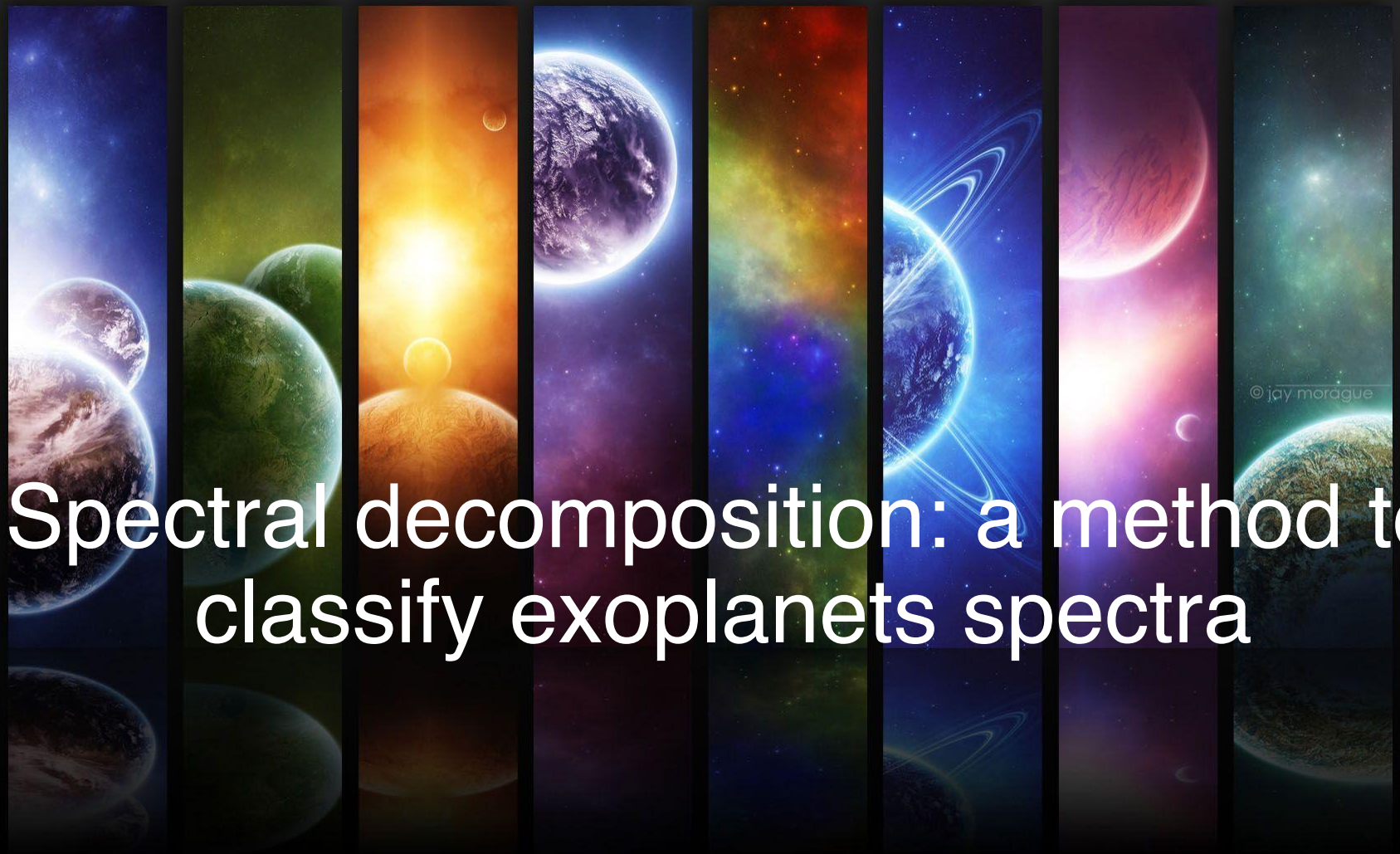


Spectral decomposition: a method to classify exoplanets spectra

Karan Molaverdikhani, Paul Mollière, Thomas Henning

