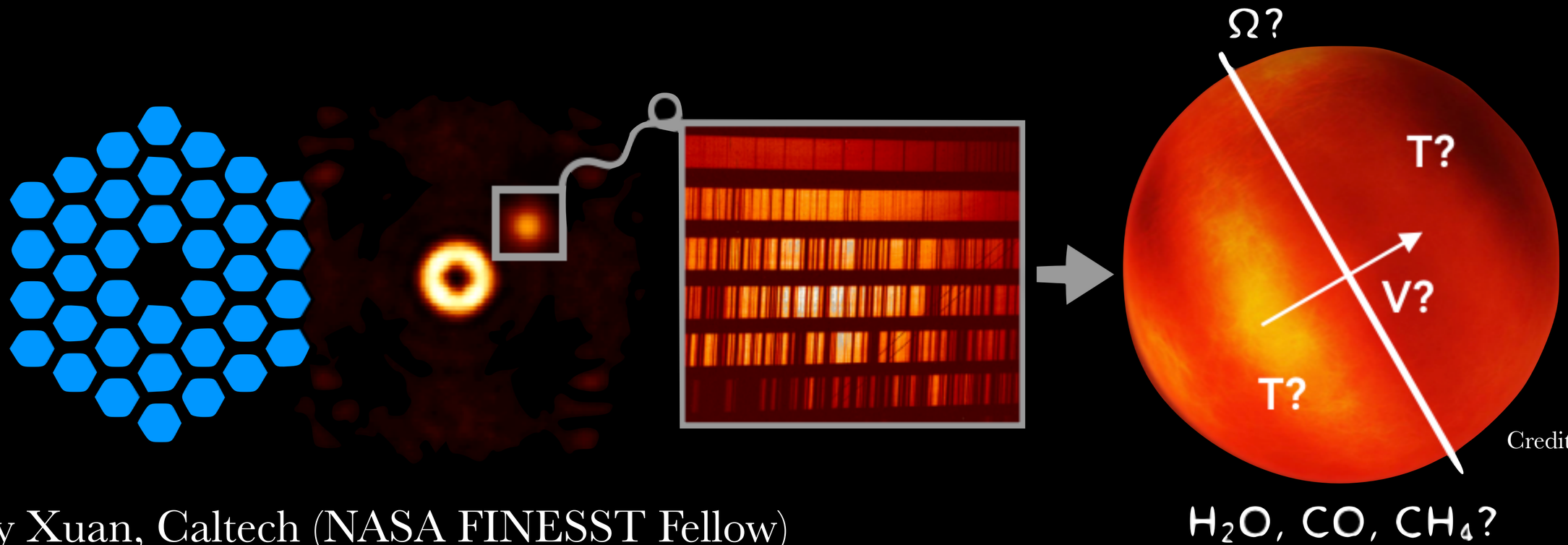
Are these planets or brown dwarfs?
Elemental abundances in atmospheres of substellar companions



Credit: D. Mawet

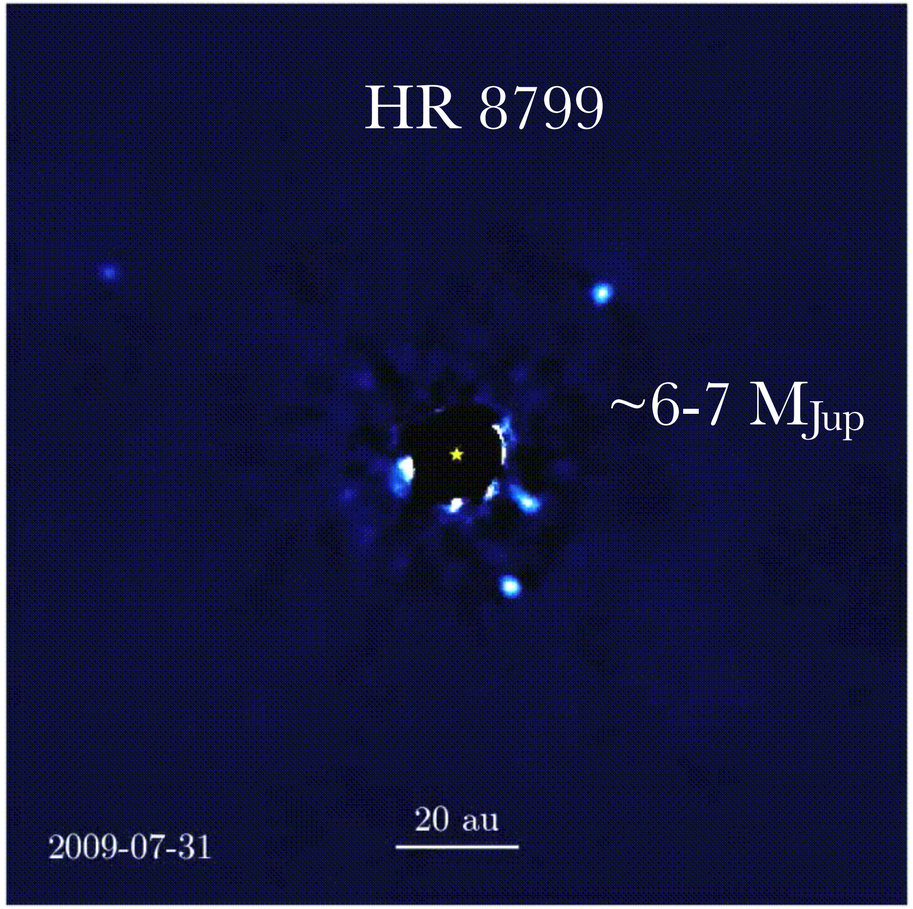
Jerry Xuan, Caltech (NASA FINESST Fellow)

With Jason Wang, Dimitri Mawet, Heather Knutson, Jean-Baptiste Ruffio, Yapeng Zhang, Dino Hsu, Eric Mamajek

+ KPIC Team

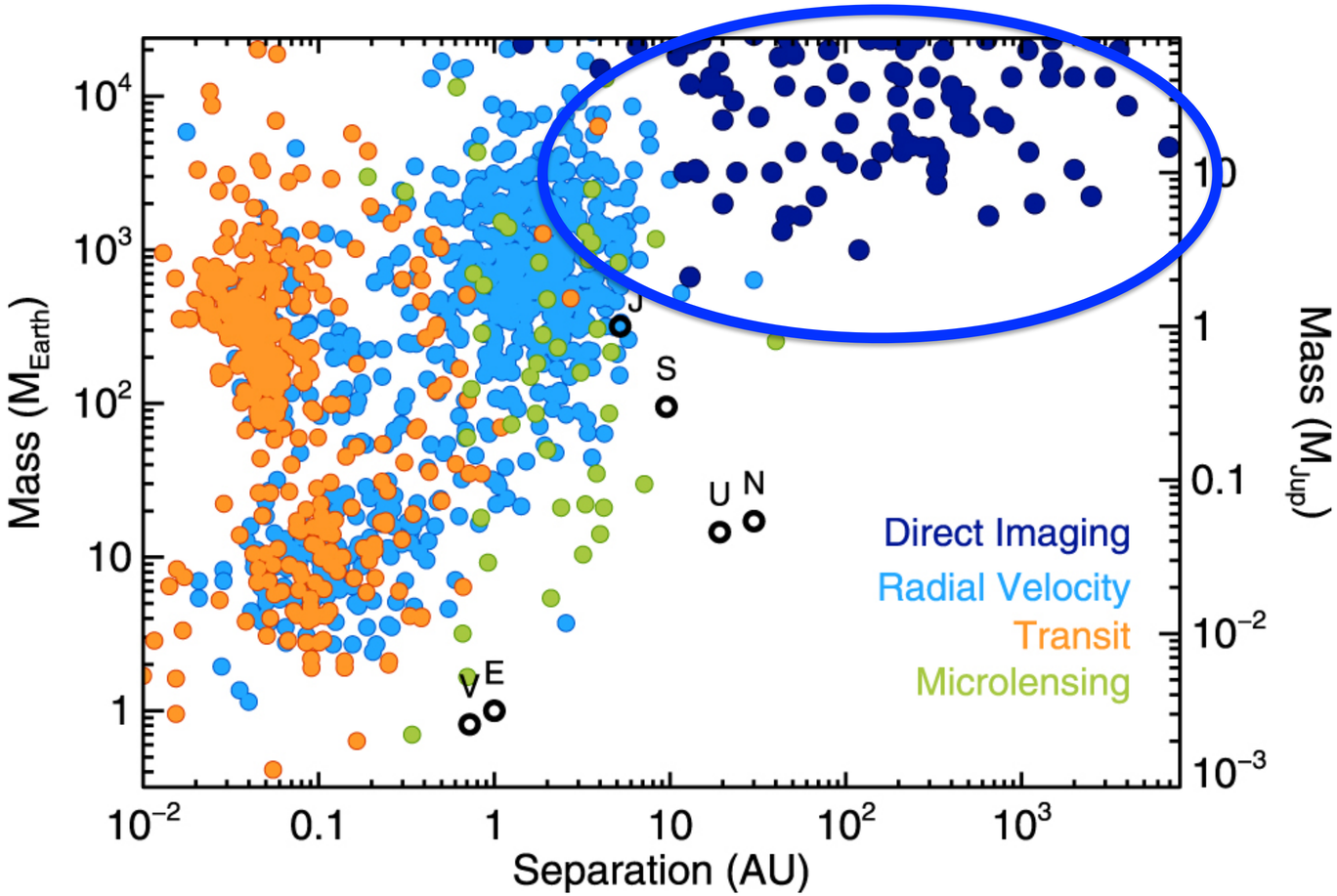
KPIC is supported by: HEISING-SIMONS FOUNDATION JPL NSF CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Substellar companions from direct imaging



Credit: Jason Wang, Christian Marois

Occurence rate: ~1-5%



Credit: NASA Exoplanet Archive

Demographic statistics indicate distinct formation mechanisms

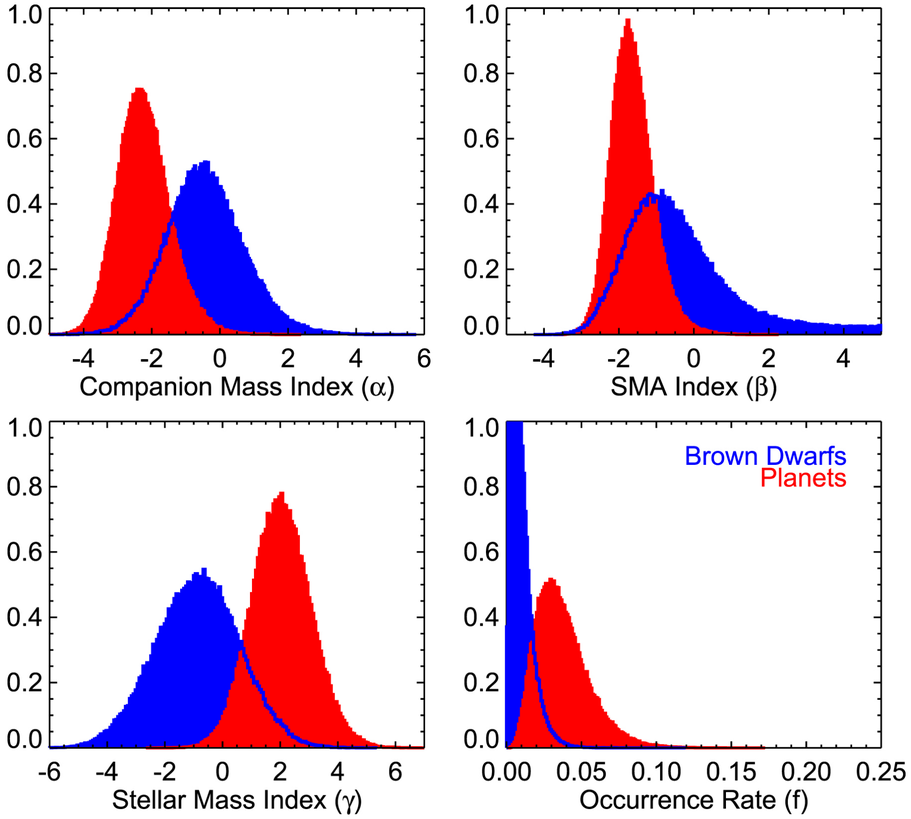
Define giant planets (m<13 M_{Jup}) and brown dwarfs (m>13 M_{Jup}).

