

Imaging exoplanetary systems

From young giant planets to Earth analogs

Arthur Vigan

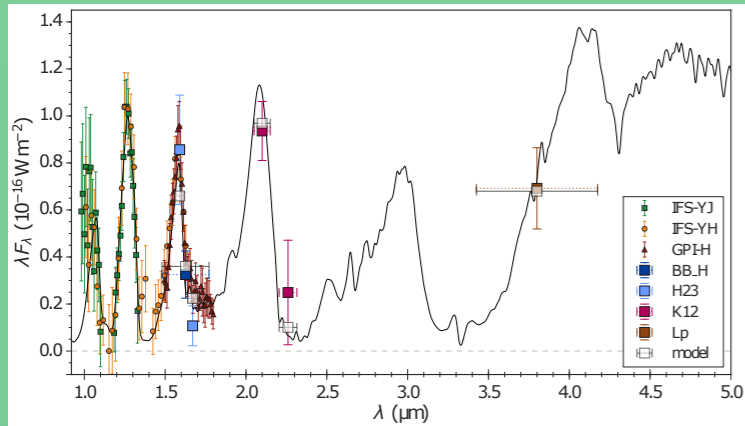
Laboratoire d'Astrophysique de Marseille (LAM)
Centre National de la Recherche Scientifique (CNRS)



Imaging of exoplanetary systems

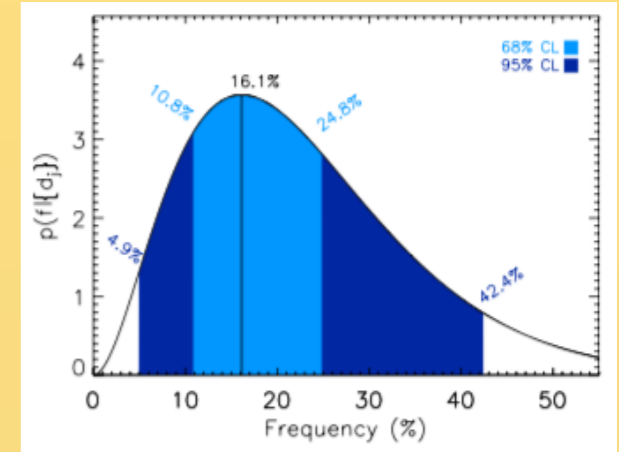
Physics of giant exoplanets

→ Atmosphere, bulk properties, comparative planetology

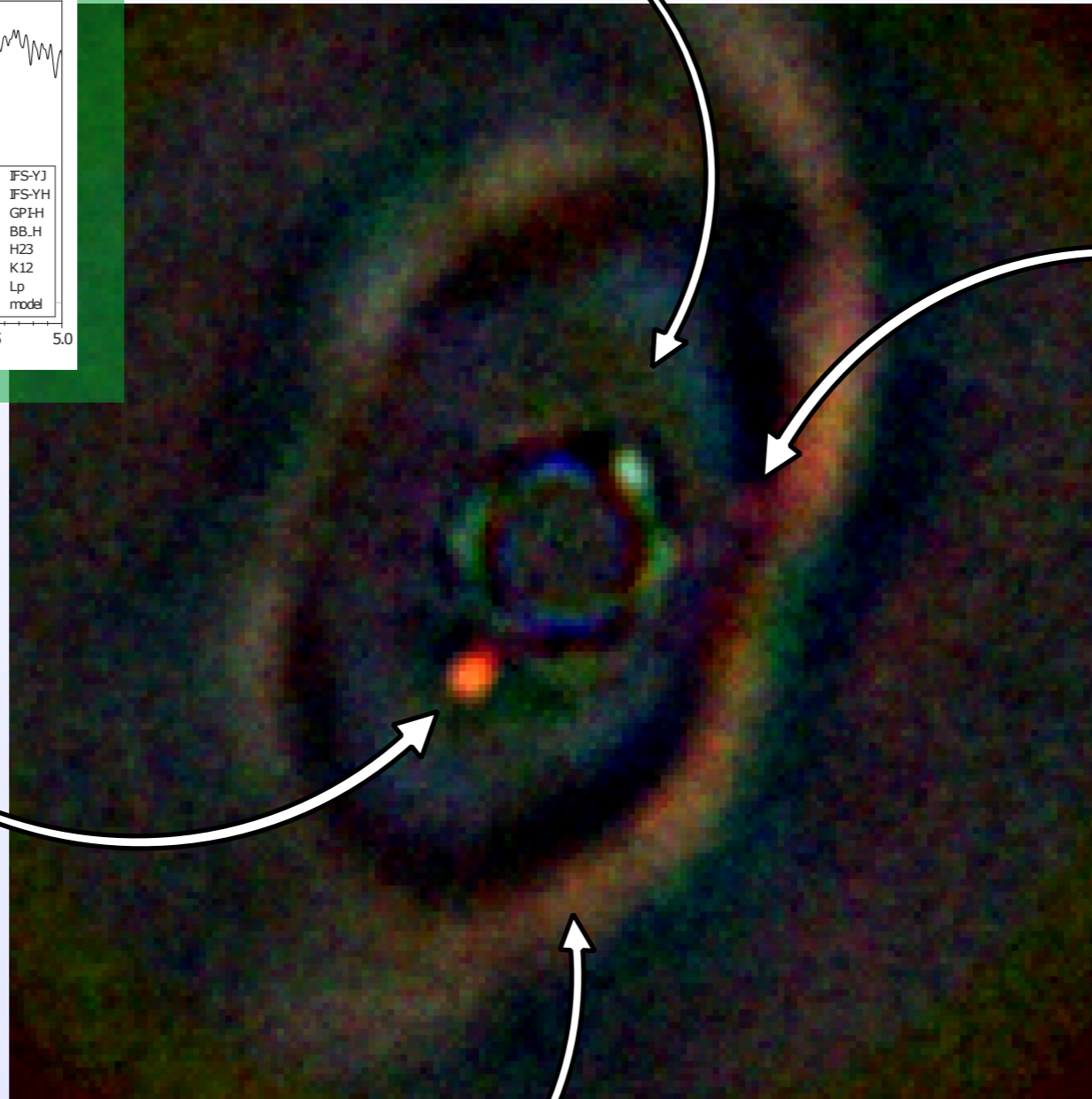


Occurrence & formation

→ Formation theories



Cavity



PDS 70 - Keppler et al. (2018)

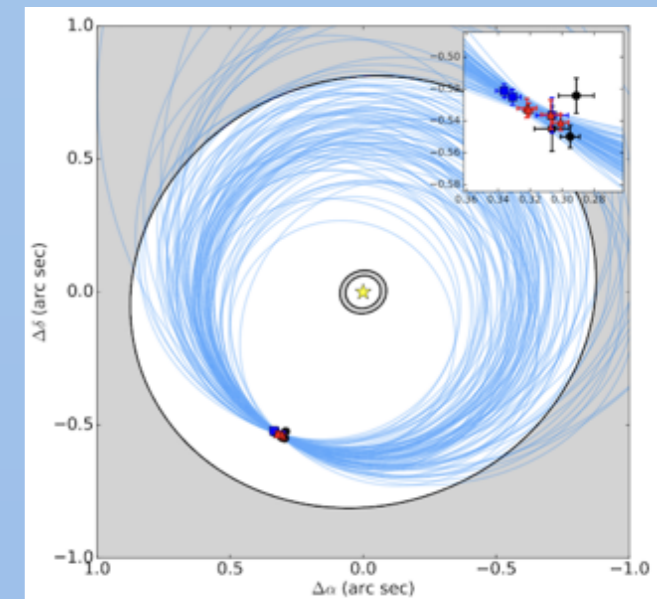
Giant planet

Giant planet

Dust & gas disk

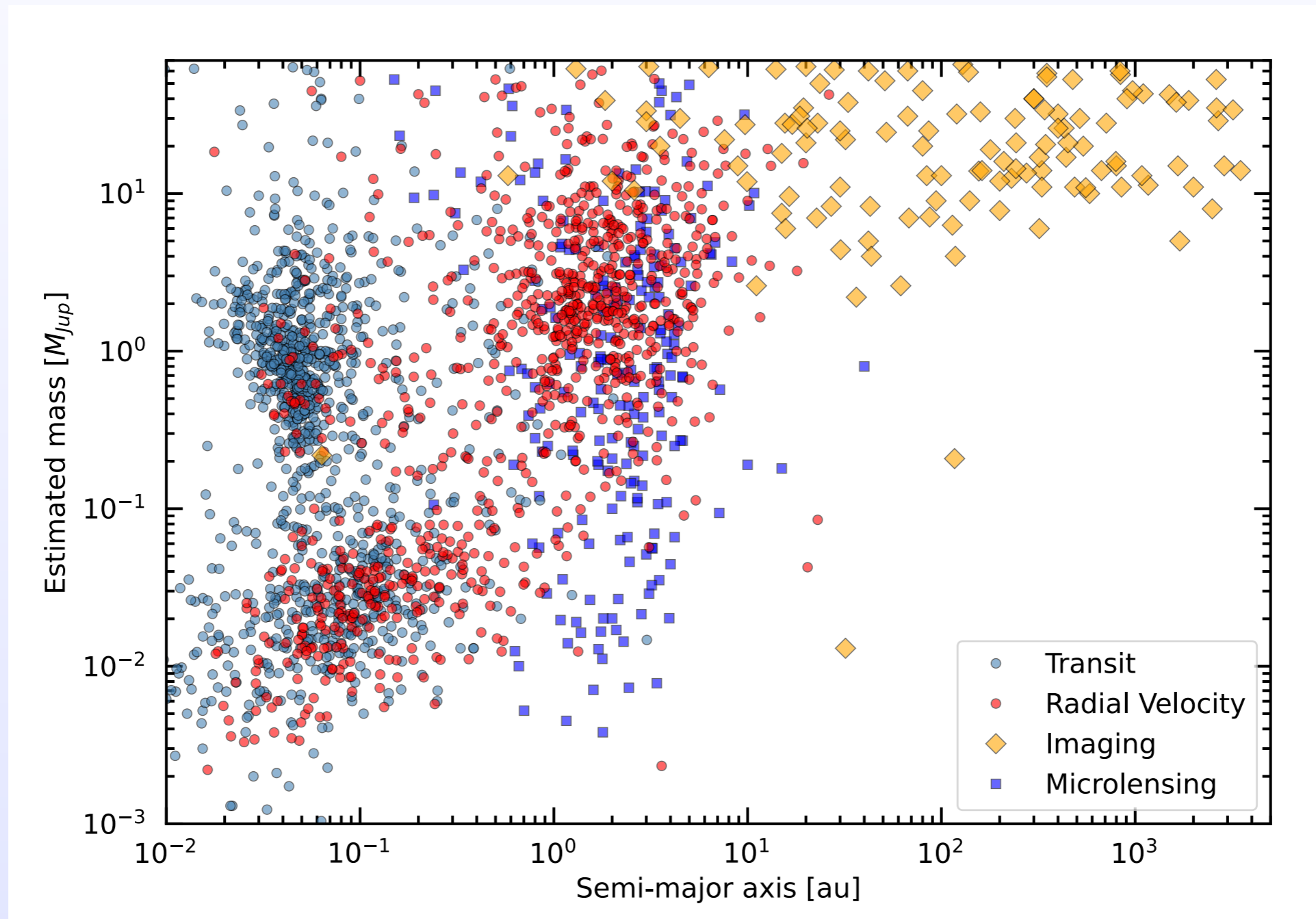
System architecture

→ Orbits, dynamical interactions, stability



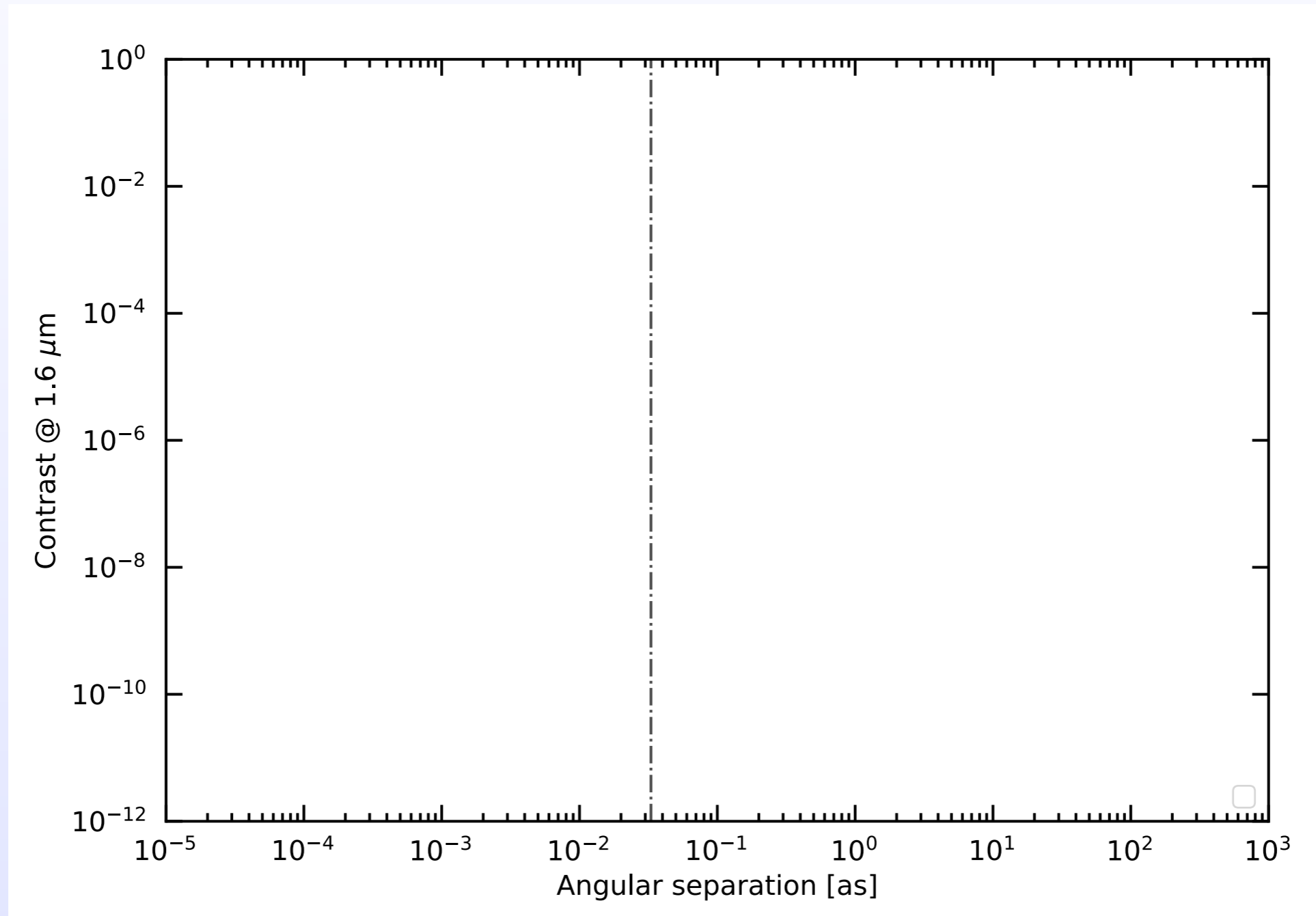
Direct imaging: the challenge

Physical units



Direct imaging: the challenge

Observables



Direct imaging: the challenge

Observables

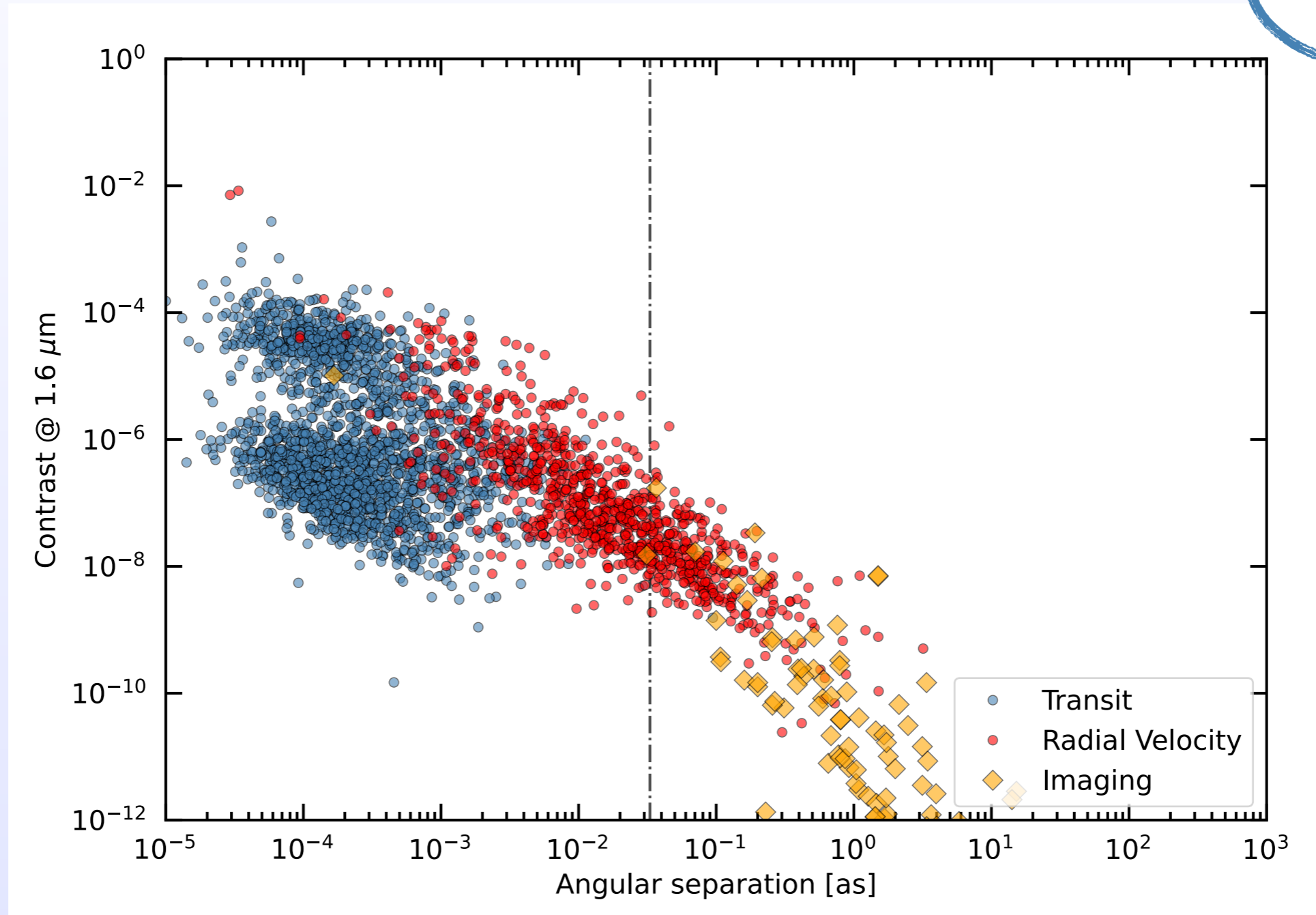
Emitted light



Direct imaging: the challenge

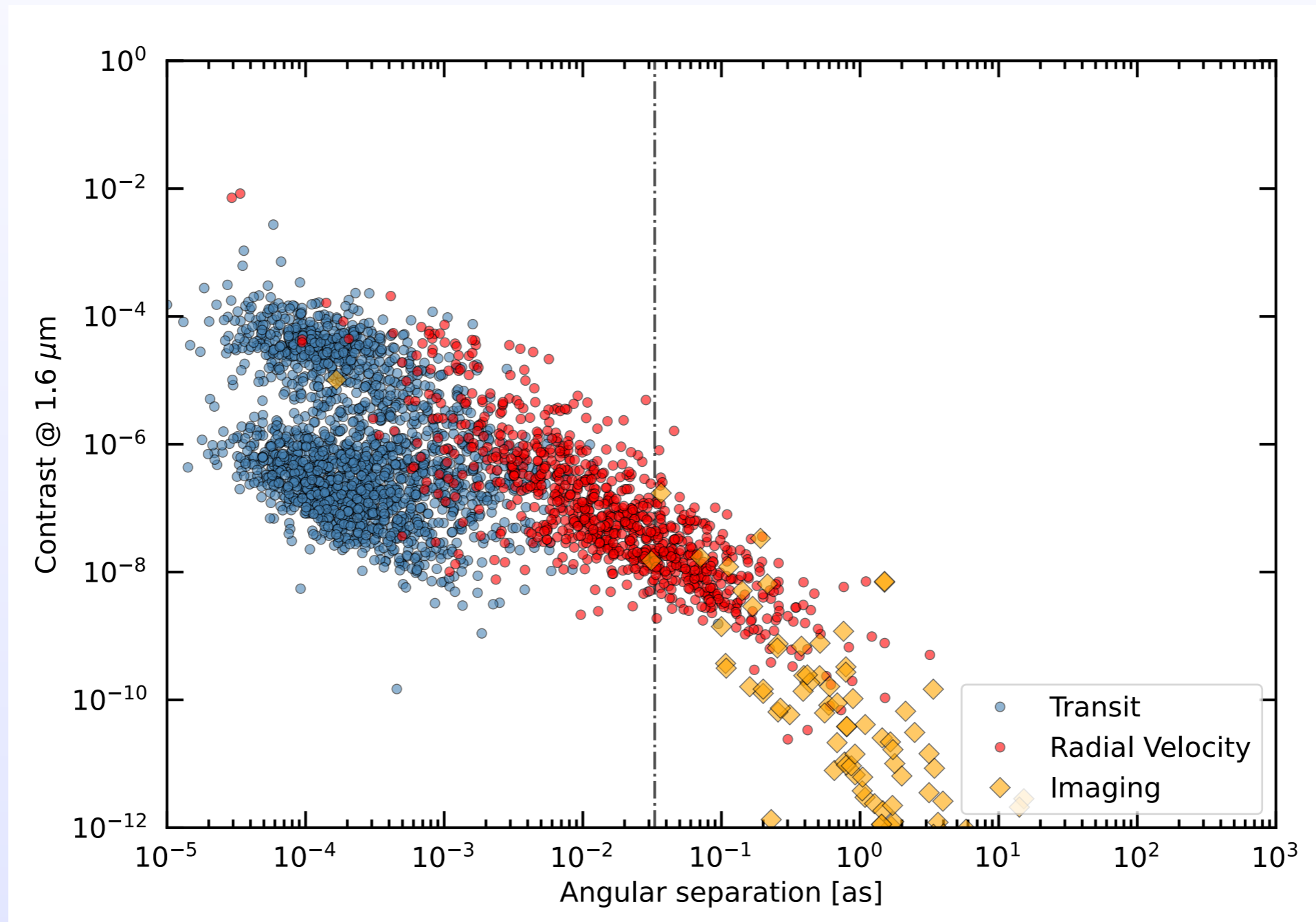
Observables

Reflected light



Direct imaging: the challenge

High-angular resolution



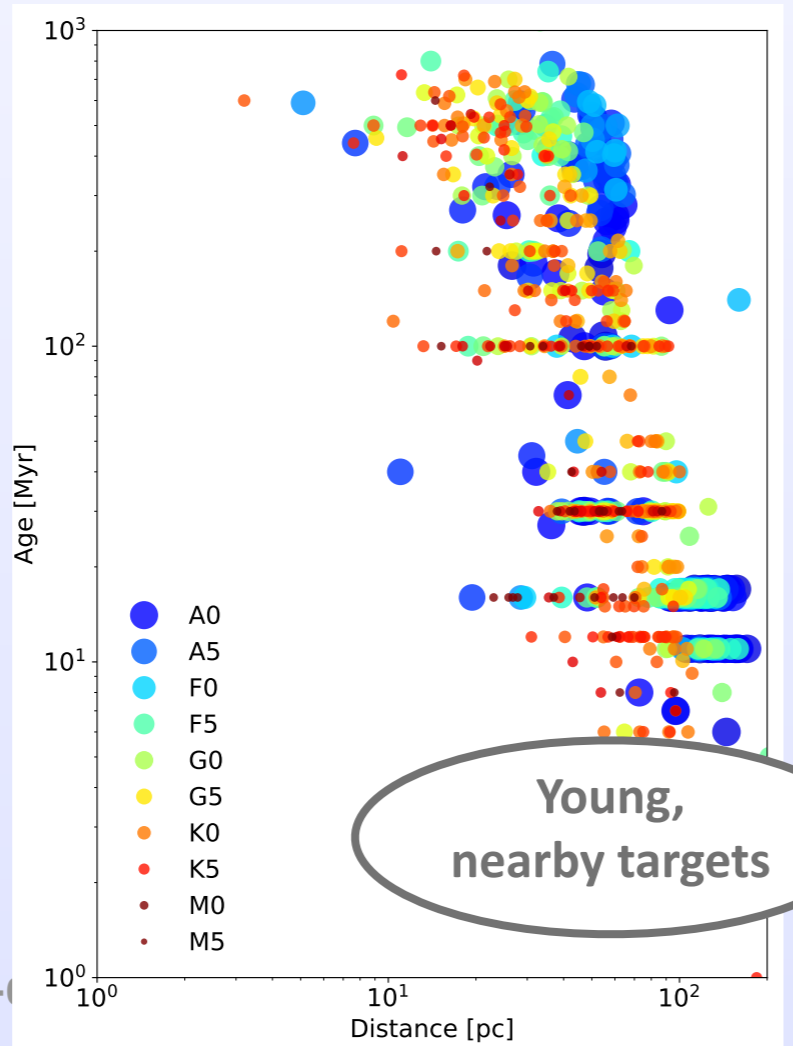
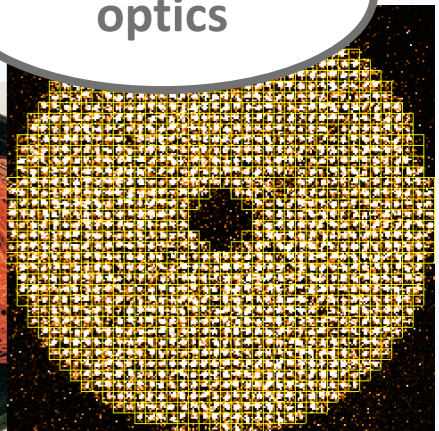
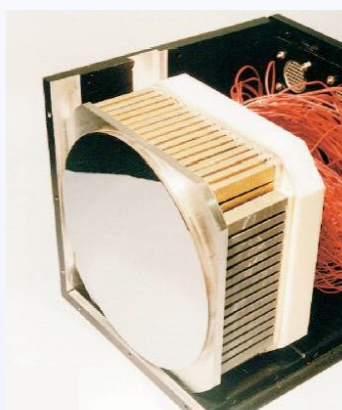
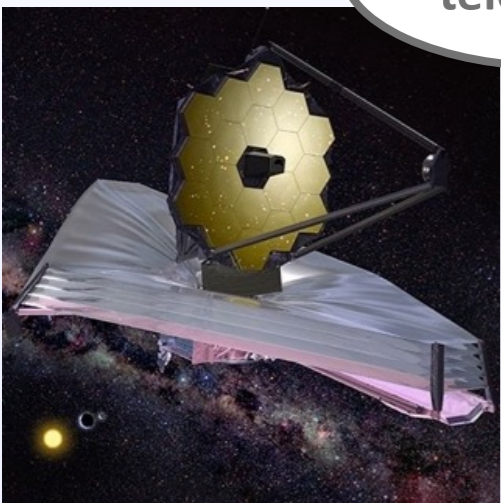
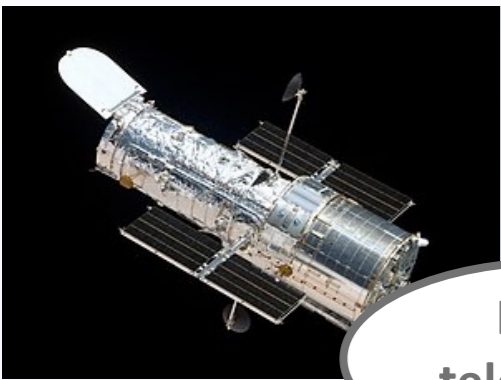
High-contrast

Direct imaging: the methods

High-angular resolution

Large telescopes

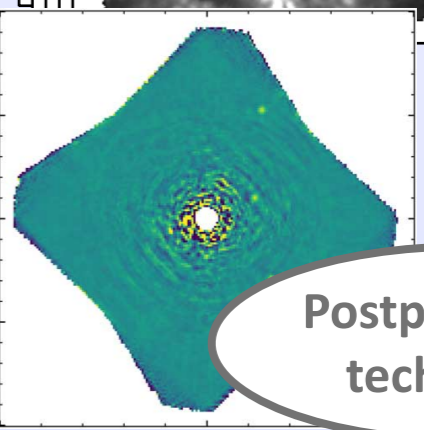
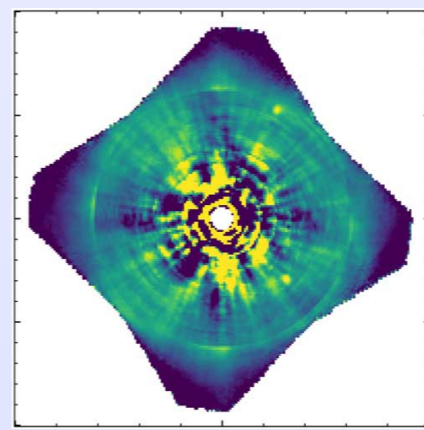
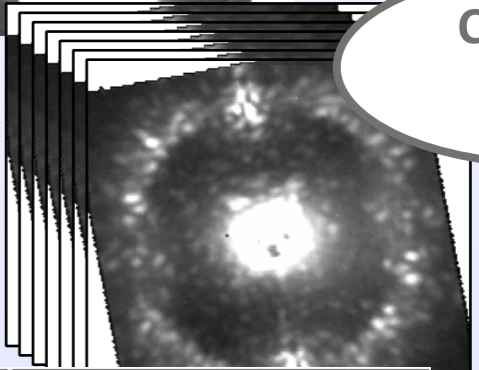
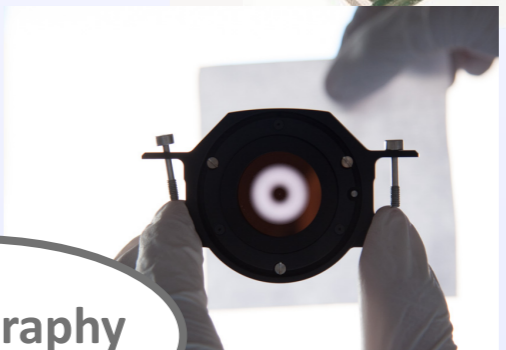
Adaptive optics



Coronagraphy

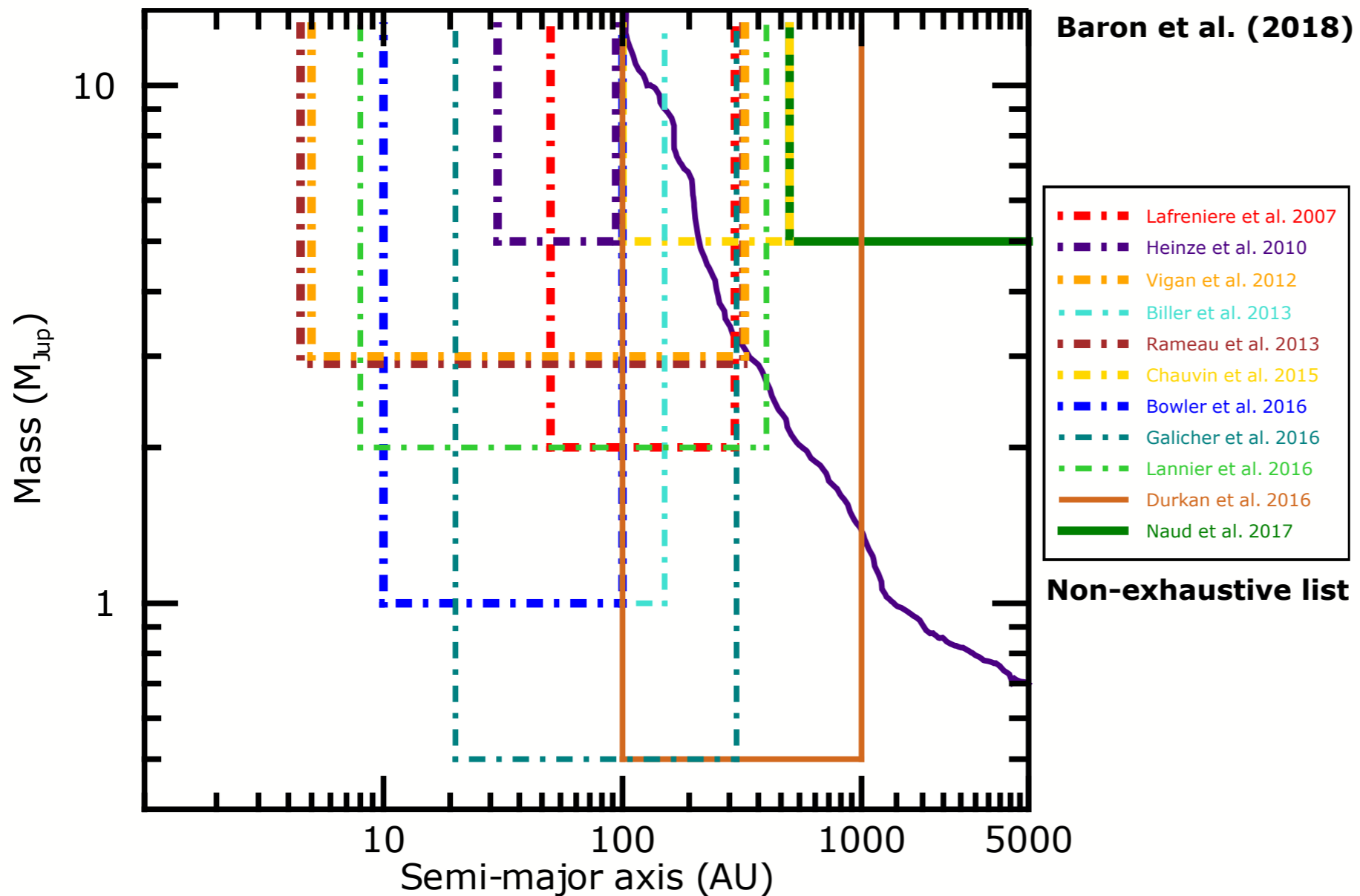
Camera, IFU

High-co



Postprocessing techniques

A multitude of surveys



- A to F stars
- Young to old
- Close an far
- Disk or not
- ...

Status in 2014-2015

>25 surveys since ~2000
~20 known companions

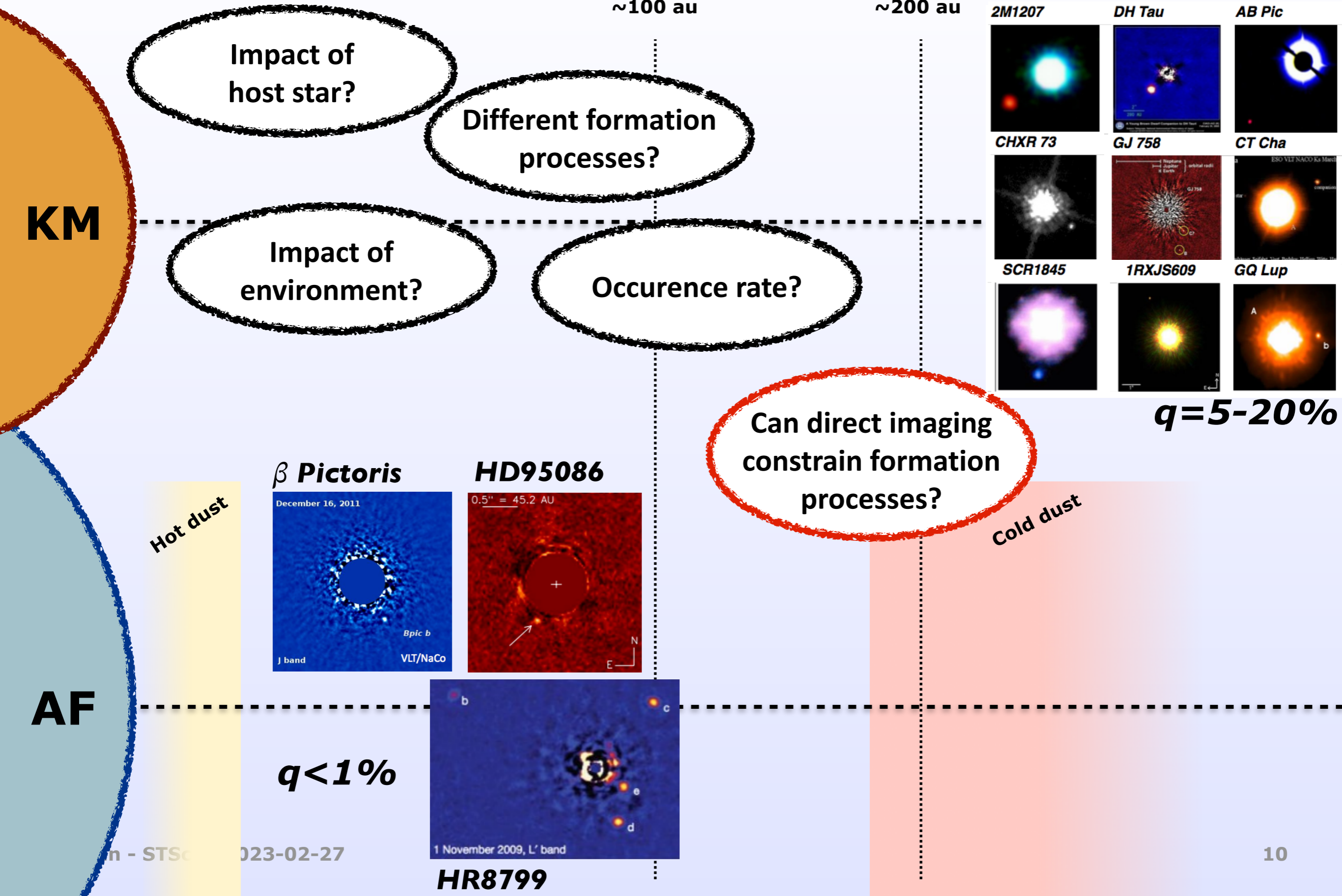
IDPS / AF-stars
PI: Christian Marois
Vigan et al. (2012)
Galicher et al. (2016)

NaCo-LP / FGK-stars
PI: Gaël Chauvin
Chauvin, Vigan et al. (2015)
Vigan et al. (2017)

SHINE / AFGKM-stars
PI: J.-L. Beuzit
Desidera et al. (2021)
Langlois et al. (2021)
Vigan et al. (2021)

Imaged companions in ~ 2015

$$q = \frac{M_p}{M_\star}$$



KM

AF

Impact of host star?

Different formation processes?

Impact of environment?

Occurrence rate?

Can direct imaging constrain formation processes?

