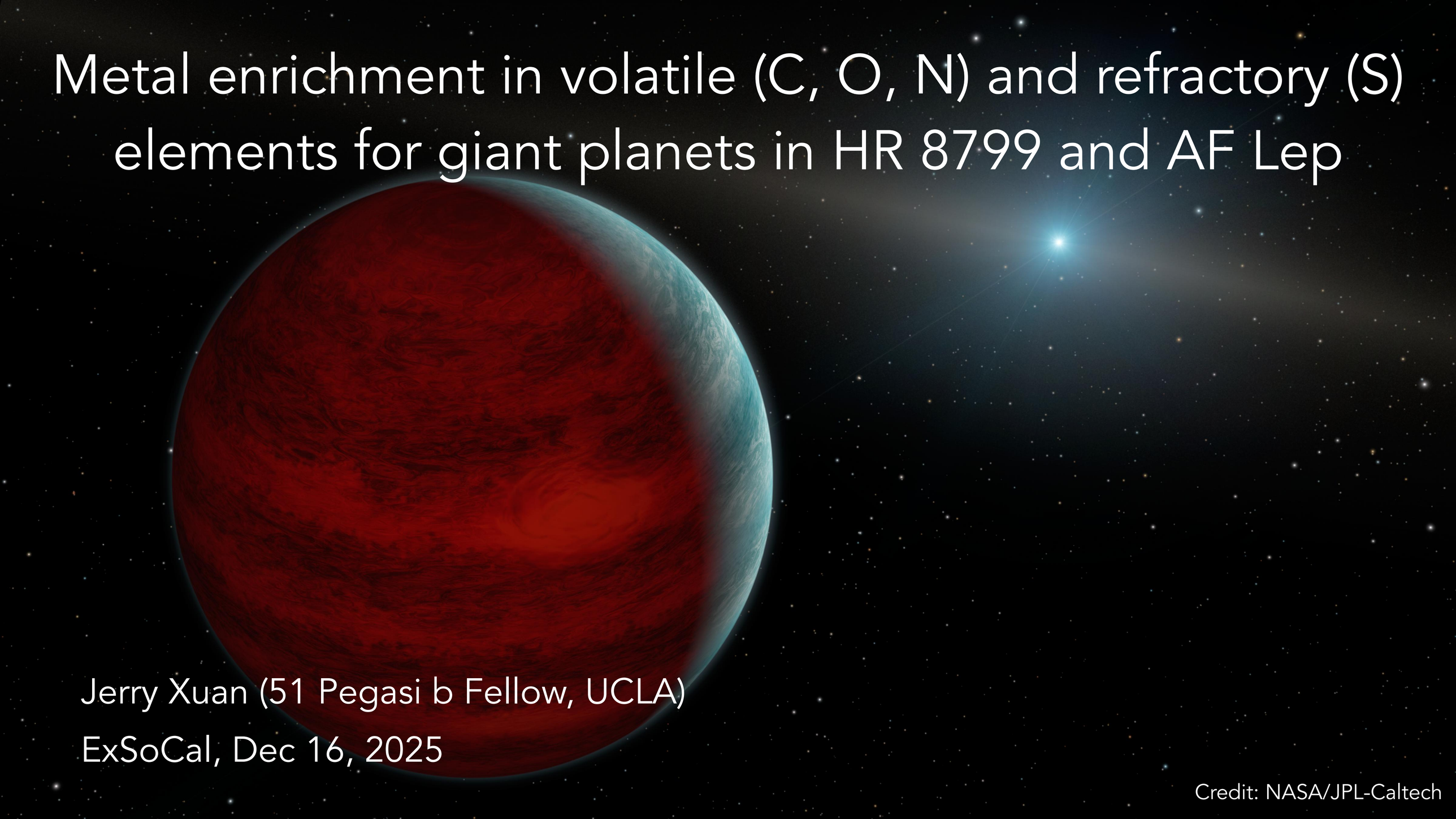
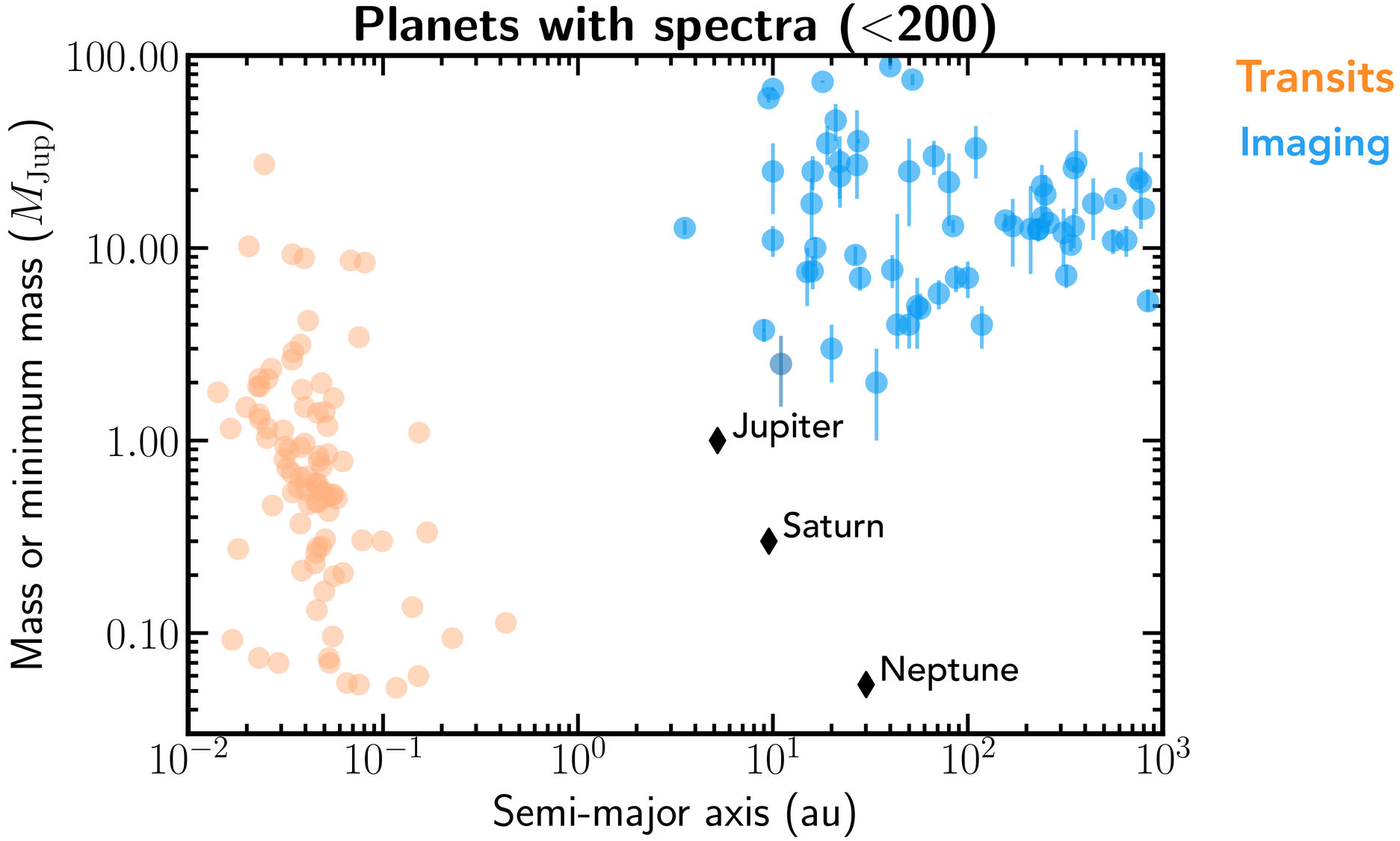
Metal enrichment in volatile (C, O, N) and refractory (S) elements for giant planets in HR 8799 and AF Lep



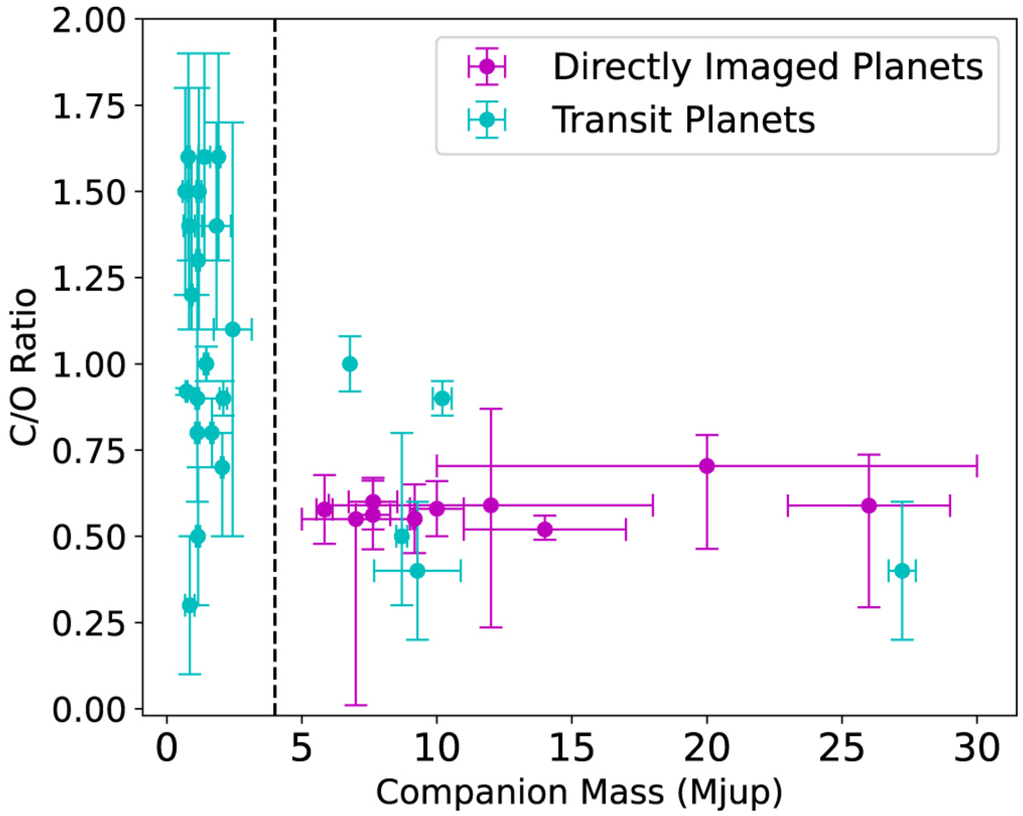
Jerry Xuan (51 Pegasi b Fellow, UCLA)

ExSoCal, Dec 16, 2025

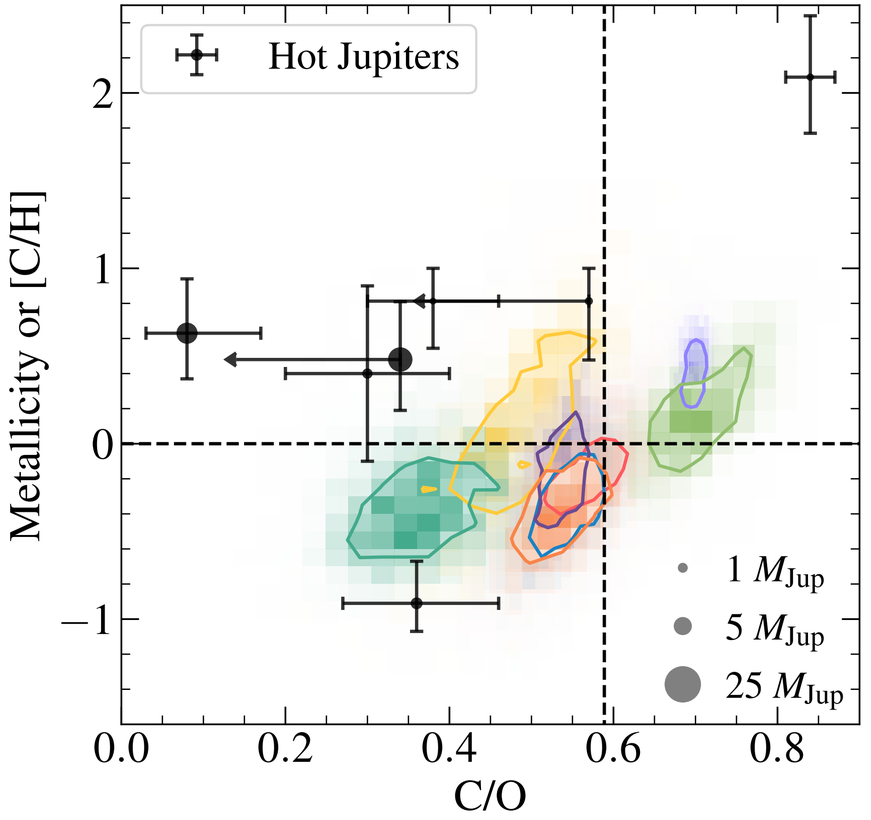
Credit: NASA/JPL-Caltech


Planets with spectra (<200)
100.00
10.00
1.00
0.10
Mass or minimum mass ($M_{\rm Jup}$)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Semi-major axis (au)
Jupiter
Saturn
Neptune
Transits
Imaging

Previous abundance measurements were mostly limited to carbon and oxygen



Hoch et al. 2023; from Keck/OSIRIS, R~4000



kap And b
ROXs 42 Bb
GQ Lup b
ROXs 12 b
HIP 79098 b
DH Tau b
GSC 6214-210 b
2M0122 b

