STRONGER TOGETHER:
USING SYNERGIES BETWEEN GROUND-BASED TELESCOPES AND JWST TO UNDERSTAND EXOPLANET ATMOSPHERES

ELT Science in Light of JWST

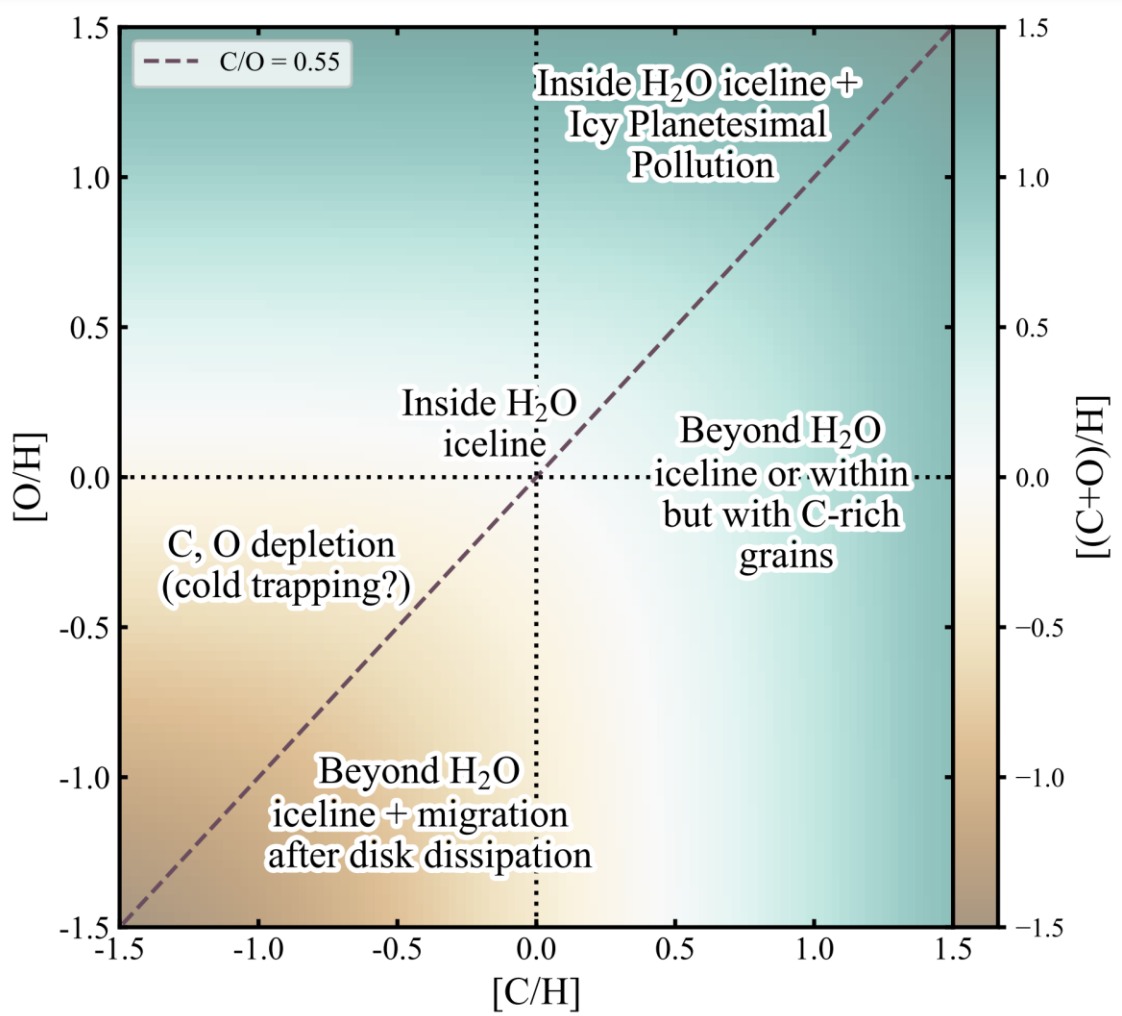
December 11, 2023

Peter Smith, M. Line, M. Brogi, J. Bean, P. August, J. Zalesky

Arizona State University

How do you make a planet?

- Composition measurements help test formation theories



Based on summarized predictions in Reggiani+ 2022

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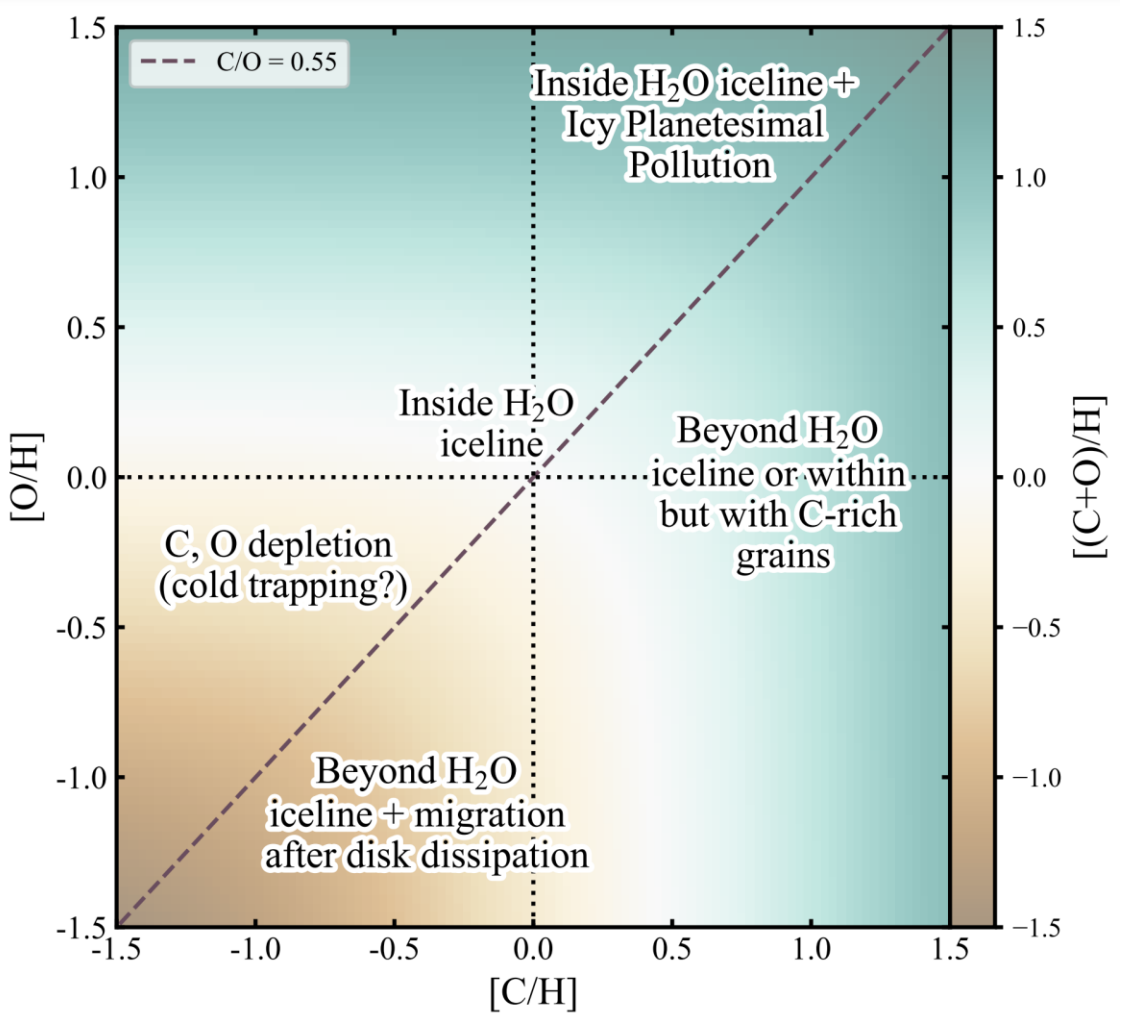
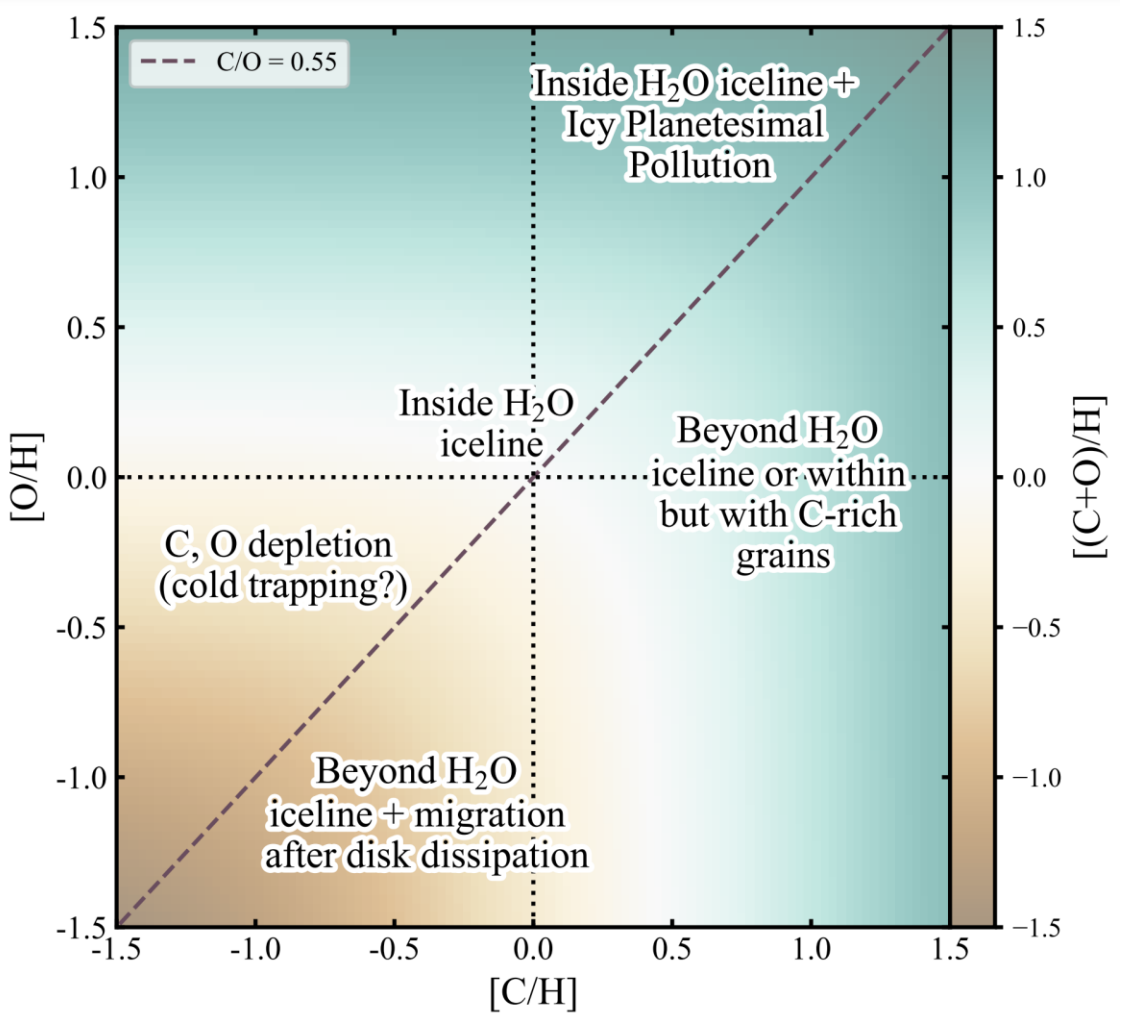
- Major goal of exoplanet science: fill out this plot!→



Based on summarized predictions in Reggiani+ 2022

How do you make a planet?

- Composition measurements help test formation theories
- Major goal of exoplanet science: fill out this plot!→
- This requires good measurements of *both* the carbon and oxygen inventories of exoplanet atmospheres



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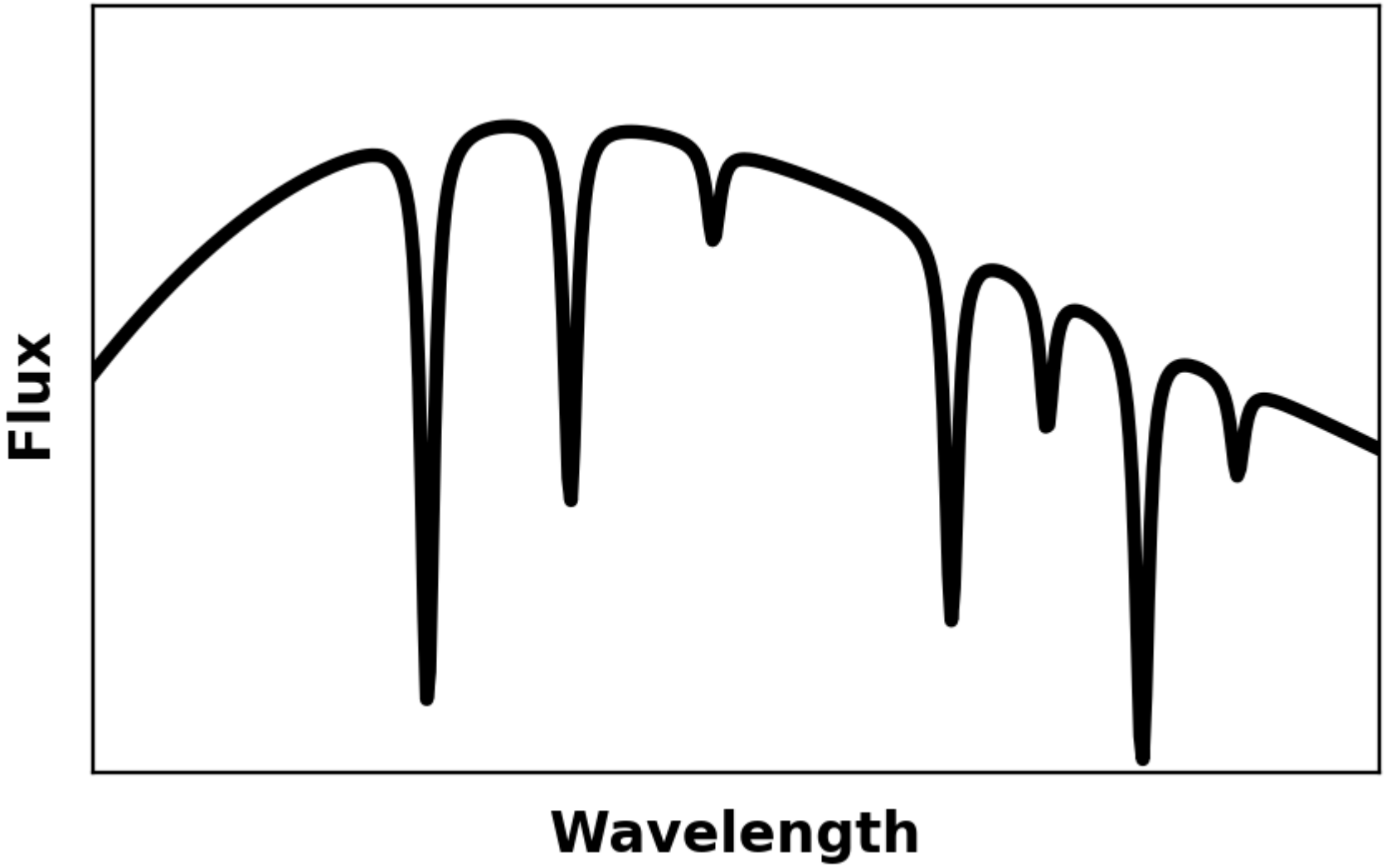
Spectroscopy of Exoplanets



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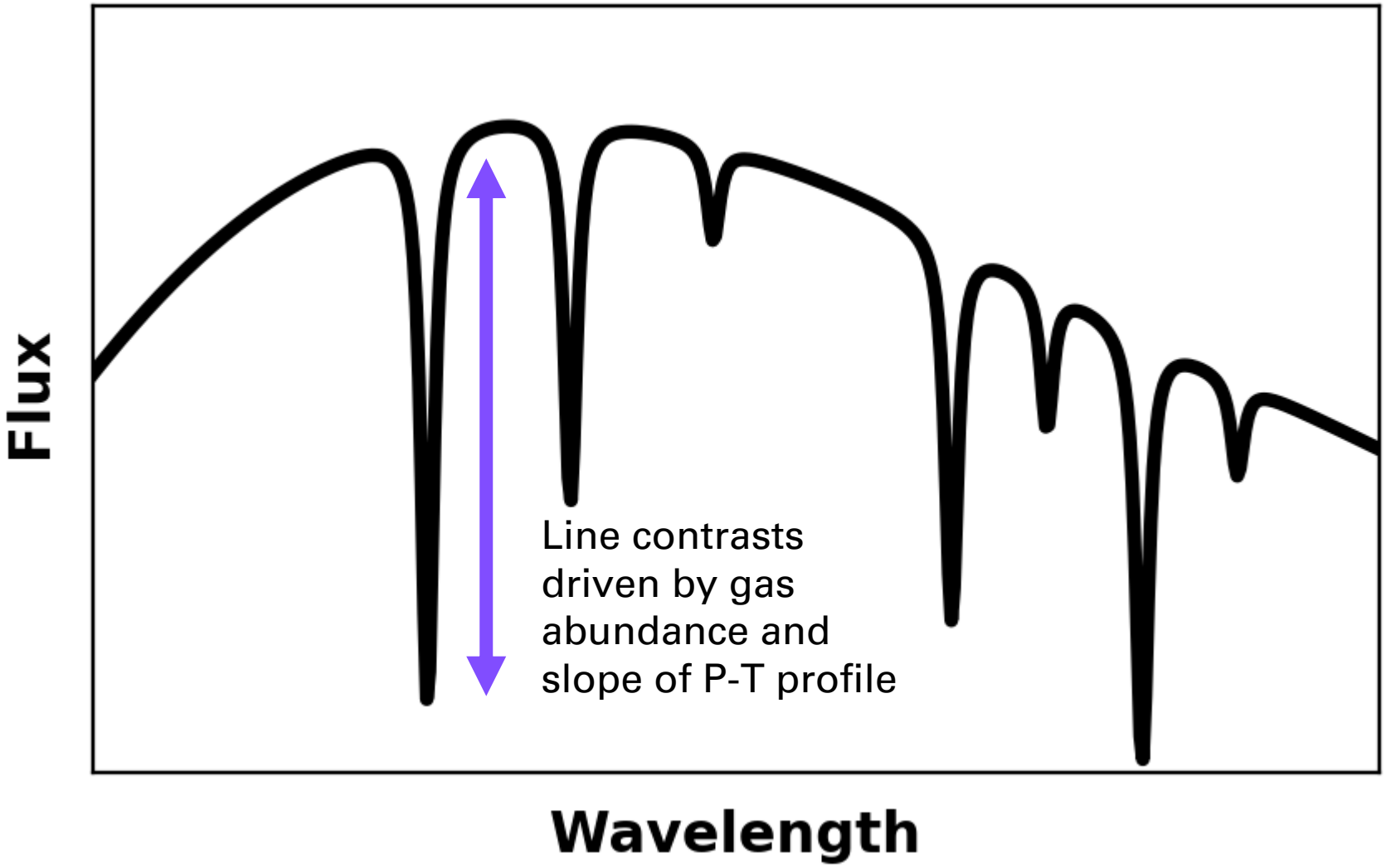

