This work is published in AJ!

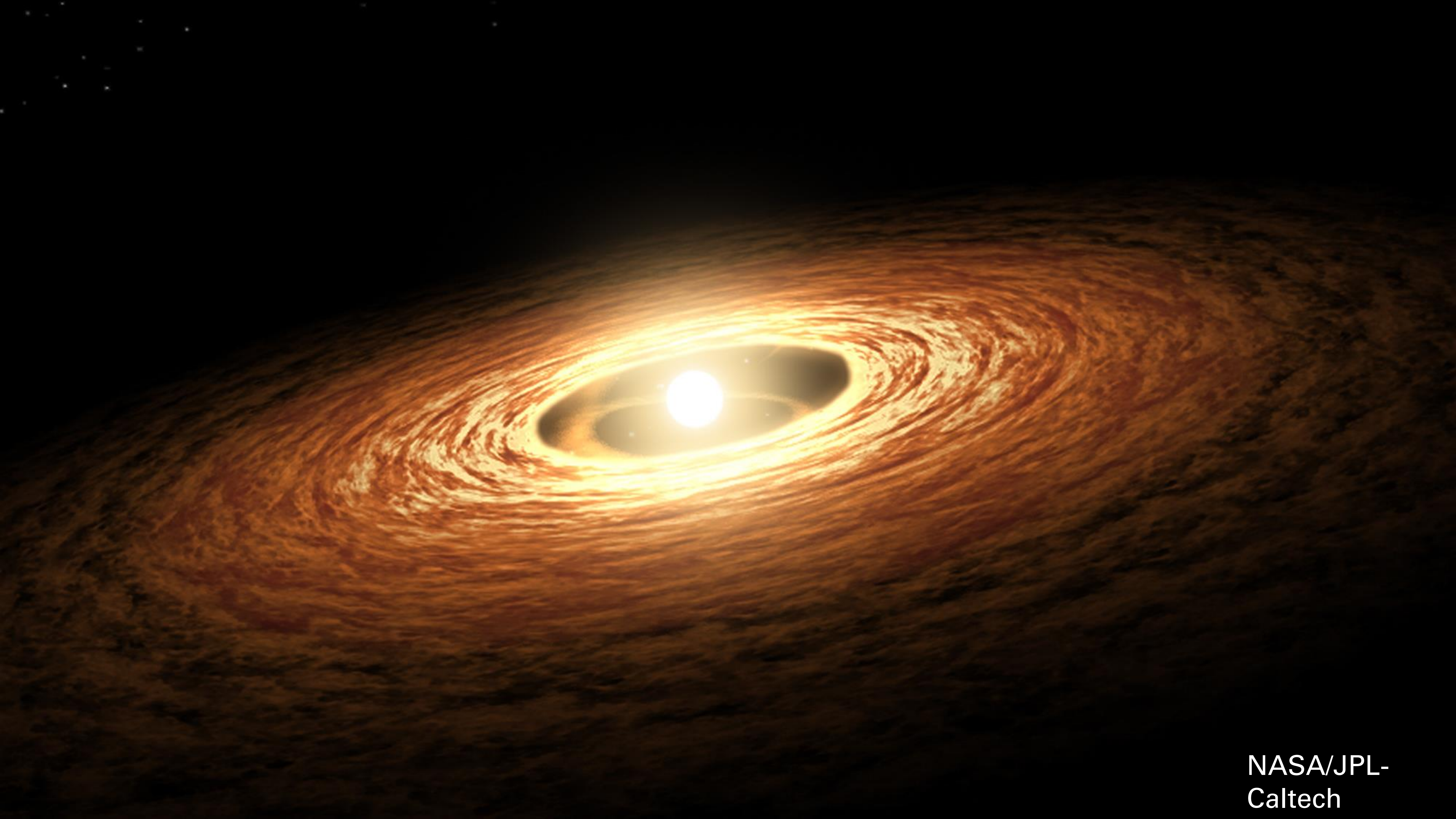
STRONGER TOGETHER:

EXPANDING ATMOSPHERIC INFERENCE CAPABILITIES BY COMBINING GROUND-BASED AND JWST SPECTRA

ExoPAG ExoExplorers Series, 7 March, 2025

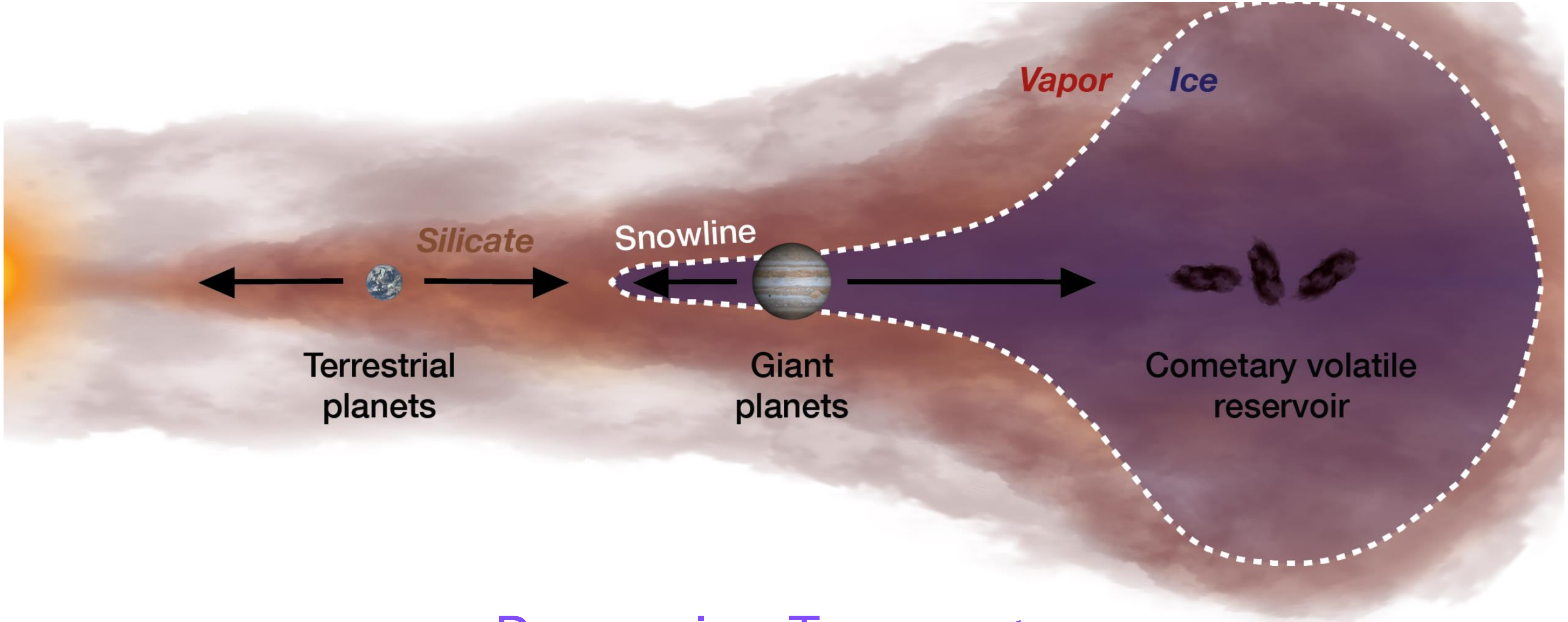
Peter Smith, Michael Line, Jacob Bean, Matteo Brogi, Prune August, Luis Welbanks, Jean-Michel Desert, Jonathan Lunine, Jorge Sanchez, Megan Weiner Mansfield, Lorenzo Pino, Emily Rauscher, Eliza Kempton, Joseph Zalesky, and Martin Fowler

Arizona State University



NASA/JPL-
Caltech

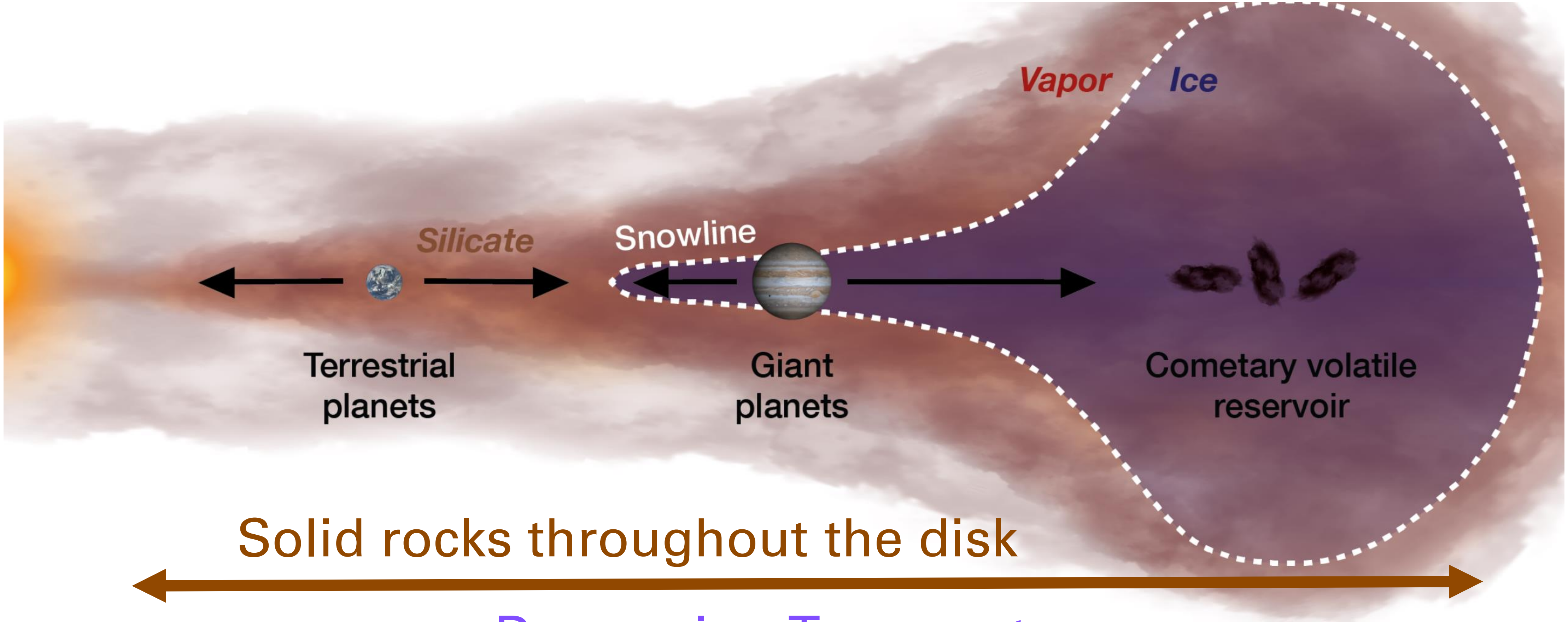
Protoplanetary Disk Cross Section



Decreasing Temperature
w/ Increasing Distance

Pontoppidan+ 2019

Protoplanetary Disk Cross Section

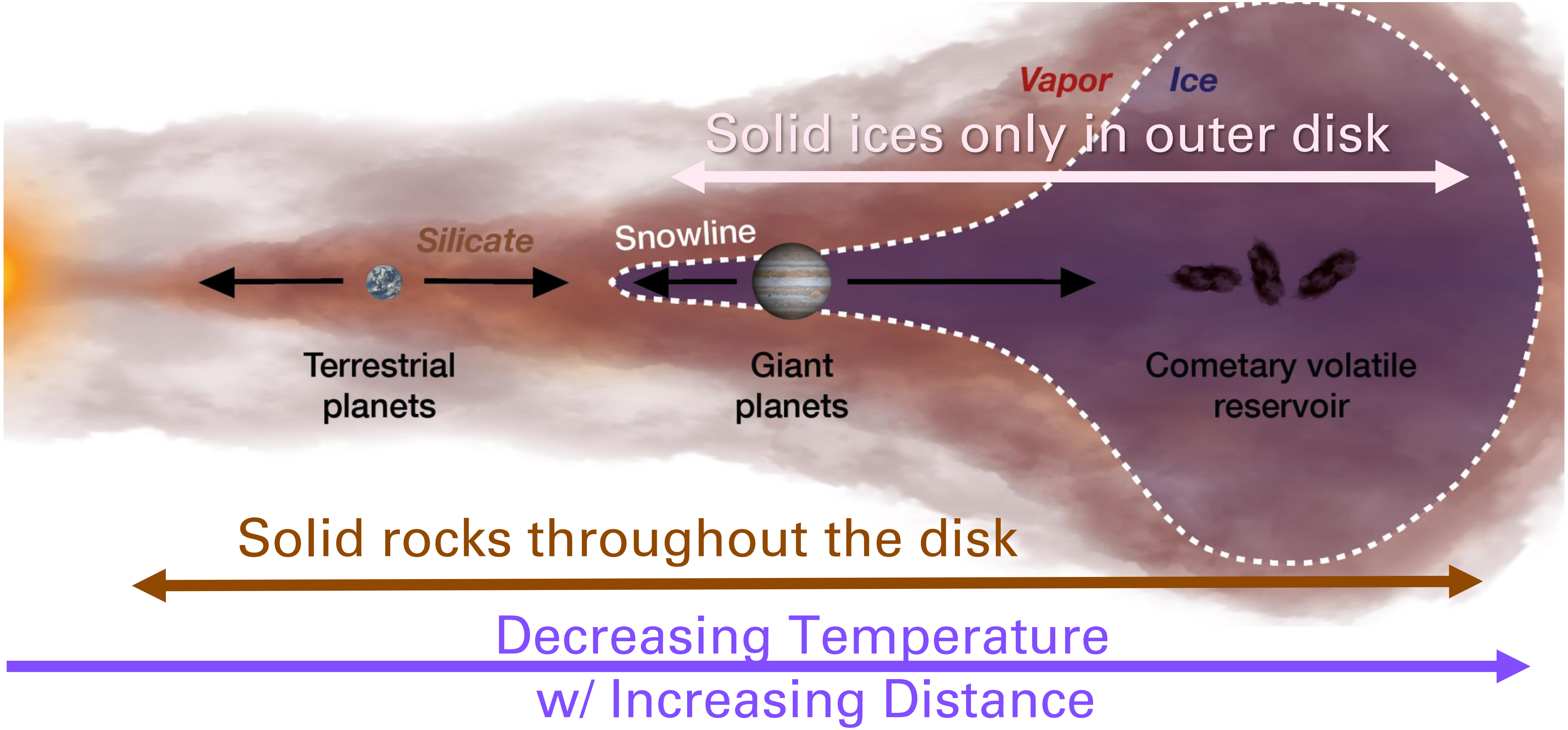


Solid rocks throughout the disk

Decreasing Temperature
w/ Increasing Distance

Pontoppidan+ 2019

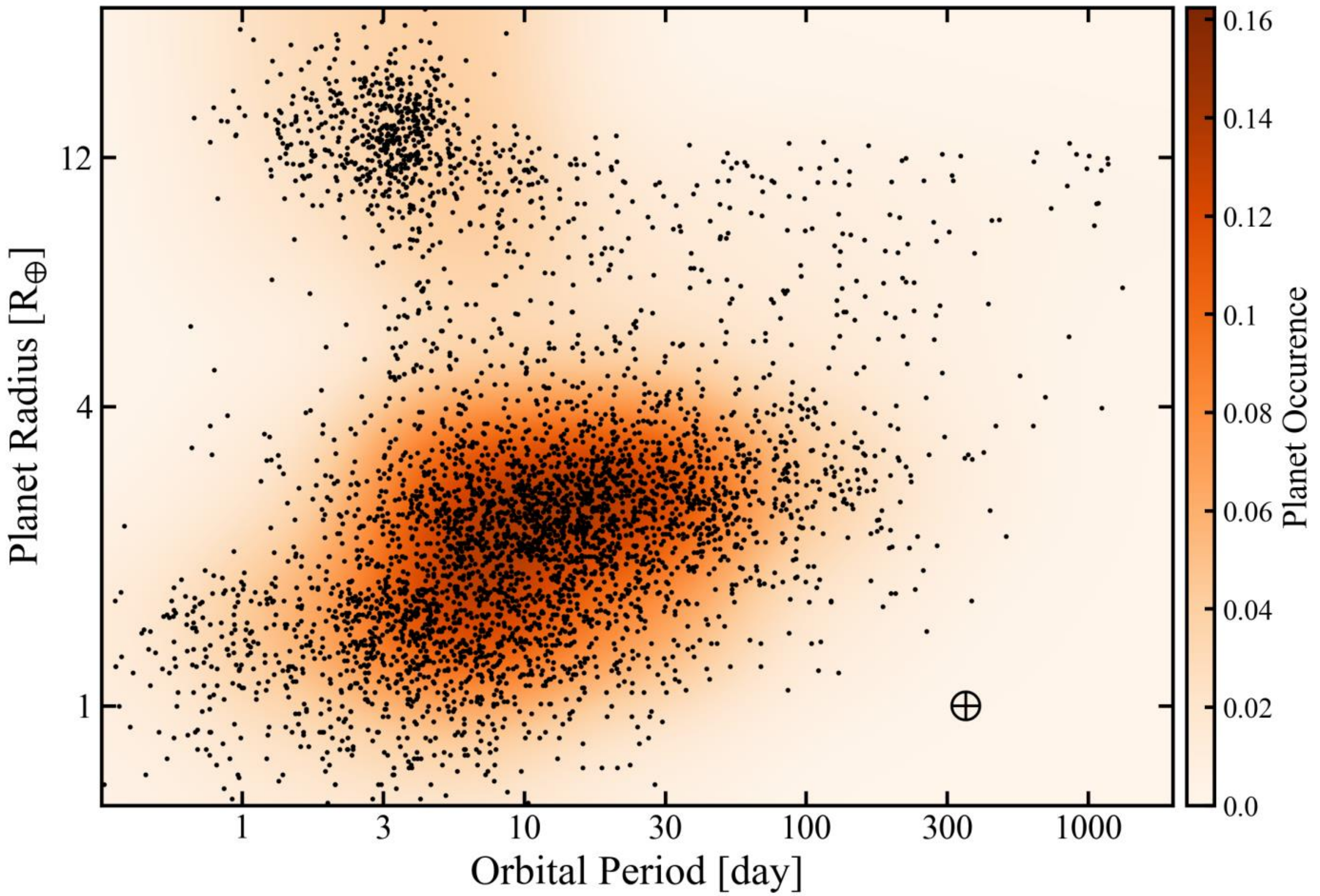
Protoplanetary Disk Cross Section



Pontoppidan+ 2019

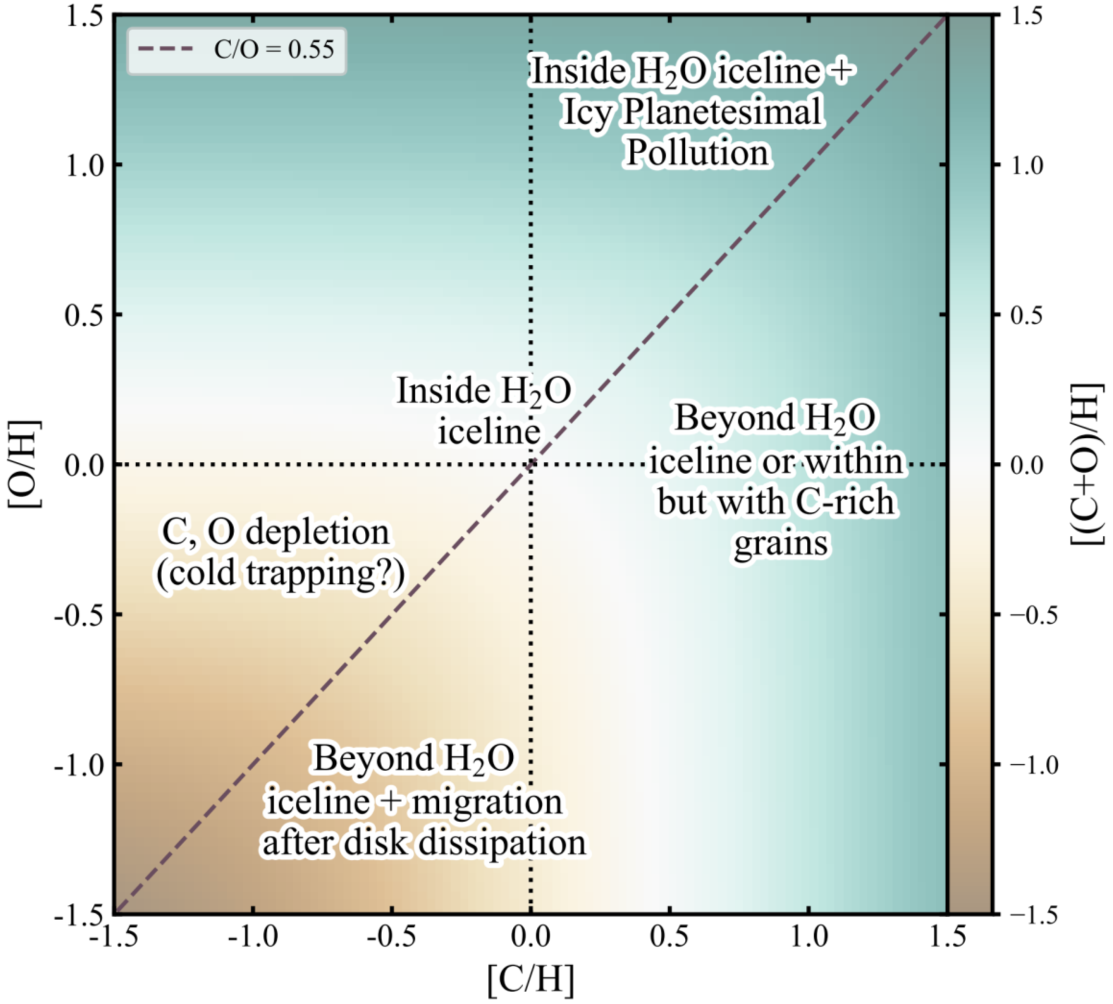
More planets, more problems

- The exoplanet population is much more diverse and varied than our own solar system
- Our solar system is atypical, posing fundamental questions about planet formation and evolution (e.g., hot Jupiters, sub-Neptunes, tidal locking)
- Fortunately, we can use the diversity of the exoplanet population to systematically fill in these knowledge gaps by studying their **atmospheres**



