HiRISE
Detection and characterisation of young giant exoplanets at high-spectral resolution

Arthur Vigan
Groupe Sciences Planétaires (GSP)
Groupe R&D en instrumentation (GRD)

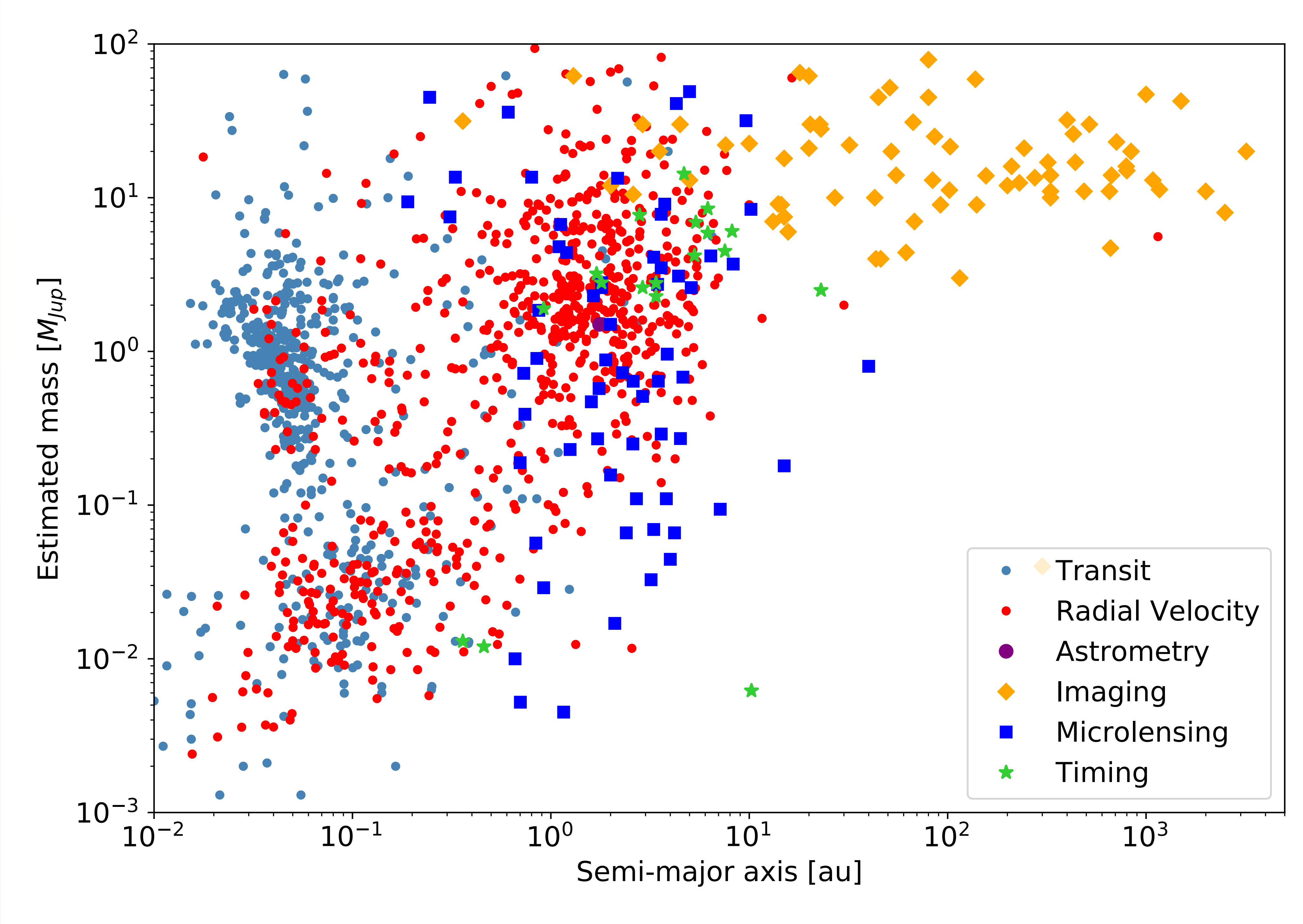
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

erc

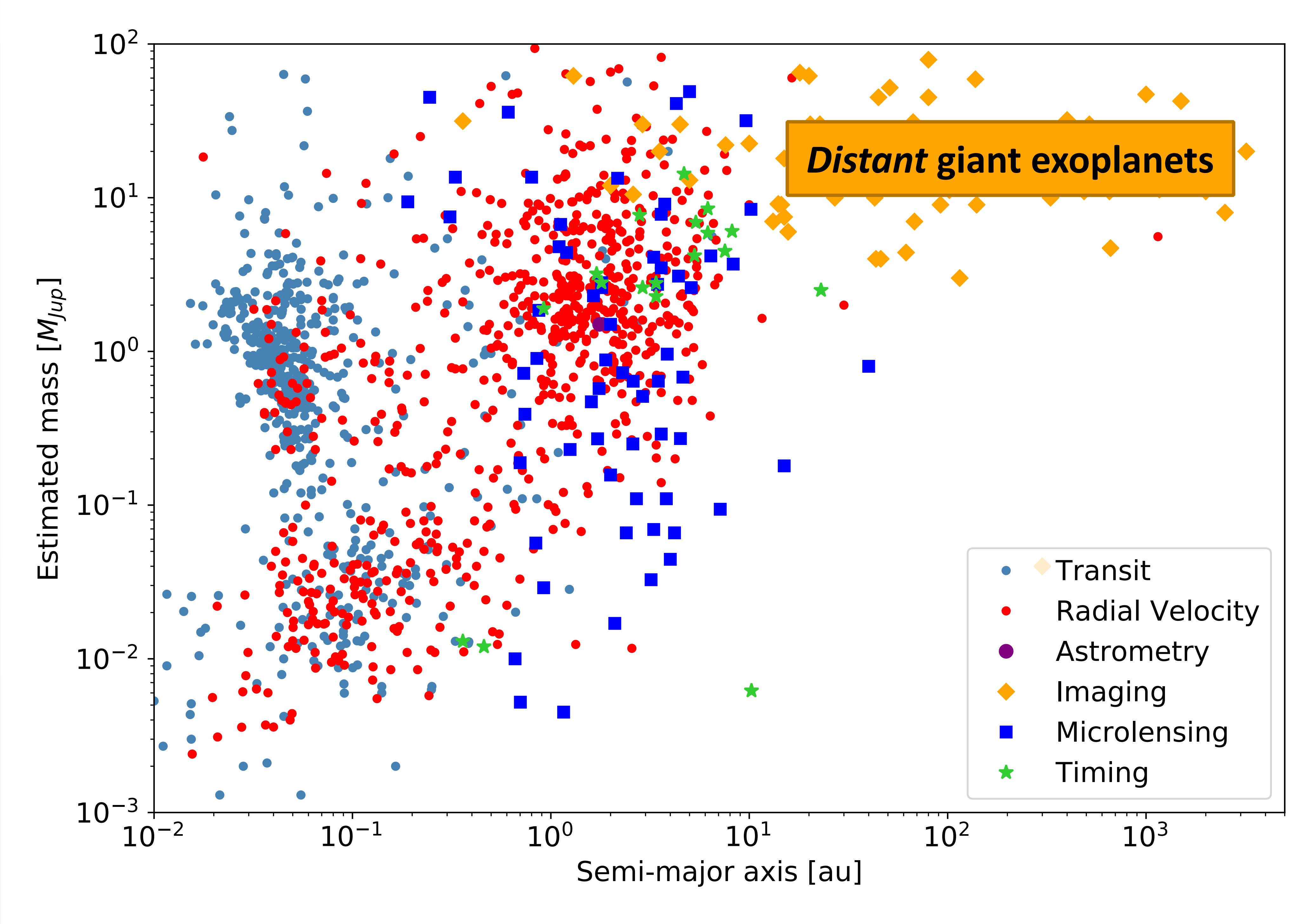
cnrs

Context

Imaging of low-mass companions

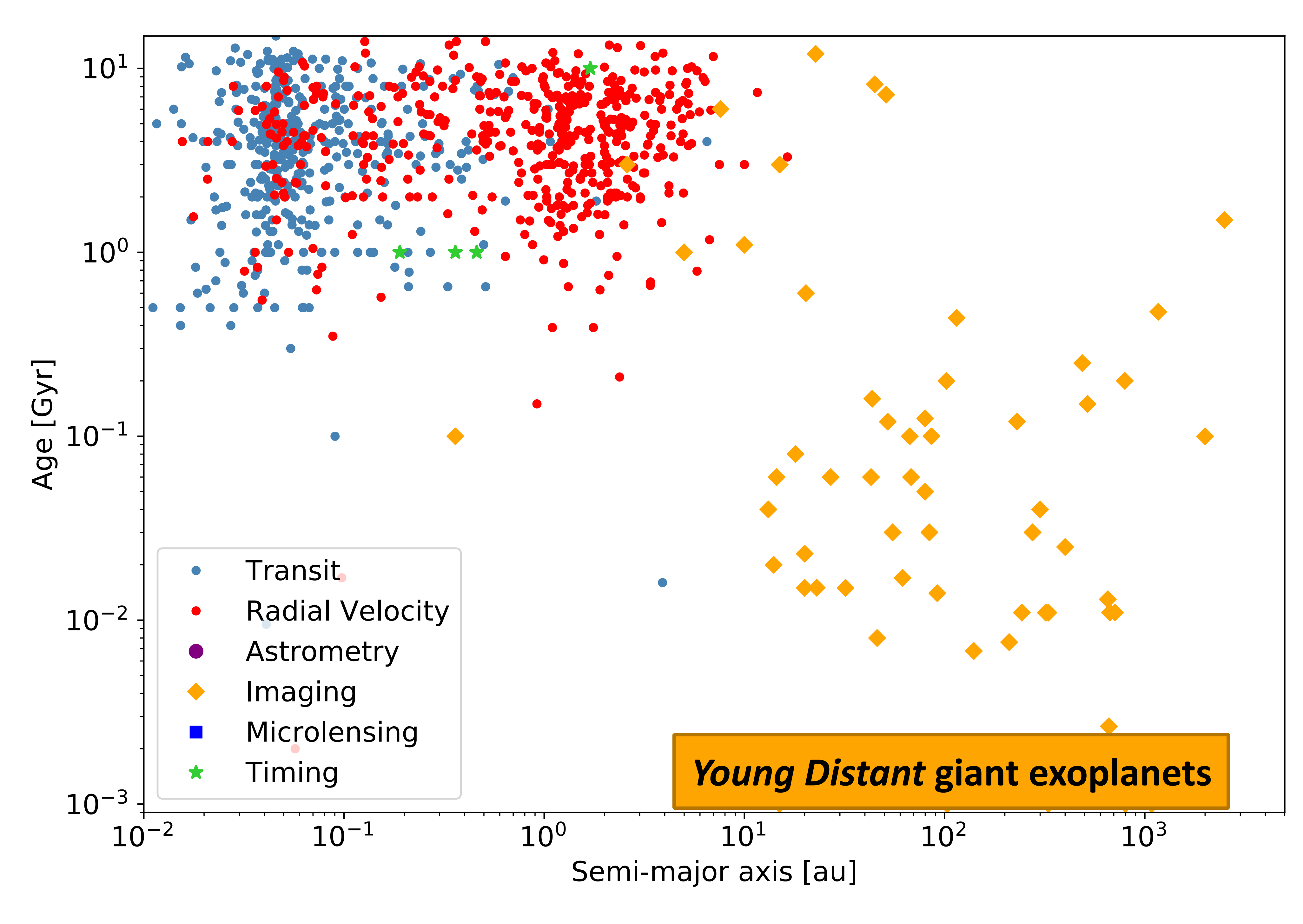


Imaging of low-mass companions



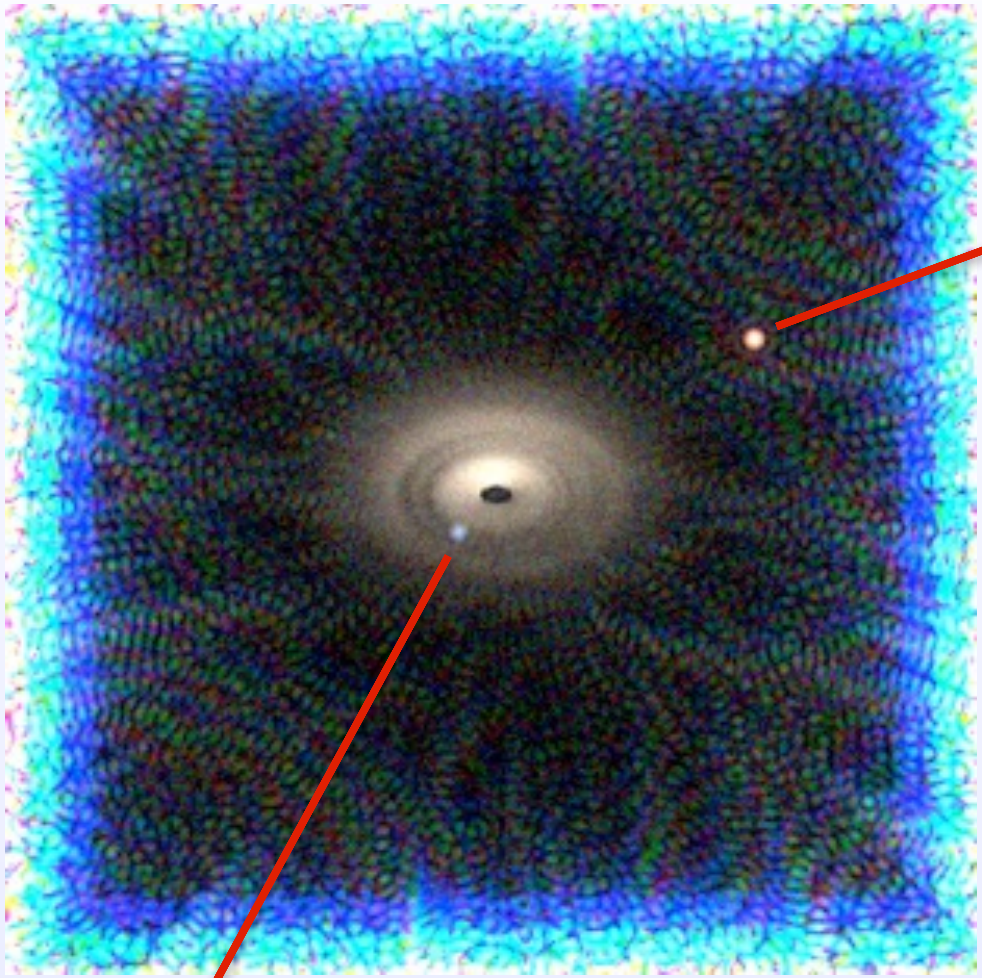
***Distant* giant exoplanets**

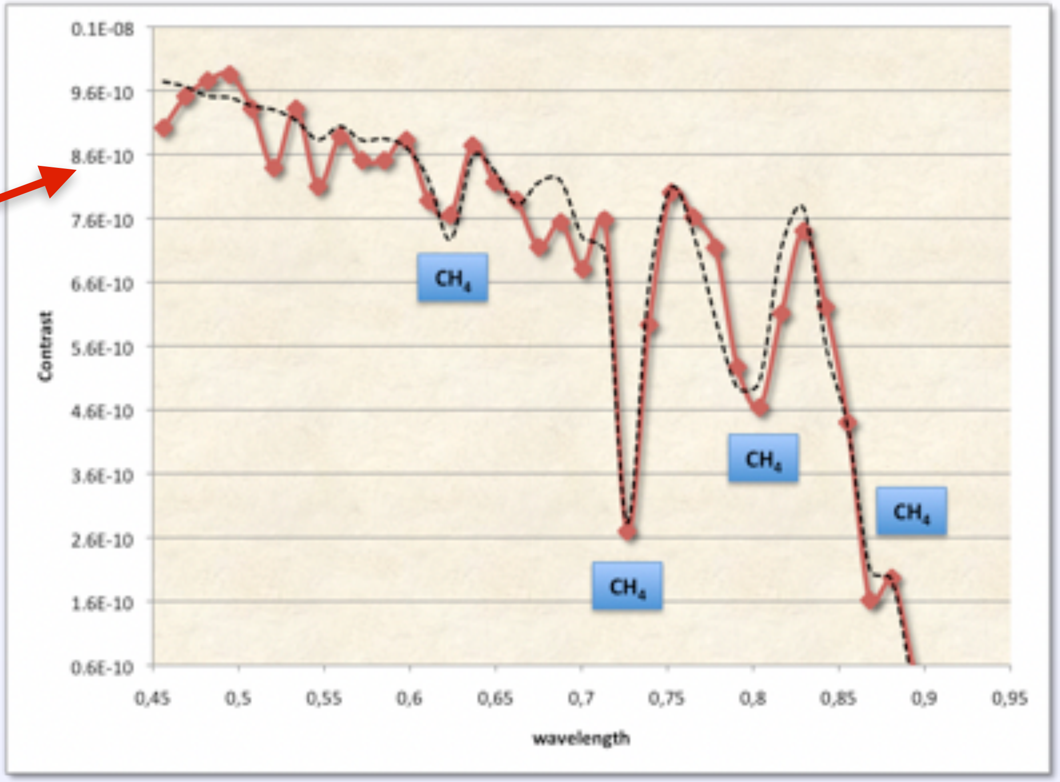
Imaging of low-mass companions

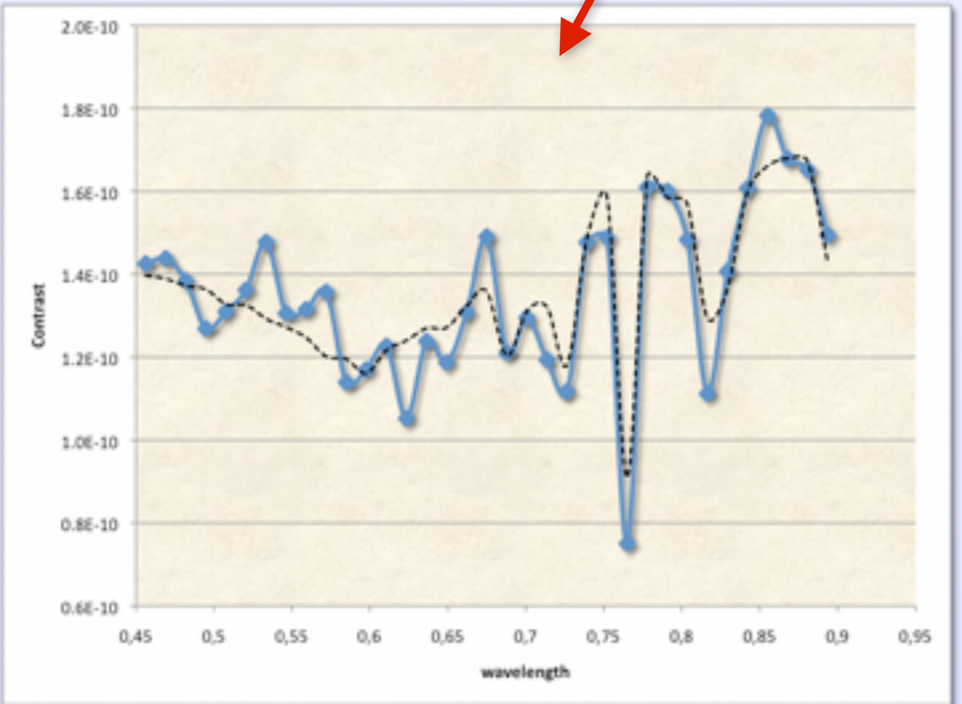


Young Distant **giant exoplanets**

Why do imaging?

