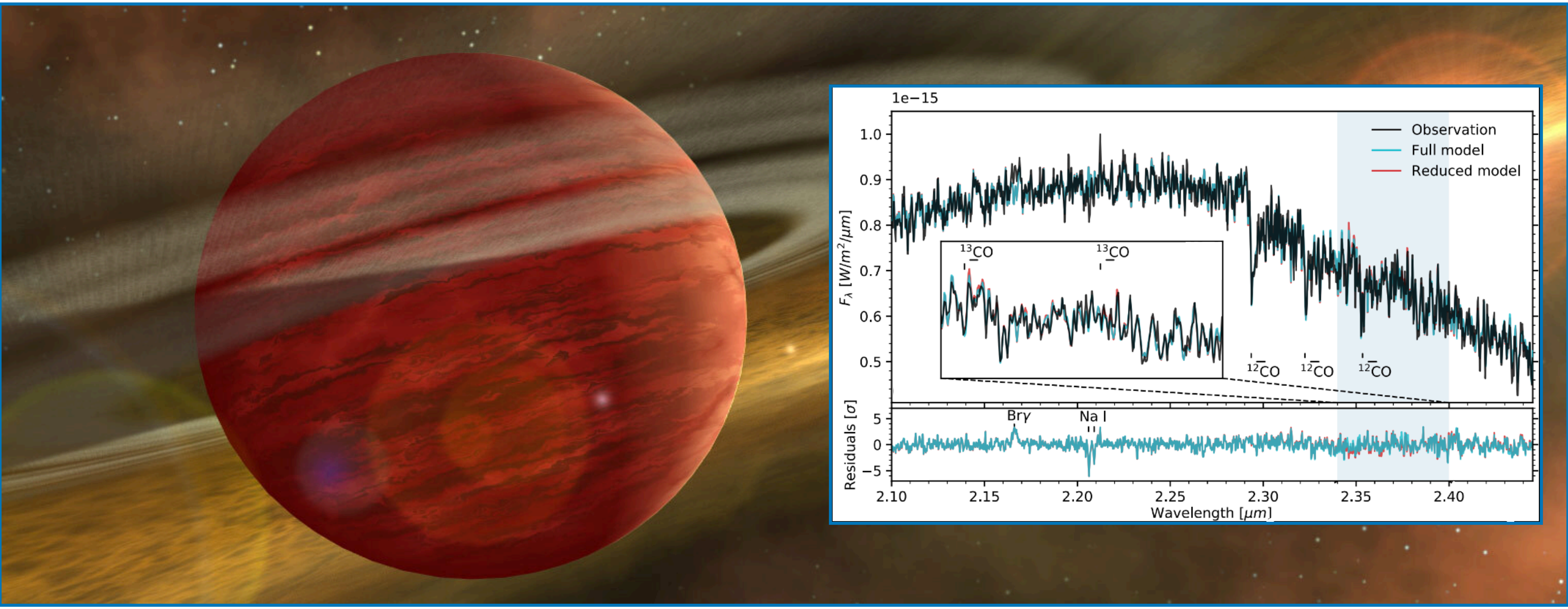
Spectra of Imaged Exoplanets

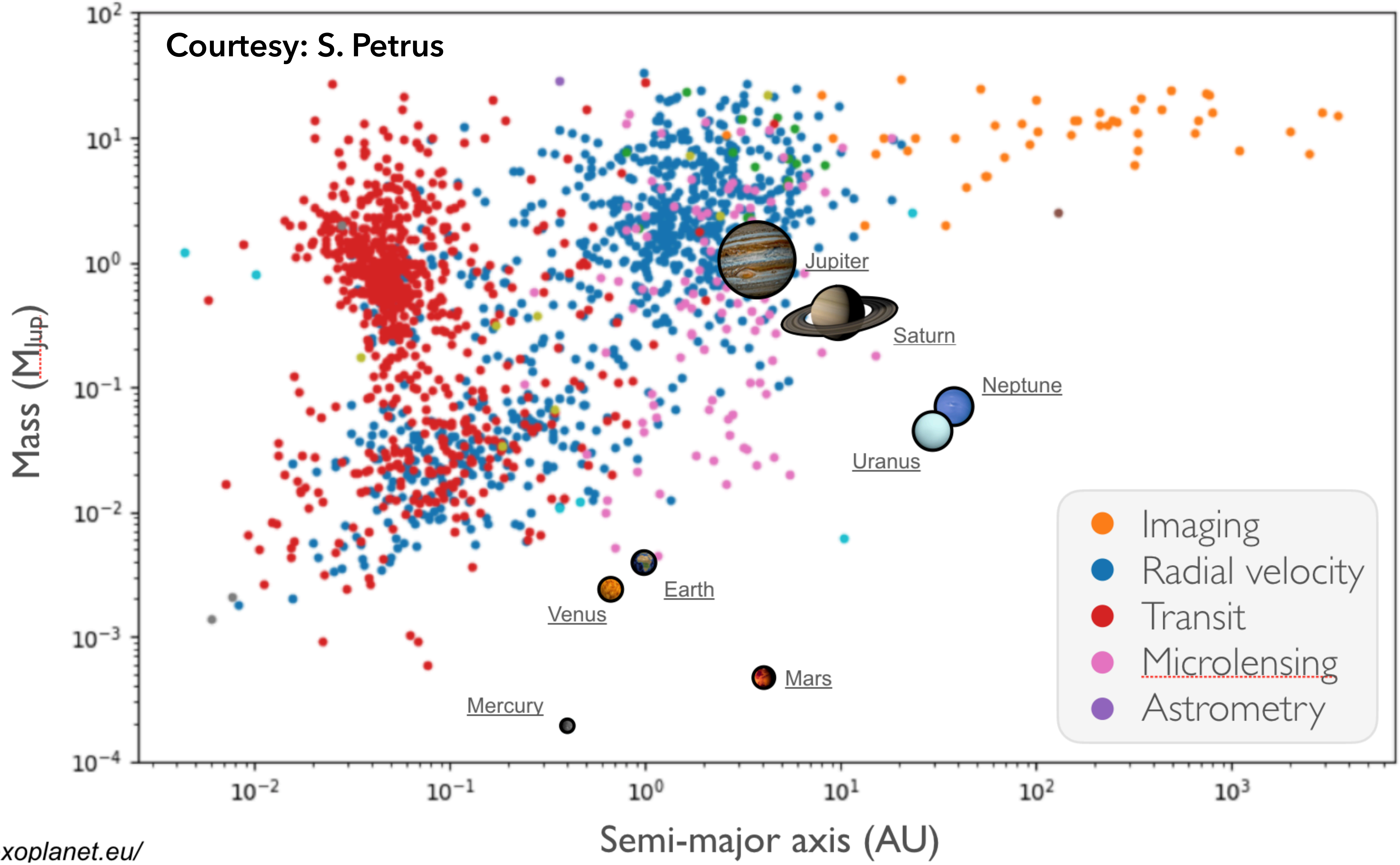
20 years of discoveries

Mickaël BONNEFOY (Institut de Planétologie et d'Astrophysique de Grenoble)



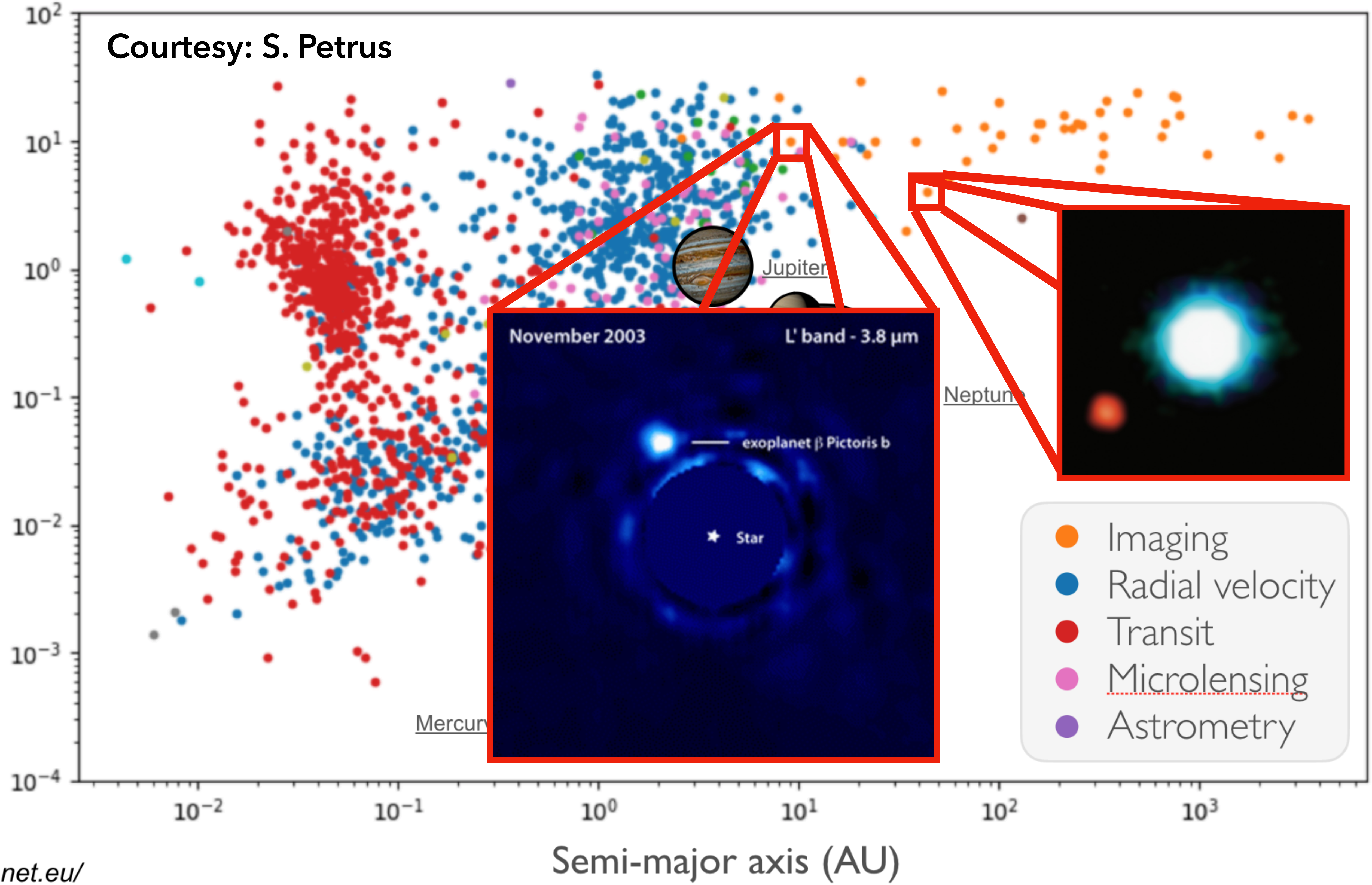
COBREX meeting · Oct 6, 2022

Motivations



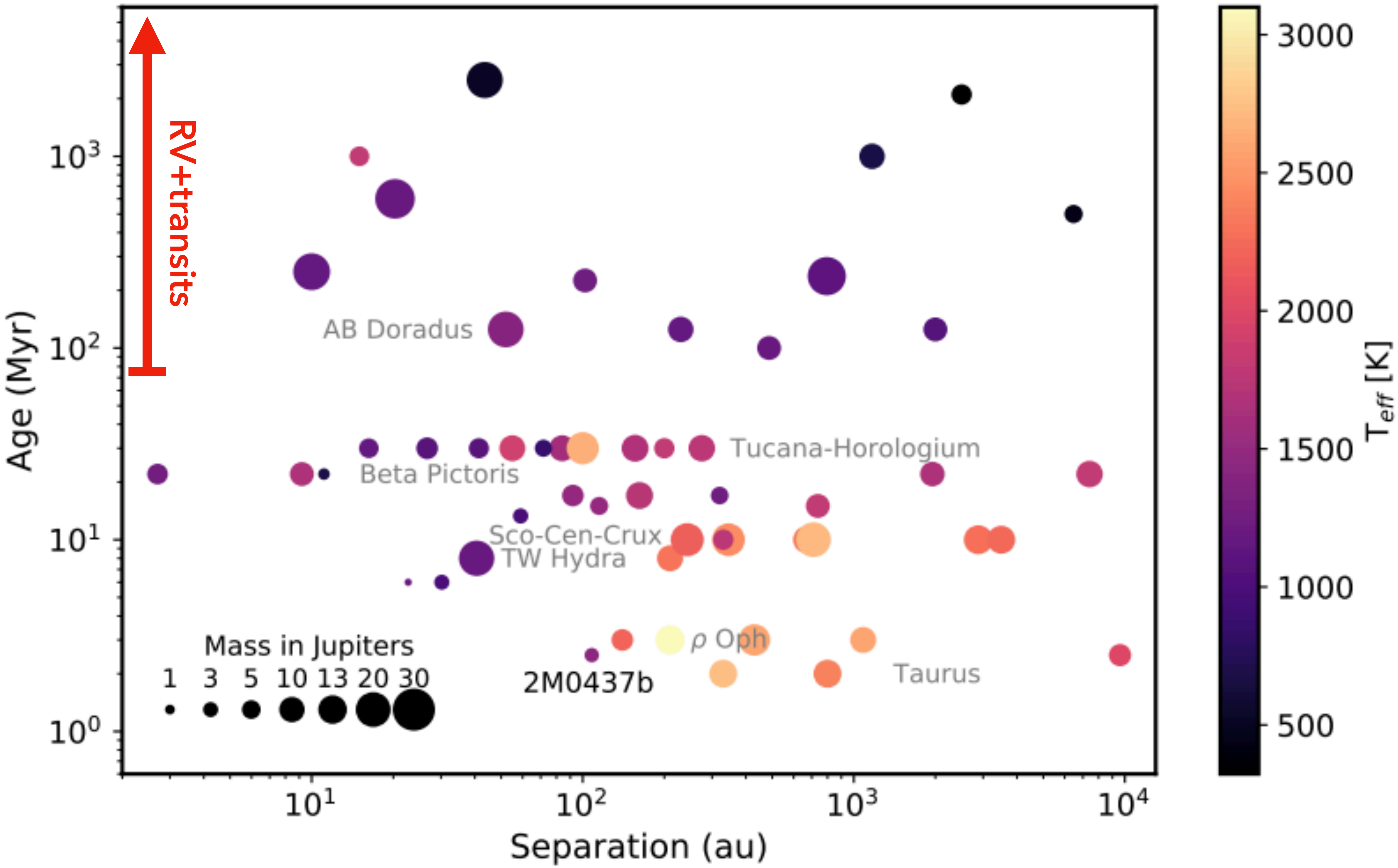
exoplanet.eu/

Motivations



exoplanet.eu/

Motivations



Motivations

Imaged planets are **young and hot**

➠ Increased luminosity

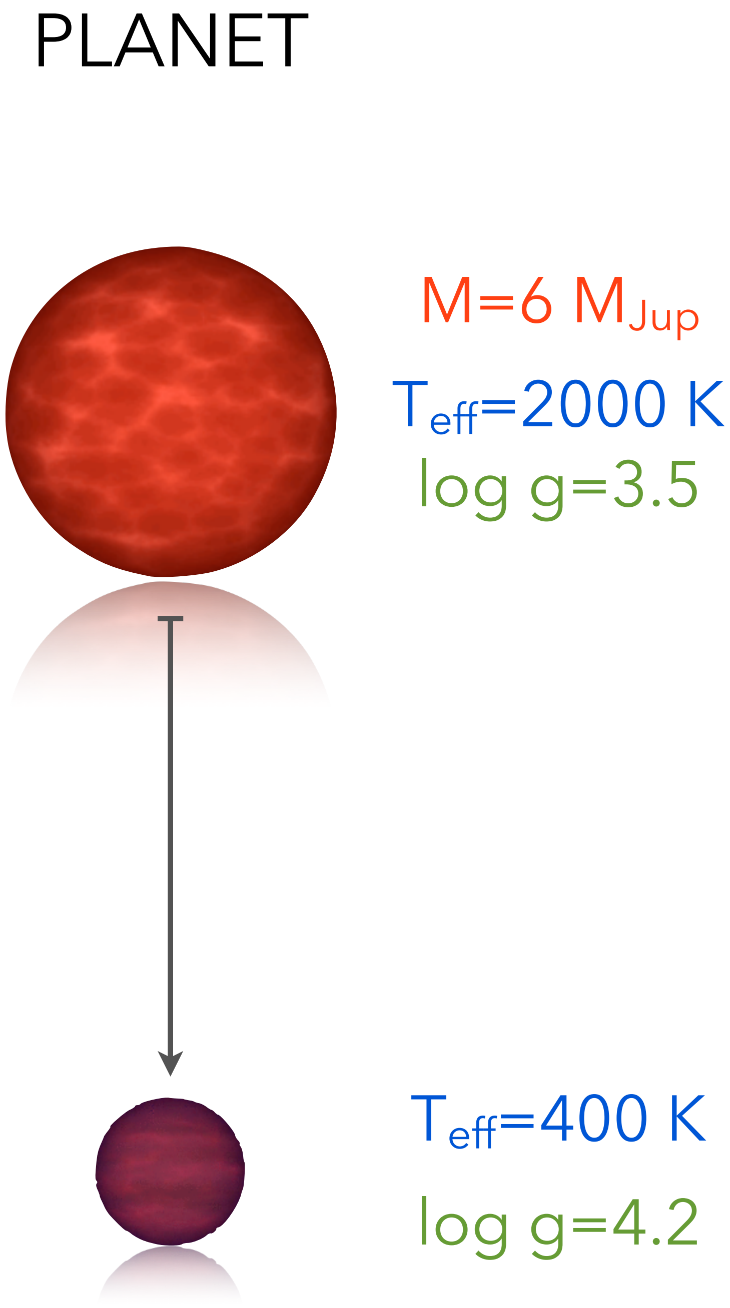
$$L = 4\pi\sigma R^2 T_{eff}^4$$

700 to 2700K

➠ Low surface gravity

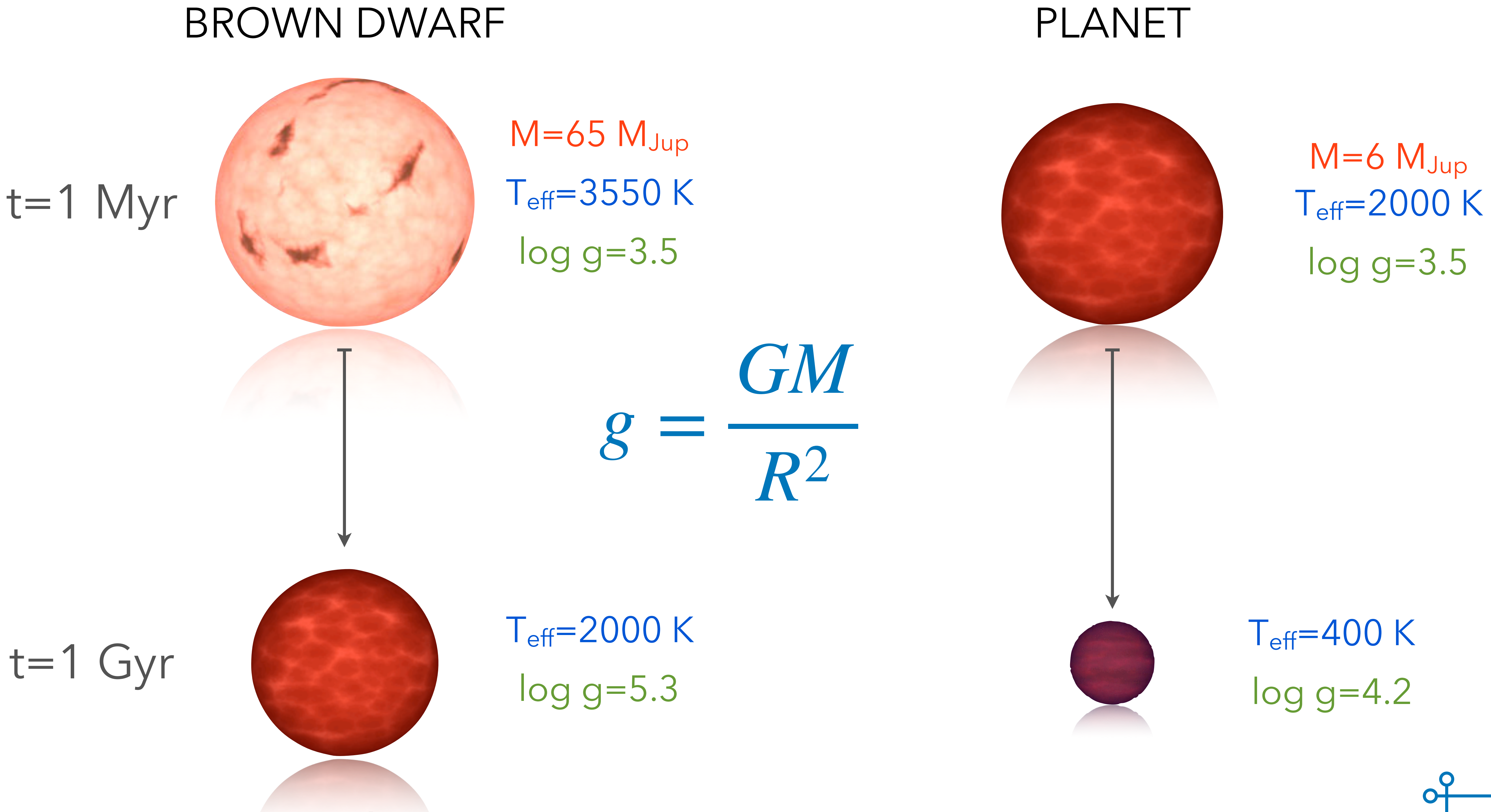
$$g = \frac{GM}{R^2}$$

1 to 3 R_{Jup}



Motivations

Temperature and gravity ➠ Mass



BROWN DWARF

PLANET

t=1 Myr

$M=65\ M_{Jup}$

$T_{eff}=3550$ K

log g=3.5

$M=6\ M_{Jup}$

$T_{eff}=2000$ K

log g=3.5

$$g = \frac{GM}{R^2}$$

t=1 Gyr

$T_{eff}=2000$ K

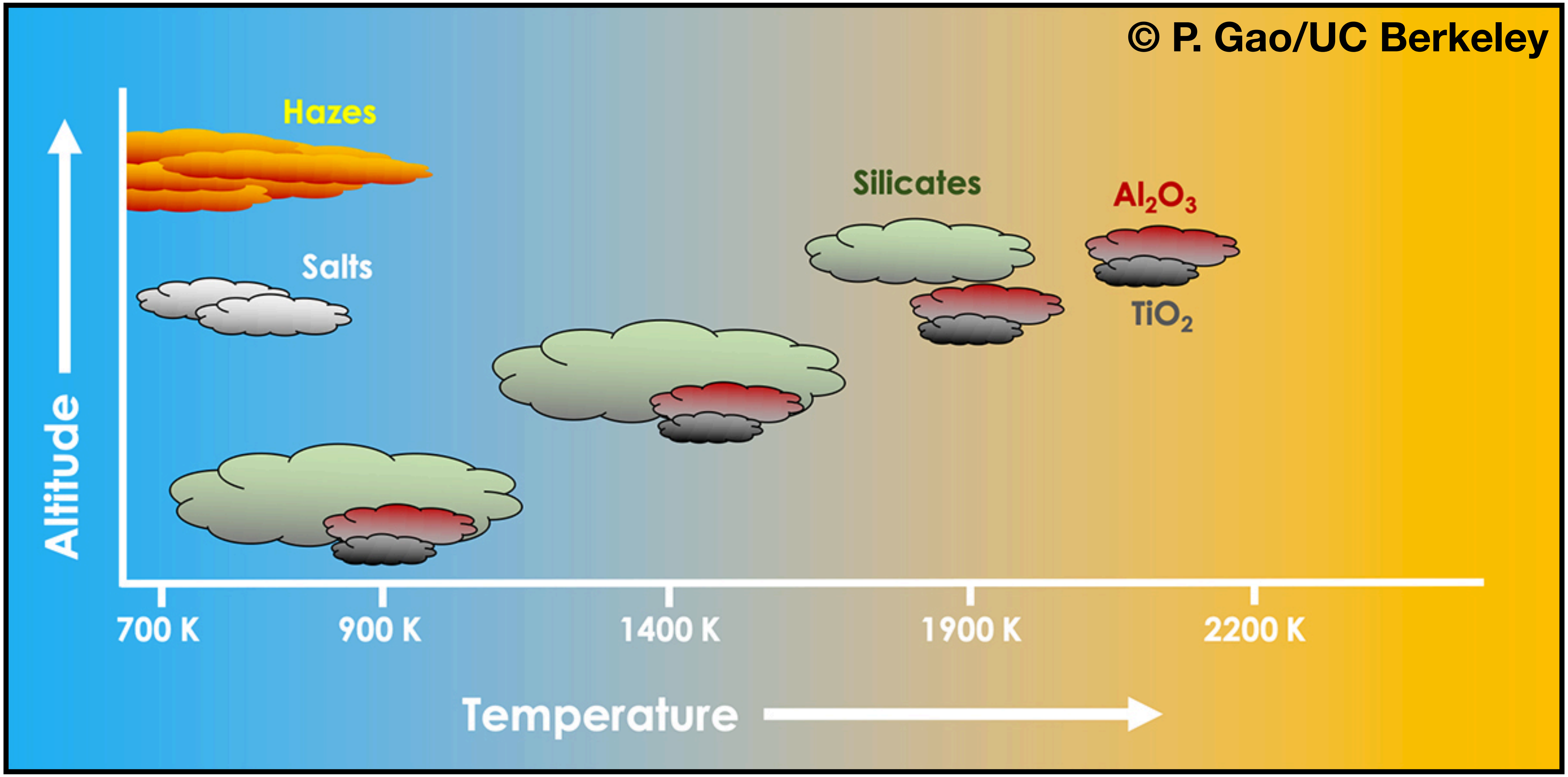
log g=5.3

$T_{eff}=400$ K

log g=4.2

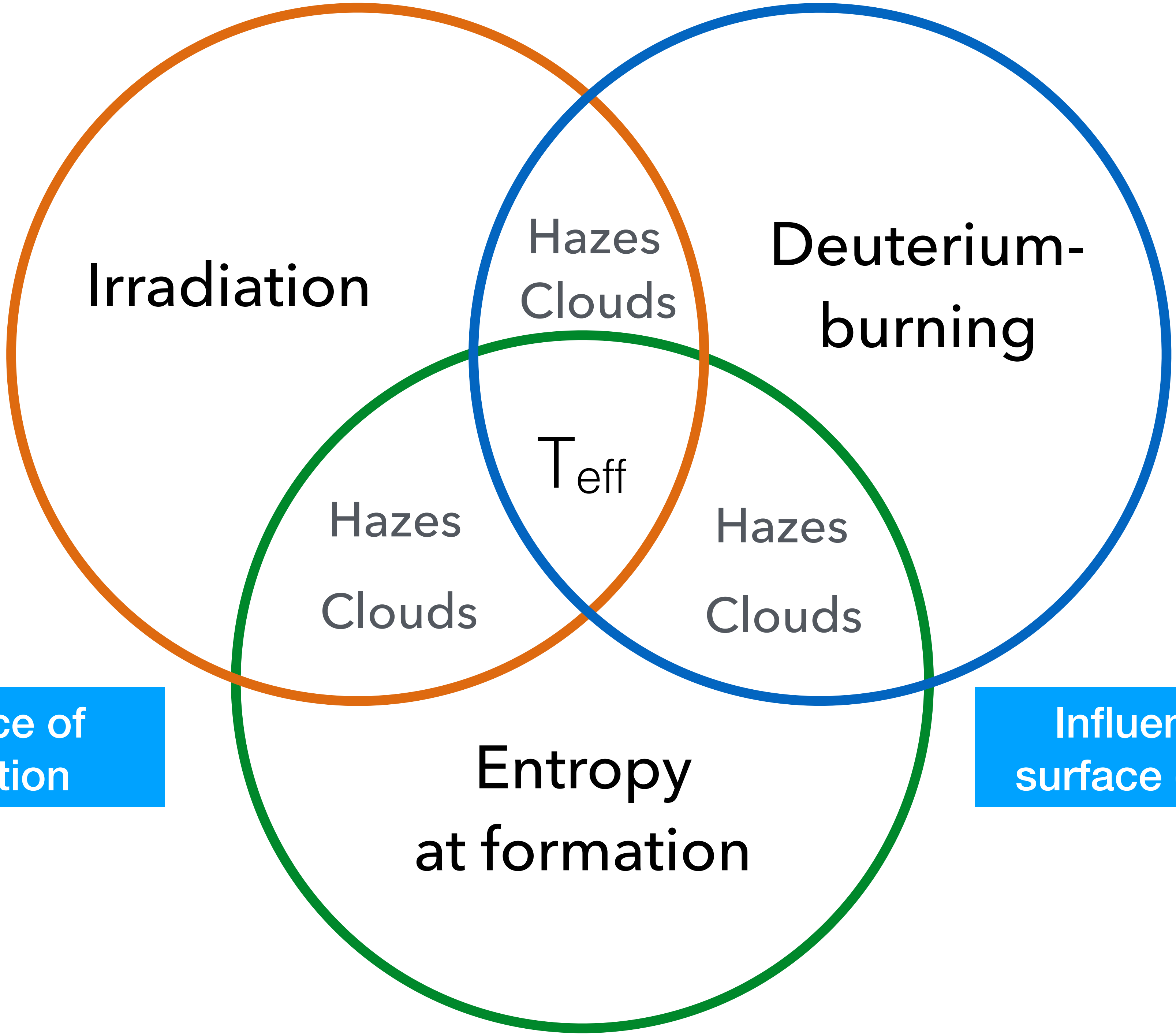
Motivations

Involved physics?