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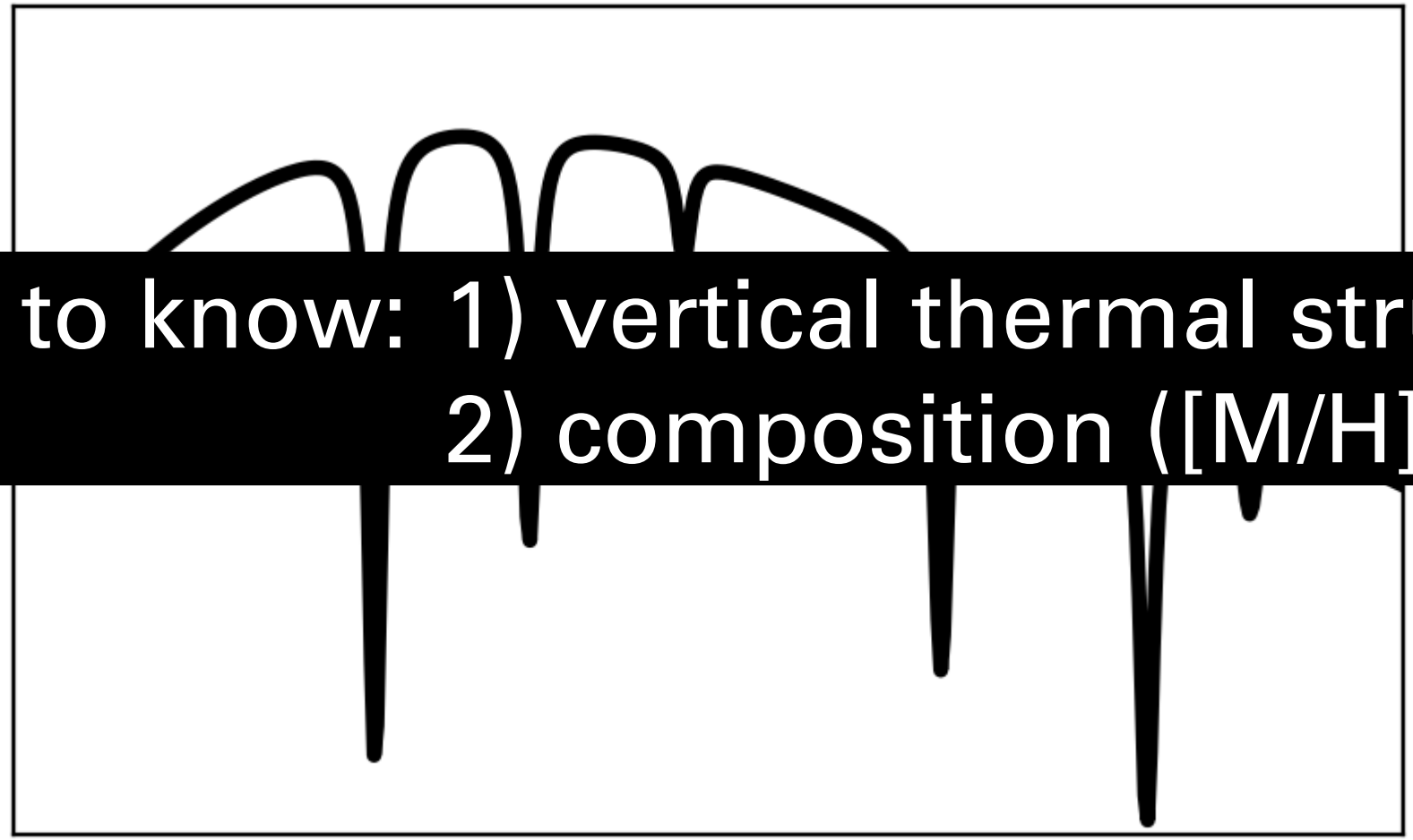
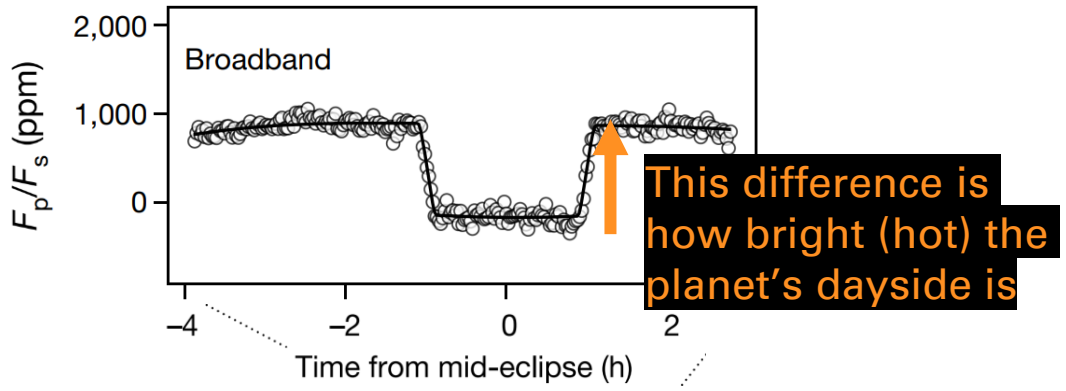


Want to know: 1) vertical thermal structure
2) composition ([M/H])

Low-Resolution Spectroscopy

1) Measure **eclipse depth**



Figures from Coulombe+ 2023

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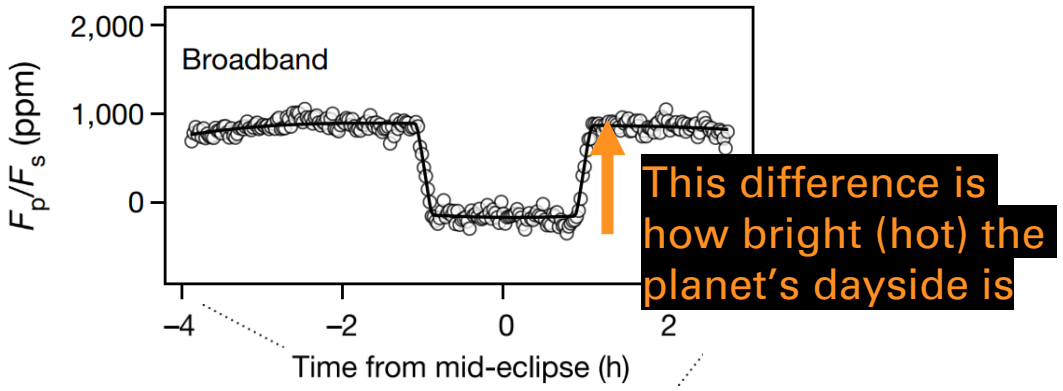
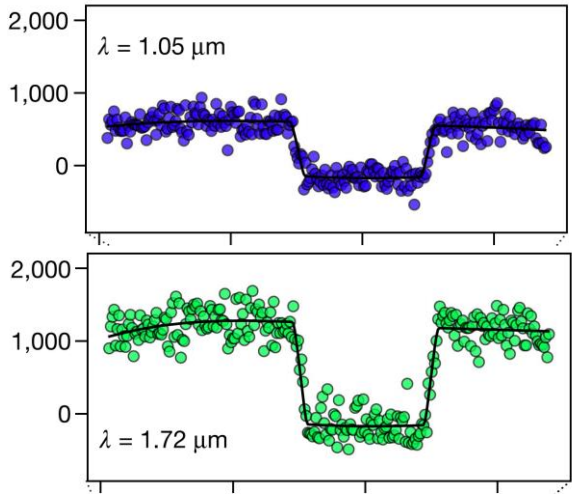


2) Measure eclipse depth in each **wavelength channel**



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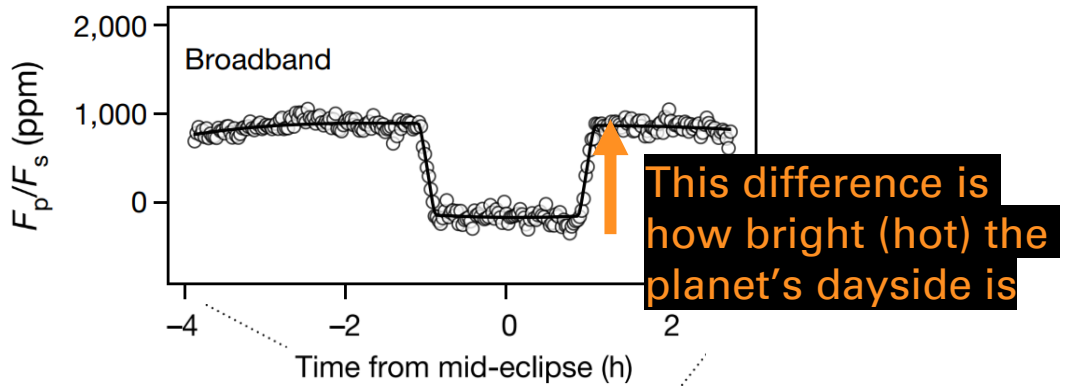

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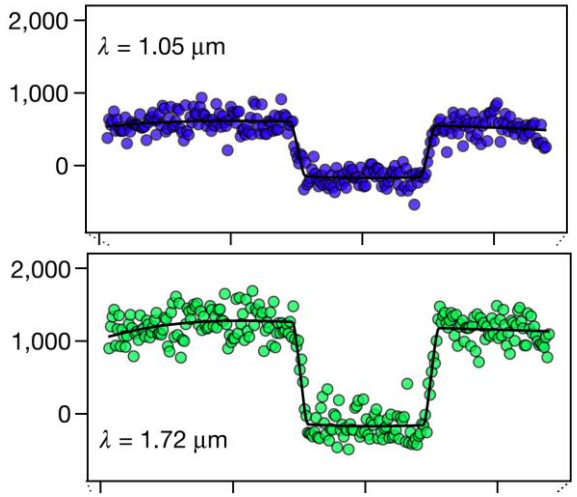
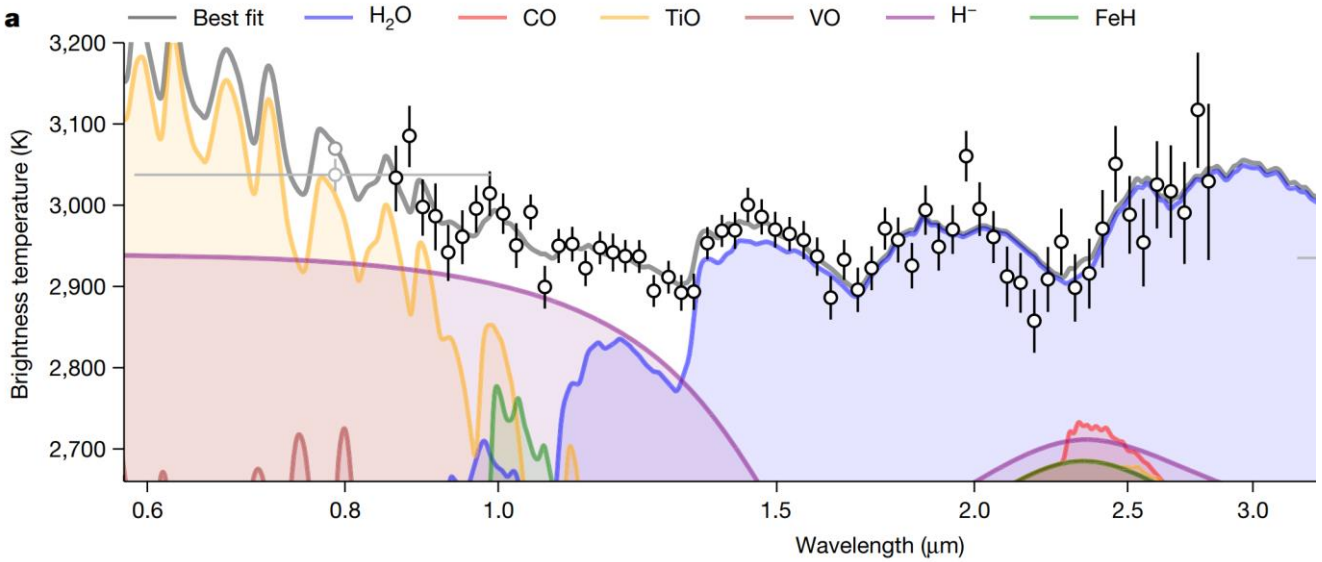


3) Eclipse Depth or Brightness Temperature **Spectrum**



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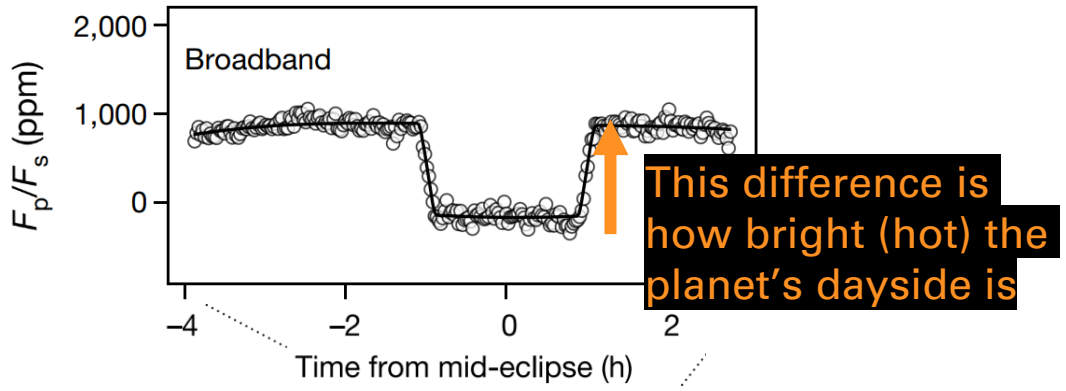

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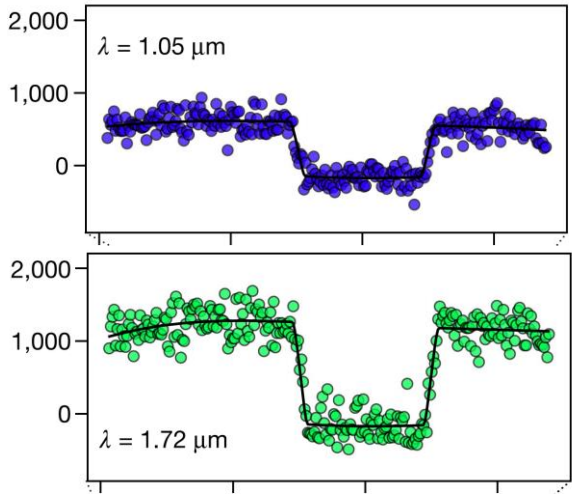

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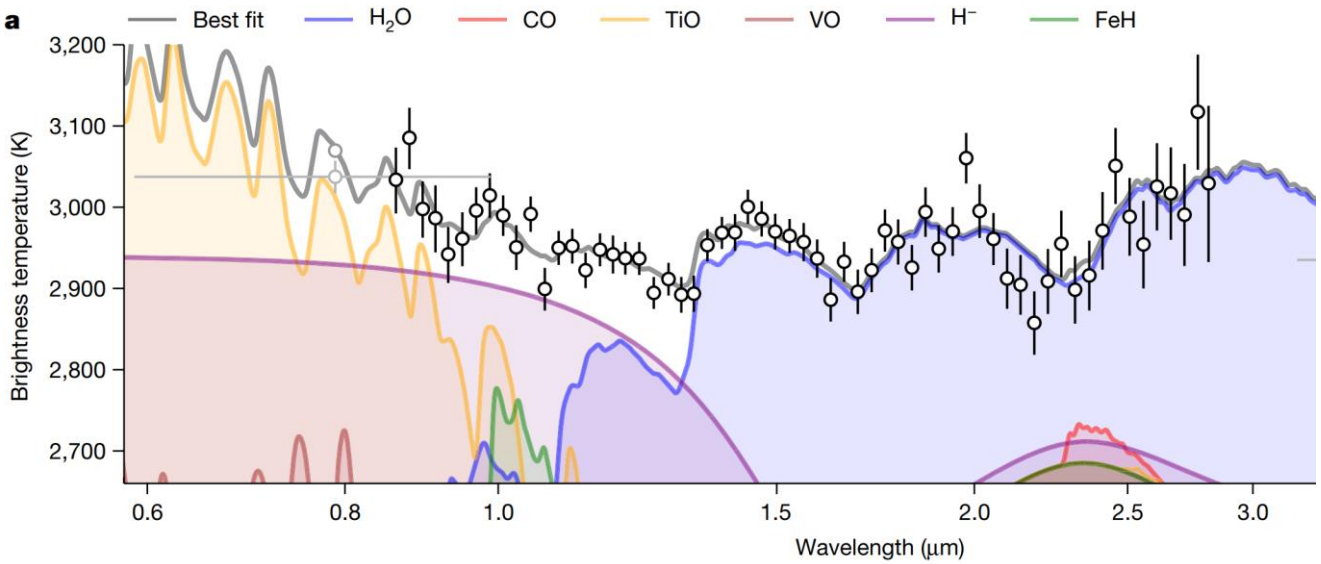
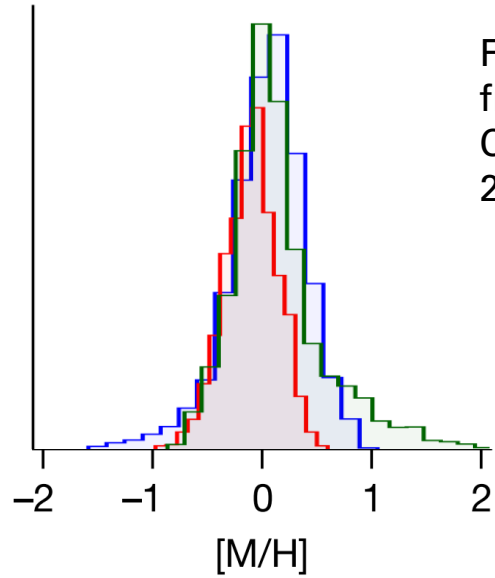


4) Bayesian Inference (**retrieval**)



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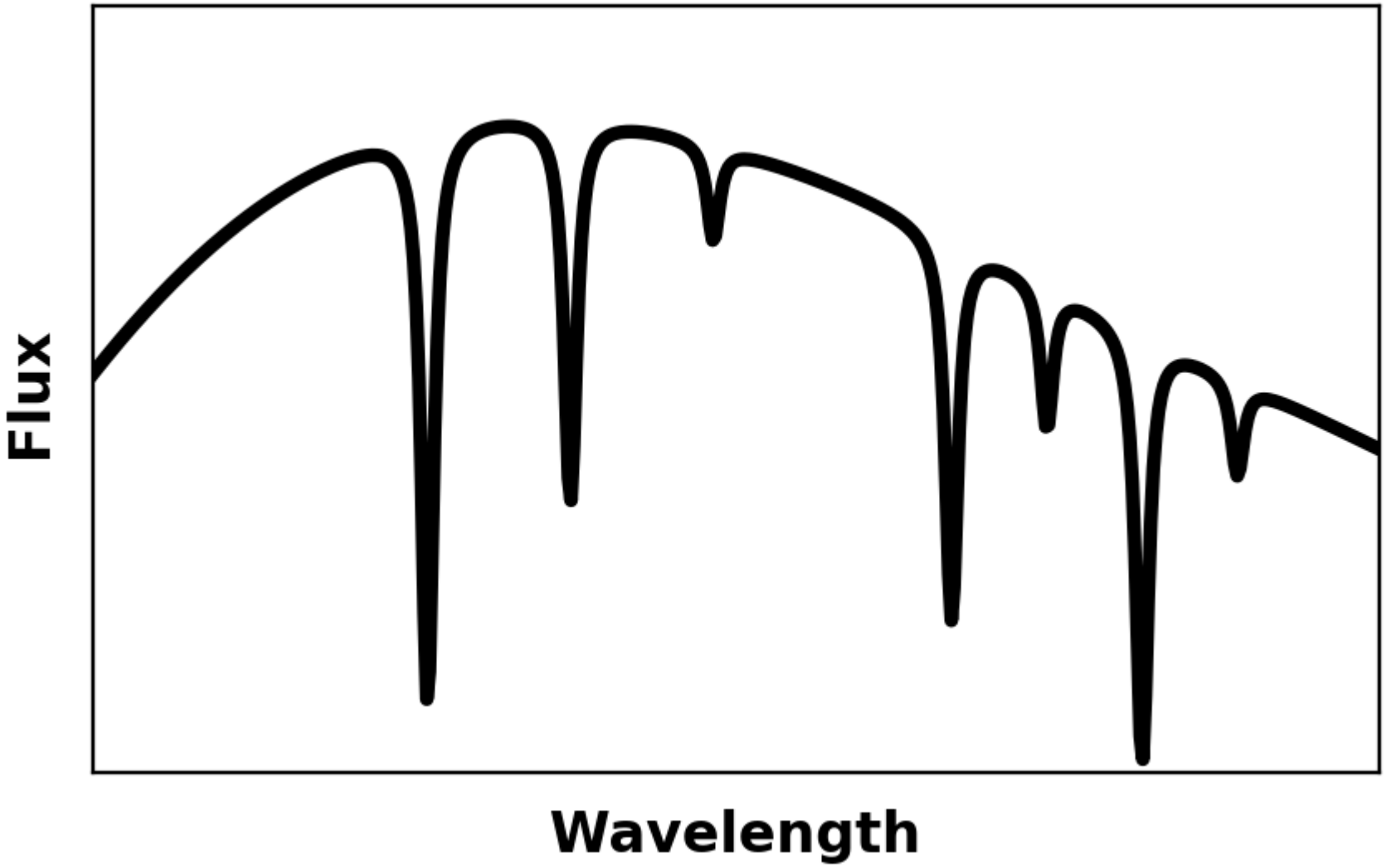

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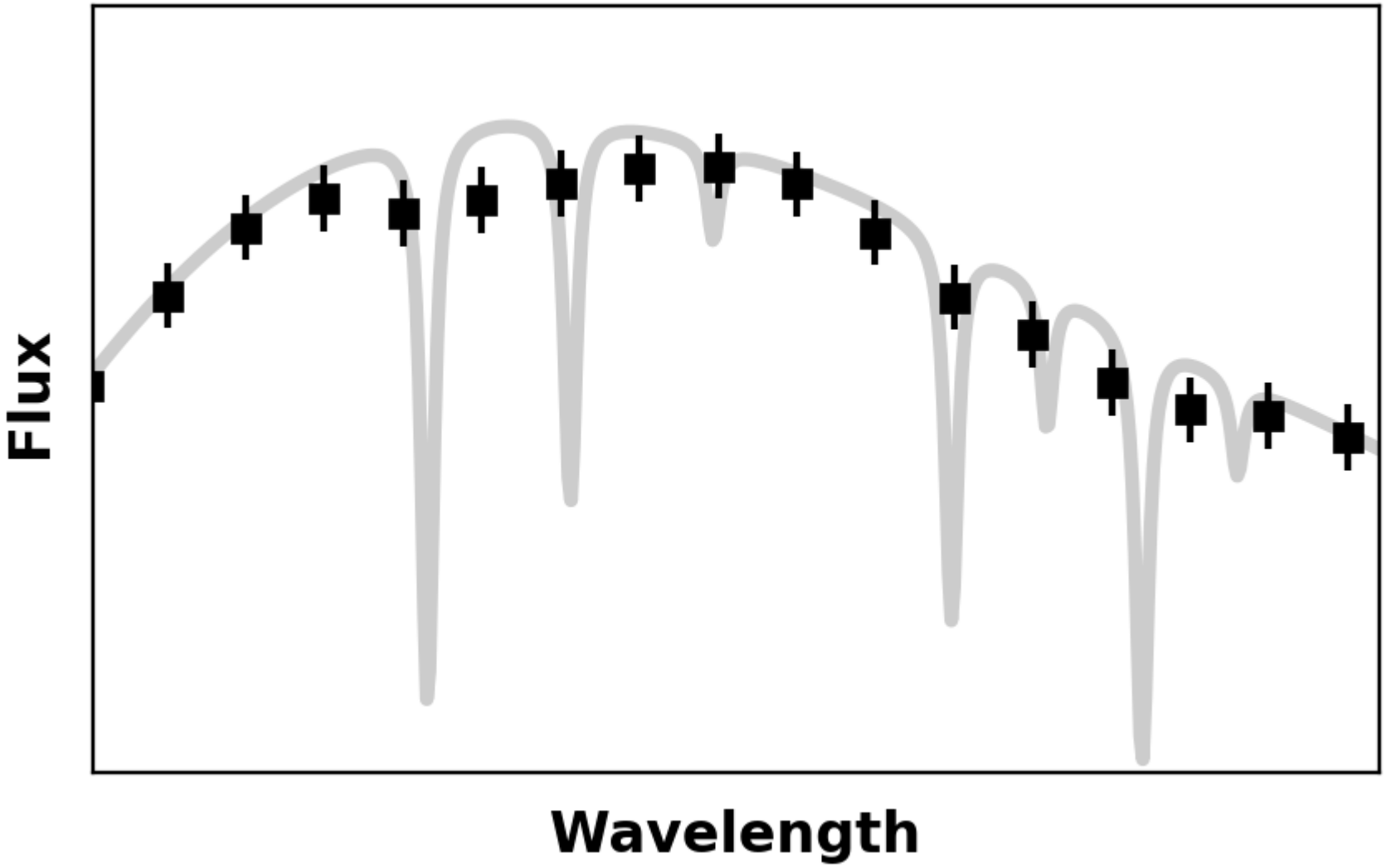

