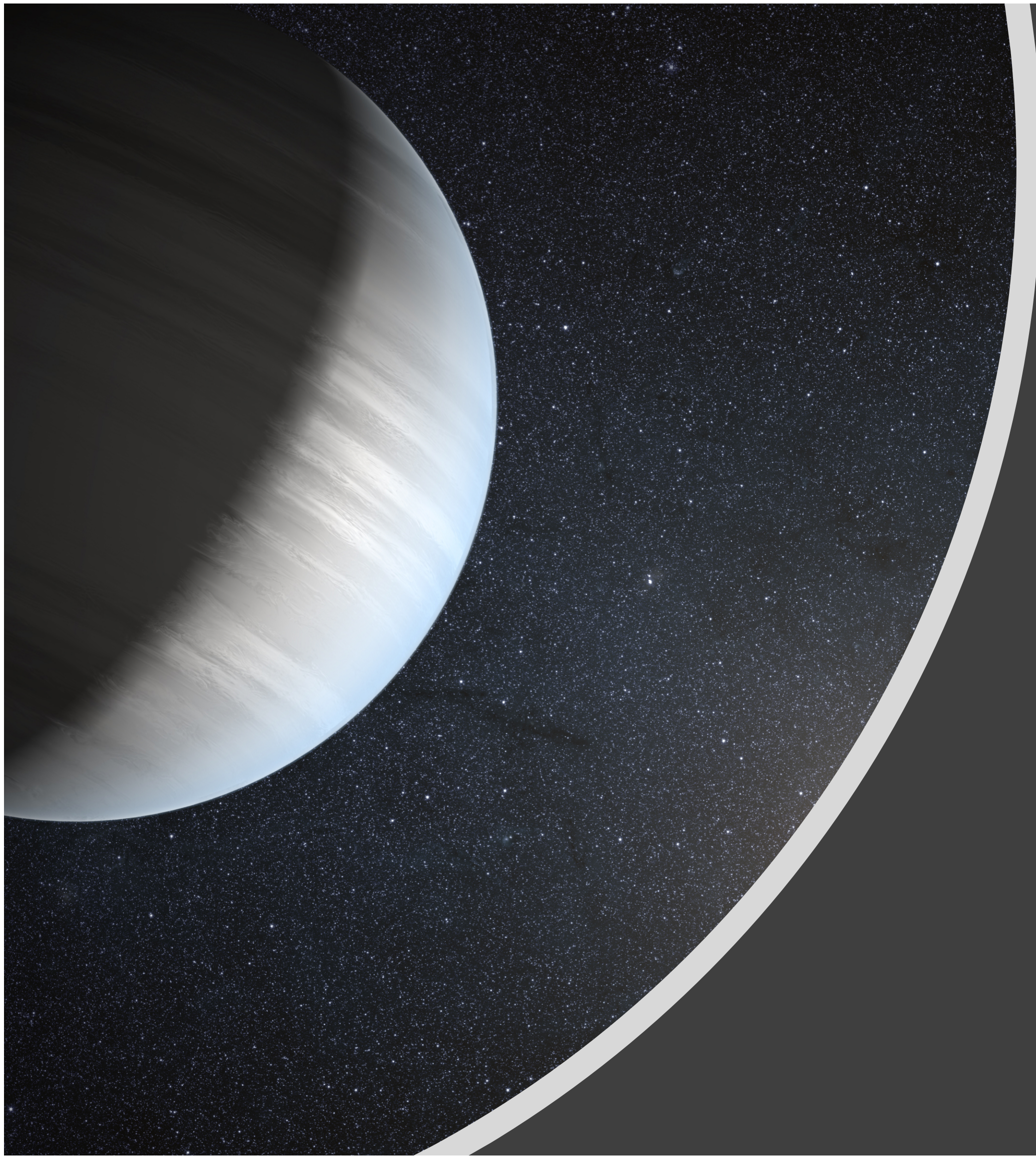


Planet models, tools, science cases, and results from Macintosh SIT

Nikole Lewis, Ryan MacDonald, and Brianna Lacy on behalf of the Macintosh SIT Exoplanet Atmospheric Modeling Team

Macintosh SIT Exoplanet Atmospheres Team

Cornell: Nikole Lewis, Ryan MacDonald

Princeton: Adam Burrows, Brianna Lacy

University of Arizona: Mark Marley

NASA Ames: Natasha Batalha, Roxana Lupu

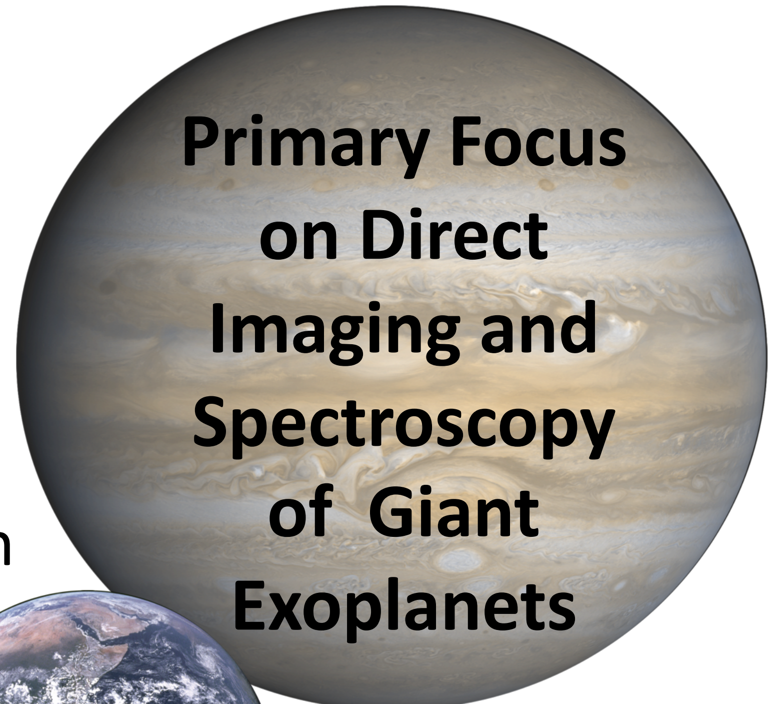
NASA JPL: Renyu Hu, Mario Damiano

Northern Arizona University: Tyler Robinson

UT Austin: Caroline Morley

UC Santa Cruz: Jonathan Fortney

+Many student researchers!!!!!

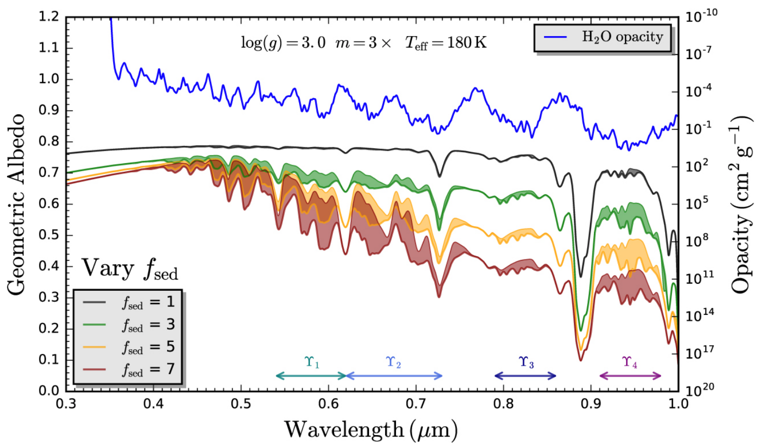


Some exploration of
direct imaging of
terrestrial exoplanets
(e.g. Feng et al. 2018)

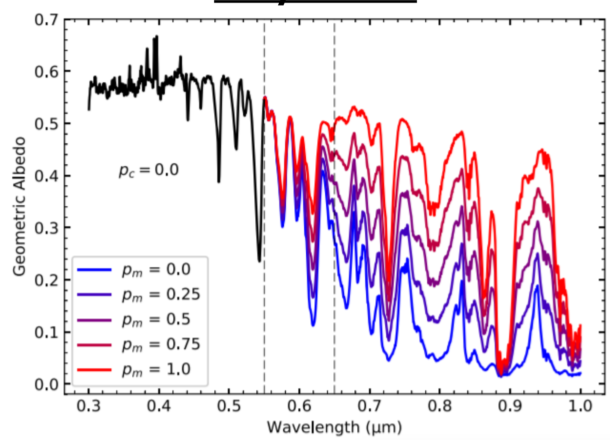
https://romancgi.sioslab.com

OPEN SOURCE MODELS: COOL & SELF-LUMINOUS GIANT PLANETS

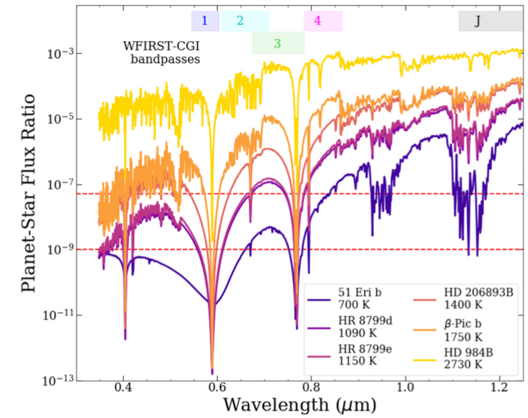
MacDonald+2018



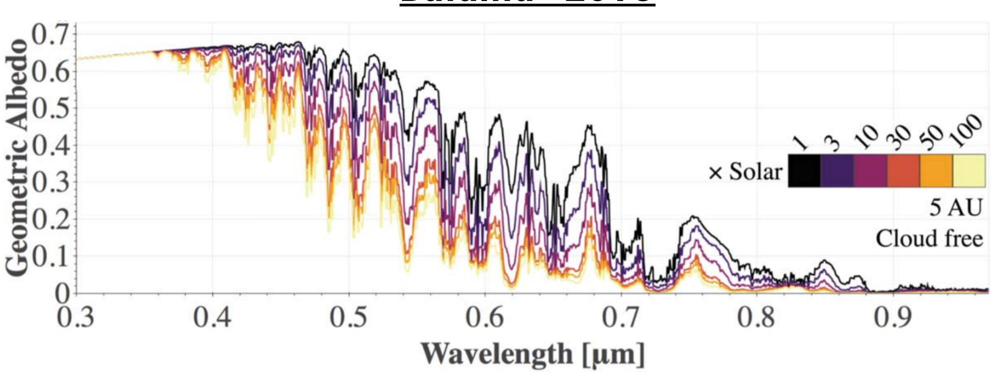
Lacy+2019



Lacy & Burrows (2020)