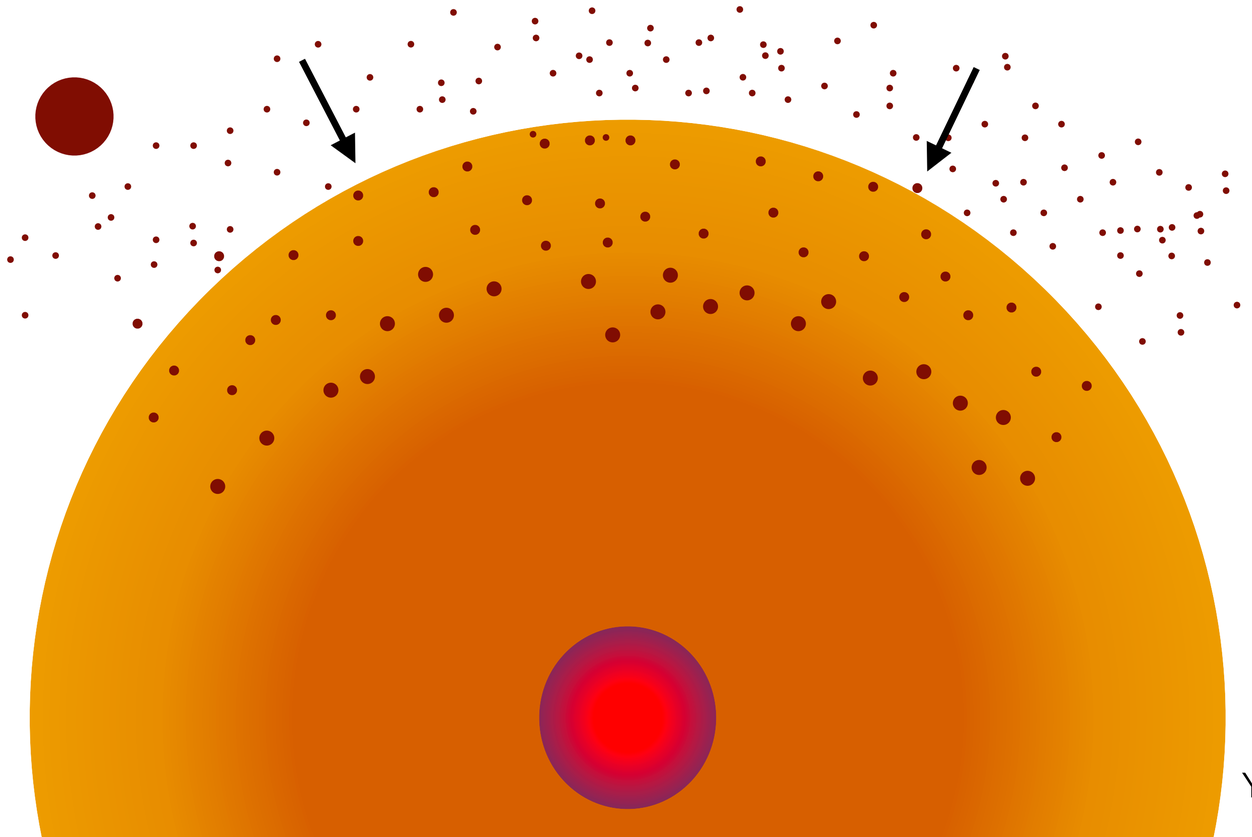
(m~10-30 M_{Jup}
a~50-350 AU)

Xuan et al. 2024b; from Keck/KPIC, R~35000

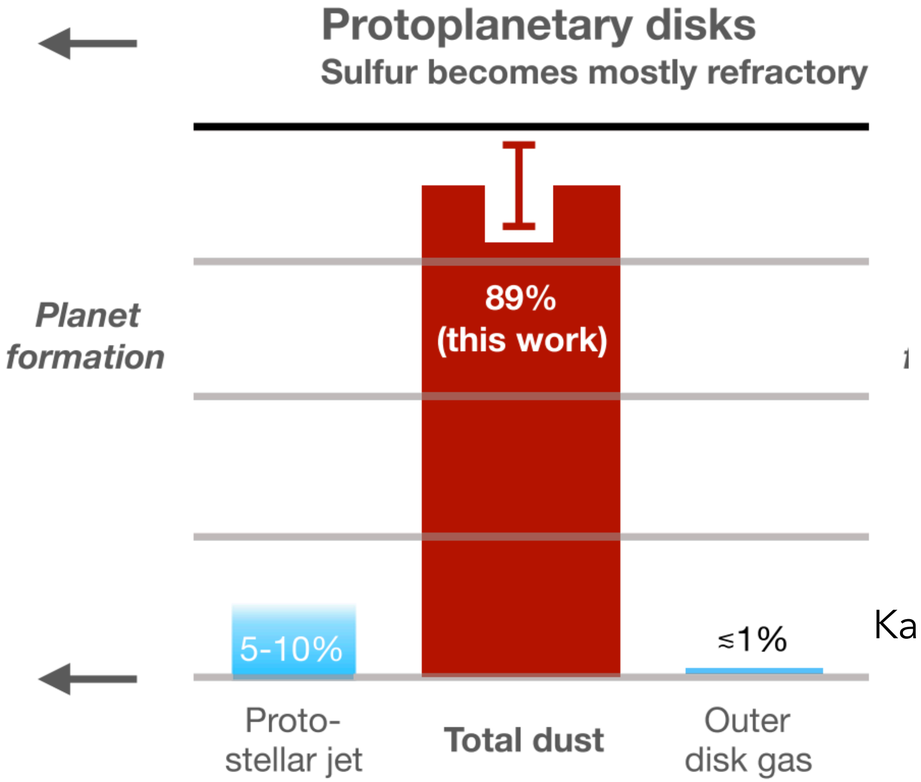
Beyond C & O: refractory elements trace **solid** accretion

(e.g. Fe, Si, S)

Accretion of solids (pebbles, planetesimals) and gas



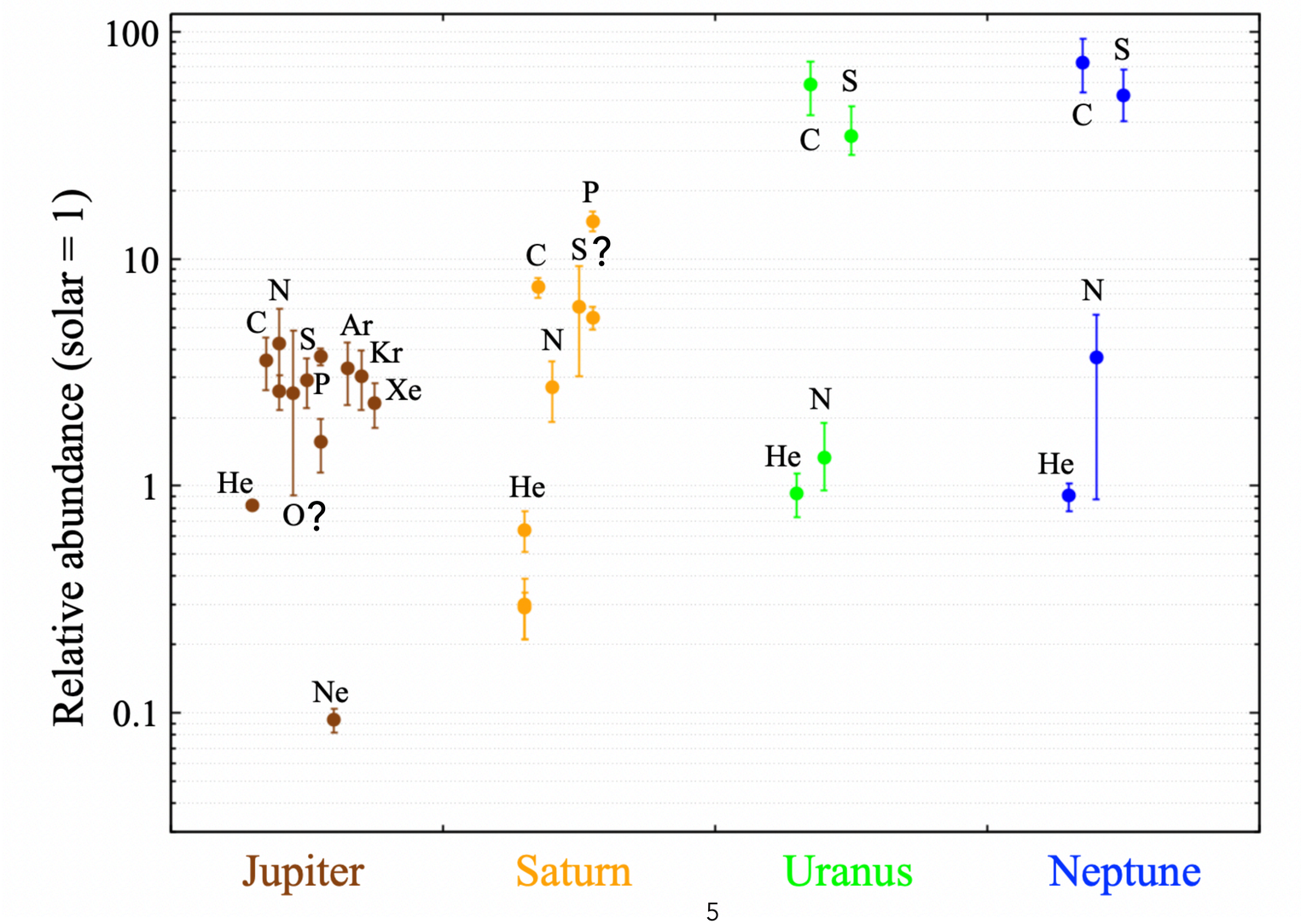
Credit:
Yayaati Chachan



Kama 2019

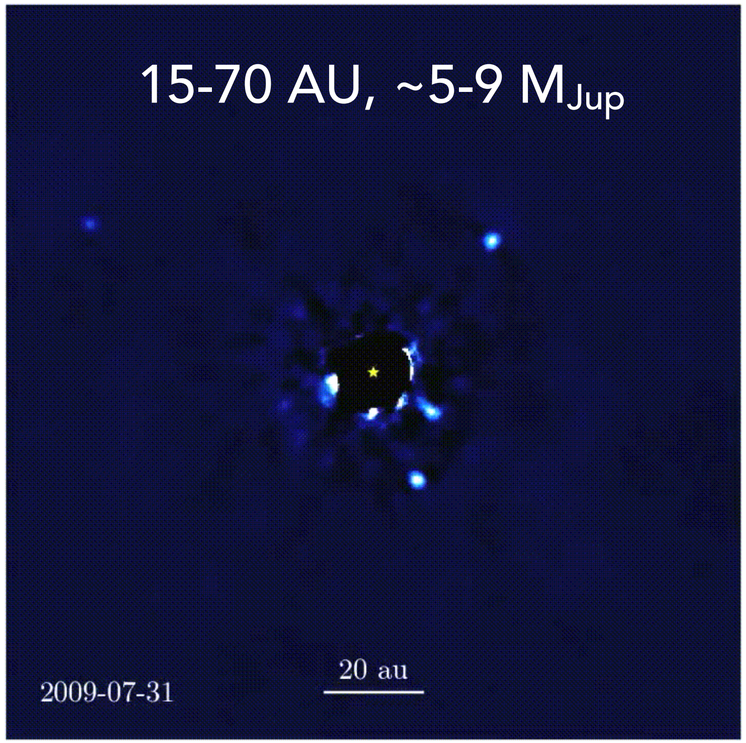
e.g. Turrini et al. 2021, Schneider & Bitsch 2021, Chachan et al. 2023, Crossfield 2023

Solar system gas and ice giants are metal-rich

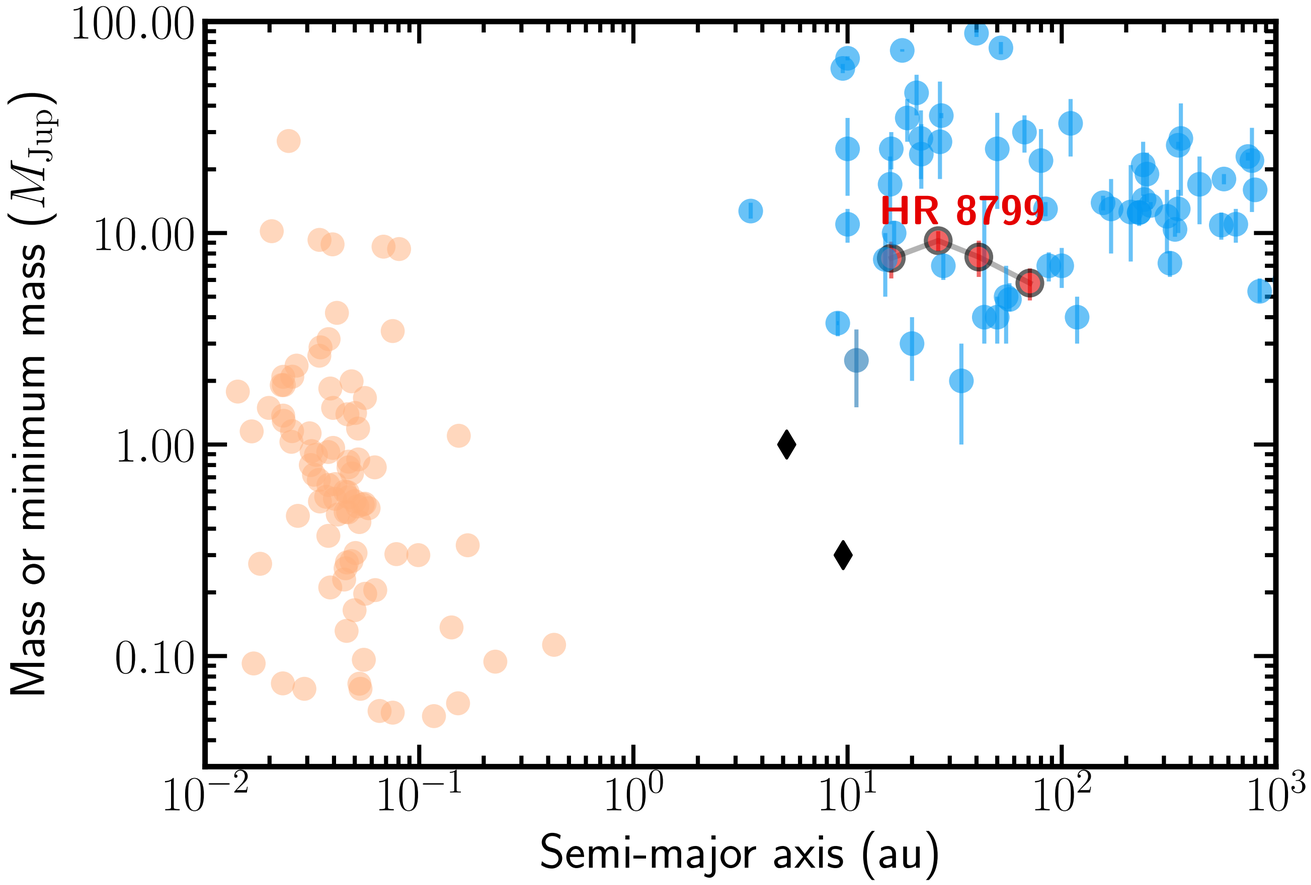


Ikoma & Kobayashi 2025
(Using data compiled in Guillot+2023)