$q=5-20\%$

β Pictoris

HD95086

Hot dust

Cold dust

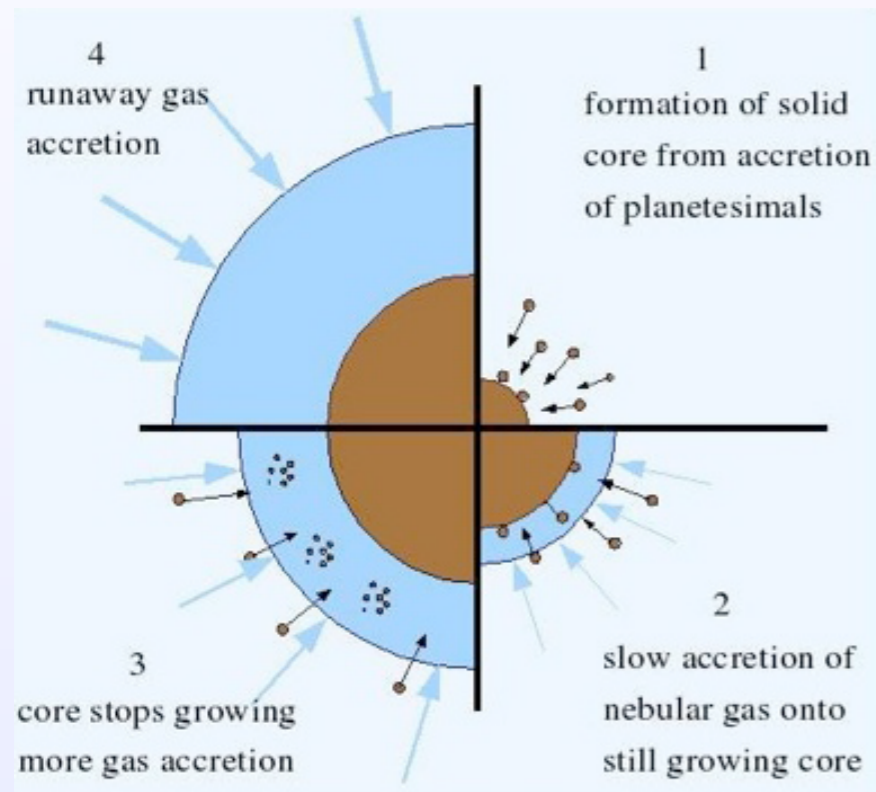
$q < 1\%$

HR8799

Formation scenarios of giant planets

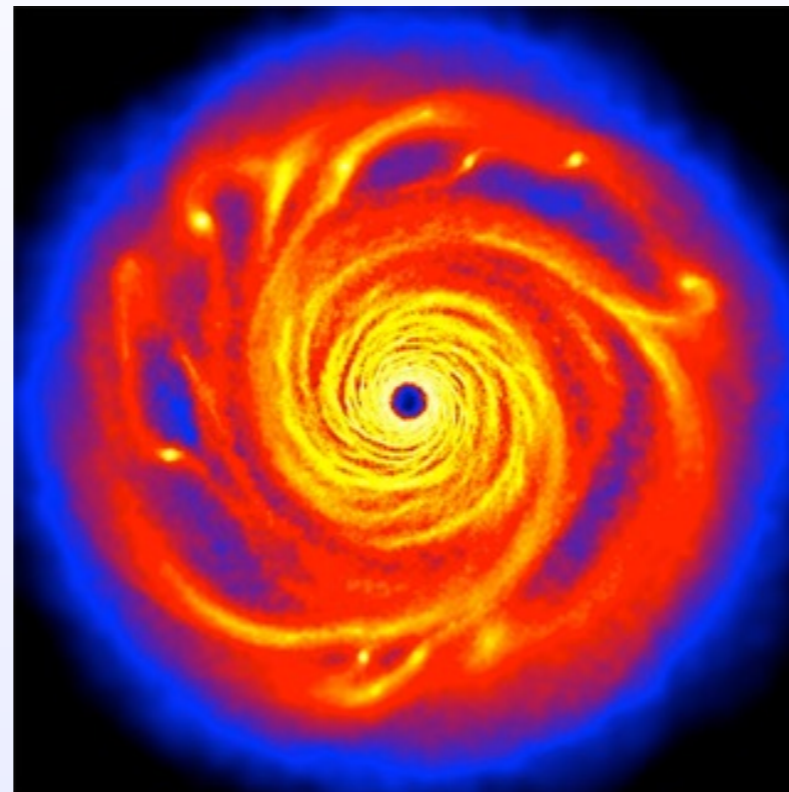
Core Accretion

Pollack et al. 1994



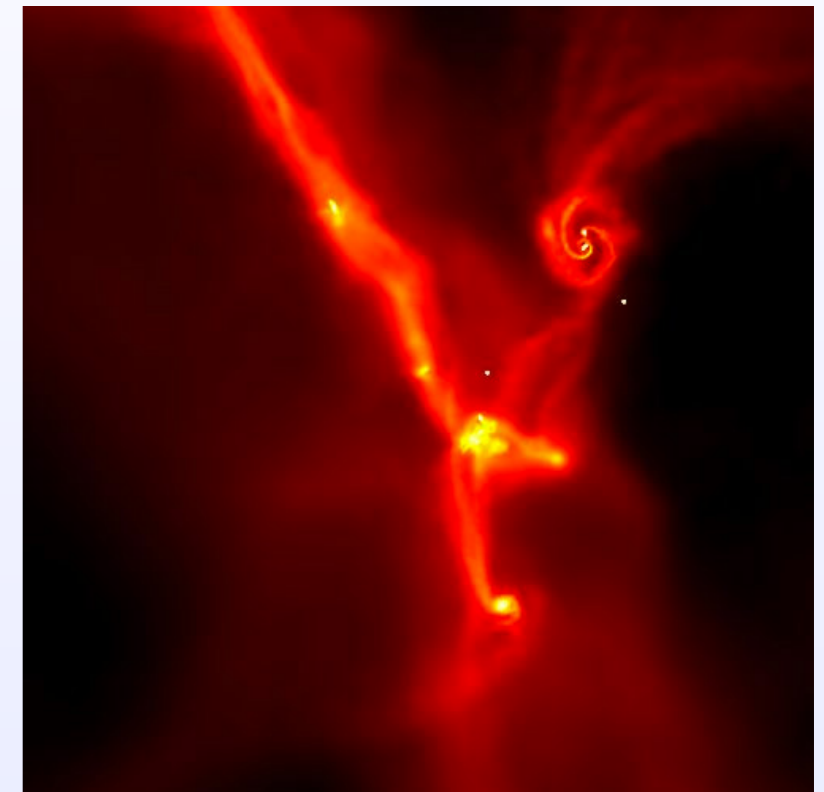
Gravitational Instability

Cameron 1978



Gravo-turbulent fragmentation

Hennebelle & Chabrier 2011



Different formation pathways will induce:

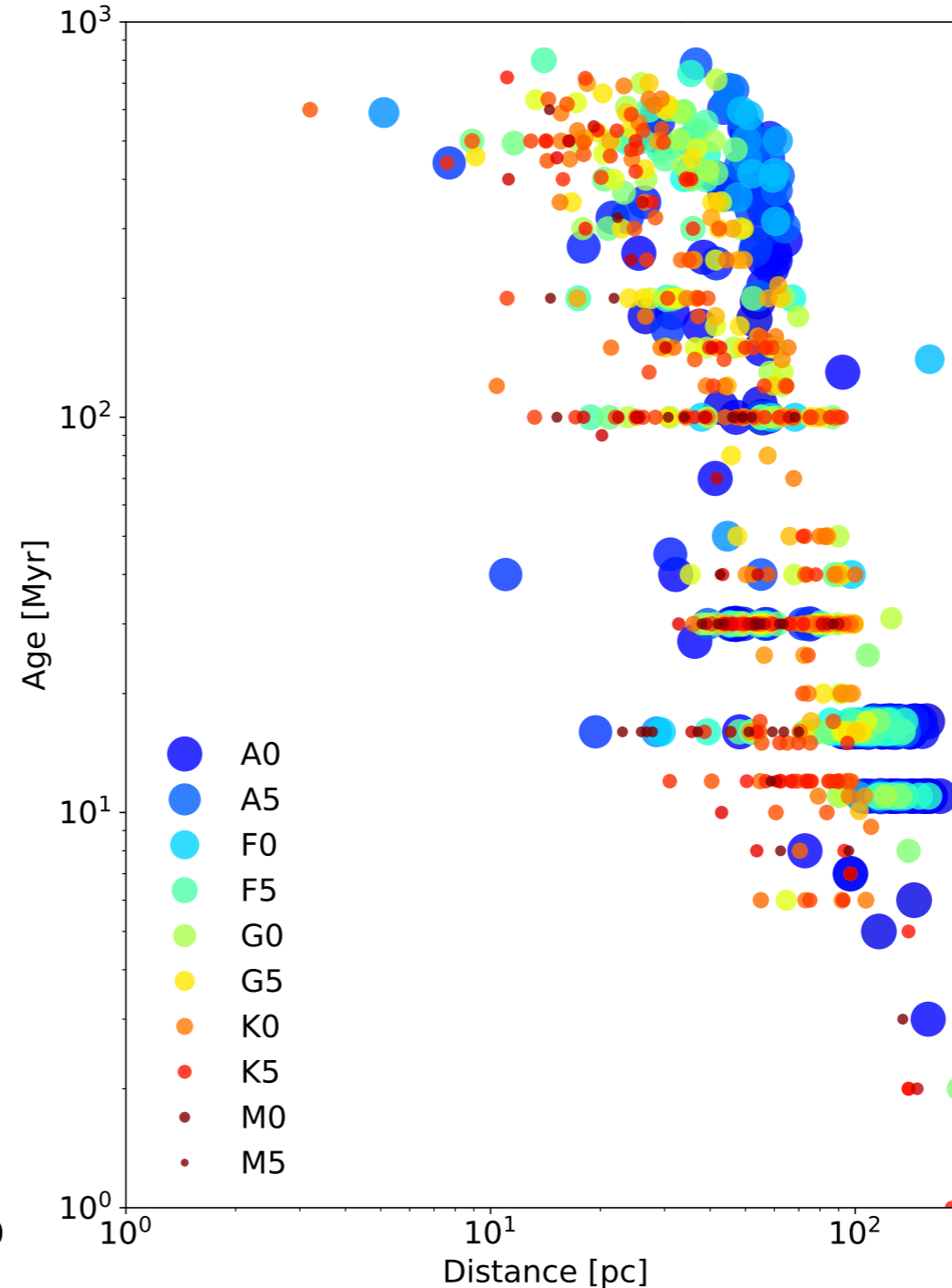
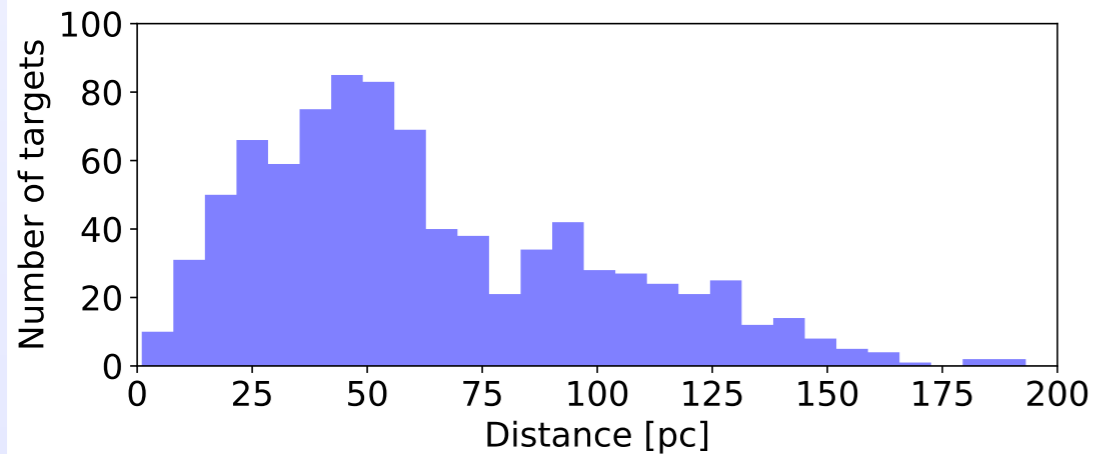
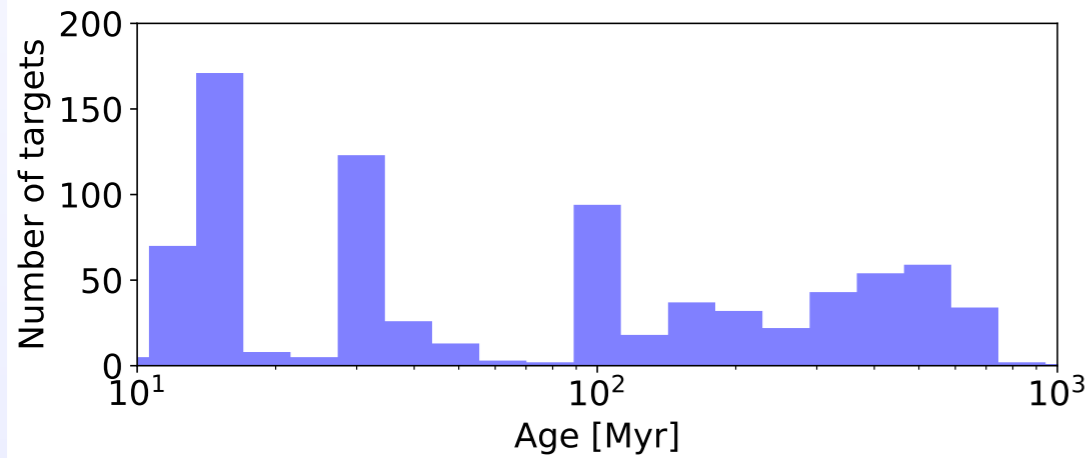
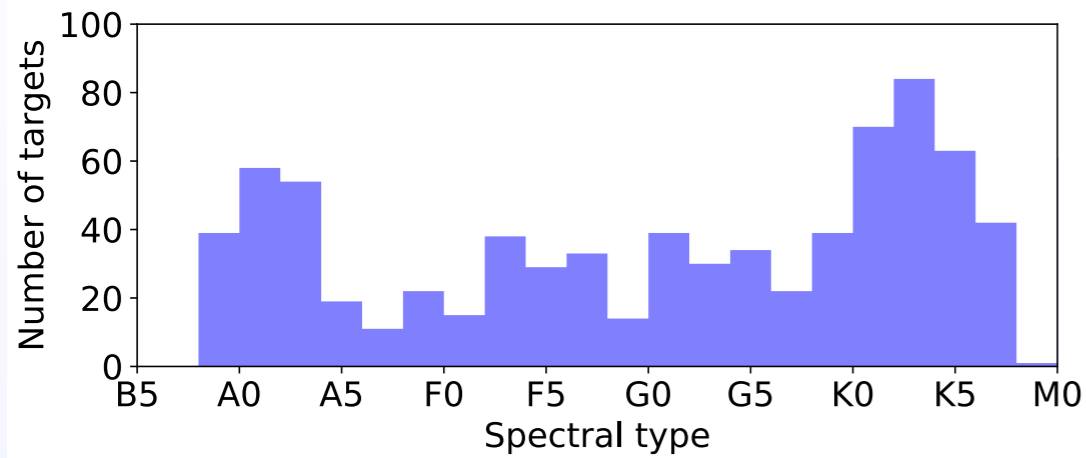
→ *Different occurrence rates*

→ *Different physical/orbital parameters*

→ *Different compositions*

→ *Different bolometric luminosities*

SHINE (& GPIES)



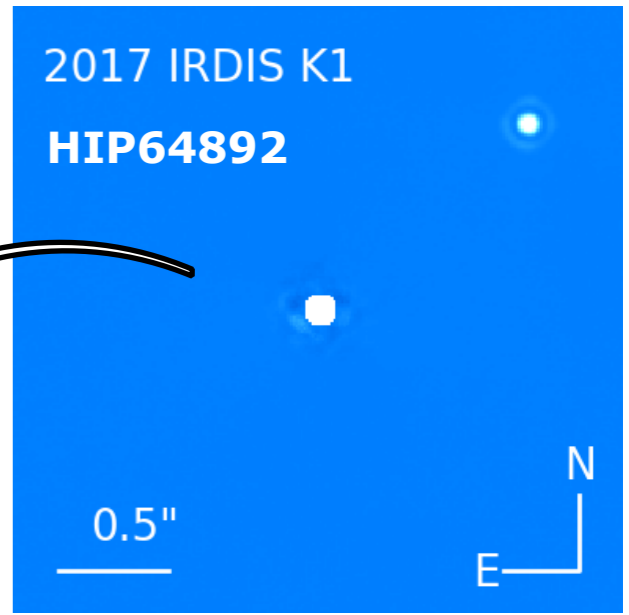
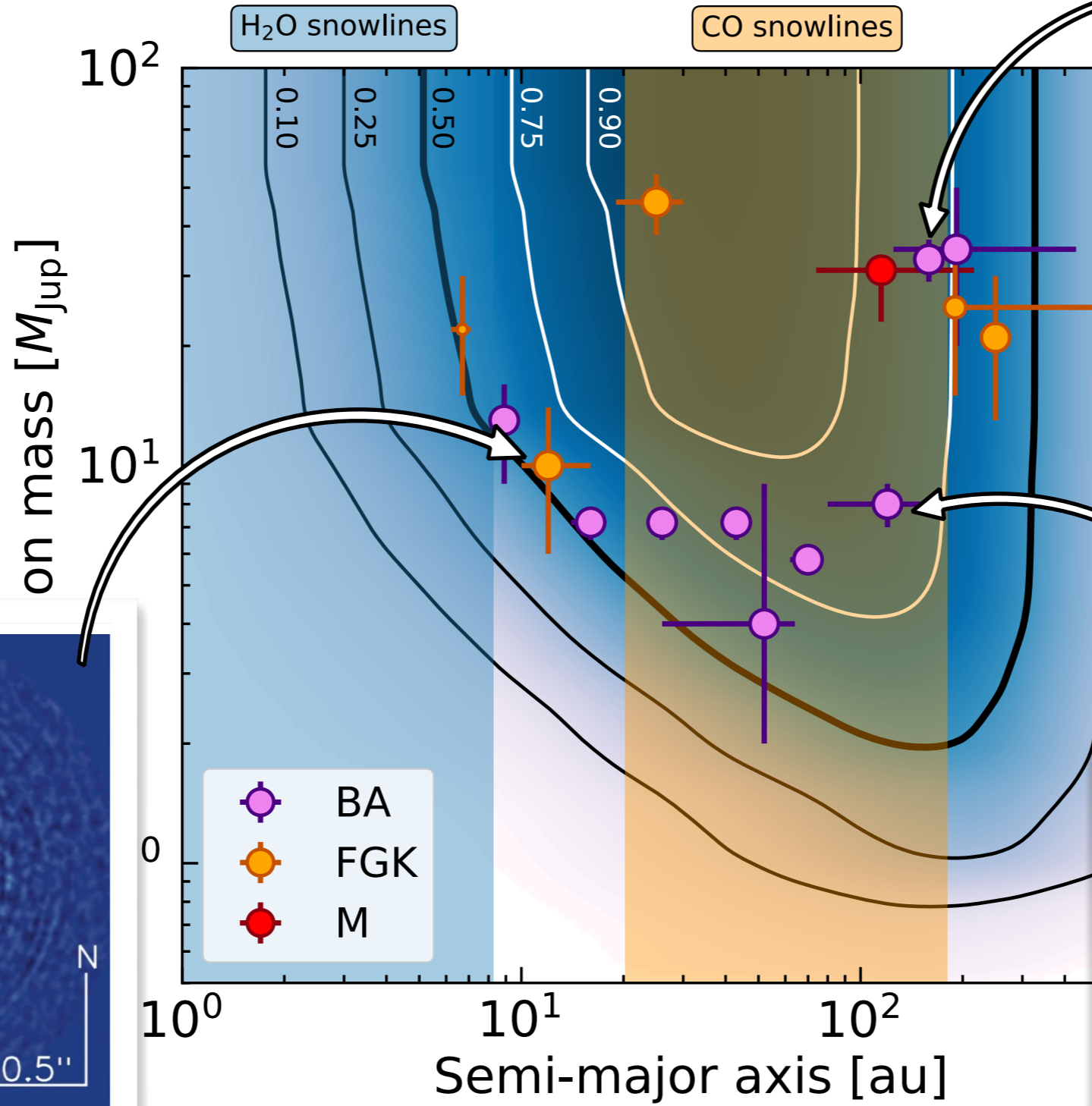
- PI J.-L. Beuzit
- 400 stars
- No binaries
- 200 nights of VLT/SPHERE
- GTO time
- Concluded in 2021
- 2 planets
- 1 brown dwarf

Intermediate survey results (150 stars)

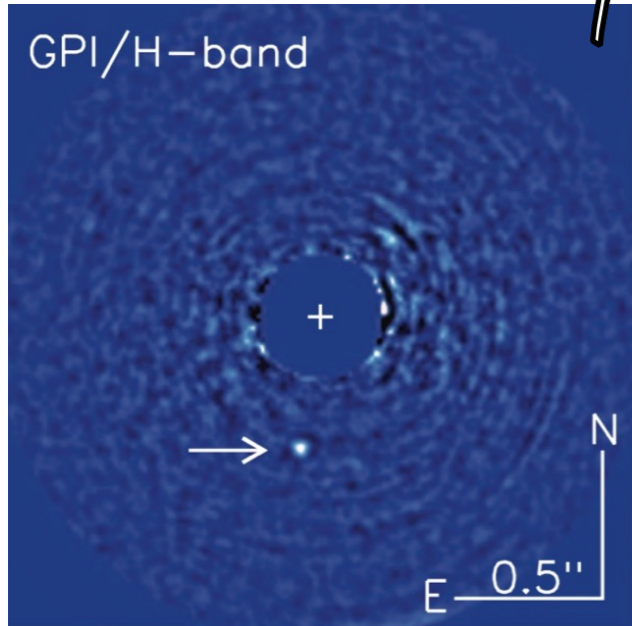
Desidera et al. (2021)
Langlois et al. (2021)
Vigan et al. (2021)

GPIES
Similar effort with
Gemini-S/GPI
PI: B. Macintosh

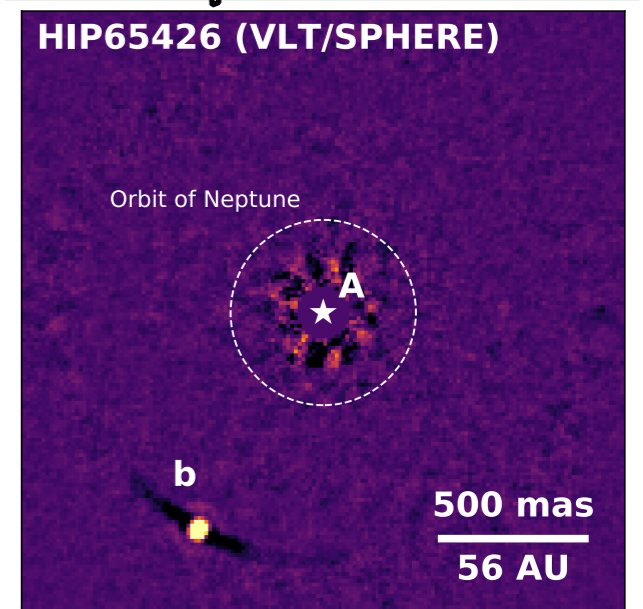
SHINE sensitivity



Cheetham et al. 2018



Macintosh et al. 2015



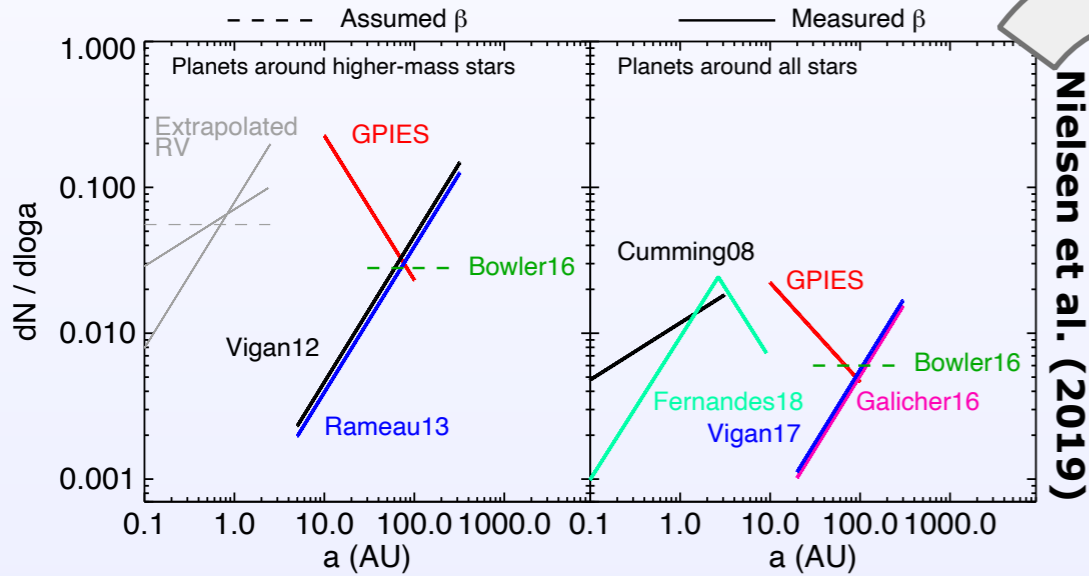
Chauvin et al. 2017

Exoplanet population modelling

Fully parametric

GPIES

$$\frac{d^2 N}{dm da} = f C_1 m^\alpha a^\beta \left(\frac{M_*}{M_\odot} \right)^\gamma$$

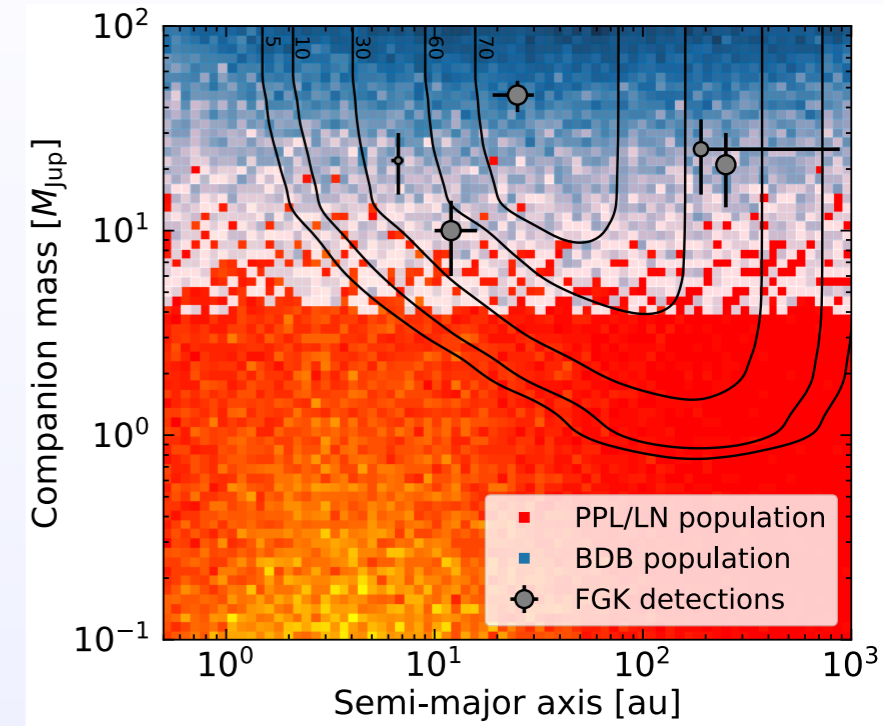


Physics-based parametric

SHINE

Regianni et al. (2016)
Vigan et al. (2021)

- Two-part model:
- Brown-dwarf binary part
 - Log-normal planet part



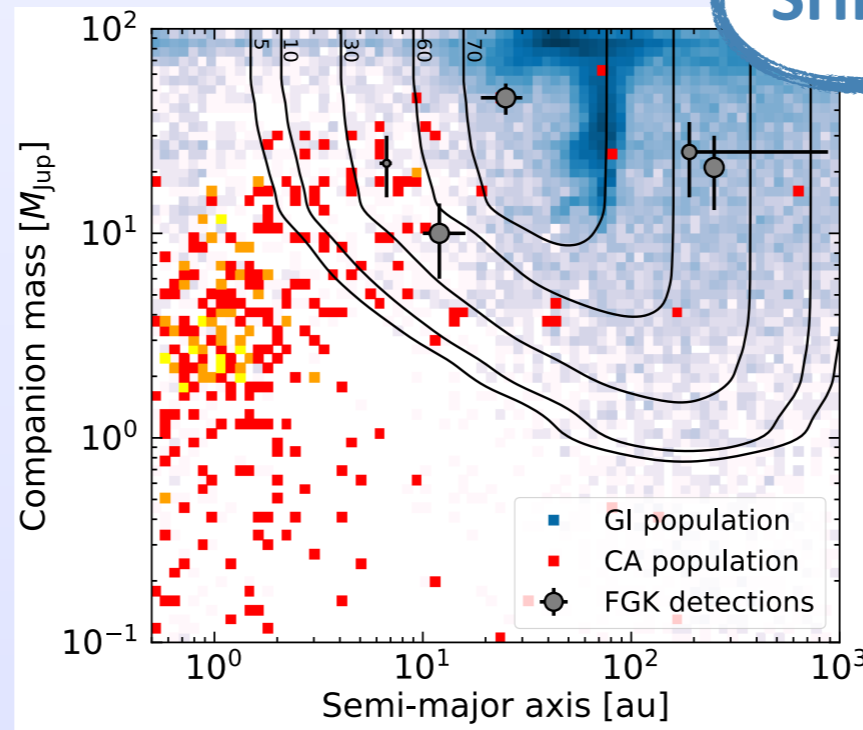
Fully physical → comparison to population synthesis!

Vigan et al. (2017)
Vigan et al. (2021)

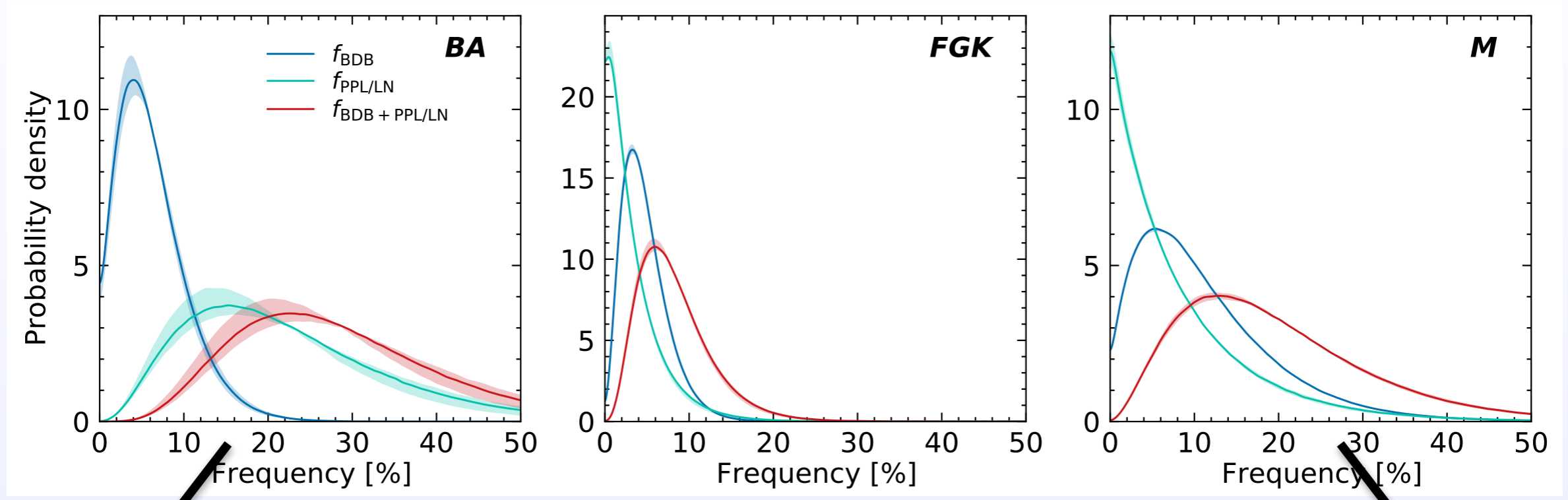
- Two-part model:
- Gravitational instability part
 - Core accretion part

**Current
state-of-the-art**

SHINE



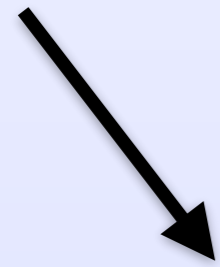
Physics-based parametric modelling



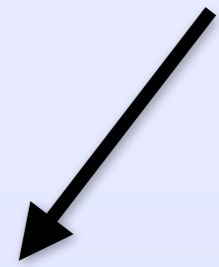
Massive companions
 \Leftrightarrow
 small q (<1-5%)

Change in dominant formation channel

Massive companions
 \Leftrightarrow
 moderate q (10-20%)

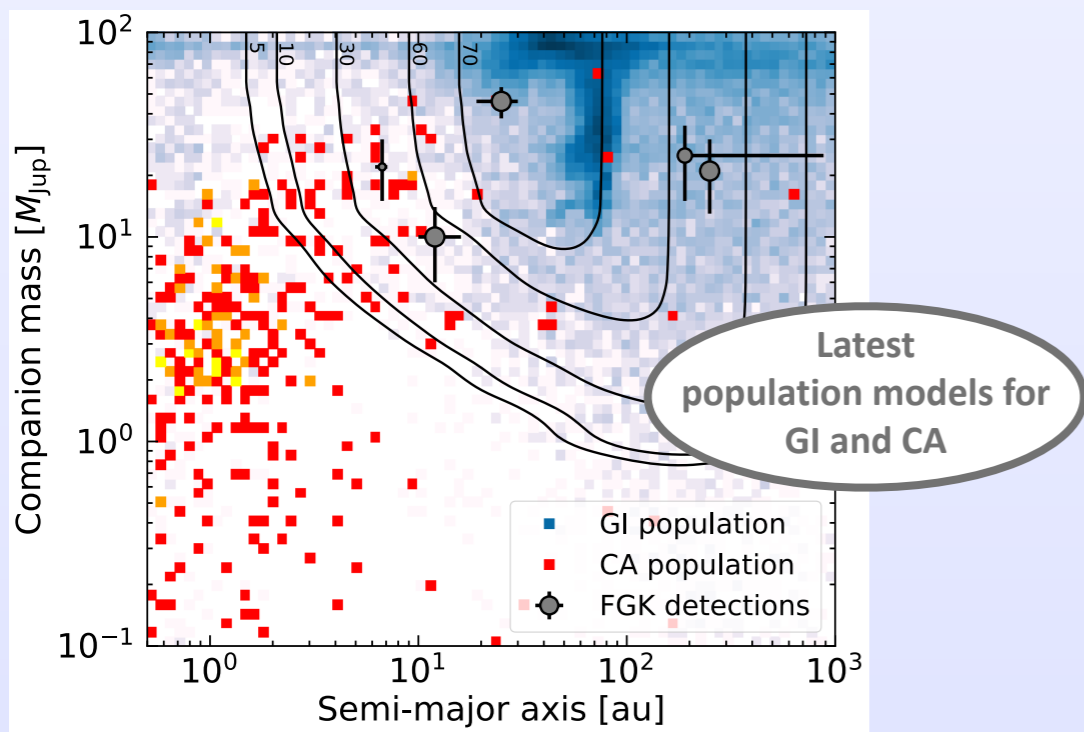
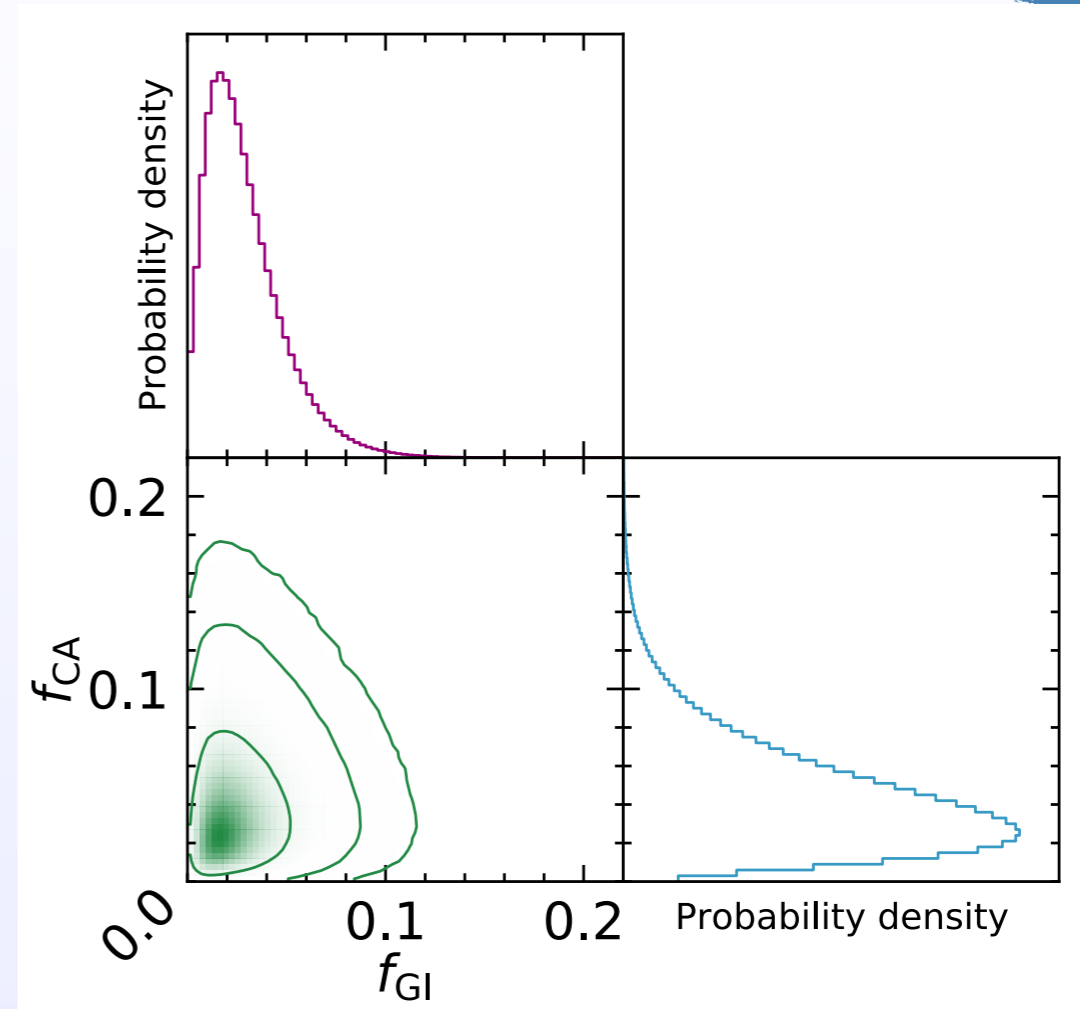
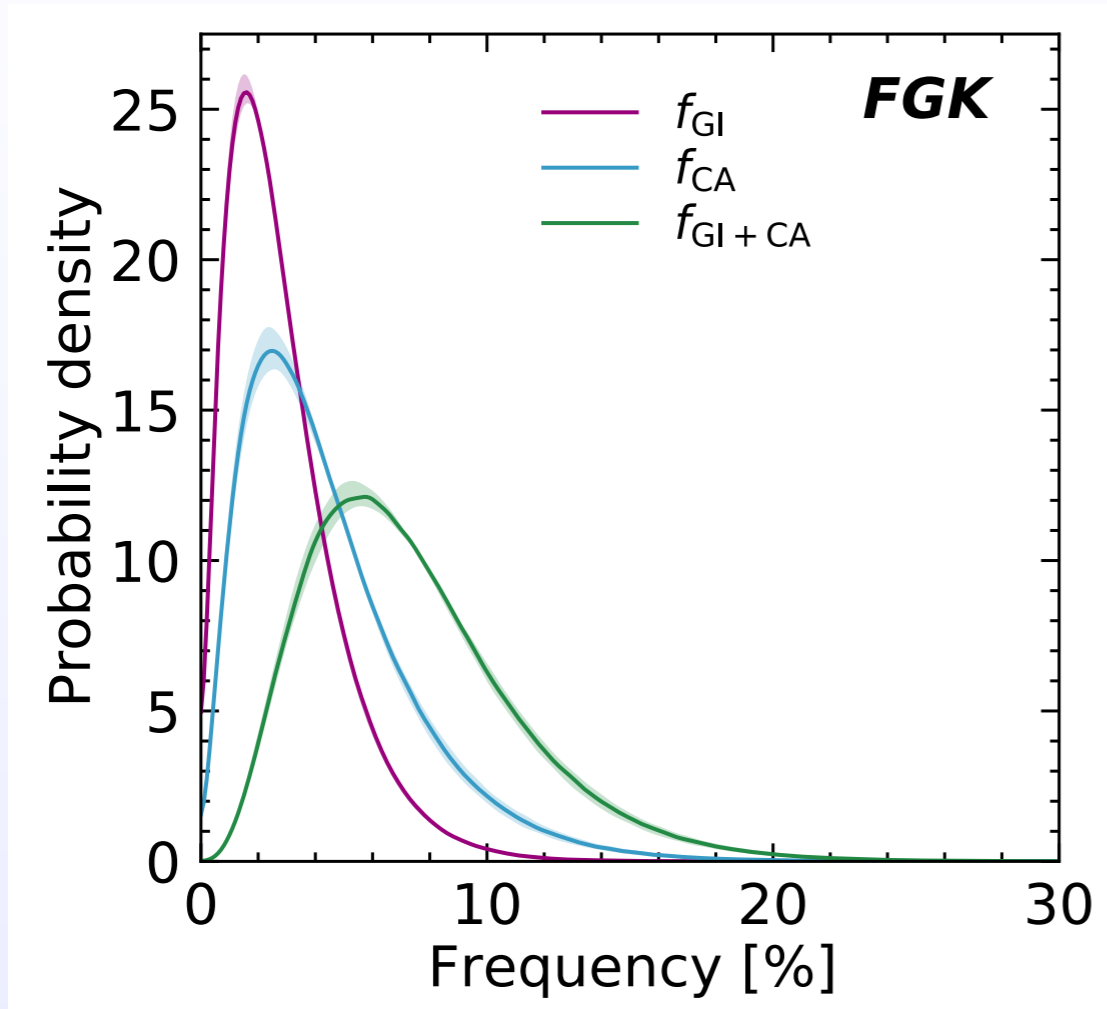


