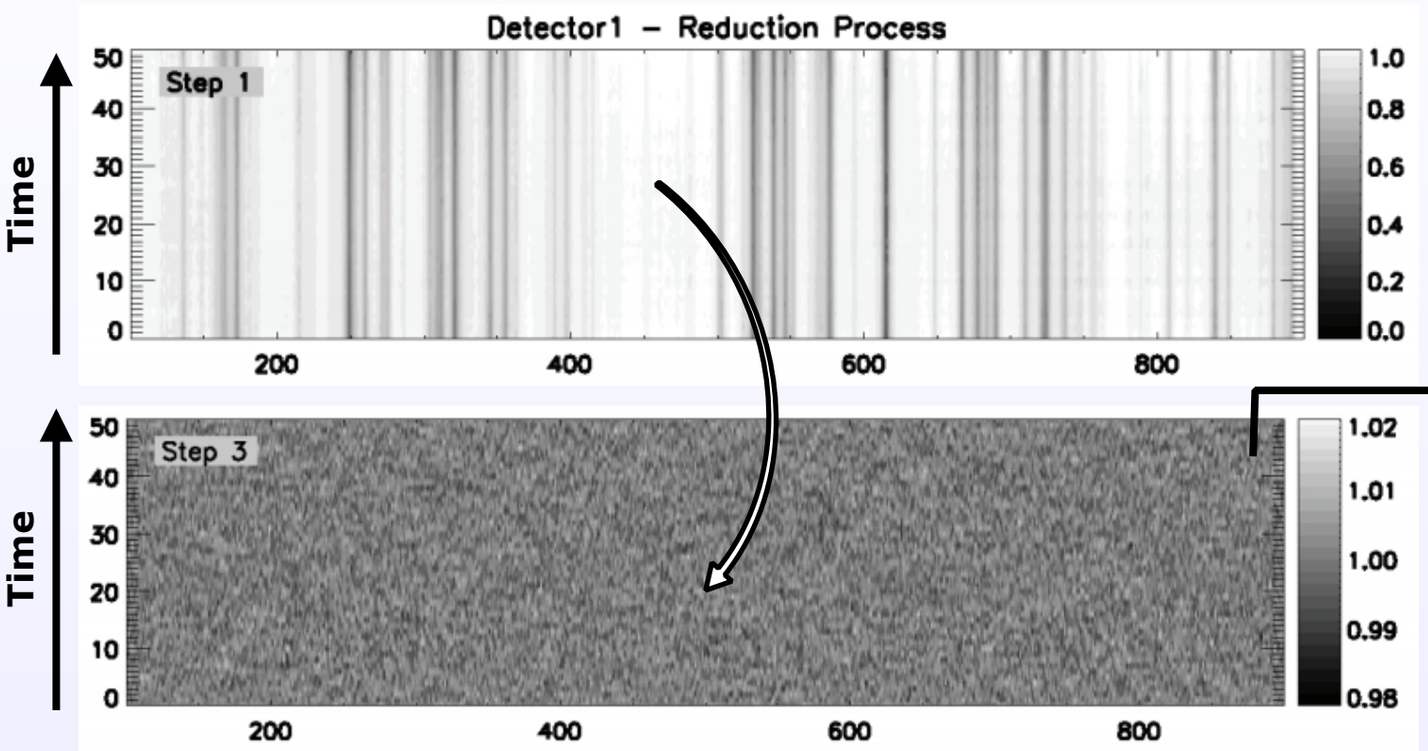


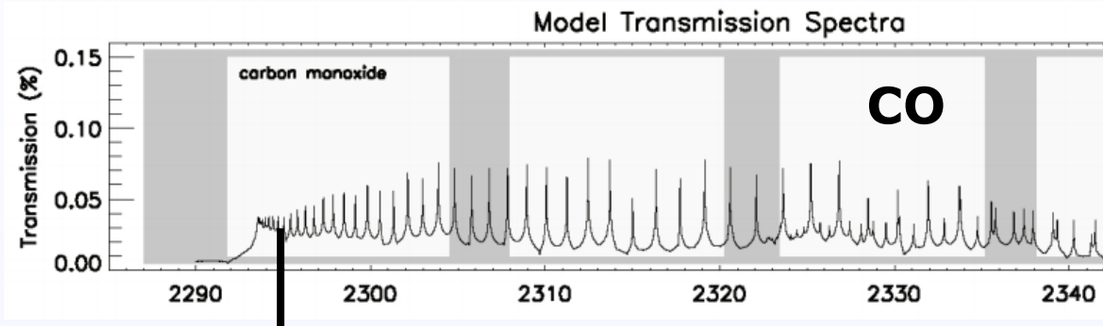


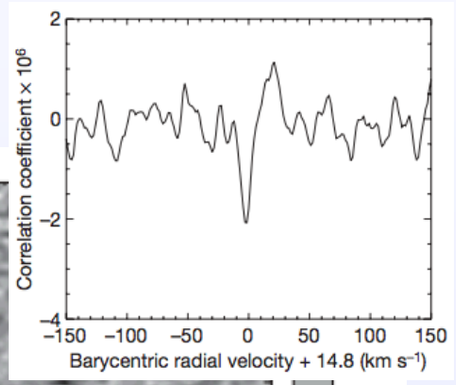


Exoplanets at high-resolution: practice

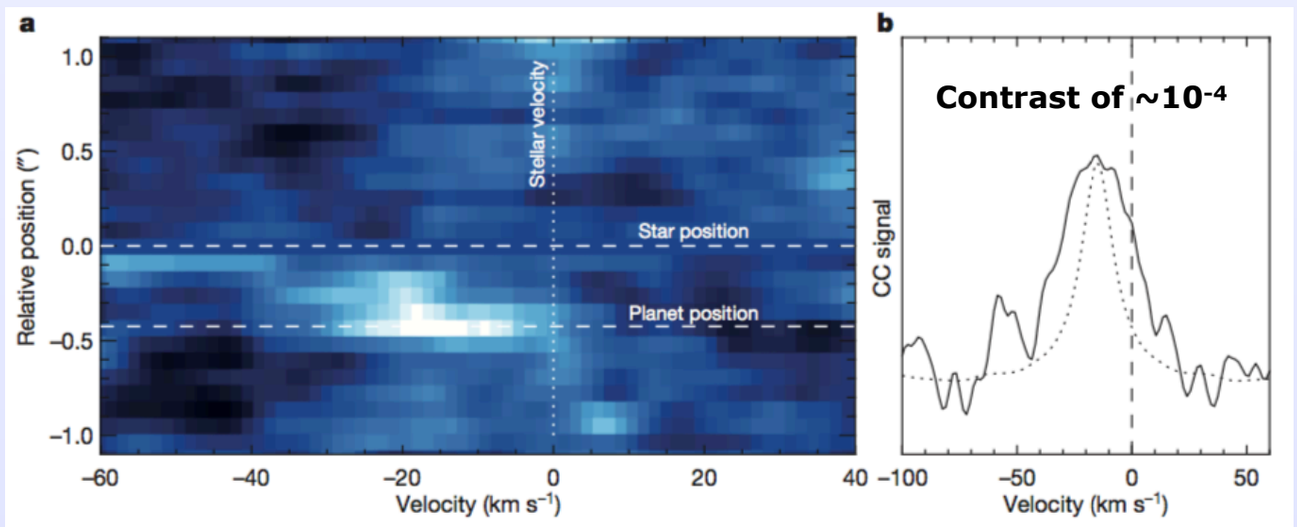
HD209458b - Snellen et al. 2010



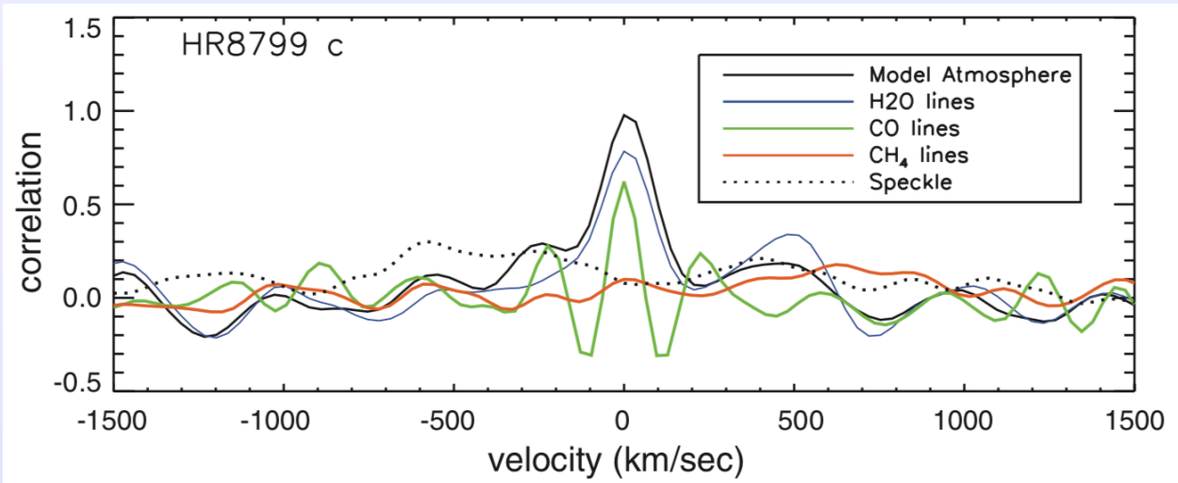




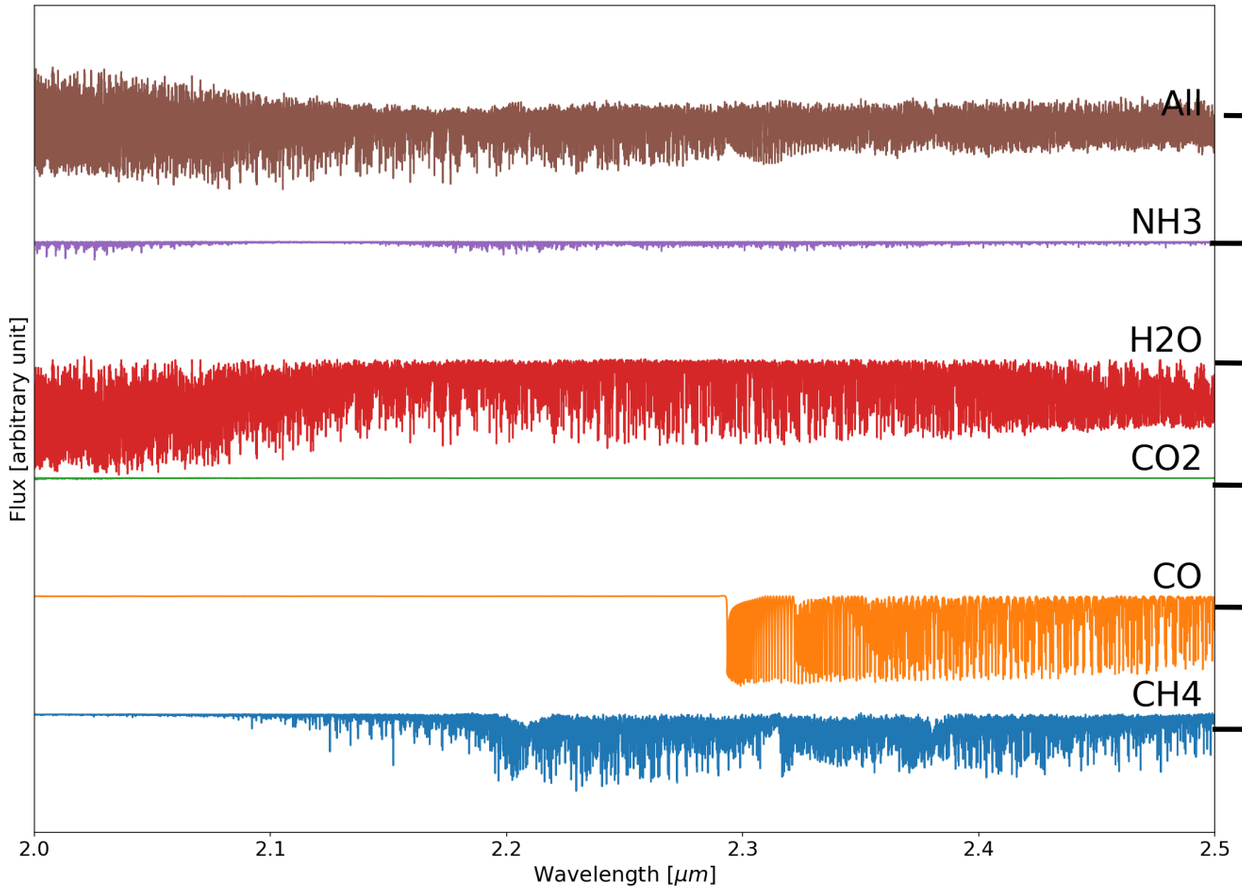
ß Pictoris b - Snellen et al. 2014



HR8799c - Konopacky et al. (2013)

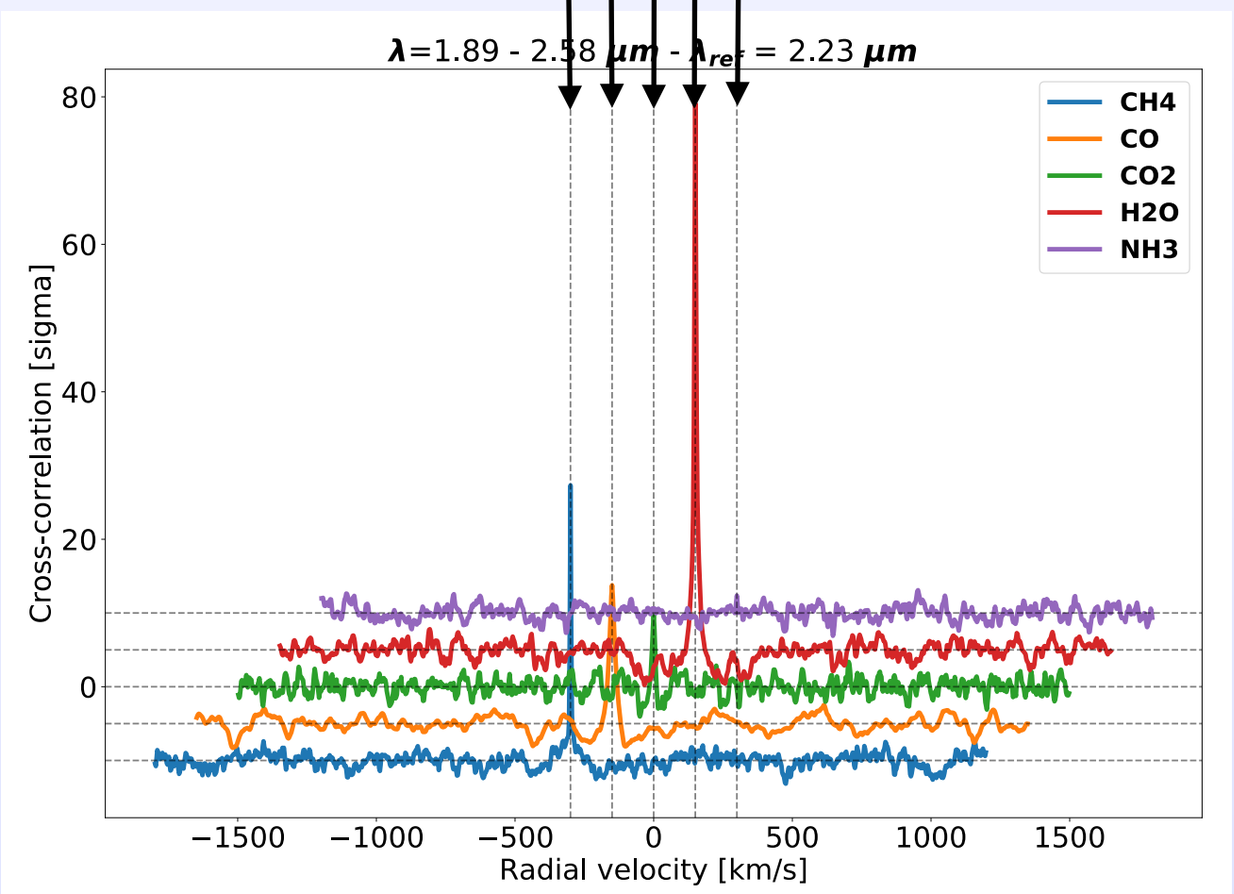


Boosting the SNR



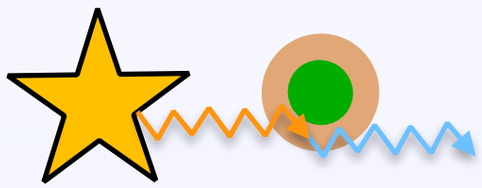
Standard CCF approach

ATMO models
Tremblin et al. (2015)
Phillips et al. in prep.