Max Planck Institute for Astronomy – Heidelberg

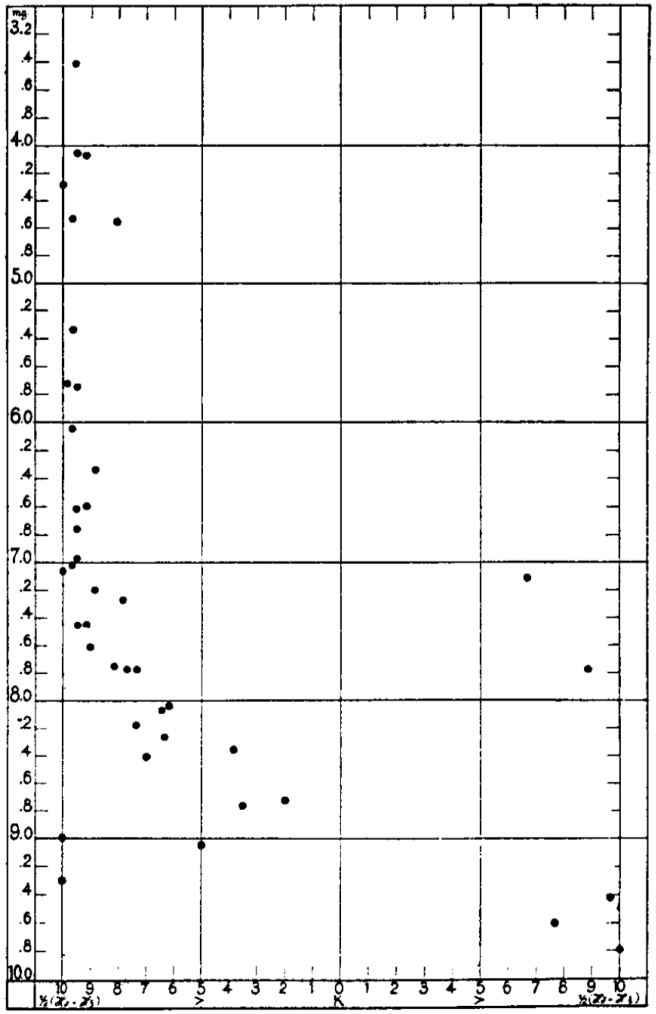
Sterrewacht Leiden

Spectroscopy of Exoplanet

11 Jul 2018, Cumberland Lodge