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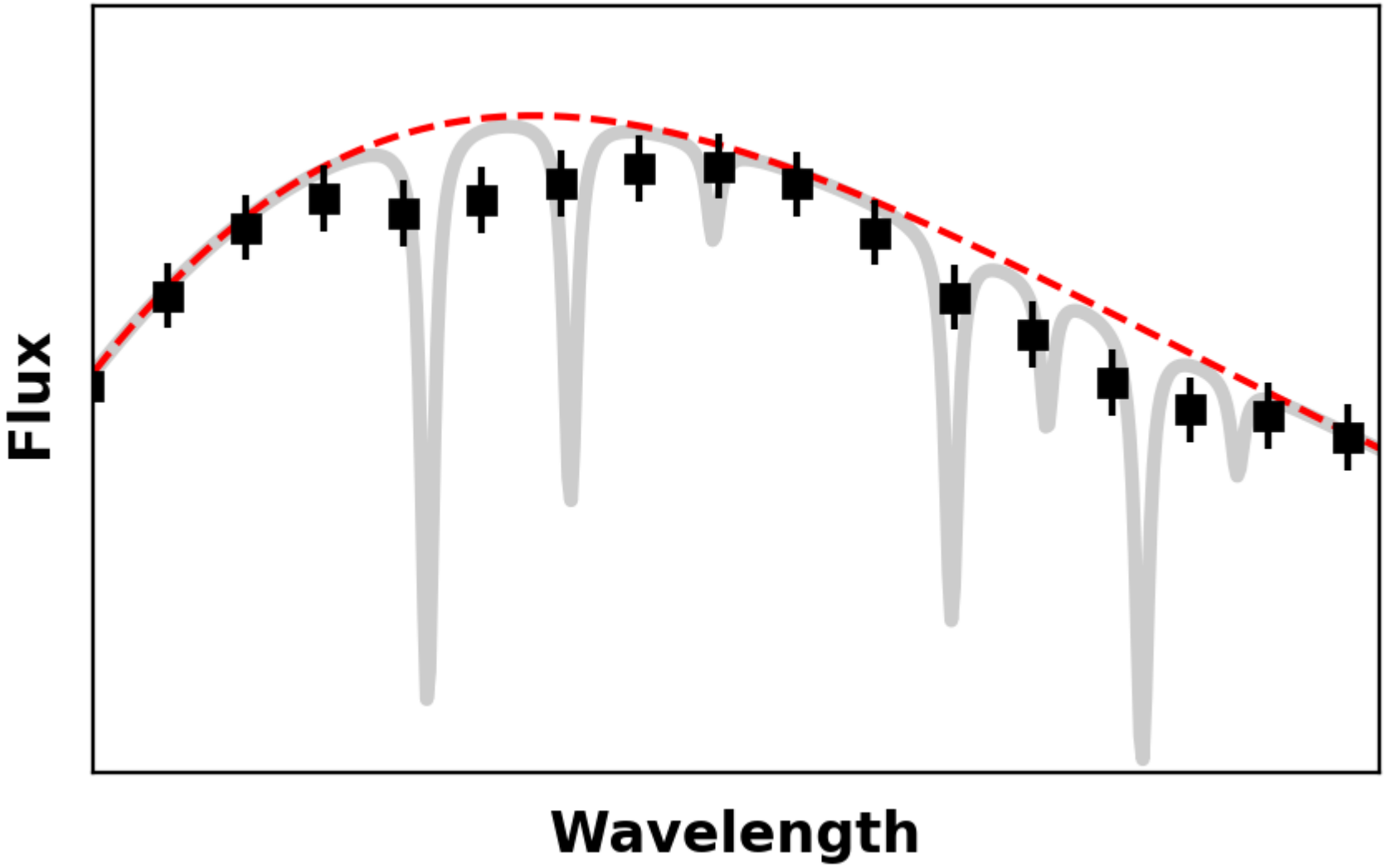
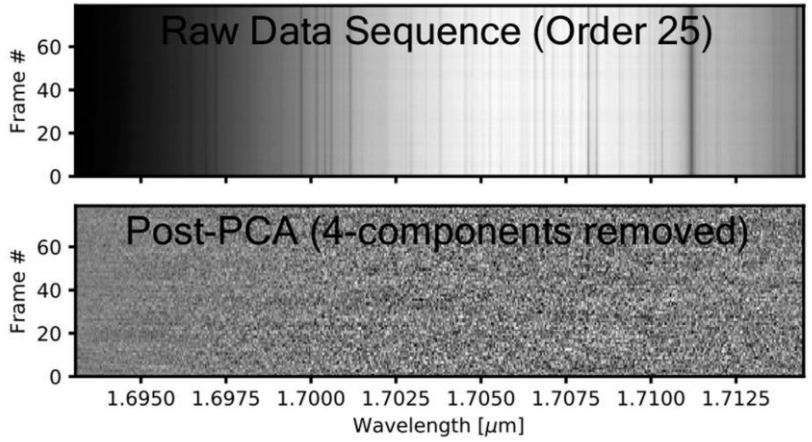


High Resolution Spectroscopy

1) Take spectra over time and **detrend**



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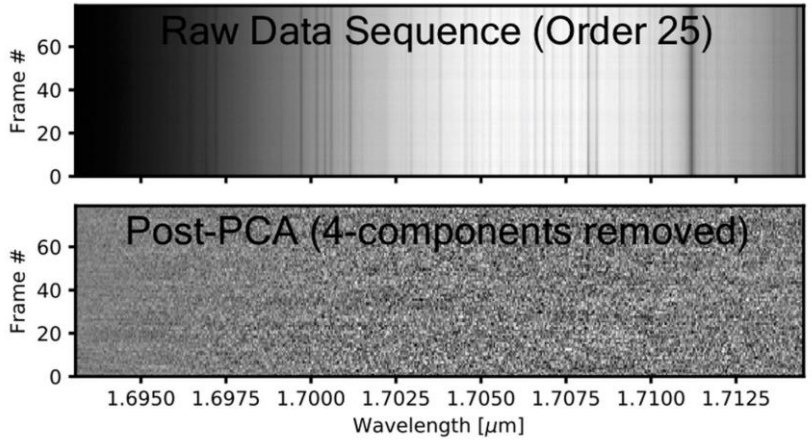
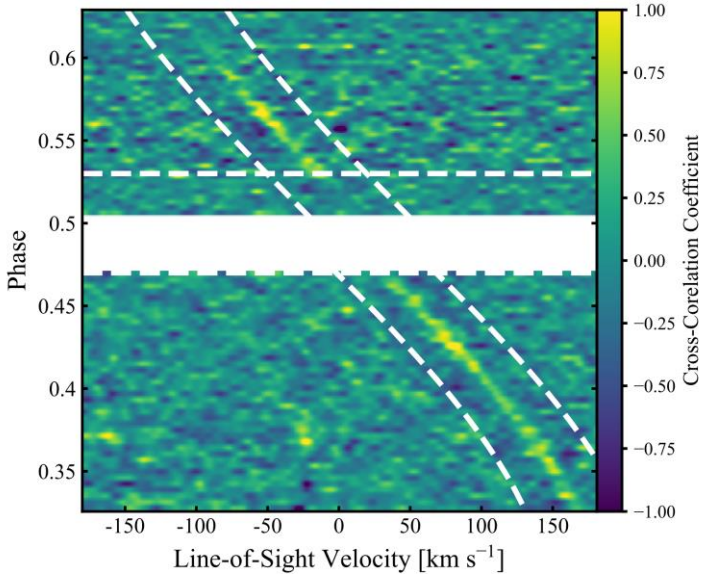


2) **Cross-correlate** a spectral template at each phase



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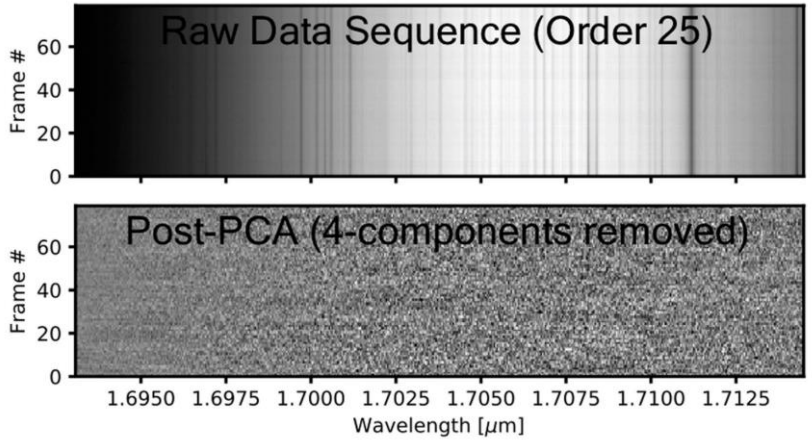

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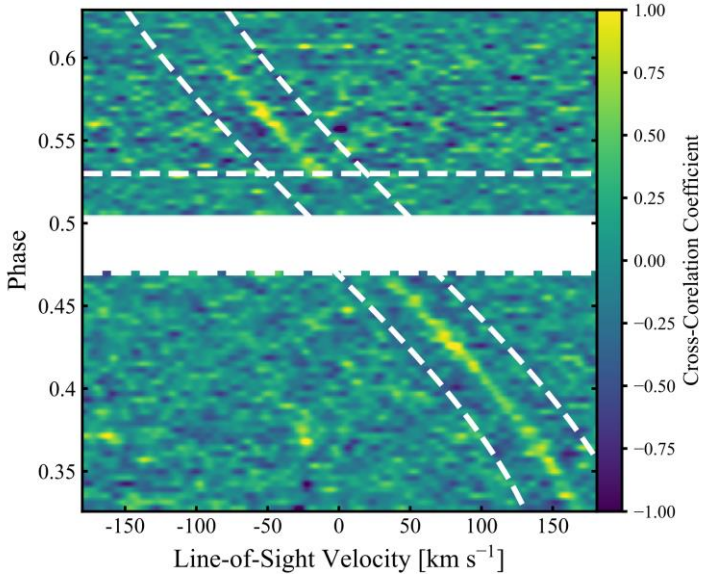

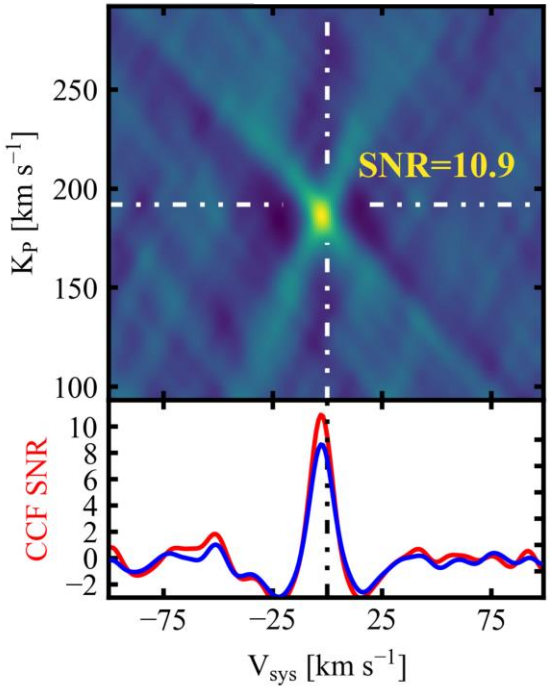

3) Sum the planet signal along the planet's **velocity in time**

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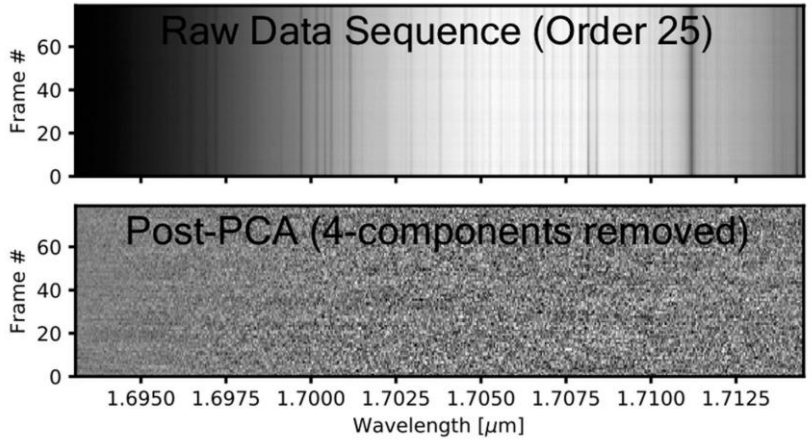

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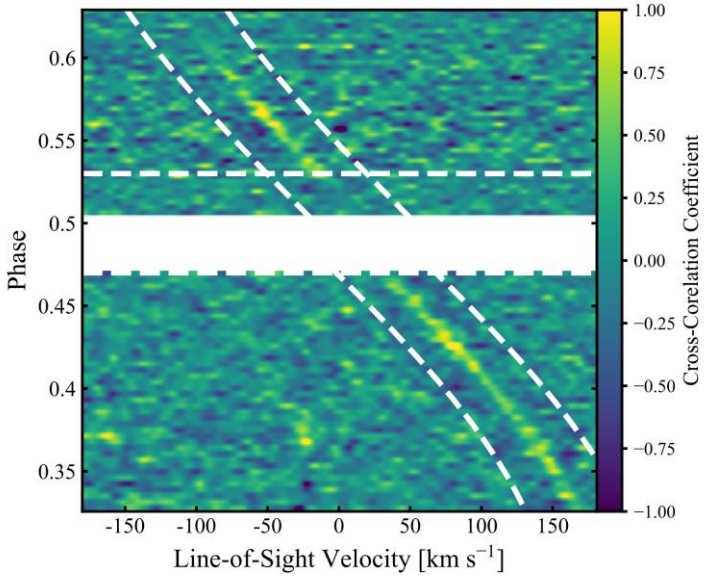

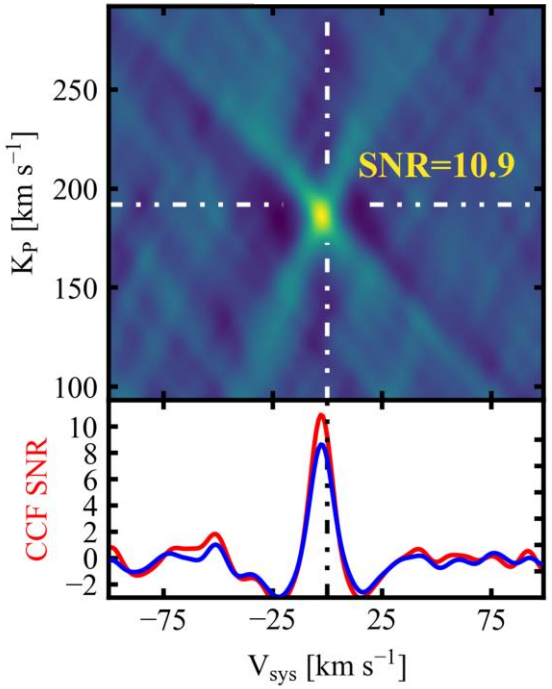

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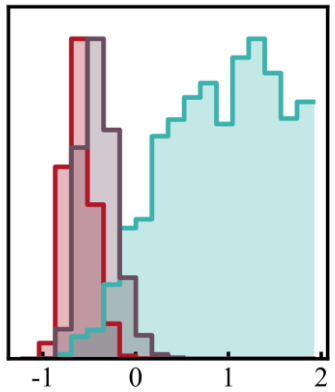

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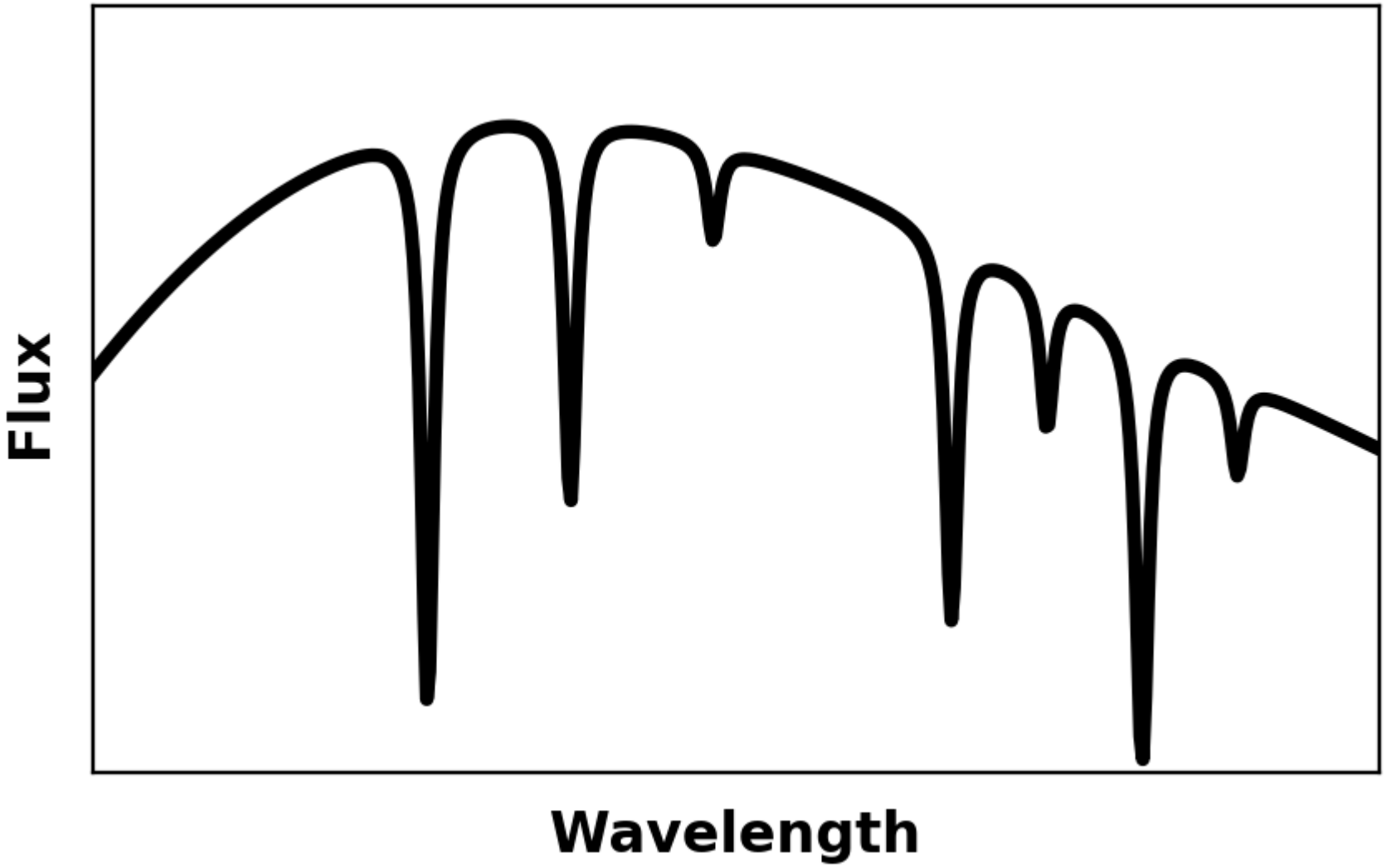

