

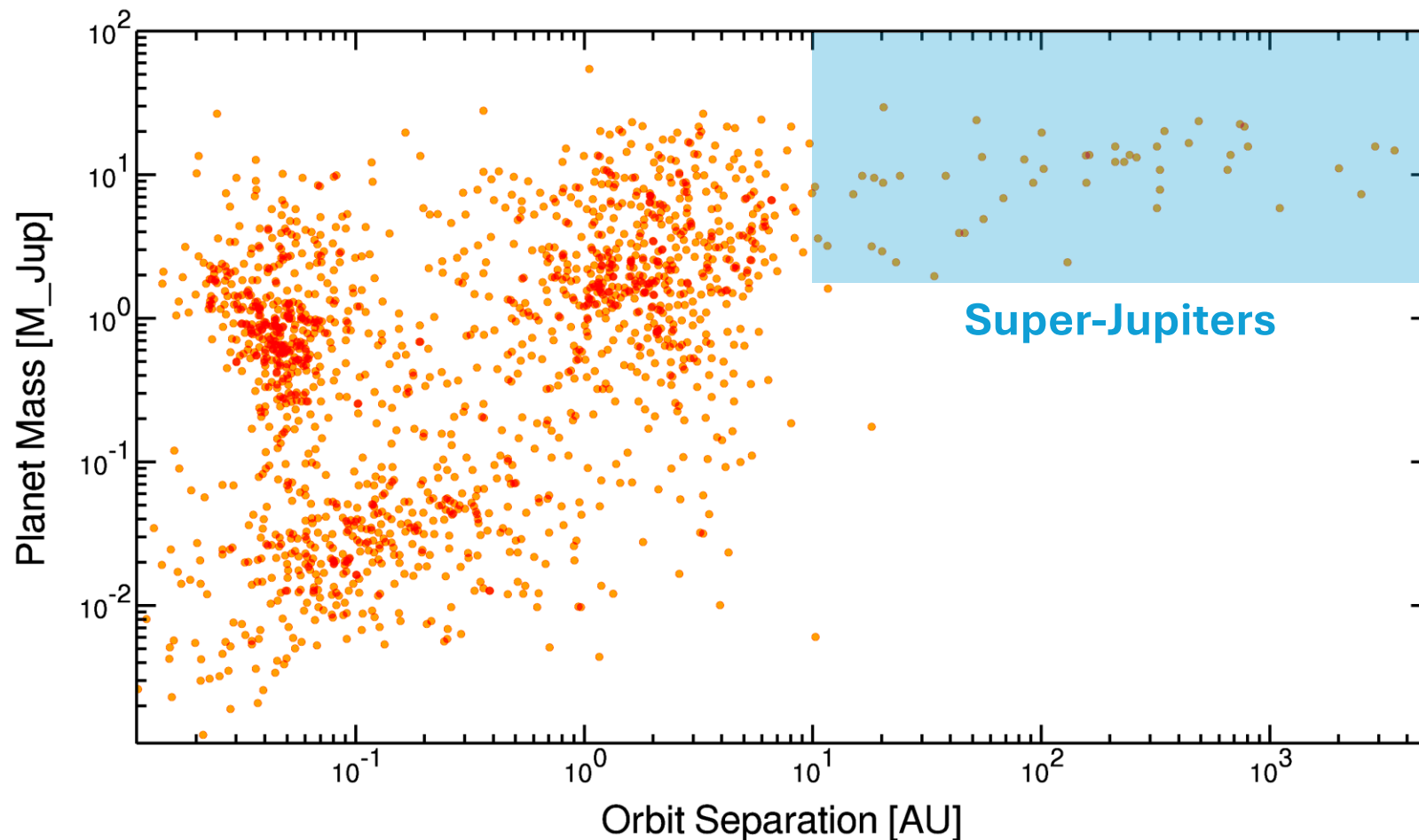
# Atmospheres of outer exoplanets: Status and prospects for the ELT

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Yapeng Zhang, Caltech  
51 Pegasi b fellow



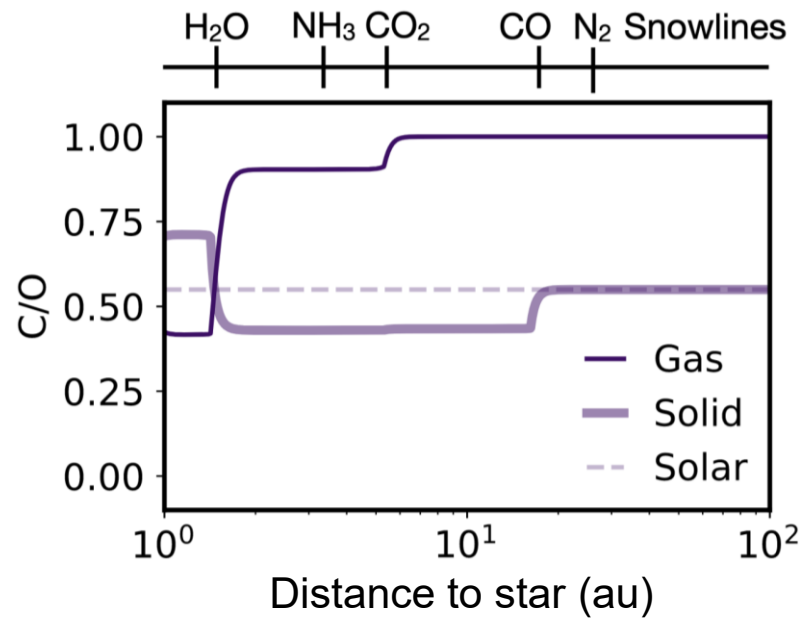
# Wide-separation giant planets offer great opportunities of detailed atmospheric characterization



# Unveil the origin of wide-separation super-Jupiters

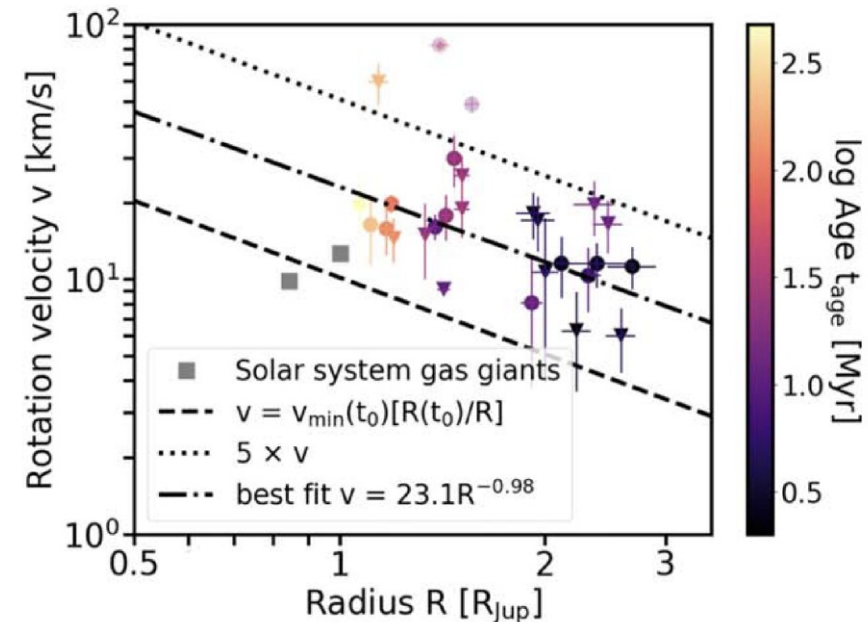
Gas giant atmosphere composition retain imprints from formation location and accretion history

Poster by Anna Miotello



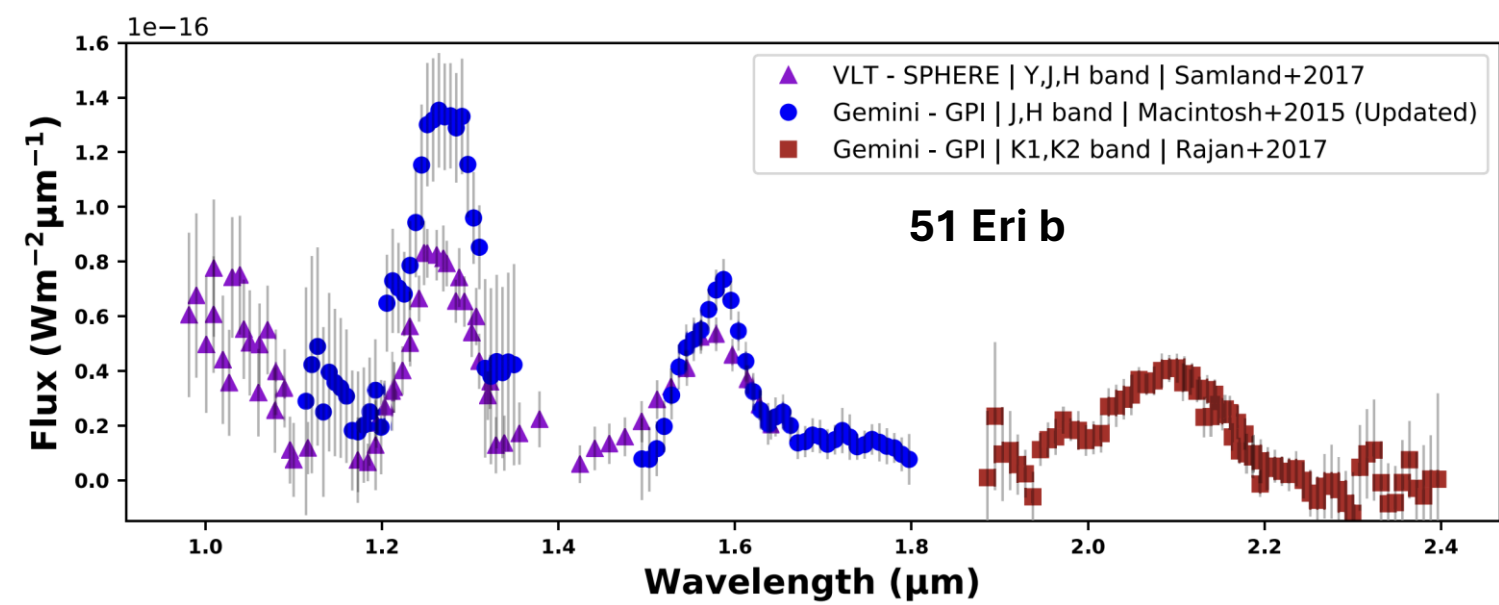
Öberg+ 2021

Spins of young gas giants unveil planet formation and evolution



Bryan+2020

# Low-resolution spectra can constrain bulk properties but less reliable chemical abundances



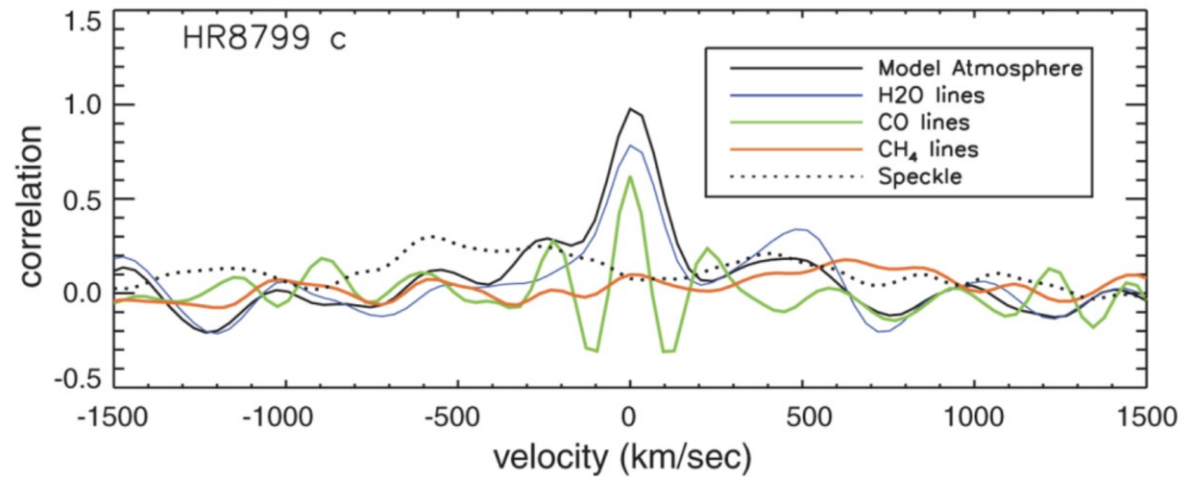
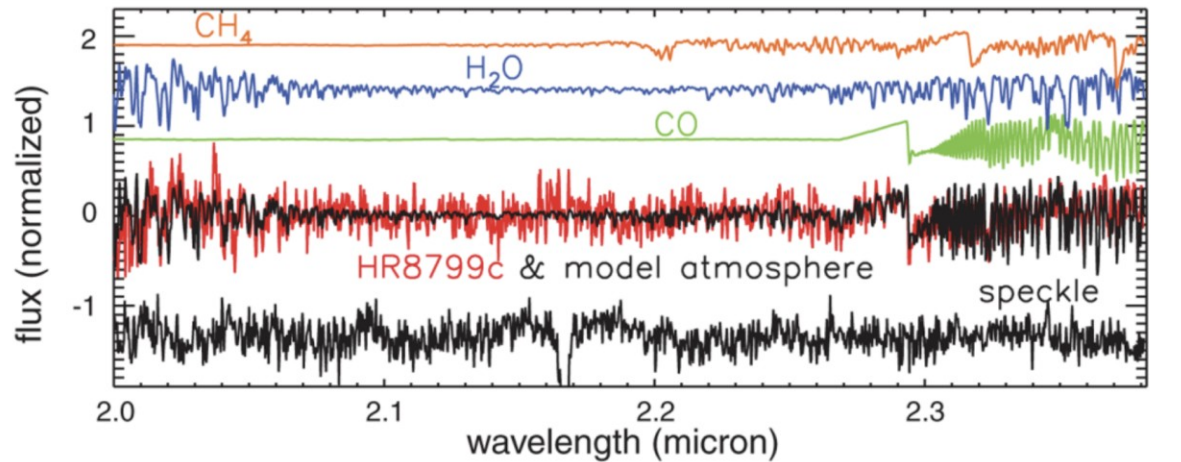
Correlated speckle noise