Tying Composition to Formation

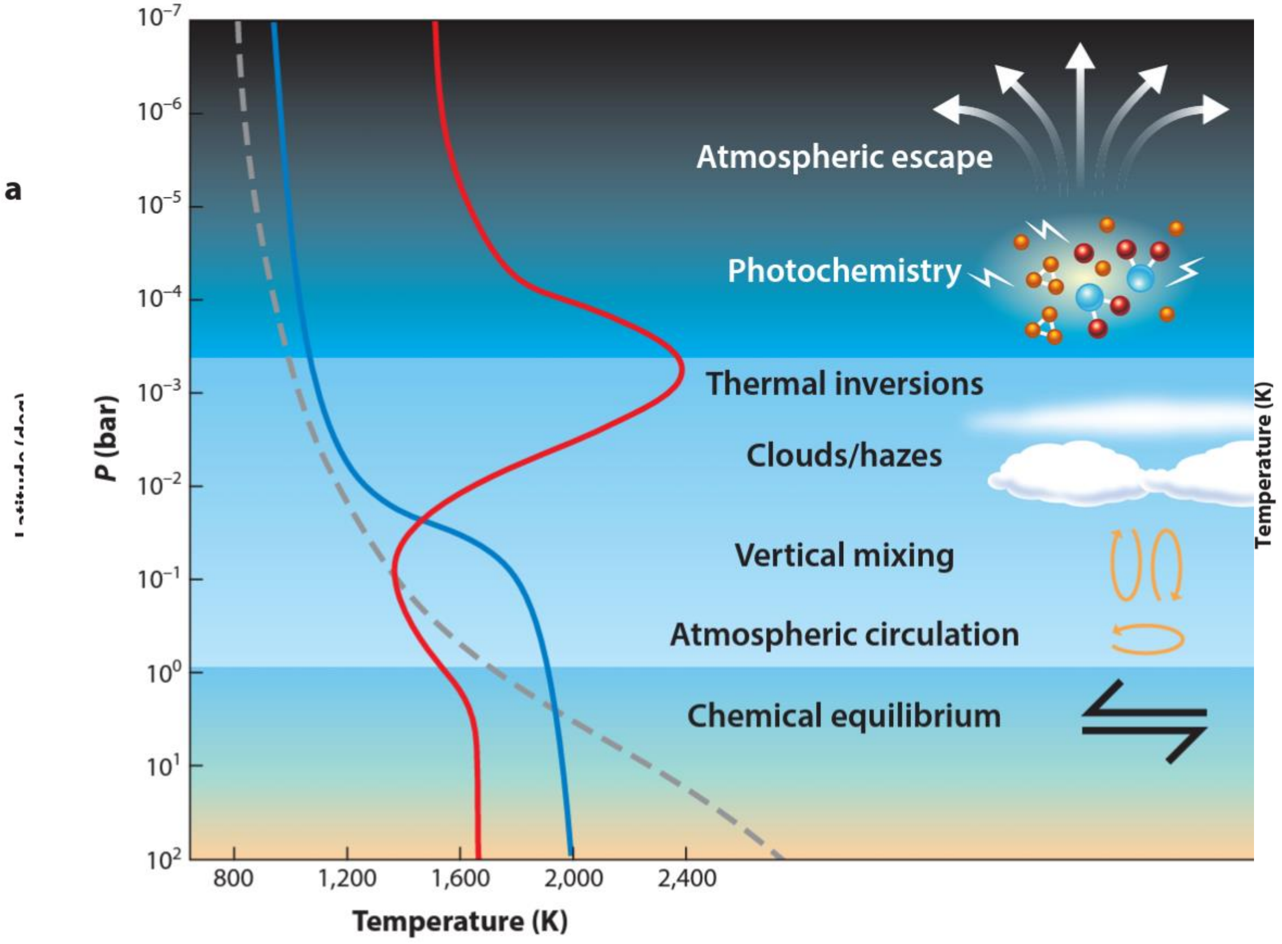
- A planet's formation conditions and migration history imprint themselves on its atmospheric composition
- Composition measurements help place the planet back to its origins and allows us to test formation theories
- Major goal of exoplanet science: fill out this plot!→
- This requires good measurements of *multiple* **elemental inventories and ratios** in exoplanet atmospheres



Based on summarized predictions in Reggiani+ 2022

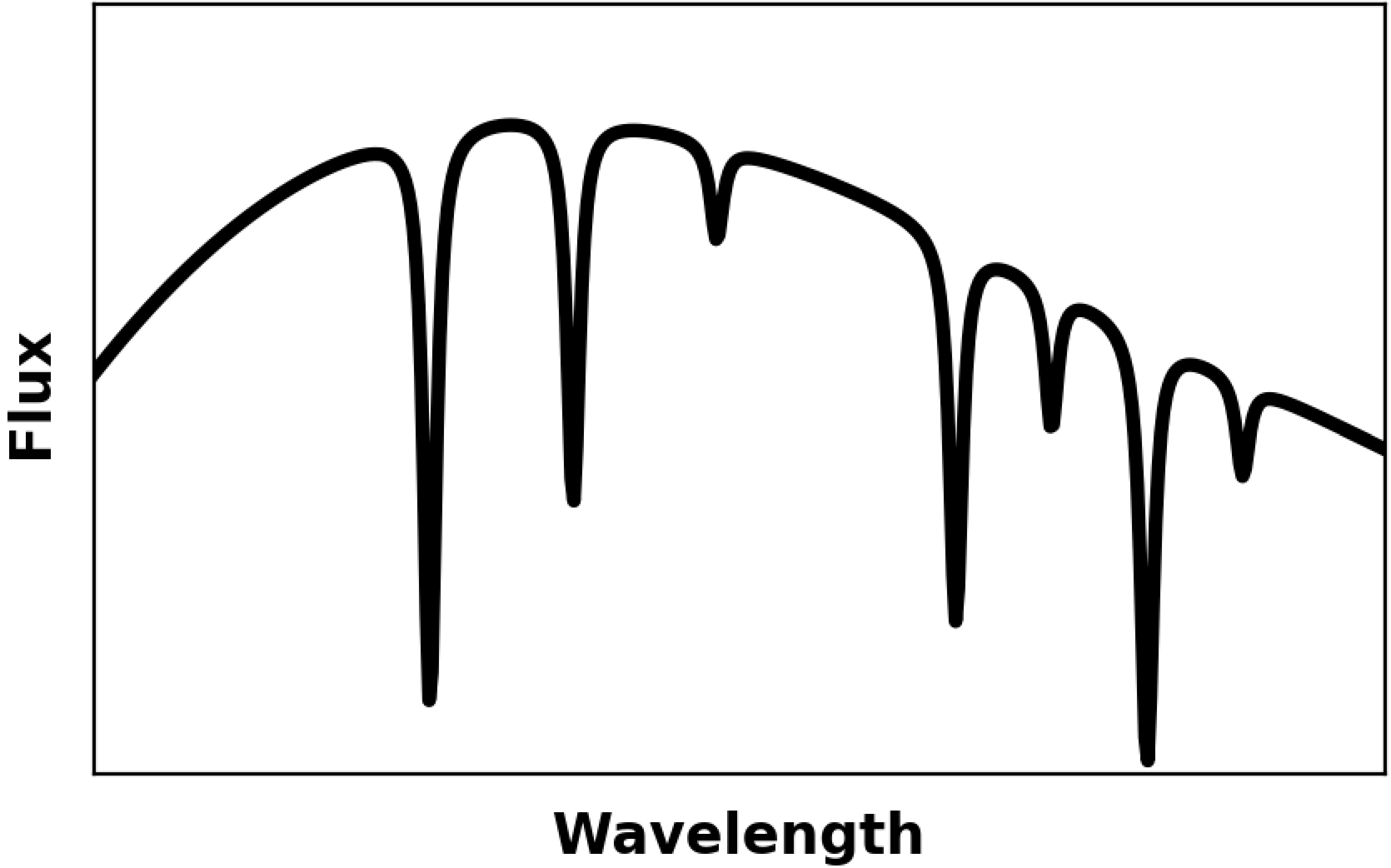
Climate and Energy

- Climate and atmospheric dynamics tells us how energy is transported around the planet
- Close in, tidally locked planets (such as TRAPPIST-1 planets) have poor, non-uniform heat redistribution
- The shape of the **vertical thermal structure** (the P-T profile) is shaped by the efficiency of heat redistribution
- We want to know the physical mechanisms that govern this efficiency

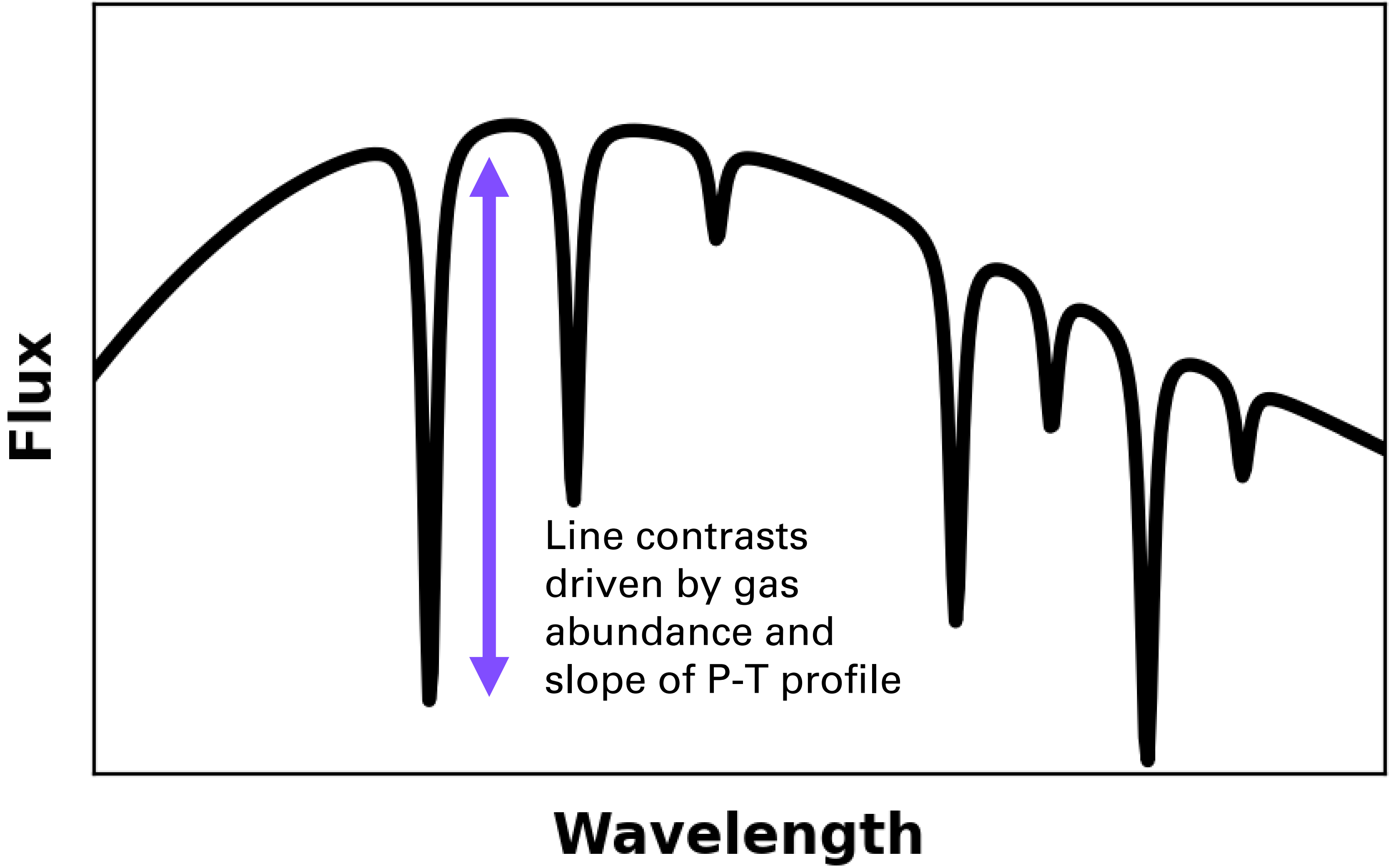


Figs. From Madhusudhan 2019

Spectroscopy of Exoplanets

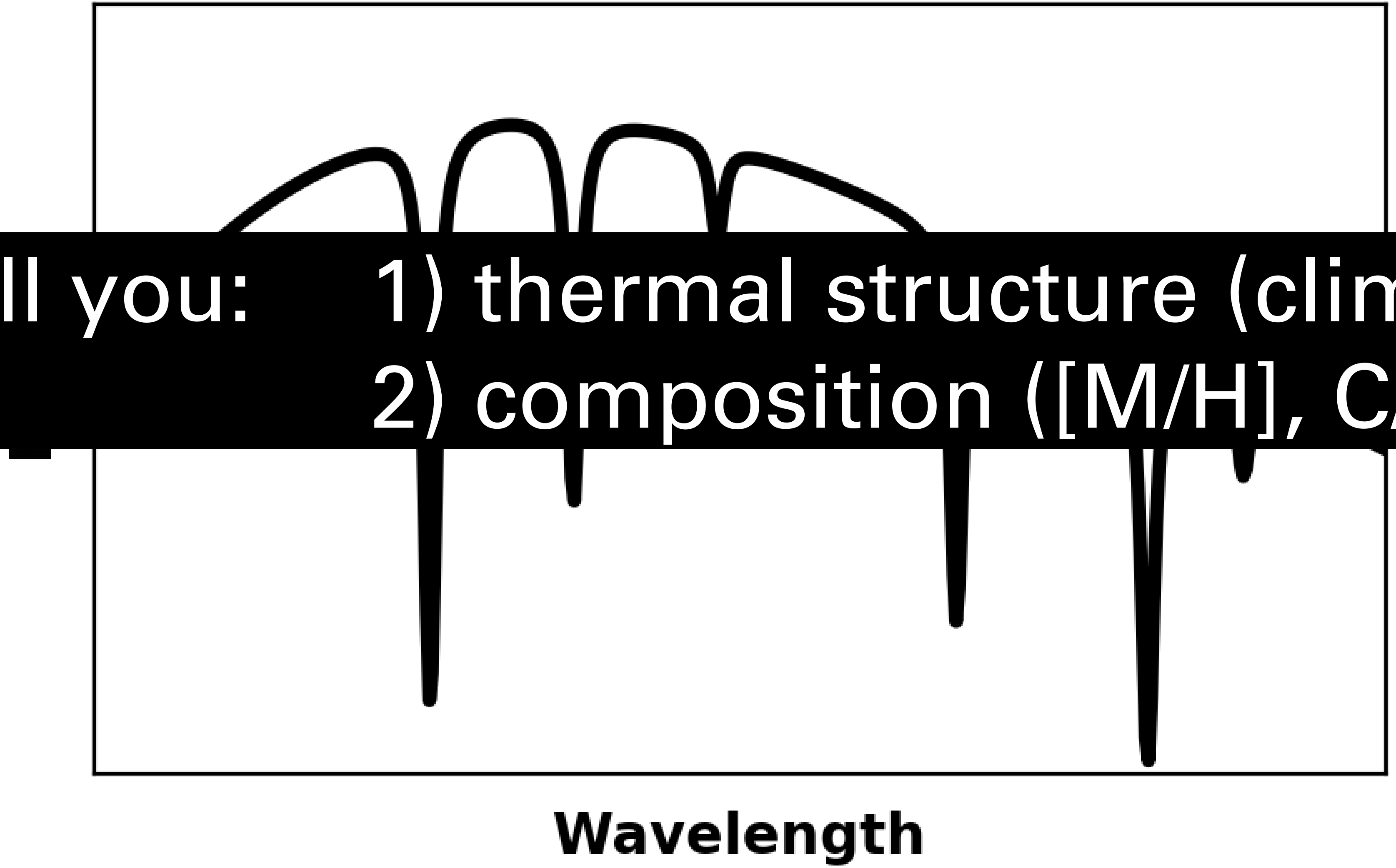


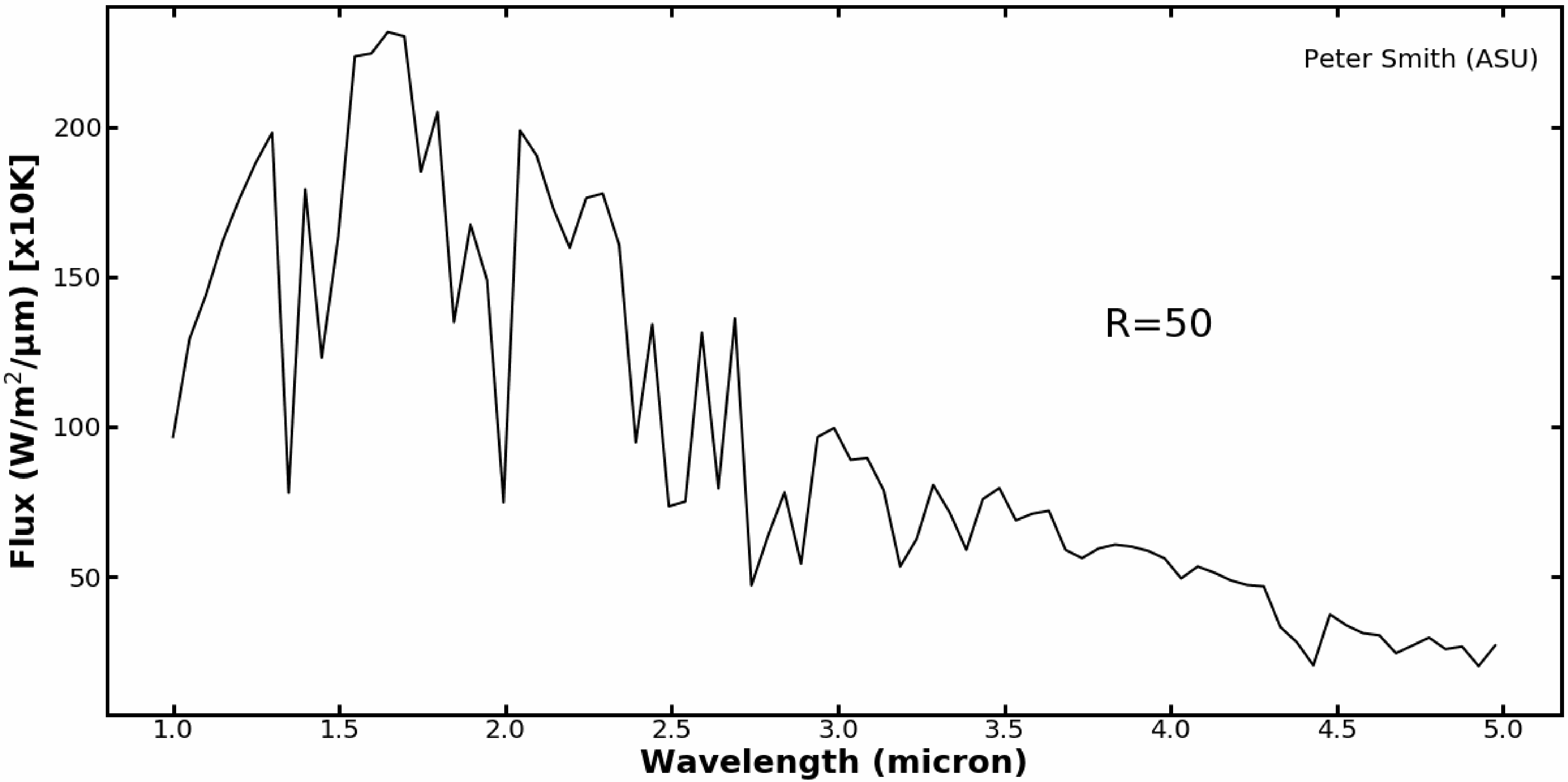
Spectroscopy of Exoplanets



Spectroscopy of Exoplanets

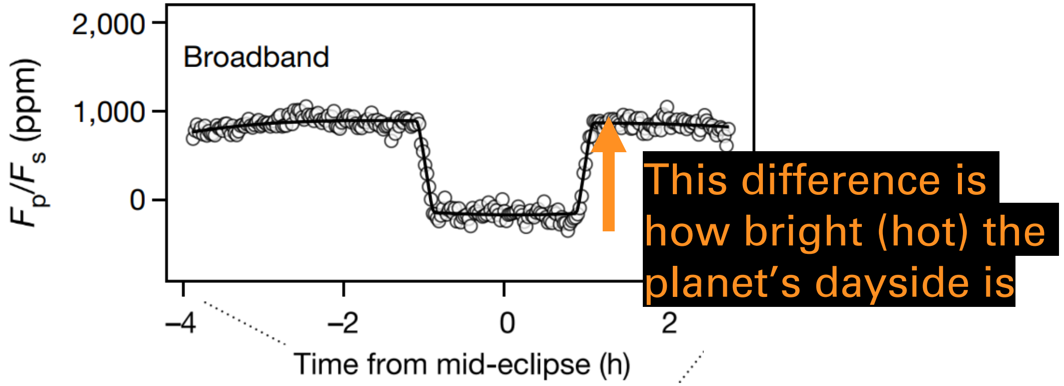
Can tell you: 1) thermal structure (climate)
2) composition ([M/H], C/O, etc)