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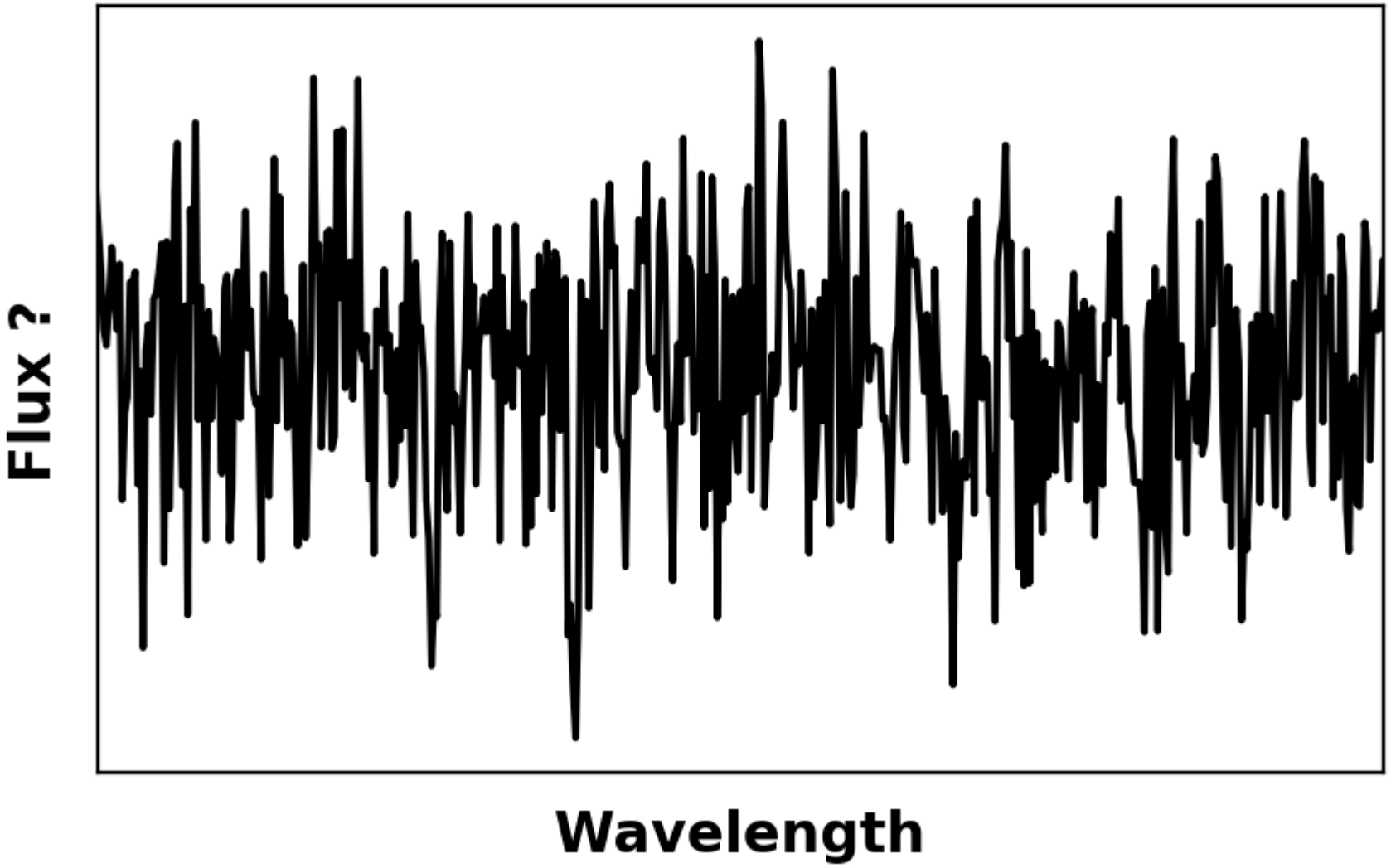

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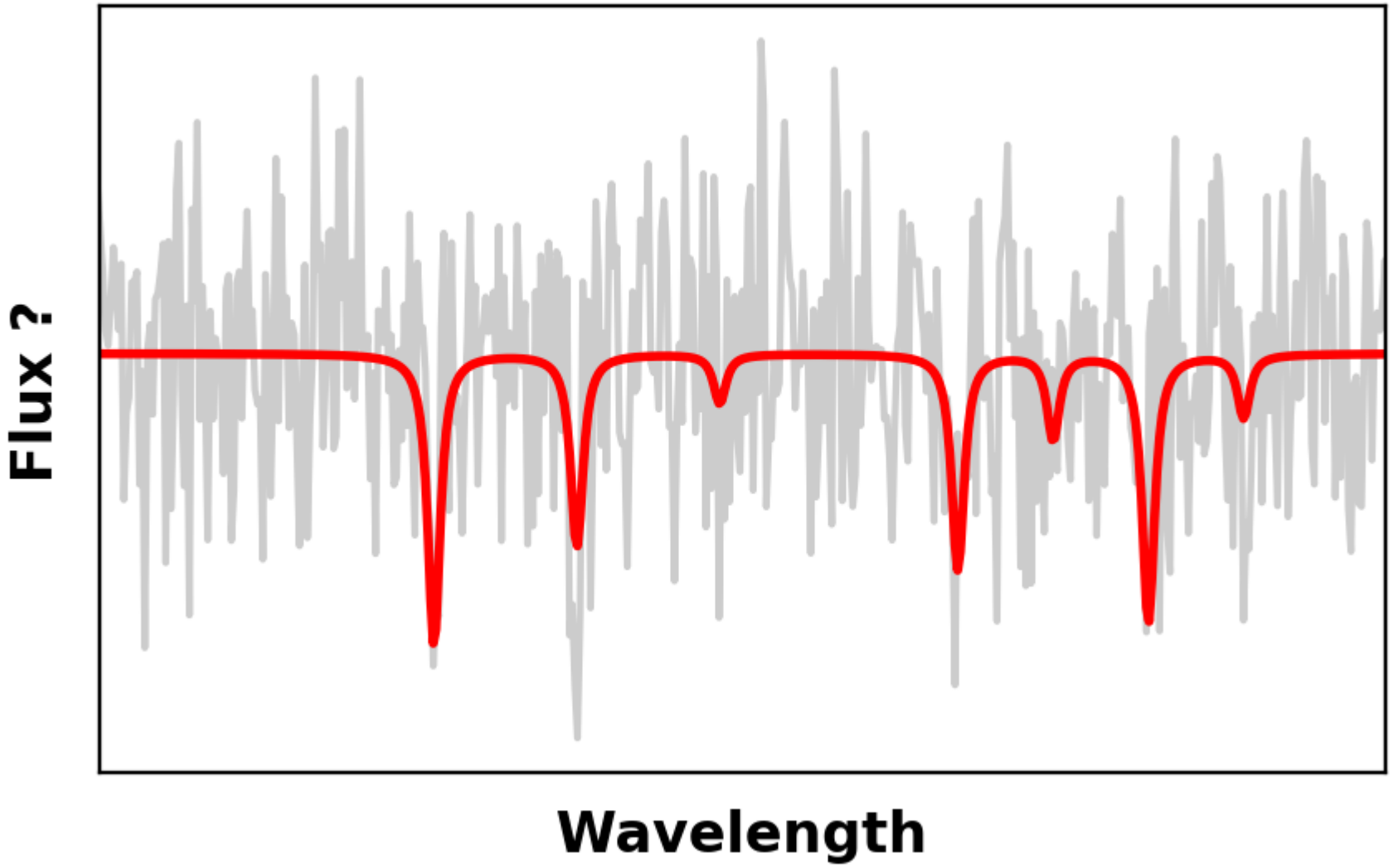

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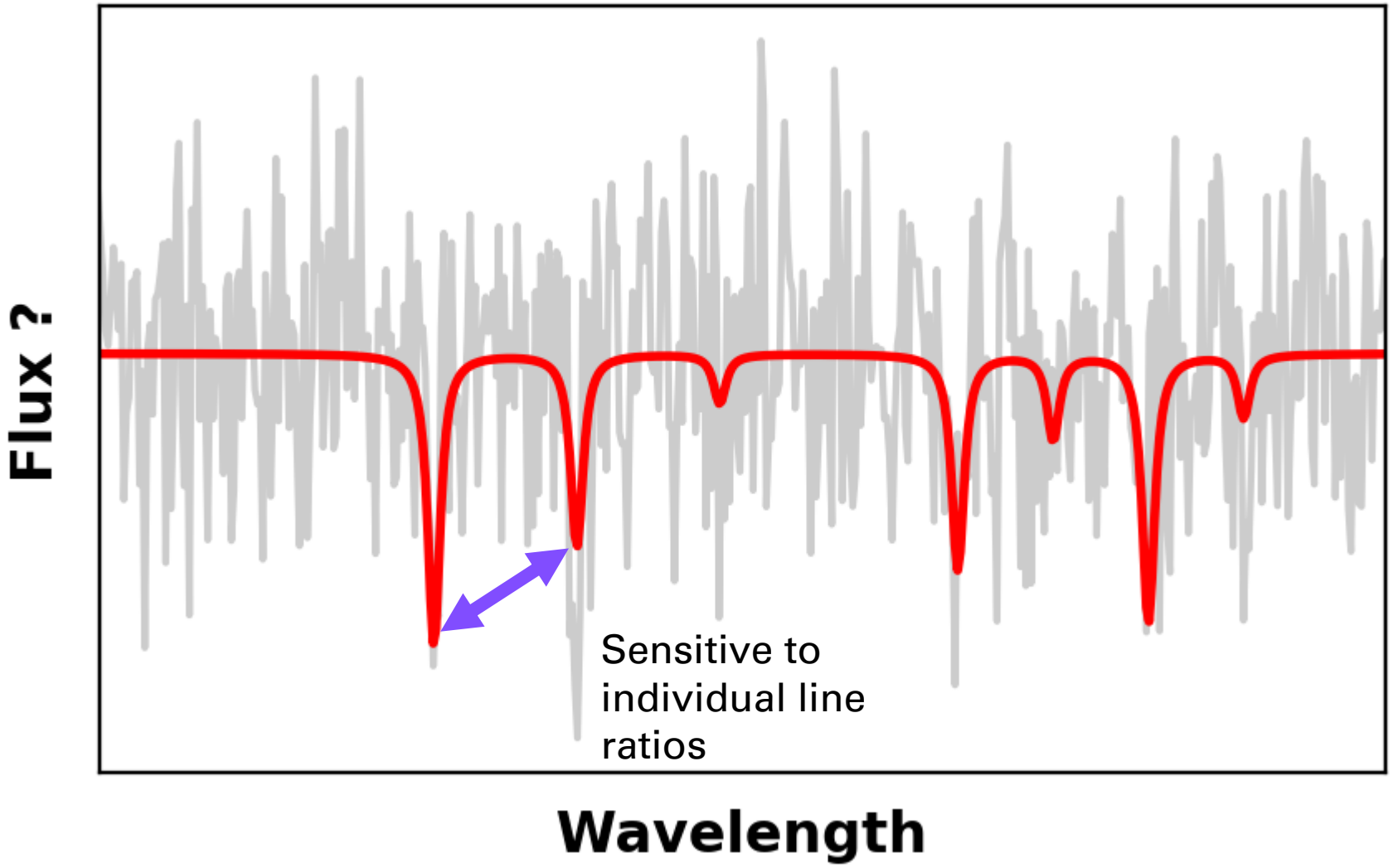

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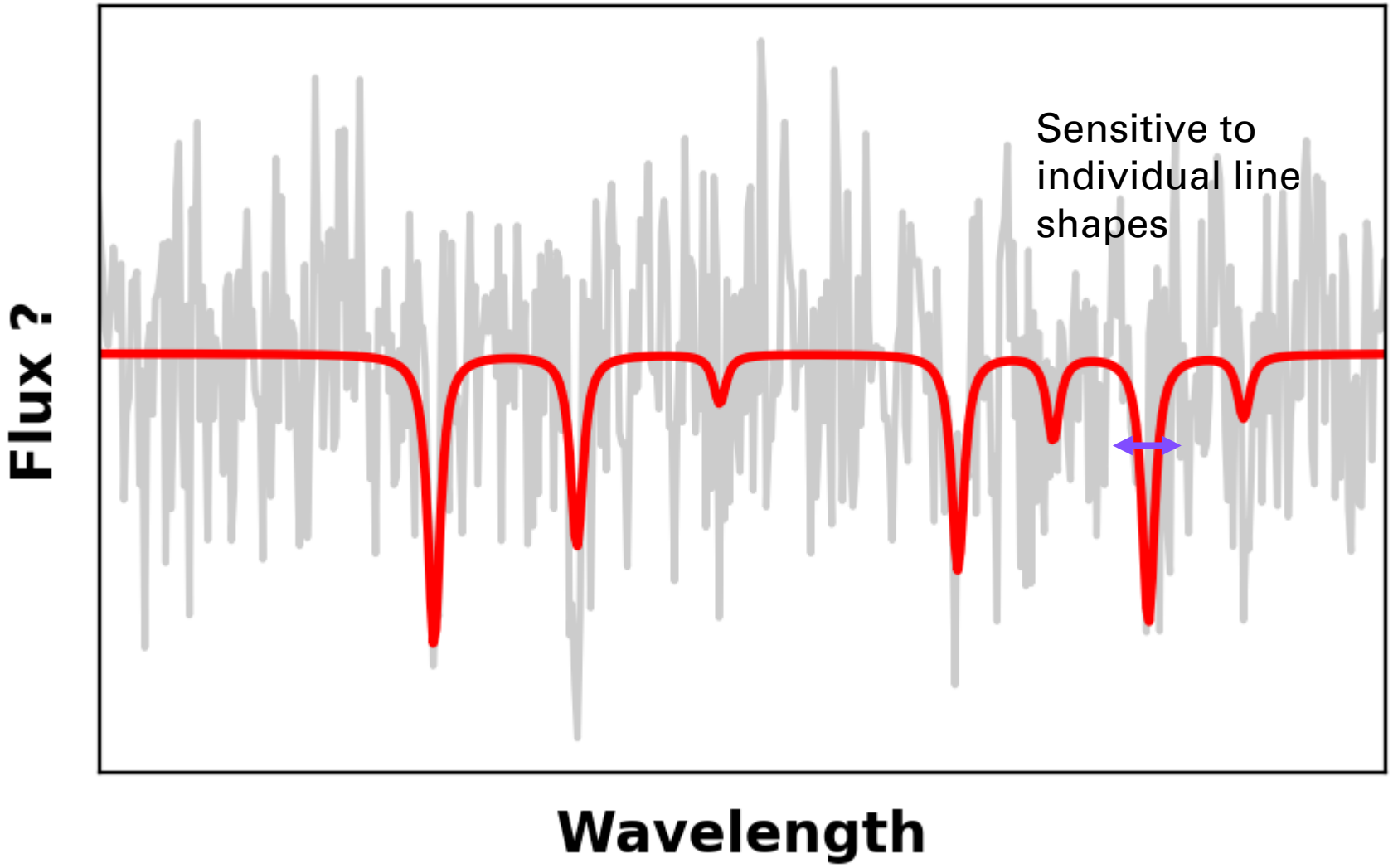


A Choice: Ground- or Space-based spectroscopy?

- Space:
  - No tellurics
  - Low spectral resolution
  - Yes continuum (temperature)

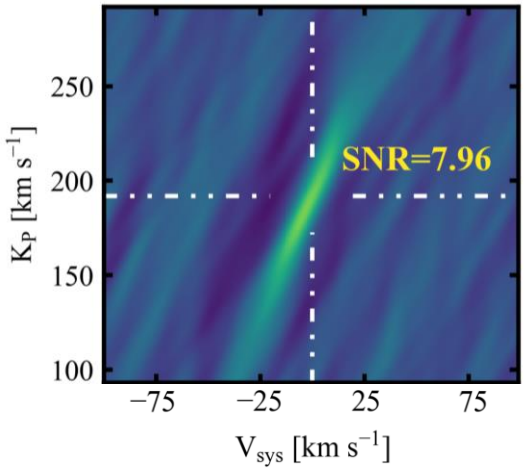
- Ground
  - Tellurics ☹
  - High spectral resolution
  - No continuum (no temperature?)

- Intuition: space good for P-T profile/climate, ground good for composition?

HIGH- AND LOW-RESOLUTION SPECTROSCOPY HAVE COMPLEMENTARY INFORMATION – DO THEM BOTH!

WASP-77A b

Gemini South/IGRINS (new)



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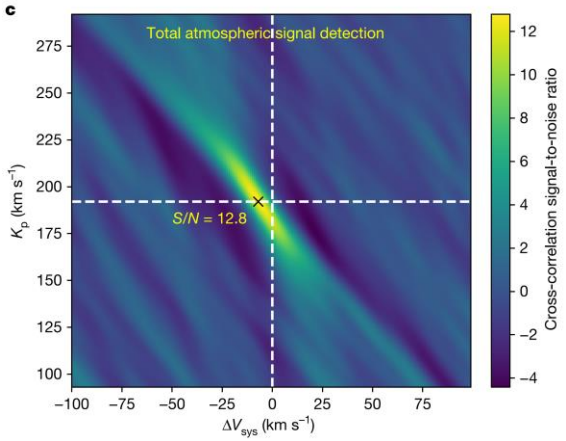
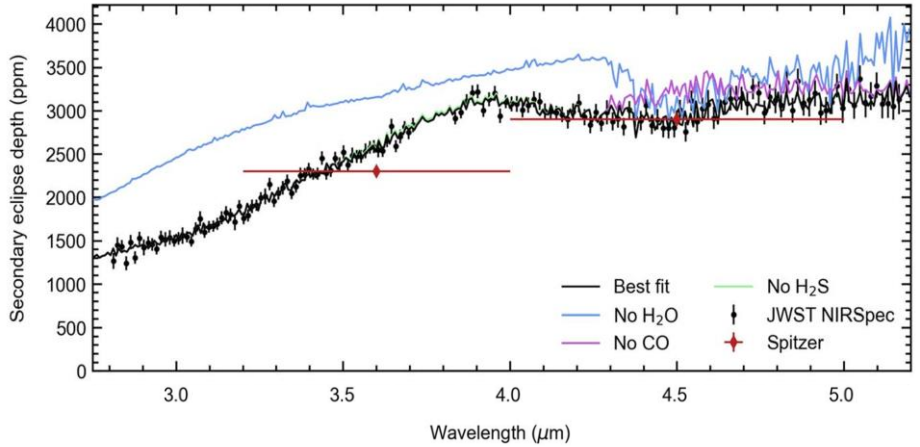
Gemini South/IGRINS; Line+ 2021