Degeneracy of composition with T-P structure and clouds

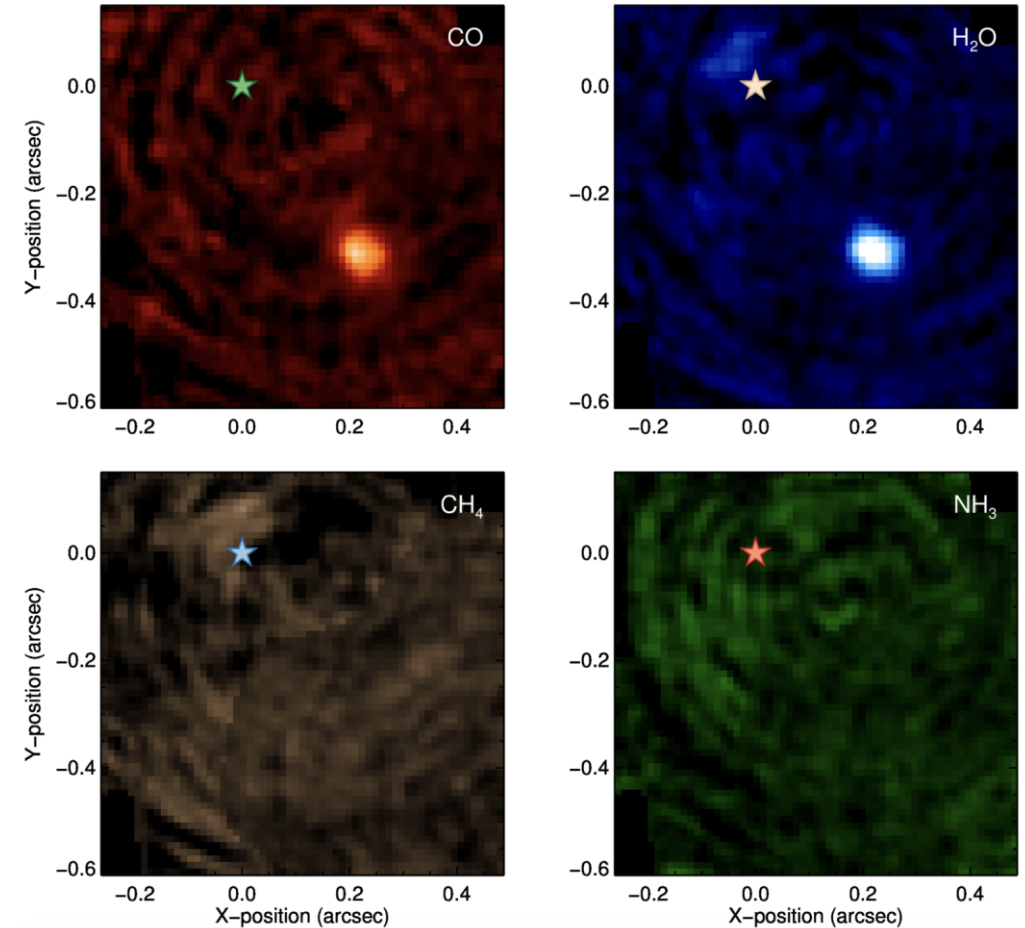
	[M/H]	C/O
Samland+17	$1.0 \pm 0.1$	
Brown-	$0.3 \pm 0.3$	$0.38 \pm 0.09$
Sevilla+23	$-0.1 \pm 0.2$	$0.80 \pm 0.18$
Whiteford+23	$-0.04^{+0.95}_{-0.49}$	$0.97^{+0.09}_{-0.20}$
	$-0.26^{+0.66}_{-0.18}$	$0.92^{+0.19}_{-0.27}$



# Boost contrast with medium-resolution ( $R \sim 5000$ ) IFU

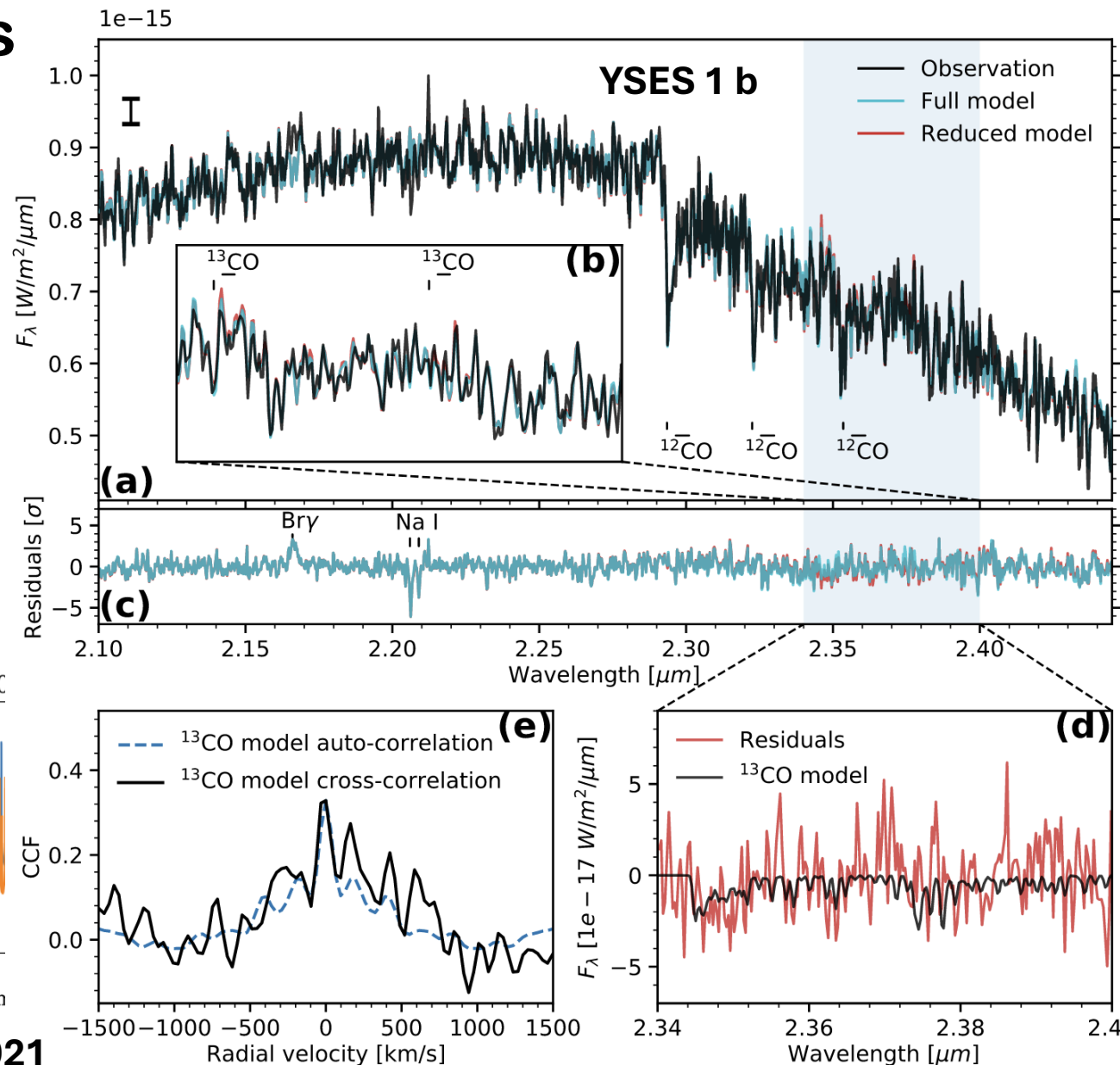
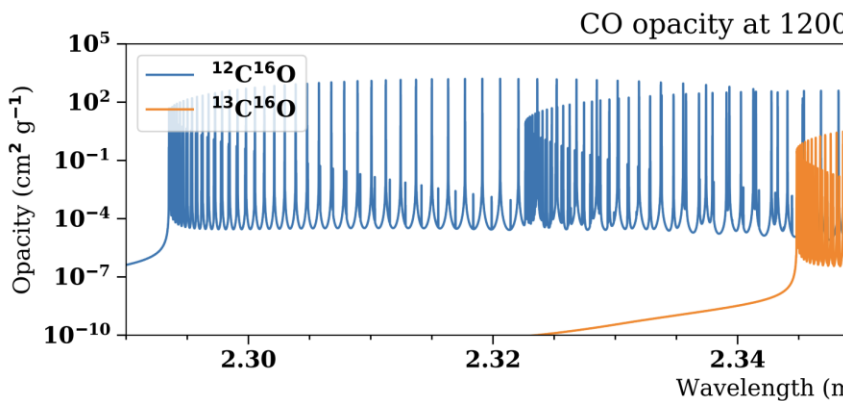
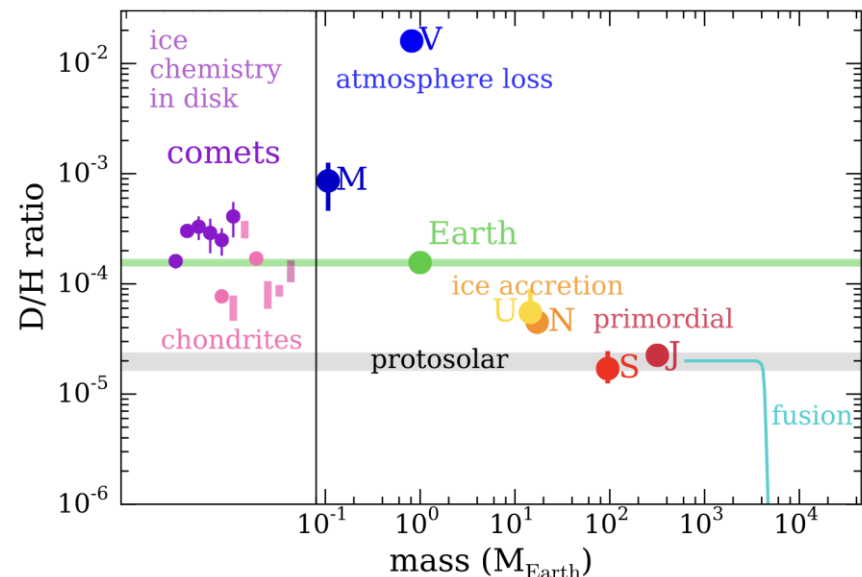


$\beta$  Pic b



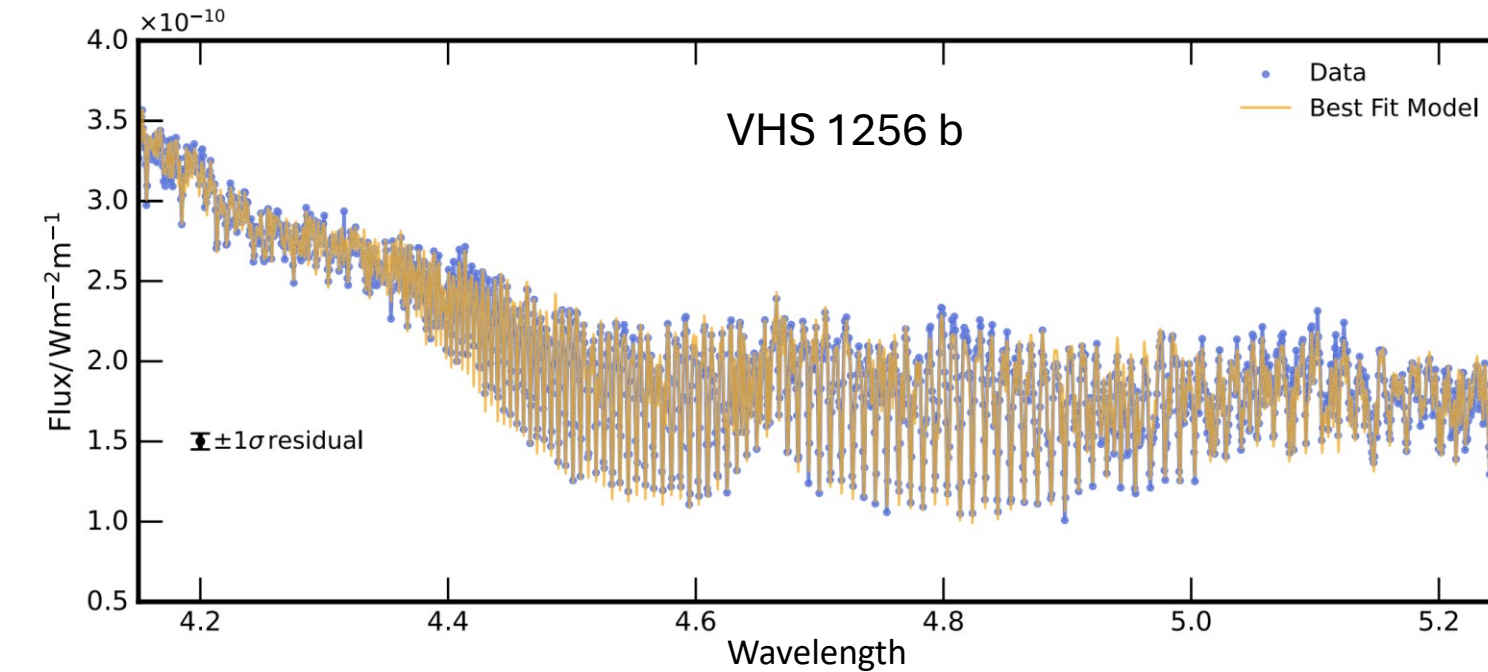
Konopacky+2013; Hoeijmakers+2018, Hayoz+2025