Peter Smith (ASU)
R=50
Flux (W/m²/μm) [x10K]
Wavelength (micron)
200
150
100
50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Low-Resolution Spectroscopy

1) Measure **eclipse depth**



Figures from Coulombe+ 2023

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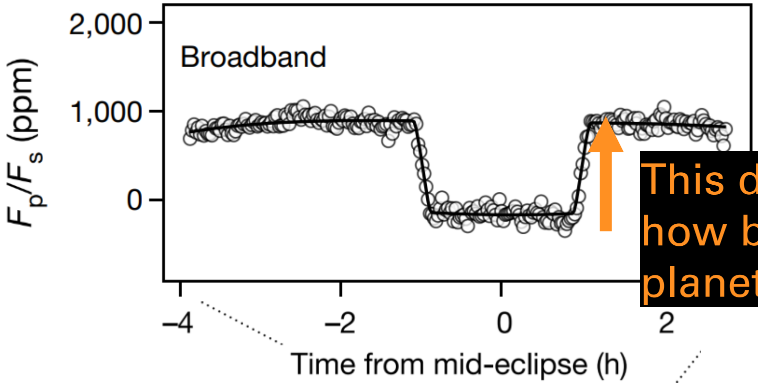
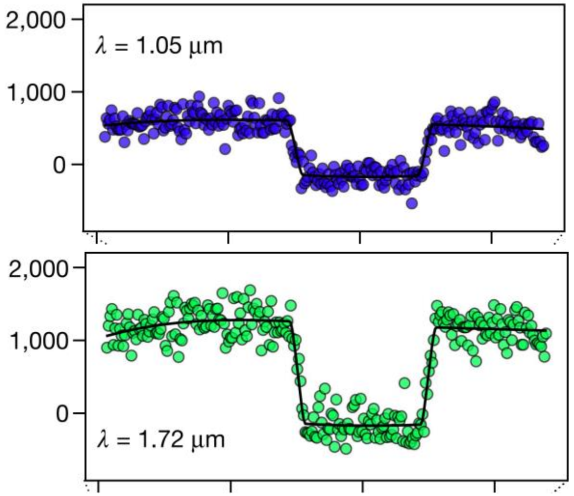


This difference is how bright (hot) the planet's dayside is

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



Figures from Coulombe+ 2023

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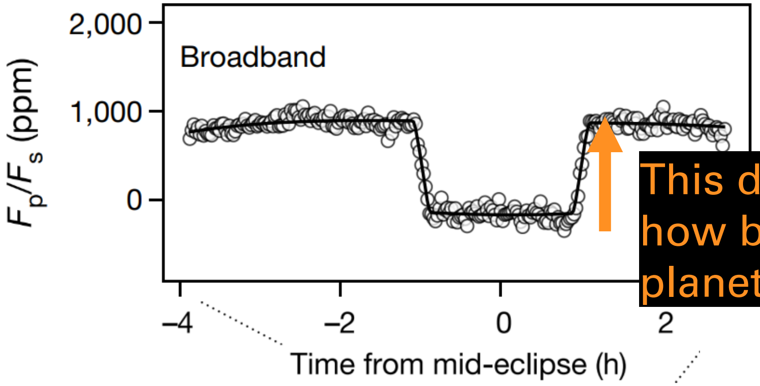

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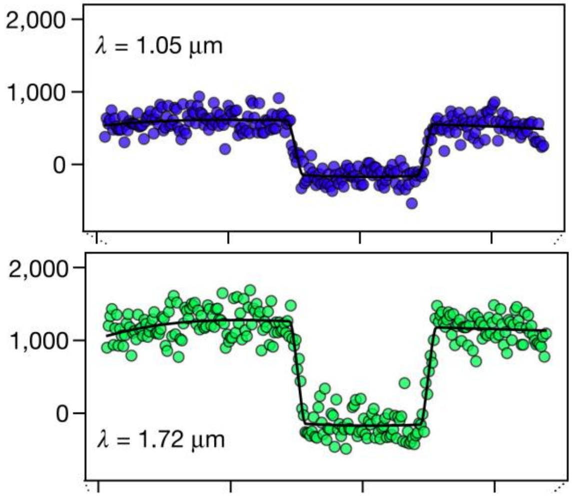
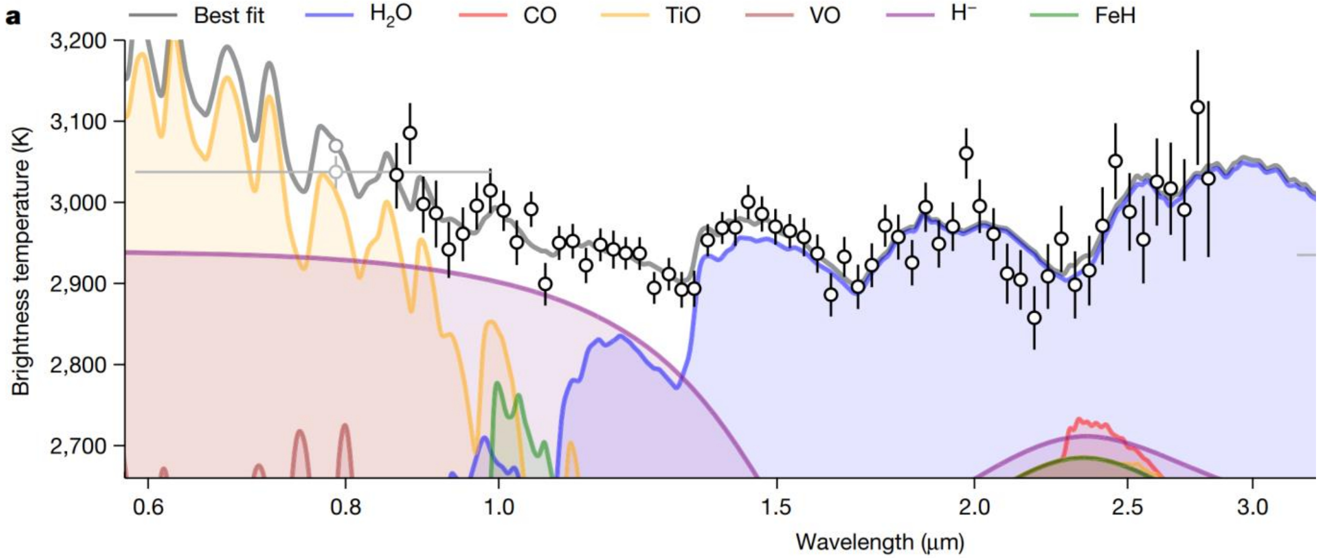


3) Eclipse Depth or Brightness Temperature **Spectrum**



Figures from Coulombe+ 2023

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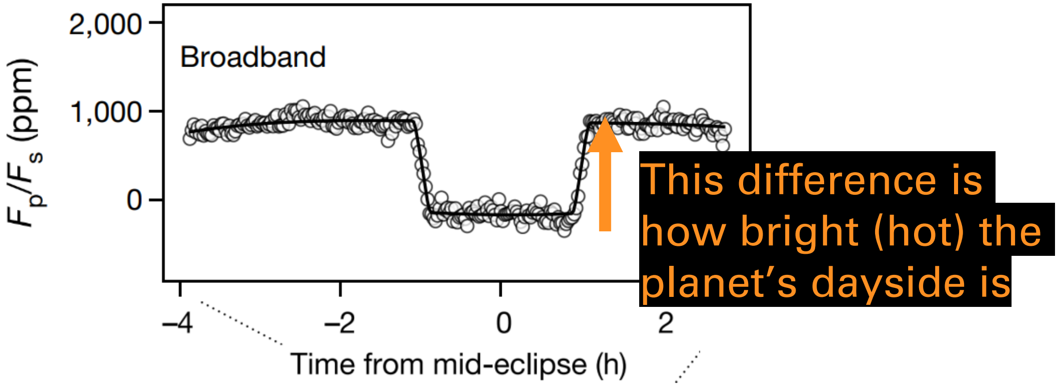

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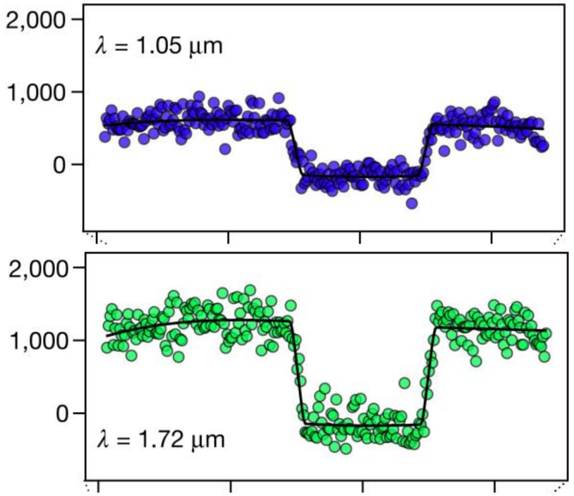

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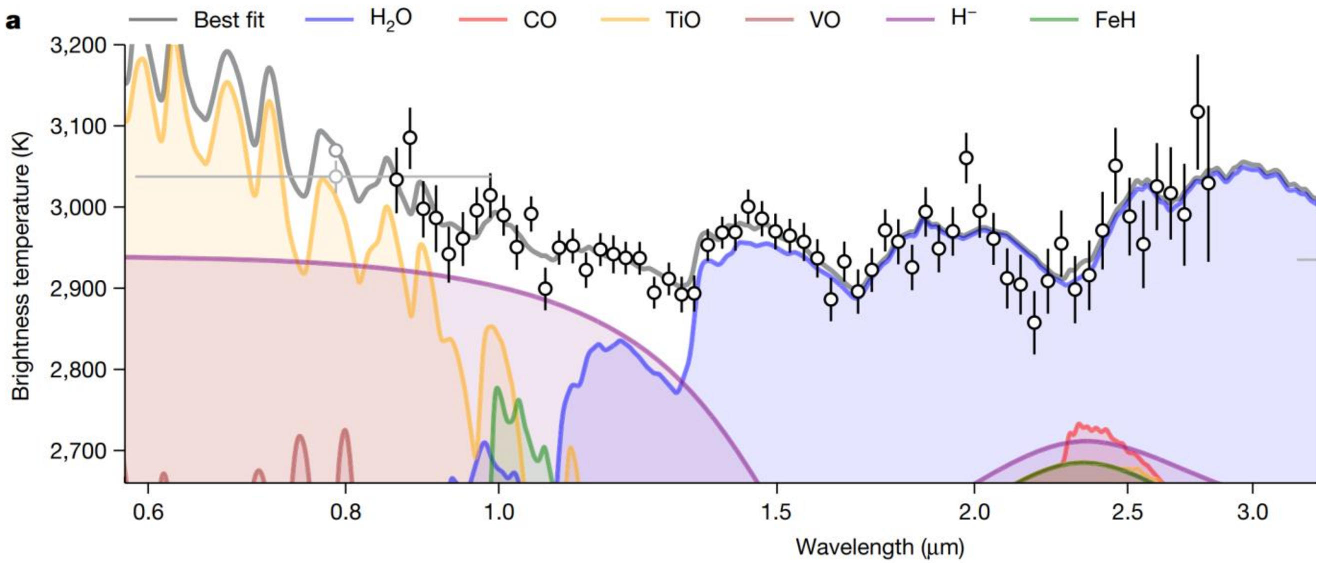
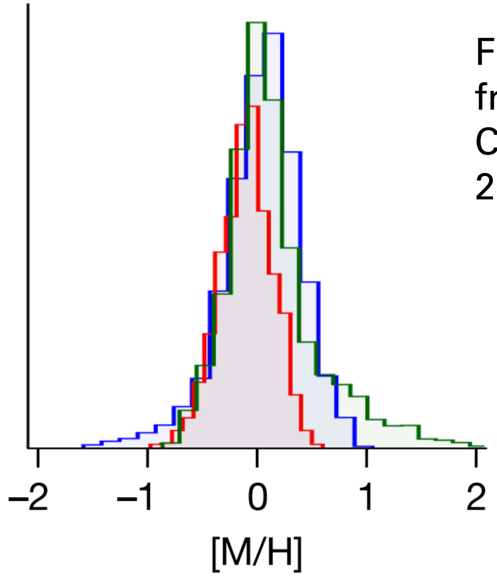
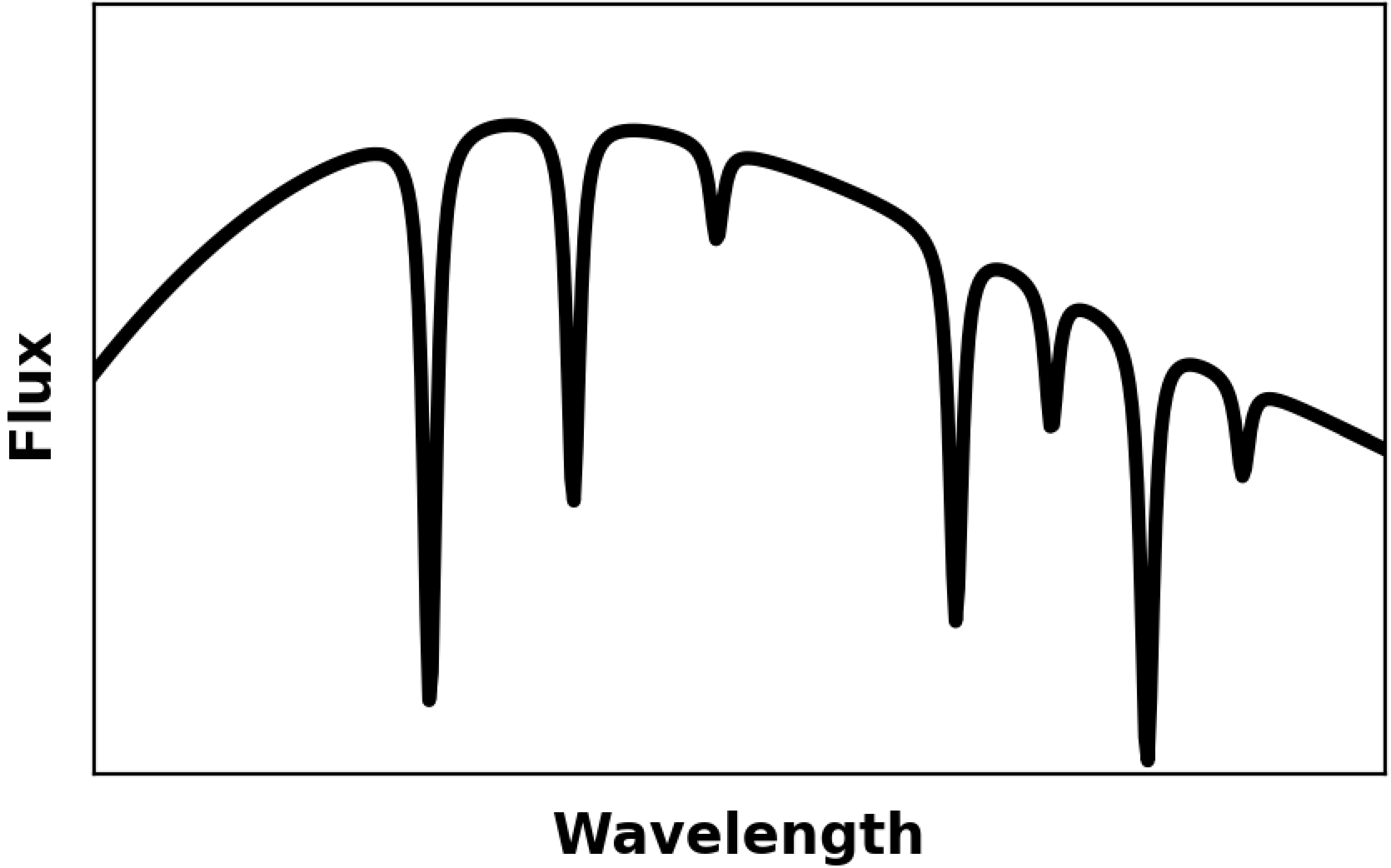


4) Bayesian Inference (**retrieval**)