Motivations

Connecting the dots



Transiting planets (day side)

«Old » brown dwarfs

Irradiation

Hazes
Clouds

Deuterium-burning

T_{eff}

Hazes

Clouds

Hazes

Clouds

Entropy
at formation

Imaged planets

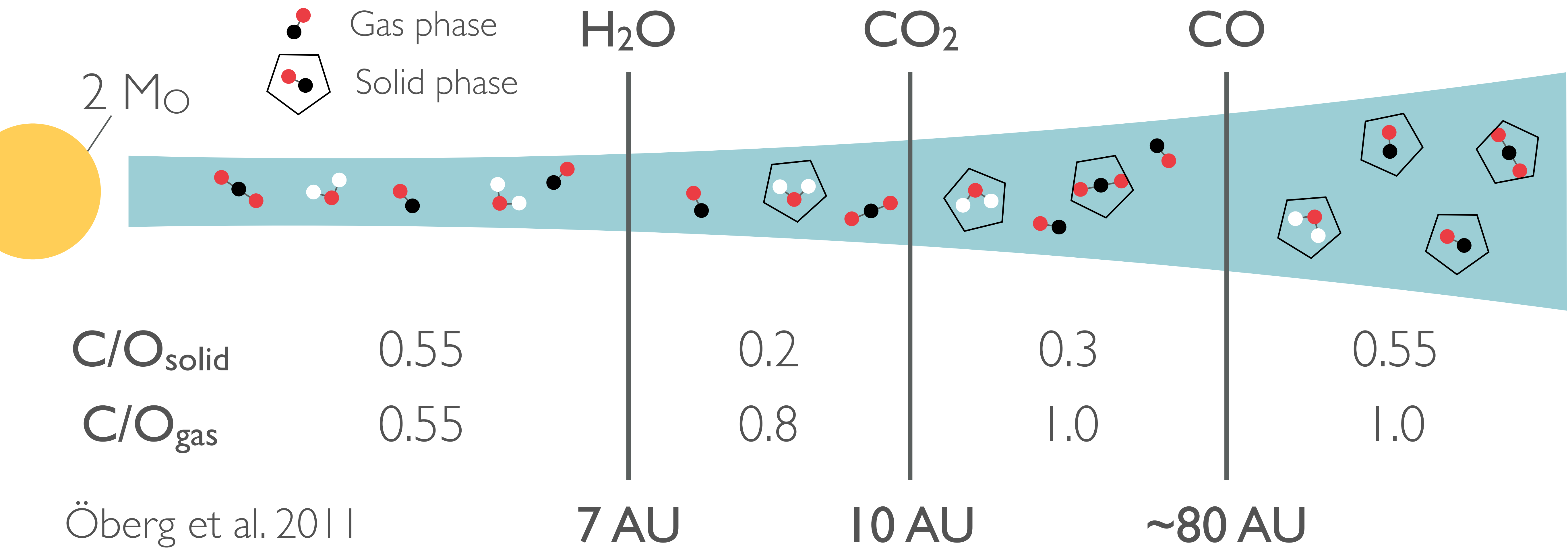
Influence of irradiation

Influence of surface gravitty

Motivations

Formation tracers

Courtesy: S. Petrus



Gas phase

Solid phase

$2\ M_{\odot}$

H_2O CO_2 CO

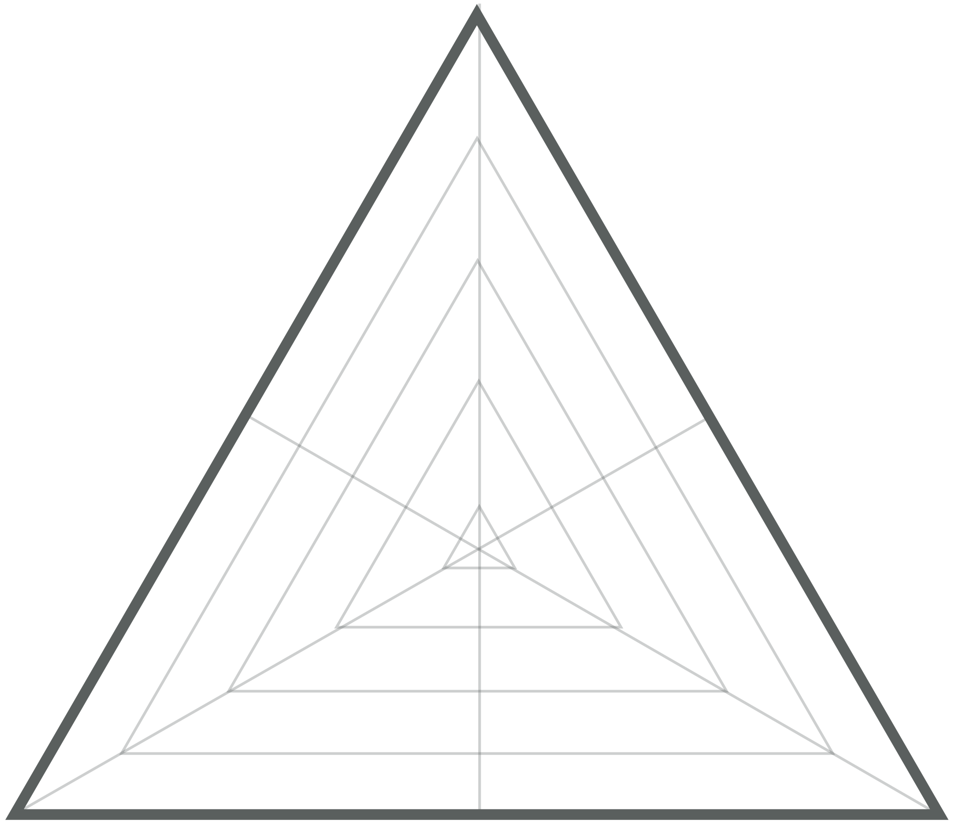
C/O_{solid}	0.55	0.2	0.3	0.55
C/O_{gas}	0.55	0.8	1.0	1.0

7 AU 10 AU ~80 AU

Öberg et al. 2011

Atmospheric composition : tracer of formation mode?

Methods



Contrast

$$\frac{F_{companion}}{F_{primary}}$$

Spatial resolution

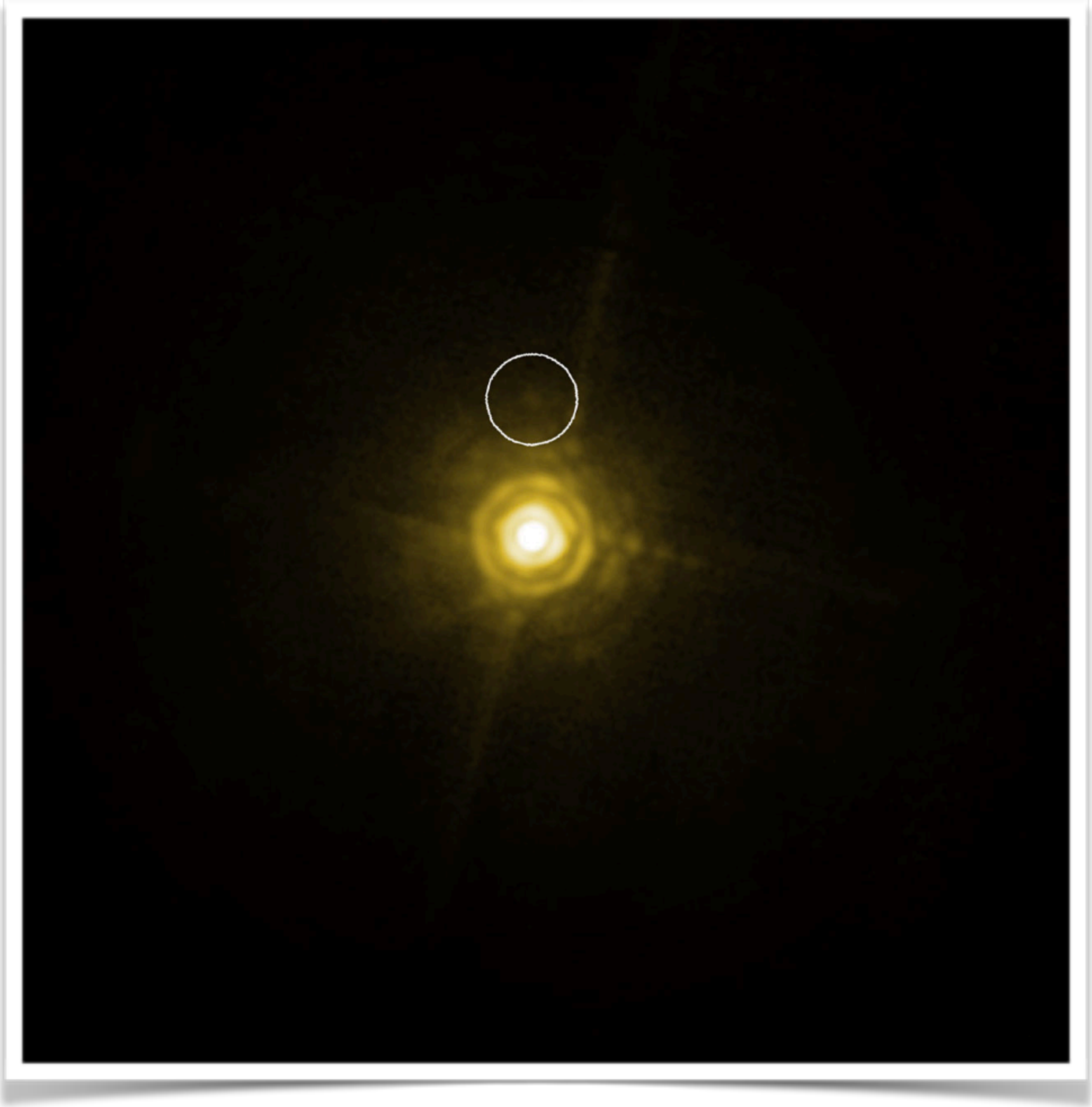
$$\theta = \frac{\lambda}{D}$$

Spectral resolution

$$R = \frac{\Delta\lambda}{\lambda}$$

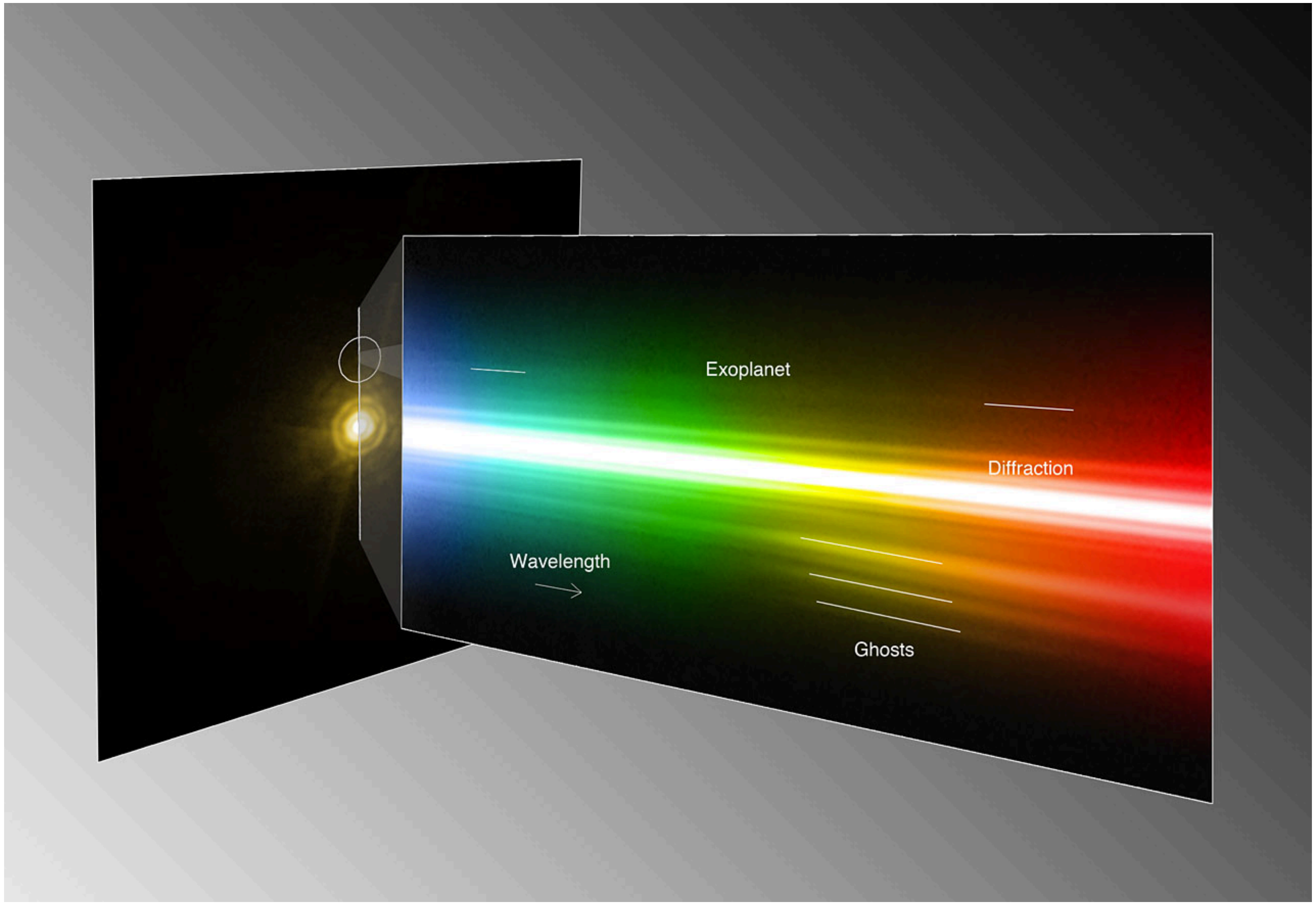
Methods

Contrast and angular resolution: Adaptive Optics & coronography



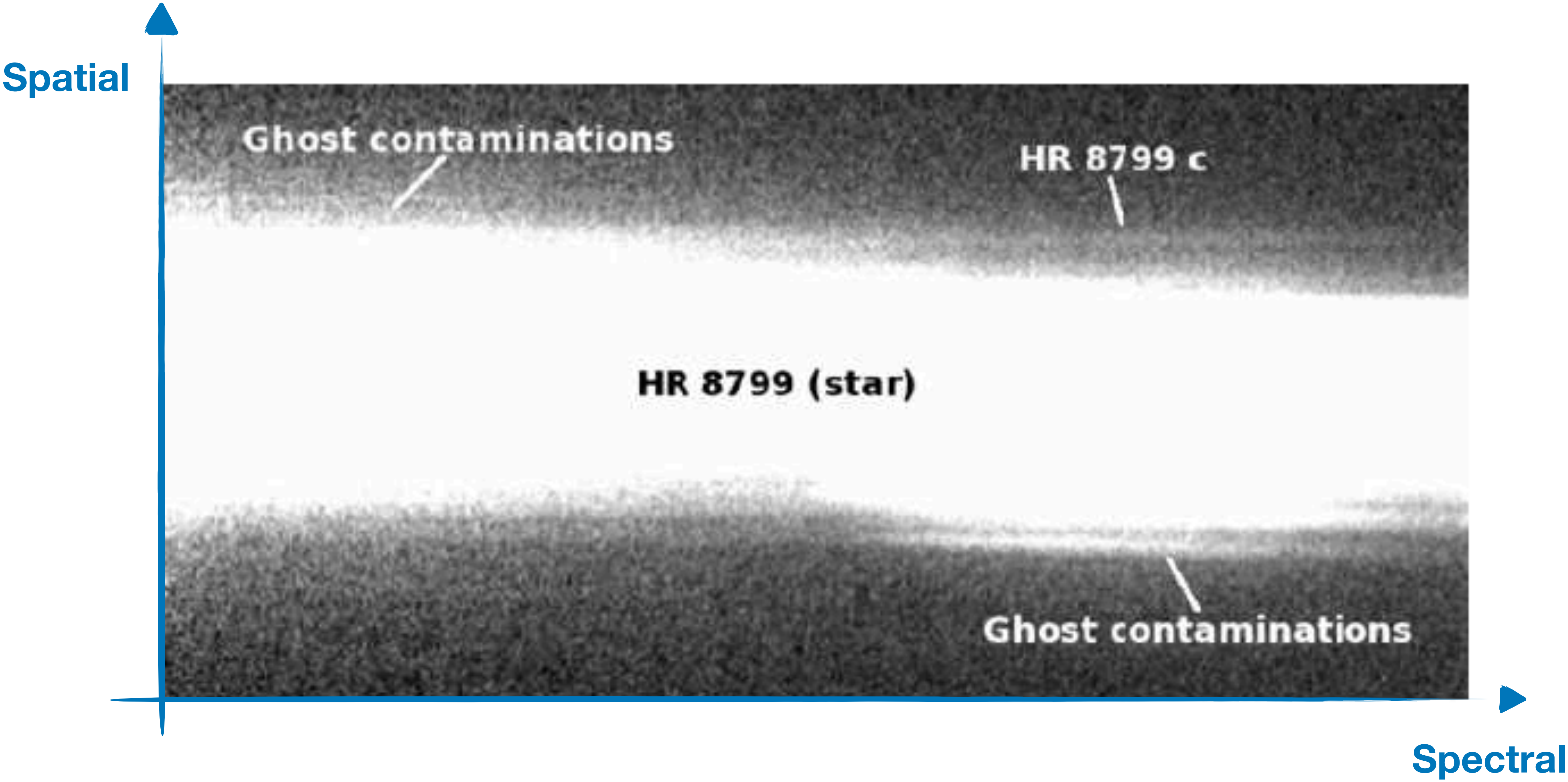
Methods

Coupling with spectrographs



Methods

Coupling with spectrographs

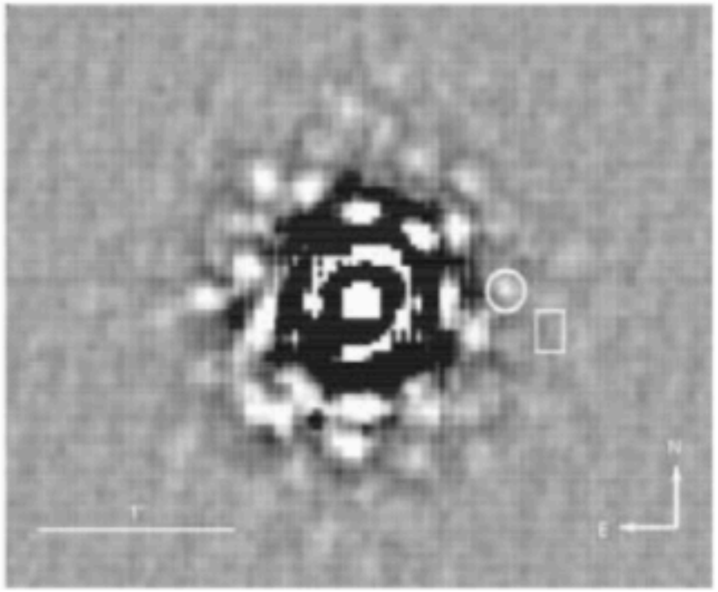


Methods

Contrast and angular resolution: Adaptive Optics & coronography

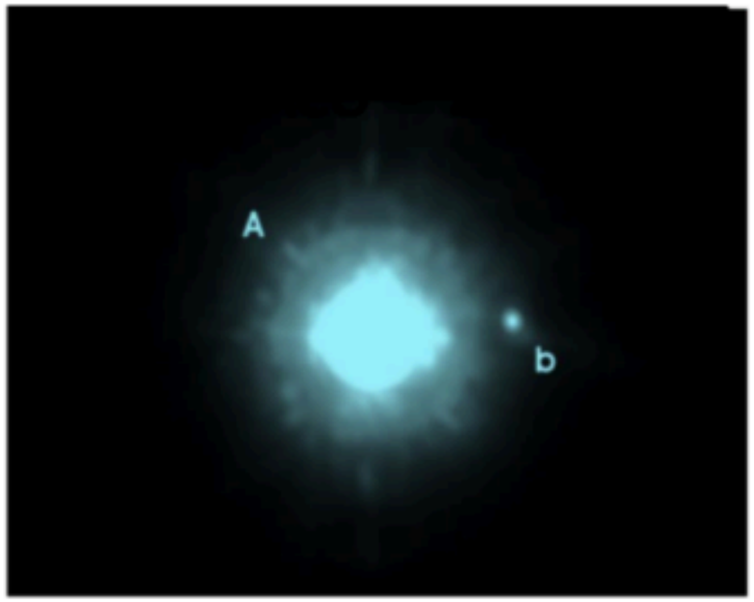
1994 -
ESO3.6m/Come-On+
SH WFS; 62 actuators;

Sr < 10% Janson et al. 07

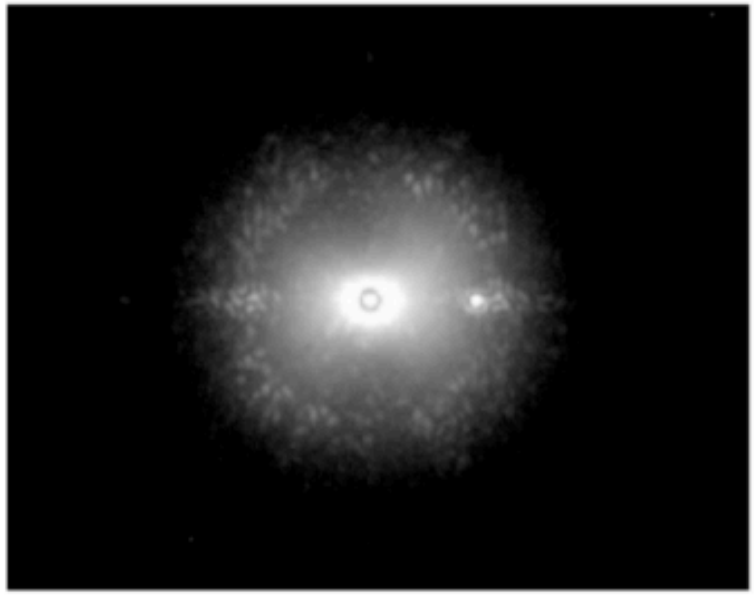


2005 -
VLT/NACO
SH WFS; 185 actuators

Sr = 40-50% Neuhäuser et al 05



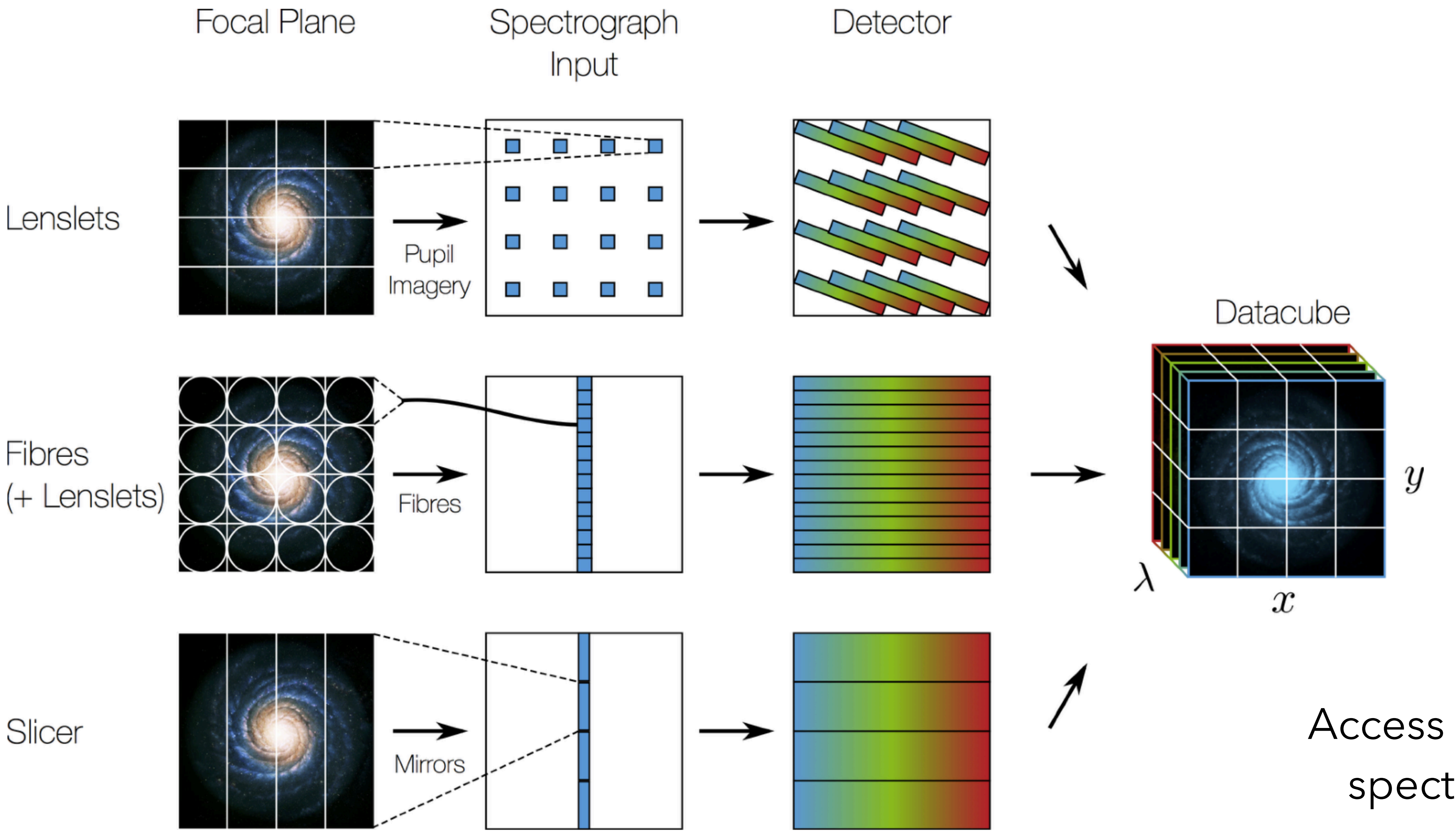
2015
SPHERE/IRDIS
SH WFS; 1200 actuators



Courtesy: G. Chauvin

Methods

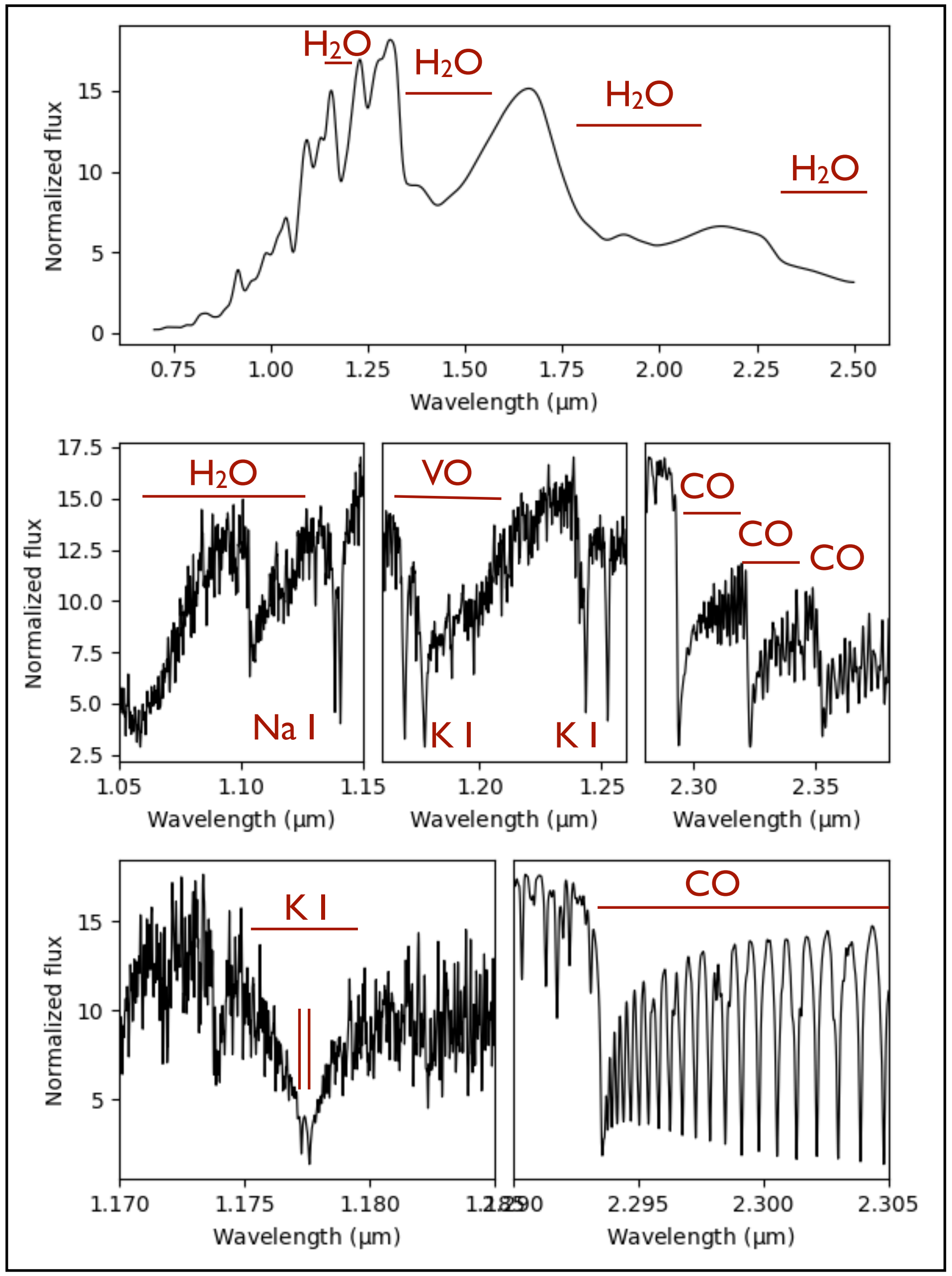
Coupling with Integral Field Spectrographs



Access to spatial and spectral diversity

Methods

Spectral resolution = quantity of spectroscopic info



$R_\lambda \sim 100$

Large absorption bands

(H_2O, CH_4, etc.)

→ T_{eff}, clouds properties

$R_\lambda \sim 5000$

Atomic and molecular absorptions

(Na I, K I, CO, VO, FeH, TiO, etc.)

→ Molecular abundances, RV (inaccurate)

$R_\lambda \sim 50000$

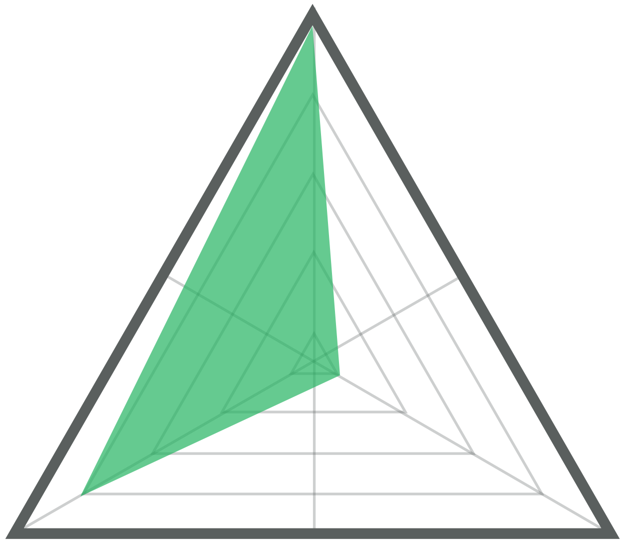
Tiny doublets resolved, line profile, comb of lines

(K I, CO, FeH, etc.)