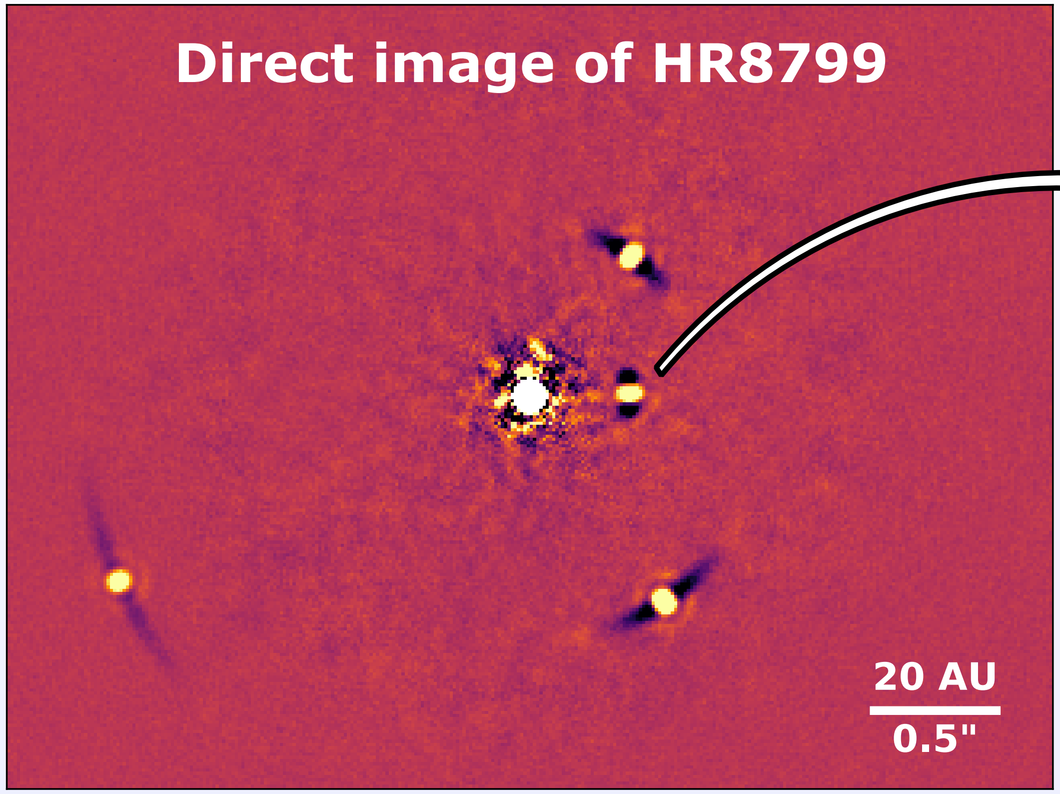






- complementary with other methods:
  - mass, semi-major axis & age
- sensitive to all spatial components: planets, disk
- direct access to:
  - architecture of systems
  - flux vs. wavelength (total and/or polarised)

Atmospheric composition of exoplanets



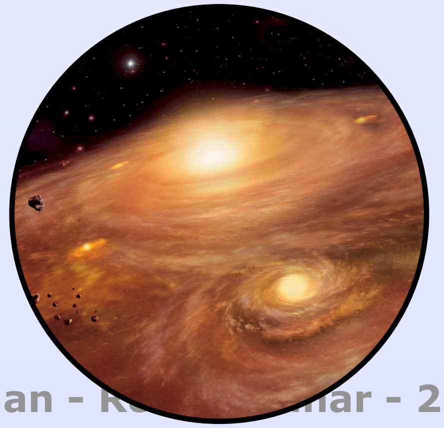
Zurlo, **Vigan** et al. (2016)

Giant exoplanets shape planetary systems

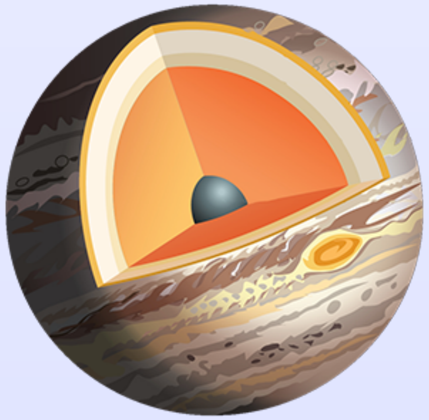
Giant: > 1 M_{Jup}
Distant: > 5 AU
Cold: < 1500K

Outstanding questions to be answered with direct imaging

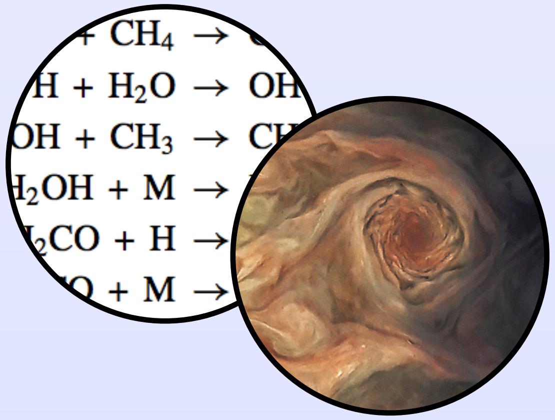
Formation & migration



Internal structure



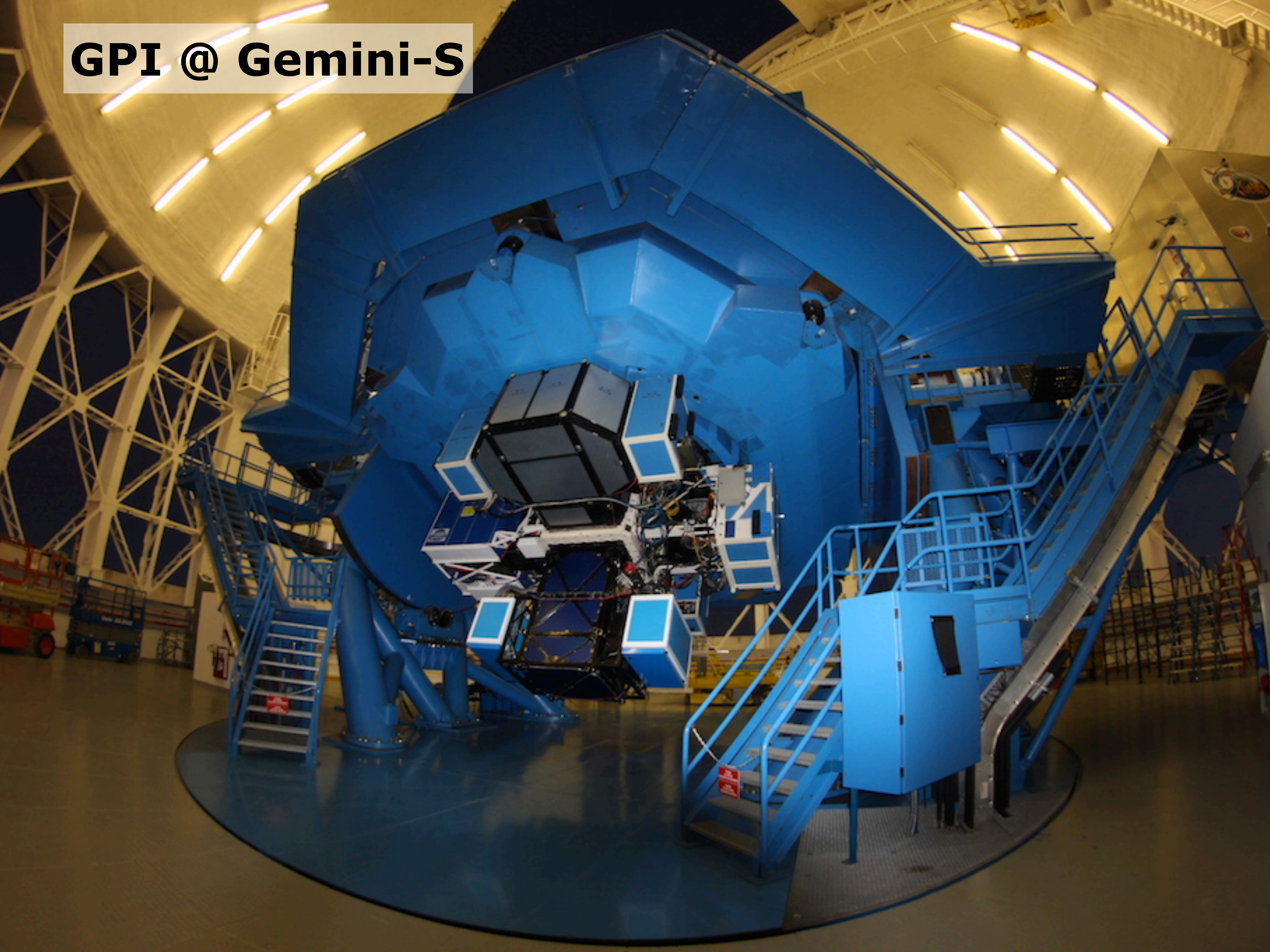
Atmosphere chemistry & dynamics



Today's high-contrast imagers

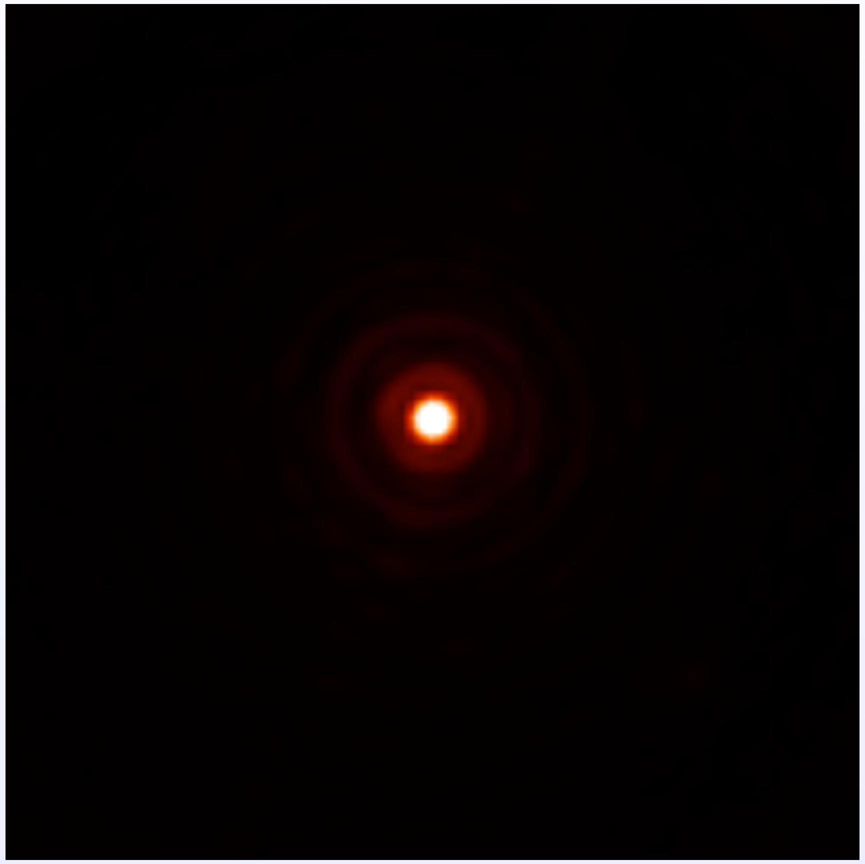
SPHERE @ VLT

GPI @ Gemini-S

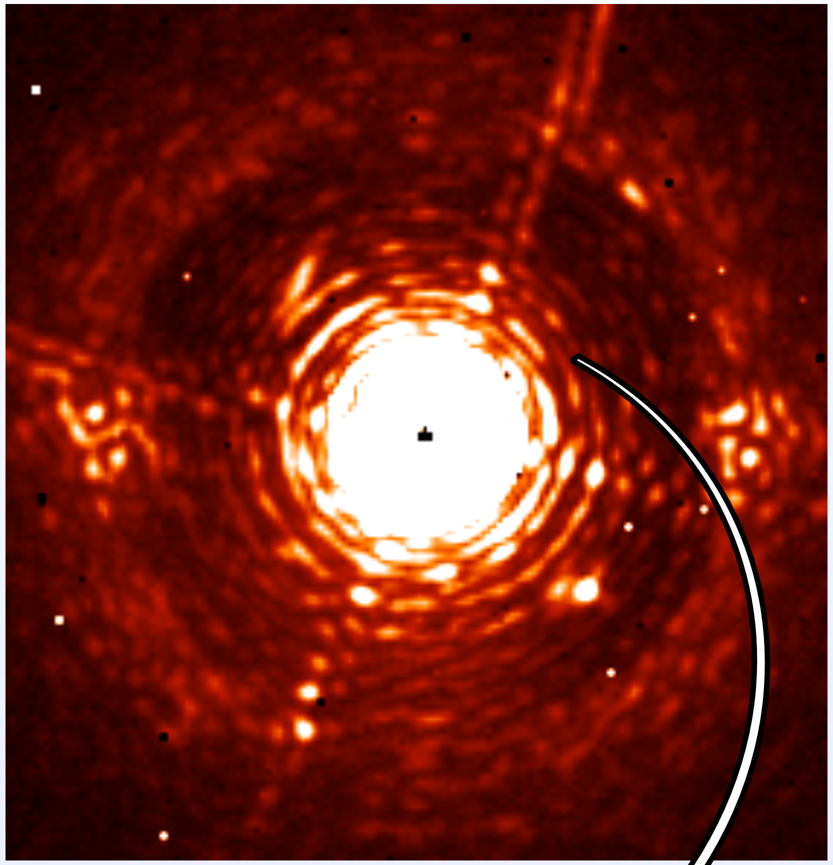


Extreme AO + coronagraphy in NIR

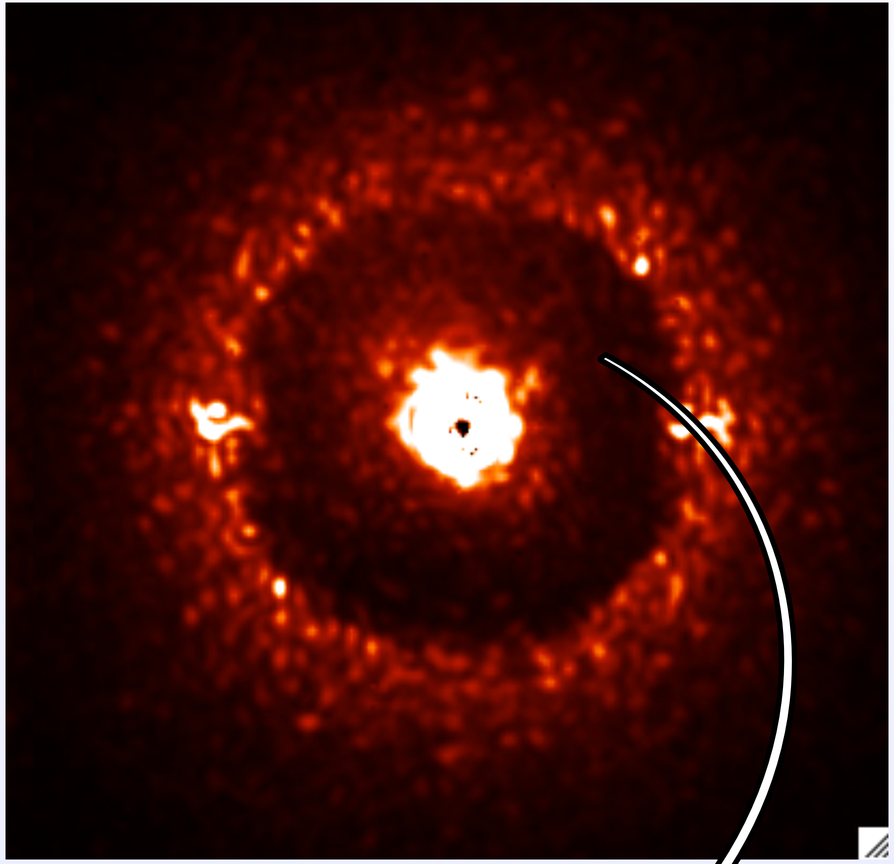
PSF



Saturated PSF



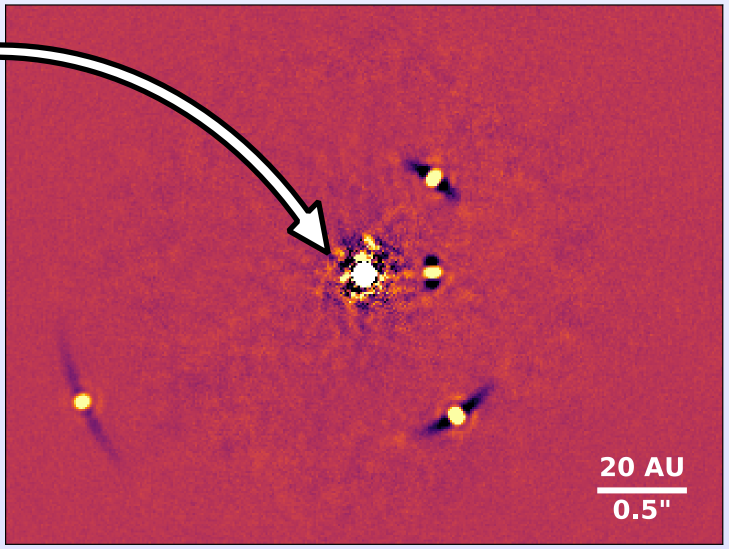
Coronagraphic image



Diffraction limited within 20 λ/D

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

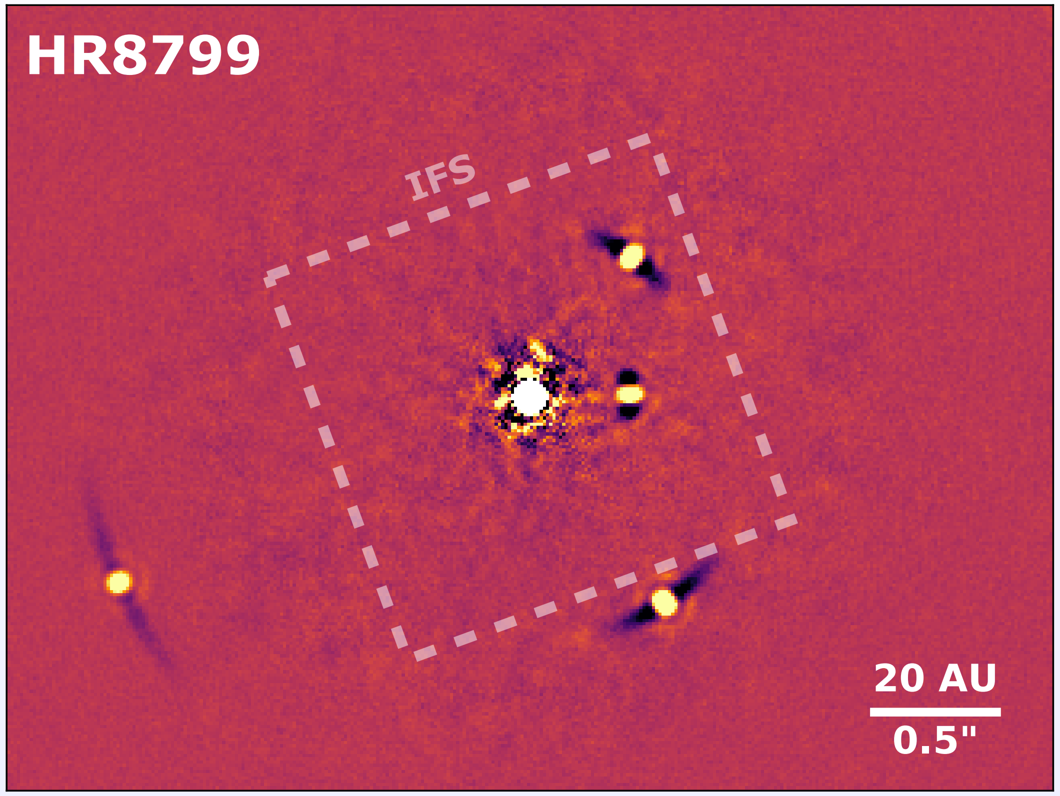
post-processing



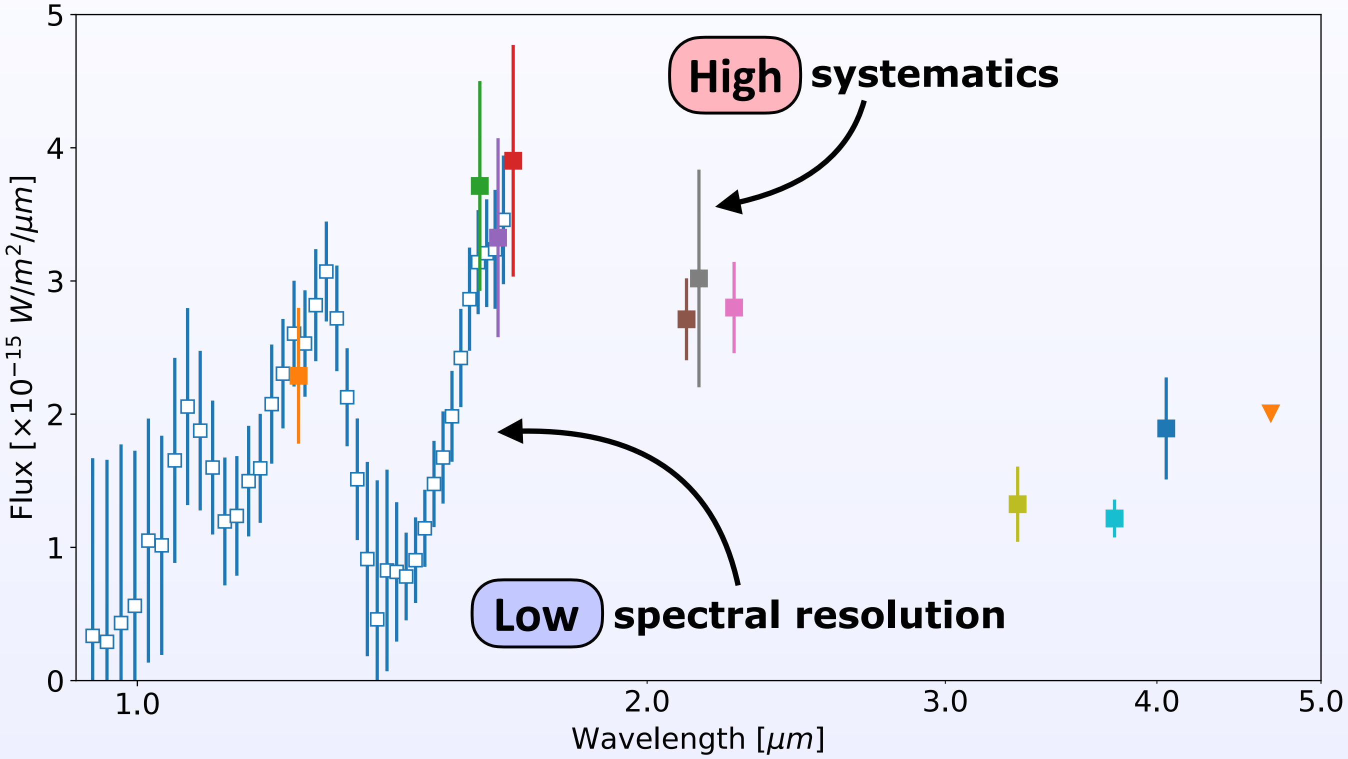
~10^{-5}-10^{-6} contrast down to 0.2"