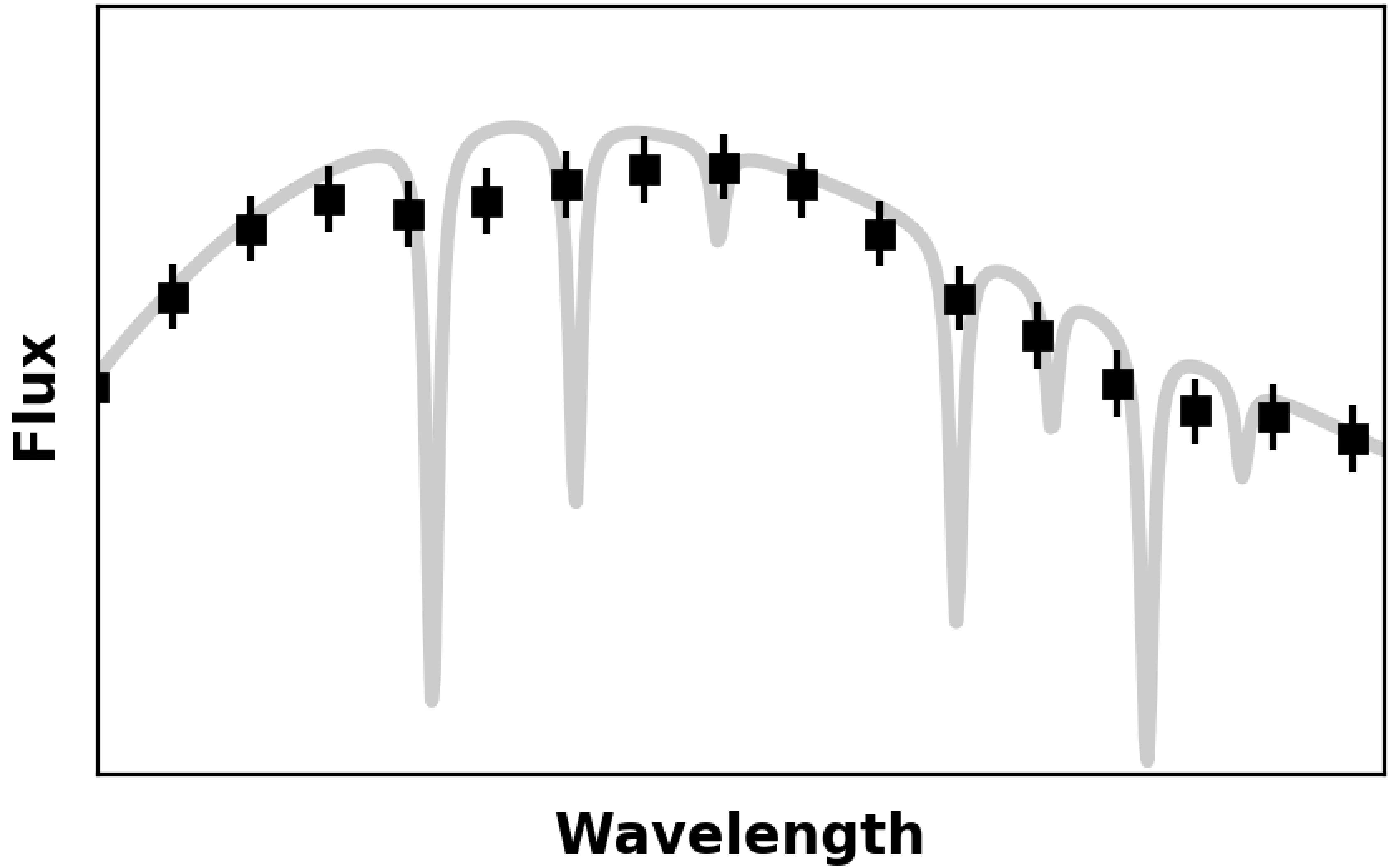


Figures from Coulombe+ 2023

Low-Resolution Spectroscopy



Low-Resolution Spectroscopy



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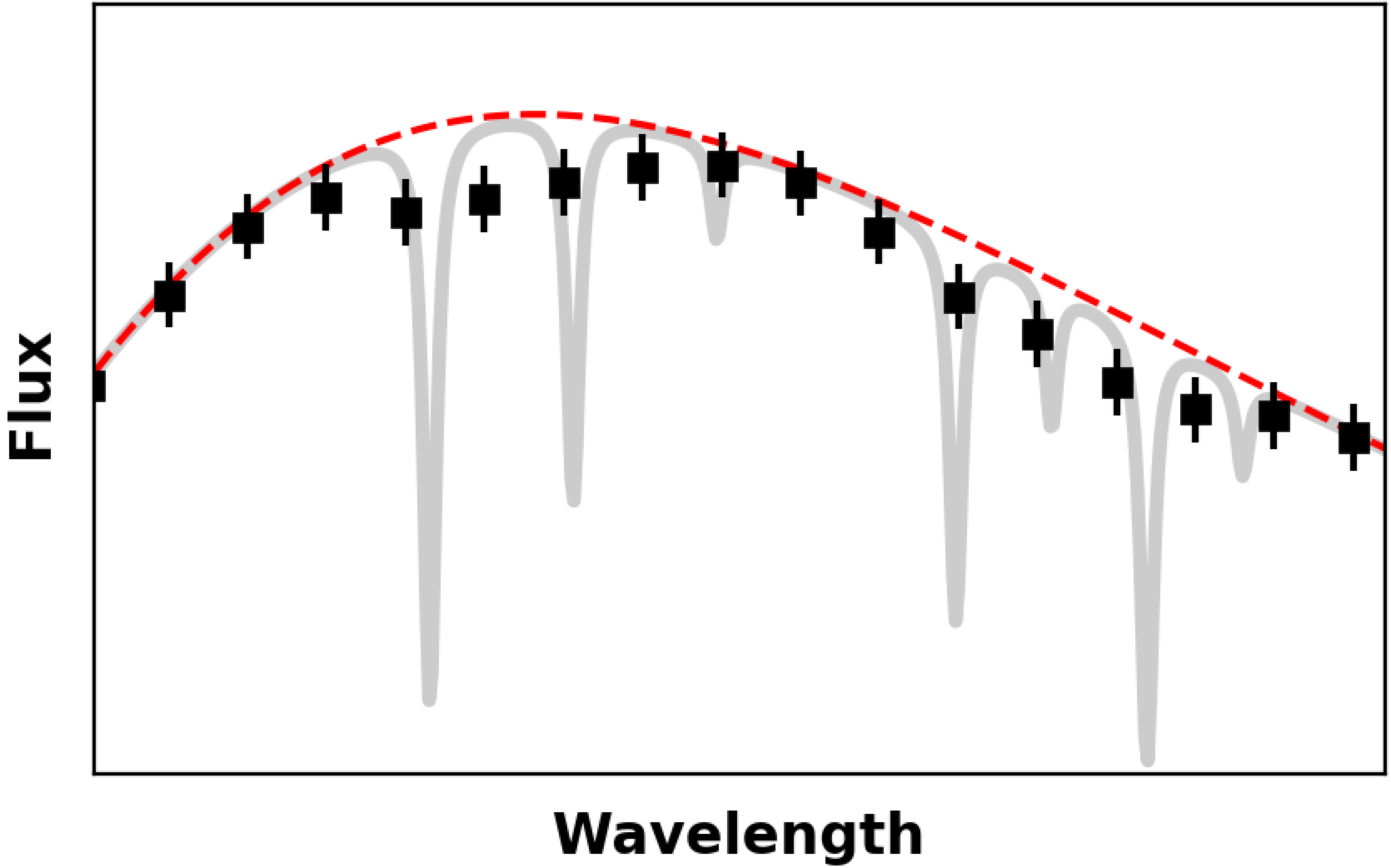
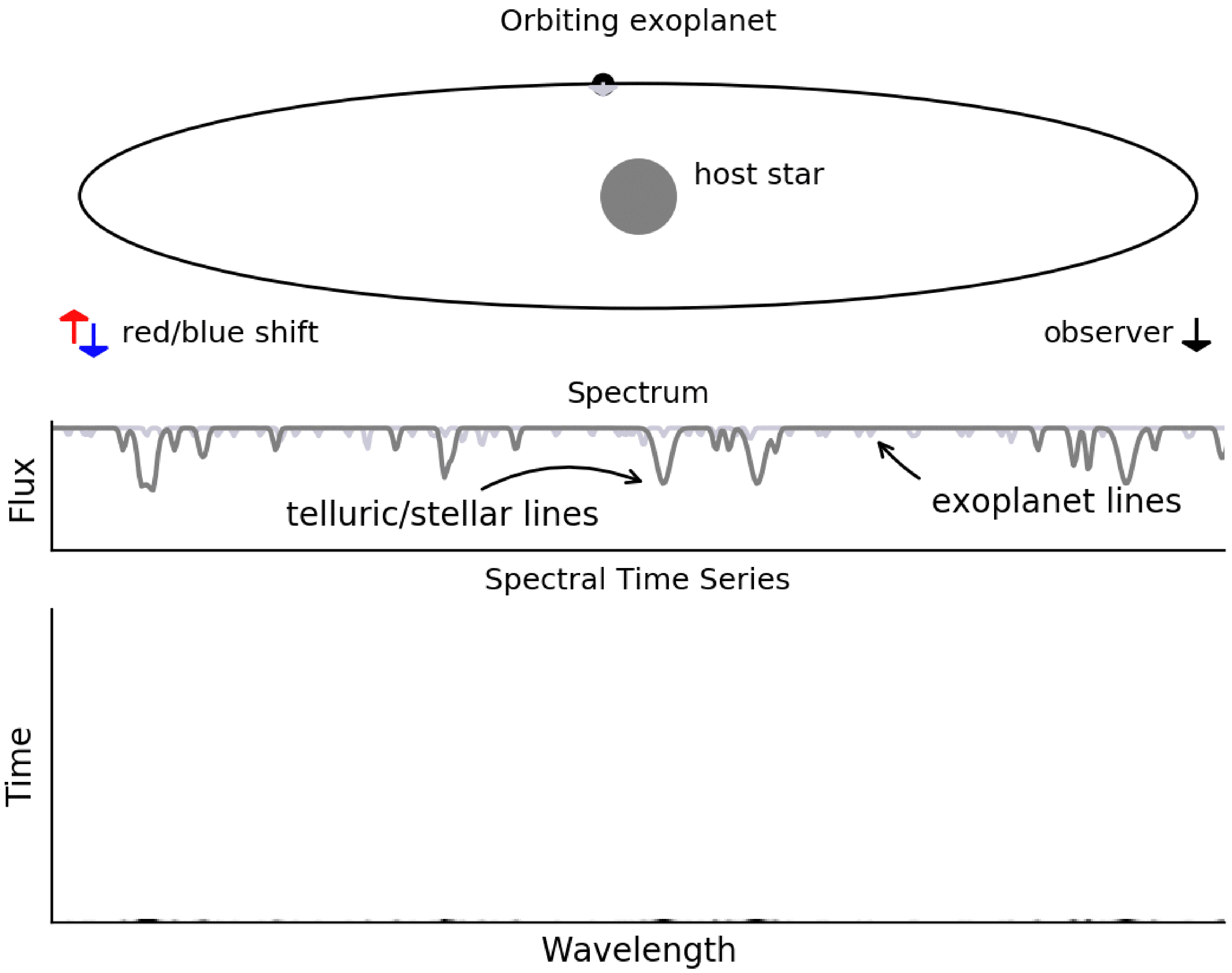
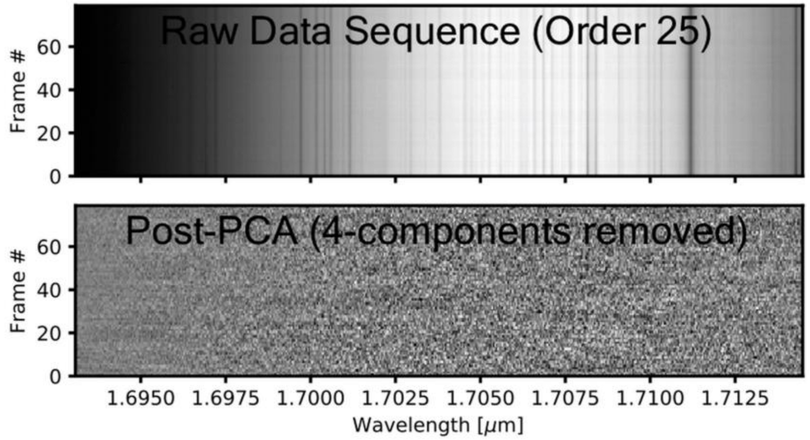


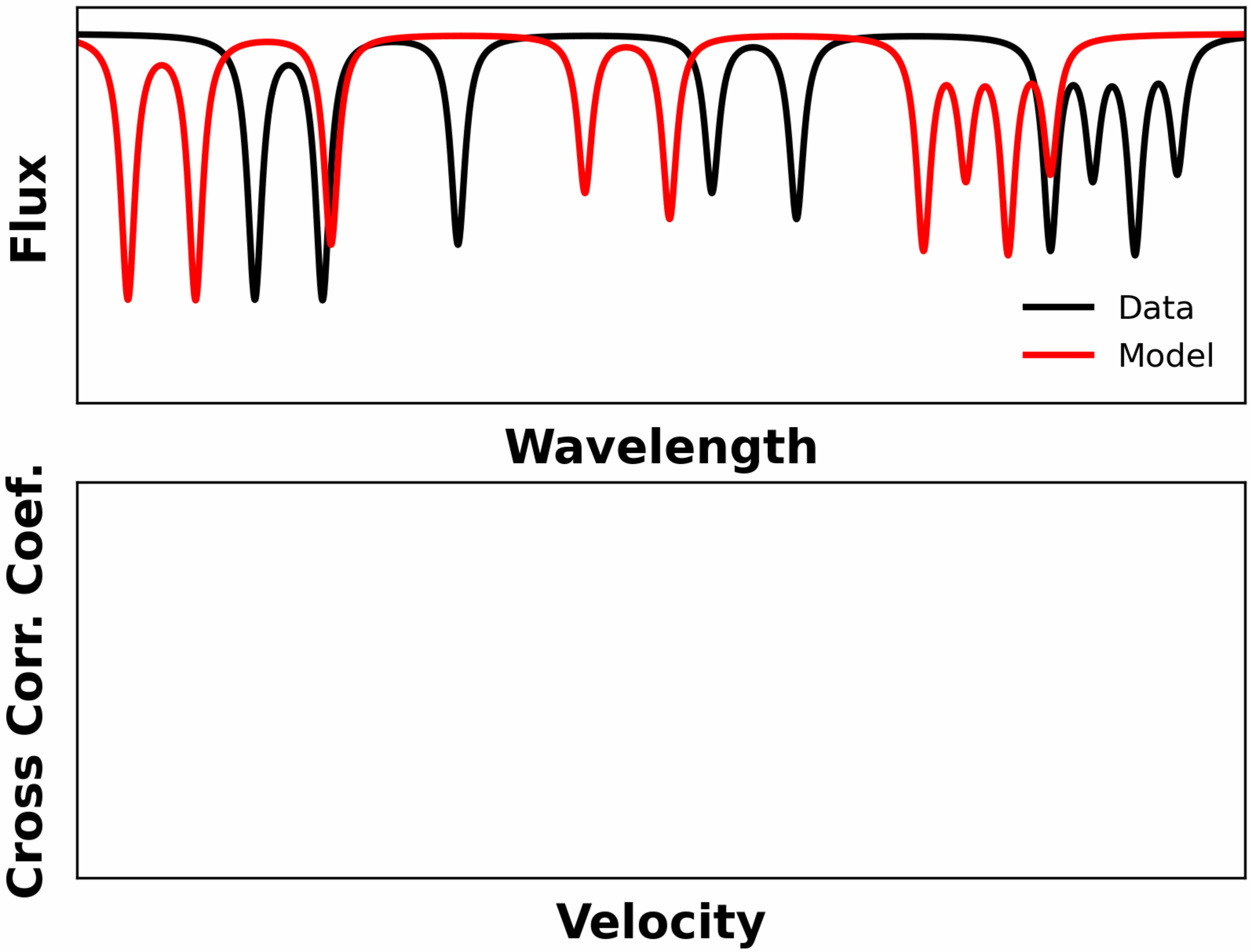


Animation by Lennart van Sluijs

High Resolution Spectroscopy

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




Flux
Data
Model
Wavelength
Cross Corr. Coef.
Velocity

High Resolution Spectroscopy

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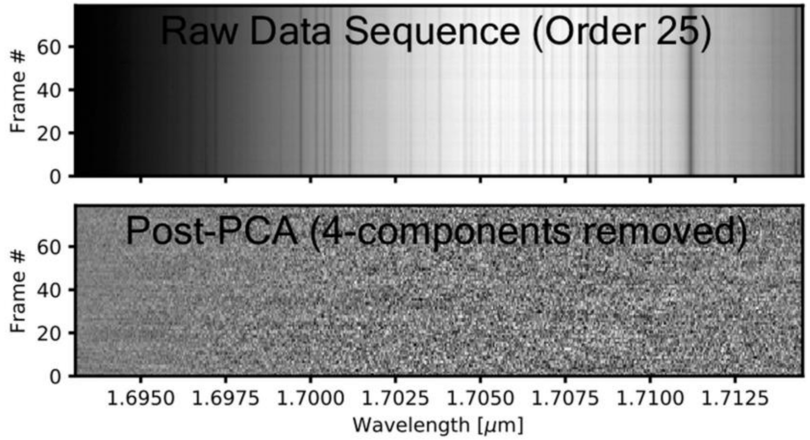
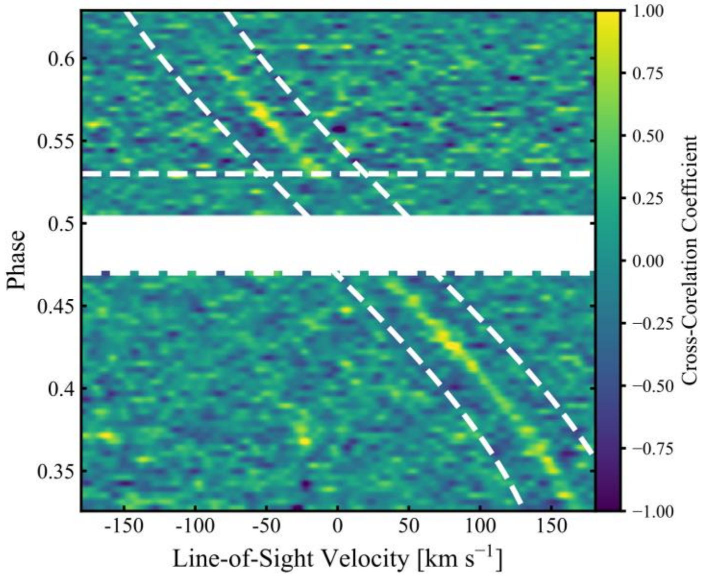
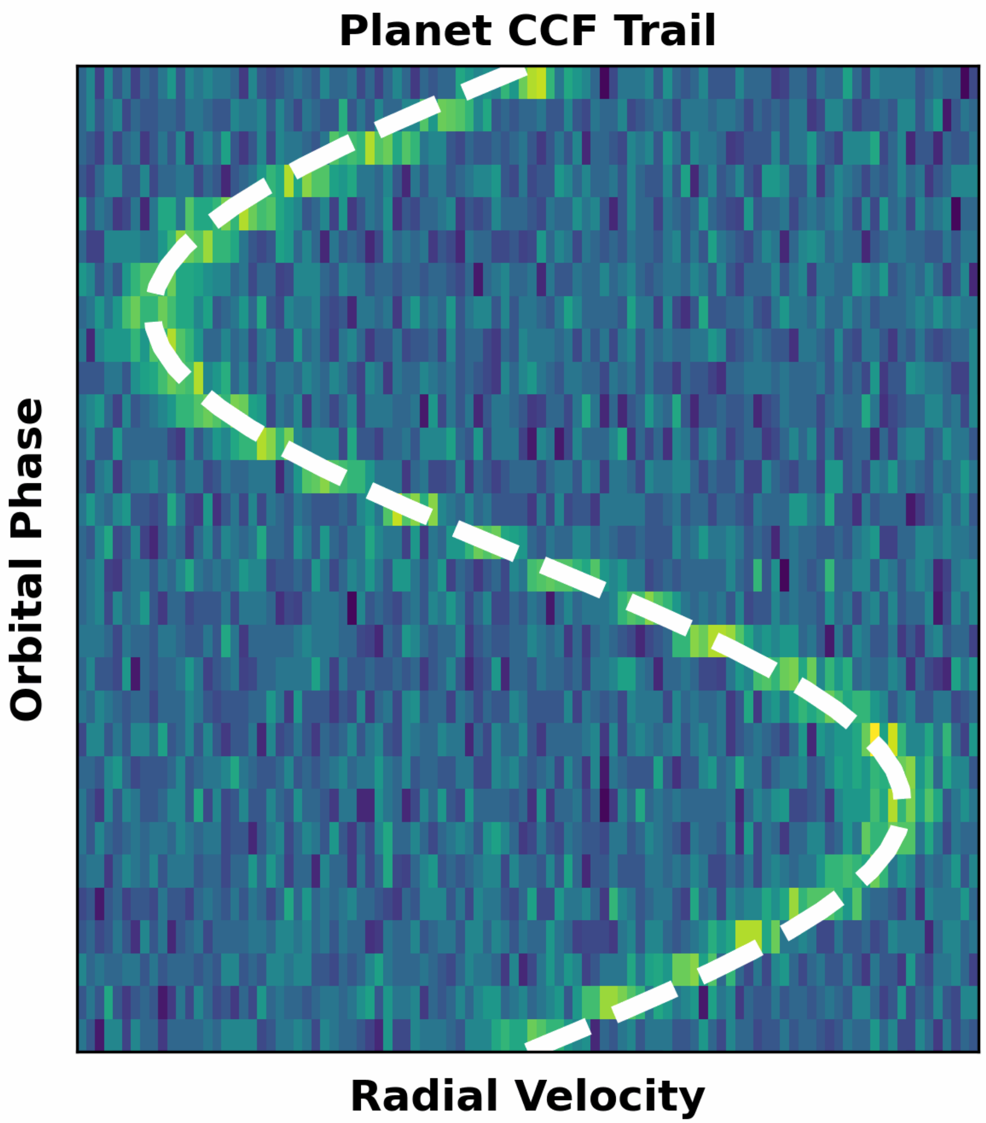