→ Accurate RV, v.sin(i), structures of the atmosphere, surface inhomogeneities

Methods

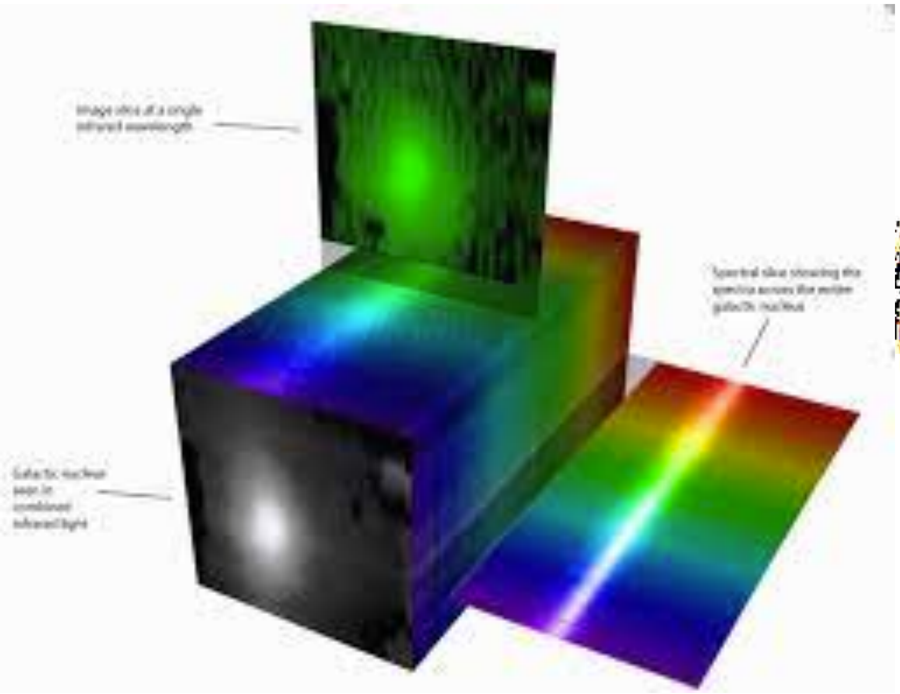
xAO + Coronograph + IFU low-R (lenslets)

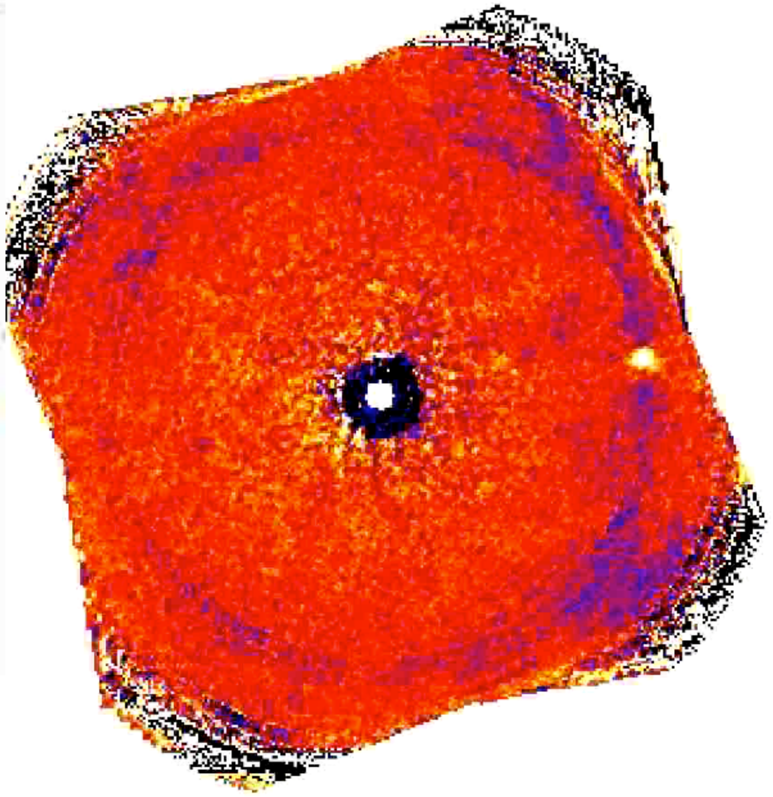


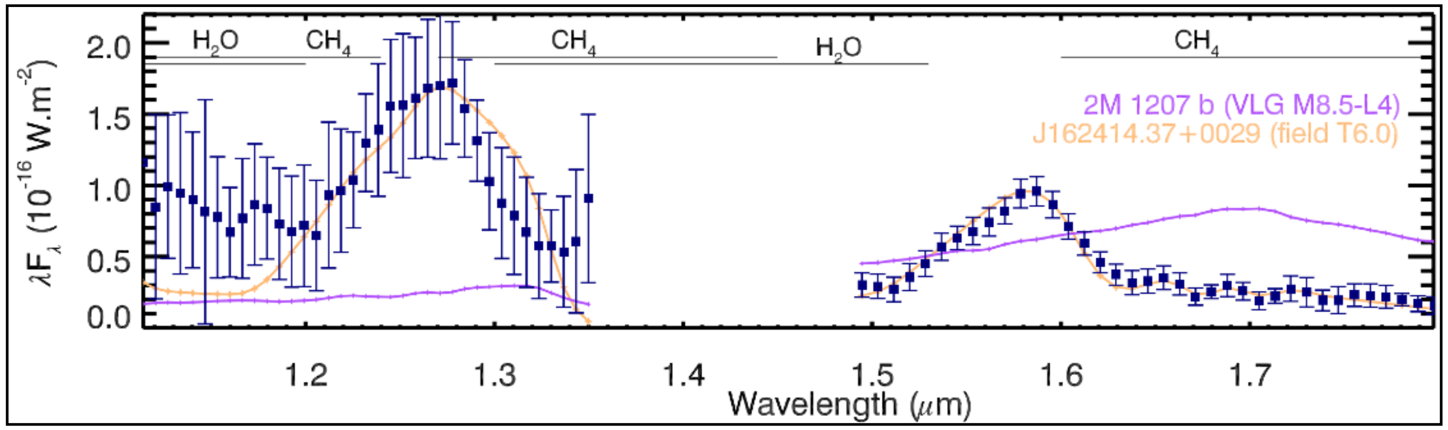
Contrast

Spatial resolution

Spectral resolution

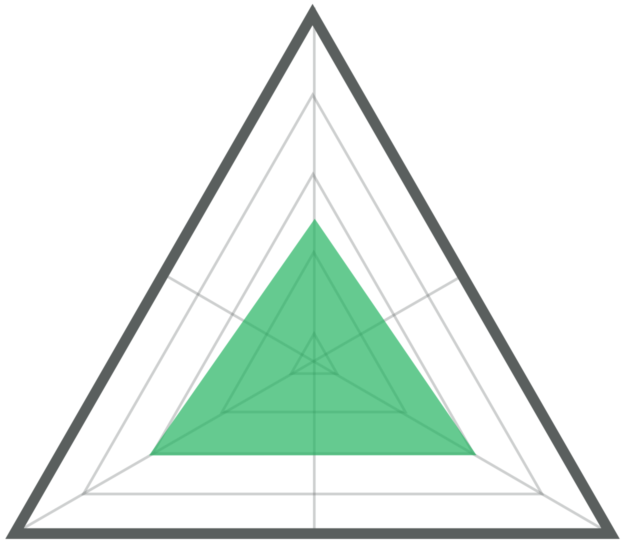






Methods

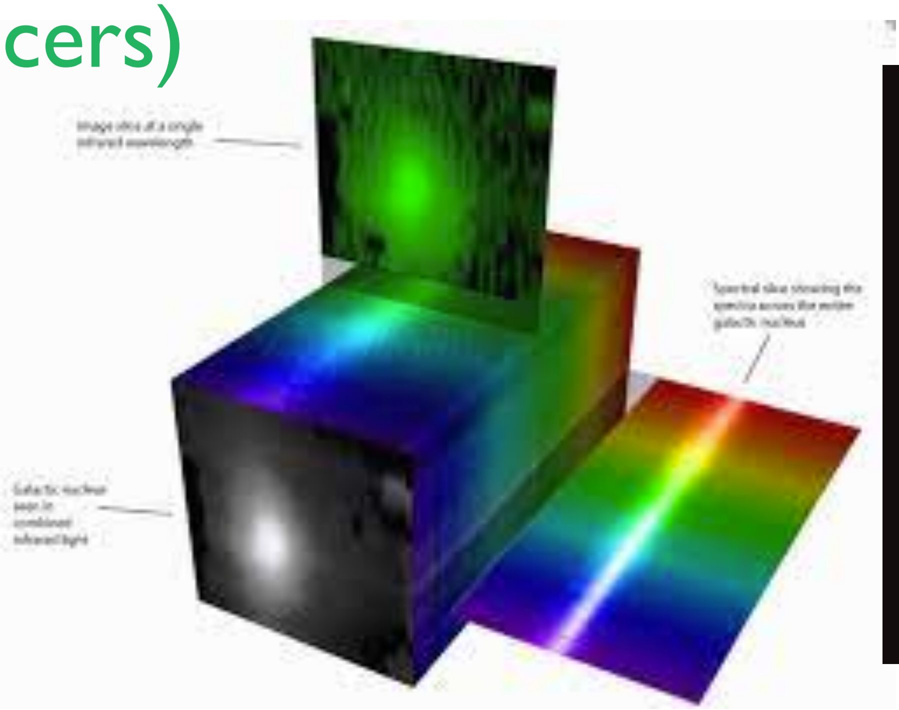
classic AO + IFU med-R (slicers)

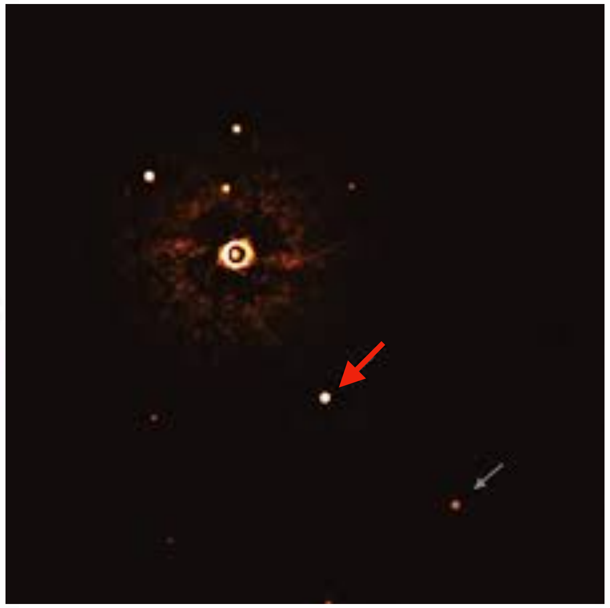


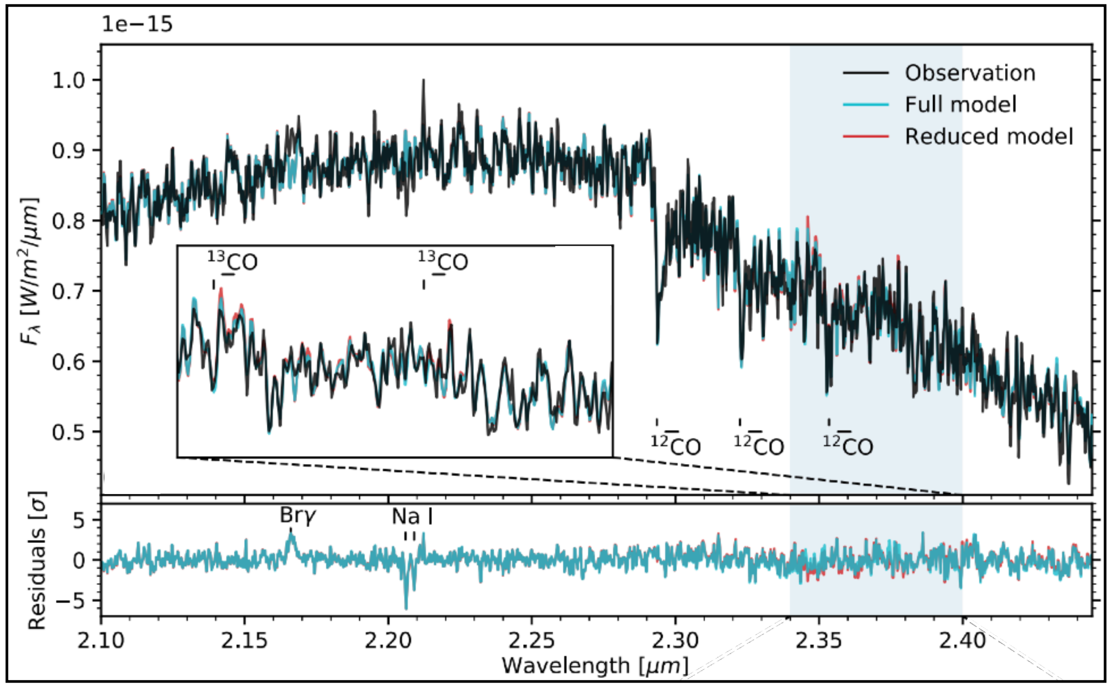
Contrast

Spatial resolution

Spectral resolution





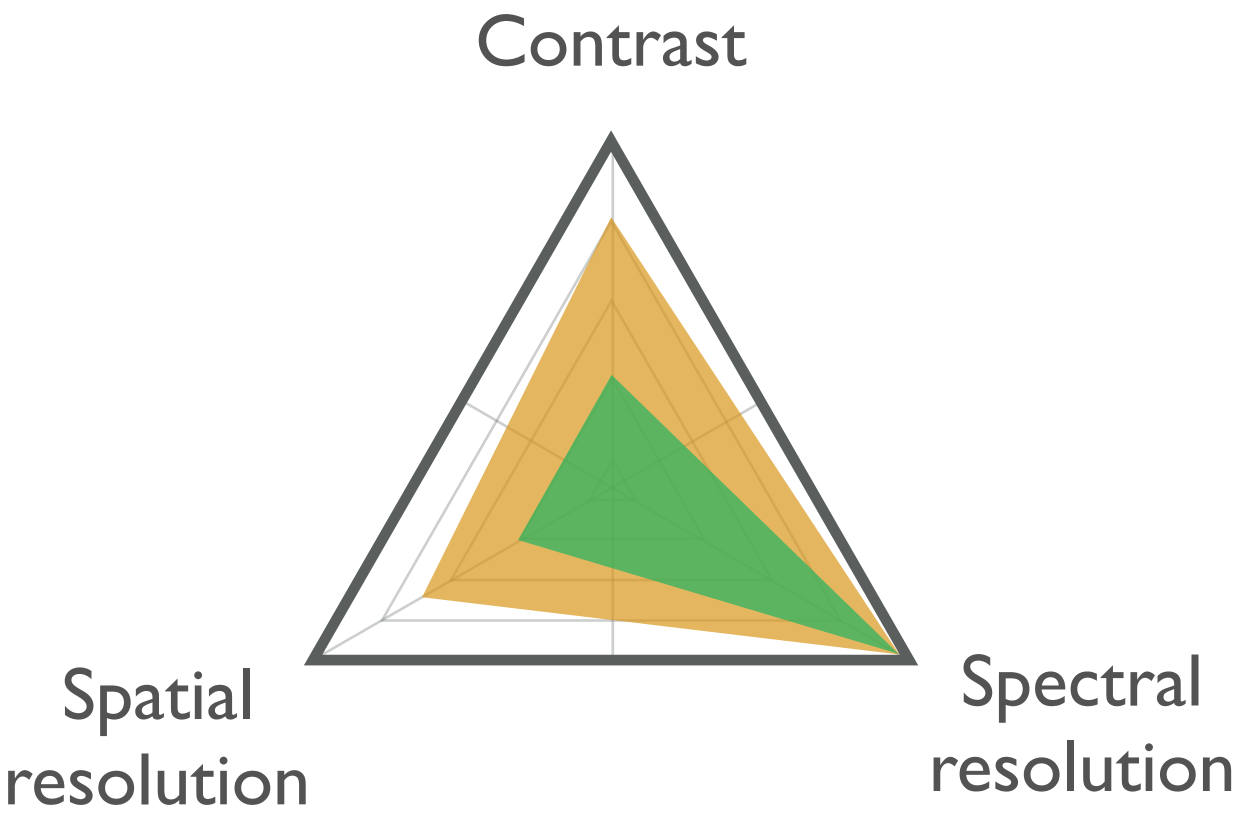


TYC 8998 b (SINFONI)
Zhang et al. (2021)

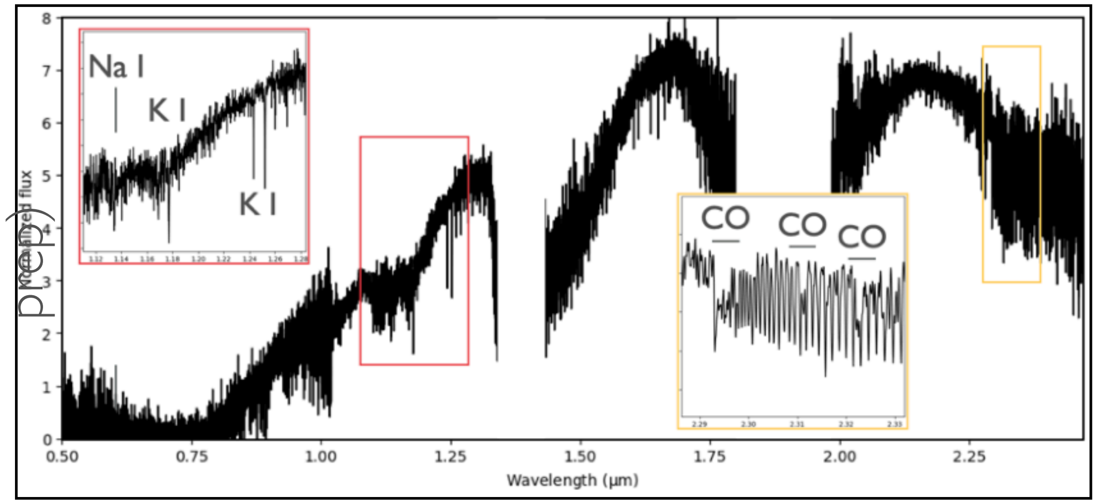
R ~ 4500

Methods

Med/high-R cross-disperser
[+ coupling to (x)AO + coronograph]

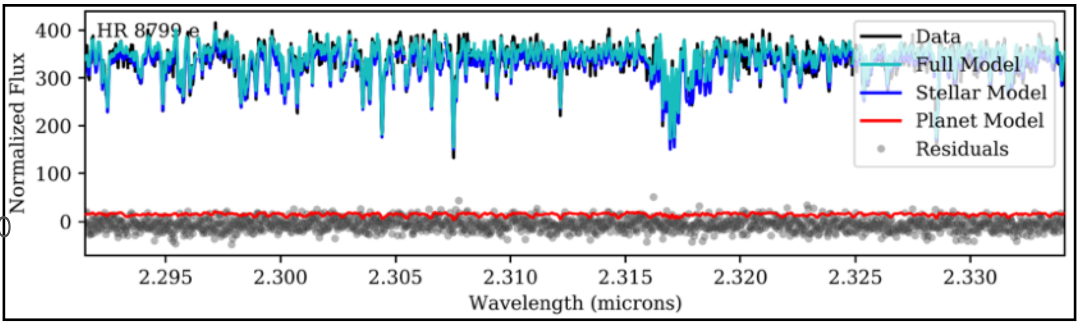


VHS 1256 b (XShooter)
Petrus et al. 2022 (in prep.)



R ~ 8000

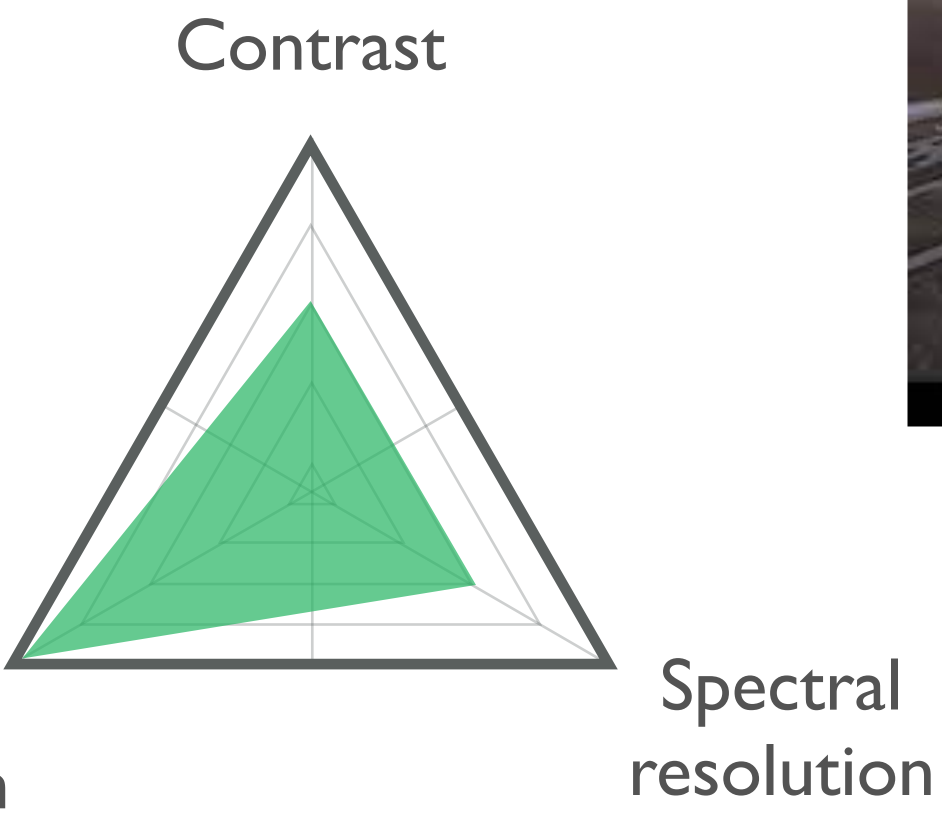
HR 8799 e (KPIC)
Wang et al. 2021

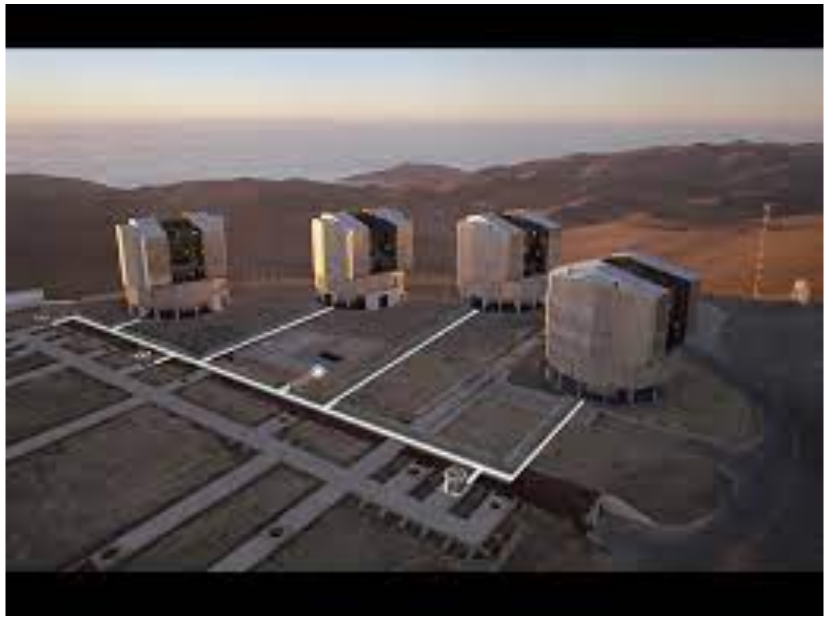


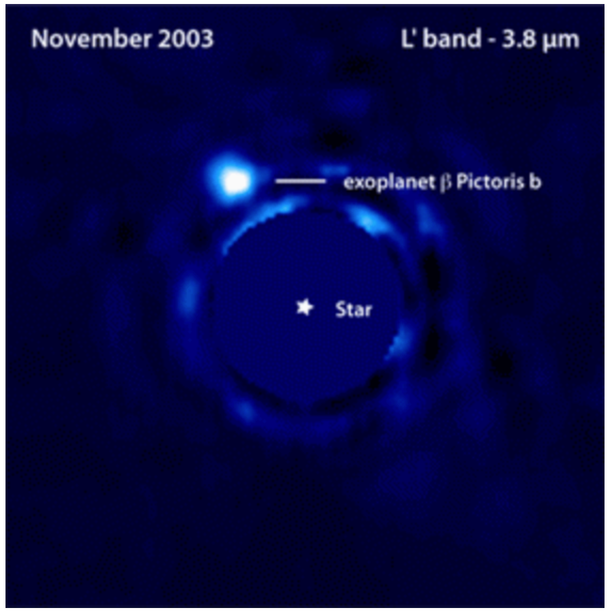
R ~ 35000

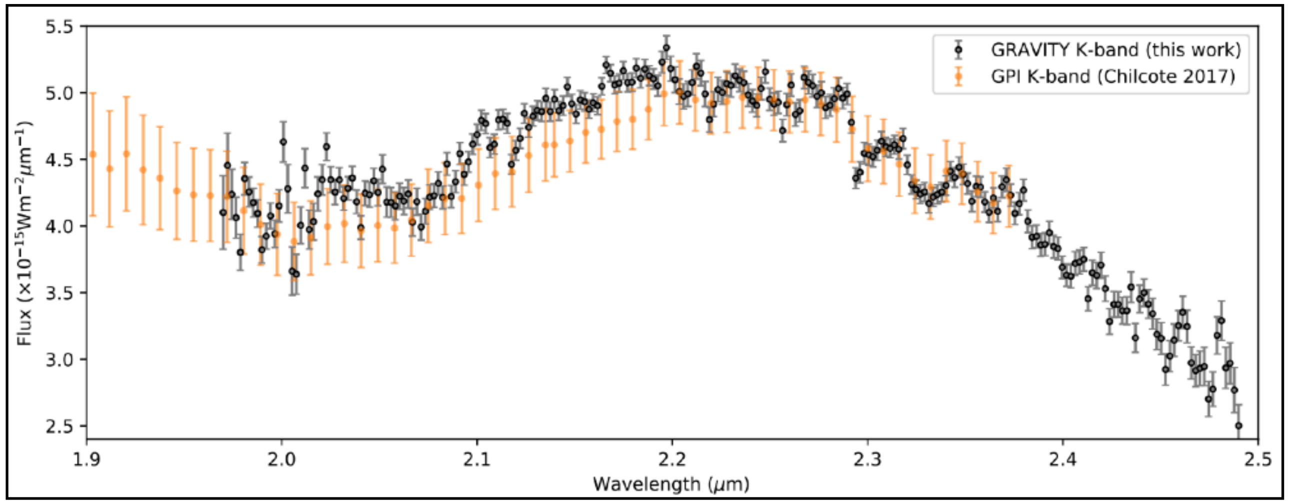
Methods

Interferometer (VLTI)





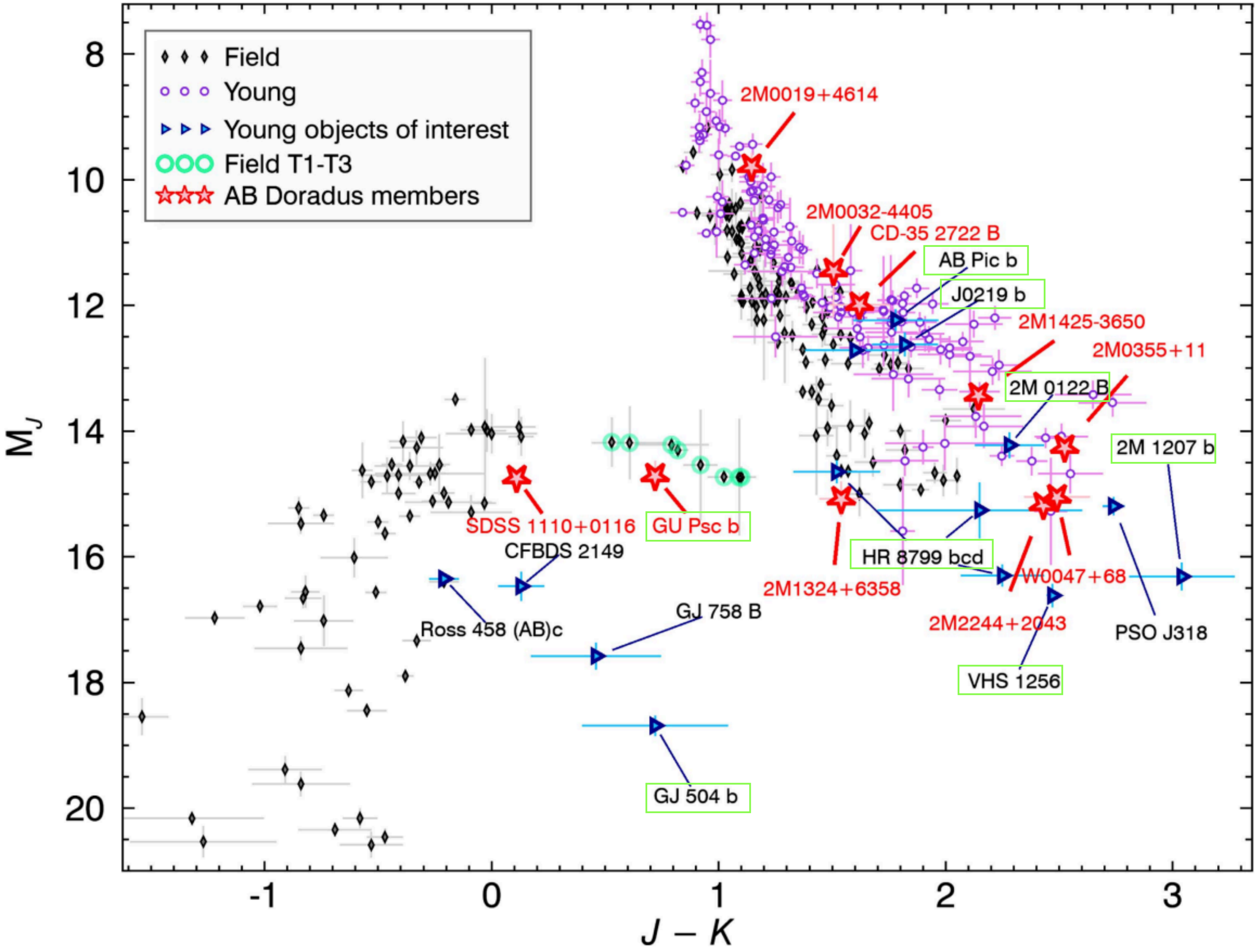




β Pictoris b (GRAVITY)
GRAVITY collab et al. (2020)

