

On the shoulders of Giants - May 25<sup>th</sup>-27<sup>th</sup>, 2026, Torino, Italy

# The ELT's Promise for Planet Formation & Exoplanet Exploration

Gaël Chauvin

(Max Planck Institute for Astronomy)

Thanks to: MORFEO-MICADO, METIS, HARMONI, ANDES, PCS science teams & particularly: O. Absil, G. Orban de Xivry, E. Huby, P. Baudoz, M. Turbet, J. Birkby, A. Carlotti, V. Christiaens, S. Hinkley, M. Houllé, E. Palte, P. Palma-Bifani, S. Quanz, E. Tolstoy, S. Desidera, A. Boccaletti, A. Vigan...



UNIVERSITÄT  
HEIDELBERG  
ZUKUNFT  
SEIT 1386

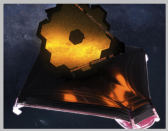


# Entering the Era of Giants

## Opening a new Horizon

- Increased **Sensitivity**
- Improved **Spatial Resolution** (10 mas scale, 1 au for a star @100pc)
- Instrumentation **Versatility** (access high- $R_\lambda$ ), & **Lifetime** over at least 40-50 years of operation...

JWST



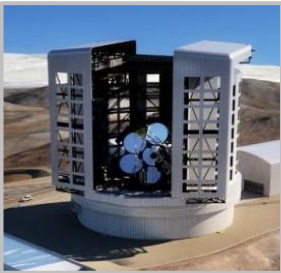
6.2m, 25m<sup>2</sup>  
68mas

VLT



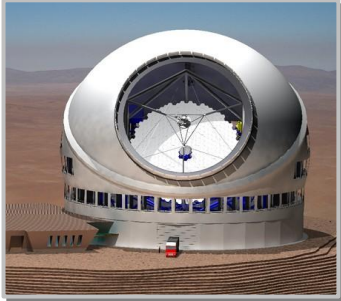
8.2m, 50m<sup>2</sup>  
50mas

GMT



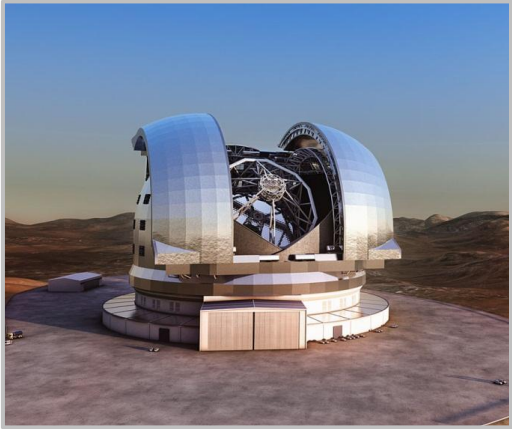
25m, 400m<sup>2</sup>  
18mas

TMT



30m, 600m<sup>2</sup>  
14mas

ELT



39m, 1200m<sup>2</sup>  
10mas

$\phi$ , area  
 $\lambda/D$  (2 $\mu$ m)

<https://www.eso.org/public/images/potw2605a/>

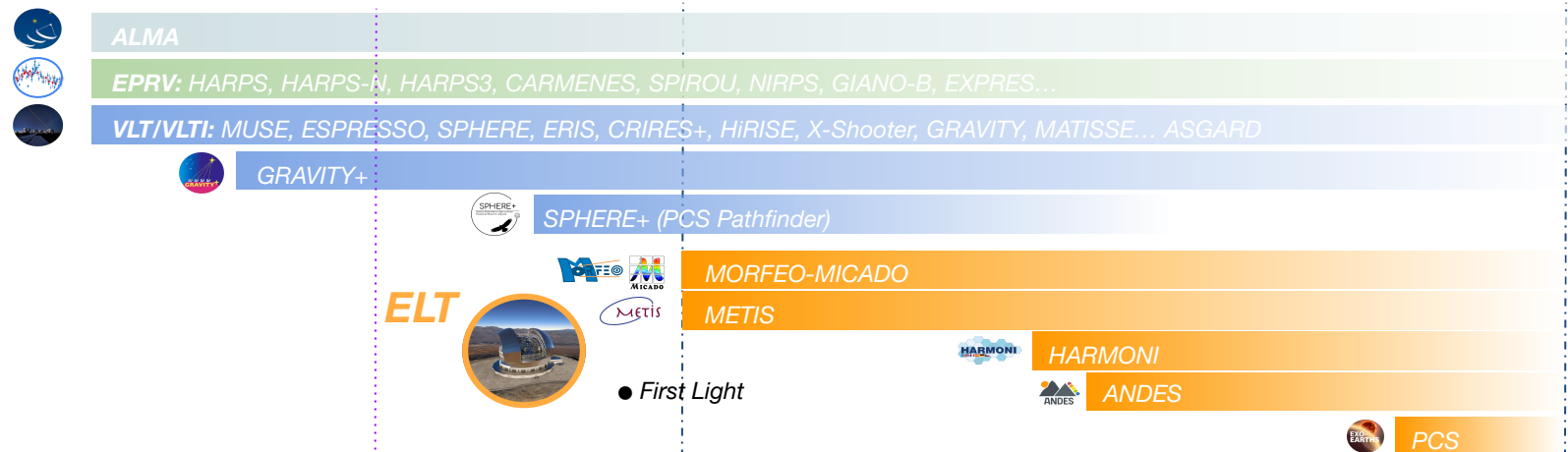
February 2026

Telescope First Light: March 2029

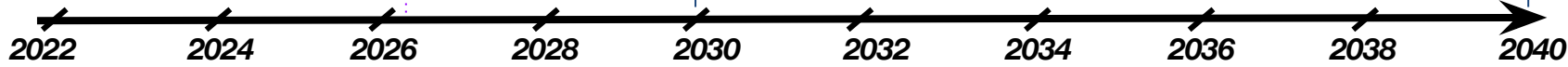


# A Golden Era for Exoplanets

## Ground



## Space



# Instrumental roadmap

★ with key science cases for planetary formation & exoplanets

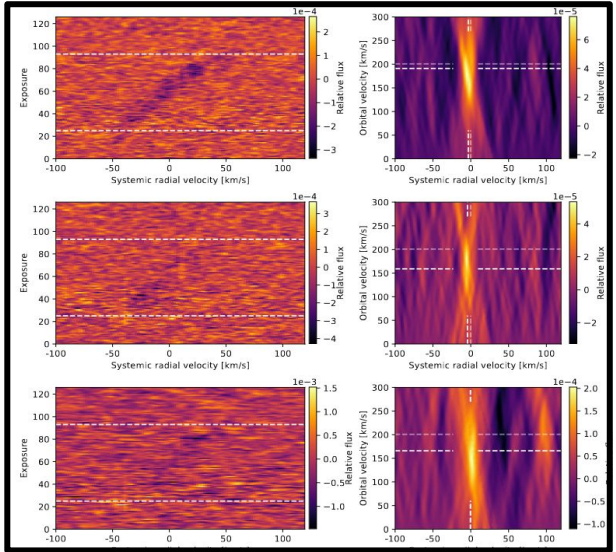
|    | Instrument                   | Main specifications  |  |                             | Schedule |               |      |     |             |           |
|----|------------------------------|--|--|-----------------------------|----------|---------------|------|-----|-------------|-----------|
|    |                              | Field of view/slit length/<br>pixel scale  | Spectral<br>resolution   | Wavelength<br>coverage (μm) | Phase A  | Project start | PDR  | FDR | First light |           |
| ★  | MICADO                       | Imager (with coronagraph)<br>50.5" × 50.5" at 4 mas/pix<br>19" × 19" at 1.5 mas/pix                              | <i>I, Z, Y, J, H, K</i> +<br>narrowbands   | 0.8–2.45                    | 2010     | 2015          | 2019 |     |             | 2030      |
|    |                              | Single slit  | <i>R</i> ~ 20 000  |                             |          |               |      |     |             |           |
|    | MORFEO                       | AO Module<br>SCAO – MCAO   |  | 0.8–2.45                    | 2010     | 2015          | 2023 |     |             | 2032      |
| ★  | HARMONI +<br><del>LTAO</del> | IFU 4 spaxel scales from:<br>0.8" × 0.6" at 4 mas/pix to<br>6.1" × 9.1" at 30 × 60 mas/pix<br>(with coronagraph) | <i>R</i> ~ 3 200<br><i>R</i> ~ 7 100<br><i>R</i> ~ 17 000                                  | 0.47–2.45                   | 2010     | 2015          | 2018 |     |             | 2034–2025 |
| ★★ | METIS                        | Imager (with coronagraph)<br>10.5" × 10.5" at 5 mas/pix in <i>L, M</i><br>13.5" × 13.5" at 7 mas/pix in <i>N</i> | <i>L, M, N</i> +<br>narrowbands  | 3–13                        | 2010     | 2015          | 2019 |     |             | 2030      |
|    |                              | Single slit  | <i>R</i> ~ 1 400 in <i>L</i><br><i>R</i> ~ 1 900 in <i>M</i><br><i>R</i> ~ 400 in <i>N</i> |                             |          |               |      |     |             |           |
|    |                              | IFU 0.6" × 0.9" at 8 mas/pix<br>(with coronagraph)   | <i>L, M</i> bands<br><i>R</i> ~ 100 000  |                             |          |               |      |     |             |           |
| ★★ | ANDES                        | Single object  | <i>R</i> ~ 100 000   | 0.4–1.8 simultaneously      | 2018     |               |      |     |             | 2034–2035 |
|    |                              | IFU (SCAO)   |  |                             |          |               |      |     |             |           |
|    |                              | Multi object (TBC)   |  |                             |          |               |      |     |             |           |
| ★★ | MOSAIC                       | ~ 7-arcminute FoV<br>~ 200 objects (TBC)   | <i>R</i> ~ 5 000–20 000  | 0.45–1.8 (TBC)              | 2018     |               |      |     |             | 2034–2035 |
|    |                              | ~ 8 IFUs (TBC)   | <i>R</i> ~ 5 000–20 000  | 0.8–1.8 (TBC)               |          |               |      |     |             |           |
| ★★ | PCS                          | Extreme AO camera and<br>spectrograph  | TBC  | TBC                         |          |               |      |     |             | 2038+     |

1 milliarcsecond (mas) = 0.001"

# Workhorse modes

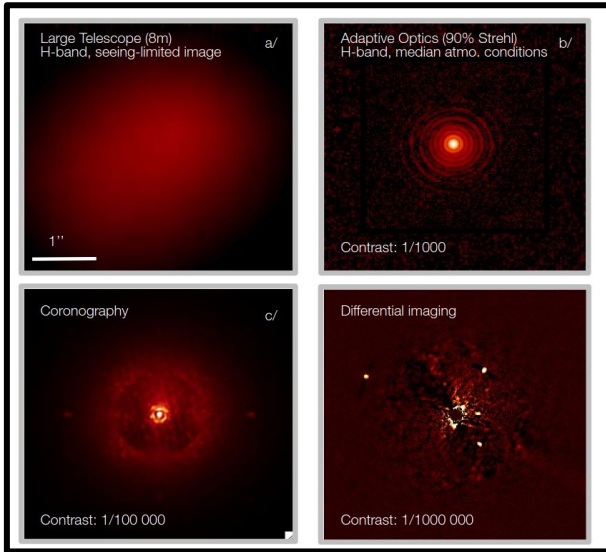
## High-Dispersed Spectroscopy

High-Resolution & Extremely Precise Spectrographs, fiber-fed or echelle (e.g. ESPRESSO, CRIRES+) and particularly METIS, ANDES, PCS at ELT