1) Giant planets tend to have smaller orbital semi-major axis

2) Giant planets have higher occurrence rates from 10-100 AU

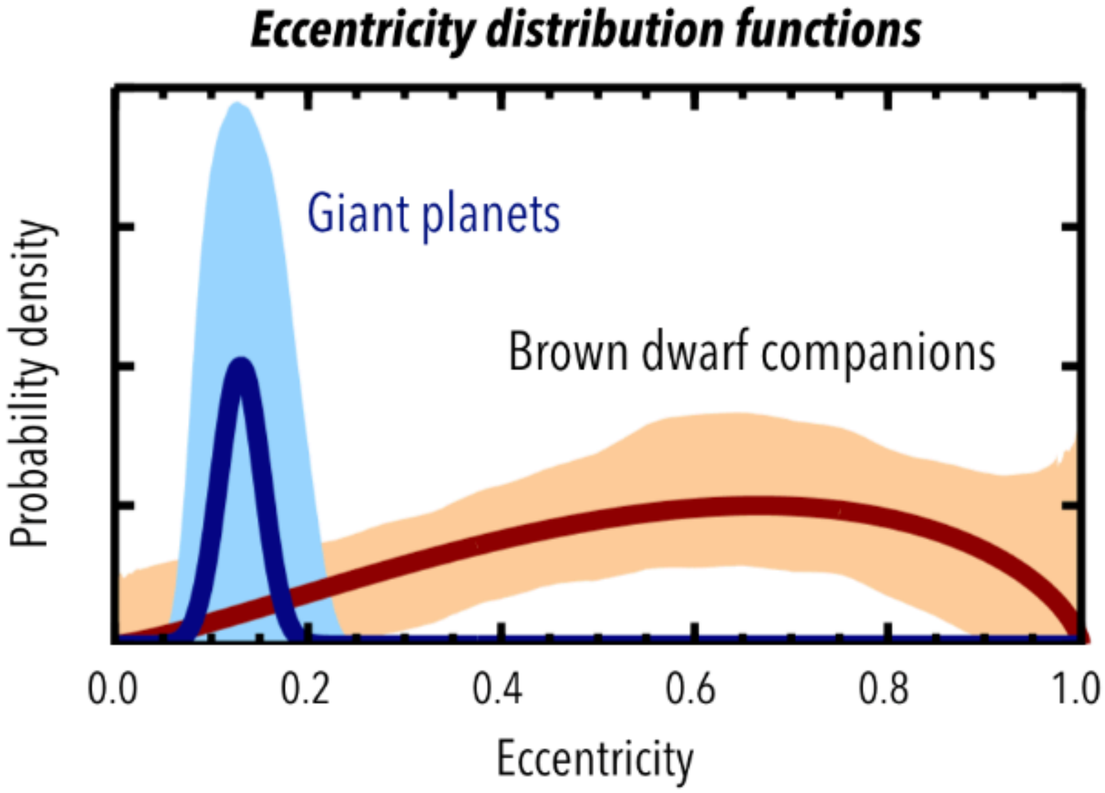
3) Giant planets preferentially exist around higher-mass stars (M>1.5 $M_{\odot}$)

$$\frac{d^2N}{dm\,da} = f\ C_1\ m^{\alpha}\ a^{\beta}\left(\frac{M_*}{1.75\ M_{\odot}}\right)^{\gamma}$$

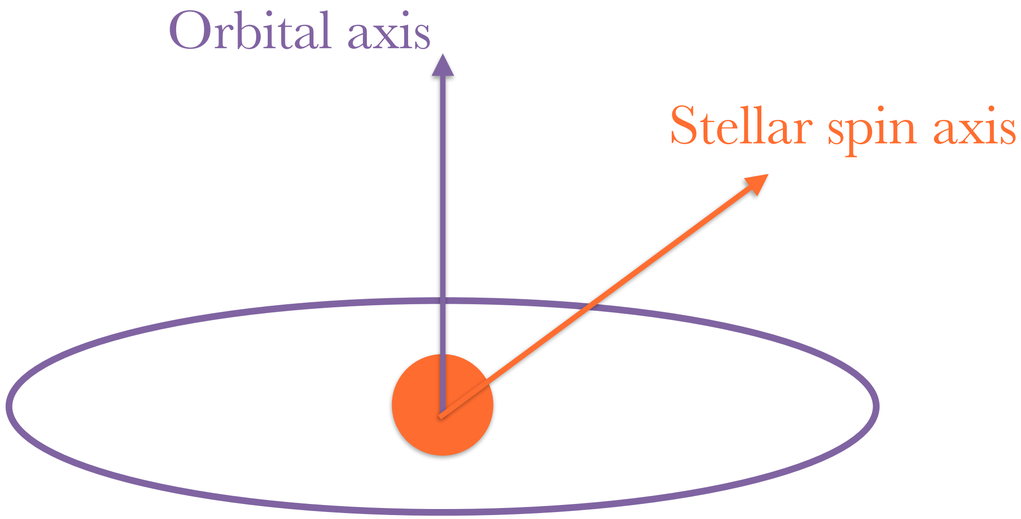


Nielsen+2019, Vigan+2021

Orbital architectures indicate distinct formation mechanisms



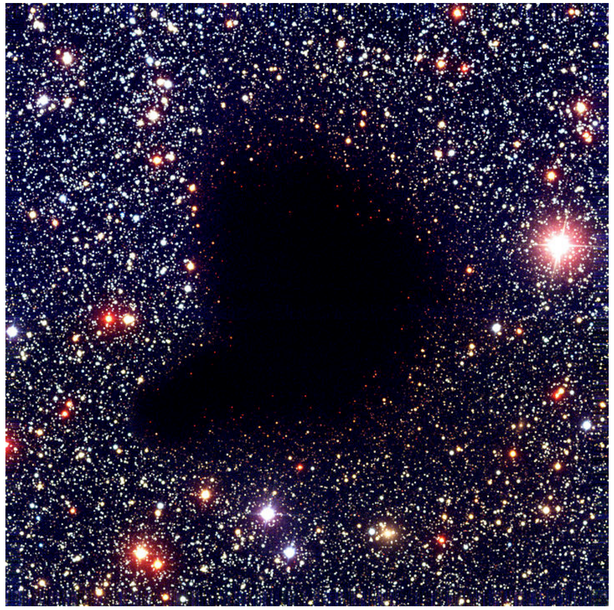
Eccentricities: Bowler+2020; see also Nagpal+2023
Do Ó+2023



Stellar obliquities: Bowler+2023

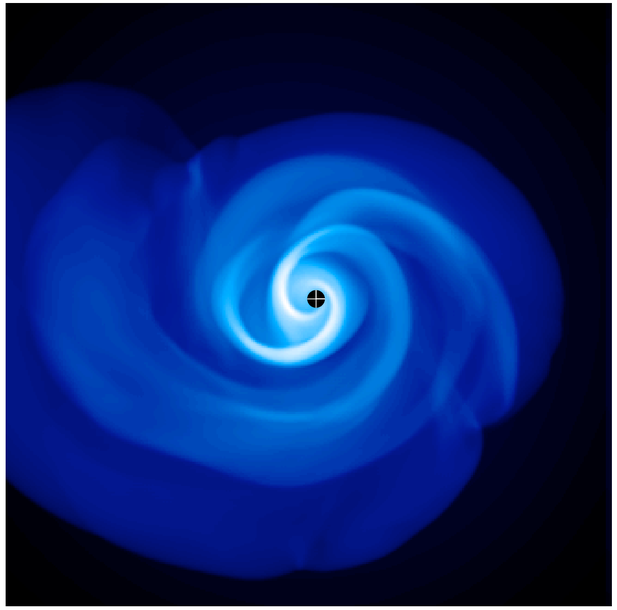
The emerging picture from previous studies

m $\gtrsim$ 10 – 15 $M_{\rm Jup}$

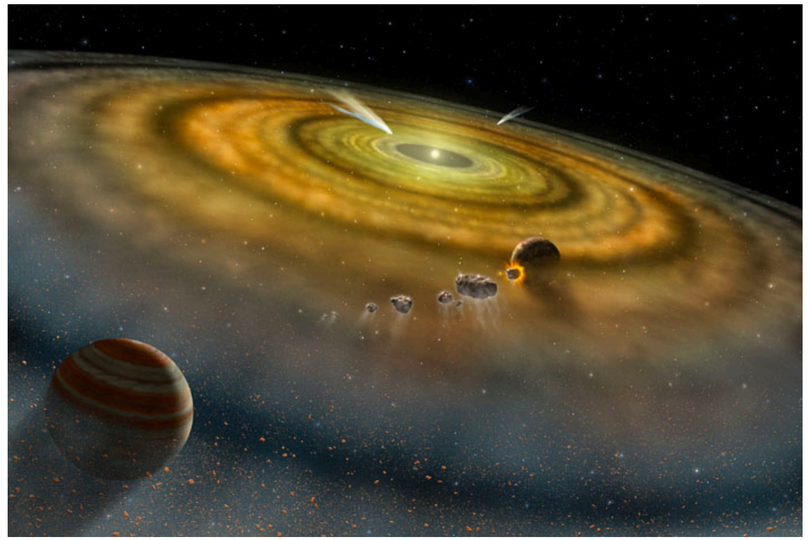


Cloud fragmentation or disk fragmentation in protostellar disk?