Planet-like formation
 dominates



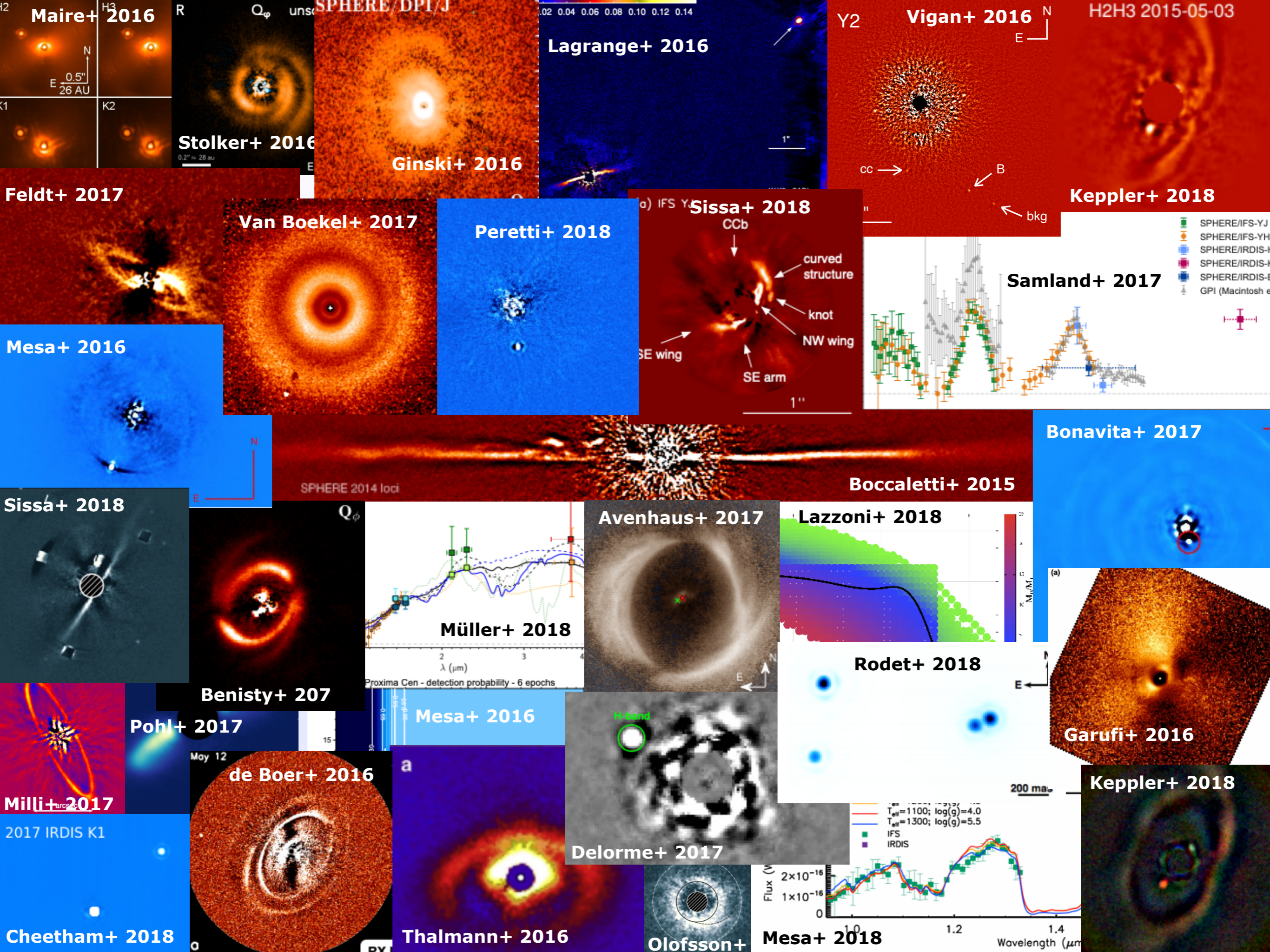
Binary-like formation
 dominates

Vigan et al. (2021)



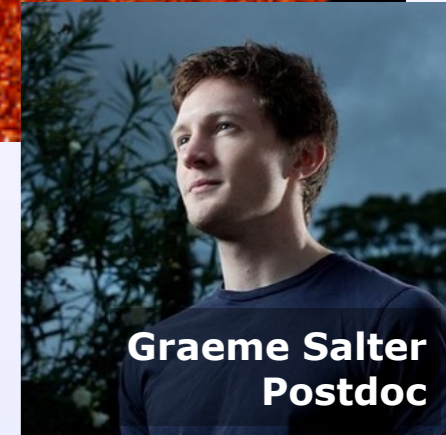
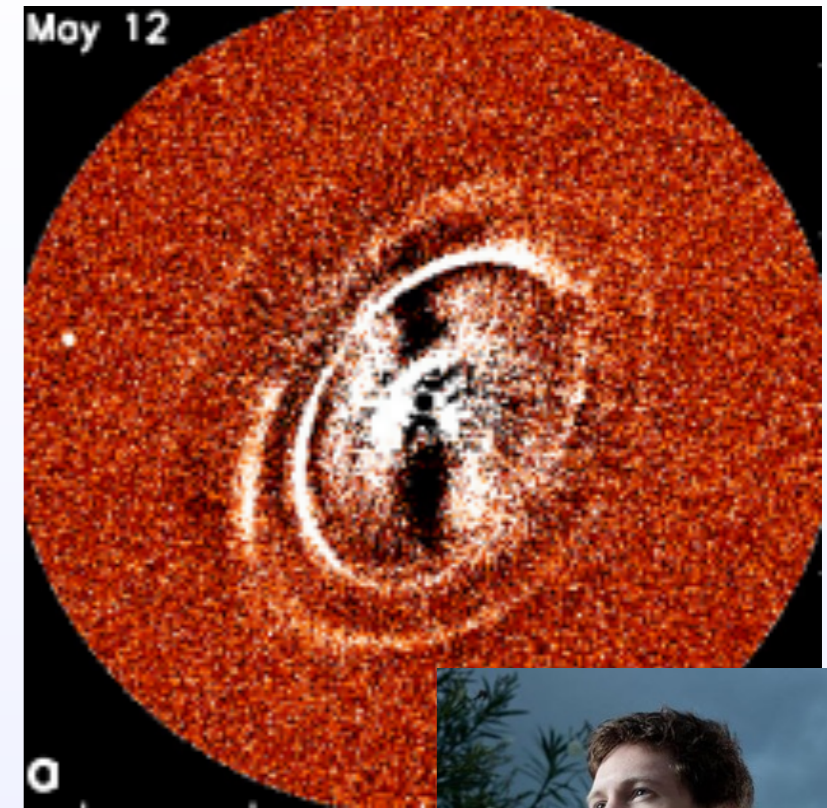
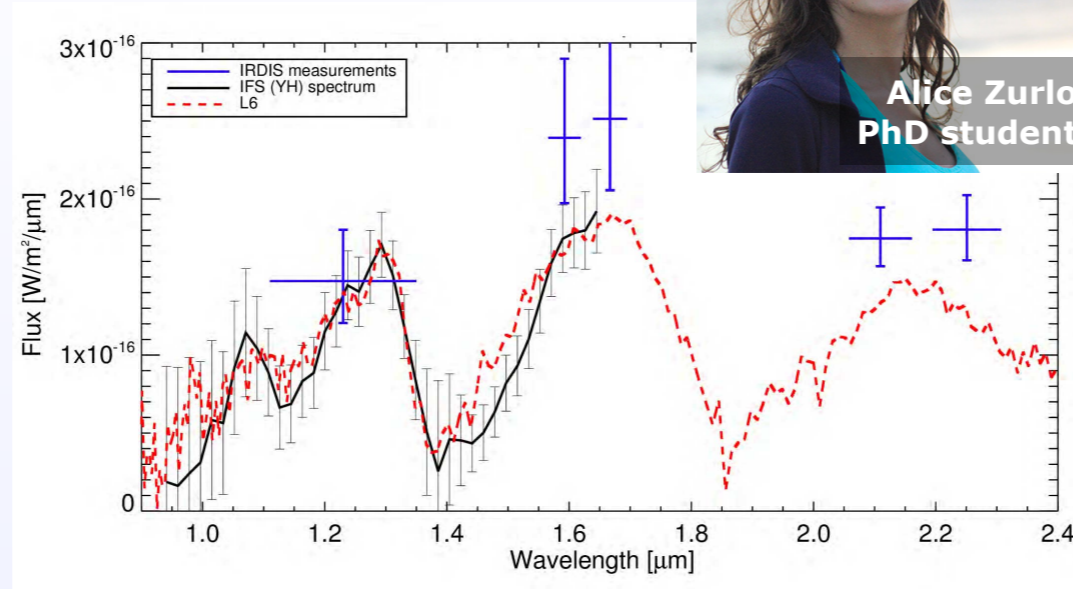
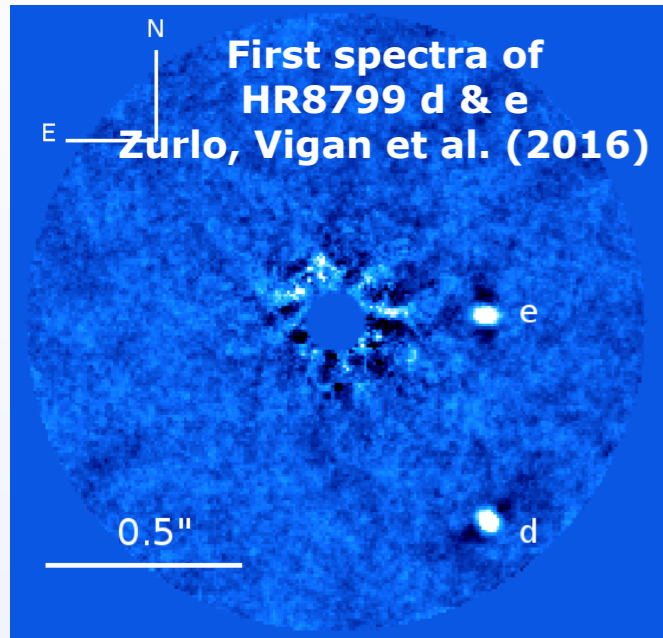
- Occurrence compatible with parametric model: $\sim 5.8\%$
- Slight predominance of CA vs. GI

To be confirmed with full SHINE sample in 2023

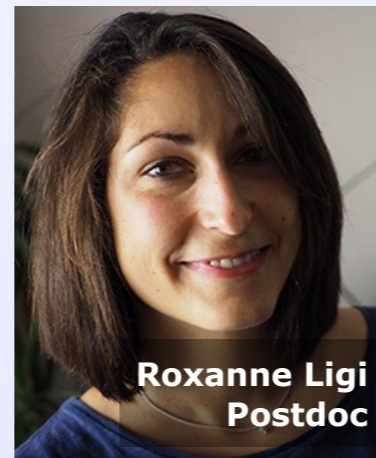
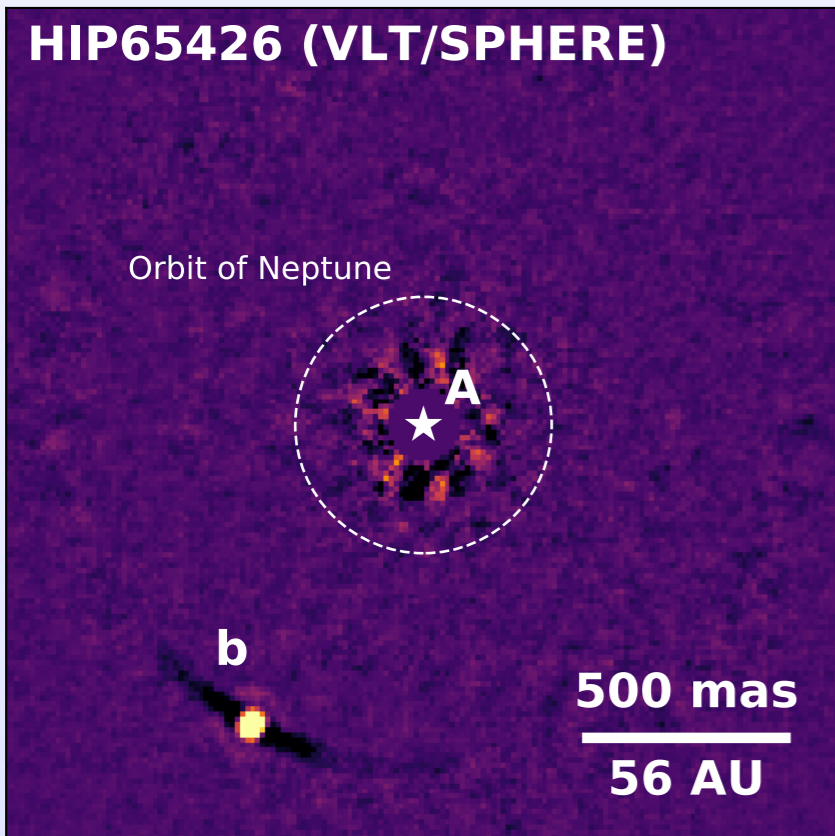


Selected SHINE results

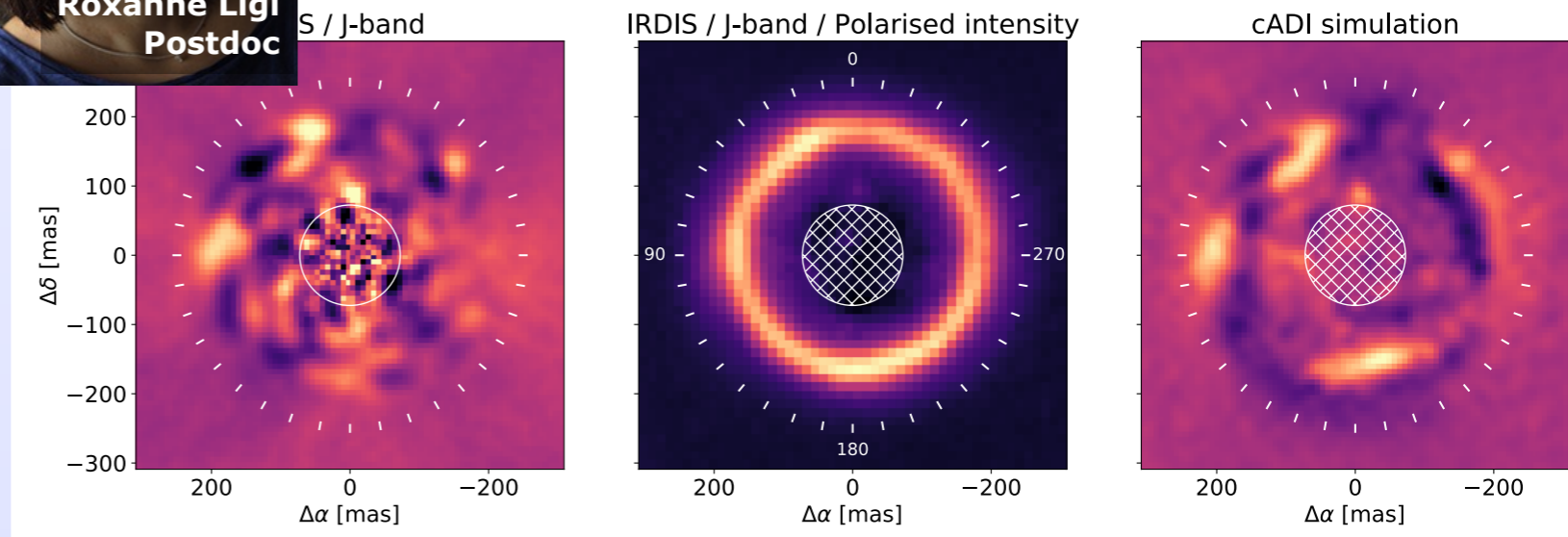
System of rings around RX J1615
(de Boer, Salter et al. 2016)



Planetary companion around
HIP65426 (Chauvin et al. 2017)



Explanation of the structures in the protoplanetary
disk around HD169142 (Ligi, Vigan et al. 2018)



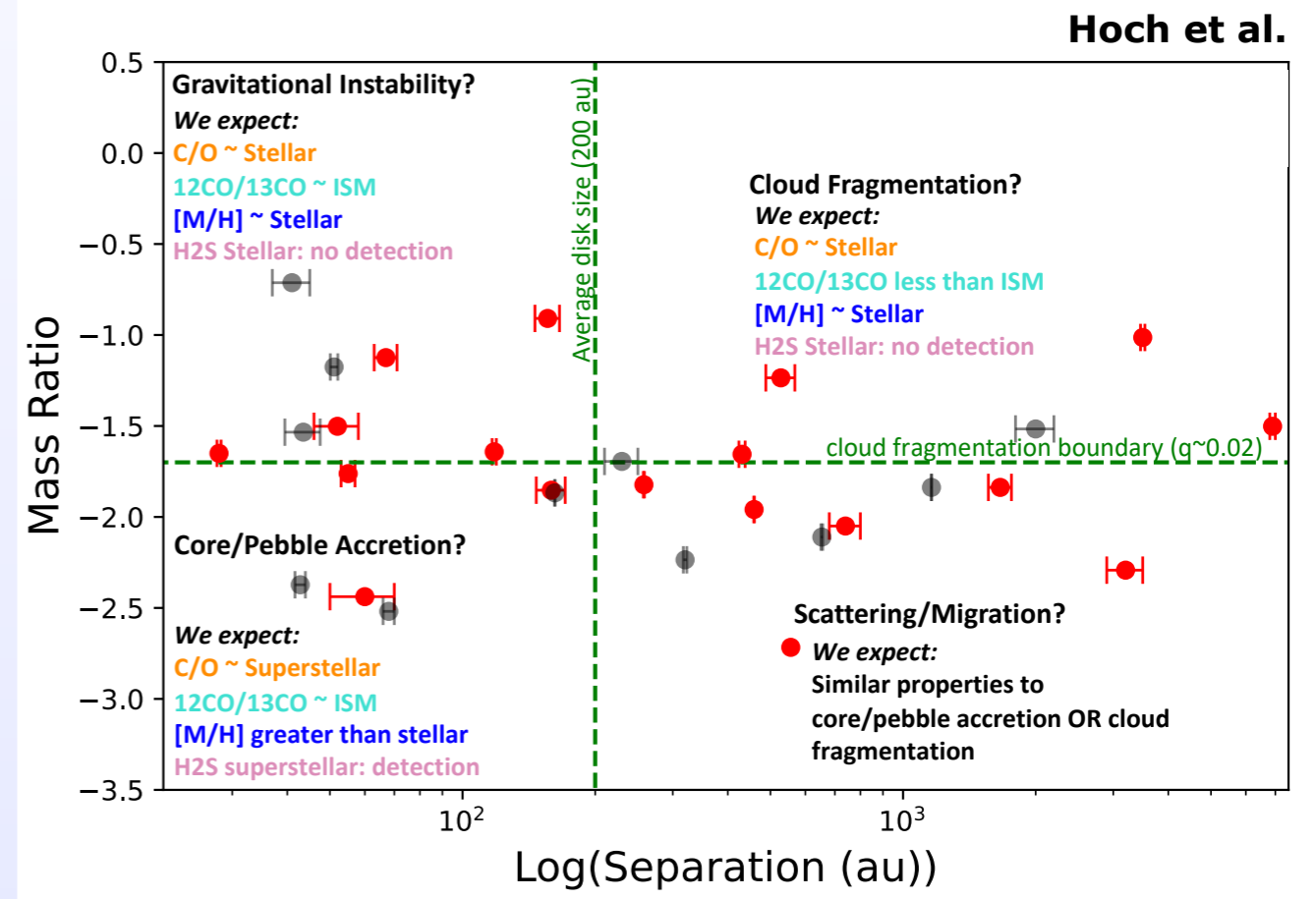
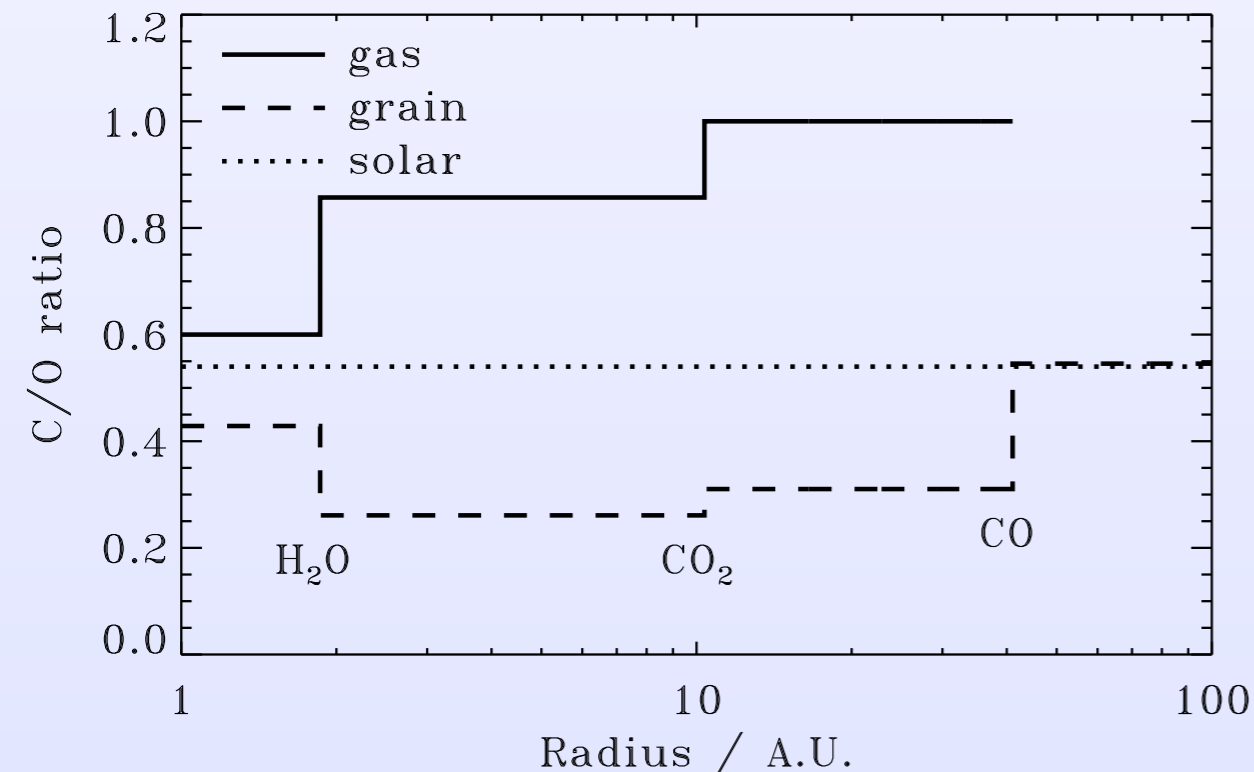
How to study the formation of a given planet?

Atmospheric composition is a key to determine the formation

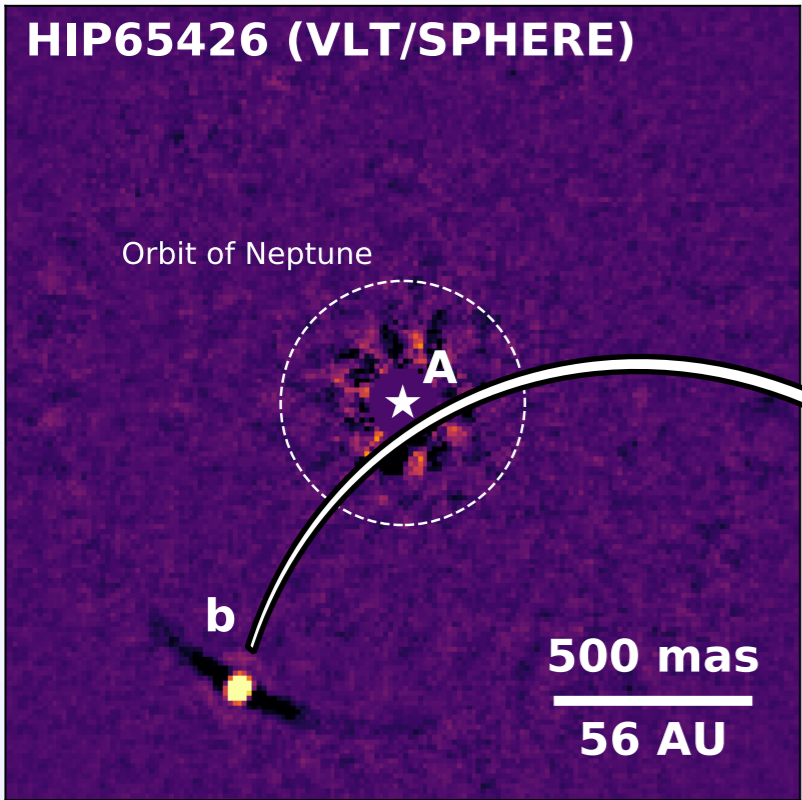
Parameters possibly linked to the formation location or the formation process

- Abundance ratios: C/O, [M/H], ...
- Isotopic ratios: D/H, $^{12}\text{CO}/^{13}\text{CO}$, ...

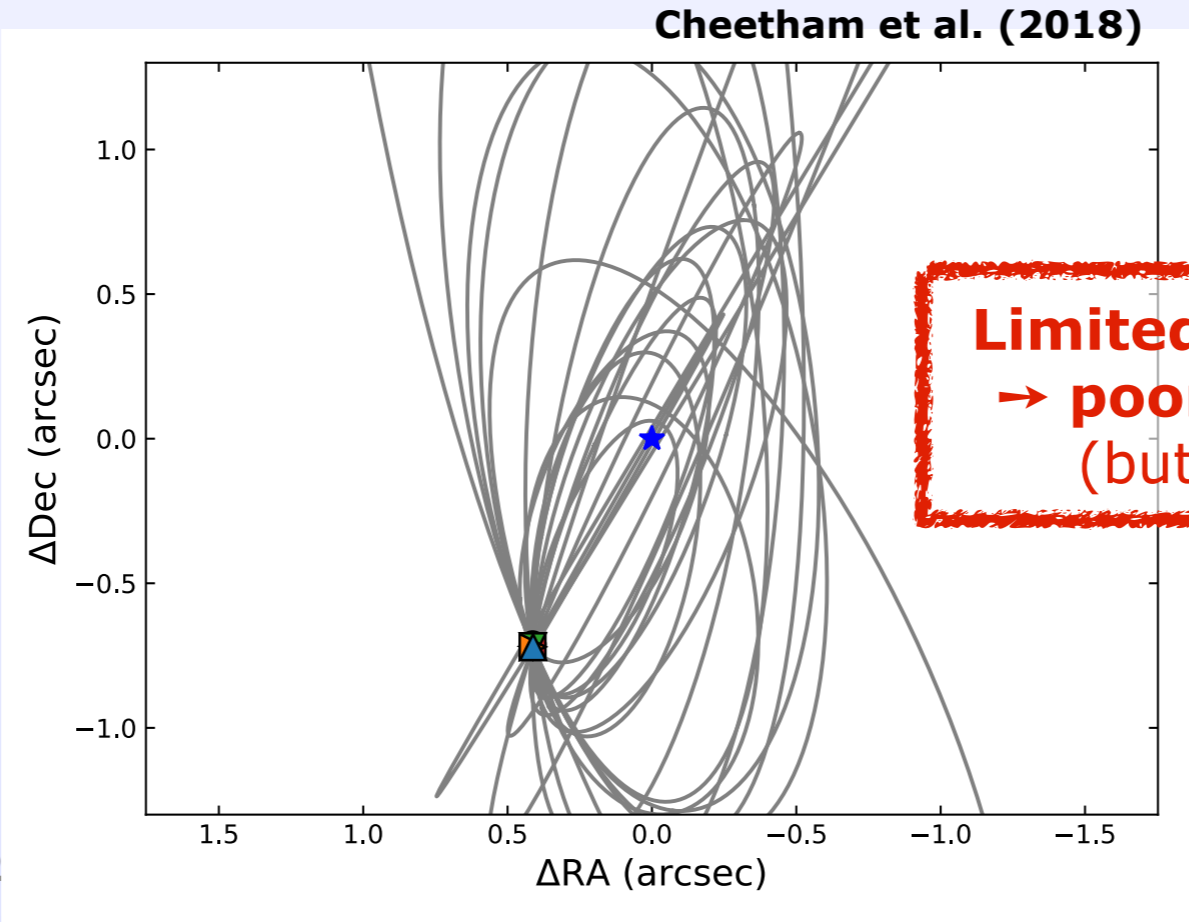
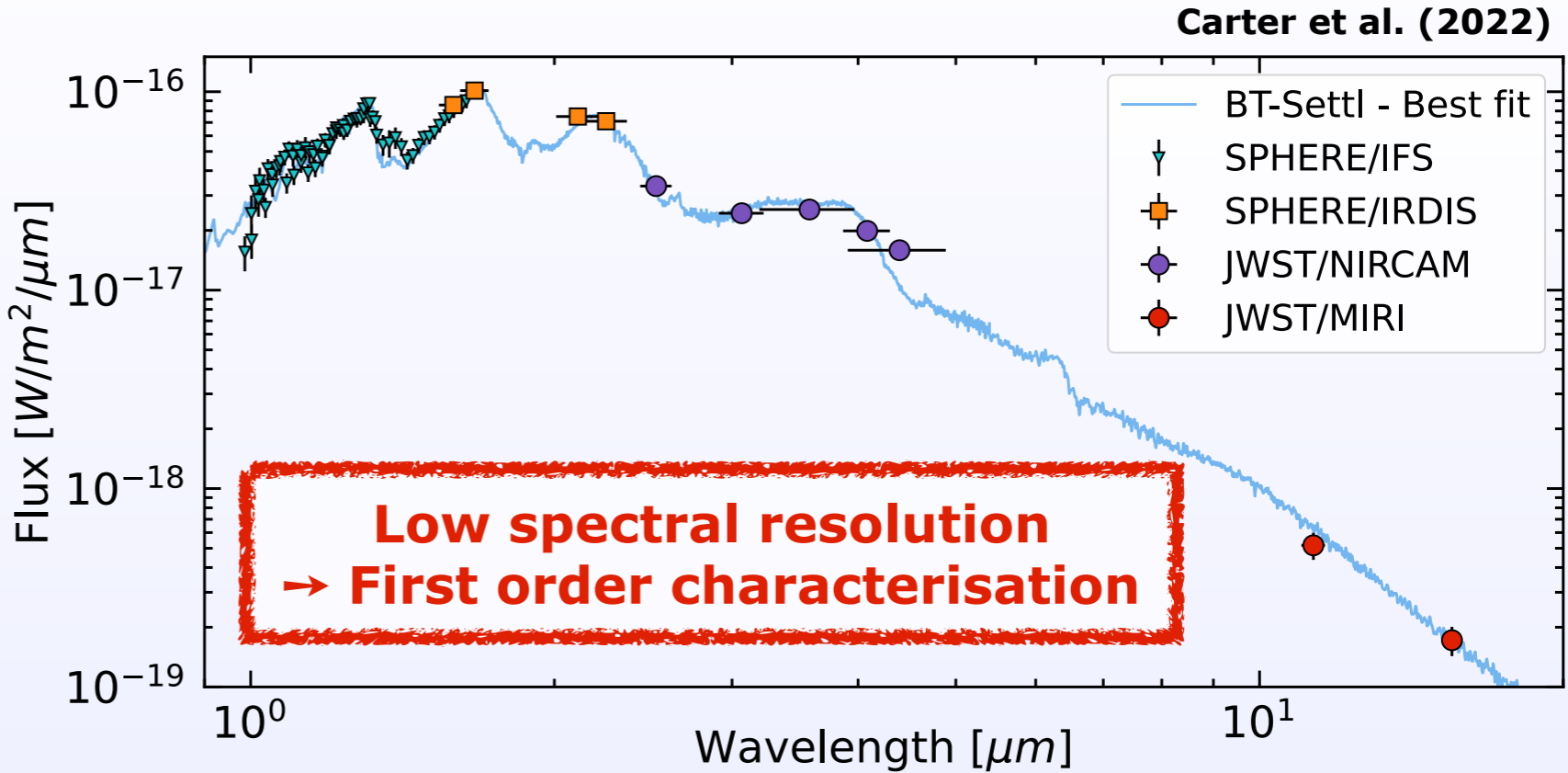
Öberg et al. (2011)



Limitations of current HCI instruments

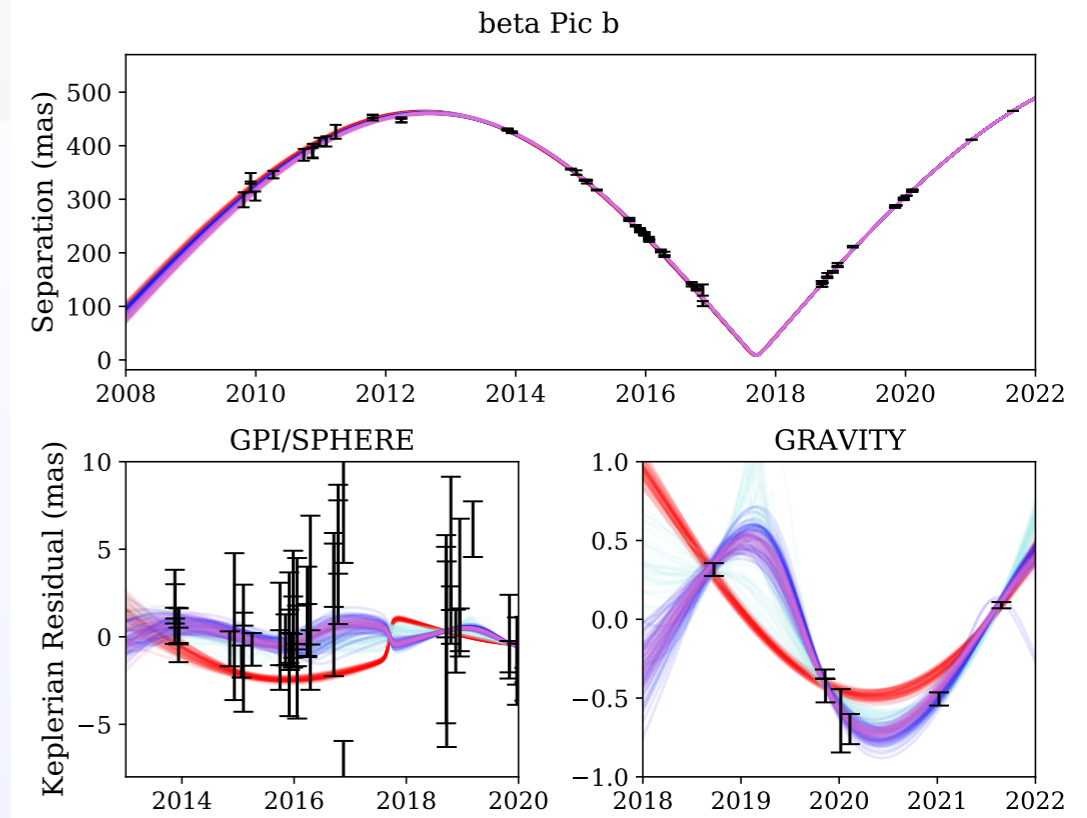


Chauvin et al. 2017

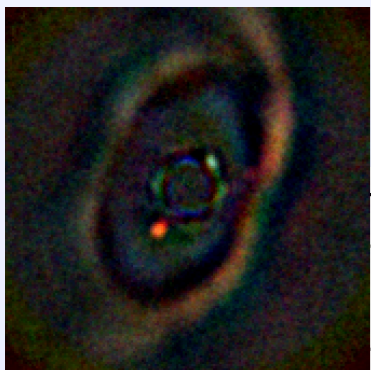


Option 1: interferometry

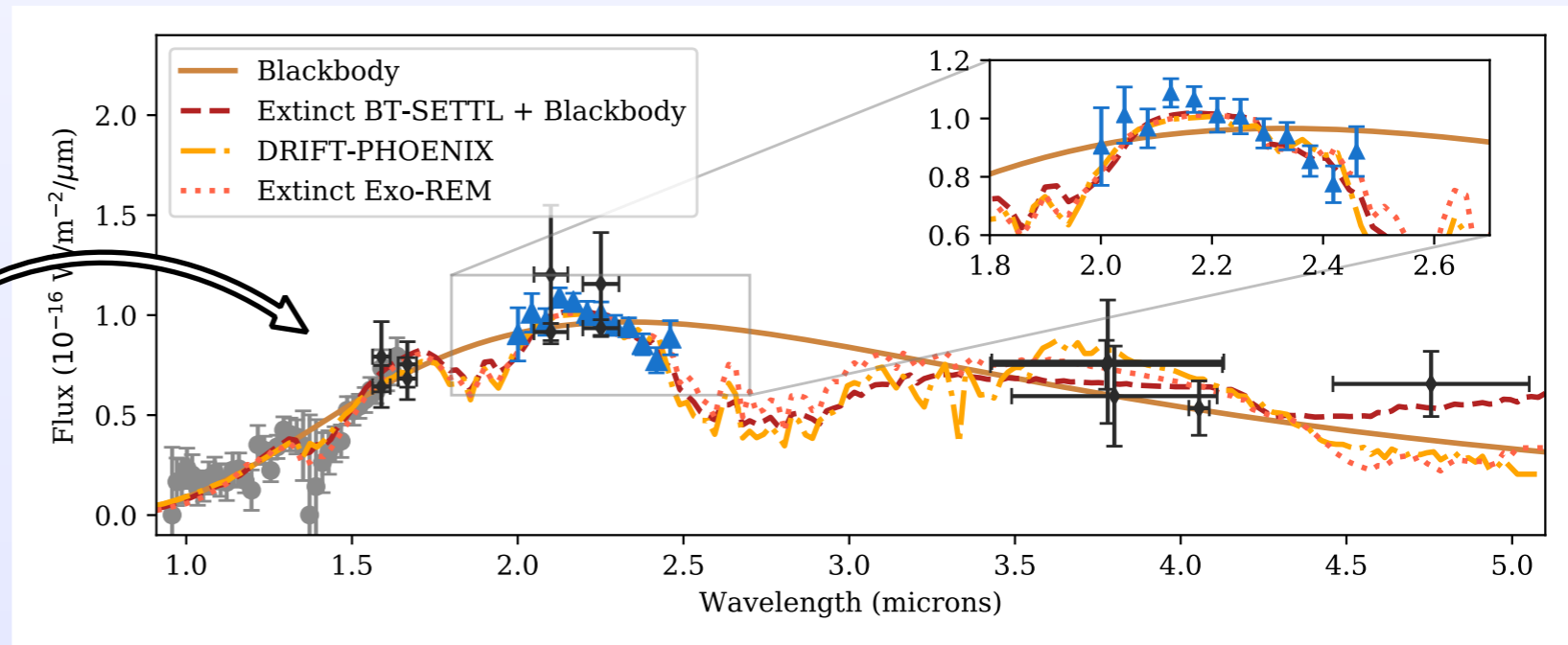
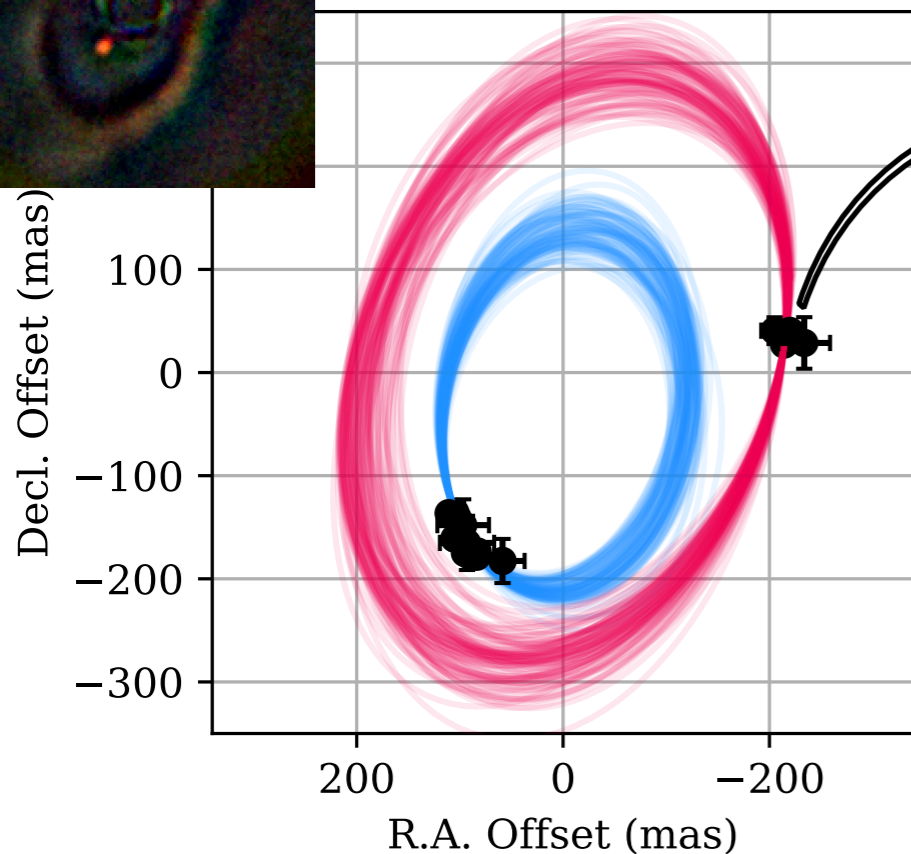
- VLT/GRAVITY
 - High astrometric accuracy in the K-band (few μas)
 - Spectral information up to $R \sim 3000$
- ExoGRAVITY programme (PI: Lacour)
 - Targets known directly-imaged companions
 - Several results so far: β Pic b & c, HR8799, HD206893, PDS70



Lacour et al. (2021)