## High-Contrast Imaging

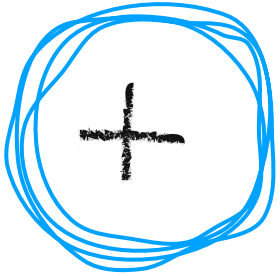
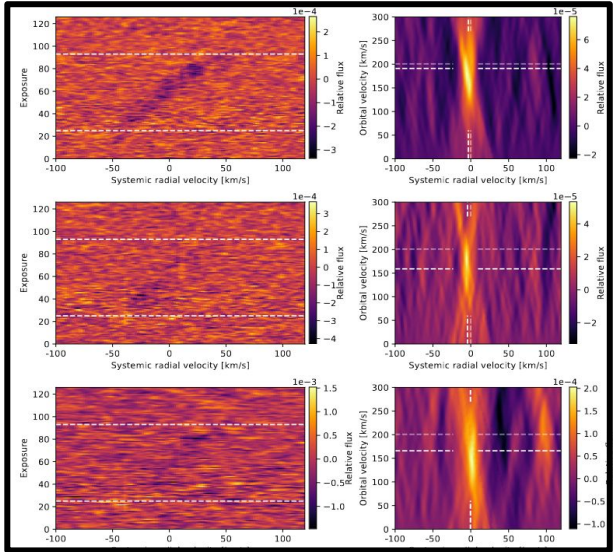
Extreme-Adaptive Optics, Coronagraphy, Angular Differential Imaging, IFS (e.g. SPHERE, ERIS) & MORFEO-MICADO, HARMONI, METIS, PCS at ELT



# Workhorse modes

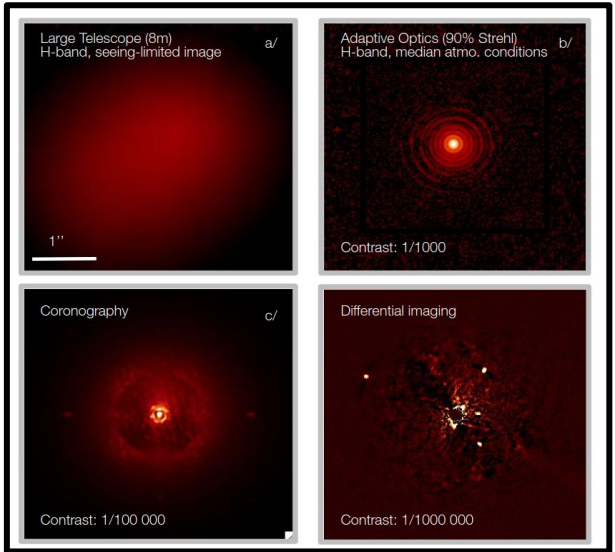
## High-Dispersed Spectroscopy

High-Resolution & Extremely Precise Spectrographs, fiber-fed or echelle (e.g. ESPRESSO, CRIRES+) and particularly METIS, ANDES, PCS at ELT



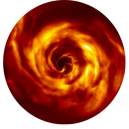
## High-Contrast Imaging

Extreme-Adaptive Optics, Coronagraphy, Angular Differential Imaging, IFS (e.g. SPHERE, ERIS) & MORFEO-MICADO, HARMONI, METIS, PCS at ELT



Combining spatial and spectral diversity, a key for detection & characterization!  
(done everywhere! MORFEO-MICADO/LSS, METIS, HARMONI, ANDES & PCS!)

# Key Science Drivers



Initial Conditions for Planetary Formation



Exoplanets, Demographics & Architecture of Planetary Systems



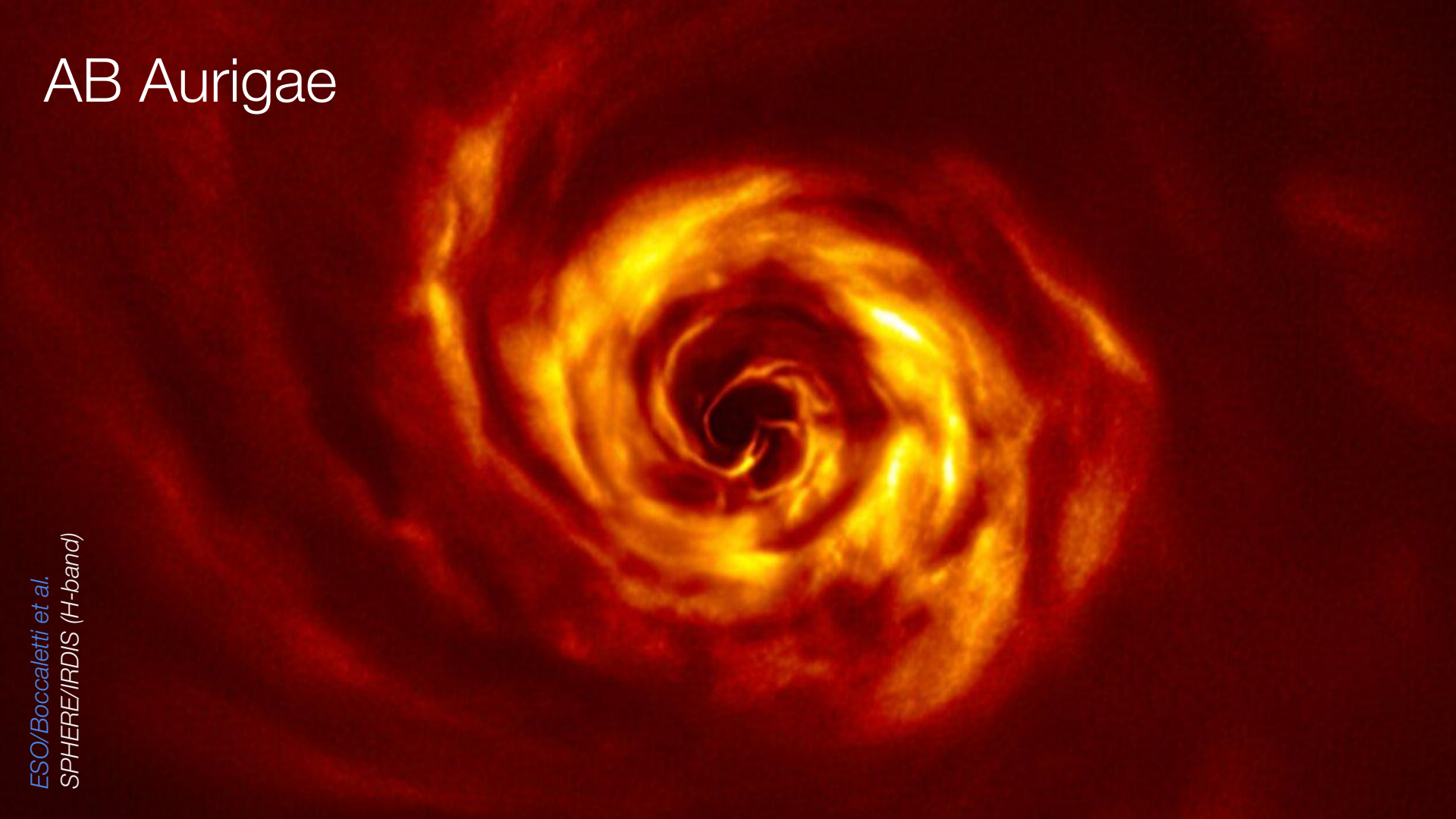
Exoplanetary Atmospheres



Rocky planets to Habitable Worlds & Life

# AB Aurigae

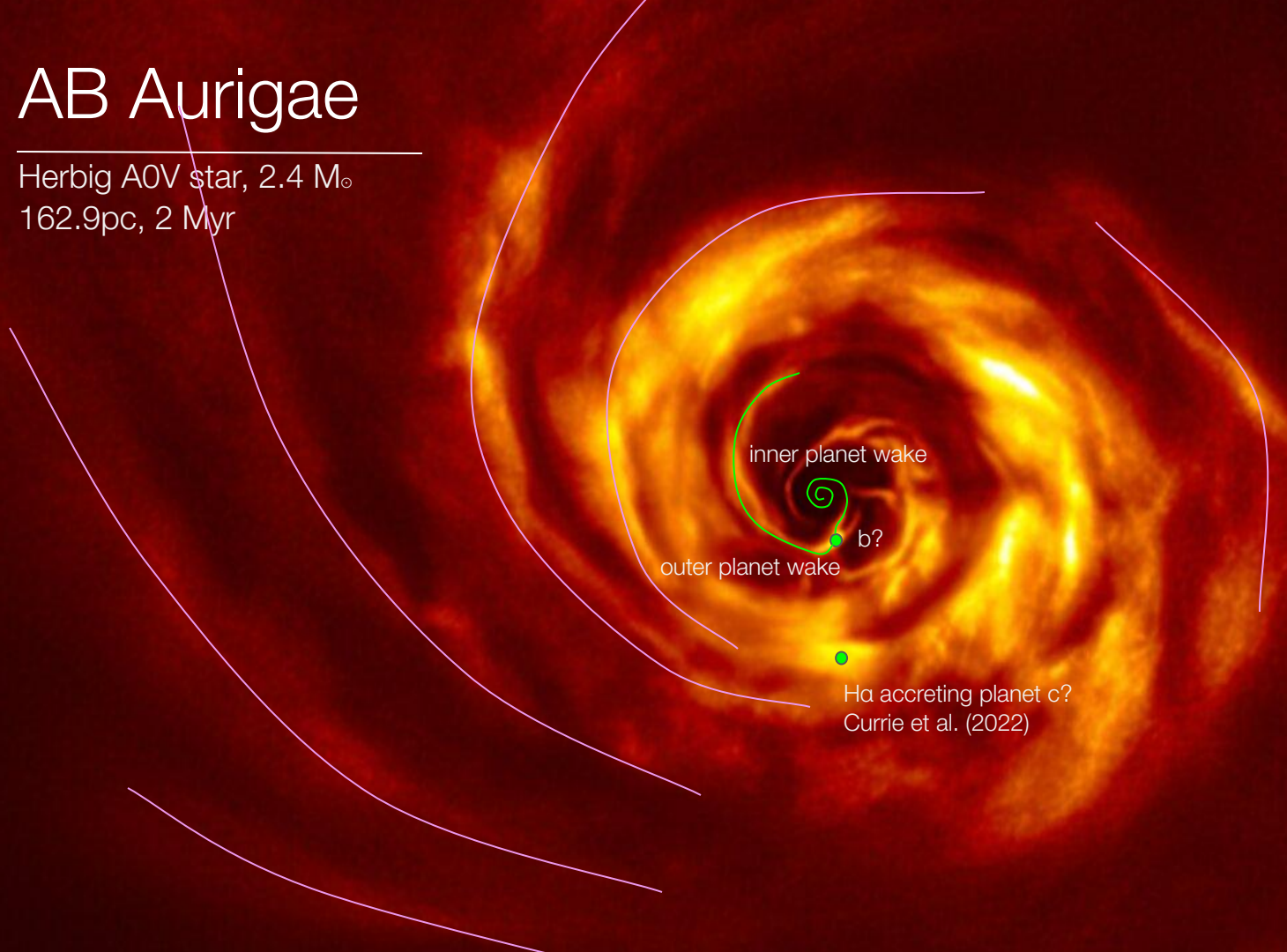
*ESO/Boccaletti et al.  
SPHERE/IRDIS (H-band)*