# Isotopes as formation tracers

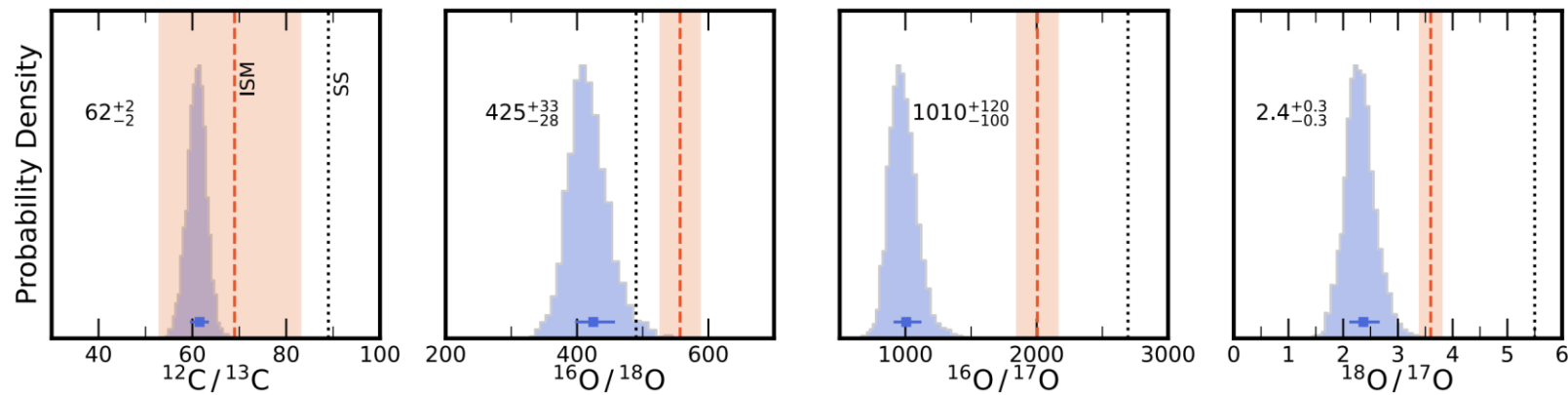


Mollière&Snellen2019, Morley+2019, Zhang+2021

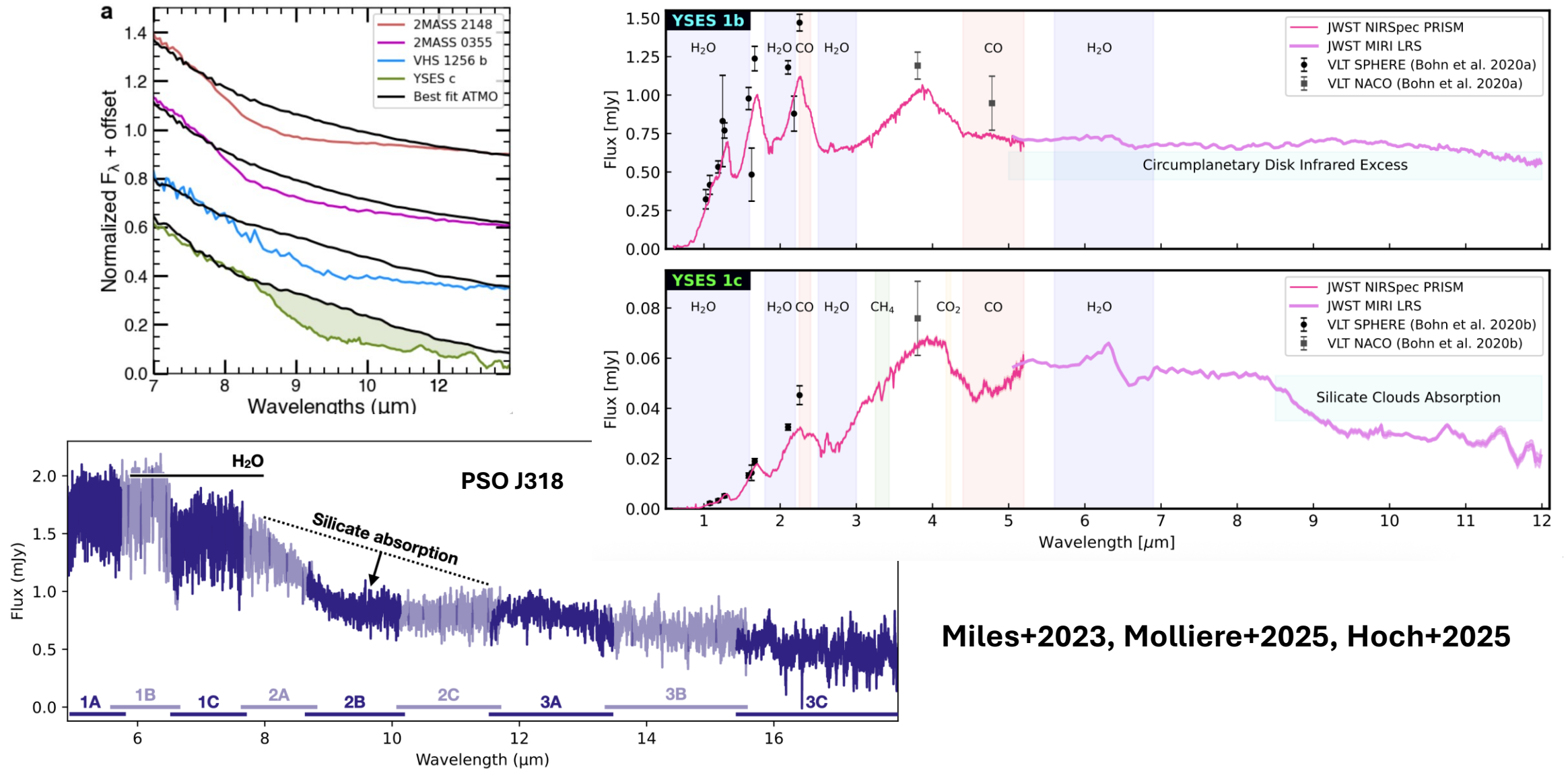
# JWST opens windows to the mid-infrared - $^{13}\text{C}$ , $^{18}\text{O}$ , $^{17}\text{O}$ , $^{15}\text{N}$ , D



**Gandhi+2023**  
**Barrado+2023**  
**Kühnle+2024**  
**Rowland+2024**  
**González Picos+2025**

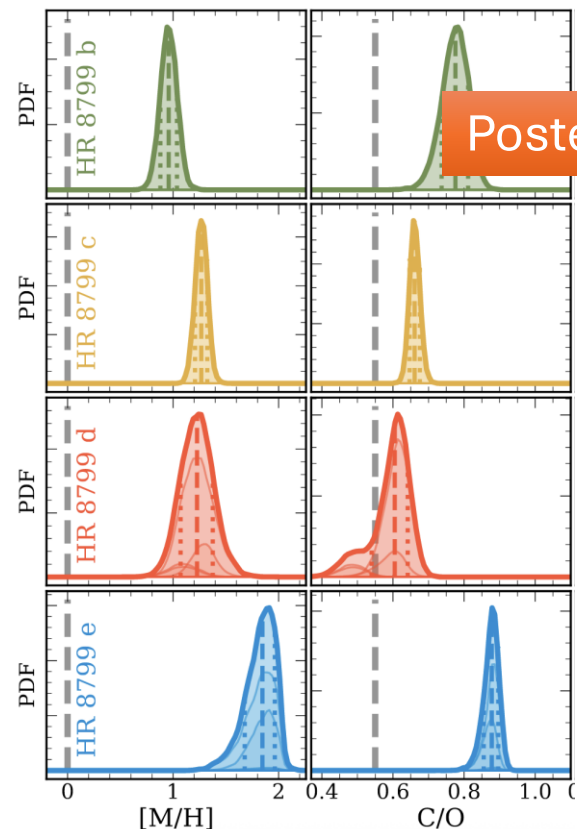
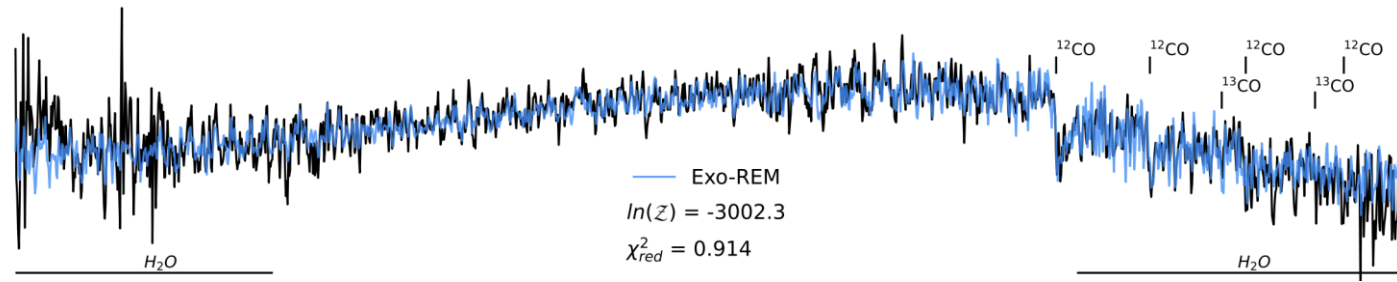
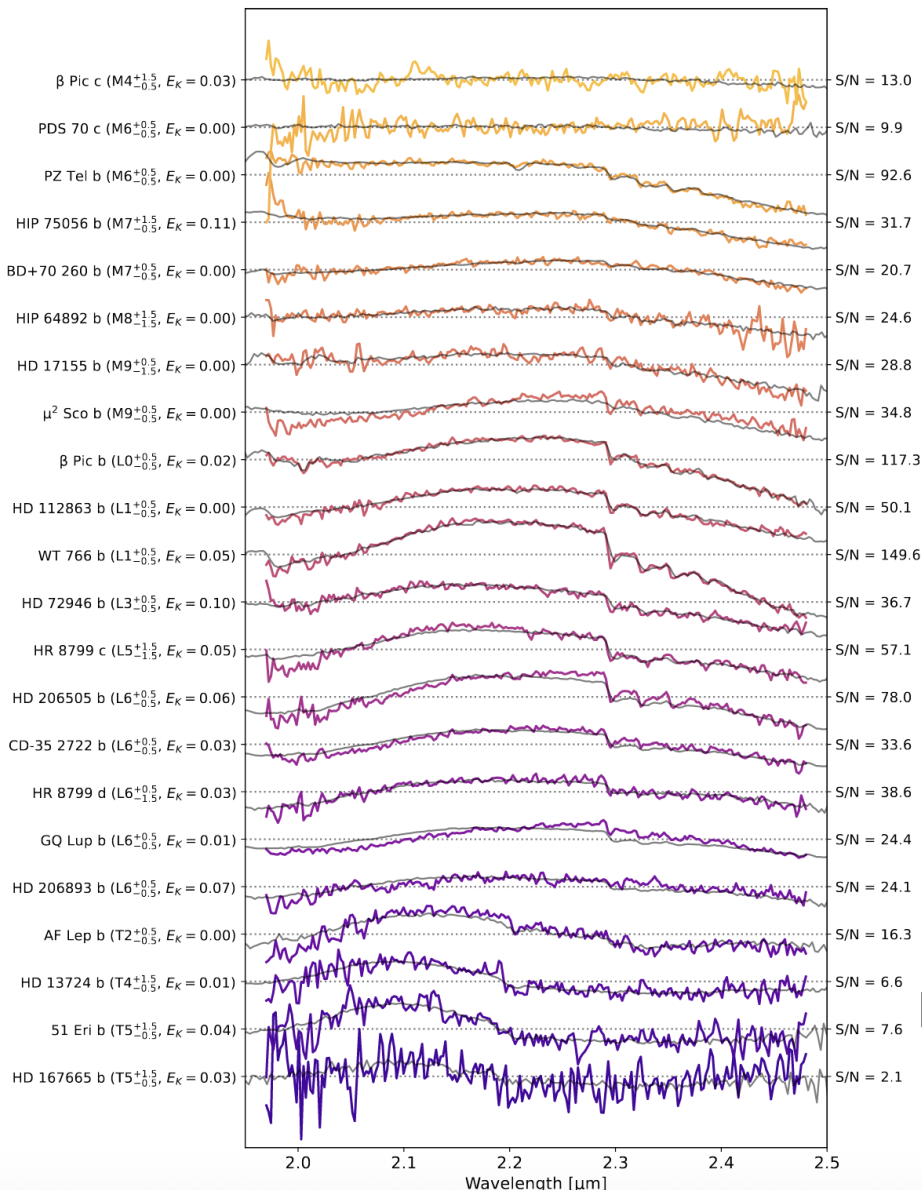