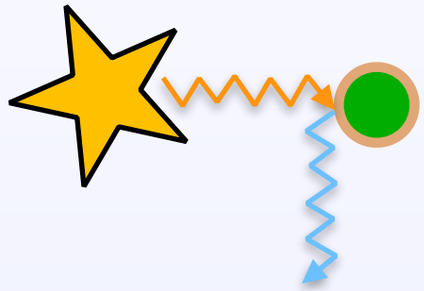


Spectral + velocity diversity

Absorption
HD209458 b (Snellen et al. 2010)



Reflection
51 Peg b (Martins et al. 2016)



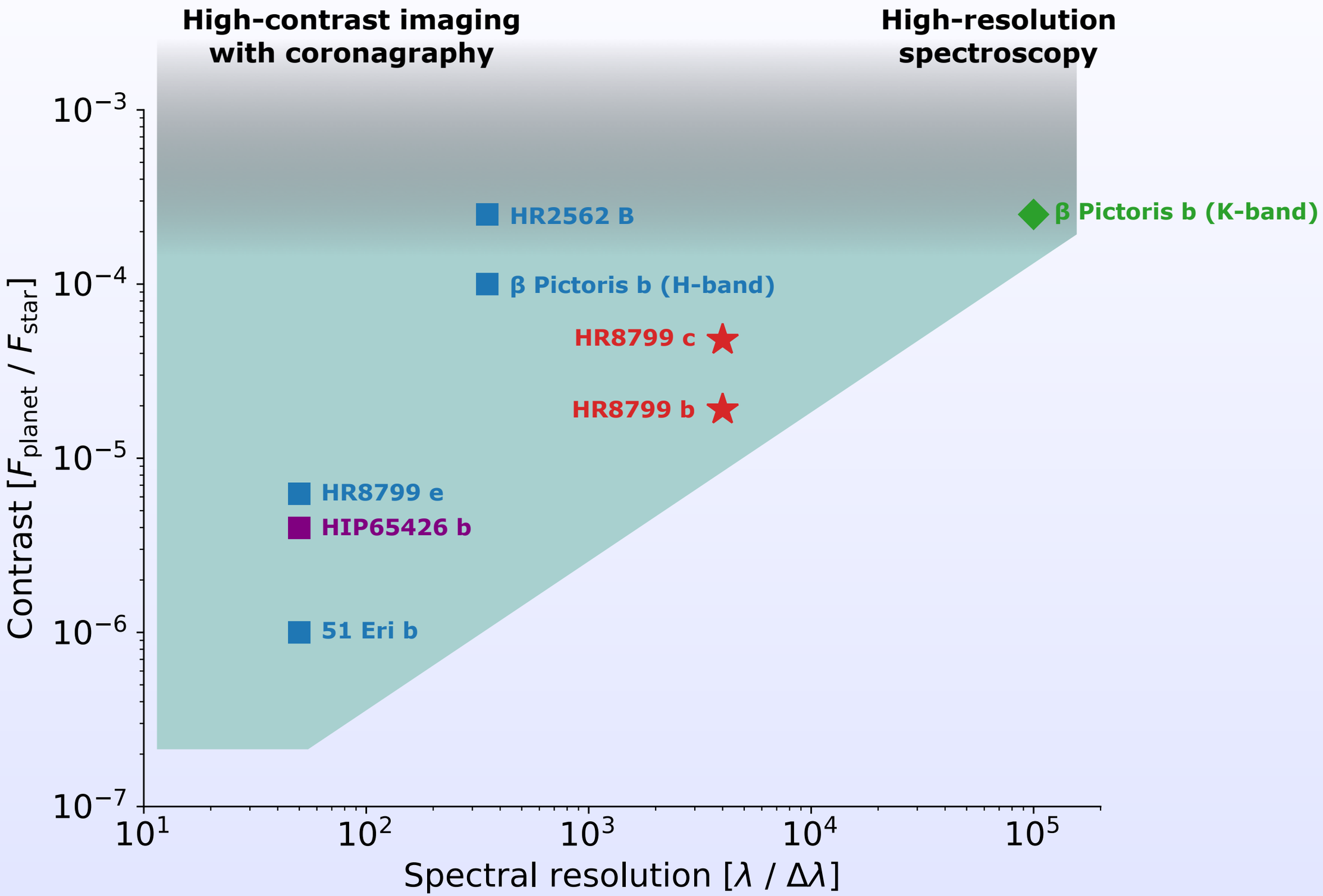
Emission
HR8799 c (Konopacky et al. 2013)

- Why does it work?
  - **strong spectral features** expected for CO, CO_2, CH_4, H_20
  - **many lines** in near-infrared

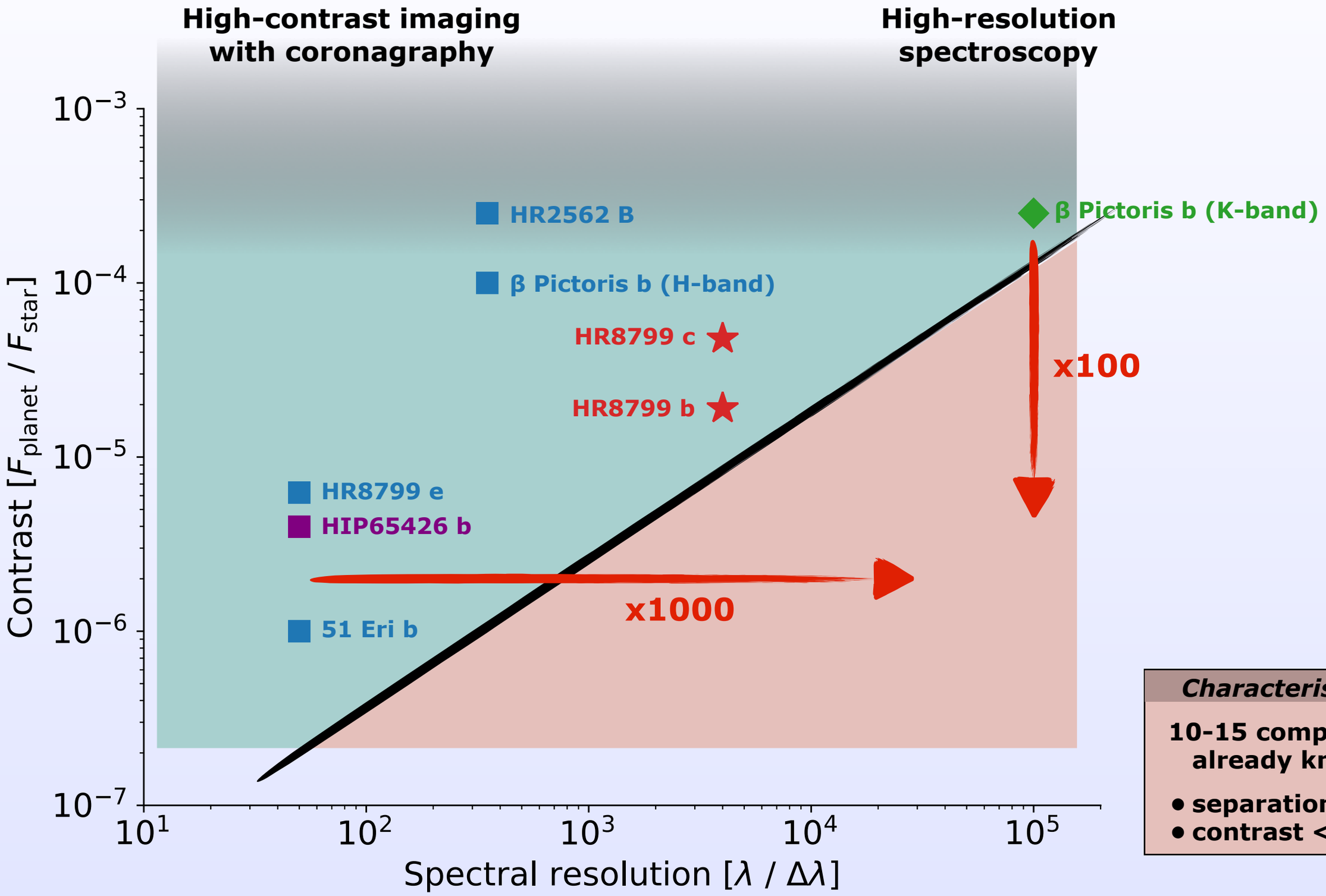
$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}} + \sigma^2_{\text{bg}} + \sigma^2_{\text{RN}} + \sigma^2_{\text{Dark}}}} \sqrt{N_{\text{lines}}},$$

- Limitations?
  - contrast between star and planet!
  - current limit at 10^{-5} on τ Boo (Hoeijmakers et al. 2017)

Young exoplanets characterisation



Young exoplanets characterisation



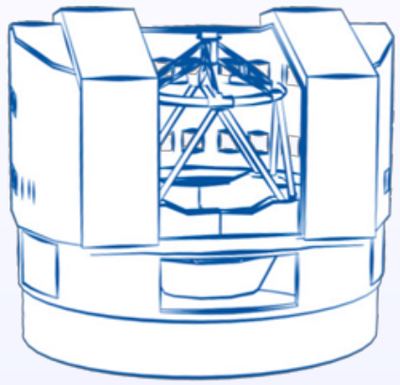
Characterisation

10-15 companions already known

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

A unique window of opportunity

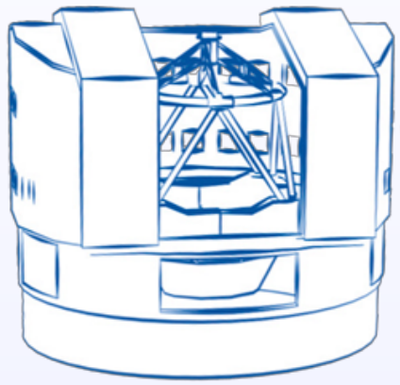
VLT/UT3



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

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

HiRISE

Fiber coupling

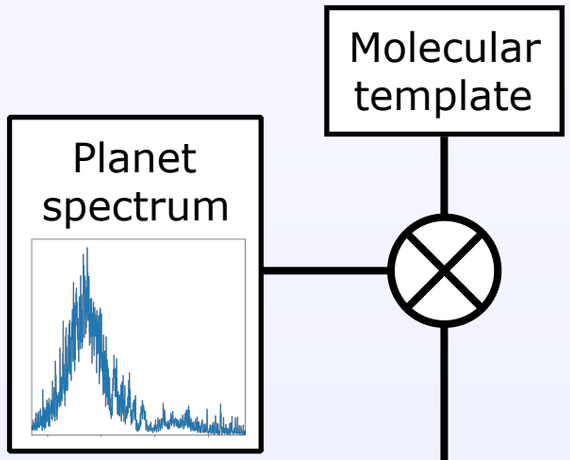
Supported by ESO

erc

Supported by CRIRES+ SPHERE

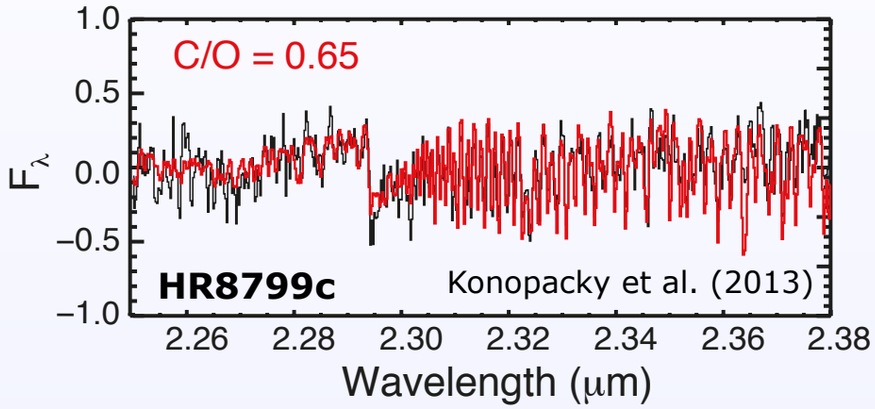
New science at high-spectral resolution

Classical approach
(e.g. Snellen et al. 2014)



- Molecule detection
- Radial velocity
- Planet rotation

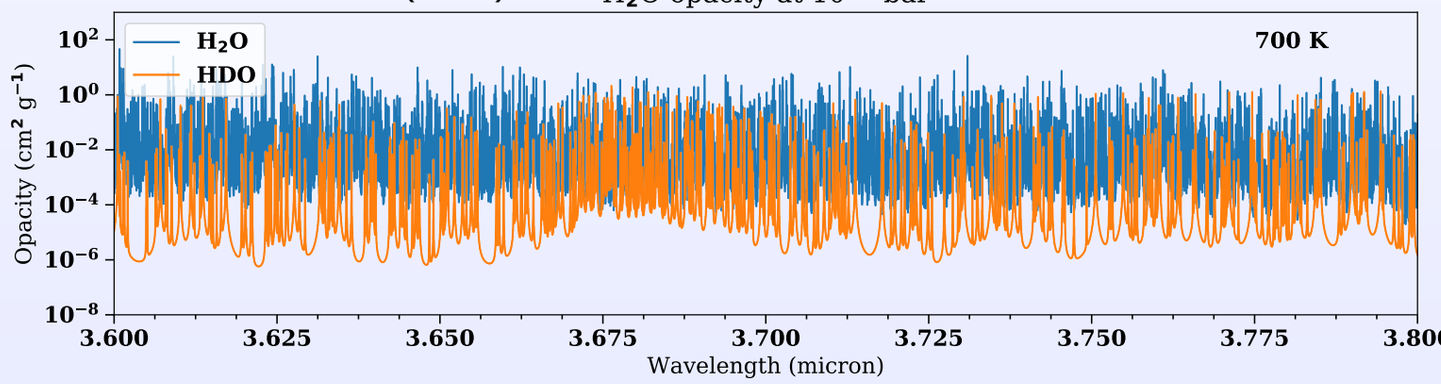
Abundances determination



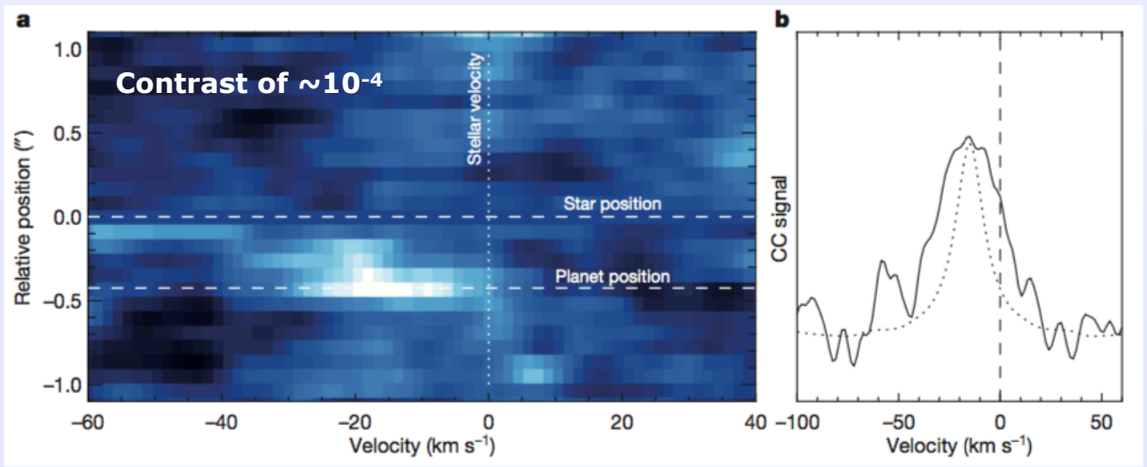
- formation scenario
- migration in the disk
- detailed composition

Isotopologues detection

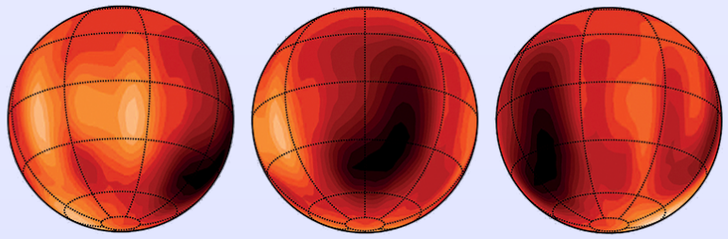
Mollière & Snellen (2019)



ß Pictoris b (Snellen et al. 2014)



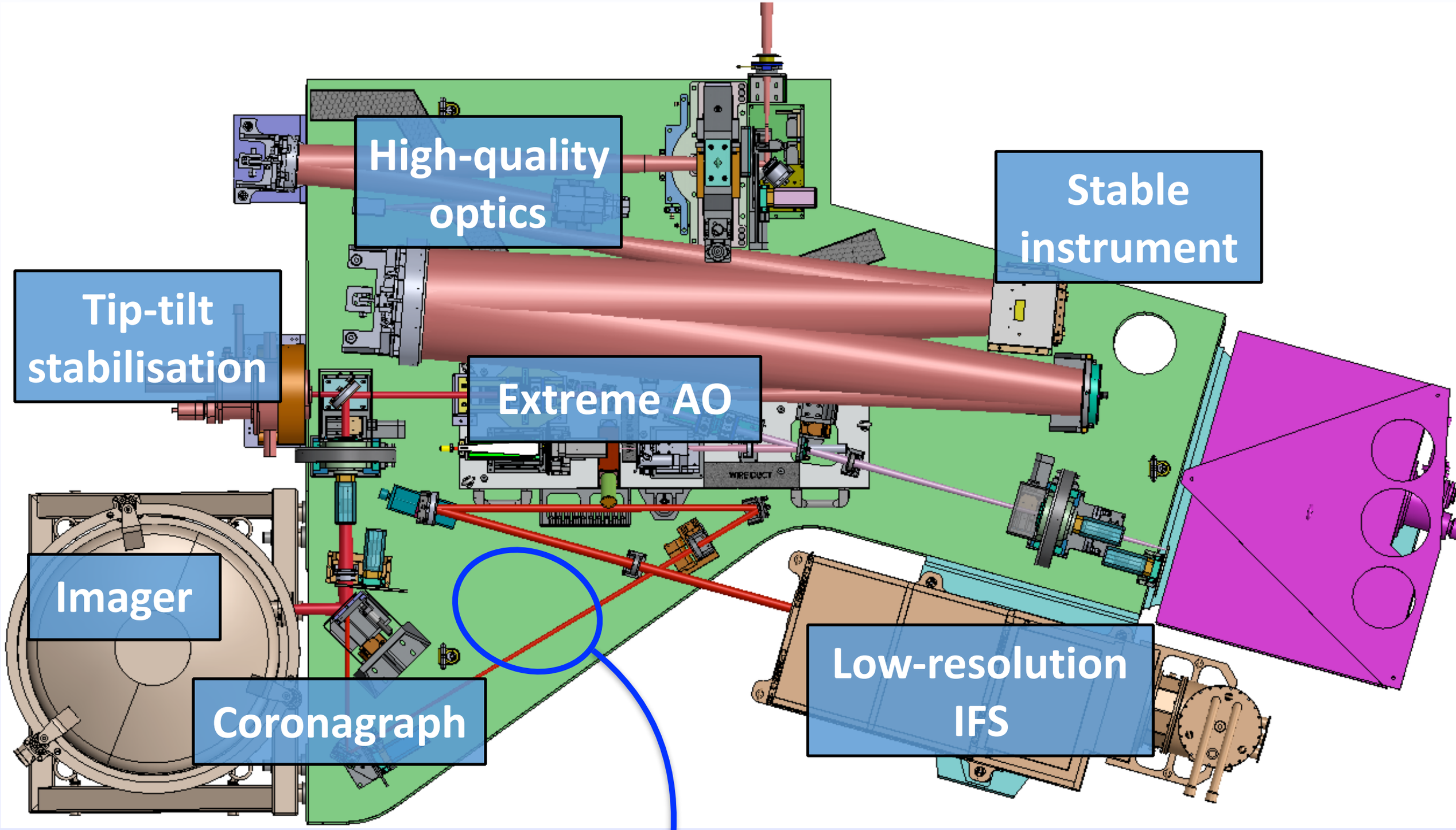
Time-resolved Doppler imaging



- rotational period
- temporal variability
- cloud and winds

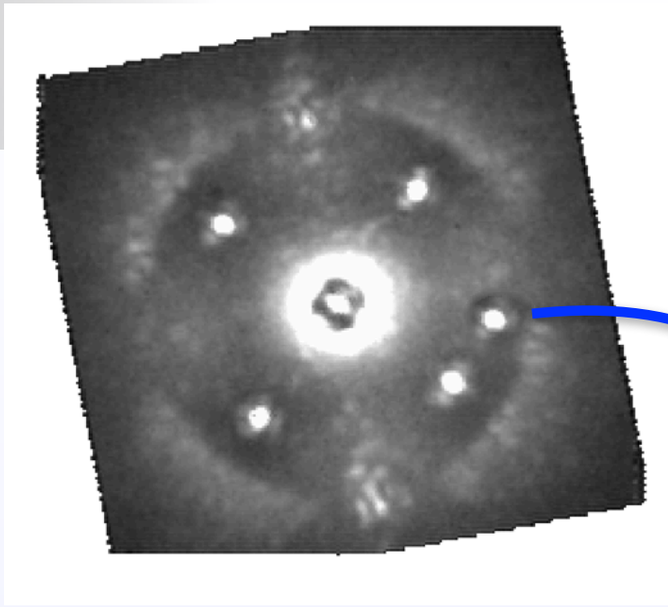
Luhman 16B (Crossfield et al. 2014)