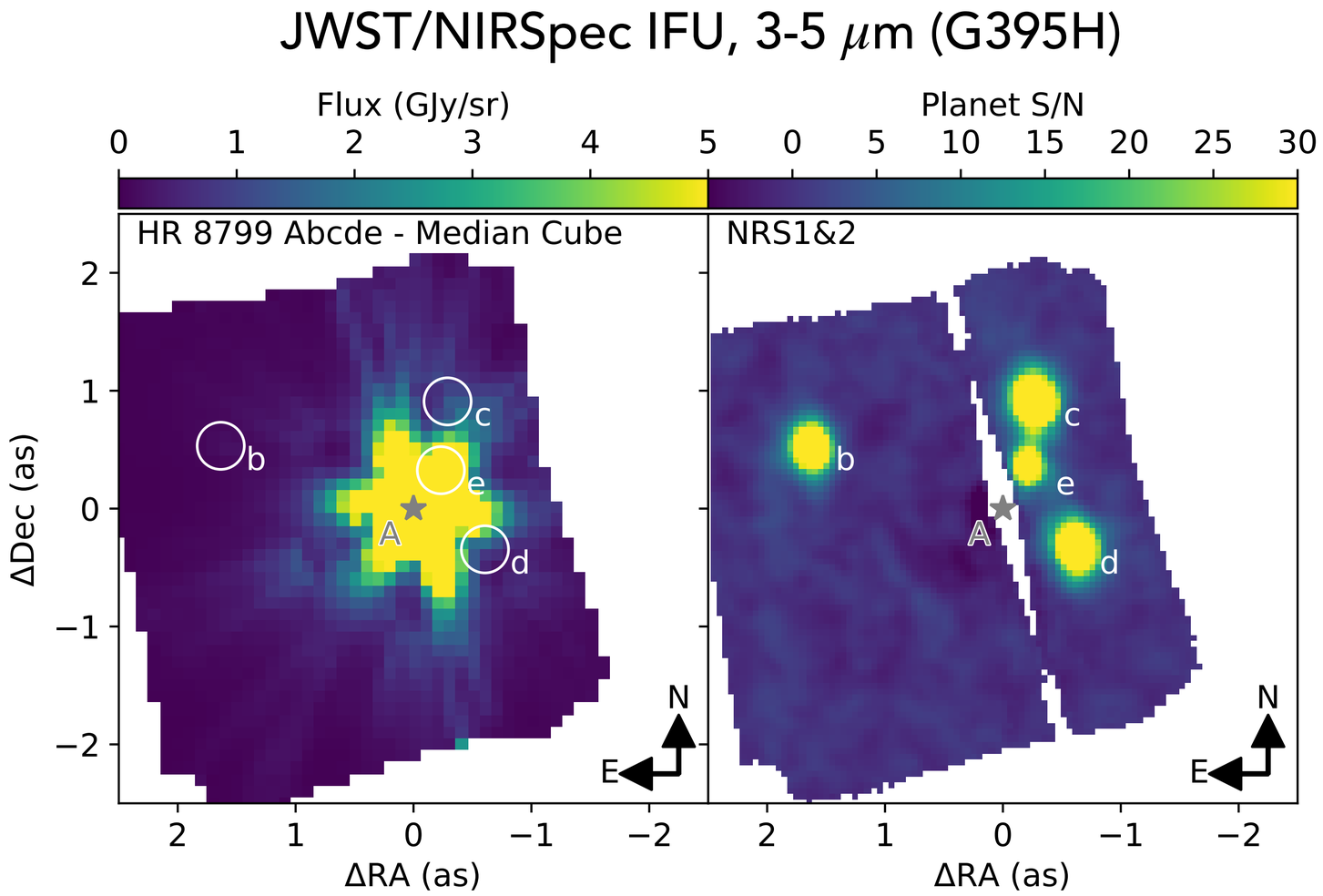
HR 8799: highest-multiplicity planetary system that is directly imaged



Marois+2008, 2010
Video by J. Wang, C. Marois



Spectrally disentangling star from planet at R~3000



Xuan & Ruffio+ submitted, data from GTO 1188 (PI: Hodapp)

Paper I: planets c, d, e only
(1st epoch)
Ruffio & Xuan+ accepted,
Nature Astronomy

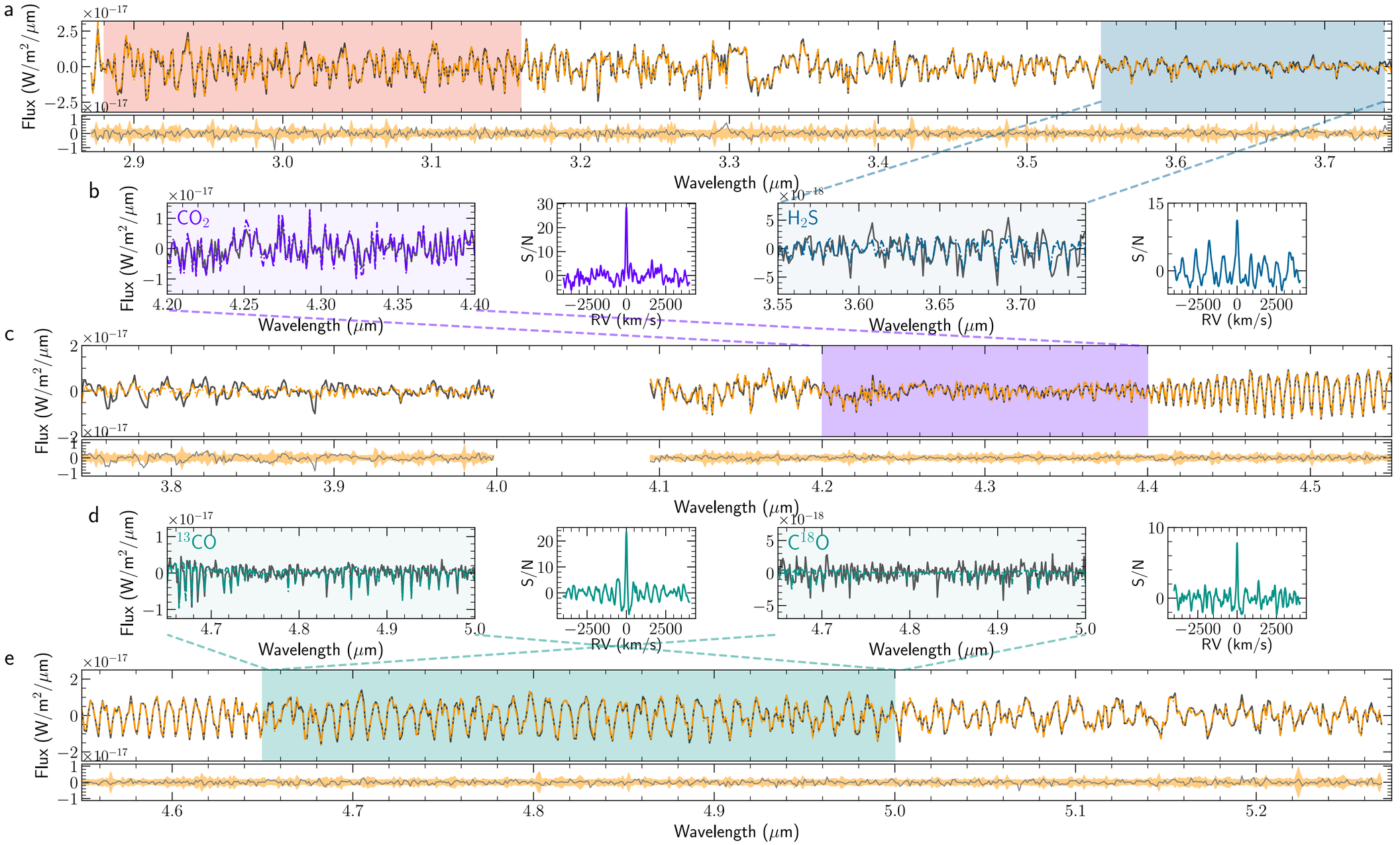
Paper II: planets b, c, d, e
(2nd epoch: **S/N ~2-3x better**)
Xuan & Ruffio+ submitted

HR 8799 c

Teff≈1100 K

Data: black

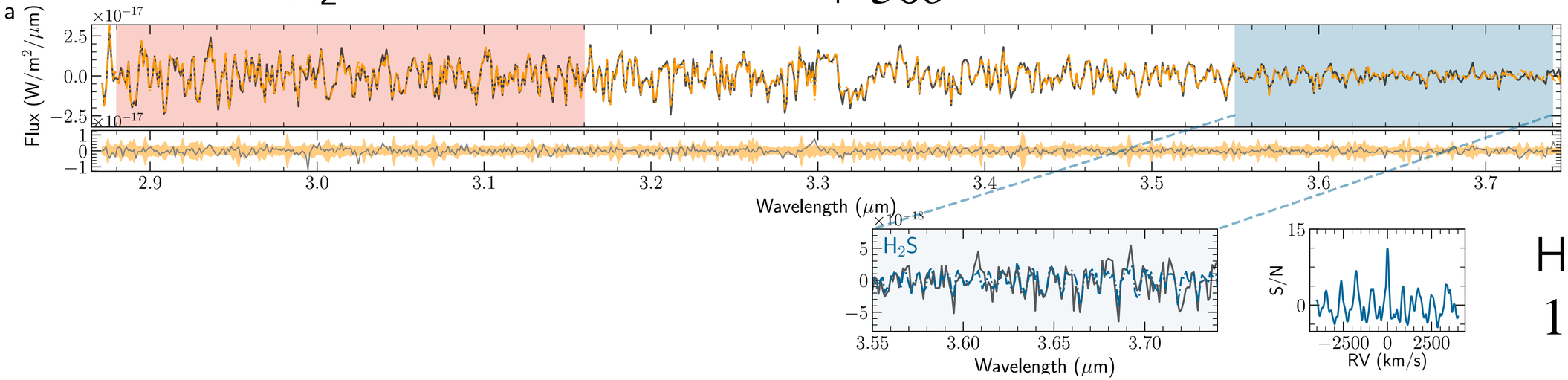
Model: orange



Xuan & Ruffio+ submitted

H_2O

CH_4: 30σ



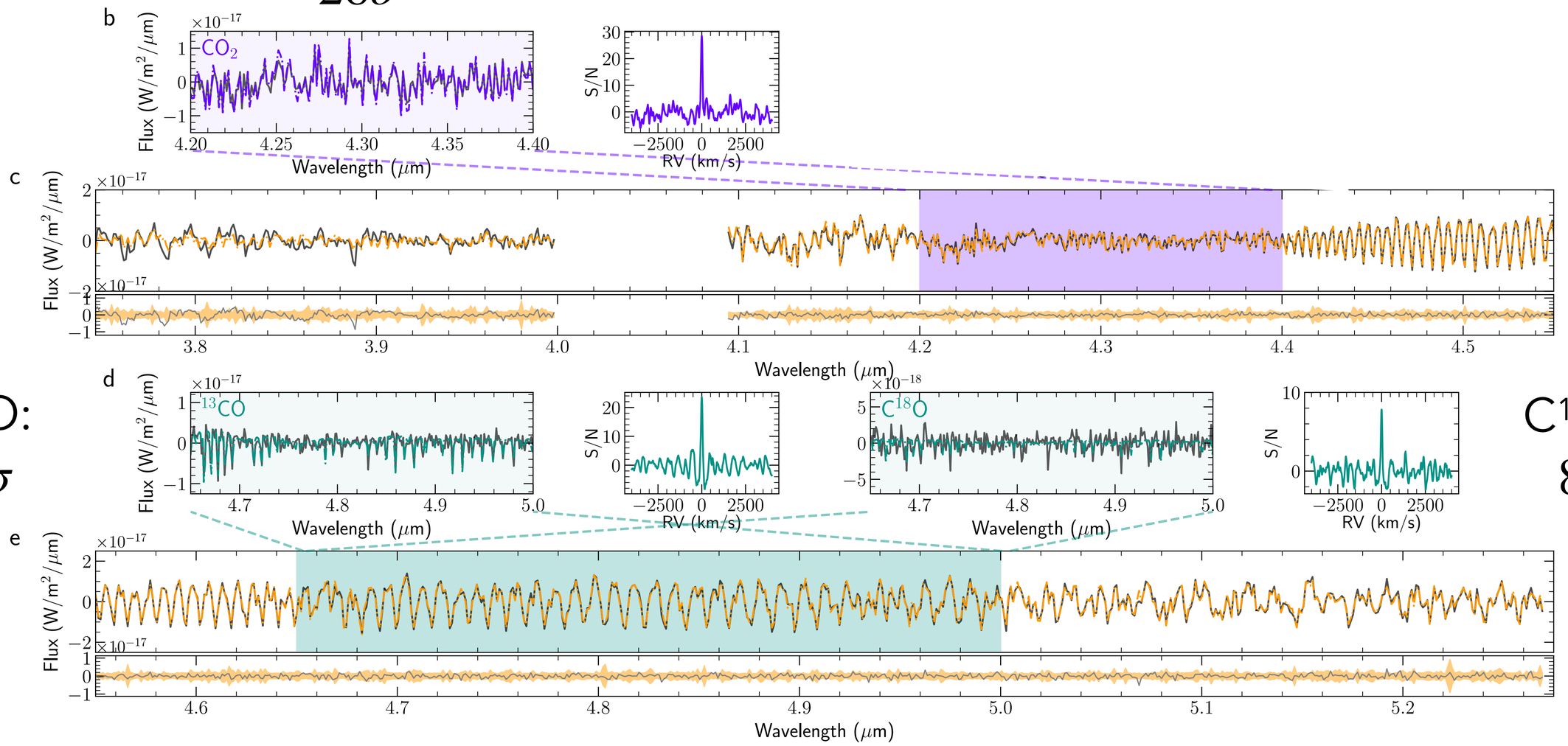
H_2S: 11σ

Black: residuals of model without H_2S

Blue: H_2S only model

CO_2:

28σ



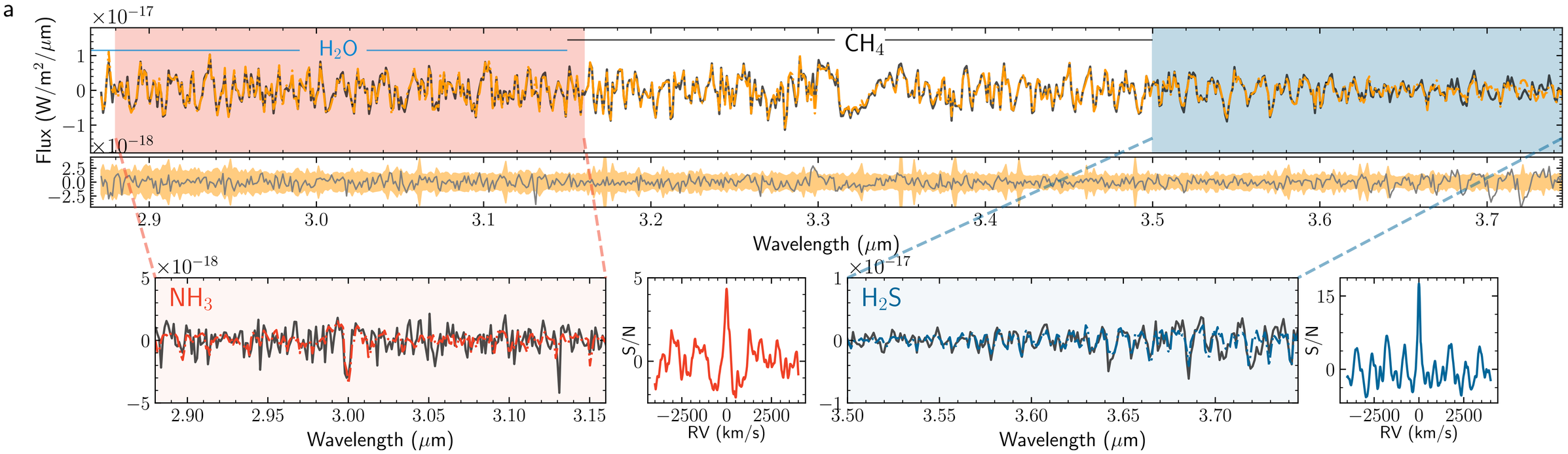
^{13}CO:

24σ

$C^{18}O$:

8σ

NH_3 in HR 8799 b (Teff~900 K, m~5 M_{Jup})

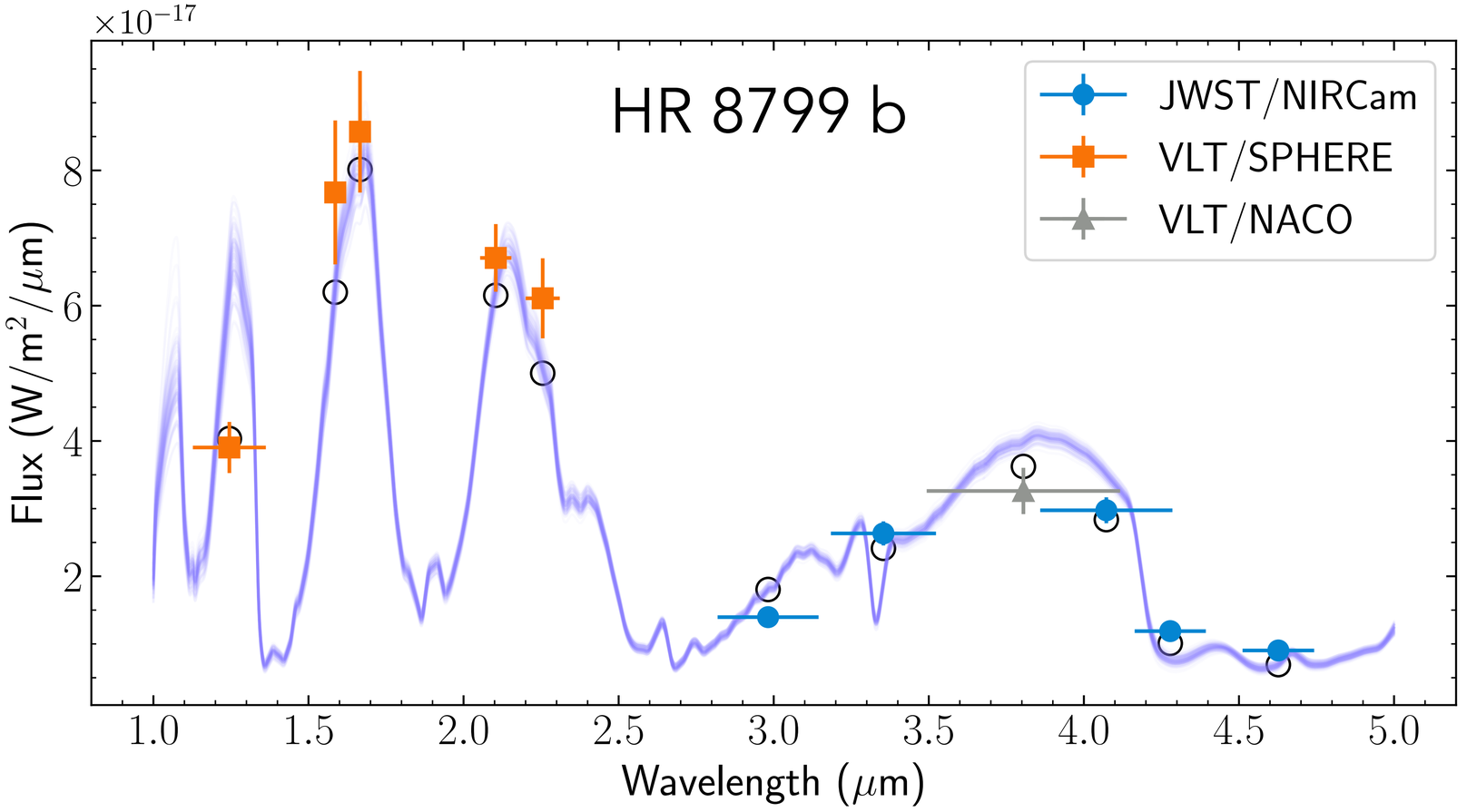


Black: residuals of model without NH_3

Red: NH_3 only model

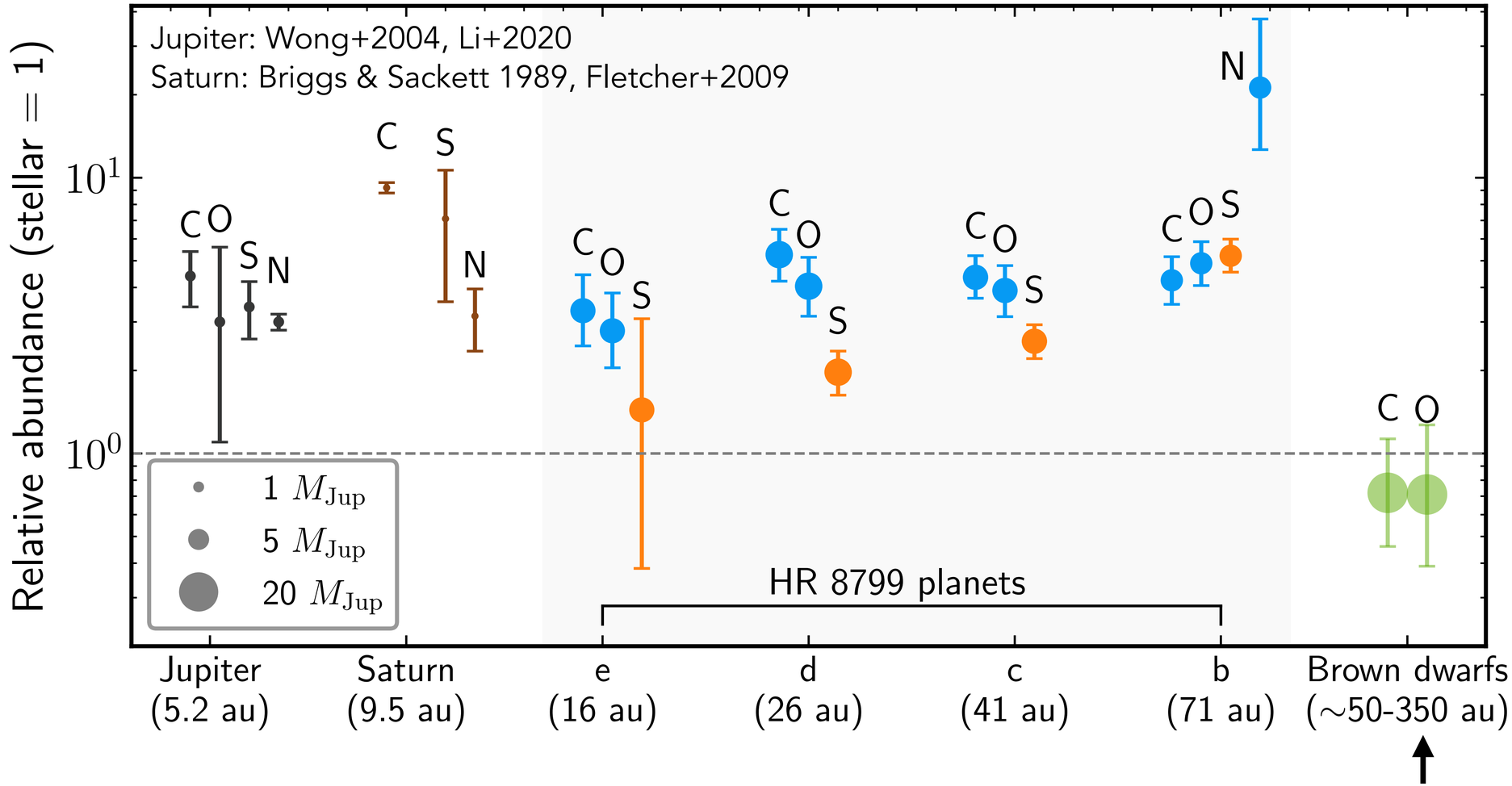
Xuan & Ruffio+submitted

Jointly fit photometry to anchor continuum



Data from JWST/NIRCam, VLT/SPHERE, NACO
(Balmer+2025, Zurlo+2016, Bergfors+2011)

Volatile and refractory enrichment in the HR 8799 planets

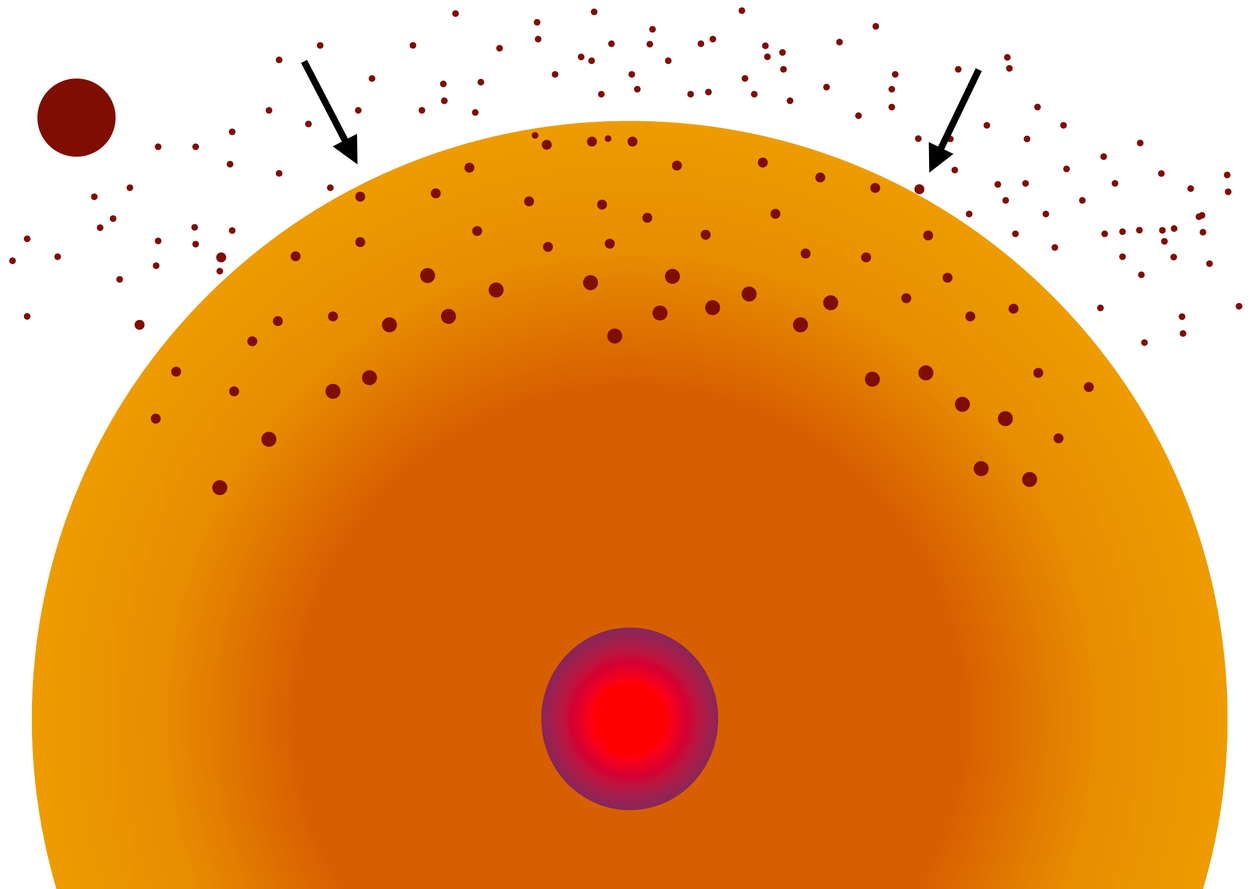


Xuan & Ruffio+submitted

~10-30 M_{Jup} companions from Keck/KPIC (Xuan+2024b)

Enrichment in **sulfur** implies efficient accretion of **solids**

Sulfur is locked in disk solids $\gtrsim$1 AU
(Kama+2019)