Enough to detect young giant exoplanets of a few Jupiter masses

Exoplanet characterisation with SPHERE

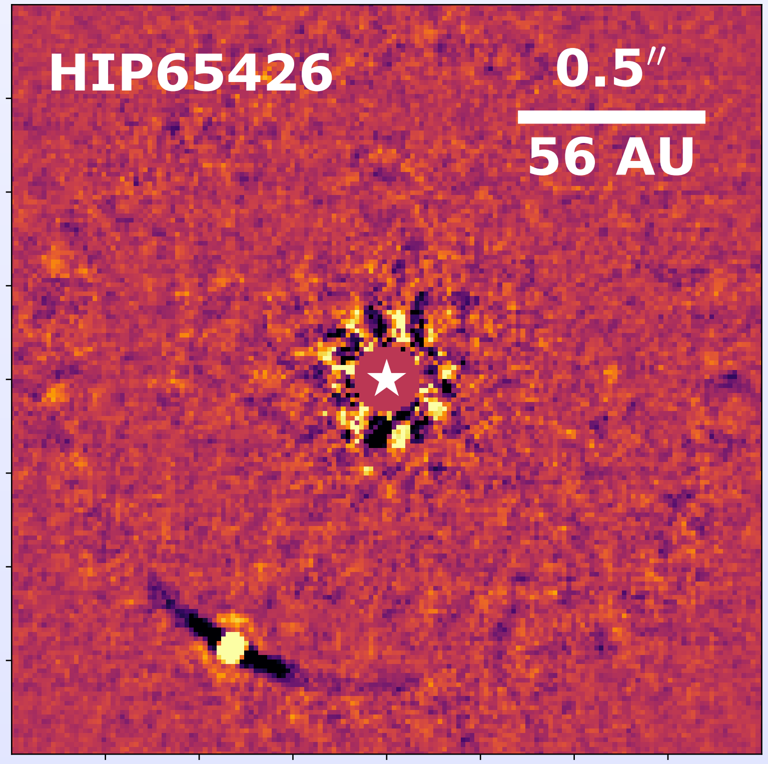


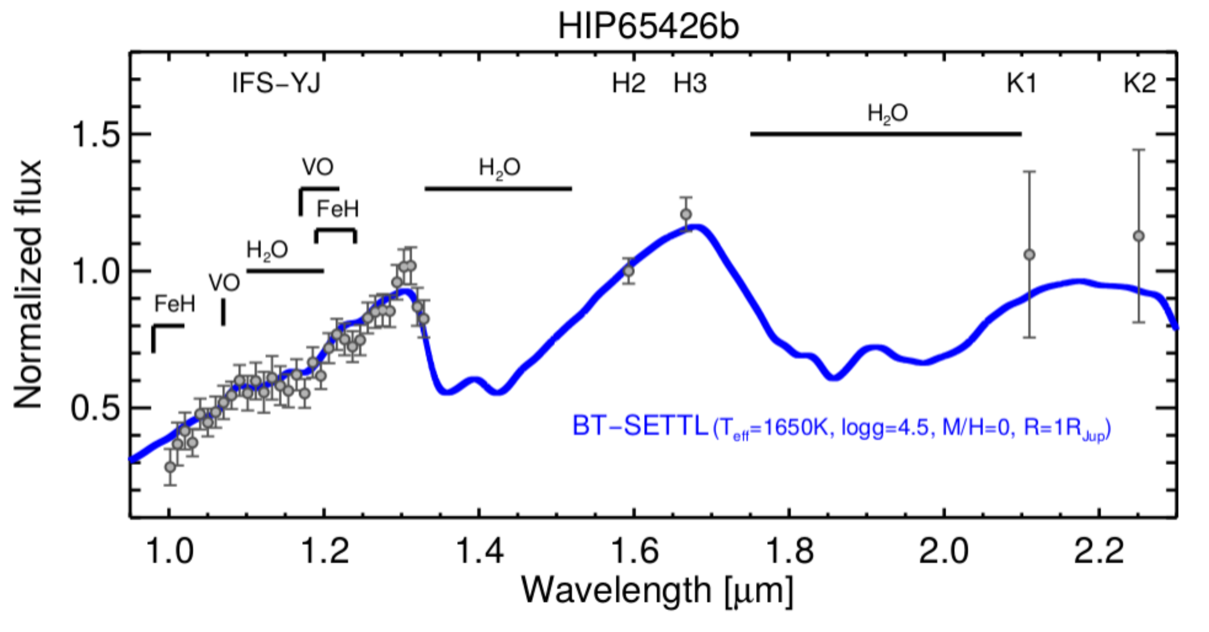
Bonnefoy, Zurlo et al. [incl. **Vigan**] (2016)



High systematics

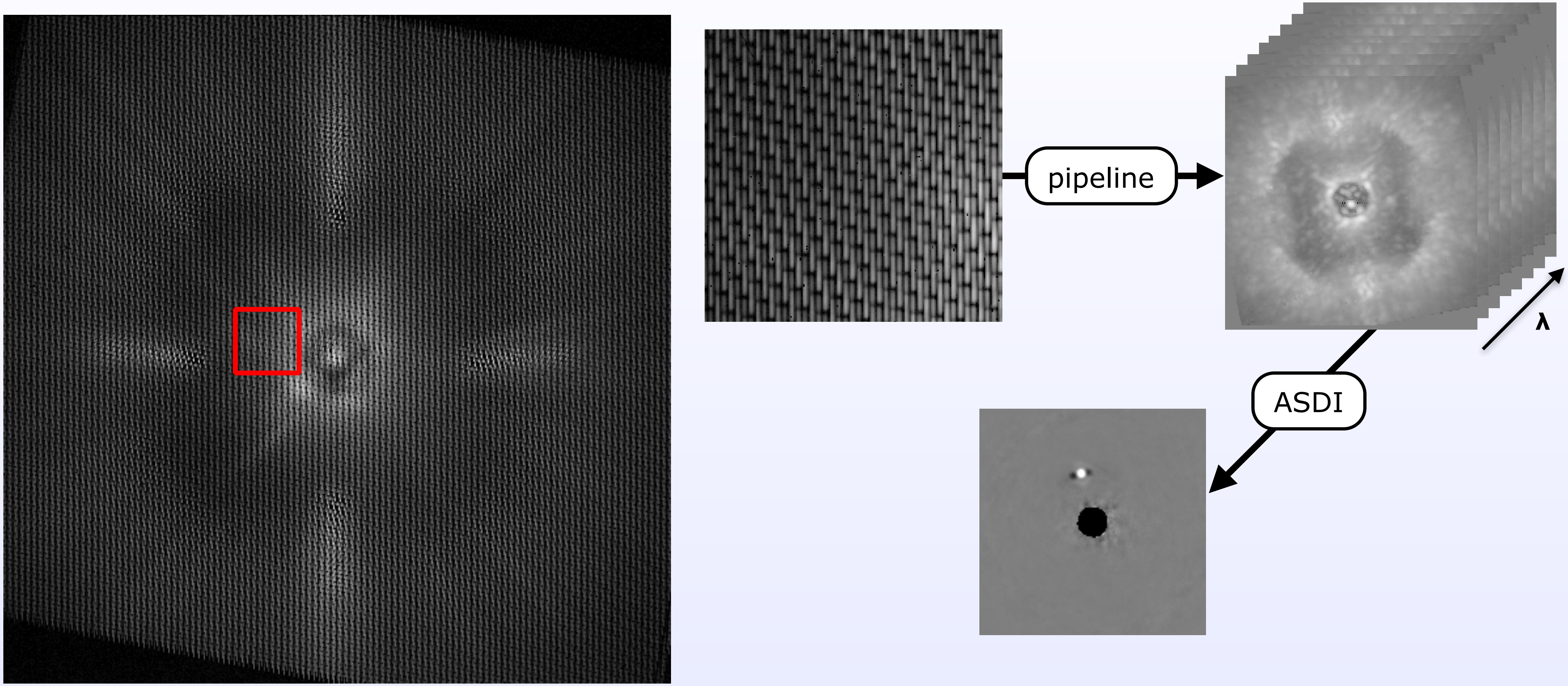
Low spectral resolution





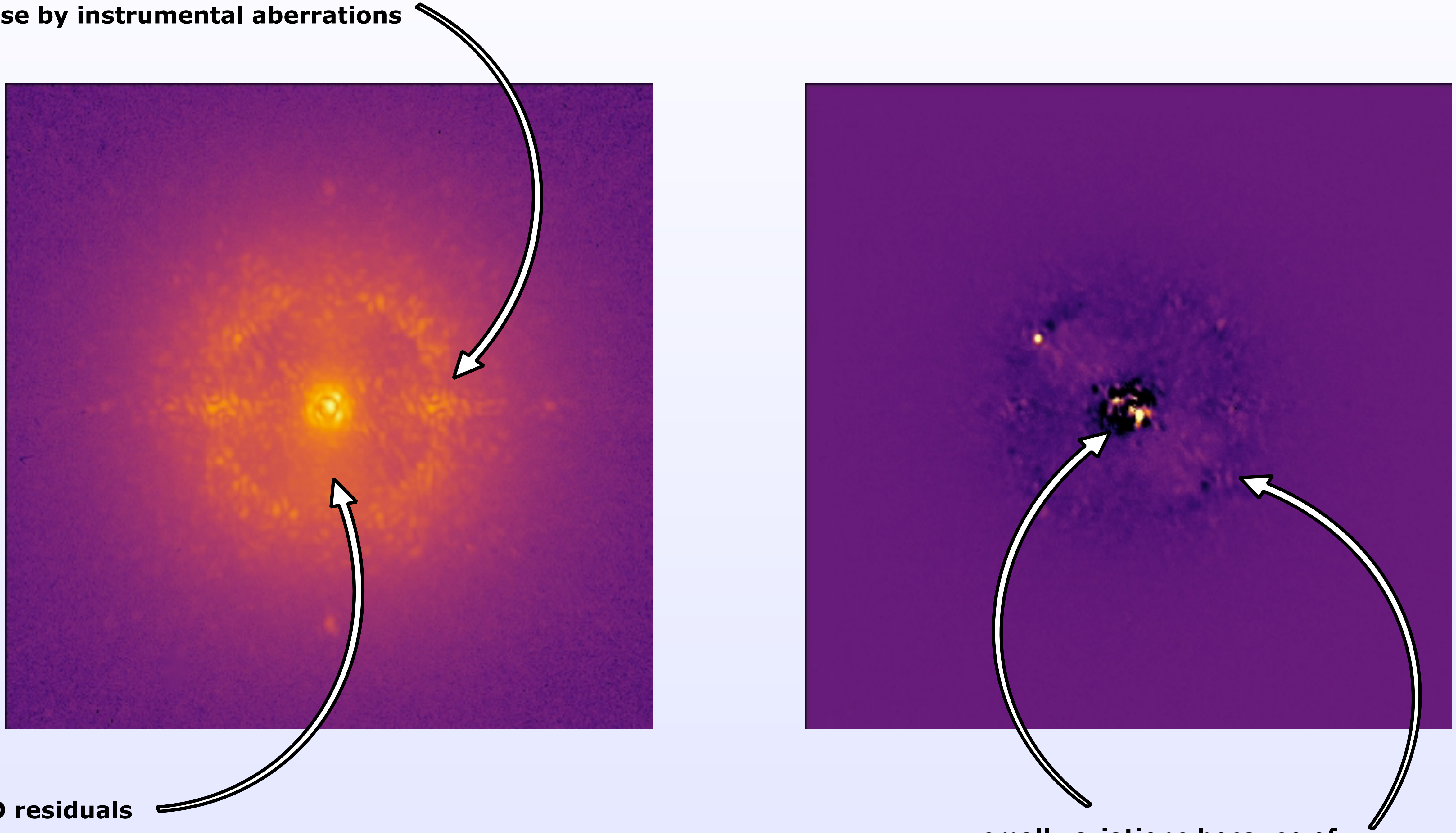
Resolution limited to R=50 for the IFS

Low resolution by design



- IFS designed to **search for planets**: need for spatial & spectral information
    - Nyquist spatial sampling: 2 pixels/PSF at 0.95 µm
    - Number of pixels limited on a 2k*2k IR detector
- **Consequence:** maximum spectral resolution ~50 for YJ coverage (~30 for YJH)

Speckle noise limitation



long-lived, quasi-static speckles
cause by instrumental aberrations

AO residuals

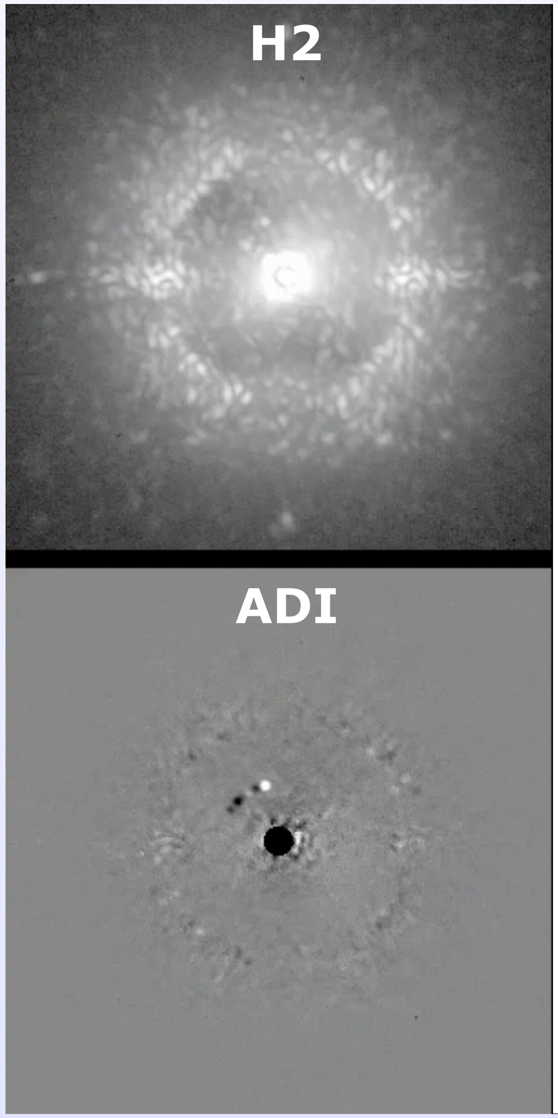
small variations because of
varying observing conditions,
thermal drift, etc

How to estimate and subtract the speckles?

Exoplanet direct detection techniques

Based on diversity intrinsic to or introduced in the data

- **Angular diversity** ➞ angular differential imaging (ADI, cADI, LOCI, KLIP, ANDROMEDA, ...)



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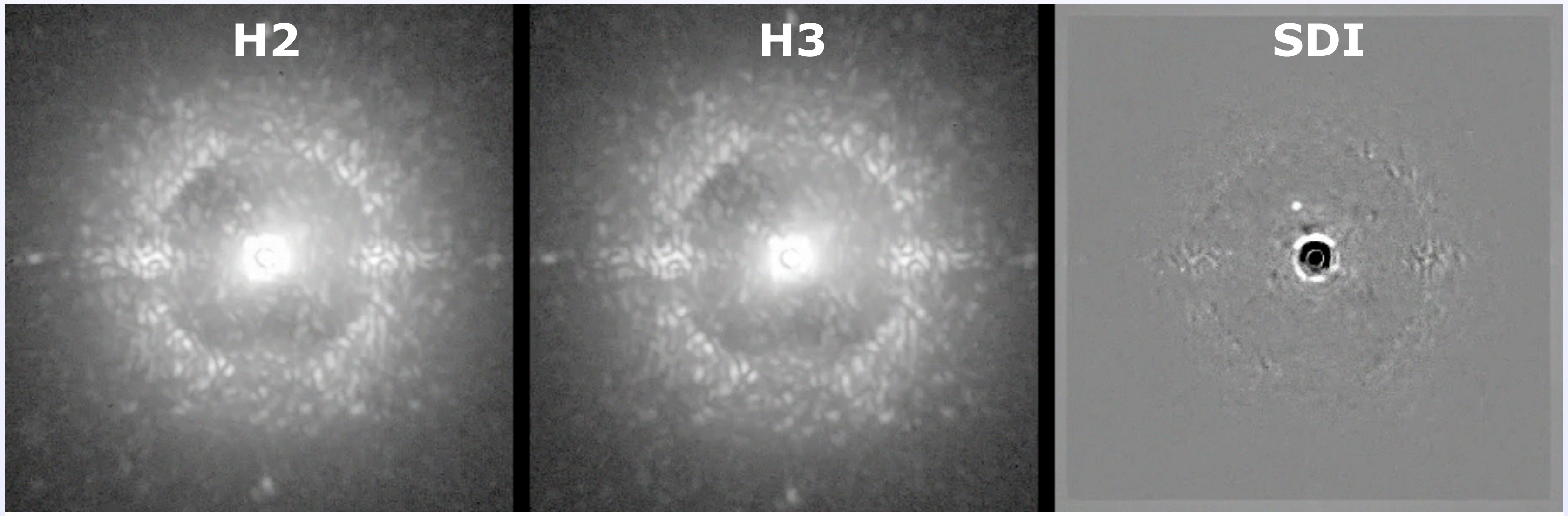