Batalha+2018



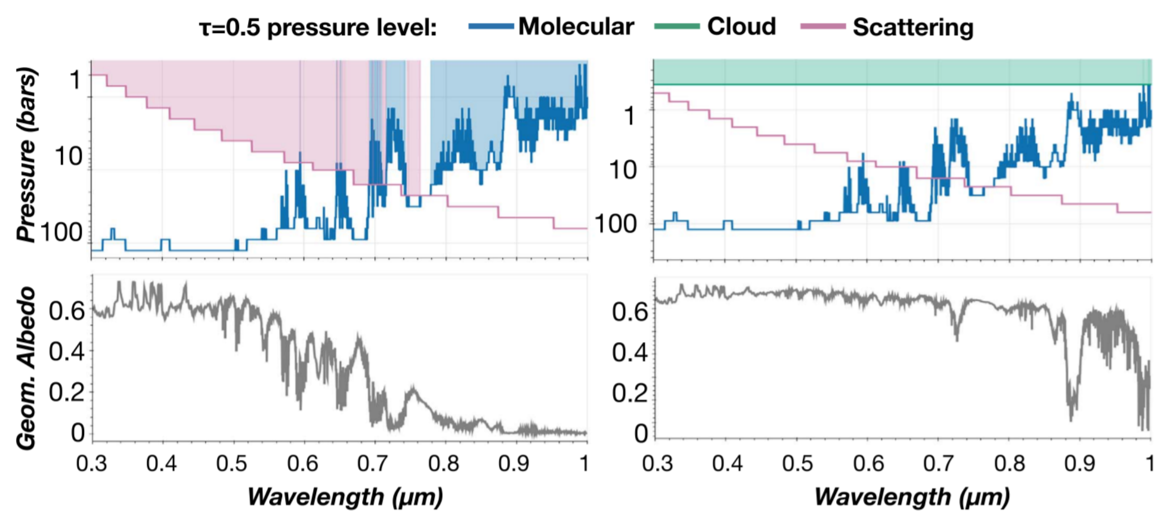
> 74,000 public models for giant exoplanets

- Spans metallicity, gravity, effective temperature / orbital distance, cloud properties, orbital phase
- Includes equilibrium models, cloudy or cloud-free, theoretical or empirical

More models will be made public soon!

OPEN SOURCE TOOLS

Batalha+2019

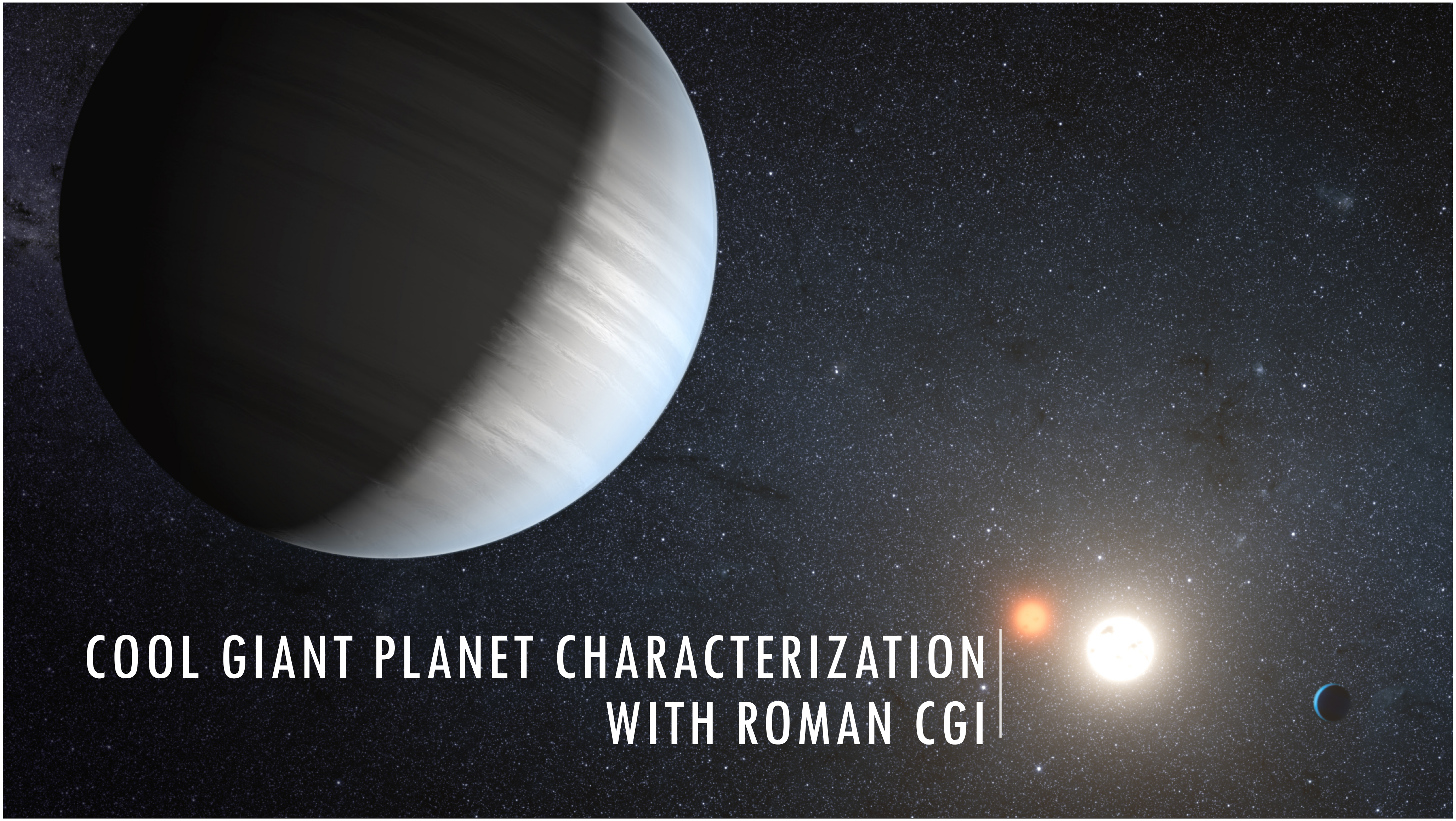


PICASO is an **open source radiative transfer code**

- Reflection + emission + transmission spectra
- Multiple scattering
- Python (and fast!)

Extensive **documentation, tutorials,** and **example code** is available for many use cases:

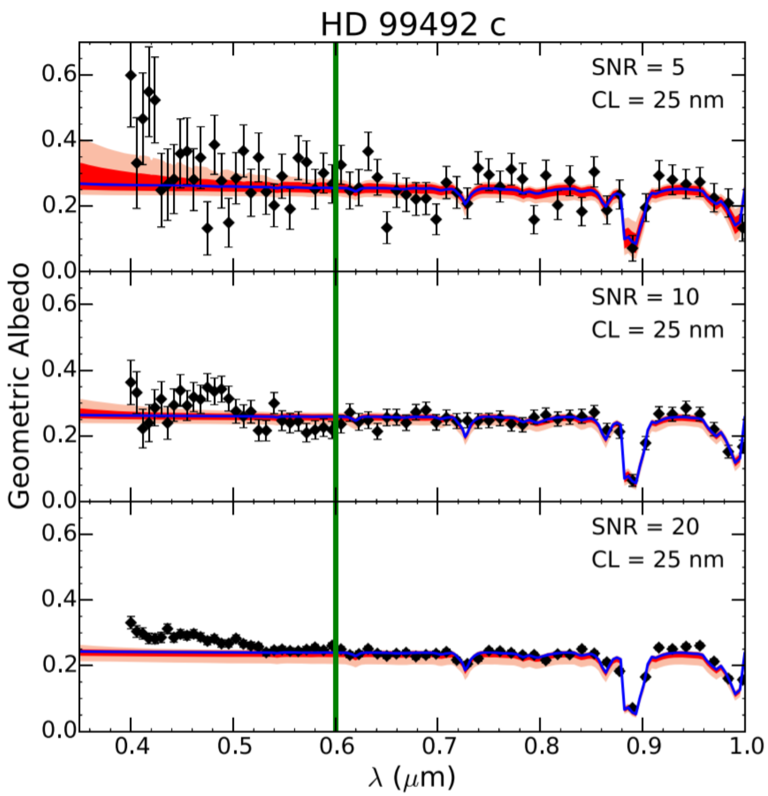
https://natashabatalha.github.io/picaso/index.html