a $\gtrsim$ 100 AU

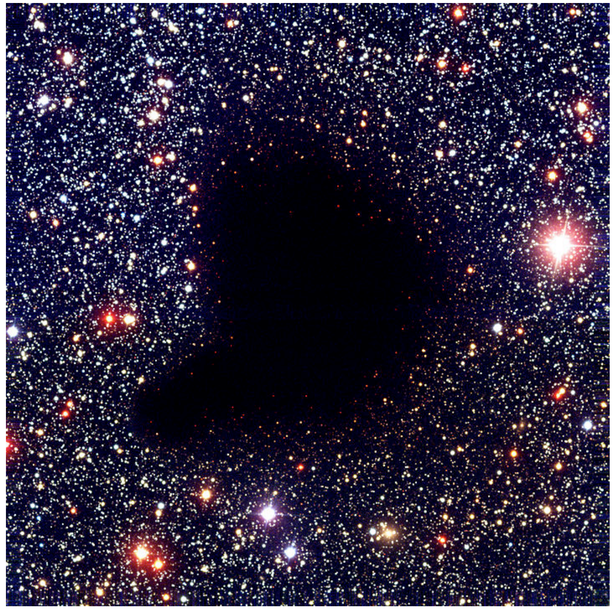


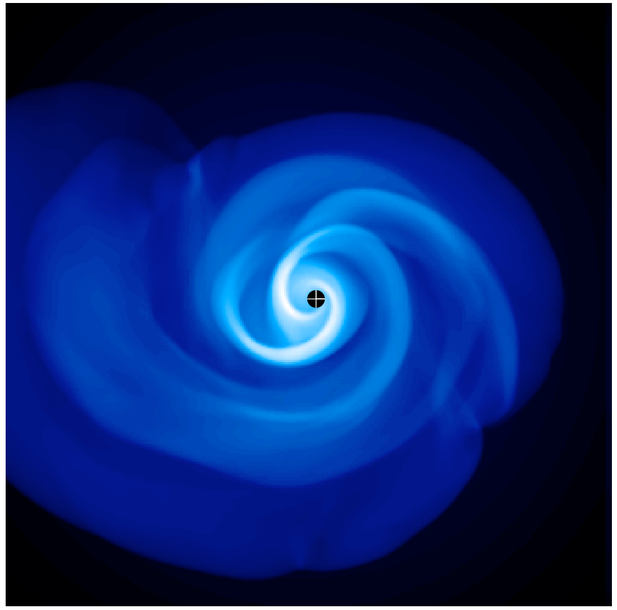
Conversely,



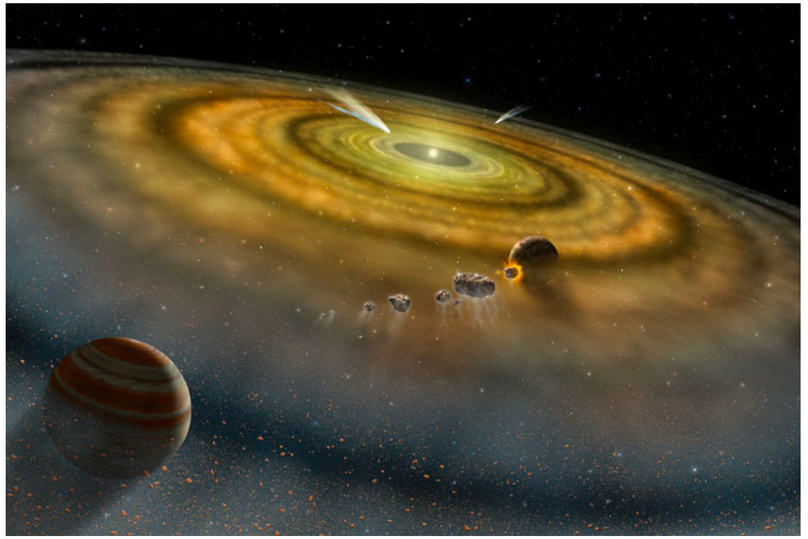
Core accretion in protoplanetary disk?

Key question: do their elemental abundances point to similar differences as orbit and demographic studies?





Likely similar compositions to their host stars, as observed for stellar binaries

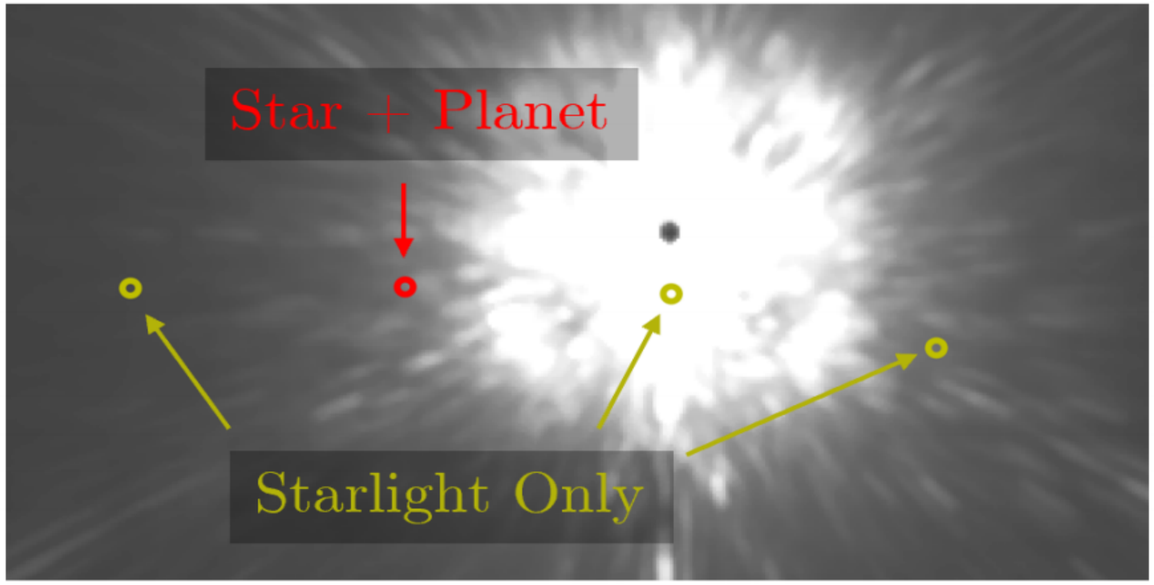


A range of possibilities depending on formation location and migration

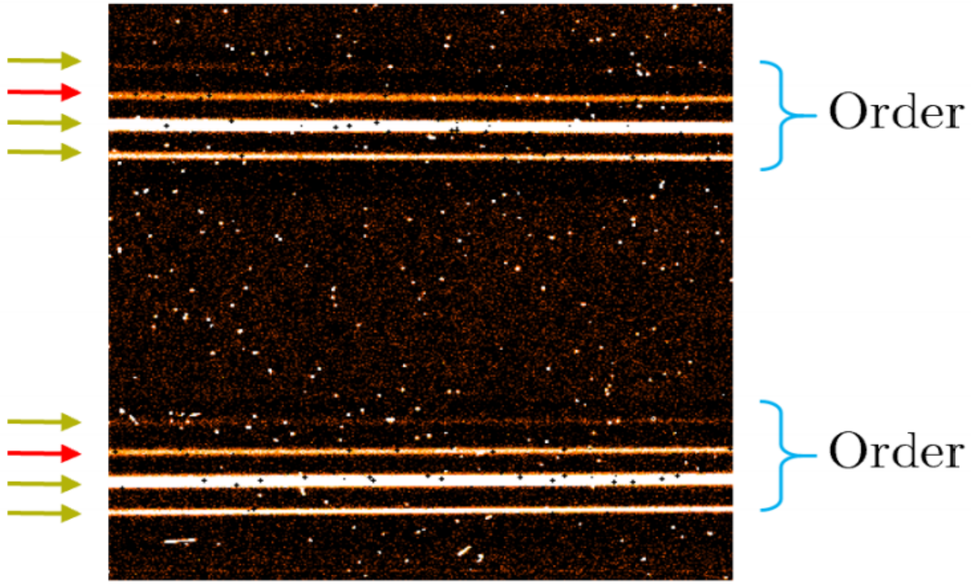
The Keck Planet Imager and Characterizer

Enabling high-resolution spectroscopy of high-contrast companions

Fiber Positions

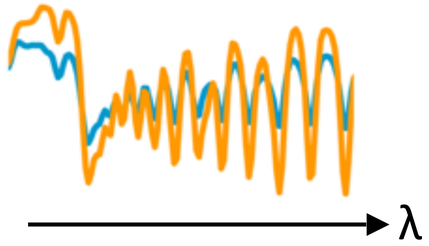


NIRSPEC



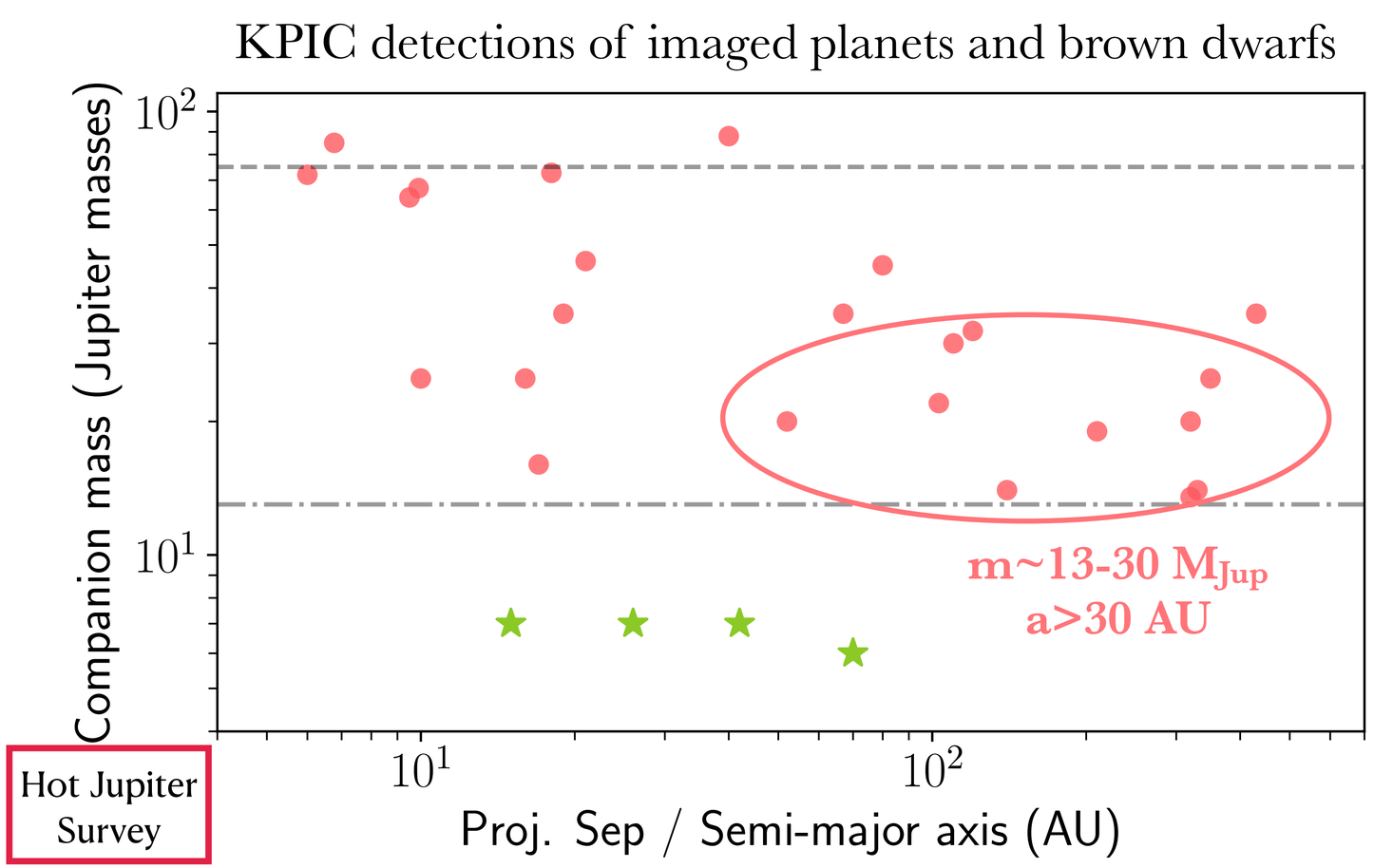
Phase I: 2019-2021
Phase II: 2022-2023
Phase III: 2024-

