Constraining Directly Imaged Planet Formation using High Resolution Spectroscopy of Host Stars

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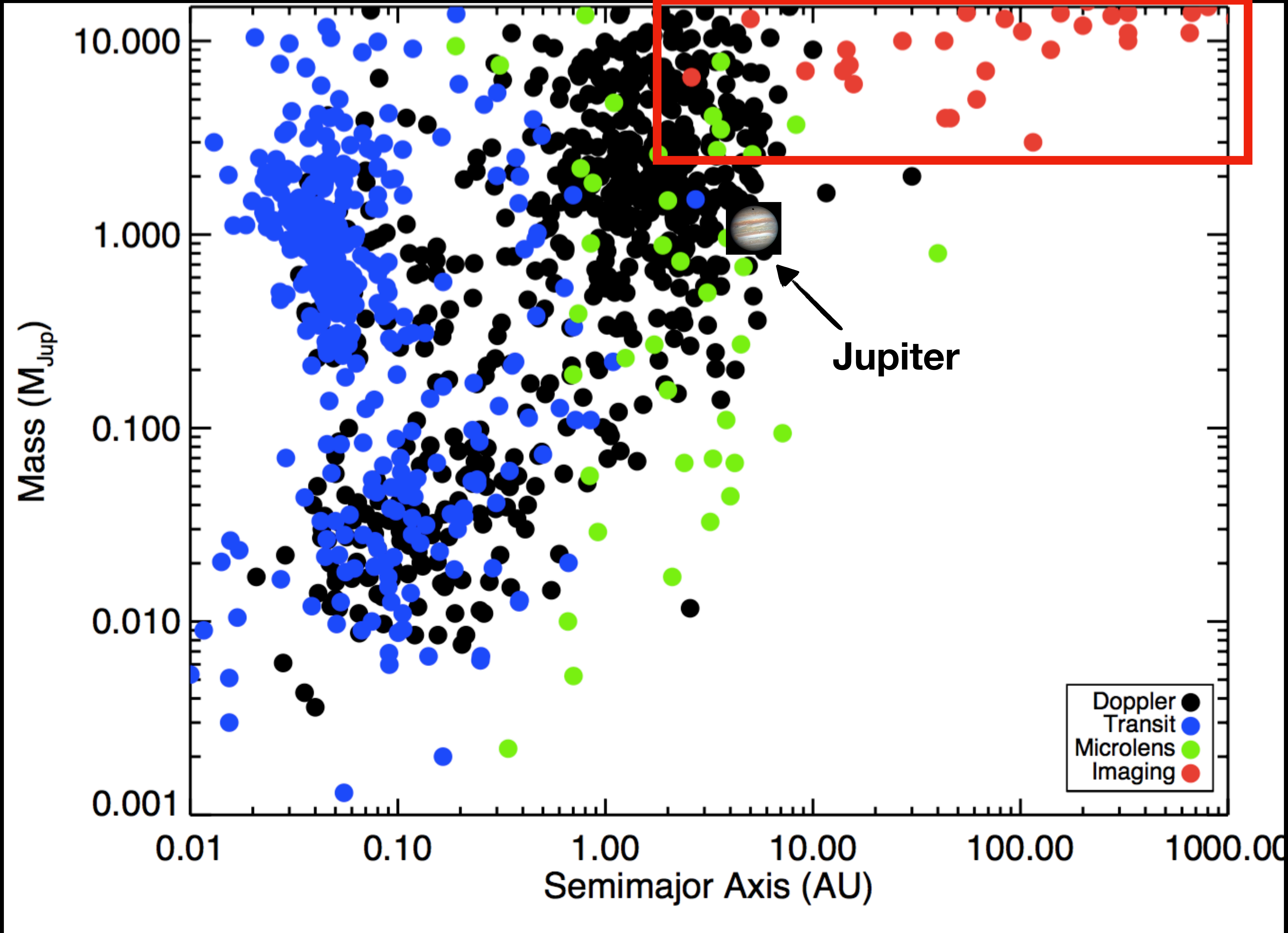
Planet formation pathways

- There are two major pathways proposed for planet formation:
  1. Core accretion
  2. Disk instability

Directly Imaged Exoplanet Population



Neither formation pathway can explain the formation of all of the directly imaged planets!

Different formation pathways can lead to differences in elemental abundances!

- For a planet formed by core accretion, the atmospheric C/O should be enhanced relative to the host star (Oberg et al. 2011).
- There is no separation of gas and solids in disk instability, hence the atmospheric C/O ratio matches the host star.

In order to test predictions regarding formation, we need abundance measurements for the planet as well as the host star!

Peering into the young planetary system AB Pic

Atmosphere, orbit, obliquity, and second planetary candidate

P. Palma-Bifani[1,2,3], G. Chauvin[2,3,4], M. Bonnefoy[4], P. M. Rojo[1], S. Petrus[4,5], L. Rodet[6], M. Langlois[7], F. Allard[7], B. Charnay[8], C. Desgrange[4,11], D. Homeier[15,16], A.-M. Lagrange[8], J.-L. Beuzit[9], P. Baudoz[8]

…oplanet HIP 65426 b★

…R. Gratton[5], A.-M. Lagrange[1], J. Rameau[1], … Allard[10★★], S.

Deep exploration of …

Jean-Baptiste … Bruce … Jason J. …

2044	Direct Imaging Spectroscopy of Two Jovian Exoplanets: Characterization of the TYC 8998-760-1 Multi-Planetary System	PI: Kielan Wilcomb Co-PIs: Marshall Perrin and Quinn Konopacky	12	5.2	NIRSpec/IFU MIRI/LRS	GO
3522	Spectroscopic characterization of the smallest and coolest directly imaged exoplanet 51 Eridani b	PI: Jean-Baptiste Ruffio	12	11.12/0	NIRSpec/FS	GO

…ry in the

H. Jens Hoeijmakers[4,5], Matthew … Maddalena Reggiani[9], Frans Snik[1]

Assessing the C/O Ratio Formation Diagnostic: A Potential Trend with Companion Mass

Kielan K. W. Hoch,[1,2] Quinn M. Konopacky,[1] Christopher A. Theissen,[1,*] Jean-Baptiste Ruffio,[3] Travis S. Barman,[4] Marshall D. Perrin,[2] Bruce Macintosh,[5] and Christian Marois[6]

MODERATE-RESOLUTION K-BAND SPECTROSCOPY …

Kielan K. Wilcomb[1], Quinn M. … Ruffio[3,4], …

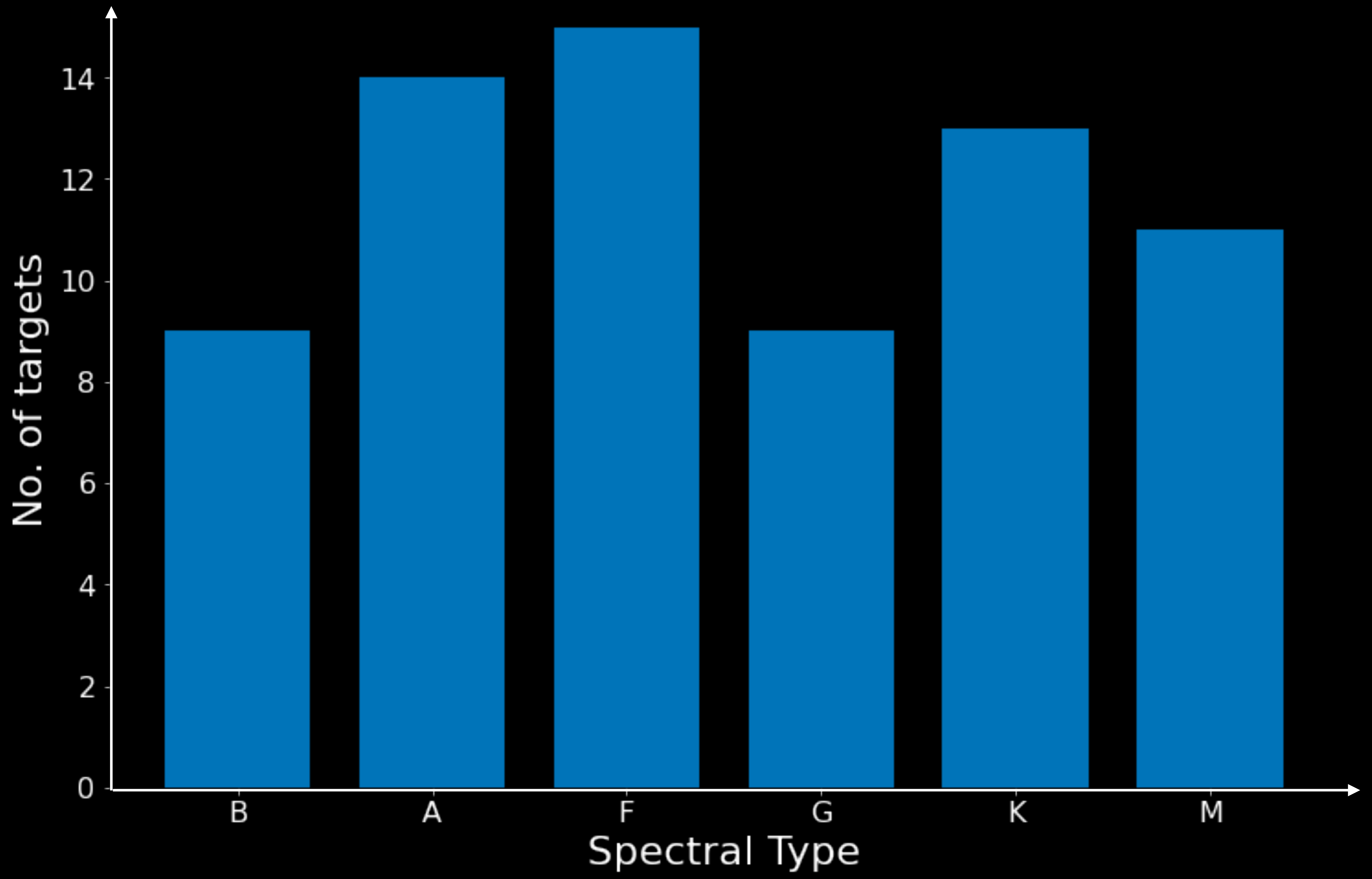
1414	Integral Field Spectroscopy of the Benchmark Substellar Companion HD 19467 B		Marshall Perrin	NIRSpec

What about the host stars?

Our goal is to perform atmospheric characterization of the host stars!

We aim to measure the abundances of 15 elements (**C**, **O**, Na, Mg, Si, S, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Zn, Y)

How many targets do we have?



69 directly imaged companion host stars!