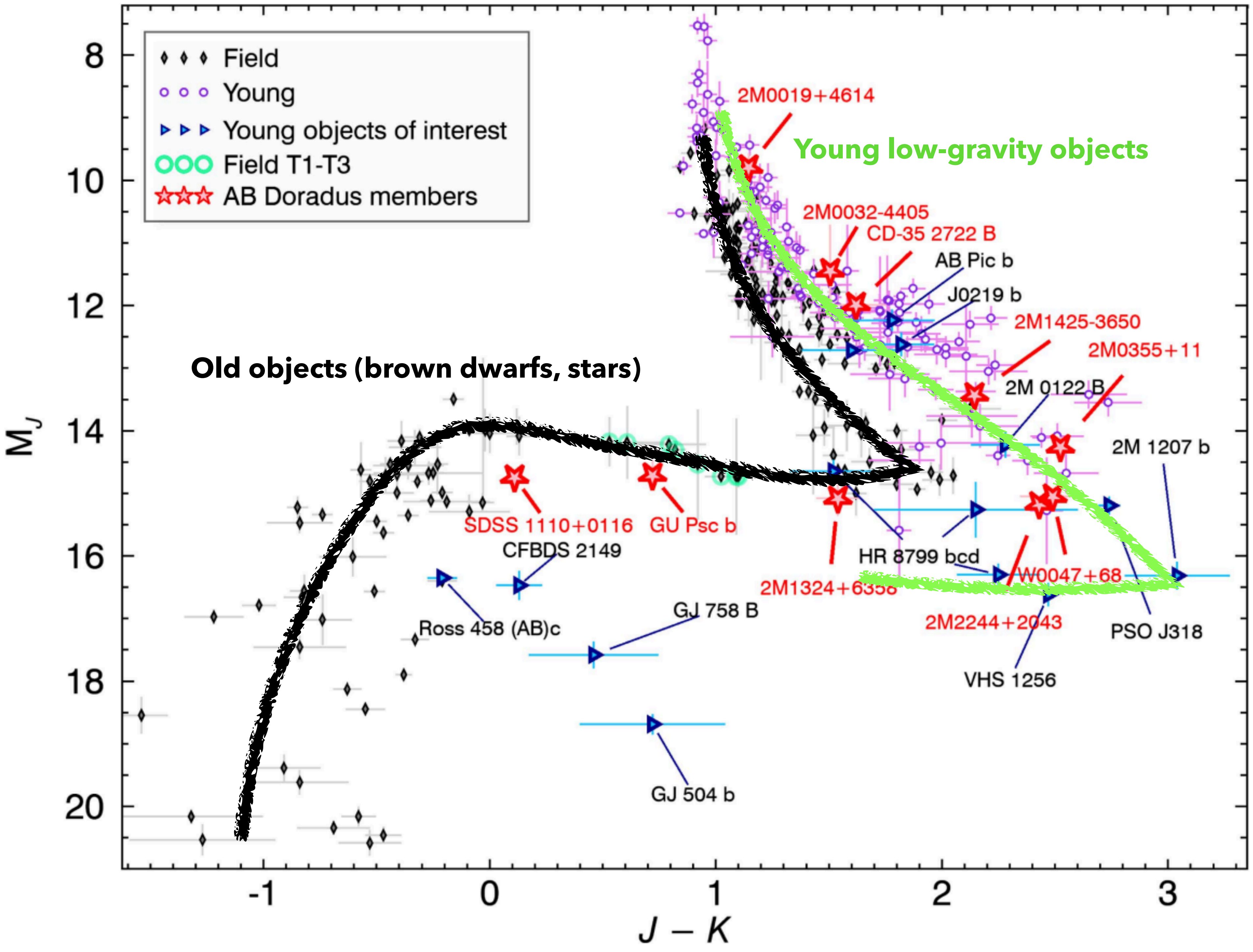
R ~ 500 to 4000

Empirical take



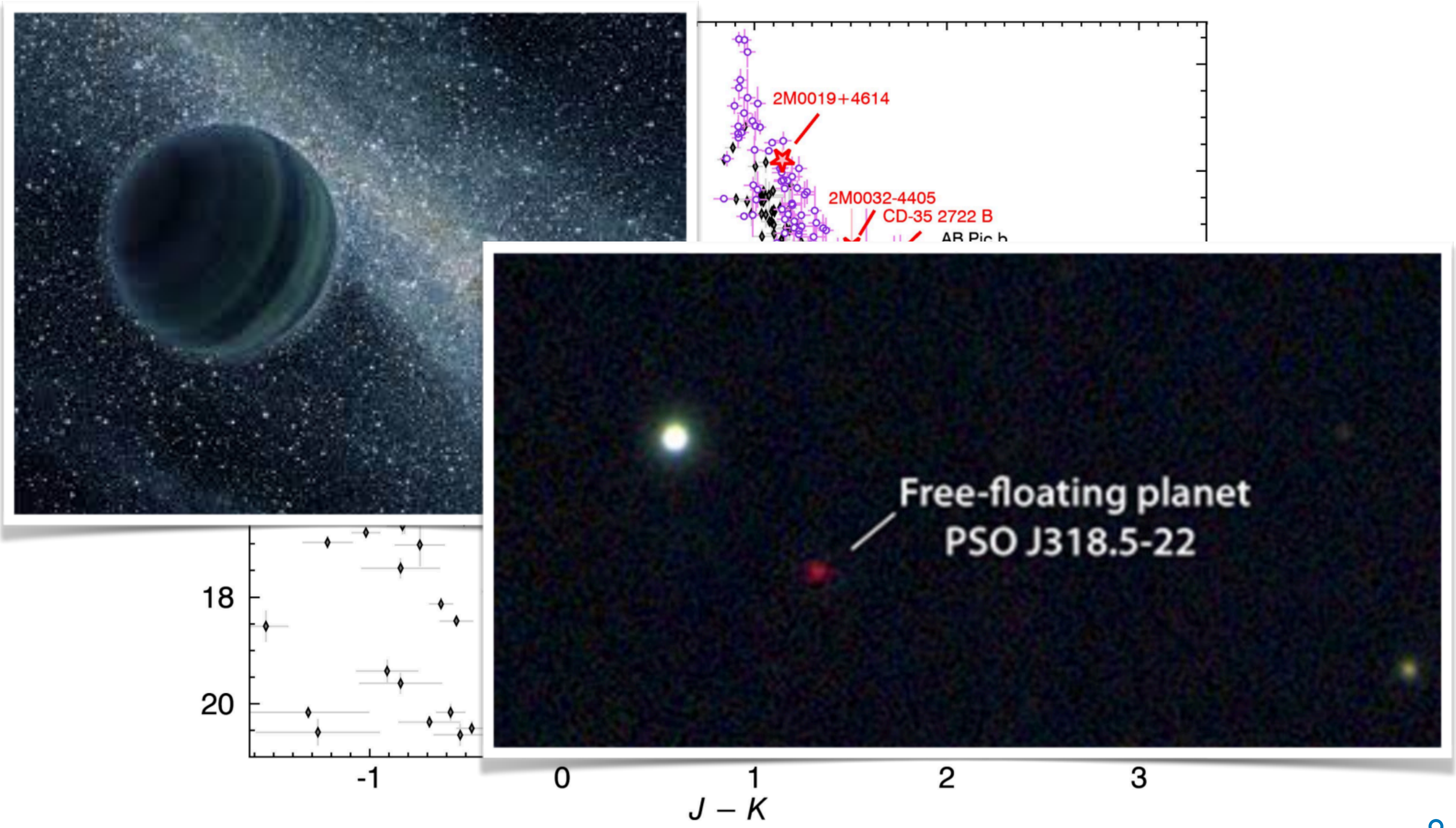
Empirical take

Young exoplanets are red and can be underluminous



Empirical take

Imaged exoplanets : similar to « free floating planets »?



Empirical take

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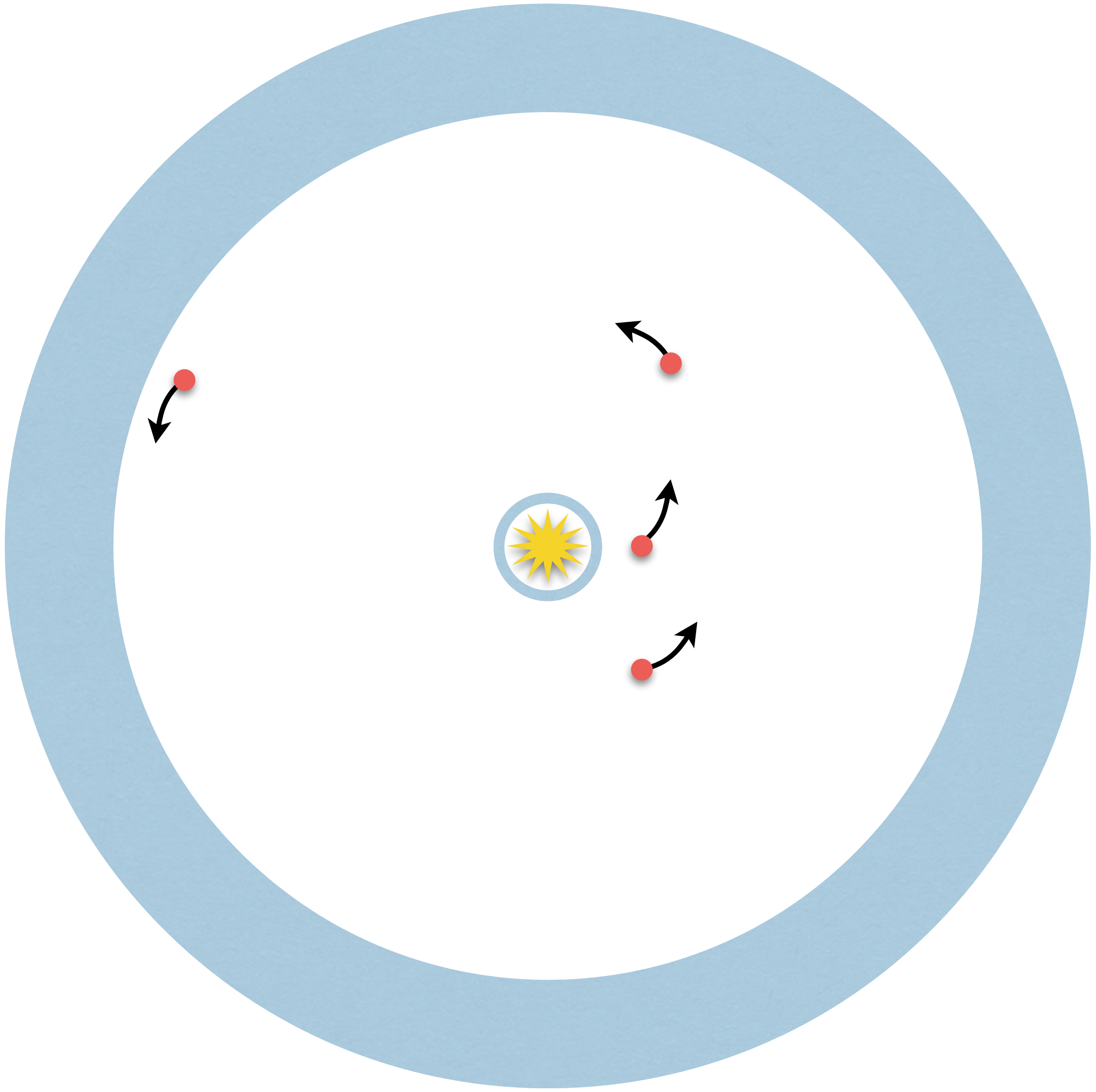
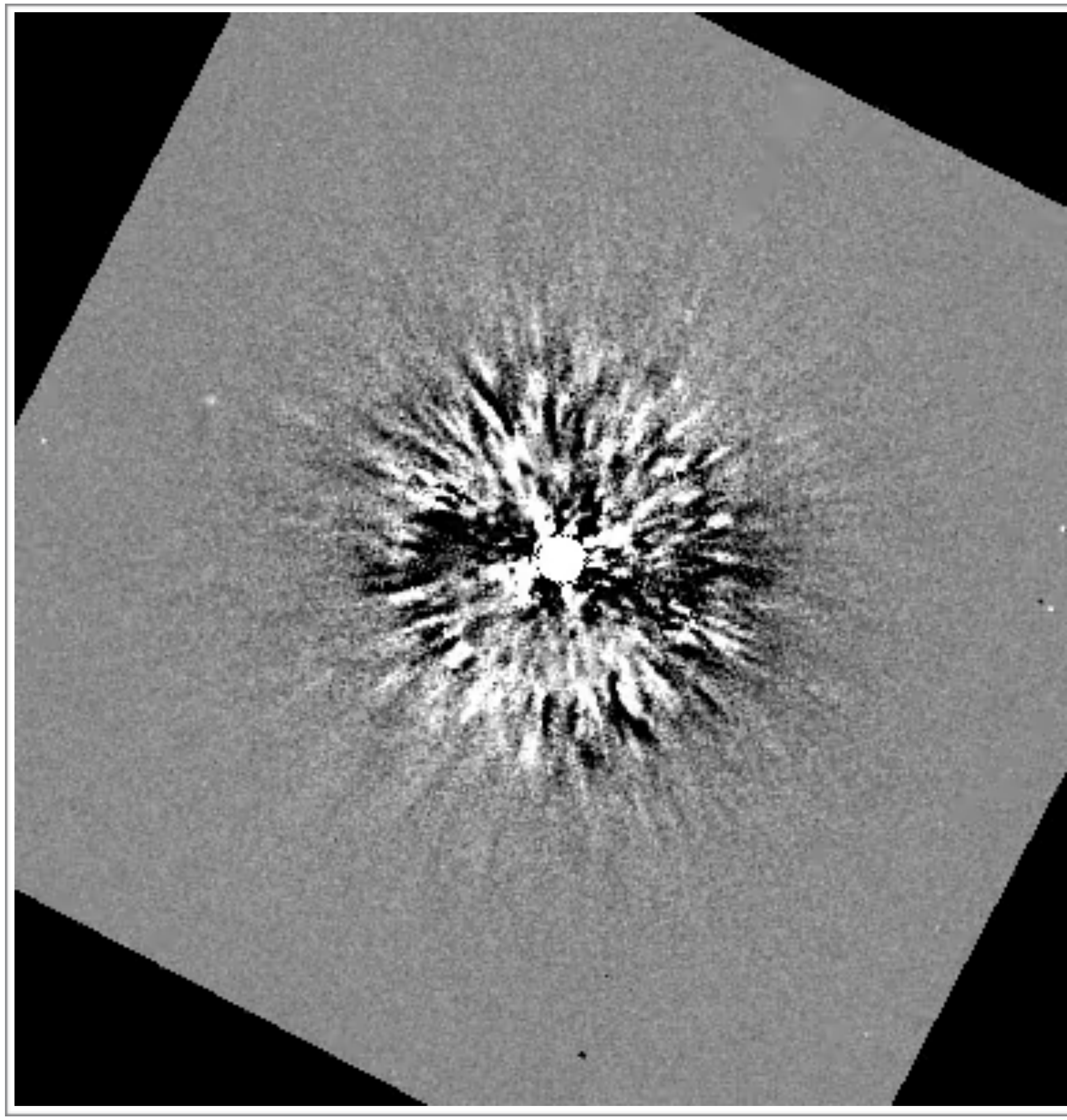
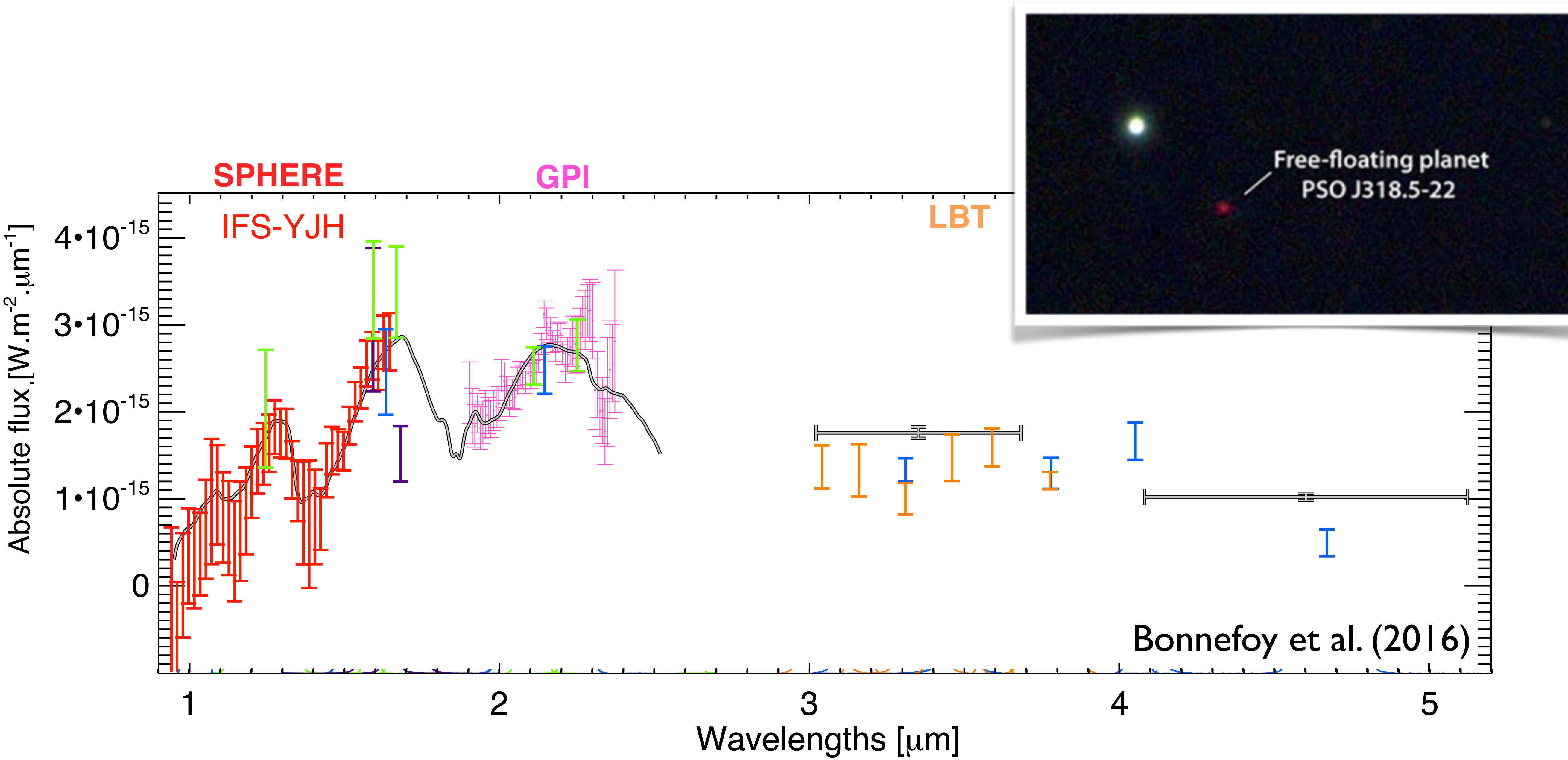




20 mins of obs. with SPHERE/IRDI

Empirical take

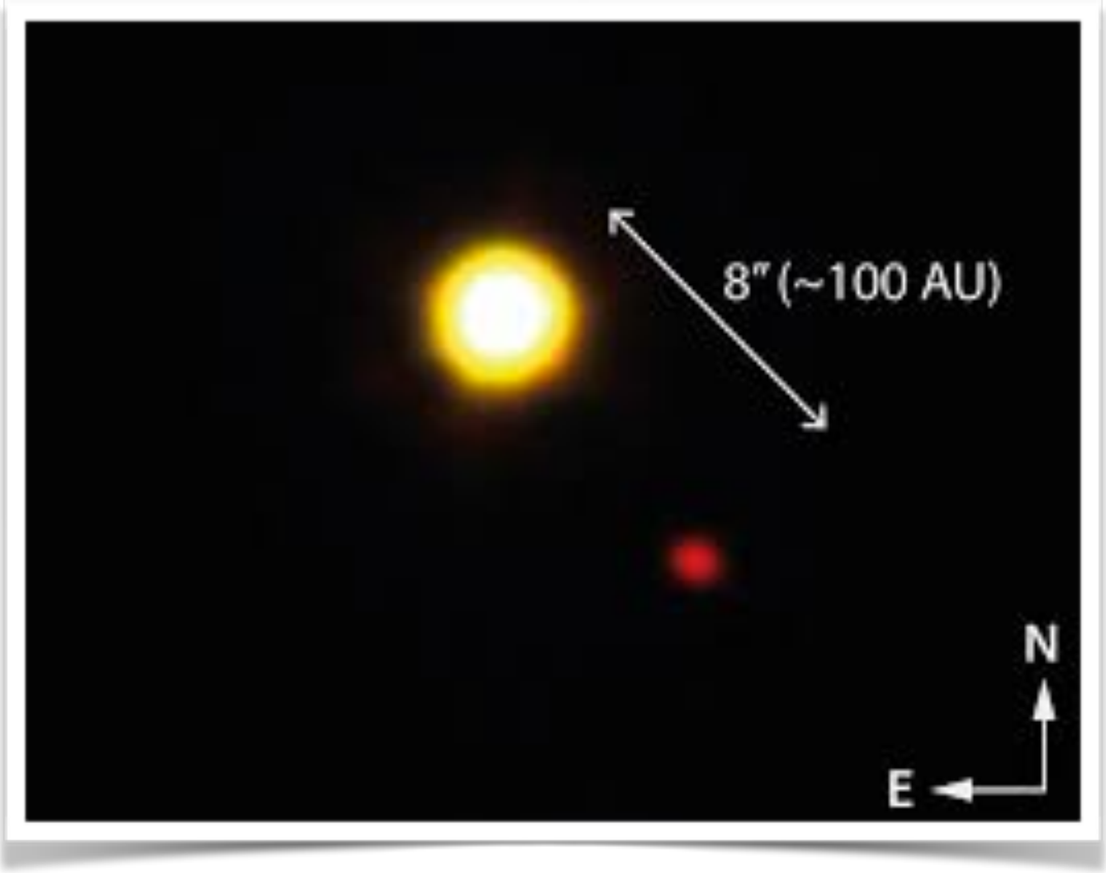
Imaged exoplanets : similar to « free floating planets »?

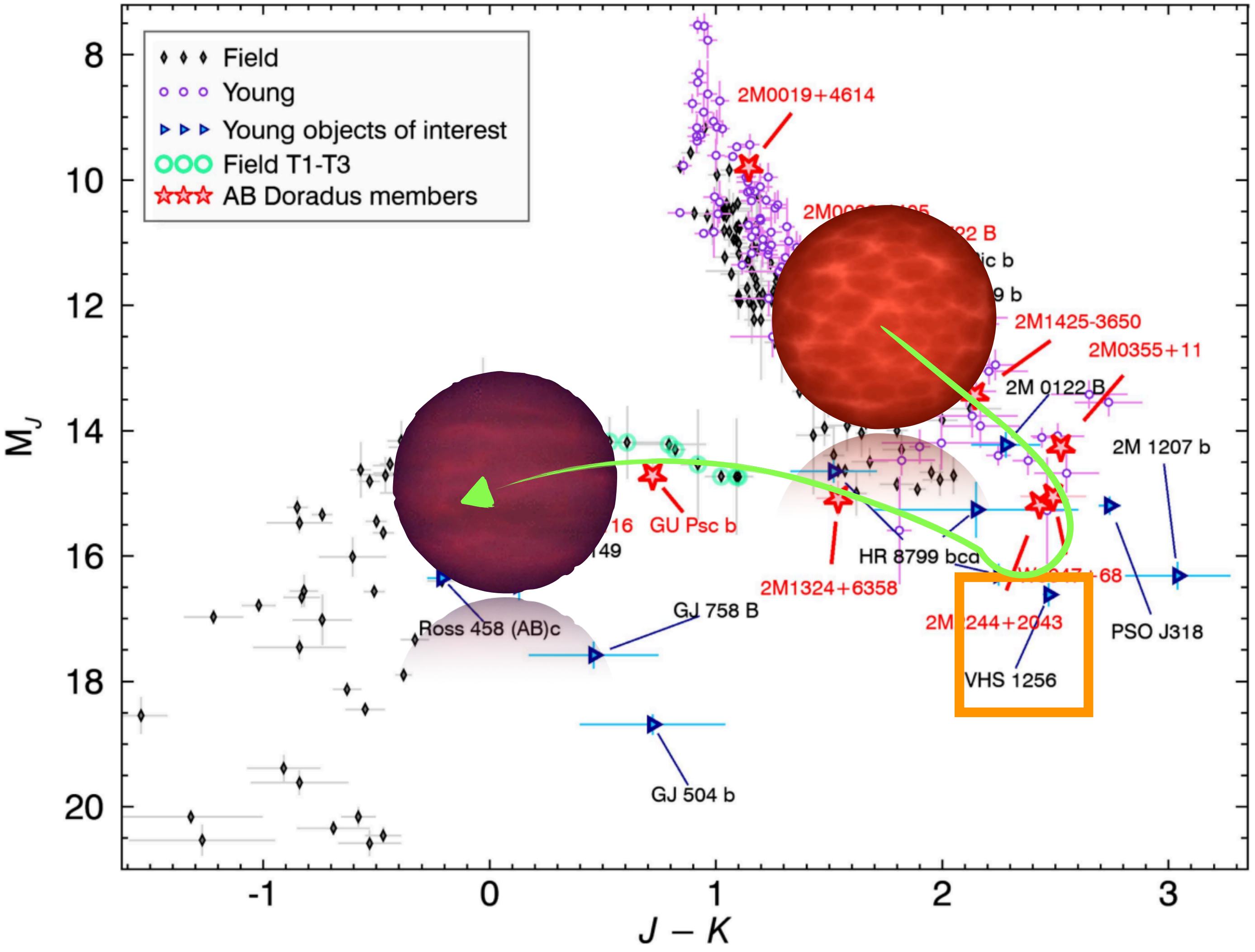


Bonnefoy et al. (2016)

Empirical take

Some hints for surface features (holes in the cloud deck)





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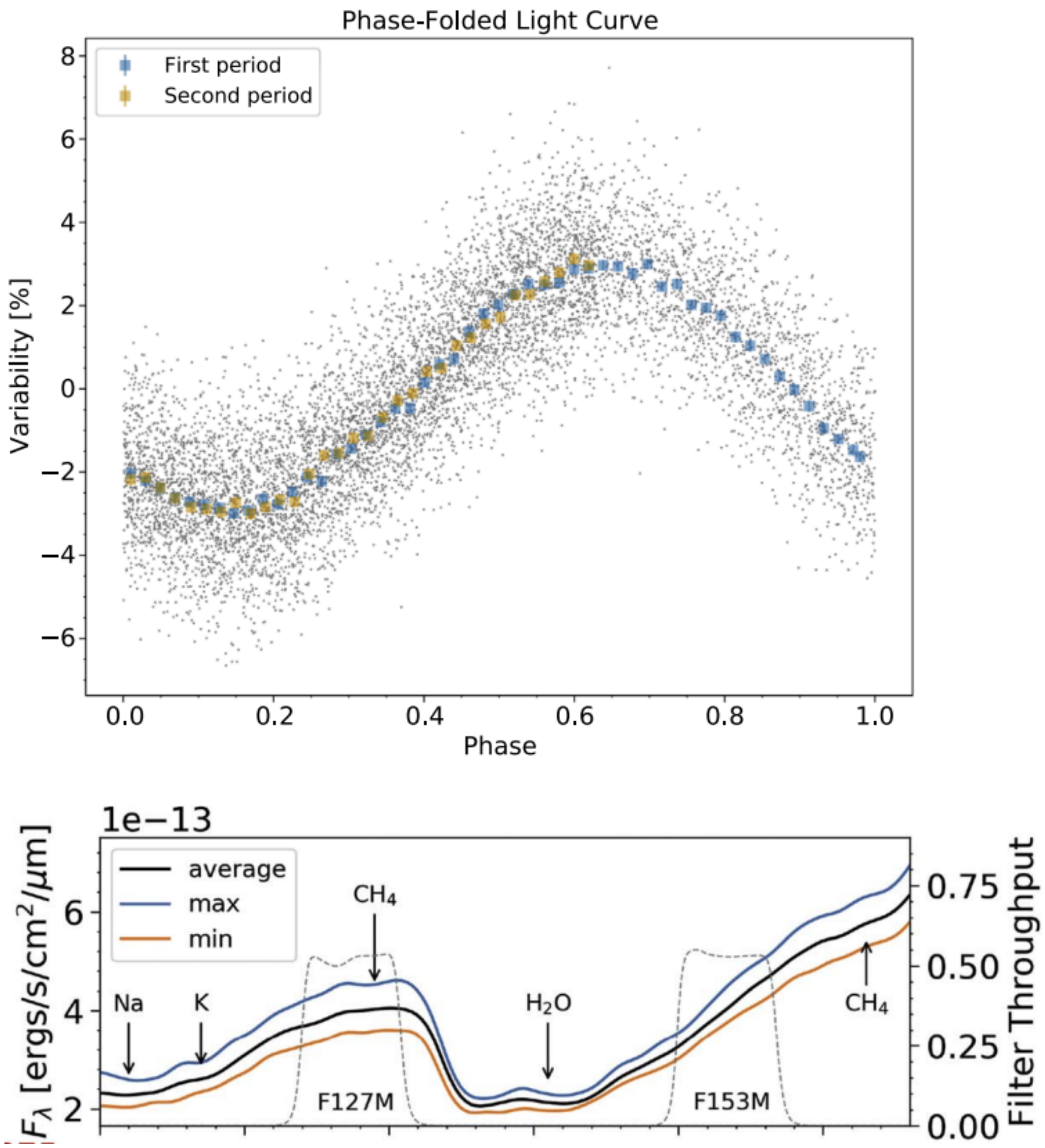
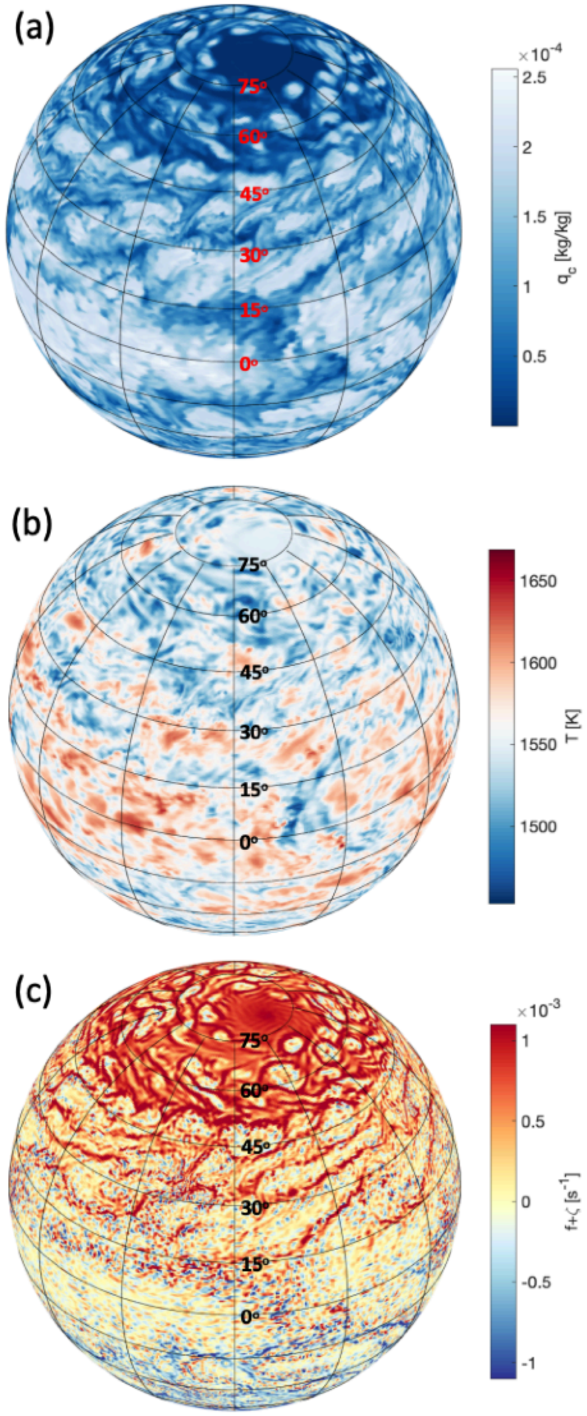