# Silicate clouds in the mid-infrared





# Closer-in companions with interferometry - ExoGRAVITY



Ravet+2025

Poster by Matthieu Ravet

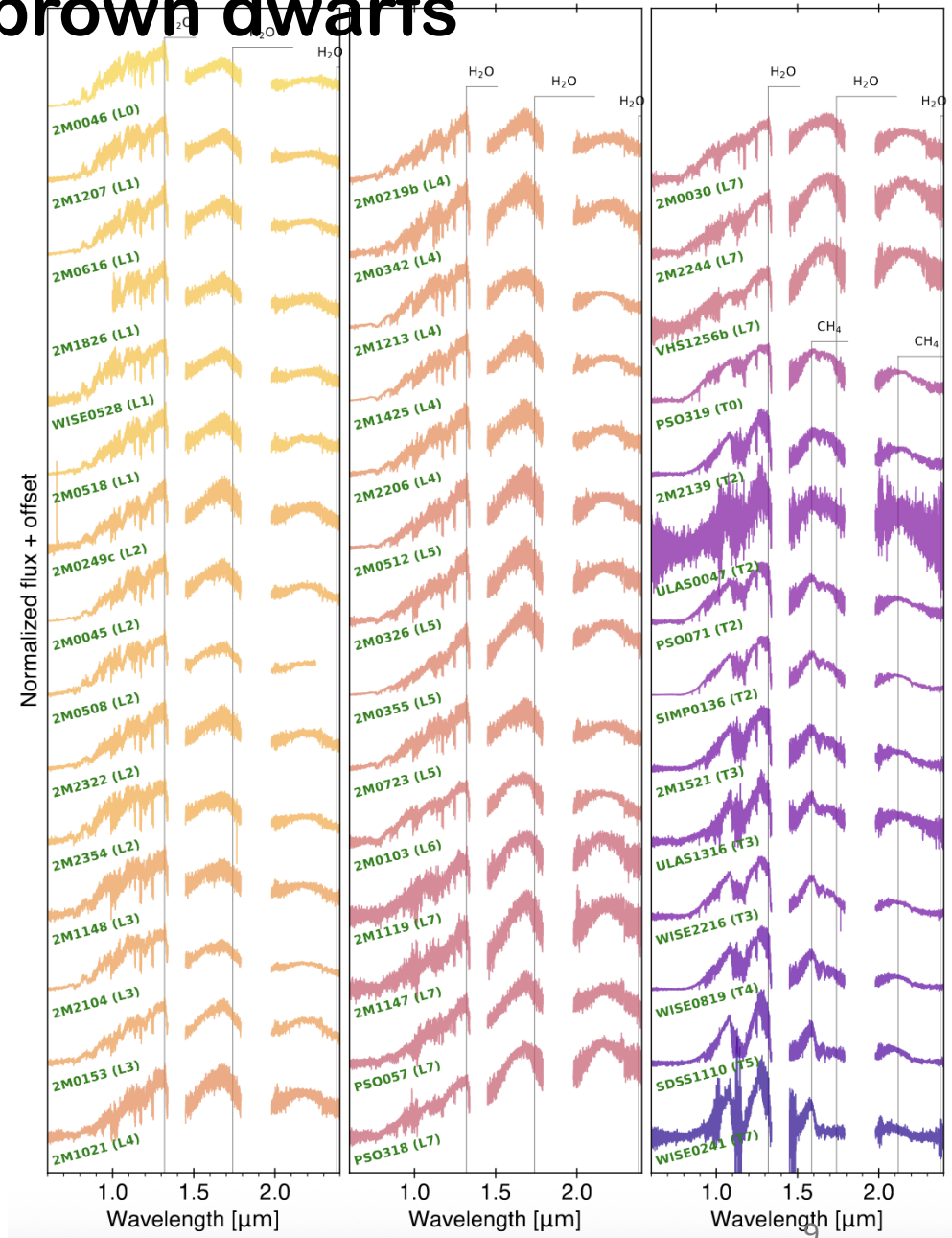
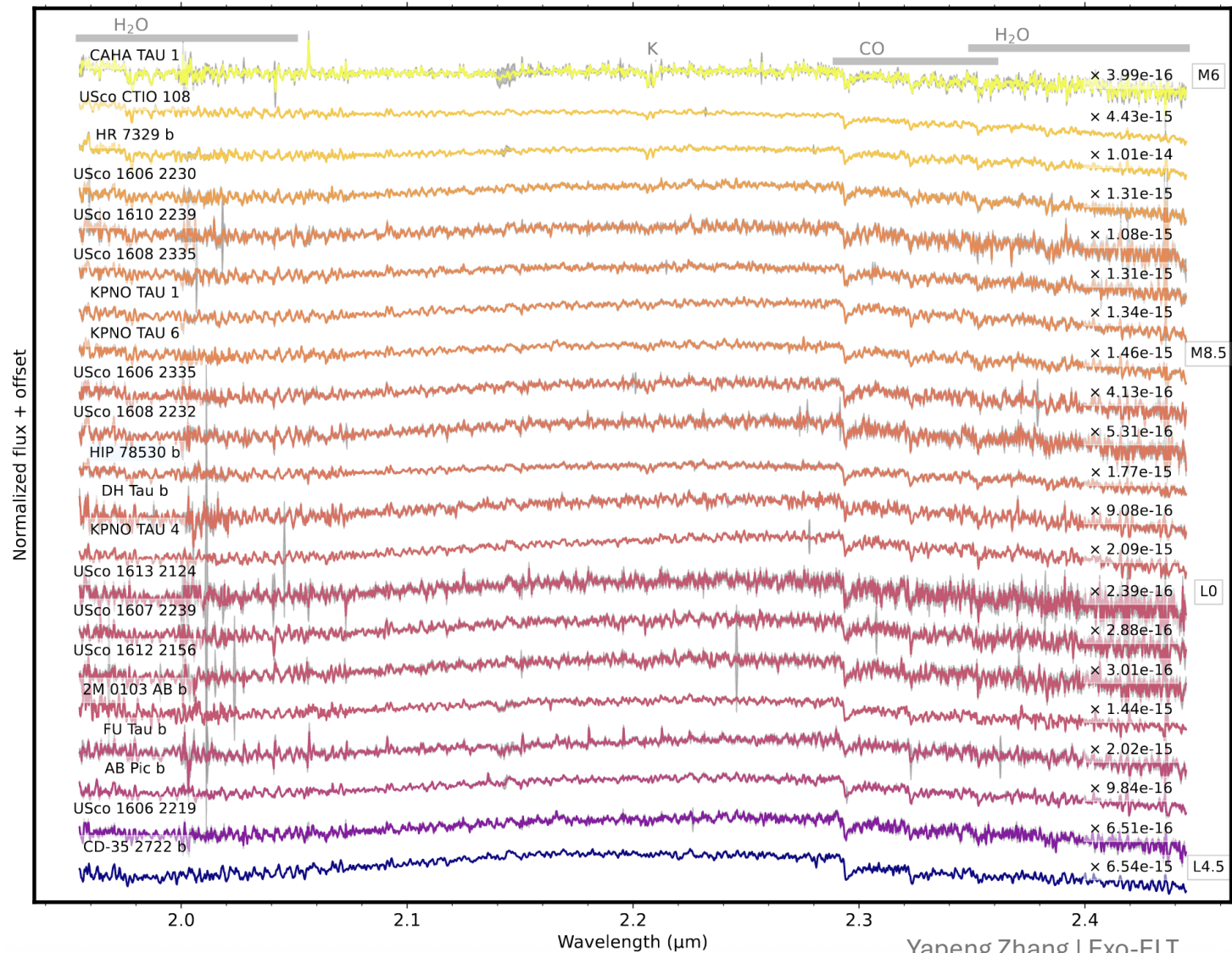
Nasedkin+2024  
Balmer+2024

VLTI/MATISSE  
Mathis+2024

Kammerer+2025

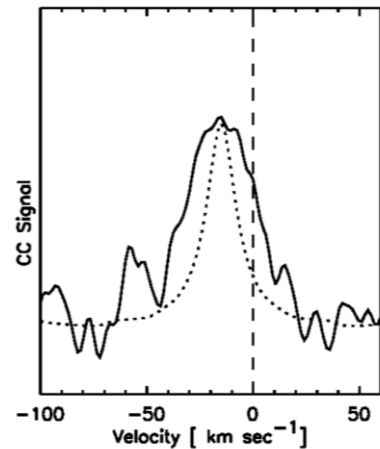
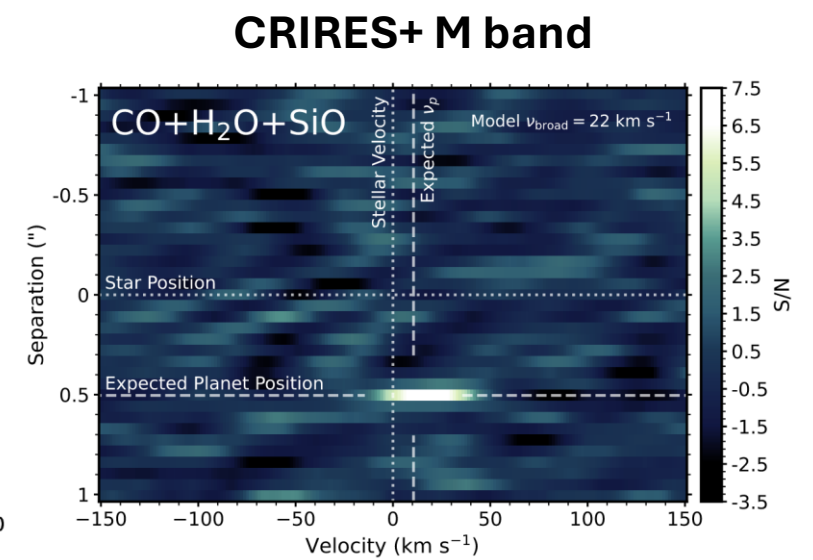
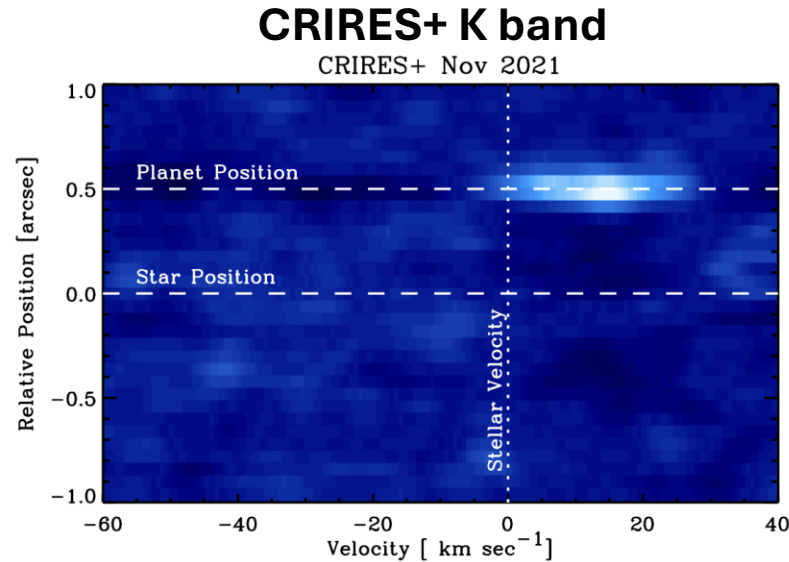
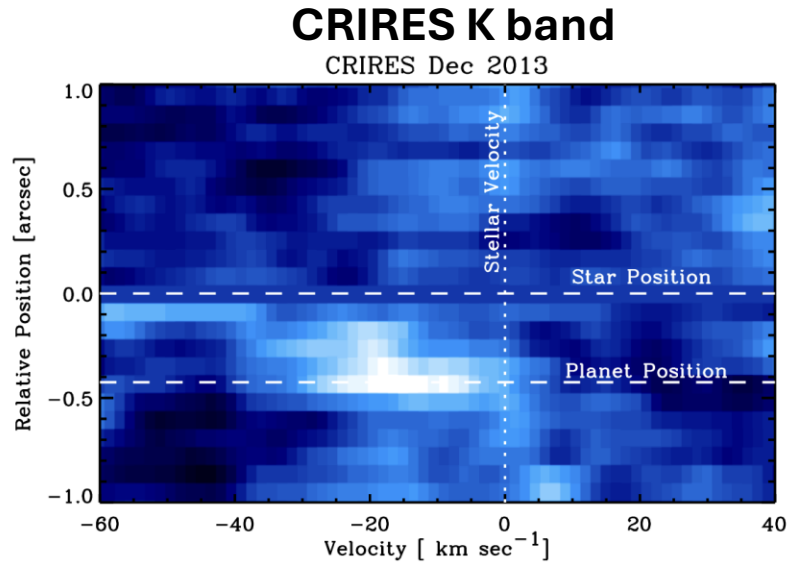
# Spectral library of super-Jupiters and brown dwarfs