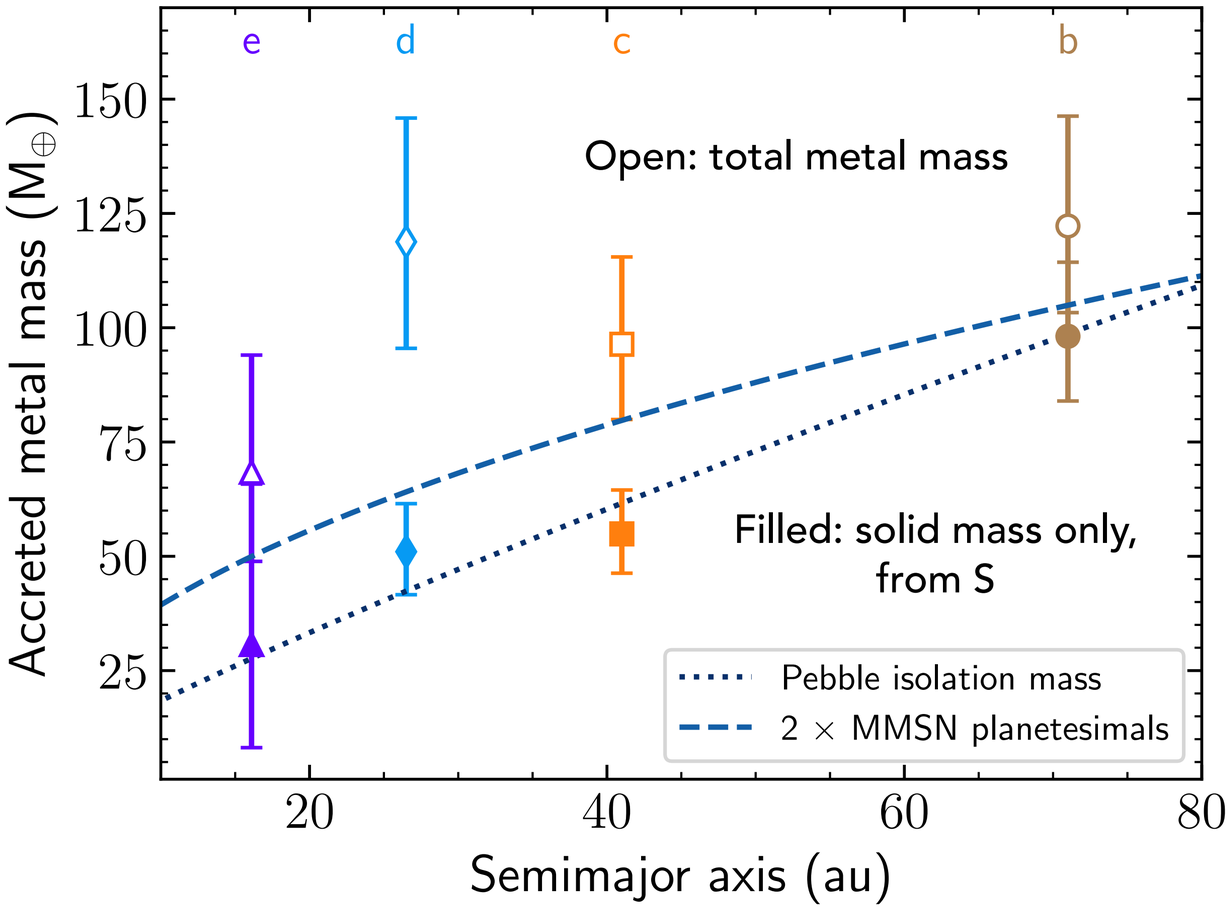
Assuming:

1) atmospheric metallicity ~ bulk metallicity

2) other refractory elements track S/H

→ Accreted mass from solids in each planet

Solid masses are consistent with classic pebble & planetesimal accretion paradigms



Pebble isolation mass
Bitsch+2018

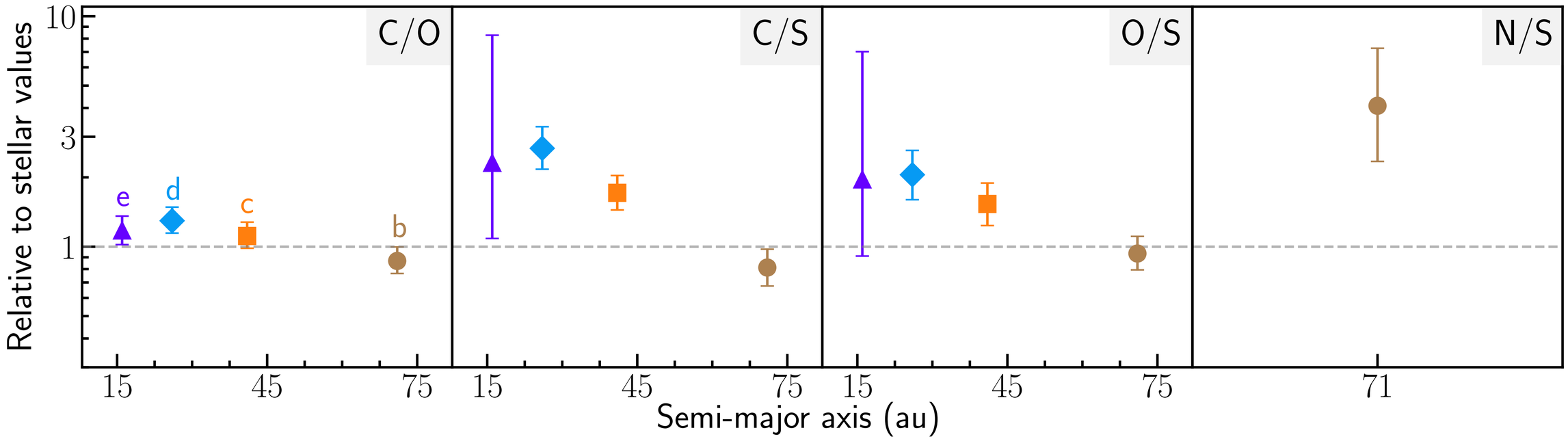
MMSN: Minimum mass solar nebula
Following Chiang & Youdin 2010

Calculation from Yayaati Chachan

Trends in volatile-to-refractory ratios (C/S, O/S, N/S) across planets

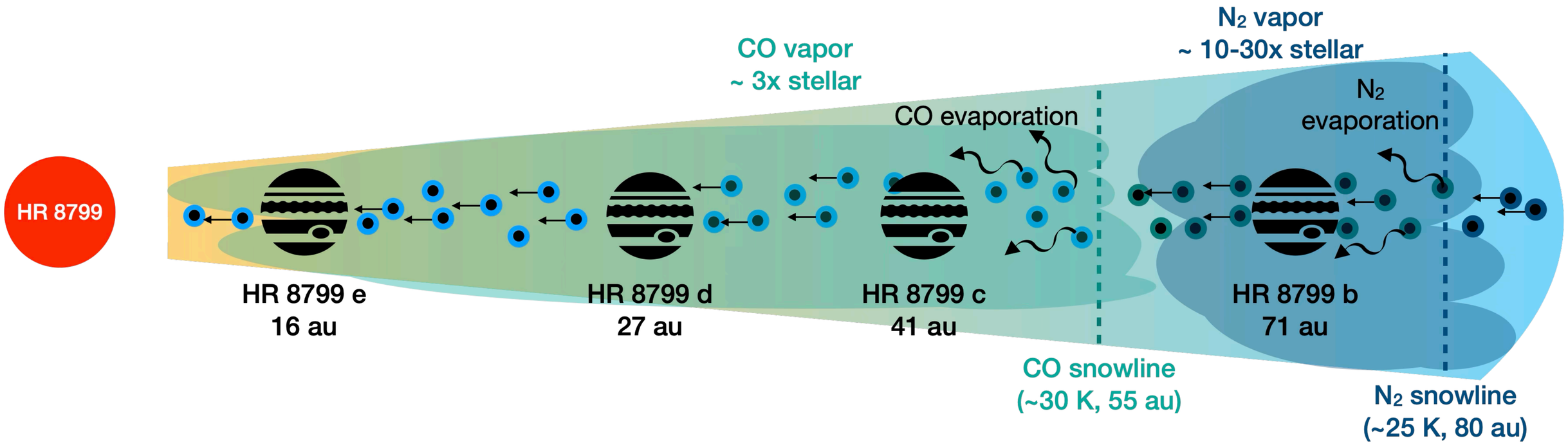
b: uniform in C, O, S, high N/S

c, d, e: uniform in C, O, high C/S



Xuan & Ruffio+submitted

Chemical trends are consistent with pebble drift and evaporation across snowlines

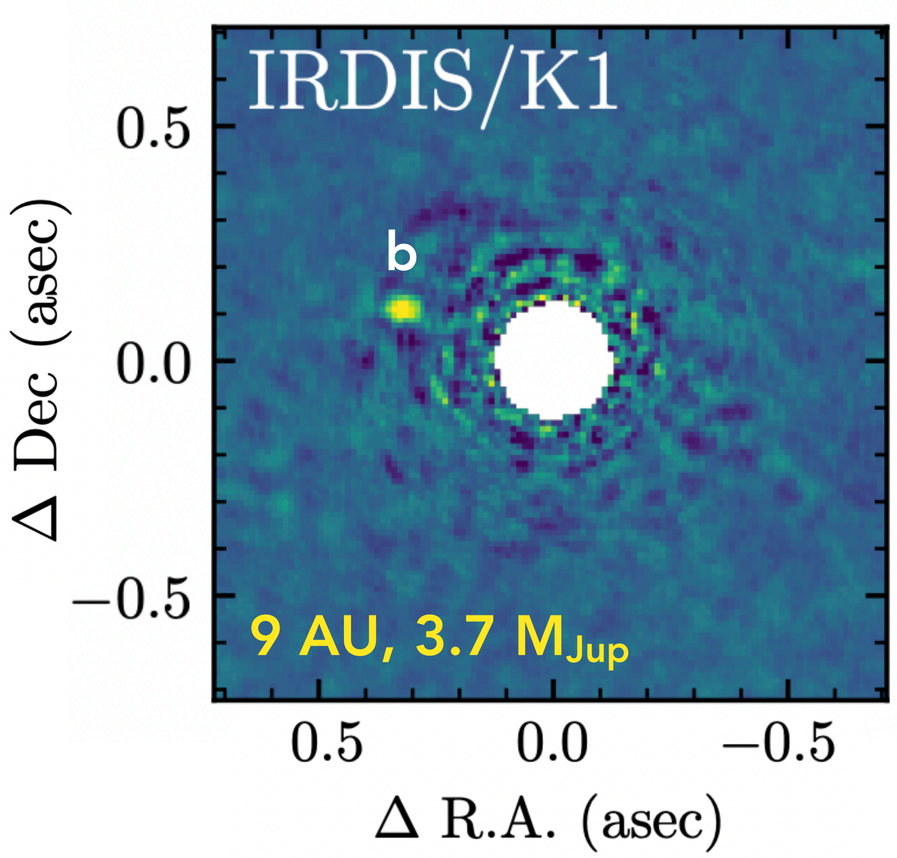


Xuan & Ruffio+submitted

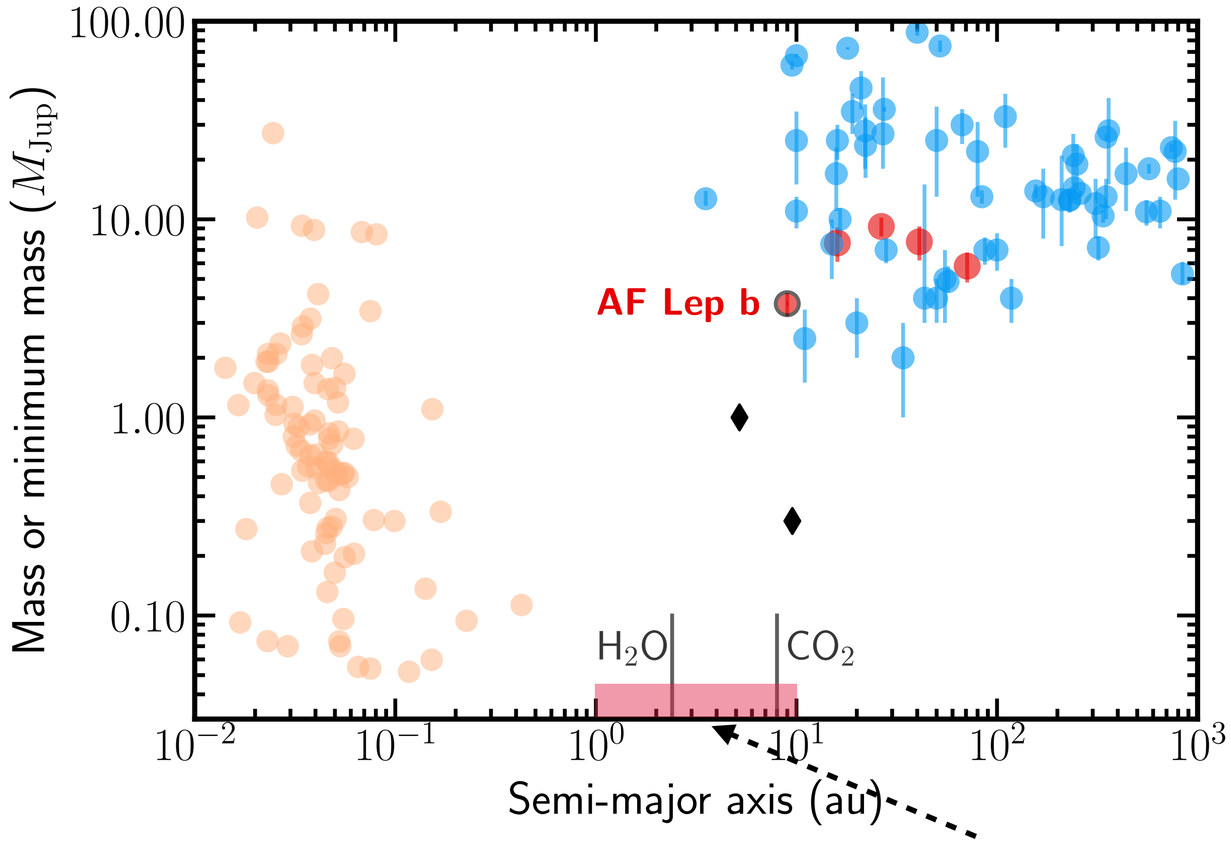
Formation model from Chachan+2023

(see also Booth+2017, Schneider & Bitsch 2021ab)