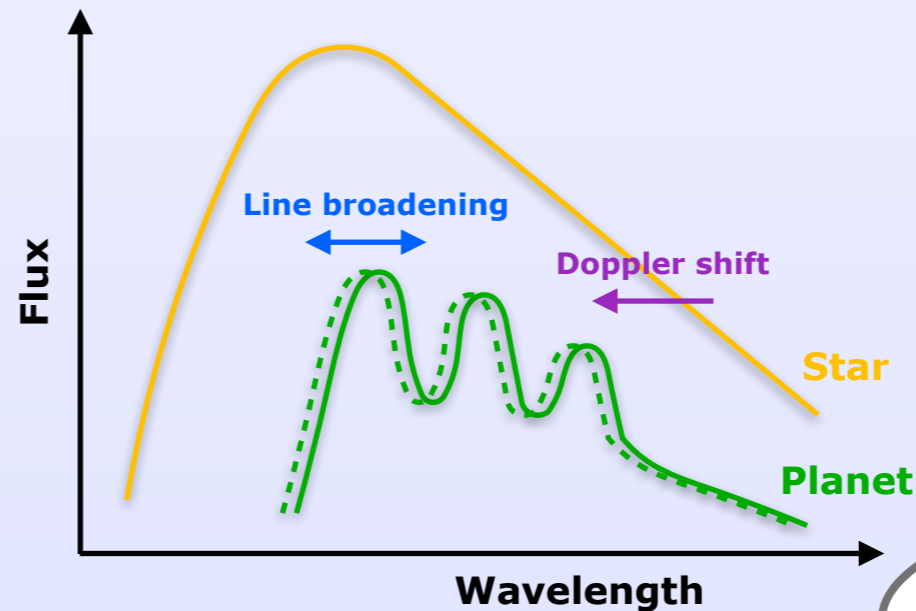
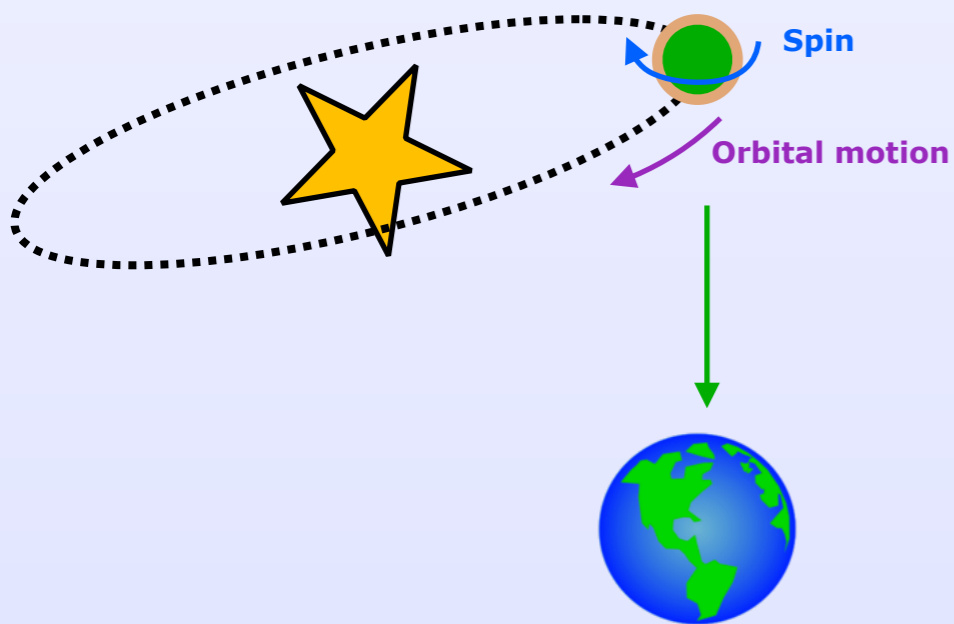
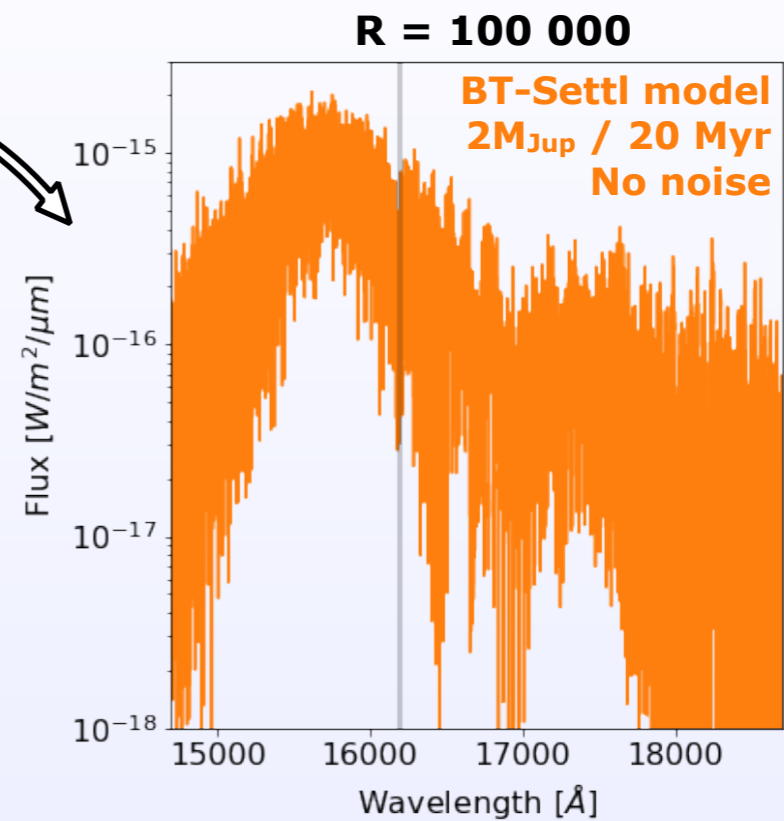
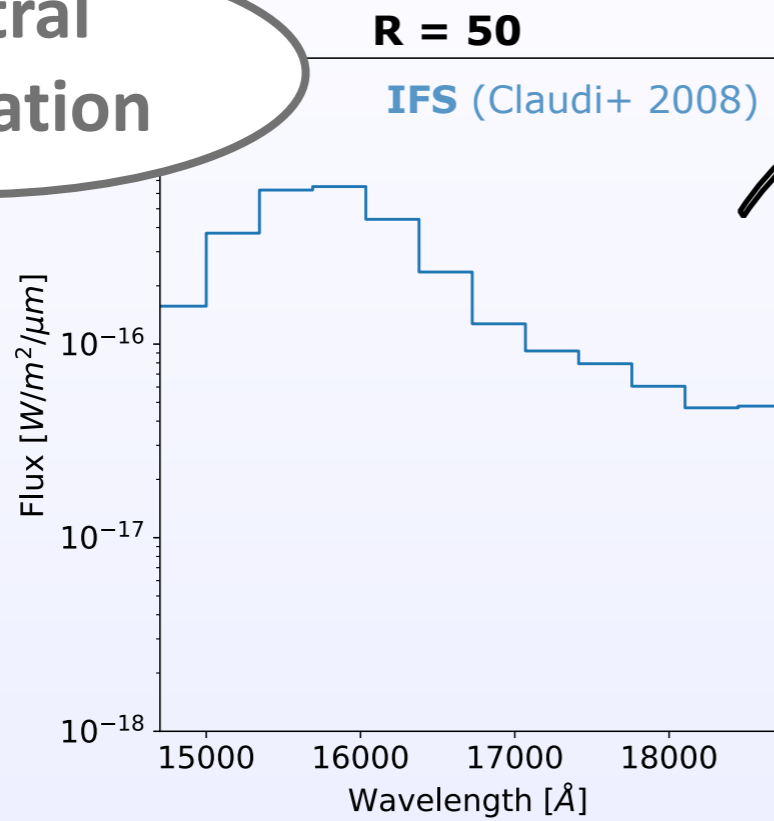
Wang, Vigan et al. (2021)



Both companions have very dusty atmospheres

Option 2: (very) high spectral resolution

Spectral information



Requires
 $R \gg 10\ 000$

Dynamical information

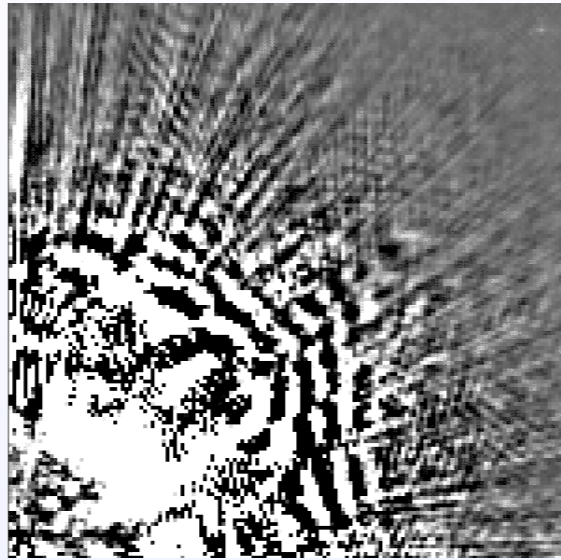
Boost in detection

HST/ACS simulation

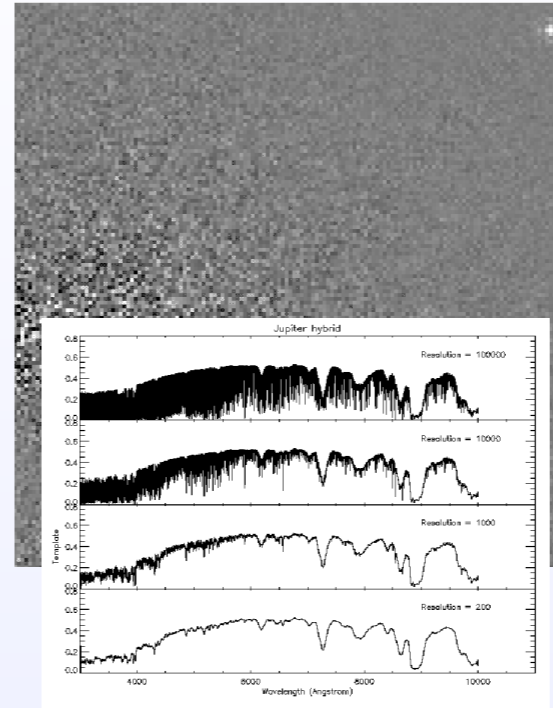


Sparks & Ford (2002)

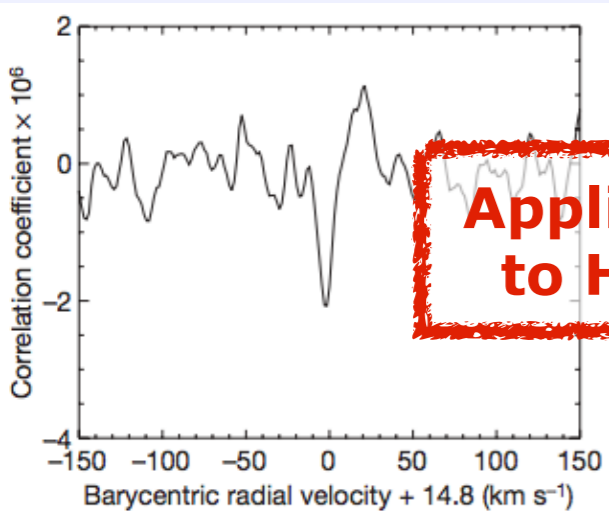
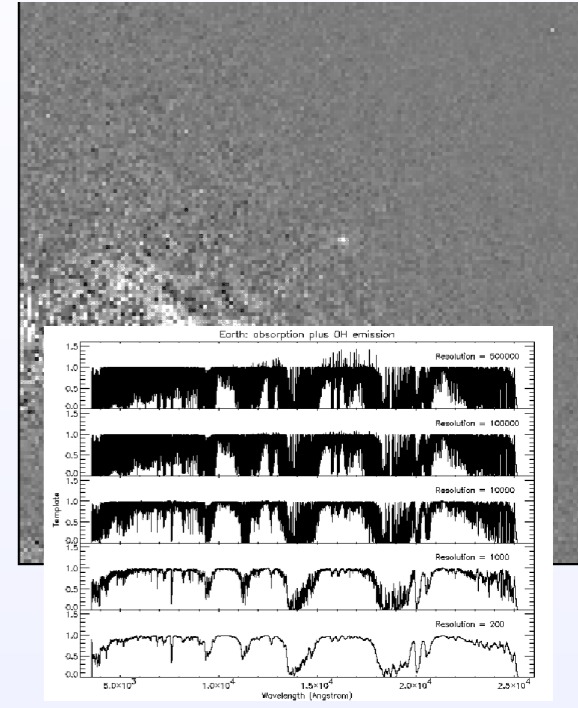
Roll-subtraction (=ADI)



Jupiter template CCF

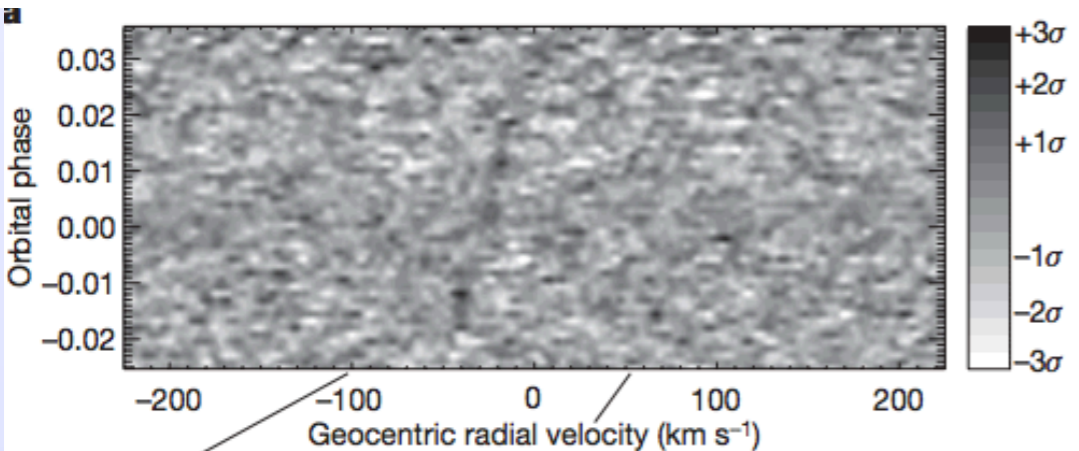


Bright Earth template CCF

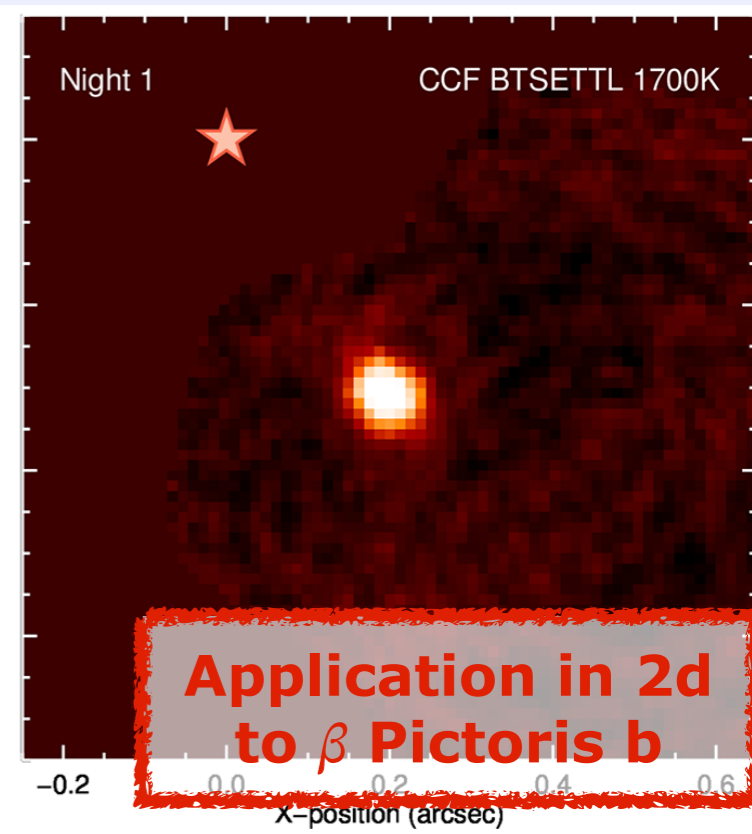
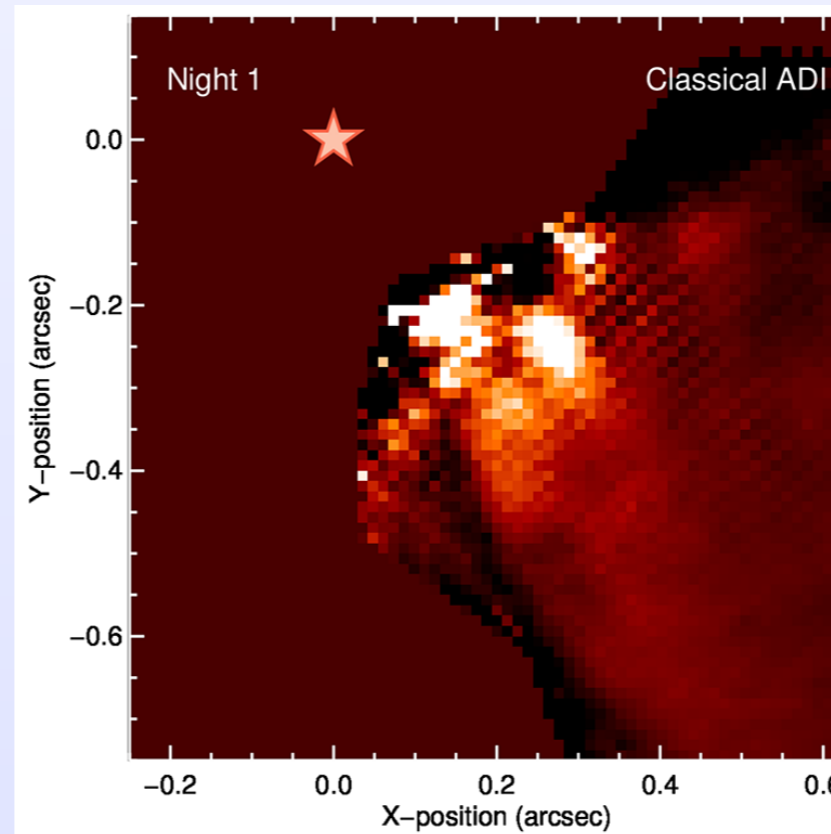


Application in 1d
to HD209458b

Snellen et al. (2010)

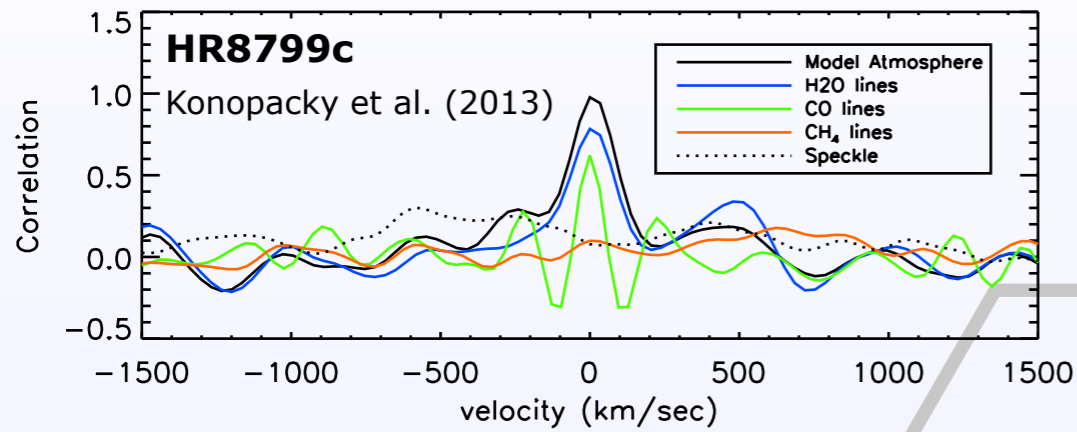


Hoeijmakers et al. (2016)

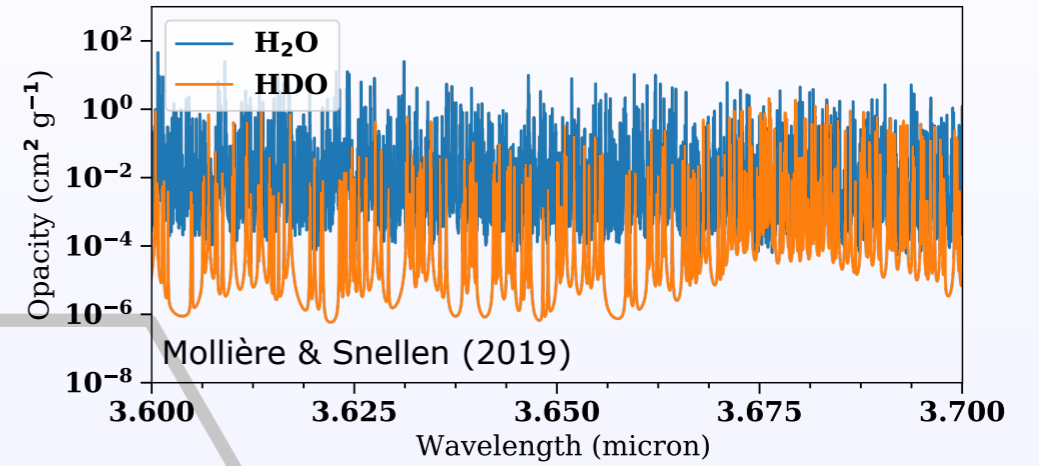


Exoplanet science at high spectral resolution

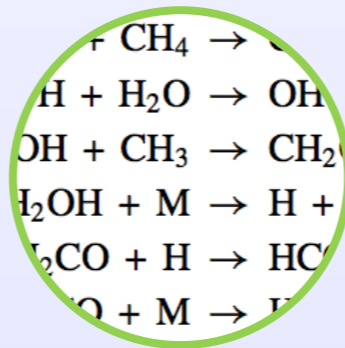
Molecules detection



Isotopologues detection

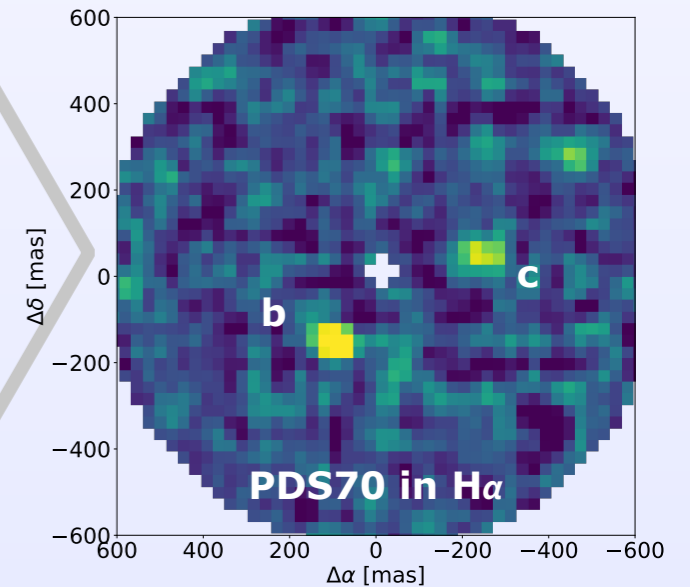


Formation,
migration & evolution

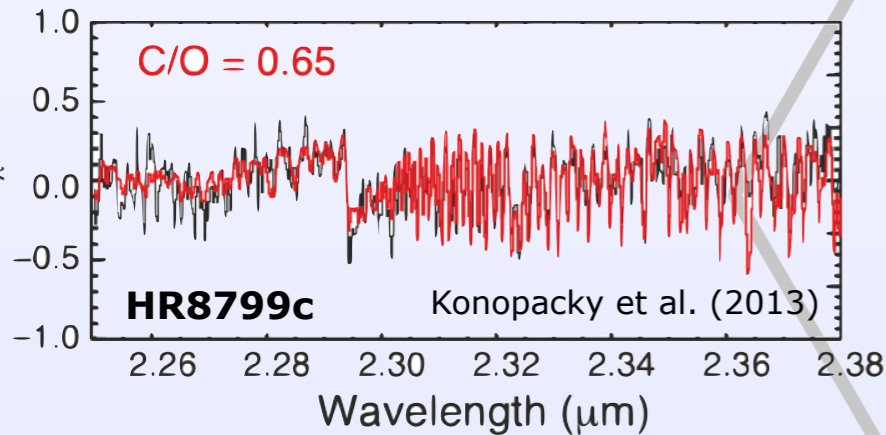


Atmospheric
chemistry & dynamics

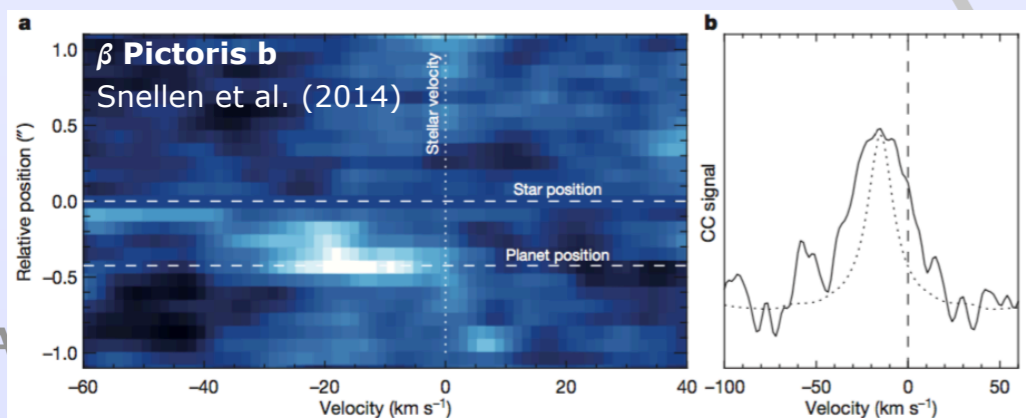
Accretion lines



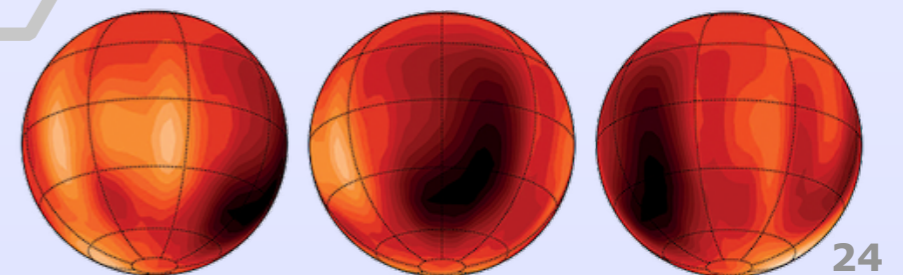
Abundances determination



Orbital and rotational velocity



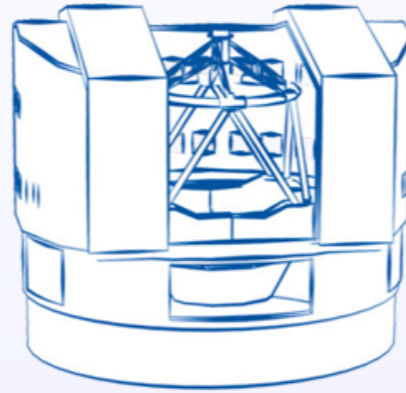
Variability & Doppler imaging



Luhman 16B (Crossfield et al. 2014)

A unique window of opportunity

VLT/UT3



High-contrast exoplanet imager



High-resolution spectrograph



Y J H K

50 - 350

Extreme adaptive optics

Coronagraphy

Spectral coverage

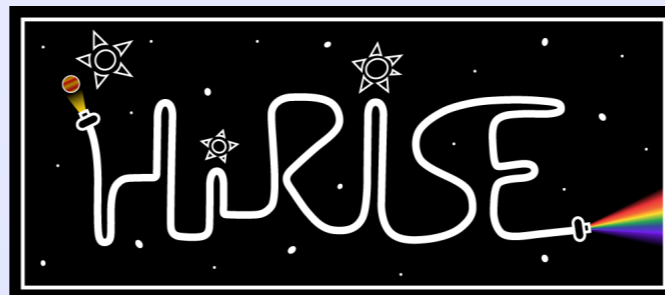
Spectral resolution



Y J H K L M

50 000 - 100 000

Fiber coupling



Overall implementation



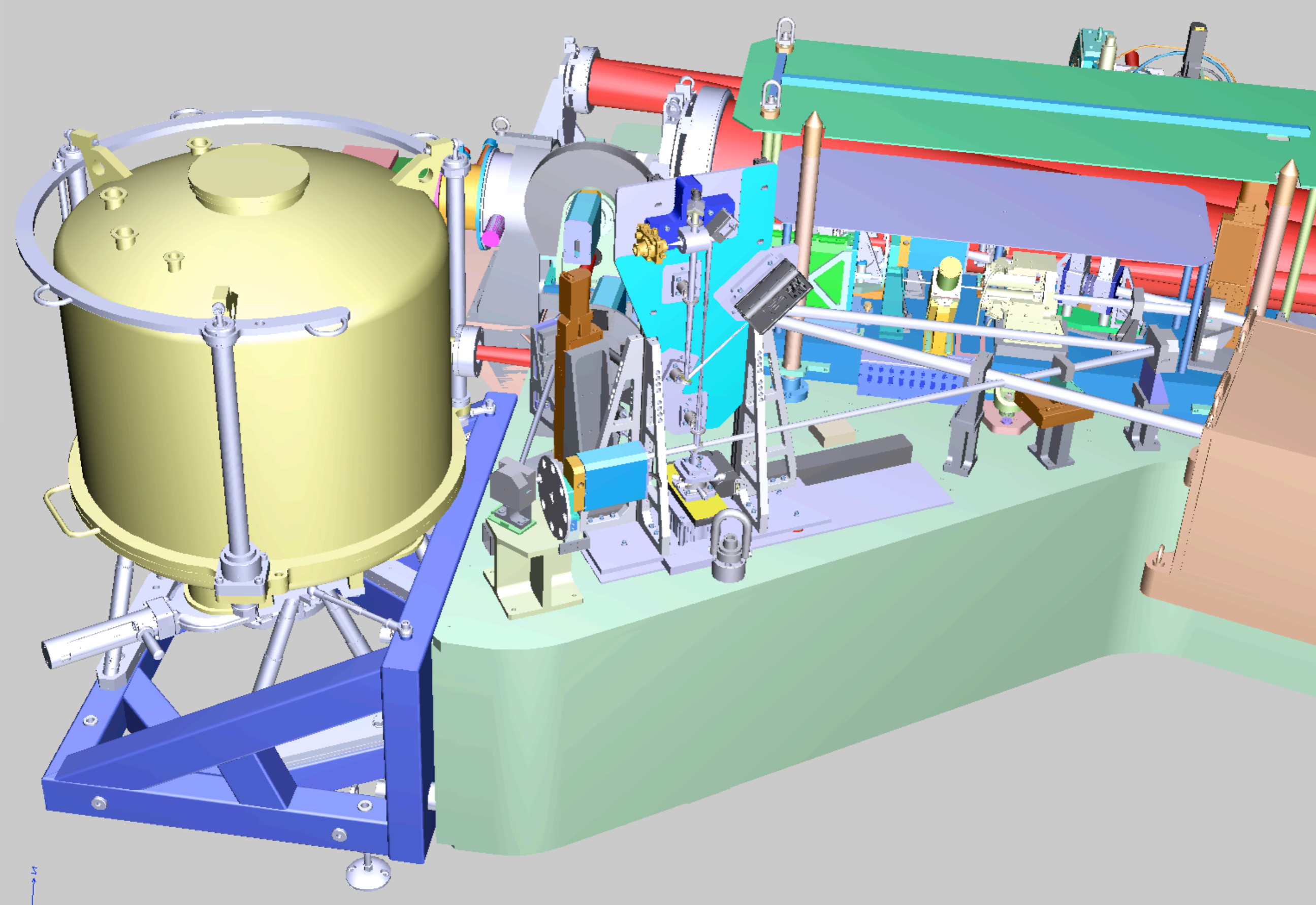
Fiber extraction module (FEM)



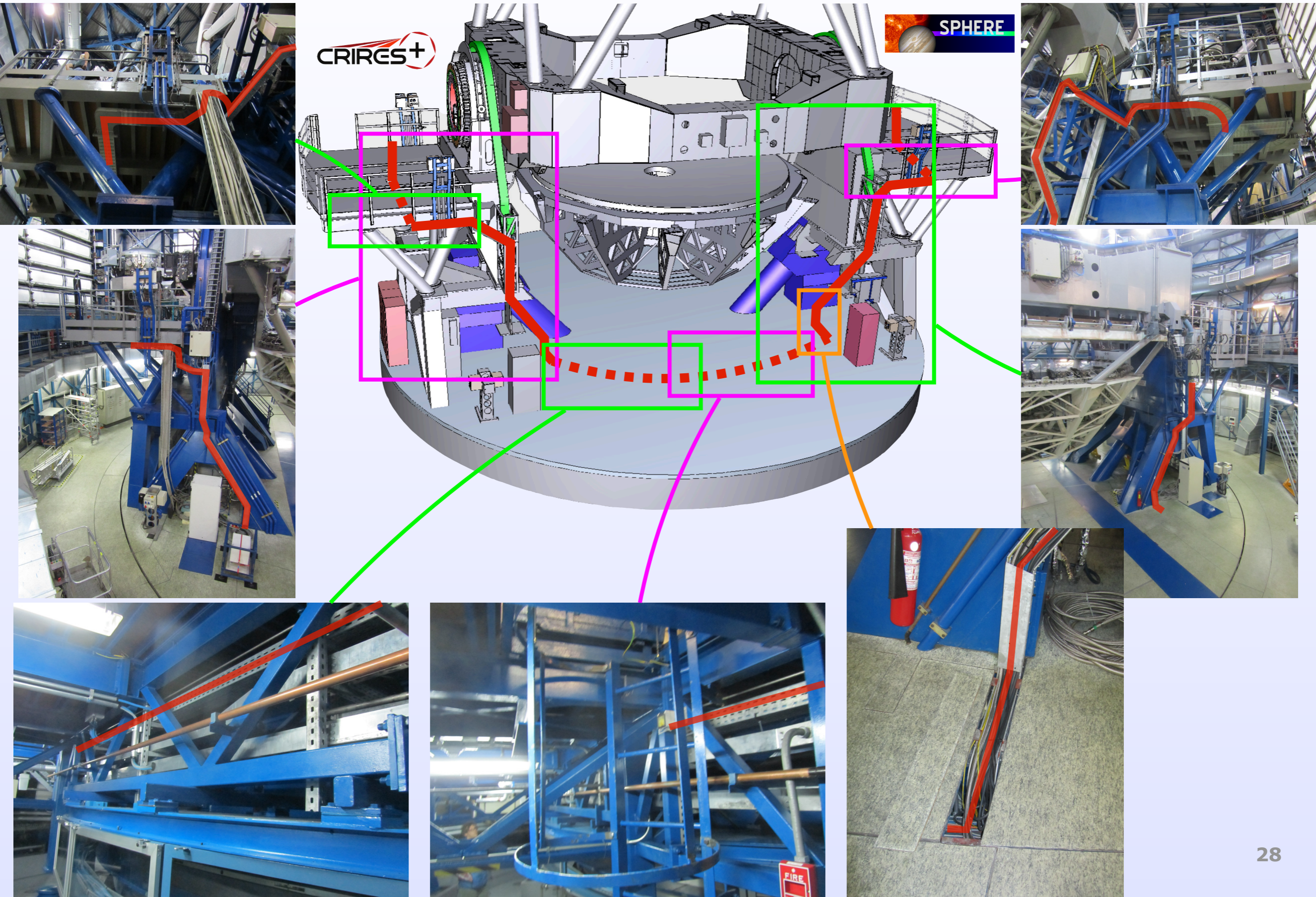
Fiber injection module (FIM)