HiRISE fiber injection in SPHERE



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

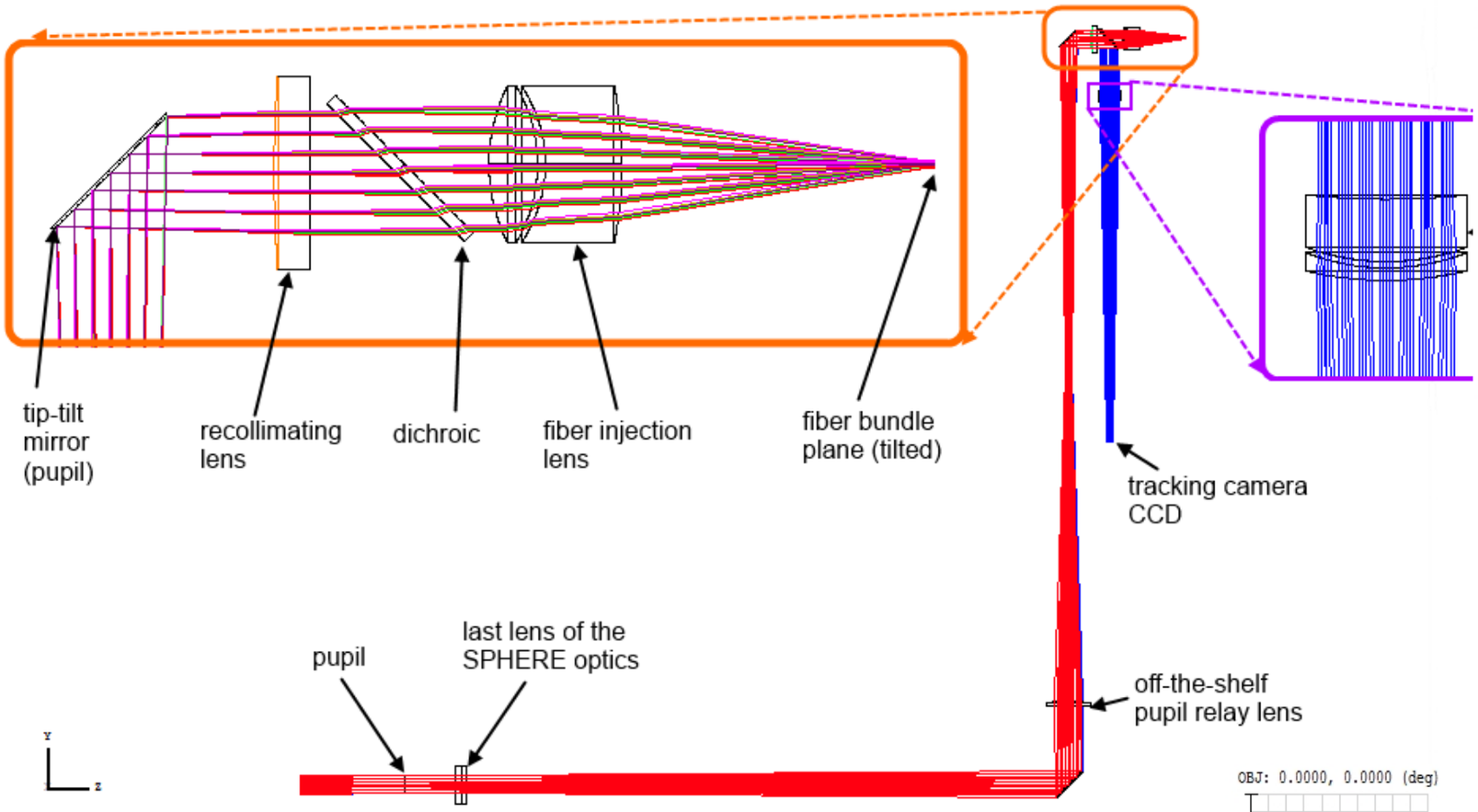


(Very bright) planet!

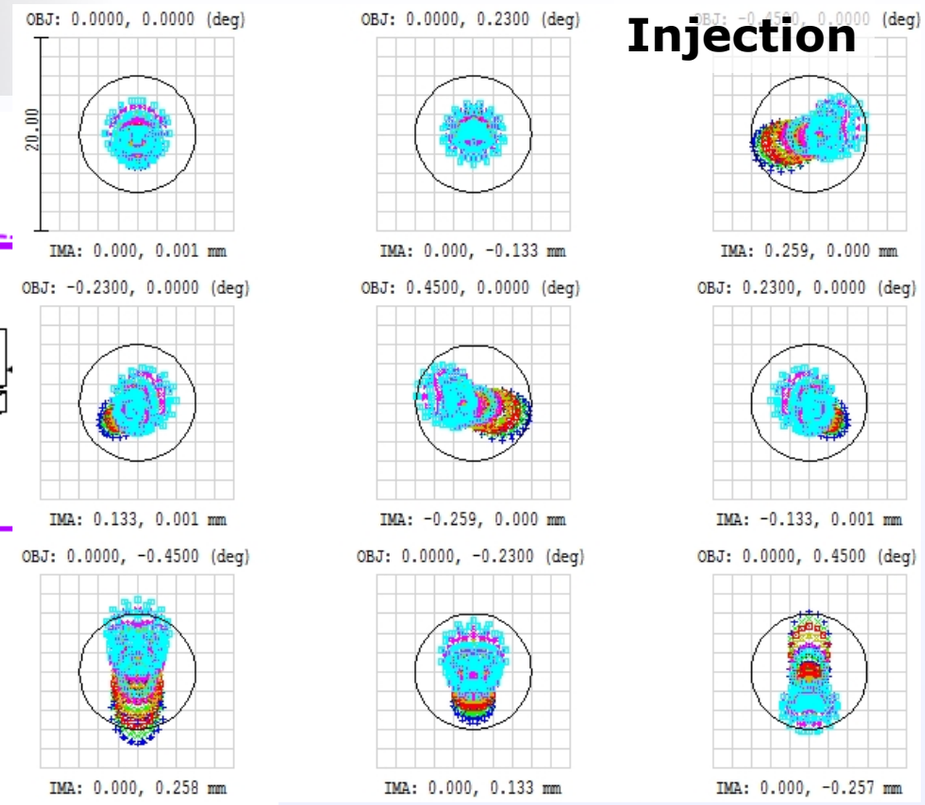
Inspired by Mawet et al. (2017)