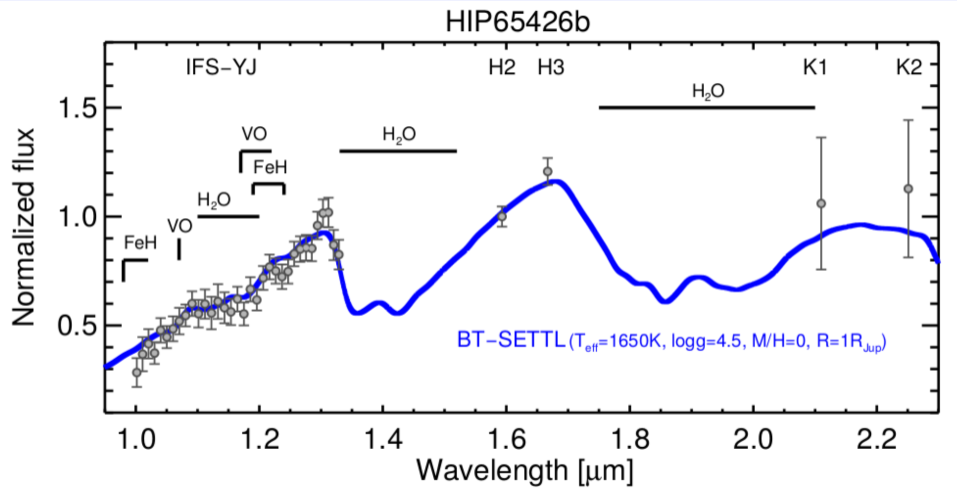

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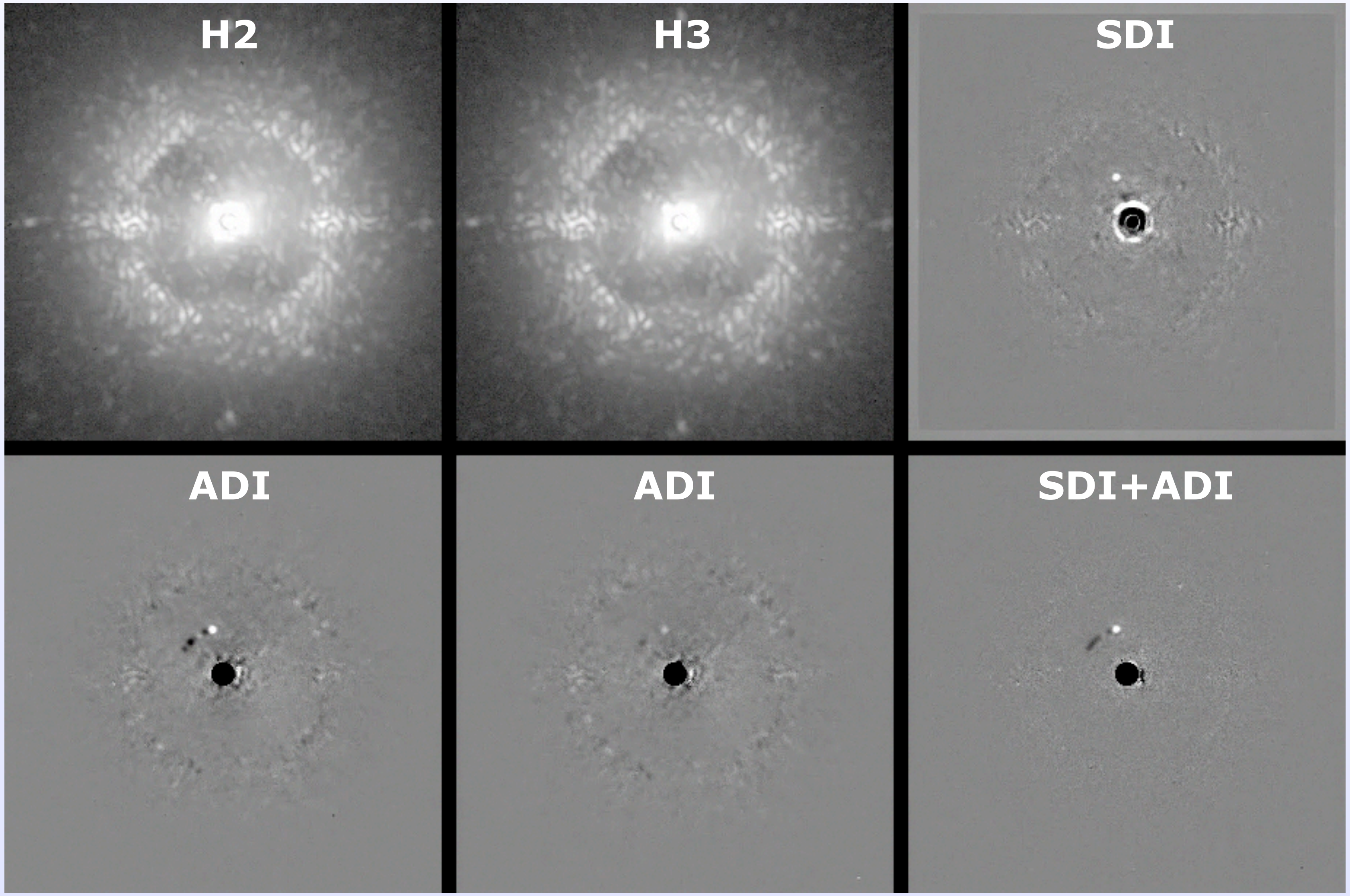

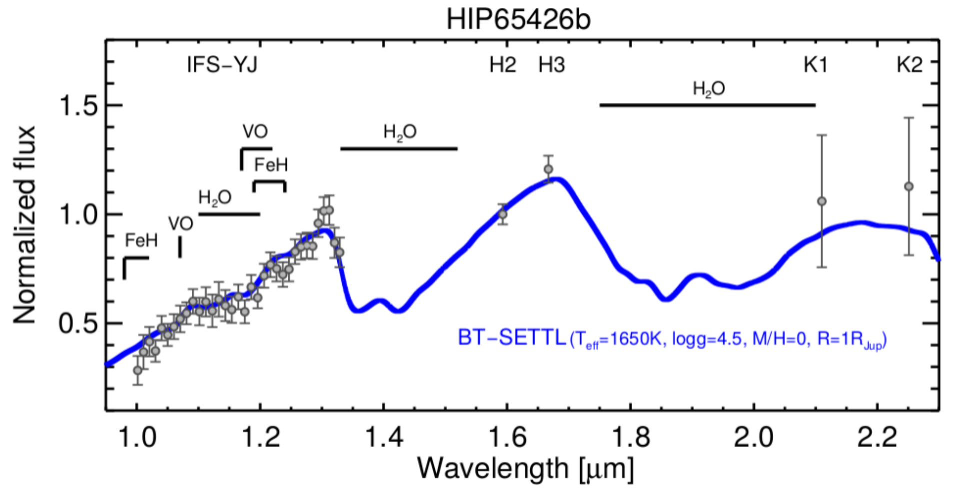

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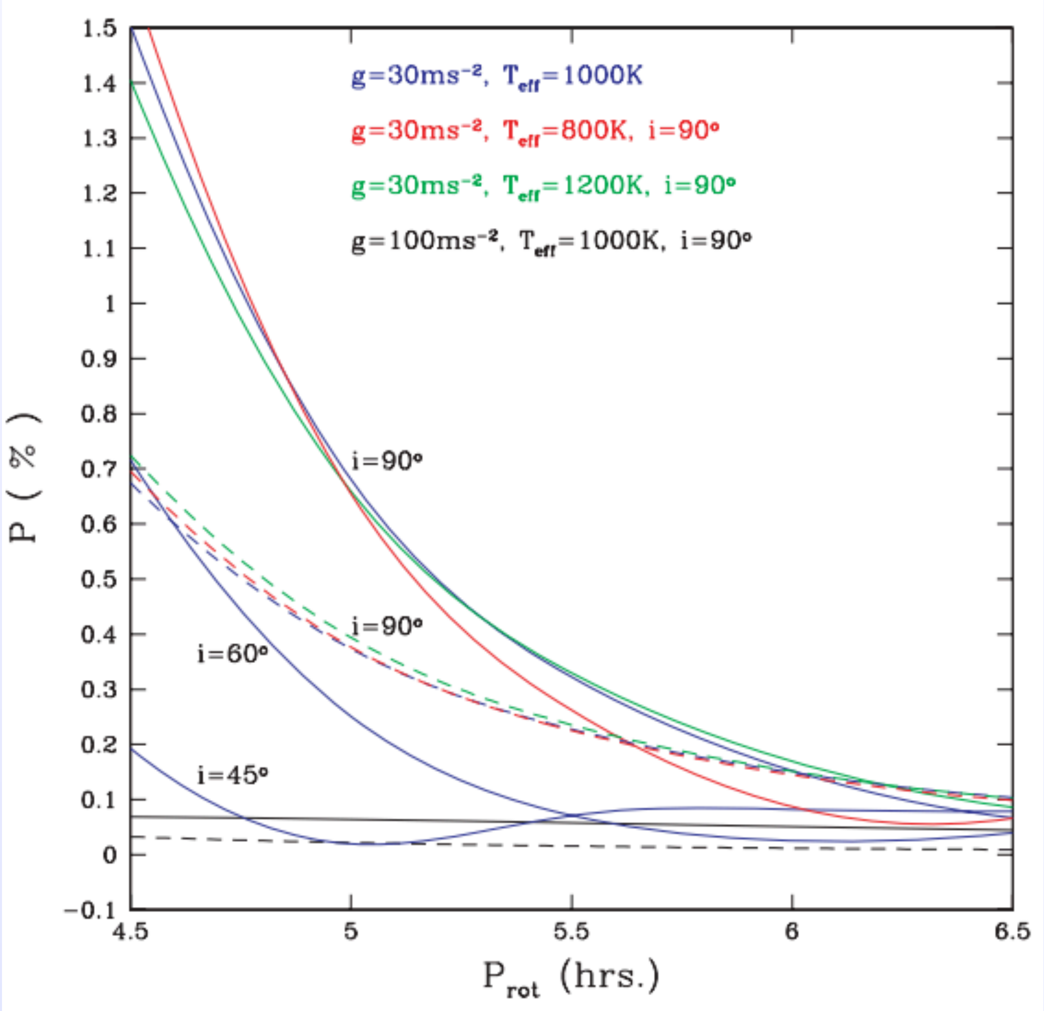

Marley & Sengupta (2011)

Polarisation induced by surface inhomogeneities (clouds) or oblateness of the planet

Exoplanet direct detection techniques

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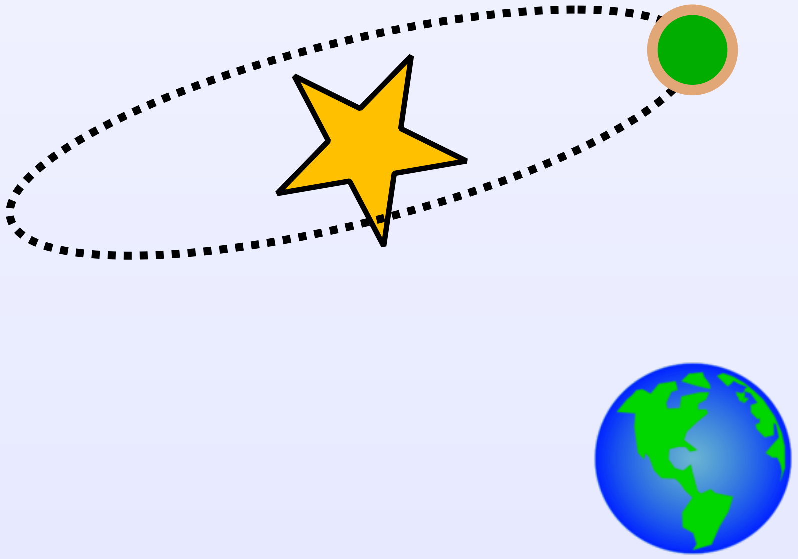
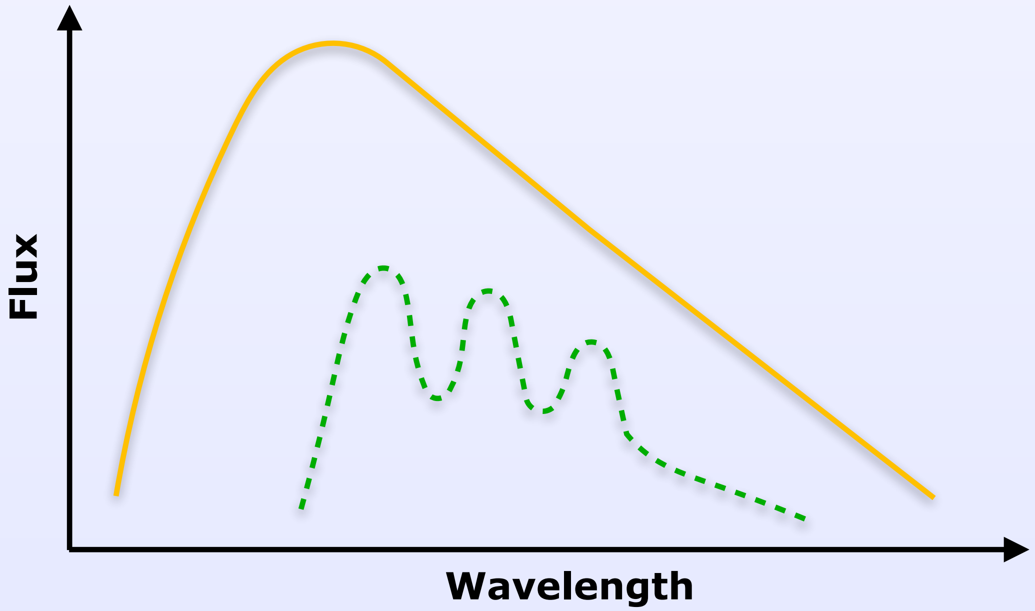
- Velocity diversity





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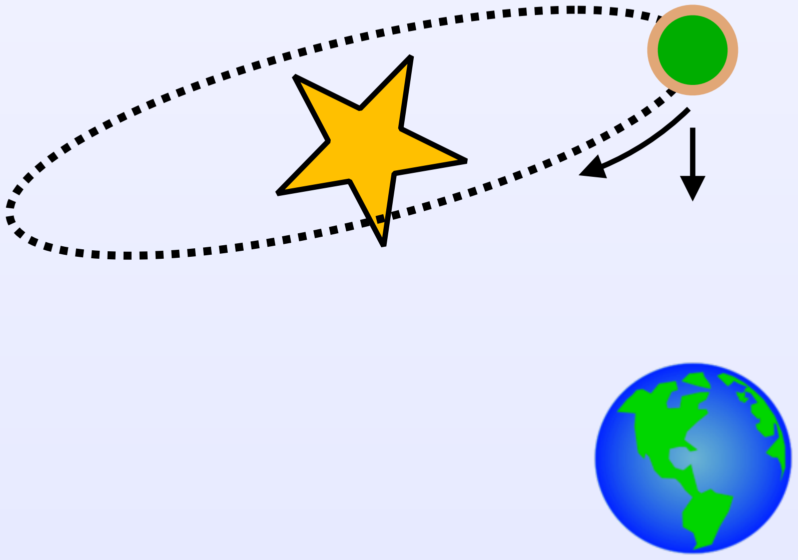
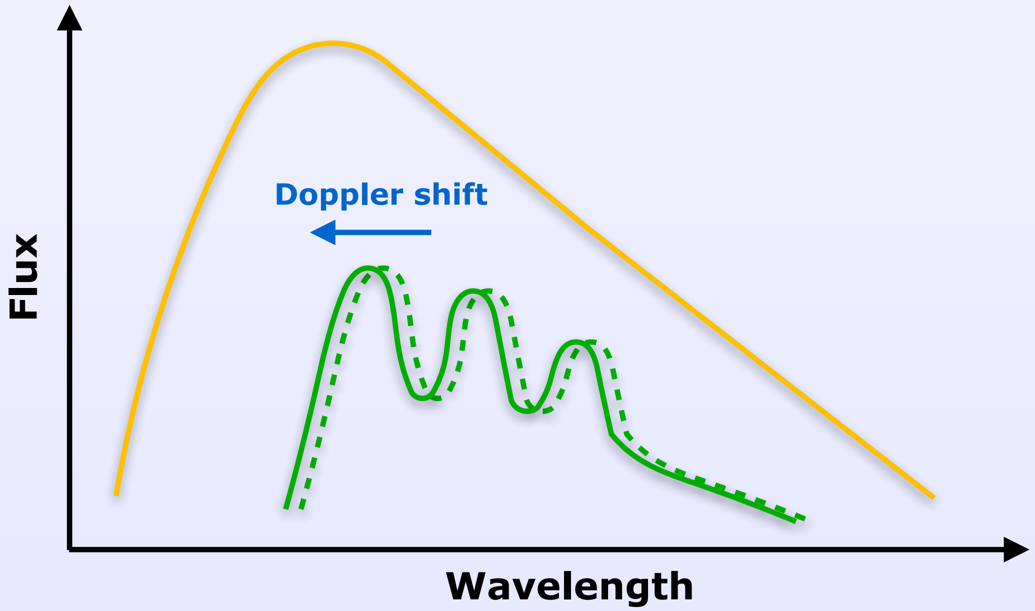


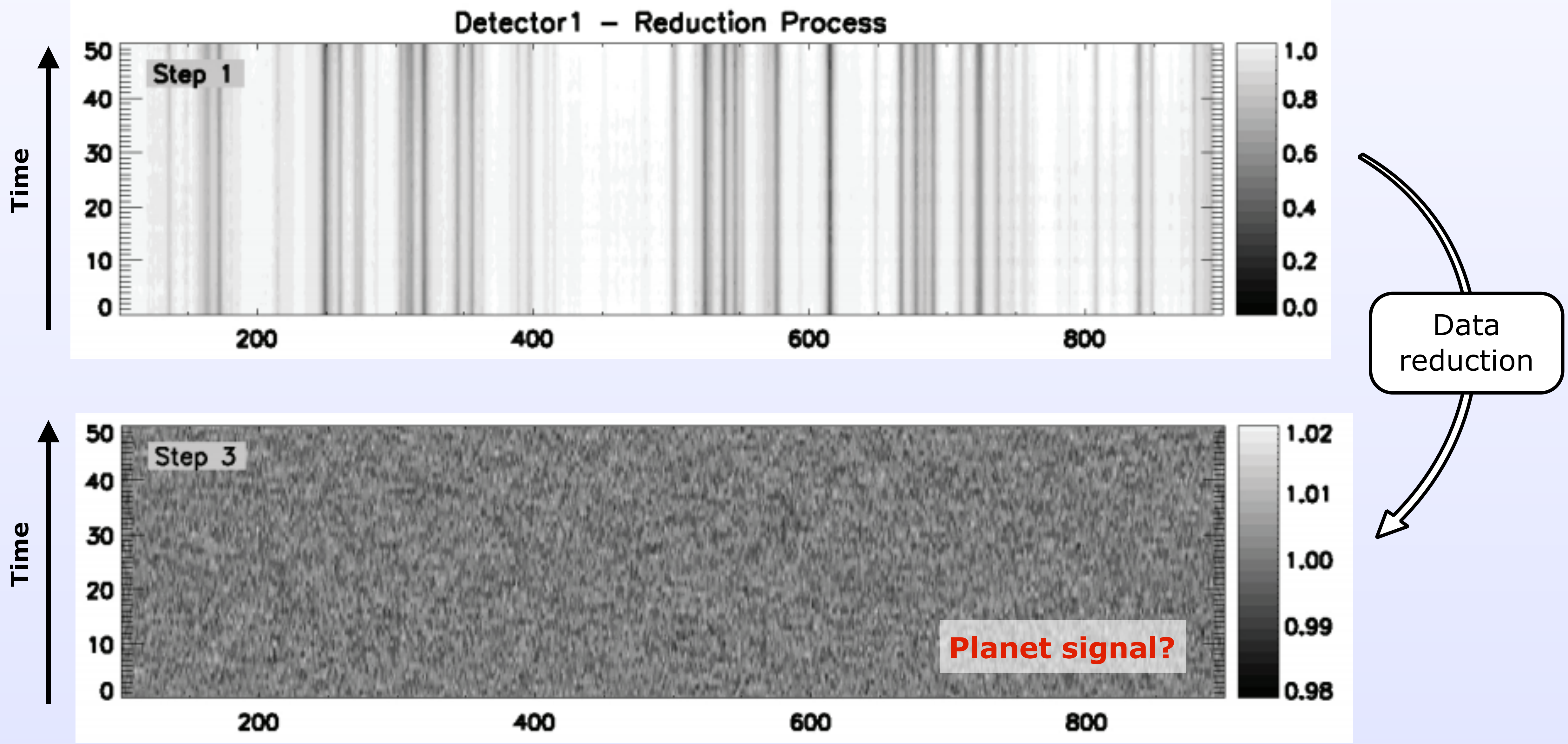


→ Resolution of at least a few 10^3 or 10^4 needed to resolve molecular lines in the planet spectrum