# AB Aurigae

Herbig A0V star, 2.4 M<sub>⊙</sub>  
162.9pc, 2 Myr

Solar System



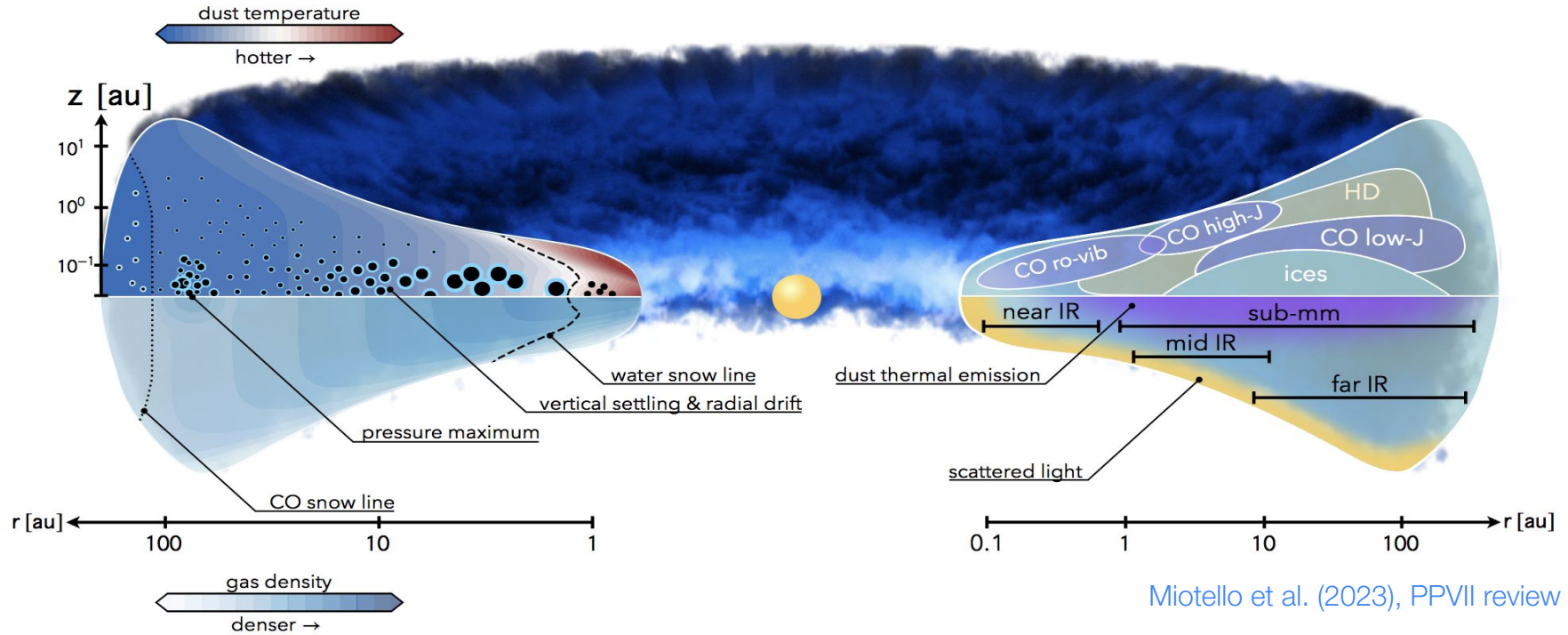
inner planet wake

b?

outer planet wake

H $\alpha$  accreting planet c?  
Currie et al. (2022)

# Diving into planet-forming disks



Disk sub-structures due to thermal/composition variations (snow lines), planets & add. instabilities (GI, MHD...)

**ELT will offers a unique access to the 1 - 10 au planet-forming region zone!**



# Diving into planet-forming disks

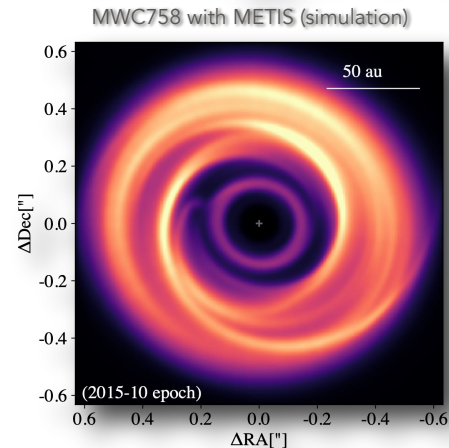
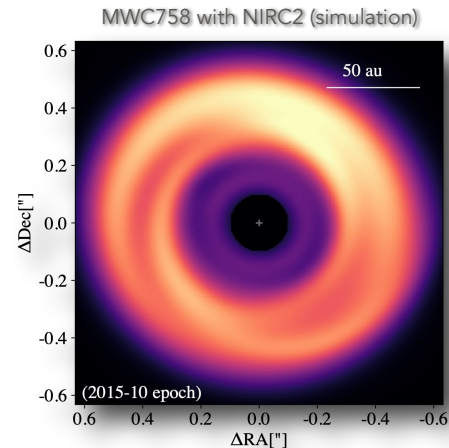
## Sub-structures (dust component)

- Spirals, Rings, Gaps, Shadows, vortices...  
(VLT/I, ALMA, SKA synergy)
- Rich perspectives:
  - Grain properties,
  - Dust filtration,
  - Pressure bump & dust trap,
  - Hot spots & proto-planets

## METIS high-contrast imaging

- L-band 3.8  $\mu\text{m}$ , Herbig-star (MWC758,  $\sim 150$  pc)
- Jupiter footprint at 30 au,
- very competitive with JWST

Simulation credits: C. Baruteau & V. Christiaens



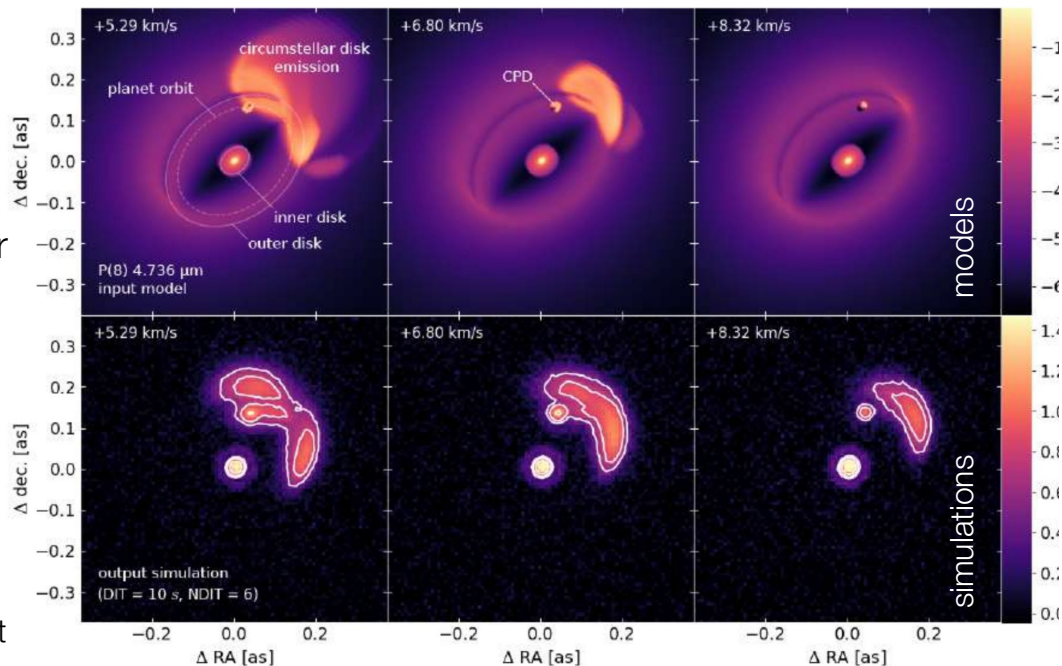
# Diving into planet-forming disks

## Sub-structures (gas kinematics)

- Wide range of gas-phase molecules: CO, OH, CH<sub>4</sub>, NH<sub>3</sub>, HCN, C<sub>2</sub>H<sub>2</sub>...
- Organic/Prebiotic chemistry, snowlines, disk cooling,
- Isotopic Fractionation of CO Water  
Transfer to Terrestrial Planets
- Dynamics: turbulence, deviation from Keplerian velocities (planetary kink?),

METIS ( $R_{\lambda} = 100\,000$ ) IFU simulations of HD100546 at 108 pc; <sup>12</sup>CO line emission at 4.7 $\mu$ m; 10 M<sub>Jup</sub> planet at 15 au with CPD; ProDiMo model (Petit dit de la Roche et al. 2021) & SimMetis (Oberg et al. 2023)

Mapping warm CO gas emission lines

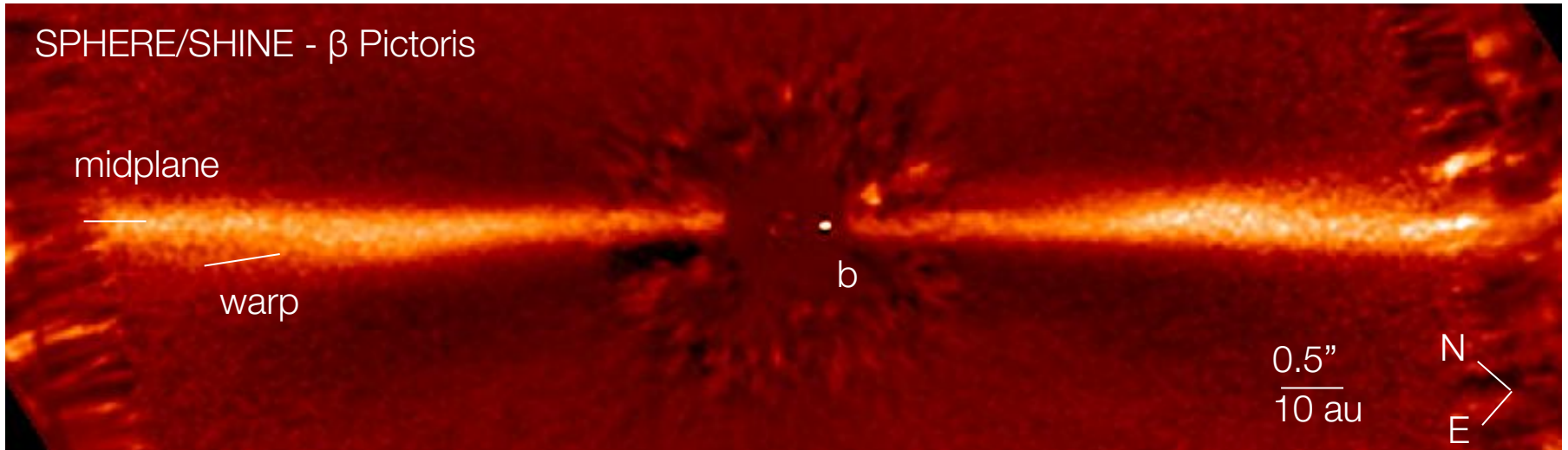


# Exoplanetary systems

## Planet(s) & belts

$\beta$  Pic (A6V), 23 Myr-old planetary system

- $\beta$  Pic b,  $13 M_{\text{Jup}}$  planet at 9au ( $e = 0.1$ ), [Lagrange et al. \(2019\)](#)
- Edge-on debris disk, [Smith & Terile \(1984\)](#)
- SPHERE/GRAVITY monitoring, [Nowak et al. \(2020\)](#)
- Second planet c detected by RV/GRAVITY