Palma-Bifani+2025, Petrus+2025





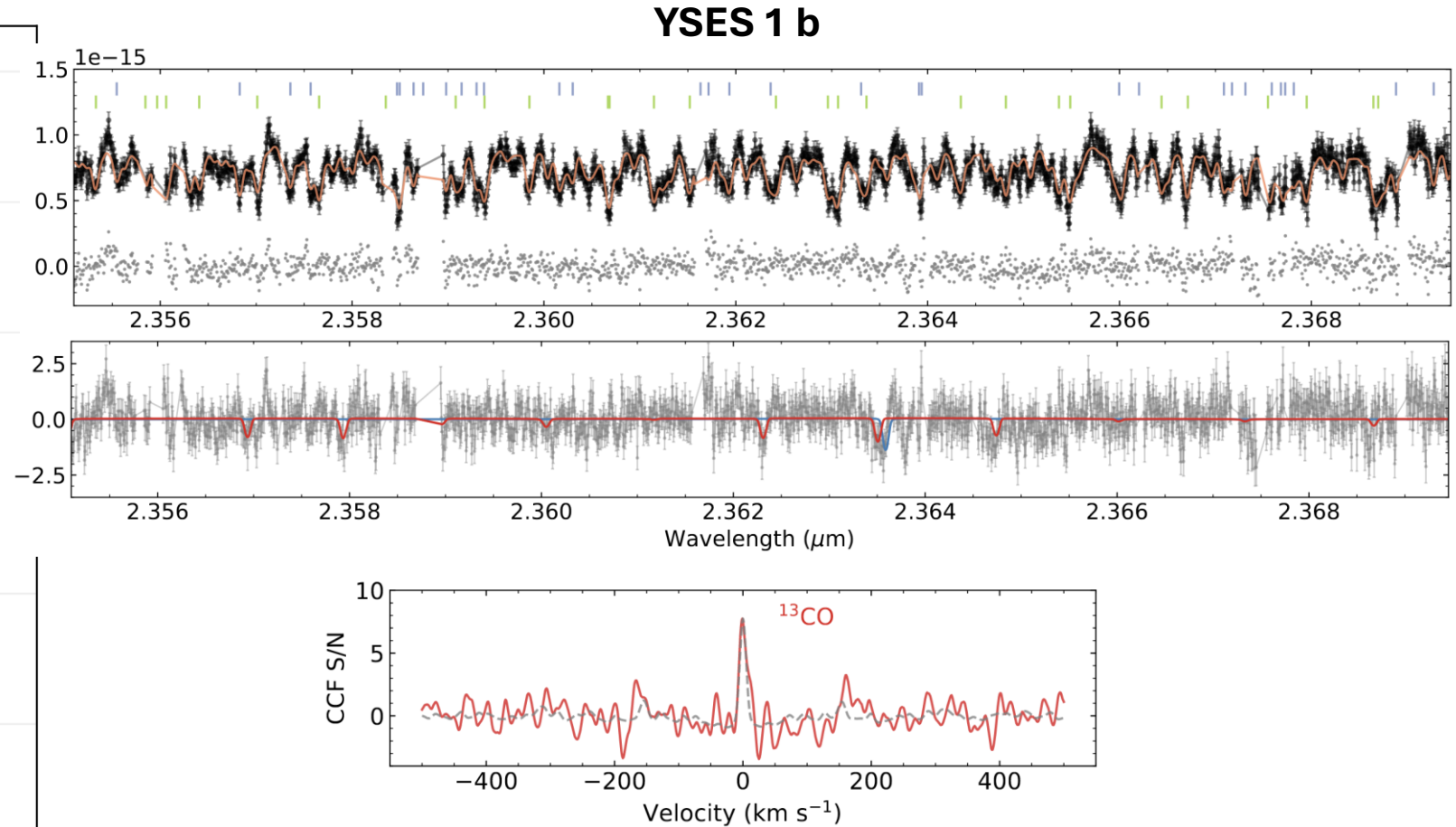
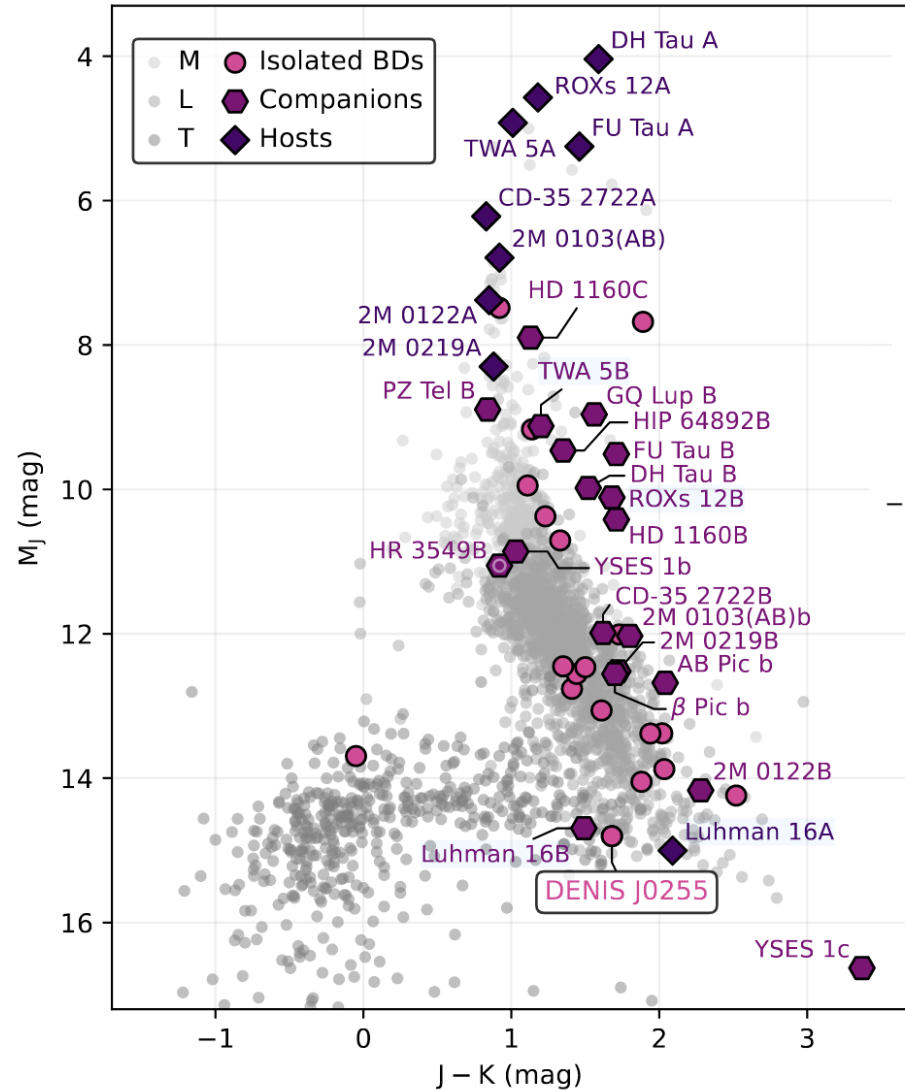
# AO-assisted high-resolution direct spectroscopy ( $R > 30,000$ )



Talks by Luke Parker;  
Dario Gonzalez Picos

**Snellen+2014, Landman+2024, Parker+2024**

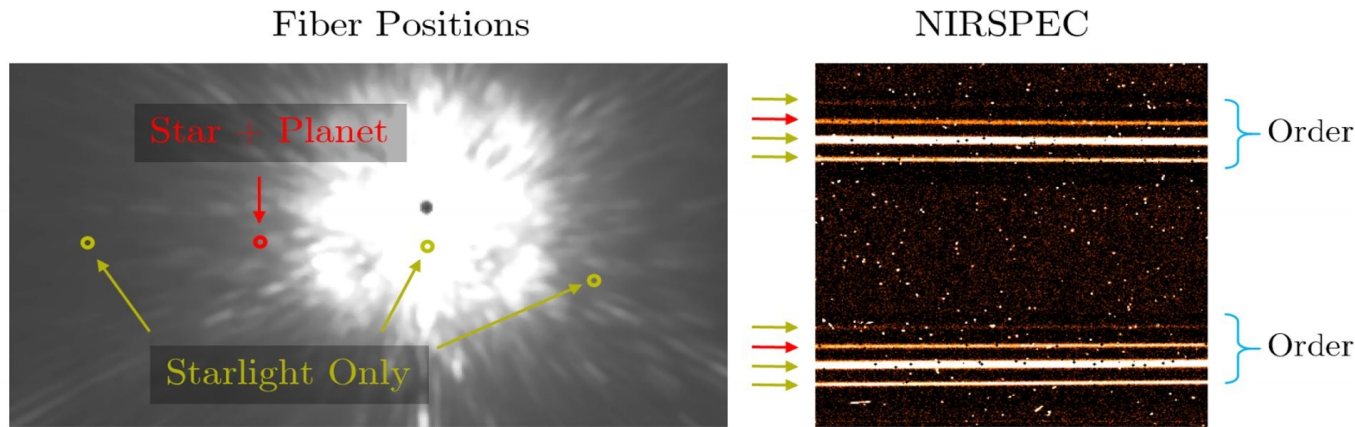
# ESO's SupJup survey with CRIRES+



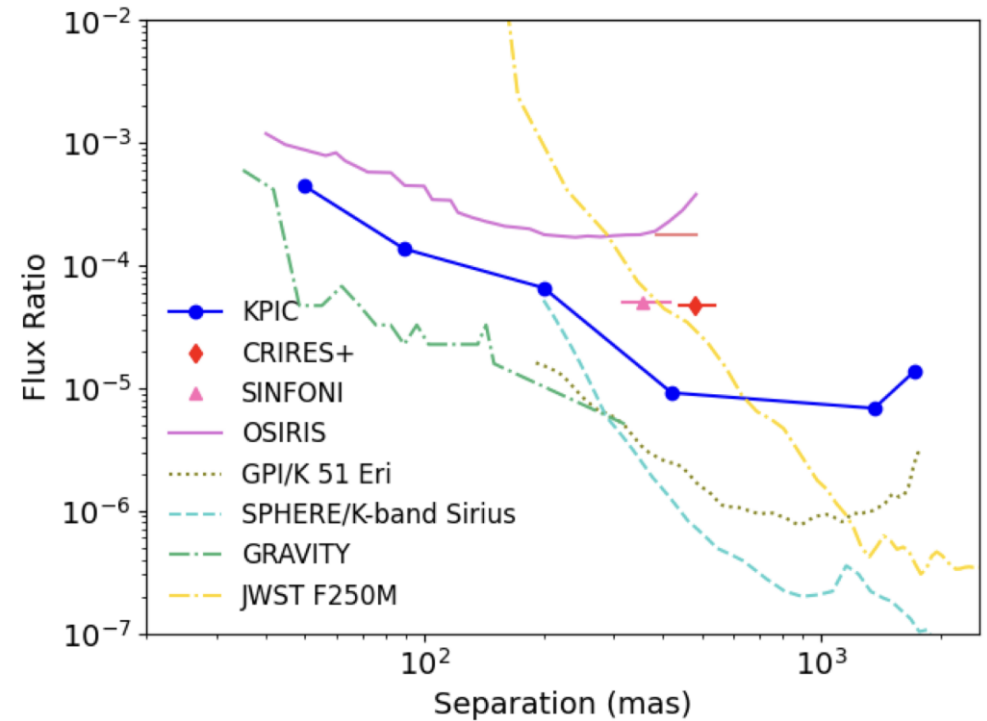
de Regt+2024, González Picos+2024, Zhang+2024, Mulder+2025, Gandhi+2025, de Regt+2025, Grasser+2025, González Picos+2025