Optical design

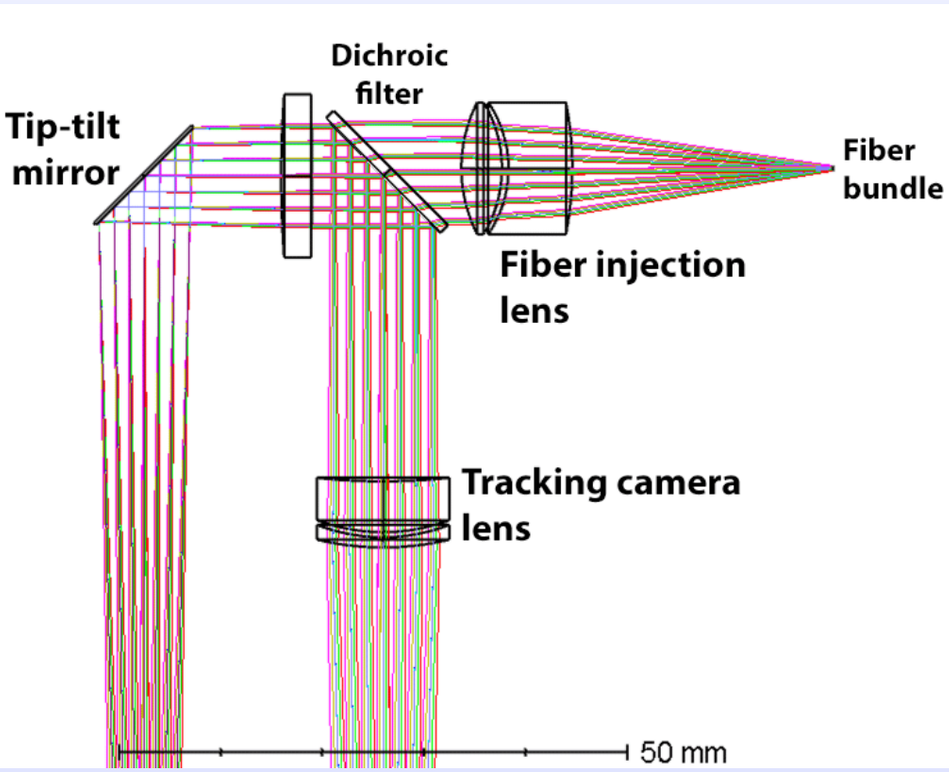
Optical design: E. Muslimov



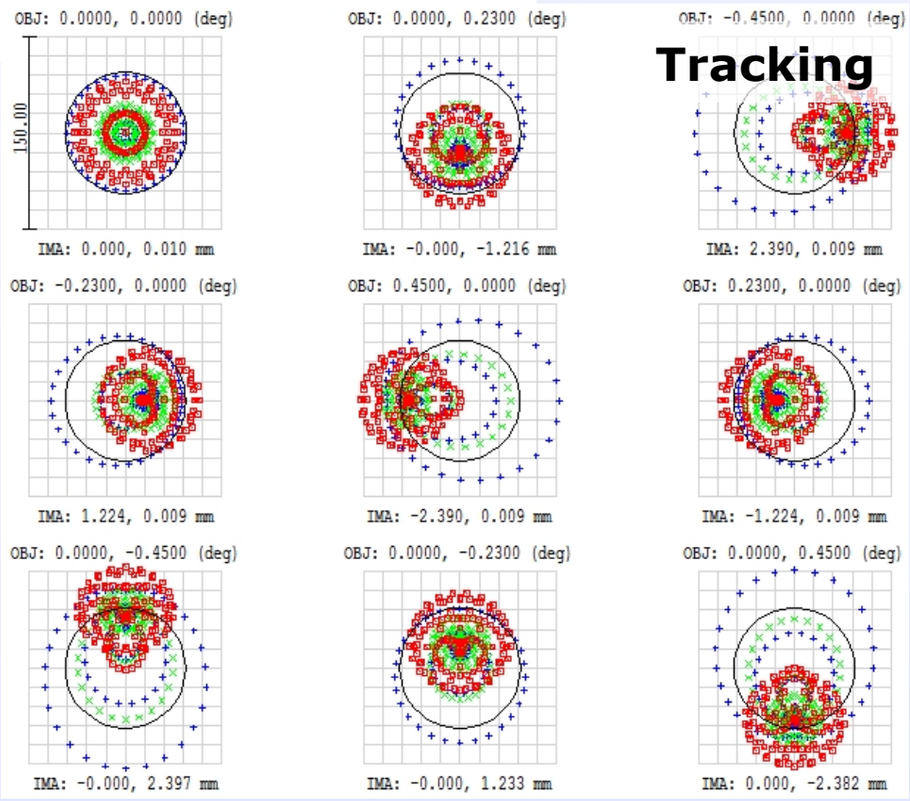
Injection



~30 nm rms on axis



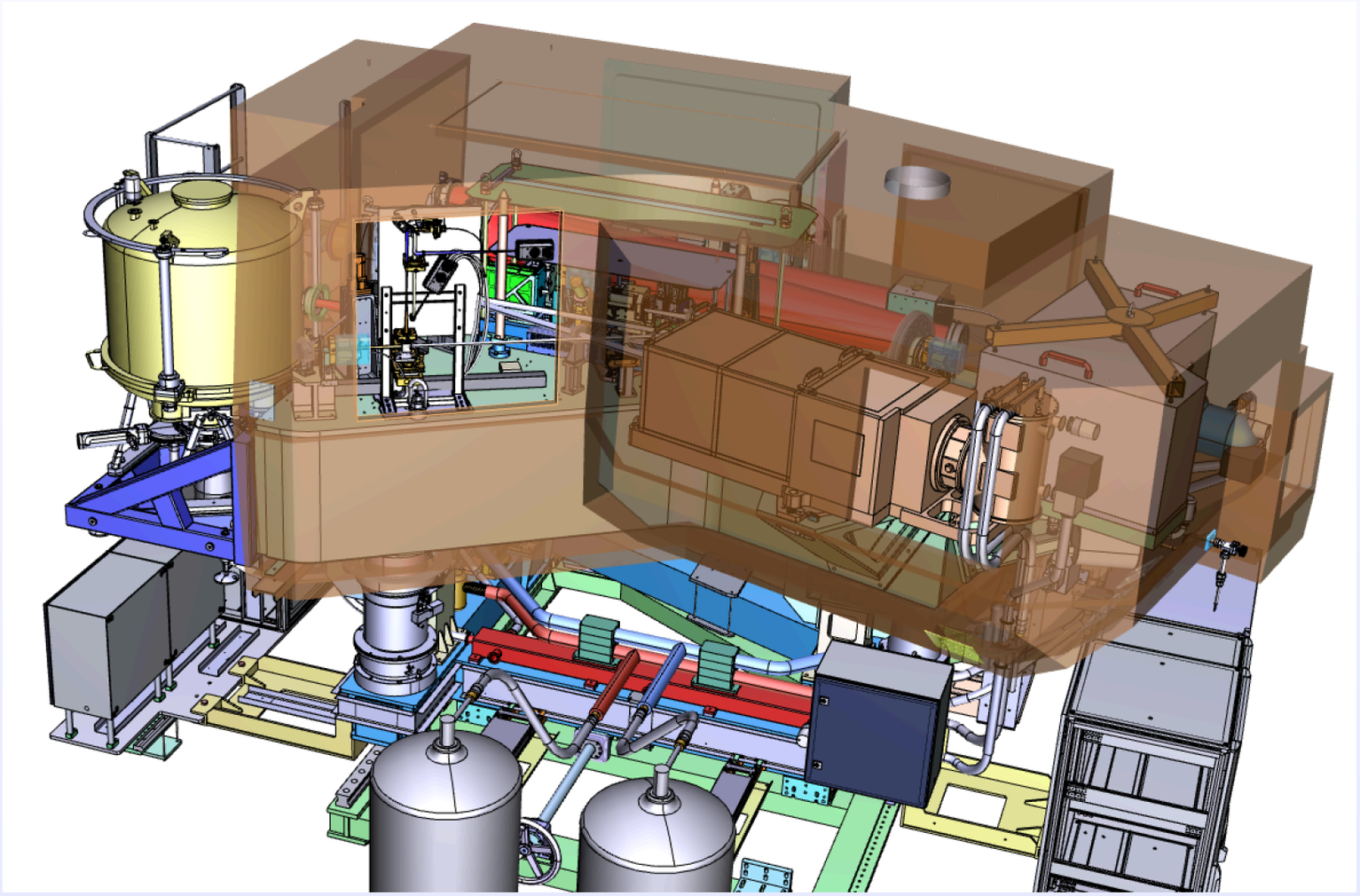
Tracking

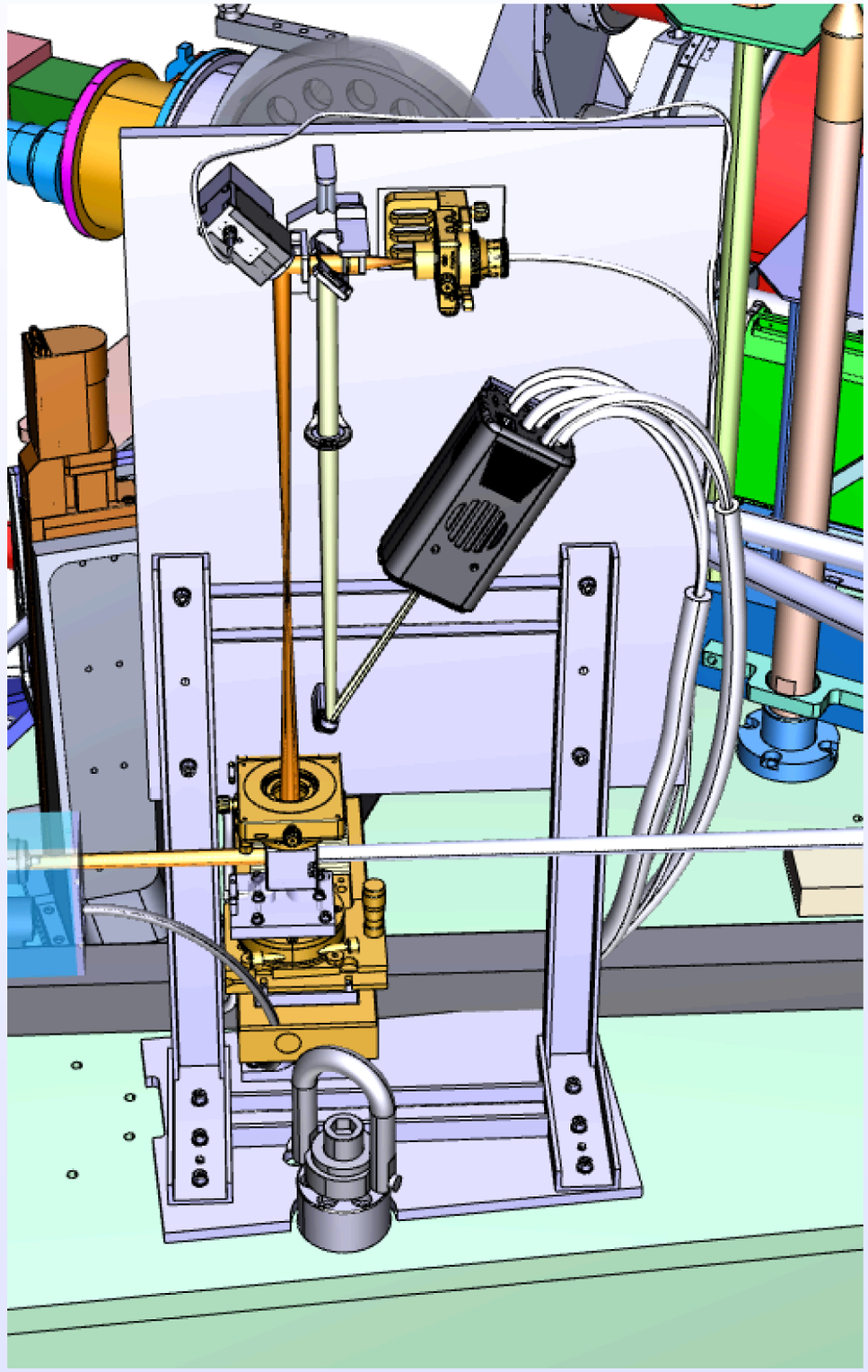


~60 nm rms on axis

Mechanical design

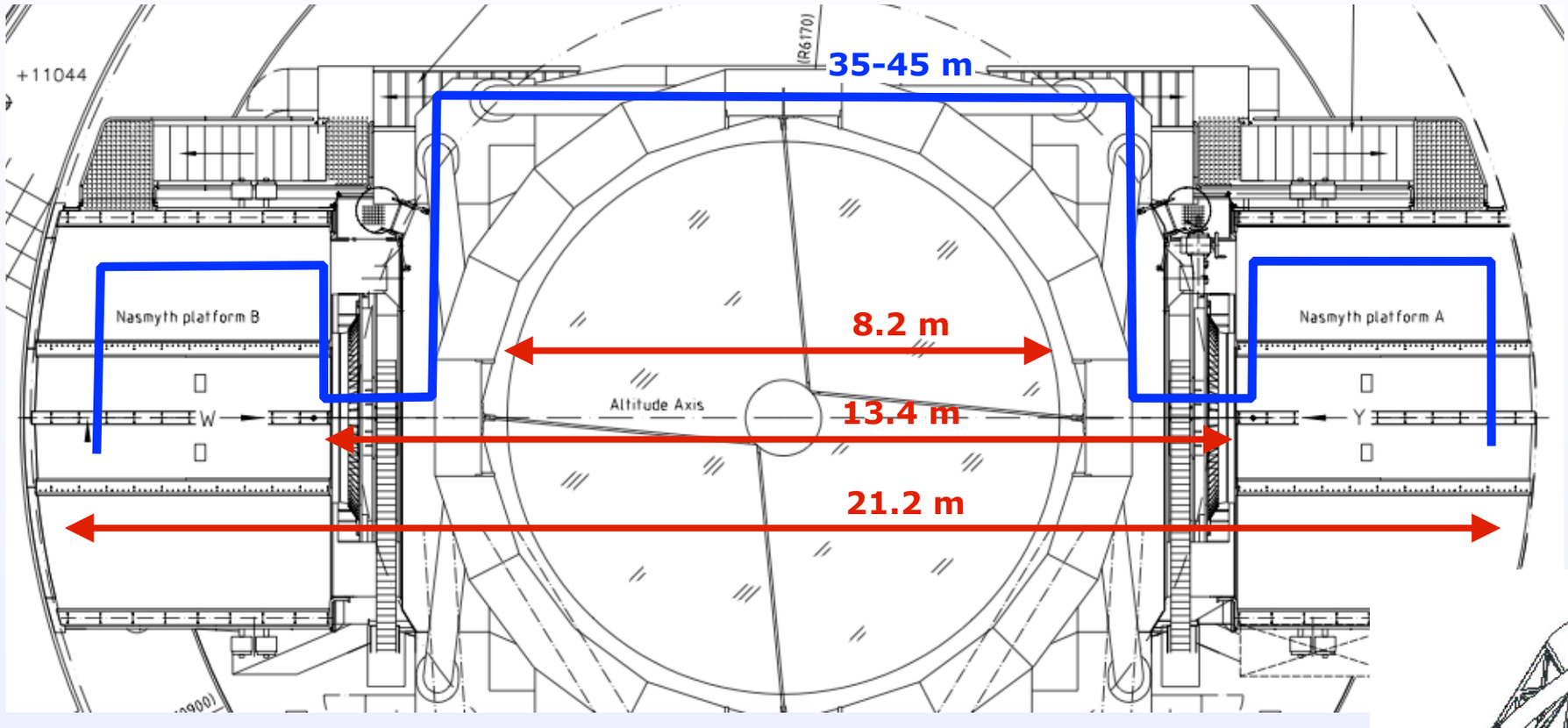
Mechanical design: Y. Charles
N. Tchoubaklian



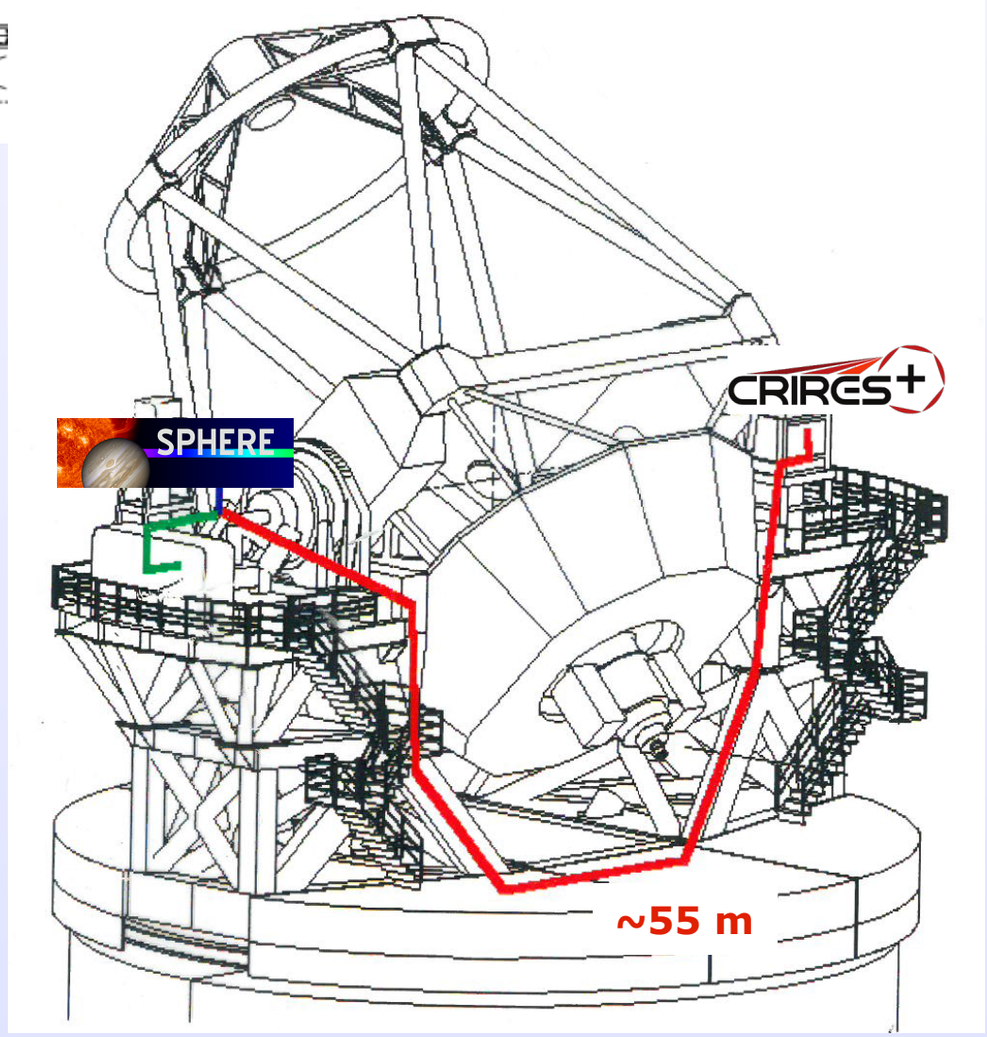


Total weight < 50 kg

NIR fibers between SPHERE and CRIRES+

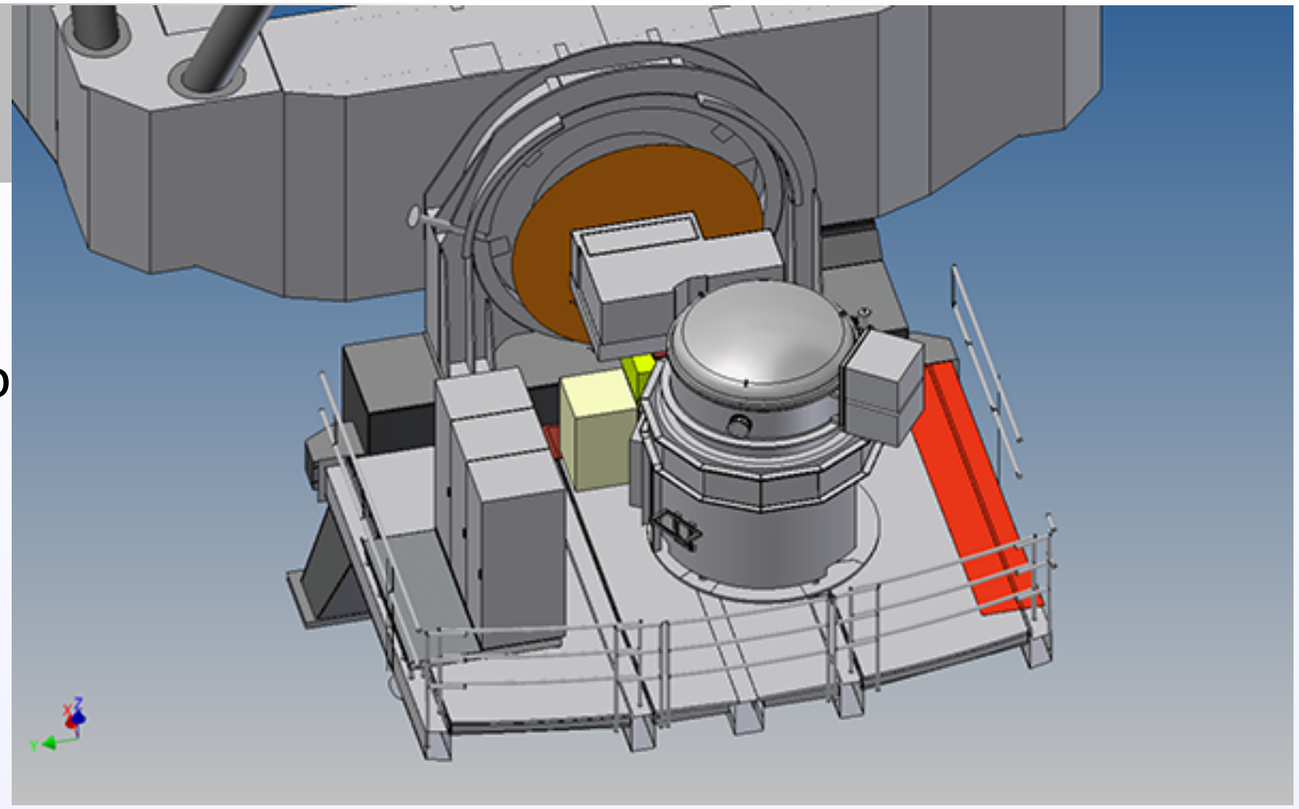


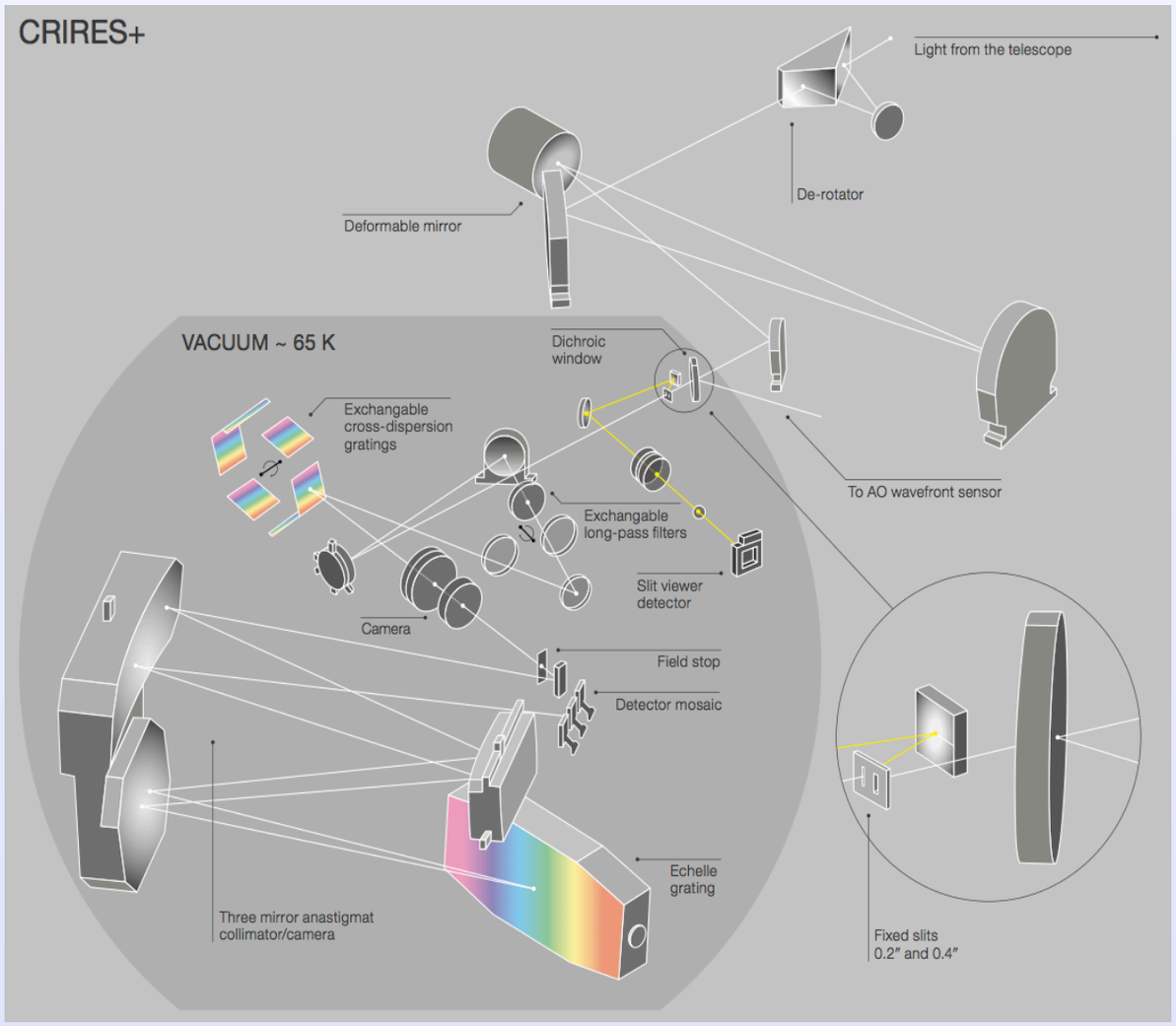
- LVF ZBLAN fibers optimised for near-infrared
- Fibre bundle must go from Nasmyth A to Nasmyth B
- Similar setup already implemented for FLAMES/UVES
  - fibre length ~55 m