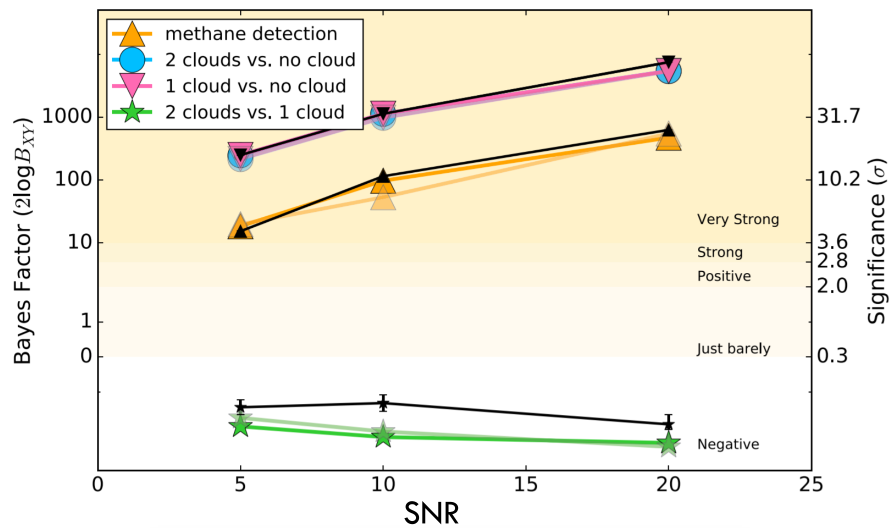
COOL GIANT PLANET CHARACTERIZATION WITH ROMAN CGI

DEVELOPMENT OF ATMOSPHERIC RETRIEVAL TECHNIQUES FOR COOL GIANT REFLECTION SPECTRA

1. Exploration of CH_4 and cloud retrievability



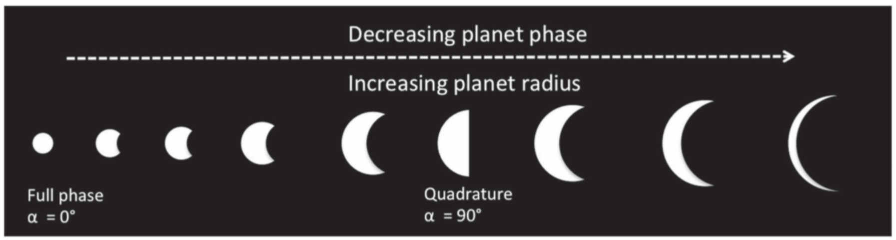
Lupu+2016

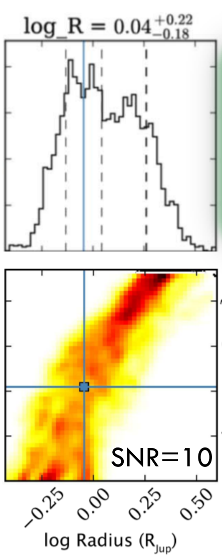


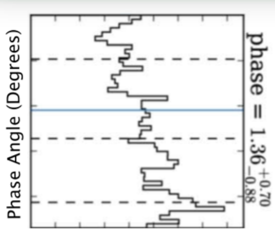
Predicted detection of **clouds** and **CH_4** to high confidence (> 5σ)

DEVELOPMENT OF ATMOSPHERIC RETRIEVAL TECHNIQUES FOR COOL GIANT REFLECTION SPECTRA

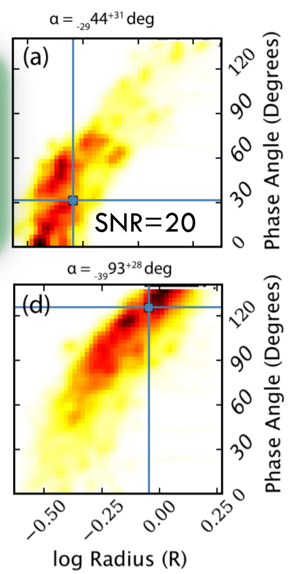
2. Retrievals at different phases



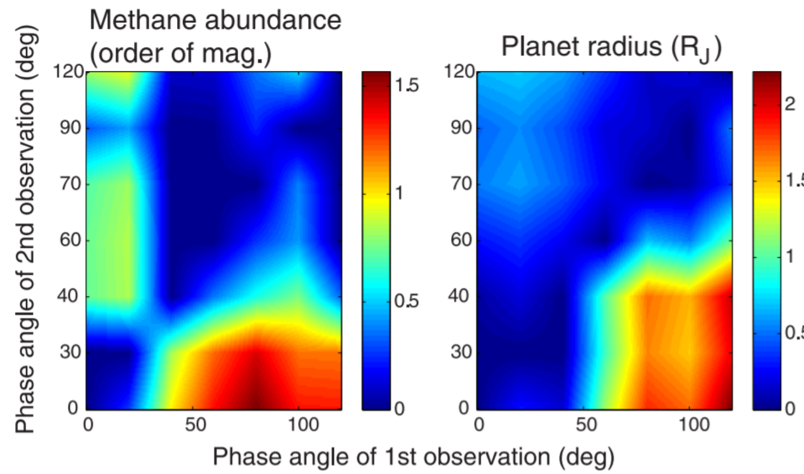




Can constrain R_p to a factor of 2 even with unknown phase



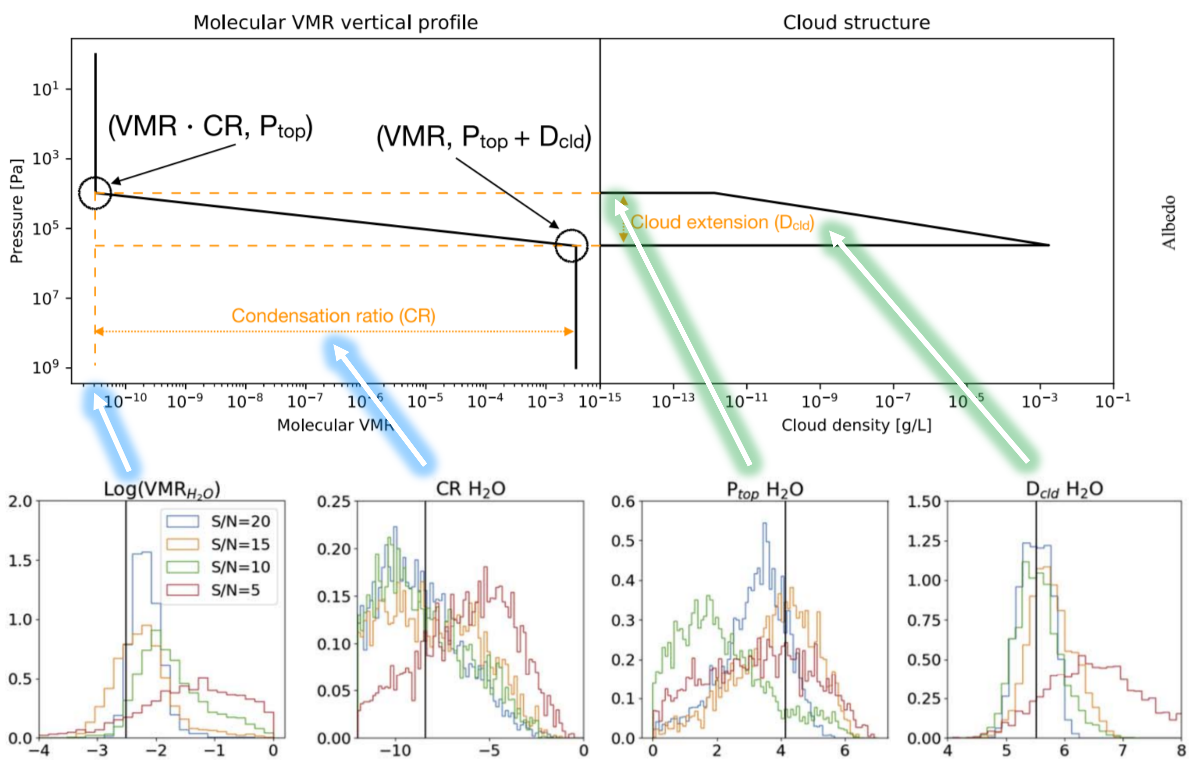
Nayak+2017



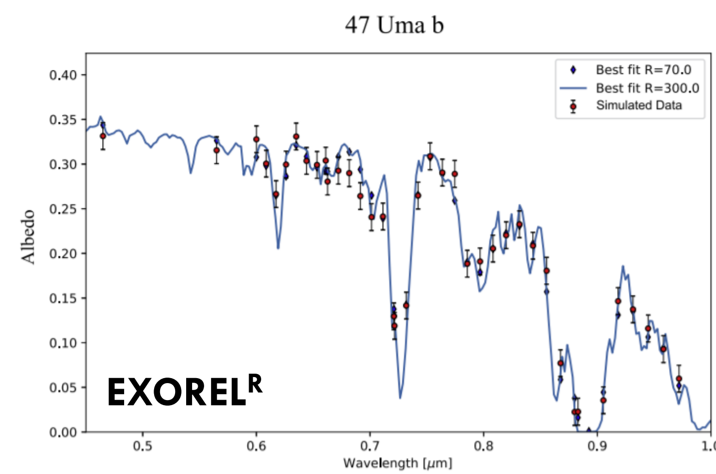
Combining low and high phases improves derived constraints on **CH_4 abundances and R_p**

DEVELOPMENT OF ATMOSPHERIC RETRIEVAL TECHNIQUES FOR COOL GIANT REFLECTION SPECTRA

3. Retrievals accounting for H_2O and NH_3 condensation



Damiano & Hu (2020)