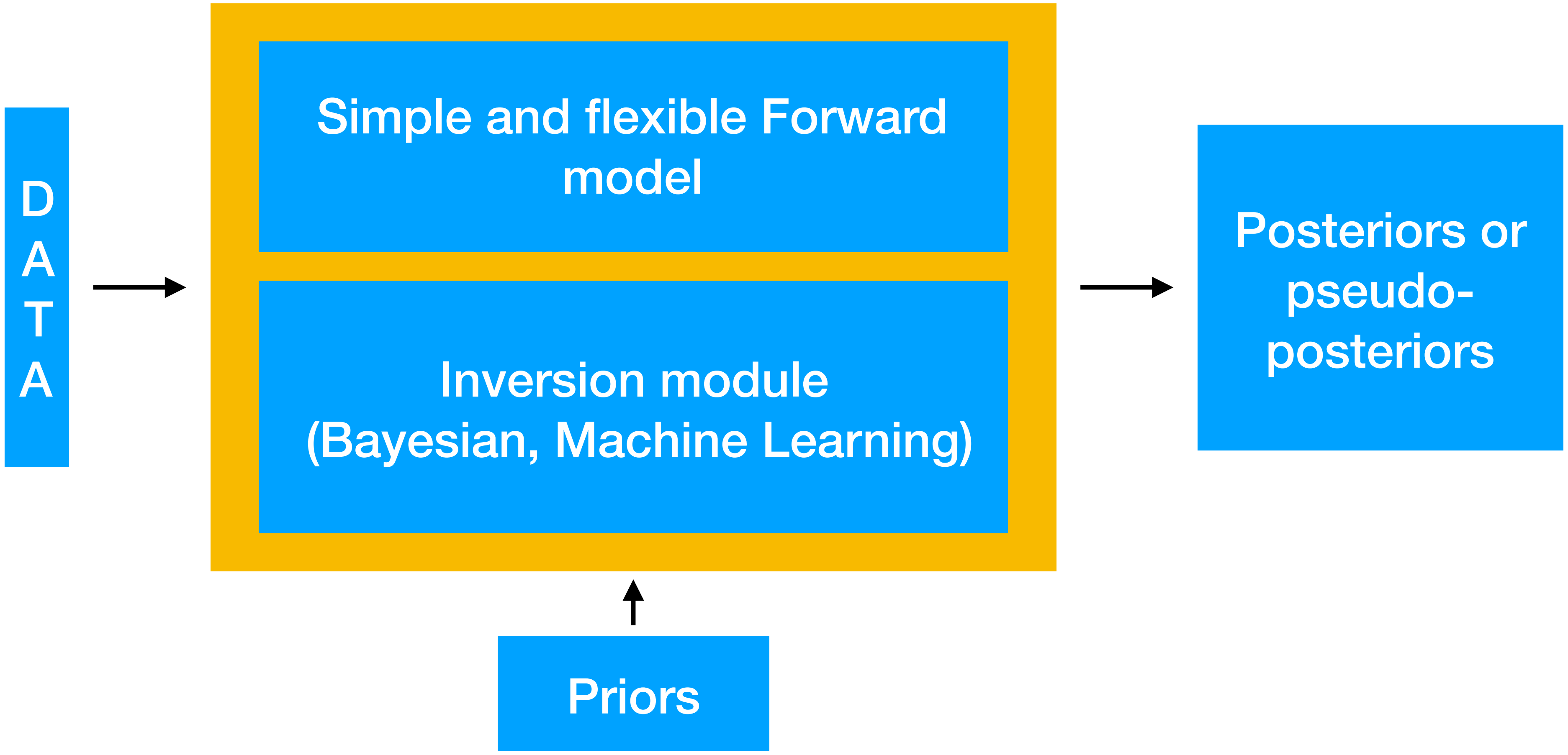
Zhou et al. 2020



Tan et al. 2021

Spectral inversion

Atmospheric retrieval: data-driven approach



DATA

Simple and flexible Forward model

Inversion module (Bayesian, Machine Learning)

Posteriors or pseudo-posteriors

Priors

Advantages

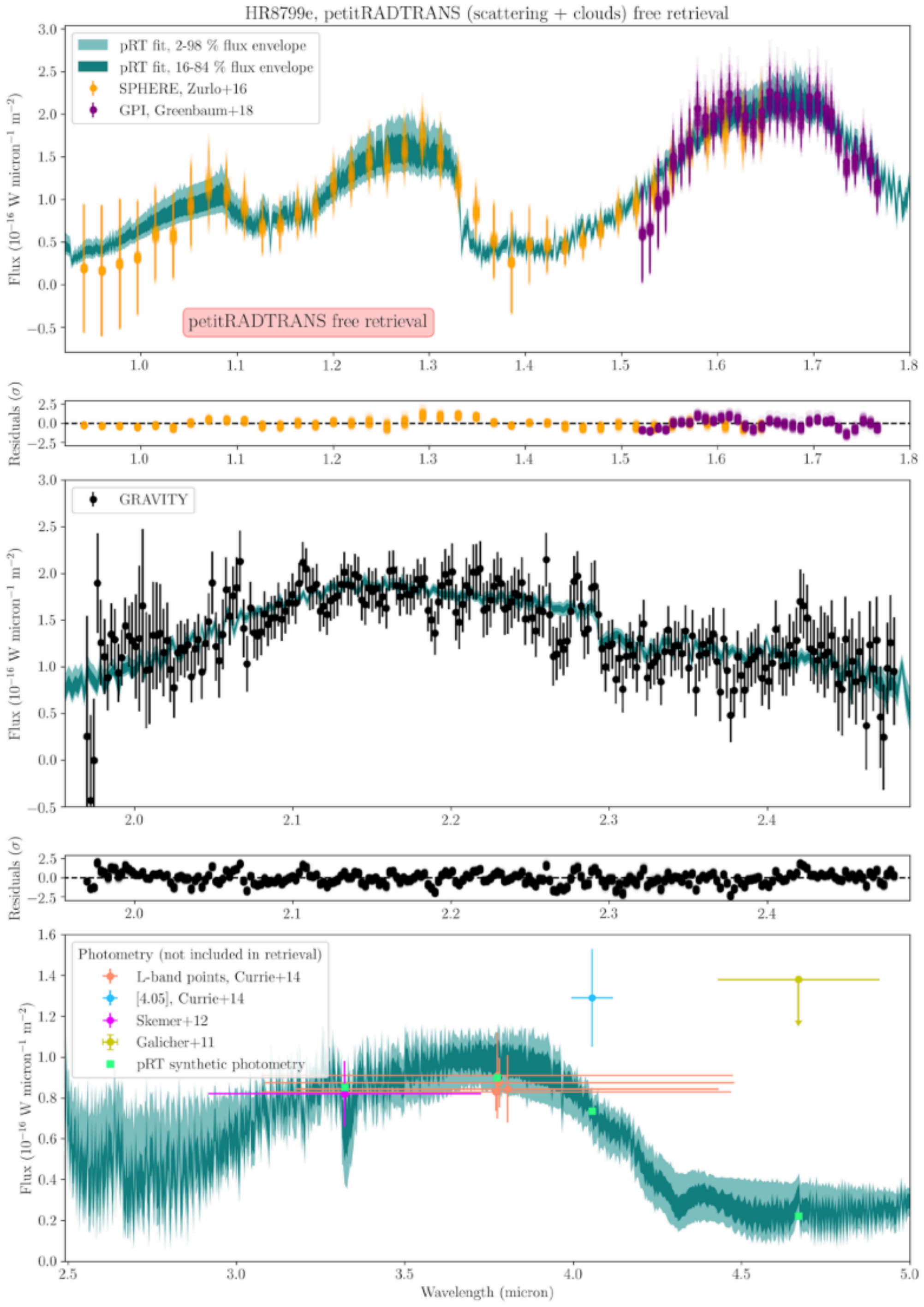
- Flexible
- Abundances of individual molecules
- Pressure-temperature profiles

Downfalls

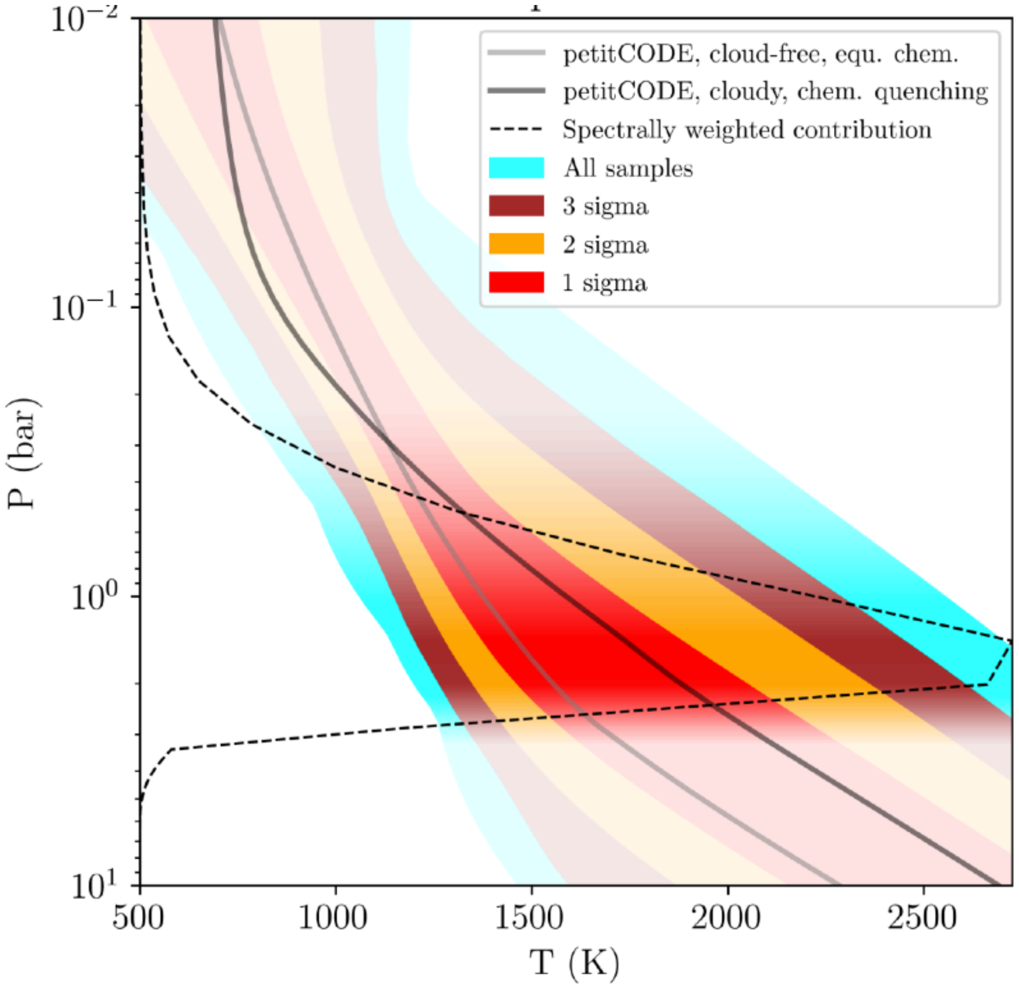
- Loose connection to physics
- Bias in the abundances (clouds)
- Computation cost

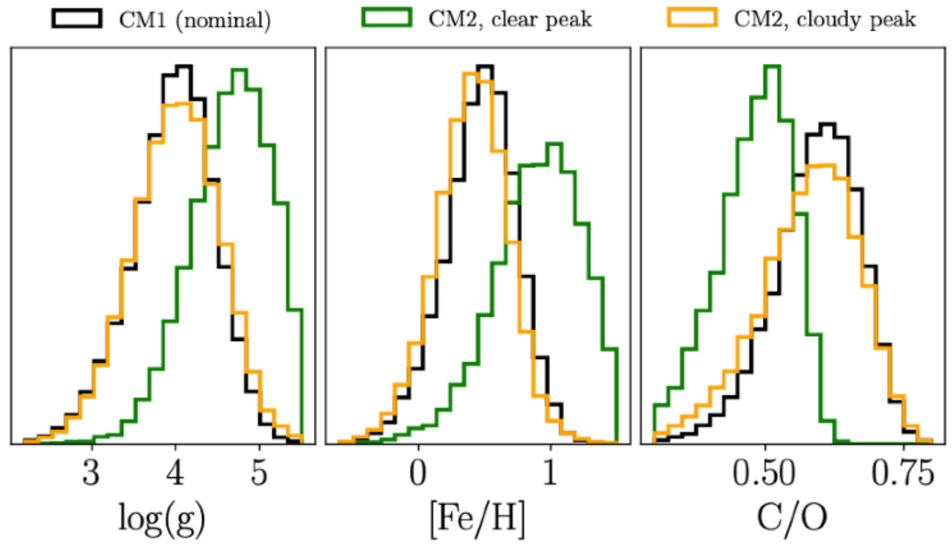
Spectral inversion

Atmospheric retrieval: some examples



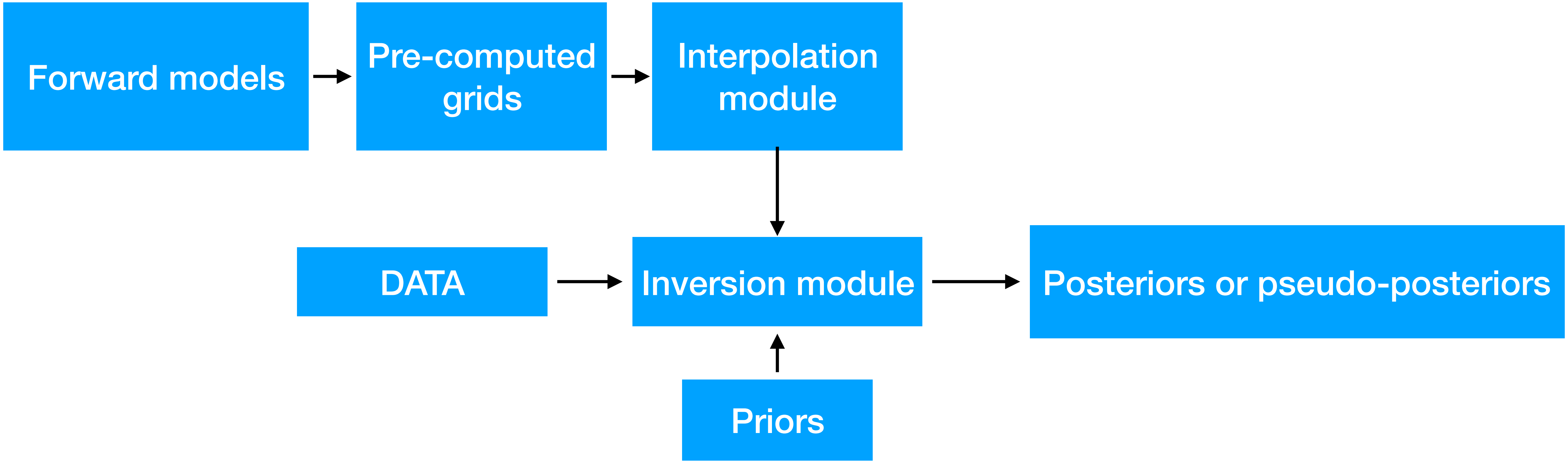
Mollière et al. 2020





Spectral inversion

Forward modeling: driven by models



Forward models

Pre-computed grids

Interpolation module

DATA

Inversion module

Posteriors or pseudo-posteriors

Priors

Advantages

- Use of detailed cloud models
- Efficient (medium and high-resolution)
- Test of model inconsistencies

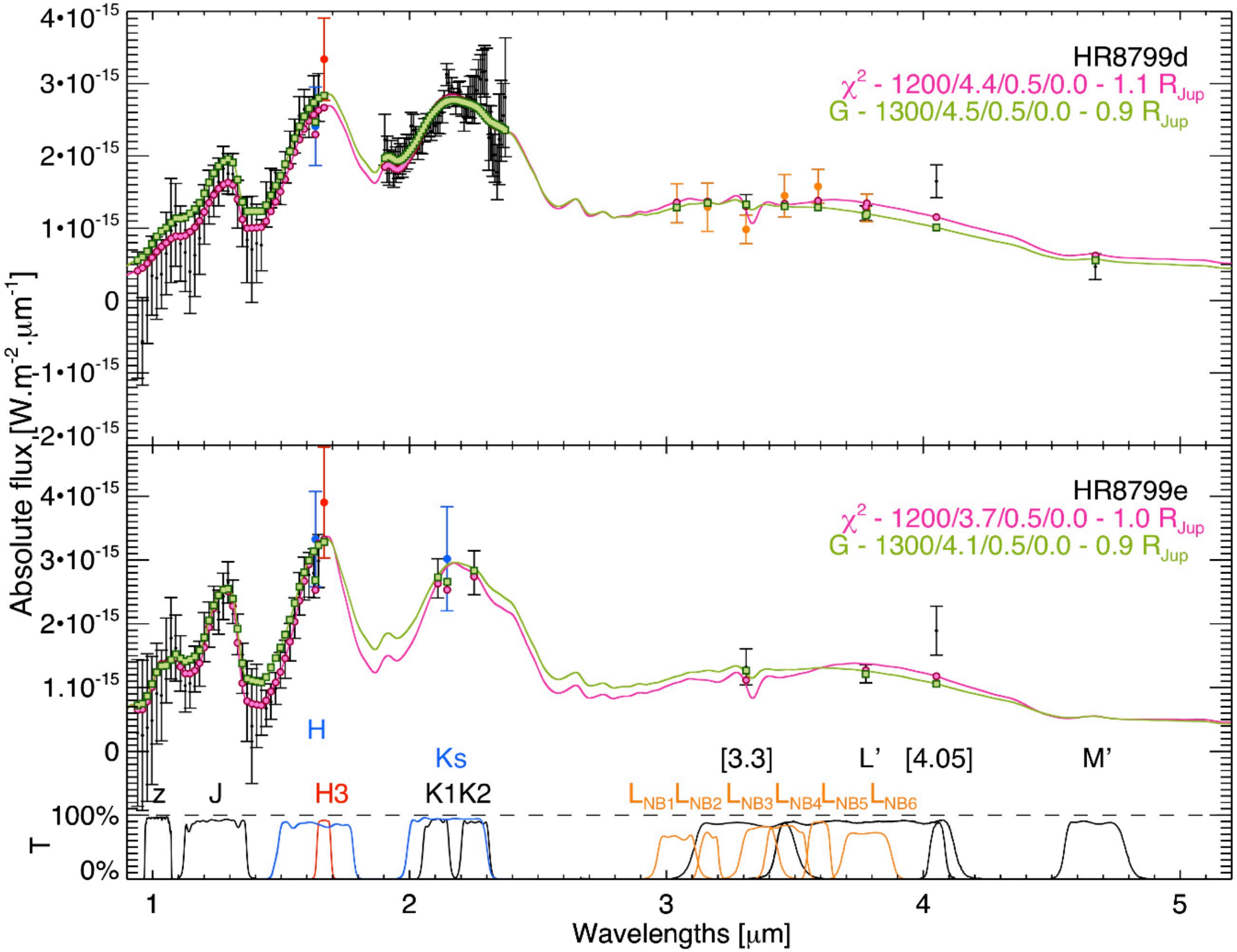
Downfalls

- Limited number of free parameters
- Not flexible
- Relies on grid interpolations

Spectral inversion

Imaged exoplanets : key role of gravity on clouds

Bonnefoy et al. (2016) Charnay et al. (2018)



Spectral inversion

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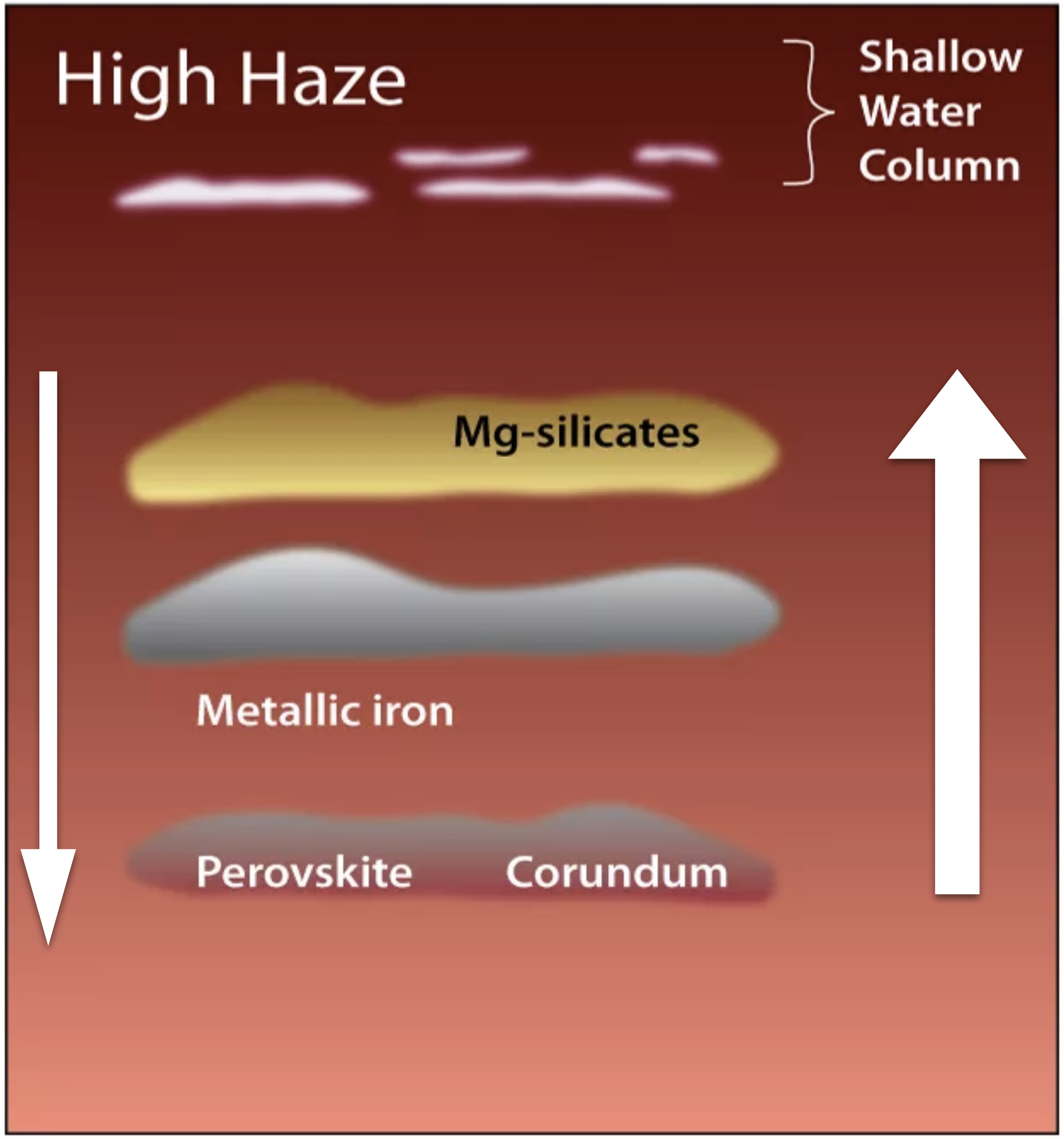
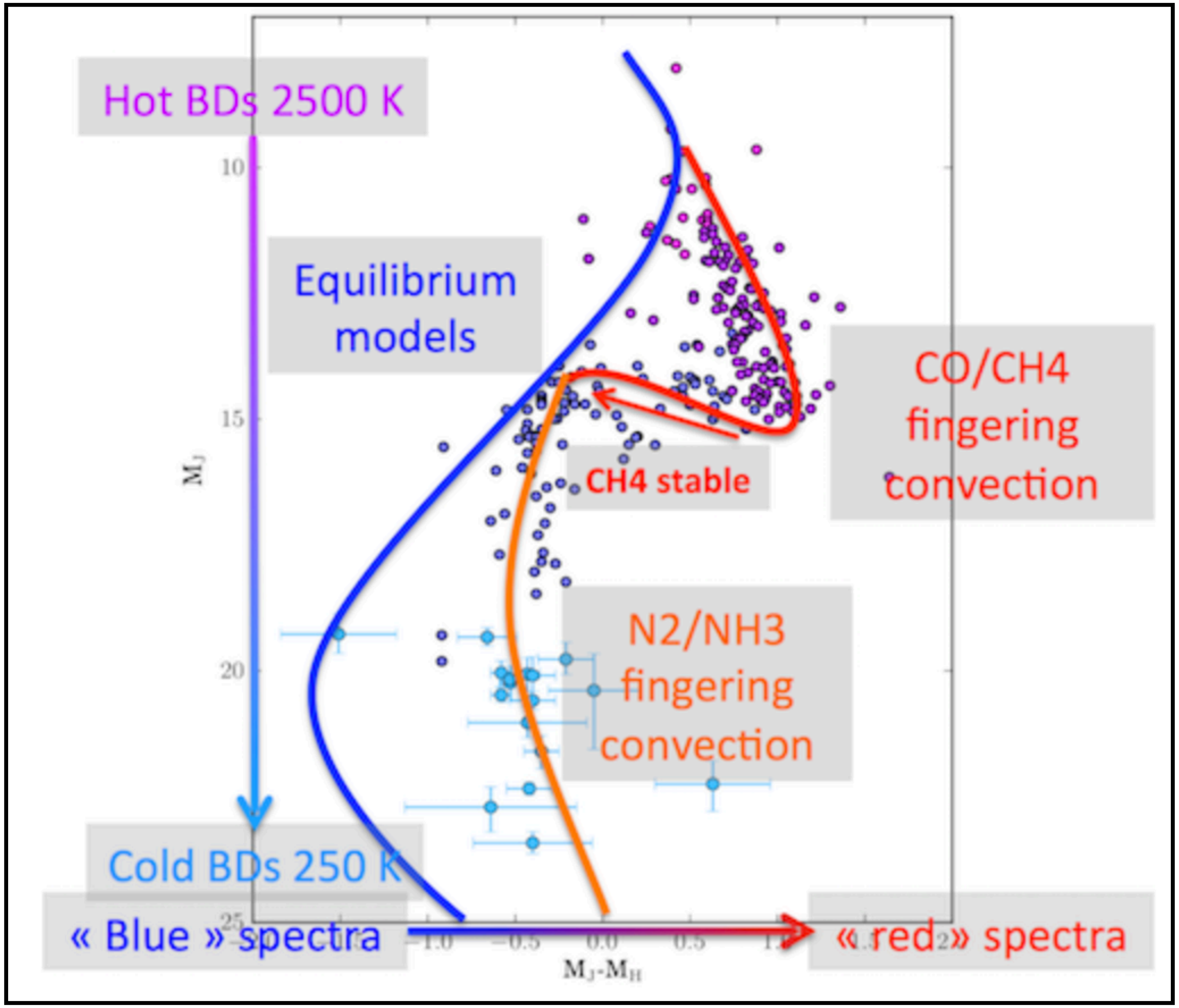


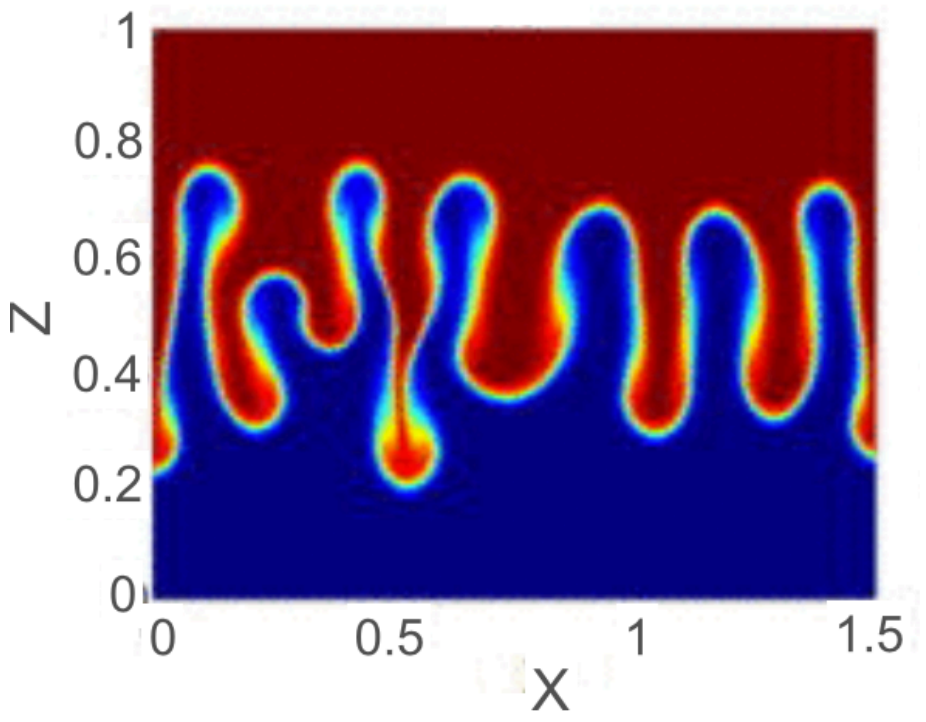
Reduced gravitational settling

Enhanced vertical mixing

Spectral inversion

Imaged exoplanets : do we really need clouds?





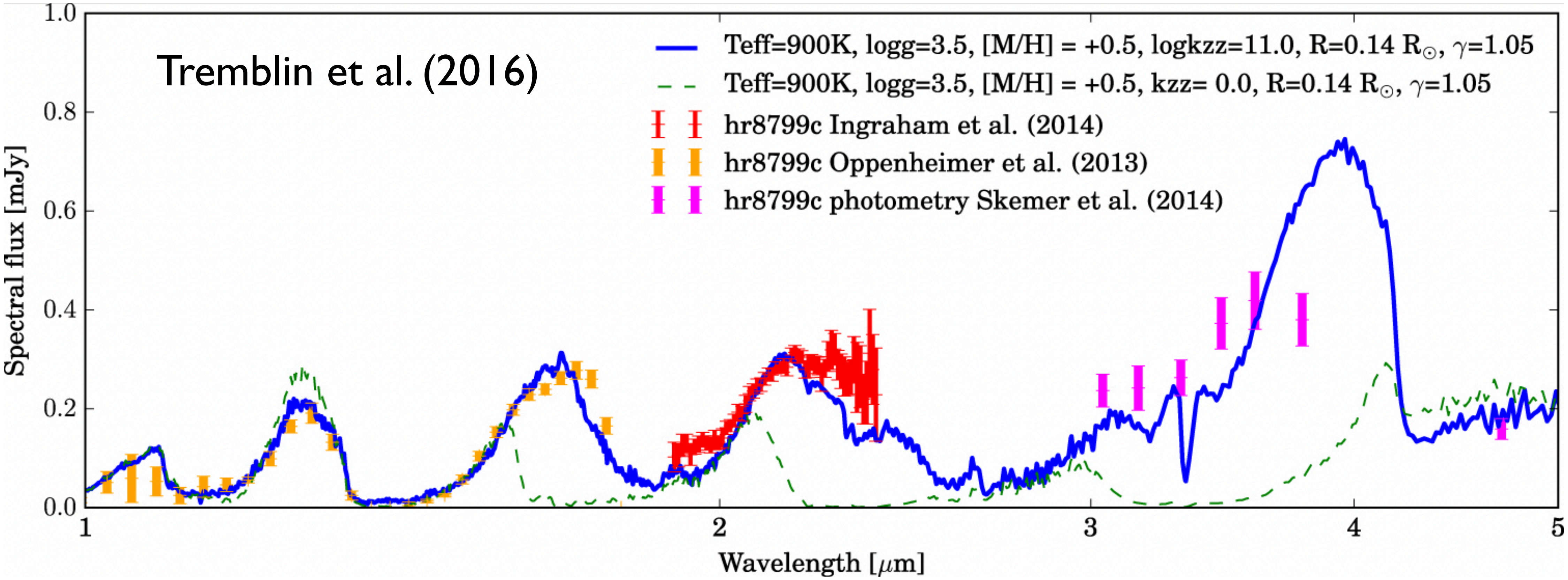
Tremblin et al. 2015, 2016

$CO+3H_2 \longrightarrow CH_4+H_2O$

$N_2+3H_2 \longrightarrow 2NH_3$

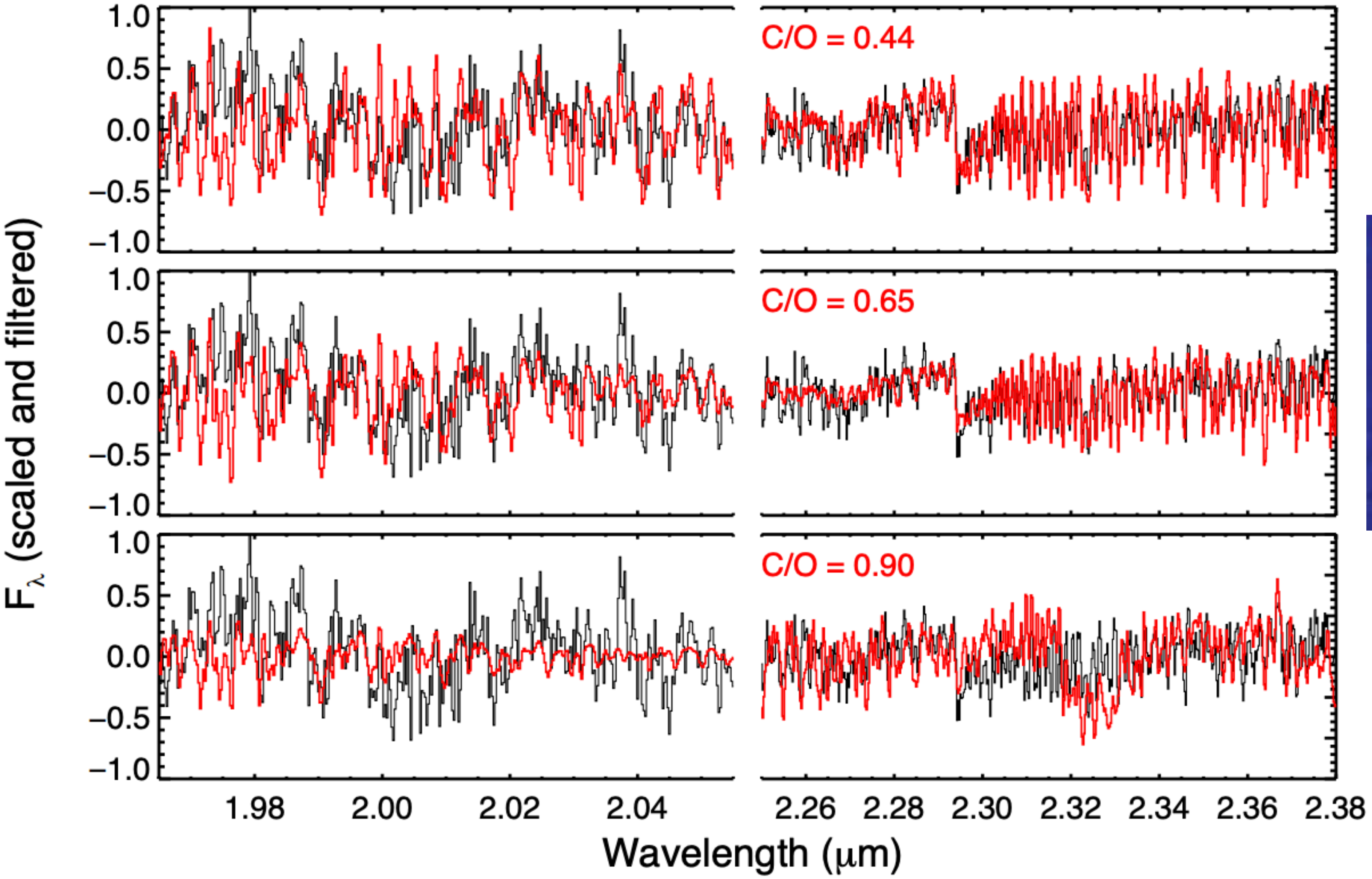
Spectral inversion

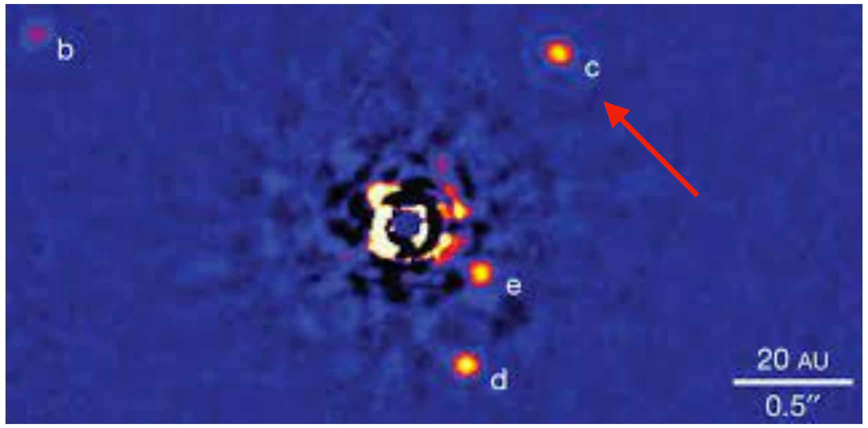
Imaged exoplanets : do we really need clouds?