Fiber bundle

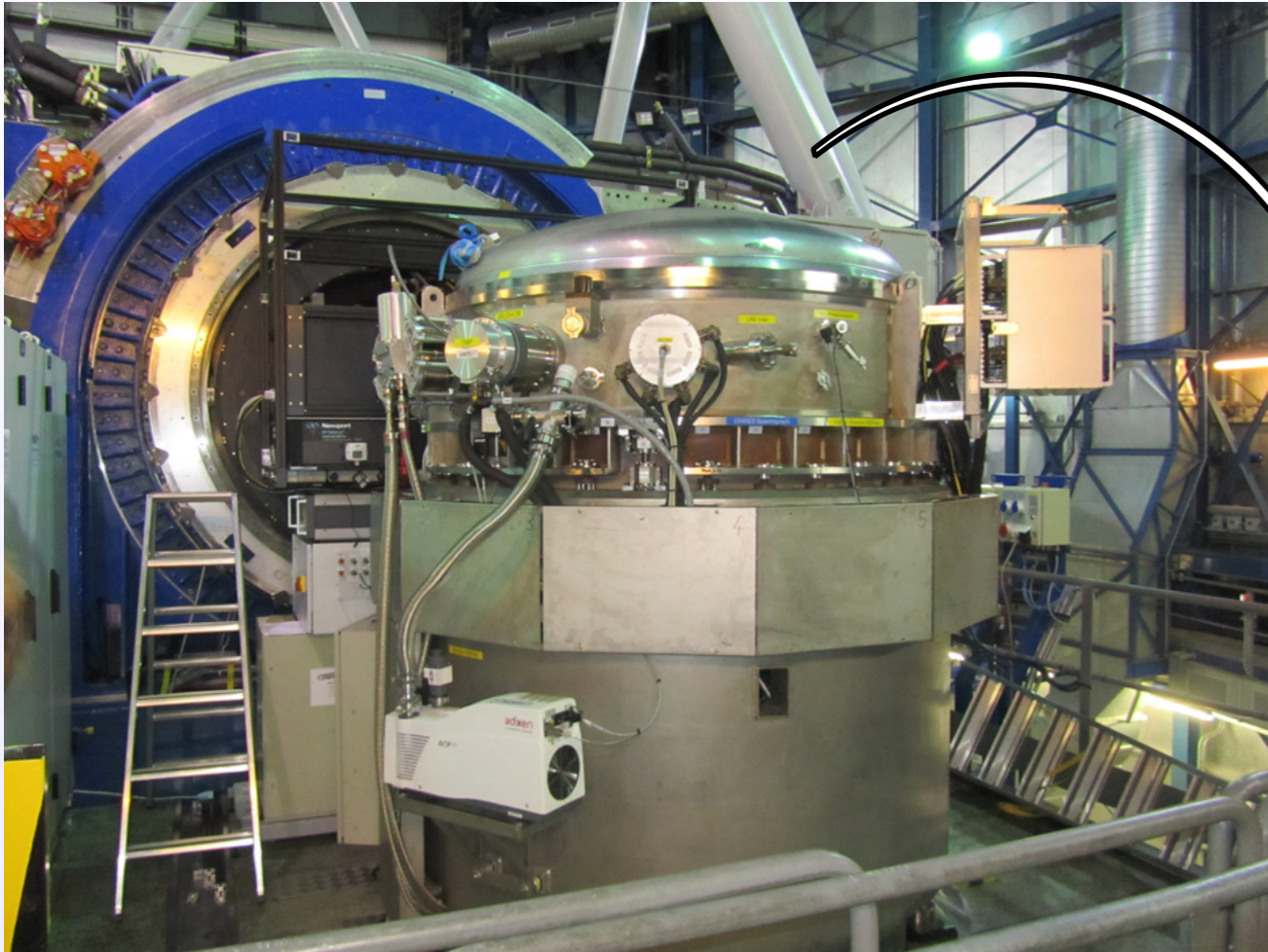
Fiber injection unit in SPHERE



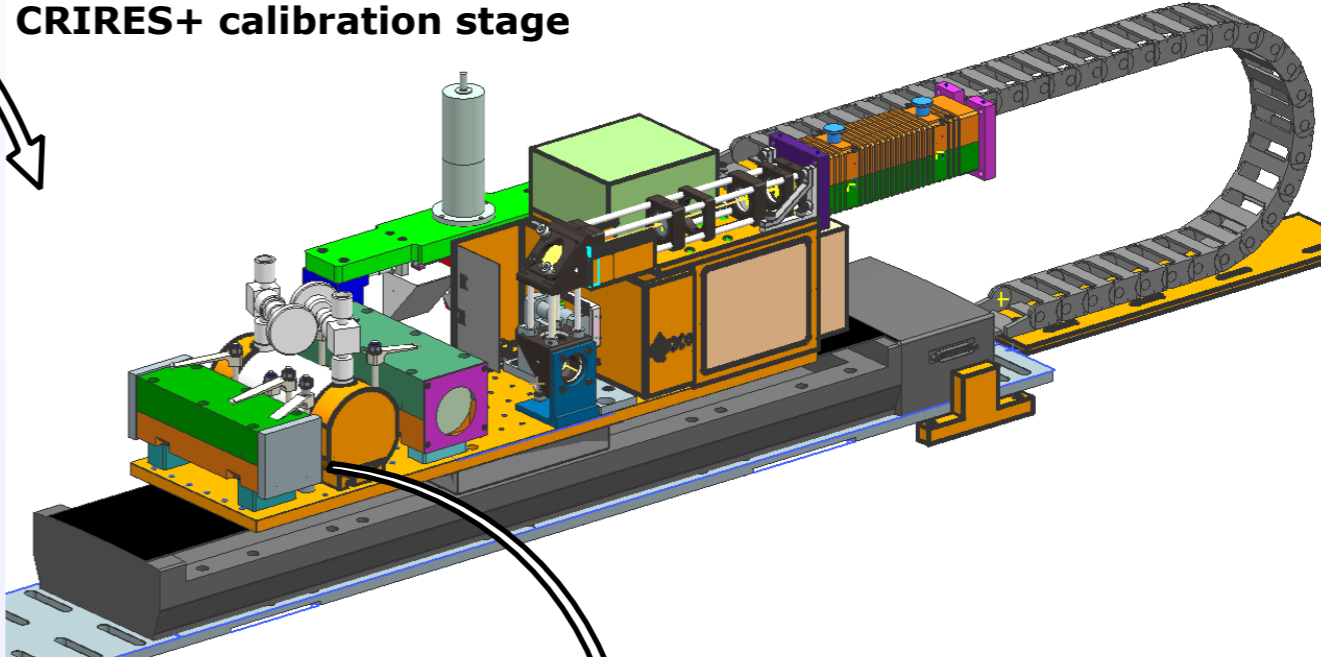
Fiber bundle around VLT-UT3



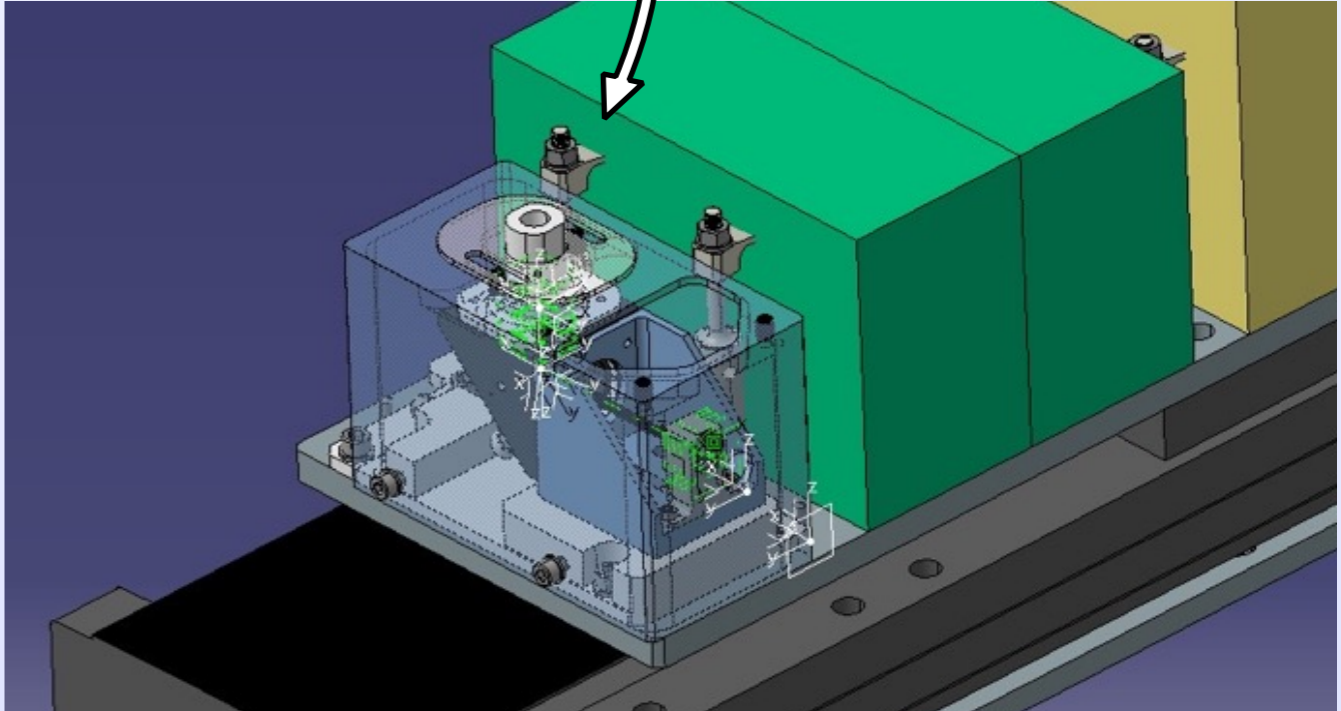
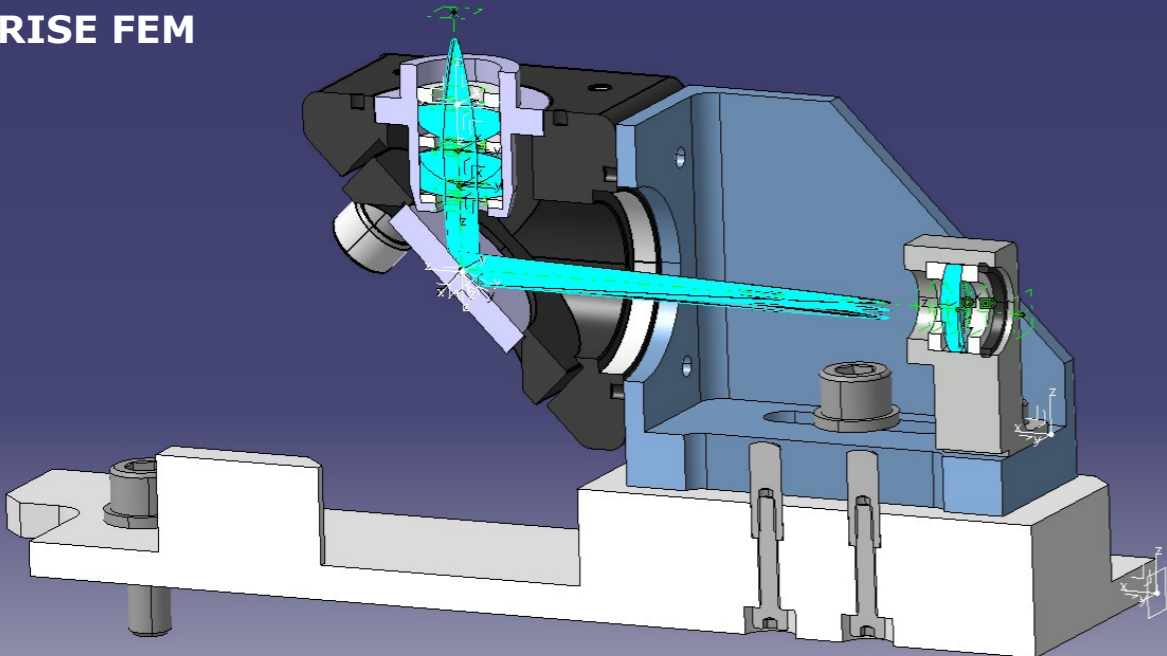
Fiber extraction unit in CRIRES+



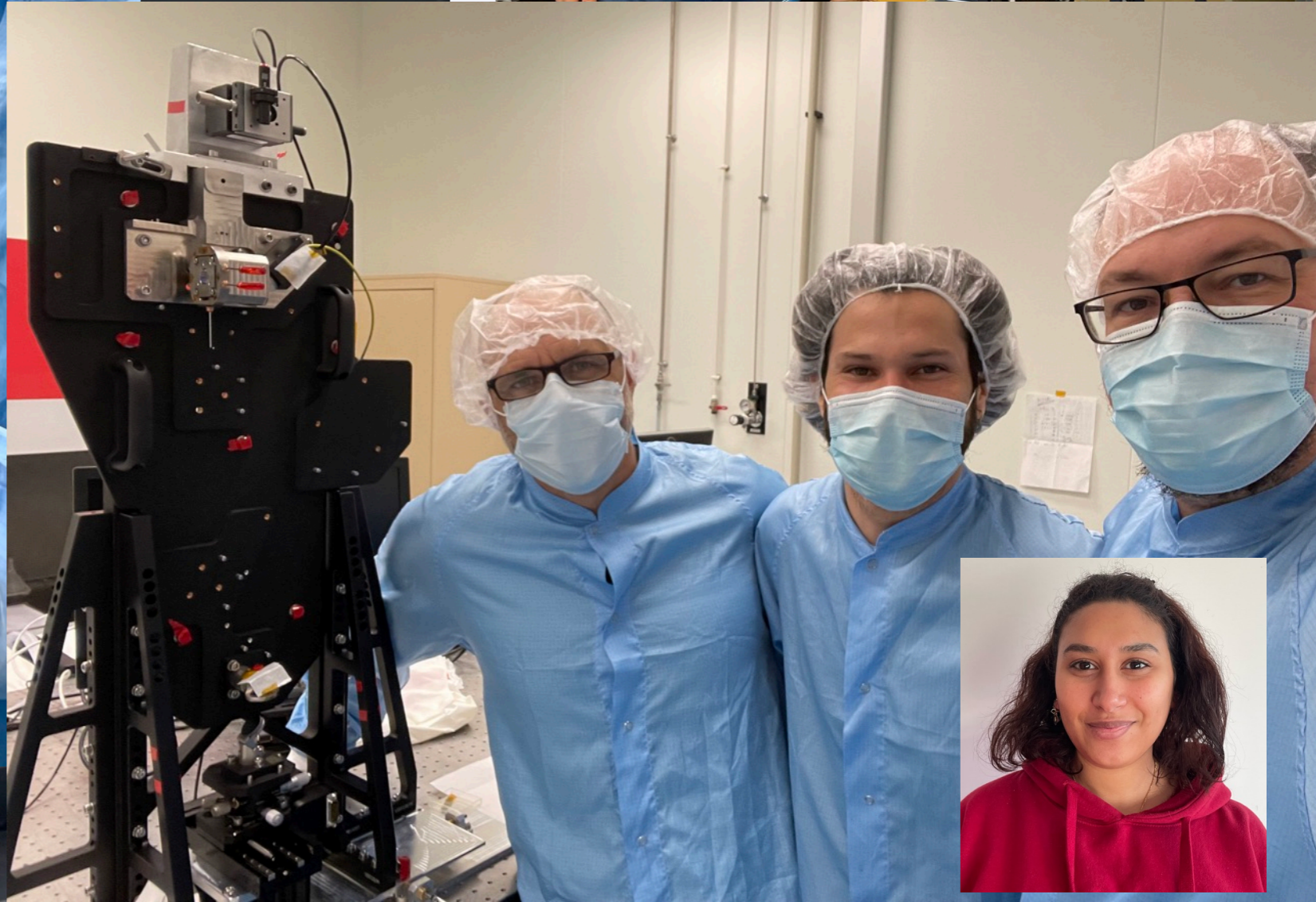
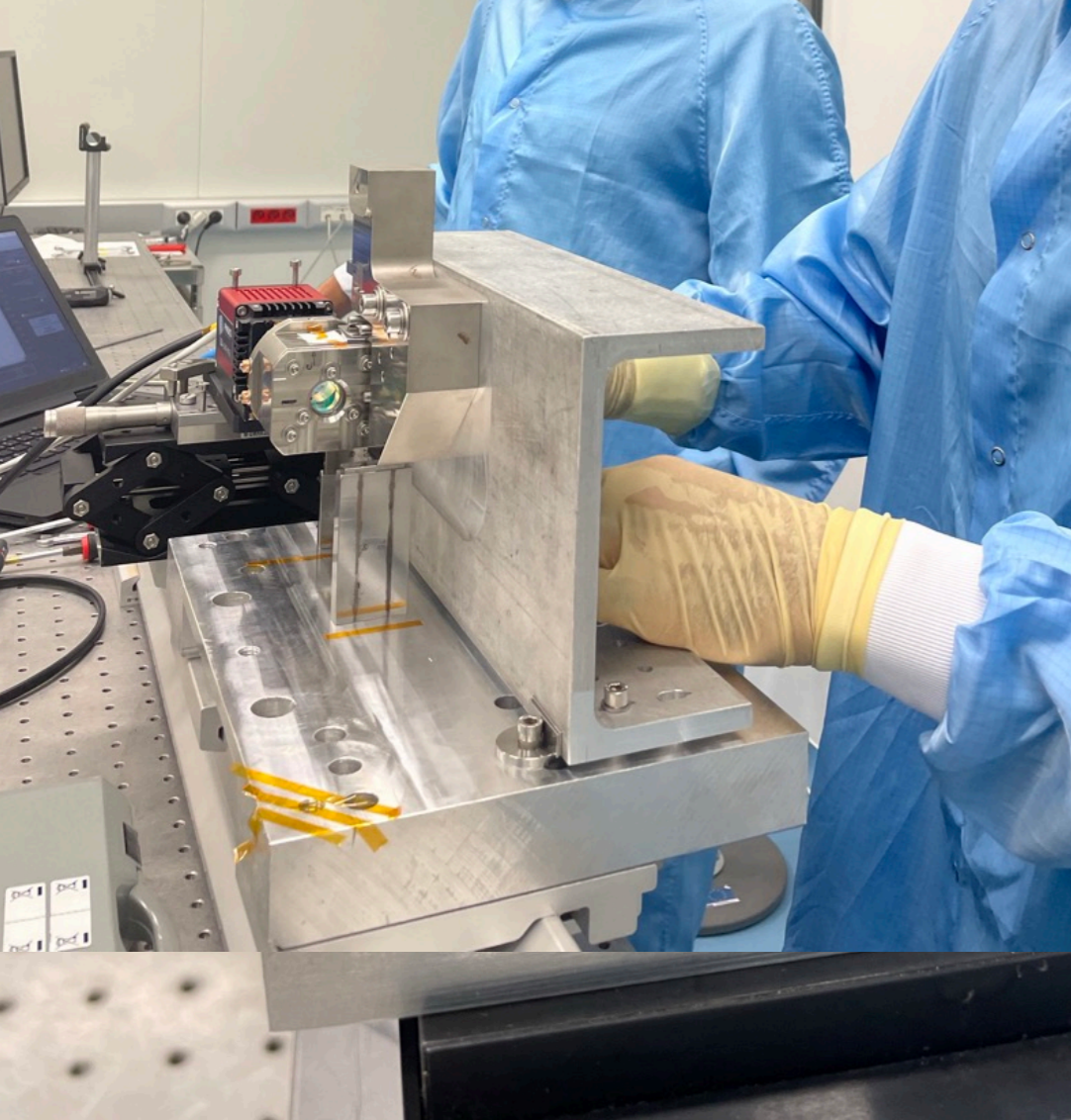
CRIRES+ calibration stage



HiRISE FEM



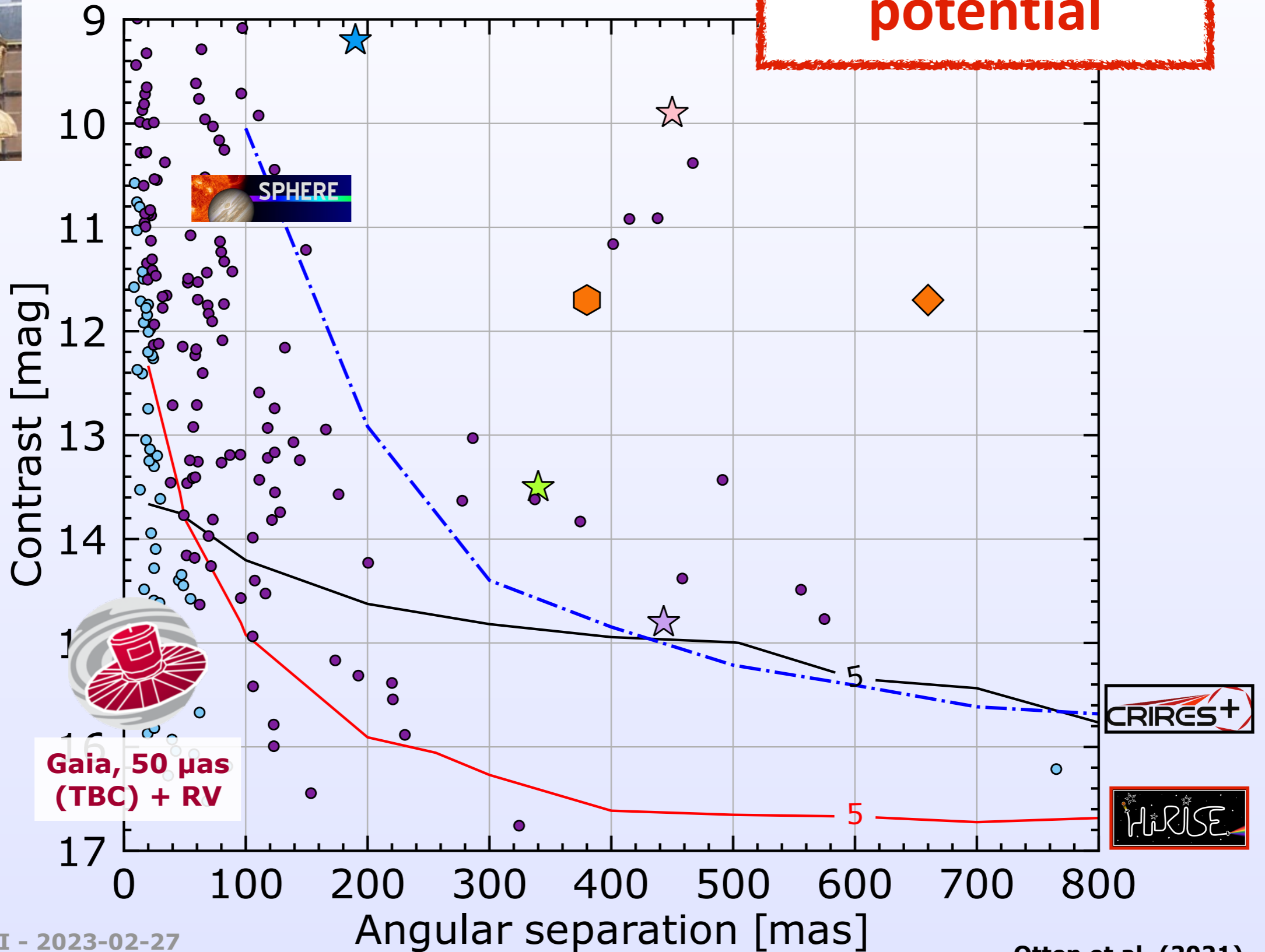
HiRISE in the laboratory



Expected performance

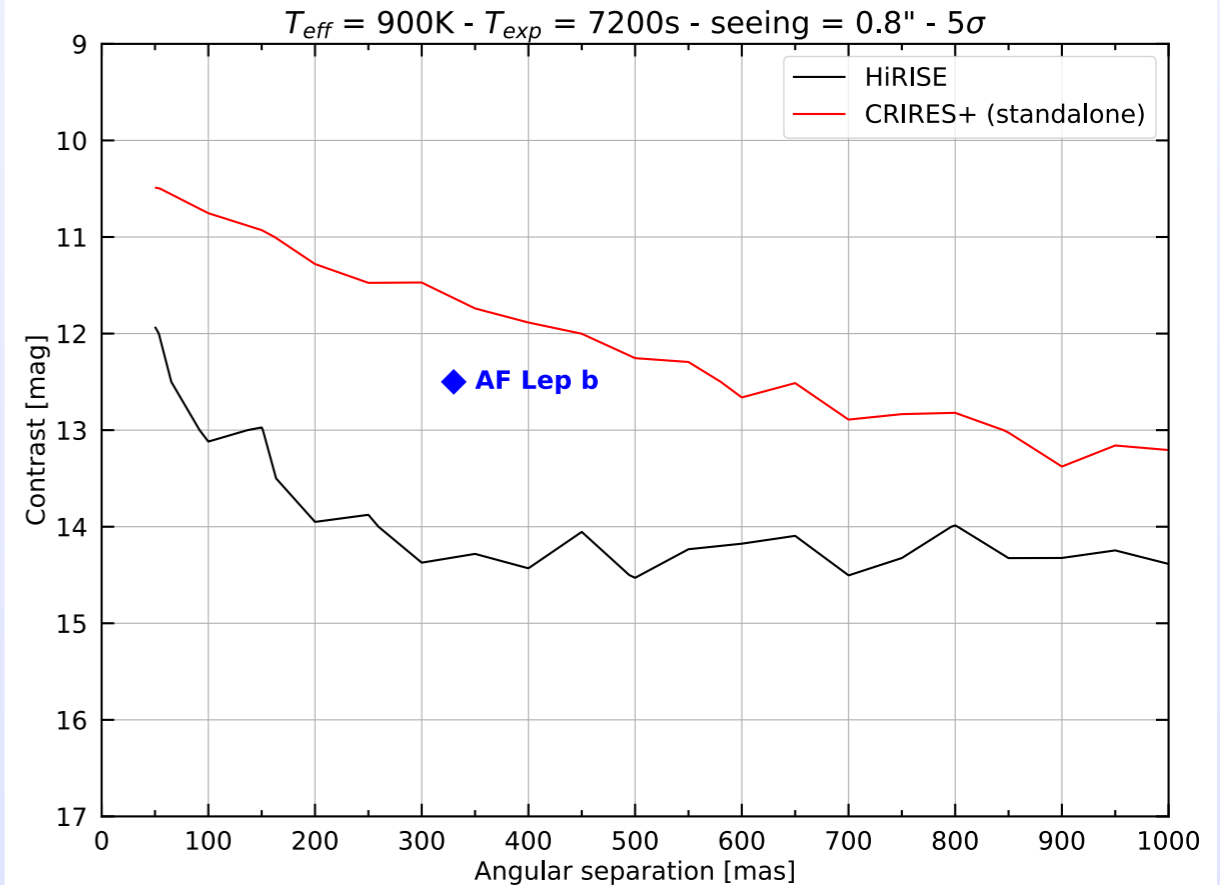
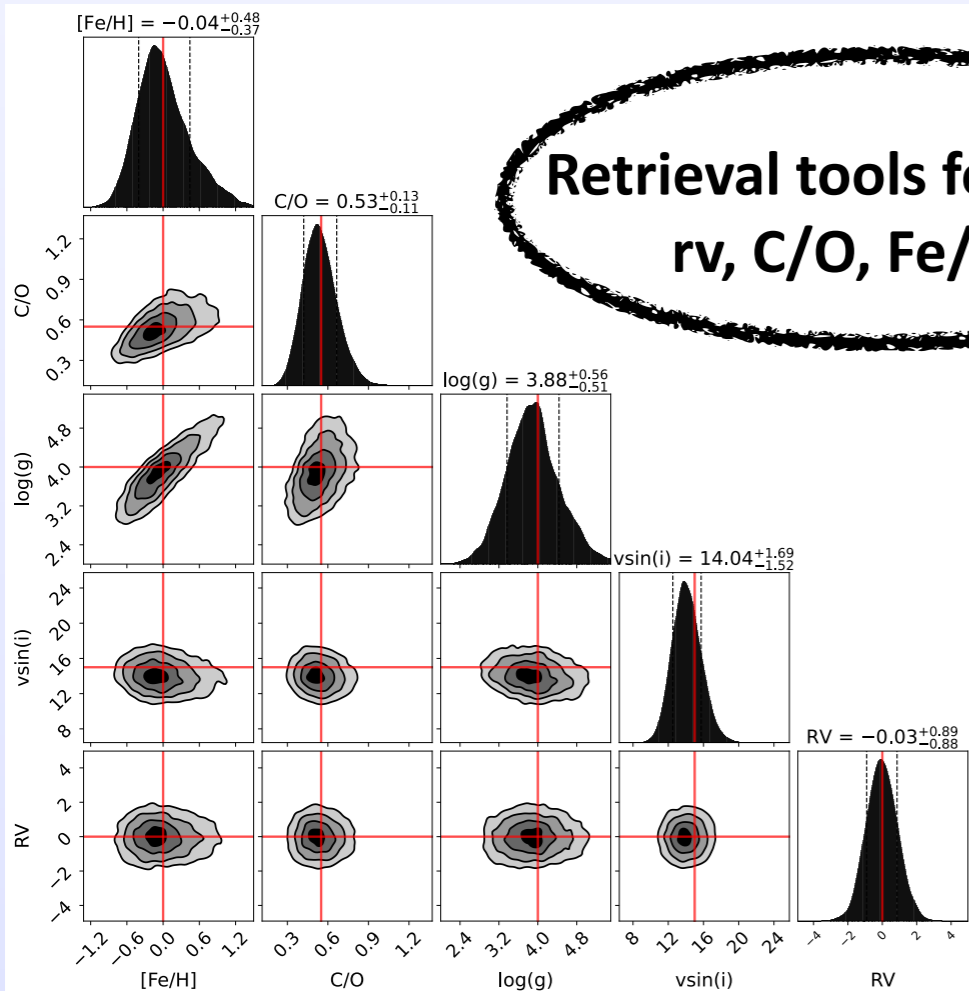
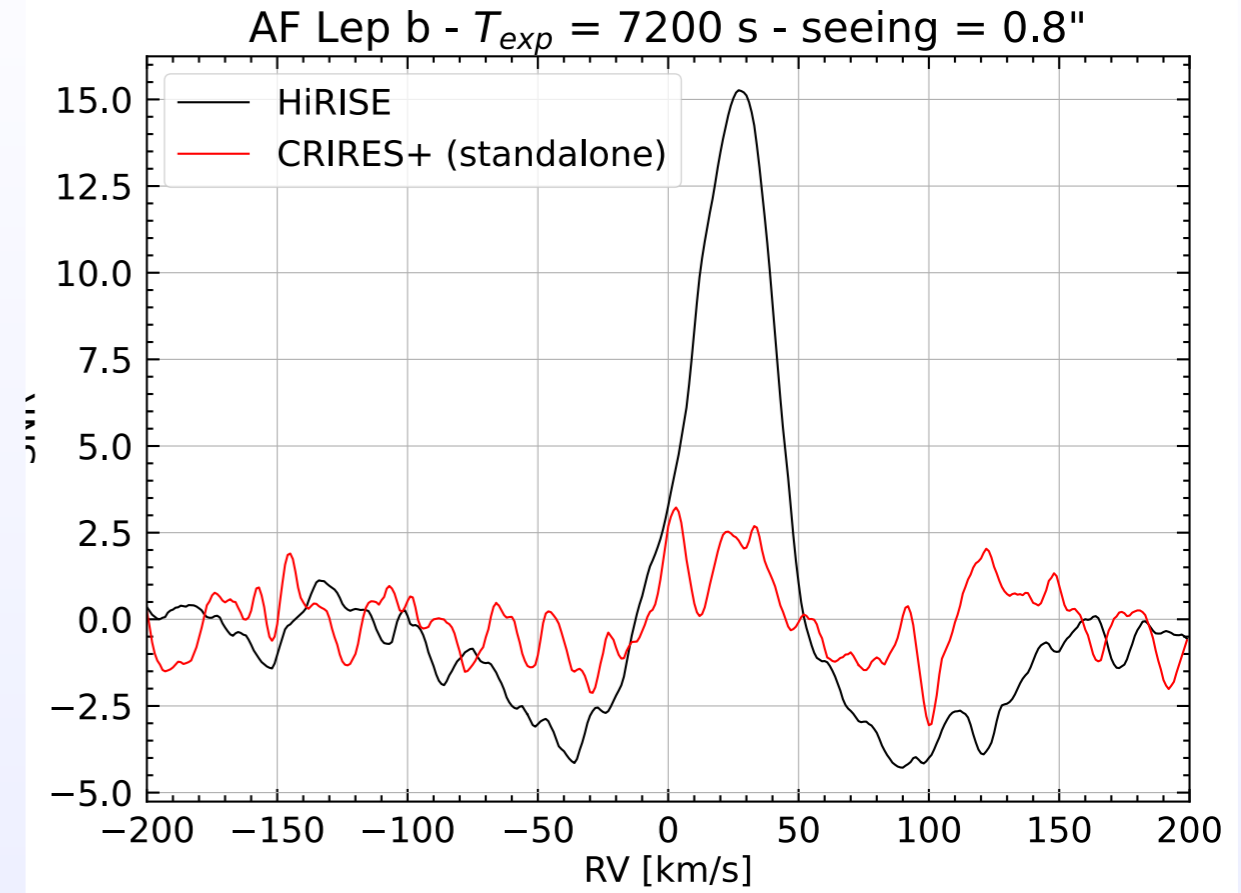
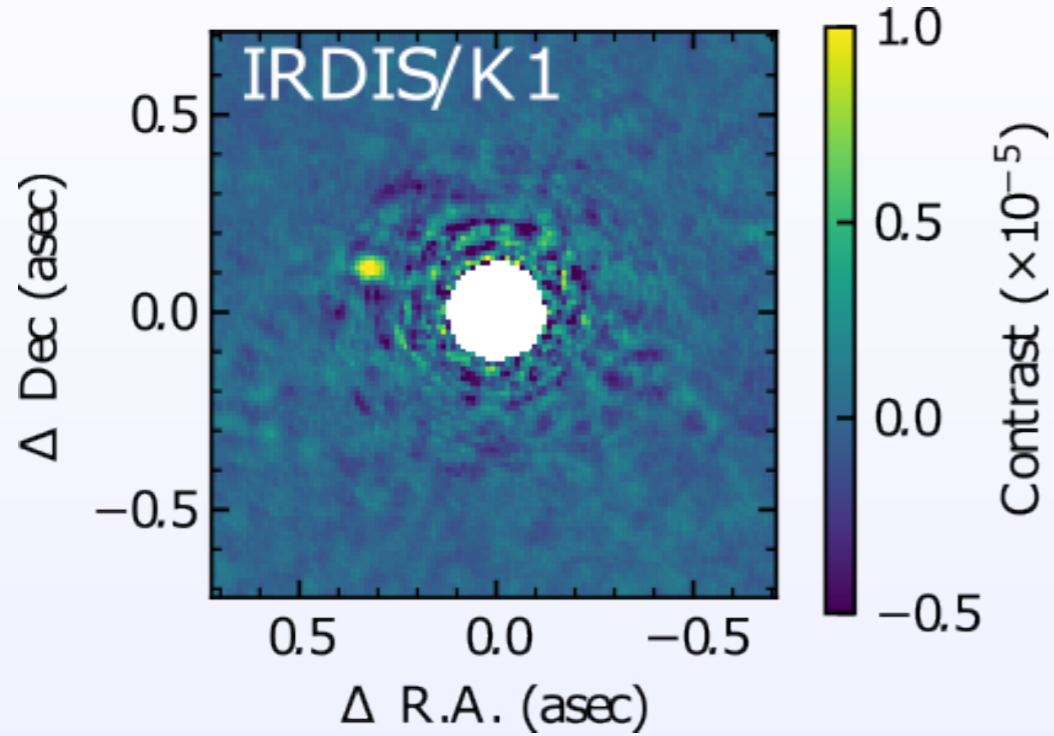


Major discovery potential



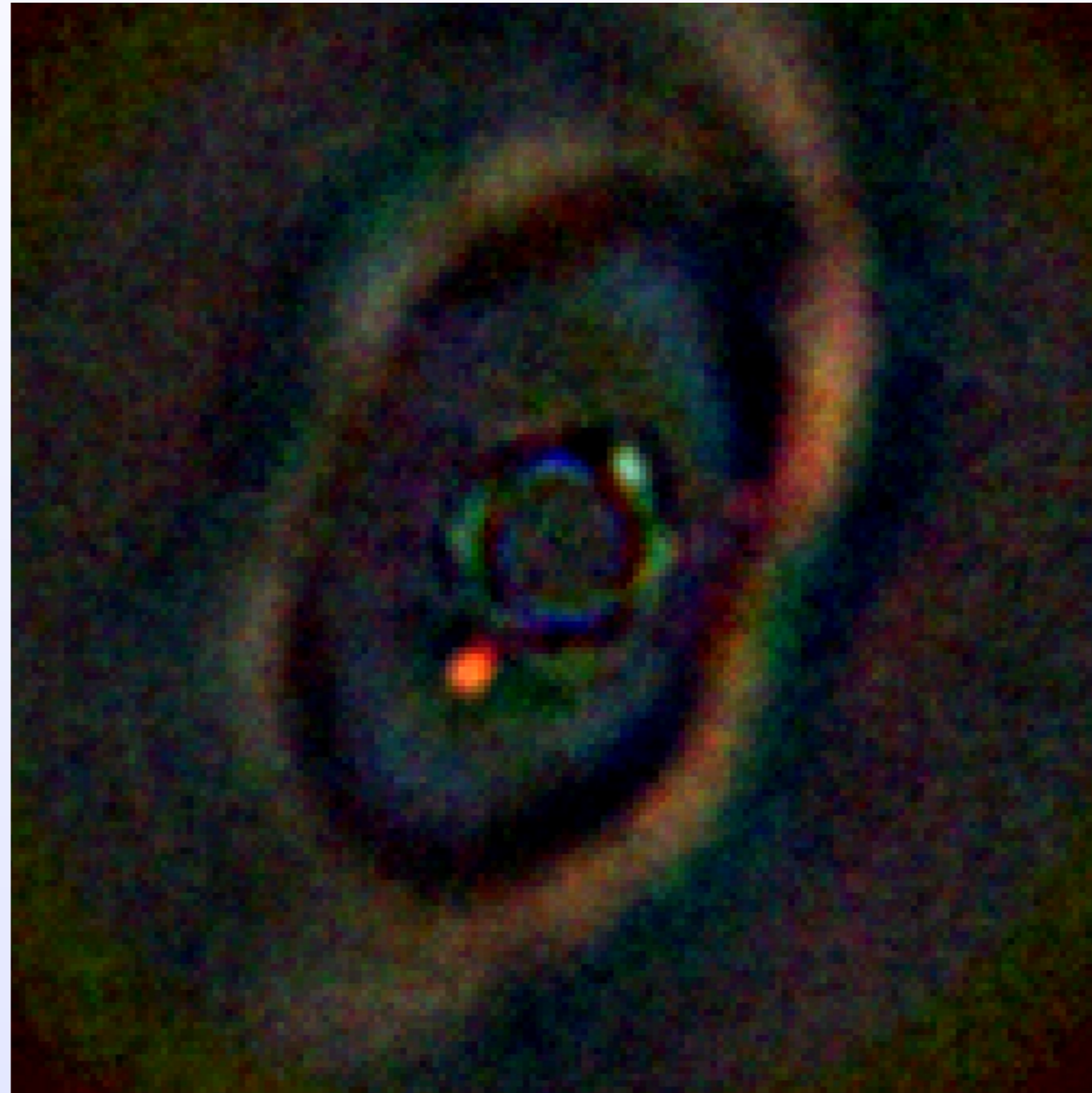
Expected performance: AF Lep b

Mesa et al. / de Rosa et al. / Franson et al. (2023)



Imaging of exoplanetary systems

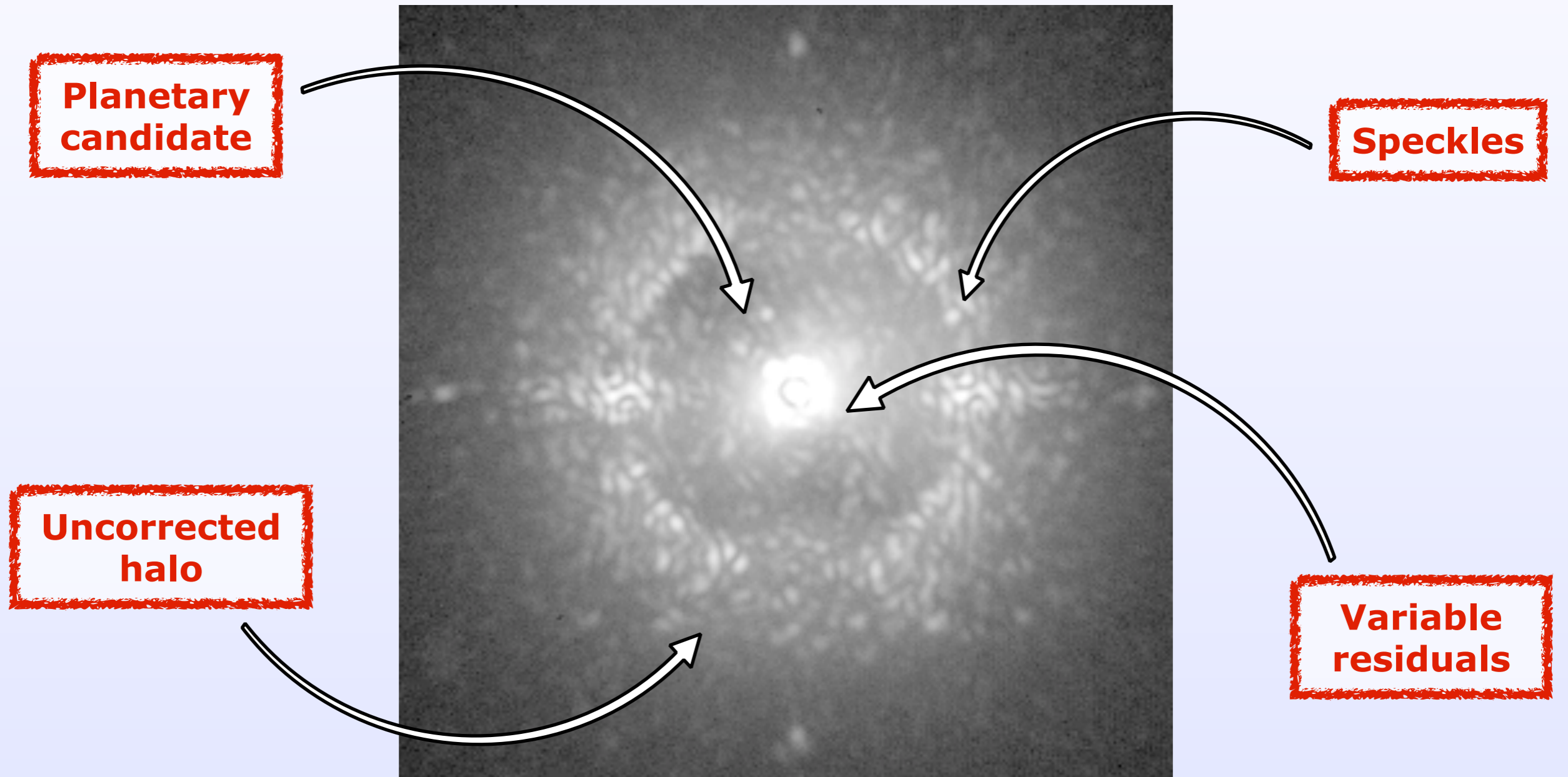
What we all want to see...



PDS 70 - Keppler et al. (2018)

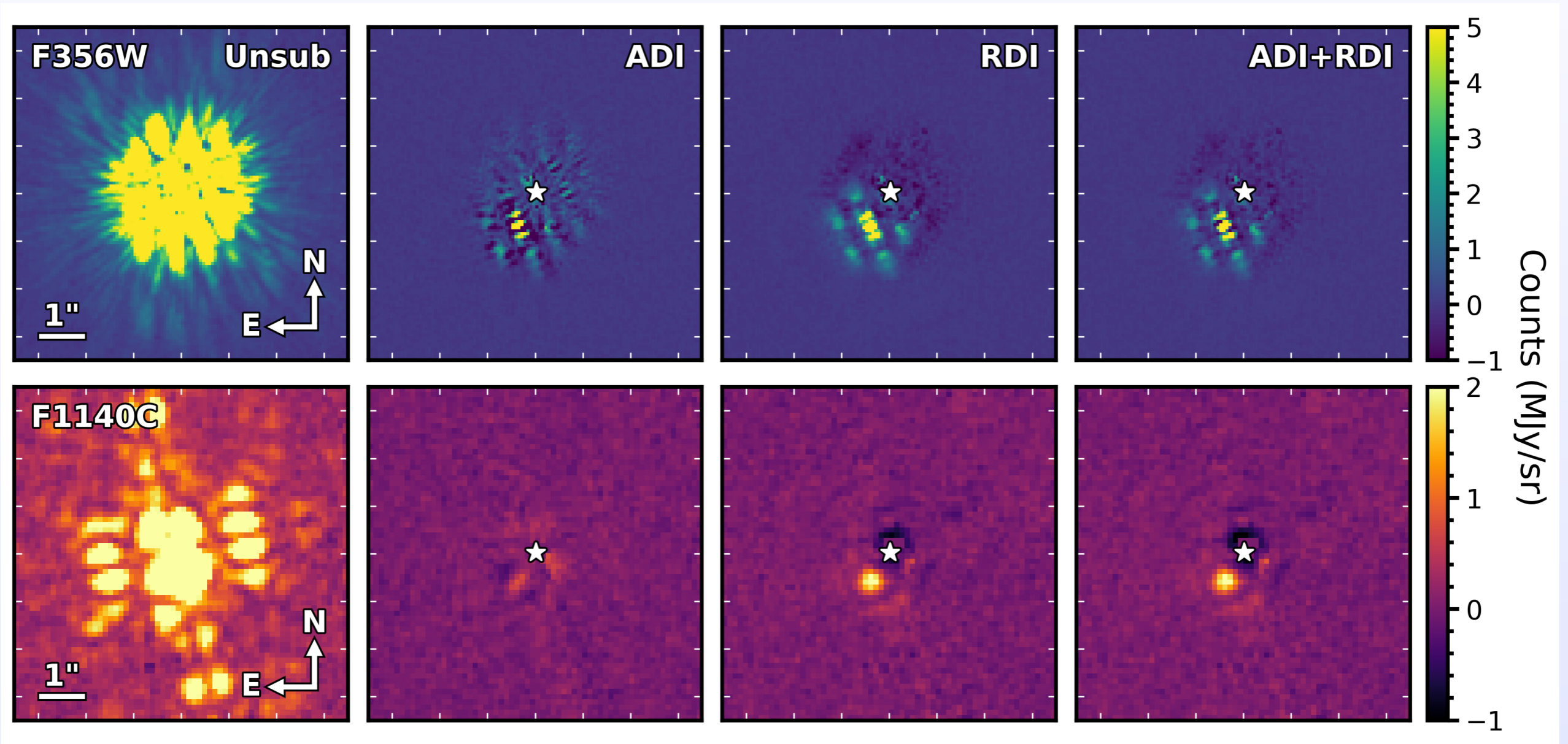
Imaging of exoplanetary systems

What we really see!