AF Lep b: an imaged planet on Jupiter-like scales

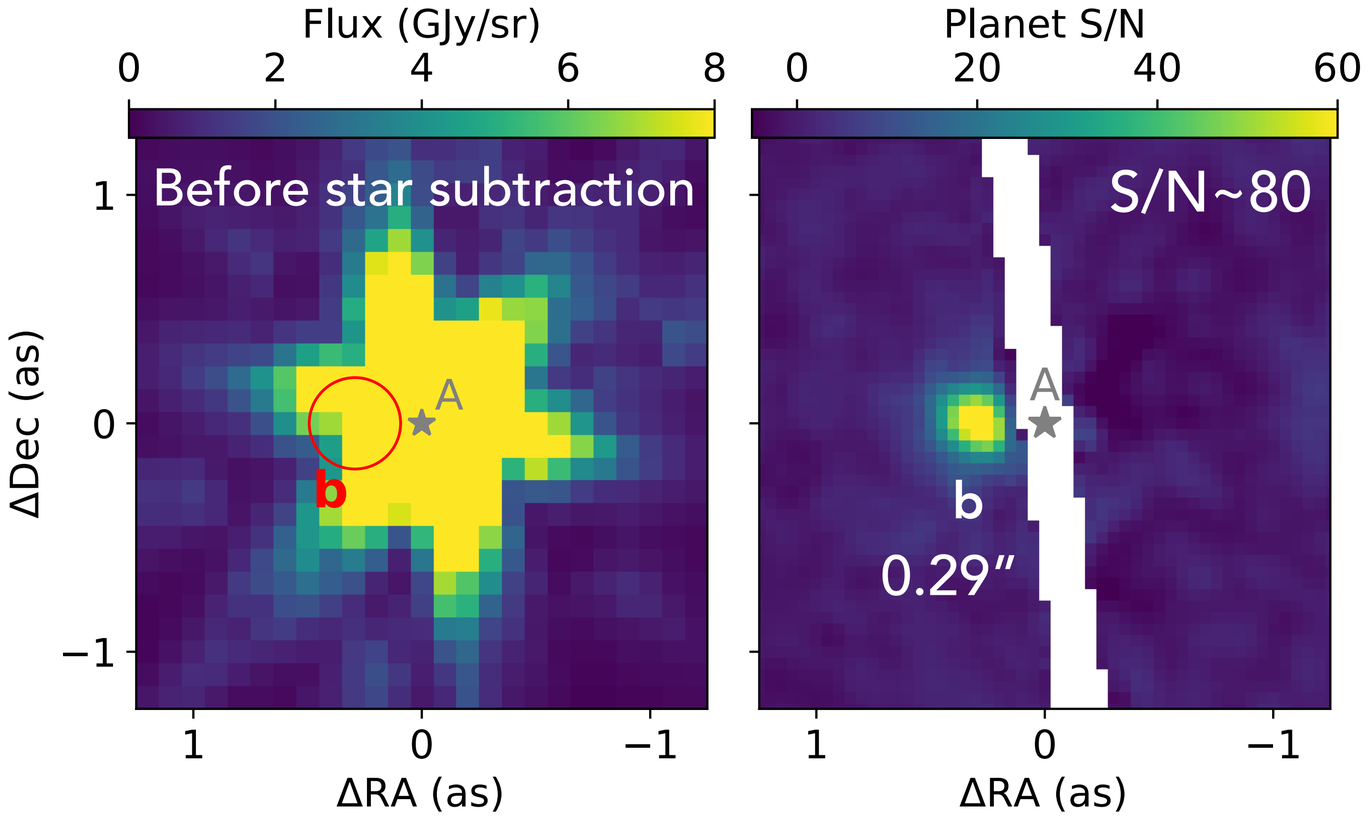


De Rosa+2023, Franson+2023, Mesa+2023



Peak of giant planet occurrence
(Fernandes+2019, Fulton+2021)

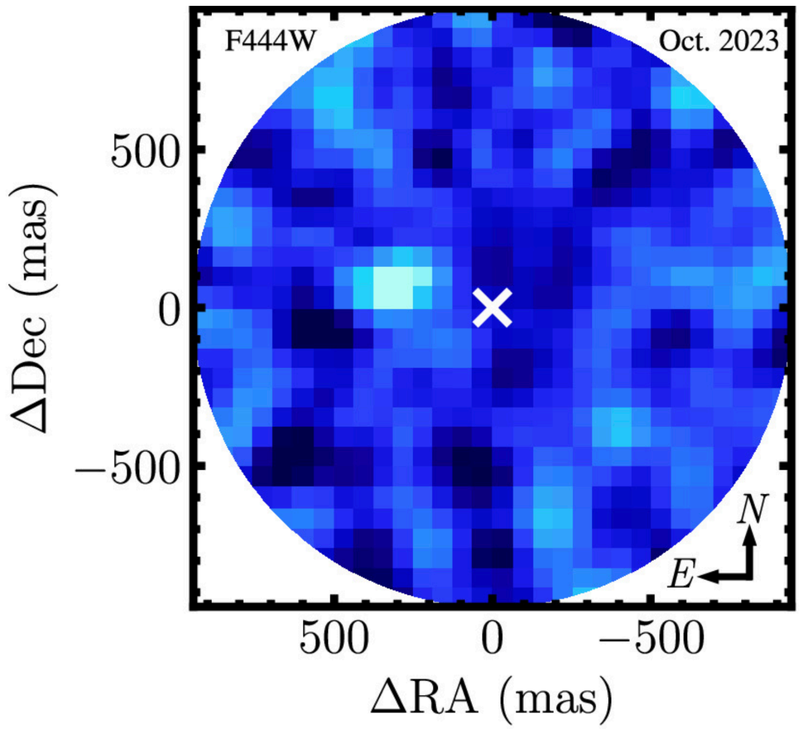
The first 3-5 μm spectroscopy of AF Lep b



R~3000 spectroscopy (GO 5342; PI: Xuan)

Xuan+in prep

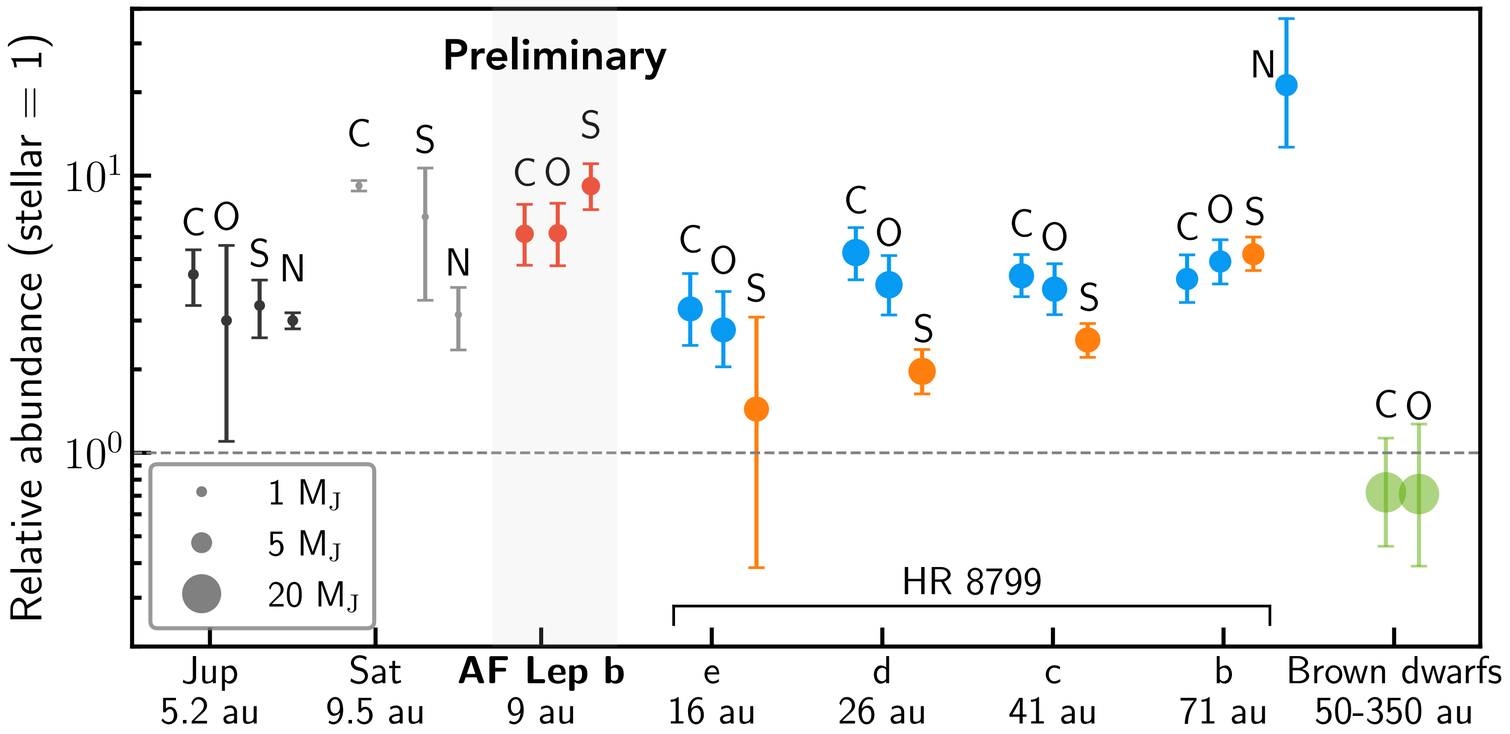
S/N~9 (in F444W)