2) **Cross-correlate** a spectral template at each phase




Planet CCF Trail
Orbital Phase
Radial Velocity

High Resolution Spectroscopy

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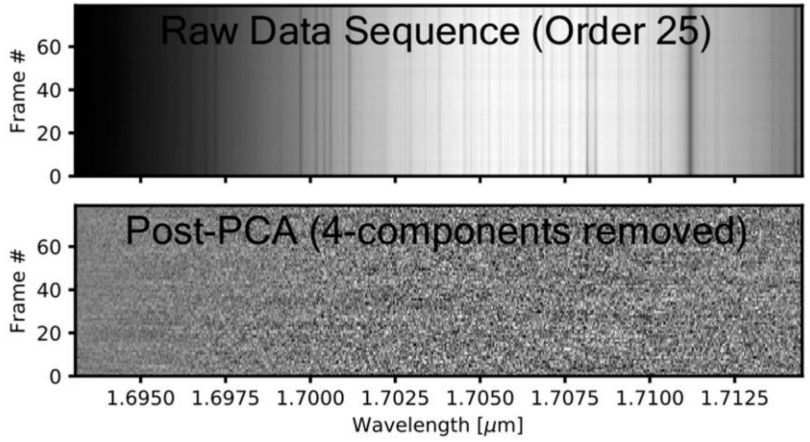

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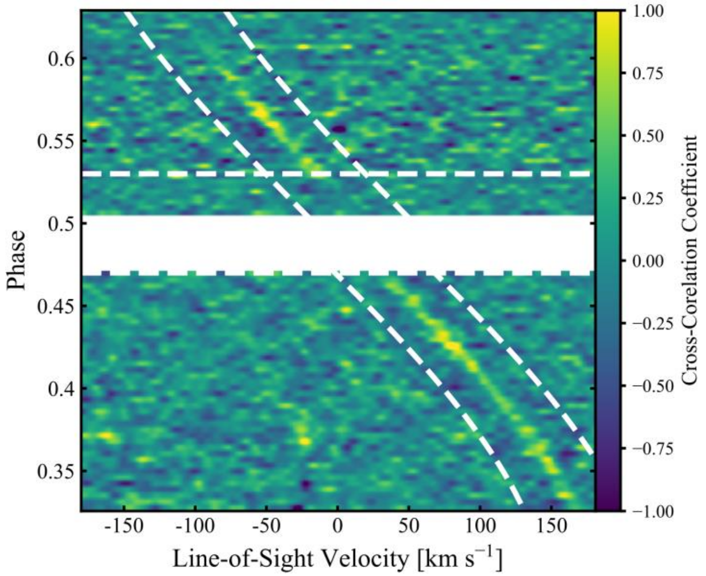

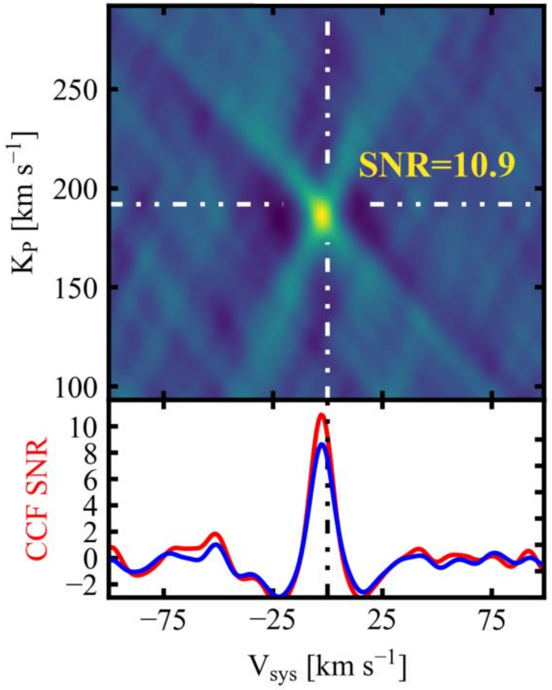

3) Sum the planet signal along the planet's **velocity in time**

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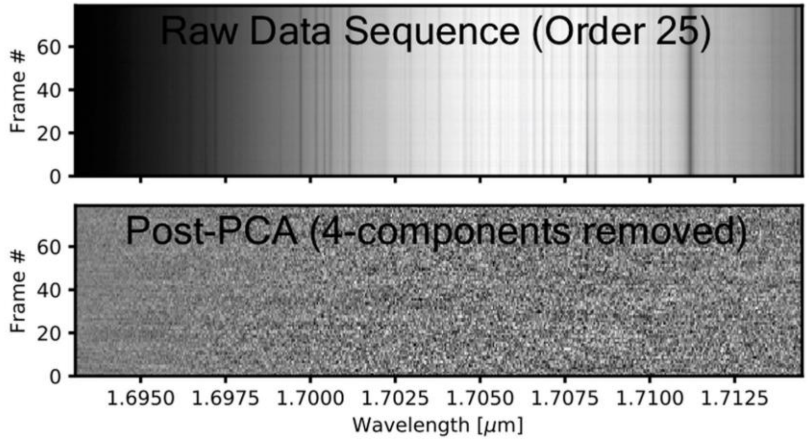

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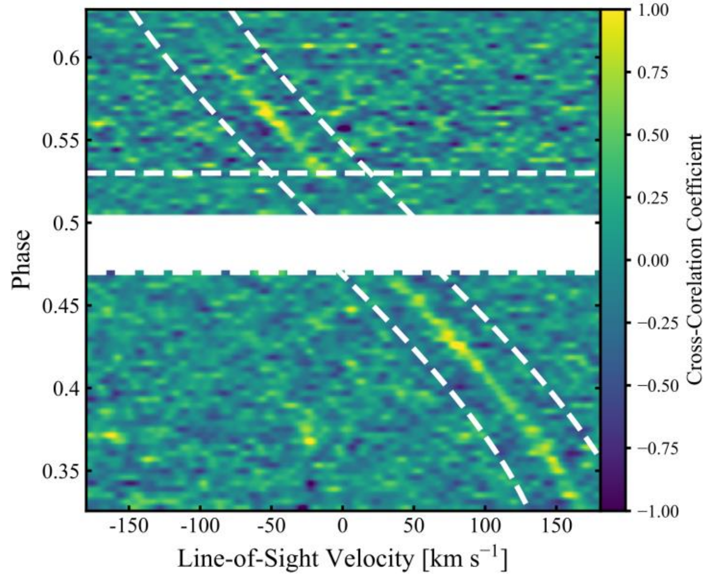

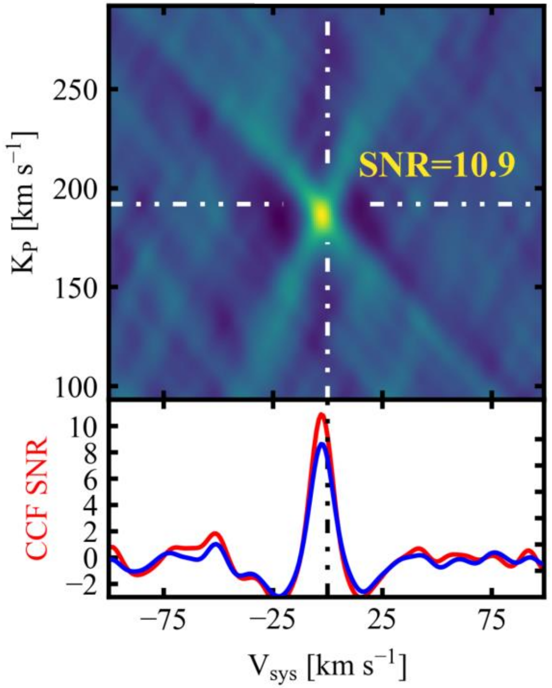

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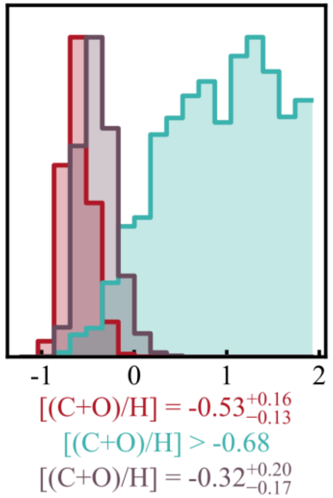
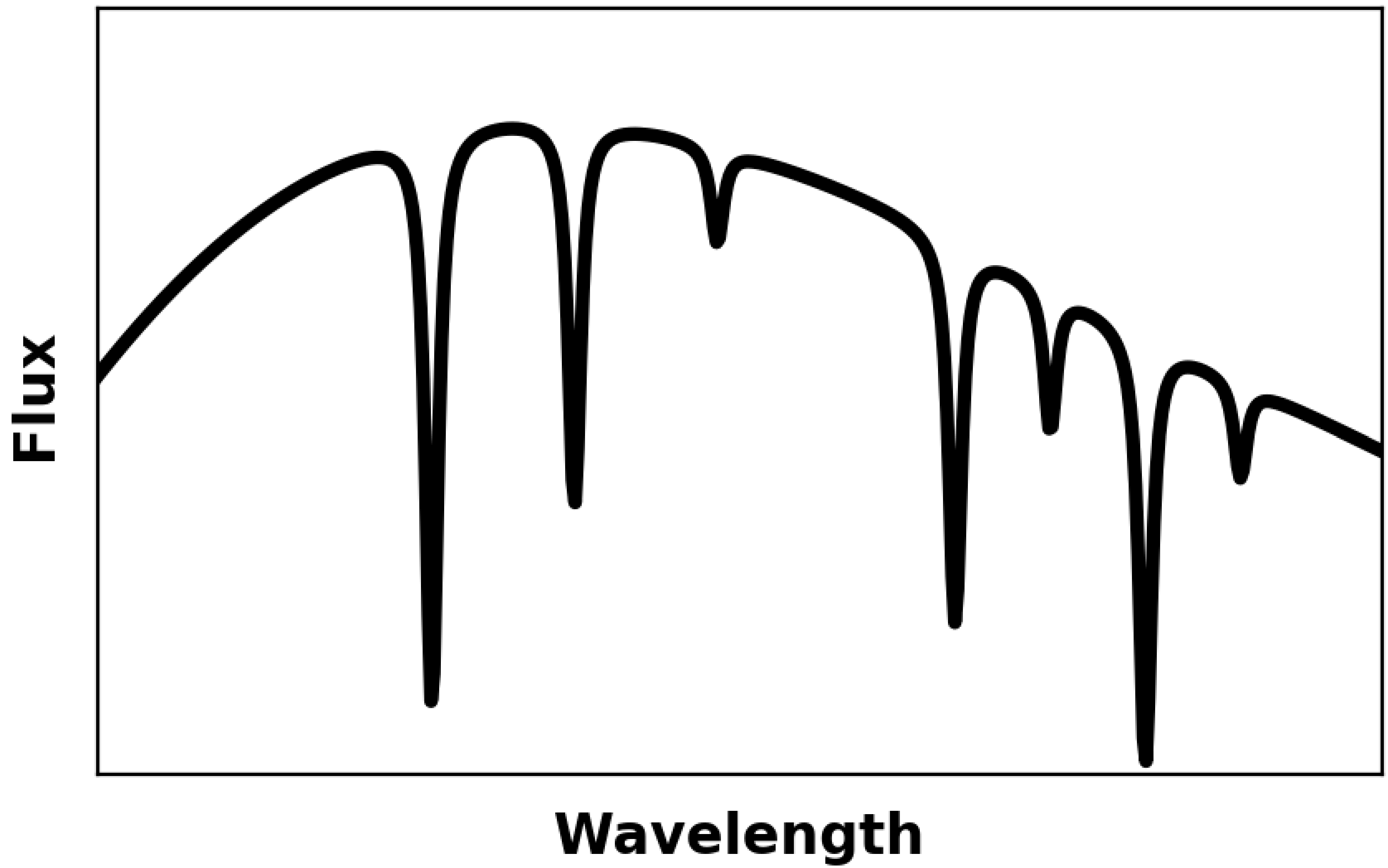


High-Resolution Spectroscopy



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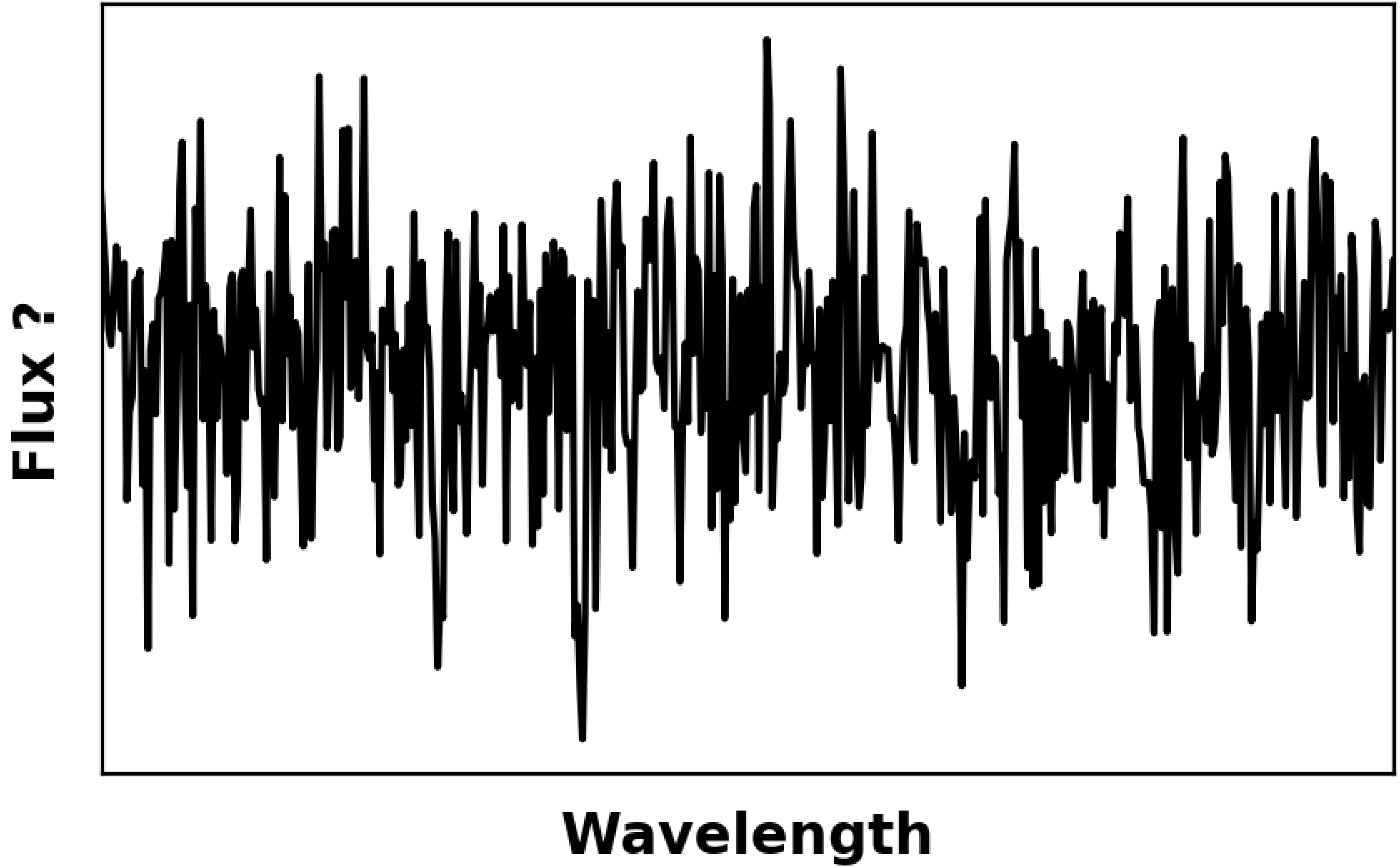

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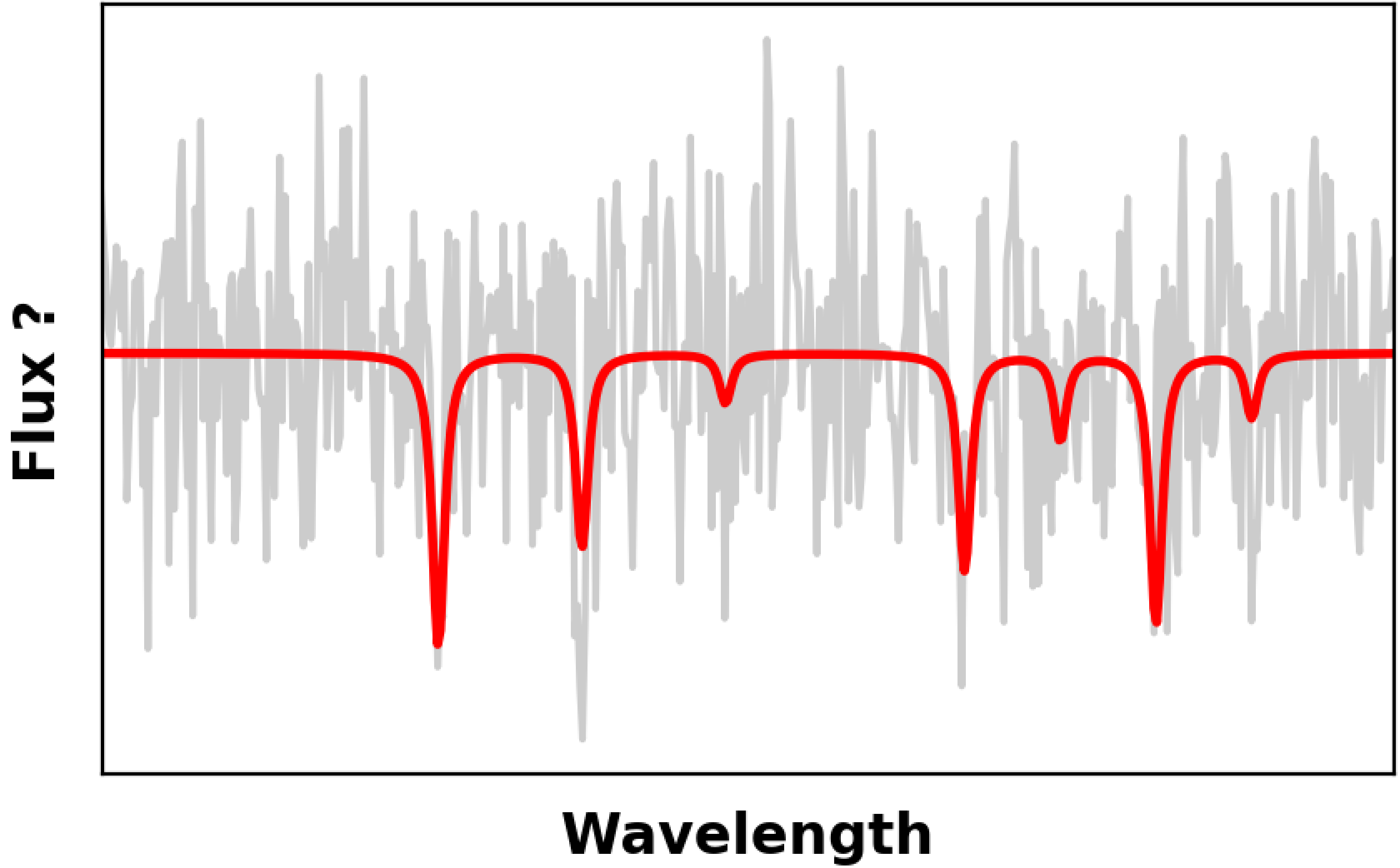