Spectral + velocity diversity

Proposed by Snellen et al. (2010) for hot Jupiters

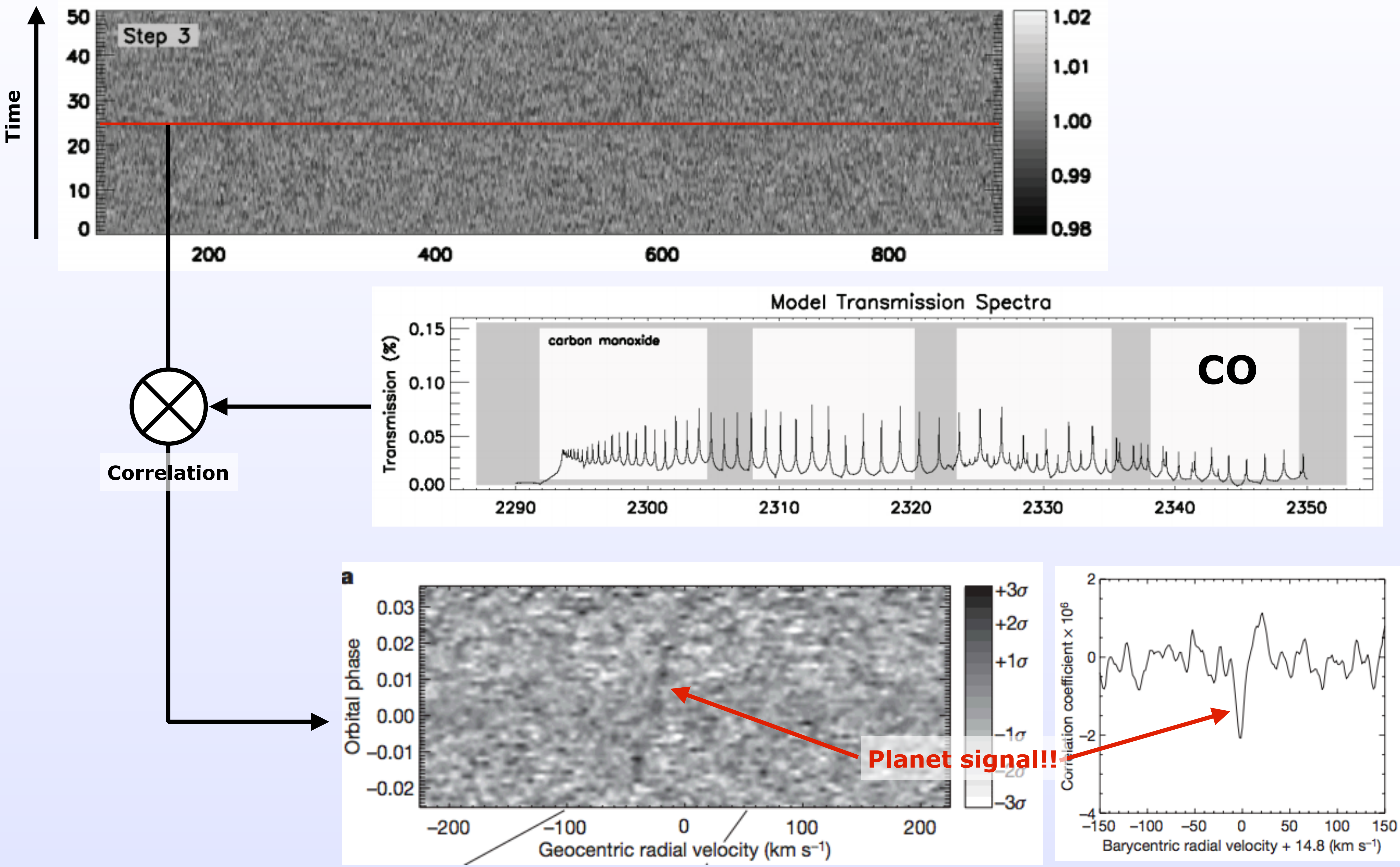
- Demonstrated on HD209458 b: period of 3.5 days, transit
- Data taken with CRIRES in K-band at R=~80 000



Data reduction

Planet signal?

Spectral + velocity diversity



Time

Correlation

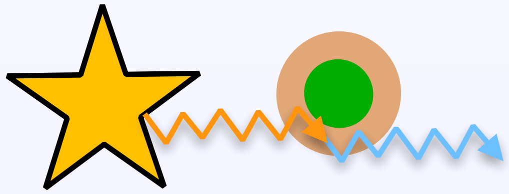
CO

Planet signal!!

Spectral + velocity diversity

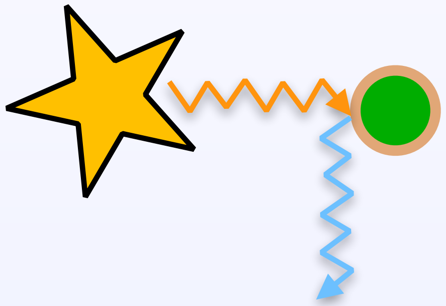
Absorption

HD209458 b (Snellen et al. 2010)



Reflection

51 Peg b (Martins et al. 2016)



Emission

HR8799 c (Konopacky et al. 2013)

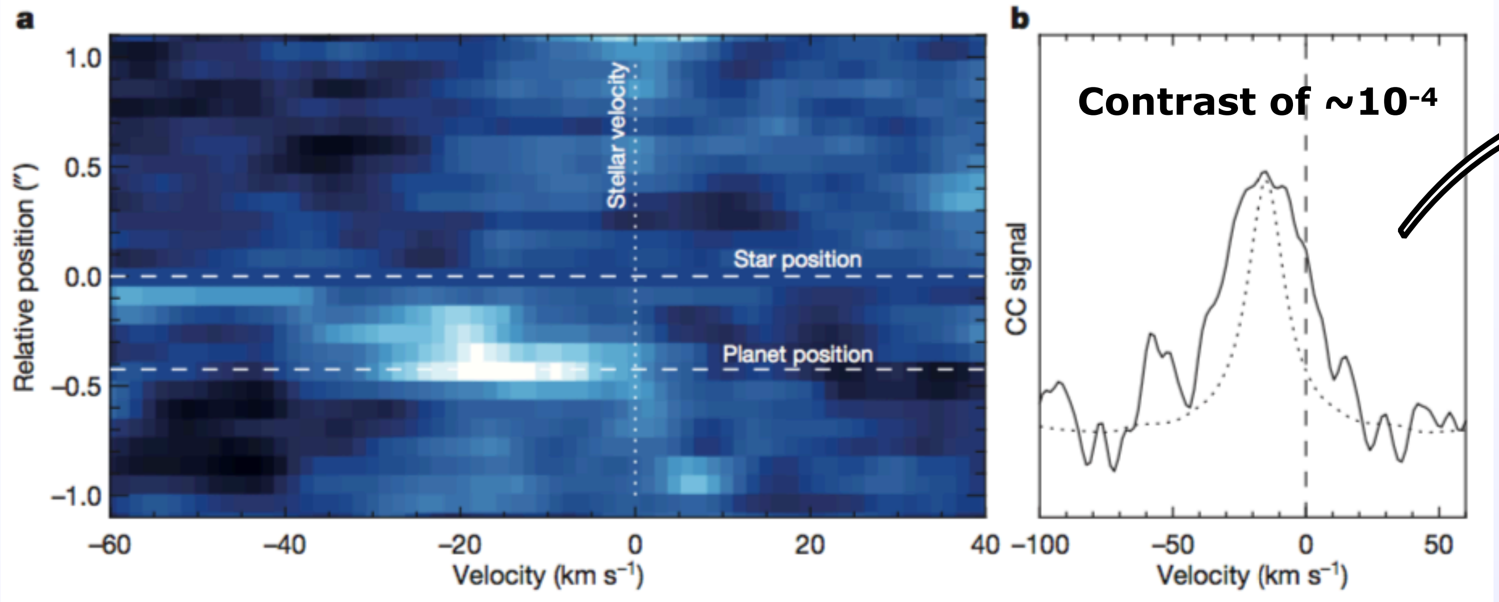
- Why does it work?
    - **strong spectral features** expected for CO, CO_2, CH_4, H_20
    - **many lines** in near-infrared

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

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

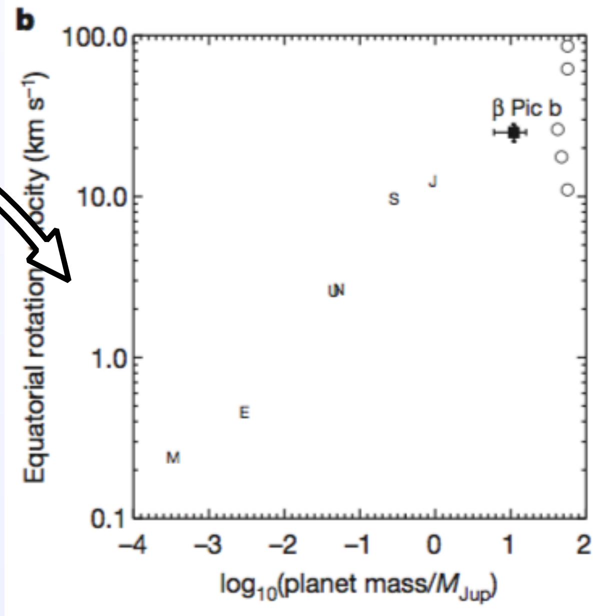
Combining HCI and HRS

- Nicely demonstrated on ß Pic b with CRIRES+ in K-band using CO templates:

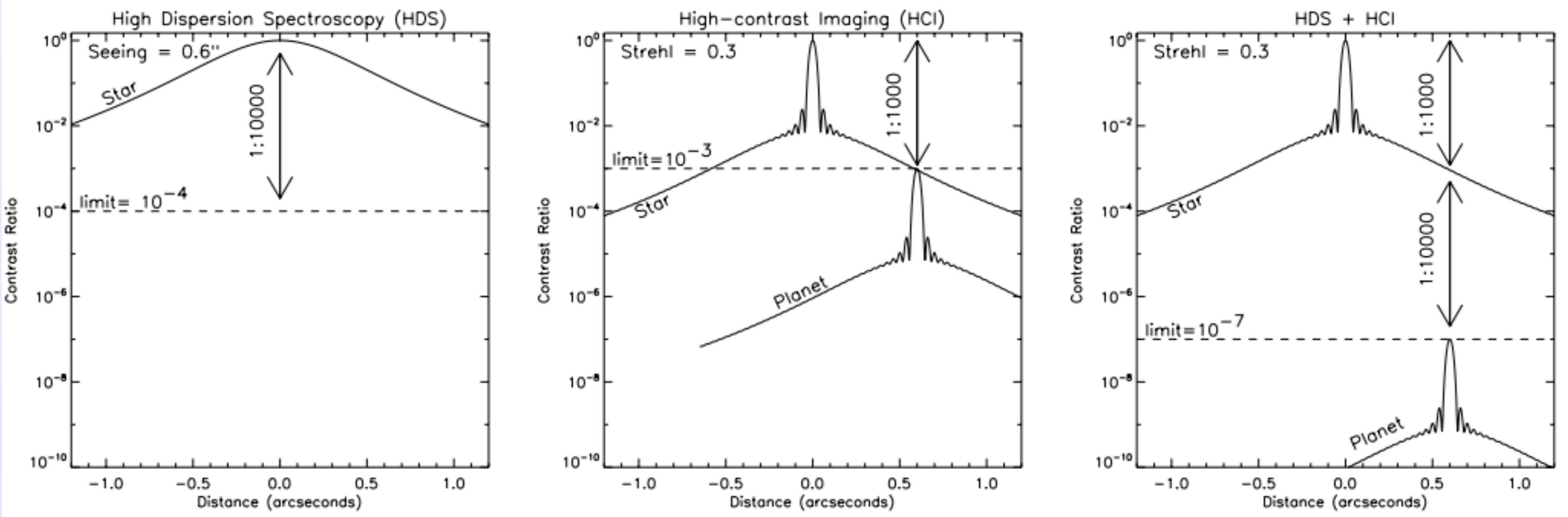


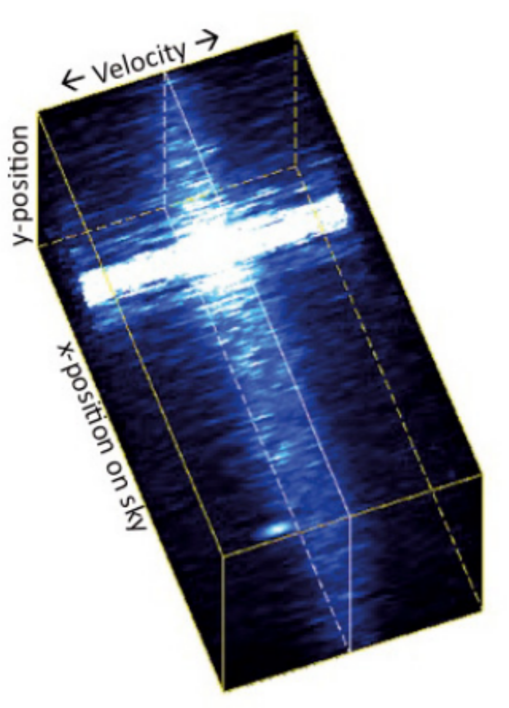
Contrast of ~10^{-4}

Rot. broadening



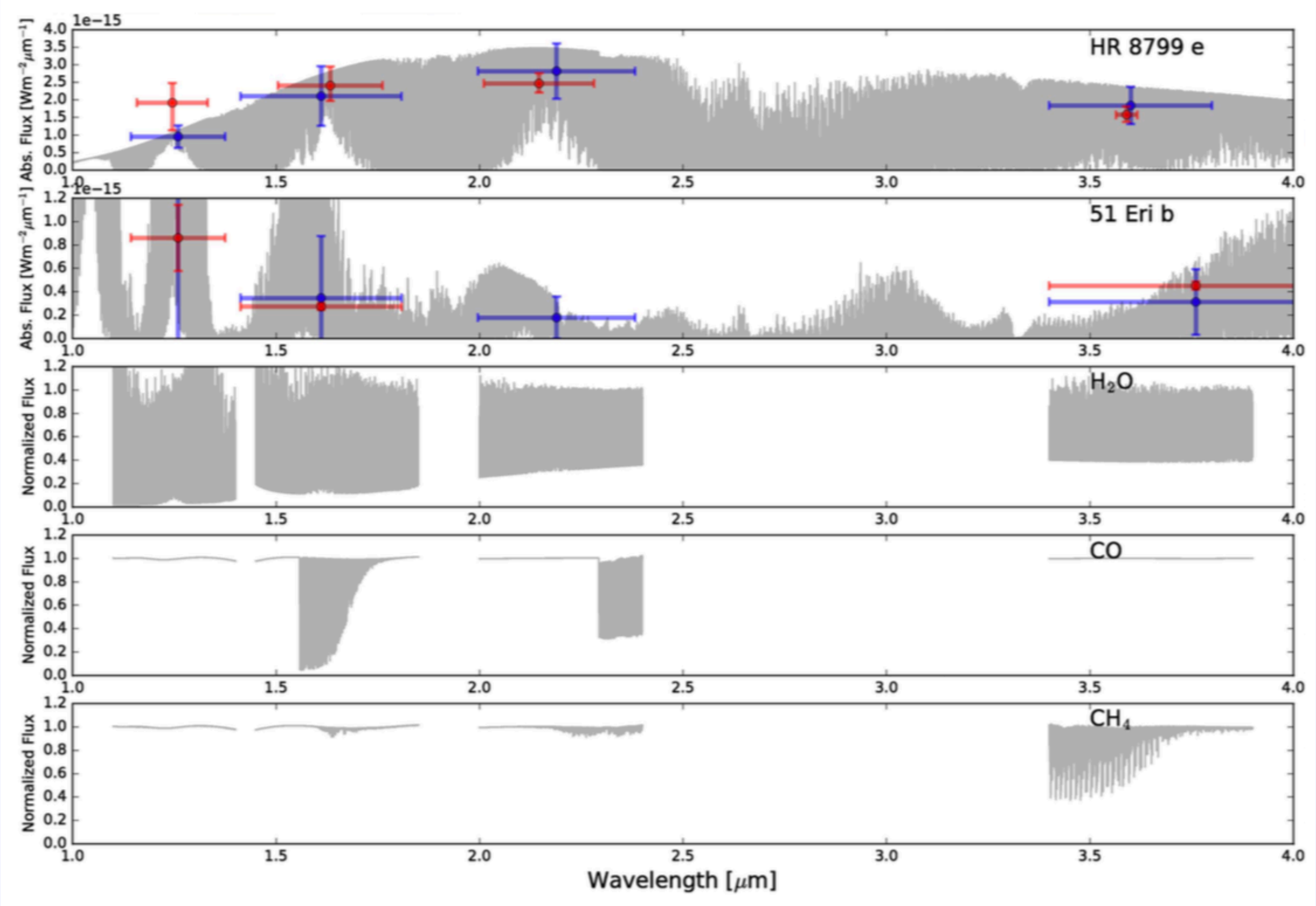
- HCI + HRS: ideal combination to reach contrasts better than 10^{-6} (Snellen et al. 2015)

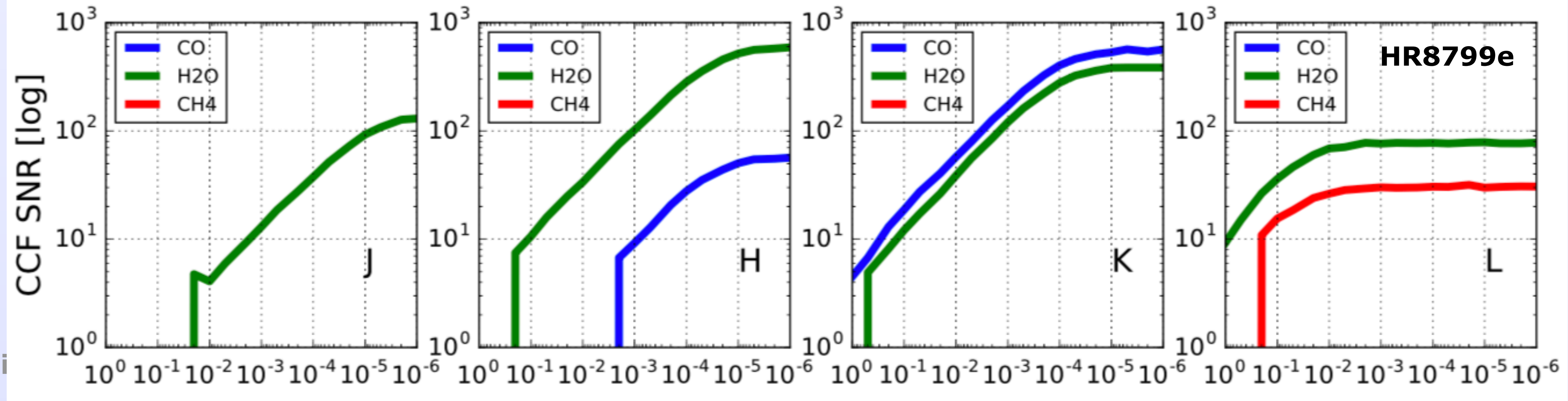




Combining HCI and HRS

In-depth study by Wang et al. (2017)