JWST coronagraphic imaging

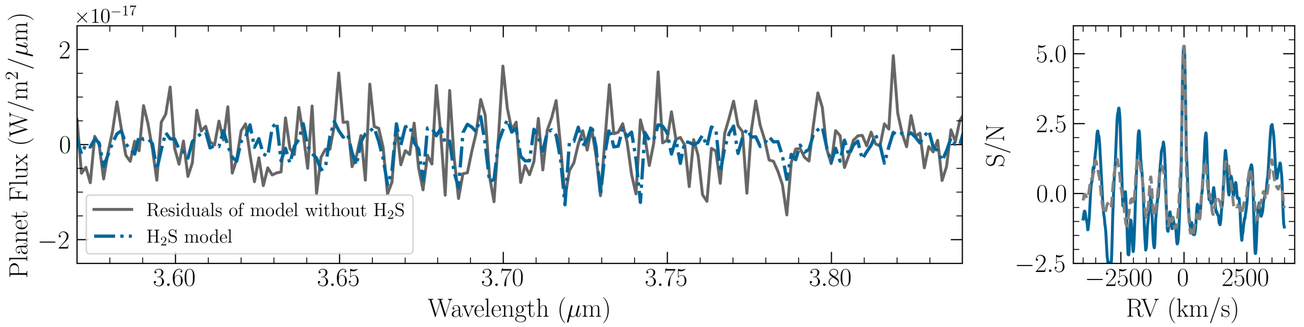
Franson et al. 2024

AF Lep b is uniformly enriched in C, O, S like Jupiter

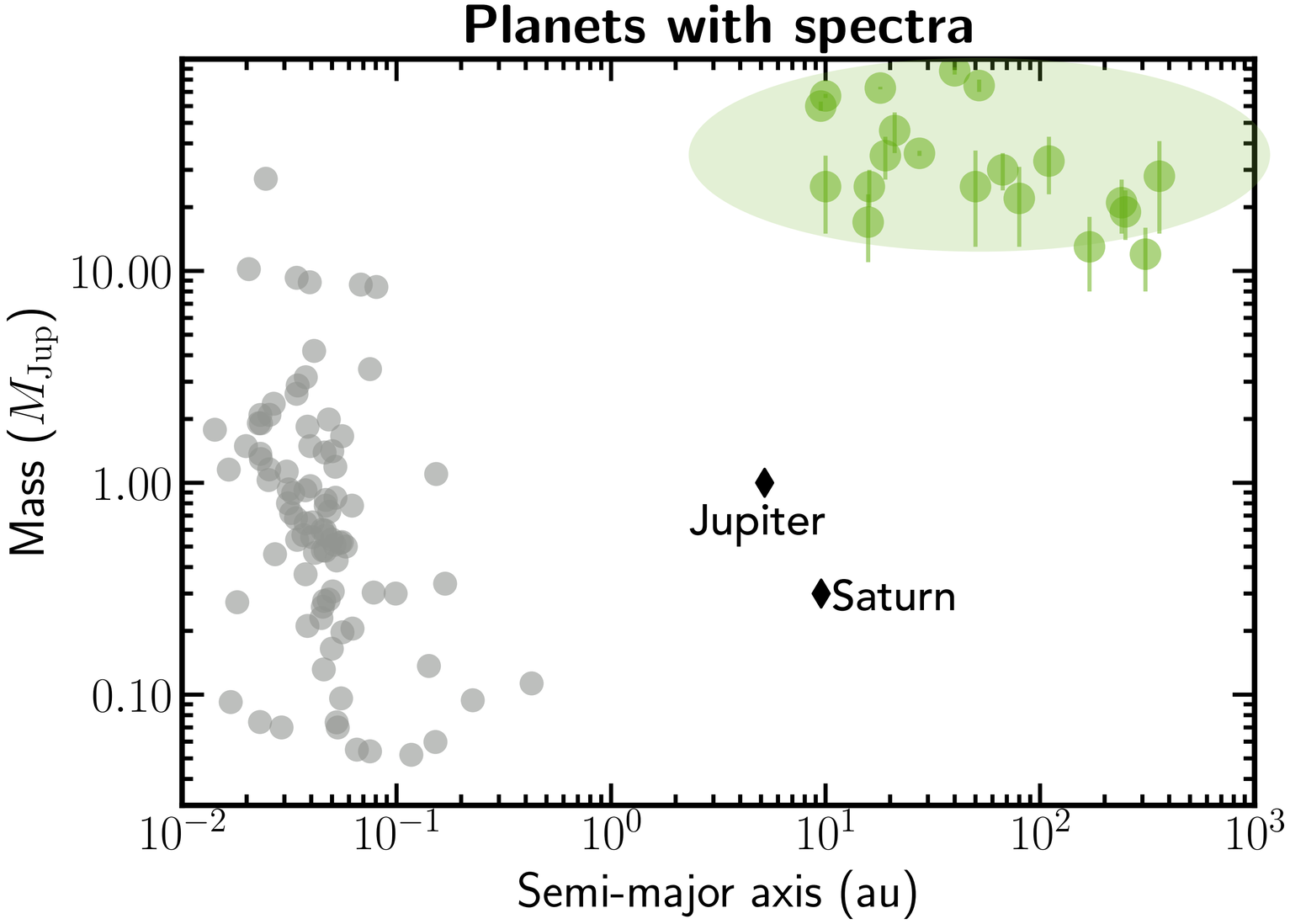


Xuan+in prep

H_2S detection

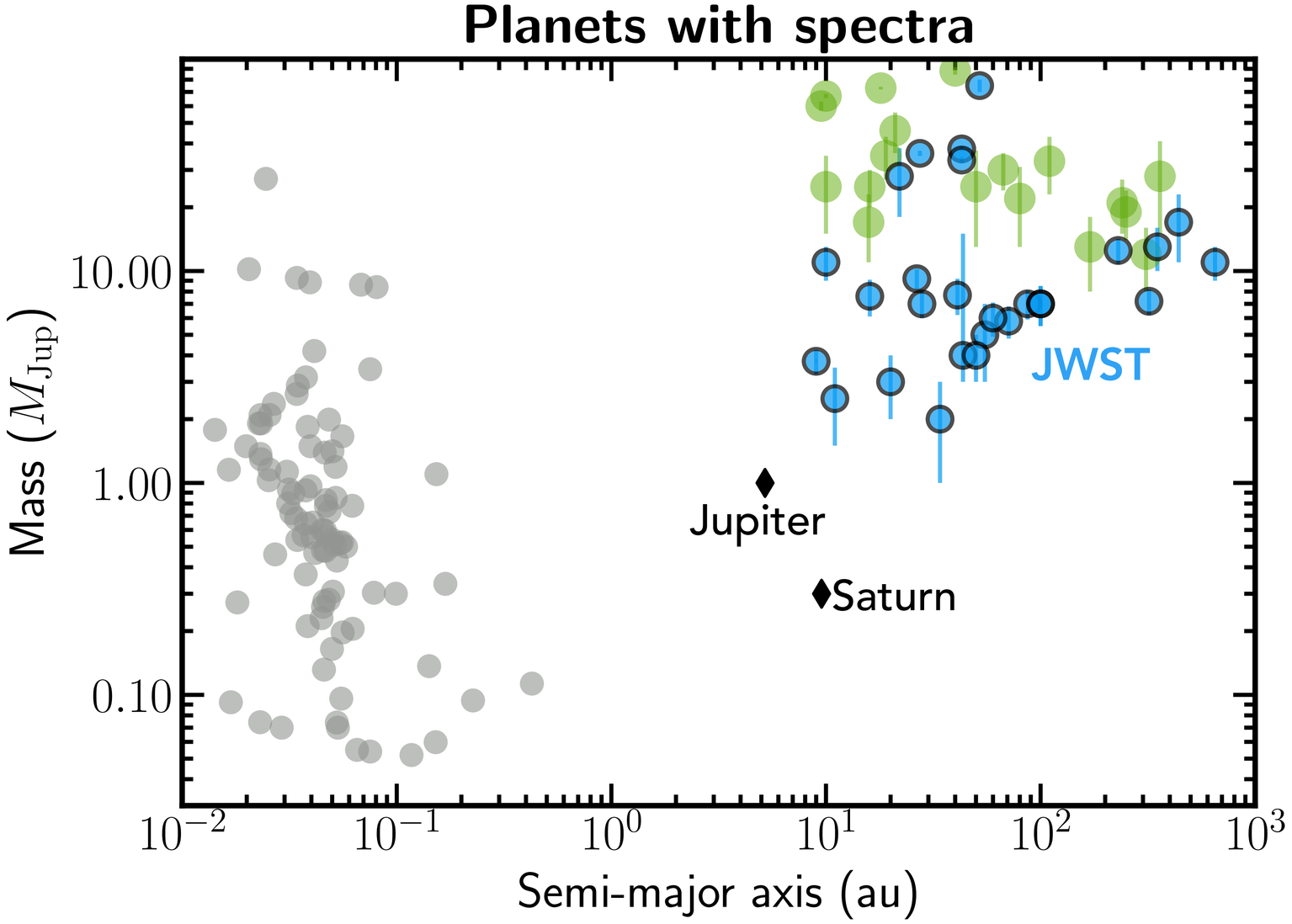


Towards comprehensive chemical surveys of distant giants



e.g. Xuan+2022, 2024ab
Ji Wang+2021, Hsu+2024,
Do O et al. 2024,
Gavin Wang+2025

Towards comprehensive chemical surveys of distant giants



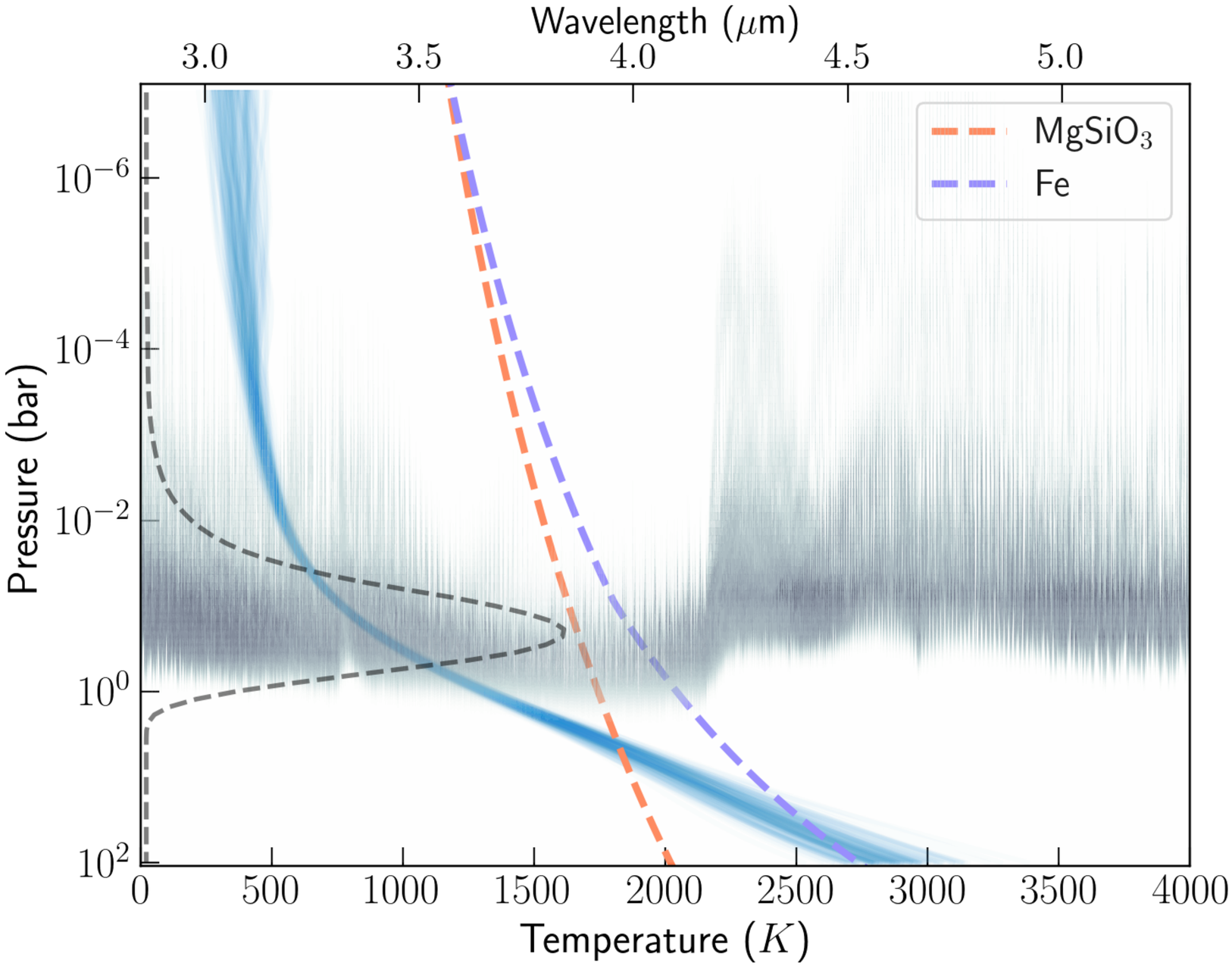
Where is the transition between core accretion & fragmentation?

GO 8714 (PI: Xuan)
GO 5342 (PI: Xuan)
GO 3762 (PI: Xuan)
GO 8063 (PI: Ruffio)
GO 4982 (PI: Ruffio)
GO 6362 (PI: Rickman)
+ archival data

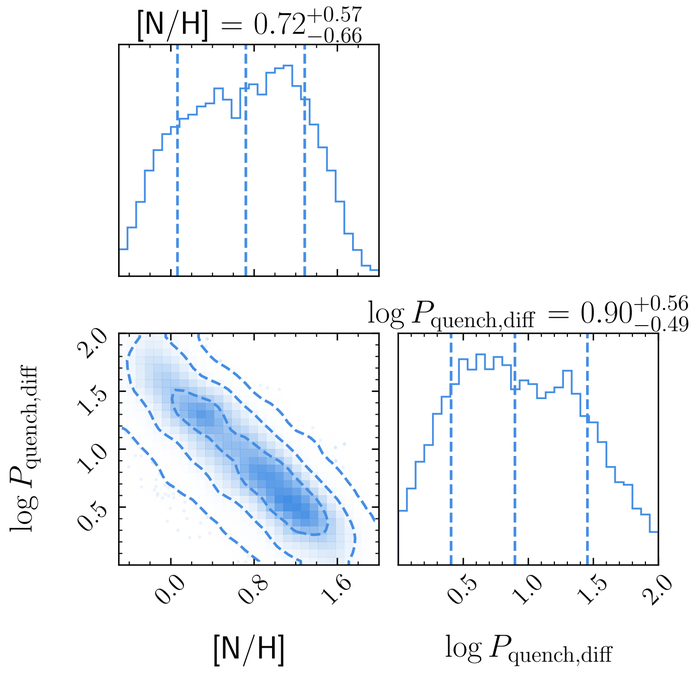
Thank you!

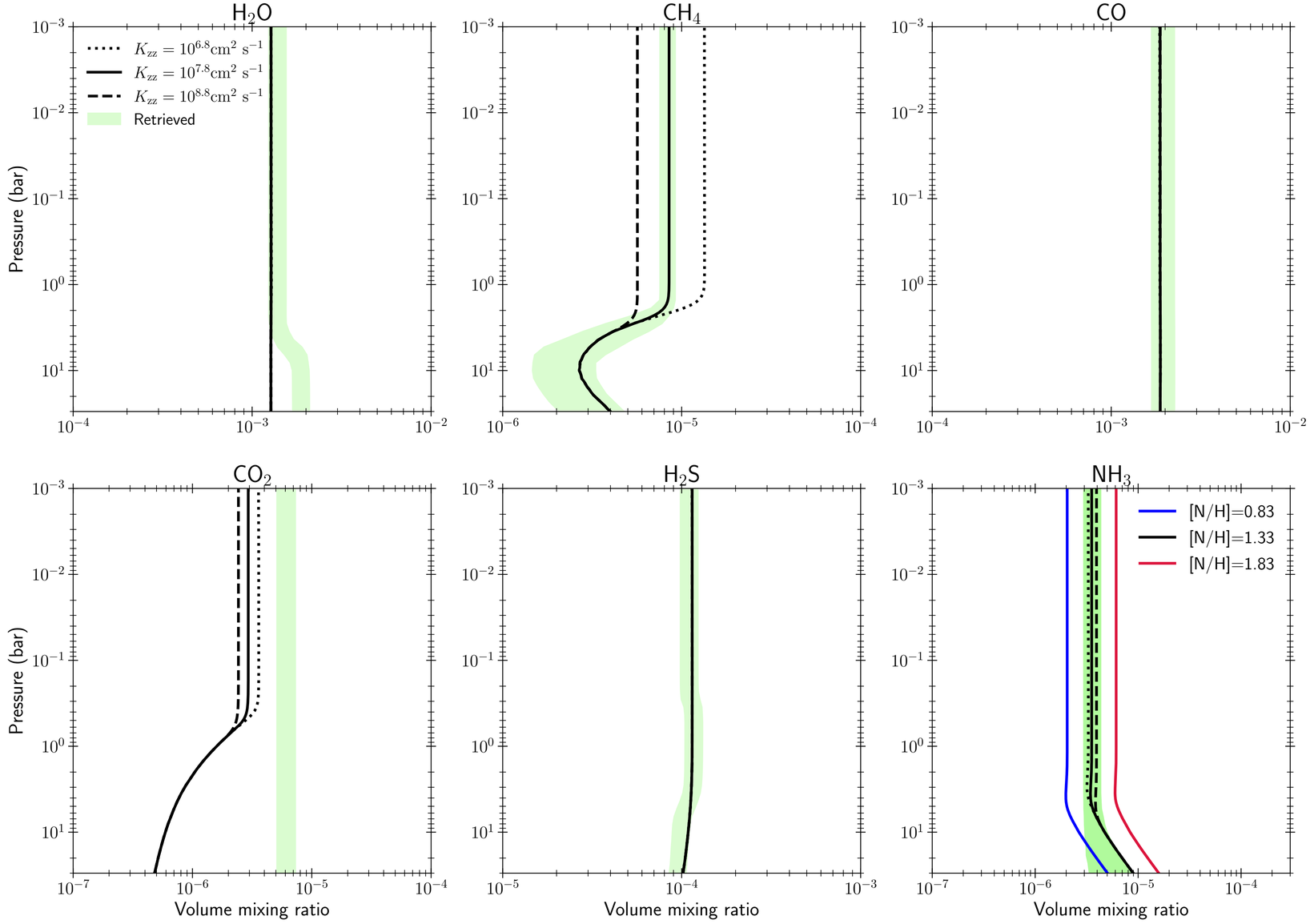
Jerry Xuan (51 Pegasi b Fellow)

jerryxuan@g.ucla.edu


Wavelength (μm)
3.0
3.5
4.0
4.5
5.0
MgSiO$_3$
Fe
Pressure (bar)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
0
500
1000
1500
2000
2500
3000
3500
4000
Temperature (K)