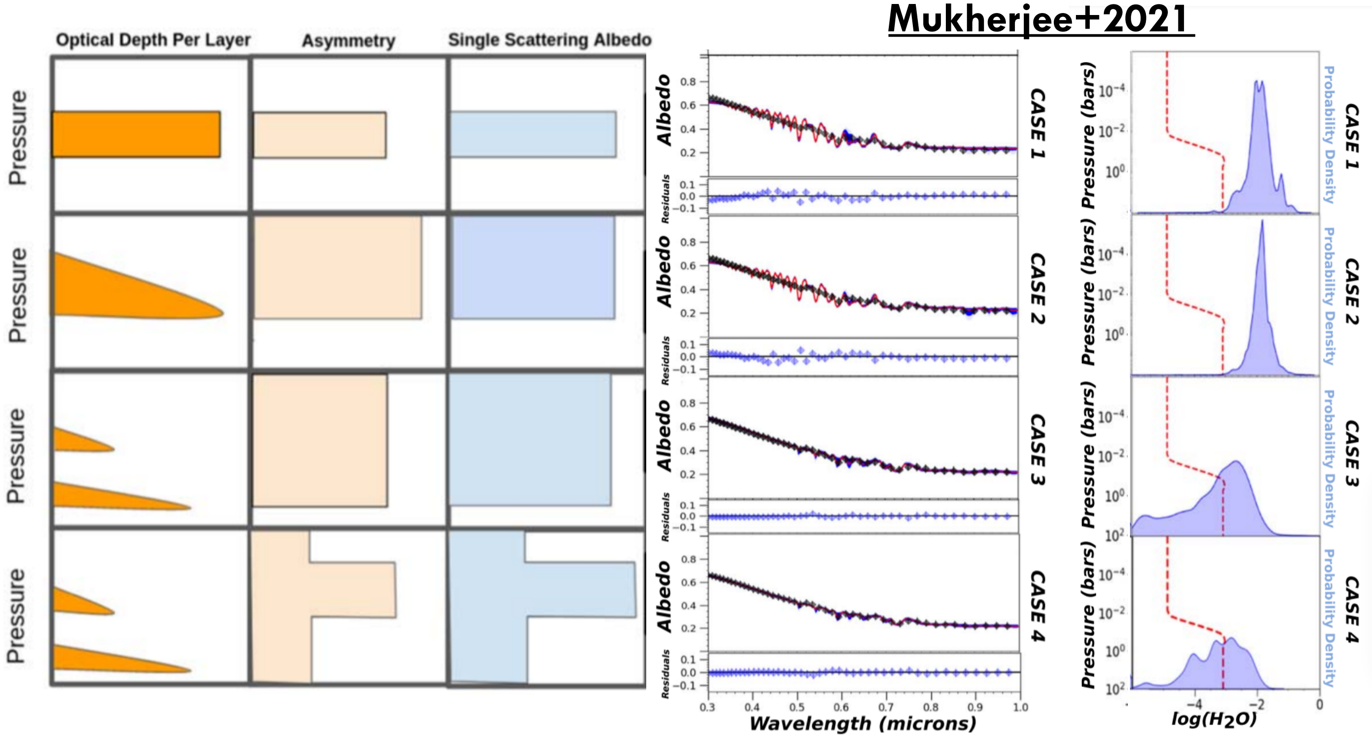


Including **vapor condensation** within atmospheric retrievals → **cloud composition + deep H_2O and NH_3** (SNR ≳ 10)

DEVELOPMENT OF ATMOSPHERIC RETRIEVAL TECHNIQUES FOR COOL GIANT REFLECTION SPECTRA

4. New cloud parametrizations for reflection spectra retrievals

Mukherjee+2021

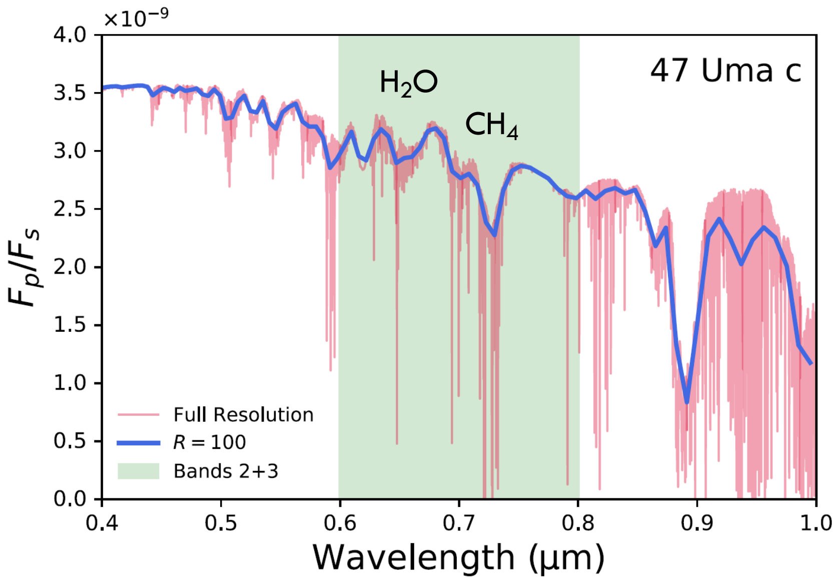


Precise spectra (SNR ~ 20) **can distinguish** between one or two **cloud decks**

↓

Insufficient cloud model complexity in retrievals → **overestimate abundances**

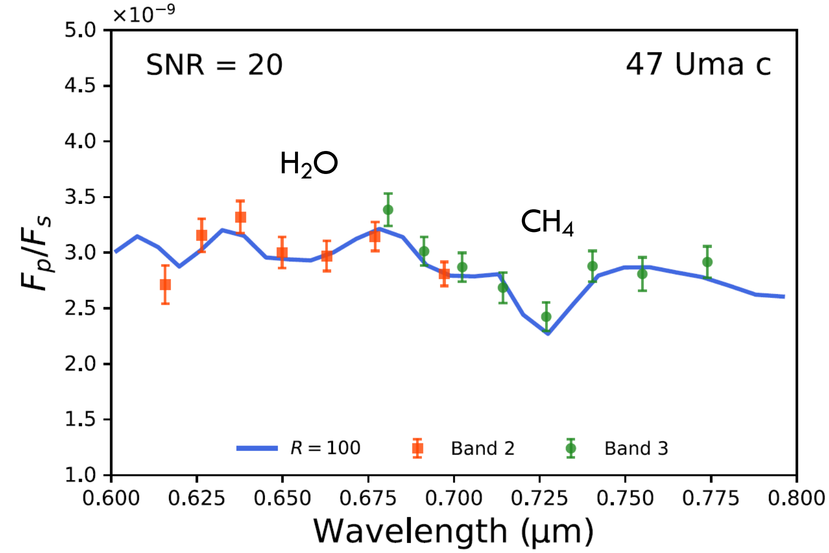
COOL GIANT CHARACTERIZATION WITH THE FINAL ROMAN CGI CONFIGURATION



Roman simulation

(GSFC / JPL)

MacDonald, Lewis, Marley+(in prep)



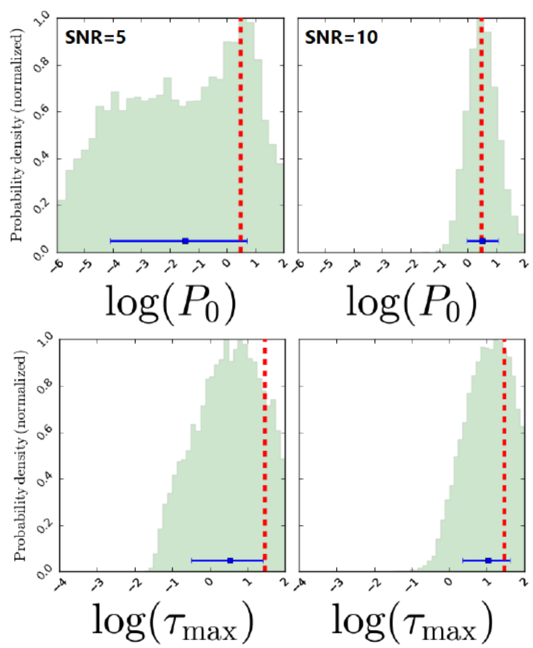
Reflection spectra of cool giant exoplanets are primarily shaped by:

1. Deep, optically thick **clouds.**
2. **CH_4** and **H_2O** absorption.

- **Band 3** spectra probe **CH_4**
- **Band 2** spectra (not baseline) probe **H_2O**
- **Both Bands** are sensitive to **clouds.**

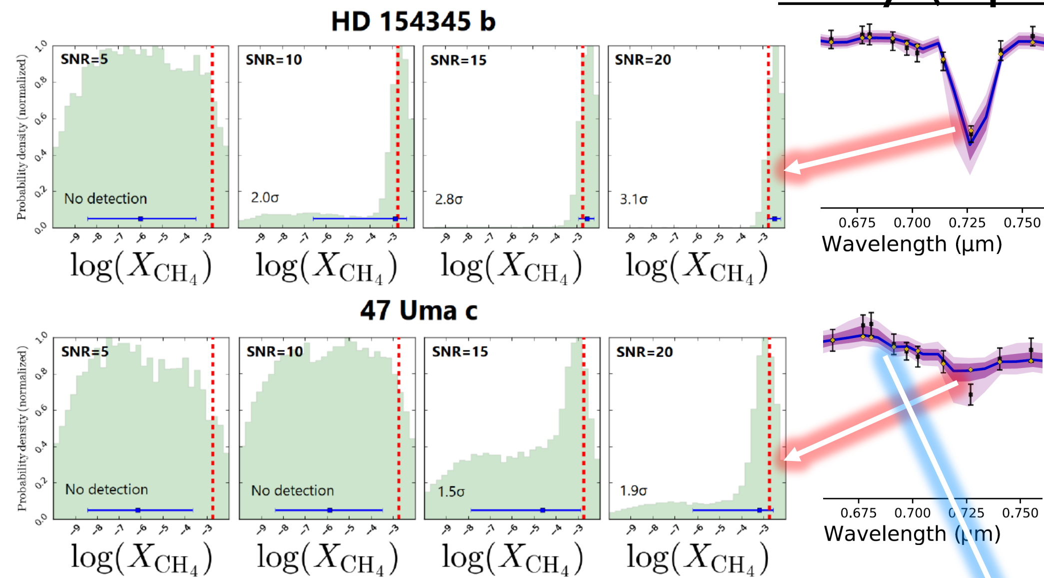
COOL GIANT CHARACTERIZATION WITH THE FINAL ROMAN CGI CONFIGURATION

MacDonald, Lewis, Marley+(in prep)