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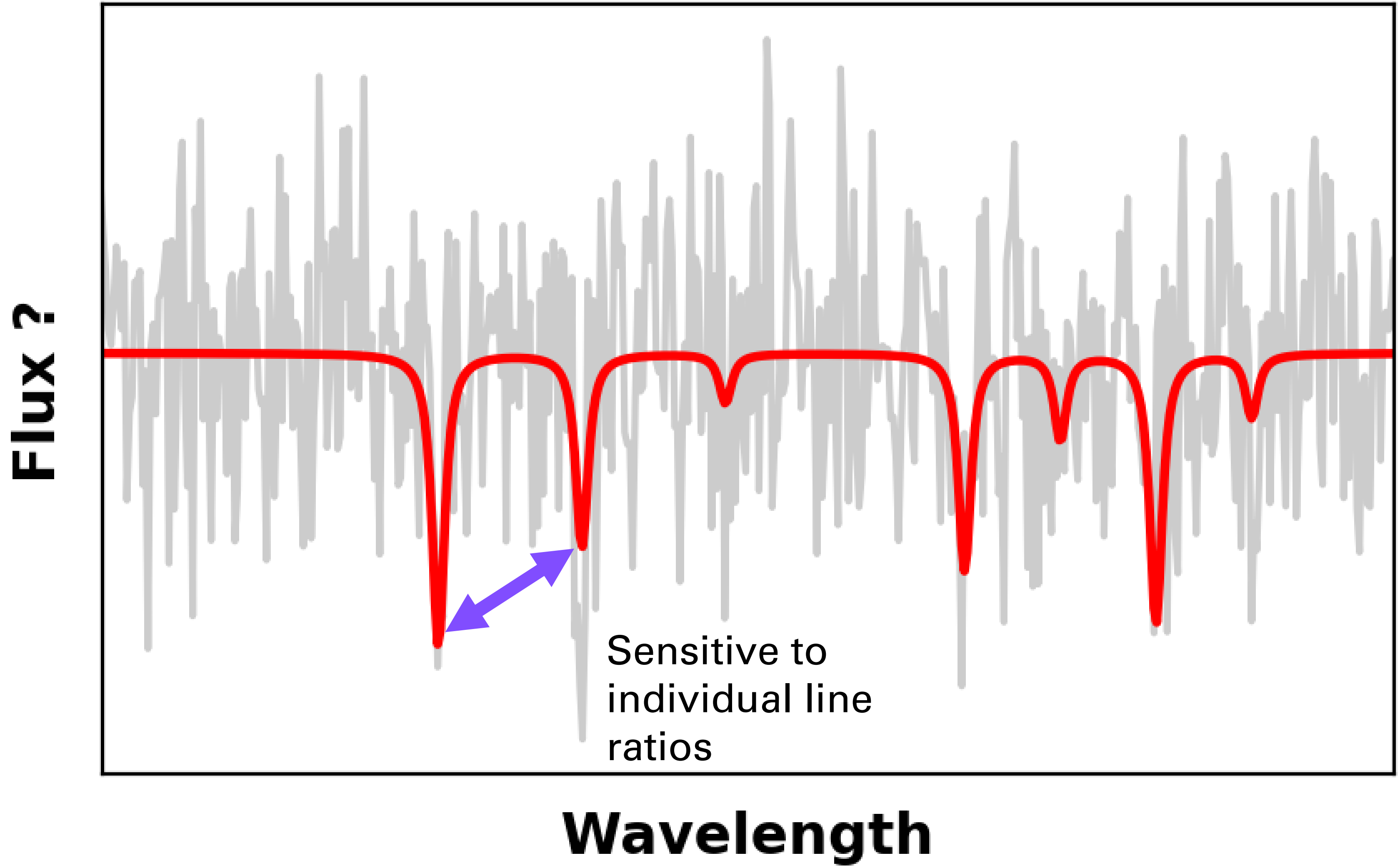

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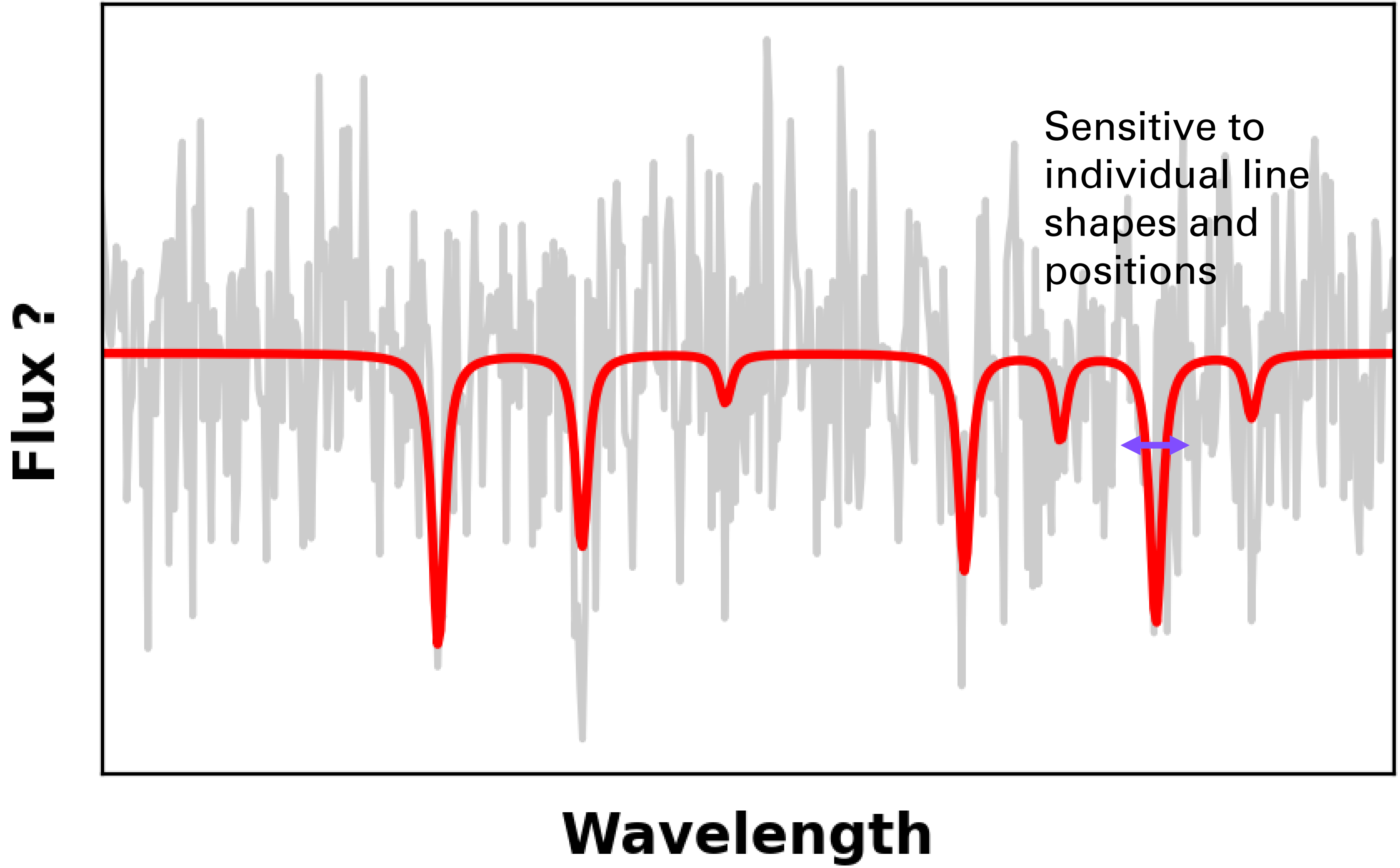
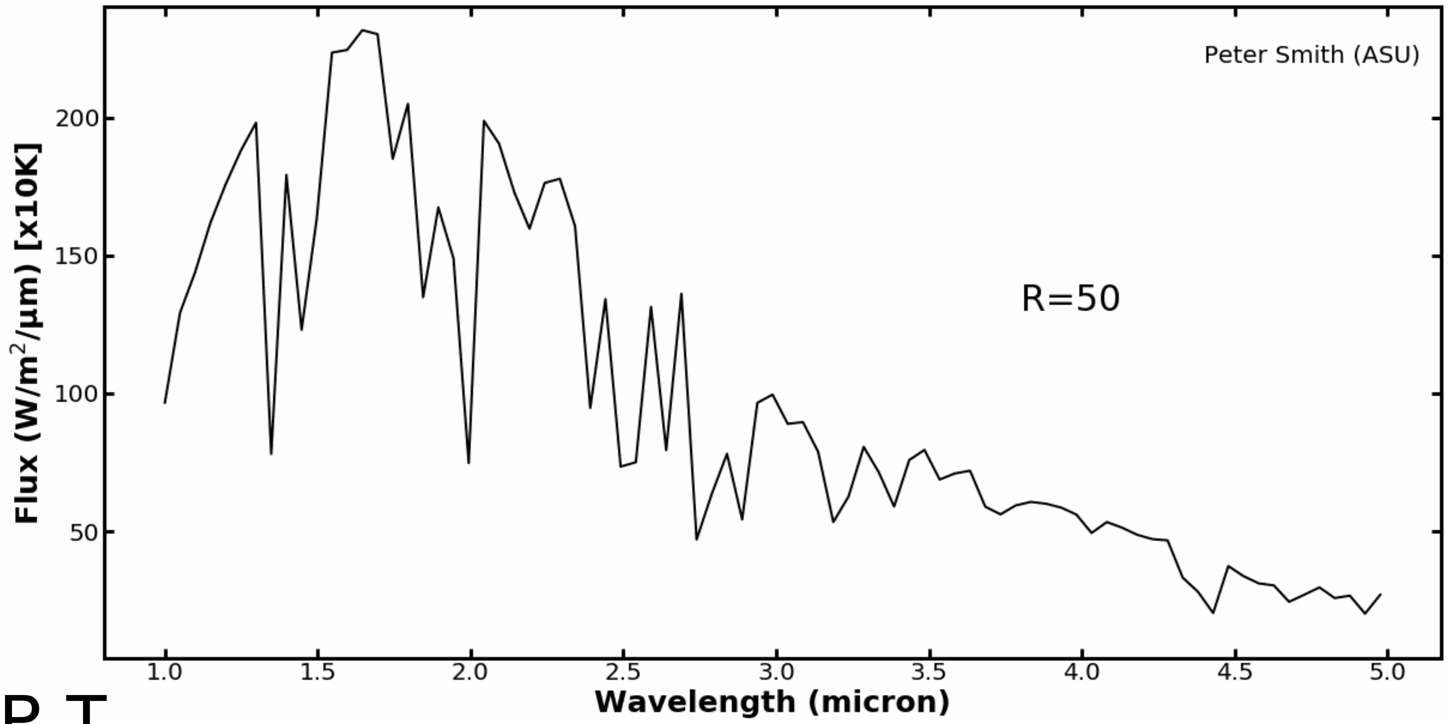


A Choice: Ground- or Space-based spectroscopy?

- Space:
  - No tellurics
  - Yes continuum (temp.)
  - Low resolution

- Ground
  - Tellurics ☹
  - No continuum?
  - High resolution

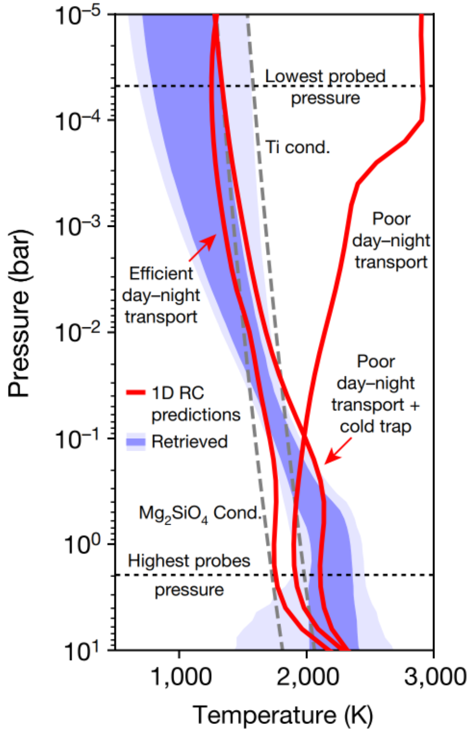
- Intuition: space good for P-T profile/climate, ground good for composition?

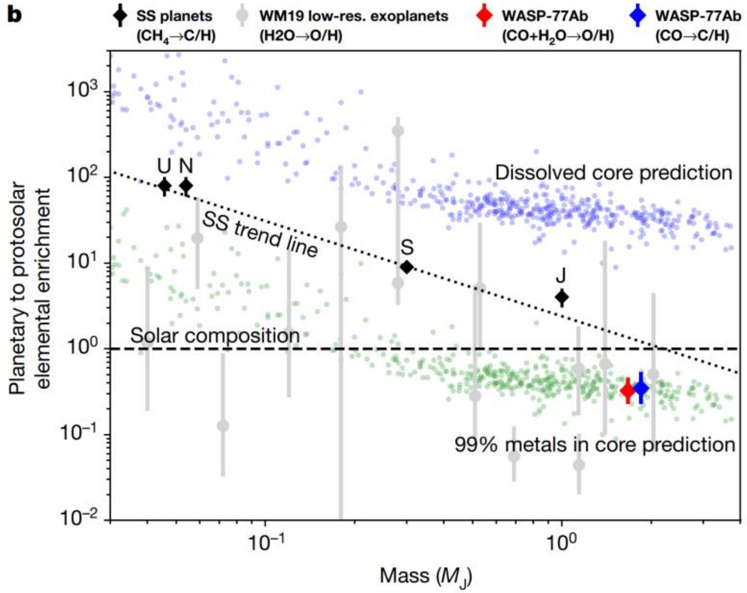


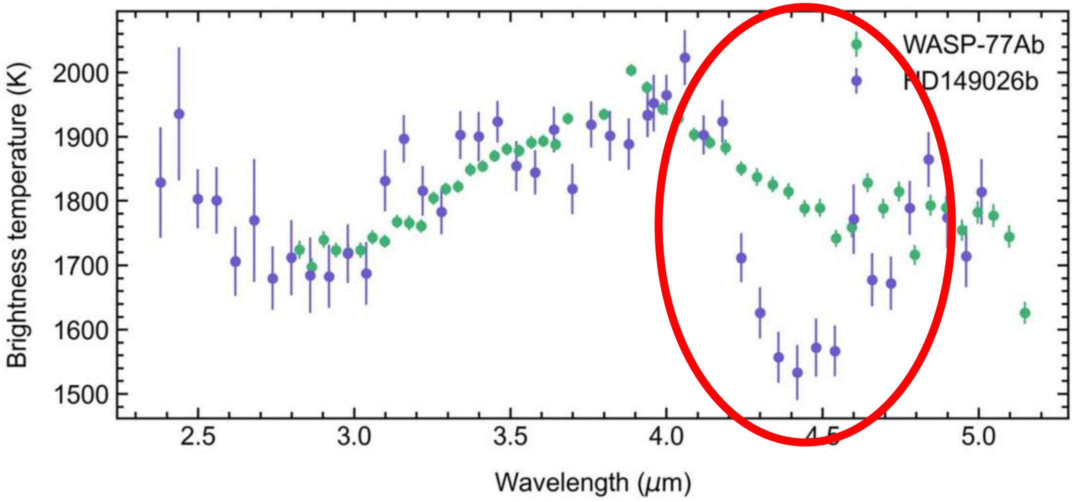
HIGH- AND LOW-RESOLUTION SPECTROSCOPY HAVE COMPLEMENTARY INFORMATION – DO THEM BOTH!

WASP-77A b

- Line+ 2021 showed capability of high res retrievals w/ IGRINS (R~45K)
- Was able to measure P-T profile and a low metallicity
- Later JWST/NIRSpec (R~250, August+ 2023) confirmed low metallicity

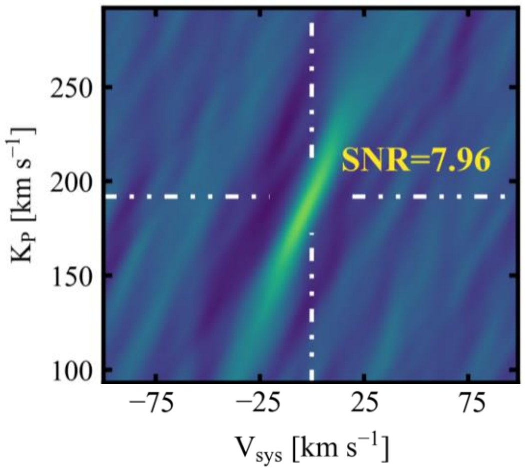






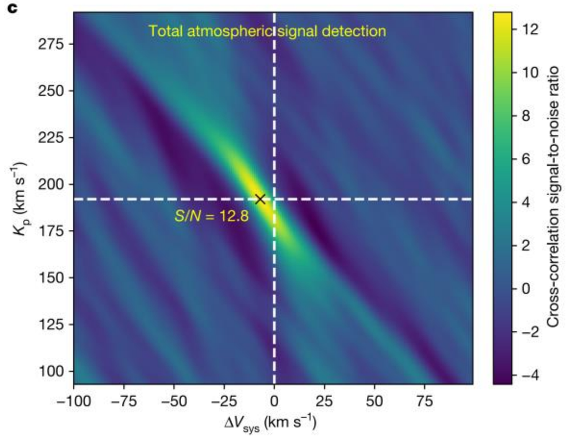
WASP-77A b

Gemini South/IGRINS (new)