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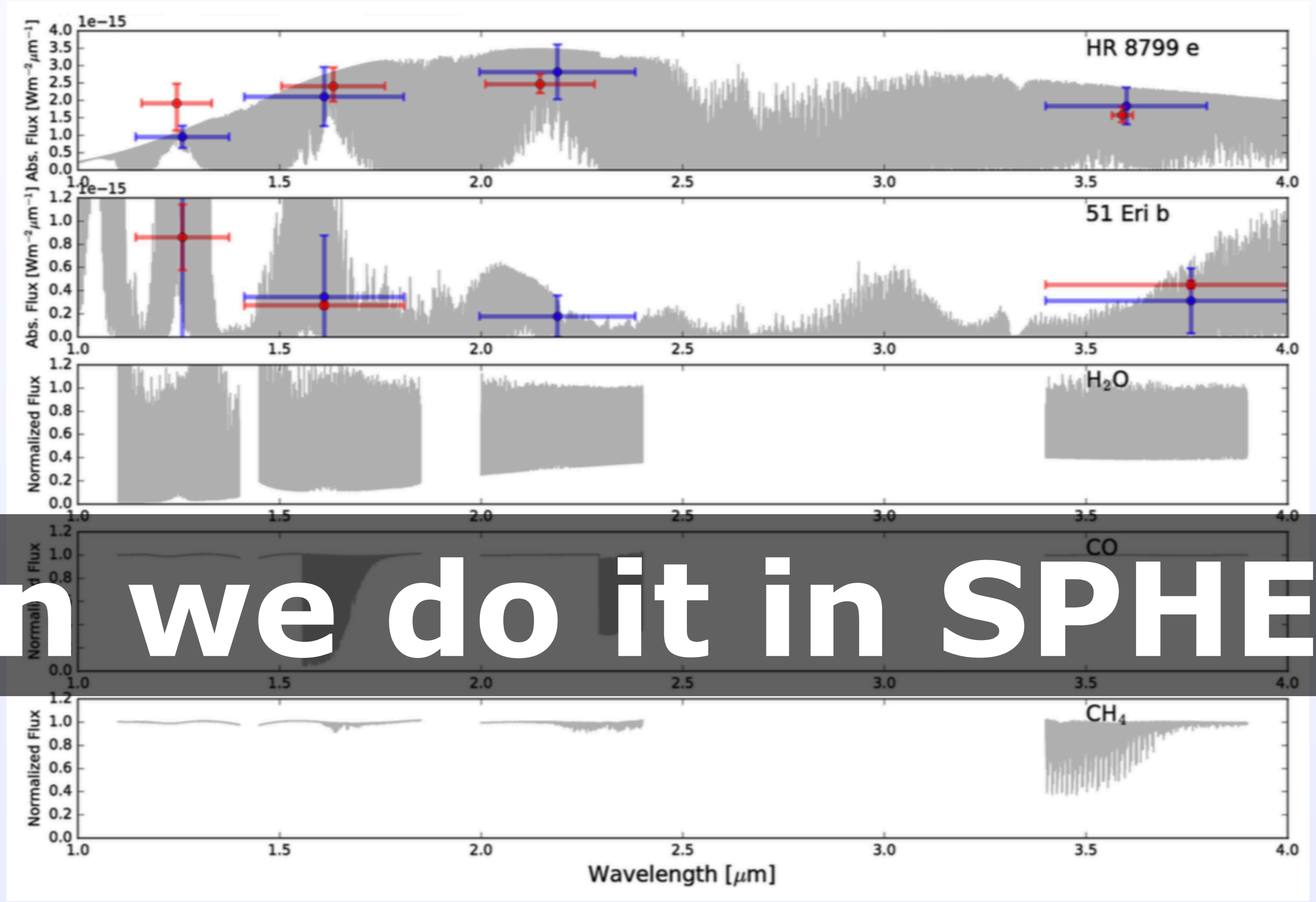
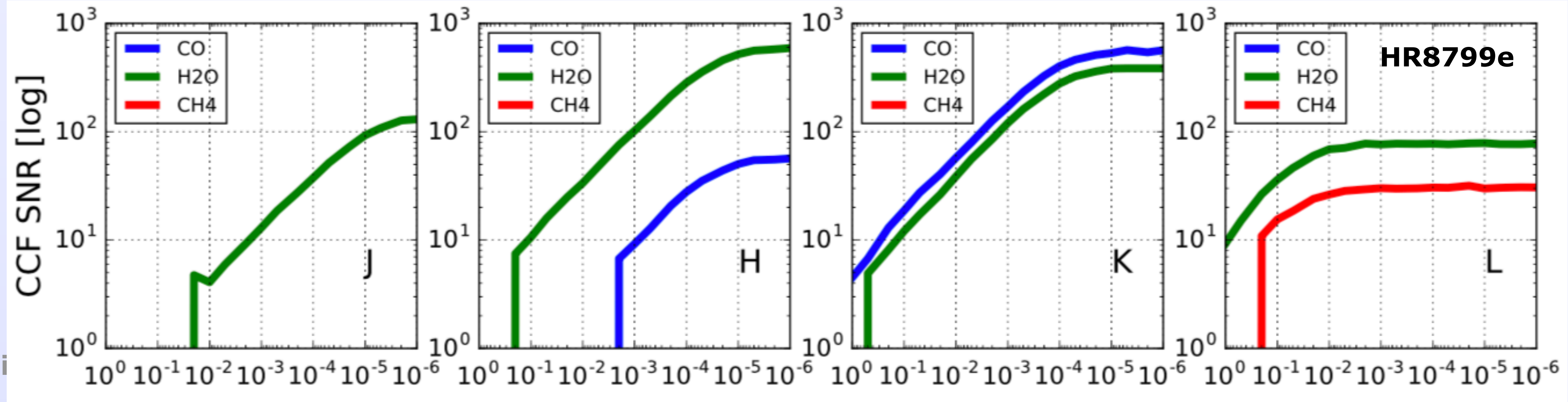
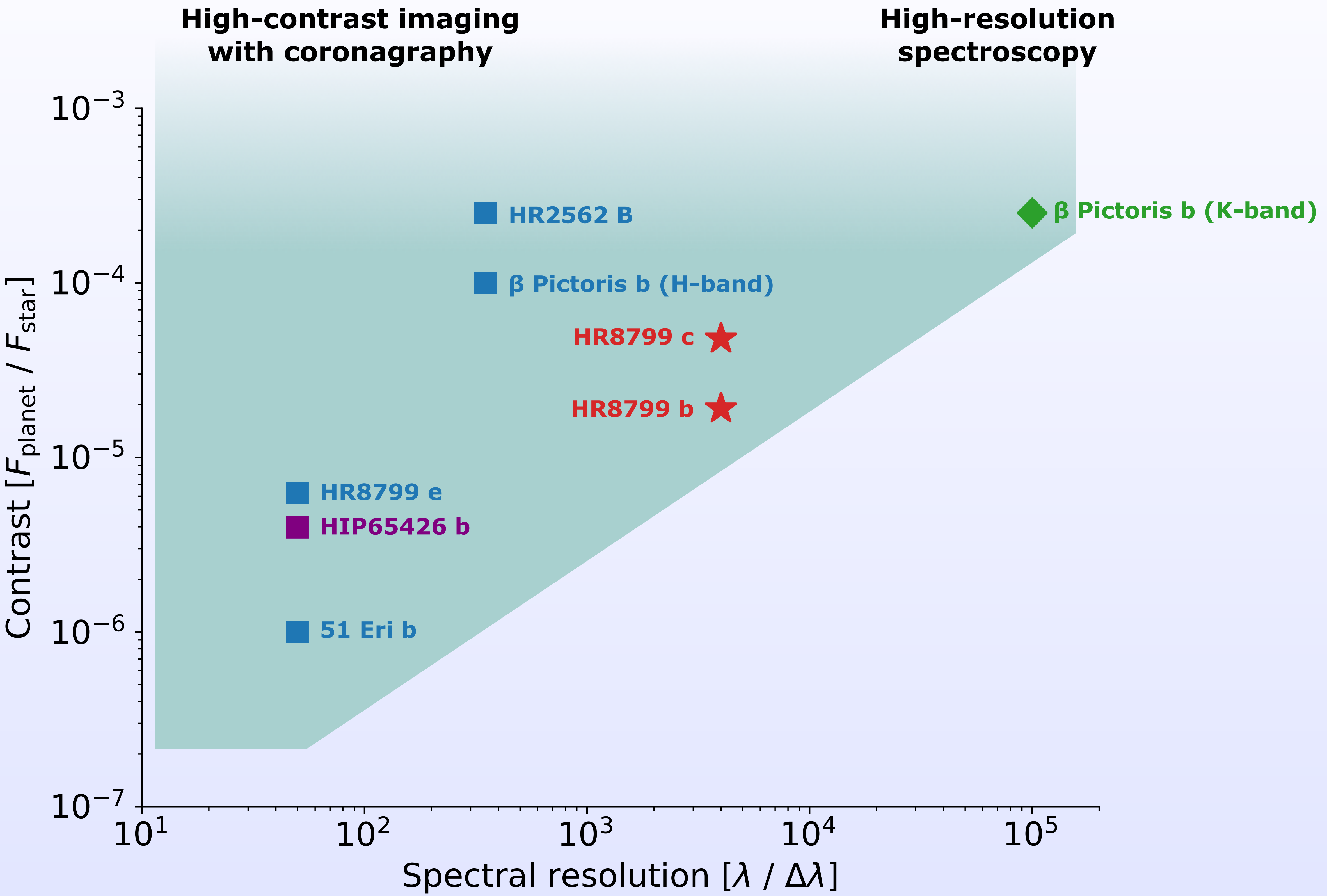


Can we do it in SPHERE?



Exoplanets at high-resolution



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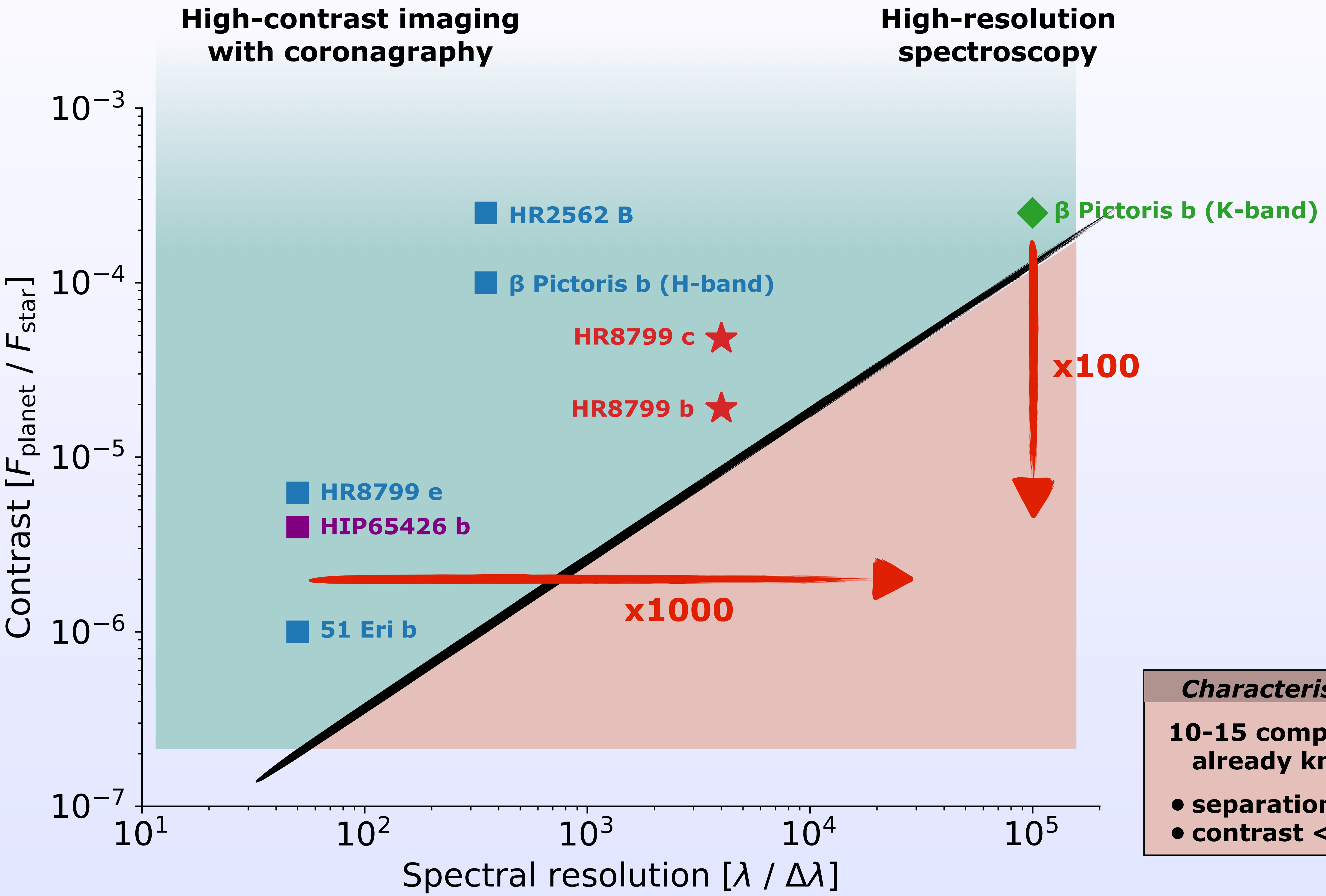


Characterisation

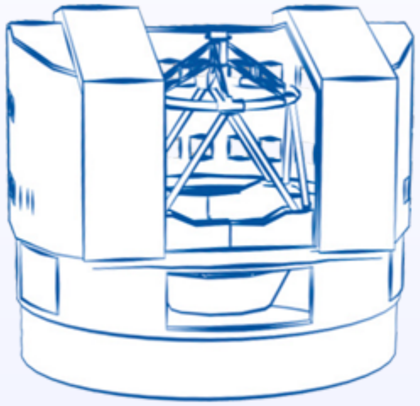
10-15 companions already known

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

HiRISE project

A unique window of opportunity

VLT/UT3



High-contrast exoplanet imager

SPHERE

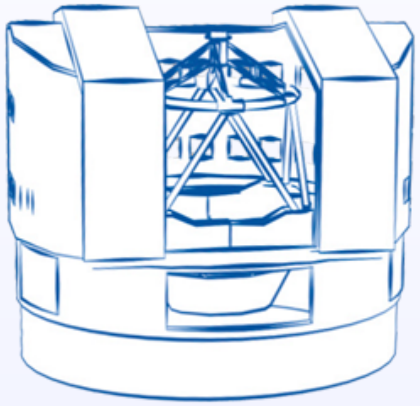
High-resolution spectrograph

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



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

HiRISE

Fiber coupling

Supported by ESO

erc

Supported by CRIRES+

HiRISE organisation

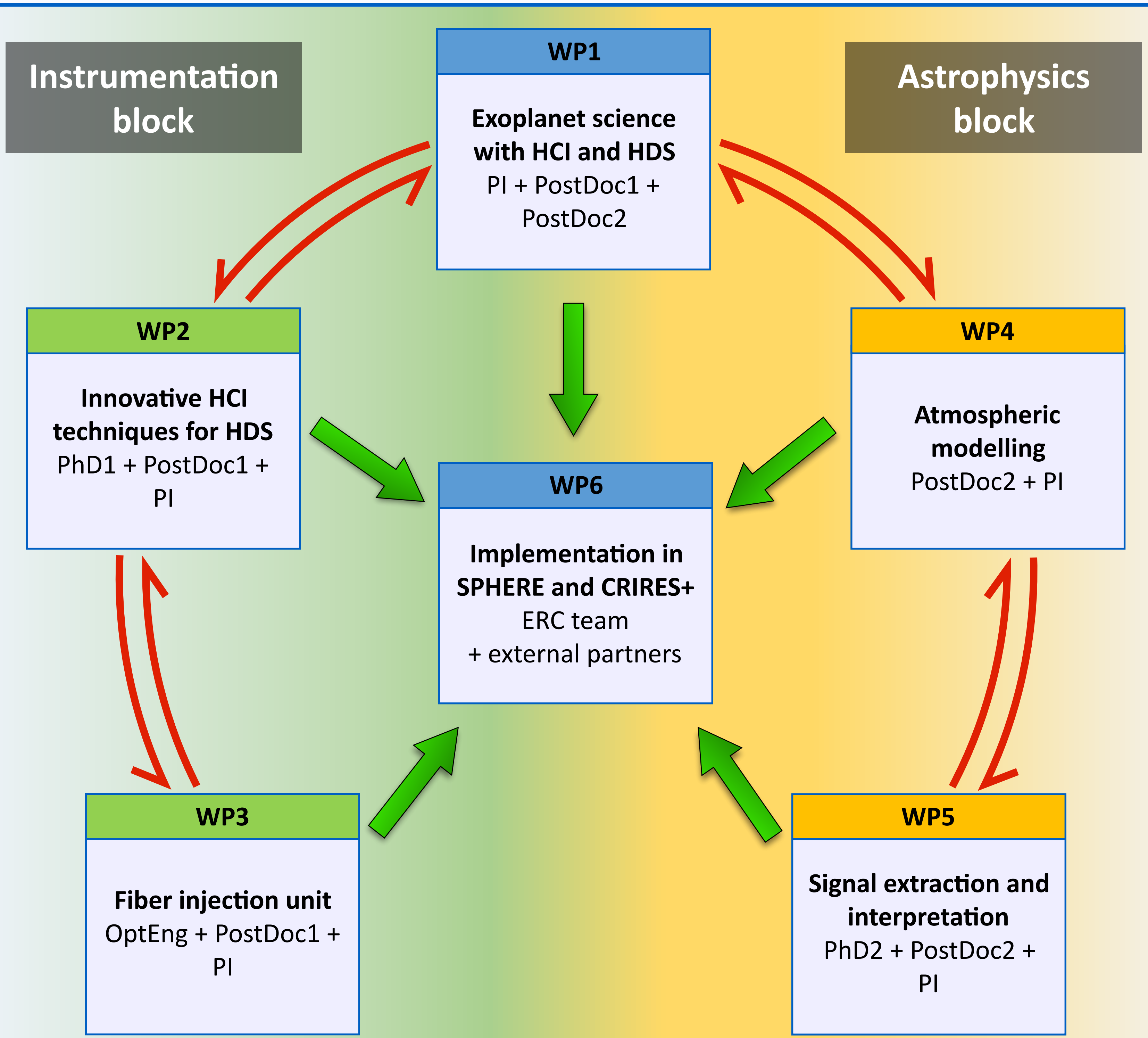
HiRISE

PI and coordinator
Arthur Vigan

Host institution
CNRS, Laboratoire d'Astrophysique de Marseille

1.5 M€ over 5 years, starting 2017-12
2 PhD students (3 yrs)
2 postdocs (3 yrs)
1 engineer (3 yrs)
+ funding for (some) hardware

External partners:
SPHERE and CRIRES+ consortia,
European Southern Observatory



Instrumentation block

Astrophysics block

WP1
Exoplanet science with HCI and HDS
PI + PostDoc1 + PostDoc2

WP2
Innovative HCI techniques for HDS
PhD1 + PostDoc1 + PI

WP3
Fiber injection unit
OptEng + PostDoc1 + PI

WP4
Atmospheric modelling
PostDoc2 + PI

WP5
Signal extraction and interpretation
PhD2 + PostDoc2 + PI

WP6
Implementation in SPHERE and CRIRES+
ERC team
+ external partners

Technical challenges?

Many technical questions!

- Do we have enough photons coming from directly imaged exoplanets?
- How to position the fibre on the planet (or the planet on the fibre)?
- How to best inject the planetary signal in the fibre?
- How to optimise the coupling?
- Is wavefront control needed to optimise the injection?
- How stable do we need to be in tip-tilt?
- What type of fibre do we use?
- How to design a module that fits within SPHERE?
- How many fibres do we need? How many can fit at the entrance of CRIRES+?
- ...