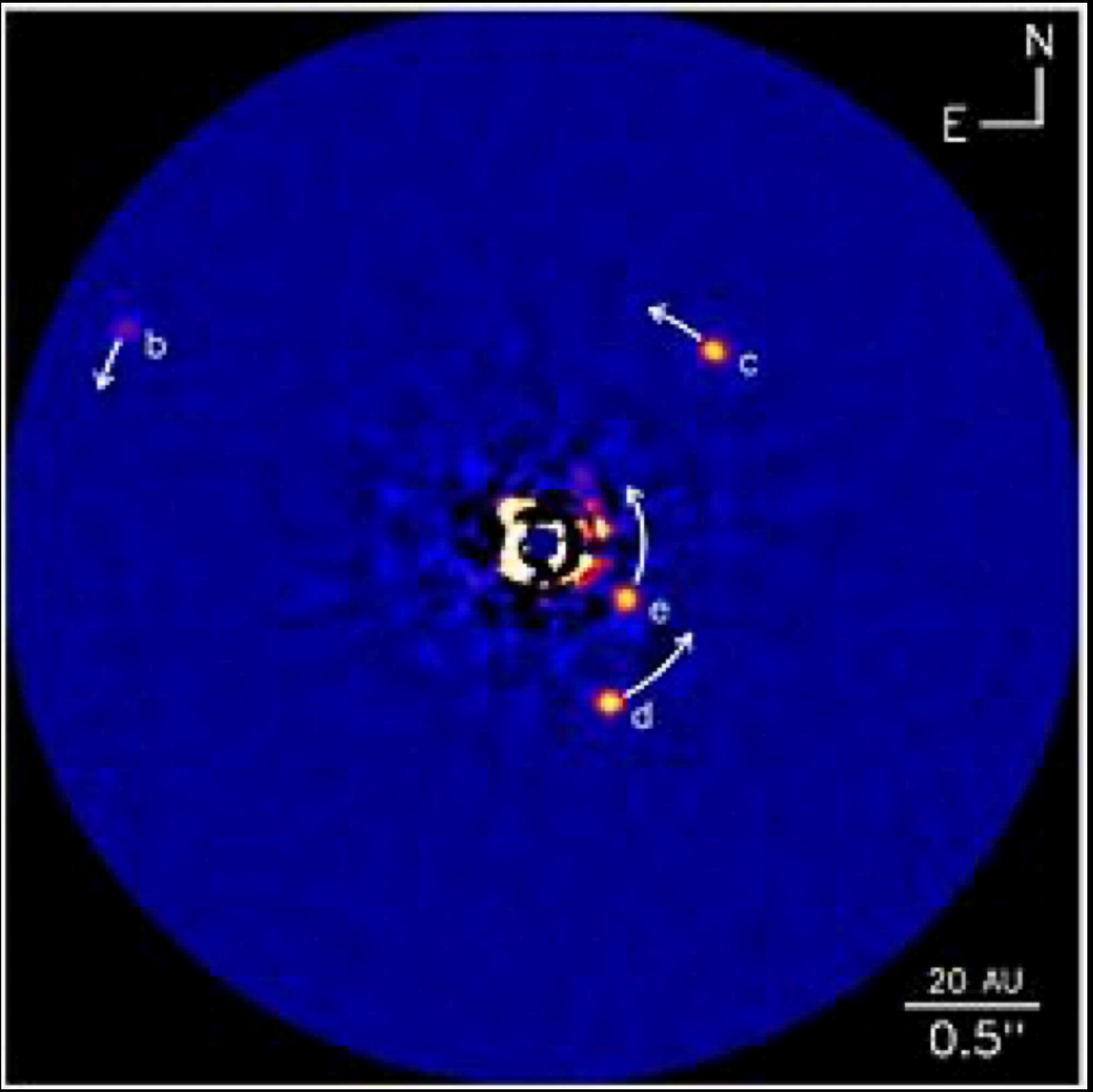
Levy spectrograph at APF

$\lambda \sim 374$–900nm

R~120,000

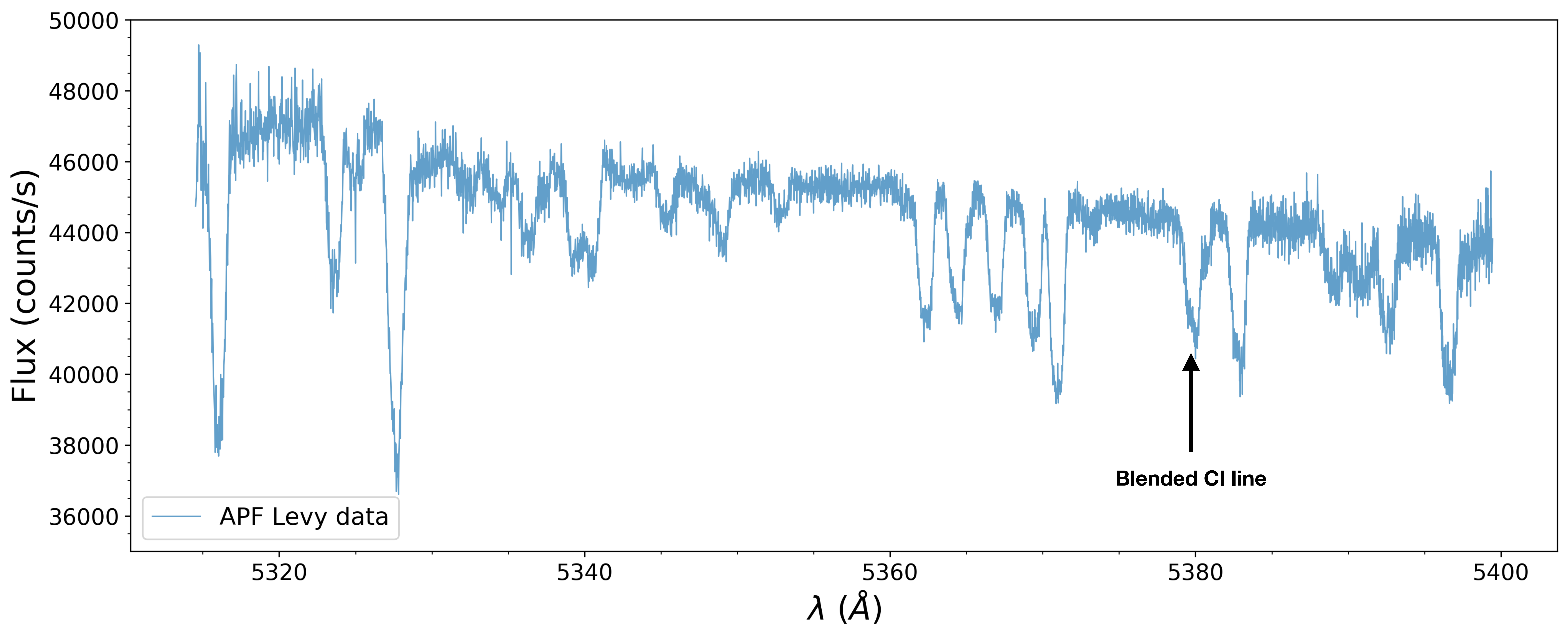
Image Credit: Laurie Hatch; https://lauriehatch.com

Directly Imaged System: HR 8799



Adapted from Marois et al. (2010)

Reduced Spectra HR 8799



HR 8799 Levy data for a single spectral order

Forward Modeling

Two part analysis:

Find the basic stellar parameters like effective temperature ($T_{\rm eff}$), surface gravity ($\log g$) and metallicity ($[M/H]$) by fitting PHOENIX models

→

Custom PHOENIX grid with fixed $[M/H]$, small range of $T_{\rm eff}$, $\log g$ and varying carbon (C) and oxygen (O) abundances used to determine abundance values

Forward Modeling: HR 8799

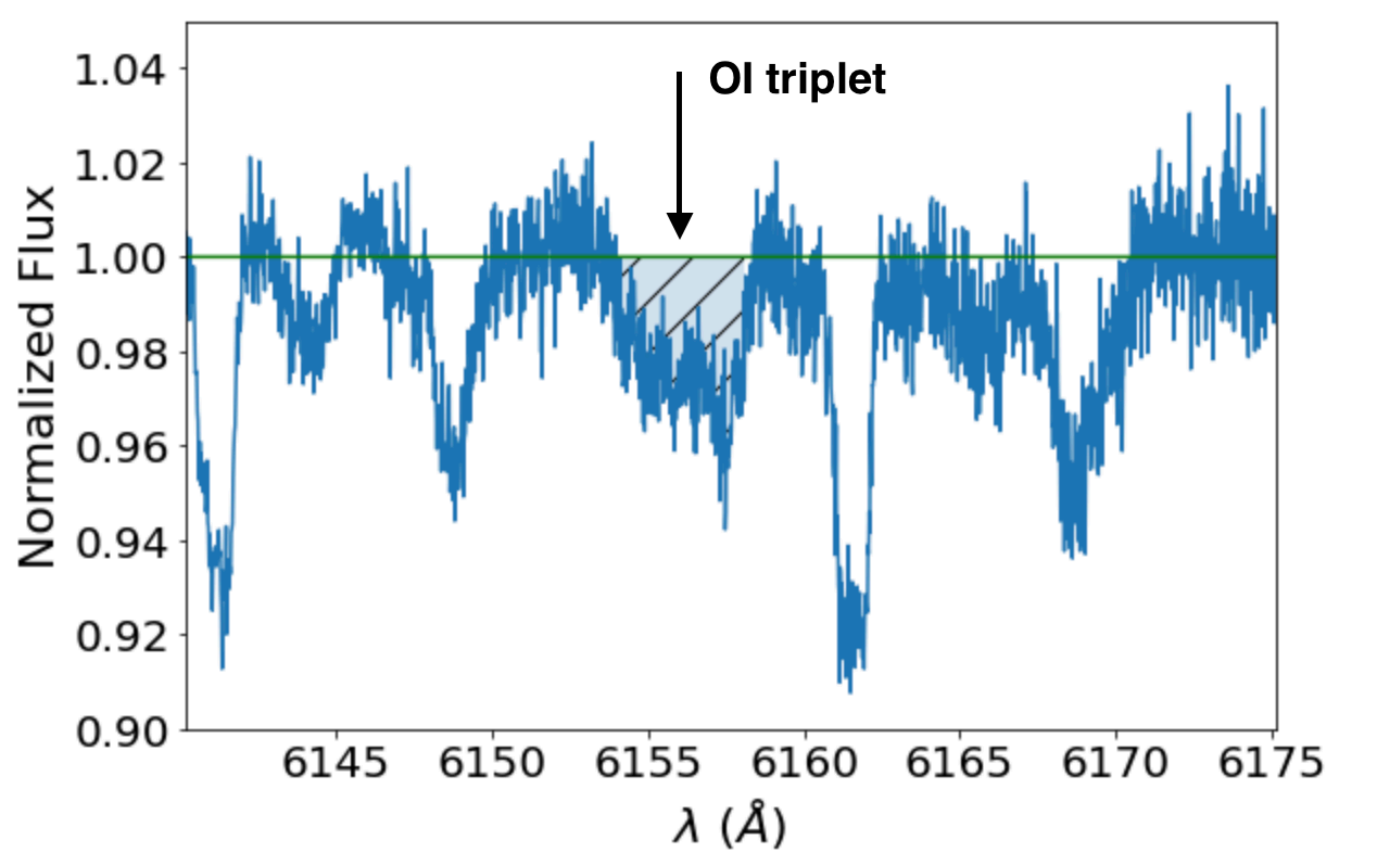
[C/H] = 0.11 ± 0.02, [O/H] = 0.15 ± 0.10

Equivalent width: HR 8799

Abundances obtained from measured equivalent widths using the non-LTE spectral analysis software MOOG (Sneden 1973)