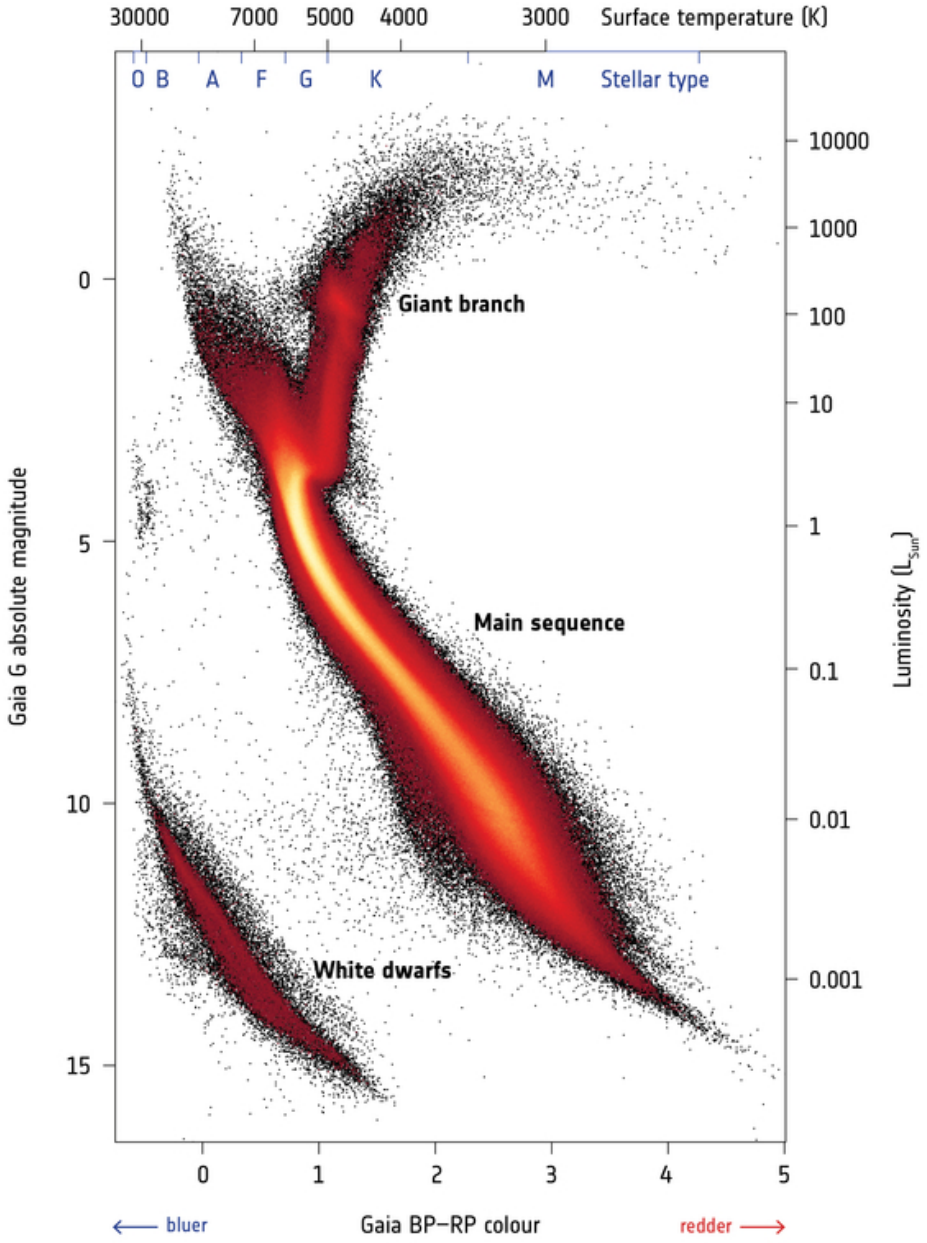
The first HR diagram: 1908

Hans Rosenberg



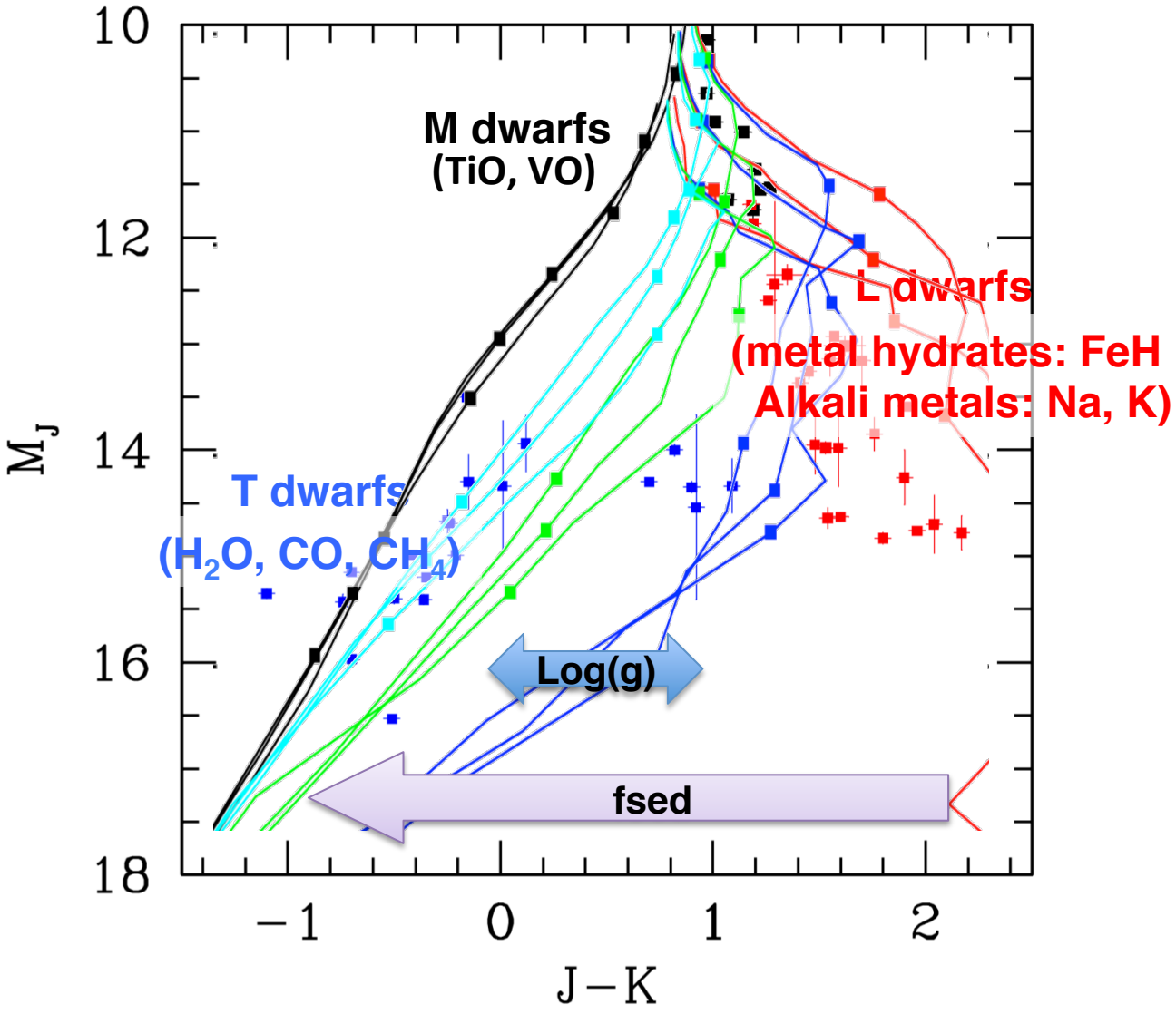
[Courtesy of Leos Ondra]