+

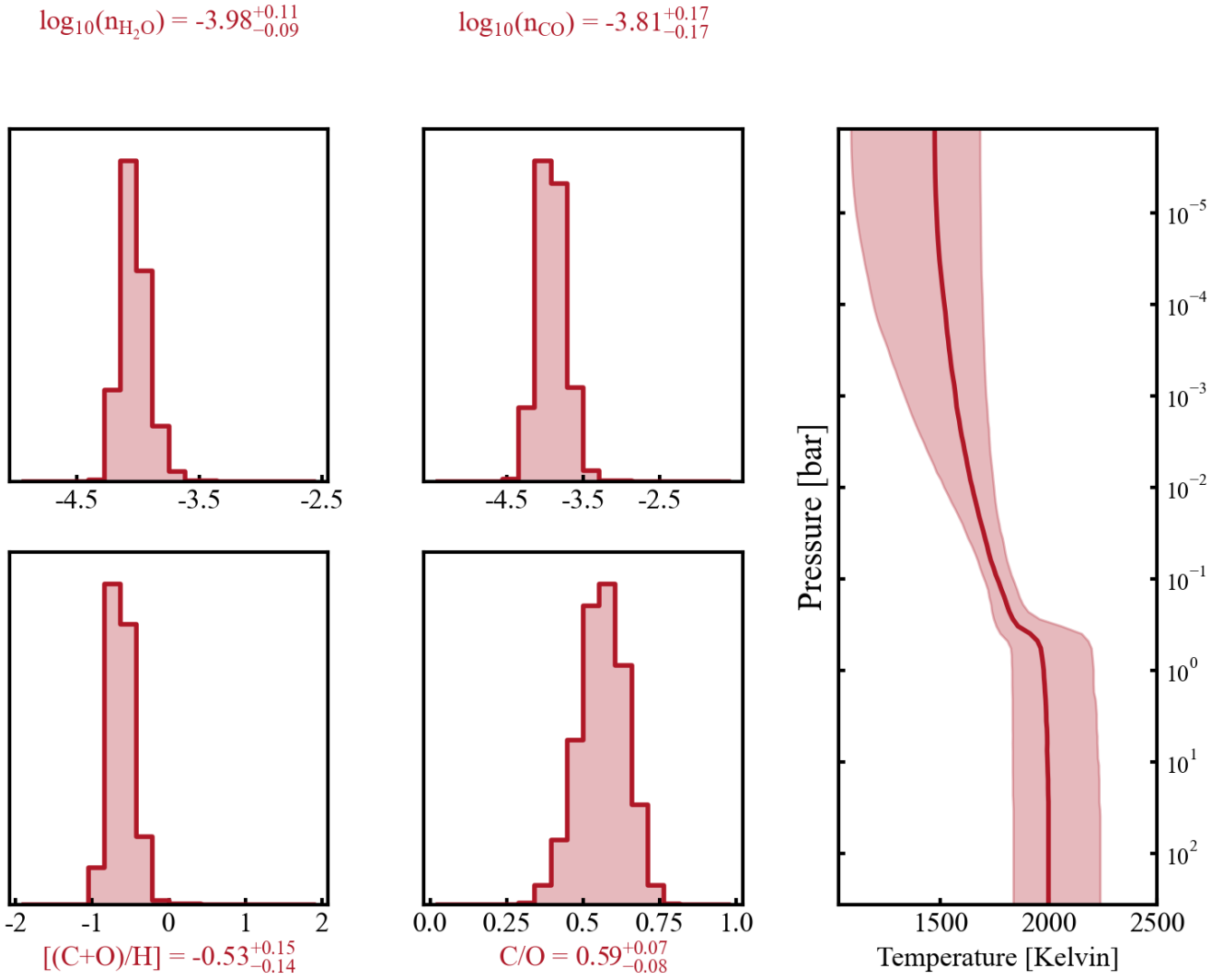
NIRSpec G395H; August+ 2023



Gemini South – 8.1 m
IGRINS – R =45K

JWST – 6.5 m
NIRSpec – R=2700, data binned to R~250

Test Case: WASP-77A b confirms intuition



IGRINS

STRONGER TOGETHER

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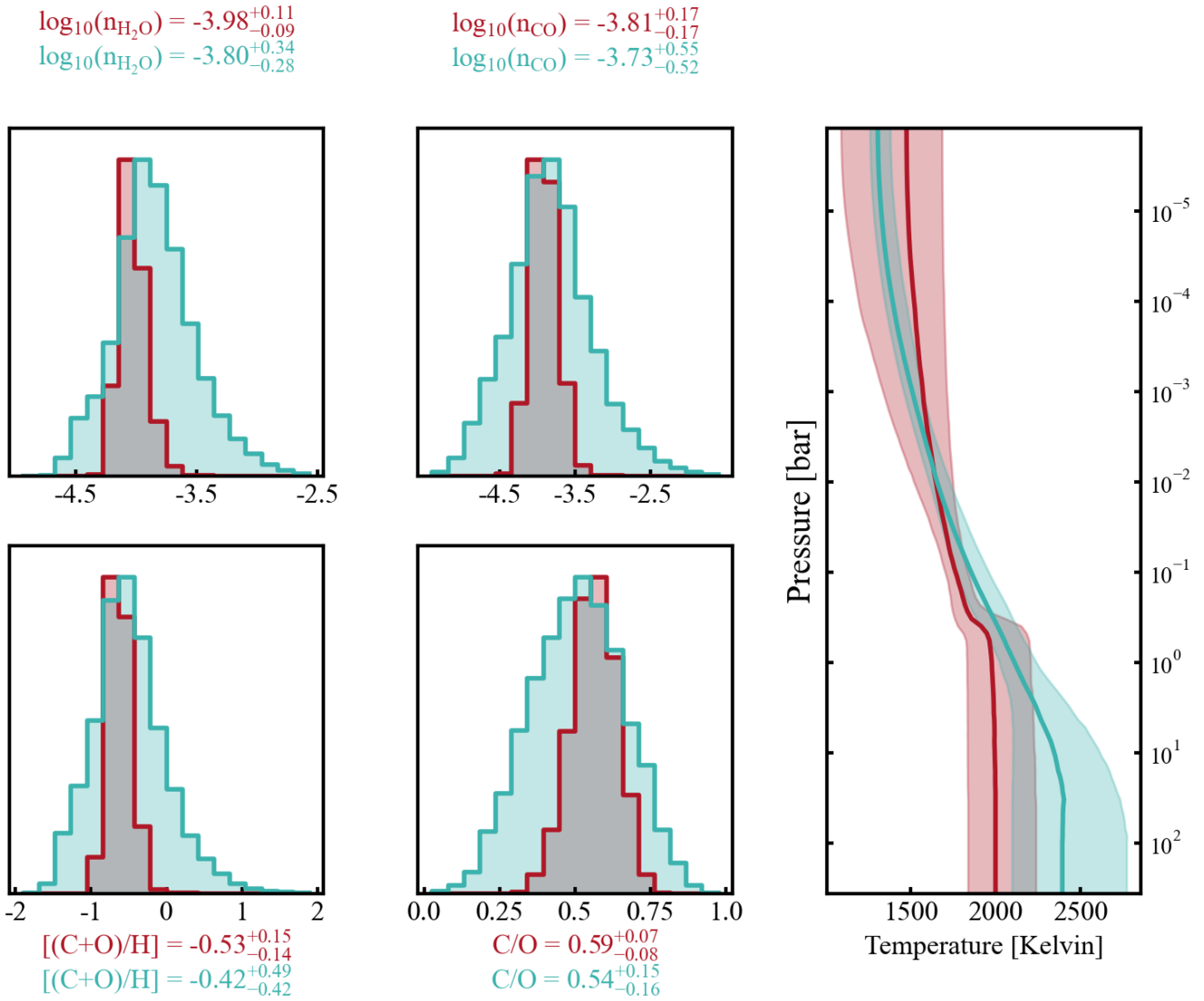

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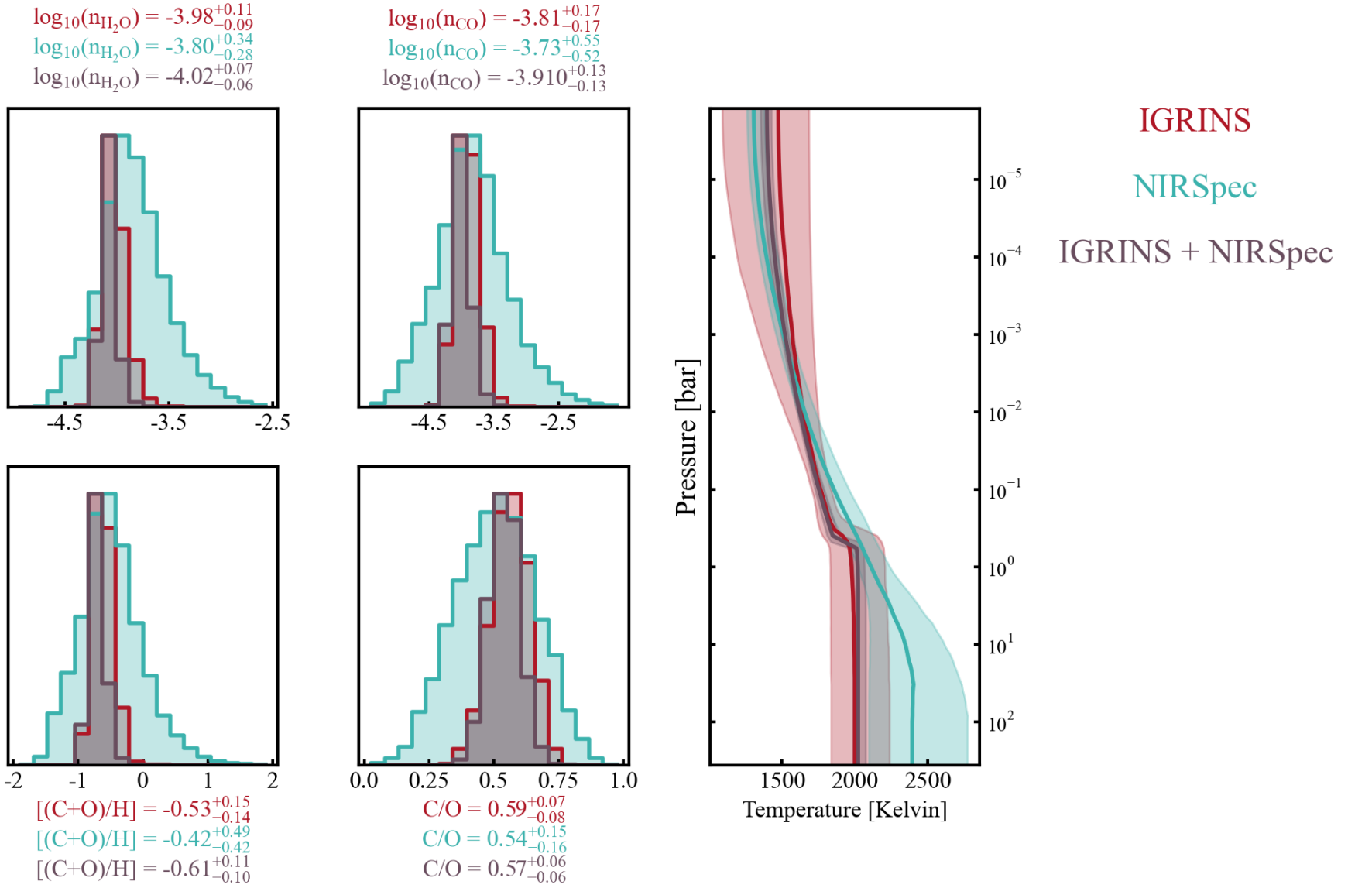
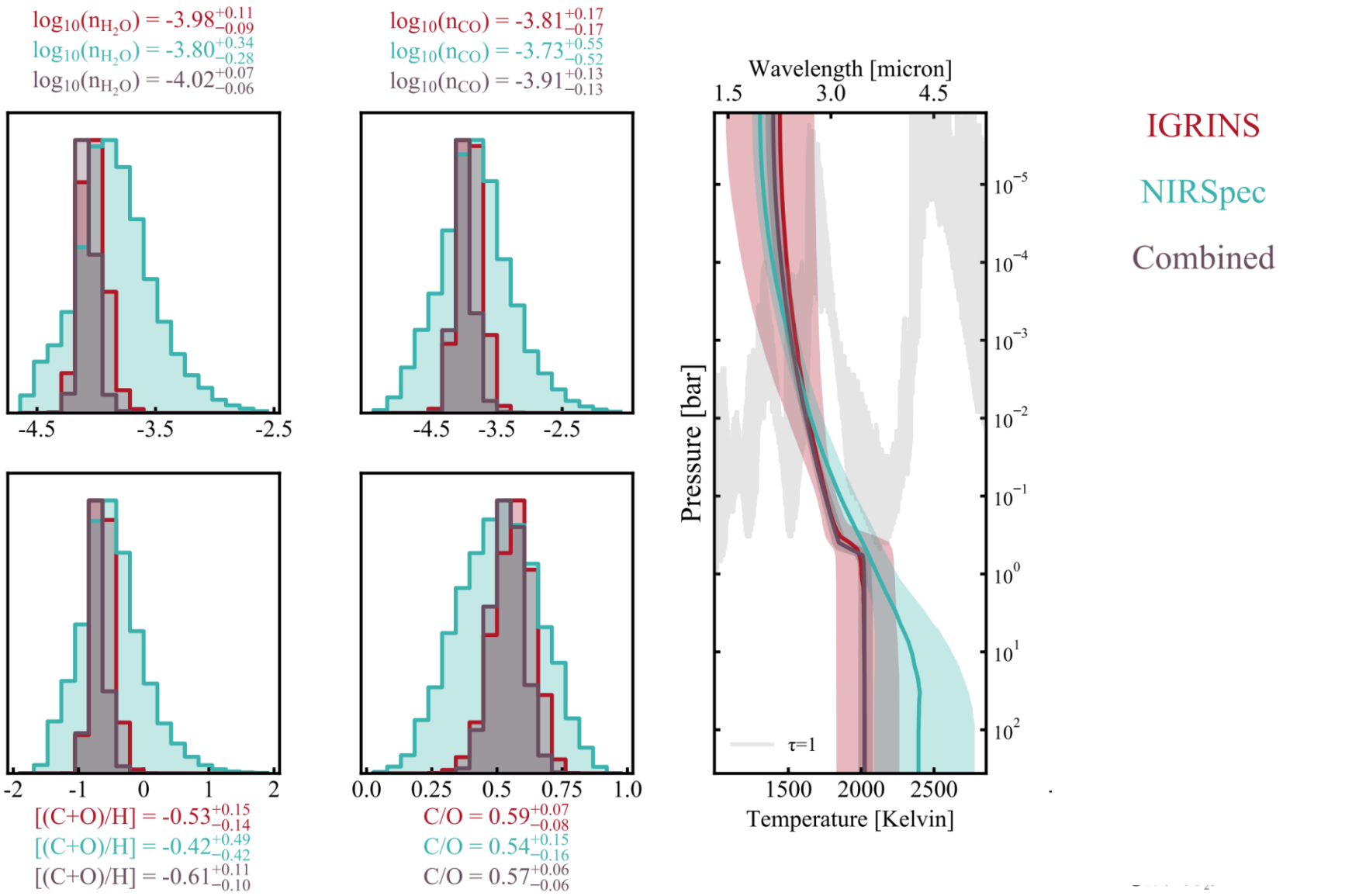


STRONGER TOGETHER

Reduced uncertainty in P-T profile reduces uncertainty in gas abundances



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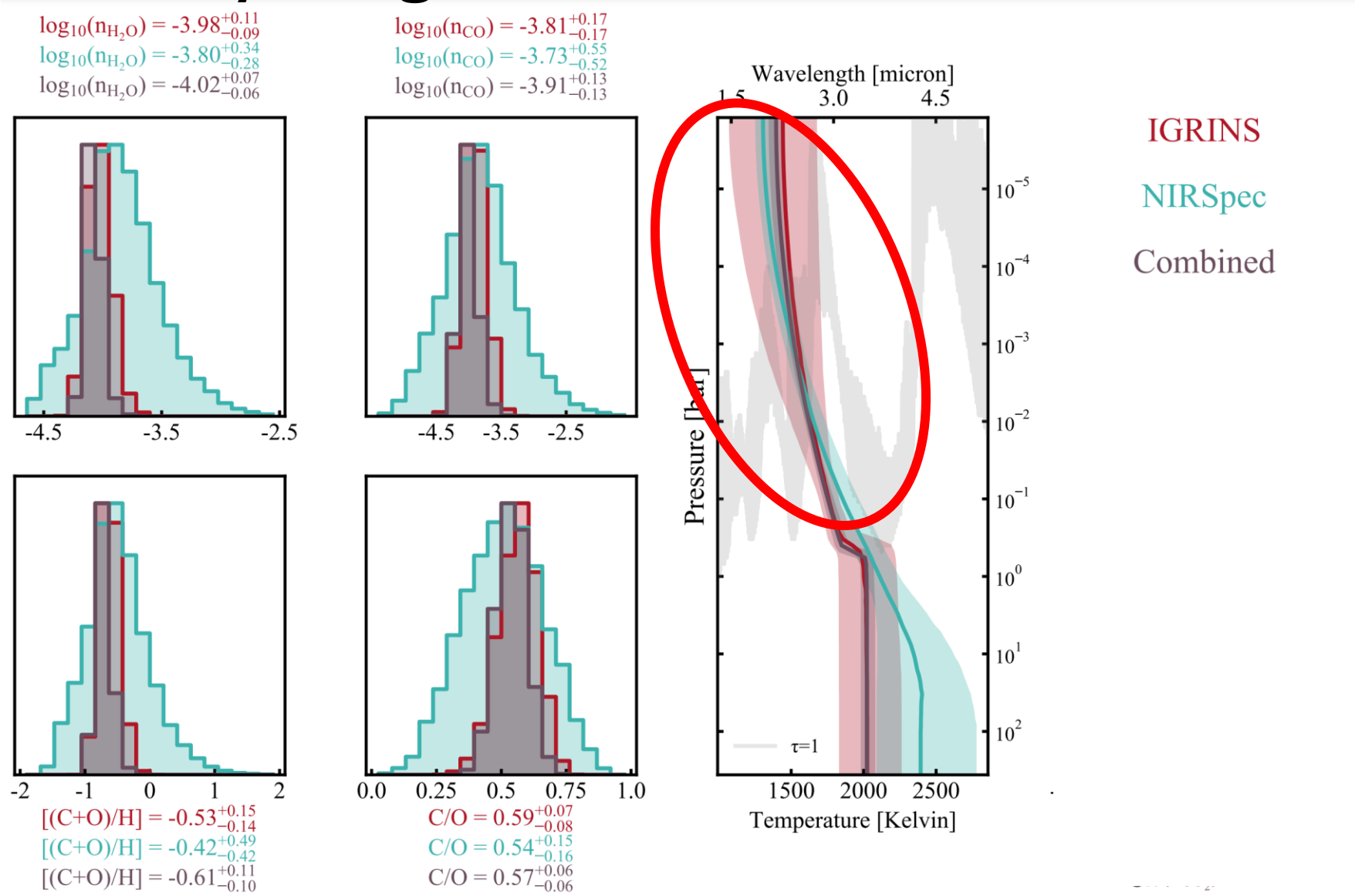

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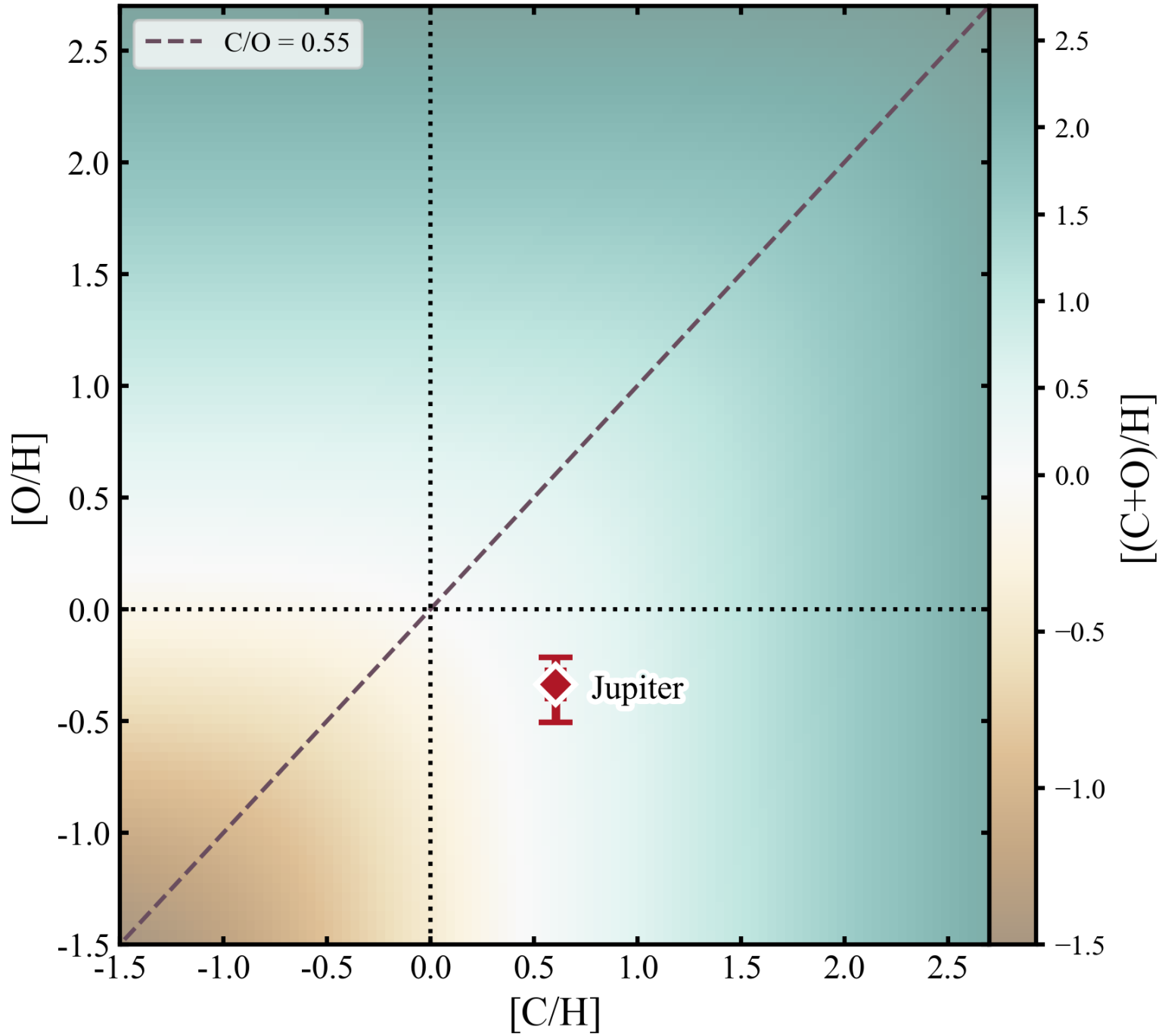
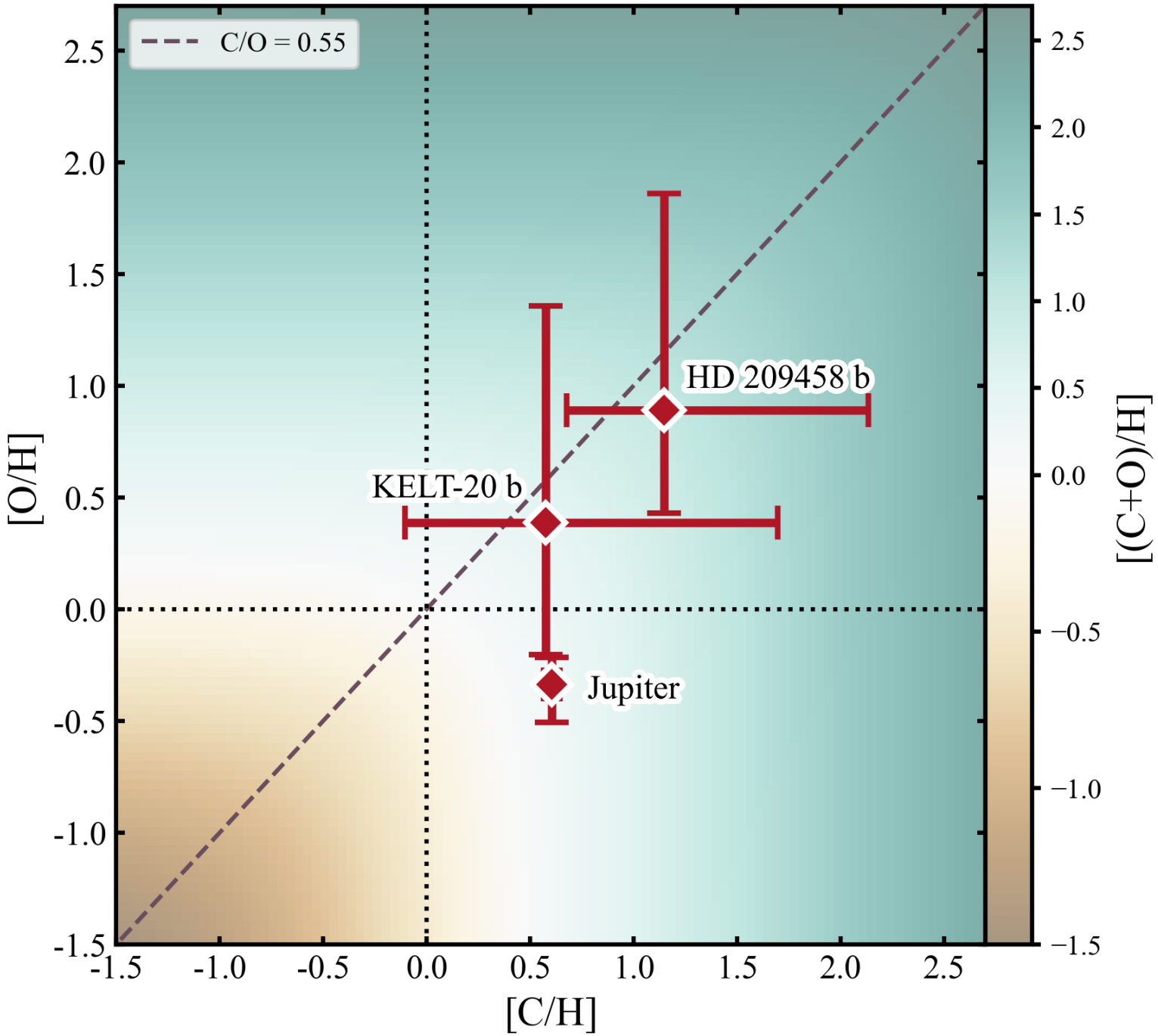