Instrument papers: Mawet+2017, Delorme+2021



K band (1.9-2.5 μm)
R~35,000

Atmospheric survey of young, intermediate-mass companions



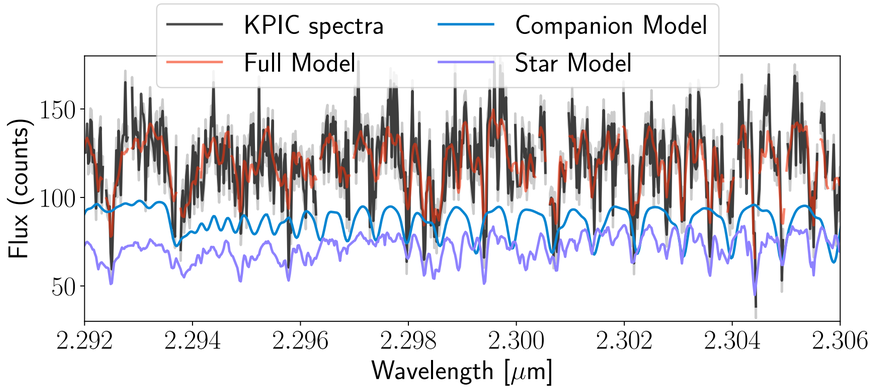
See Luke Finnerty's talk tomorrow (2:00pm)

Name	Teff	log(g)
GQ Lup b	2500-2700	3.5-4.0
HIP 79098 b	2400-2700	4.0-4.5
DH Tau b	2100-2500	~3.5
ROXs 42 Bb	1900-2400	~3.5-4.0
ROXs 12 b	2300-2600	~4.0
2M 0122 b	1300-1600	4.0-5.0
kap And b	1700-2000	4.0-4.5
GSC 6214-210 b	1900-2300	4.0-4.5

See Katelyn Horstman's talk tomorrow (11:15 am) on GQ Lup b

The atmospheric retrieval framework I use

Forward model of the spectrum



Including telluric and instrumental response, speckle light

Wang+2021, Xuan+2022

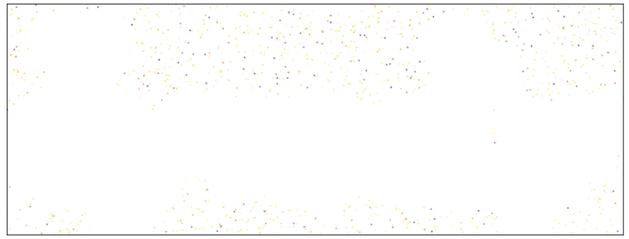
Radiative transfer code

petit RADTRANS

Upgraded opacity data from new line lists (DACE)

Mollière+2019, 2020
Grimm+2021

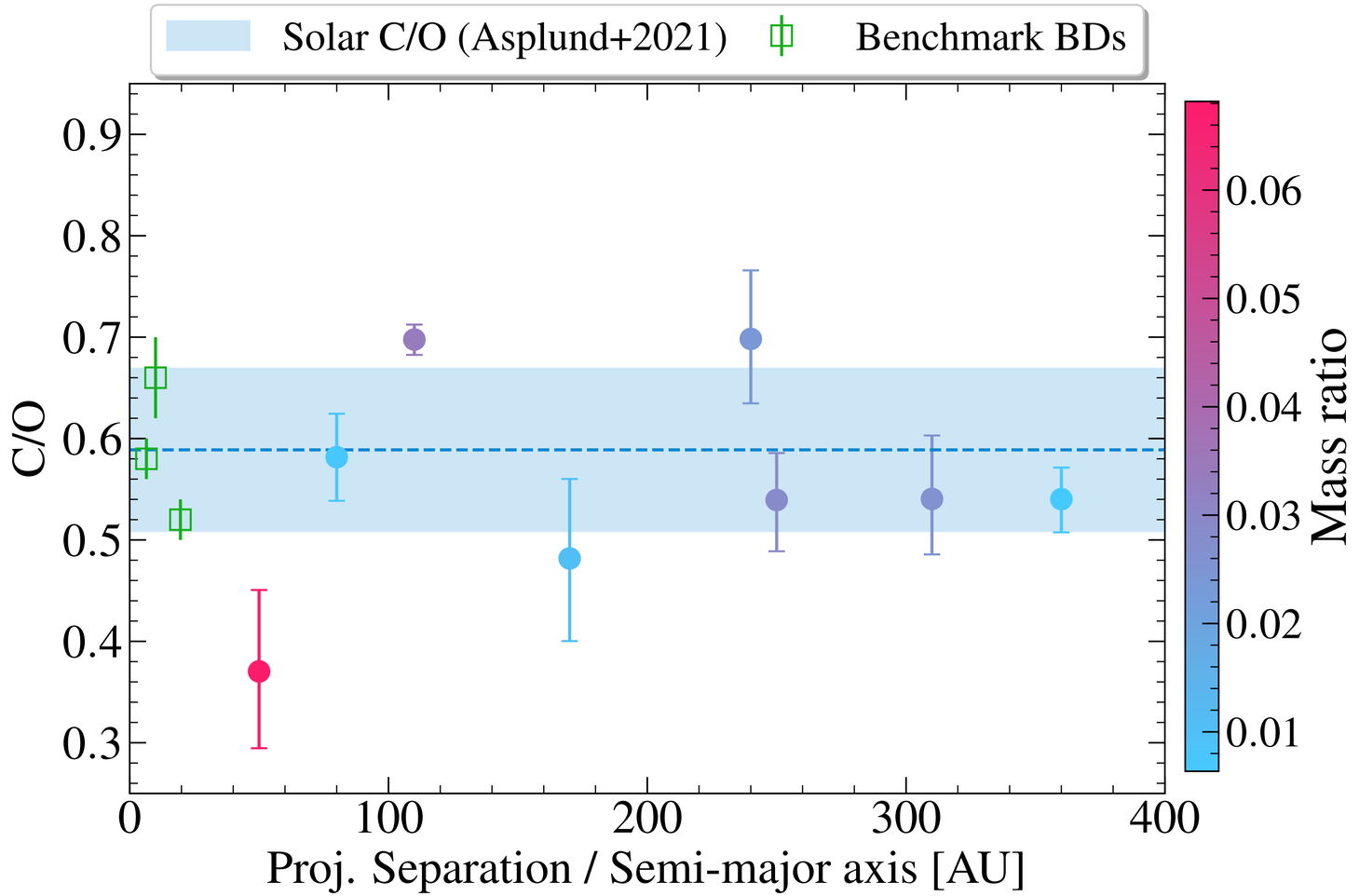
Parameter estimation with nested sampling



Pressure-temperature profile, **C/O, [C/H], isotopic ratios,** cloud parameters

Speagle 2020

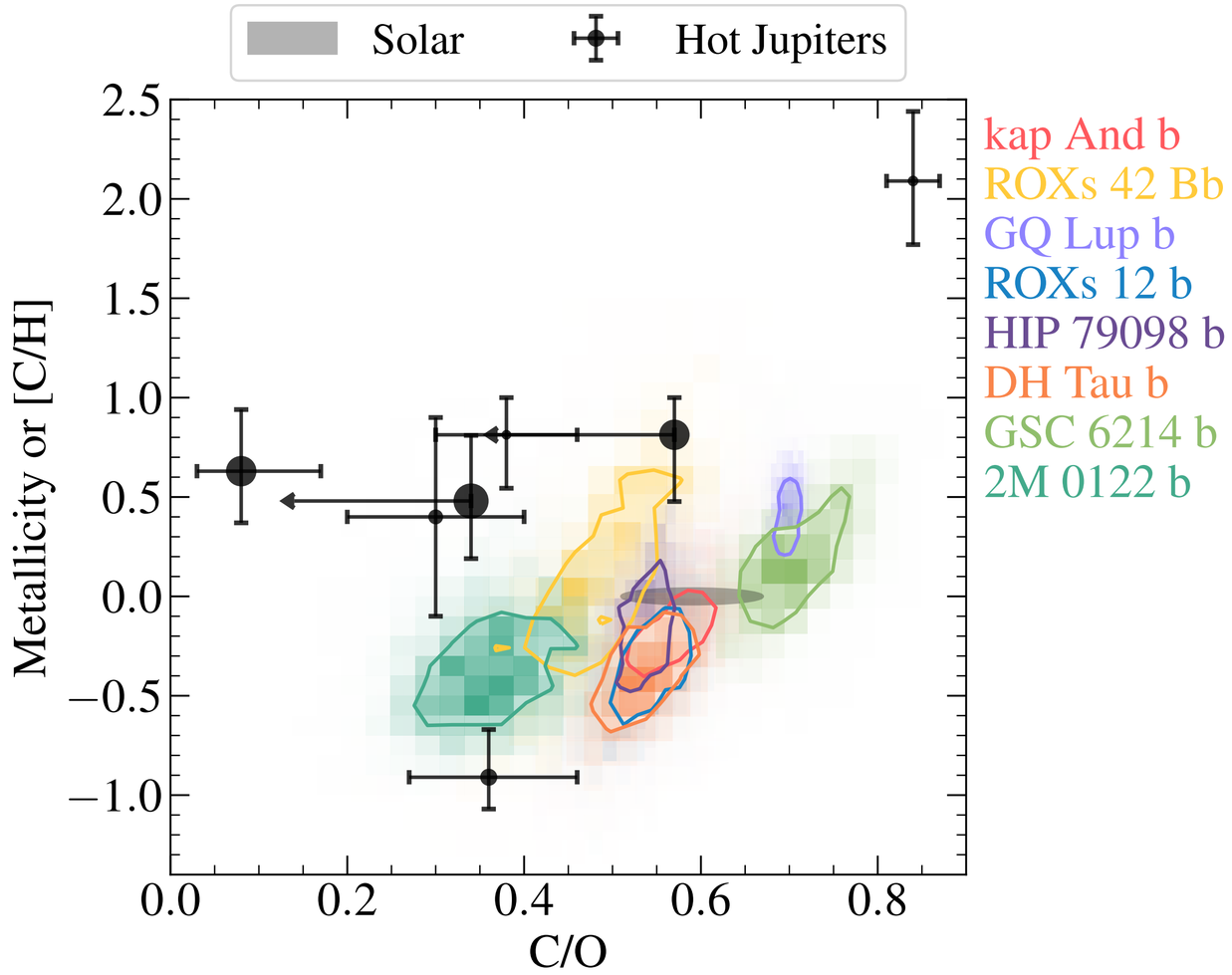
C/O for most of the sample is similar to the Sun