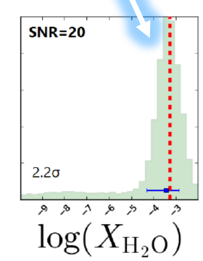
Detection of clouds:	SNR=5	SNR=10
	4.8σ	9.2σ

SNR ≥ 10 → constrain **cloud base pressure** and **optical depth** within an order of magnitude

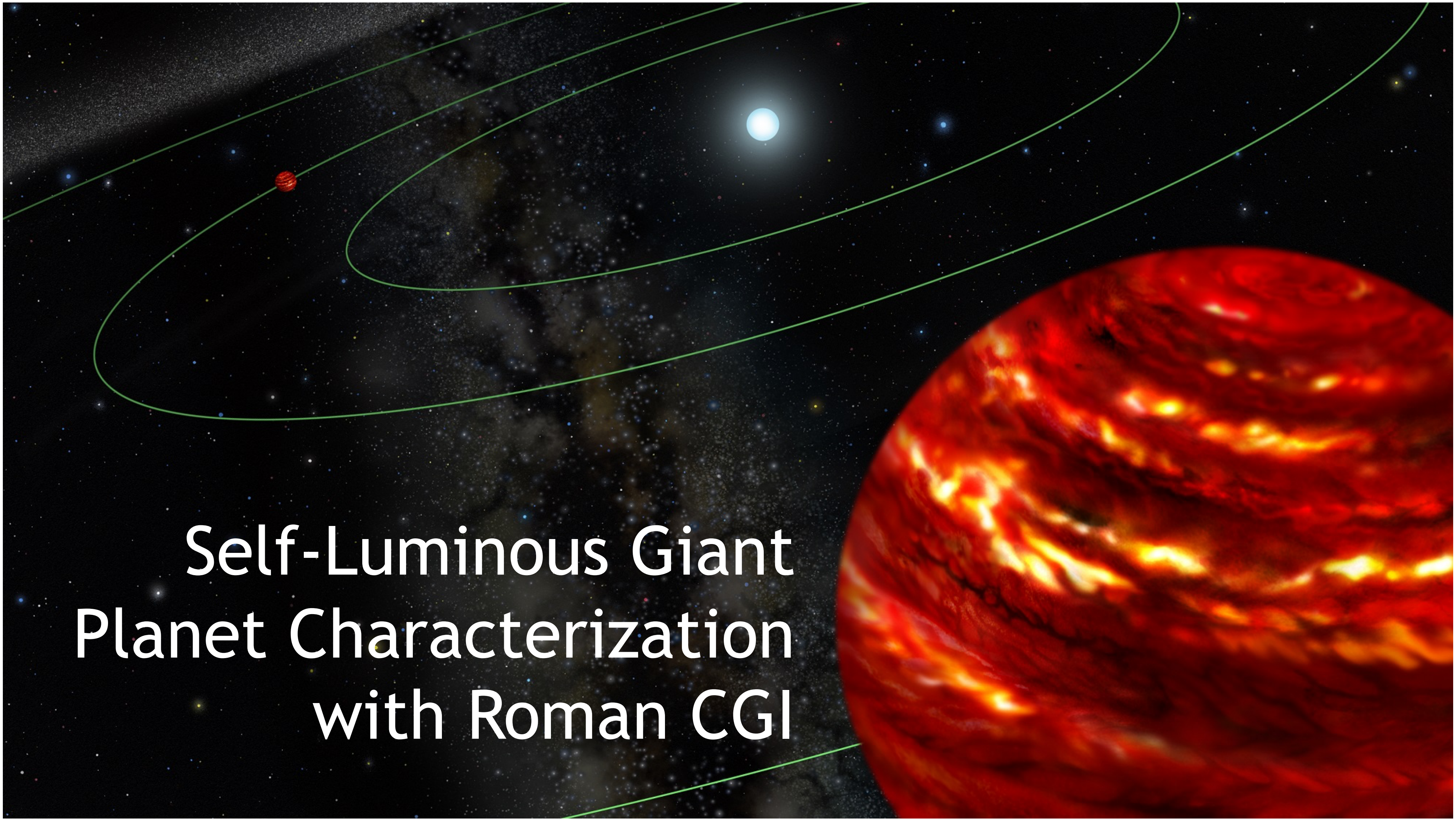


Clouds affect CH_4 detectability and constraints:

- Prominent clouds → high CH_4 contrast at 0.725 μm
- Weaker clouds → reduced CH_4 contrast

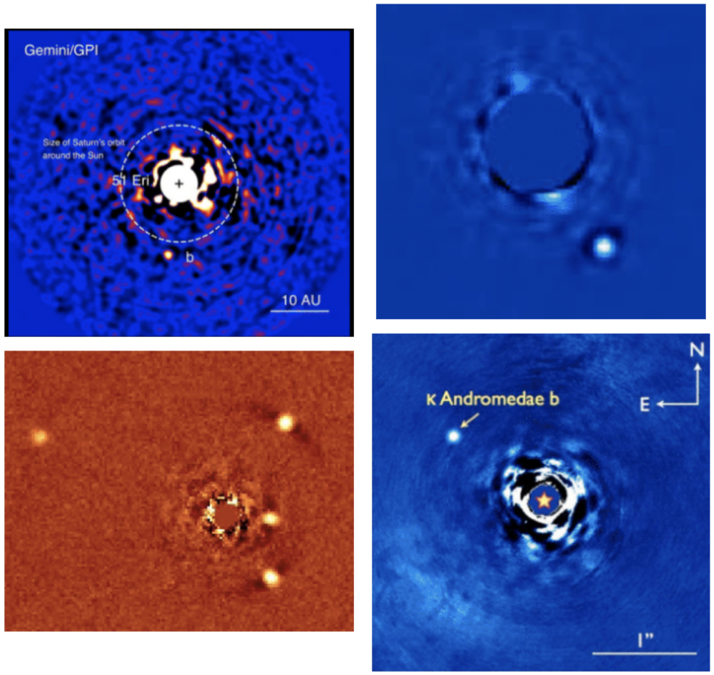


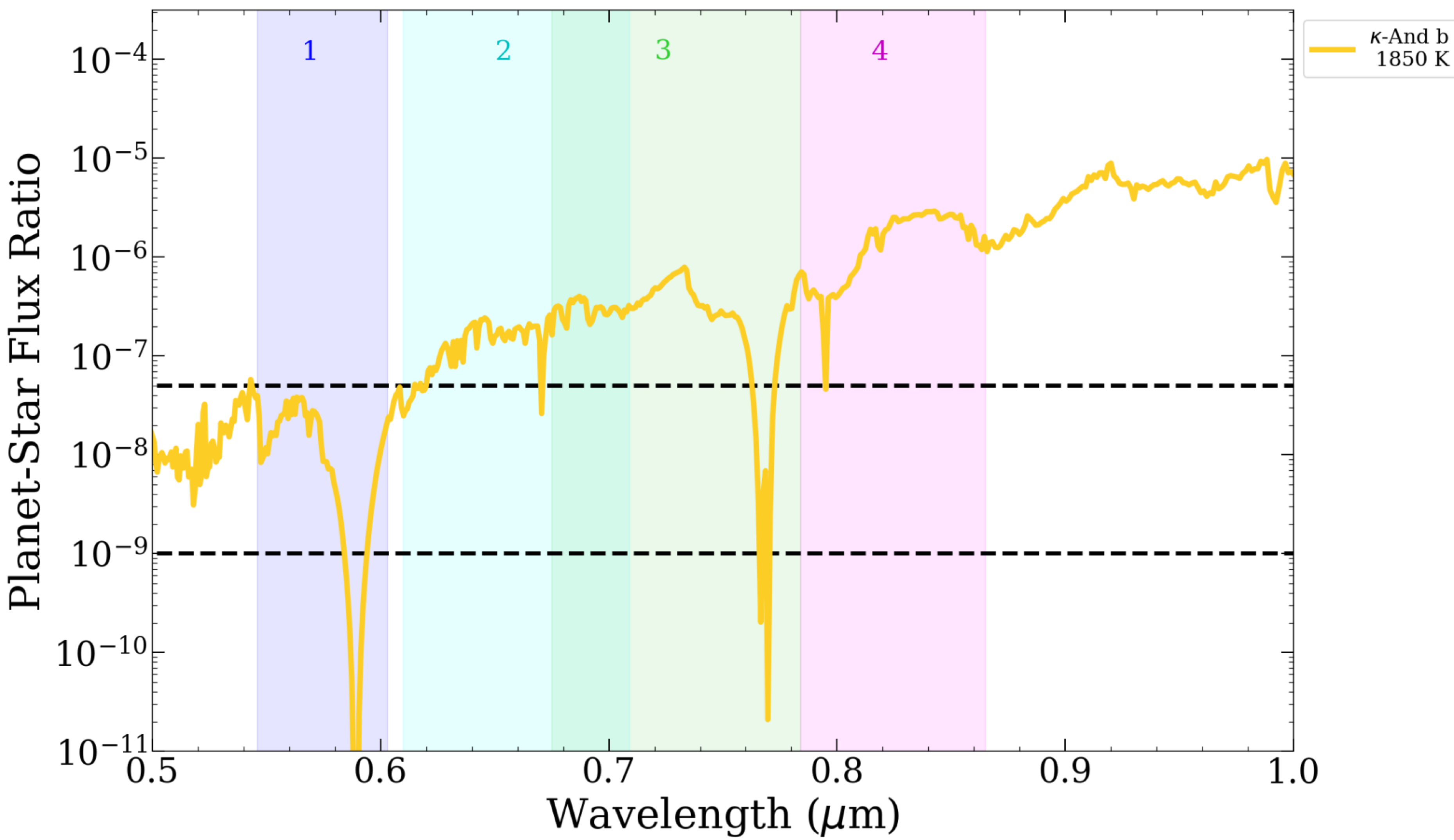
SNR ~ 20 → constrain **CH_4** within **1 dex** (prominent clouds), **H_2O** within **1.5 dex** (weak clouds)