C/O = 0.55
Jupiter
[O/H]
[C/H]
[(C+O)/H]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
−0.5
−1.0
−1.5


C/O = 0.55
HD 209458 b
KELT-20 b
Jupiter
[O/H]
[C/H]
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2.5
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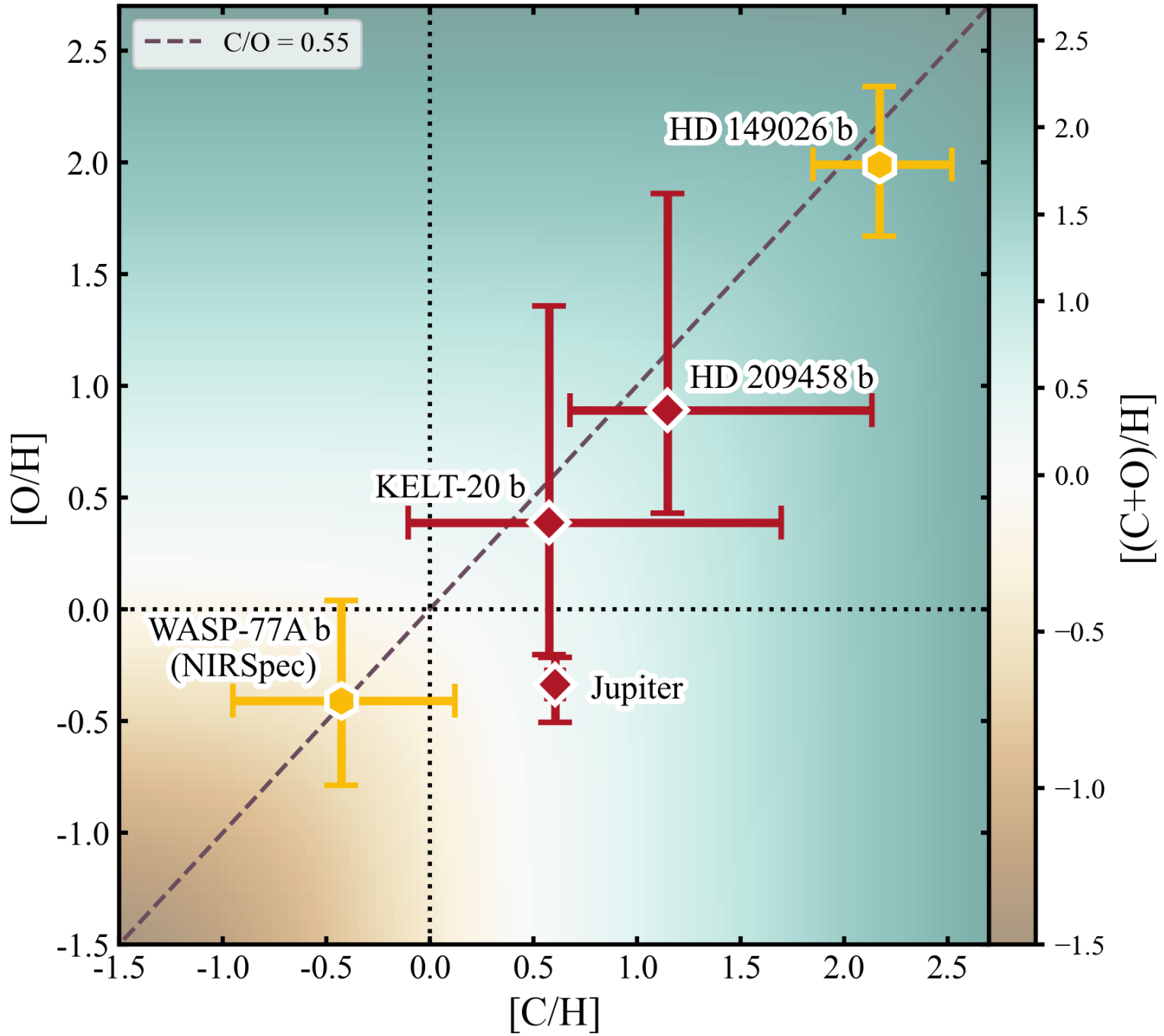
C/O = 0.55
HD 149026 b
HD 209458 b
KELT-20 b
WASP-77A b
(NIRSpec)
Jupiter
[O/H]
[C/H]
[(C+O)/H]
2.5
2.0
1.5
1.0
0.5
0.0
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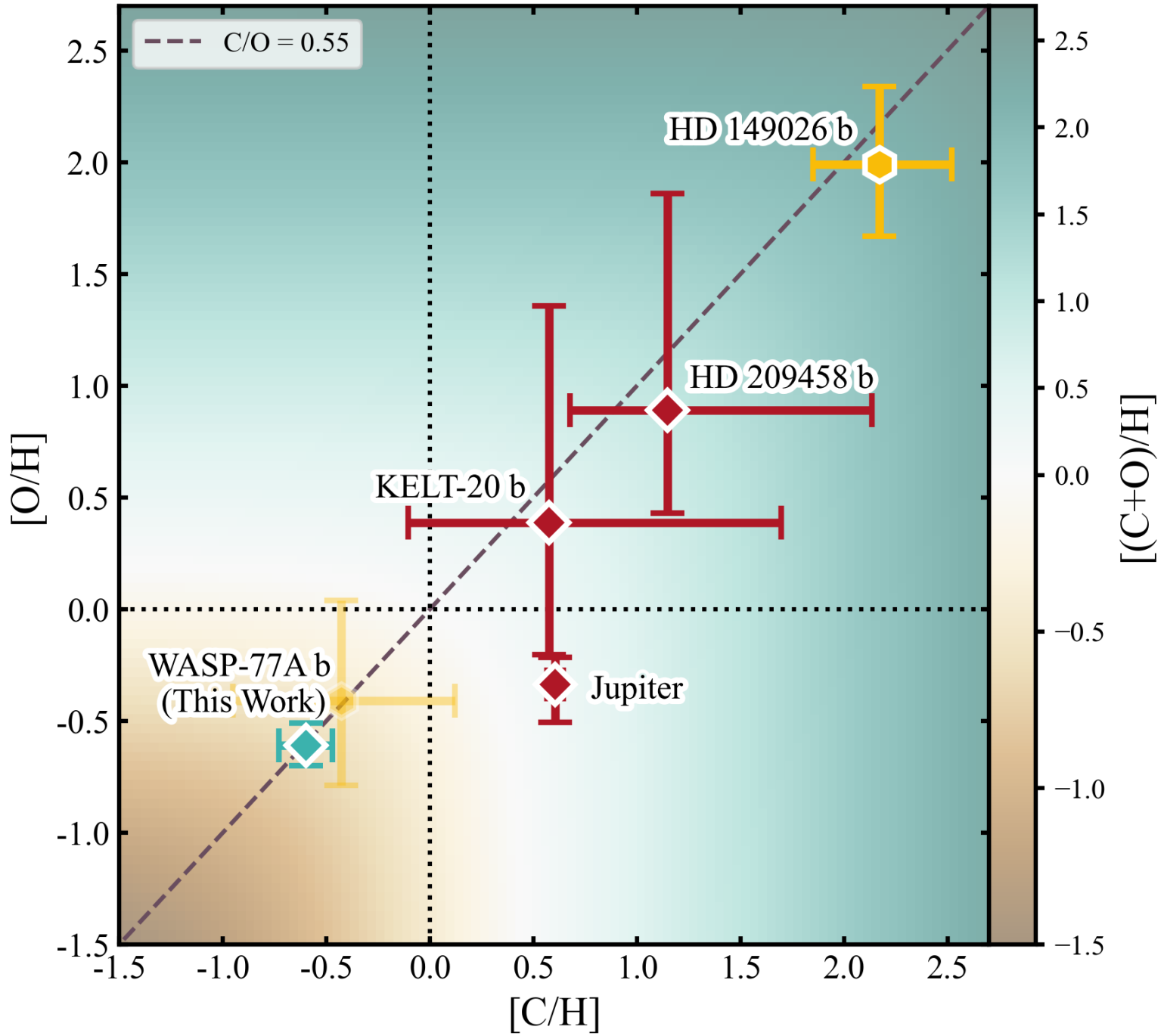
-1.0
-1.5
−0.5
−1.0
−1.5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(This Work)
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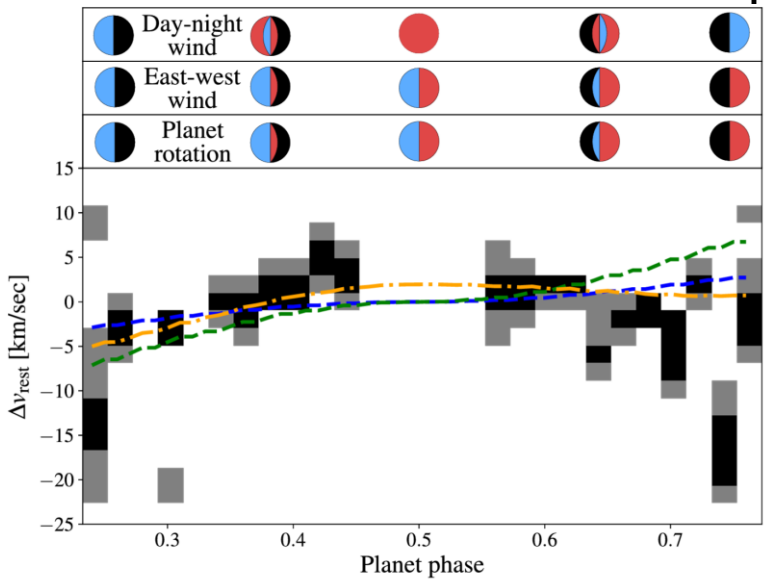
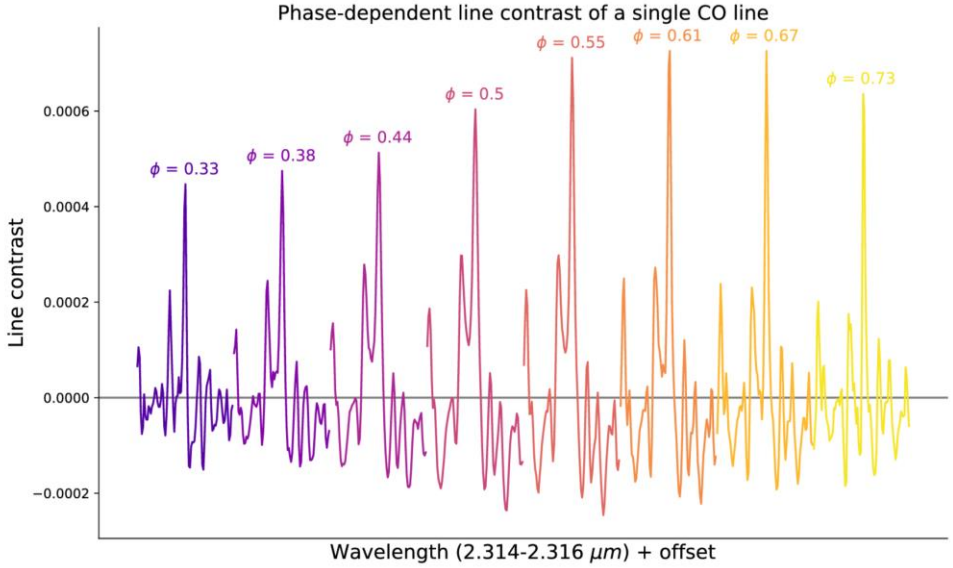
The Future: Measuring Climate from the ground

- Low resolution data is used to measure global climate/temperature maps through e.g., phase curves and eclipse mapping

Pino+ 2022



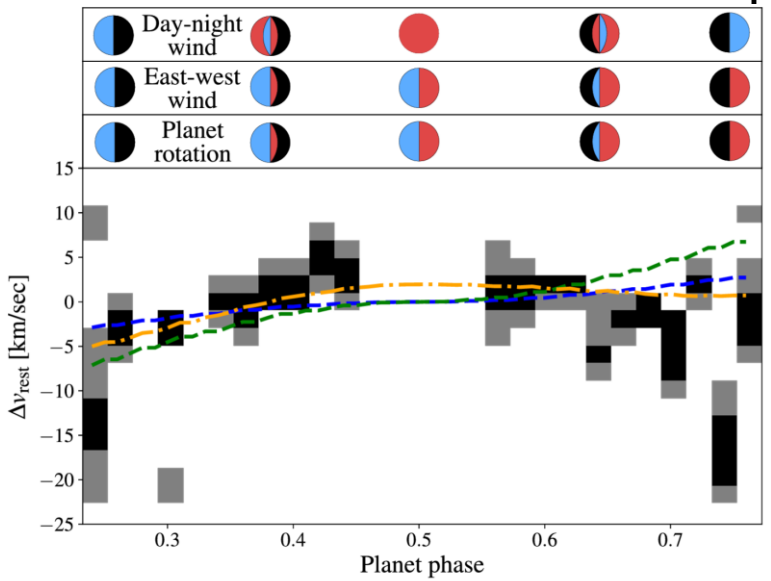
van Sluijs+ 2023



The Future: Measuring Climate from the ground

- Low resolution data is used to measure global climate/temperature maps through e.g., phase curves and eclipse mapping
- High resolution data are sensitive to winds/jets

Pino+ 2022



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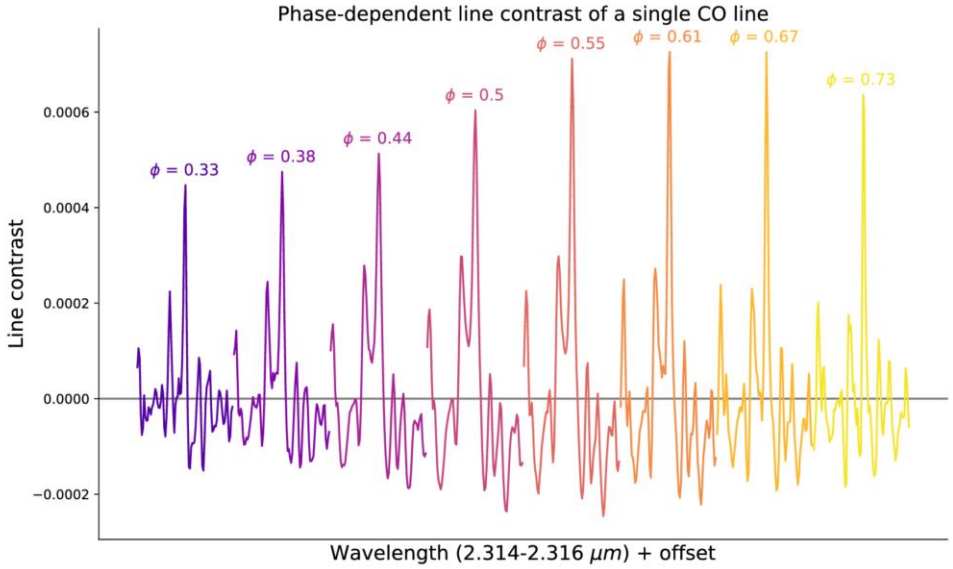
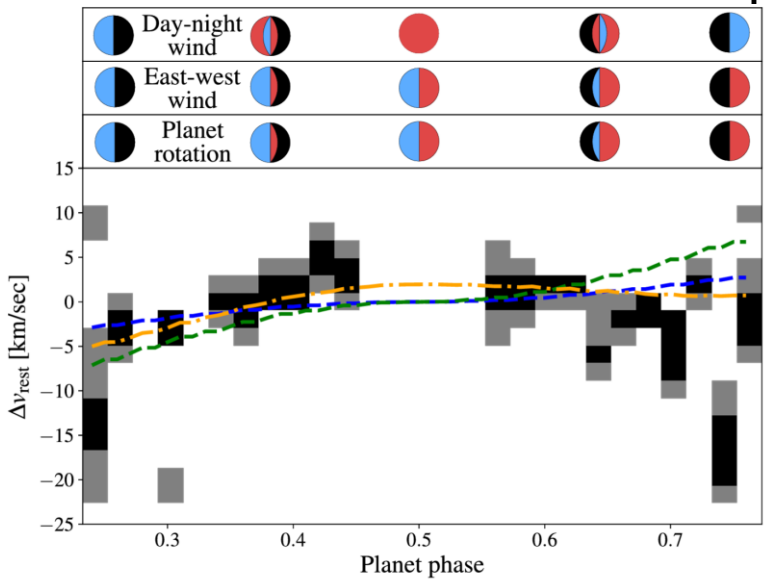


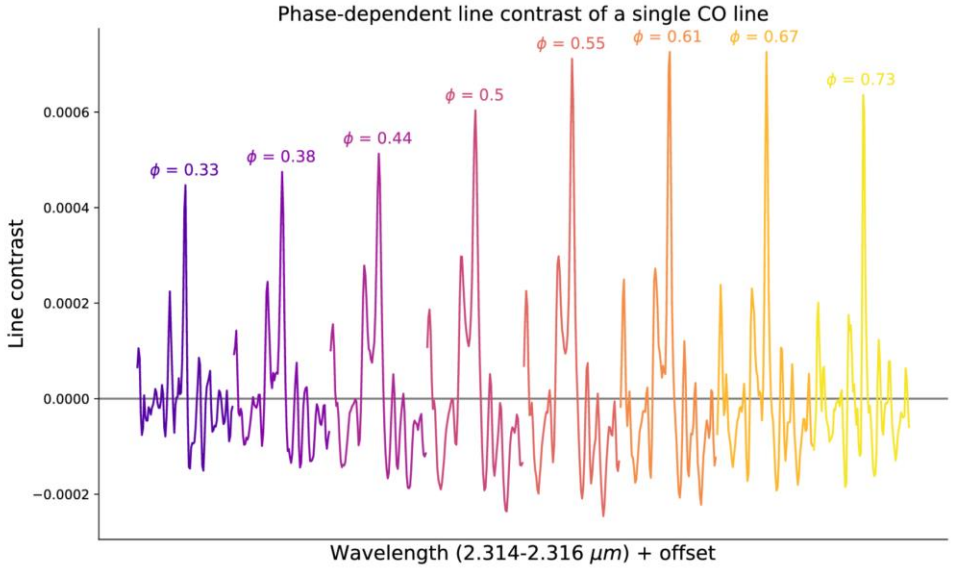
The Future: Measuring Climate from the ground

- Low resolution data is used to measure global climate/temperature maps through e.g., phase curves and eclipse mapping
- High resolution data are sensitive to winds/jets
- Jets and thermal structure are linked – measuring one will help constrain the other