Imaging of exoplanetary systems

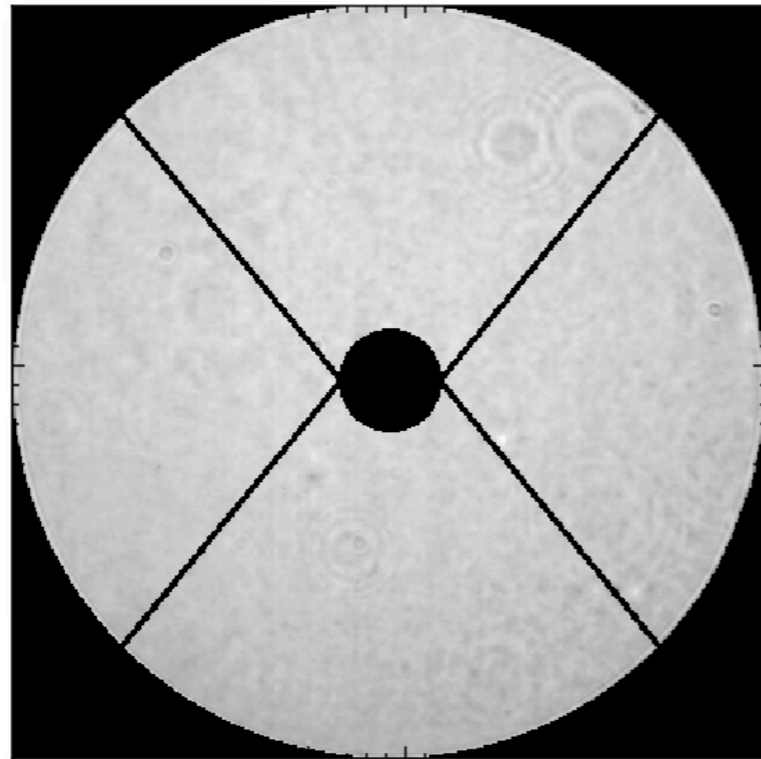
And sorry guys, but that's the same in space 😊



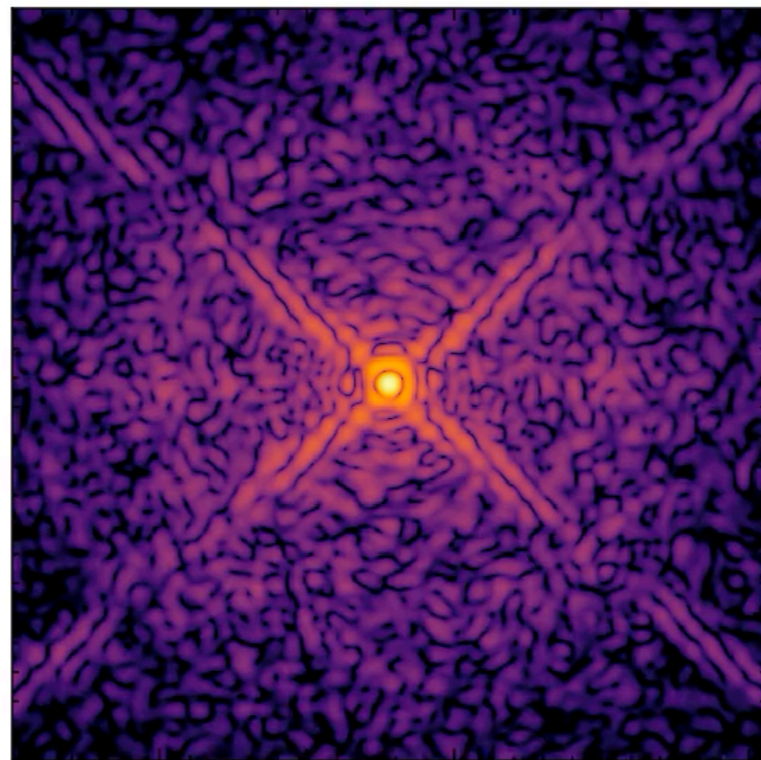
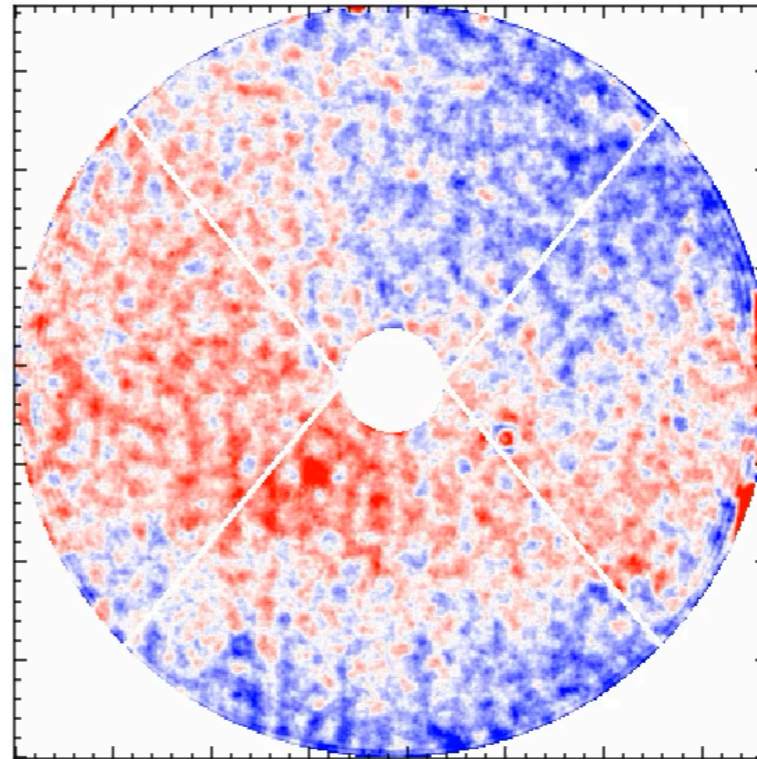
HIP65426 - ERS - Carter et al. (2022)

Back to optics: coronagraphic image formation

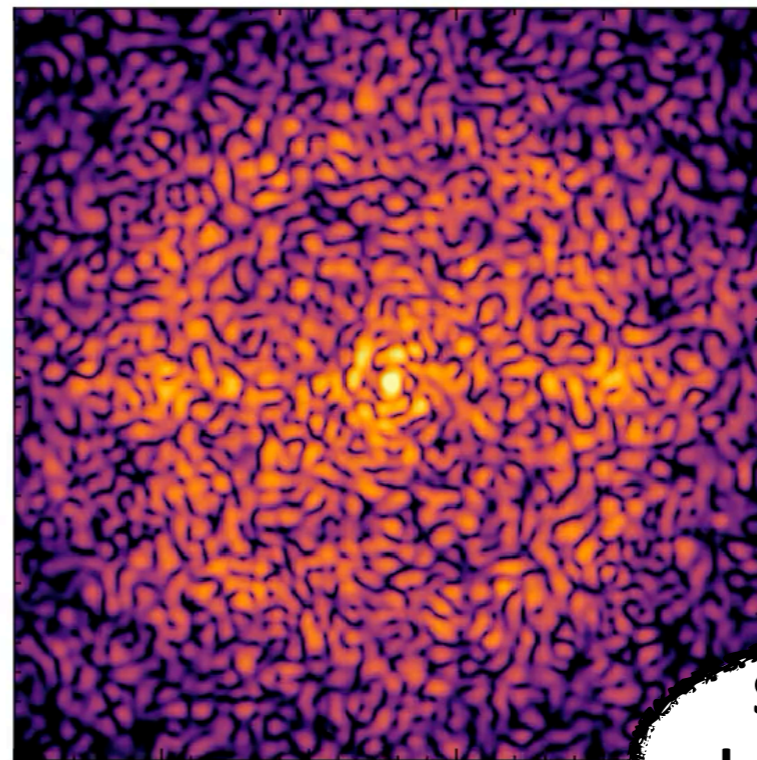
Amplitude errors



Phase errors



Direct image



Coronagraphic image

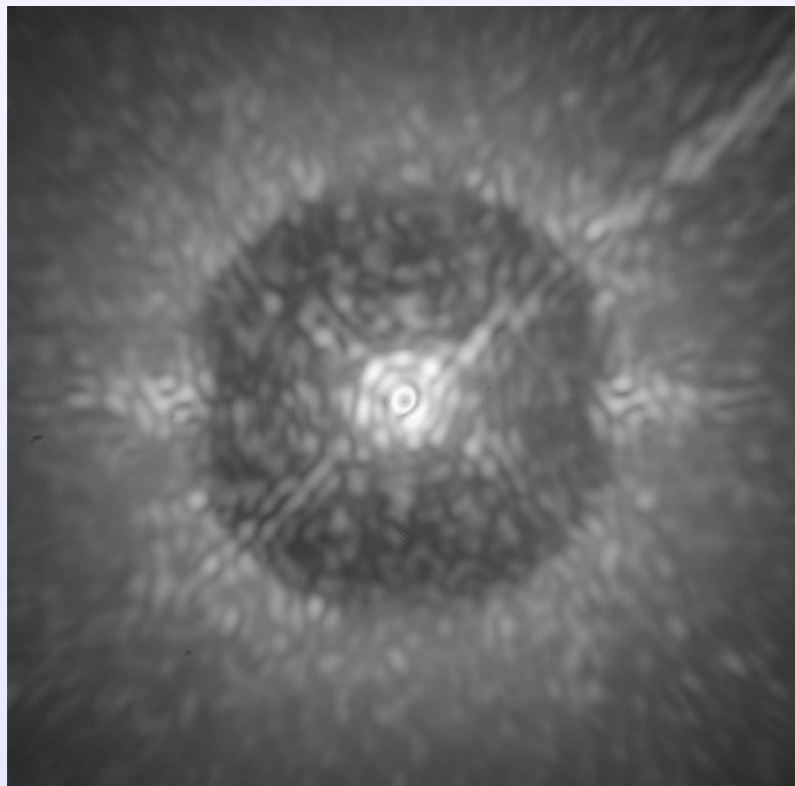
Speckles are caused by uncorrected optical aberrations

Quasi-static speckles

The Good

Aberrations can be measured and corrected, speckles can be averaged

T_0



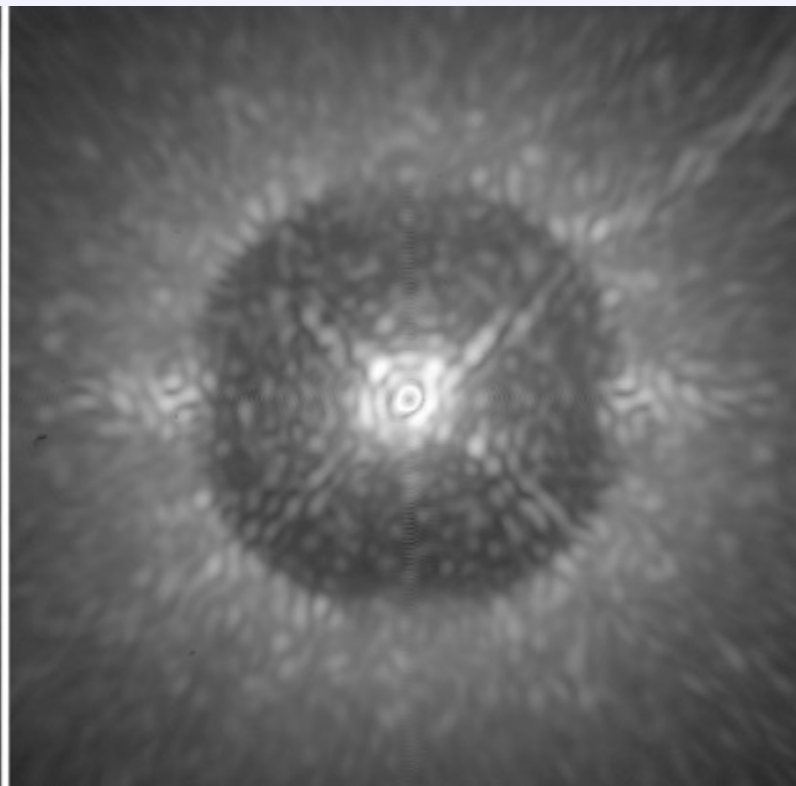
VLT/SPHERE

Racine et al. (1999)
Macintosh et al. (2005)

The Bad

Speckles are not static, but definitely not random

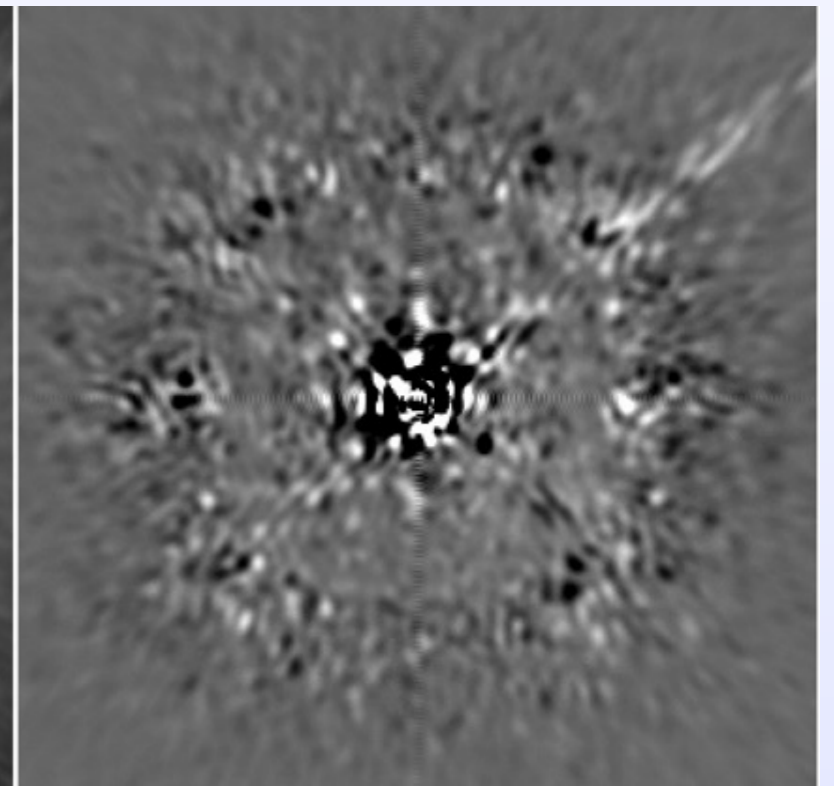
$T_1 = T_0 + 20 \text{ min}$



Soummer et al. (2007)
Hinkley et al. (2007)

The Ugly

Multiple spatial frequencies and timescales are involved



Martinez et al. (2013, 2013)
Milli et al. (2016)

Zernike wavefront sensor

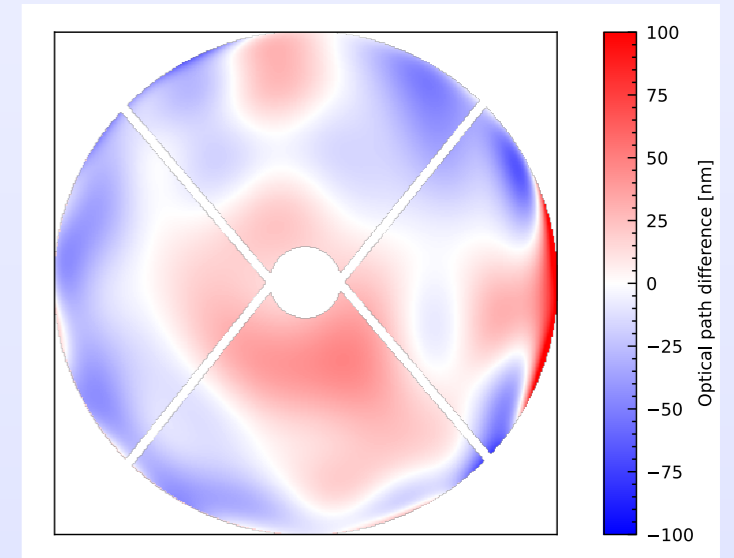
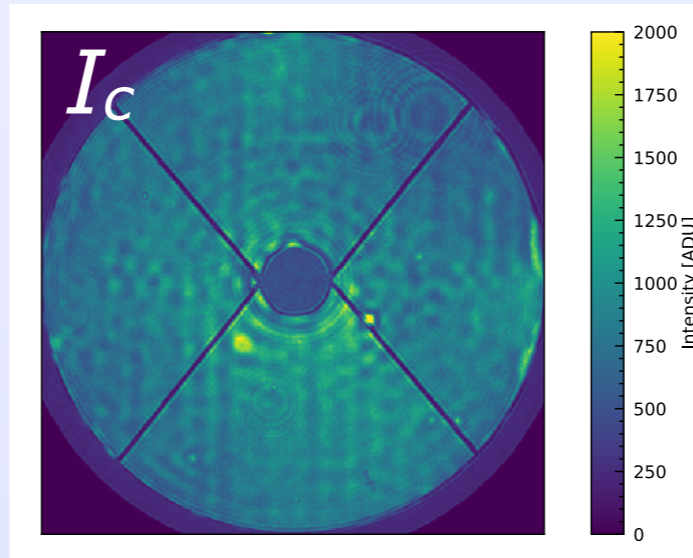
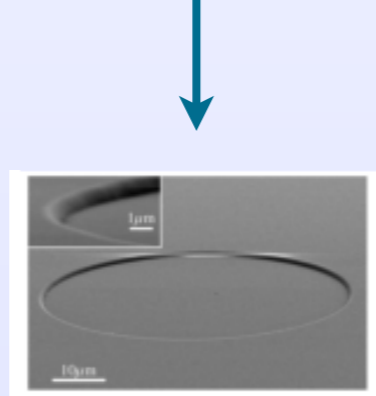
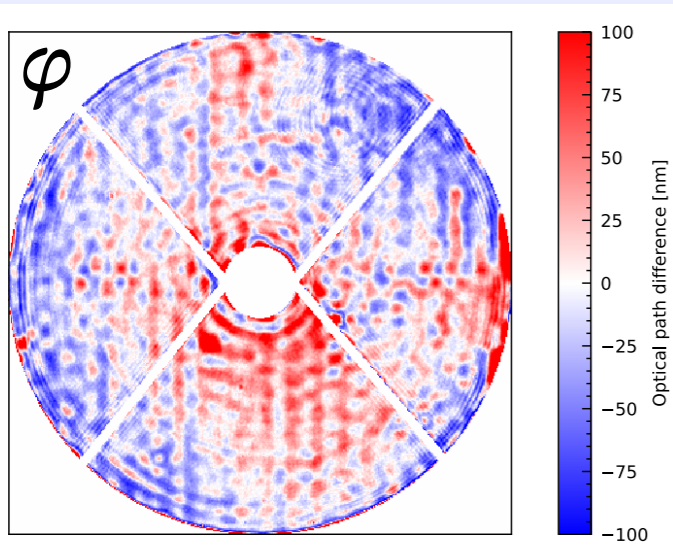
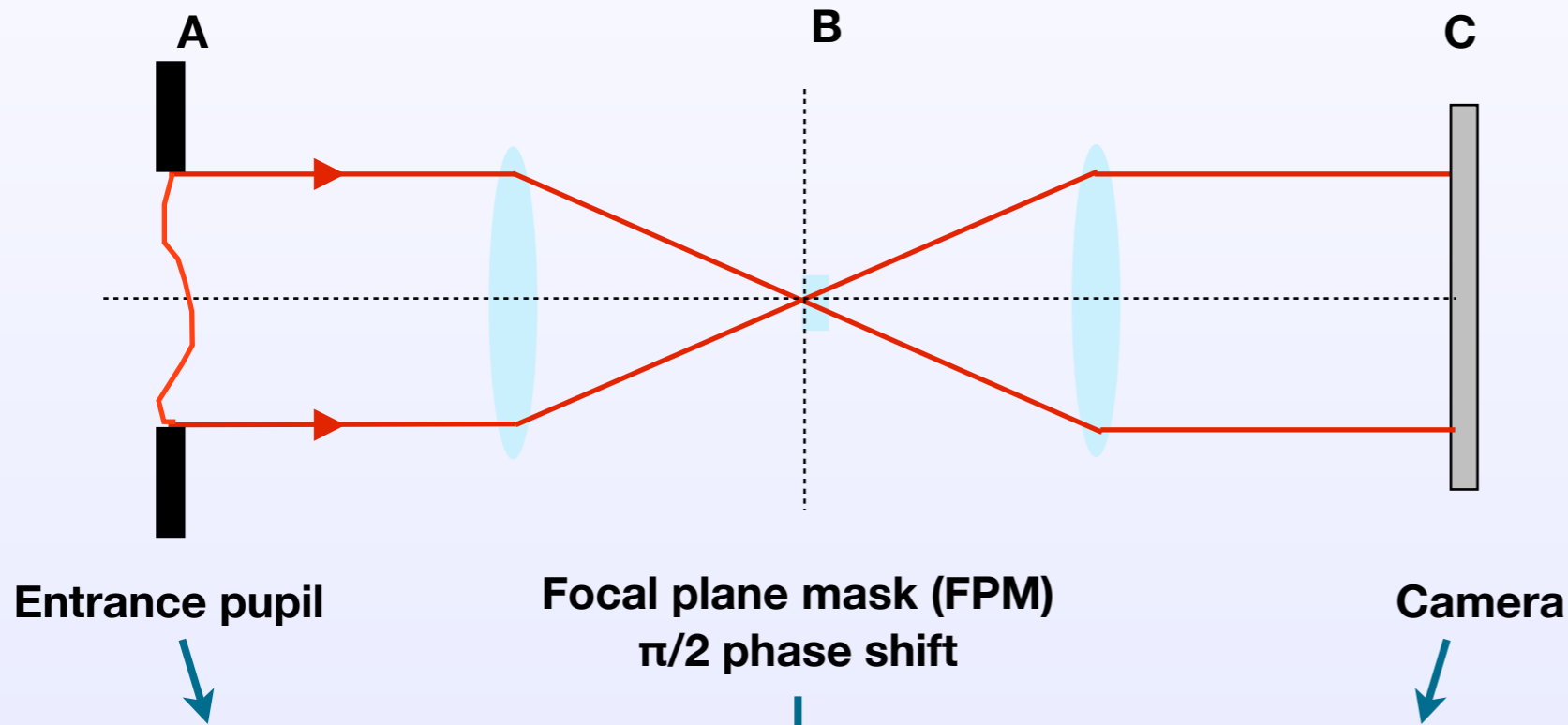
Converts (small) phase aberrations into intensity variations

N'Diaye et al. (2013):

$$\varphi = -1 + \sqrt{3 - 2b - (1 - I_C)/b}$$

φ → Phase errors
Intensity

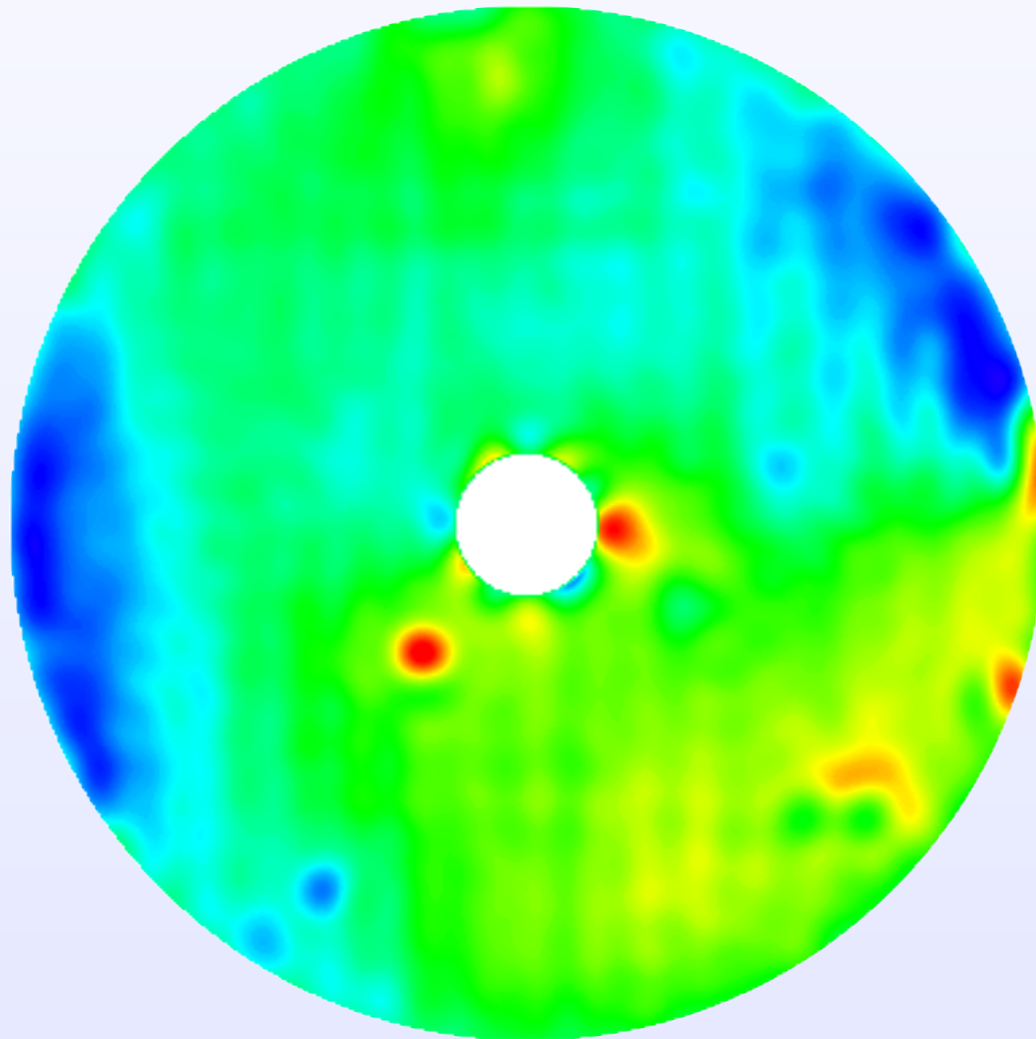
- Simple analytical expression between φ and I
- pyZELDA open source tool



Compensation of aberrations in SPHERE

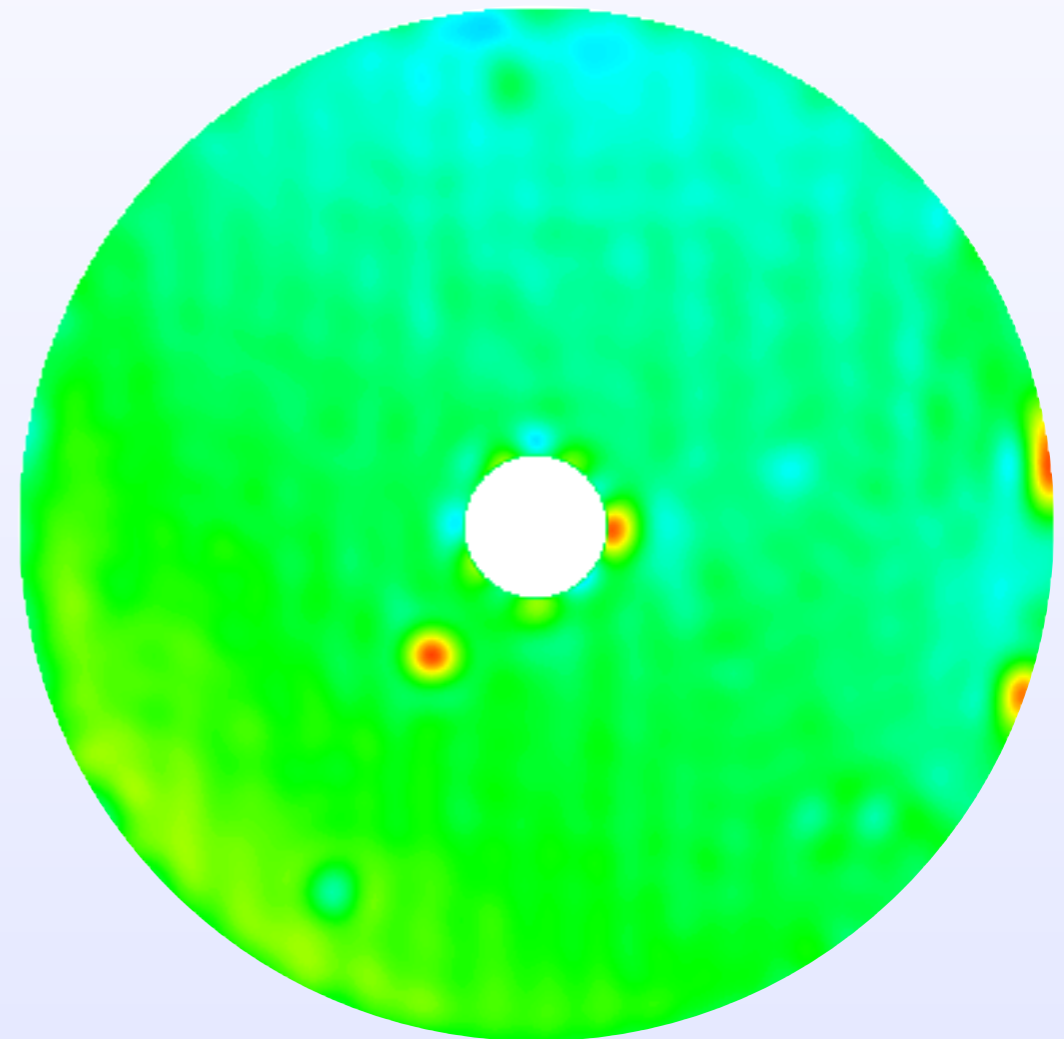
Zernike wavefront sensor measurements

Before calibration



30 nm RMS
 $f < 20$ c/p

After calibration

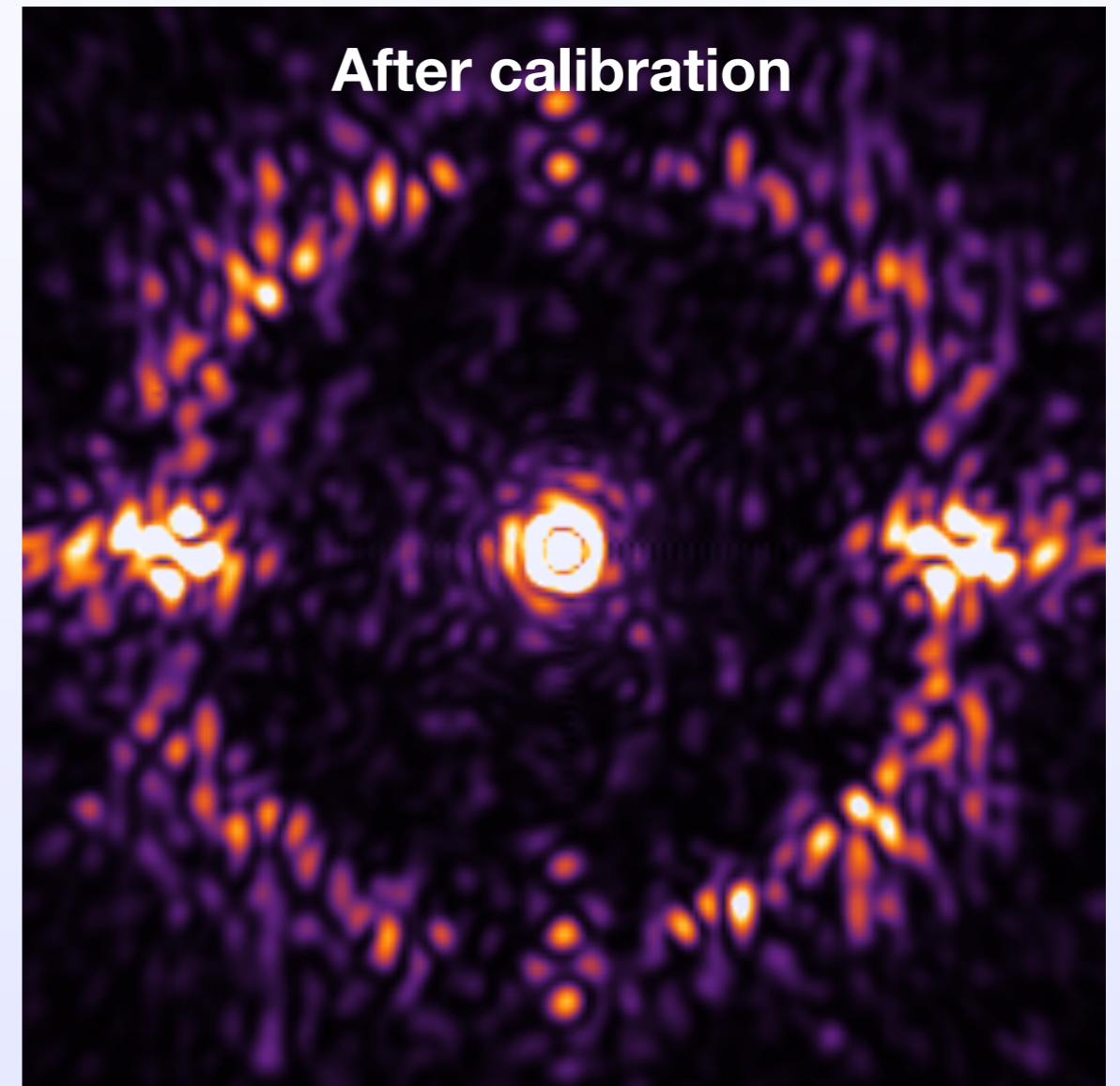
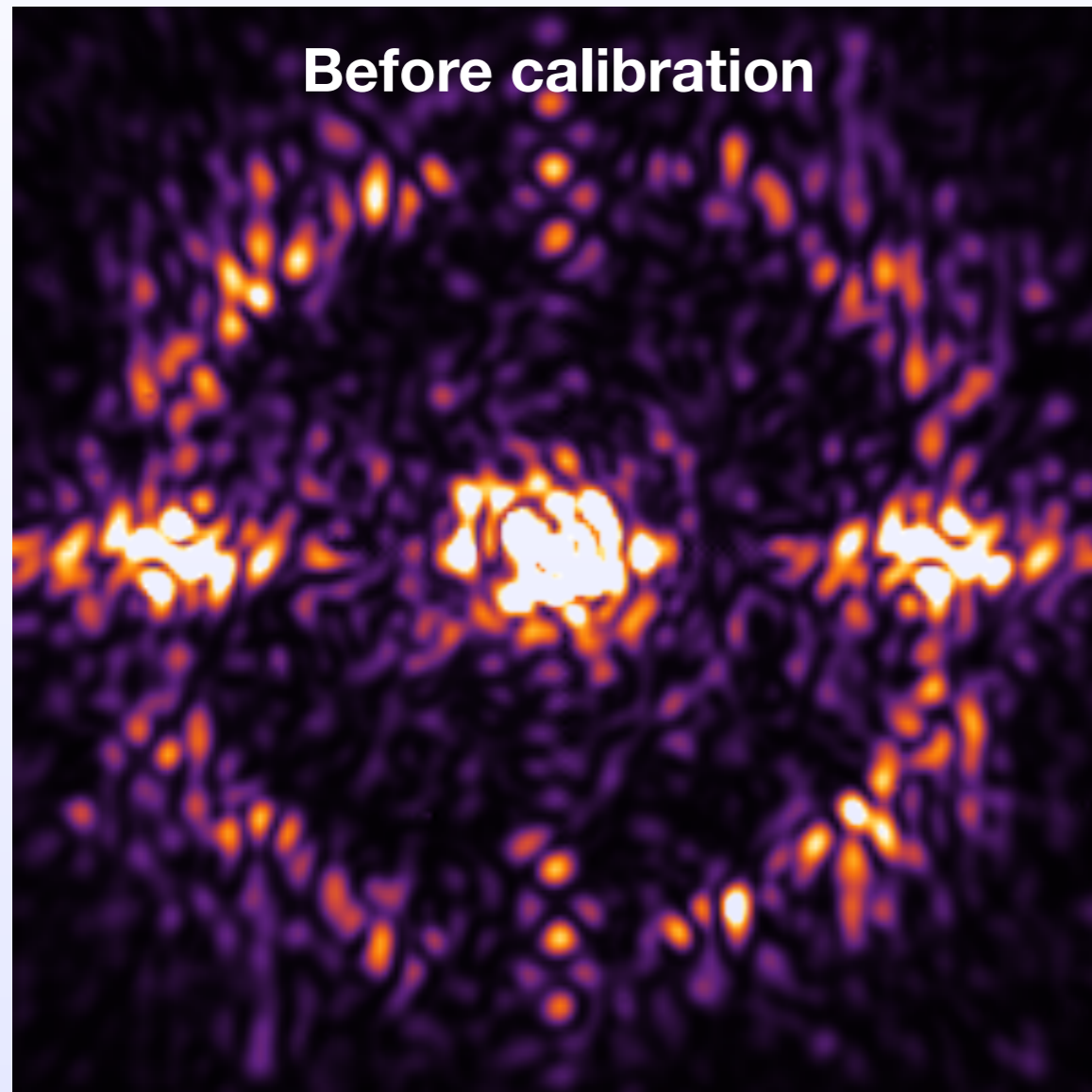


16 nm RMS

N'Diaye, Vigan, et al. (2016)