[C/H] = 0.04 ± 0.16

[O/H] = 0.18 ± 0.16

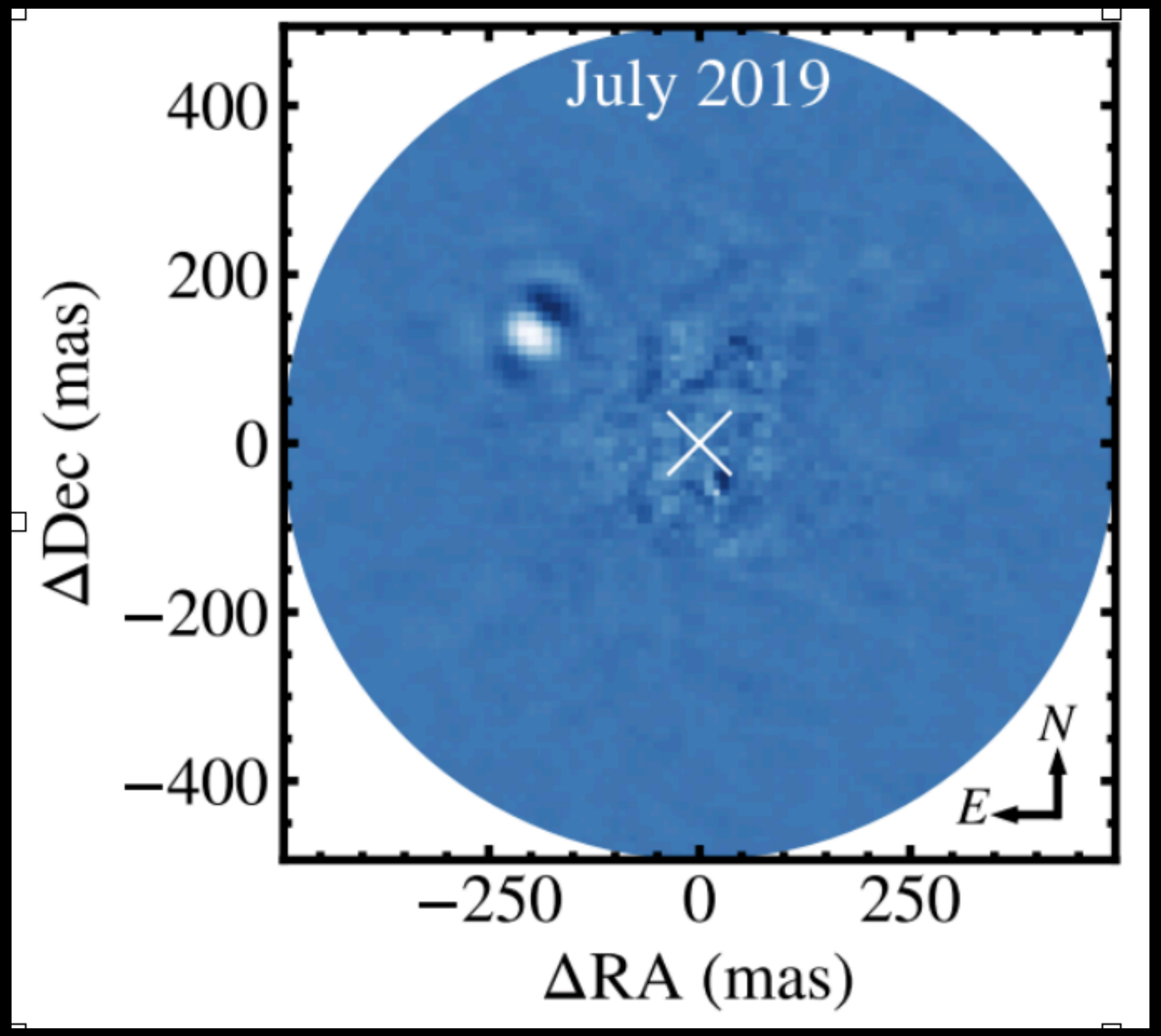


How do the C/O by the two methods compare?

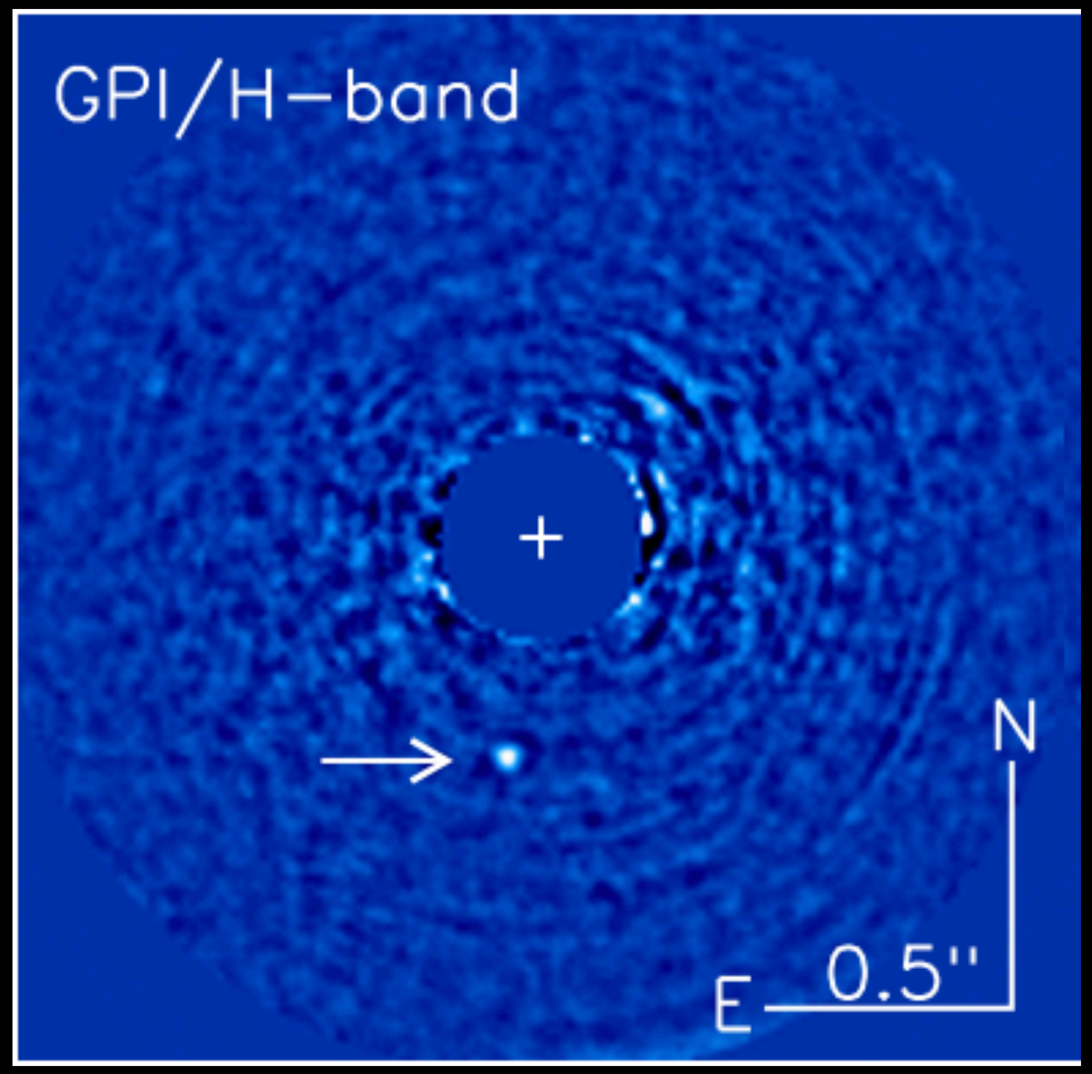
	[C/H]	[O/H]	C/O
Forward Modeling	0.11 ± 0.02	0.15 ± 0.10	0.50 ± 0.11
Equivalent Width	0.04 ± 0.16	0.18 ± 0.16	0.40 ± 0.15

Solar C/O ~ 0.55

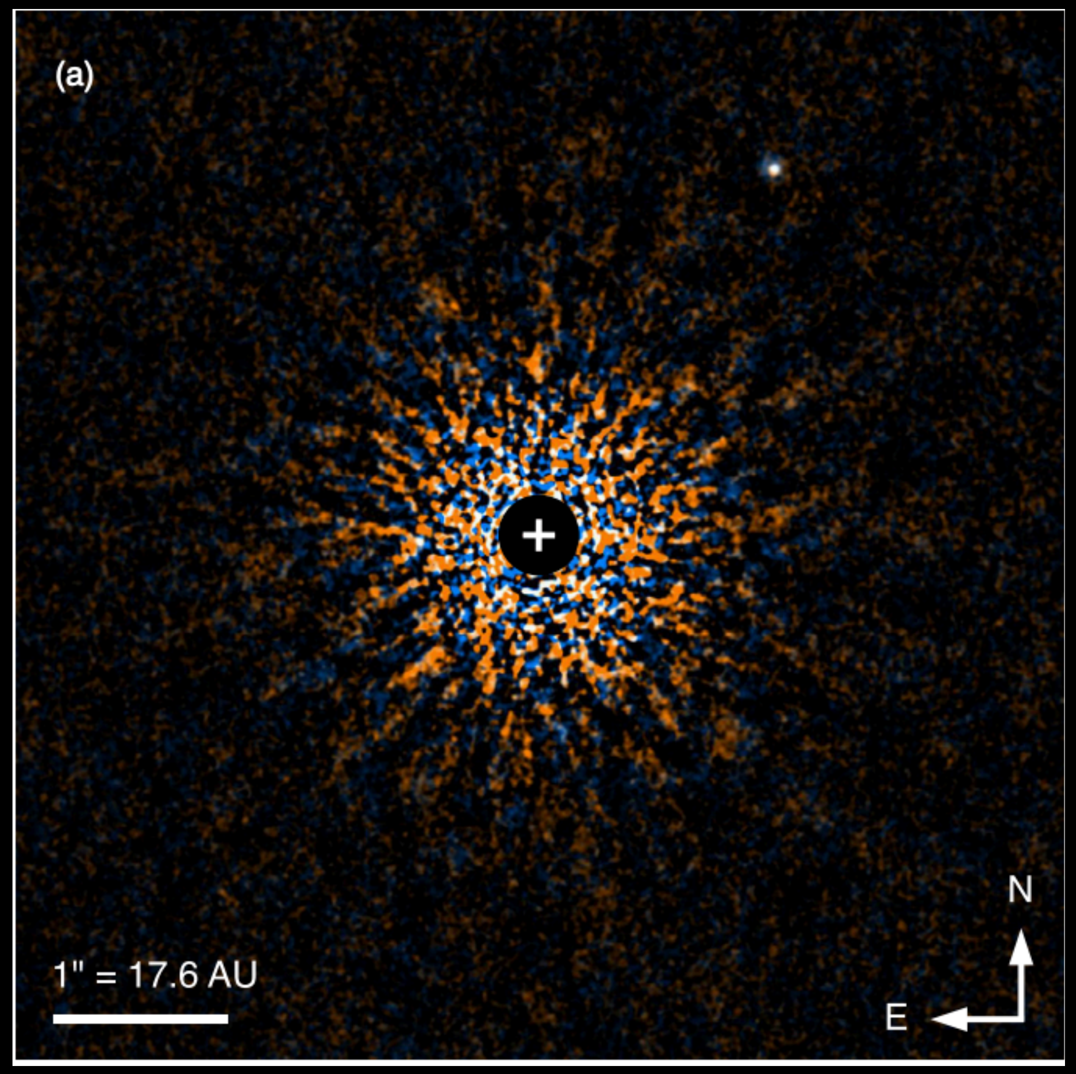
What other targets have we measured?