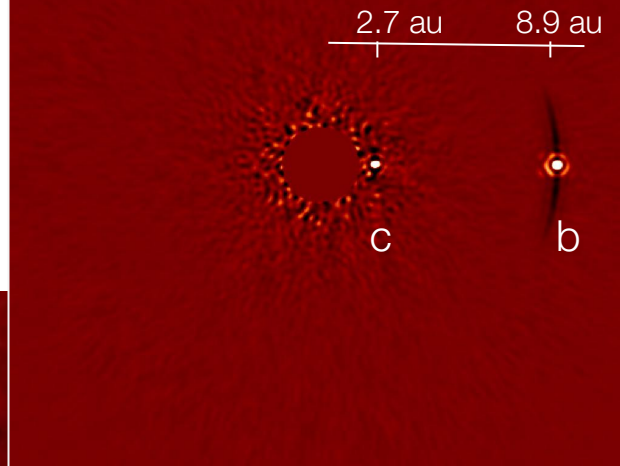
# Exoplanetary systems

## Planet(s) & belts

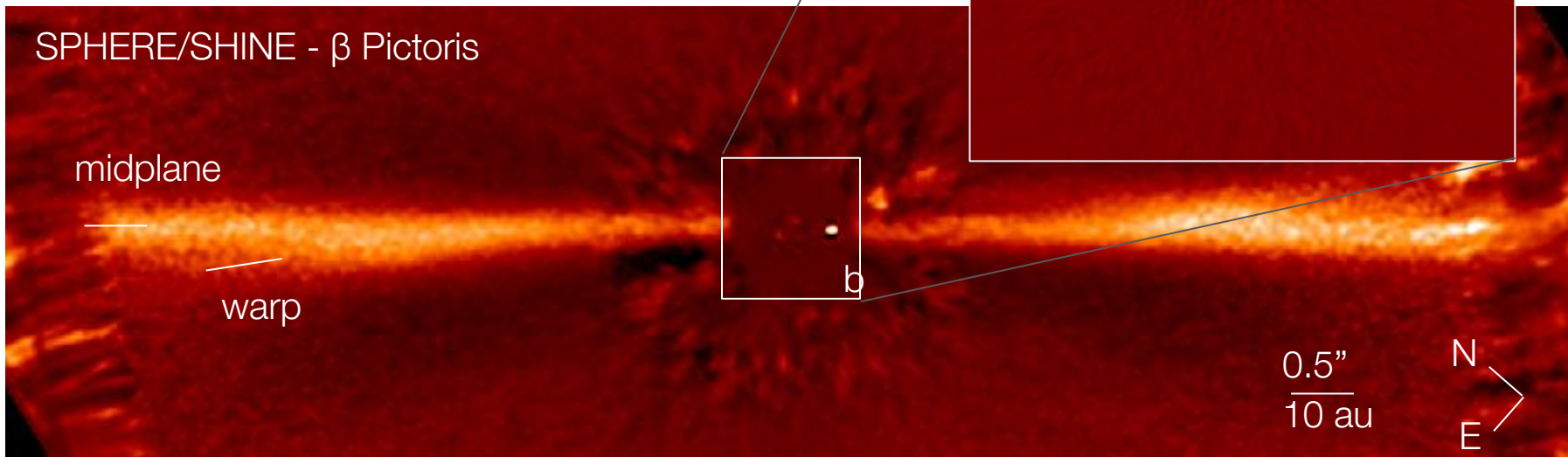
COMPASS/MISTHIC ([Baudoz/Huby - MISTHIC simulations](#)):

- $\beta$  Pic c,  $9 M_{\text{Jup}}$  planet at 2.7 au ( $e = 0.24$ )
- MICADO ADI sequence (1hr-meridian),  
Telescope, SCAO, NCPA, Coronagraph...

MICADO -  $\beta$  Pictoris b & c  
K-band



SPHERE/SHINE -  $\beta$  Pictoris



# Exoplanetary systems

## Planet(s) & belts

- Connecting Planet(s) physical properties (orbit, mass) & structures of debris disks
- Global dynamical stability & evolution,
- Telluric planets in stable HZ (our Solar System into context)?

SPHERE/SHINE -  $\beta$  Pictoris

midplane

warp

b

0.5"  
10 au

N  
E

MICADO -  $\beta$  Pictoris b & c  
K-band

2.7 au      8.9 au

c

b

# Exoplanetary systems

Young (<1 Gyr) giant planets down to the snow line

Down to  $1 M_{\text{Jup}}$  @1 au, 400K-2000K

At ELT 1<sup>st</sup> Science Lights (2030):  
Complete census of nearby  
planetary systems (RV, DR4, DR5)?

GAIA - HCI synergy

**Informed targeted surveys!**

[Houllé et al. \(2021\)](#)

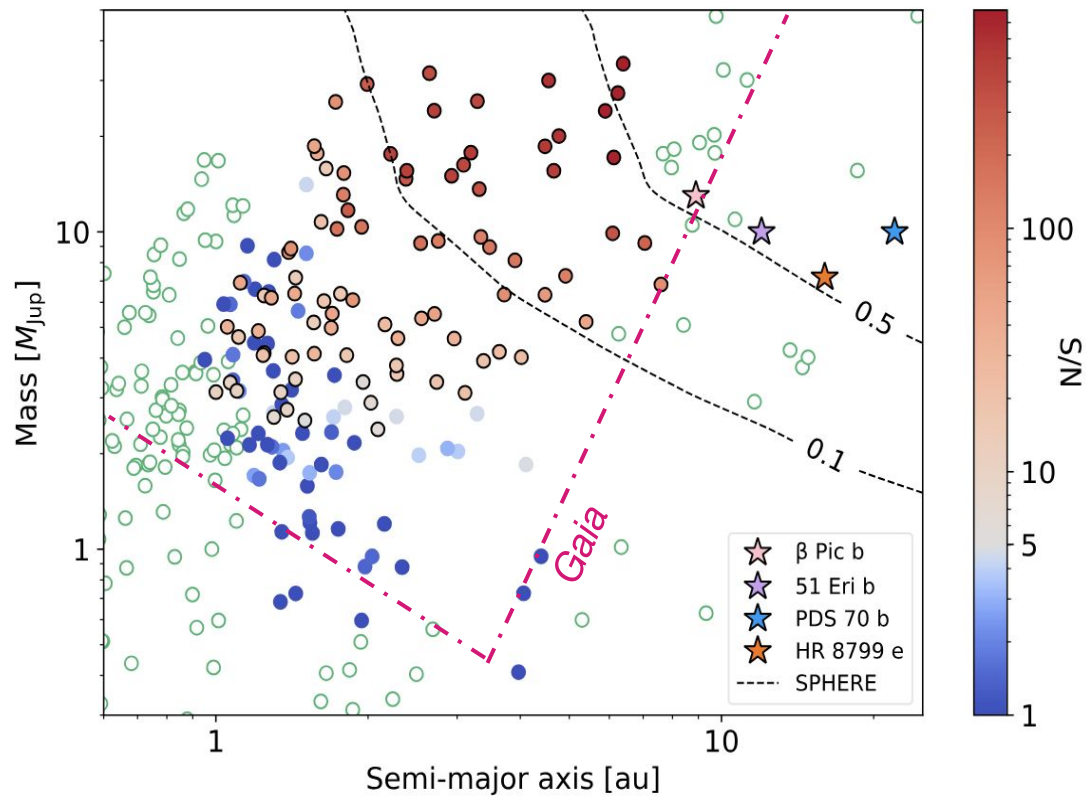
HARMONI versus SPHERE/SHINE

150 stars (50 pc, 100 Myr)

NGPPS Bern model (*green*)

[Emsenhuber et al. \(2020ab\)](#)

HSIM2 simulations (A. Carlotti)