Spectral inversion

Medium/high resolution : abundance ratio

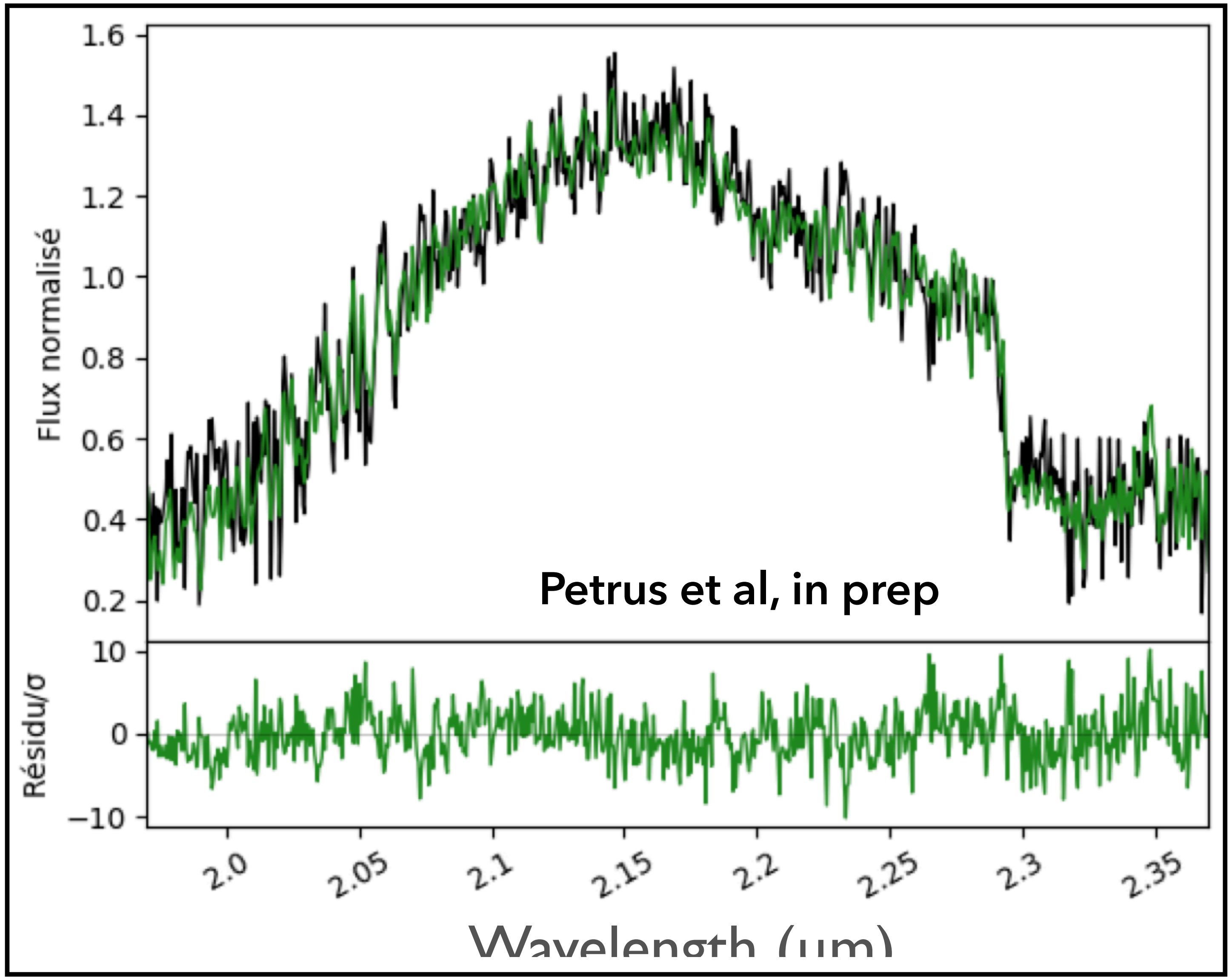




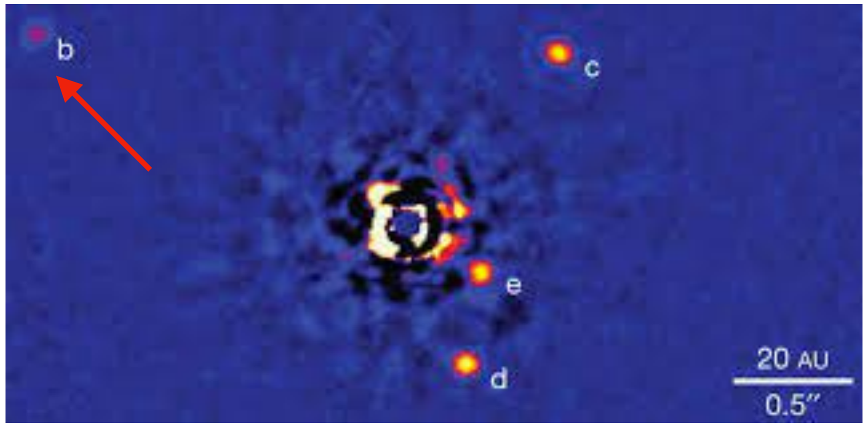
Konopacky et al. 2013

Spectral inversion

Medium/high resolution : abundance ratio



Petrus et al, in prep

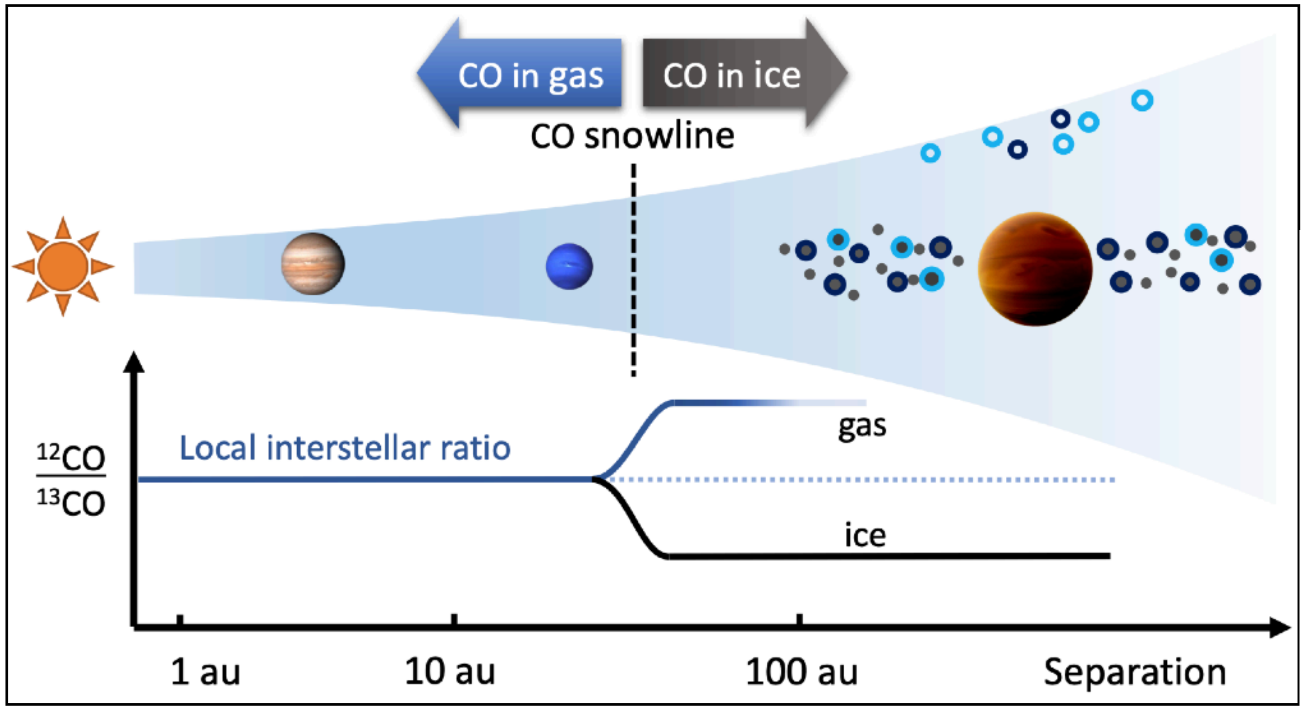


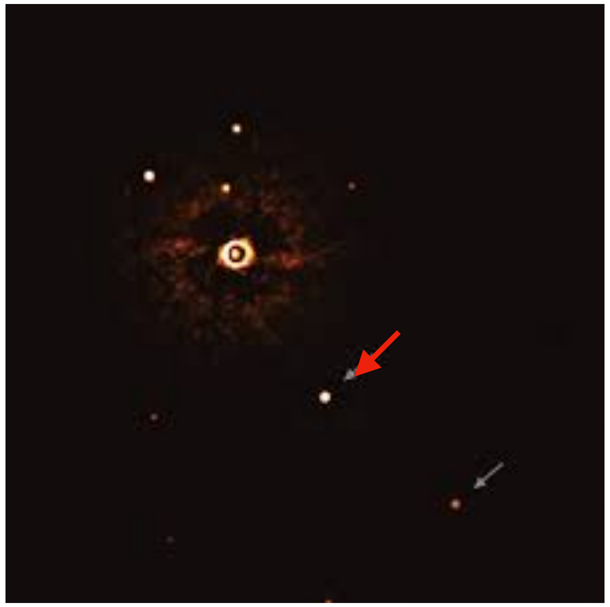
- ■ HR 8799 b (OSIRIS, Barman et al. 2015)
- 🟩 Exo-REM (T_{eff} ~ 1015 K ; C/O ~ 0.55)

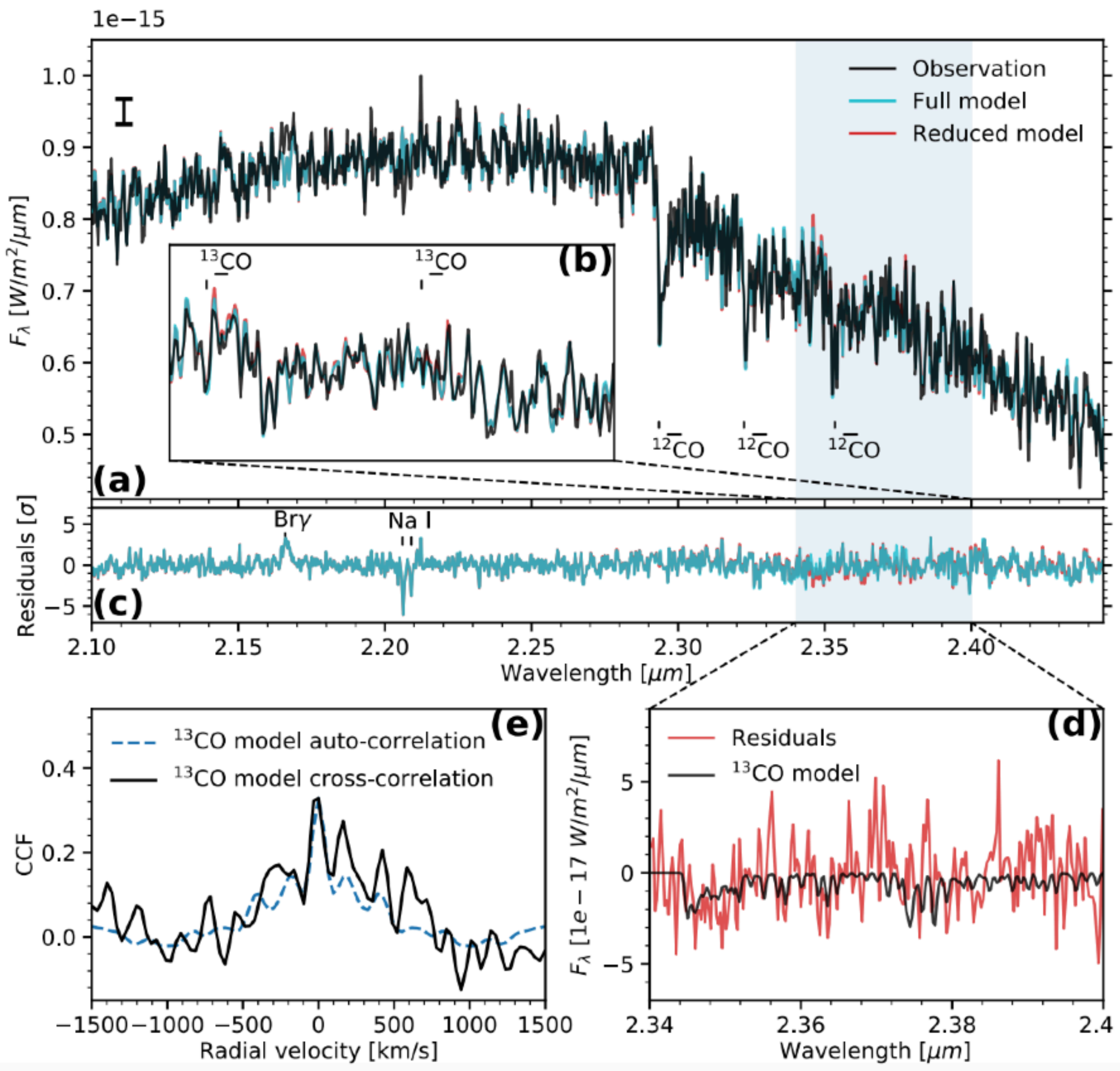
Spectral inversion

Medium/high resolution : isotopic abundance ratio

Zhang et al. 2021



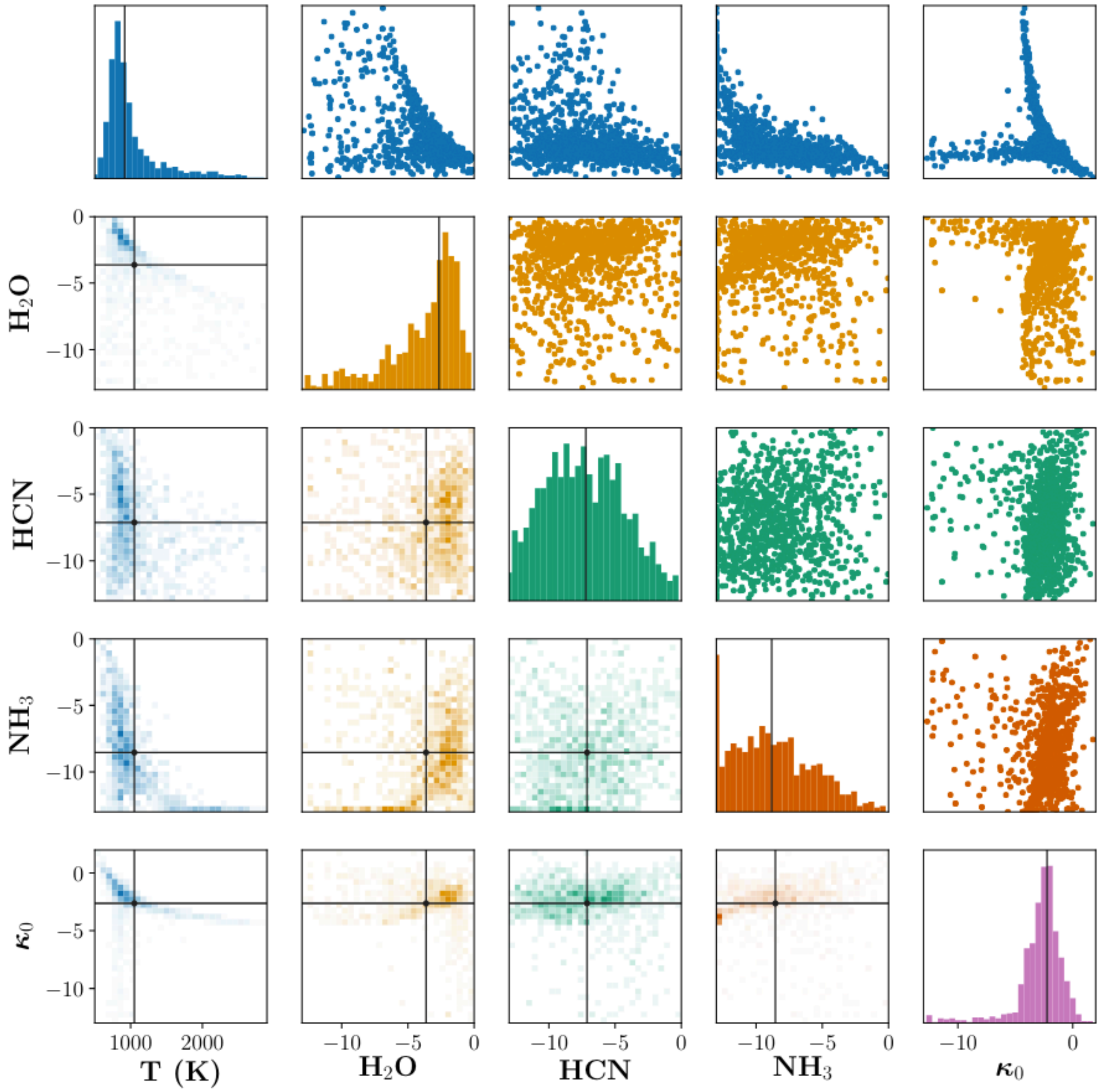




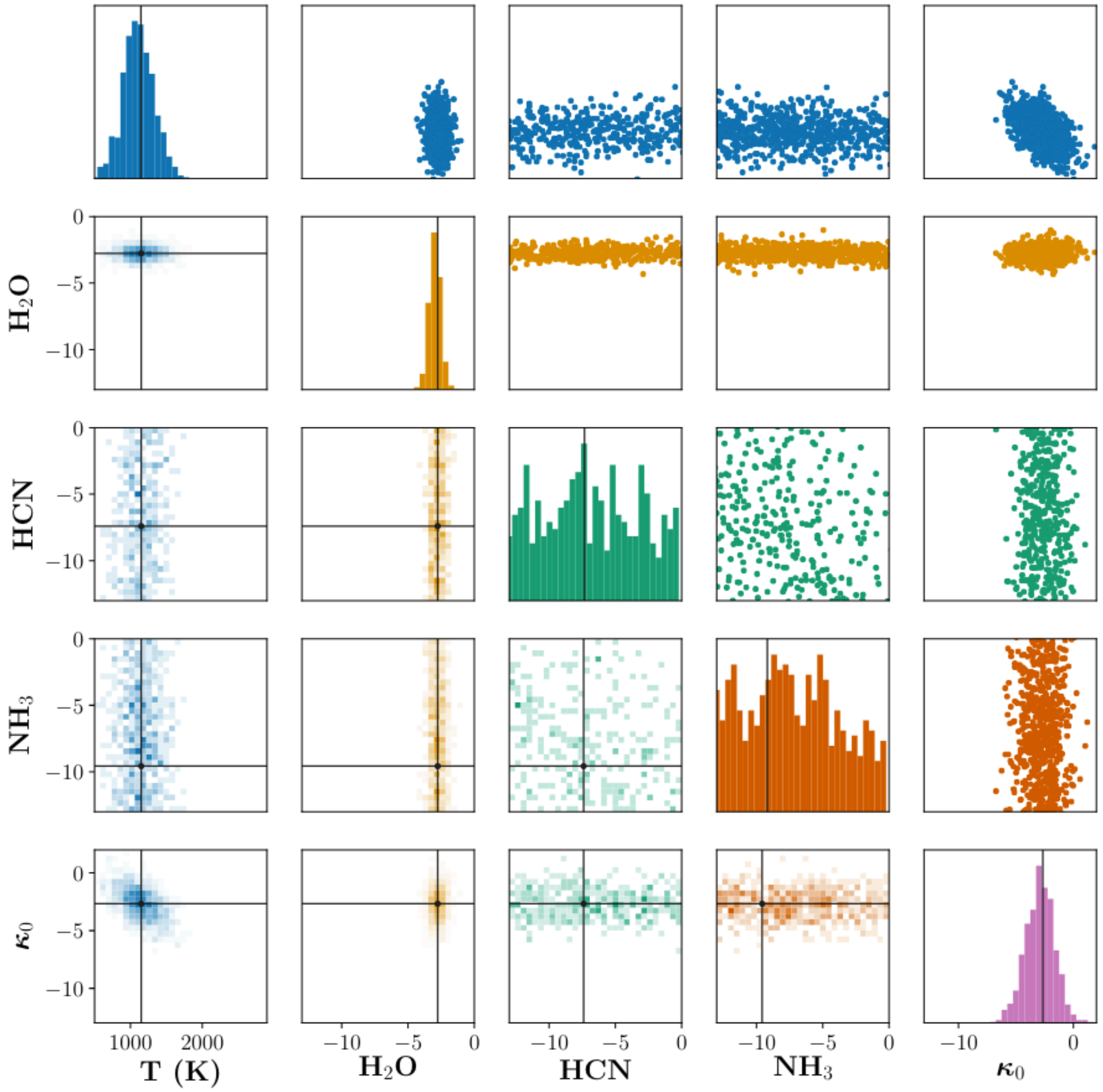
Spectral inversion

Recent promising frameworks

Random Forests
(Marquez-Neila et al. 2018)
(Komba et al. in prep)



Bayesian Neural Network
(Cobb et al. 2019)



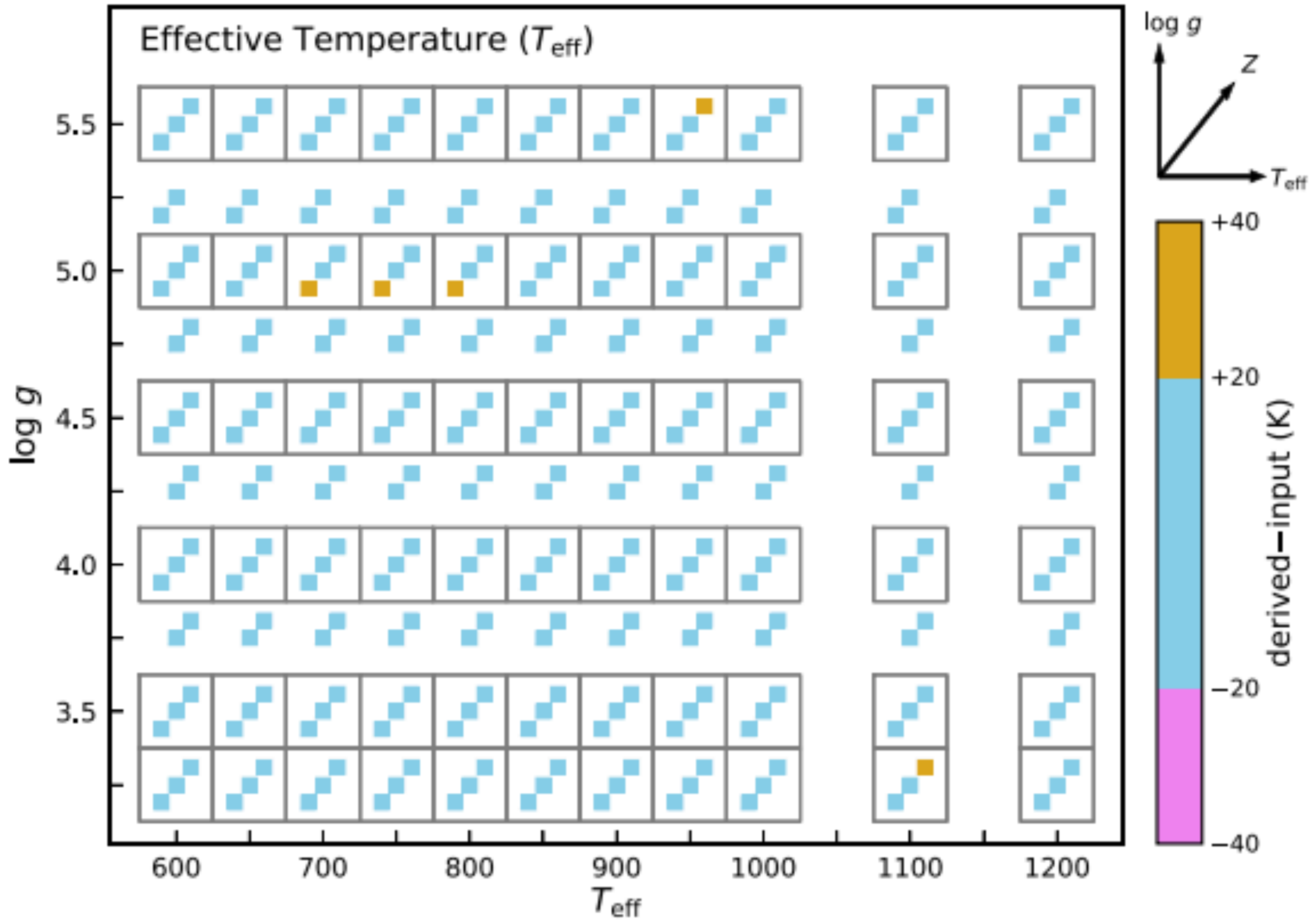
Spectral inversion

Recent promising frameworks

Bayesian inference with model and instrument error imputation

(STARFISH: Czekala et al. 2015)

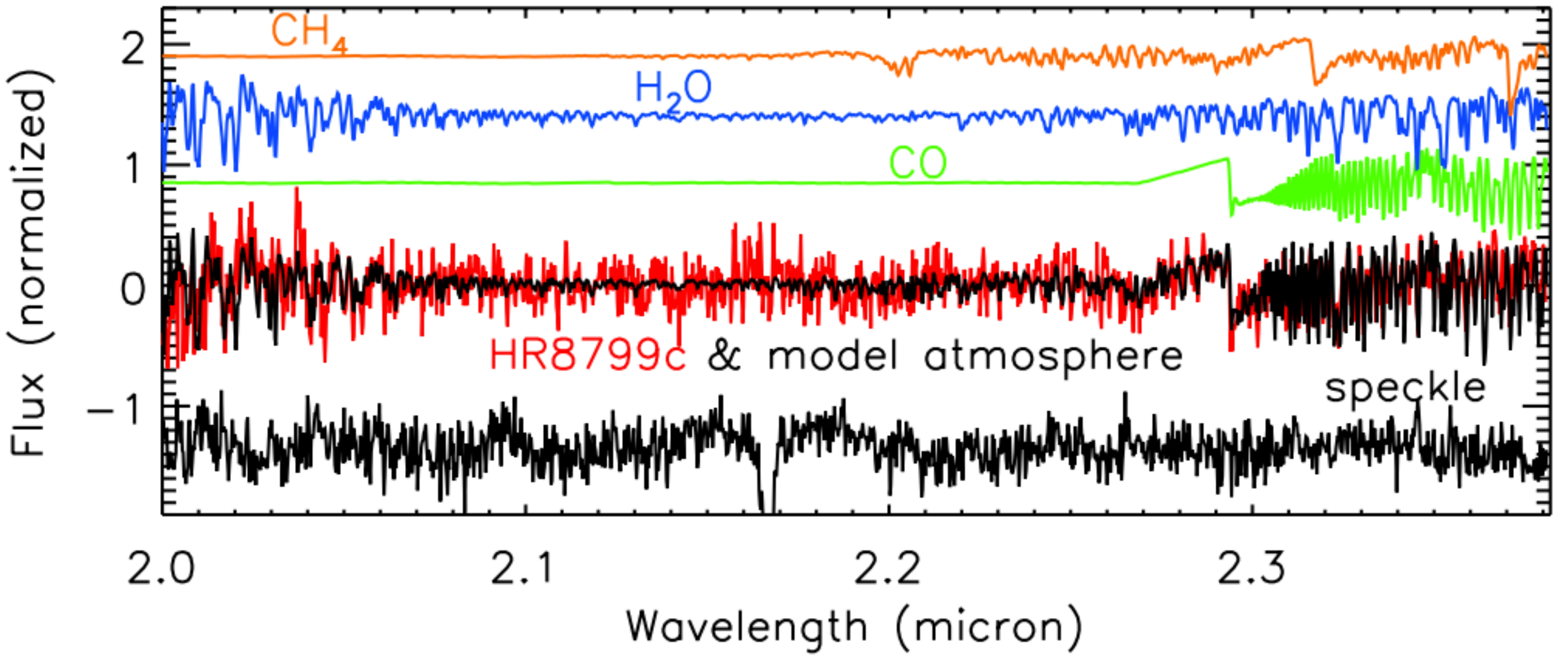
(ZAPSE : Brahm et al. 2017)