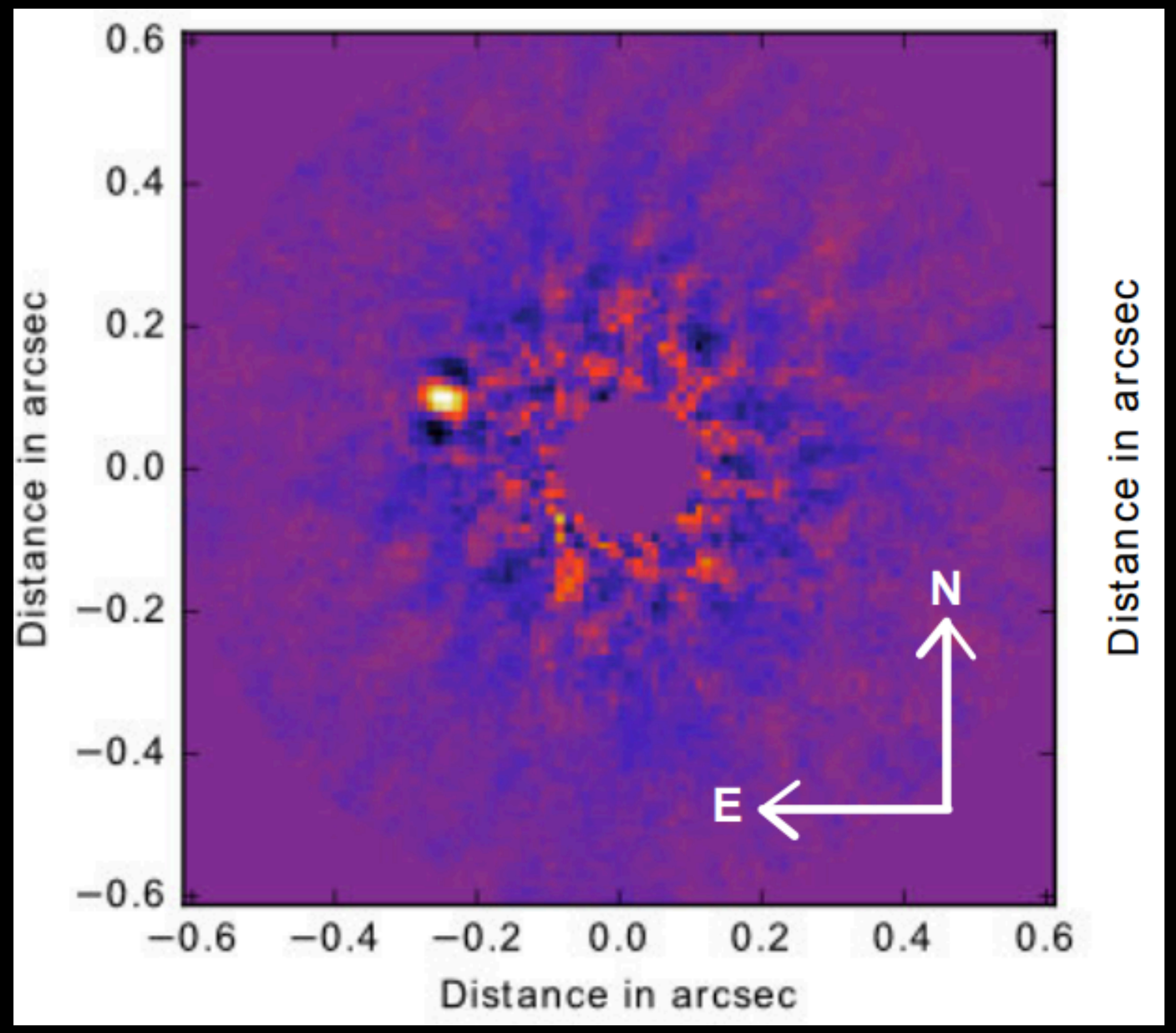
HD 984



51 Eri



GJ 504

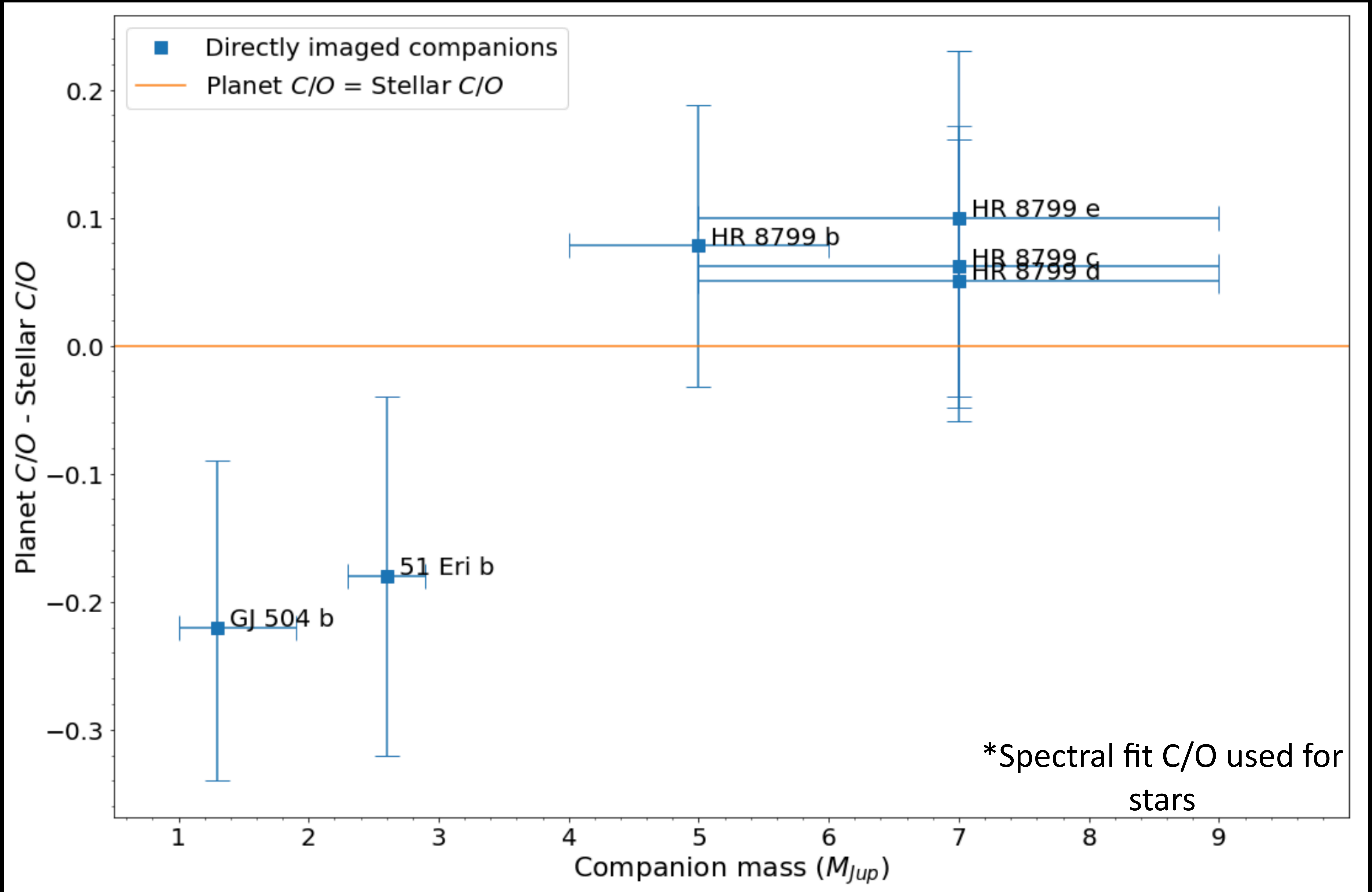


HD 206893

HD 206893 has a **super-solar C/O** (**0.71 ± 0.12**), while the other three targets have a **solar C/O** ratio ($\sim$**0.55**) within 1σ.

Adapted from Franson et al. (2022), Macintosh et al. (2015), Kuzuhara et al. (2013), and Milli et al. (2017) respectively.

How do planet and stellar C/O compare?

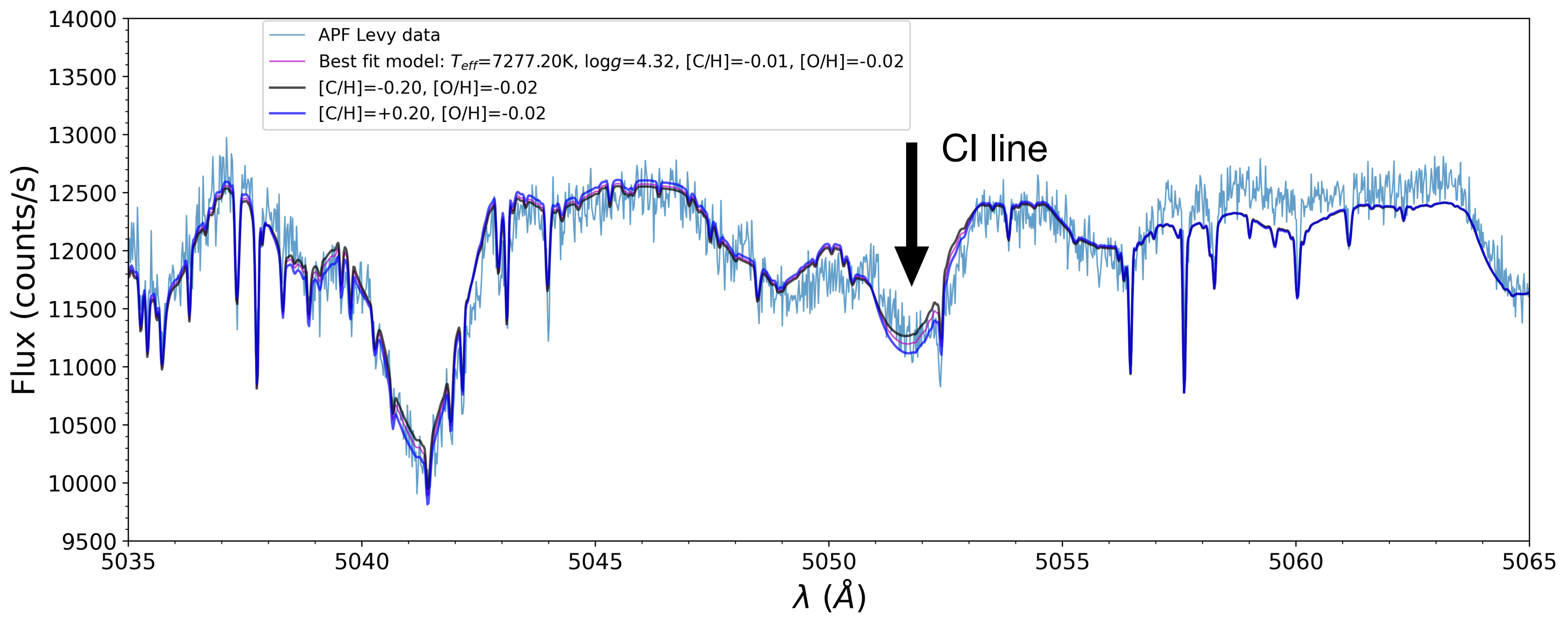


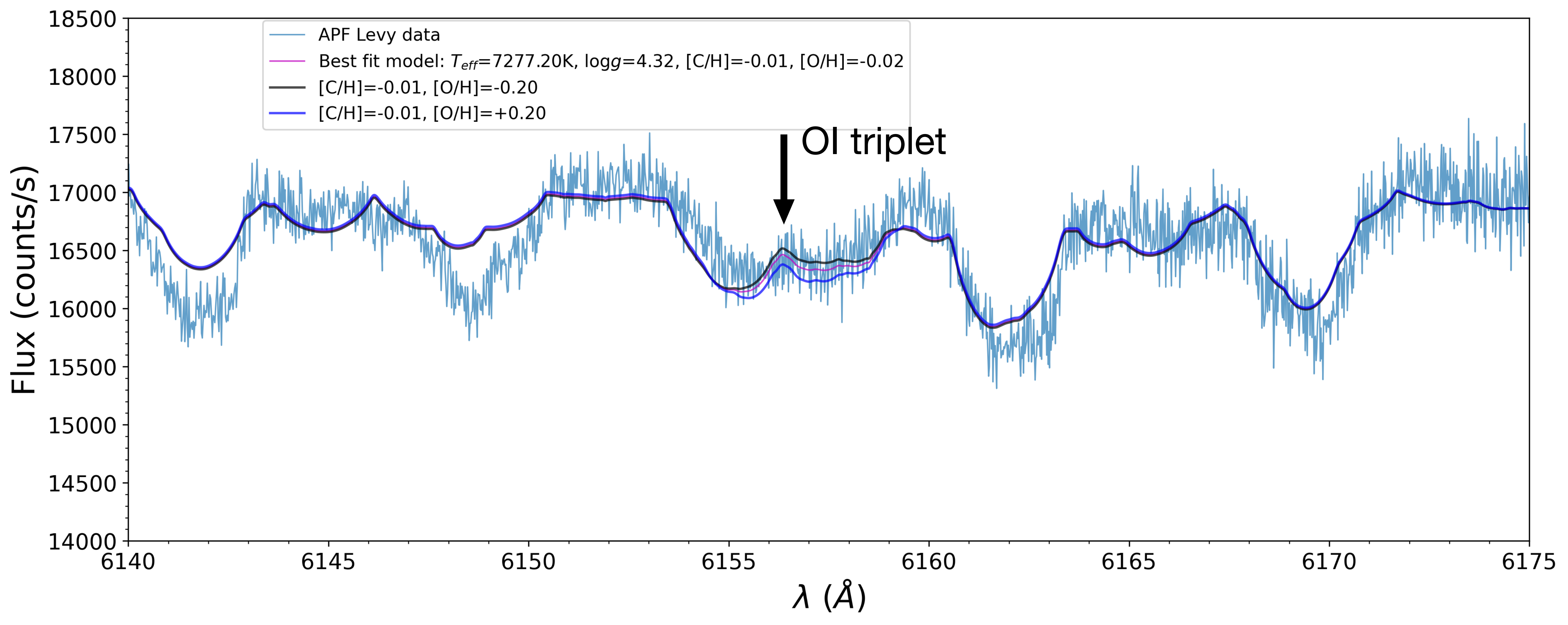
What are the next steps?