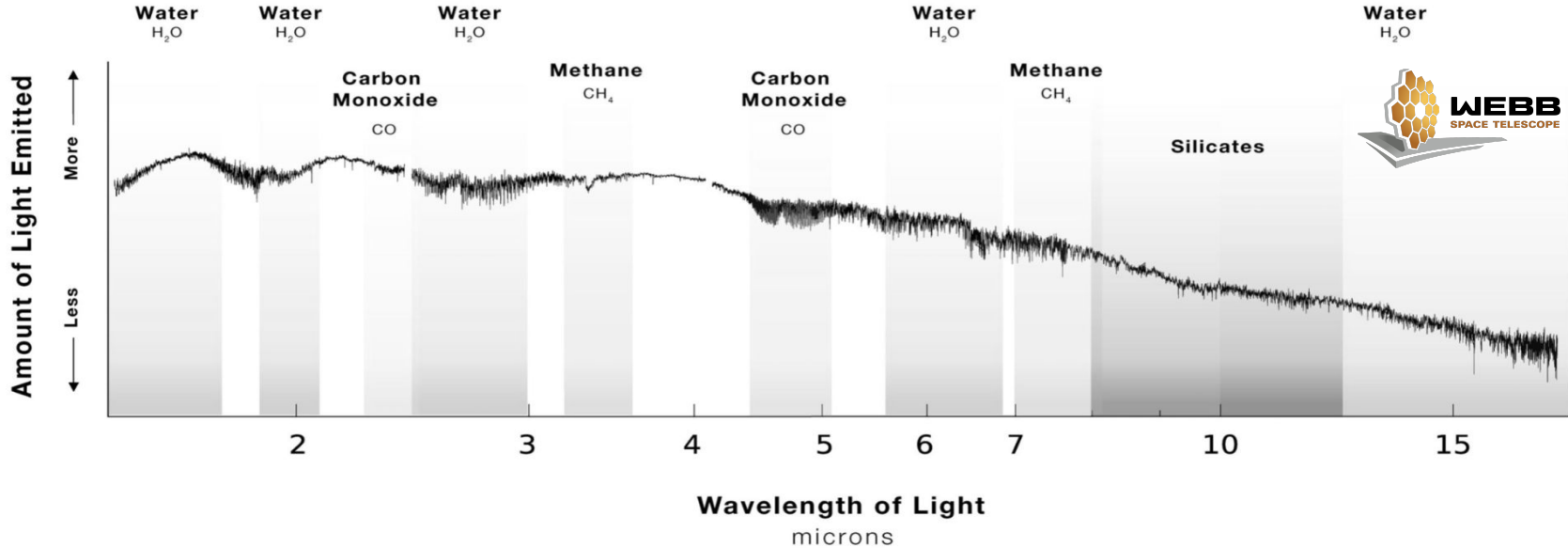




# Exoplanetary atmospheres



## Young Giant Planets - High-Contrast Spectroscopy



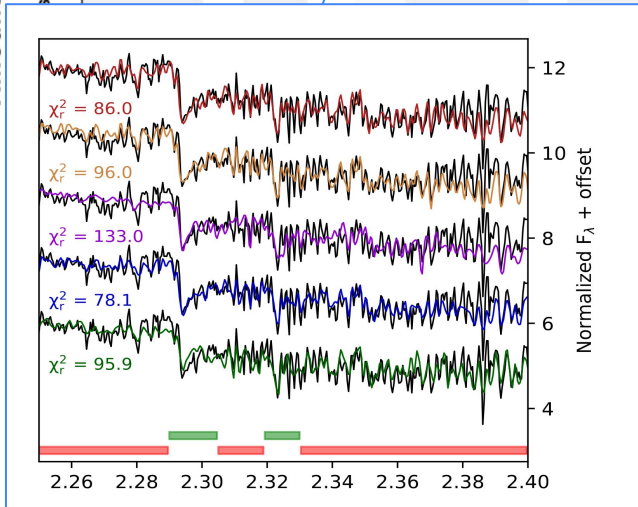
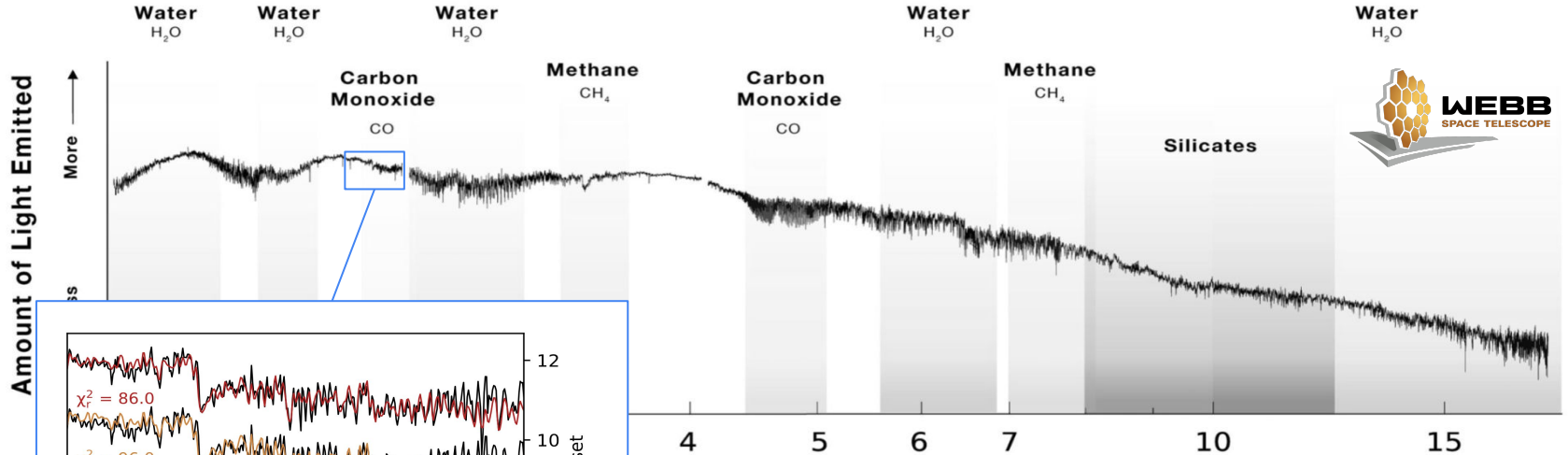
- ERS characterization of VHS1256 b
    - Young super-Jupiter (15-19 M<sub>Jup</sub>, 140 Myr, sep = 8.0as, 150au)
    - 1 to 18 um medium-resolution spectrum combining NIRSPec & MIRI MRS
    - T<sub>eff</sub>=1150K, log(g)=3.3, M/H=0.03, C/O=0.4
- e.g. [Bauza et al. \(2015\)](#), [Miles et al. \(2023\)](#), [Petrus et al. \(2024\)](#)



# Exoplanetary atmospheres



## Young Giant Planets - High-Contrast Spectroscopy



**Goldmine to explore diversity of exoplanetary atmospheres!**

Bulk properties:  $T_{\text{eff}}$ ,  $\log(g)$ , T/P profile... mass, radius, Lum.

Composition: M/H, molecular abundances, isotopologues

Cloud composition & spatial distribution, 3Dness

Connection to formation/location processes

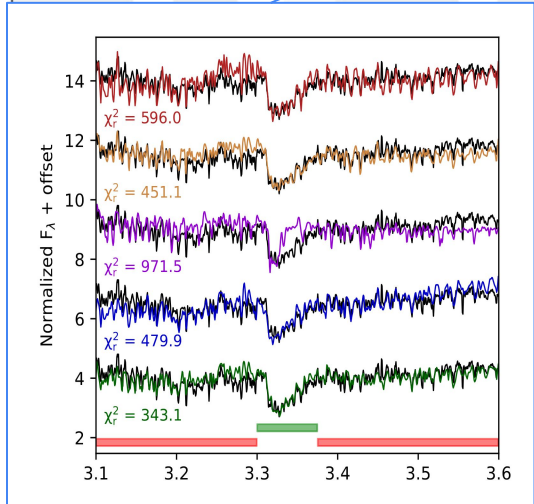
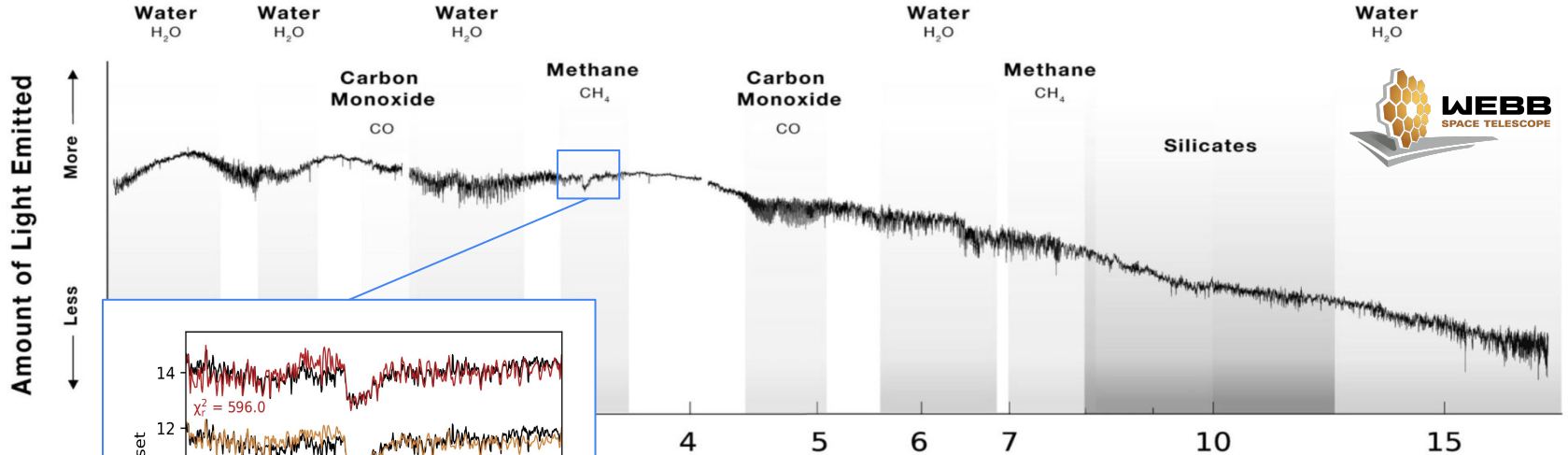
(Oberg et al. 2011, Mollière et al. 2022)



# Exoplanetary atmospheres



## Young Giant Planets - High-Contrast Spectroscopy



**Goldmine to explore diversity of exoplanetary atmospheres!**

Bulk properties:  $T_{\text{eff}}$ ,  $\log(g)$ , T/P profile... mass, radius, Lum.

Composition: M/H, molecular abundances, isotopologues

Cloud composition & spatial distribution, 3Dness

Connection to formation/location processes

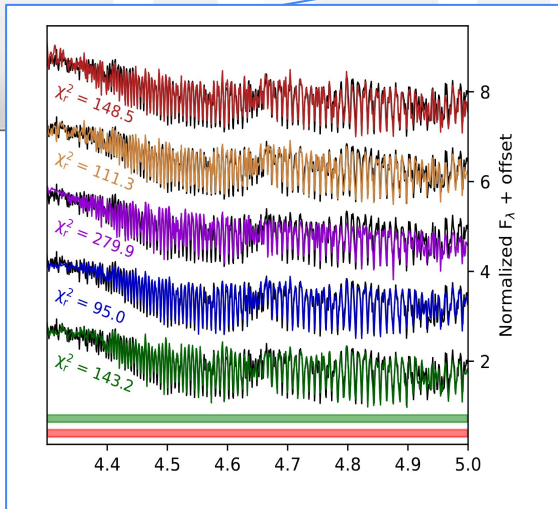
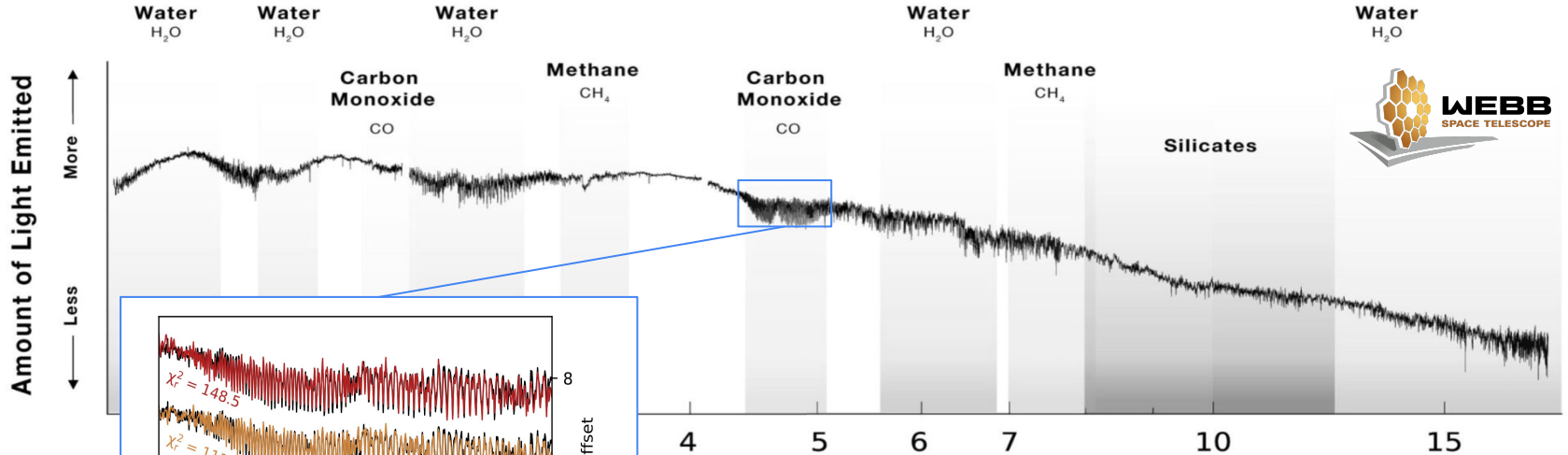
(Oberg et al. 2011, Mollière et al. 2022)



# Exoplanetary atmospheres



## Young Giant Planets - High-Contrast Spectroscopy



**Goldmine to explore diversity of exoplanetary atmospheres!**

Bulk properties:  $T_{\text{eff}}$ ,  $\log(g)$ , T/P profile... mass, radius, Lum.