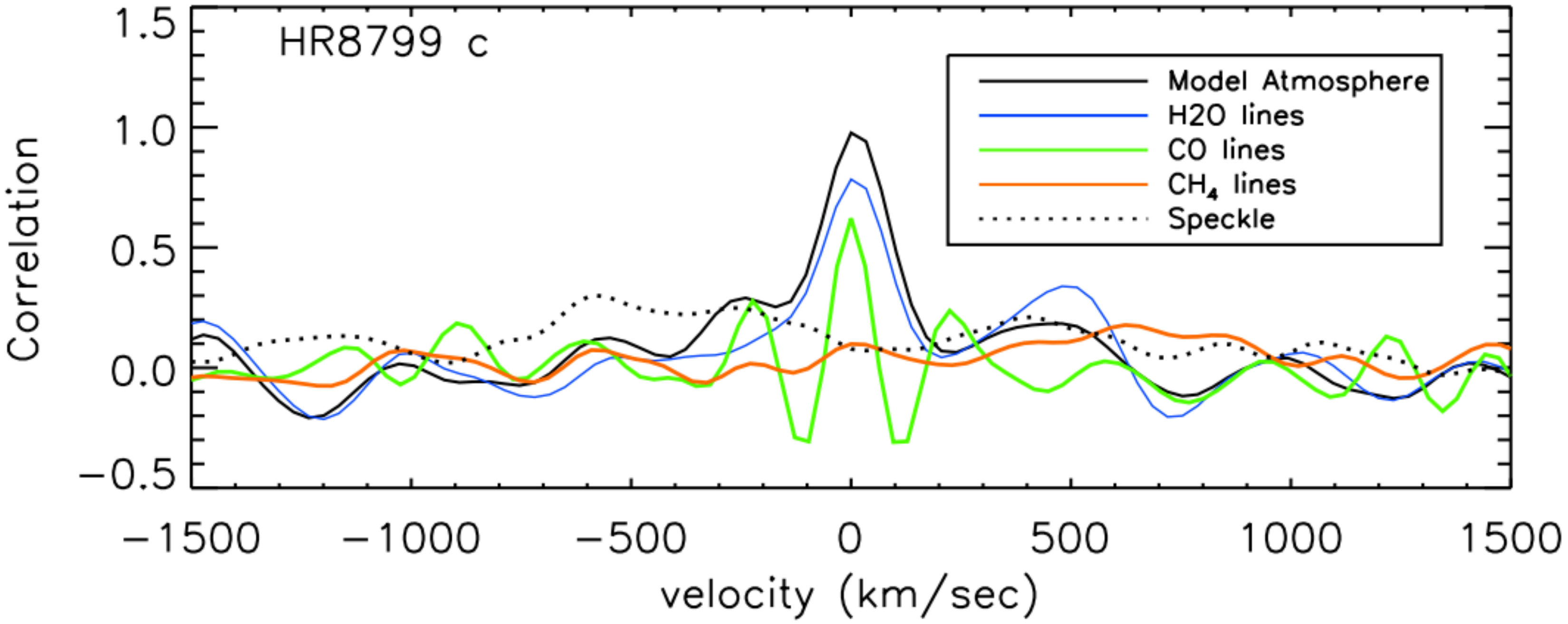
(Zhang et al. 2022)