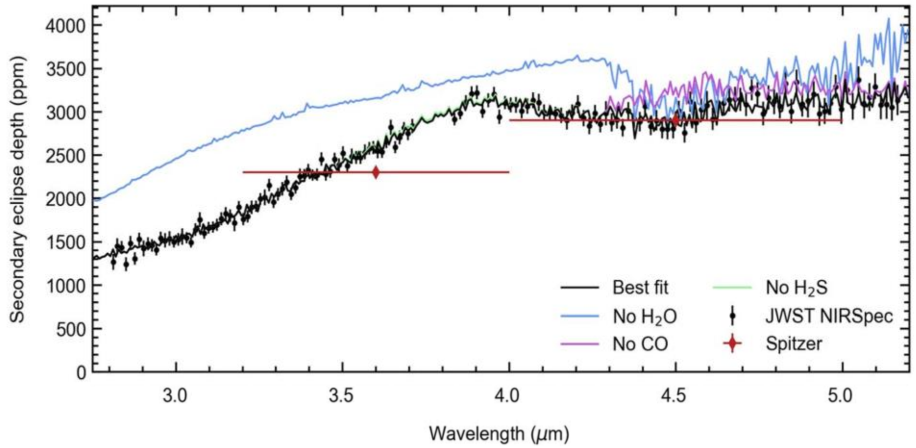
+

Gemini South/IGRINS; Line+ 2021



+

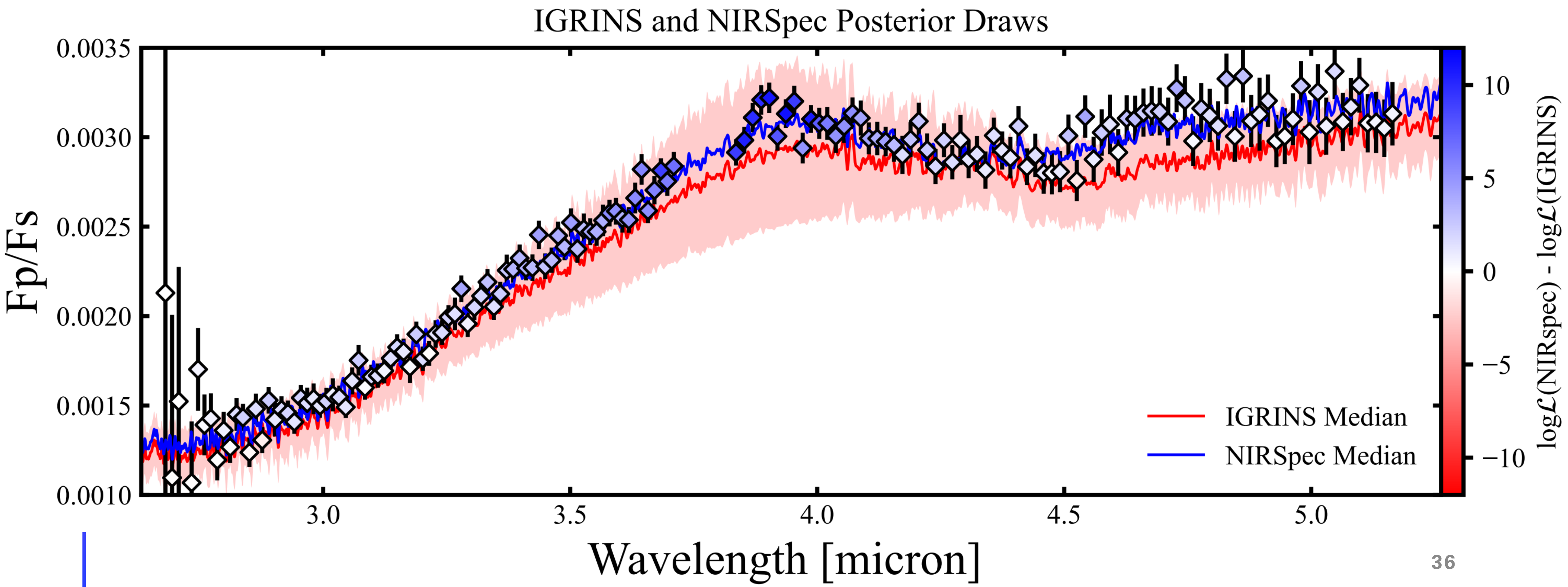
NIRSpec G395H; August+ 2023



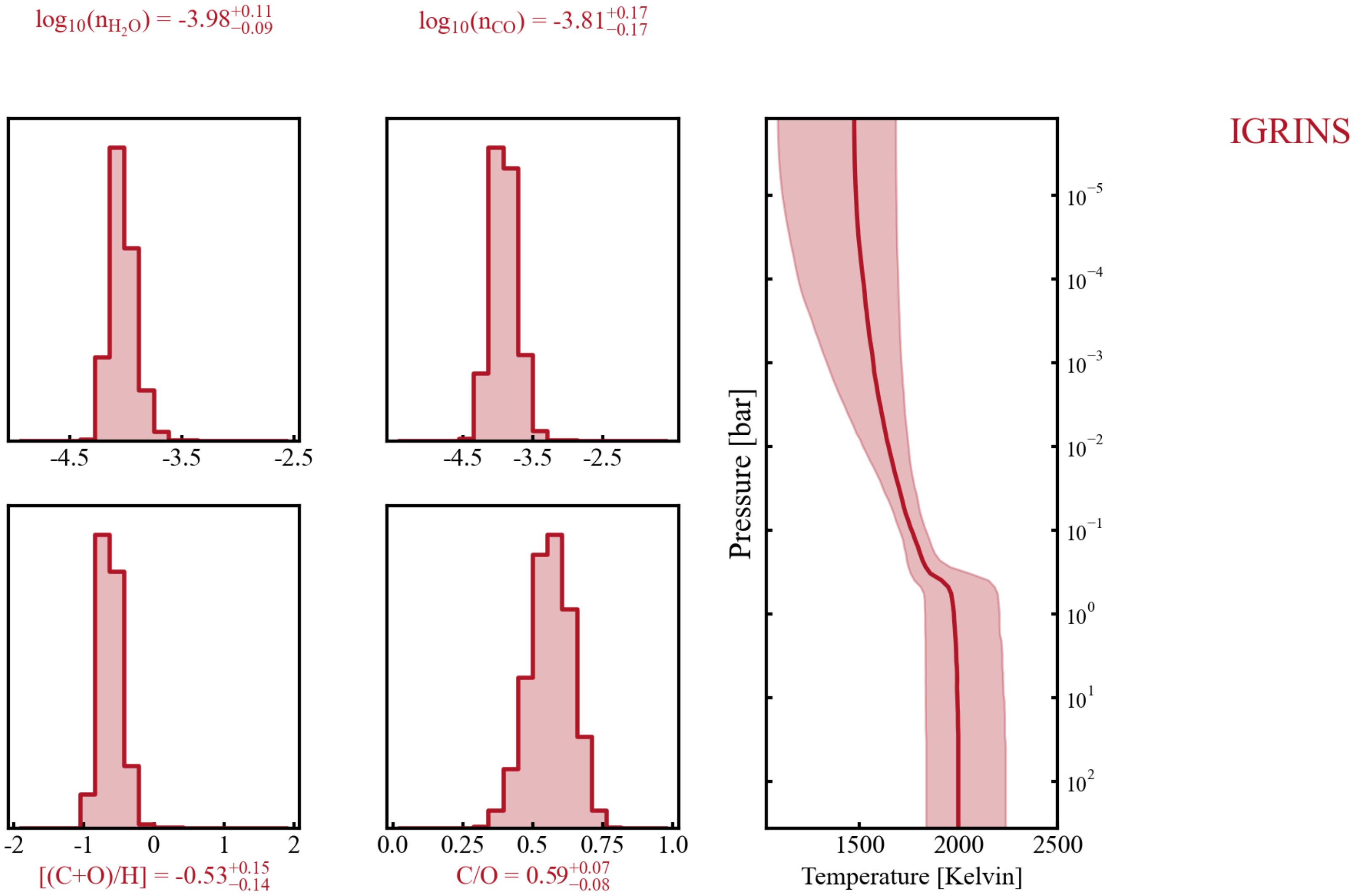
Gemini South – 8.1 m
IGRINS – R =45K

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

The two data types predict each other well



Test Case: WASP-77A b confirms intuition



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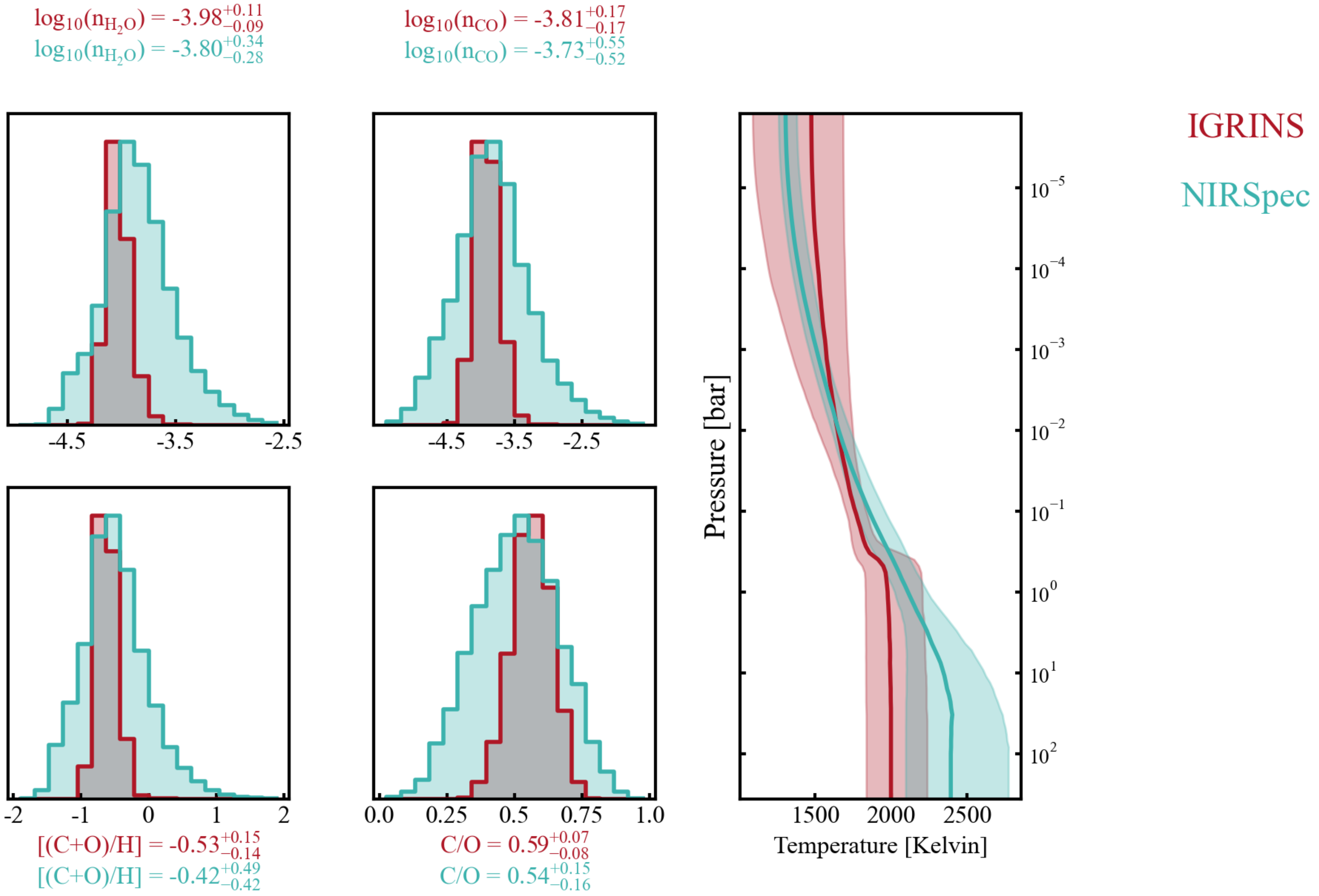
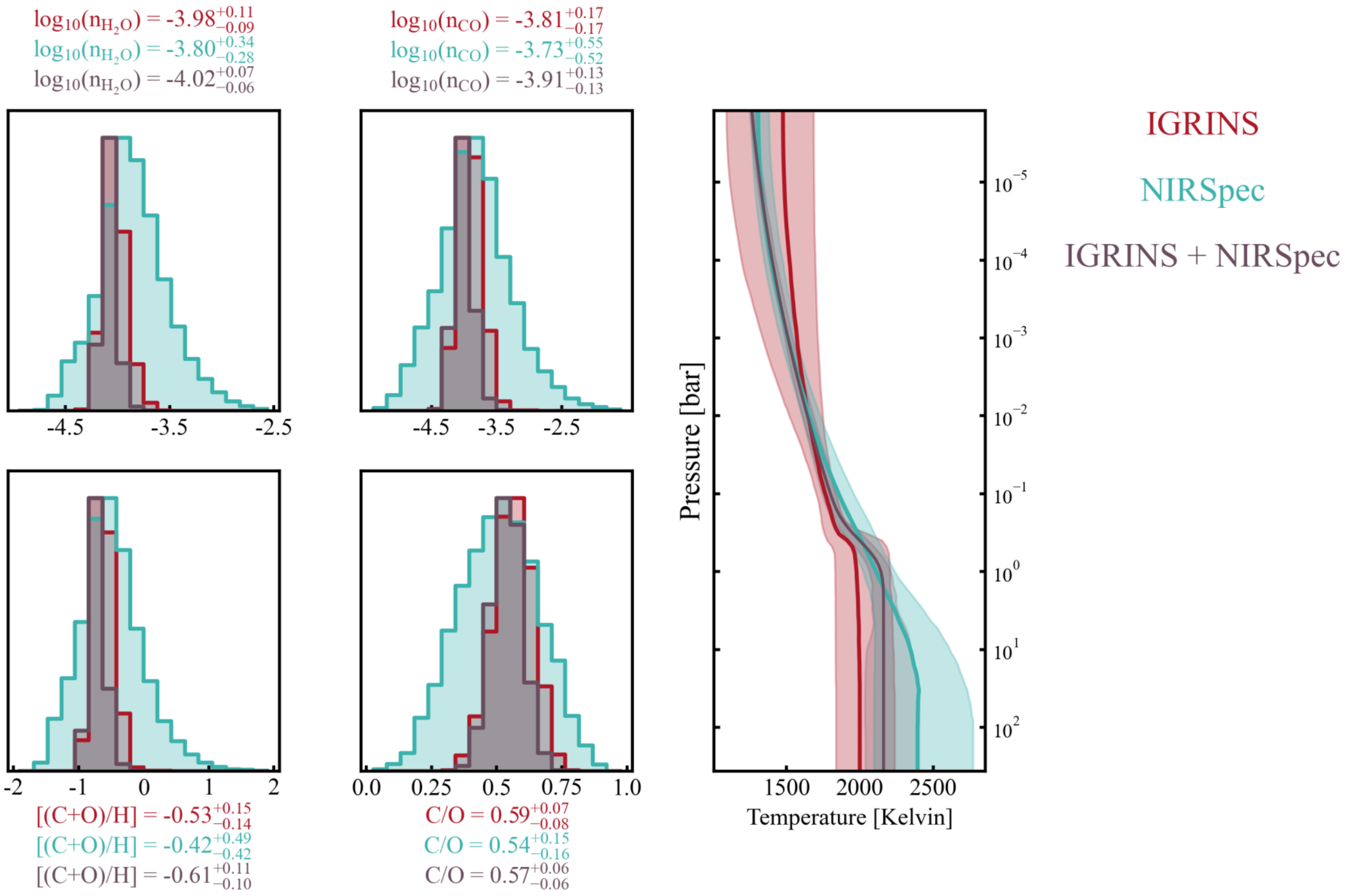
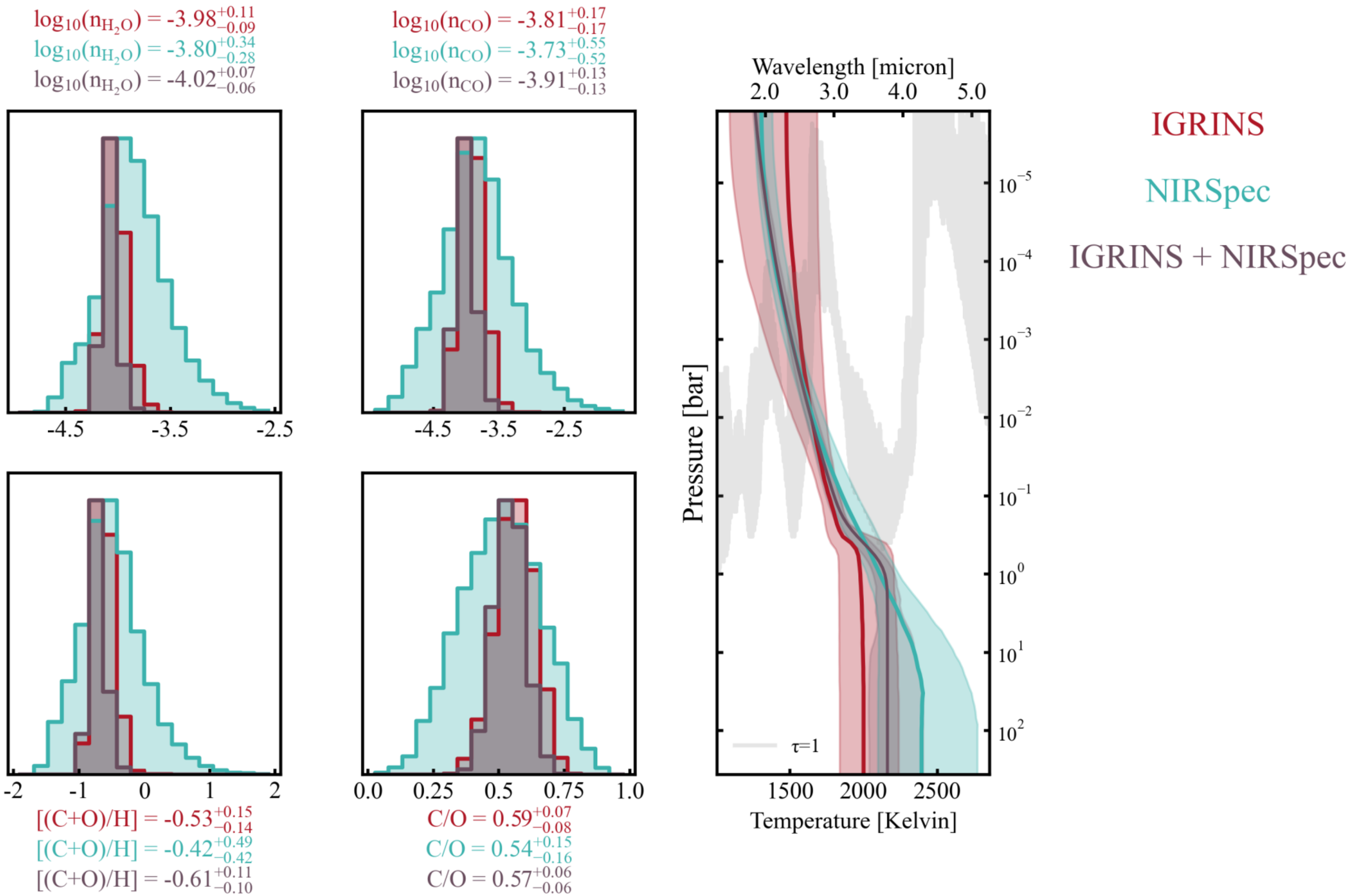


STRONGER TOGETHER

Test Case: WASP-77A b confirms intuition



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



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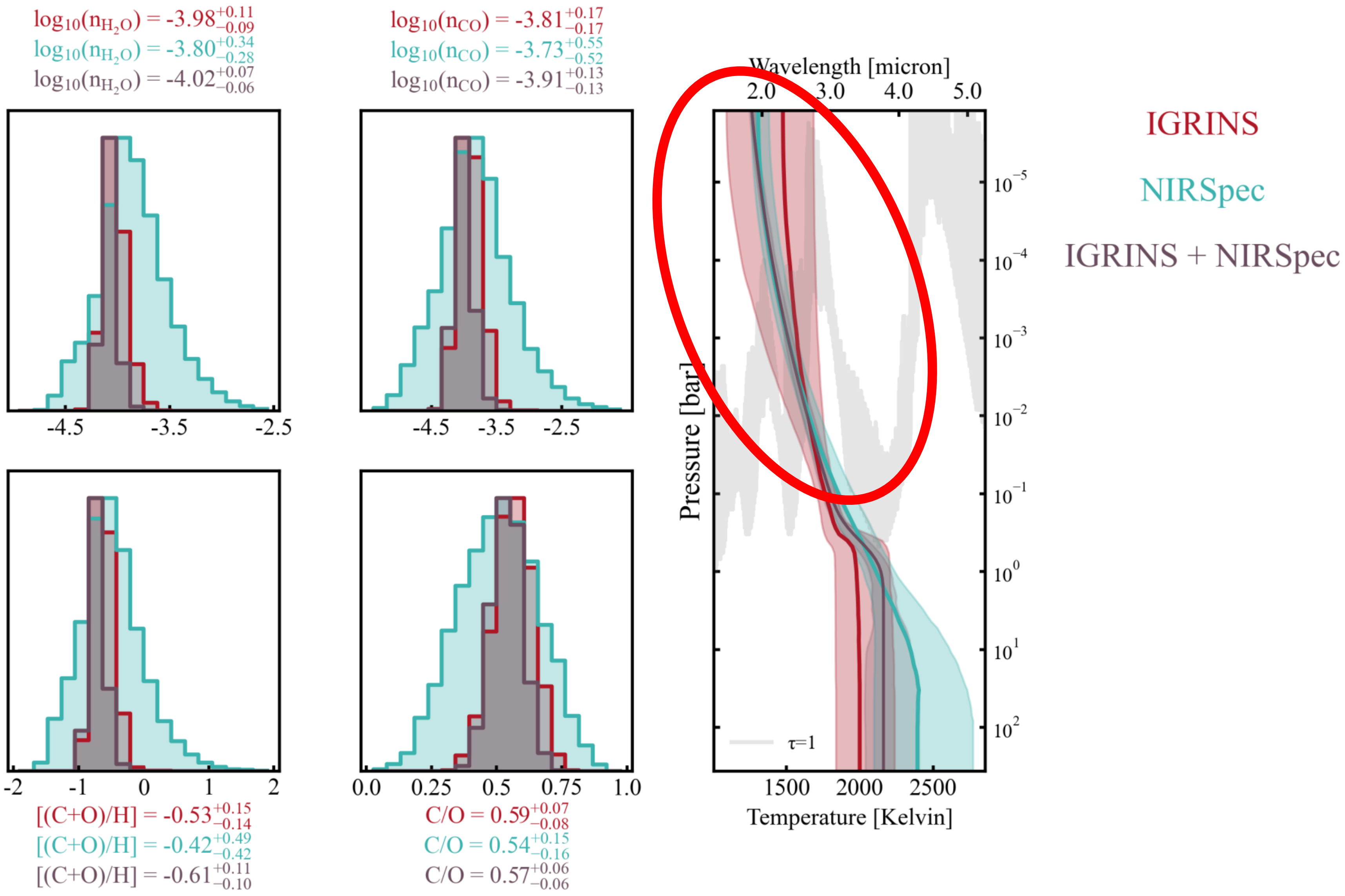