# Single-mode fiber injection unit + high resolution spectroscopy

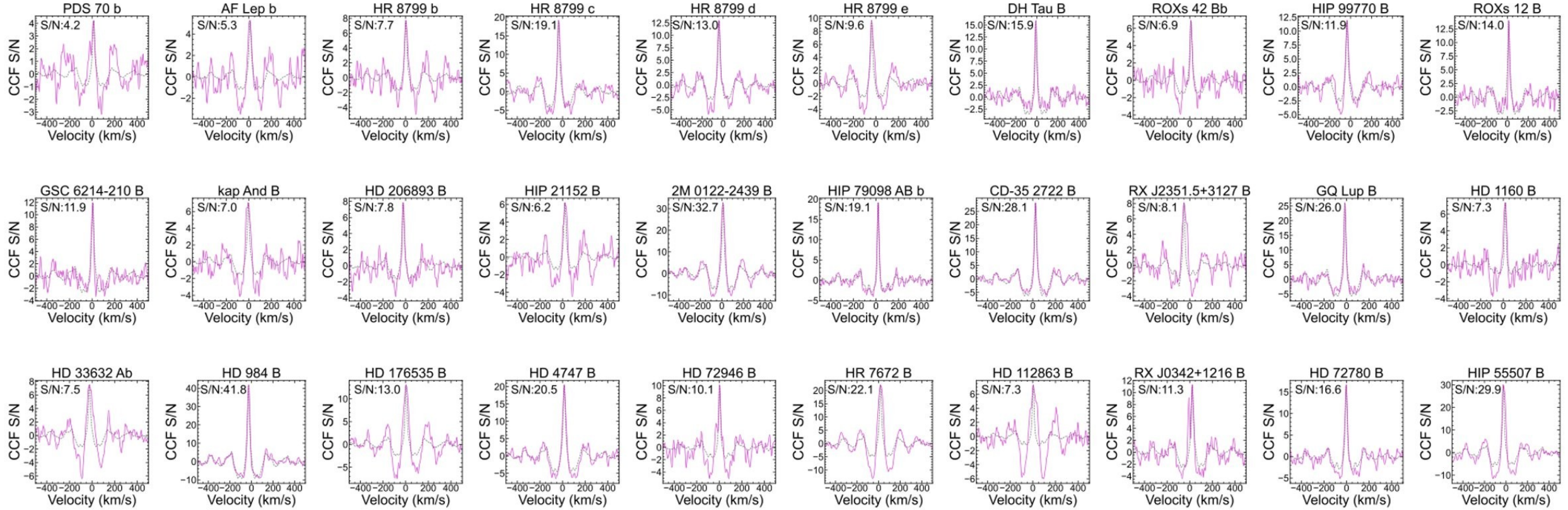
## Keck Planet Imager and Characterizer (KPIC)



Mawet+2017, Delorme+2021, Wang+2021, Wang+2024



# Keck/KPIC survey



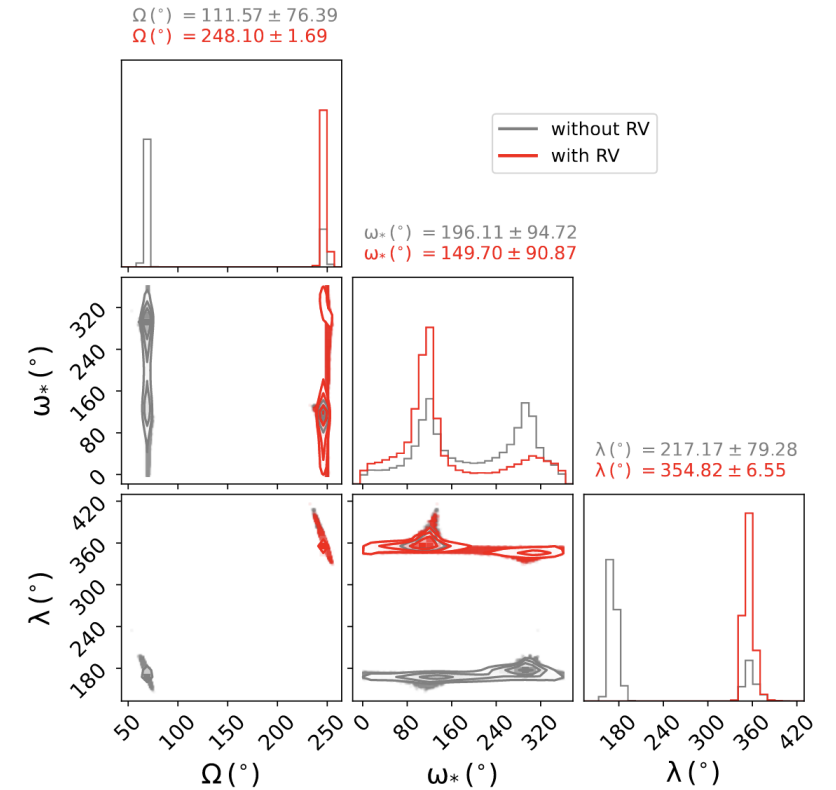
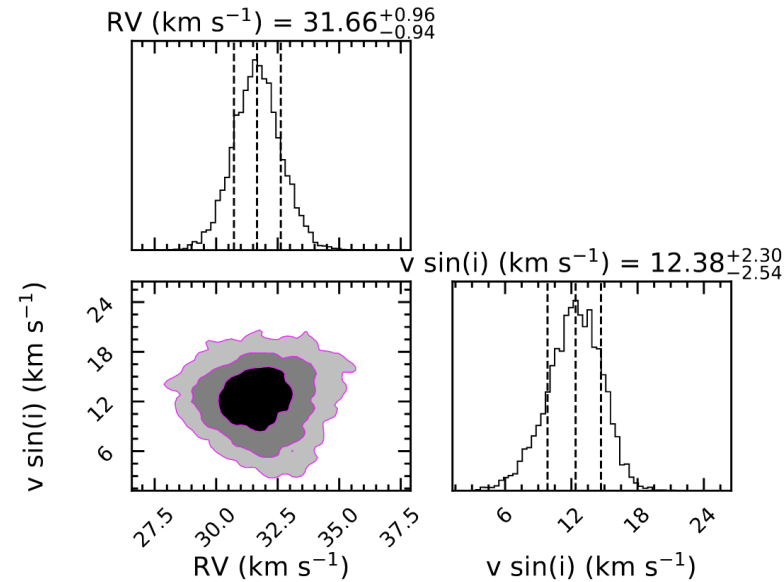
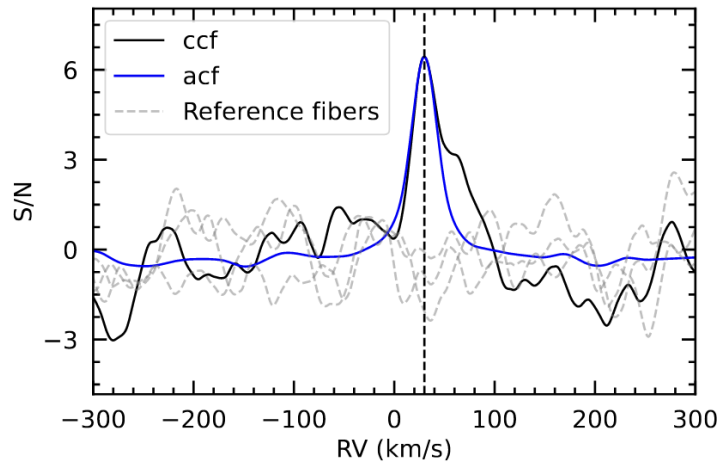
**e.g., Wang+2021, Wang+2022, Xuan+2024ab, Costes+2024,  
Zhang+2024b, Hsu+2024ab, Sappey+2025, Hsu+submitted**



# VLT/HIRISE; Subaru/REACH

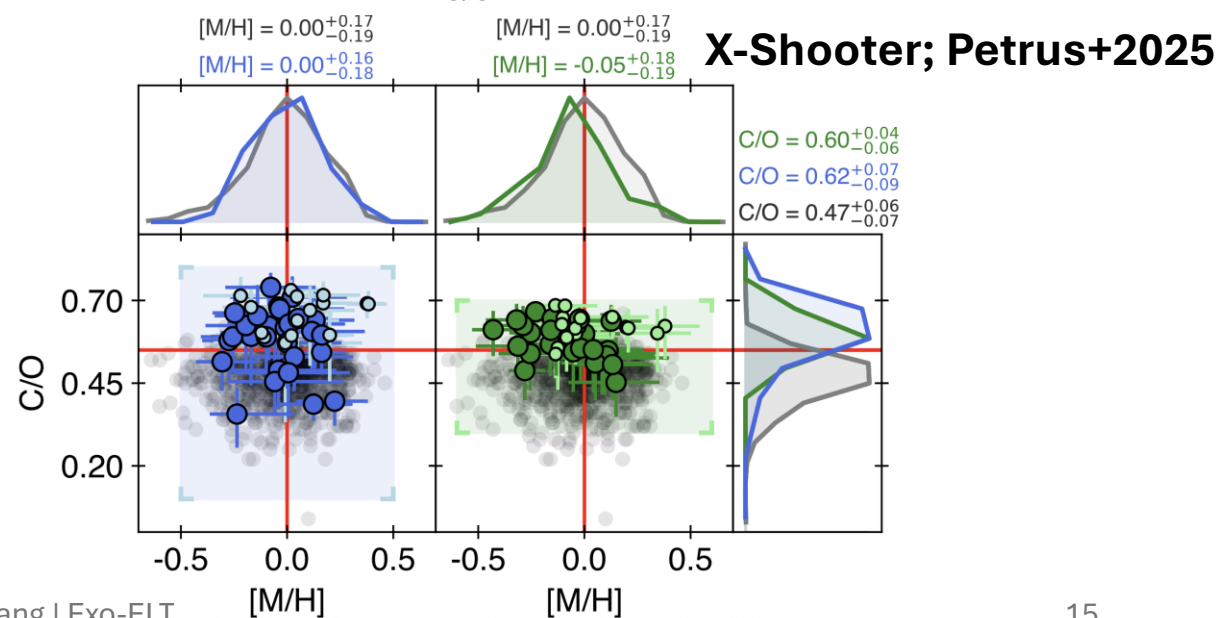
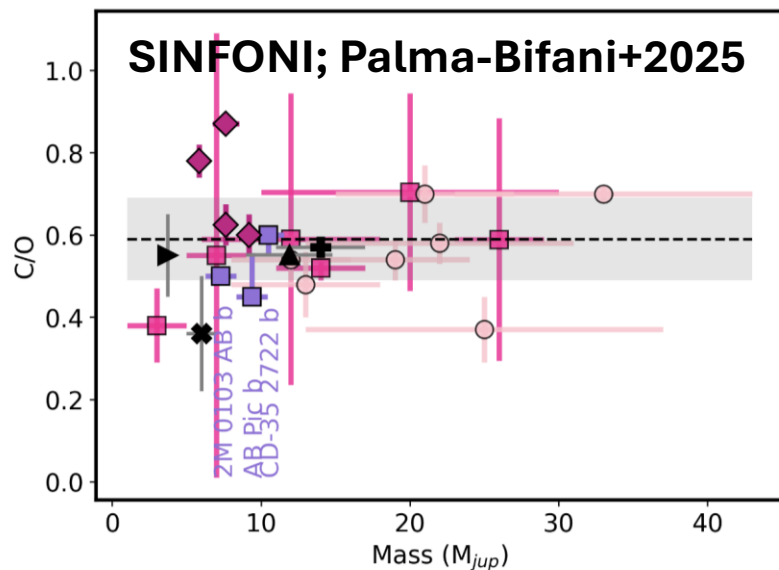
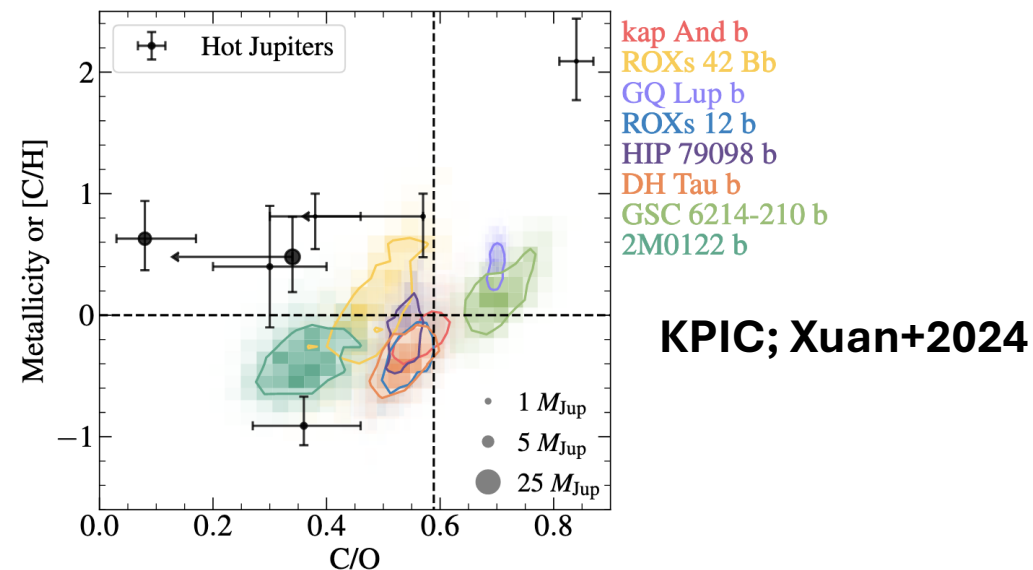
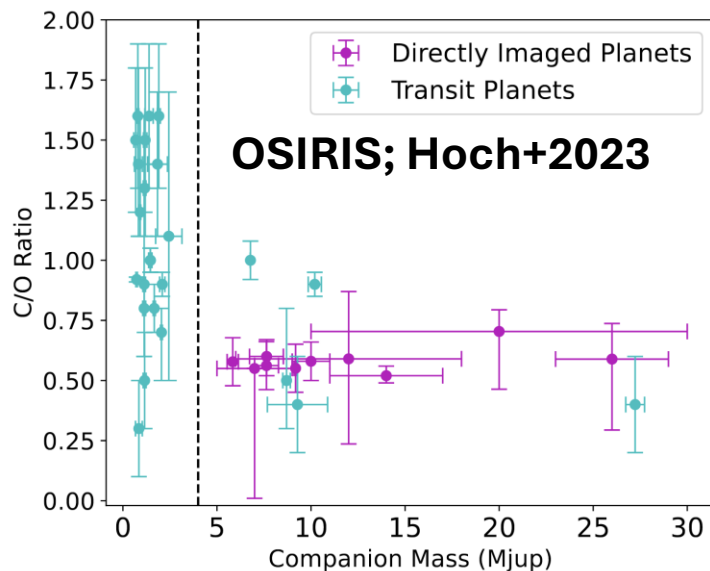
Talk by Allan Denis