Brown dwarfs from
Xuan+2022, Wang+2022,
Balmer+2023

Xuan+ in prep. 2024

[C/H] is also consistent with solar across the sample



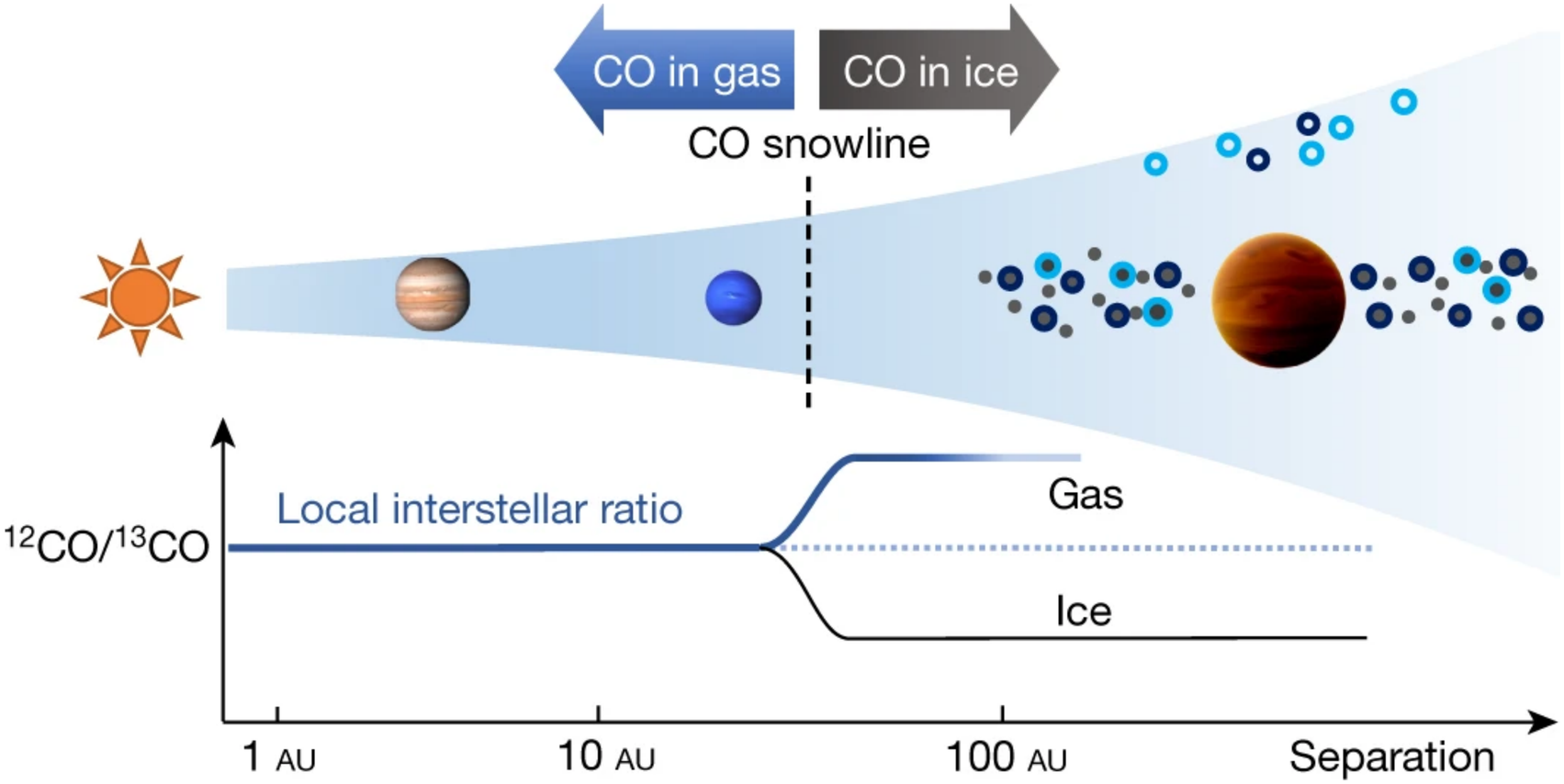
Young stars in the same associations are found to have [C/H]~0, [O/H]~0, [Fe/H]~0 etc.

Santos+2008, D'Orazi+2011, Biazzo+2017, Reggiani+2023

Therefore, these ~10-30 M_J companions are likely chemically similar to their host stars.

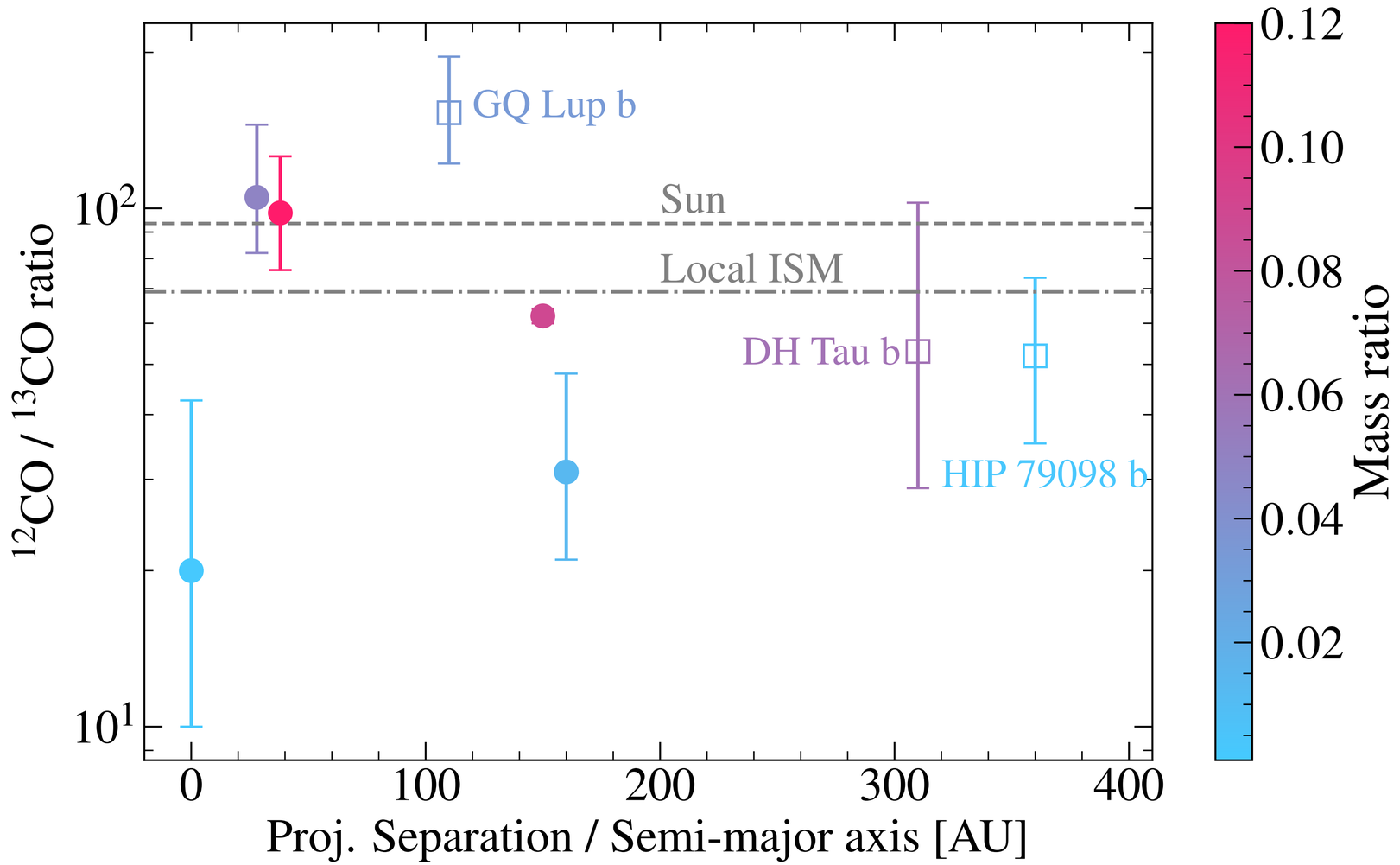
Xuan+ in prep. 2024

Isotopologue ratios such as $^{12}CO/^{13}CO$ are a new observable for substellar companions



Zhang+2021

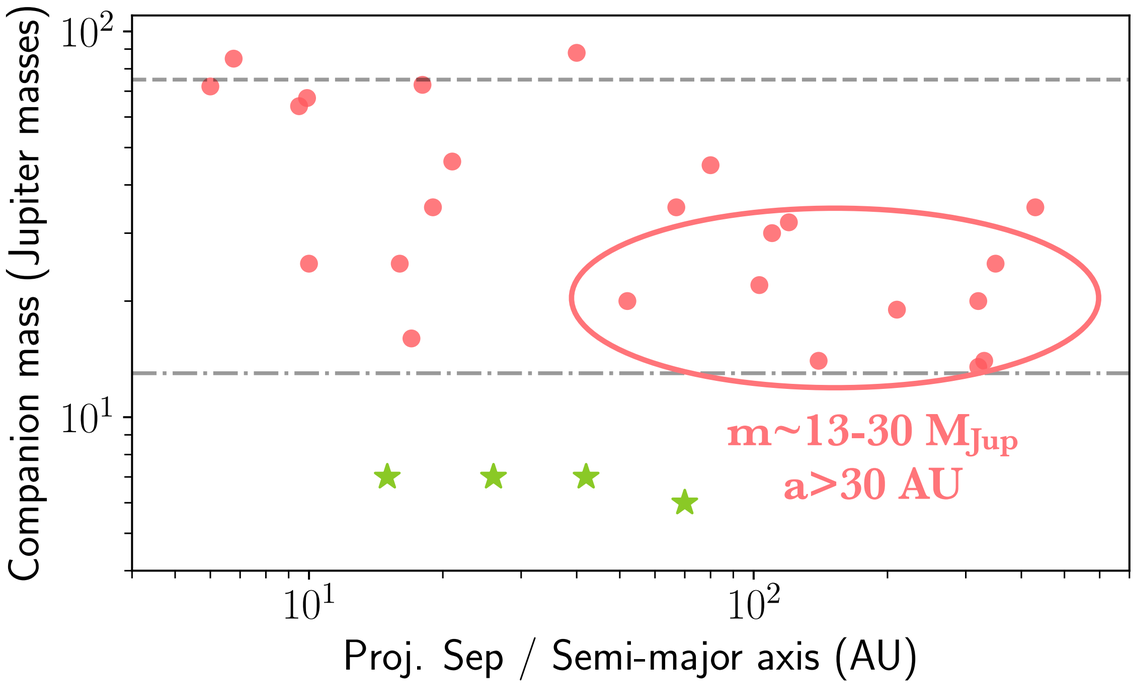
We measure $^{12}CO/^{13}CO$ in 3/8 of the companions studied so far