- Abundance measurements of host stars with companions that are part of ongoing JWST programs/proposals.
- Comparison of stellar and planetary C/O ratios as further planet C/O are measured and current uncertainties are improved.
- Expand host star analysis to remaining targets, including K/M spectral types
- Investigate possible trends between host star abundances and planet occurrence

Takeaways

- Testing predictions regarding formation, require abundance measurements for the planet as well as the host star
- Both forward modeling and equivalent width methods yield similar abundances: within 2σ, all five host stars have solar C/O
- Need to improve error margins on stellar and planetary C/O measurements in order to have conclusive arguments regarding formation/evolution histories





51 Eri

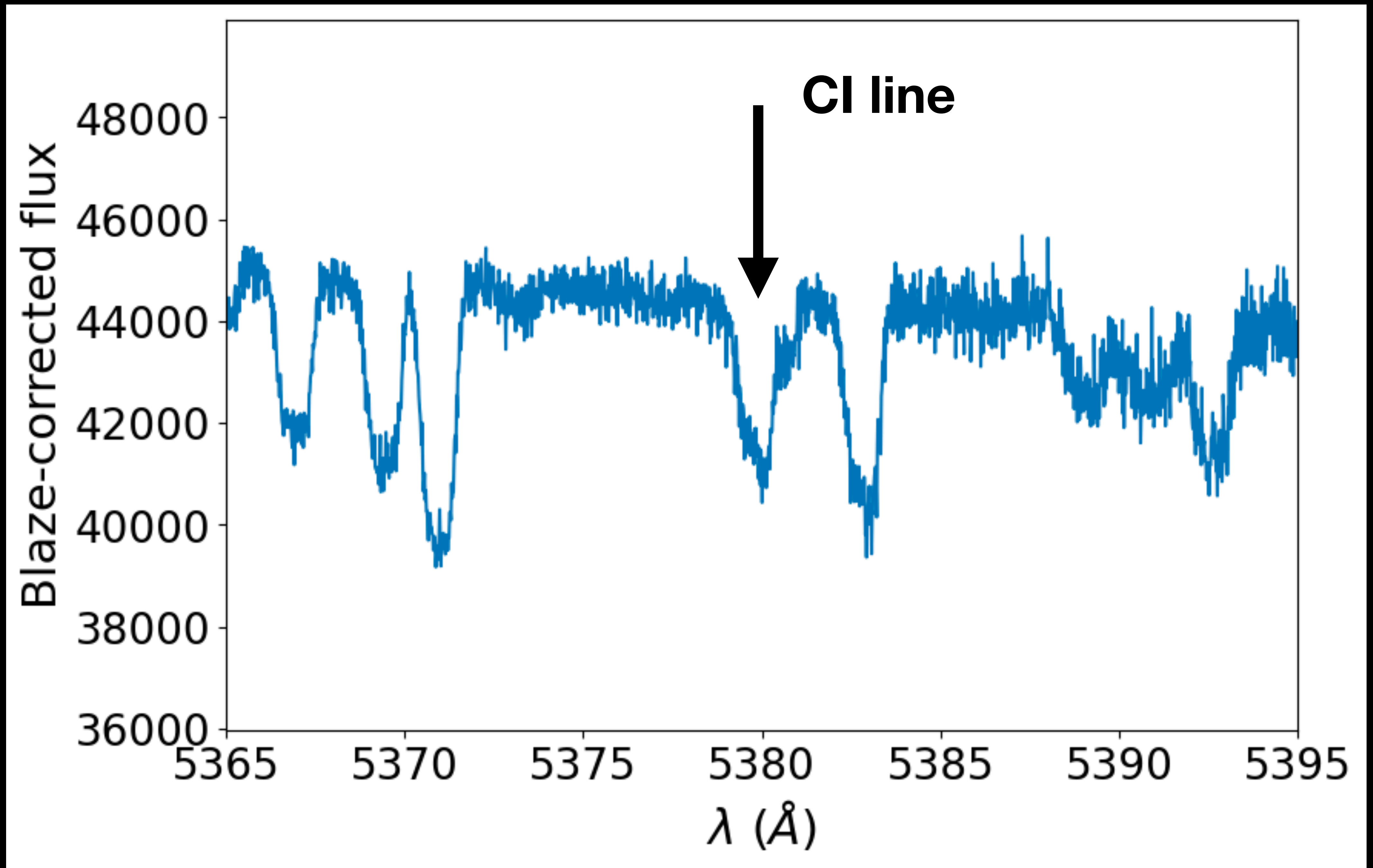
[C/H] = -0.01 ± 0.07

[O/H] = -0.02 ± 0.09

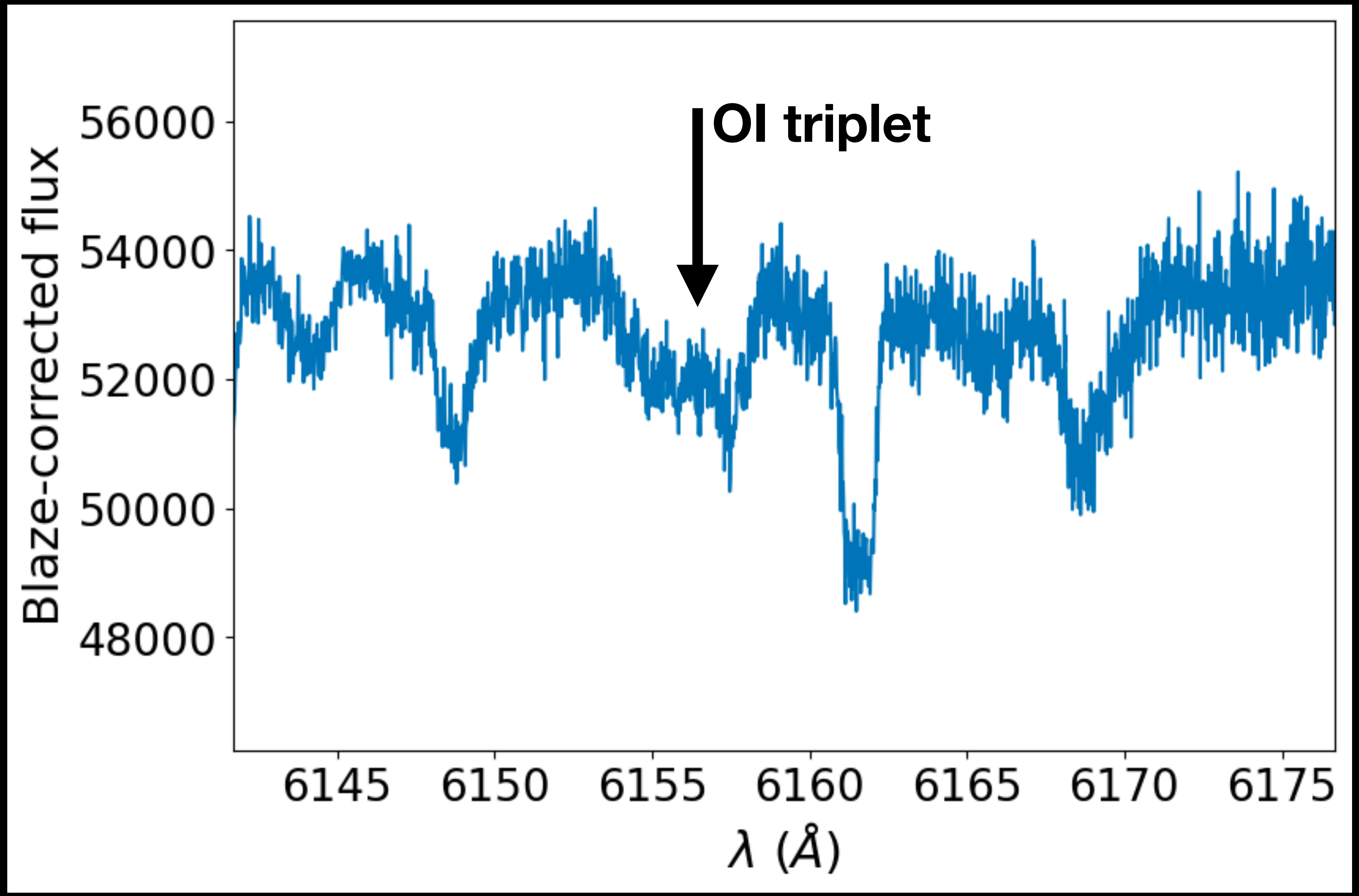
C/O = 0.56 ± 0.11

Spectral lines: C and O

- Carbon lines include CI line at 4772, 4930, 5052, 5380 and 6587 Å.

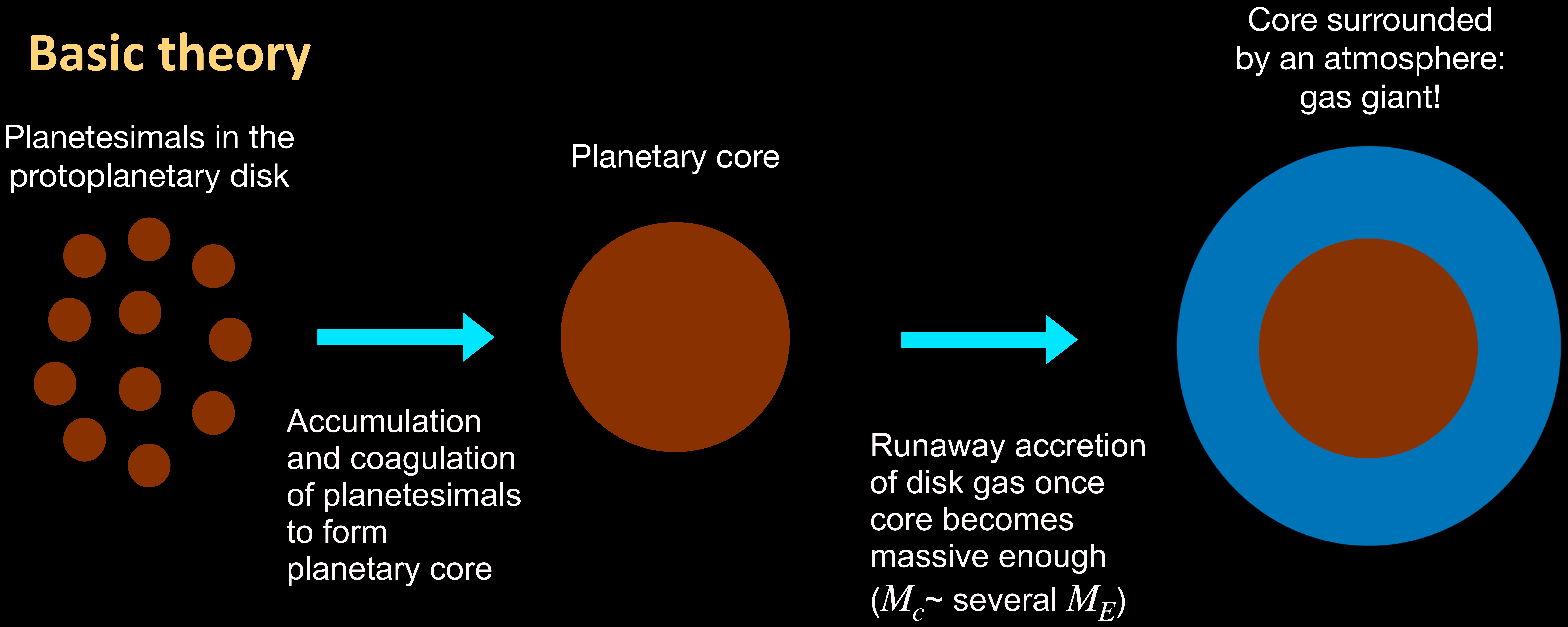


- Oxygen lines include a forbidden OI line at 6300Å, an OI triplet at 6155-6158 and an OI triplet at 7771-7775Å