Composition: M/H, molecular abundances, isotopologues

Cloud composition & spatial distribution, 3Dn<sub>ess</sub>

Connection to formation/location processes

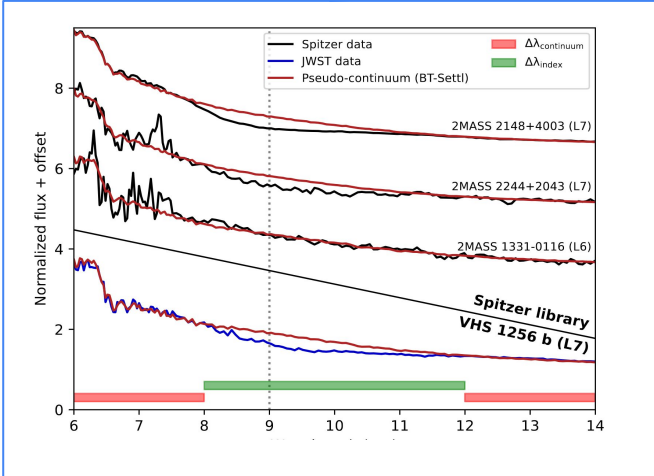
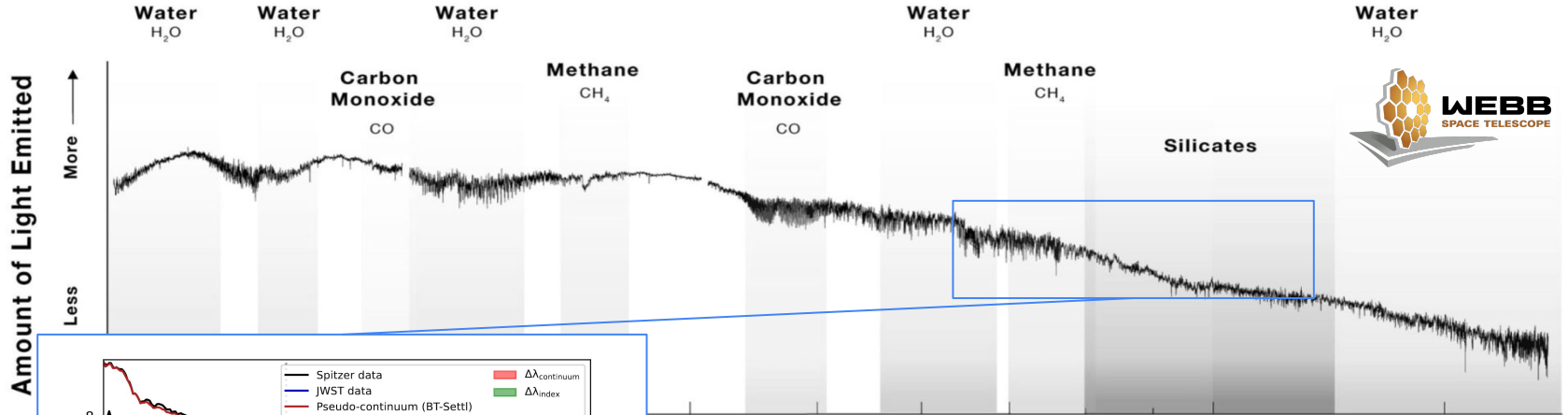
(Oberg et al. 2011, Mollière et al. 2022)



# Exoplanetary atmospheres



## Young Giant Planets - High-Contrast Spectroscopy



4    5    6    7    10    15

**Goldmine to explore diversity of exoplanetary atmospheres!**

Bulk properties:  $T_{eff}$ ,  $\log(g)$ , T/P profile... mass, radius, Lum.

Composition: M/H, molecular abundances, isotopologues

Cloud composition & spatial distribution, 3Dn<sub>ess</sub>

Connection to formation/location processes

(Oberg et al. 2011, Mollière et al. 2022)

# Exoplanetary atmospheres

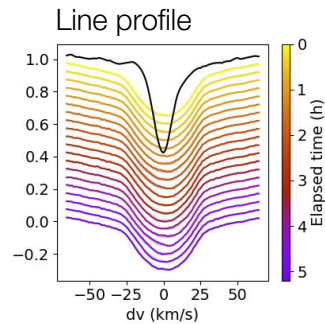
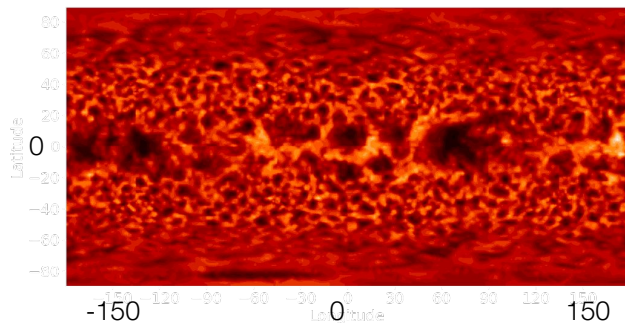
Young Giant Planets - Time-resolved spectroscopy & 3Dness

Global Mapping of directly imaged planets and brown dwarfs

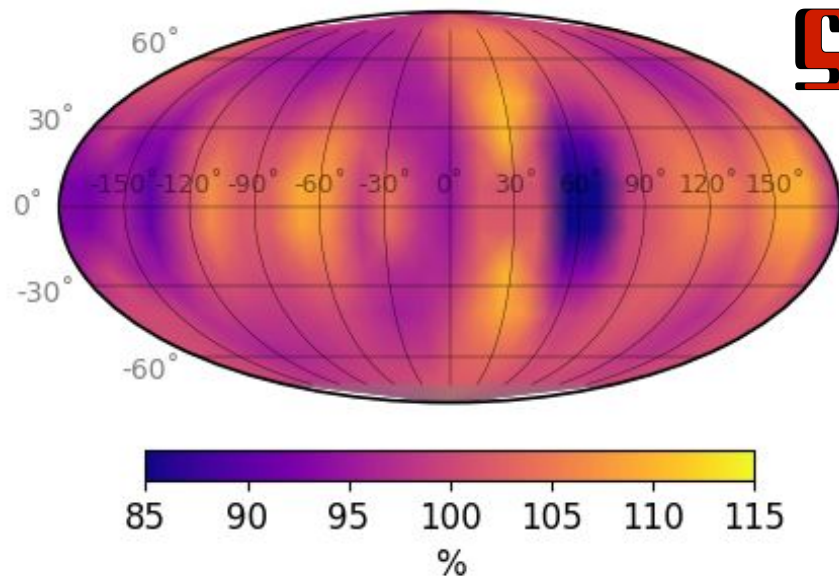
WISE0849 B (Luhman 16 B), 2 pc, Rotation 4.9hrs.  
CO M-band. [METIS Doppler Imaging simulations.](#)

GCM: circulation, cloud radiative feedback,  
global & equatorial dynamics  
([Tan et al. 2022, 2021](#))

Instantaneous global map of outgoing  
top-of-atmosphere thermal flux



Doppler map





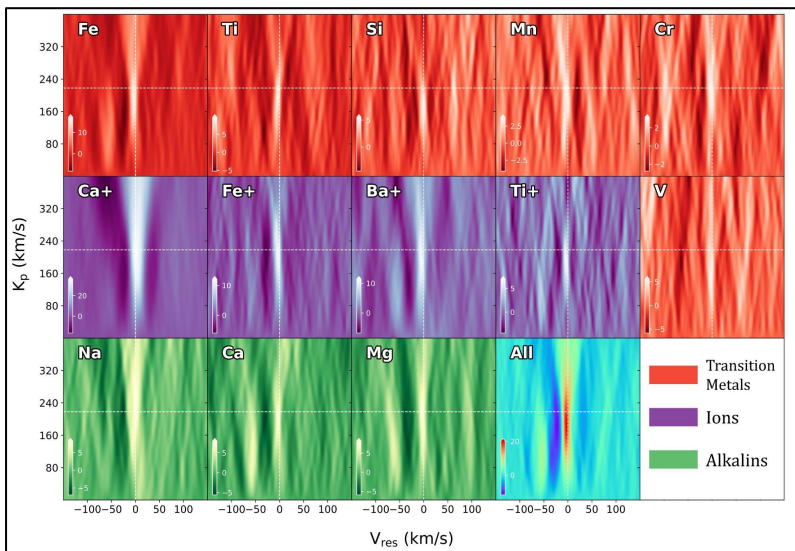
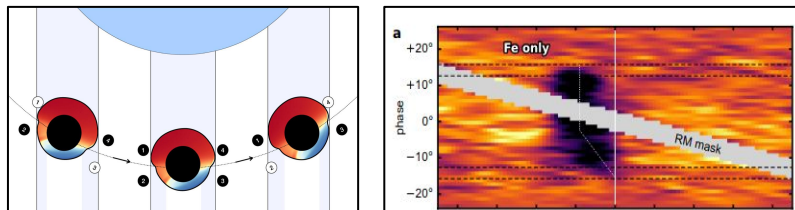
# Exoplanetary atmospheres



## Hot Jupiters to sub-Neptunes - Transm./Eclipse Spectrosc. at high-Res

- Refractory & Volatiles elements
  - Abundances & Ice/rock ratio,
- Global circulation
  - Time-resolved spectroscopy
  - Atmosphere 3Dness,
  - Night/day side
  - Winds & Clouds...
- TOI-1518b & WASP-76b
  - Maroon-X - UHJs ( $1.5-1.8 M_{\text{Jup}}$ , 2200-2500K)
  - Complementary to JWST

e.g. [Simonnin et al. \(2024\)](#), [Pelletier et al. \(2023\)](#), [Prinoth et al. \(2024\)](#), [Ehrenreich et al. \(2020\)](#), [Pallé et al. \(2024\)](#), [Seidel et al. \(2025\)](#)