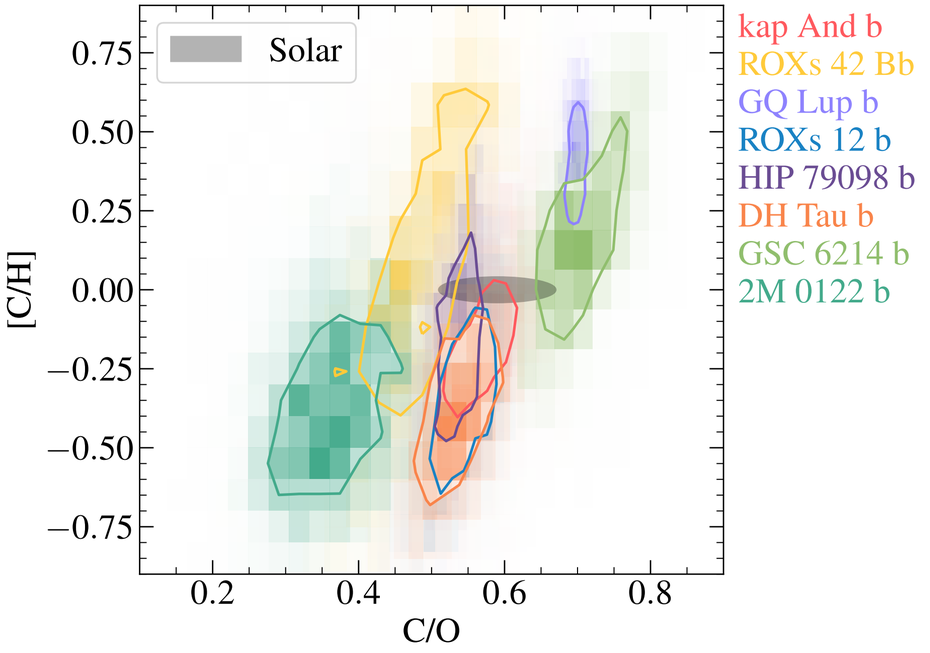
Xuan+ in prep. 2024

Summary

We studied a sample of widely separated, intermediate-mass companions



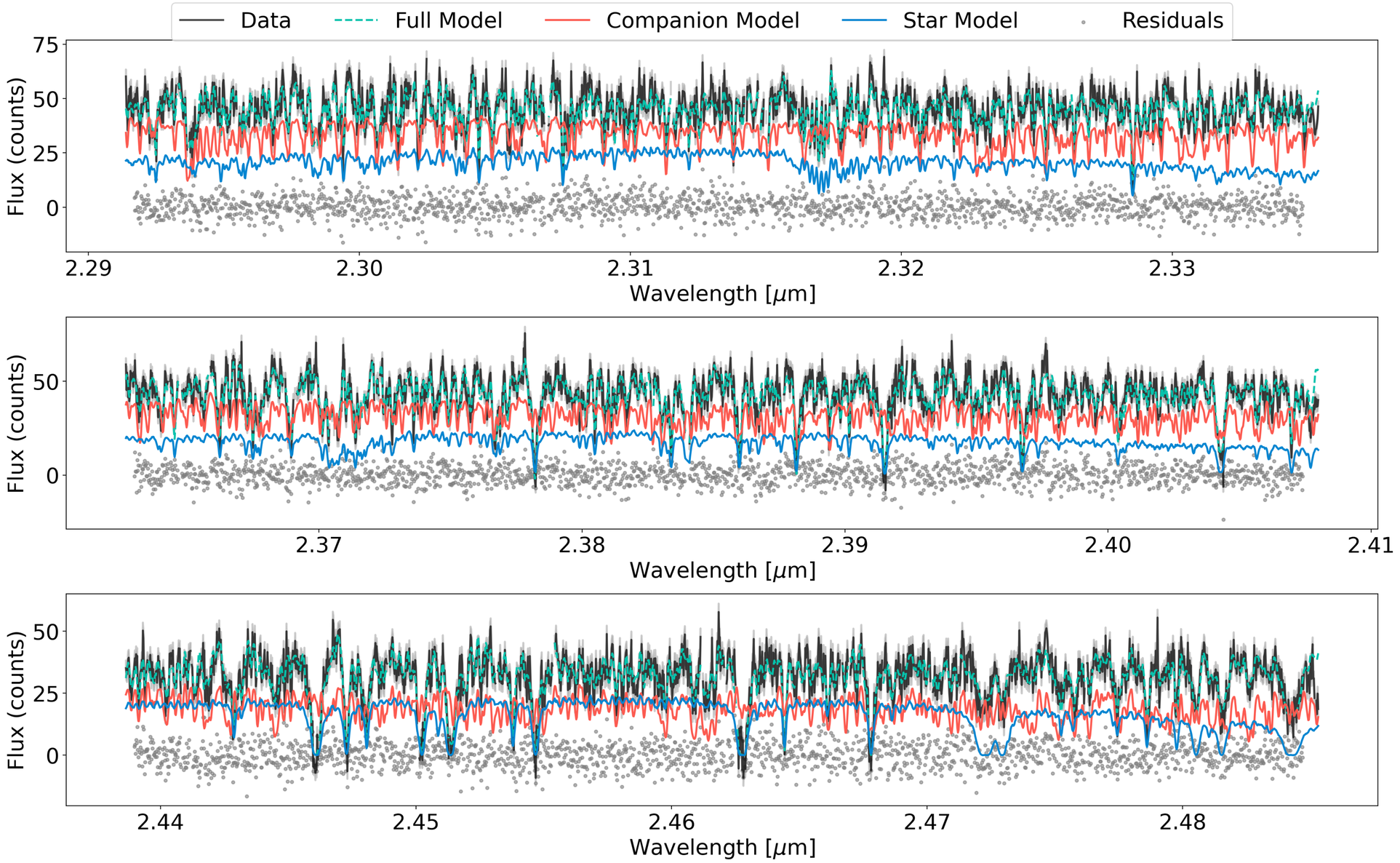
The sample has roughly solar composition, and likely stellar composition



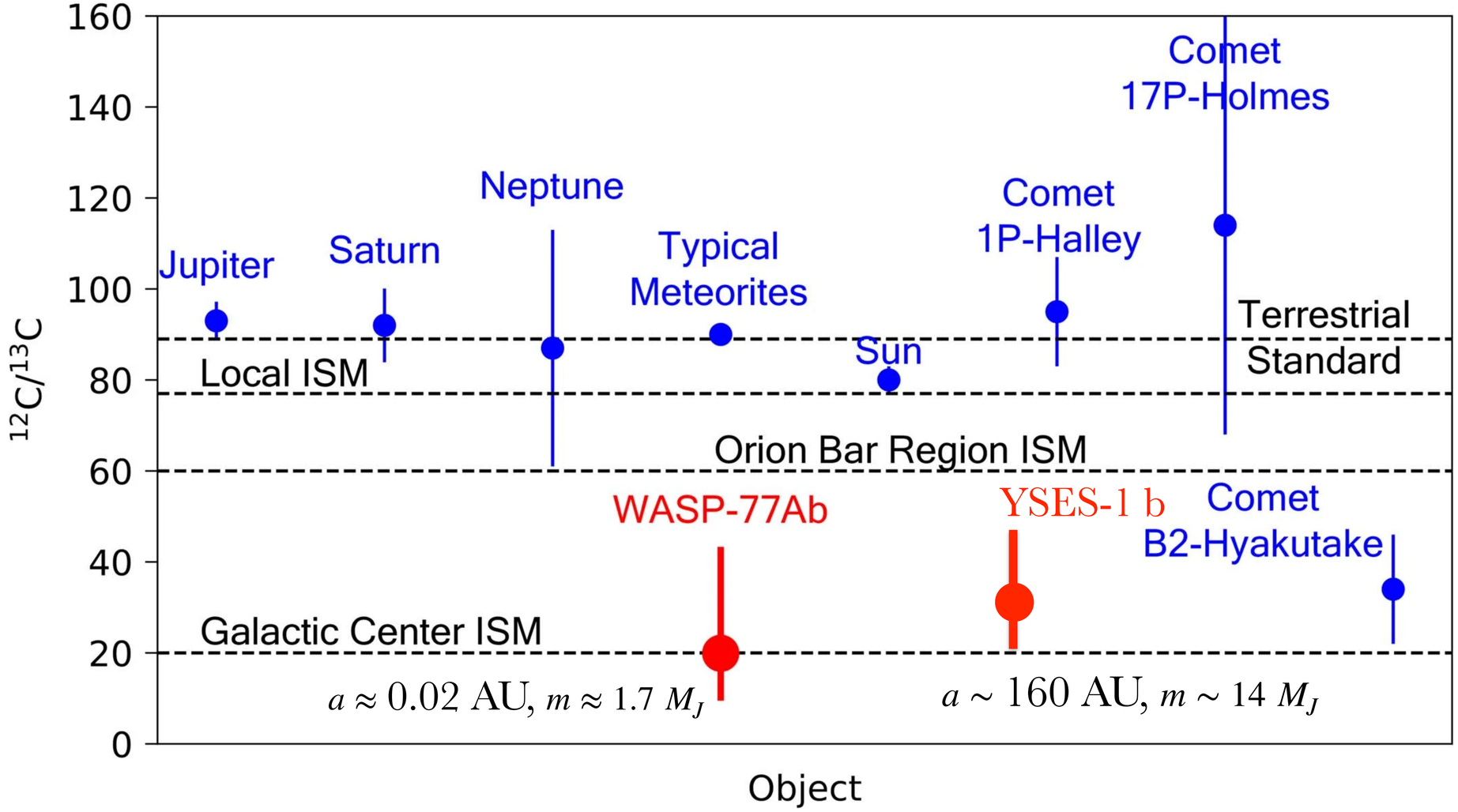
These companions are likely consistent with a star-like formation