Compling the detection and characterization

Cross-correlation of spectra with molecular templates



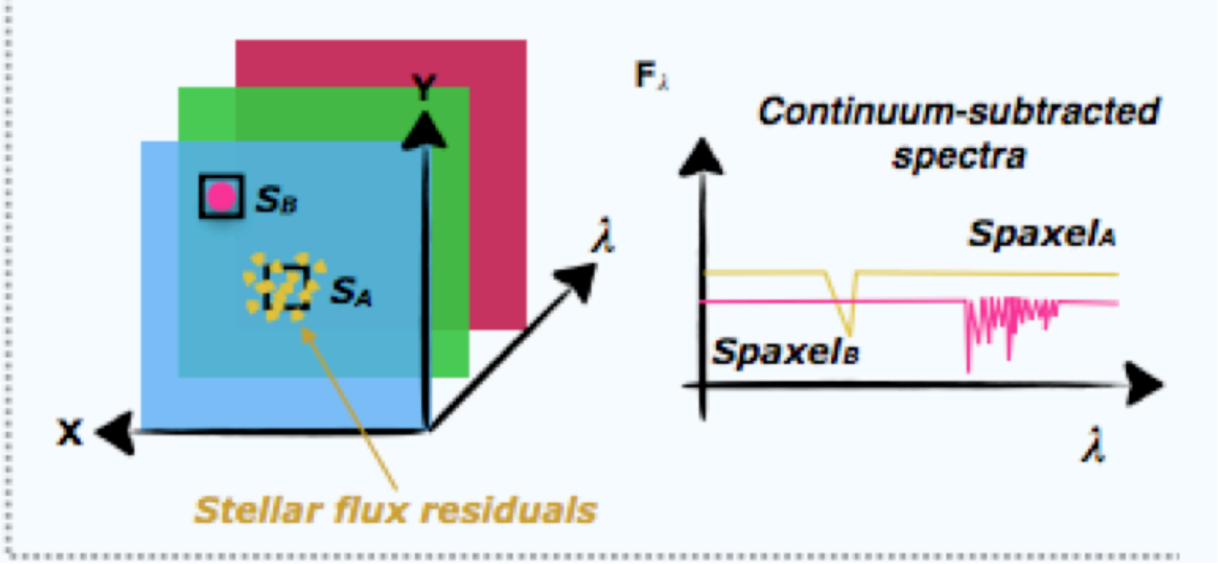
Konopacky et al. 2013

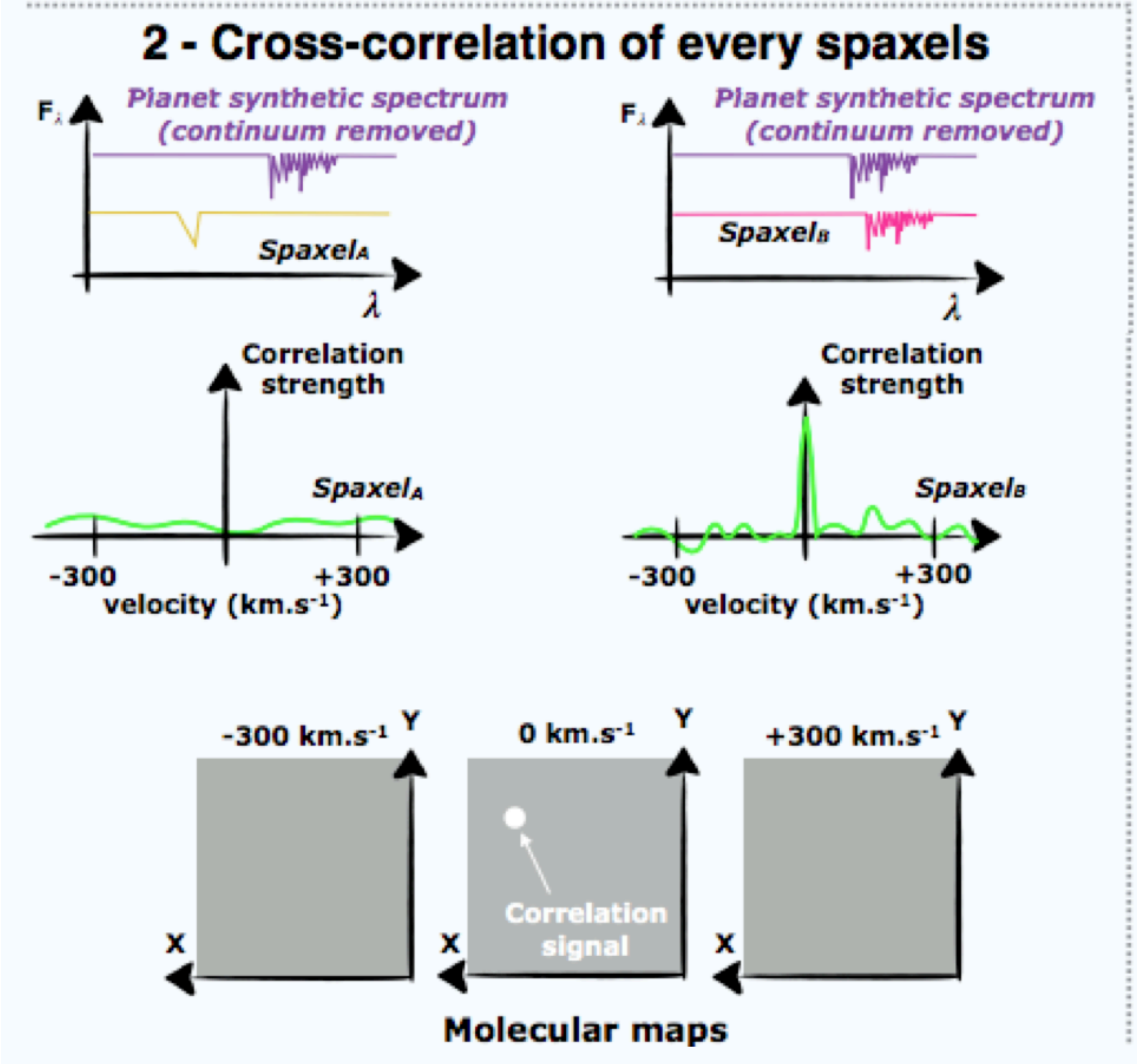


$$r_{x_1,x_2}(\tau) = \sum_{t=1}^{T} x_1(t)x_2(t-\tau)$$

Compling the detection and characterization

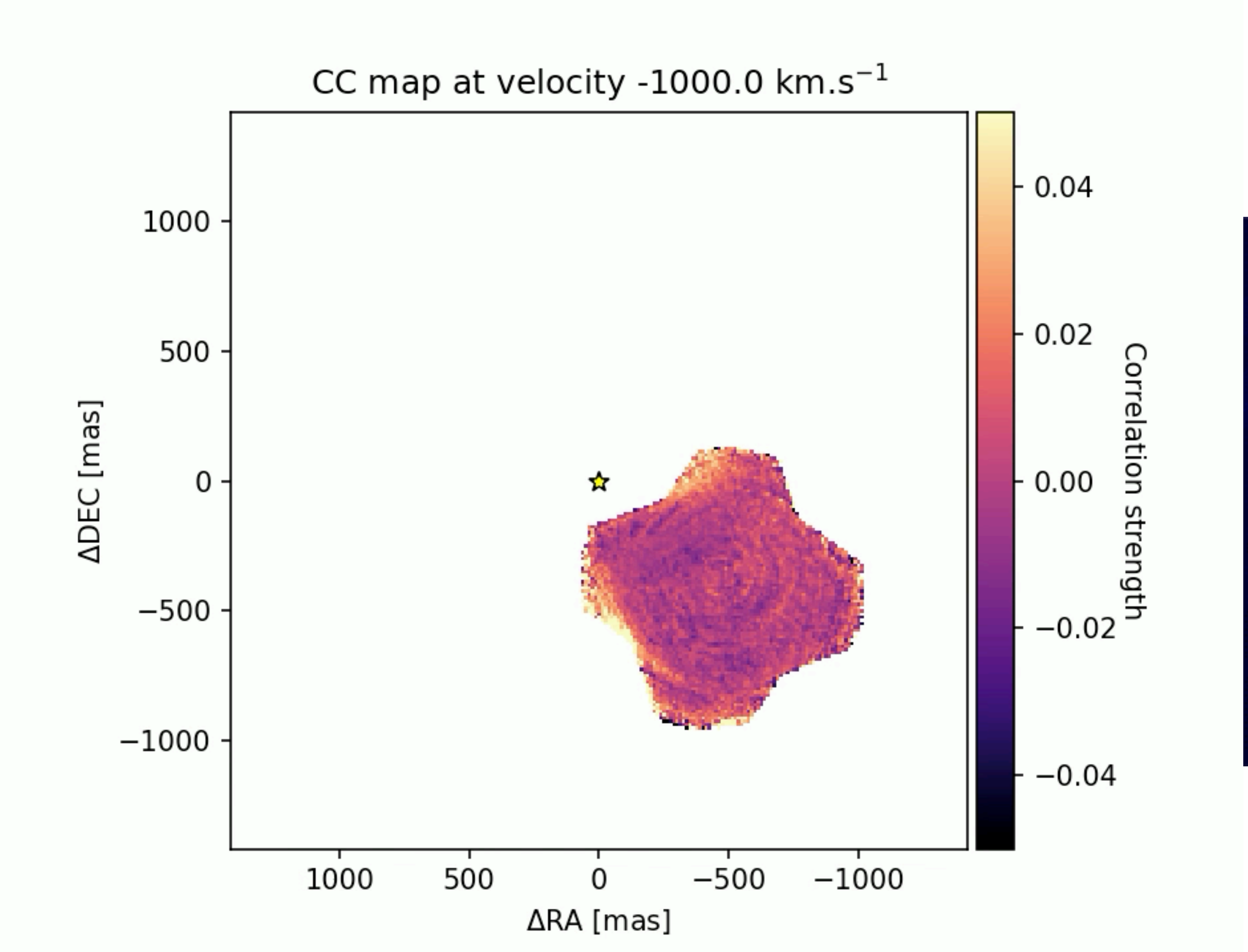
The molecular mapping technique

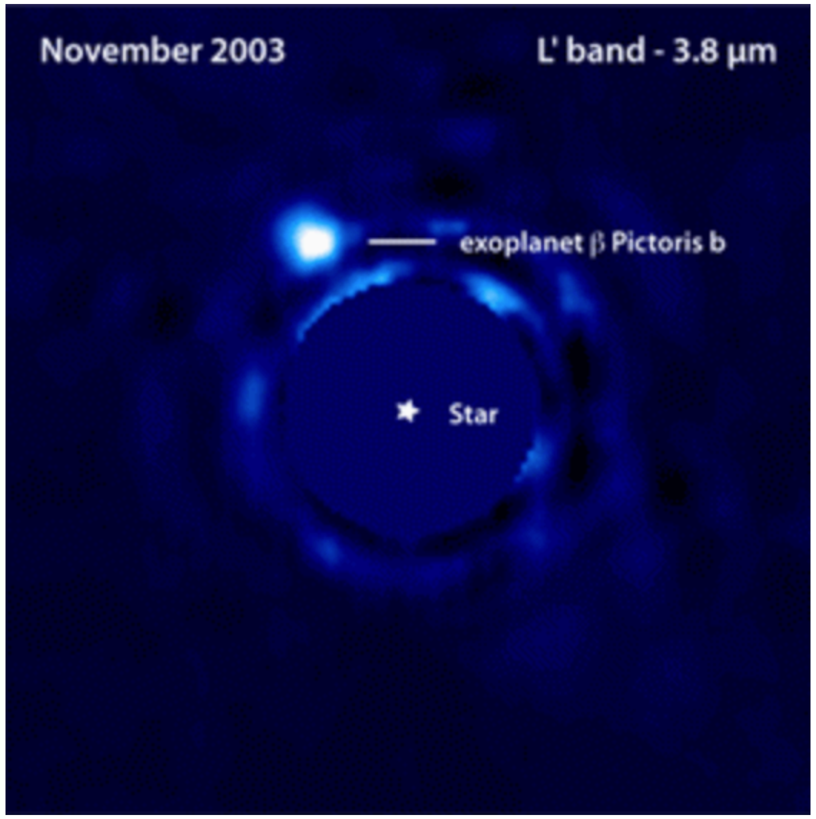




Compling the detection and characterization

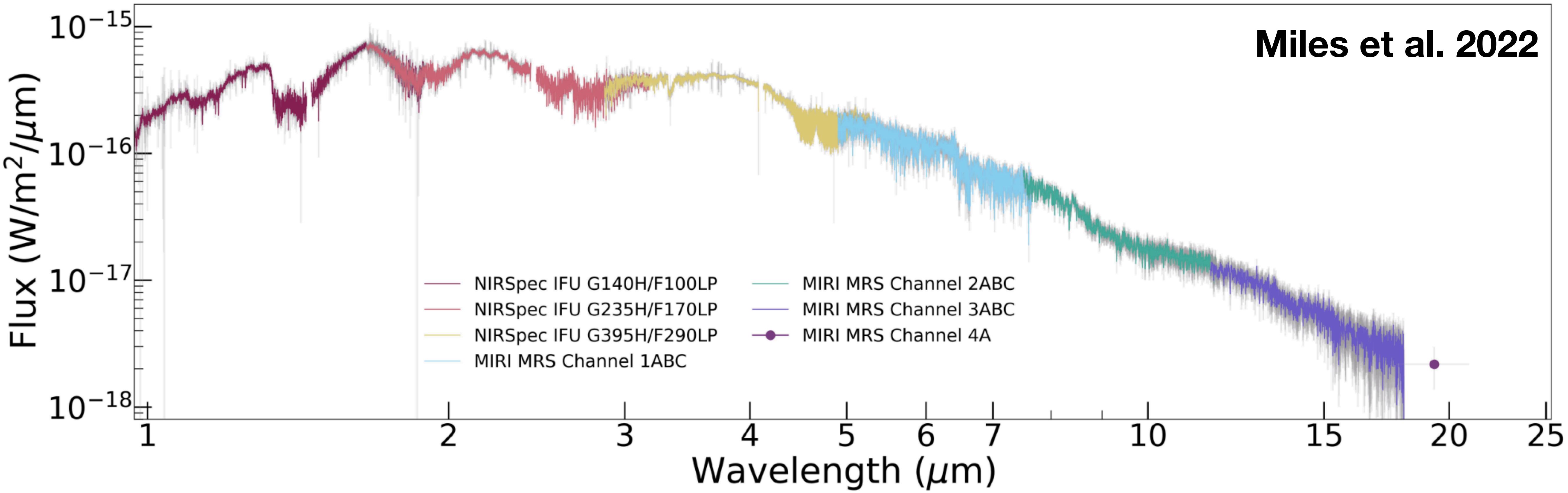
The molecular mapping technique



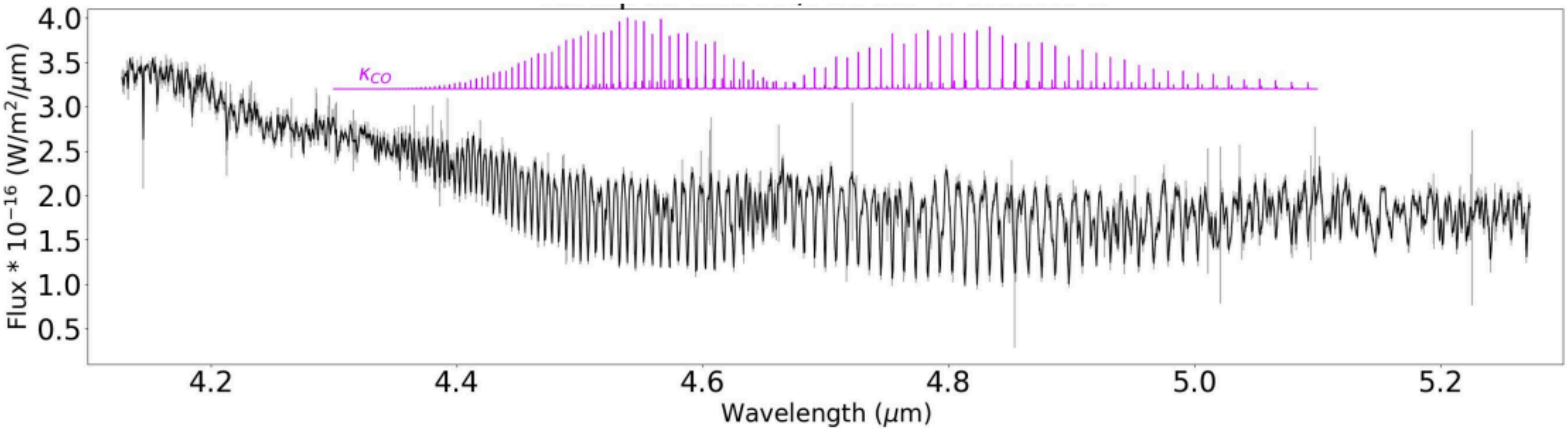


Hoeijmakers et al. 2018

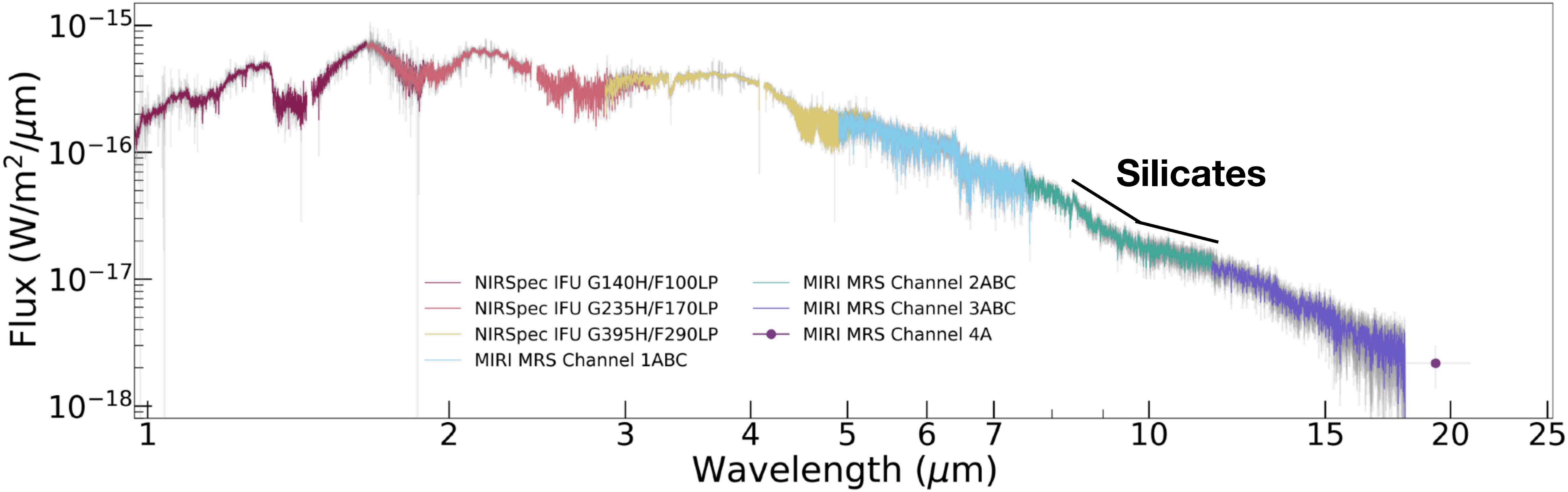
Access to MIR



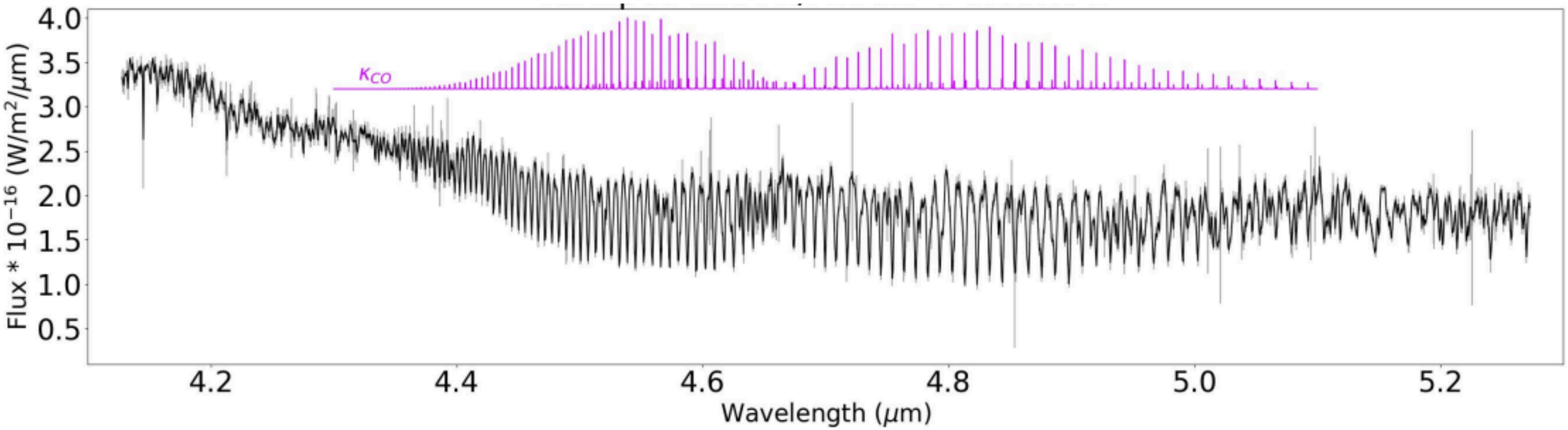
Miles et al. 2022



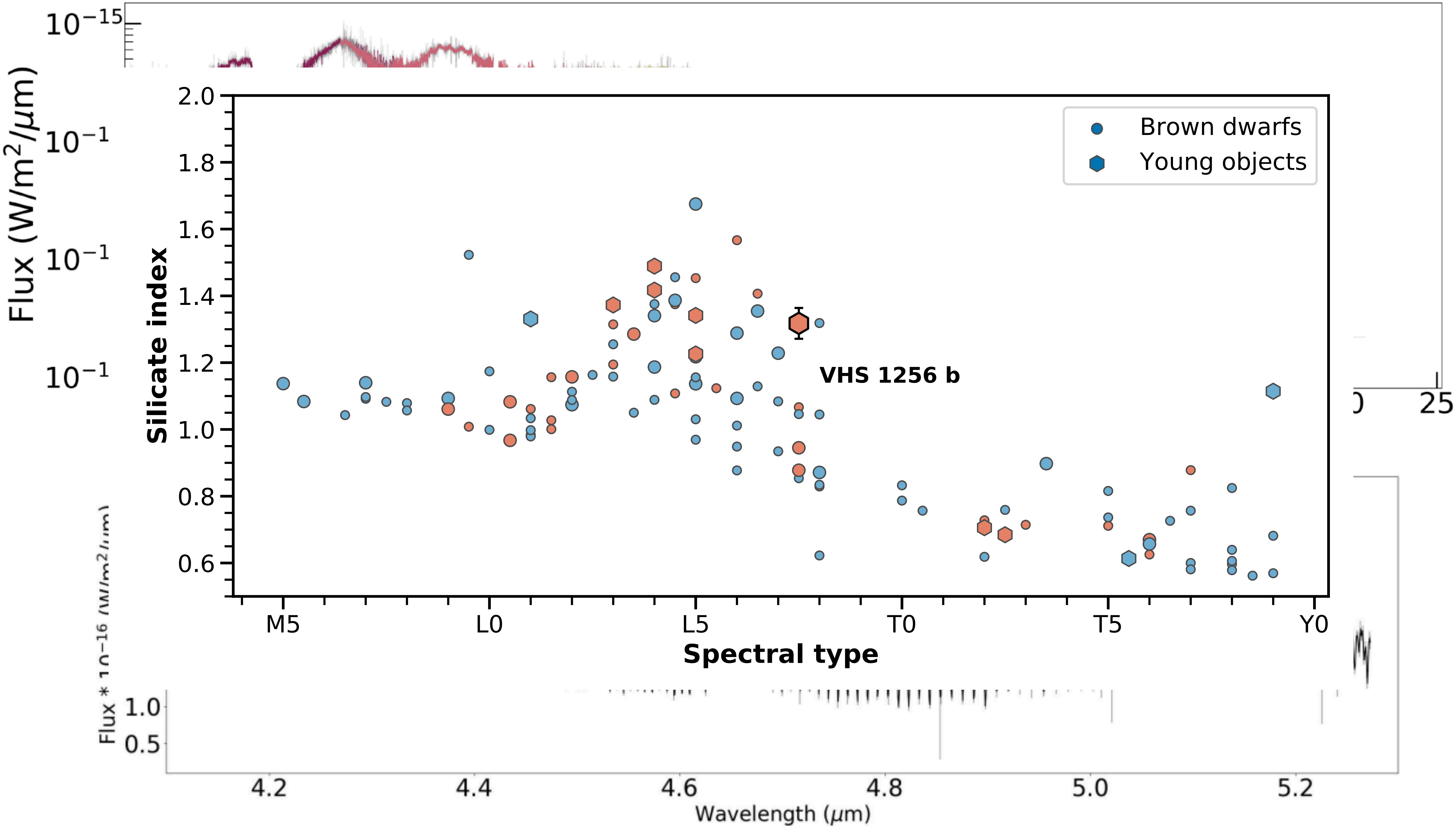
Access to MIR



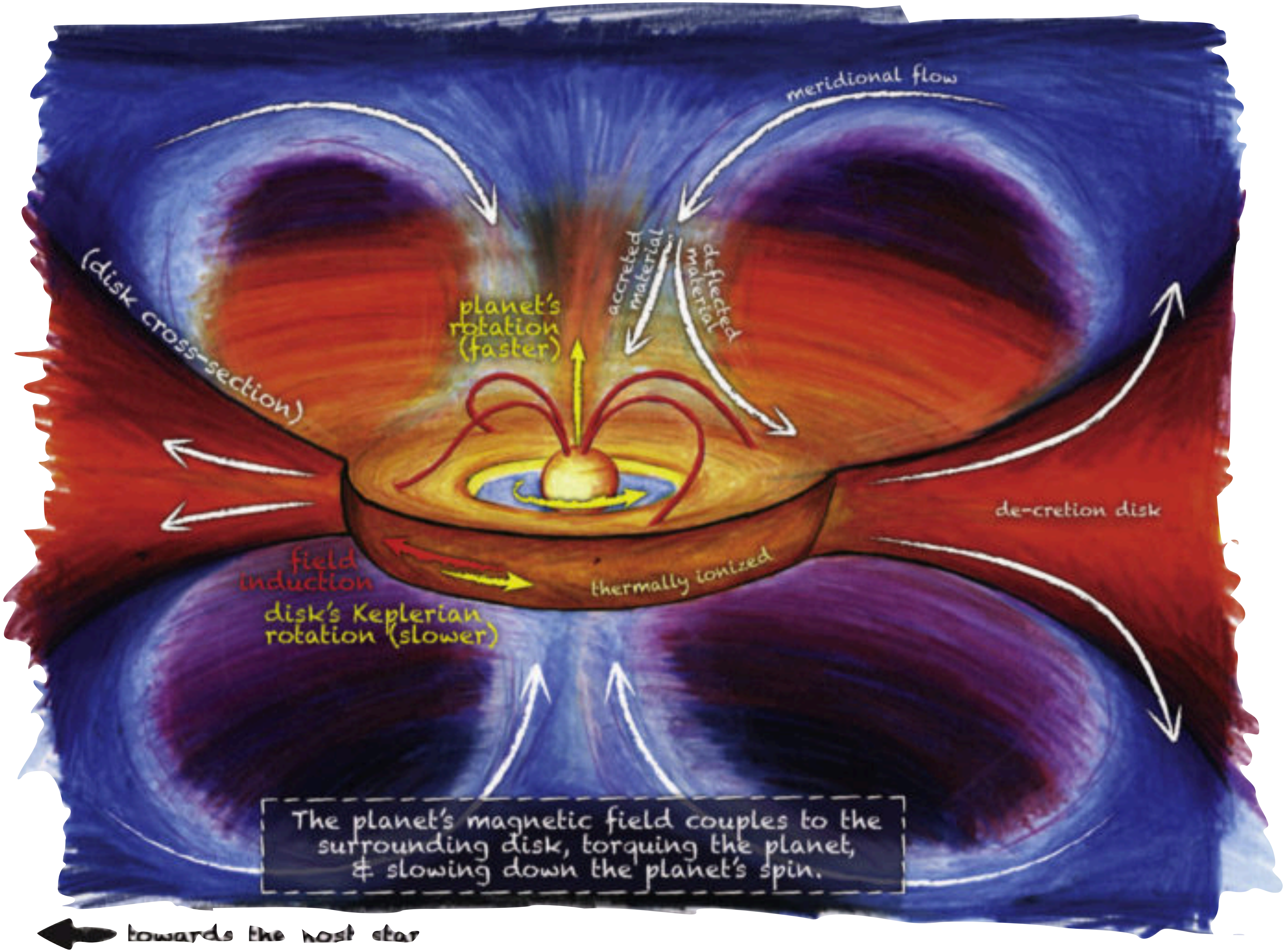
Silicates



Access to MIR

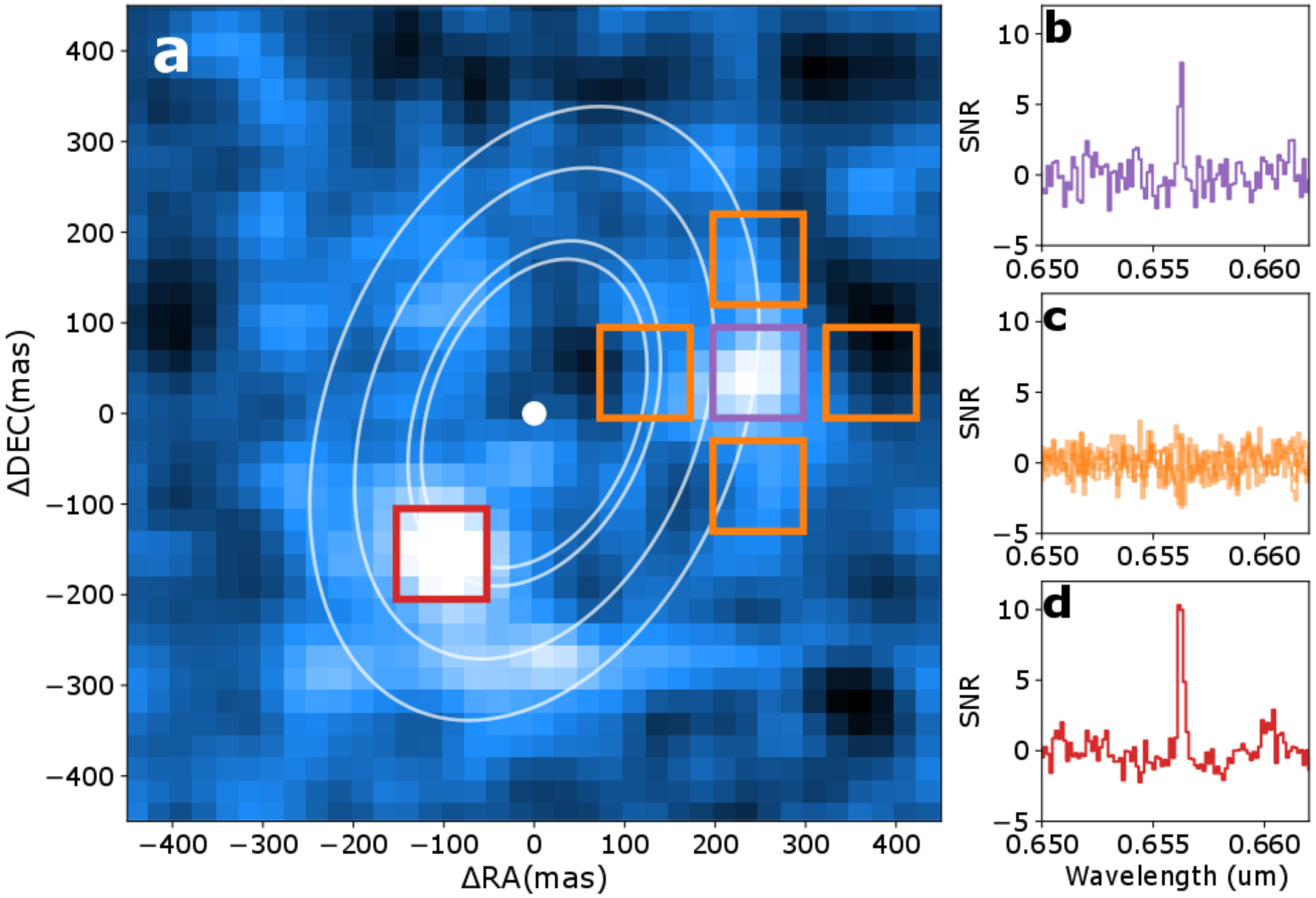


Characterizing the youngest exoplanets



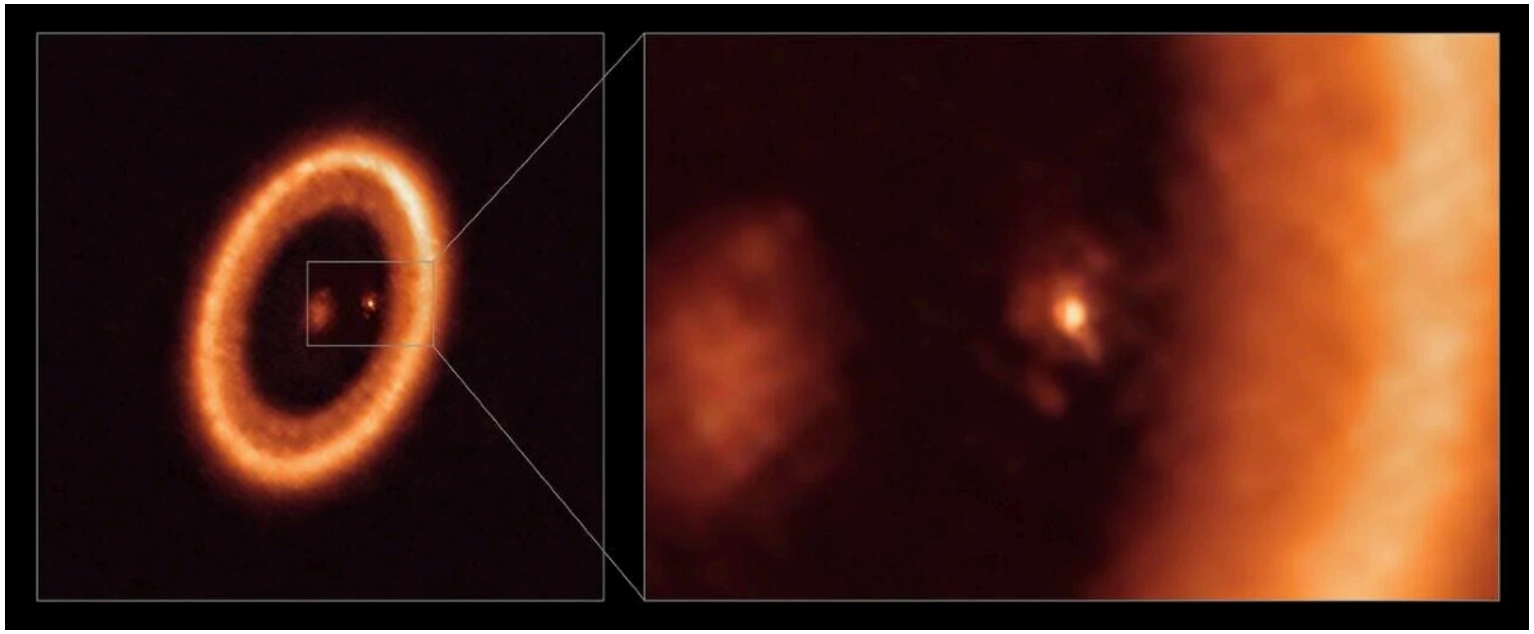
Characterizing the youngest exoplanets

Discovery of forming exoplanets



PDS70 b and c

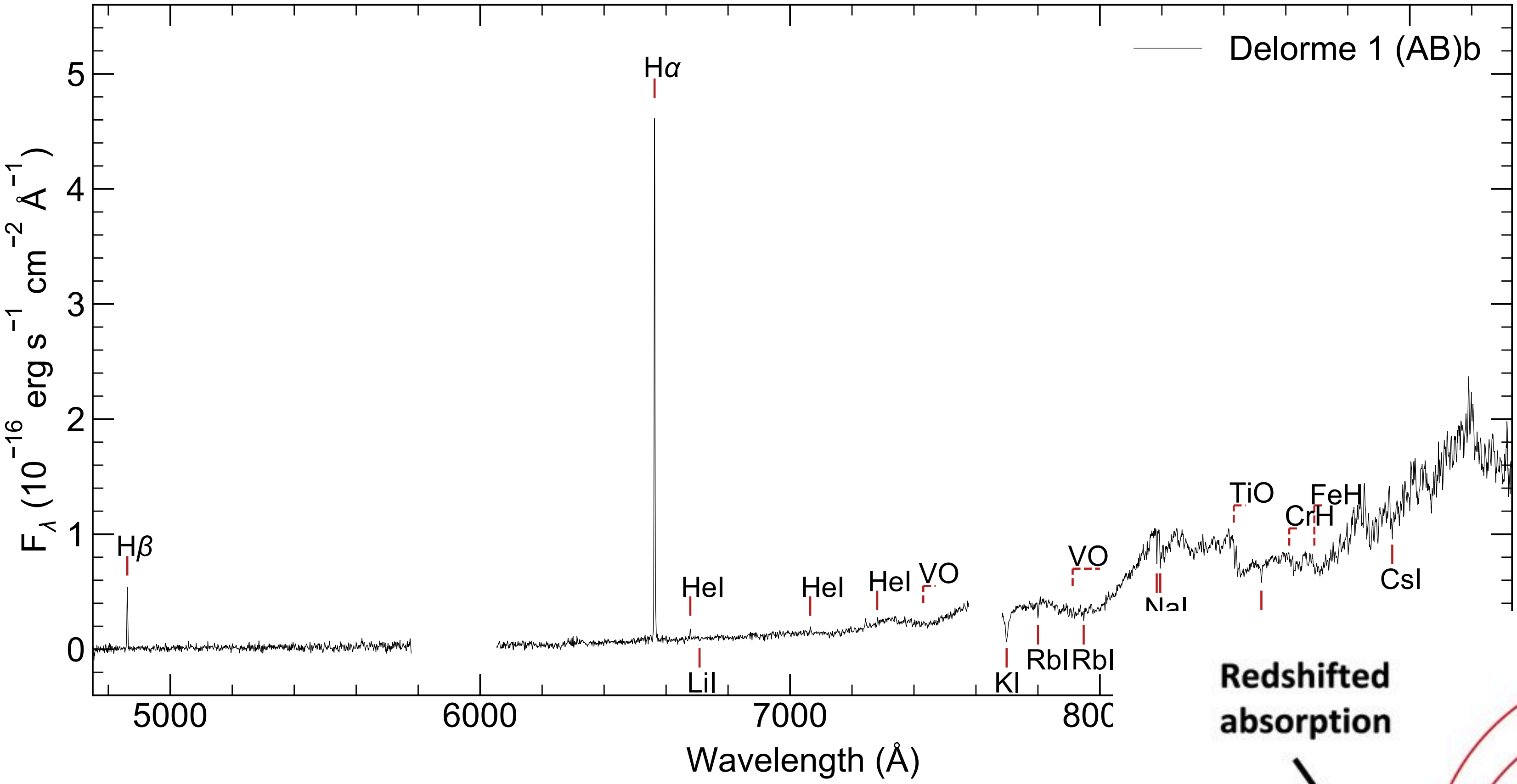
- Two accreting giant planets at 22 and 34au
- Within a circumstellar disk cavity

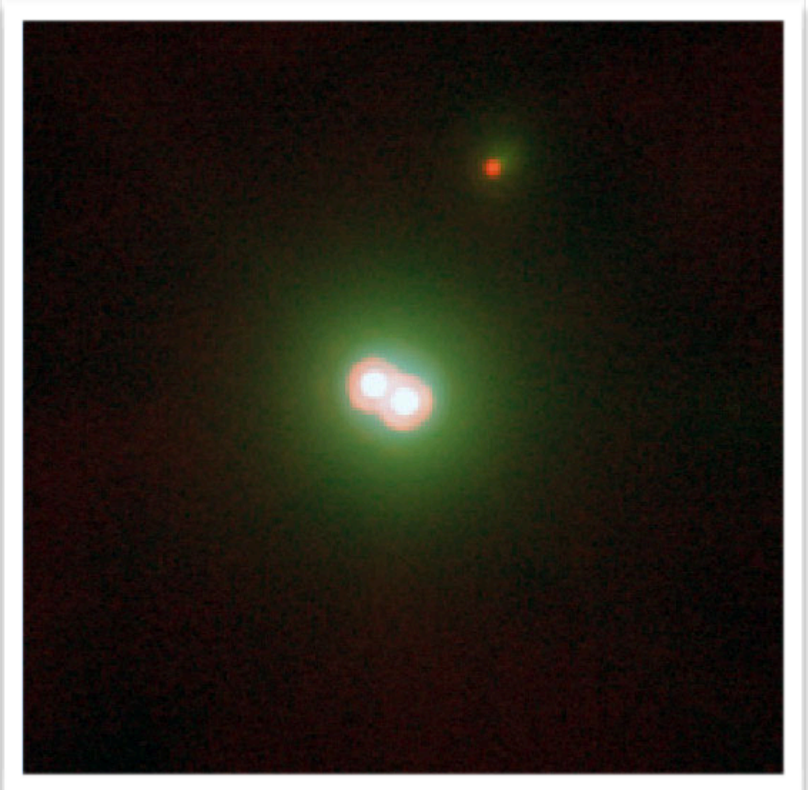


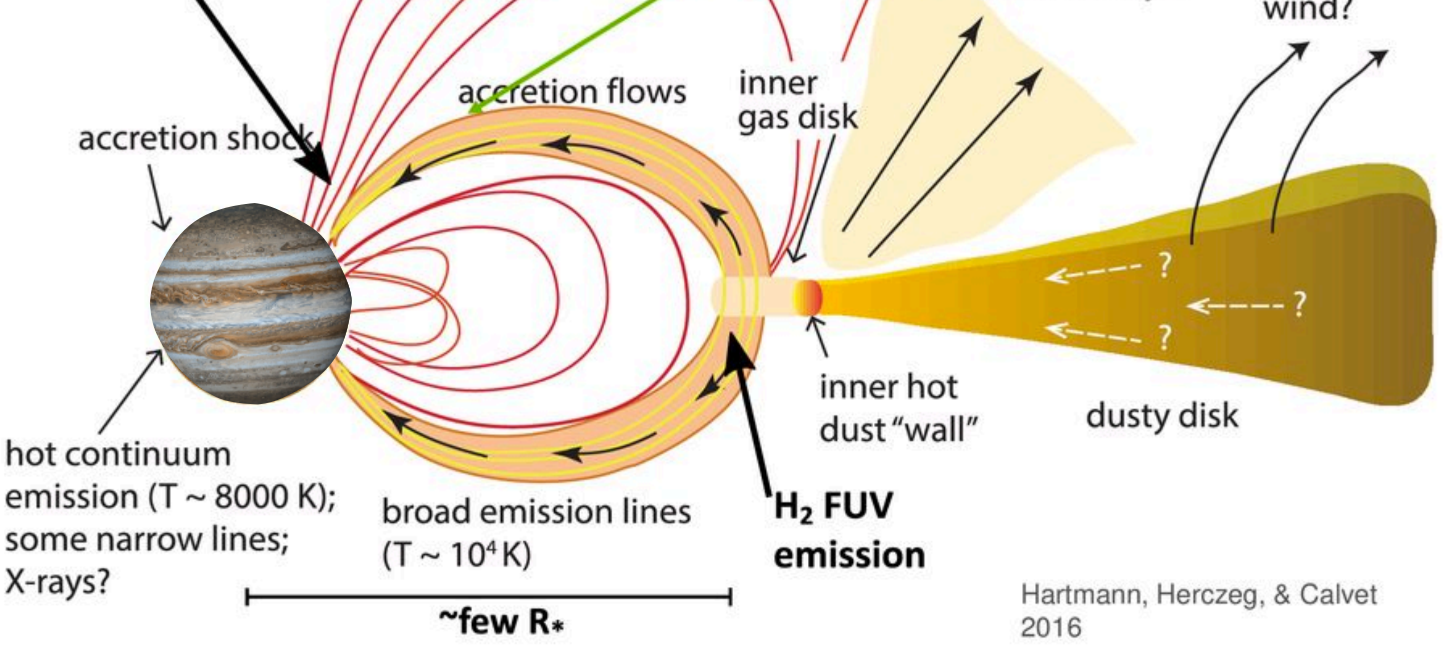
Keppler et al. 2018
Haffert et al. 2019
Benisty et al. 2021

Characterizing the youngest exoplanets

Discovery of forming exoplanets



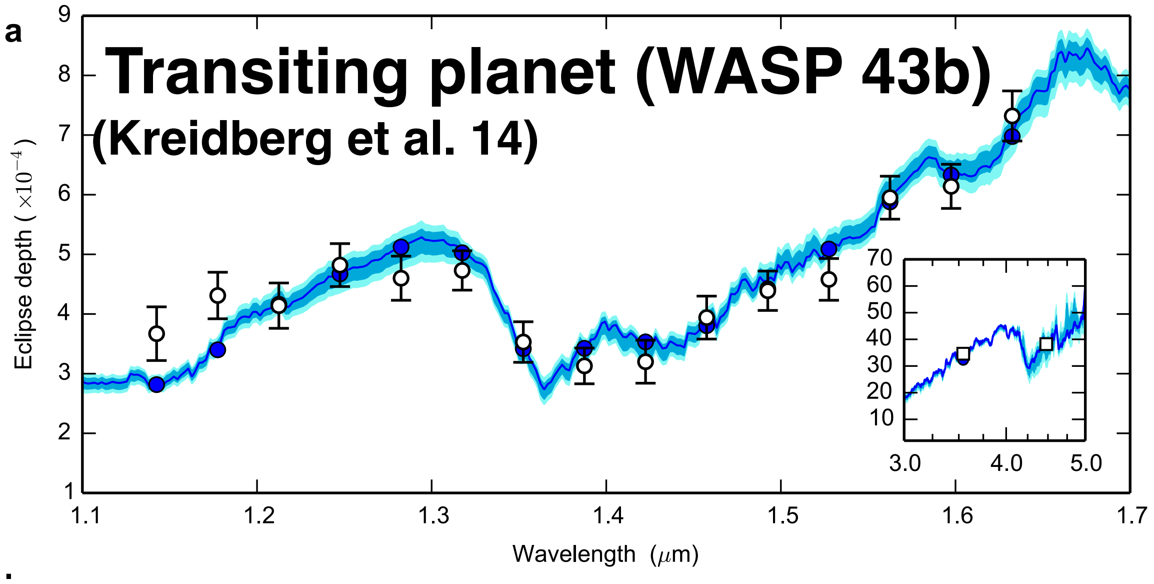


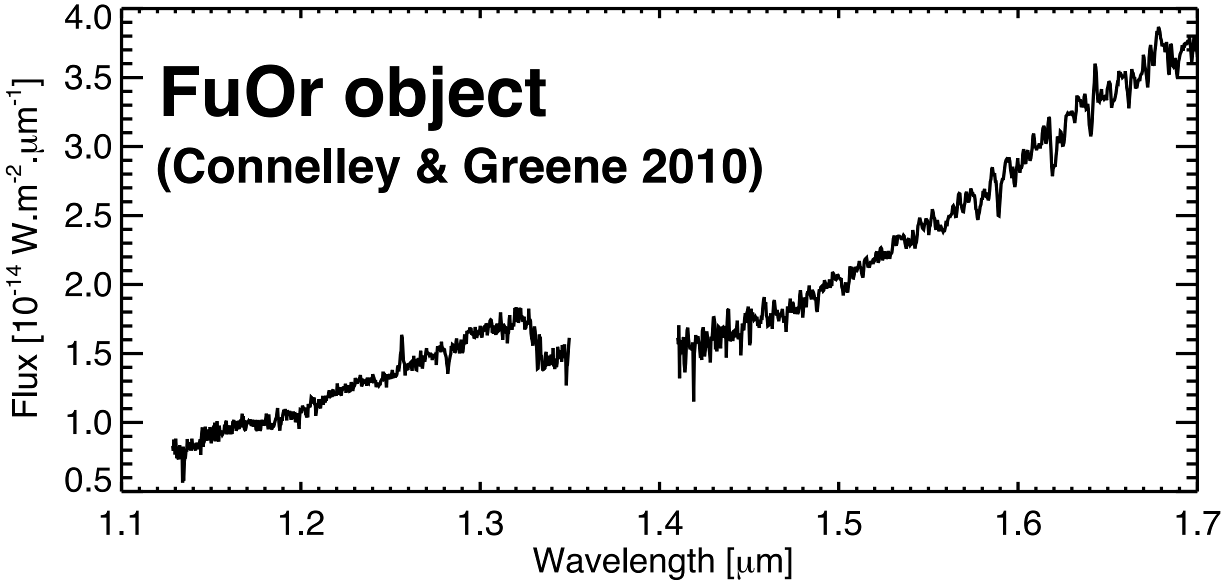


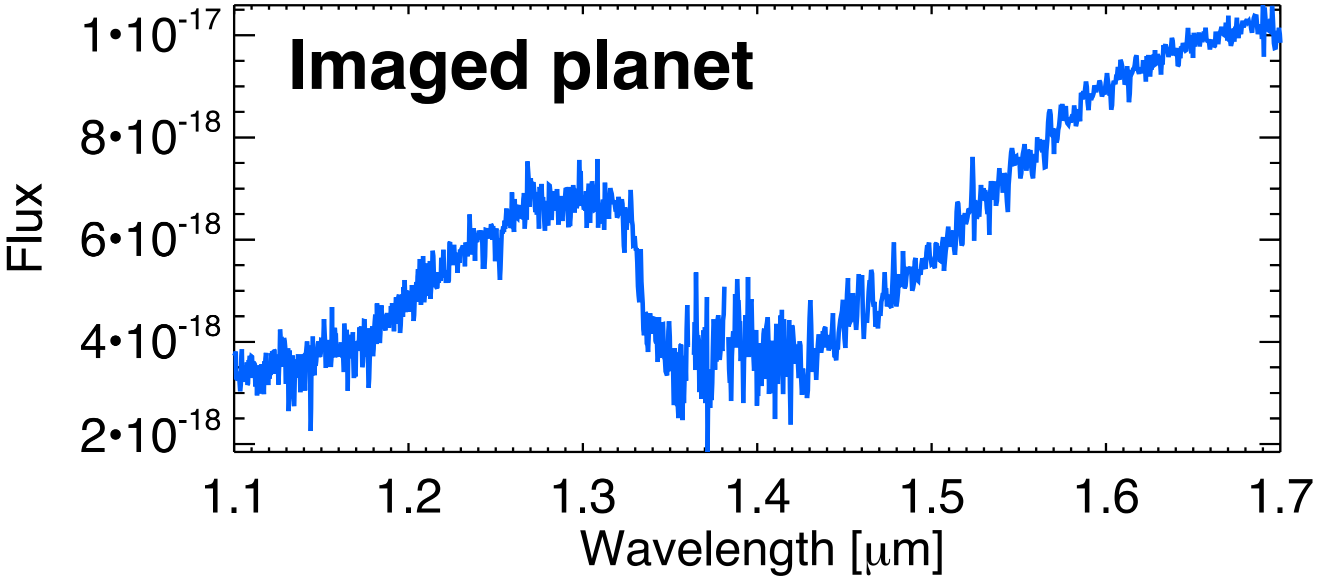
Hartmann, Herczeg, & Calvet 2016

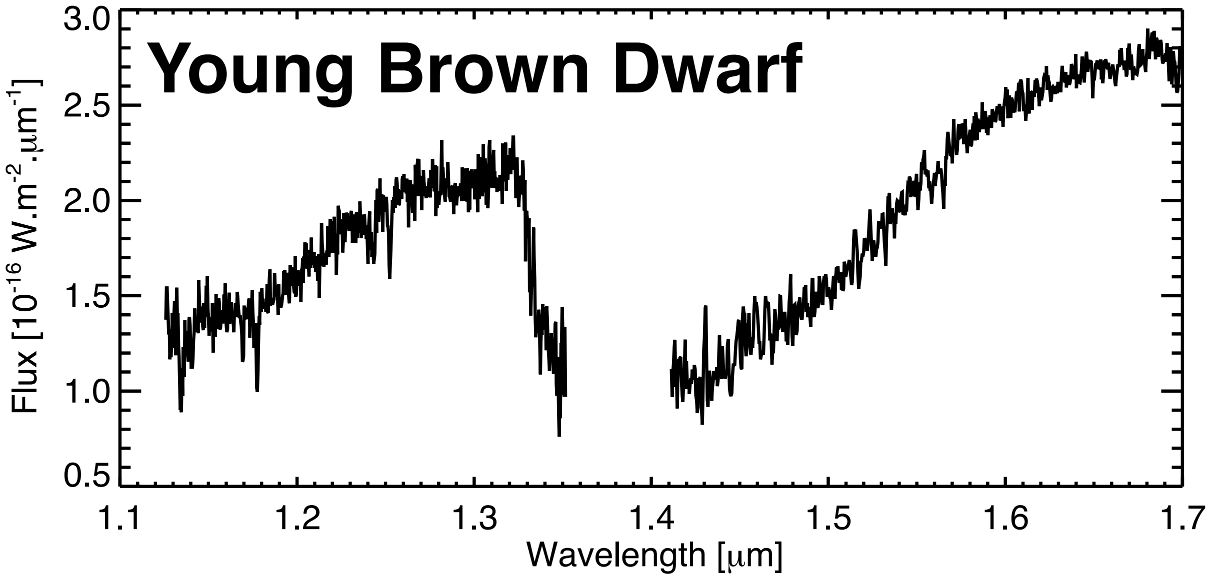
Characterizing the youngest exoplanets

Discovery of forming exoplanets


Transiting planet (WASP 43b)
(Kreidberg et al. 14)


FuOr object
(Connelley & Greene 2010)


Imaged planet


Young Brown Dwarf

Summary

- High-fidelity spectra of young Jovian exoplanets
- Empirical approach:

  young planets are red and faint: role of dust clouds?

  free-floating exoplanets = analogues of imaged exoplanets around stars

- Modeling:

  two different inversion methods (forward modelling and retrieval)

  models with different proposed ingredients

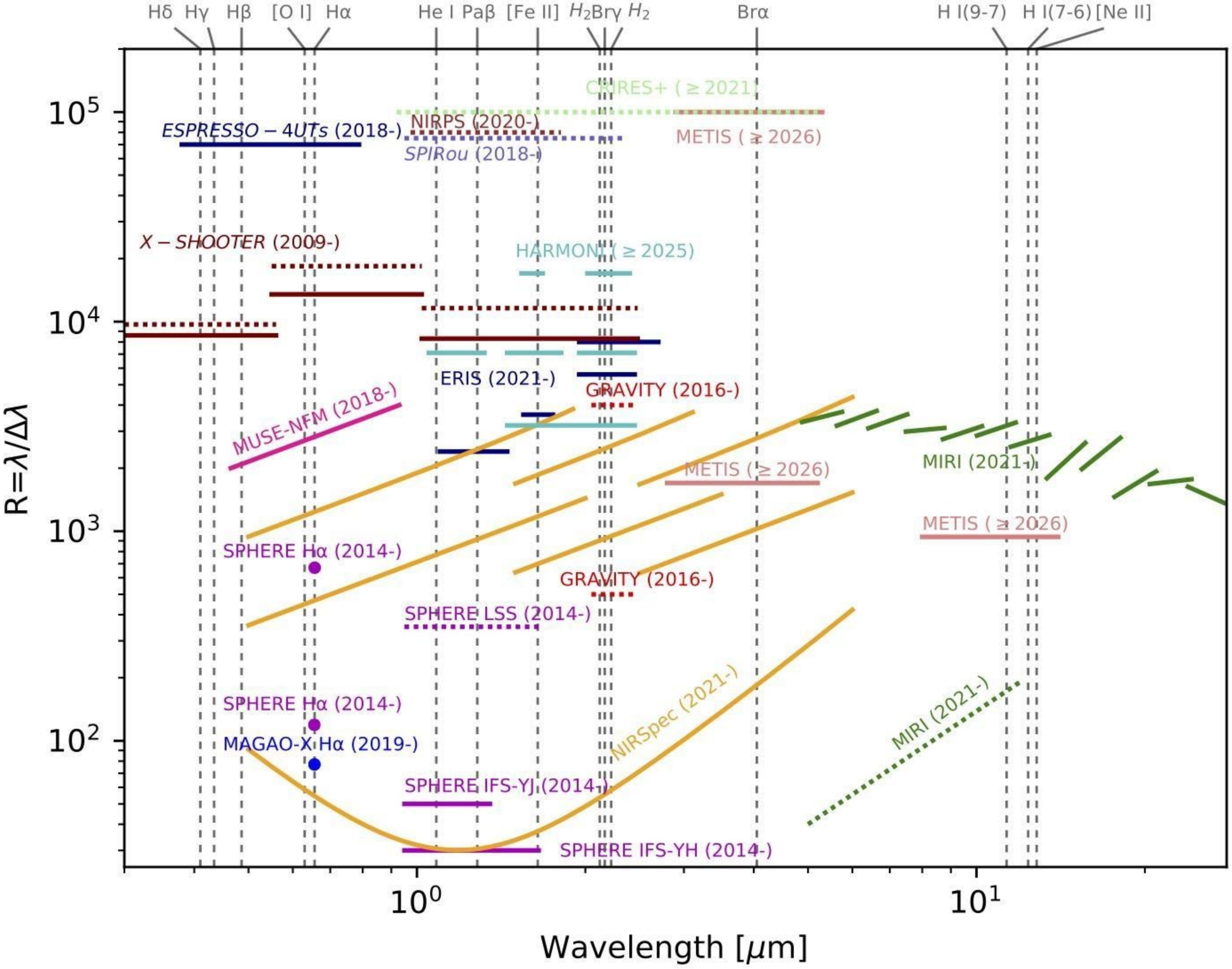
  new problematics emerging (systematics in models, etc)

- Youngest exoplanets

  witnessing accretion phenomenon

  complex environment around the planet (disk material)

Prospects


Hδ
Hγ
Hβ
[O I]
Hα
He I
Paβ
[Fe II]
H_2
Brγ
H_2
Brα
H I(9-7)
H I(7-6)
[Ne II]
10^5
10^4
10^3
10^2
R=λ/Δλ
10^0
10^1
Wavelength [μm]
CRIRES+ (≥ 2021)
ESPRESSO − 4UTs (2018-)
NIRPS (2020-)
SPIRou (2018-)
METIS (≥ 2026)
X − SHOOTER (2009-)
HARMONI (≥ 2025)
ERIS (2021-)
GRAVITY (2016-)
MUSE-NFM (2018-)
METIS (≥ 2026)
MIRI (2021-)
METIS (≥ 2026)
SPHERE Hα (2014-)
GRAVITY (2016-)
SPHERE LSS (2014-)
SPHERE Hα (2014-)
MAGAO-X Hα (2019-)
NIRSpec (2021-)
MIRI (2021-)
SPHERE IFS-YJ (2014-)
SPHERE IFS-YH (2014-)