Self-Luminous Giant
Planet Characterization
with Roman CGI

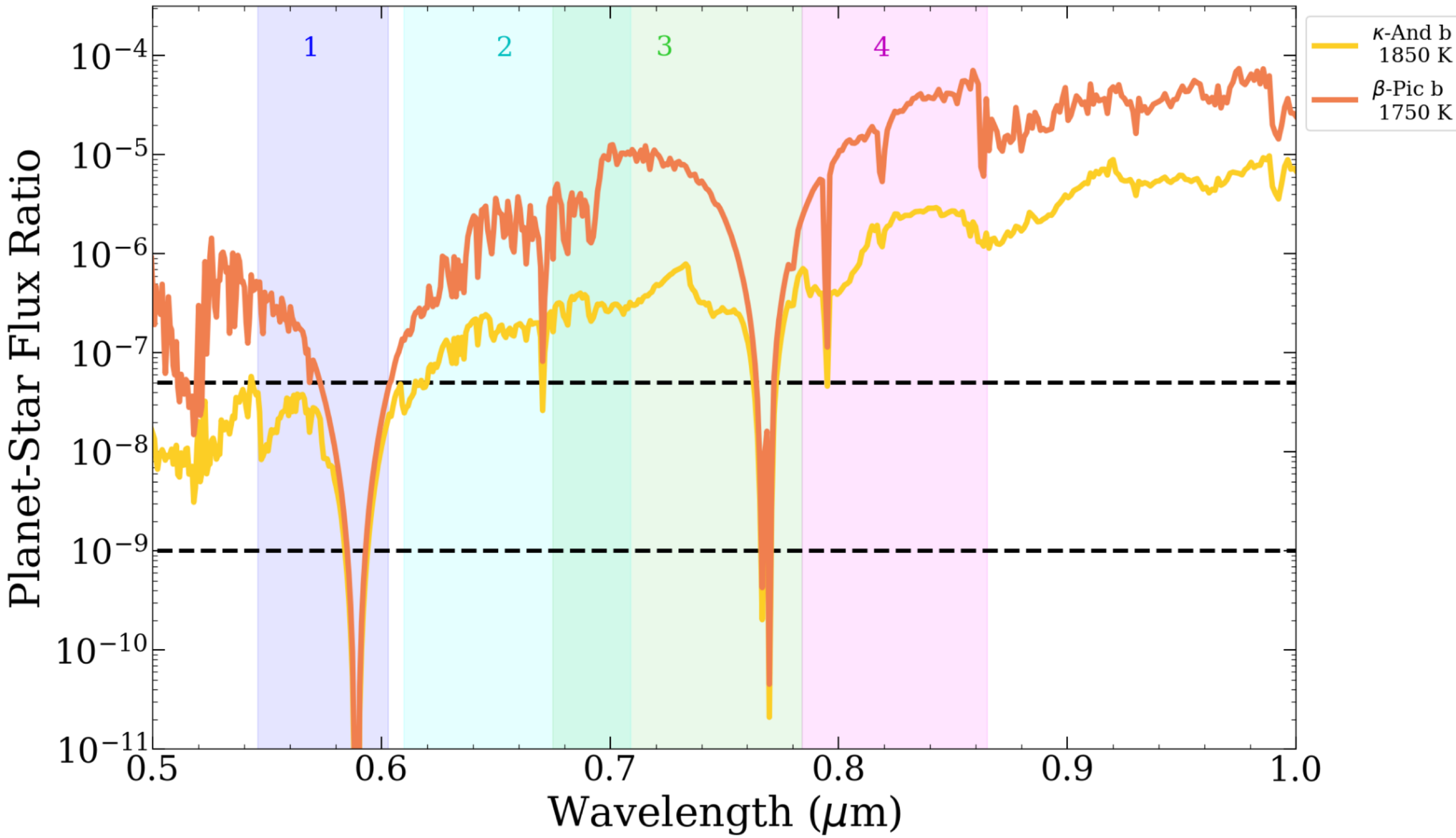
Possible science questions for self-luminous targets:

- Do spectra of planetary mass companions follow the optical sequence seen in brown dwarfs?
- Can we improve constraints on basic properties: effective temperature, surface gravity, metallicity?
- Can we leverage the additional wavelength coverage to learn more details about the clouds/dust present in these atmospheres?