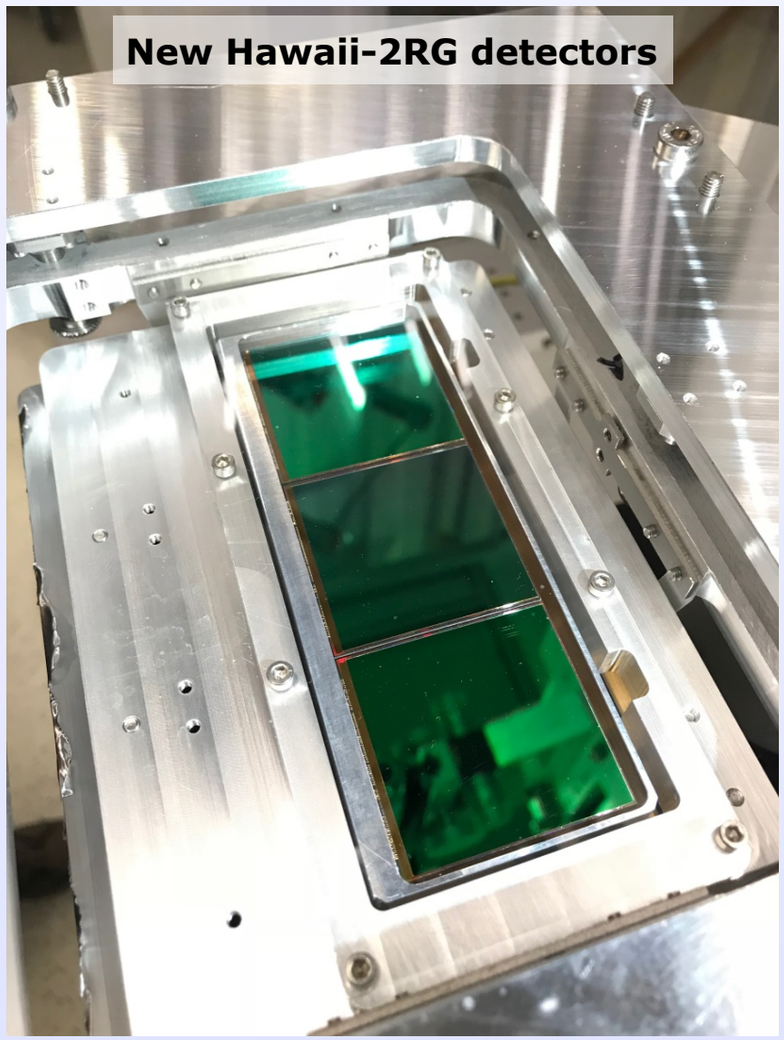


CRIRES+

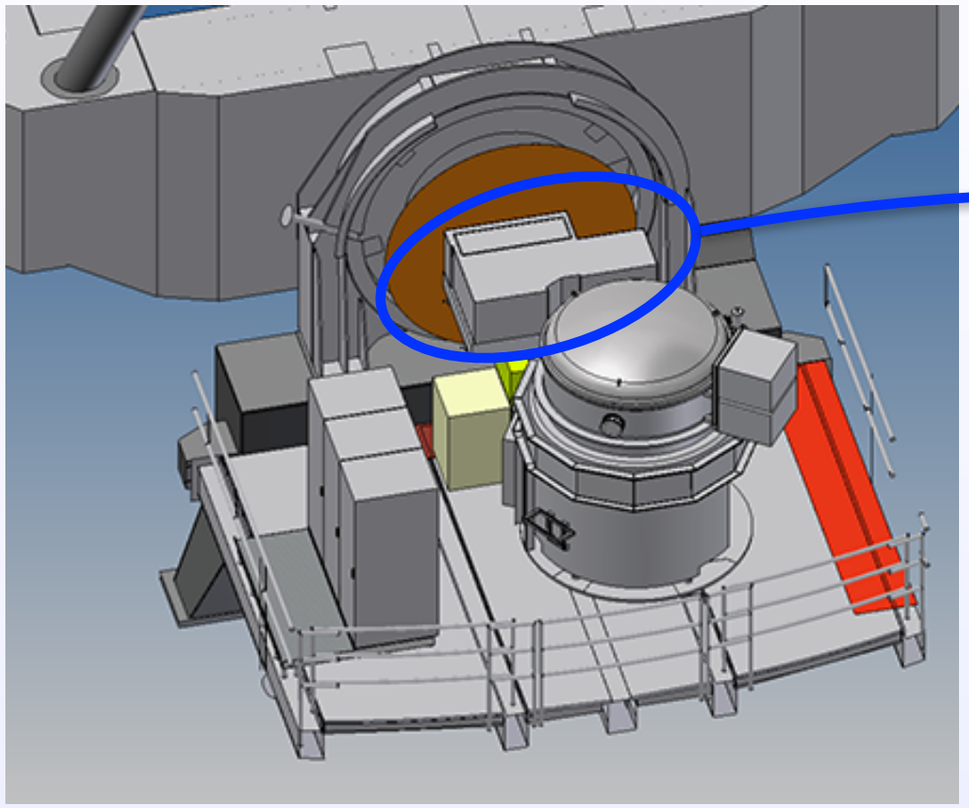
- NIR infrared echelle spectrograph
- Being upgraded to a cross-dispersed spectro
  - new cross-dispersion gratings stage
  - new detectors
  - slit reduced from 40" to 10"

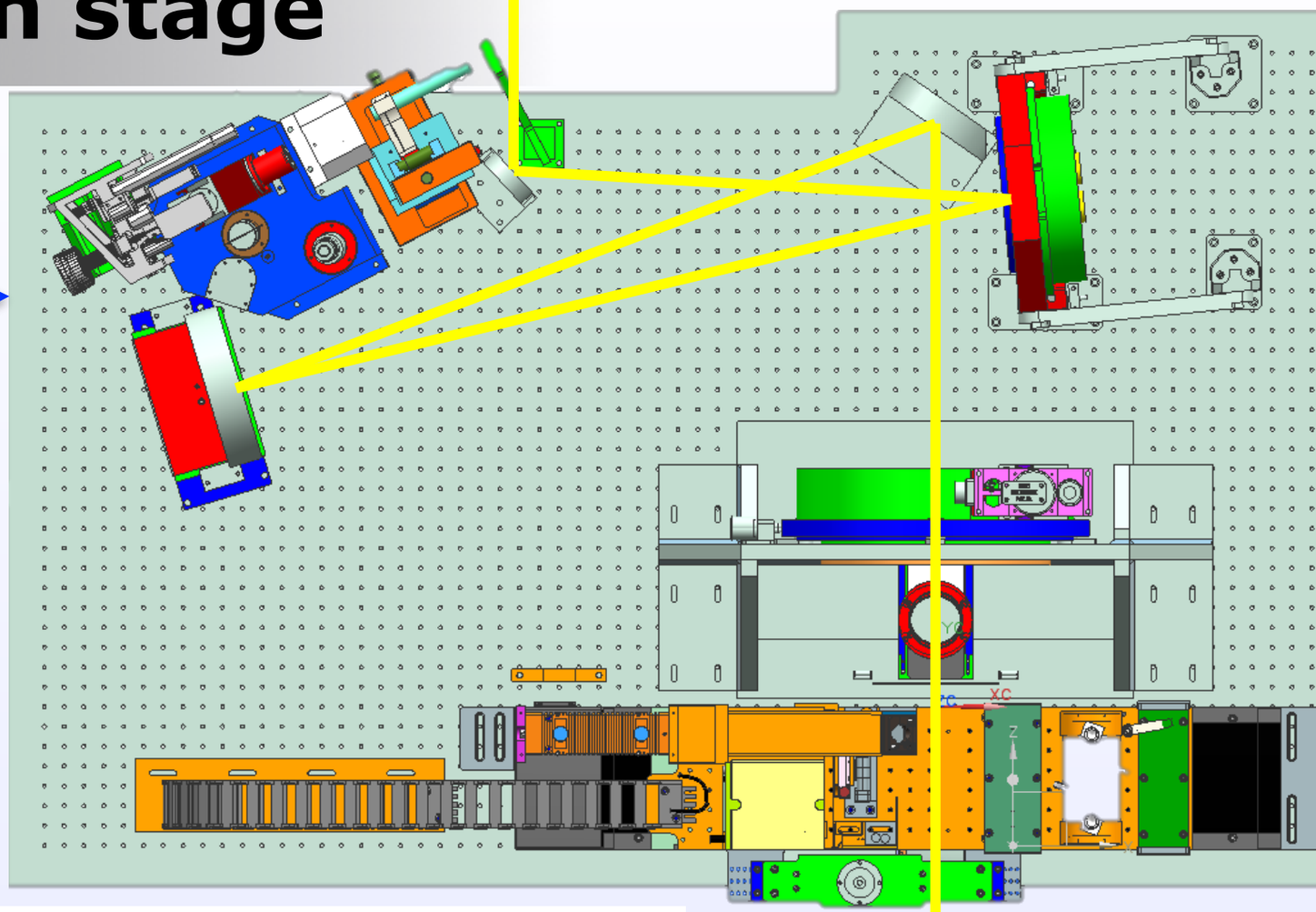


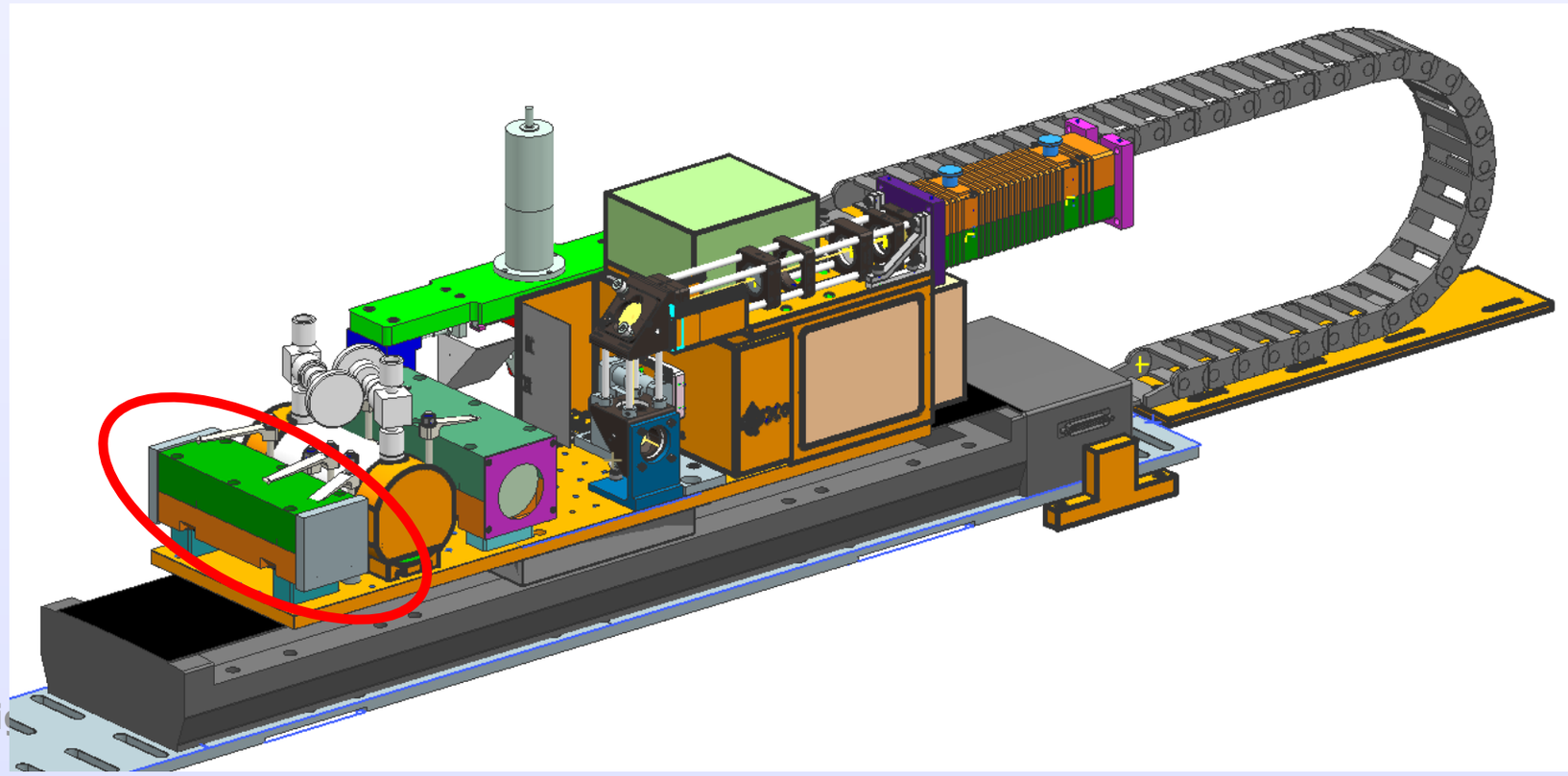




CRIRES+ calibration stage







Performance: HiRISE simulation tool

Otten et al. (in prep.)

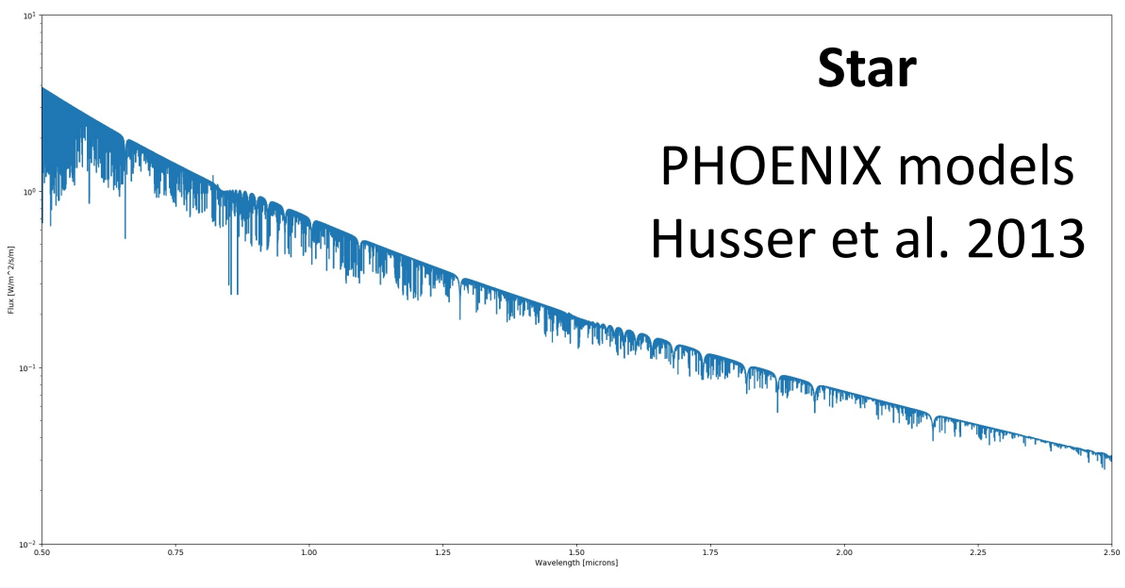
Input spectra	***Earth's Atmosphere***	**Telescope**	***AO + Direct imager***	***HiRISE***	**High resolution spectrograph**
BTSETTL-Nextgen PHOENIX Phillips, Baraffe, 2018	ESO SkyCalc	VLT	SAXO + SPHERE		CRIRES+
R>=10^5, stellar mag planet-star contrast	Emission + Absorption	Transmission, lambda/D	strehl ratio stellar halo, coronagraph	coupling efficiency, transmission	R=100k, transmission, detector noise

- Flexible configuration of HDS + HCI components
- Input spectra at high resolution of known targets
- Include major noise sources
  - Transmission losses (optics, injection)
  - Stellar halo (post-AO + coronagraph)
  - Earth’s atmosphere
  - Detector noise