The last HR diagram: 1908+110



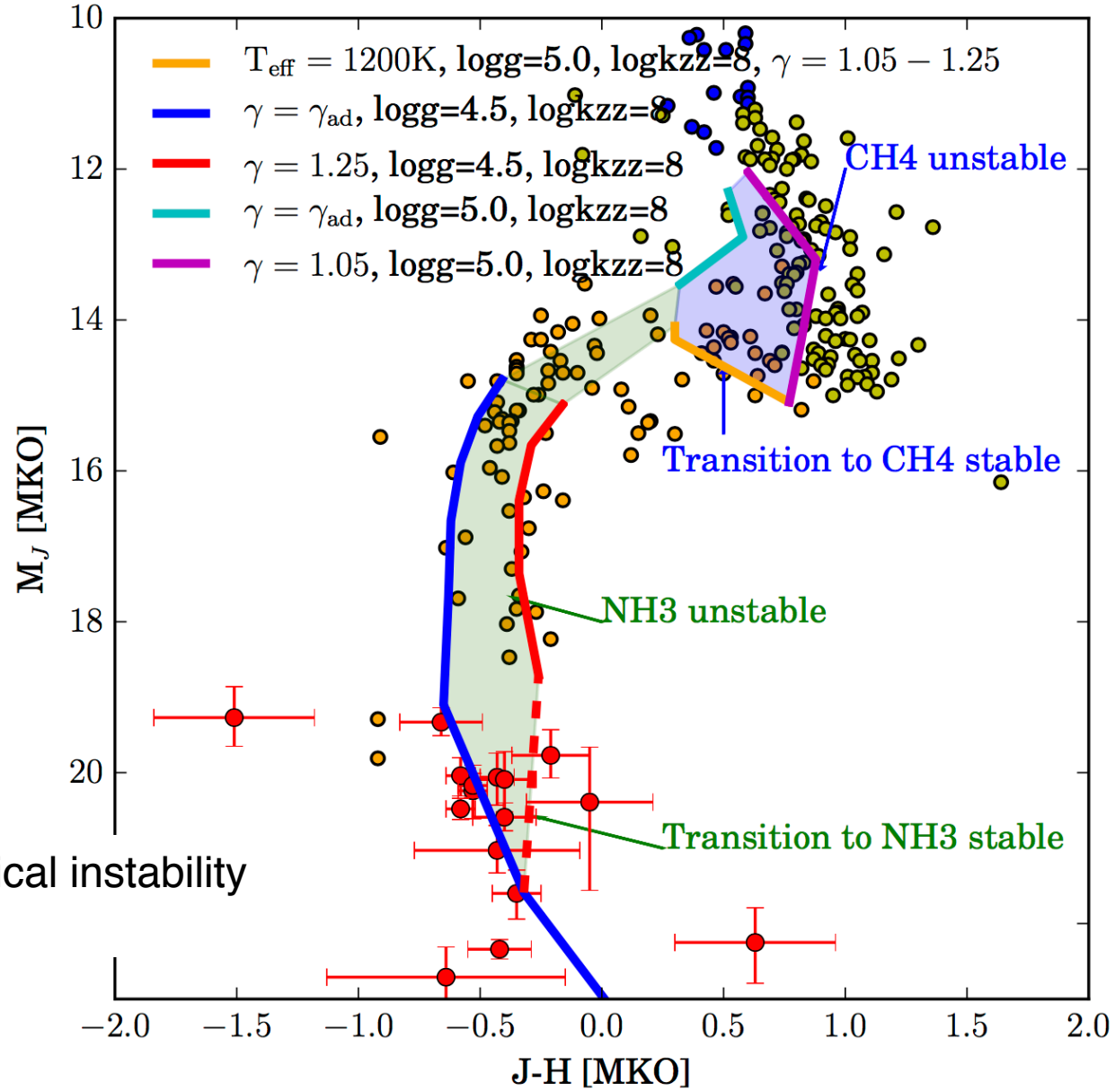
[Gaia DR2]