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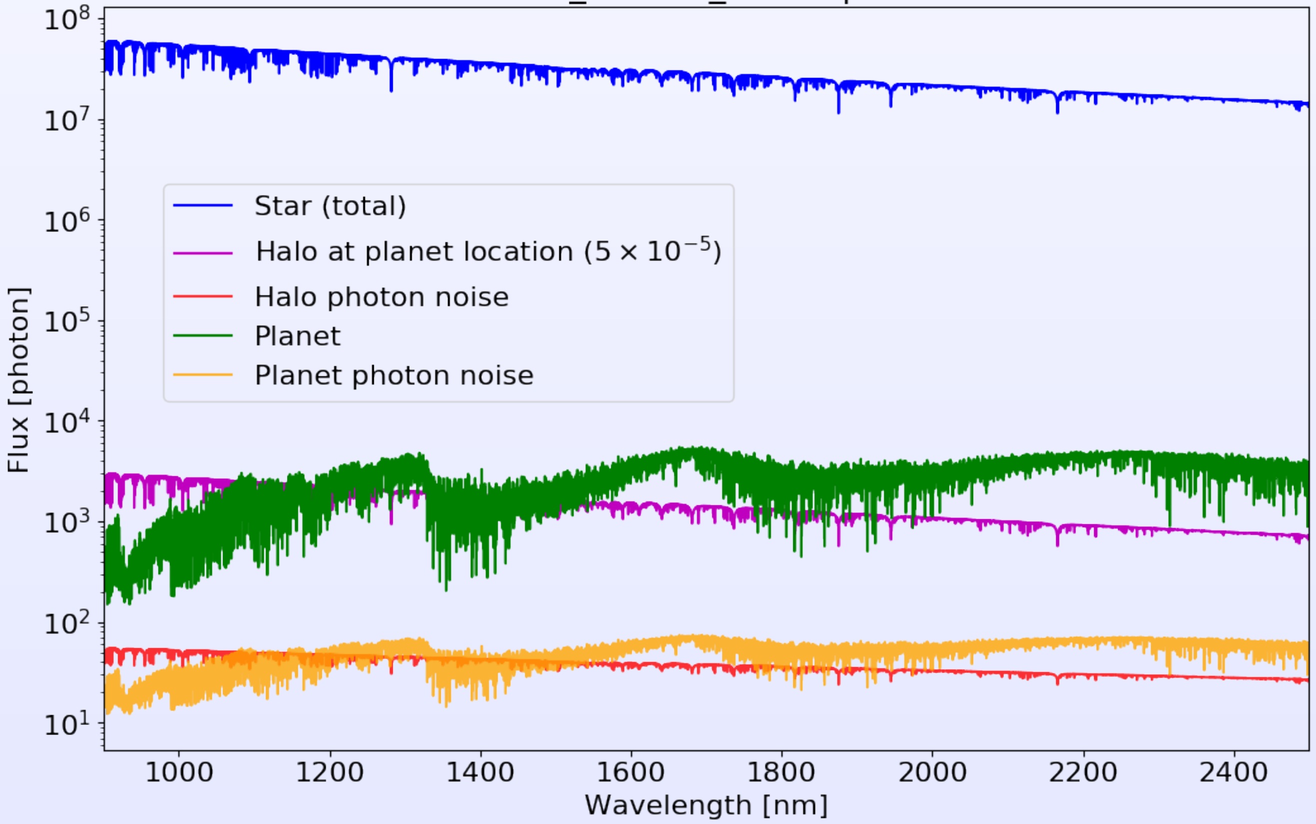
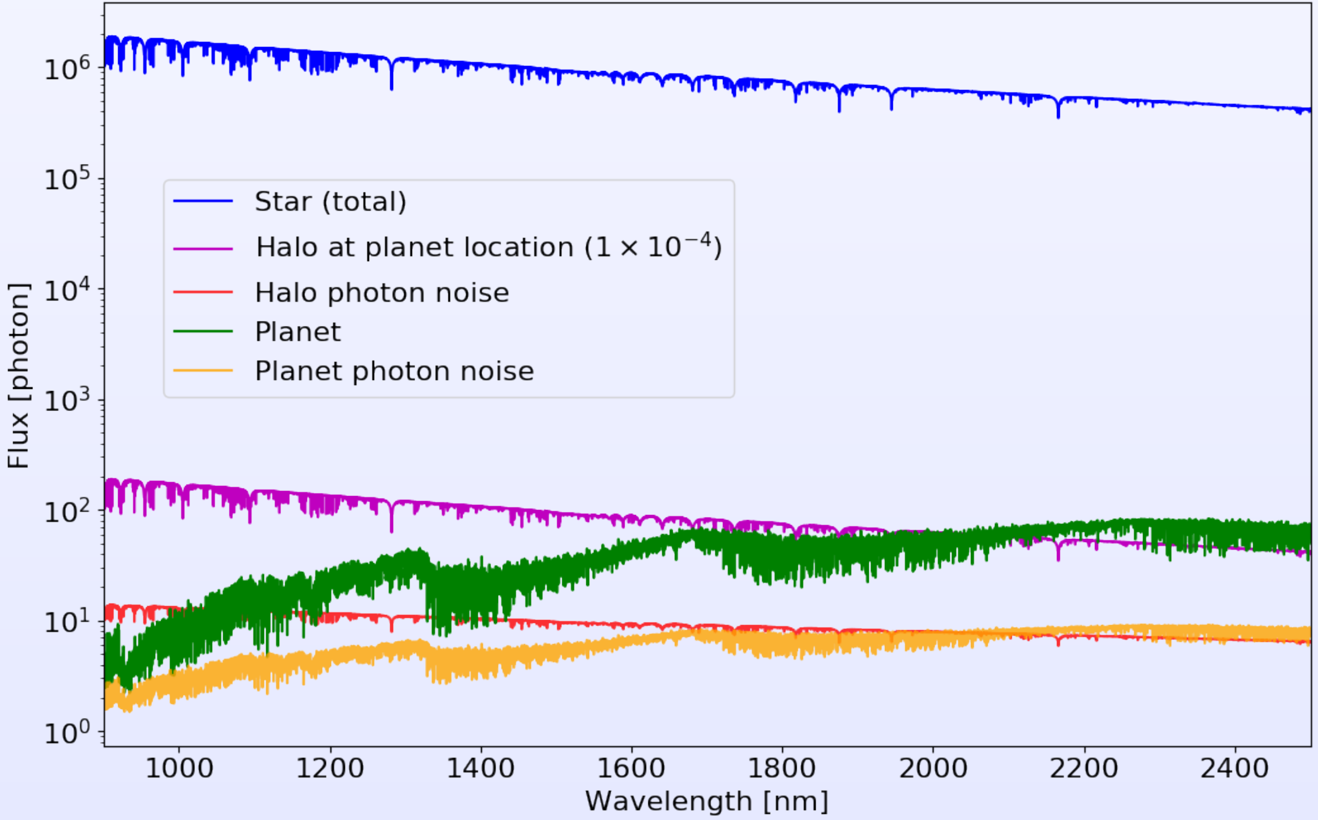
Preliminary simulations

- BT-NextGen model for the star
- BT-Settl model for the planet
- Magnitudes from the literature

- Texp = 1 hr
- R=10^5
- no spectral binning
- Realistic values for transmission

	Transmission
SPHERE	15 %
Injection	70 %
Fiber	99 %
CRIRES+	15 %


SPHERE+CRIRES - beta_Pictoris_b - Texp = 1.0hr - R = 100000


SPHERE+CRIRES - HIP65426b - Texp = 1.0hr - R = 100000

>1000 photon/channel
SNR > 100

>100 photon/channel
SNR > 10

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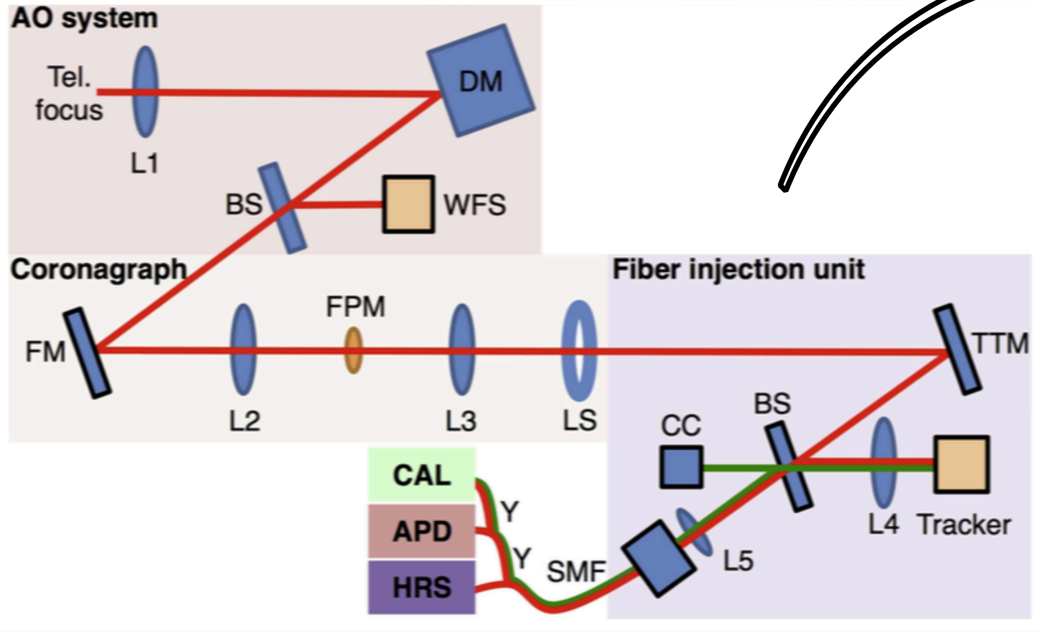
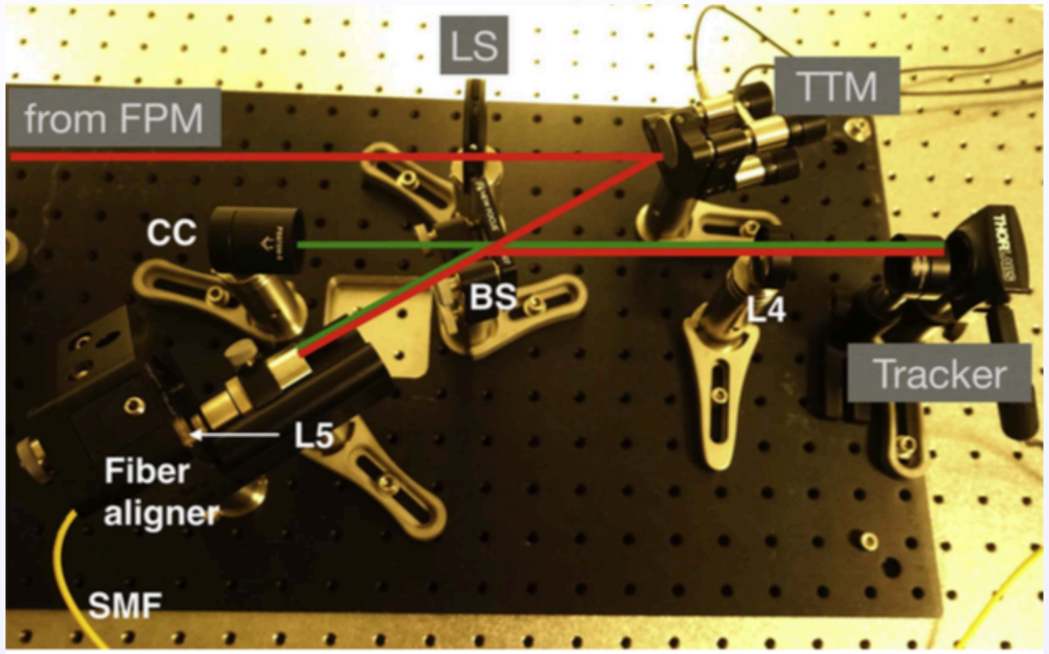
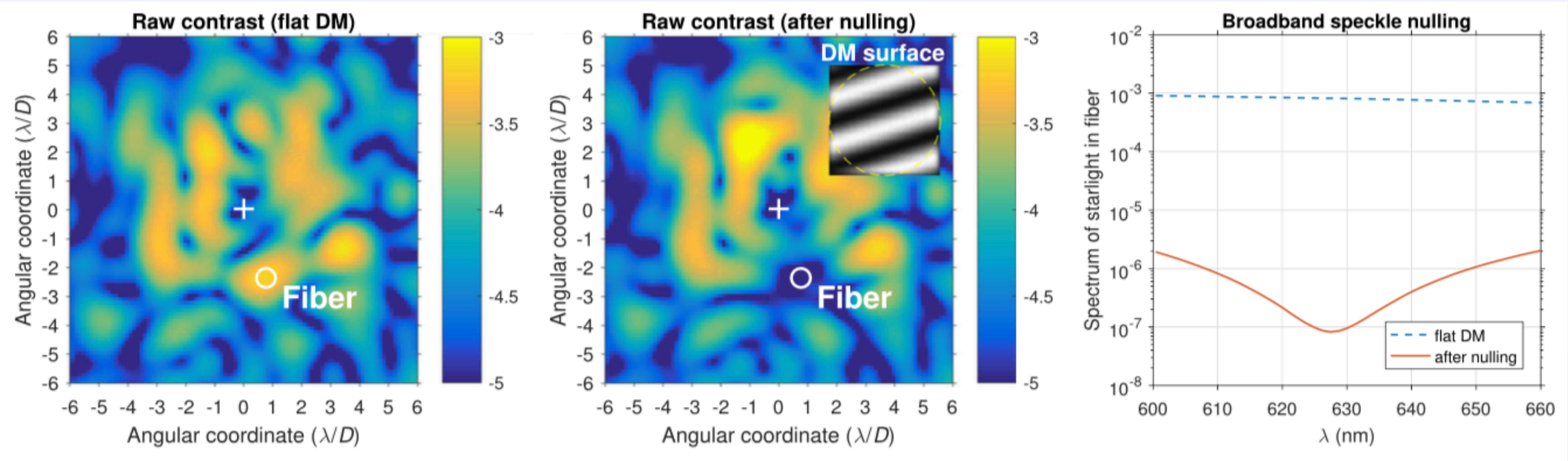
- …

The Caltech approach



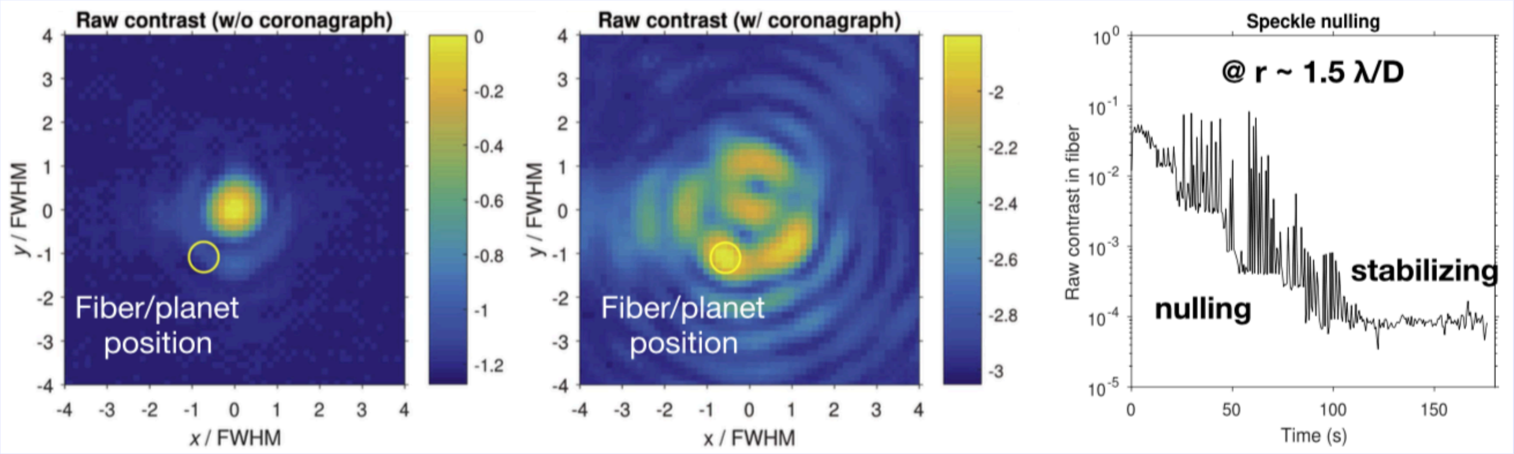


Mawet et al. (2017)



Simulation

Lab demonstration

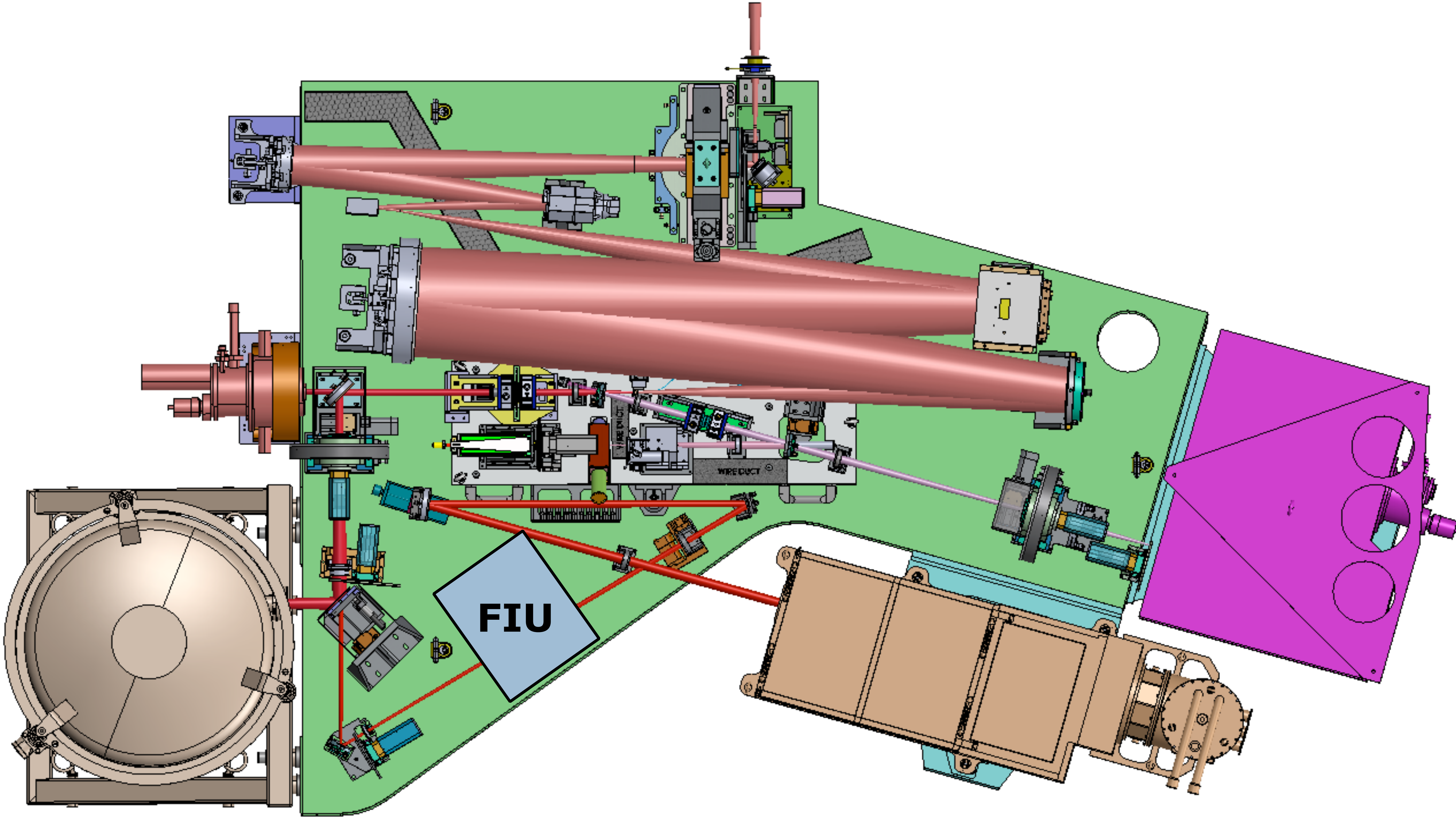


Technical challenges?

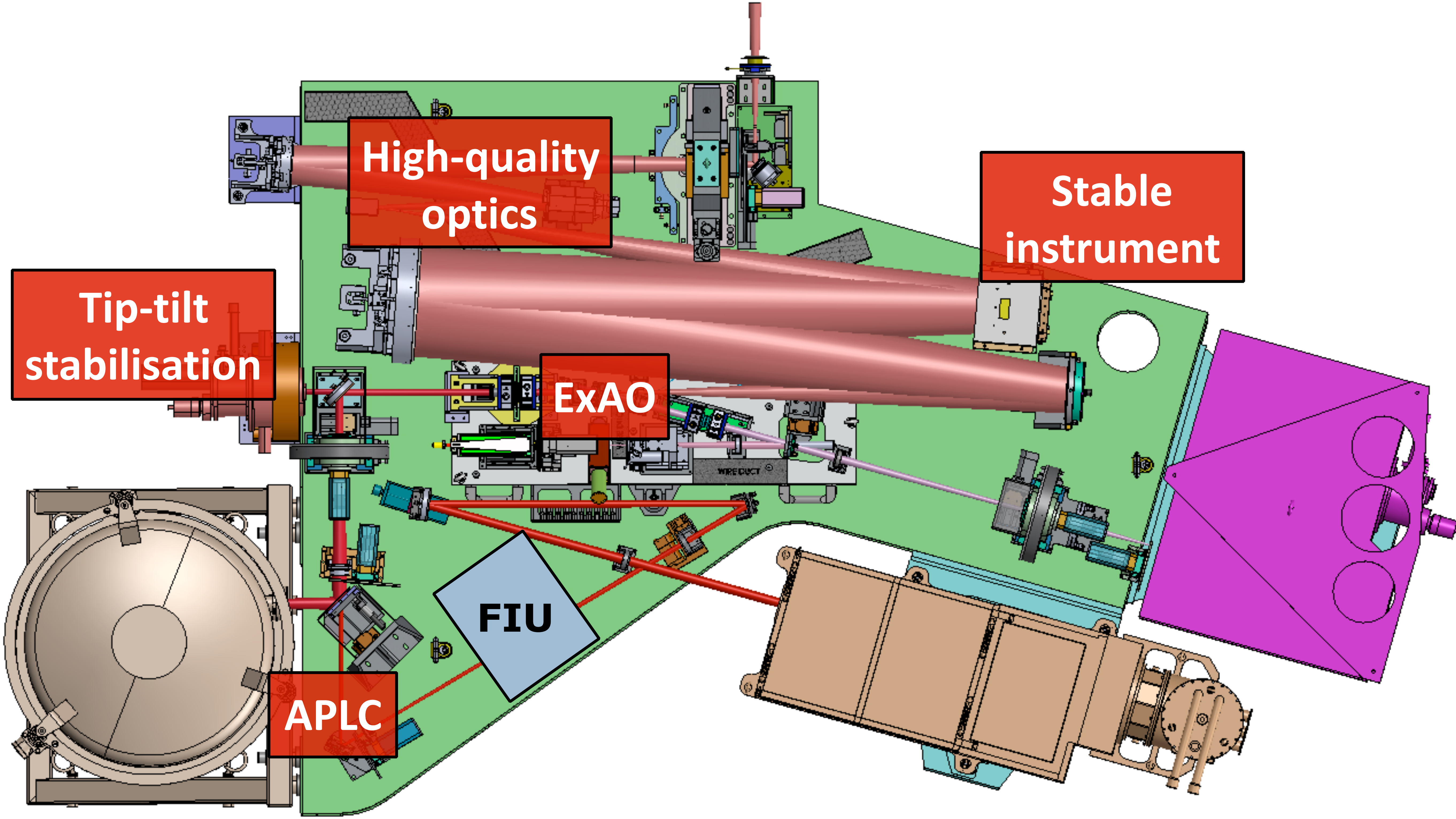
Many technical questions!