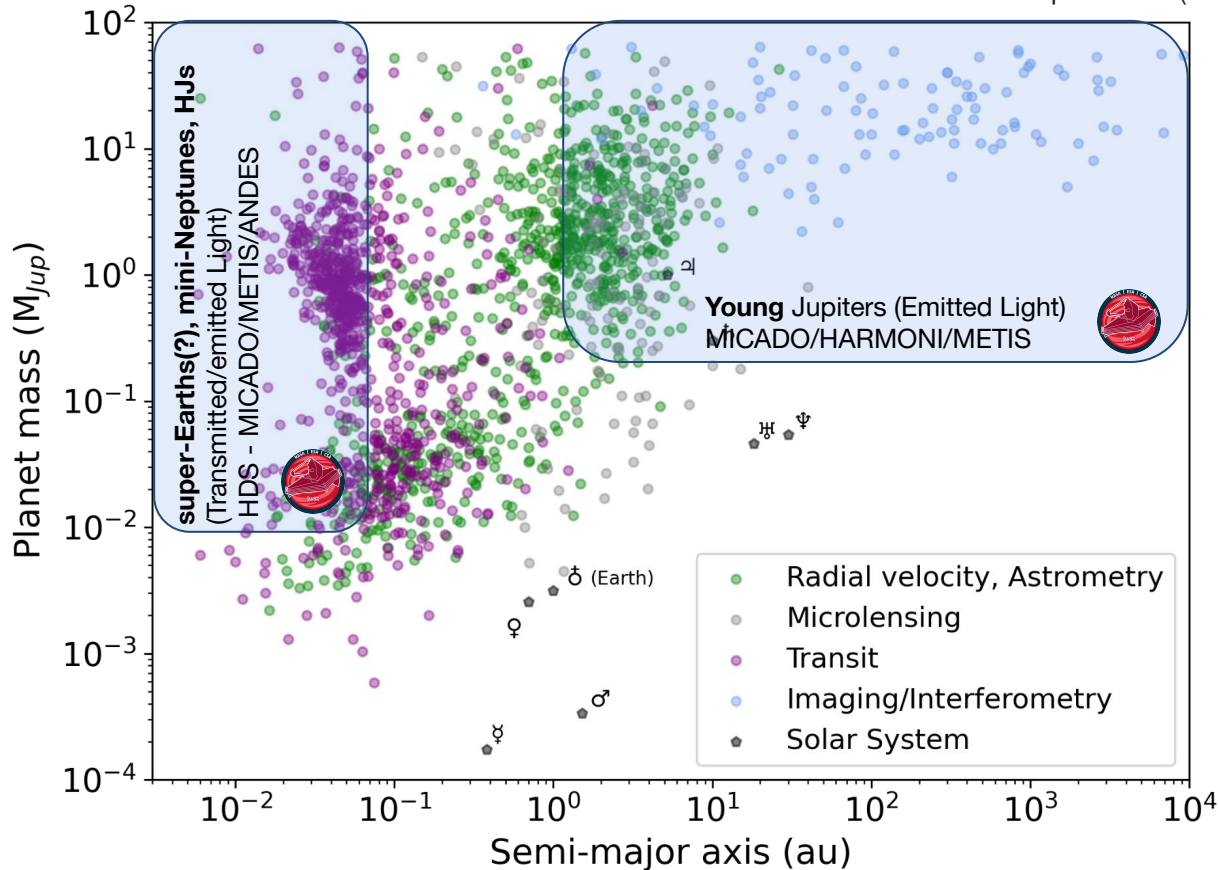






# Rocky planets to Habitable Worlds & Life

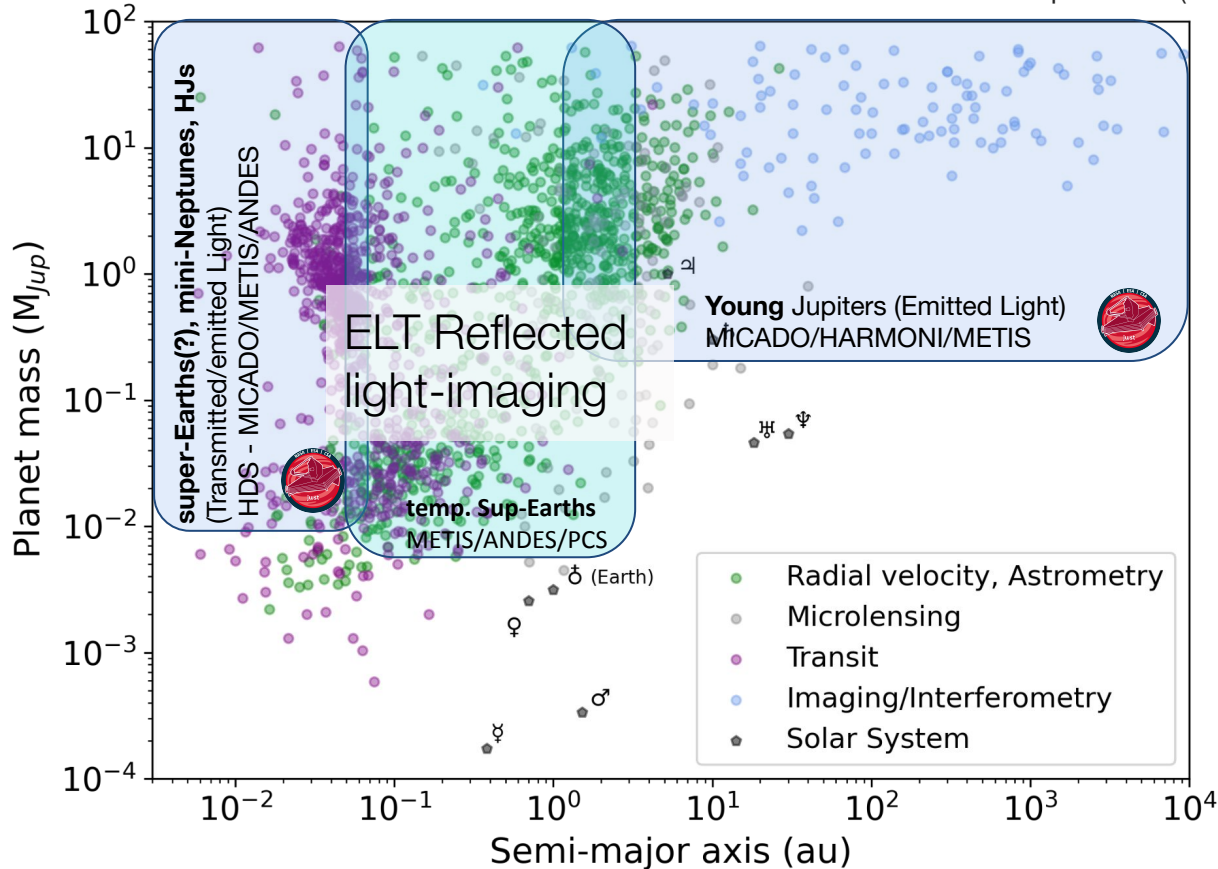
6000+ discovered exoplanets (<http://exoplanets.eu/>)





# Rocky planets to Habitable Worlds & Life

6000+ discovered exoplanets (<http://exoplanets.eu/>)





# Rocky planets to Habitable Worlds & Life

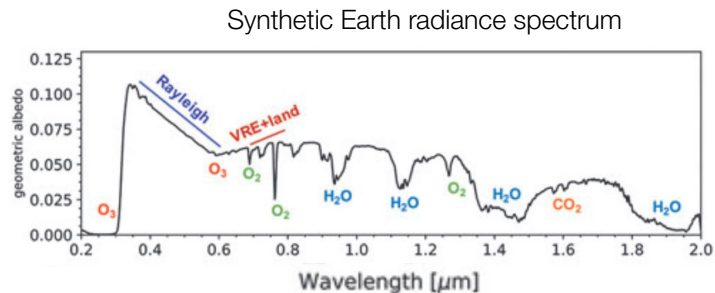
Direct imaging in reflected light, a game changer!

From young, giant planets to old, rocky worlds around KM stars

- Contrast:  $10^{-6}$  (50mas) to  $10^{-8}/10^{-9}$  (10mas/100mas)
- Emitted (1<sup>st</sup> Gen) & **Reflected** (2<sup>nd</sup> Gen) light
- From Giant planets to **super-Earths & rocky worlds!**
- around Young stars & **Nearby/old KM dwarfs**

↓  
 MORFEO-MICADO (2030)  
 HARMONI (2034)  
 METIS (2030)

↓  
 METIS/HARMONI  
 ANDES (2034)  
 PCS (2038+)



Schwieterman et al. (2018)

**Ultimate Goal:** Characterization of temperate rocky planets around nearby stars

A large sample of temperate exoplanets already known and to be discovered before METIS, and particularly ANDES/PCS First Light...



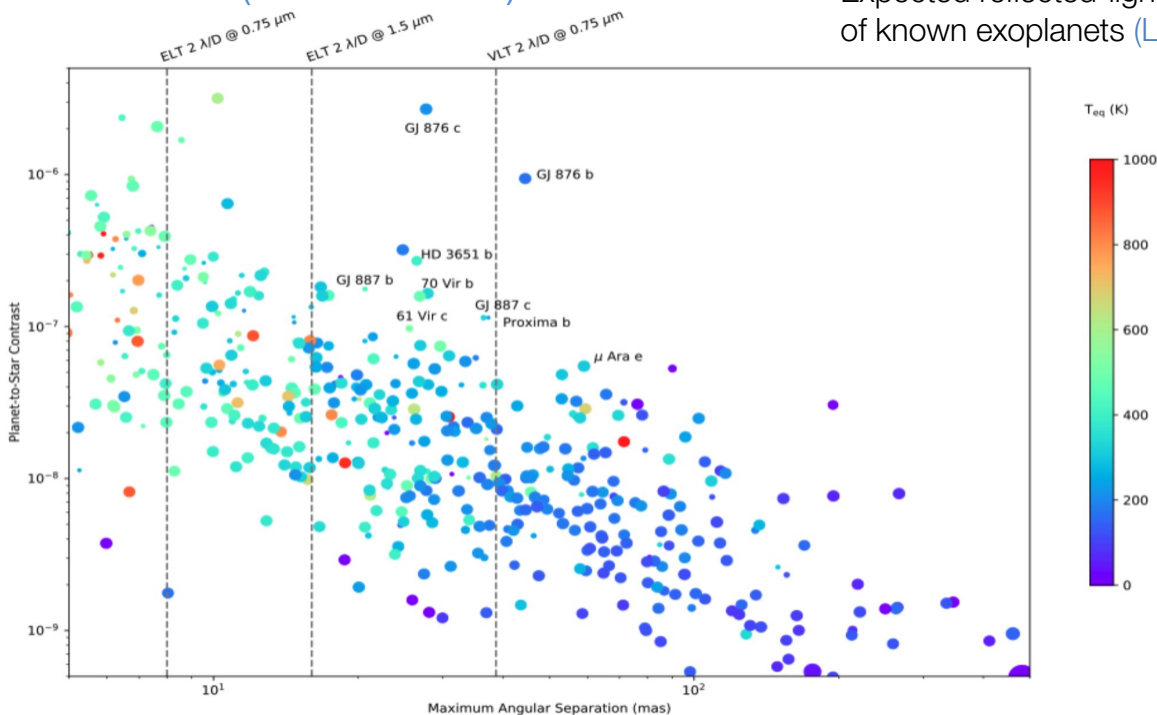
# Rocky planets to Habitable Worlds & Life

Direct imaging in reflected light, a game changer!