N/H for HR 8799 b

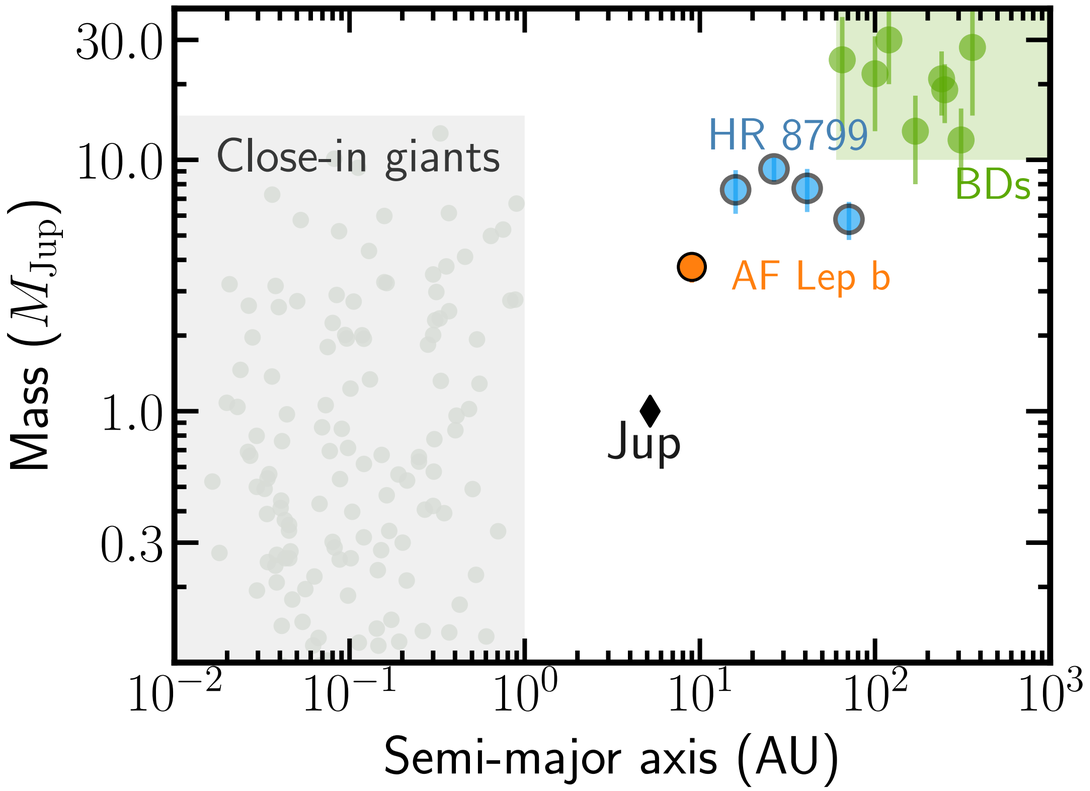


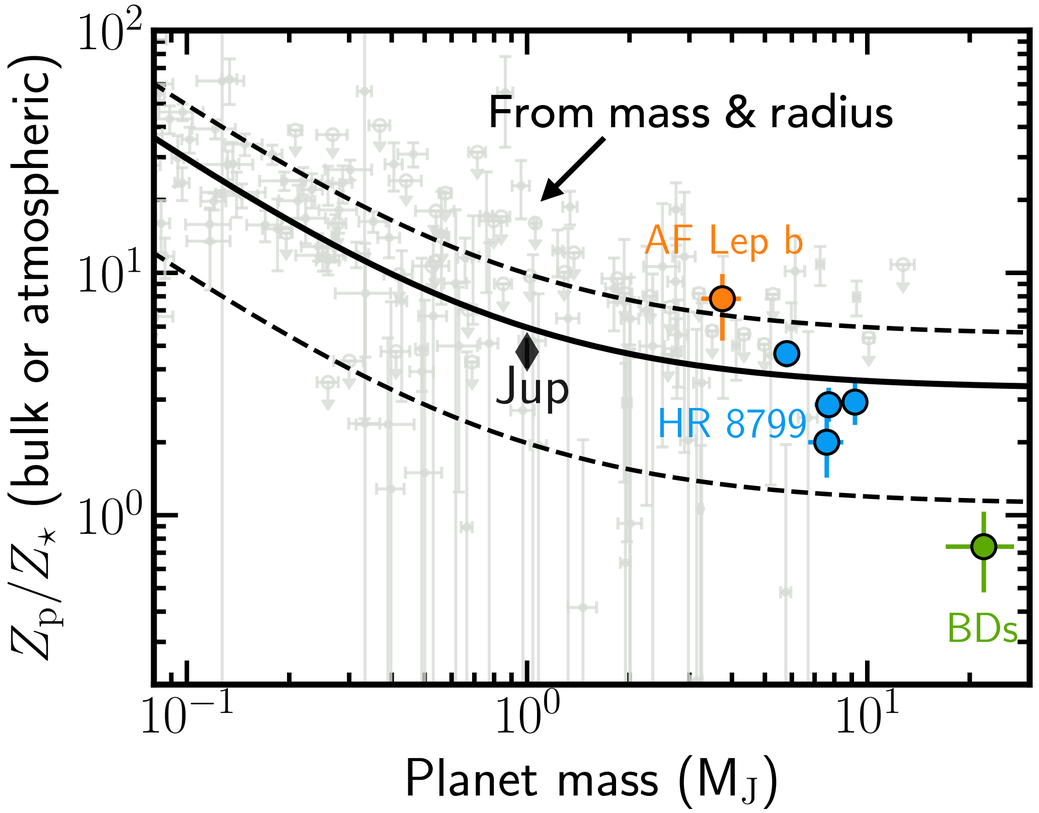


VULCAN models from Kazumasa Ohno

Metal enrichment in both close-in & distant giants

Super-Jupiters continue to be metal-rich up to ~10 MJup?

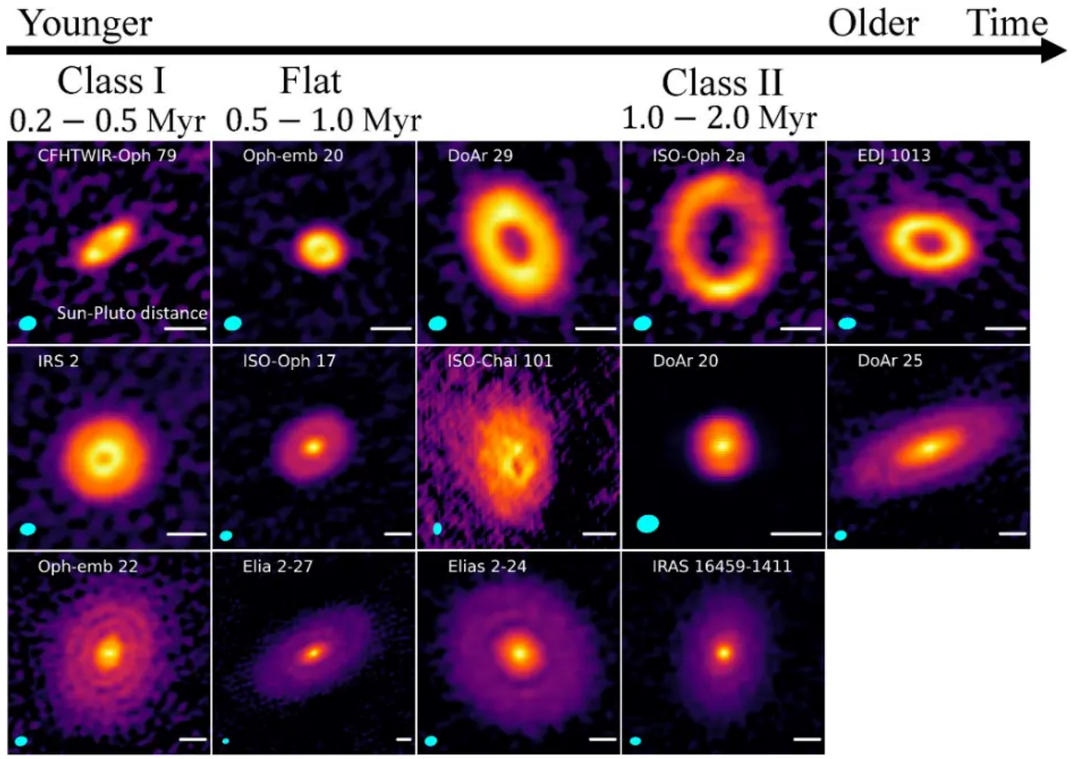




Gray points from Chachan+2025

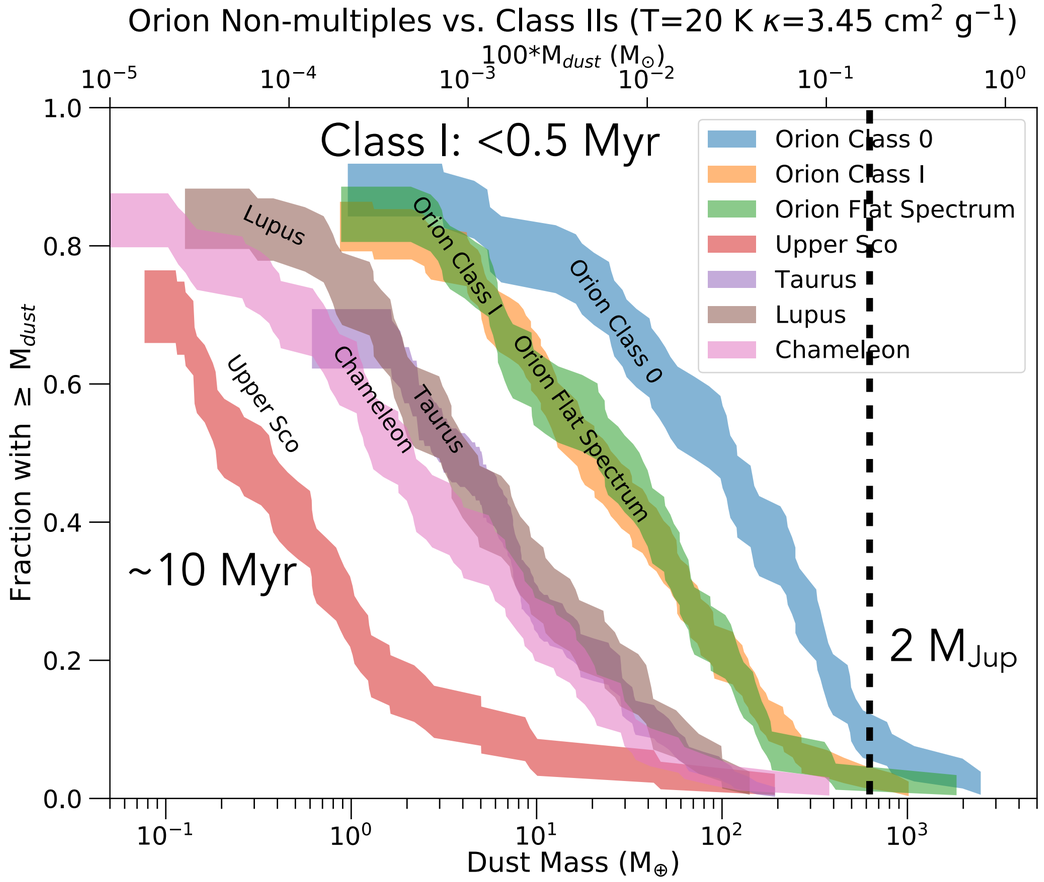
Disks studies also indicate early planet formation

Structure in Class I disks

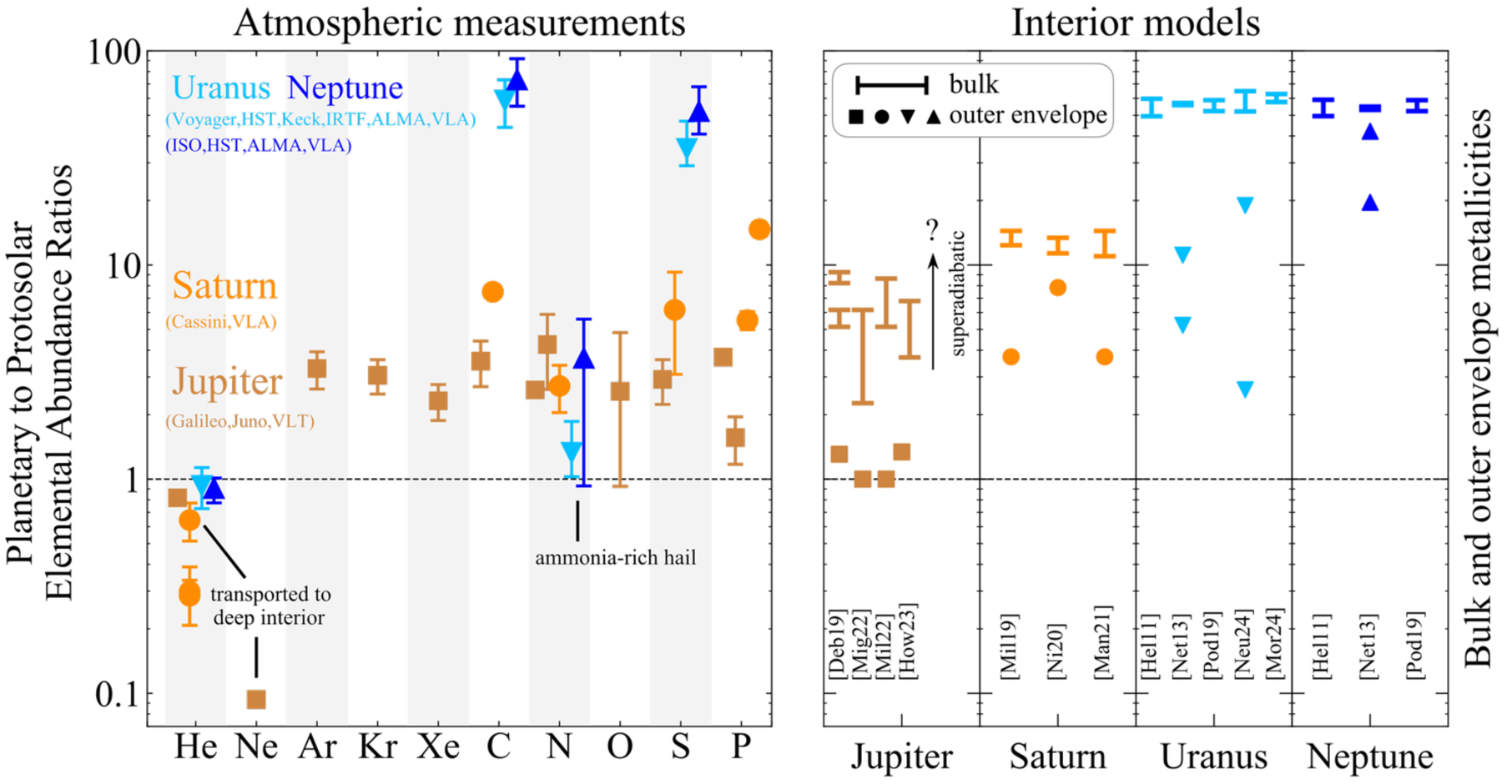


Credit: ALMA/Hsieh et al. 2024

Class 0/I disks required for solid budget



Tobin et al. 2020



Helled & Howard 2024, review paper