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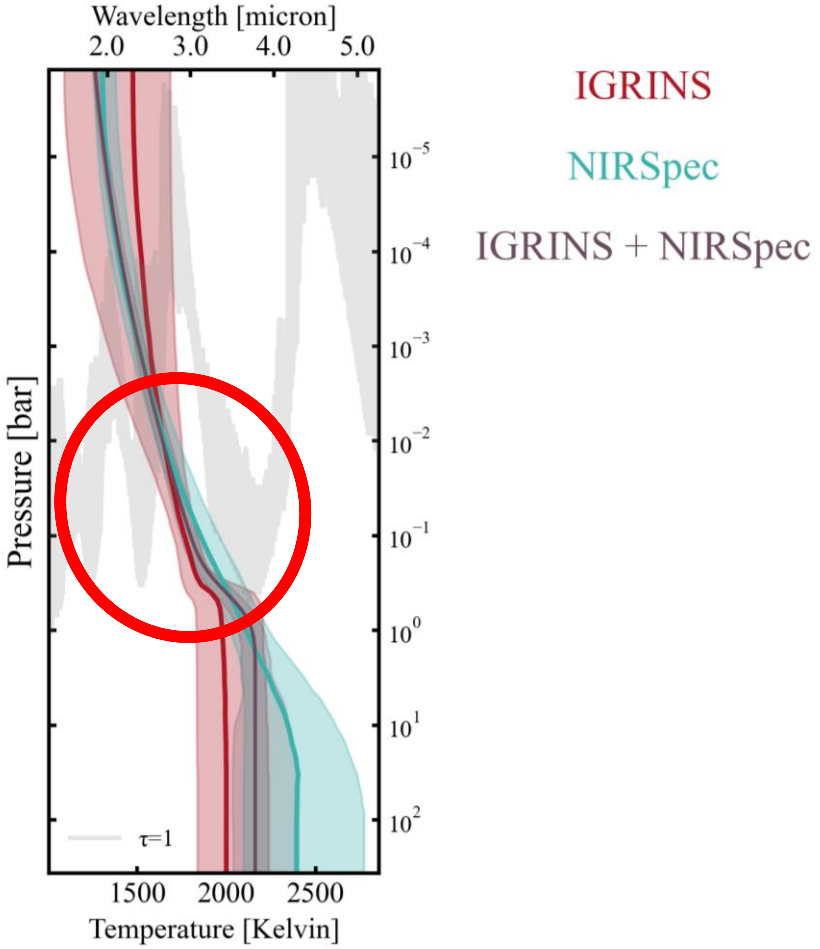
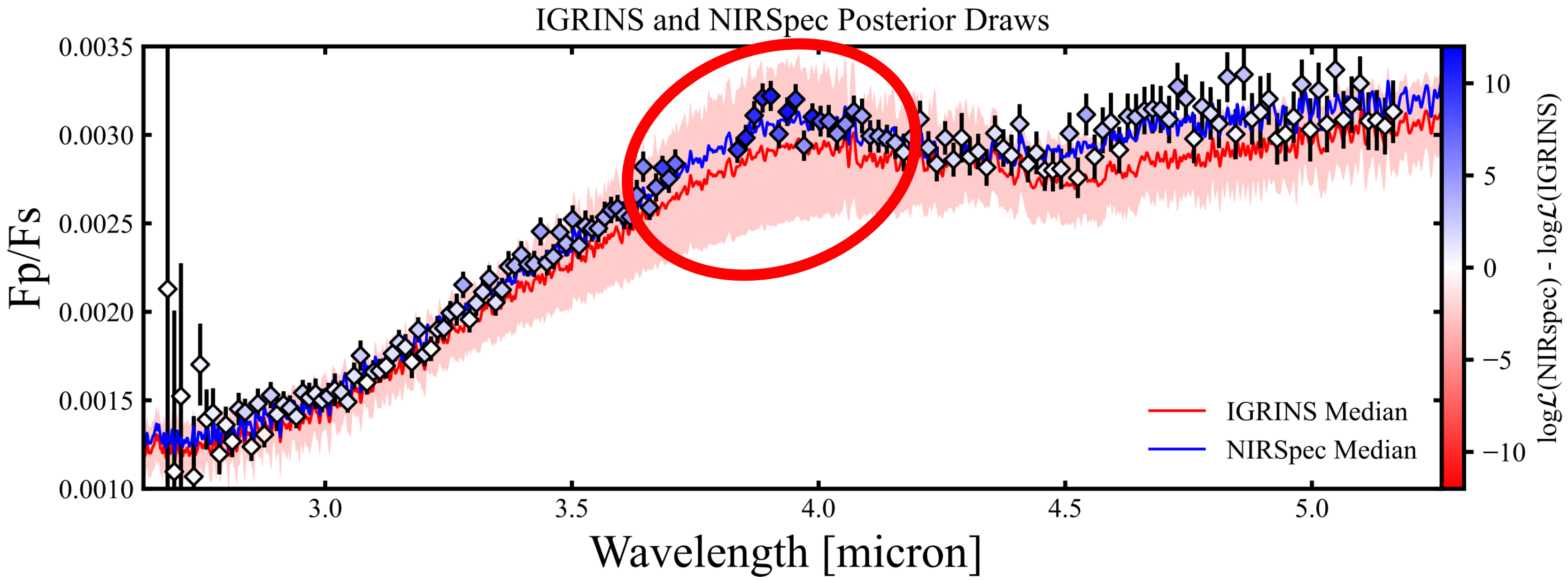
Improvements not just due to increased wavelength coverage





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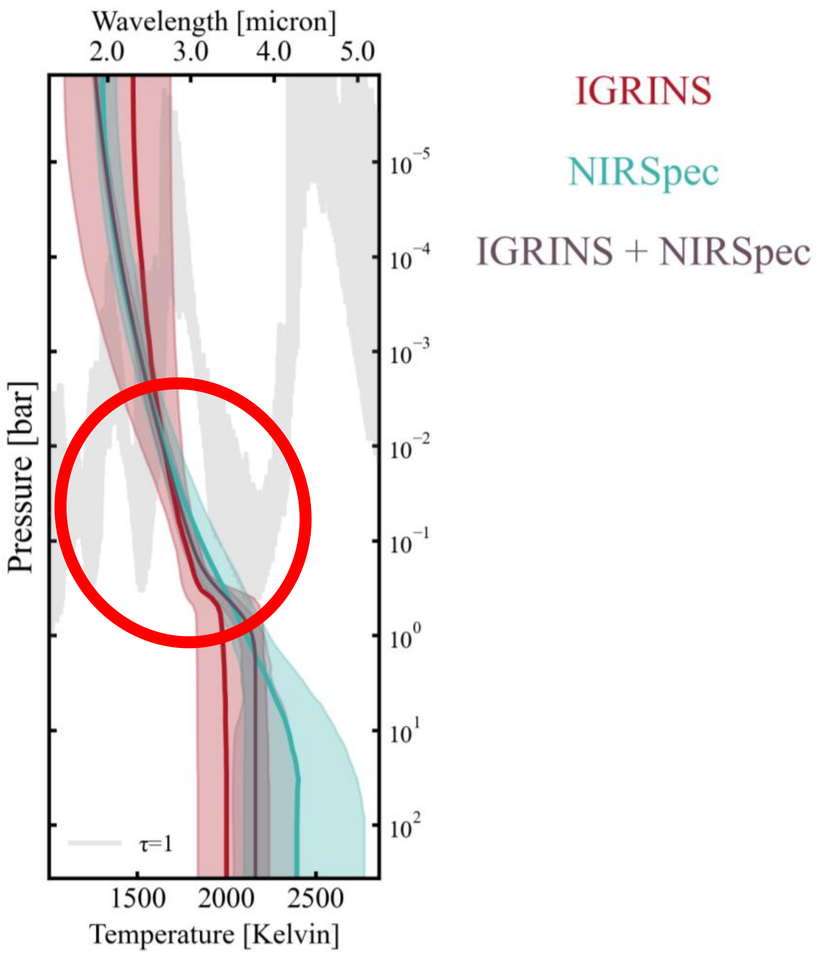
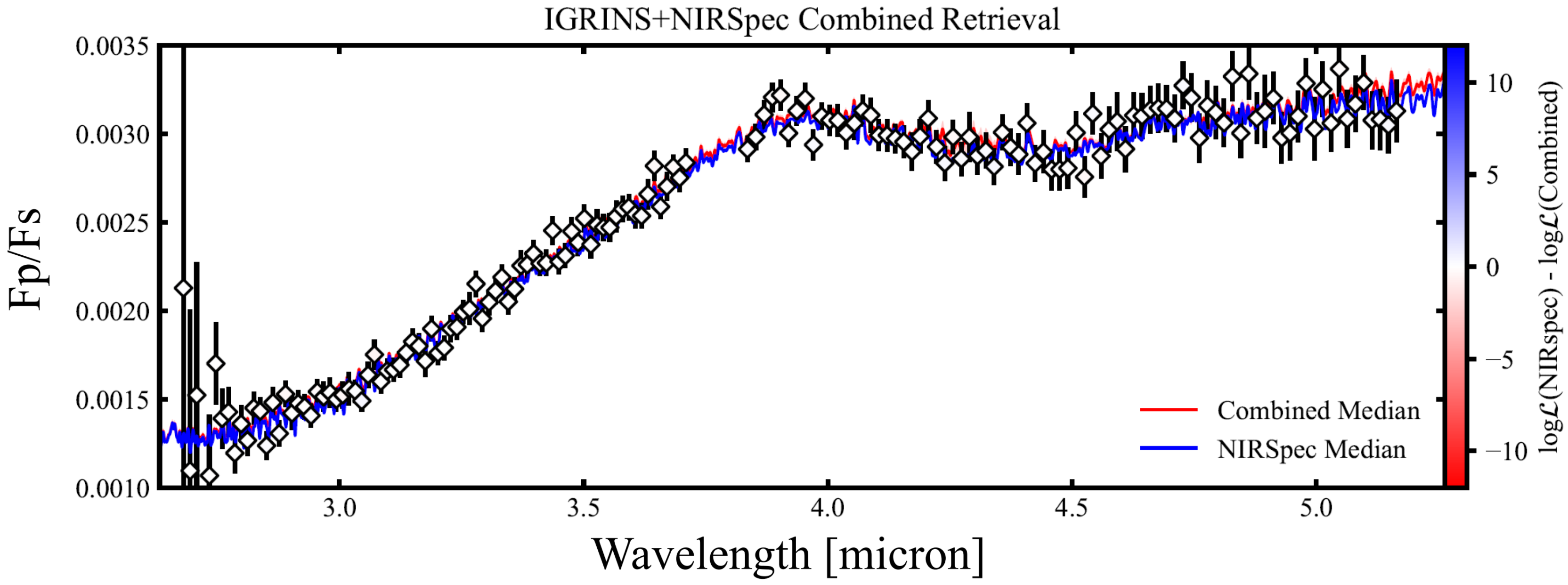
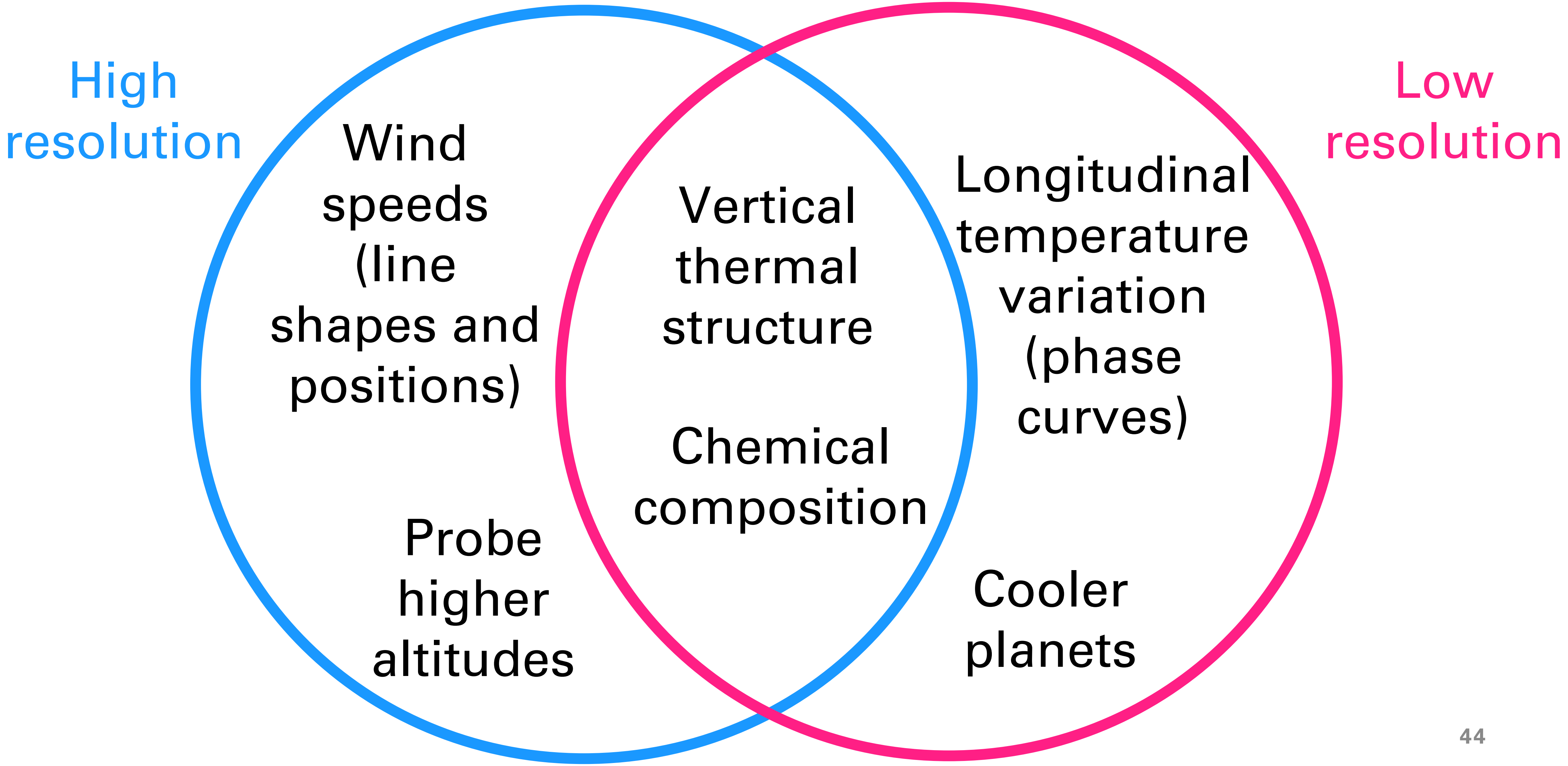


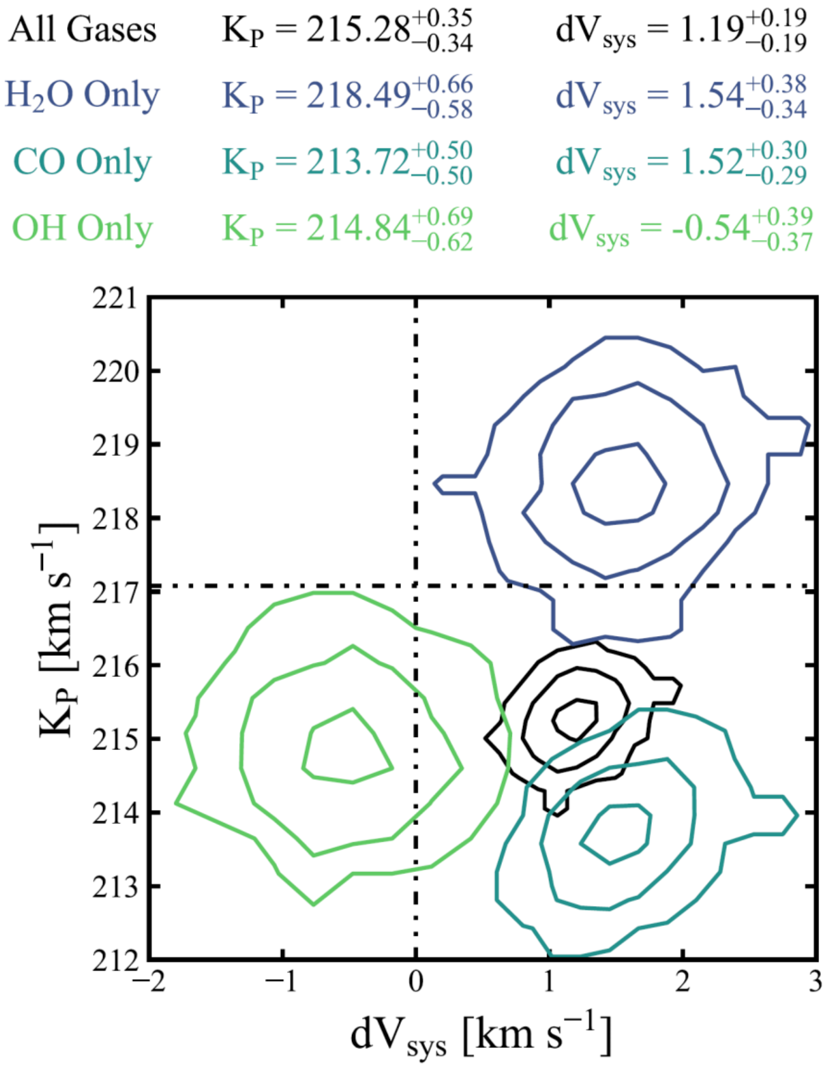


Deciding what’s best for your science



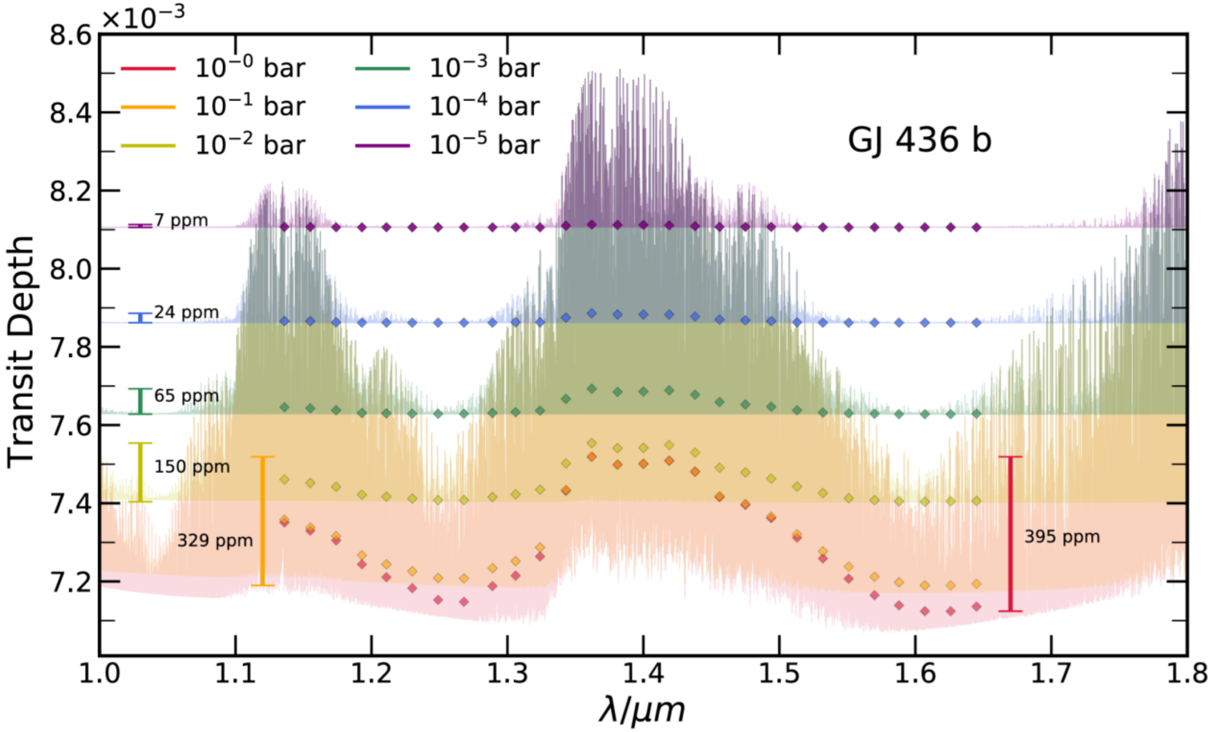
The future: climate and dynamics

- Wind speeds, dynamics, and thermal structure are intrinsically, physically linked, so measuring one will help constrain the other
- Such complementary data sets already exist – e.g., WASP-121 b



The future: peering above the clouds

- High res infamously struggles with placing the continuum and absolute abundances
- Low res infamously thwarted by high altitude clouds
- Using both can be a powerful method for bypassing both of these shortcomings as high res can probe low pressures while low res can identify the true transit depth



From Gandhi+ 2020

SUMMARY

- Studying exoplanet atmospheres are the key to solving outstanding questions in planetary science
- High and low resolution spectroscopy are sensitive to different information and have complementary strengths and weaknesses
- Combining the two can provide a more complete and precise view of an atmosphere than from either method individually

This work is published in AJ!

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