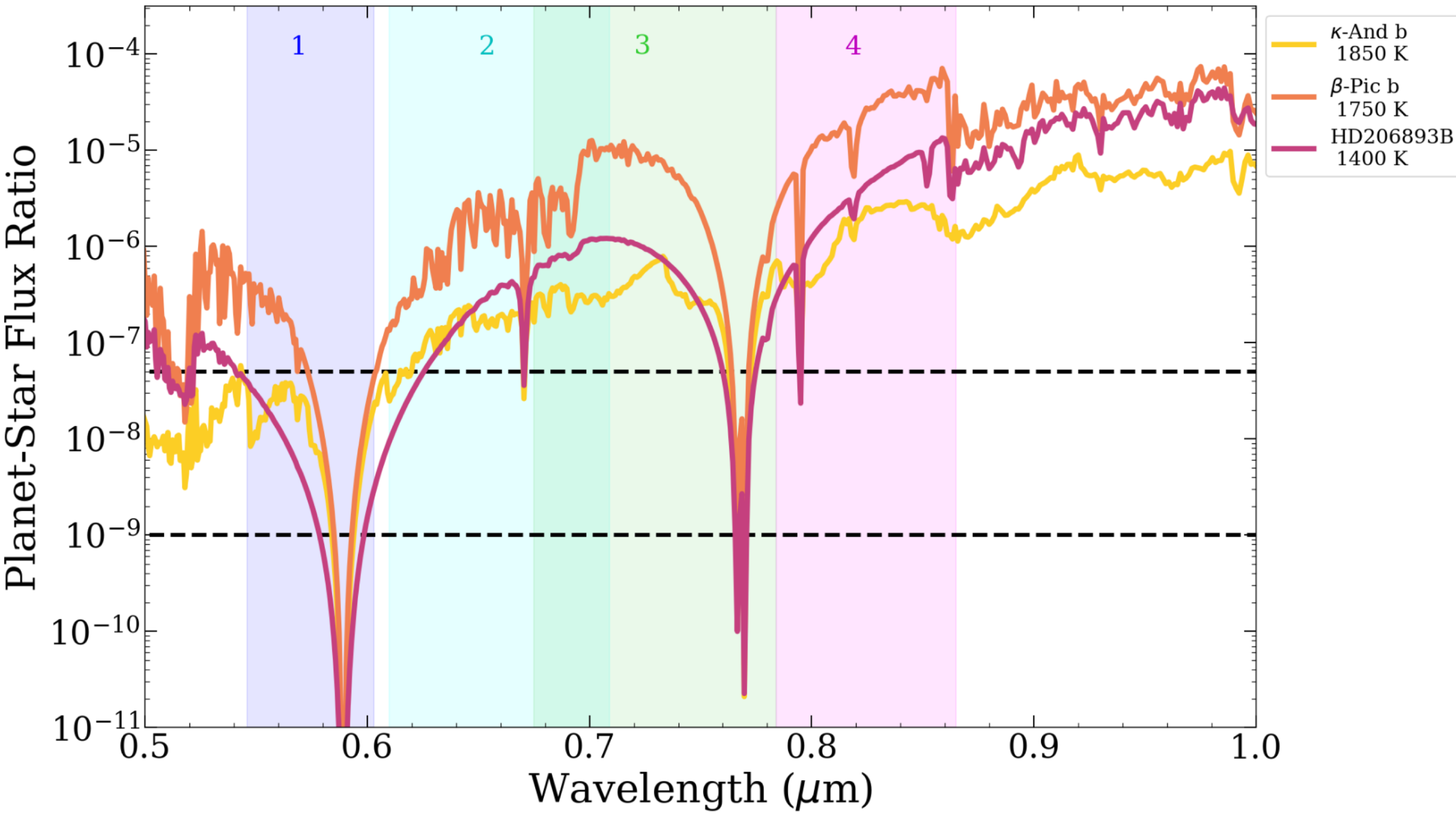




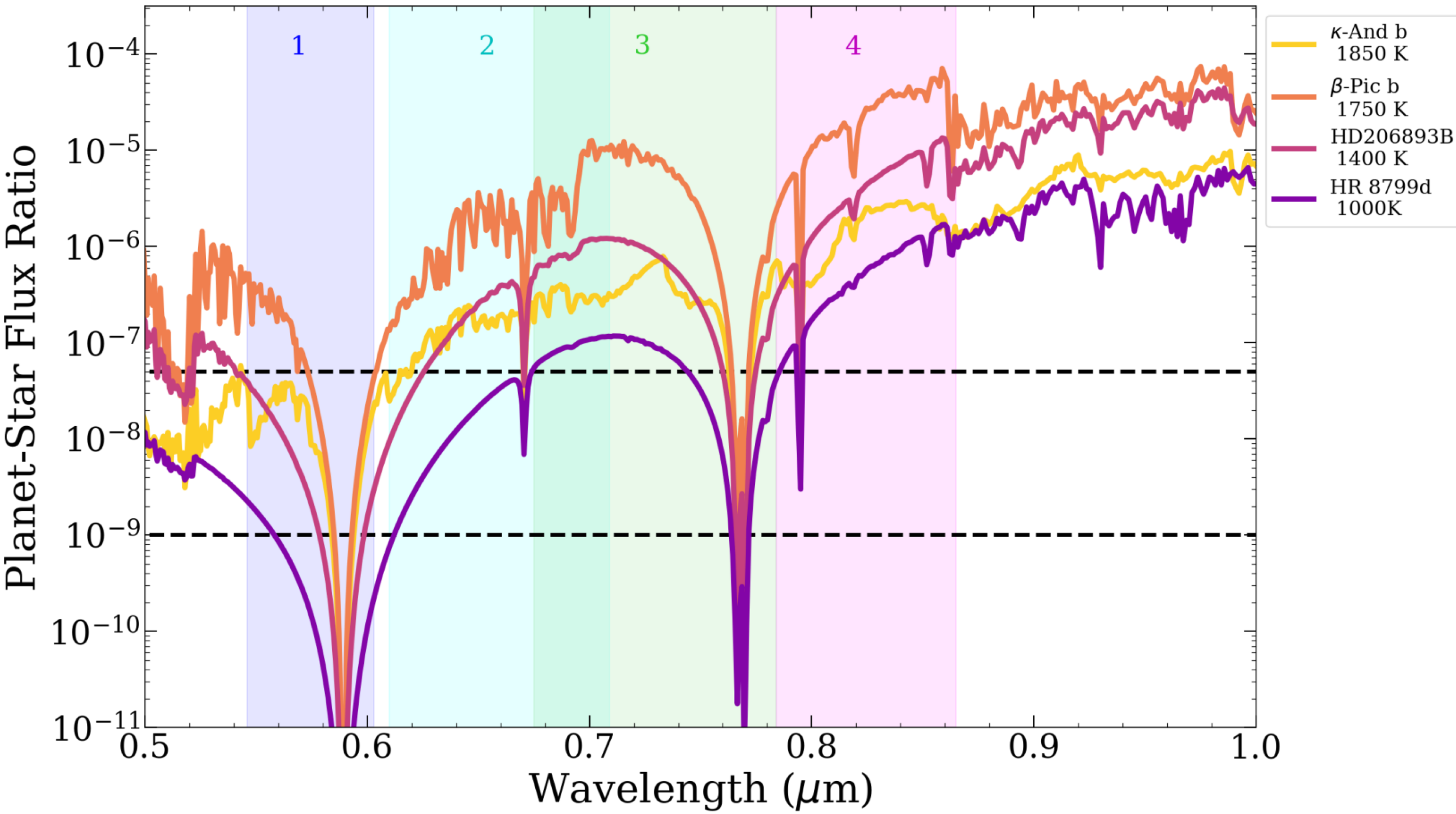
Planet-Star Flux Ratio
Wavelength (μm)
κ-And b
1850 K
1
2
3
4
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.5
0.6
0.7
0.8
0.9
1.0



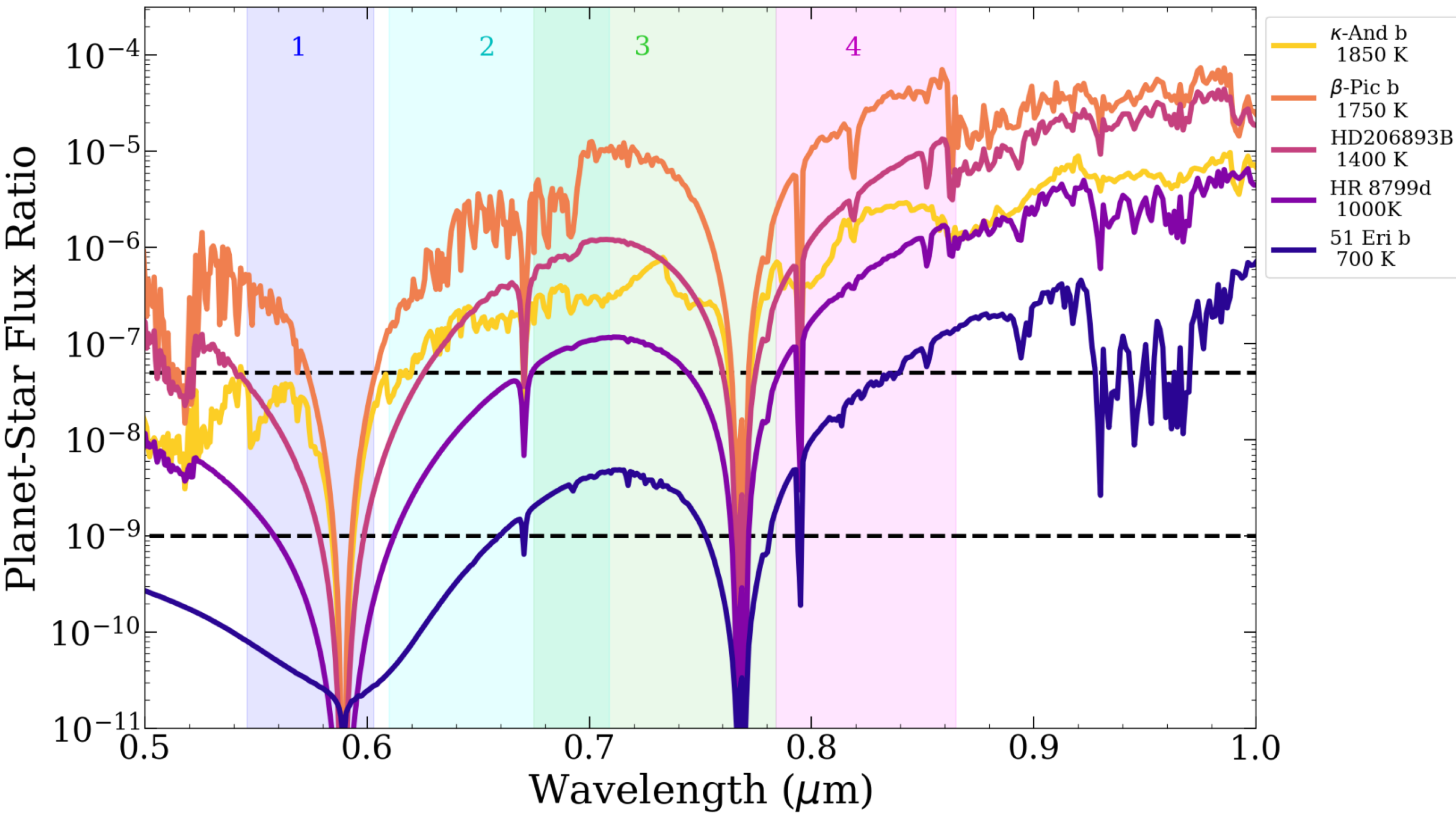
1
2
3
4
κ-And b
1850 K
β-Pic b
1750 K
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.5
0.6
0.7
0.8
0.9
1.0
Planet-Star Flux Ratio
Wavelength (μm)



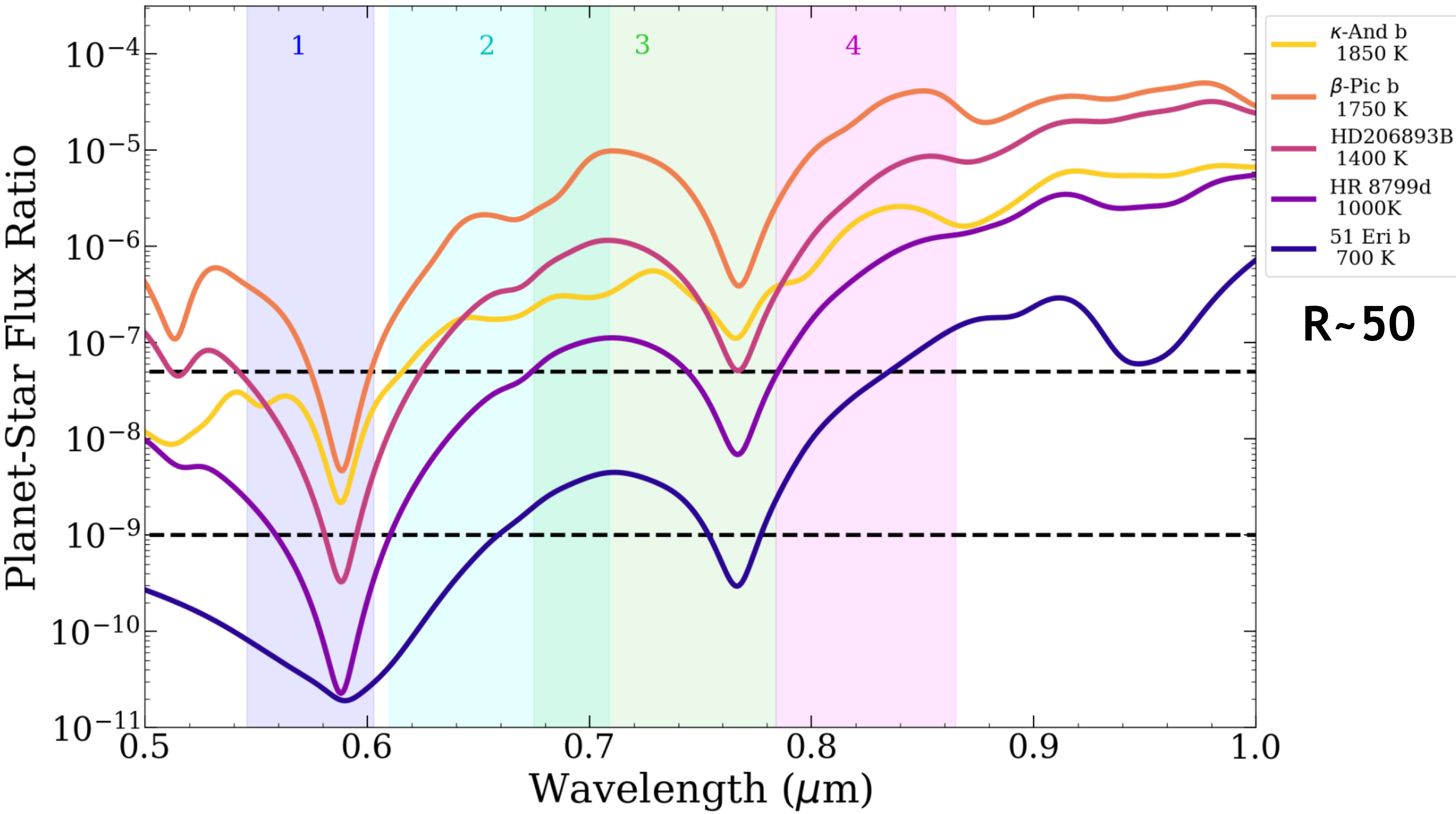
1
2
3
4
κ-And b 1850 K
β-Pic b 1750 K
HD206893B 1400 K
Planet-Star Flux Ratio
Wavelength (μm)
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
0.5
0.6
0.7
0.8
0.9
1.0