Explore feasibility and expected S/N for known directly imaged planets

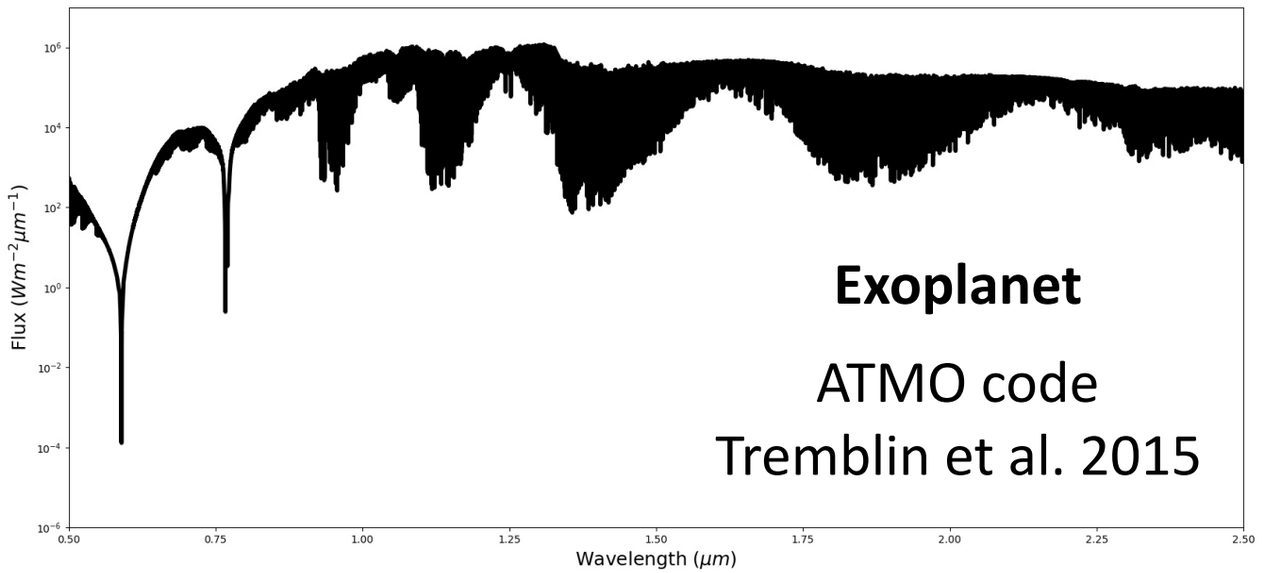
Explore science cases

Input high-resolution models



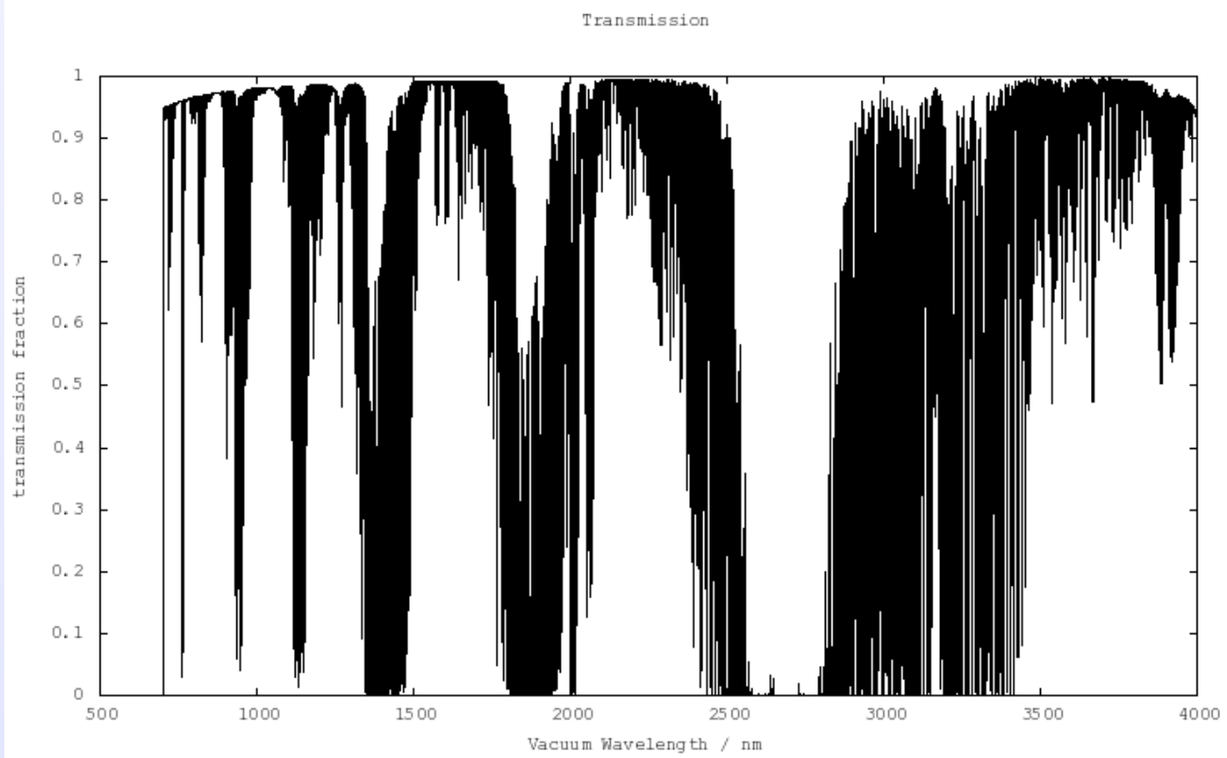
Star

PHOENIX models
Husser et al. 2013



Exoplanet

ATMO code
Tremblin et al. 2015

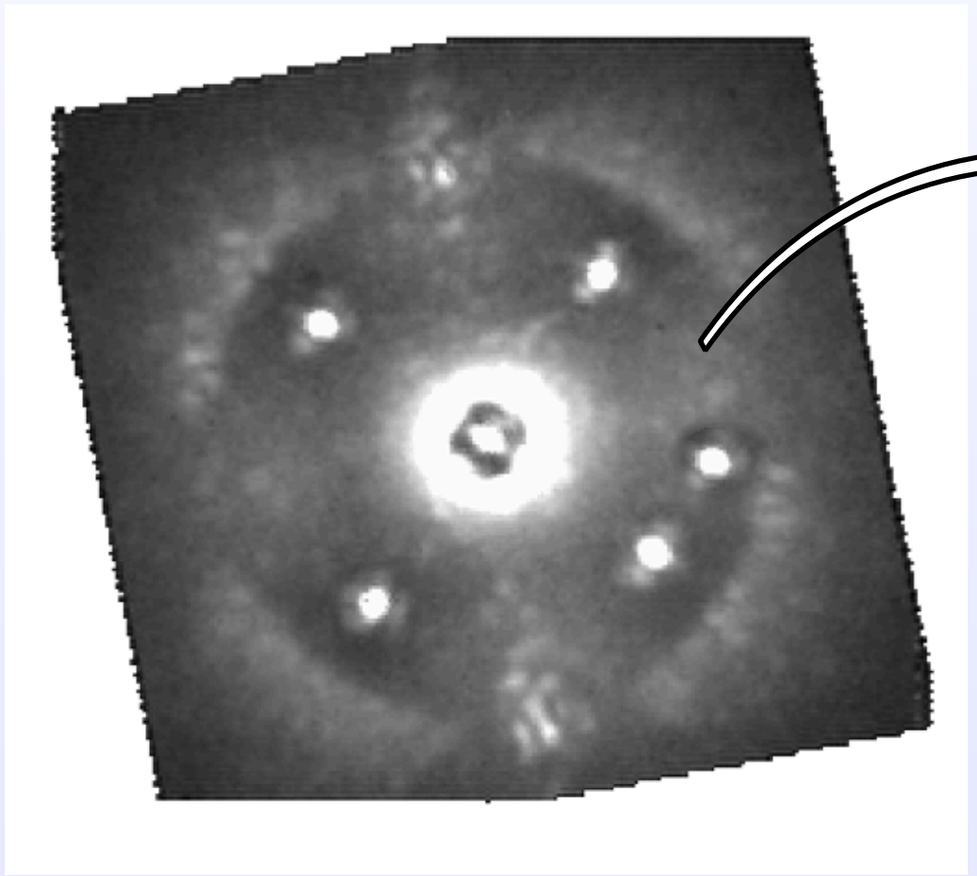


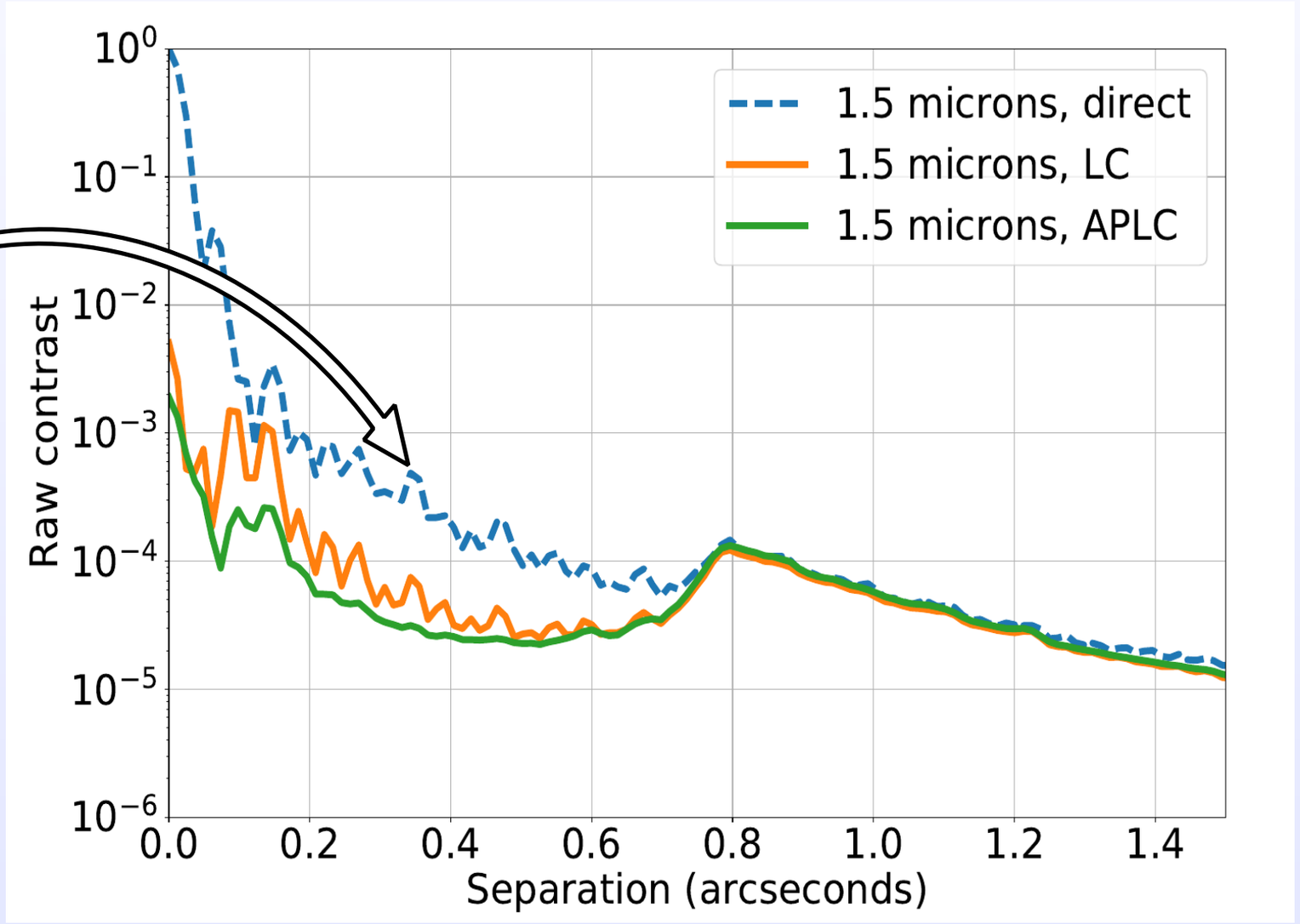
Earth's atmosphere

ESO SkyCalc
Noll et al. 2012
Jones et al. 2013

VLT + AO + SPHERE

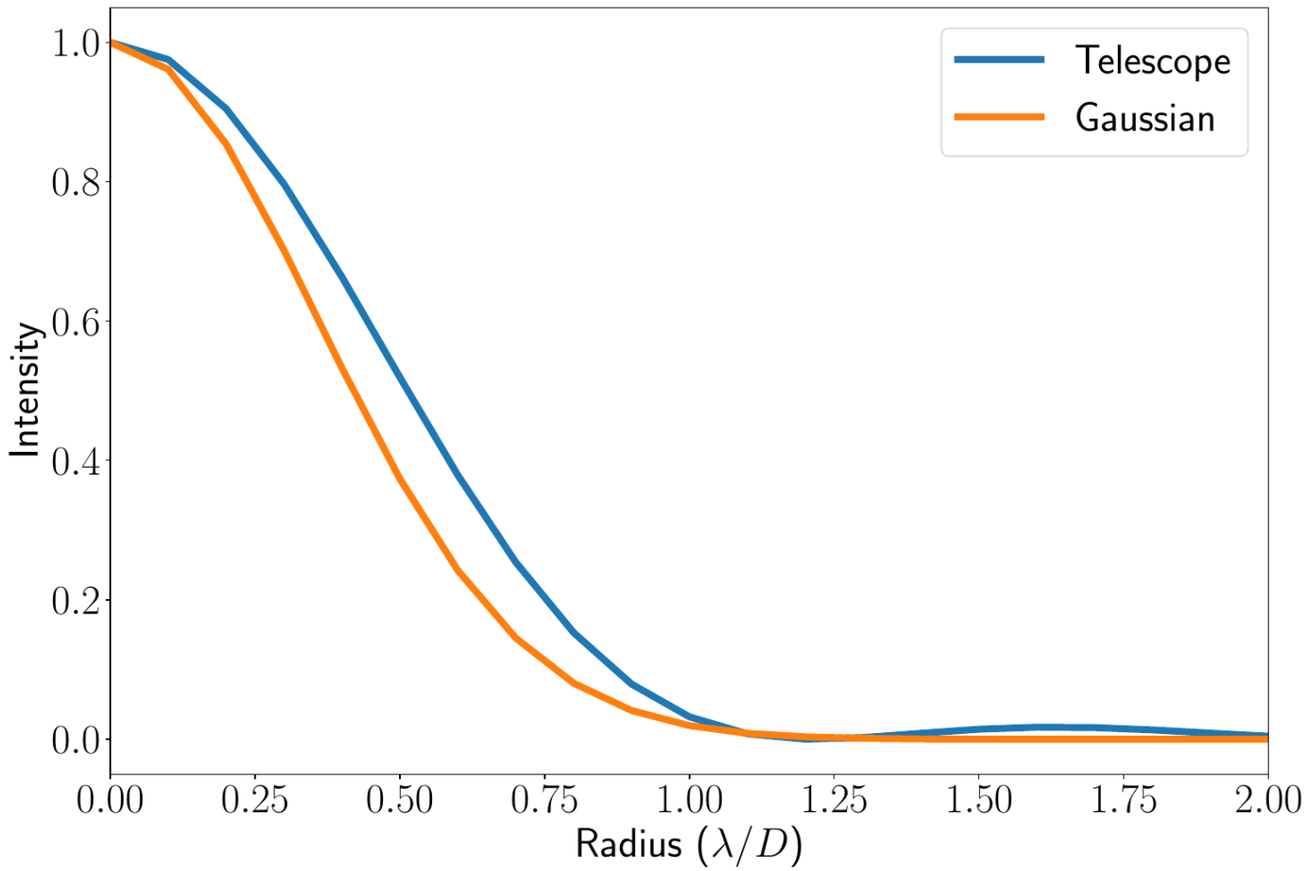
- Halo of star at location of planet, throughput
  - Based on SPHERE measurements and real data





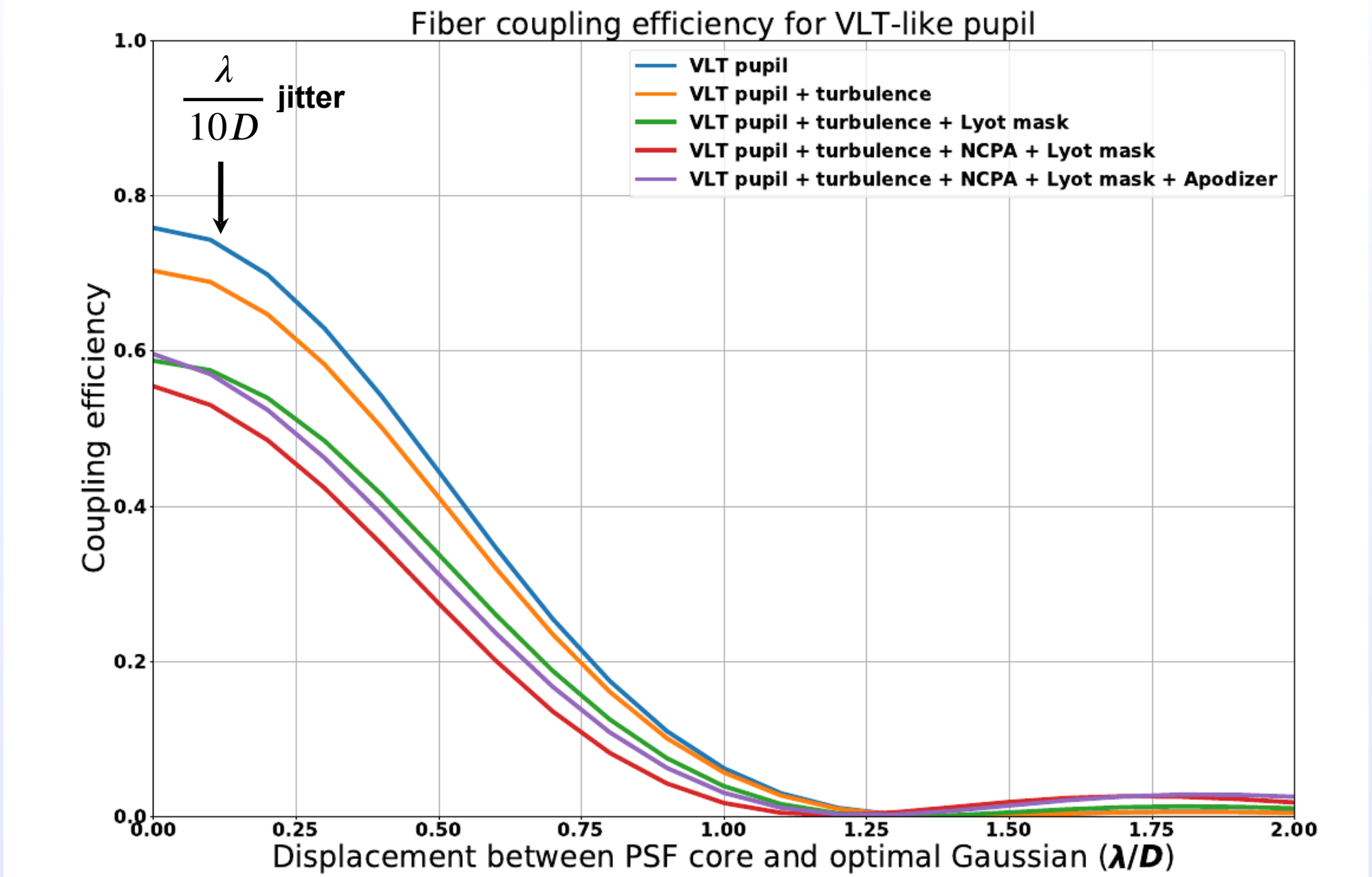
HiRISE injection efficiency

Need to match telescope PSF to Gaussian mode of fiber



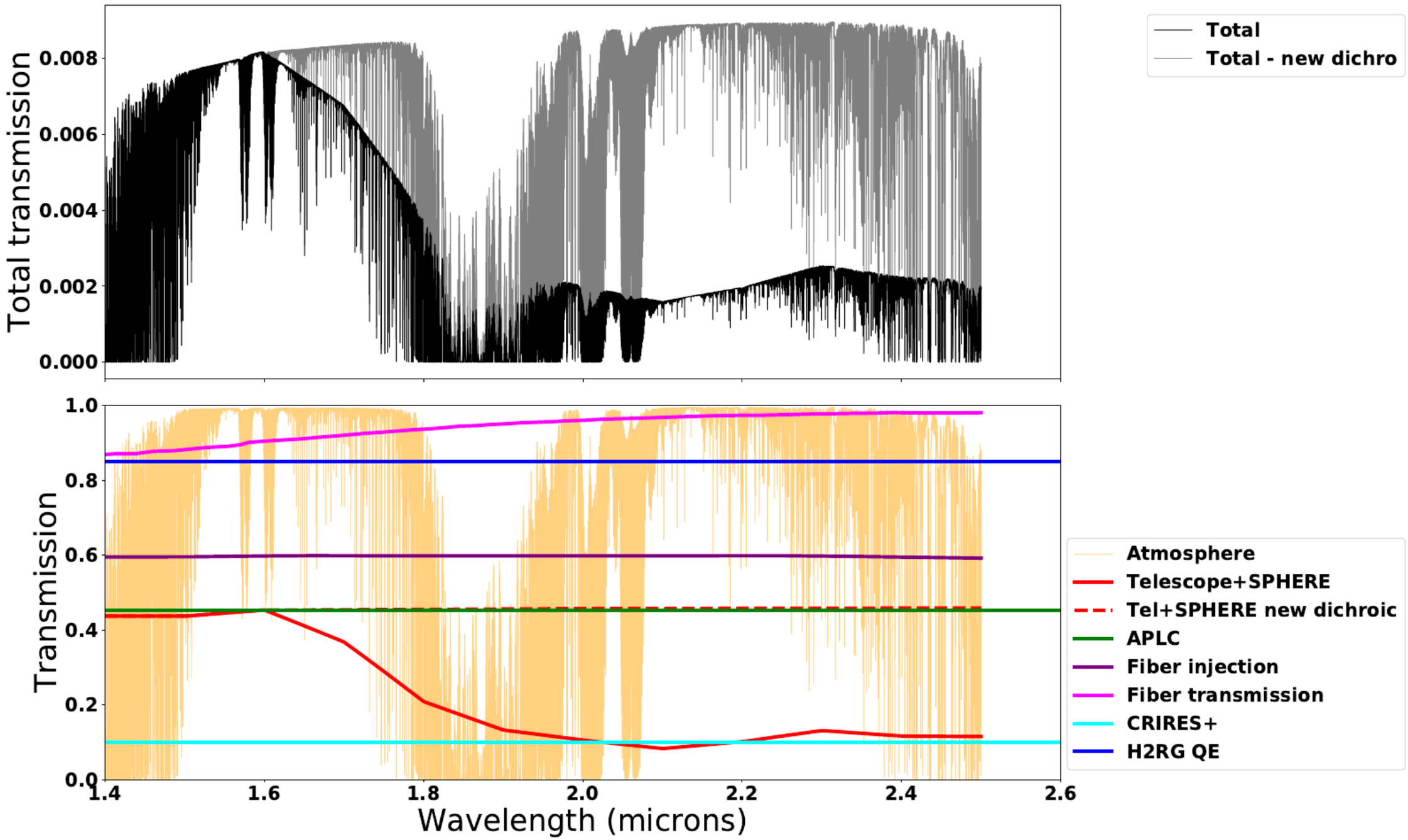
$$\eta = \frac{|\int E_1^* E_2 dA|^2}{\int |E_1|^2 dA \int |E_2|^2 dA}$$