Compensation of aberrations in SPHERE

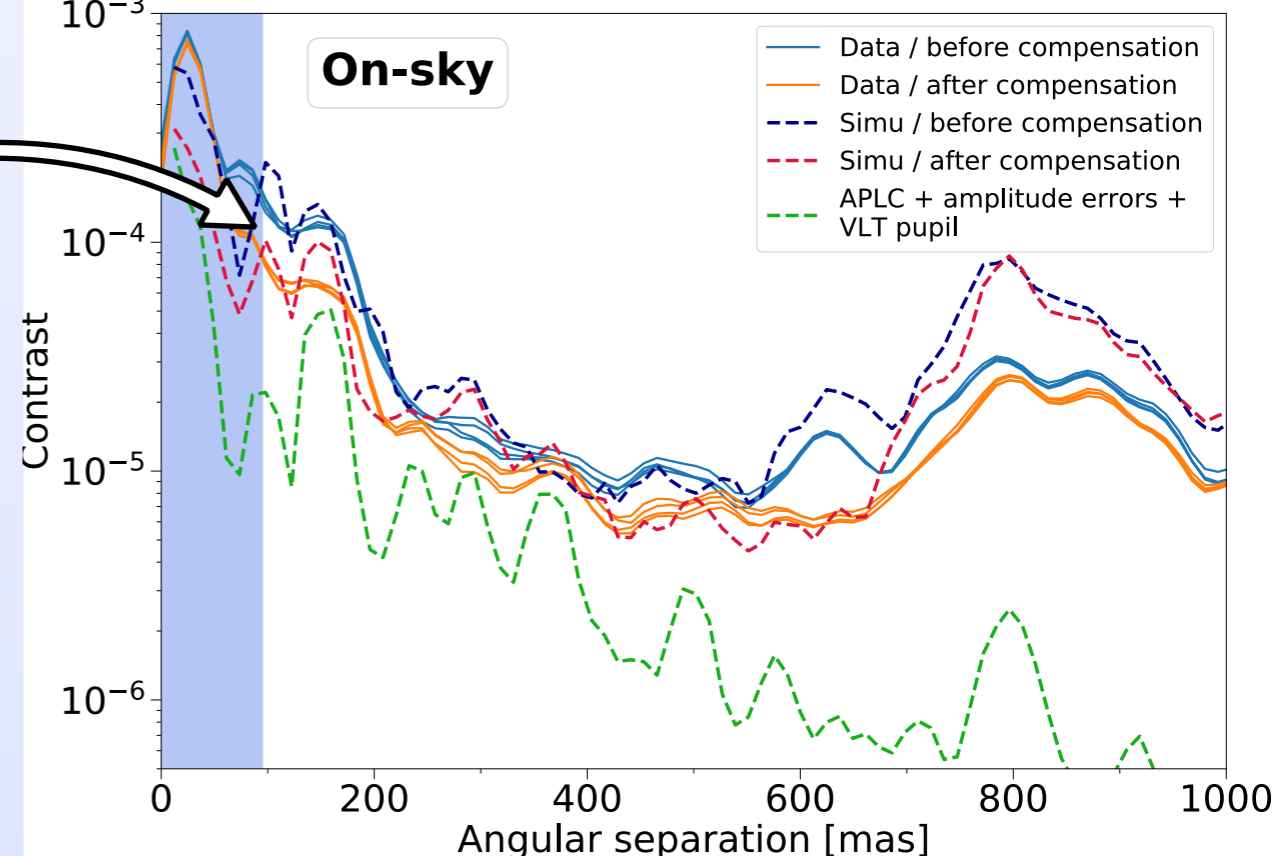
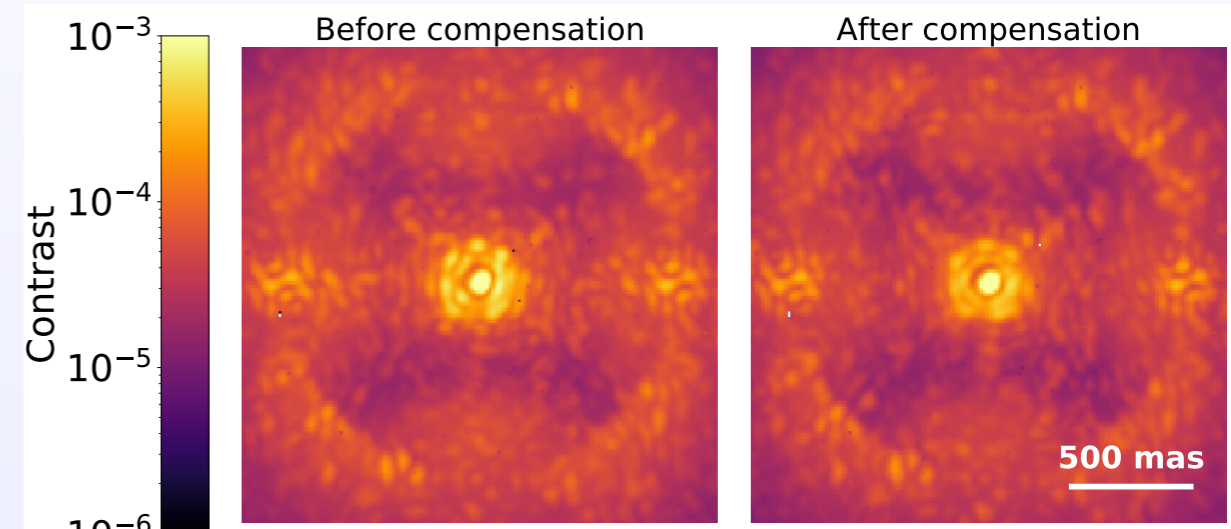
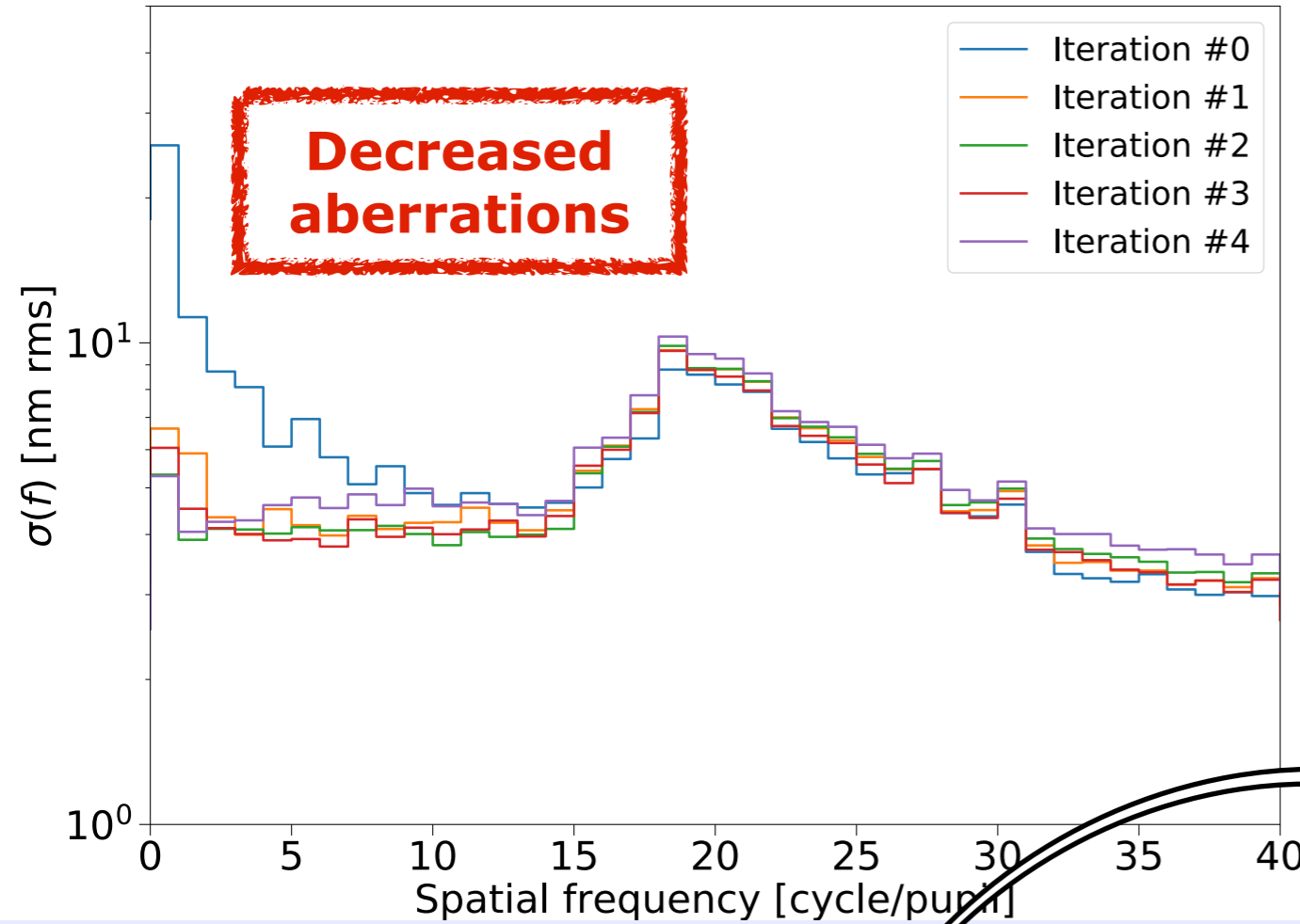
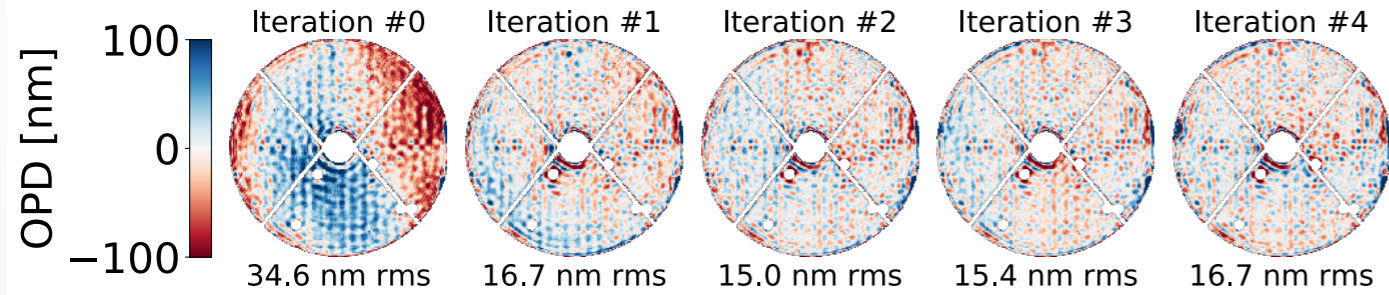
Apodised pupil Lyot coronagraph, H-band



N'Diaye, Vigan, et al. (2016)

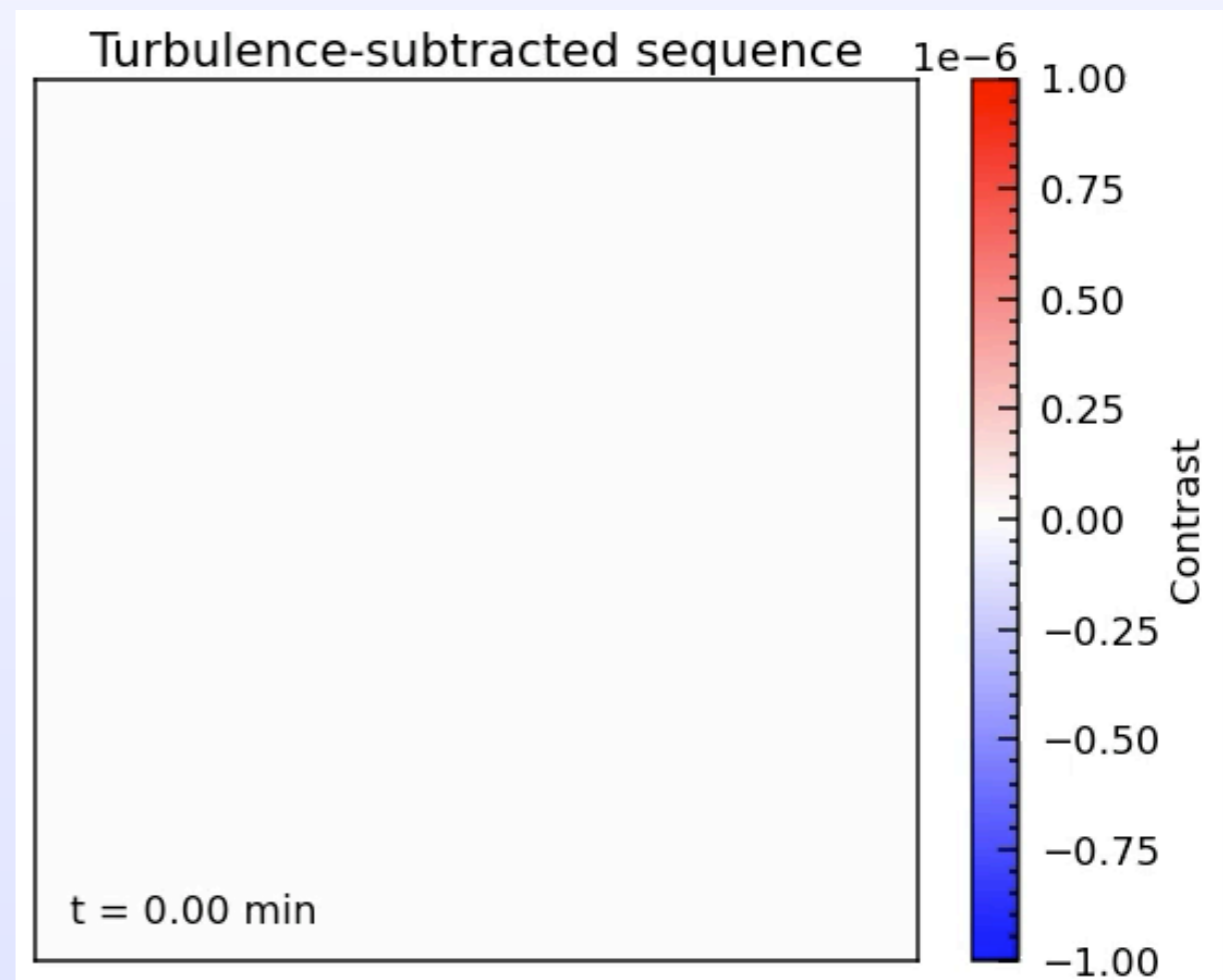
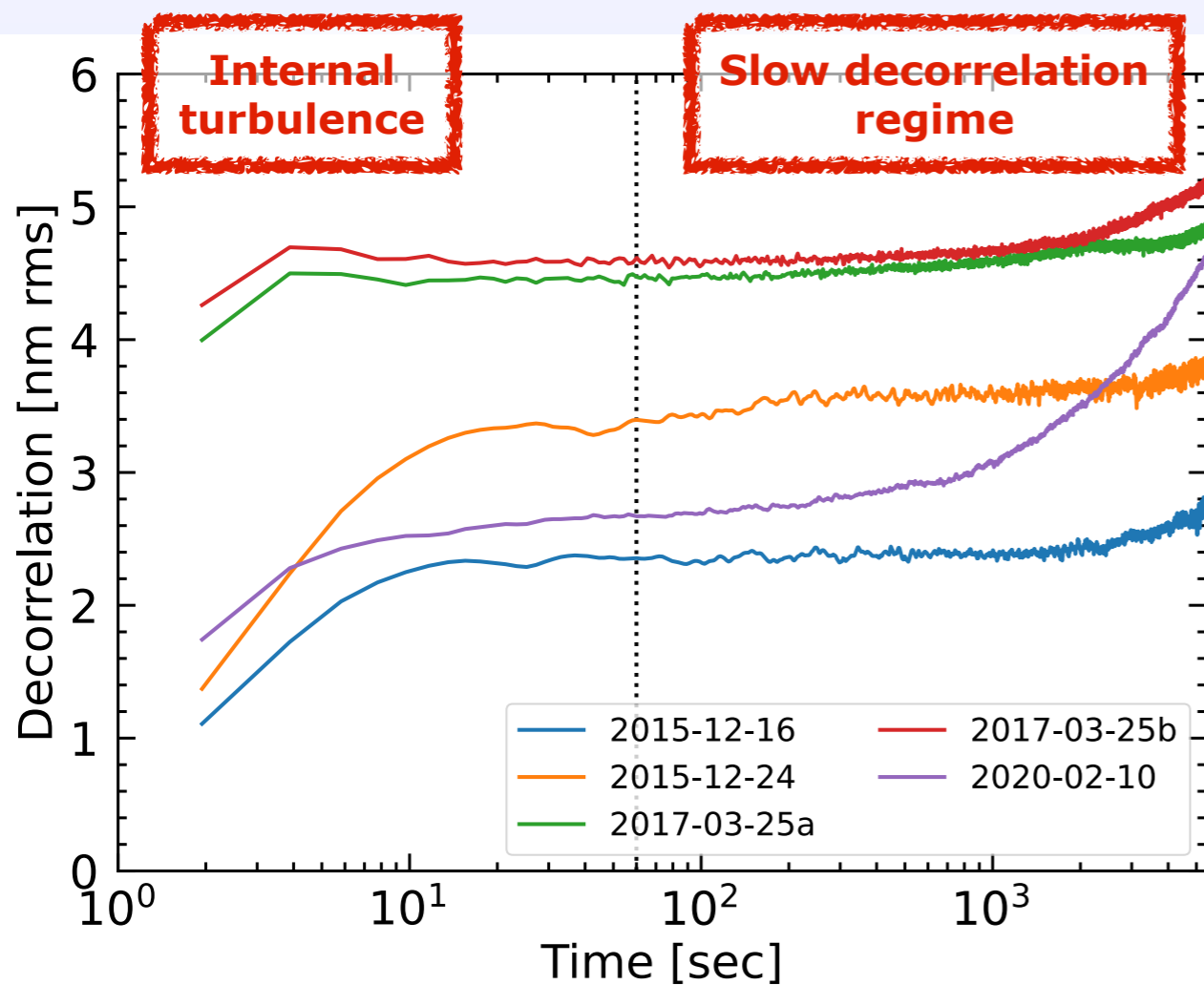
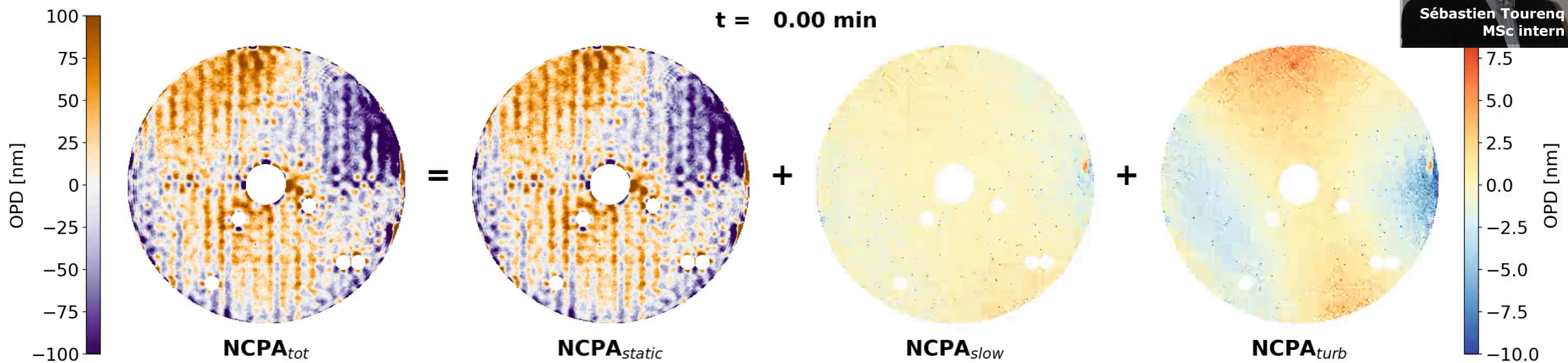
Compensation of aberrations on sky

Vigan, N'Diaye et al. (2019)



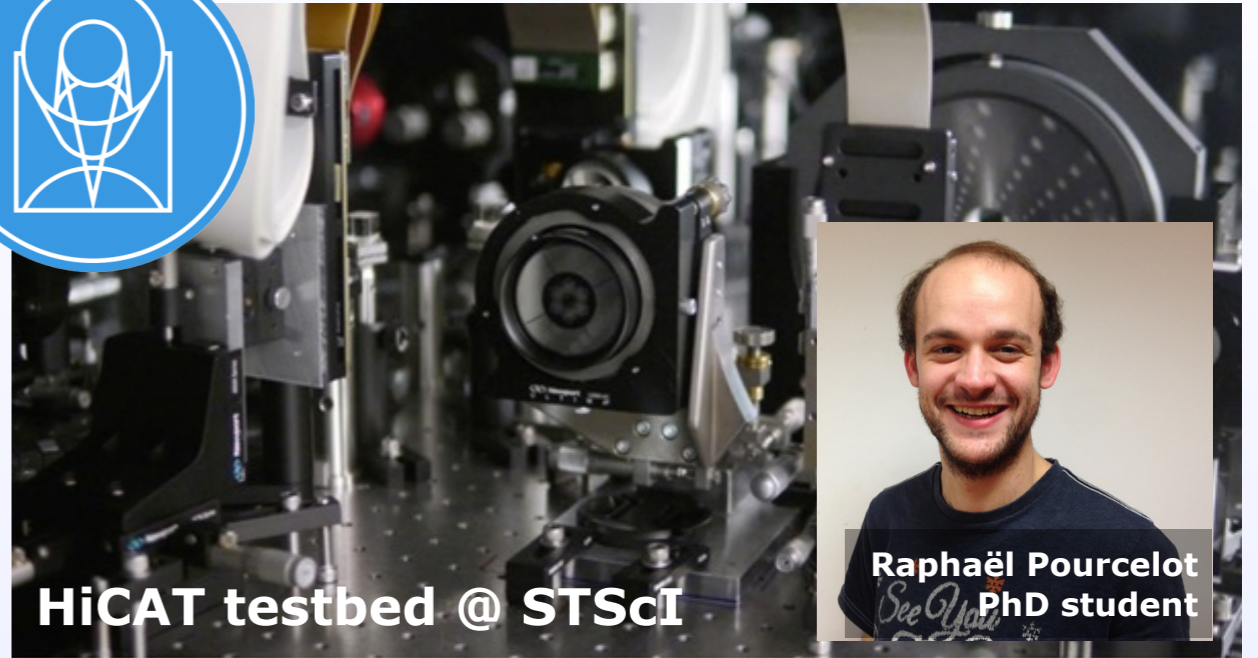
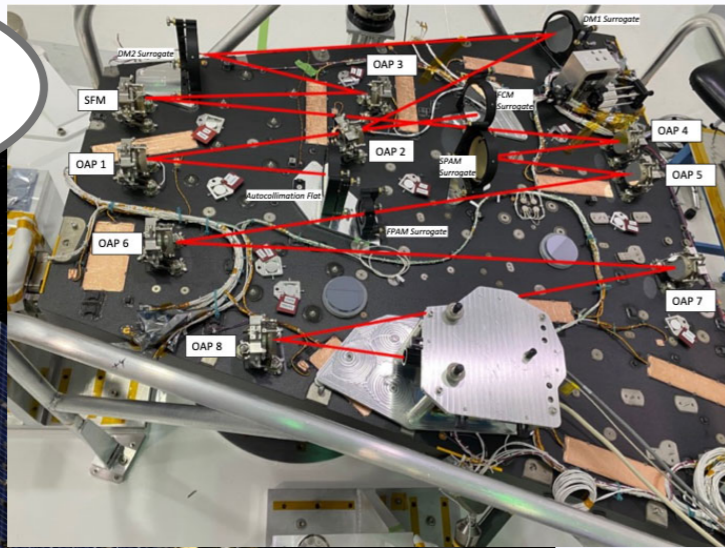
**(small)
Contrast gain**

Temporal variations of aberrations in SPHER

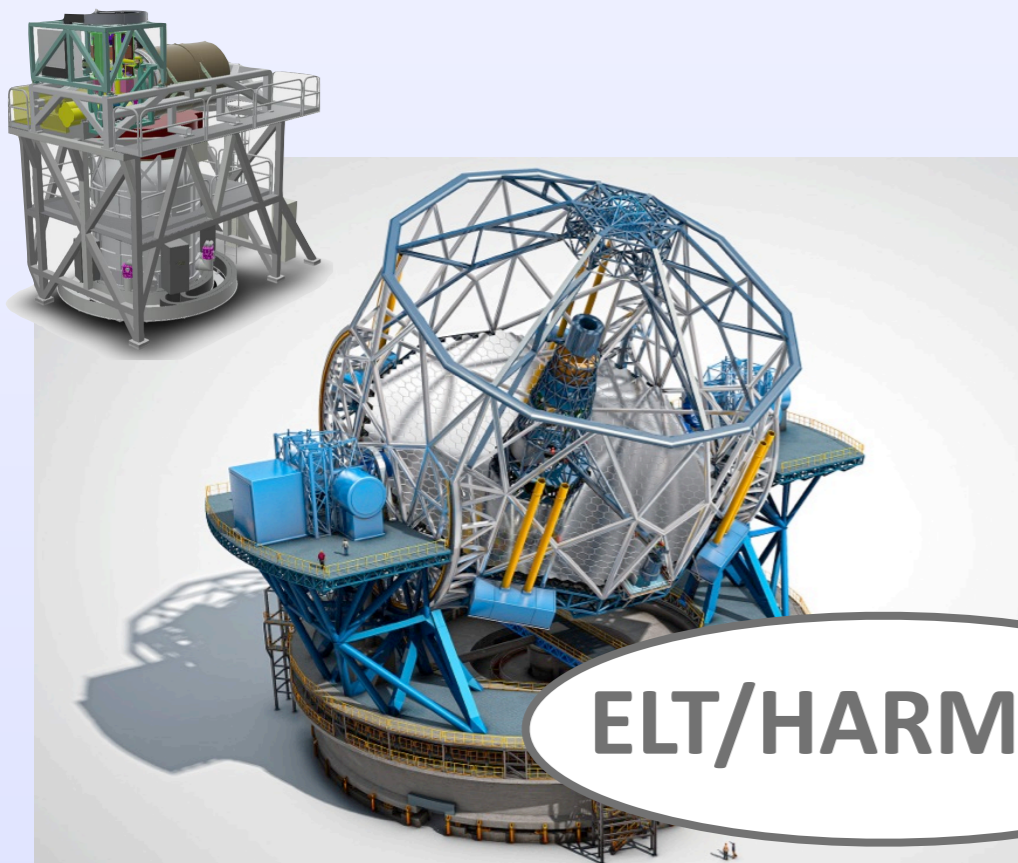


Zernike wavefront sensors are everywhere

RST/CGI



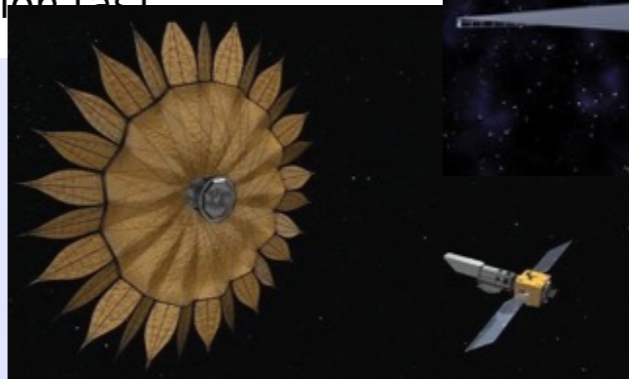
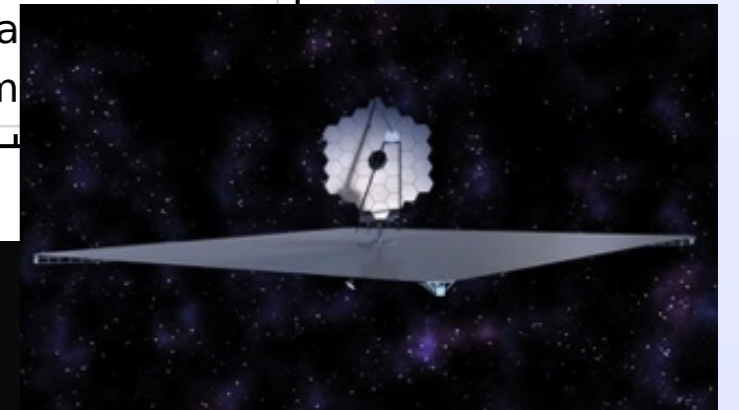
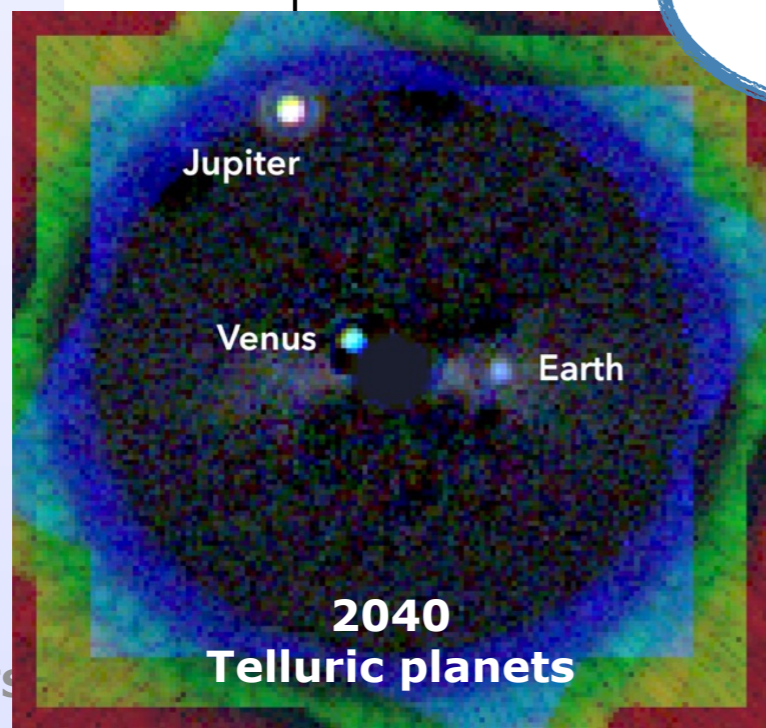
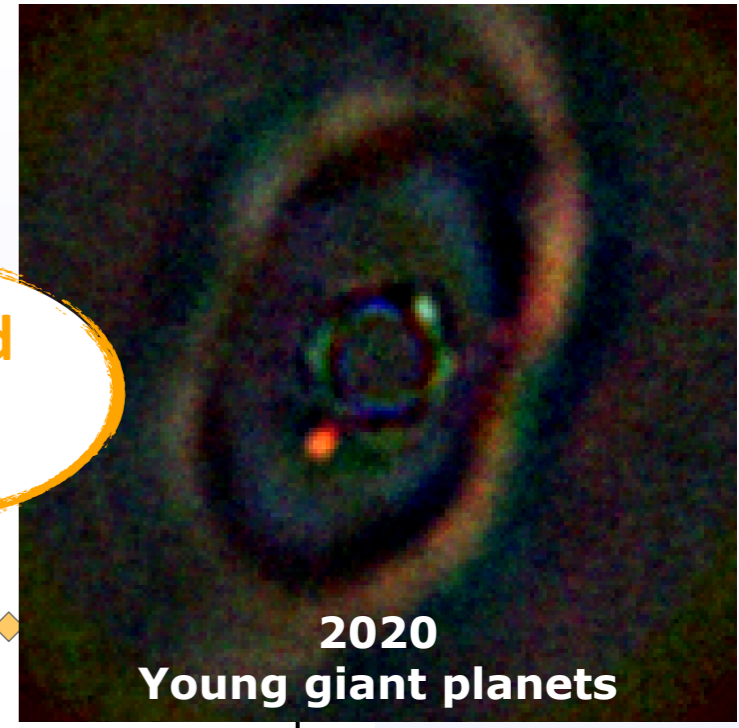
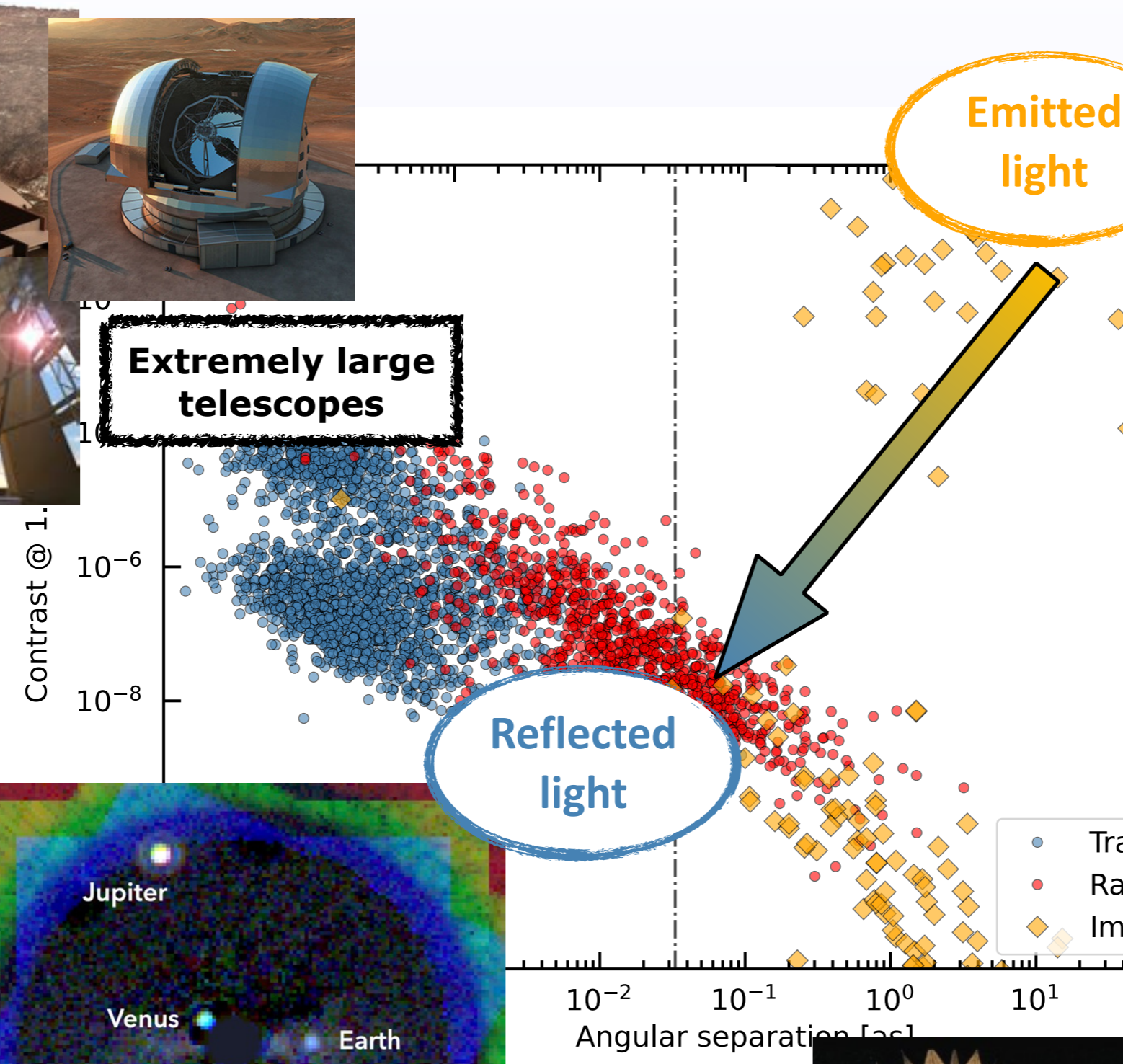
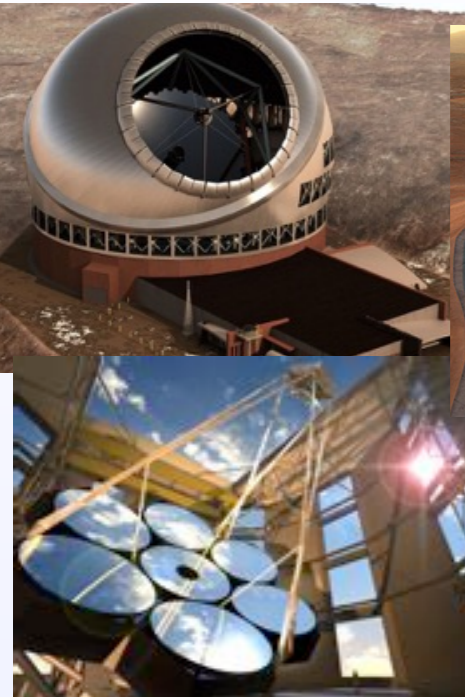
HiCAT testbed @ STScI



ELT/HARMONI



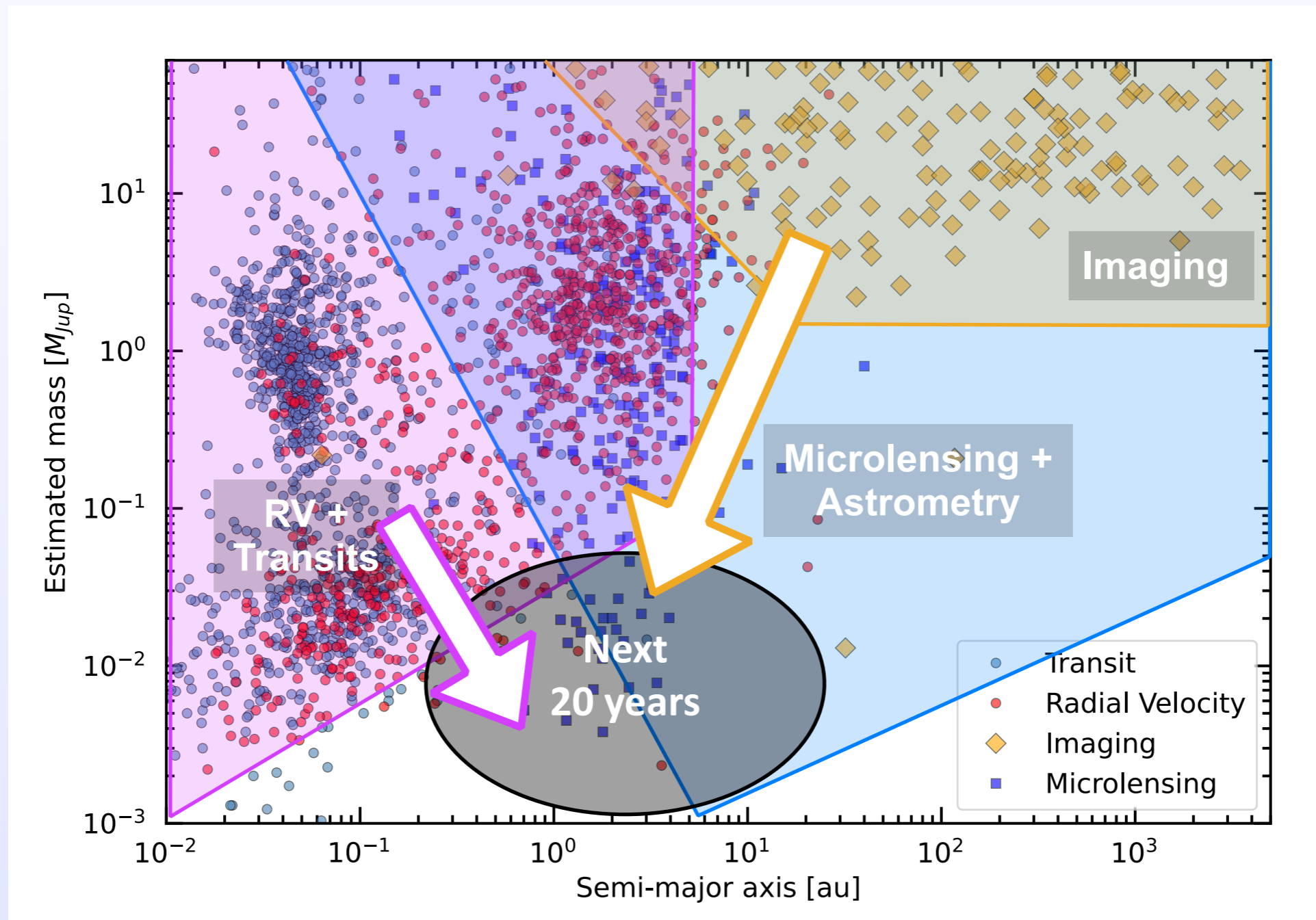
Towards imaging Earth analogs



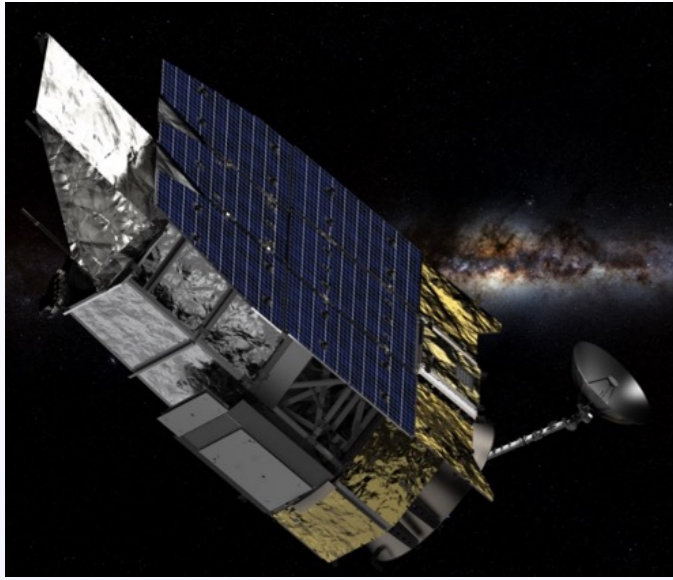
Space missions

Convergence of the detection methods

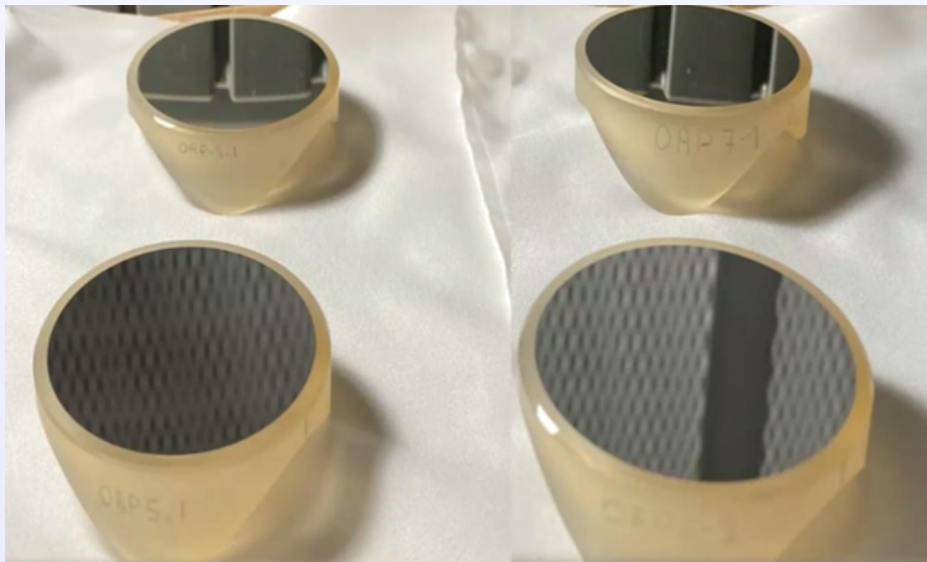
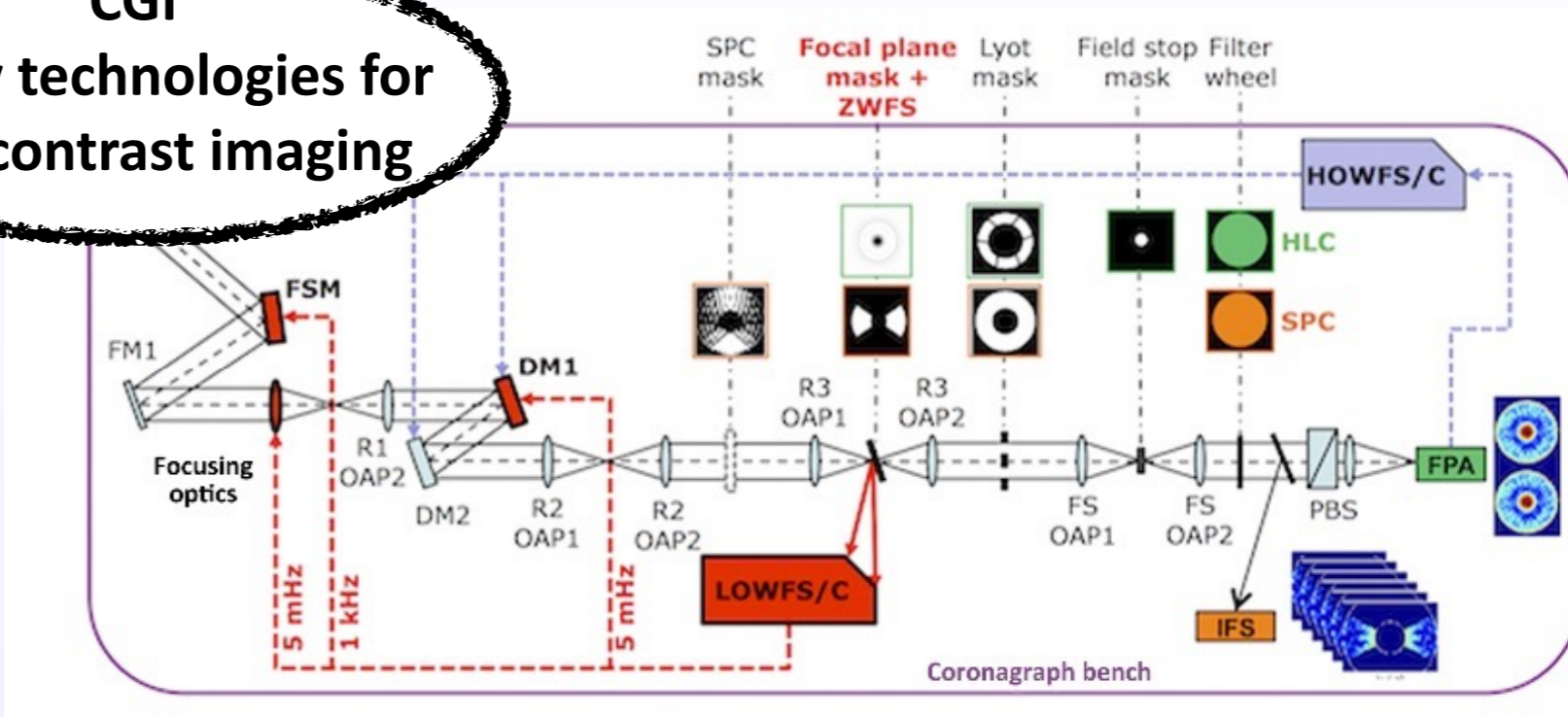
Directly-detectable Earths analogs will likely come from RV and transit