Planet-Star Flux Ratio
Wavelength (μm)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
κ-And b 1850 K
β-Pic b 1750 K
HD206893B 1400 K
HR 8799d 1000K

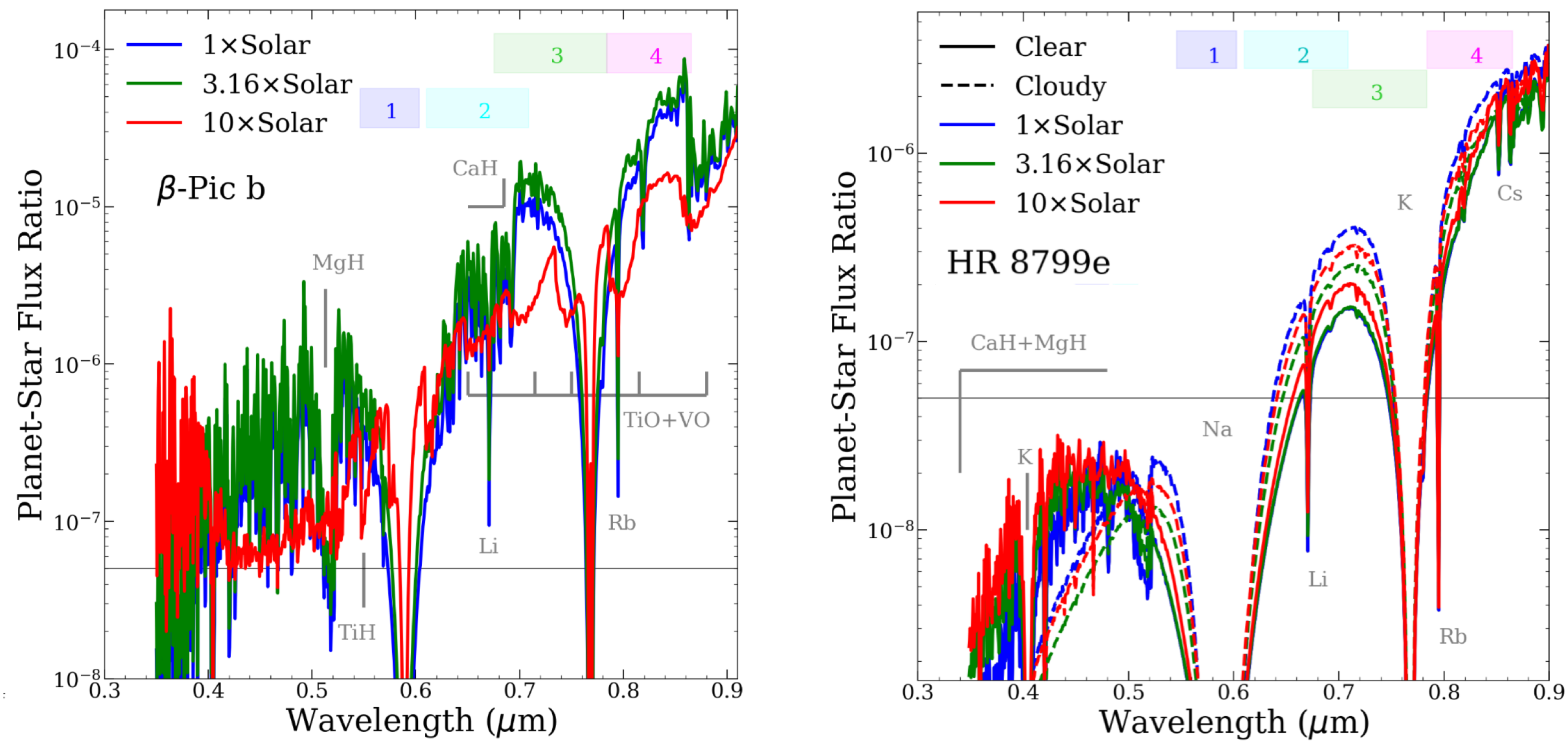


1
2
3
4
κ-And b 1850 K
β-Pic b 1750 K
HD206893B 1400 K
HR 8799d 1000K
51 Eri b 700 K
Planet-Star Flux Ratio
Wavelength (μm)
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
0.5
0.6
0.7
0.8
0.9
1.0



1
2
3
4
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Planet-Star Flux Ratio
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (μm)
κ-And b 1850 K
β-Pic b 1750 K
HD206893B 1400 K
HR 8799d 1000K
51 Eri b 700 K
R~50

Lacy & Burrows 2020 showed optical wavelengths are sensitive to *metallicity* and *clouds* :



Two projects are following up to quantify constraining power for self-luminous planets on properties of interest:

- ***Ryan MacDonald*** at Cornell, using free retrievals
- ***Arlene Alemán*** at Stanford, using a grid-based fit for gravity, metallicity

Simulated Roman CGI spectrum:

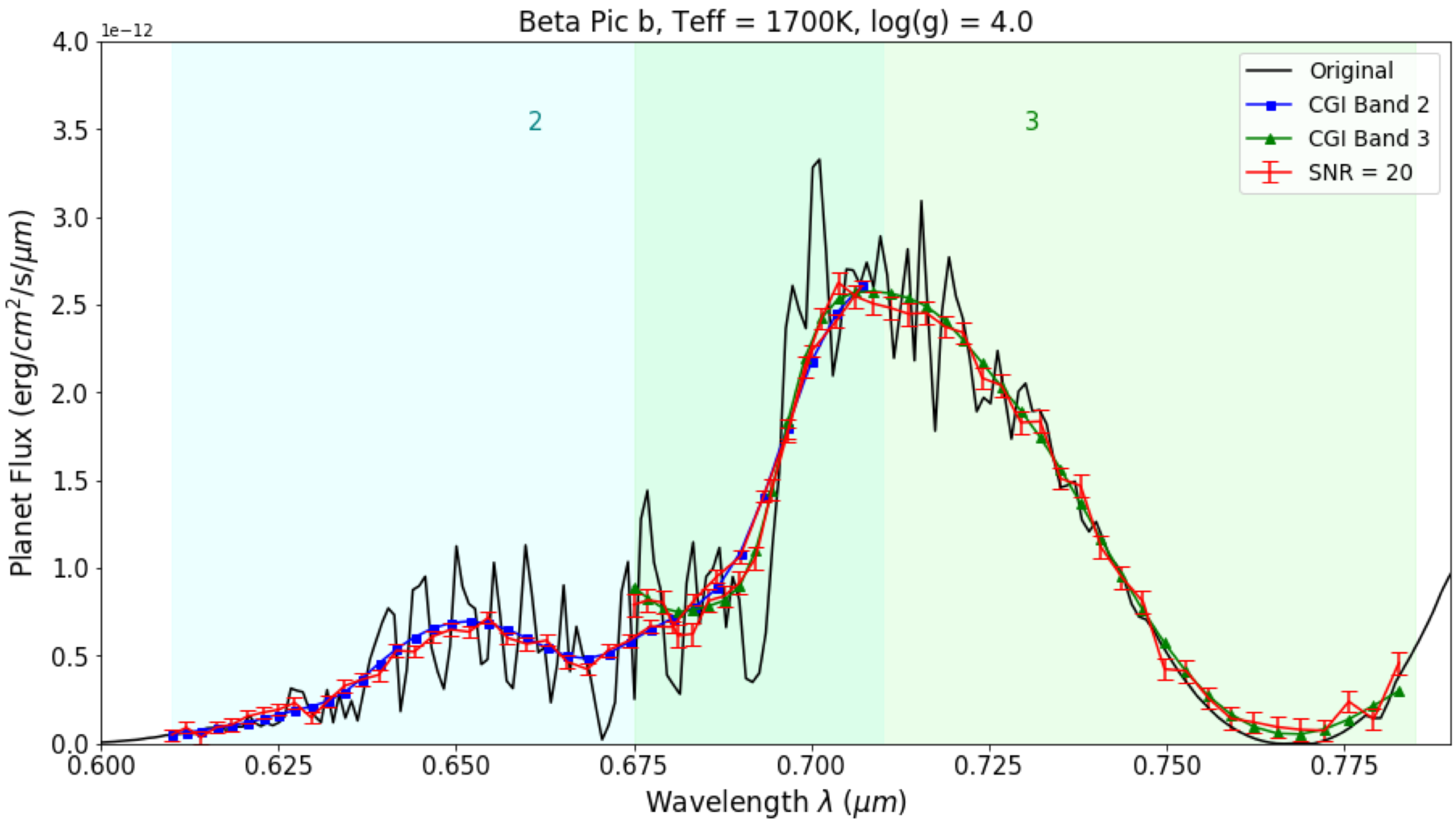


Fig. courtesy of Arlene Alemán

Ideas for future work:

Self-Luminous planets

- Take a more detailed look at clouds+dust
- Consider deviations from a solar C:O ratio
- Explore how the presence of debris disks can complicate matters
- Account for patchiness, quantify optical variability
- Models for additional objects
- Models for the youngest planets with active accretion signatures

Cool giants

- Utility of Band 1+2 photometry for atmospheric characterization
- Impact of hazes on retrievals of bluest data
- Revisit multi-phase retrievals with final CGI configuration