HiRISE injection efficiency



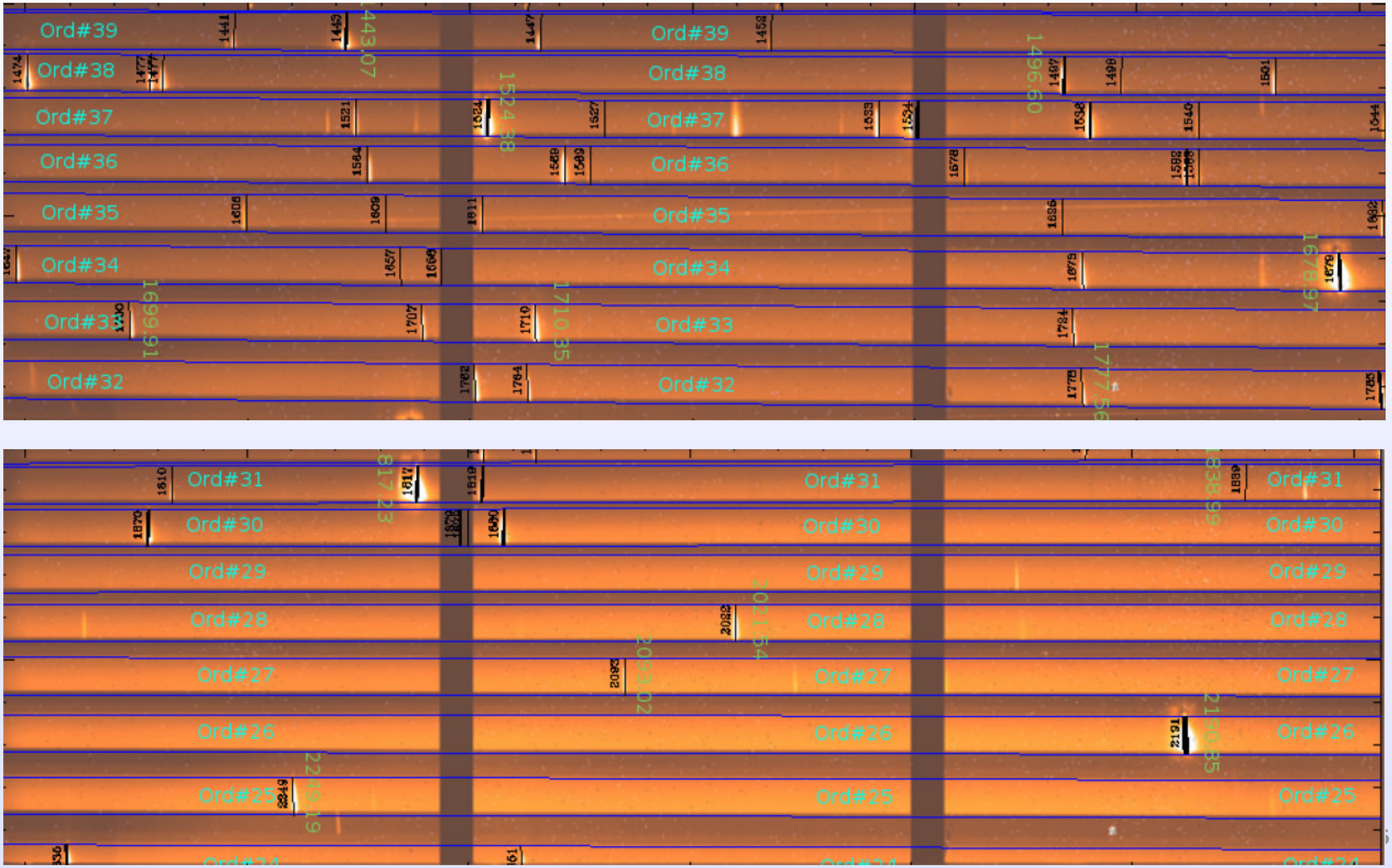
Total throughput

Expected total throughput < 1%



CRIRES+ wavelength settings

Almost a full band in a single observation!



CRIRES+ wavelength settings

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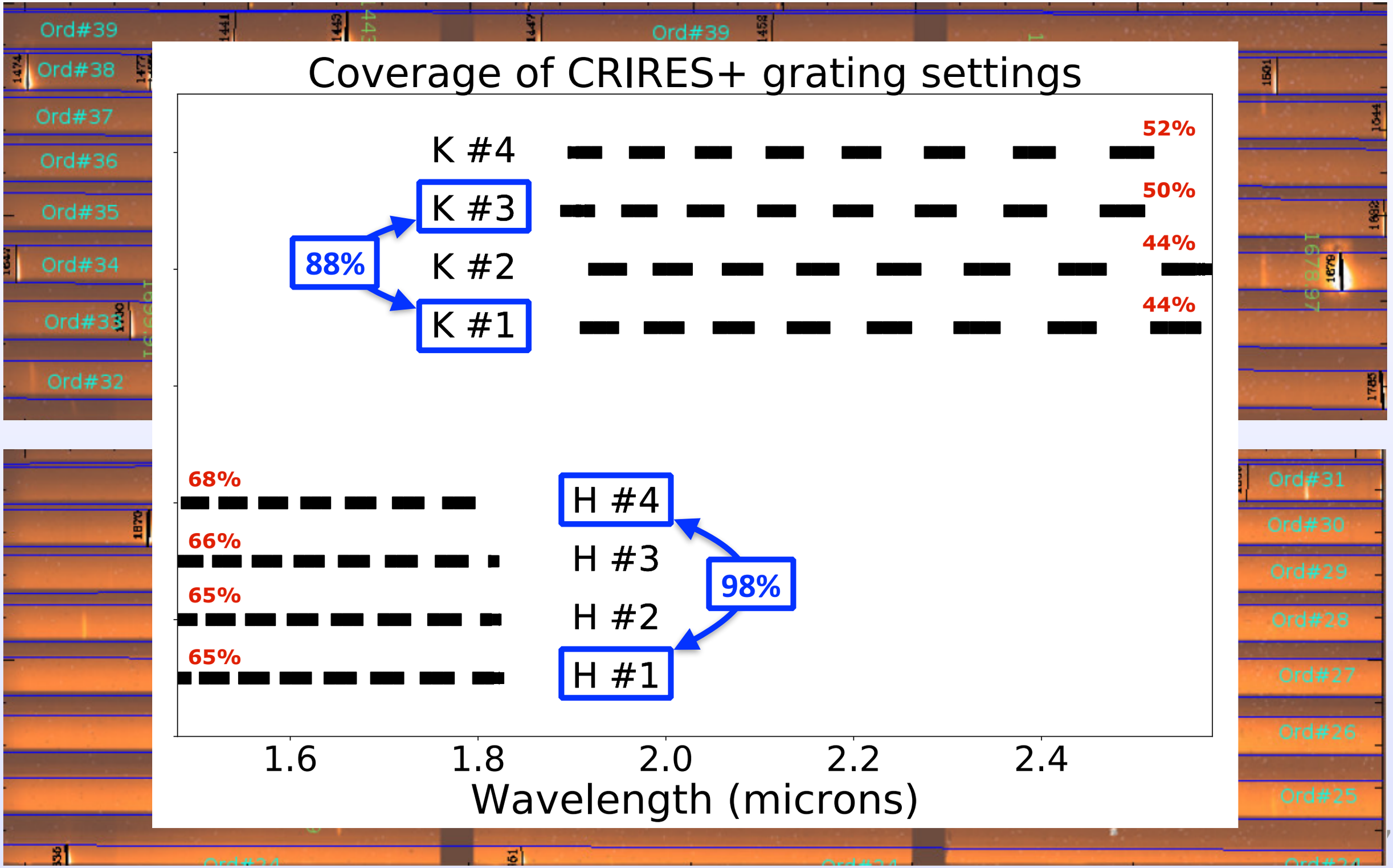
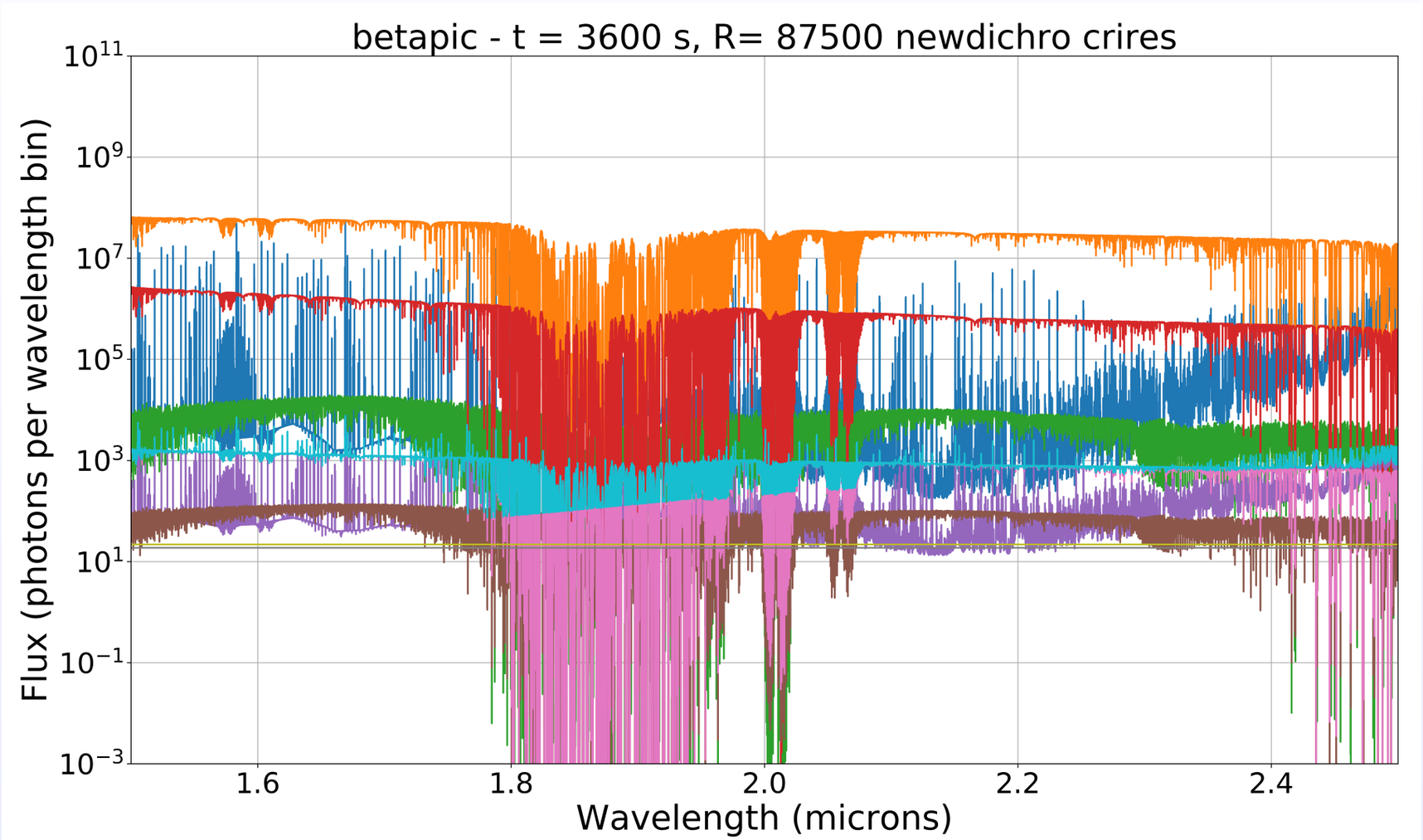
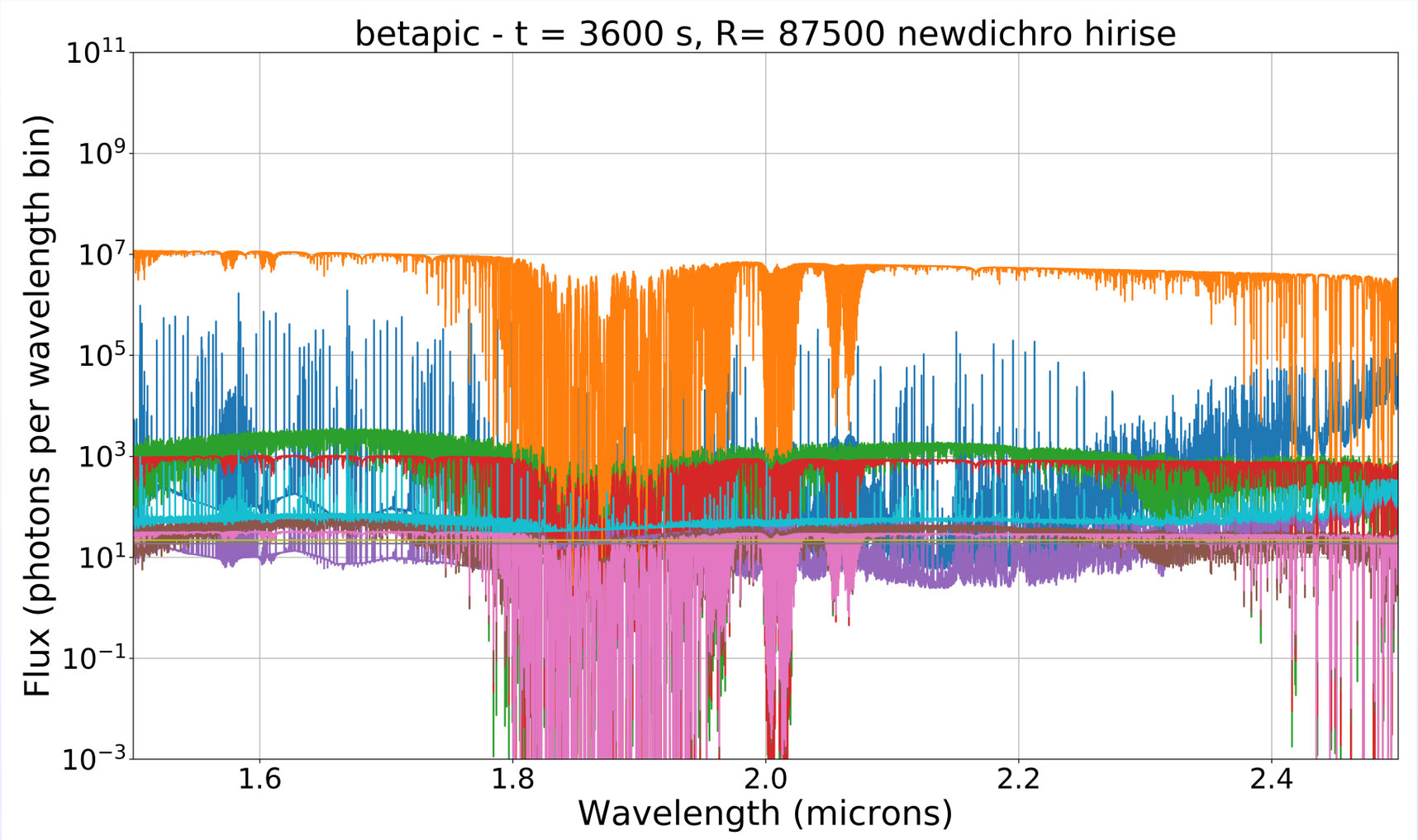


ß Pictoris b: noise breakdown for CRIRES+



- Dominant noise sources
  1. Stellar halo
  2. noise of planet and sky background
- so if we can switch off the stellar halo we potentially gain a factor of 10 in S/N for beta pic b

ß Pictoris b: noise breakdown for HiRISE

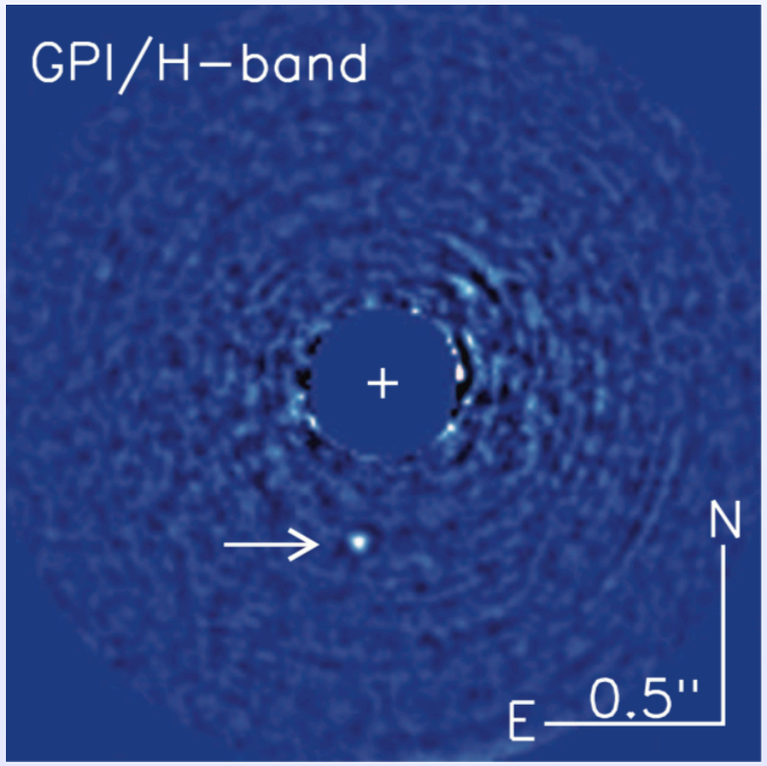


- Dominant noise sources
  1. No specific noise source now!