- Do we have enough photons coming from directly imaged exoplanets?
- How to position the fibre on the planet (or the planet on the fibre)?
- How to best inject the planetary signal in the fibre?
- How to optimise the coupling?
- Is wavefront control needed to optimise the injection?
- How stable do we need to be in tip-tilt?
- What type of fibre do we use?
- **How to design a module that fits within SPHERE?**
- **How many fibres do we need? How many can fit at the entrance of CRIRES+?**
- ...

A prototype fiber injection in SPHERE

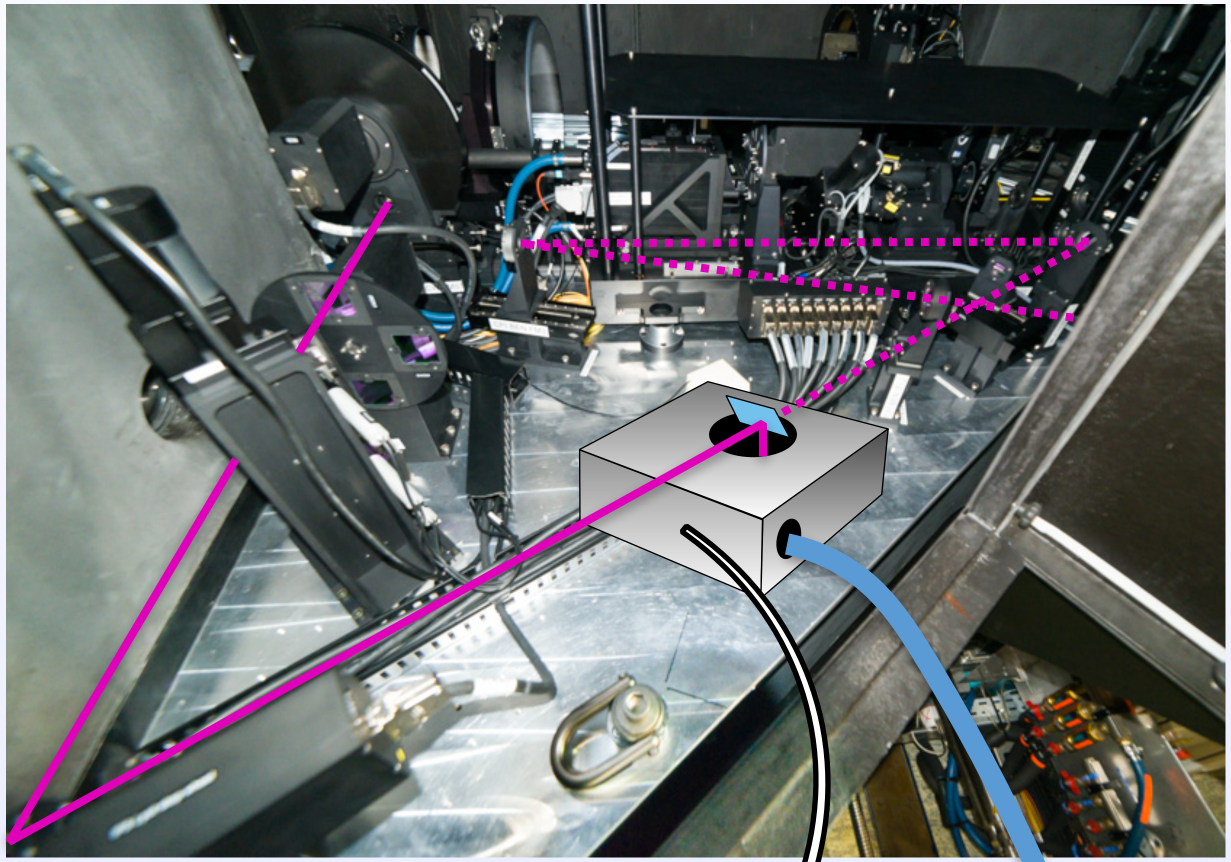


A prototype fiber injection in SPHERE



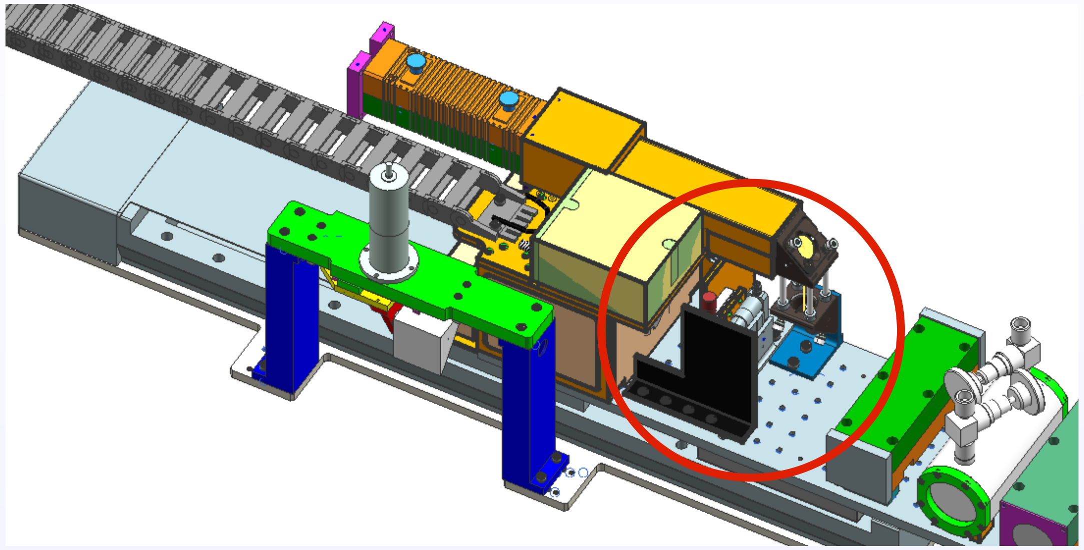
A prototype fiber injection in SPHERE

SPHERE near-infrared arm



Fiber injection unit

Optical design and system implementation



CRIRES+ calibration unit stage

Fiber entrance **already available** in CRIRES+

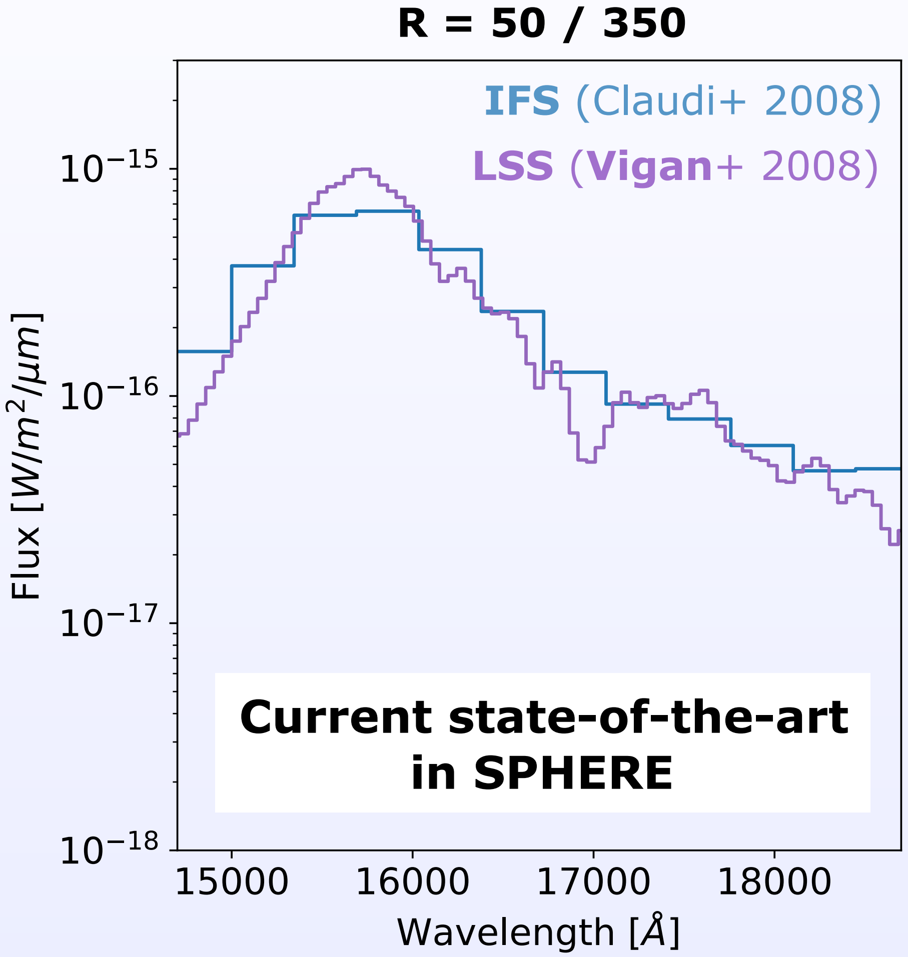
Fiber link

Astrophysical challenges?

Many astrophysical questions!

- What planets can be detected?
- What level of characterisation can be reached?
- Can we quantify abundances?
- Can we measure atmospheric variability?
- Can we bring additional constraints for dynamical mass estimations?
- ...

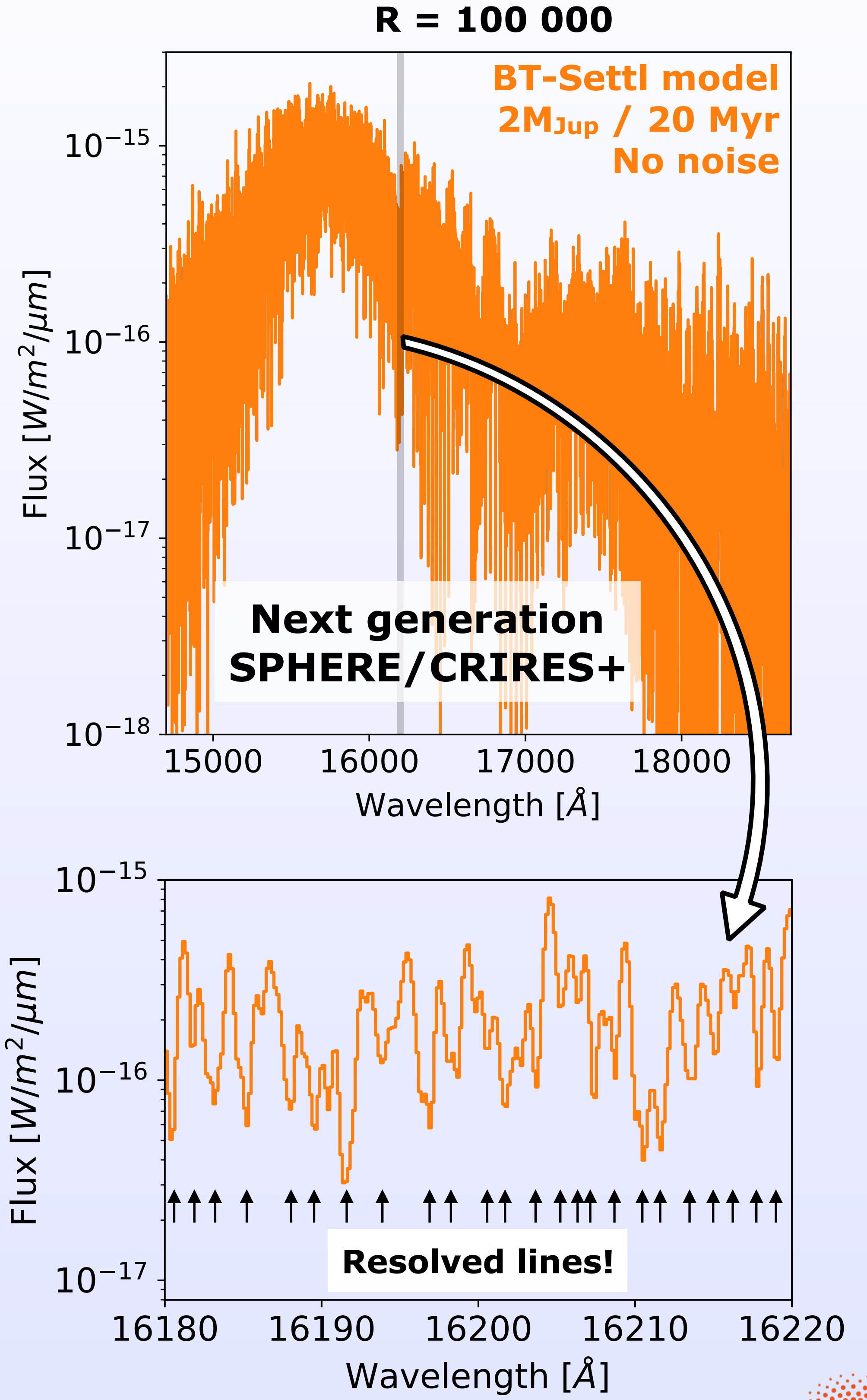
New science at high-spectral resolution



Current state-of-the-art in SPHERE

HiRISE

Resolution x300 to x2000

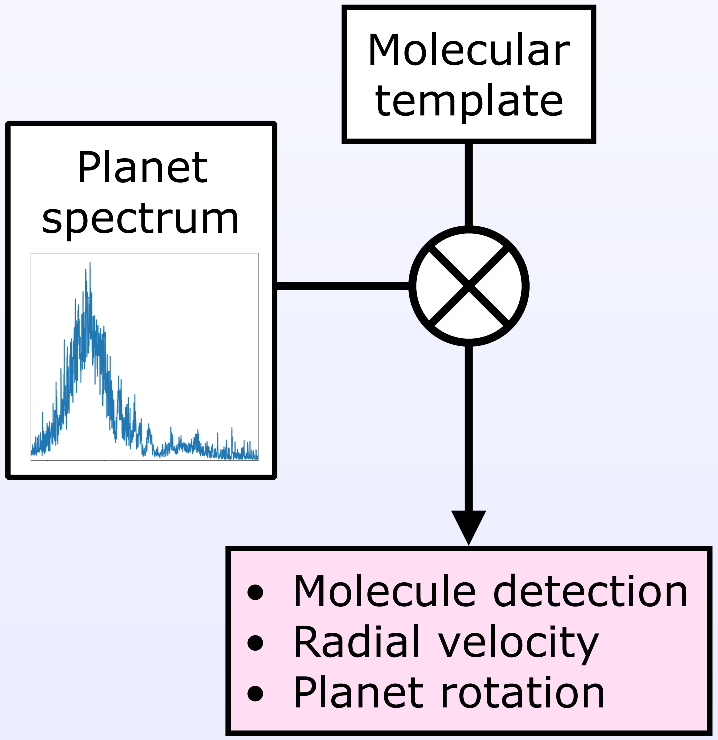


Next generation SPHERE/CRIRES+

Resolved lines!

New science at high-spectral resolution

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



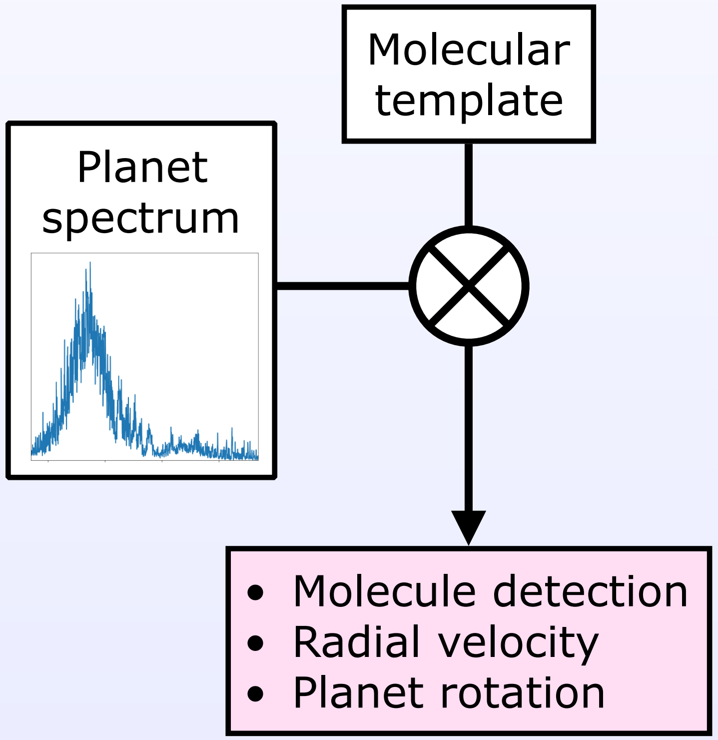
Molecular template

Planet spectrum

- Molecule detection
- Radial velocity
- Planet rotation

New science at high-spectral resolution

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



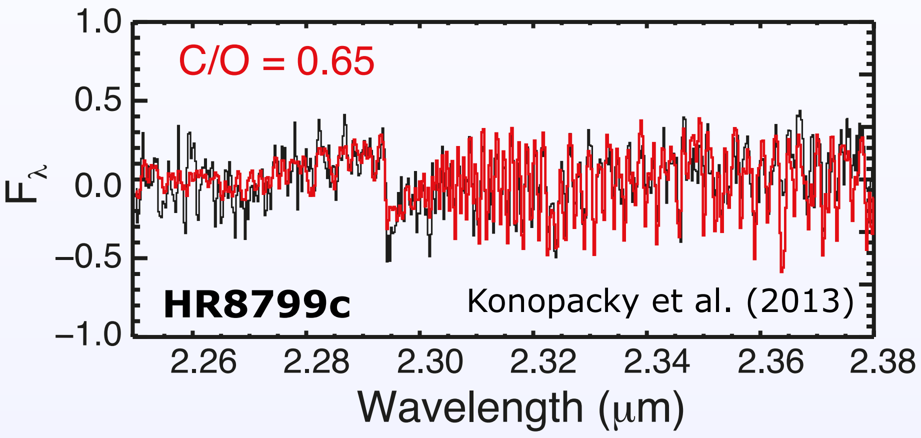
Molecular template

Planet spectrum

- Molecule detection
- Radial velocity
- Planet rotation

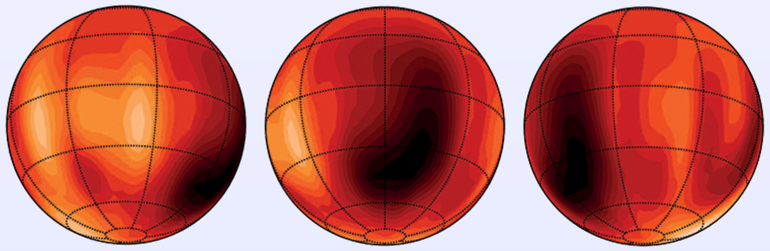
Molecular lines shape

Abundances determination



- formation scenario
- migration in the disk
- detailed composition

Time-resolved Doppler imaging



Luhman 16B (Crossfield et al. 2014)

- rotational period
- temporal variability
- cloud and winds

A brand new window on young giant exoplanets
Only feasible with high-spectral resolution

Prospects

- SPHERE/CRIRES+ implementation:
  - many technical challenges
  - brand new science within reach on young, giant exoplanets
- Long term:
  - ELT/HARMONI:
    - R=3000-20000
    - H- and K-band
  - ELT/PCS:
    - design studies will restart in coming years
    - HRS probably the only method to reach super-Earths
  - Space observations:
    - ~~WFIRST~~: low-resolution IFS (or no IFS)
    - LUVOIR: dedicated corono instrument