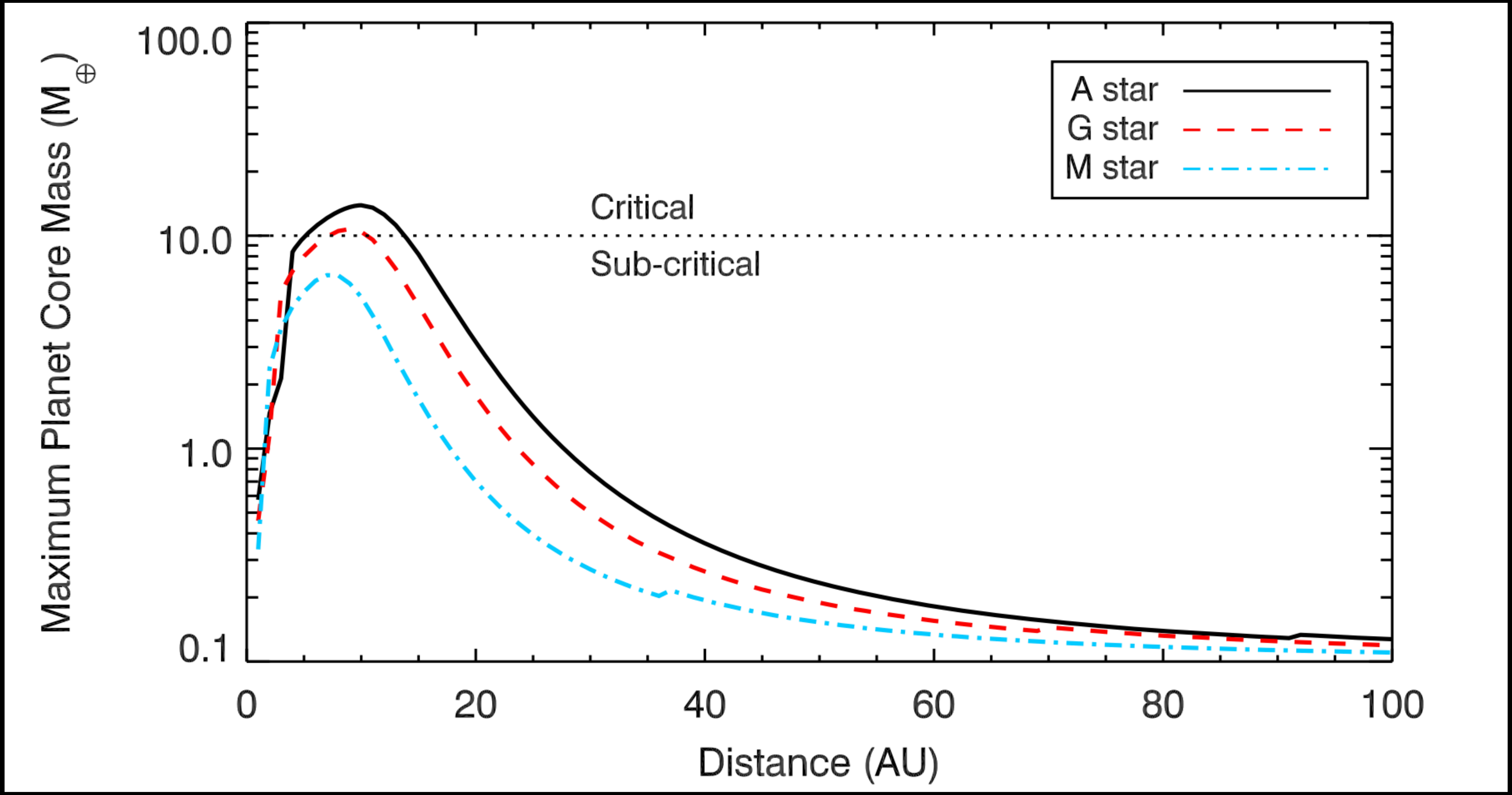
Planet formation - Core accretion

Basic theory



Planet formation - Core accretion

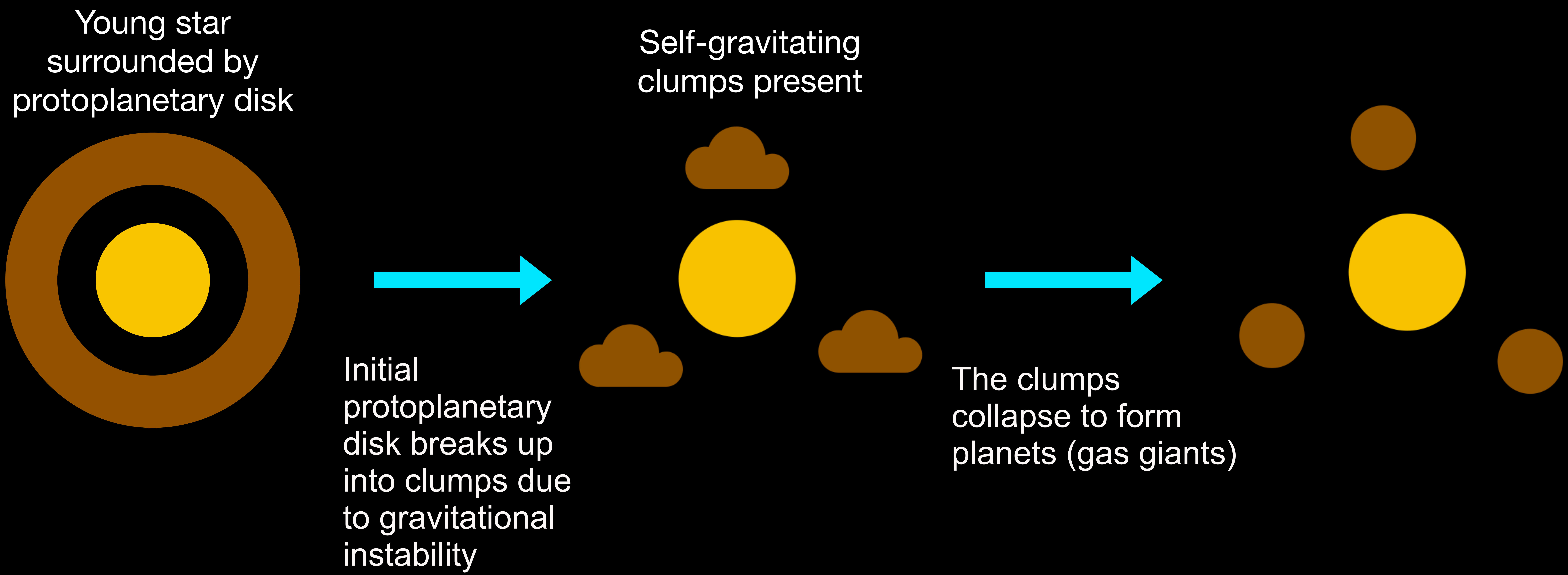
Why doesn't it work?



Maximum planetary core mass with distance
(Dodson-Robinson et al. 2009)

Planet formation - Gravitational instability

Basic theory



Planet formation - Gravitational instability

Why doesn't it work?

- This mechanism cannot explain the formation of Jupiter-sized planets closer than 40 AU (Dodson-Robinson et al. 2009)
- Self-gravitating clumps are more likely to evolve into brown dwarfs or low-mass stars (Kratter et al. 2010), but no such population has been found yet (Nielsen et al. 2019).
- Fragments are susceptible to tidal disruptions and shearing (Mejia et al. 2005, Helled & Bodenheimer 2011).

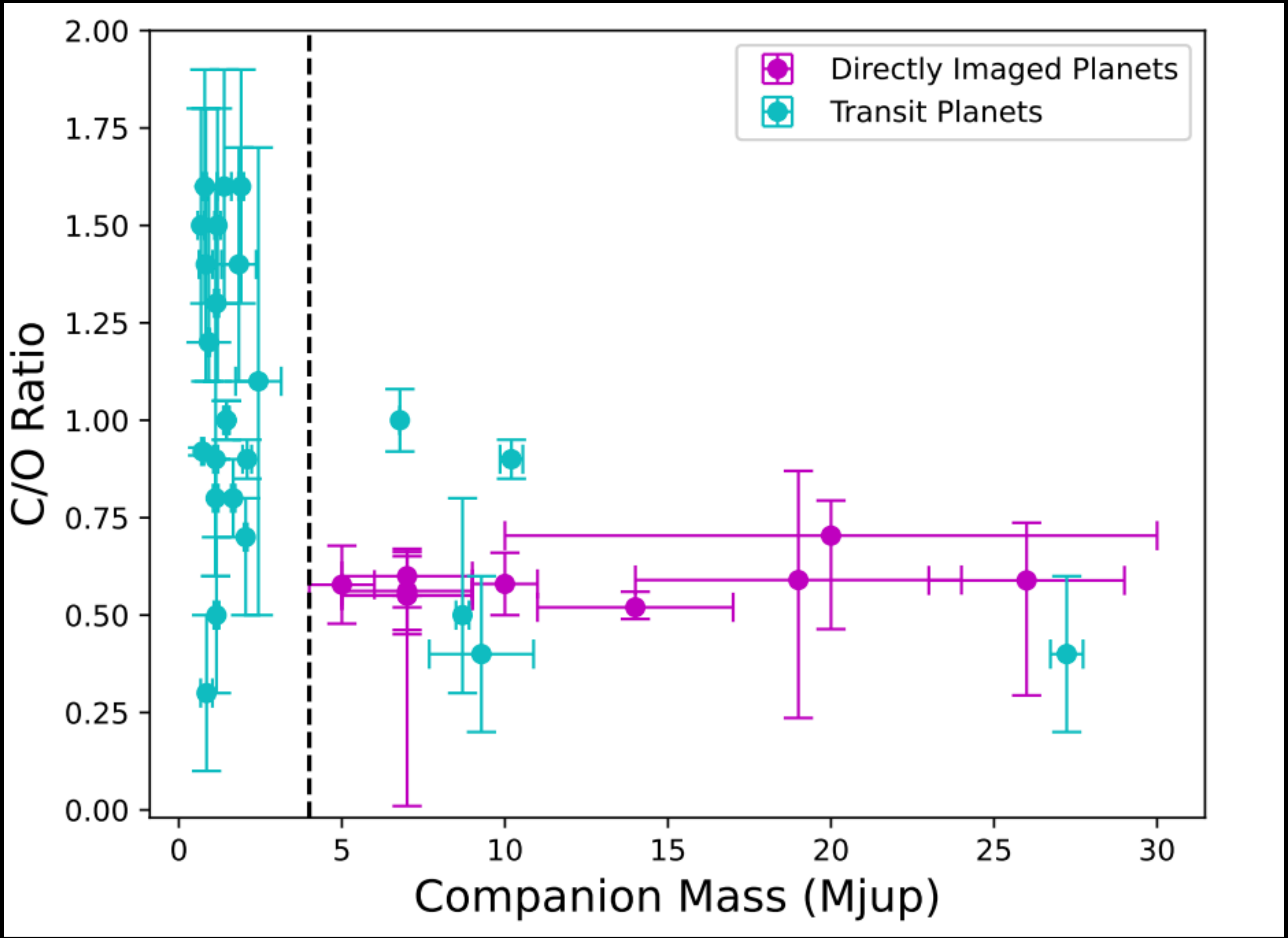


Figure from Hoch et al. (2023)