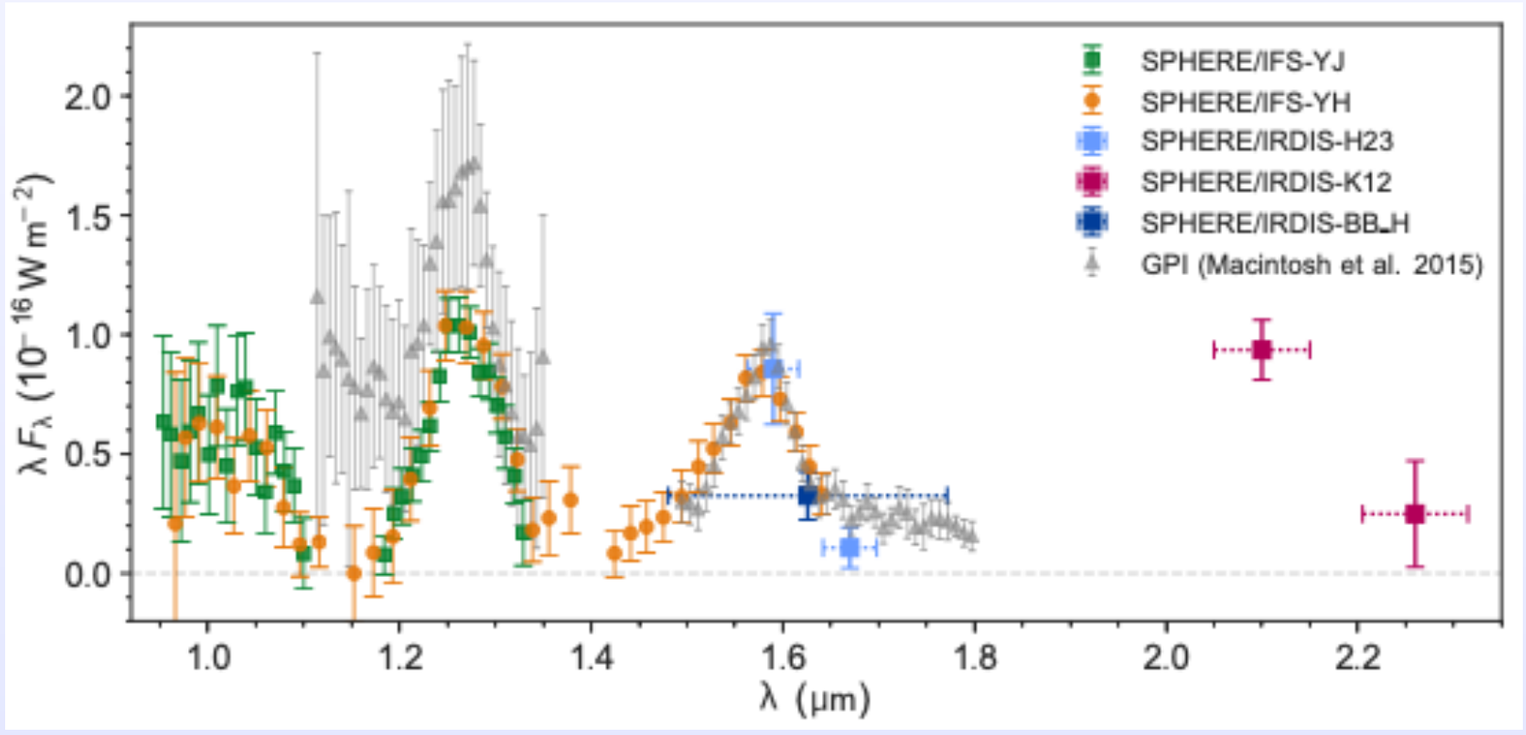
Practical example: 51 Eri b

51 Eri: highest contrast directly imaged exoplanet known today

Contrast: 2×10^{-6} in H-band
Separation: 0.450"



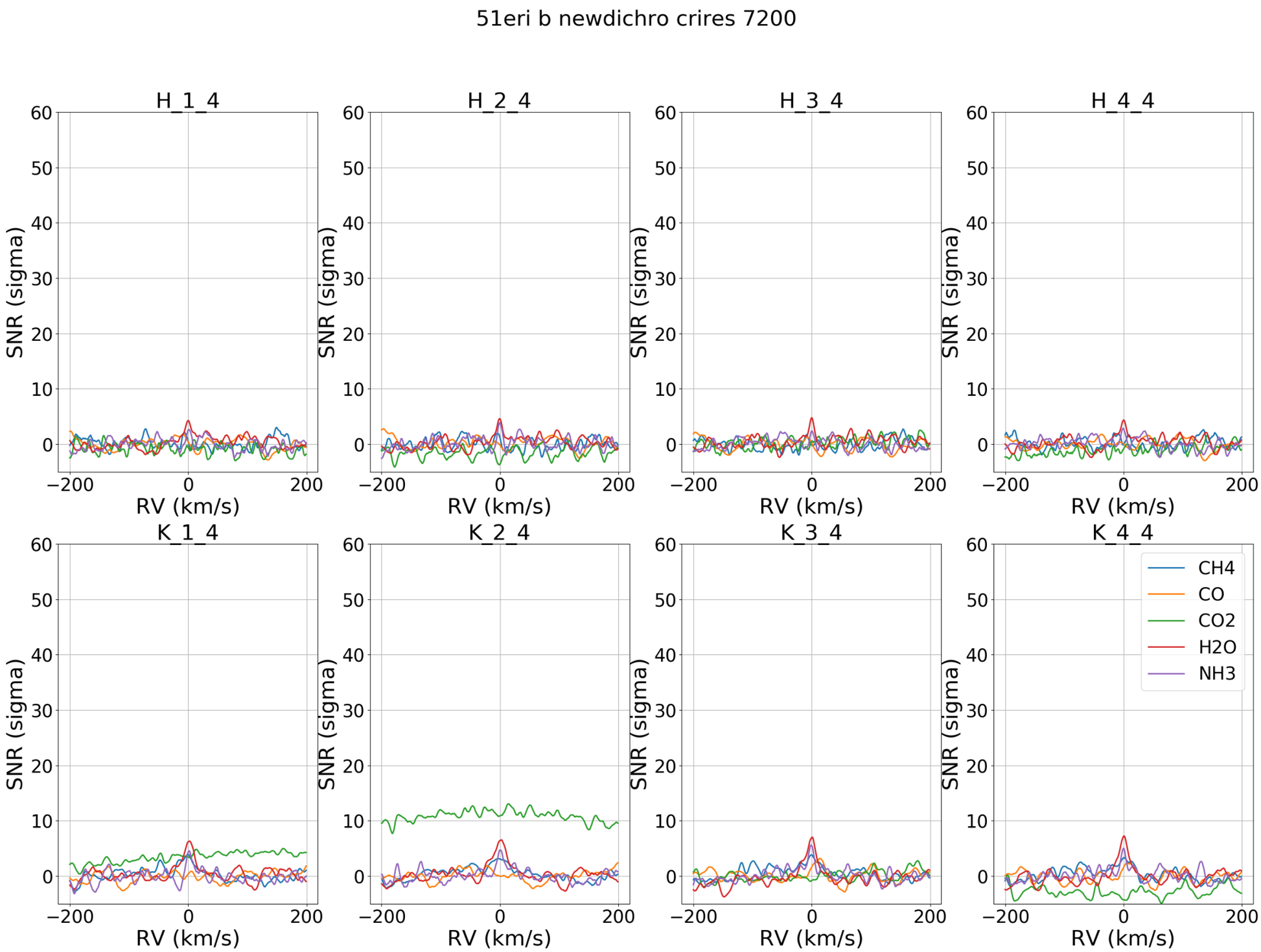
Macintosh et al. 2015



Detection thresholds - 51 Eri b

2 hours of integration time

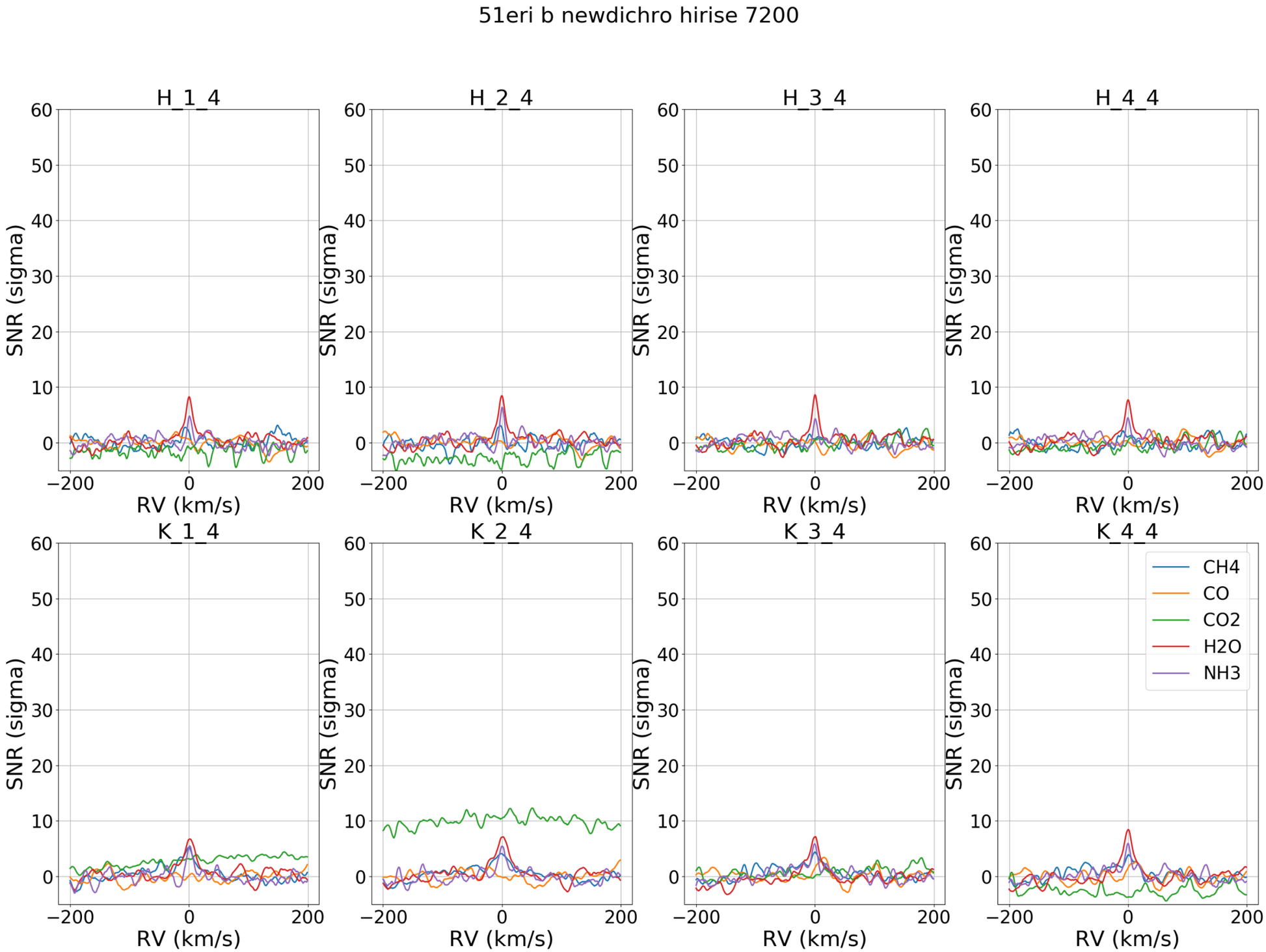
CRIRES+ standalone



Detection thresholds - 51 Eri b

2 hours of integration time

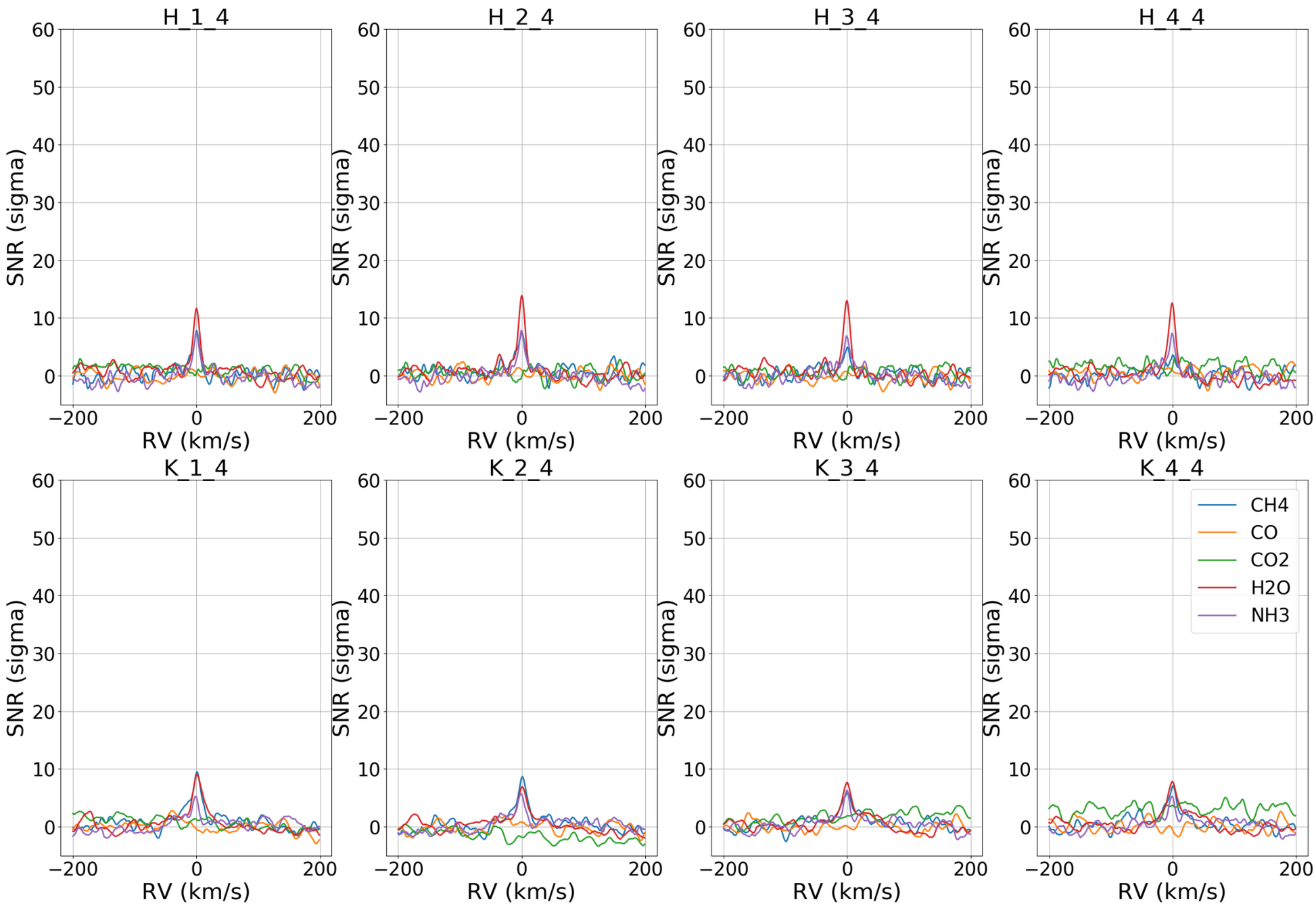
HiRISE with APLC
(assuming dedicated dichroic)



Detection thresholds - 51 Eri b

2 hours of integration time

HiRISE without APLC
(assuming dedicated dichroic)



Conclusions

- **SPHERE is a powerful direct imaging instrument**
  - ... but characterisation capabilities are limited by the low spectral resolution (R<100)
- **HiRISE: proposed fiber optics coupling with CRIRES+**
  - Goal: fine characterisation of known directly imaged exoplanets
  - Implementation: Fiber injection module in SPHERE + ~50 m of infrared fibers + Fiber extraction module in CRIRES+
  - Current status:
    - Opto-mechanical design on-going
    - Discussions with ESO for a first version as a "visitor instrument"
- **Possible timeline:**
  - mid-2019: finalising the design
  - 2019-2020: integration and testing @ LAM
  - Early 2021 (?): on-sky validation

http://astro.vigan.fr/ **arthur.vigan@lam.fr** **@ArthurVigan**