## AF Lep b



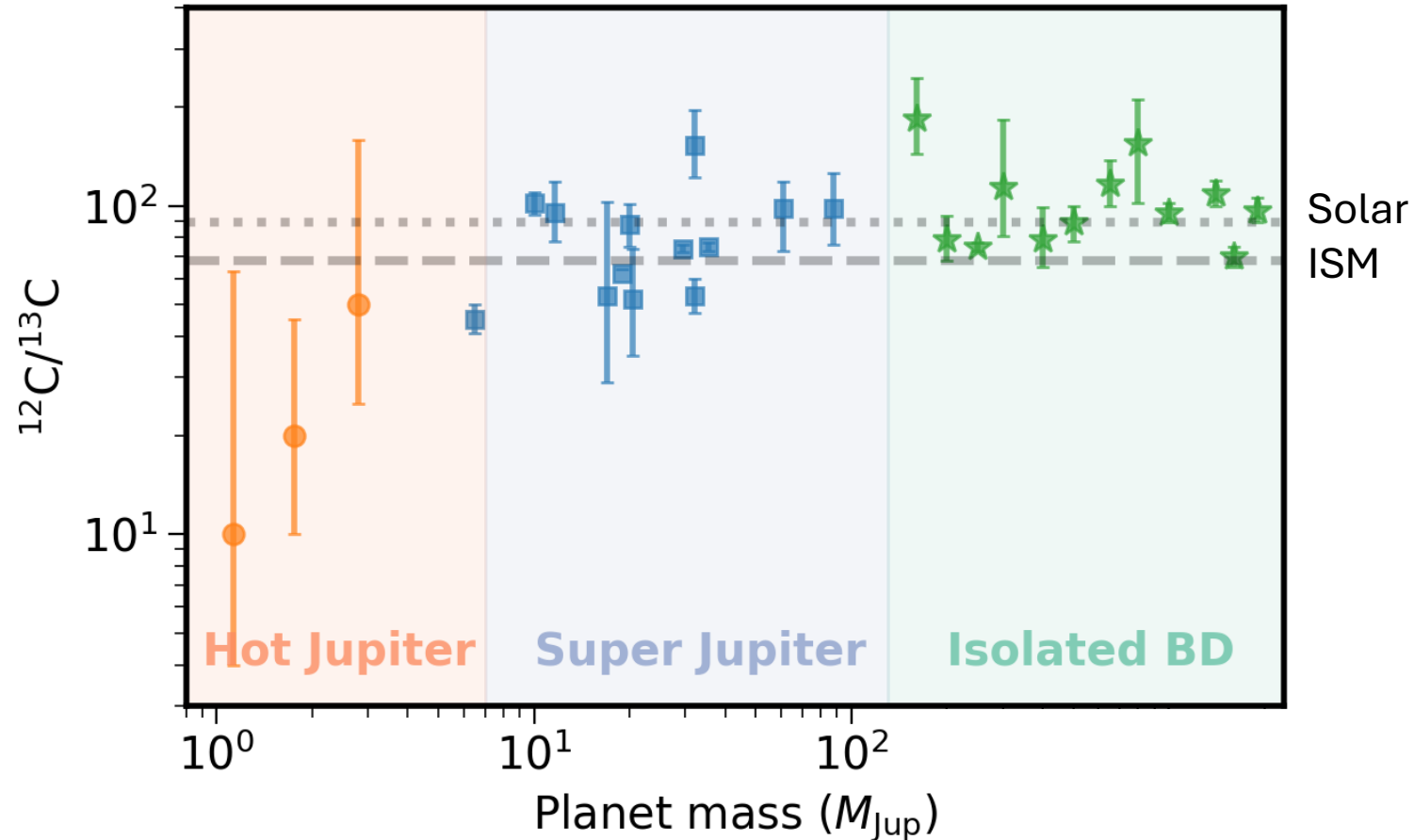
Vigan+2022, Denis+2025

# Solar-like composition for wide-separation super-Jupiters $>10 M_{\text{Jup}}$





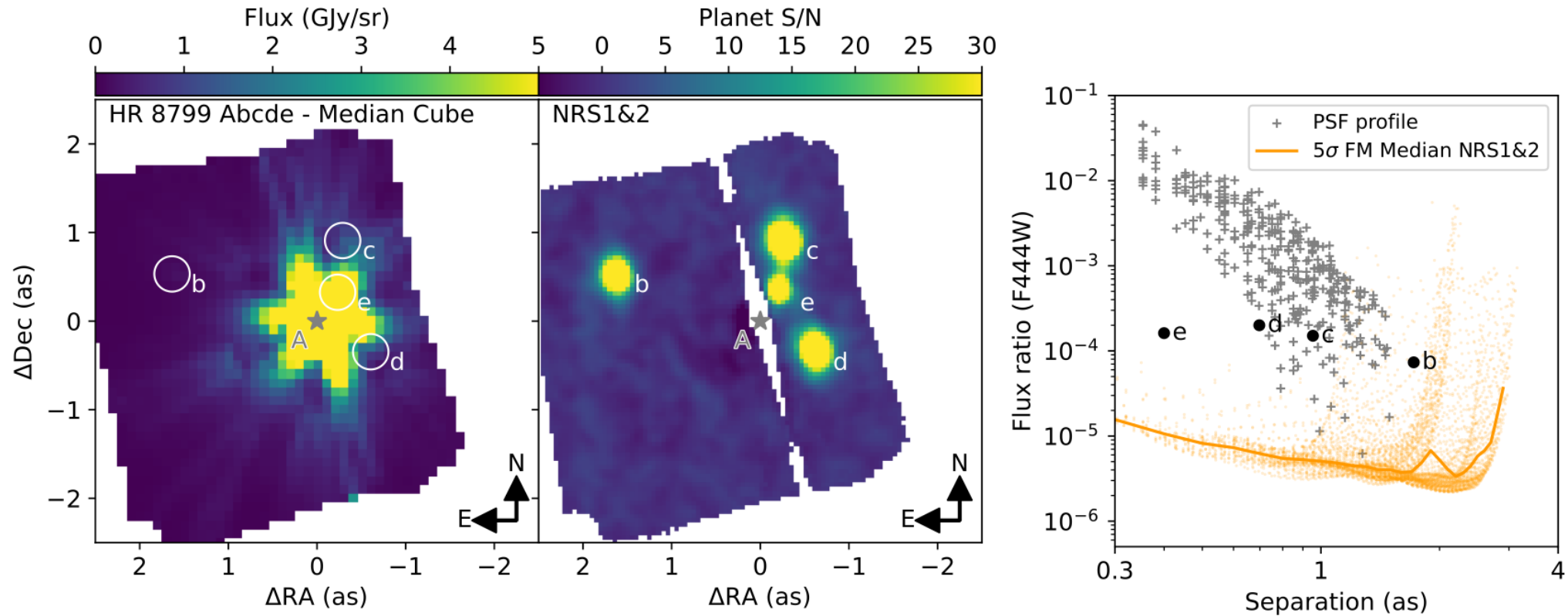
# Solar-like carbon isotope ratios for super-Jupiters



Zhang+2021ab, Line+2021, Zhang+2022, Finnerty+2023, Gandhi+2023, Costes+2024, Finnerty+2024, Xuan+2024ab, de Regt+2024, González Picos+2024, Zhang+2024, Hood+2024, Mulder+2025, Gandhi+2025, de Regt+2025, Grasser+2025, González Picos+2025, Mollière+2025

# Pushing towards high-contrast planets with IFU

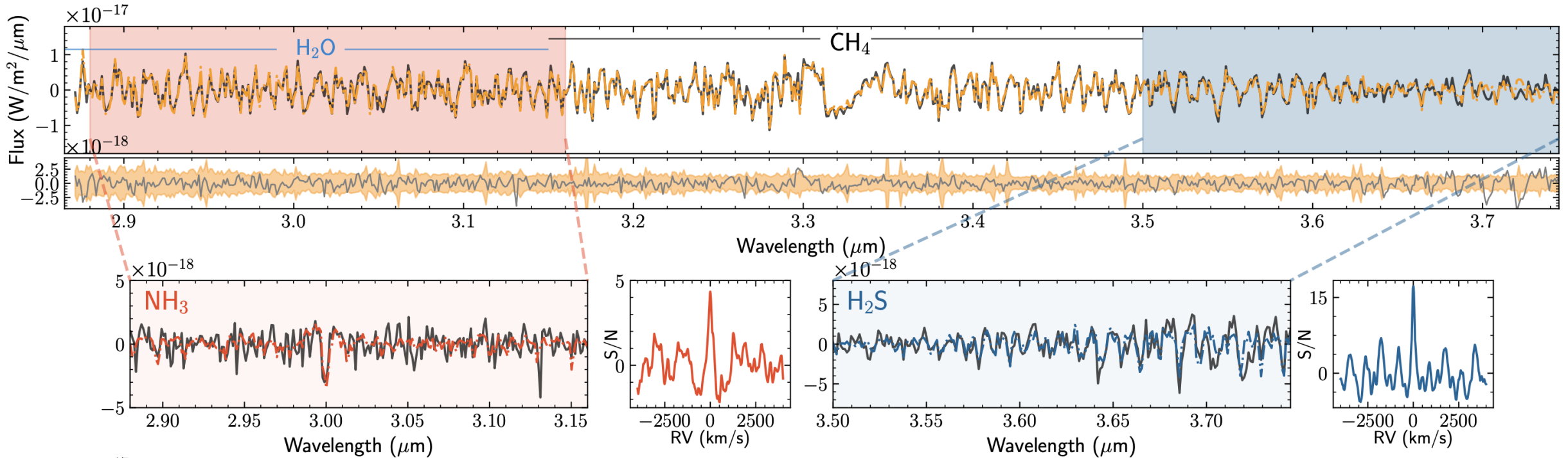
JWST/NIRSpec IFU, 3-5 microns,  $R \sim 2700$  (GTO 1188)



Ruffio+2024, Xuan&Ruffio+ in prep.

# Inventory of volatile and refractory elements: C, O, N, S

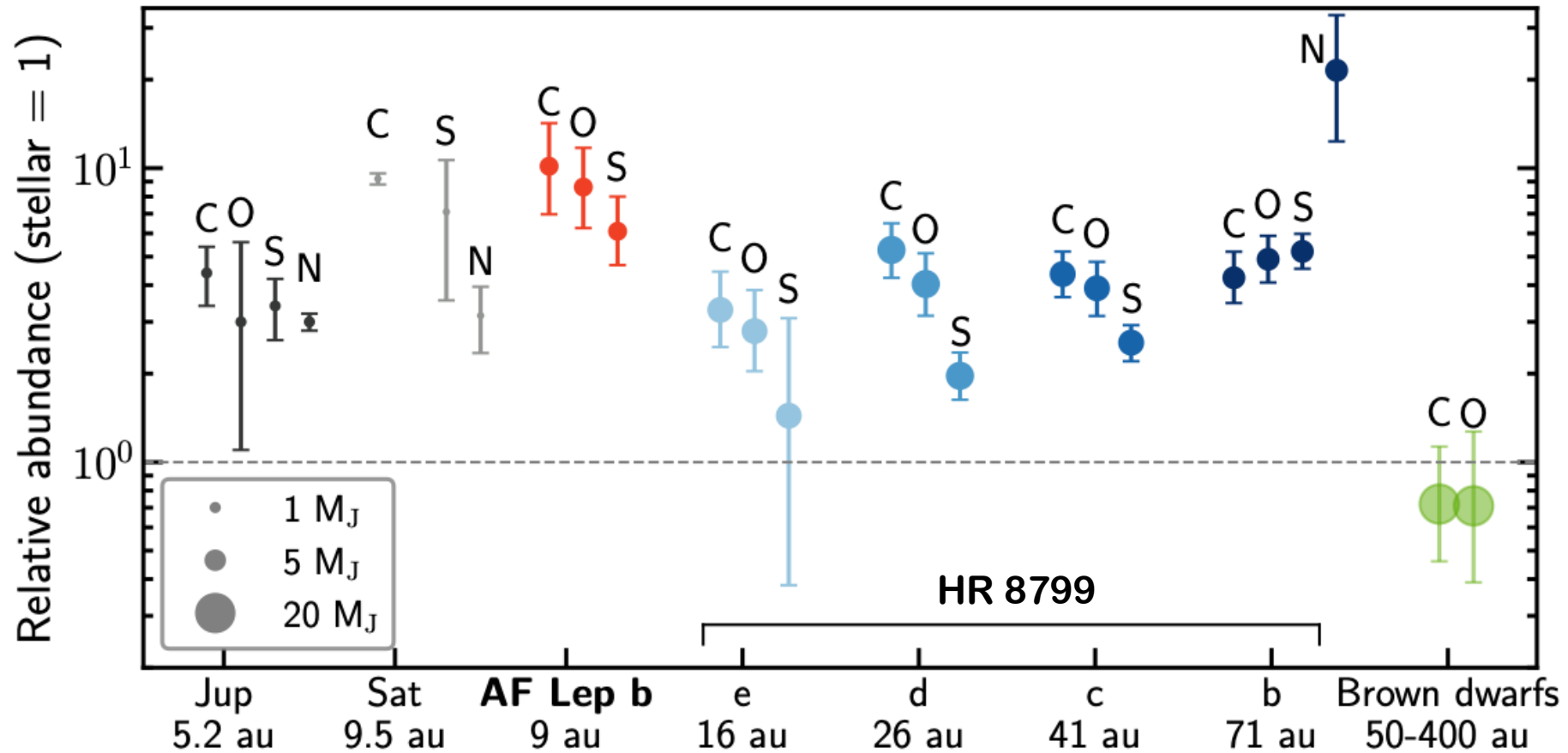
## HR 8799 b



Xuan&Ruffio+ in prep.