Spectral Template Fitting

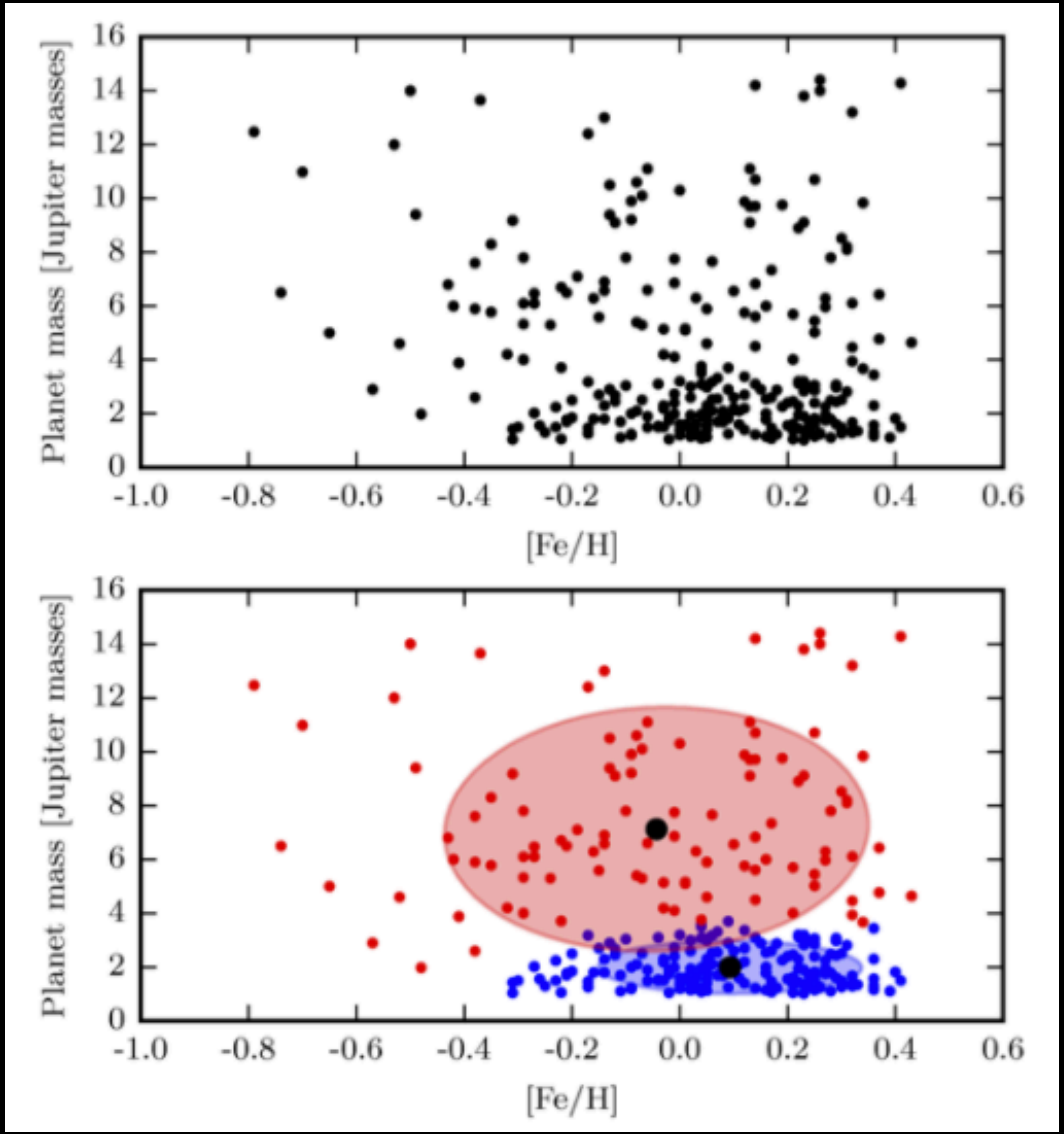
Forward Modeling procedure

Forward modeling code uses PHOENIX and telluric (PSG) models to get best-fit spectral model

Residuals of best-fit model and data calculated

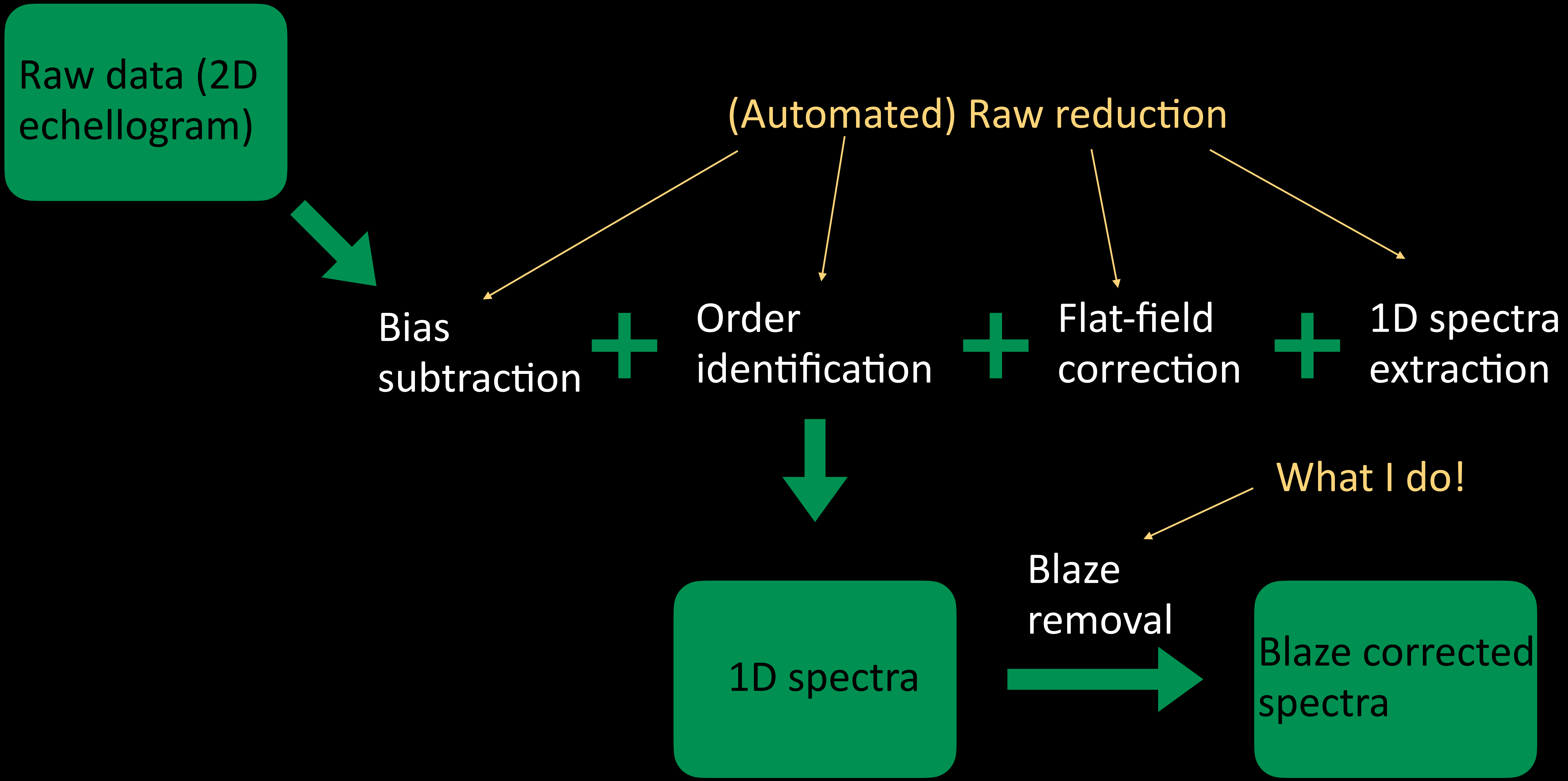
Residuals and data noise compared to apply 3σ mask to data

Forward modeling run on masked data to get best-fit value and uncertainties for all parameters

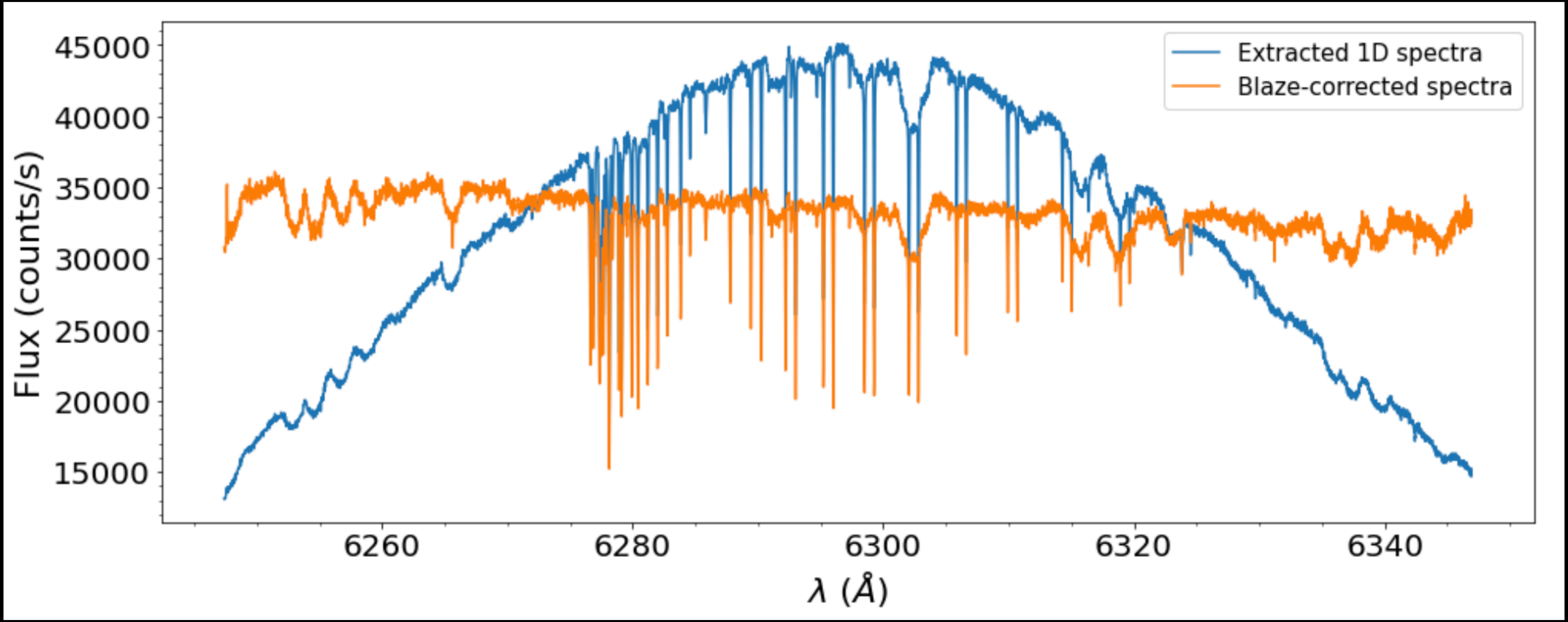


(Figure from Santos et al. 2017)

Data Reduction



Data Reduction



Spectral Template Fitting

Forward Modeling procedure: C/O

Forward modeling code uses custom PHOENIX (varying C, O) and PSG models to get best-fit spectral model

→

Residuals of best-fit model and data calculated

↓

Residuals and data noise compared to apply 3σ mask to data

←

Forward modeling run on masked data to get best-fit value and uncertainties for C and O abundances

Echelle order

- The light entering the spectrograph is passed through a echelle grating that diffracts the light.
- For a certain wavelength of light, depending upon which order maxima overlaps, echelle orders are defined.