Future work: measure host star C and O abundances, including $^{12}CO/^{13}CO$

Backup slides

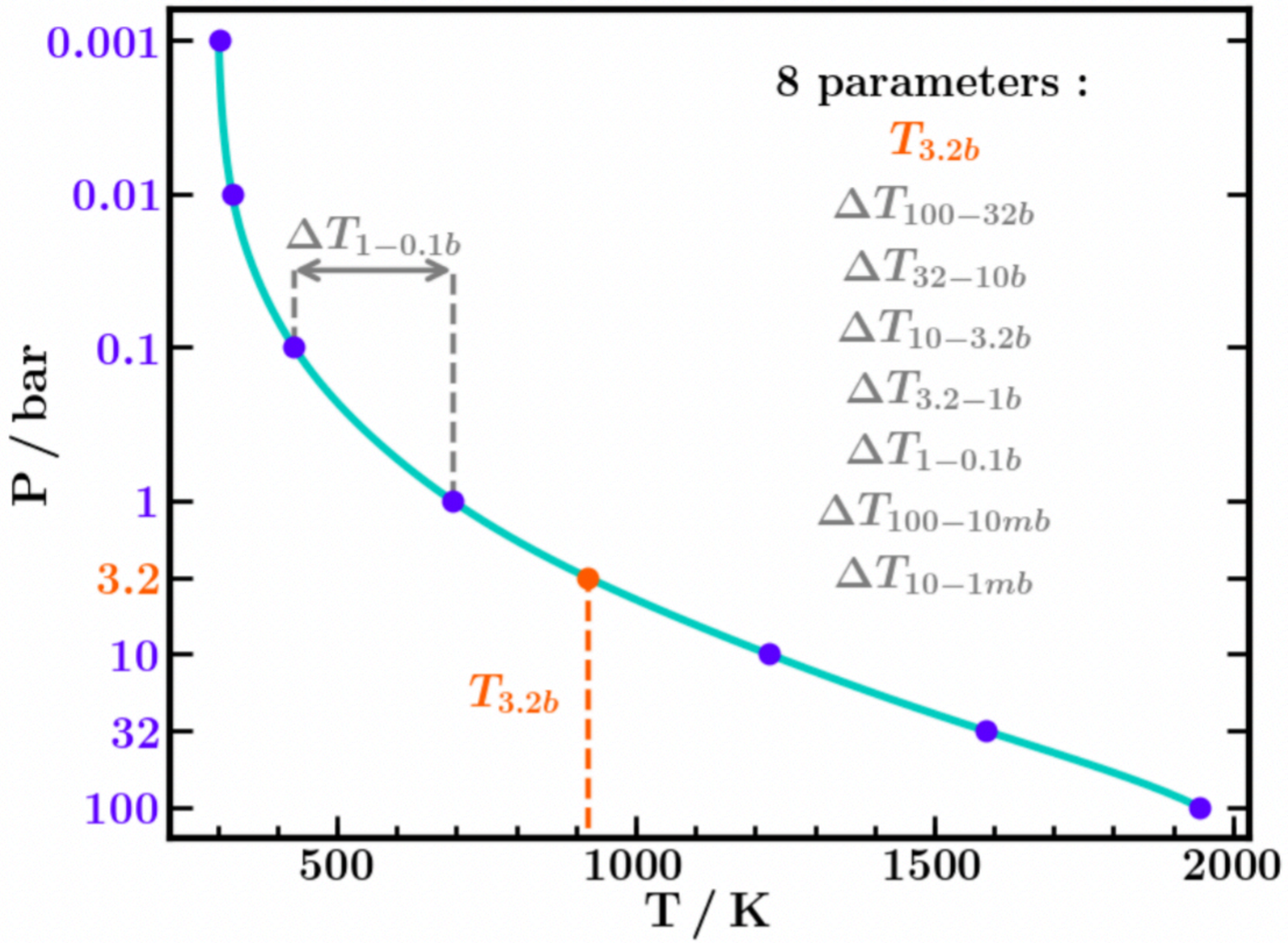

Data
Full Model
Companion Model
Star Model
Residuals
Flux (counts)
75
50
25
0
2.29
2.30
2.31
2.32
2.33
Wavelength [μm]
Flux (counts)
50
0
2.37
2.38
2.39
2.40
2.41
Wavelength [μm]
Flux (counts)
50
25
0
2.44
2.45
2.46
2.47
2.48
Wavelength [μm]

Isotopologue ratios such as $^{12}CO/^{13}CO$ are a new observable for substellar companions