Roman Space Telescope / CGI



CGI
All key technologies for high-contrast imaging



Ultra high quality optics provided by France

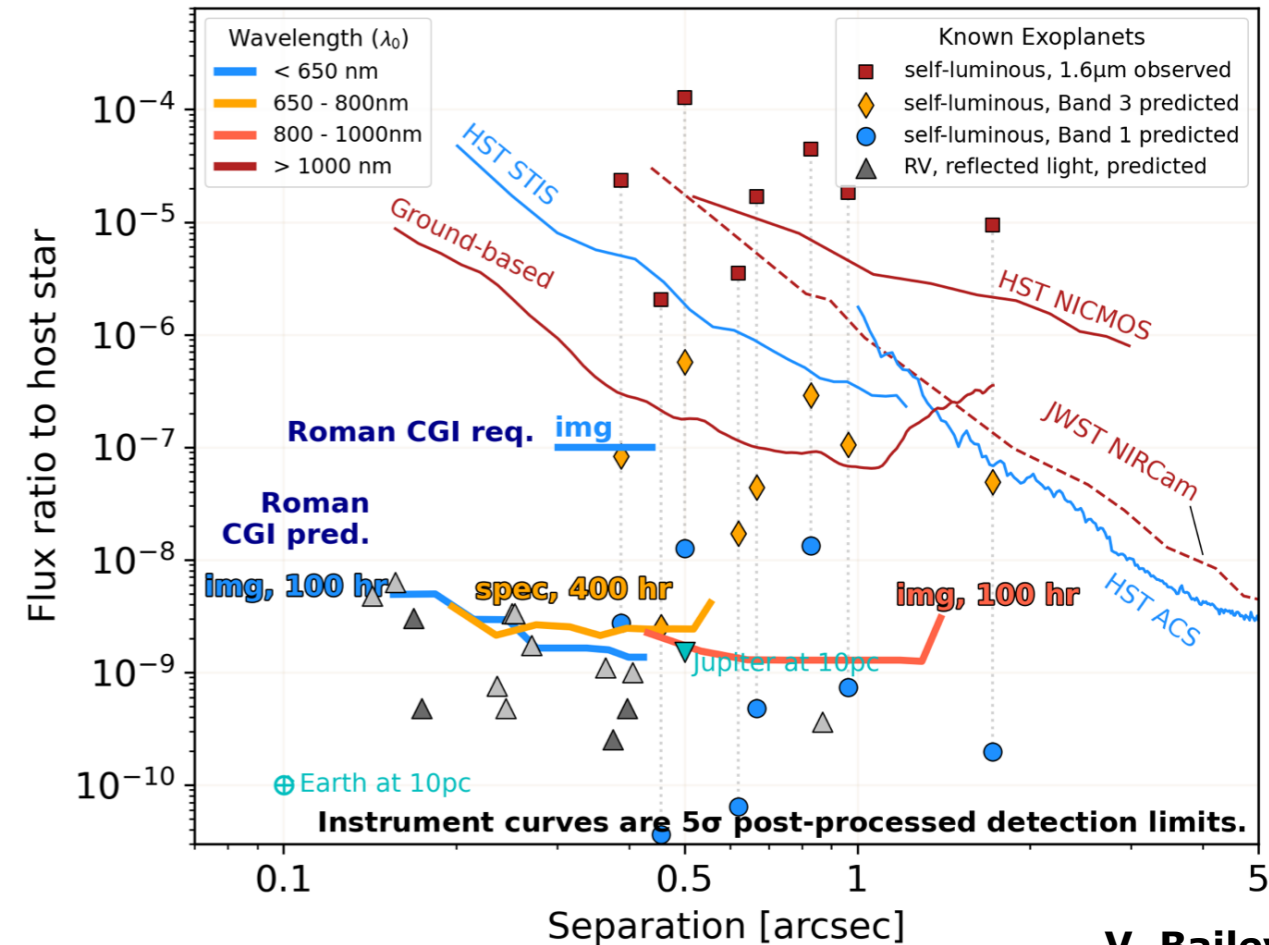


Representative in the coronagraph community participation programme



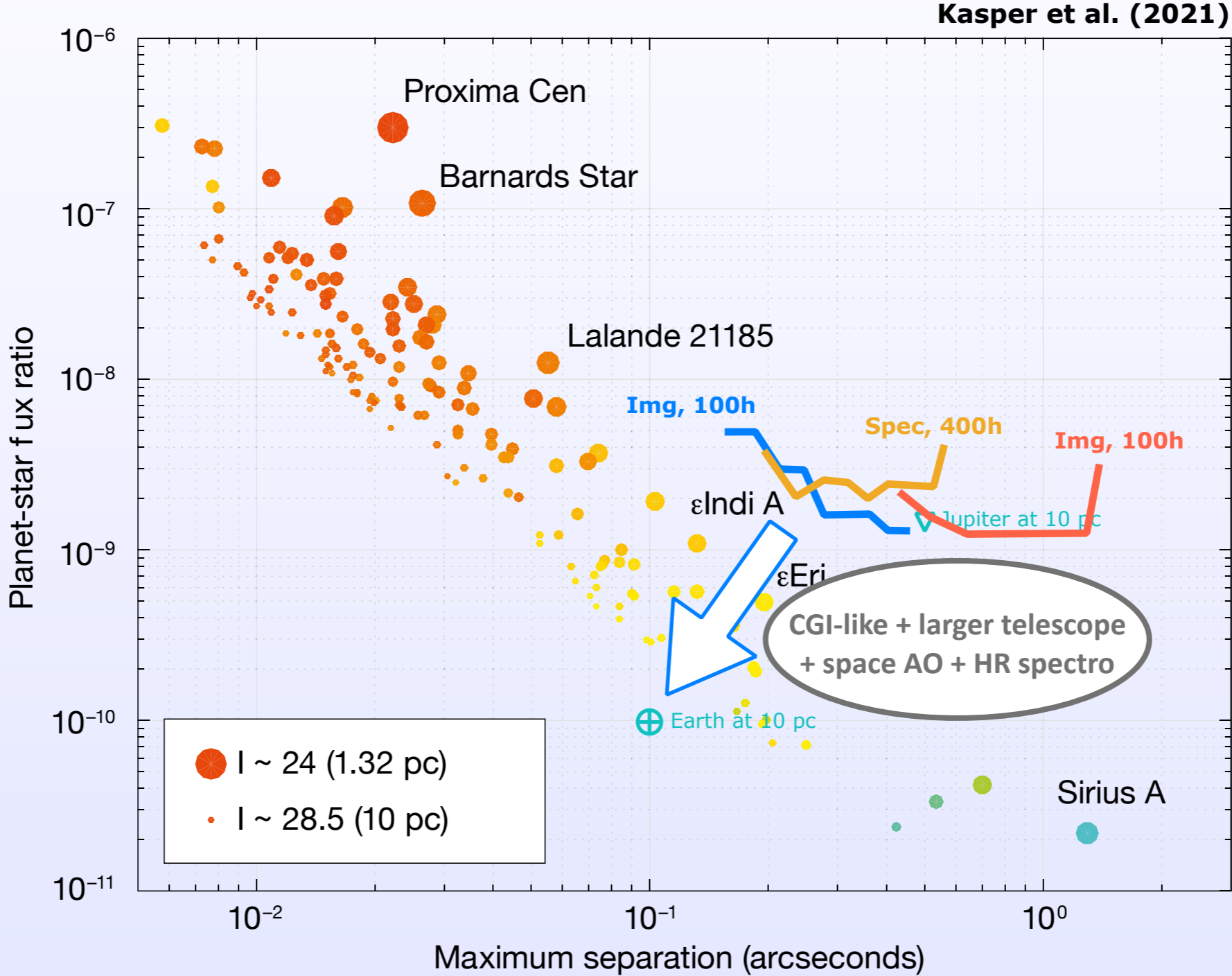
- Synergies with STScI**
- Zernike wavefront control
 - Operations

A. Vigan - STScI - 2023-02-27

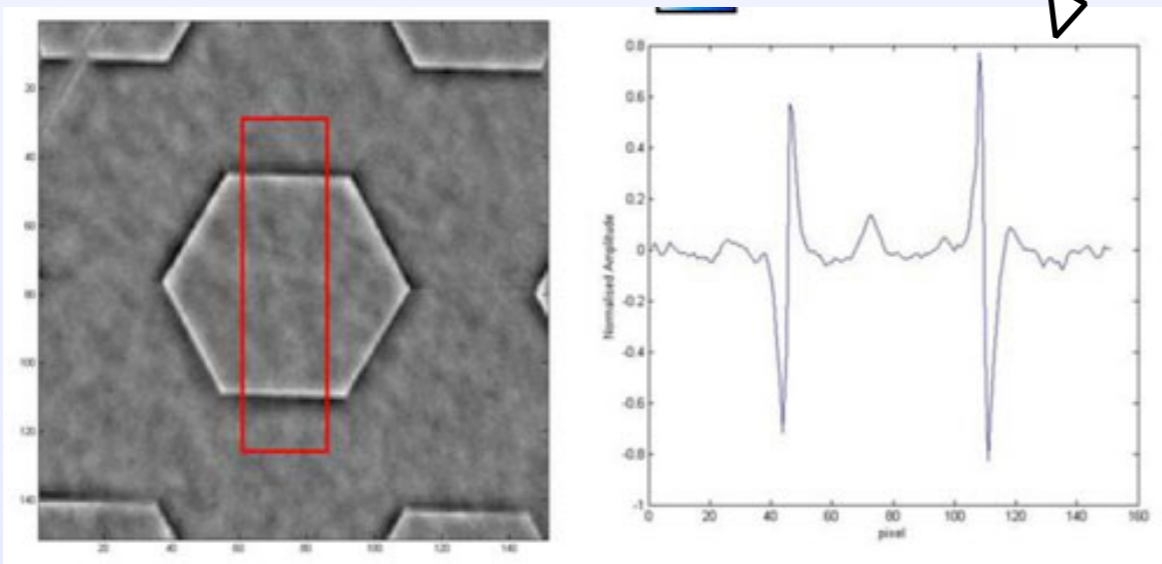
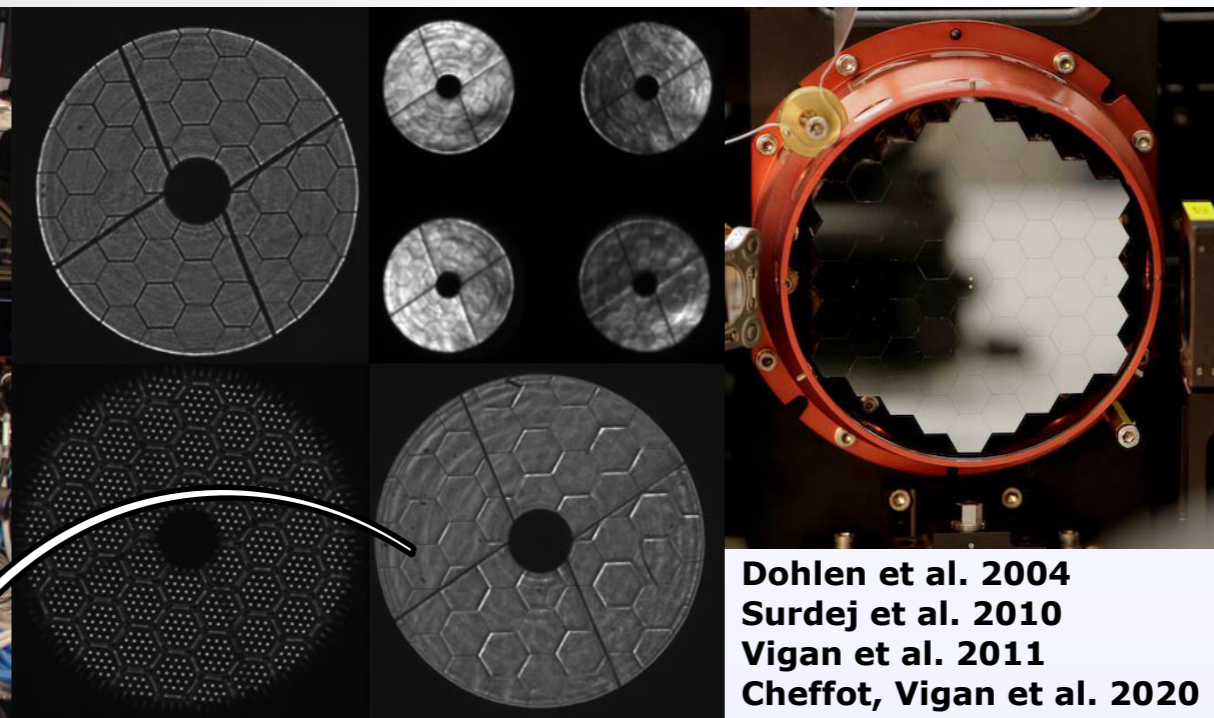
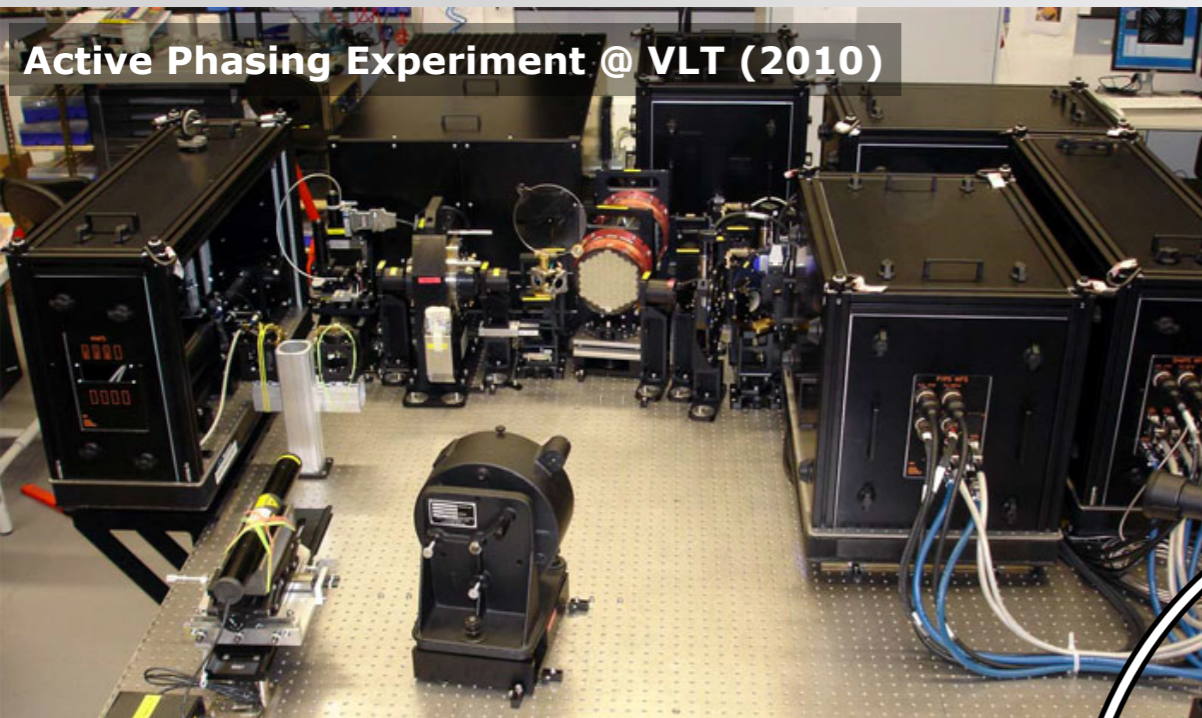


V. Bailey

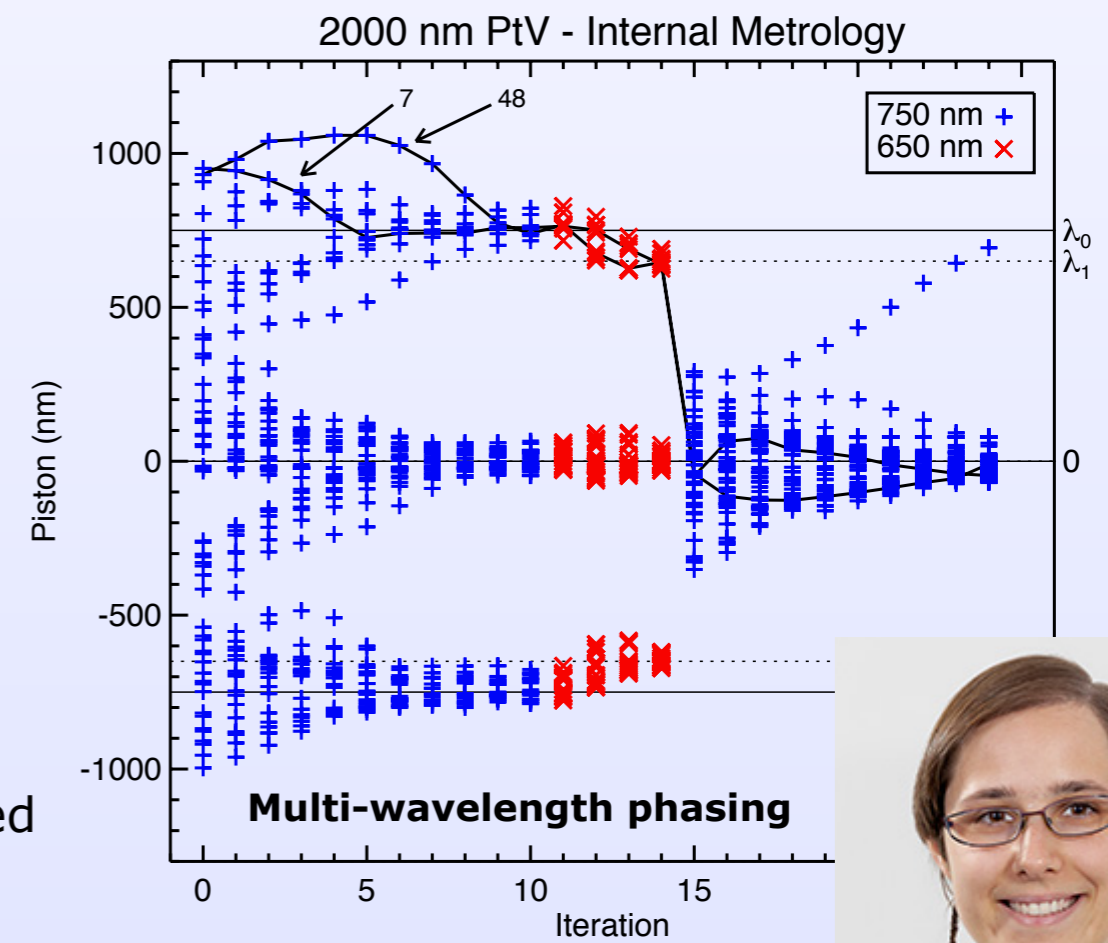
Roadmap to Earth 2.0



Cophasing of (large) segmented telescopes



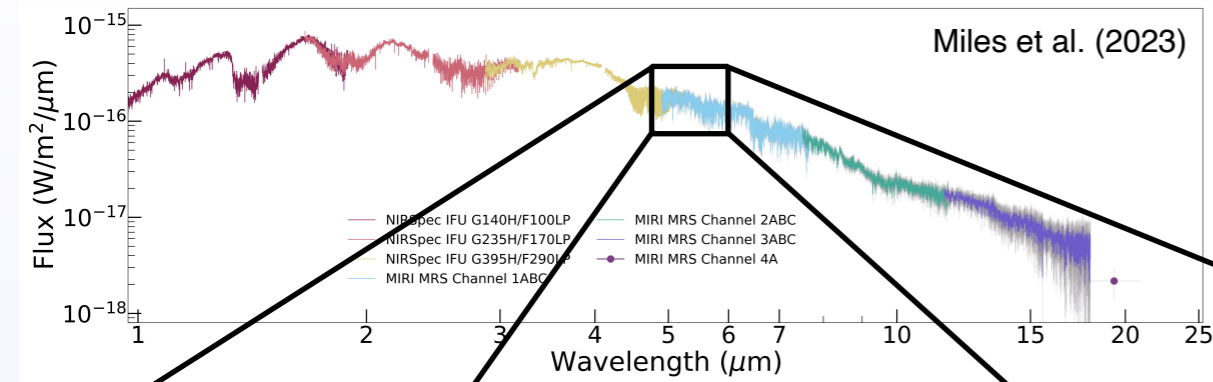
Zernike wavefront sensor (ZEUS)
 Will be included in the ELT prefocal station



- Synergies with STScI**
- Phasing stabilisation for large segmented telescopes in space
 - Experiments to be conducted on HiCAT

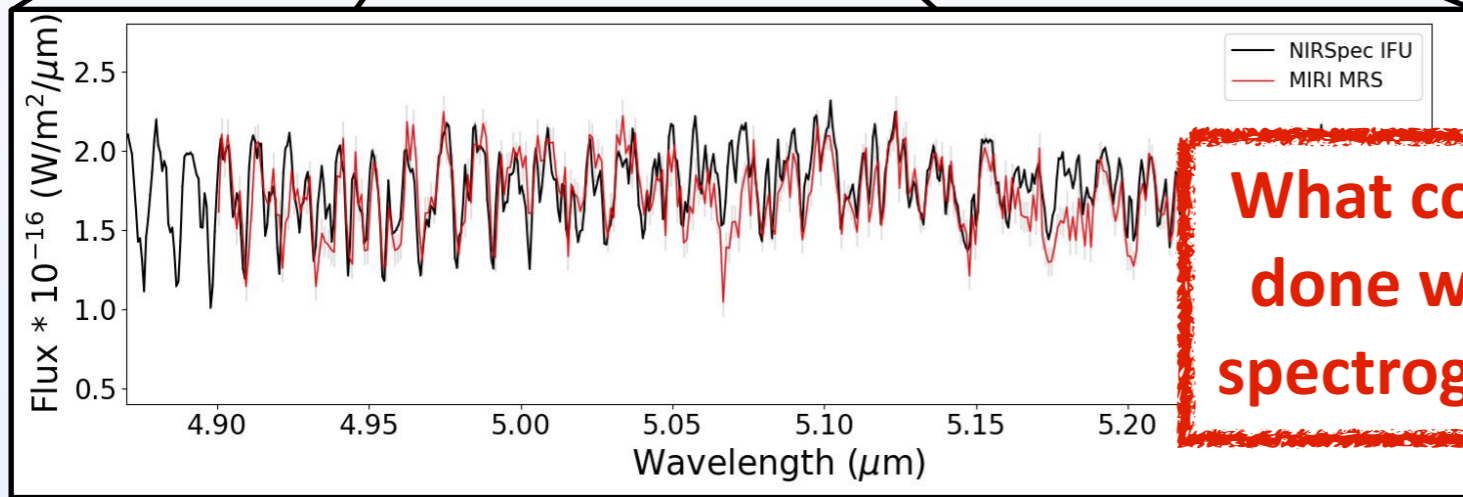


High-resolution spectroscopy in space

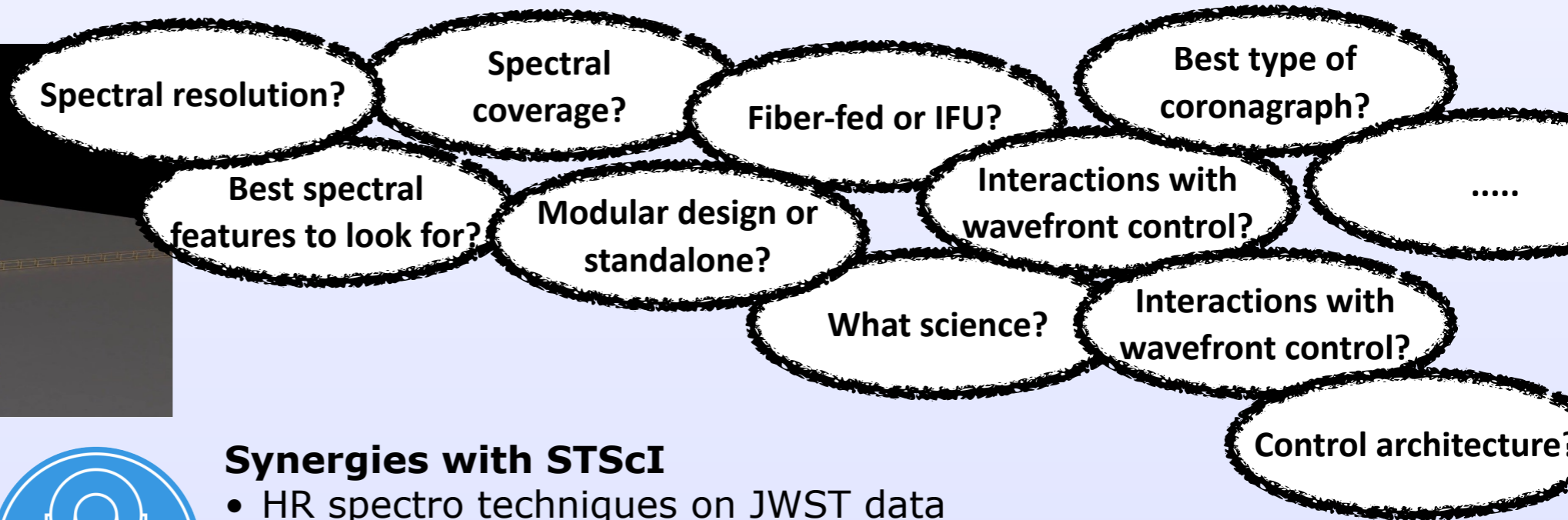
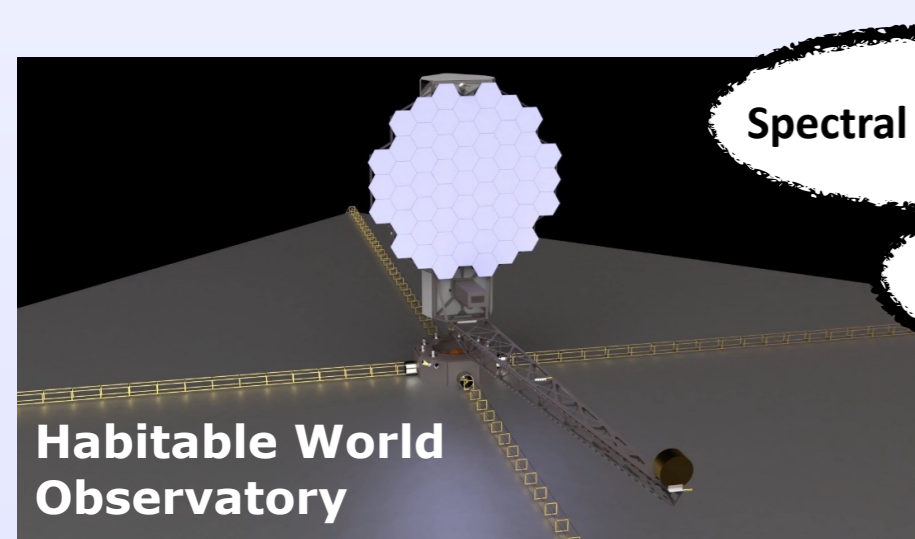
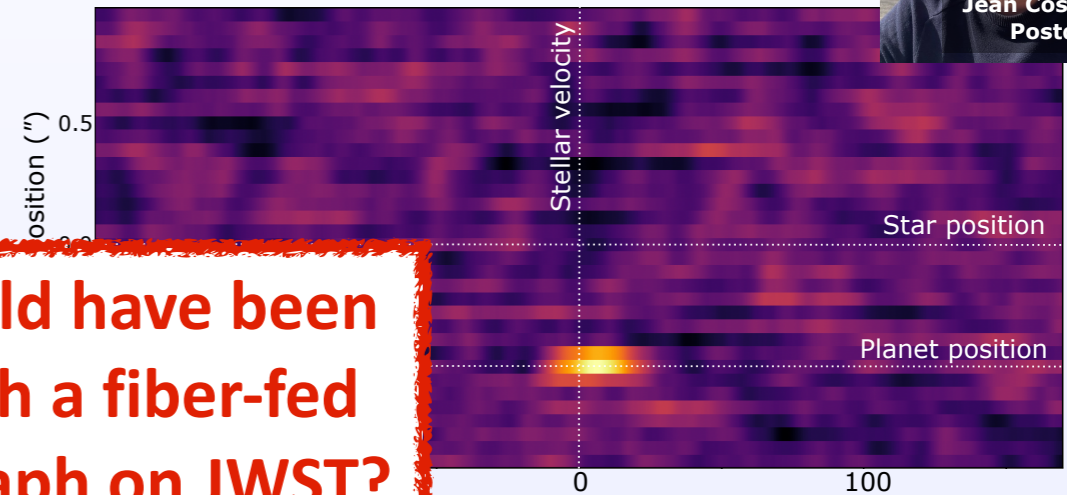


VHS 1256
20 M_{Jup}
8" from host star
JWST/MIRI

β Pic b
8 M_{Jup}
0.4" from host star
VLT/CRIRES+



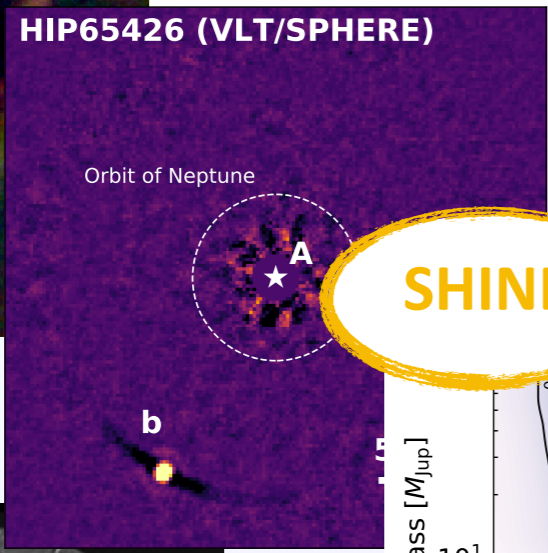
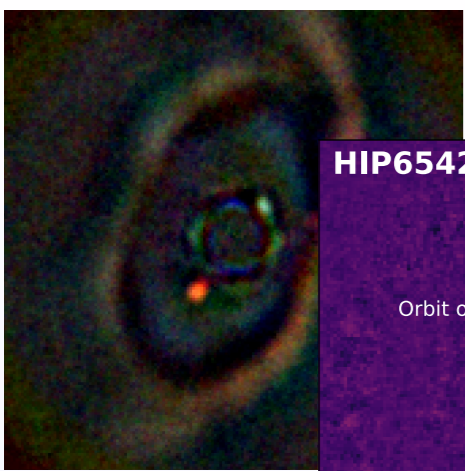
What could have been done with a fiber-fed spectrograph on JWST?



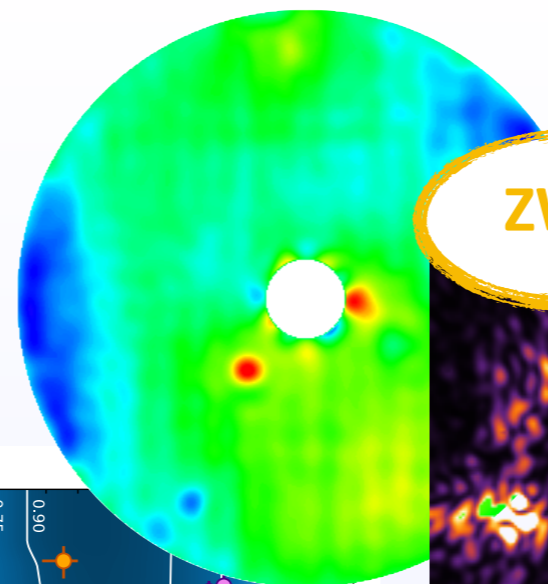
Synergies with STScI

- HR spectro techniques on JWST data
- Preparation of future large space missions
- Fiber injection on HiCAT
- Operations



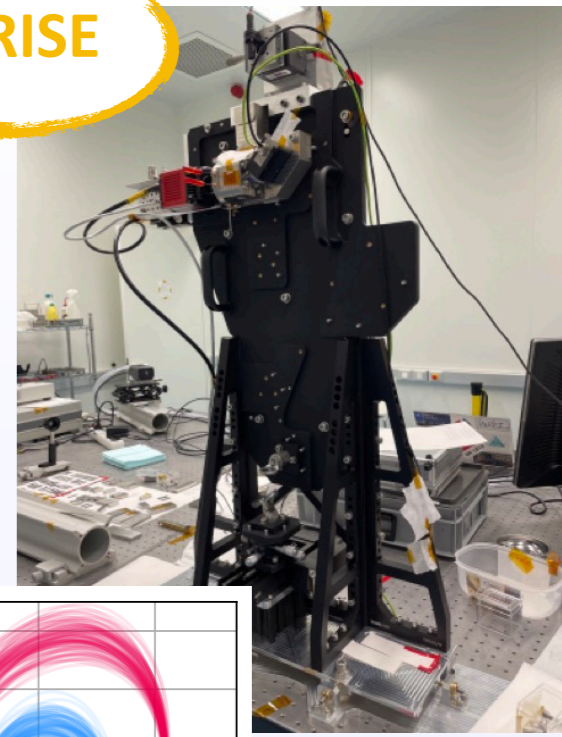
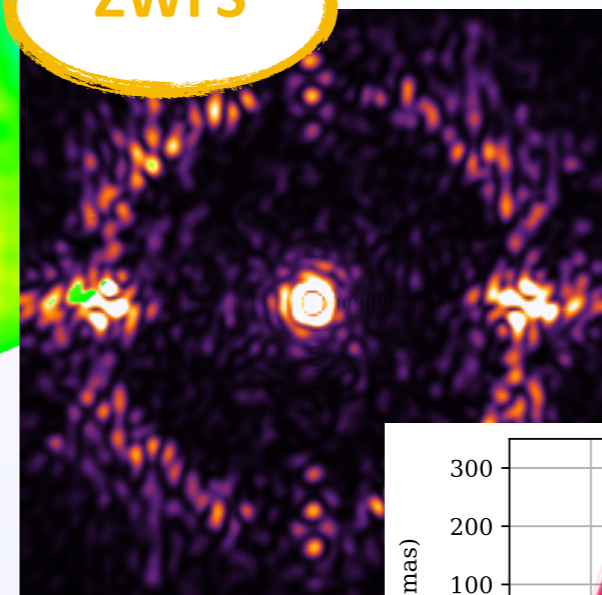


SHINE

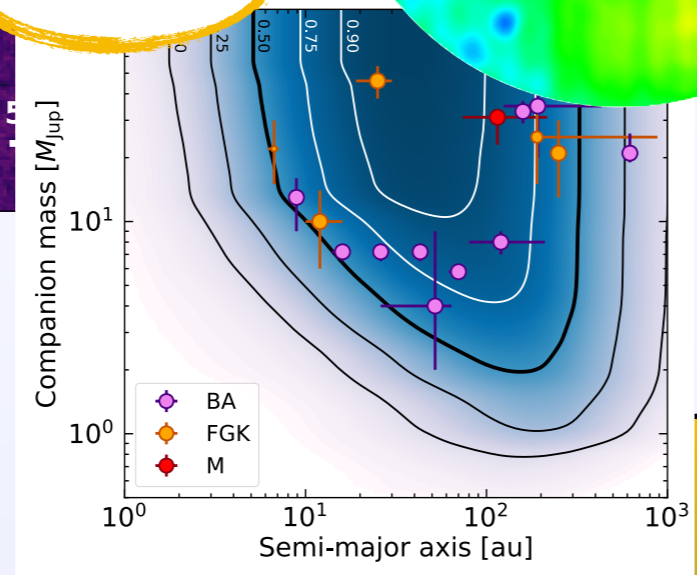
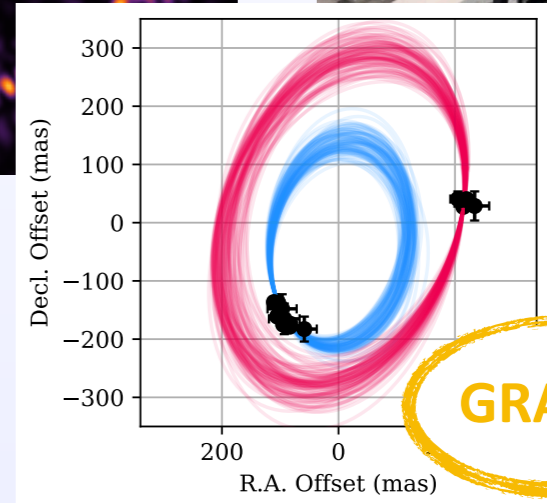


ZWFS

HiRISE



GRAVITY

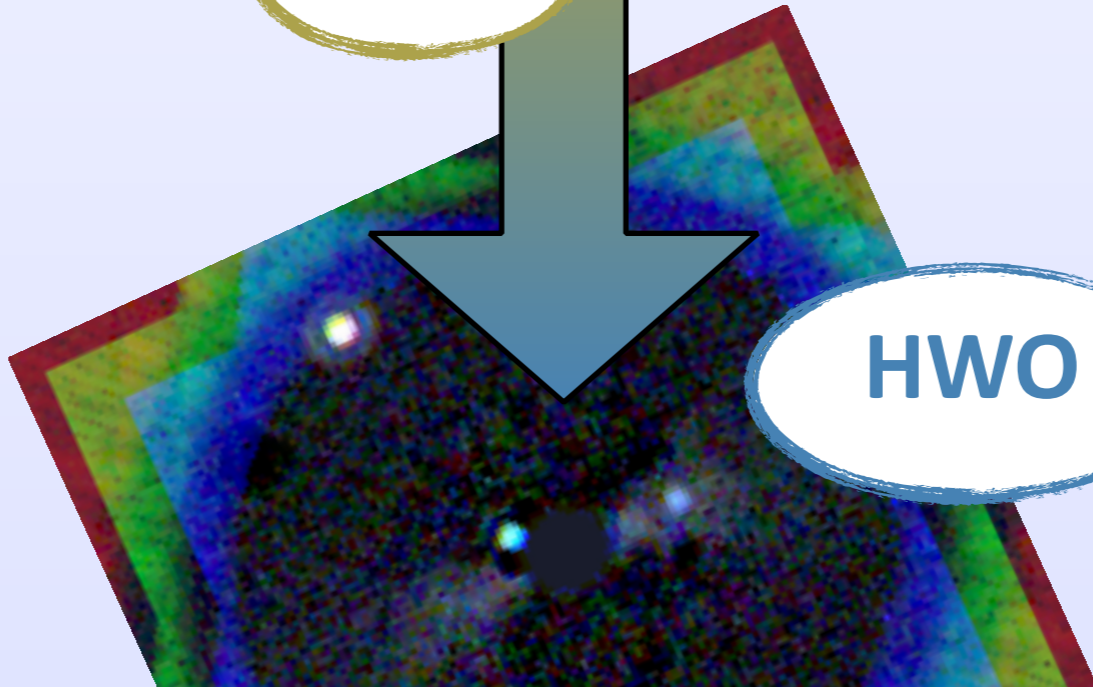


APE



RST

HWO



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