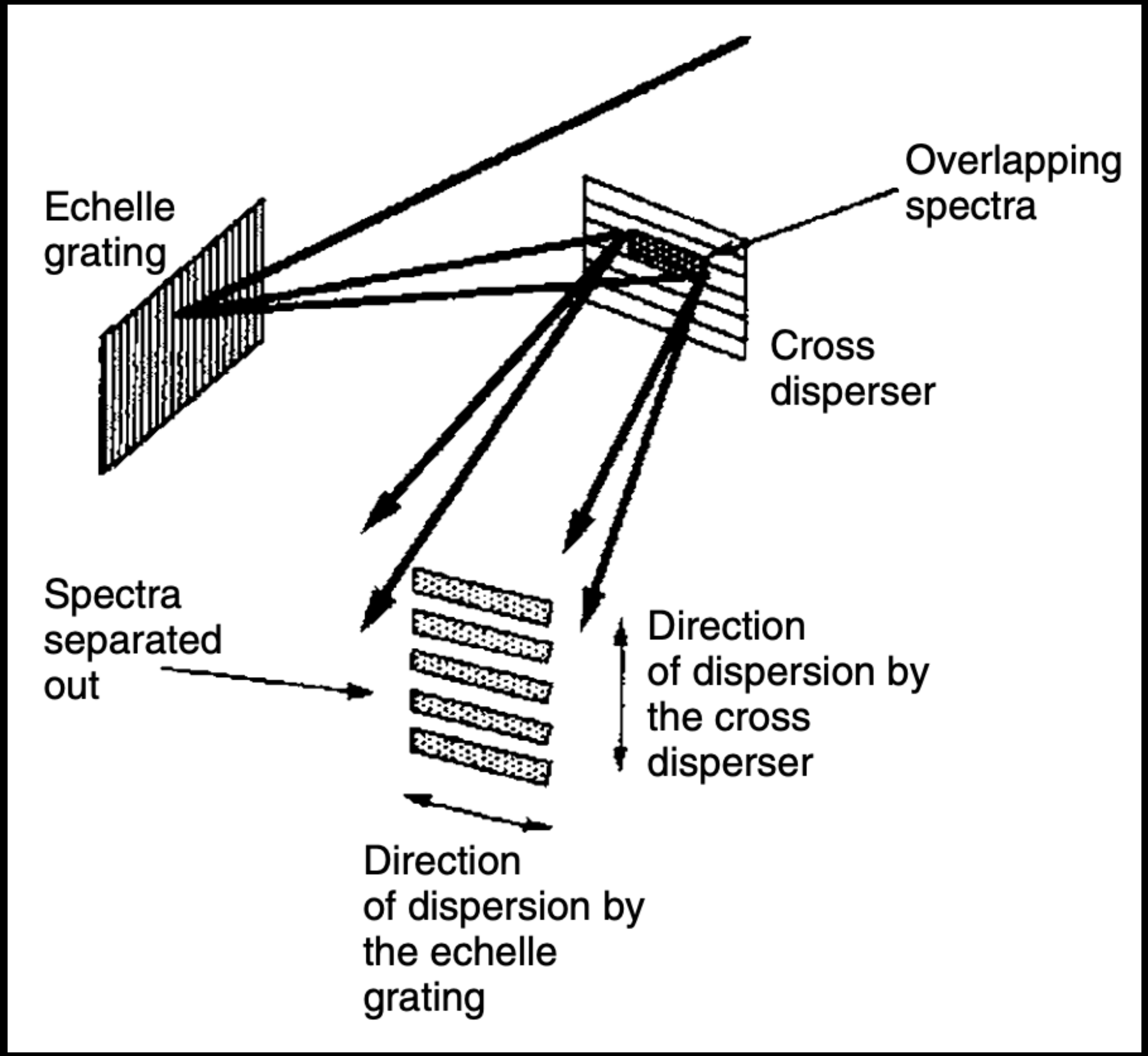


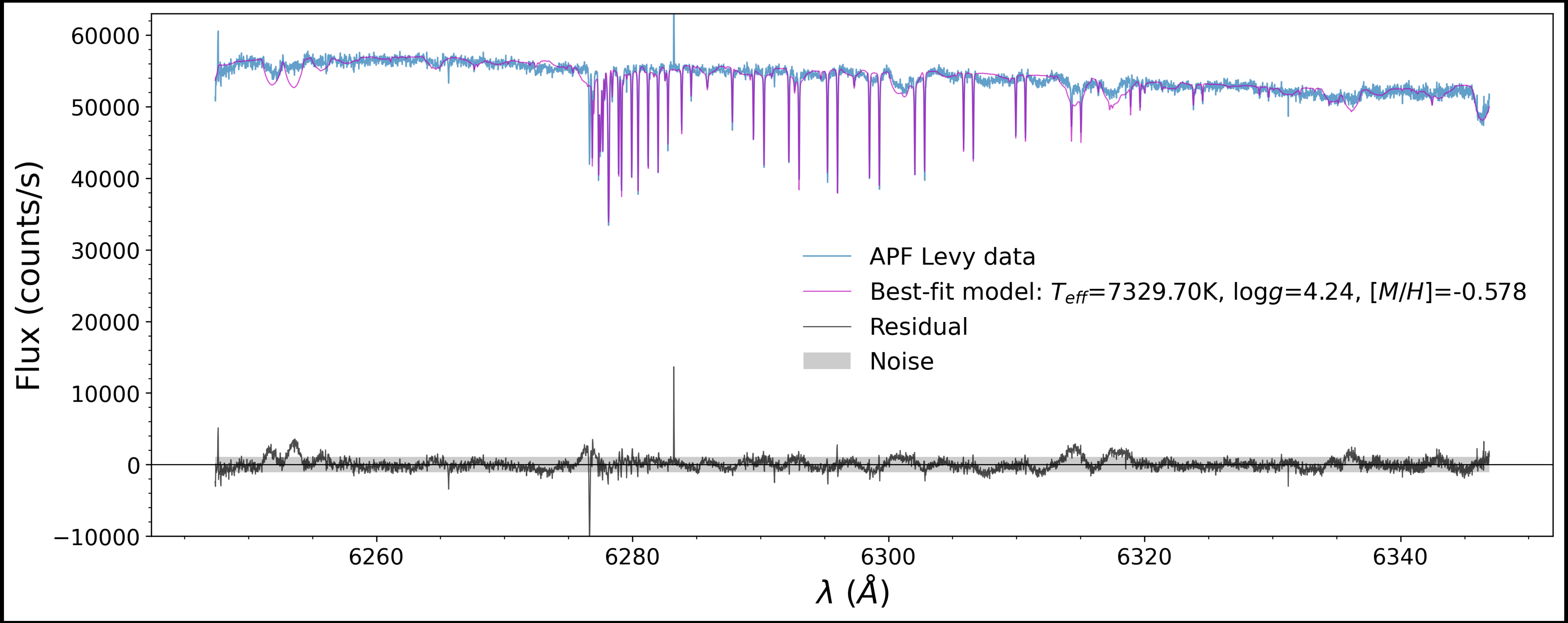
Image Credit: HOWELL, STEVE & Tavackolimehr, Ali. (2019). Handbook of CCD Astronomy.

Spectral Template Fitting

Telluric models

- Telluric spectra are generated using the Planetary Spectrum Generator (PSG) software by NASA.
- The tool is used to access a database of 20 pre-computed telluric transmittances at 5 different altitudes and 4 different atmospheric water vapor levels (precipitable water vapor/pwv).
- Another parameter called telluric alpha (α) also included in the model to strengthen/weaken the telluric lines.

Spectral Fitting



Single order fit for one of the echelle orders (Order# 74) for HR 8799

Equivalent width determination

Basic Premise

- Equivalent width of a spectral line measures the area of the line relative to the continuum level

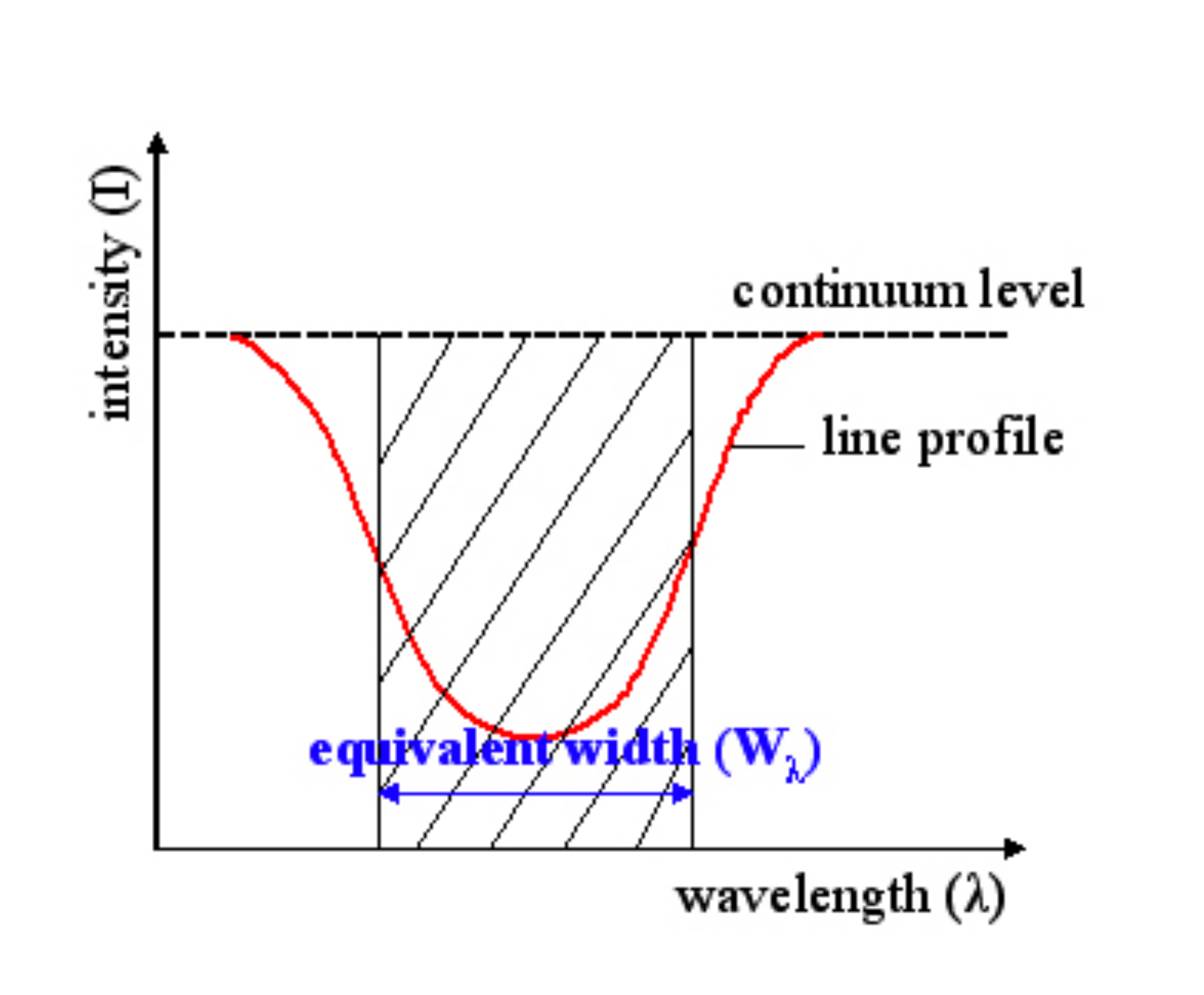


Image Credit: https://en.wikipedia.org/wiki/Equivalent_width