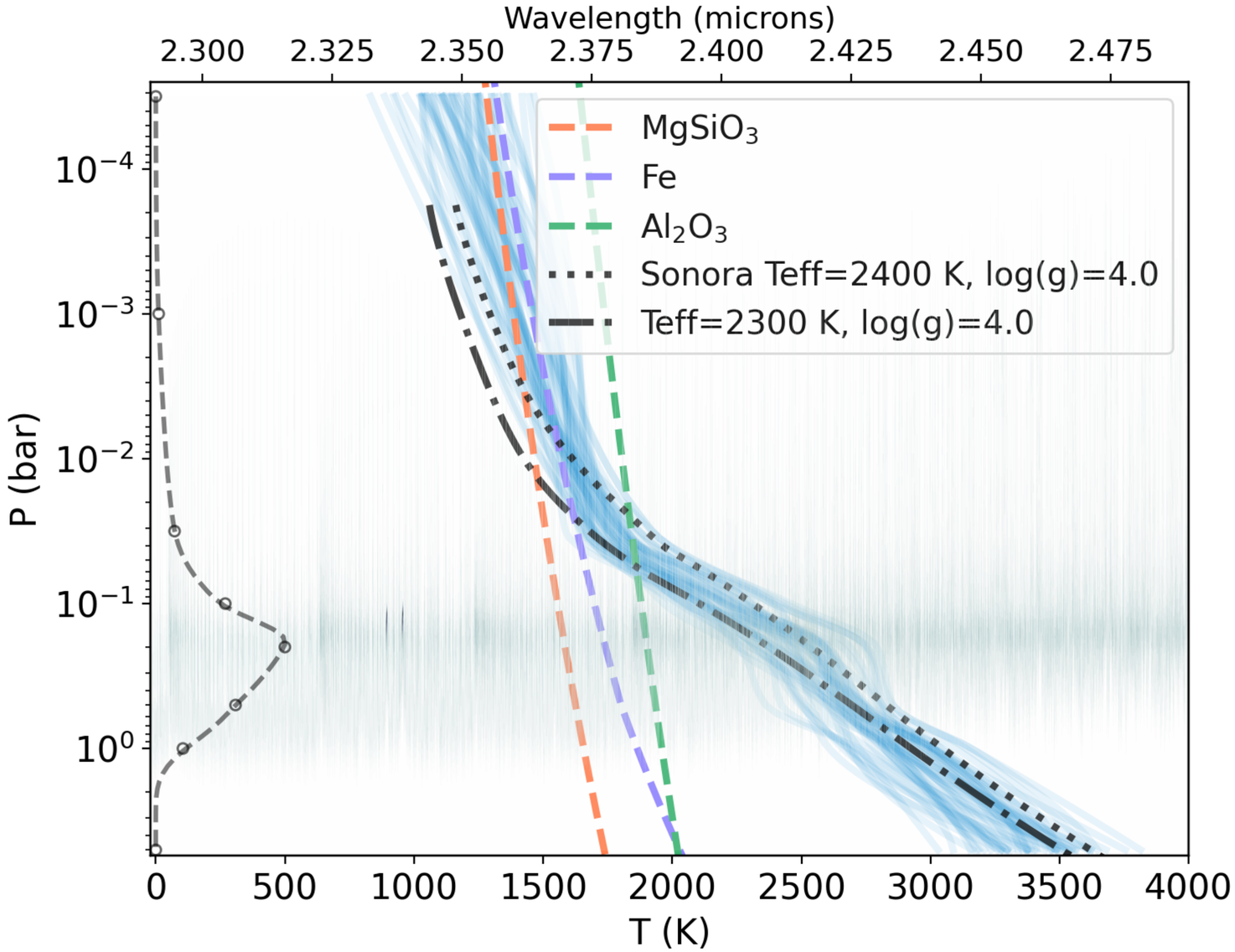
Adopted from Line+2021, Zhang+2021

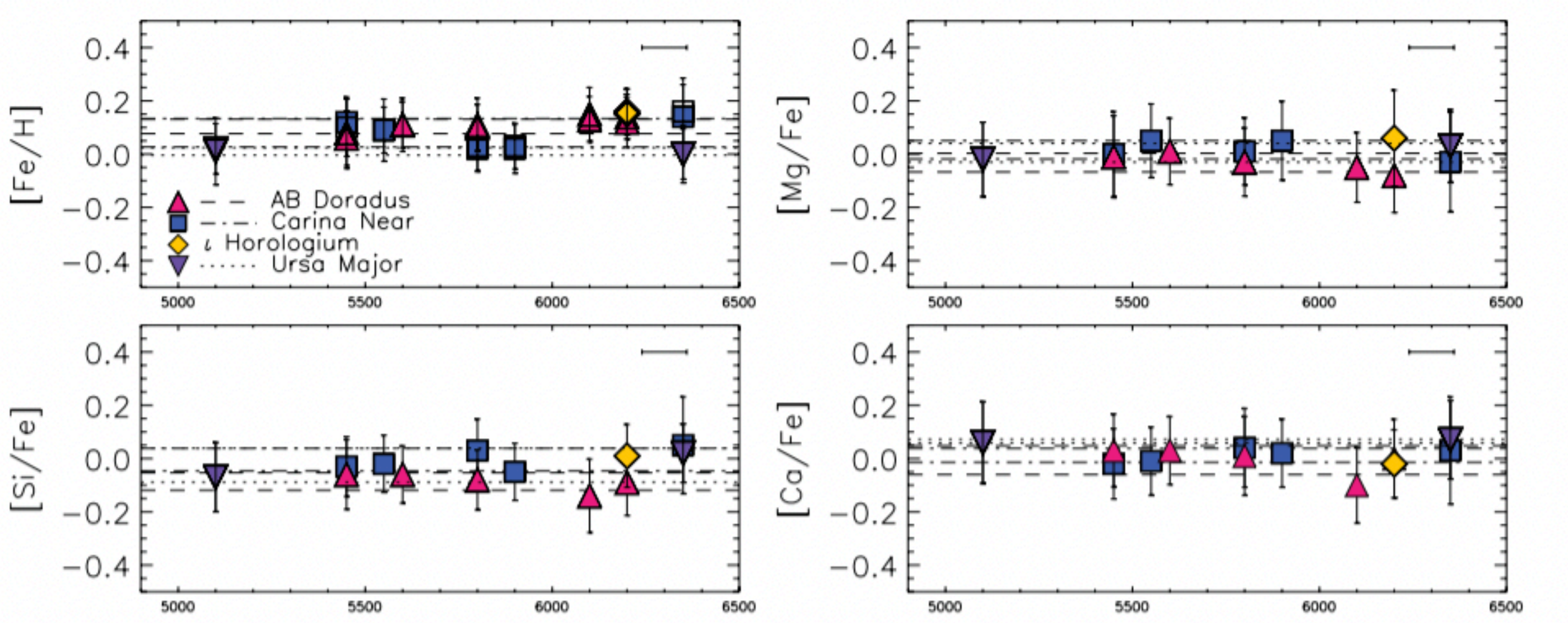
PT profile parametrization



Piette & Madhusudhan 2020

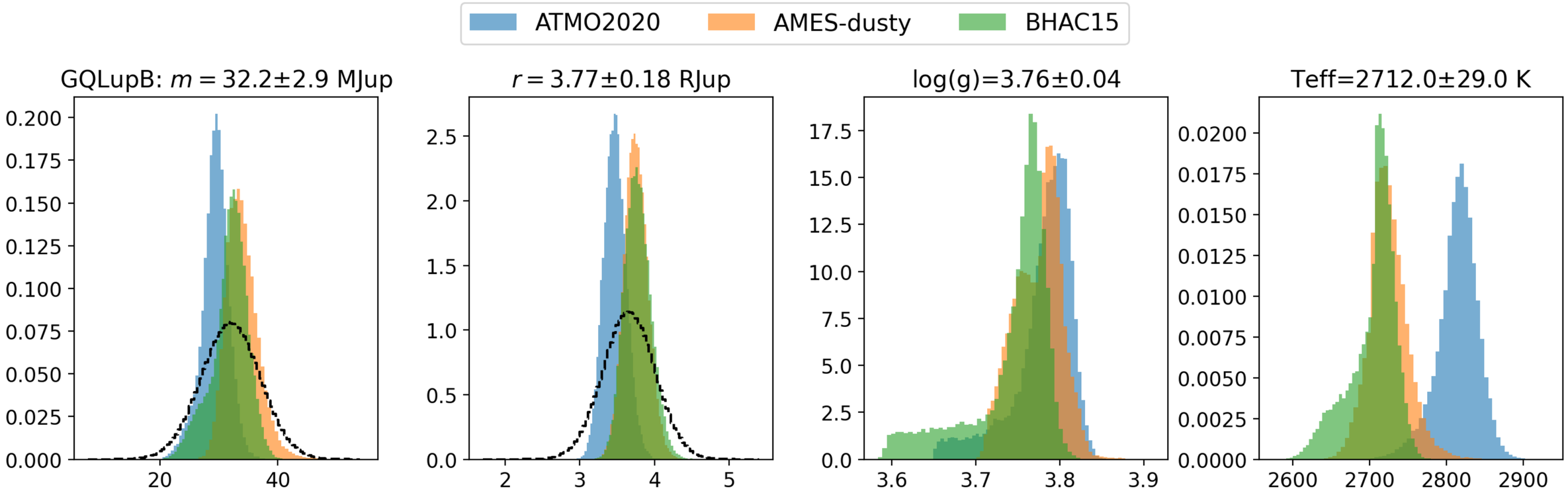
PT profile parametrization





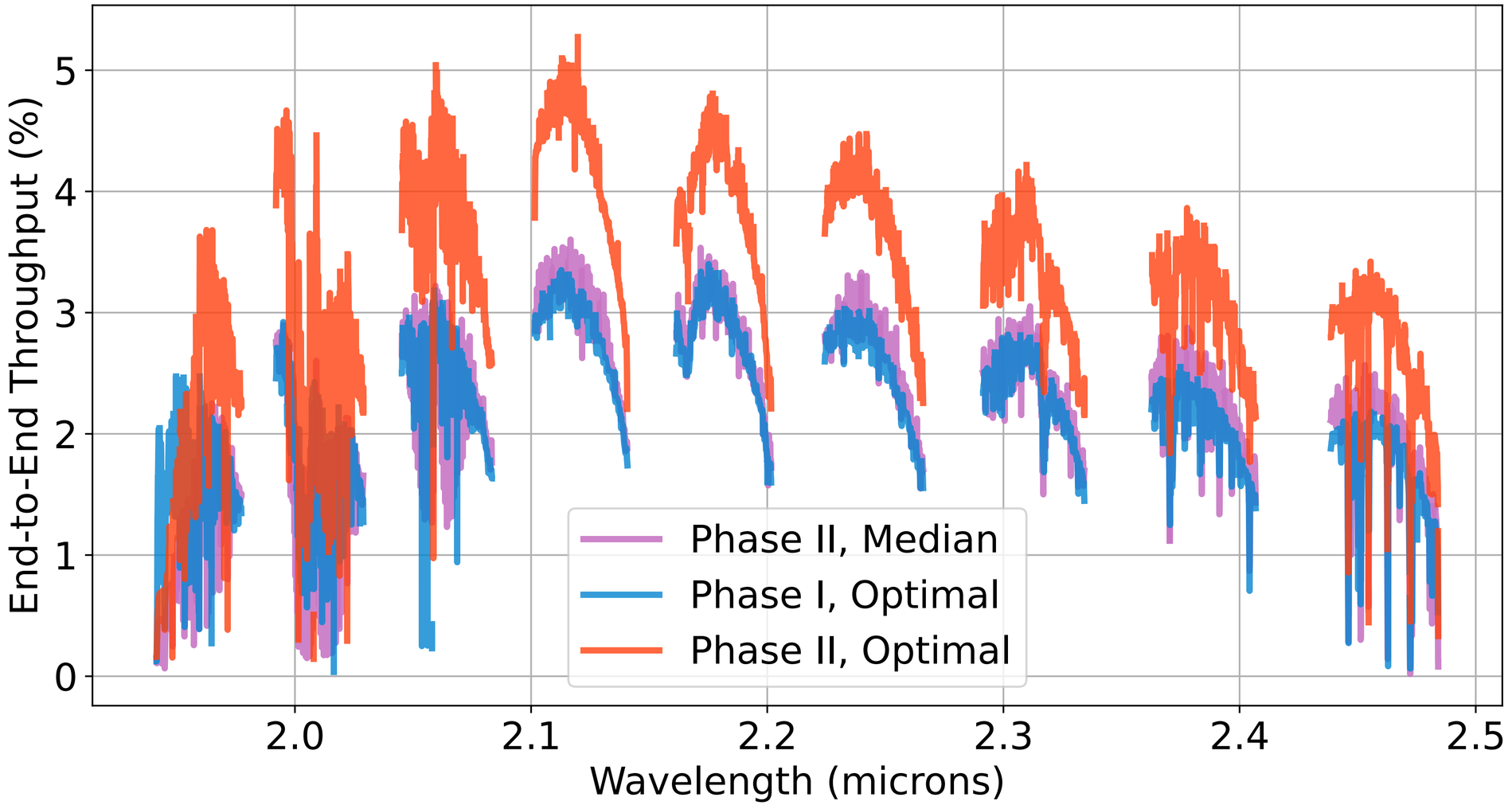
Elemental abundances of low-mass stars in nearby young associations:
AB Doradus, Carina Near and Ursa Major
Biazzo et al. 2012

Retrievals with mass & radius priors to get more reliable [C/H]



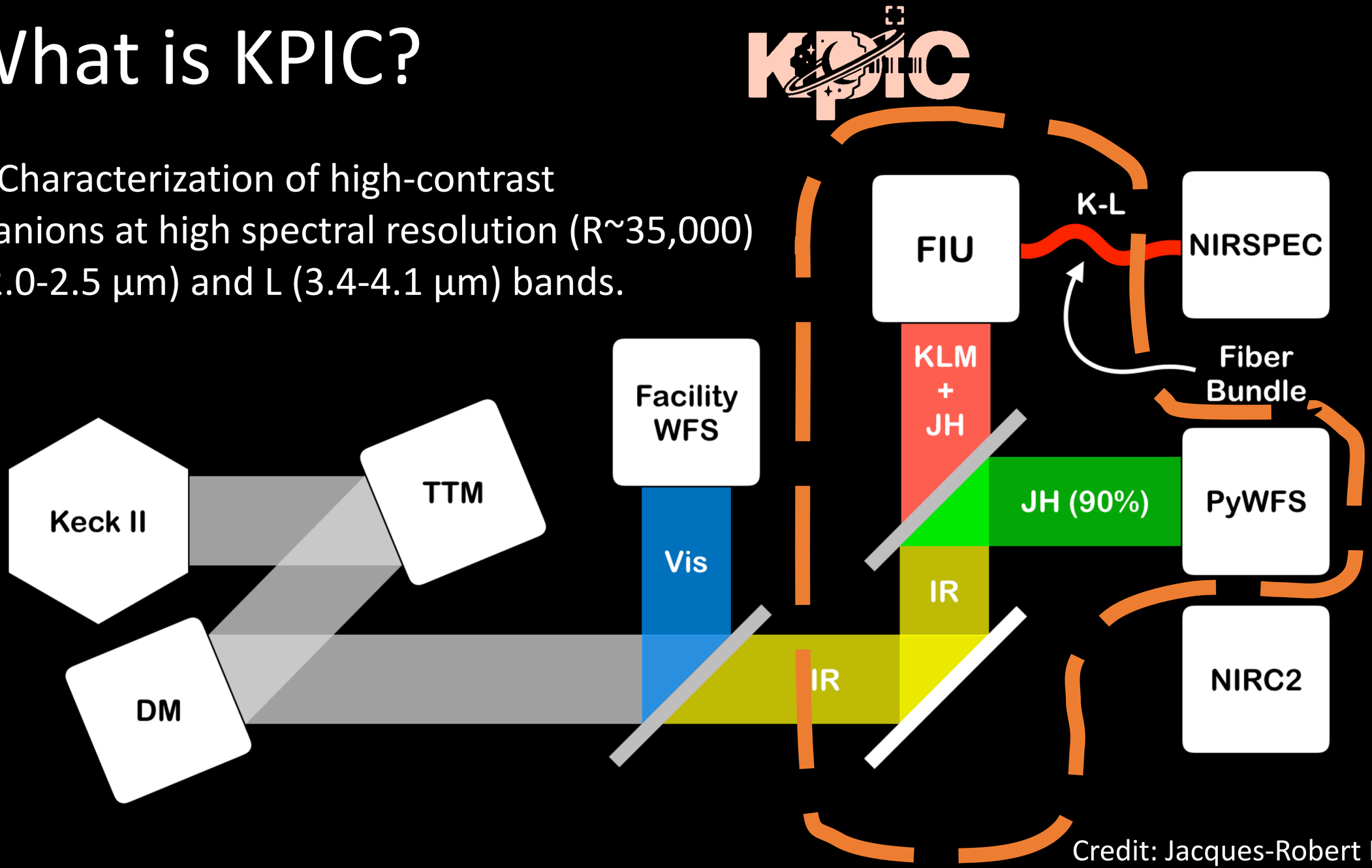
Inputs:
age = 1-5 Myr (uniform)
log(Lbol/Lsun) = -2.15+/-0.05 (Stolker+2021)

Throughput in Phase II is consistently better than in Phase I



What is KPIC?

Goal: Characterization of high-contrast companions at high spectral resolution (R~35,000) in K (2.0-2.5 µm) and L (3.4-4.1 µm) bands.



Credit: Jacques-Robert Delorme