TurriniEtAl2021, Lothringer+2021, Chachan+2023, Bergin+2024

# Uniform enrichment of C, O, S in outer planets



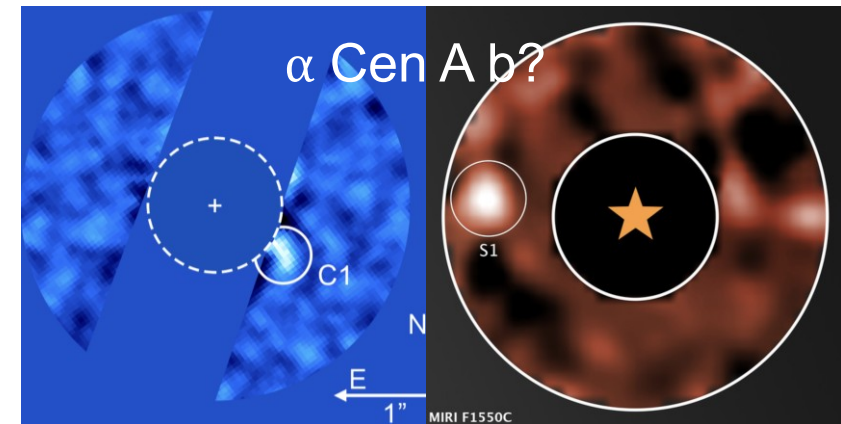
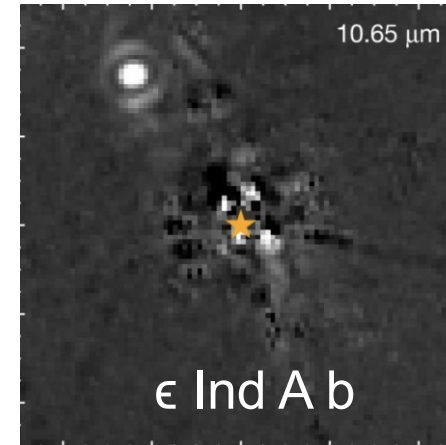
Xuan+in prep.

# Future prospects: colder, lower-mass, closer-in giant planets

JWST spectroscopy on  $\epsilon$  Ind A b (GO 8714) will provide first D/H and  $^{15}\text{N}/^{14}\text{N}$  measurements in exoplanets

Talks by Paulina Palma-Bifani;  
Adrien Simonnin

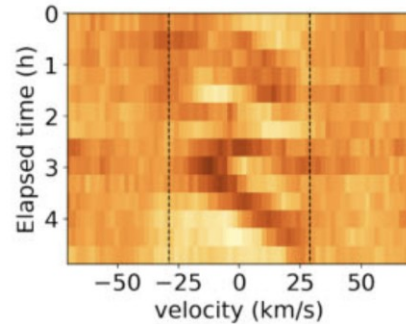
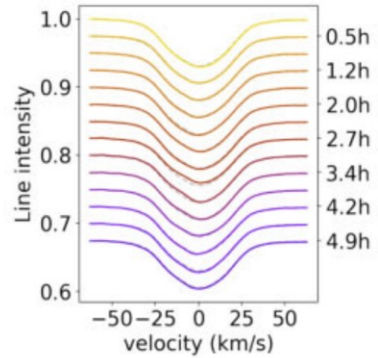
ELT can push to closer-in ( $\sim$ au scale)  
Jupiter analogs



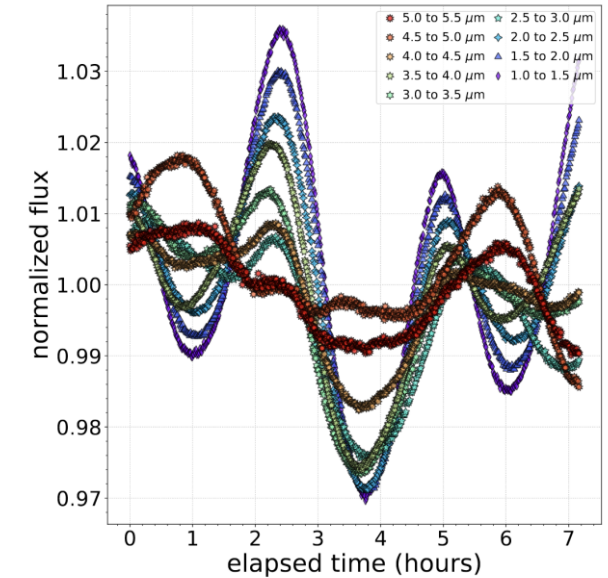
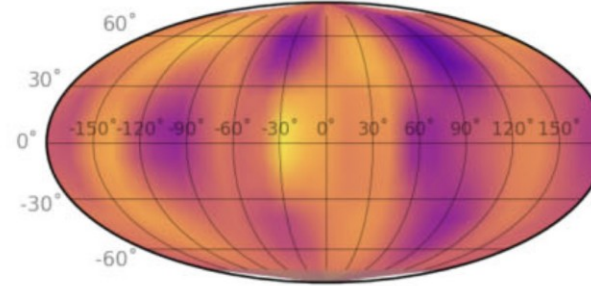
**Matthews+2024, Wagner+2021, Beichman+2025, Sanghi+2025**

# Atmospheric dynamics with ELT

## Doppler Imaging of young super Jupiters

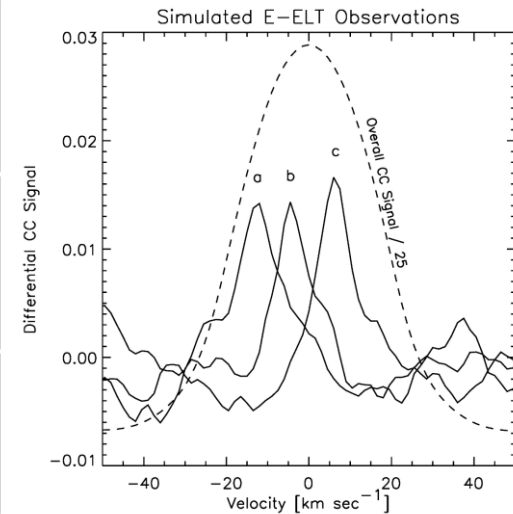
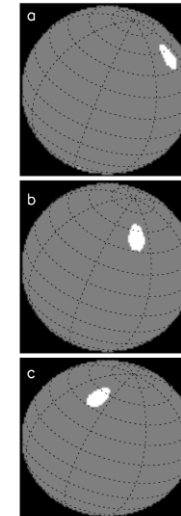
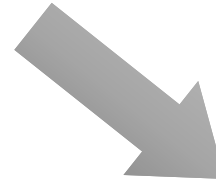


Luhman 16



Crossfield+2014ab, Biller+2024, Chen+2024

Talk by Xueqing Chen

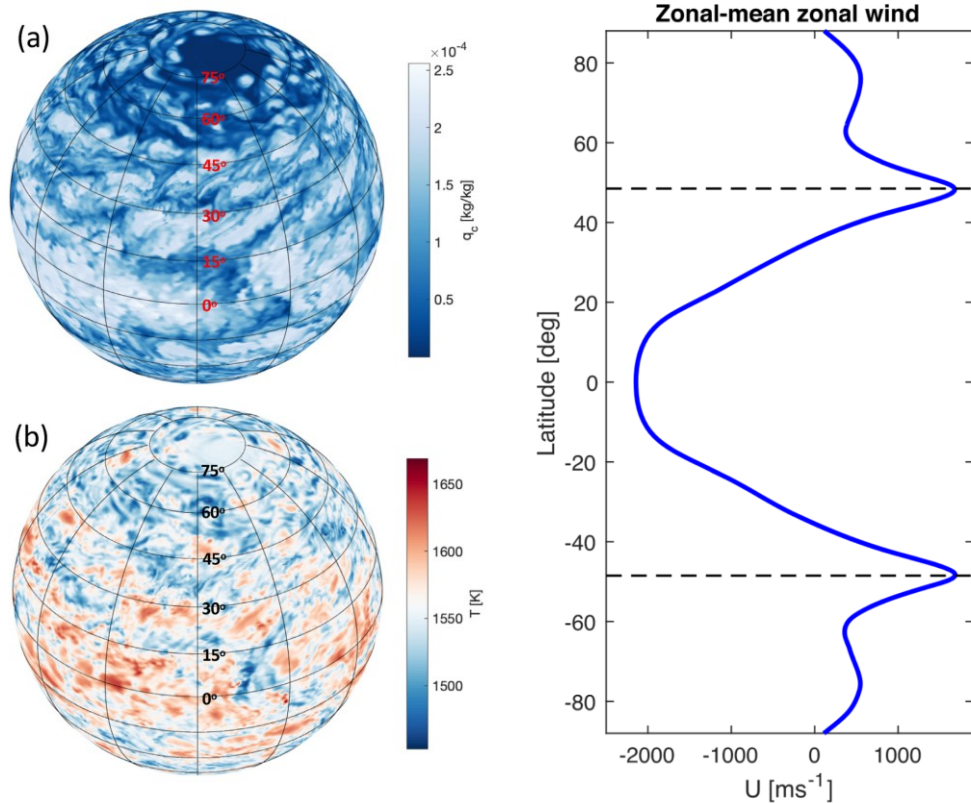


$\beta$  Pic b Snellen+2014

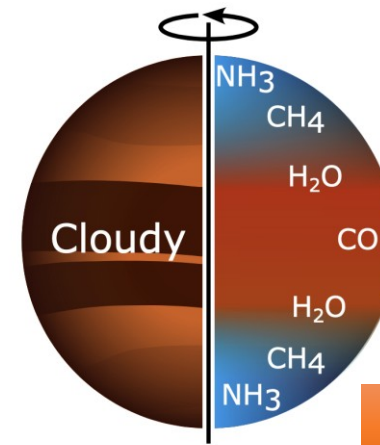


# Atmospheric dynamics with ELT

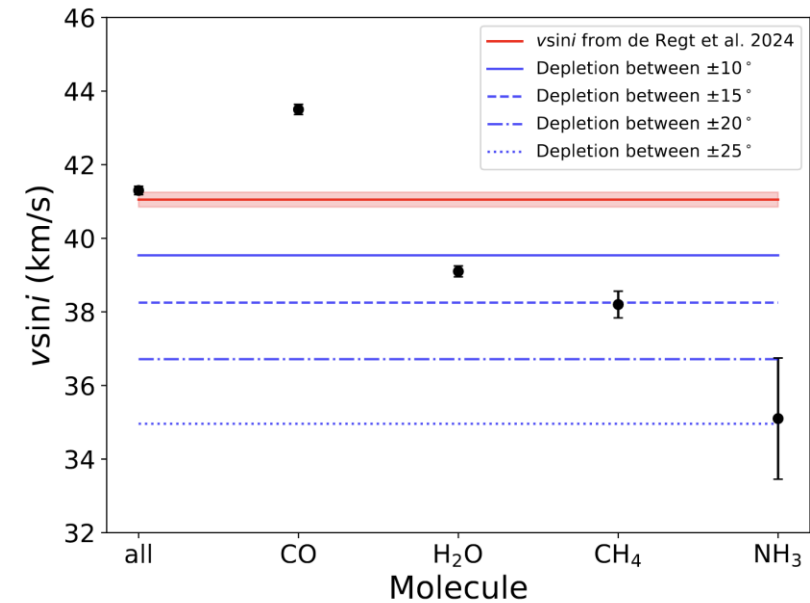
## Zonal bands and winds in young gas giants



Tan&Showman2021



Poster by Benjamin Charnay



Charnay+2025

# Summary

- Wide-separation massive super-Jupiters ( $> 10 M_{\text{Jup}}$ ) and brown dwarfs show solar-like atmospheric compositions.
- Outer exoplanets, such as AF Lep b and HR 8799 bcde, show metal enrichment in C, O, S, like the Jupiter.
- This points to different formation pathways. The mass boundary between the two population is still an open question.
- ELT can routinely deliver the inventory of chemical and isotopic abundance measurements in a larger population of outer gas giants, providing deeper insights into gas giant formation.
- Probing atmospheric dynamics in brown dwarfs has become feasible. ELT will be able to push these towards outer exoplanets.