From young, giant planets to old, rocky worlds around KM stars

- TLR in contrast:  $10^{-8}/10^{-9}$  (10mas/100mas)

Expected reflected-light contrast of known exoplanets (Lovis et al. 2022)





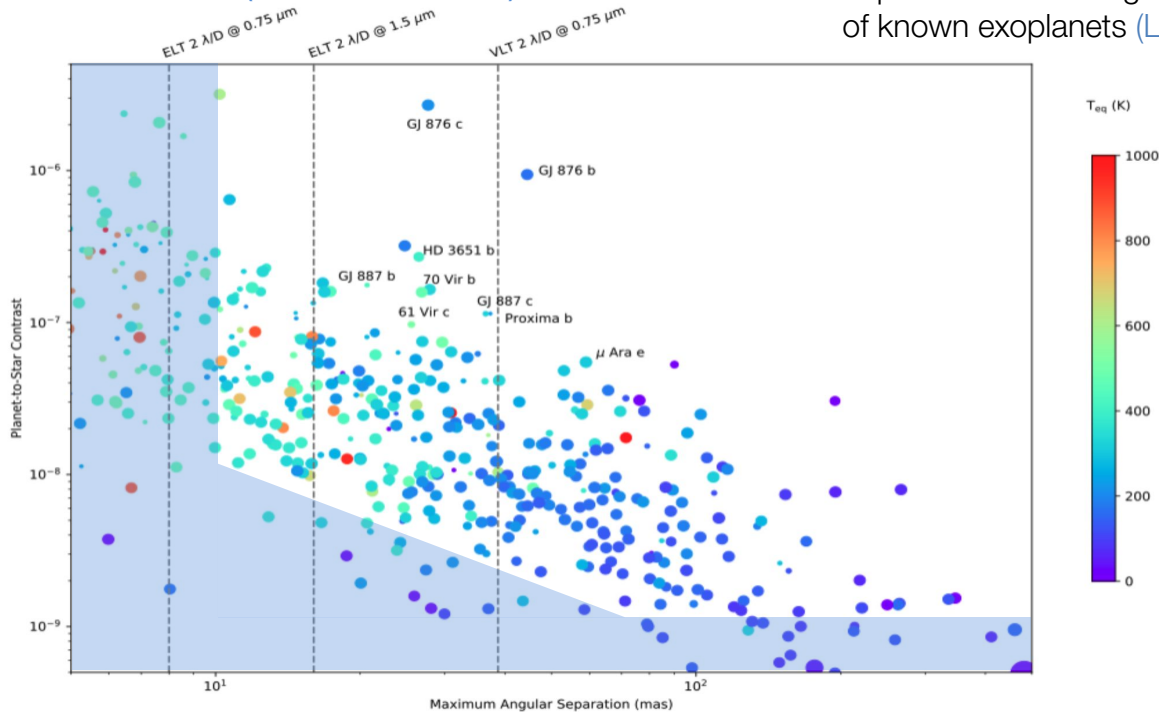
# Rocky planets to Habitable Worlds & Life

Direct imaging in reflected light, a game changer!

From young, giant planets to old, rocky worlds around KM stars

- TLR in contrast:  $10^{-8}/10^{-9}$  (10mas/100mas)

Expected reflected-light contrast of known exoplanets (Lovis et al. 2022)





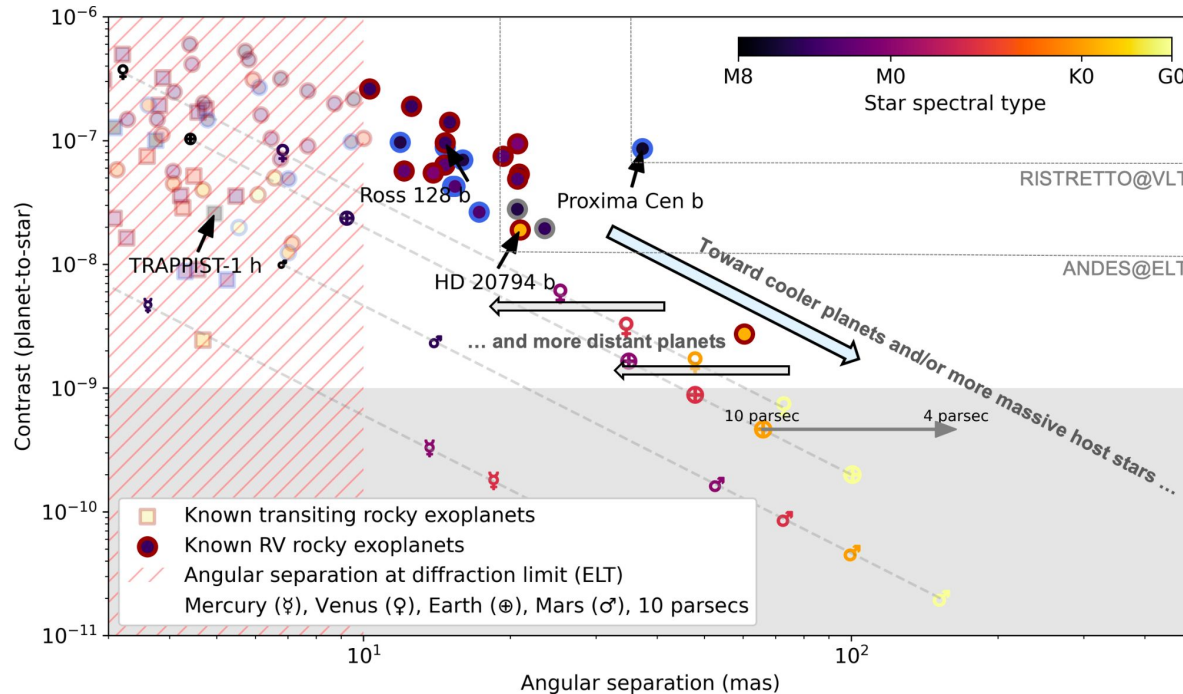
# Rocky planets to Habitable Worlds & Life



Direct imaging in reflected light, a game changer!

From young, giant planets to old, rocky worlds around KM stars

- TLR in contrast:  $10^{-8}/10^{-9}$  (10mas/100mas)



Expected reflected-light contrast of **known rocky exoplanets**  
 mass < 5 Earth masses  
 radius < 1.7 Earth radii

Planet's insolation regime:

- within the Habitable Zone (HZ),
- interior to the HZ inner edge, and
- beyond the outer edge.

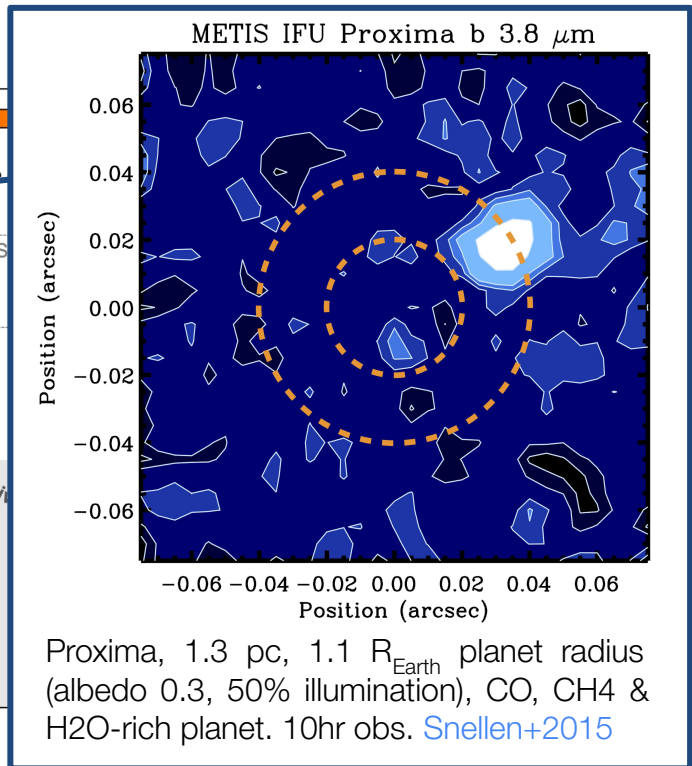
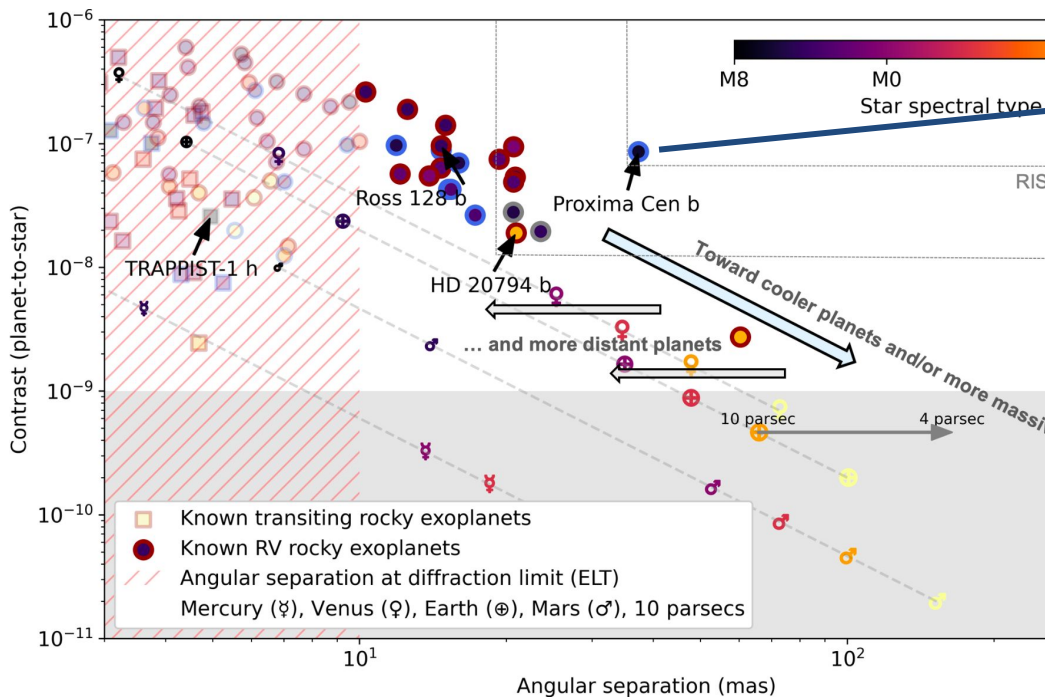


# Rocky planets to Habitable Worlds & Life

Direct imaging in reflected light, a game changer!

From young, giant planets to old, rocky worlds around KM stars

- TLR in contrast:  $10^{-8}/10^{-9}$  (10mas/100mas)



# Take away



- **Key fundamental questions unanswered!**
  - Planetary Formation, Discovery space & Demographics
  - How does the Solar System fit in?
  - Planet Characterization: What are planets made of? Biological activity?
- **Important development before ELT's First Light (mid 2029)**
  - A revolution in space (Gaia, JWST... PLATO, Roman)
  - Preparing ELT science for guaranteed and open time observations!
  - Consolidating the R&D/Science roadmap for future ELT instruments (PCS)
- **In operation: A characterization machine for disks, giant & rocky planets!**
  - Unique spatial resolution, sensitivity, versatility & lifetime,
  - Synergies with ground/space telescope(s),
  - Amazing toolbox to study planetary formation (substructures, chemistry...)
  - From Young/mature giant planets down to mature, nearby super-Earths
  - Population/atmospheric demographics studies & first indications of Life



# Exoplanetary systems

## Global content of giant planets down to the snow line

At ELT 1<sup>st</sup> Science Lights (2030)

HR8799 completeness  
(F0, 30 Myr, 40pc)

Observations:

- VLT/SPHERE
- JWST/NIRCam

Predictions;

- Roman/CGI (NFM, WFM)
- ELT/MICADO
- ELT/METIS