Pino+ 2022

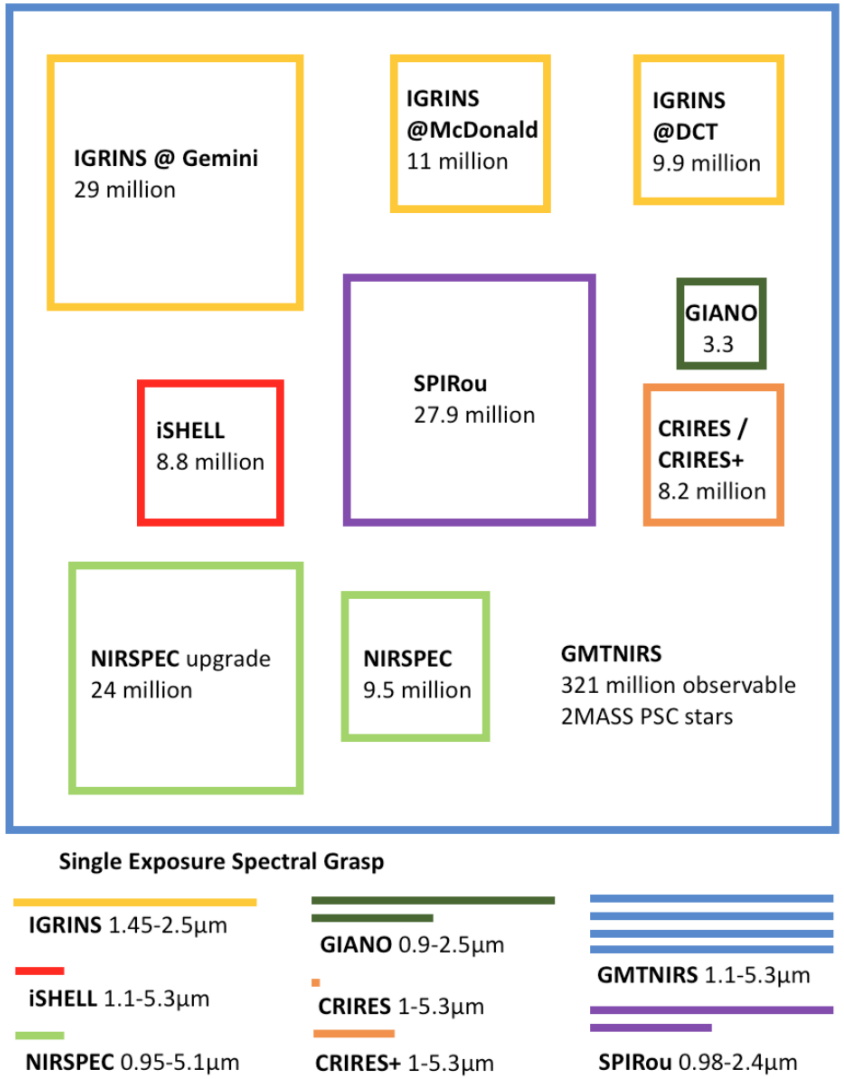


van Sluijs+ 2023



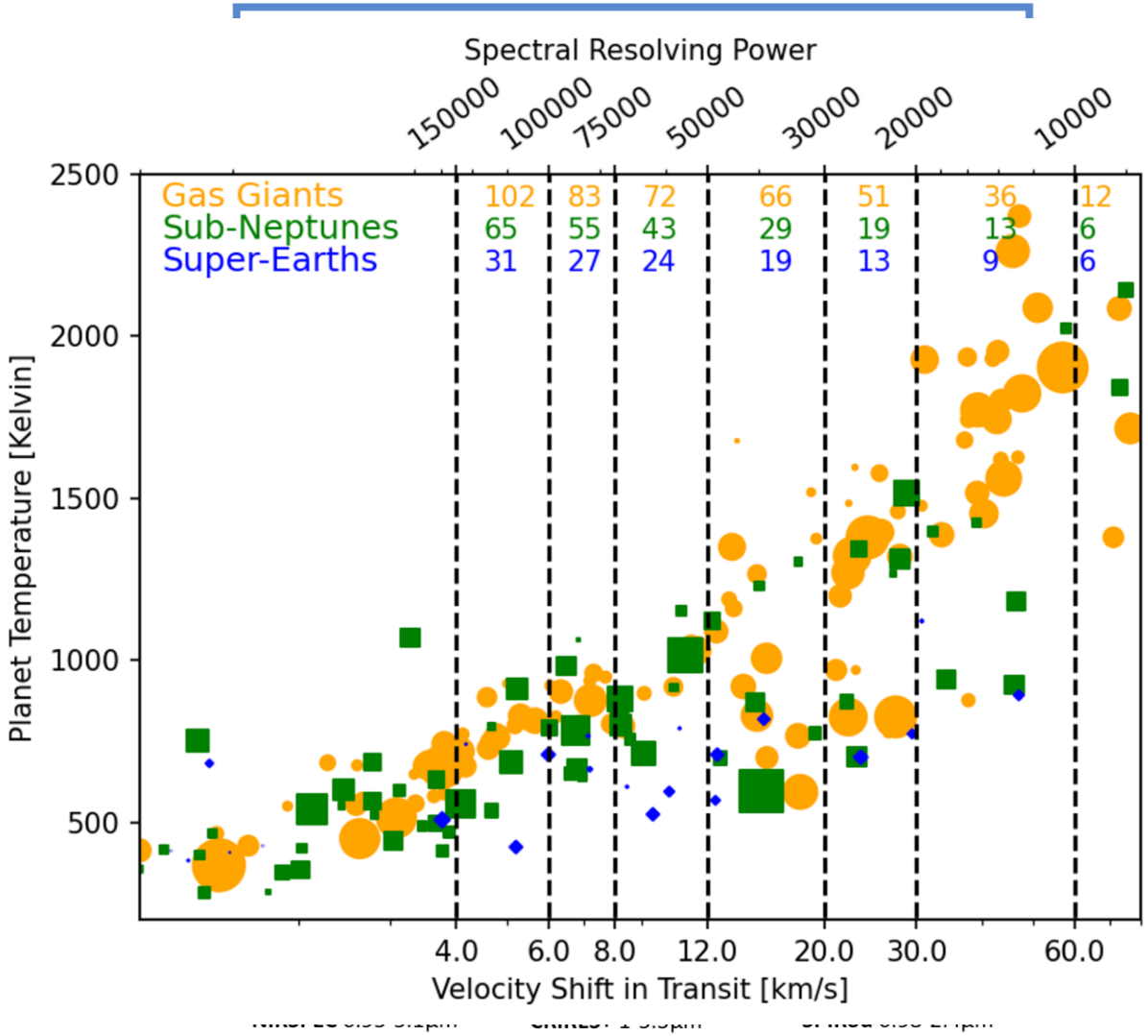
The Future: accessing cooler planets with ELTs

- Ground-based telescopes are doing great for HJs and UHJs, but for cooler planets JWST will have an advantage
- ELTs will have ~10X IGRINS CCF SNR capabilities

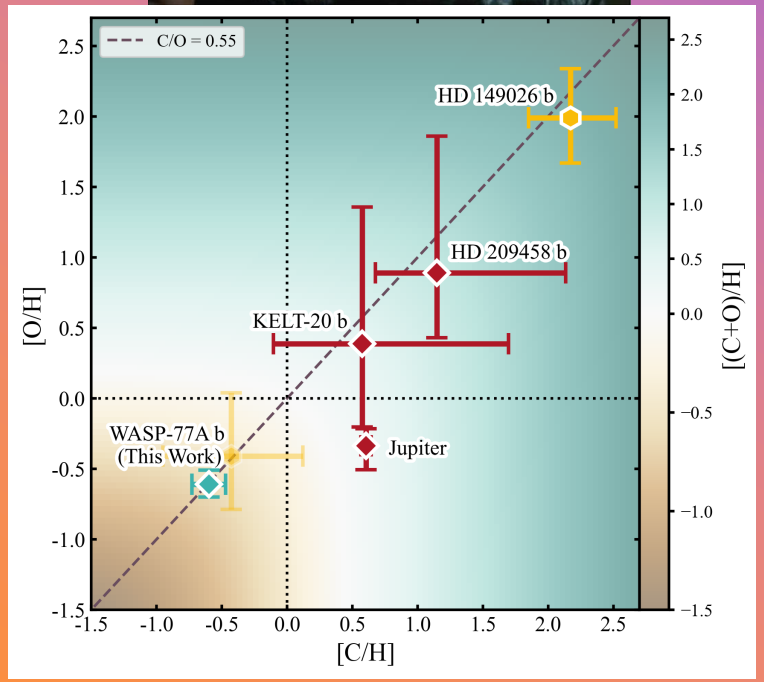


The Future: accessing cooler planets with ELTs

- Ground-based telescopes are doing great for HJs and UHJs, but for cooler planets JWST will have an advantage
- ELTs will have ~10X IGRINS CCF SNR capabilities
- This will allow it to access cooler planets that are slower and fainter
- Once online ELTs will *probably* drive composition constraints like IGRINS is currently



STRONGER TOGETHER



^Let's fill this out!^

SUMMARY

- Ground- and space-based data hold complementary information
- Each can alleviate the shortcomings of the other while combining their strengths
- Currently ground-based data is driving composition constraints for transiting hot giant planets (N=2 ;))
- Once online, ELTs will do the same for cooler planets as well

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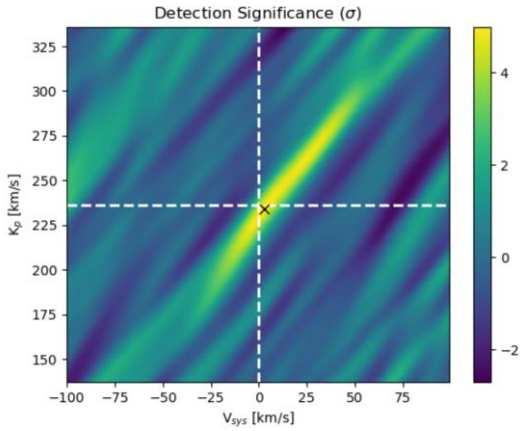
@ExoplanetPete

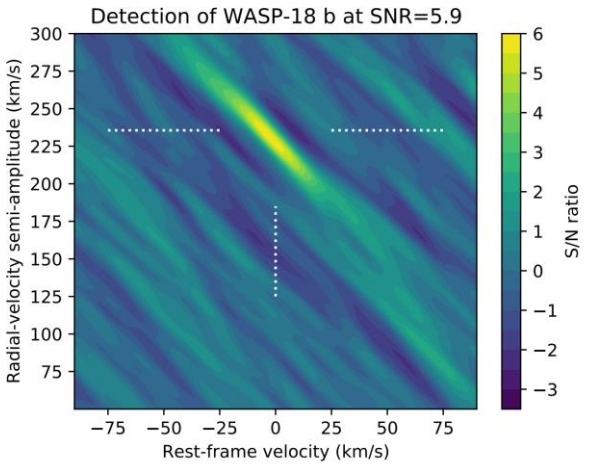
WASP-18 b

Gemini South/IGRINS (new)



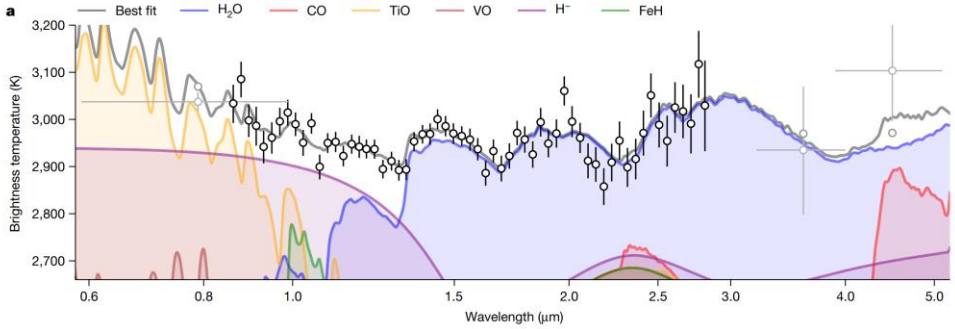
+

Gemini South/IGRINS; Brogi+ 2023



+

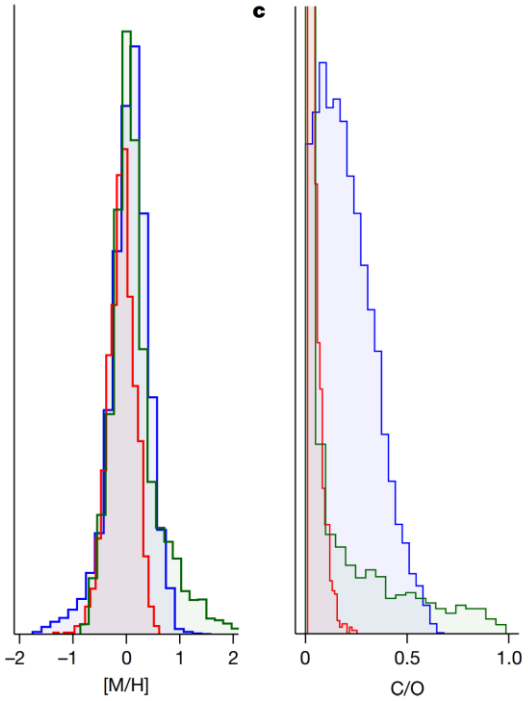
NIRISS SOSS; Coulombe+ 2023

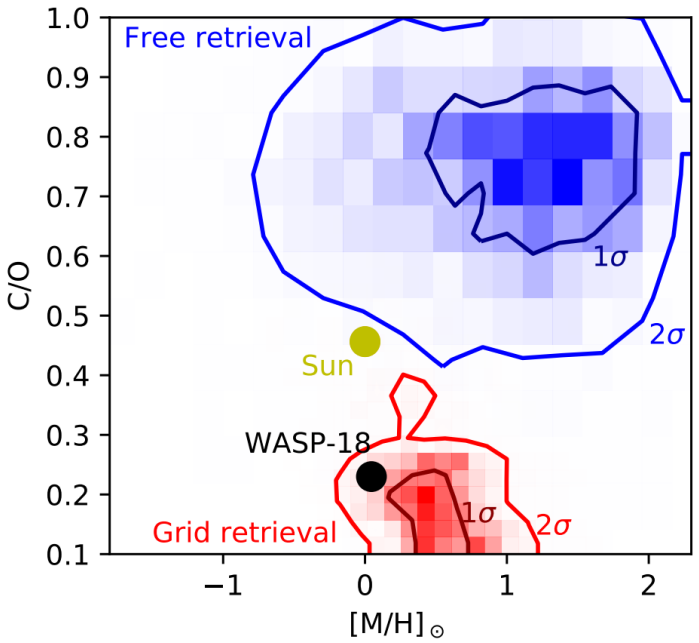


WASP-18 b

- [M/H] measured both with IGRINS and NIRISS SOSS
- Both instruments could only place upper limits on C/O broadly consistent with host star
- UHJ – unique challenges for high or low resolution

Coulombe+ 2023

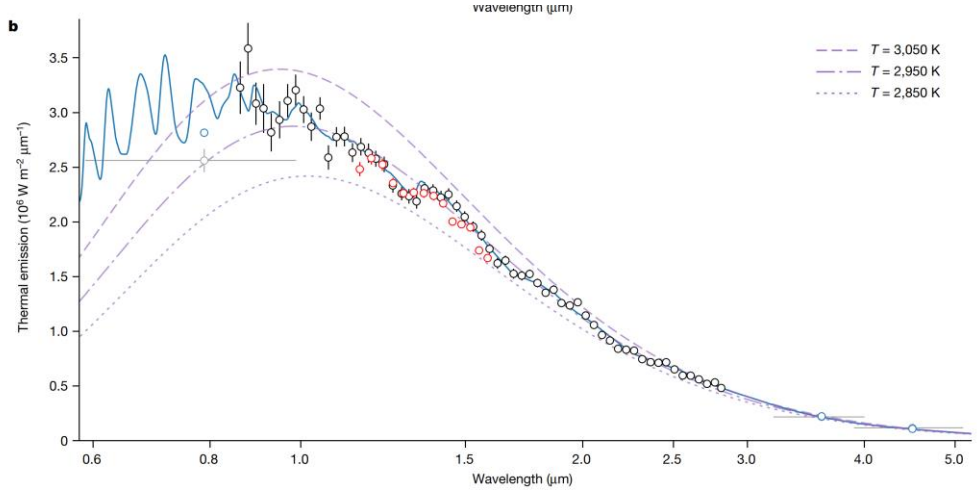


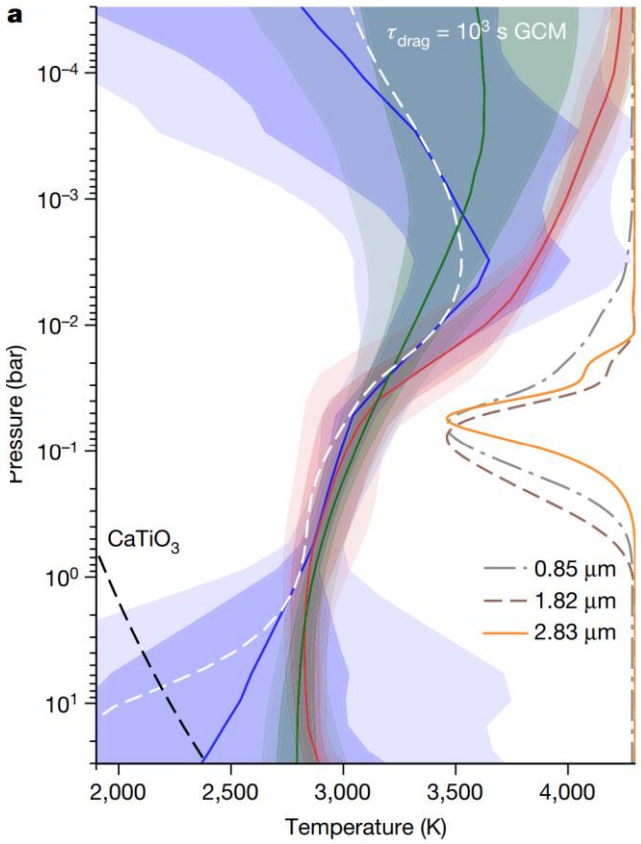


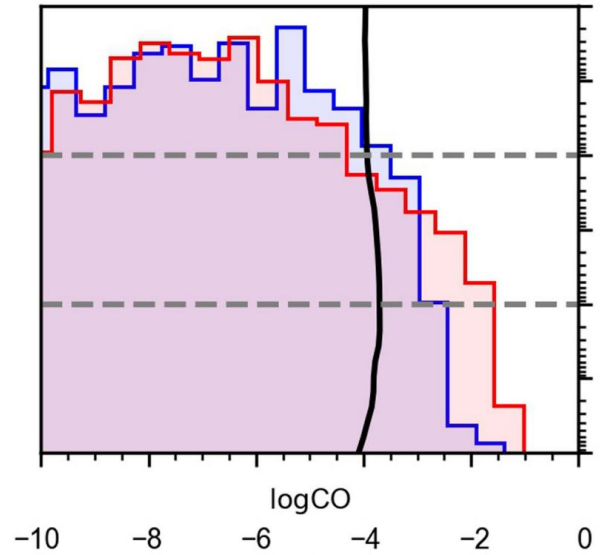
Brogi+ 2023

IGRINS and SOSS have complementary strengths and weaknesses

- SOSS has good grasp of W18's temperature…
- …but probes deep atmosphere where spectral features are weak (e.g., didn't detect CO)

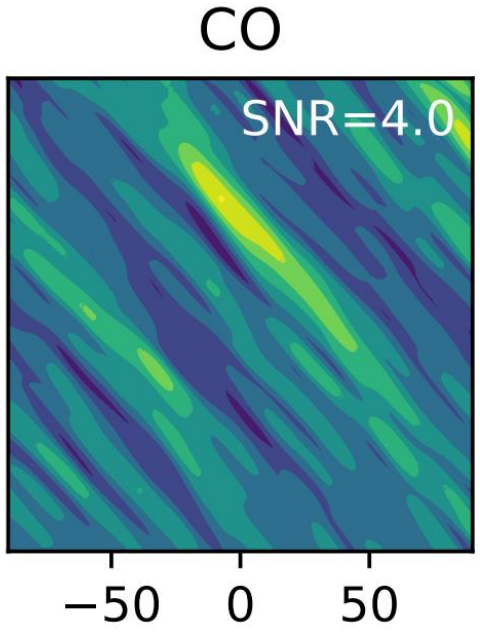


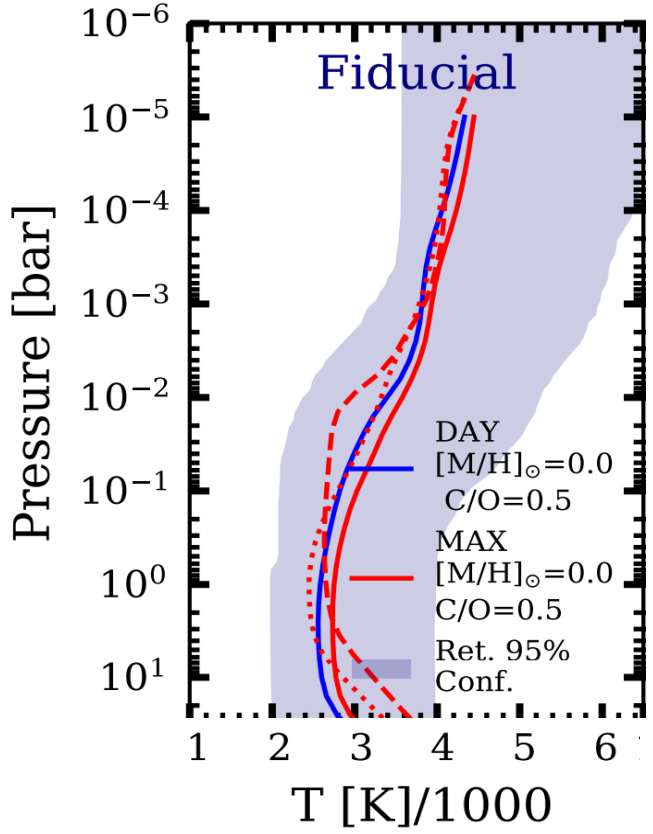




IGRINS and SOSS have complementary strengths and weaknesses

- IGRINS has access to individual line cores at high altitudes…
- …but struggles to break degeneracies with P-T profile (e.g., poorly constrained dilution factor and heat redistribution)

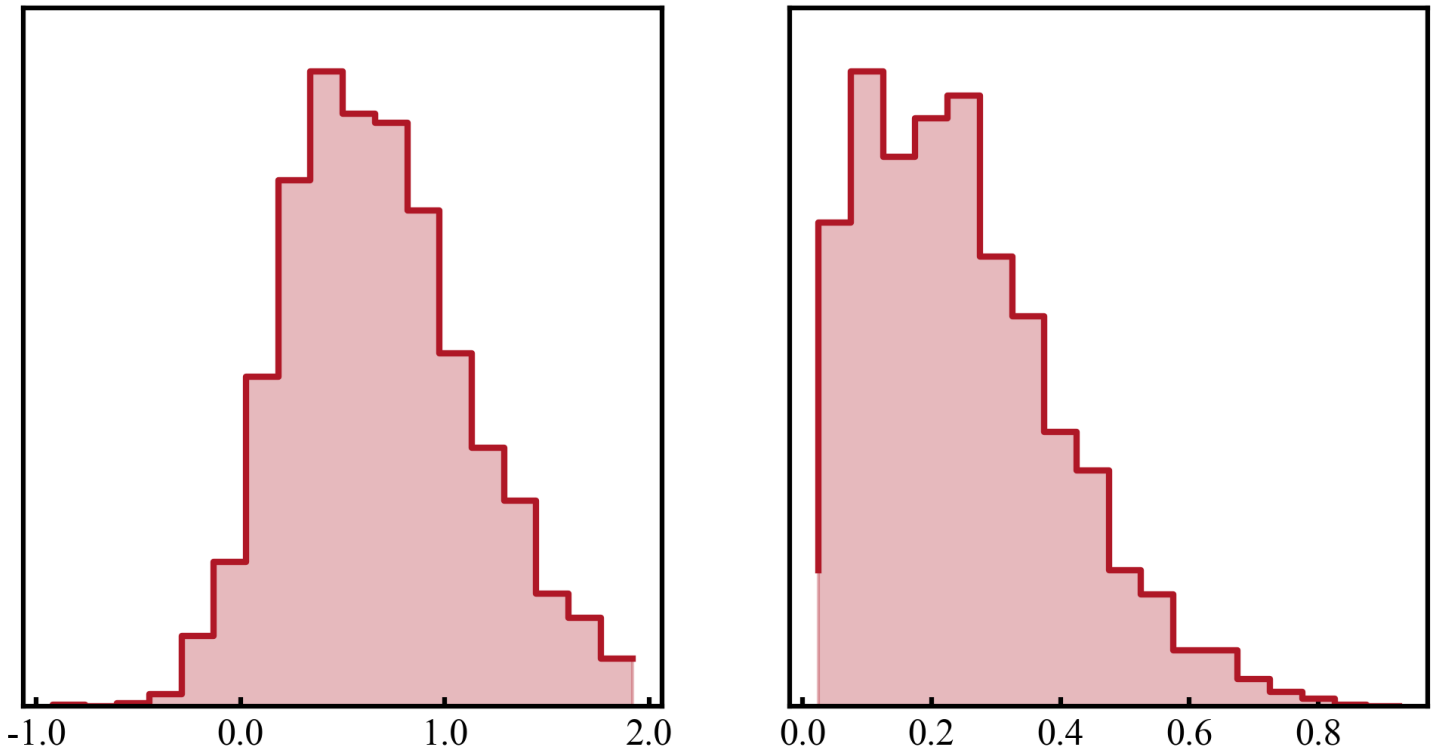




Gas info from IGRINS + PT info from SOSS = increased inference power

$[M/H] = 0.71^{+0.5}_{-0.4}$

$C/O < 0.77$



IGRINS

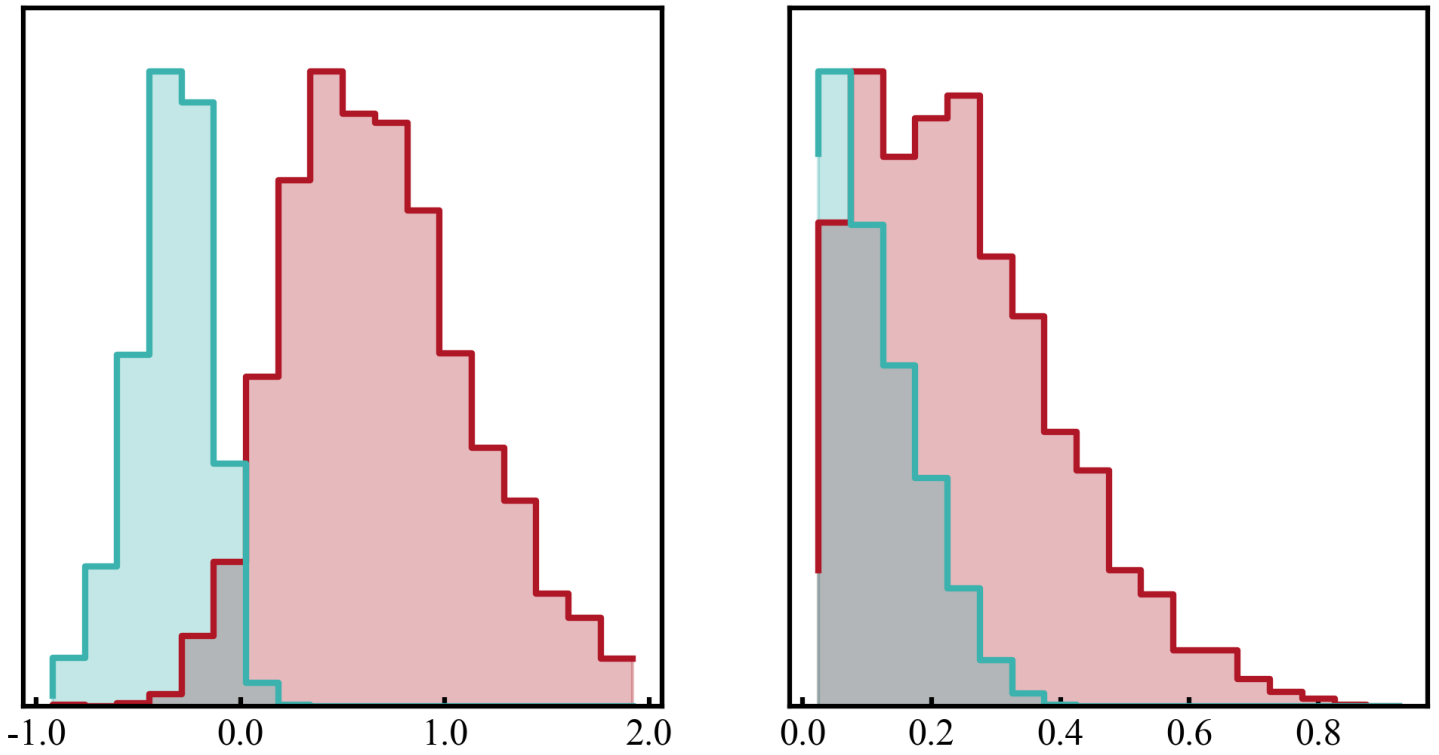
Gas info from IGRINS + PT info from SOSS = increased inference power

$[M/H] = 0.71^{+0.5}_{-0.4}$

$[M/H] = -0.25^{+0.17}_{-0.21}$

$C/O < 0.77$

$C/O < 0.37$



IGRINS

SOSS

Gas info from IGRINS + PT info from SOSS = increased inference power

$[M/H] = 0.71^{+0.5}_{-0.4}$

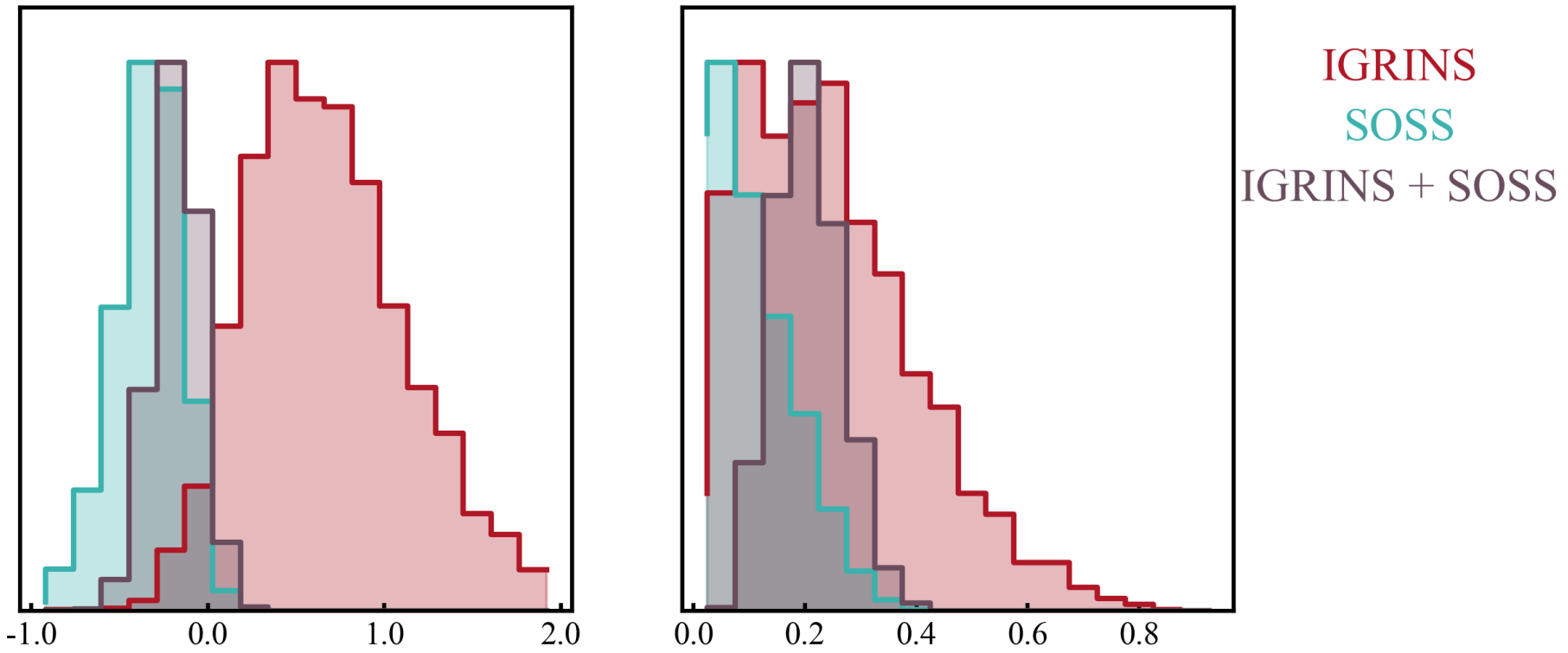
$[M/H] = -0.25^{+0.17}_{-0.21}$

$[M/H] = -0.1^{+0.12}_{-0.14}$

$C/O < 0.77$

$C/O < 0.37$

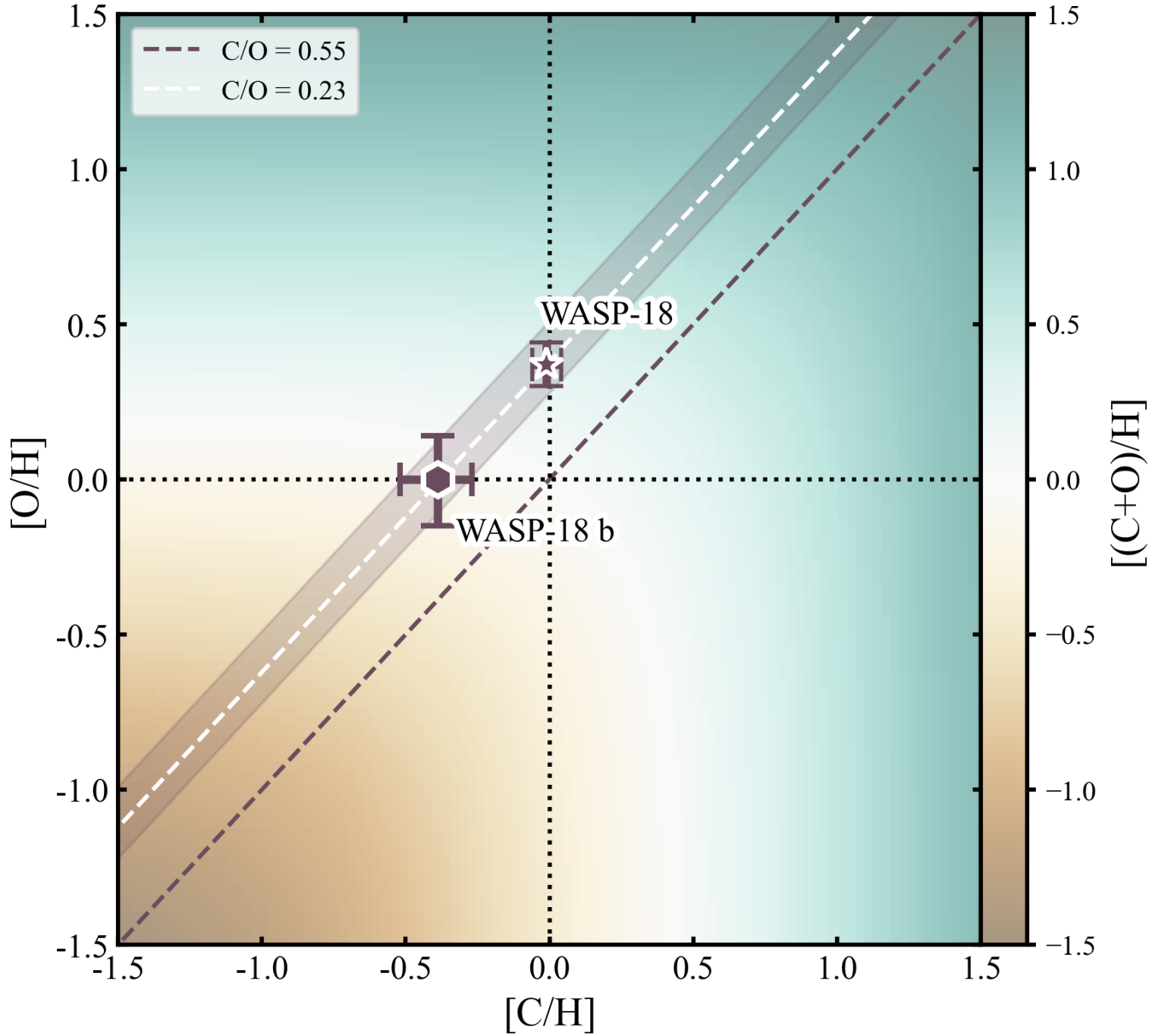
$C/O = 0.23^{+0.06}_{-0.06}$

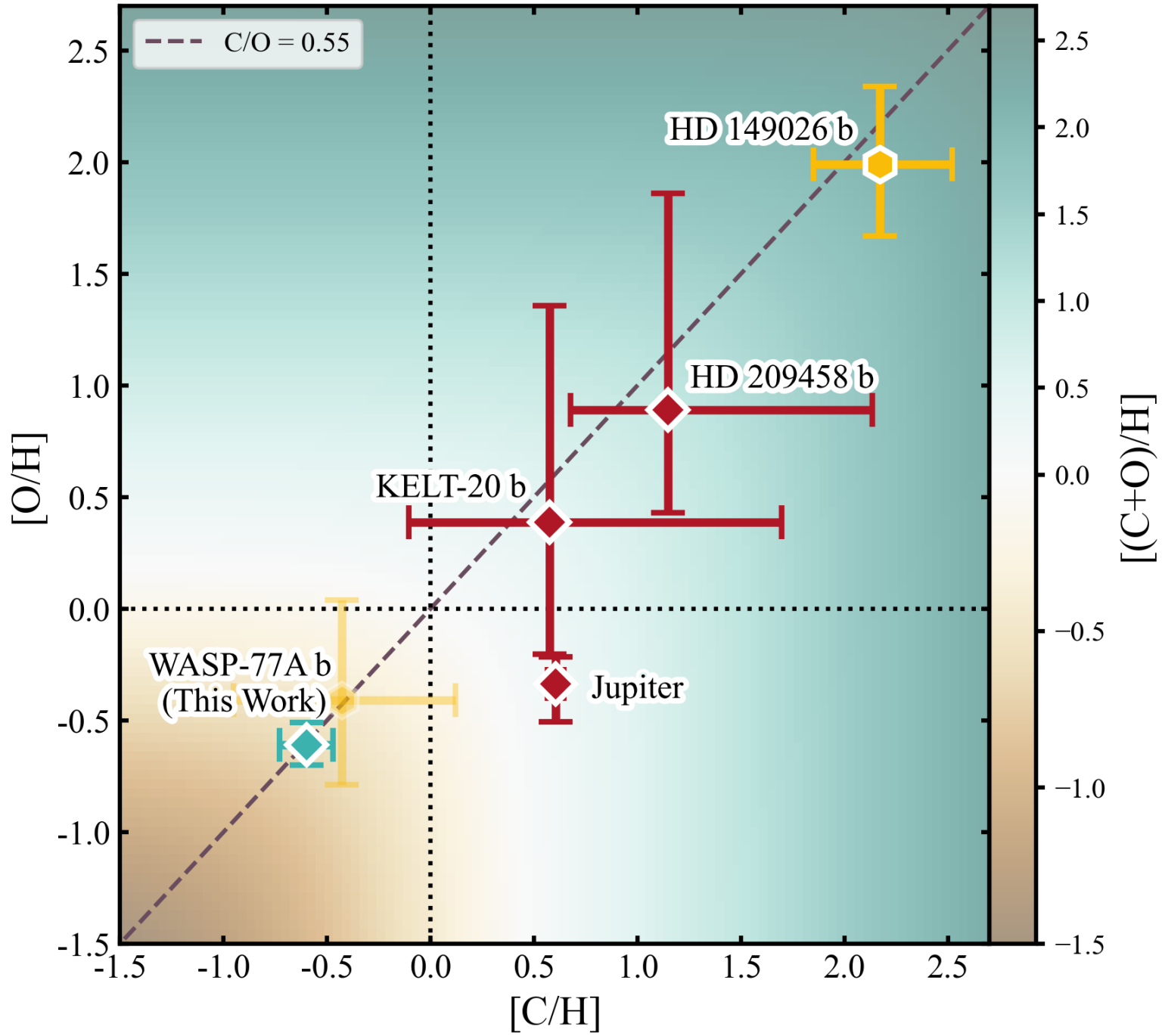


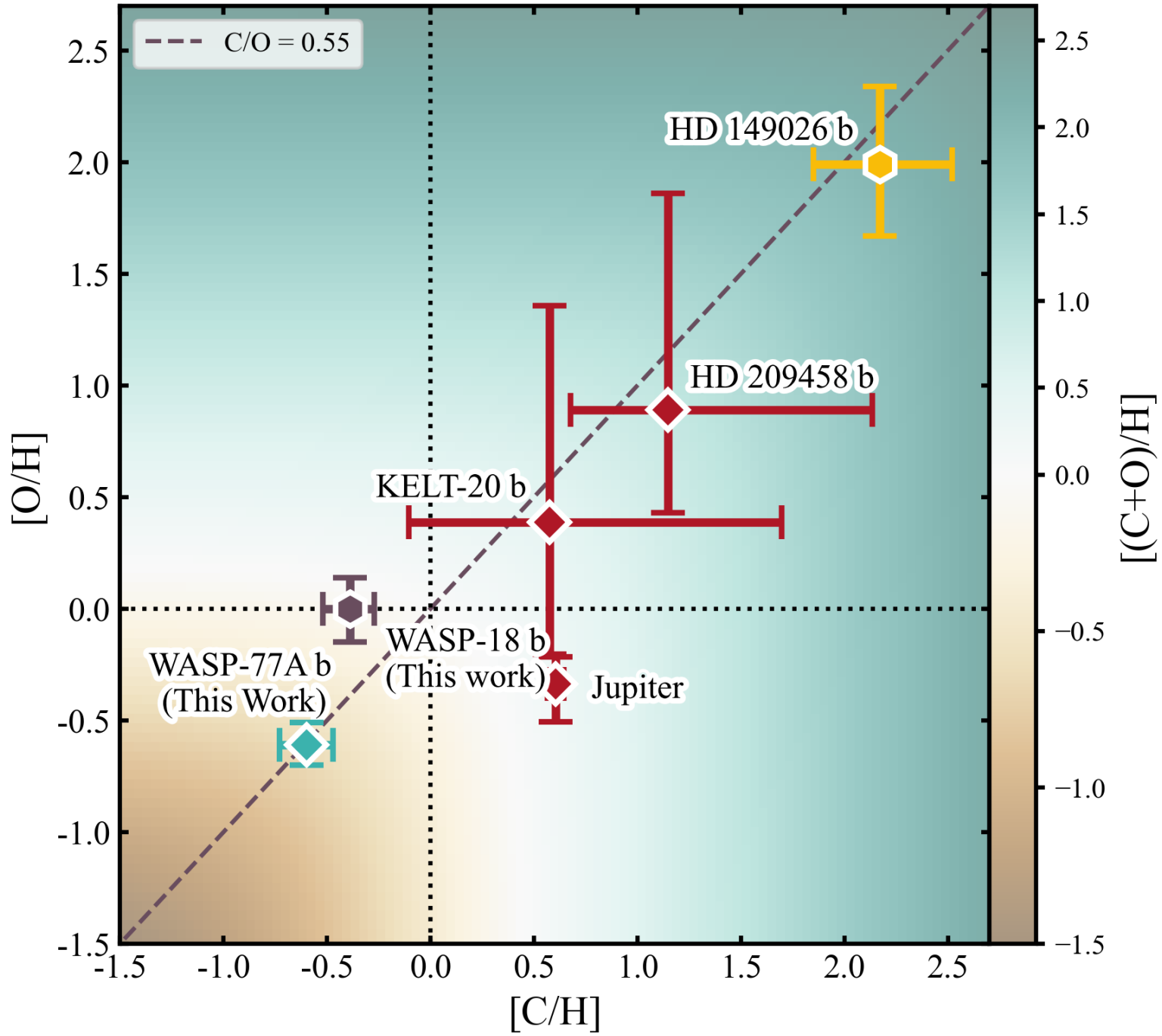
IGRINS

SOSS

IGRINS + SOSS


C/O = 0.55
C/O = 0.23
WASP-18
WASP-18 b
[O/H]
[C/H]
[(C+O)/H]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
−0.5
−1.0
−1.5


C/O = 0.55
HD 149026 b
HD 209458 b
KELT-20 b
Jupiter
WASP-77A b
(This Work)
[O/H]
[C/H]
[(C+O)/H]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5


C/O = 0.55
HD 149026 b
HD 209458 b
KELT-20 b
WASP-18 b
(This work)
WASP-77A b
(This Work)
Jupiter
[O/H]
[C/H]
[(C+O)/H]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5