Brown Dwarfs: ~2000



[Saumon & Marley 2008]

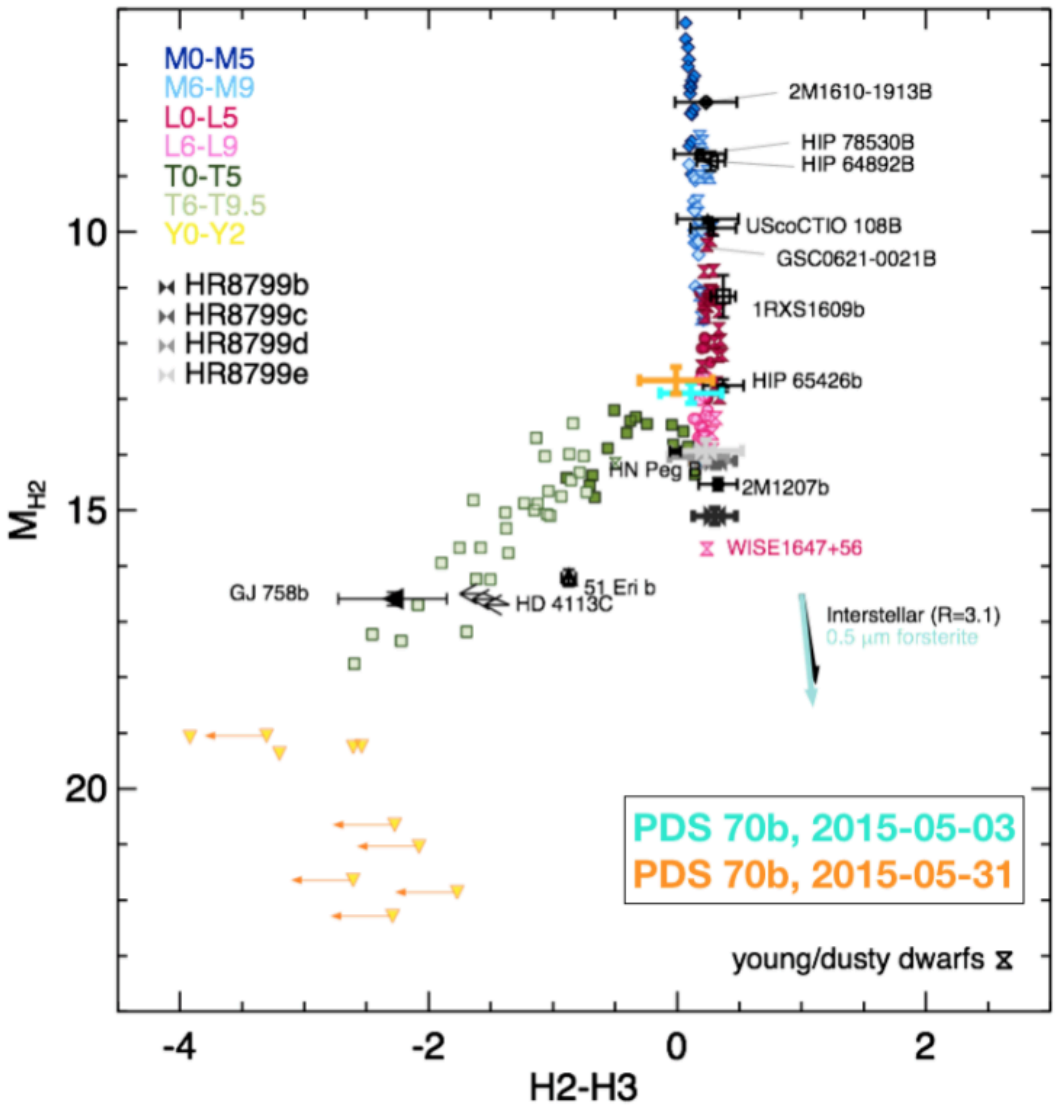
Brown Dwarfs: ~2000 + 10



Thermo-chemical instability
Not clouds

[Tremblin et al. 2016]

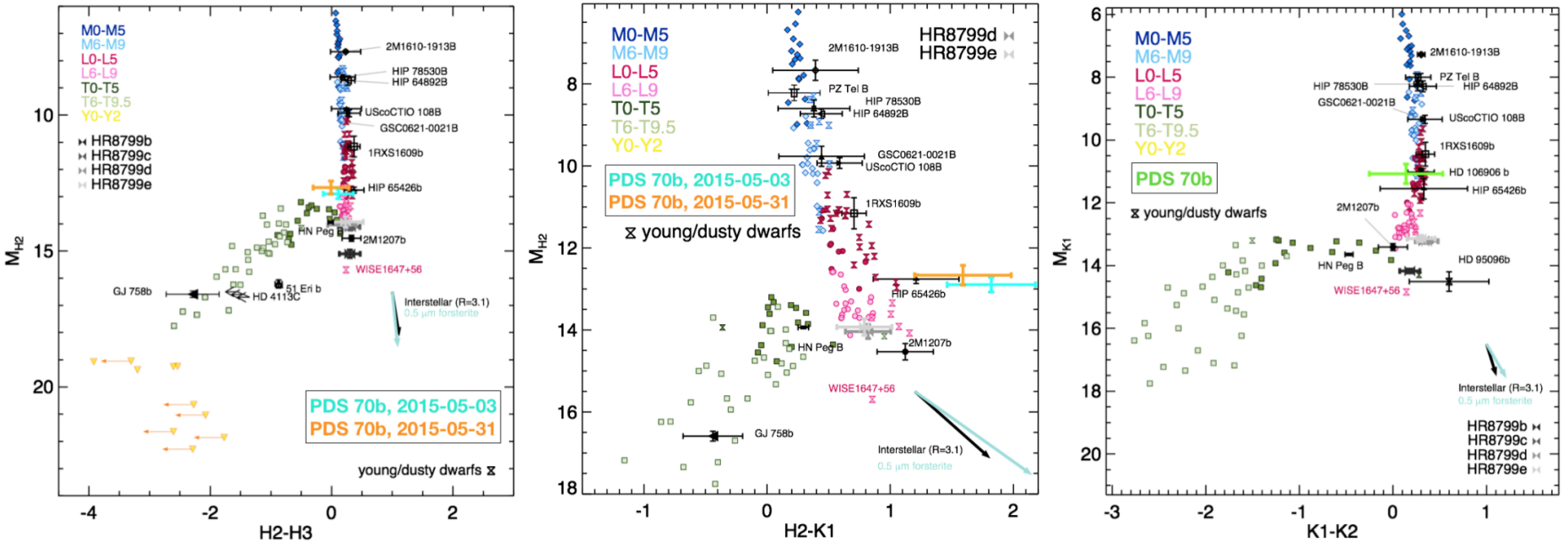
BD + Self-luminous planets



H2 = 1.593 μm
H3 = 1.667 μm
K1 = 2.11 μm
K2 = 2.25 μm

[Kepler et al. 2018]

BD + Self-luminous planets



H2 = 1.593 μm
H3 = 1.667 μm
K1 = 2.11 μm
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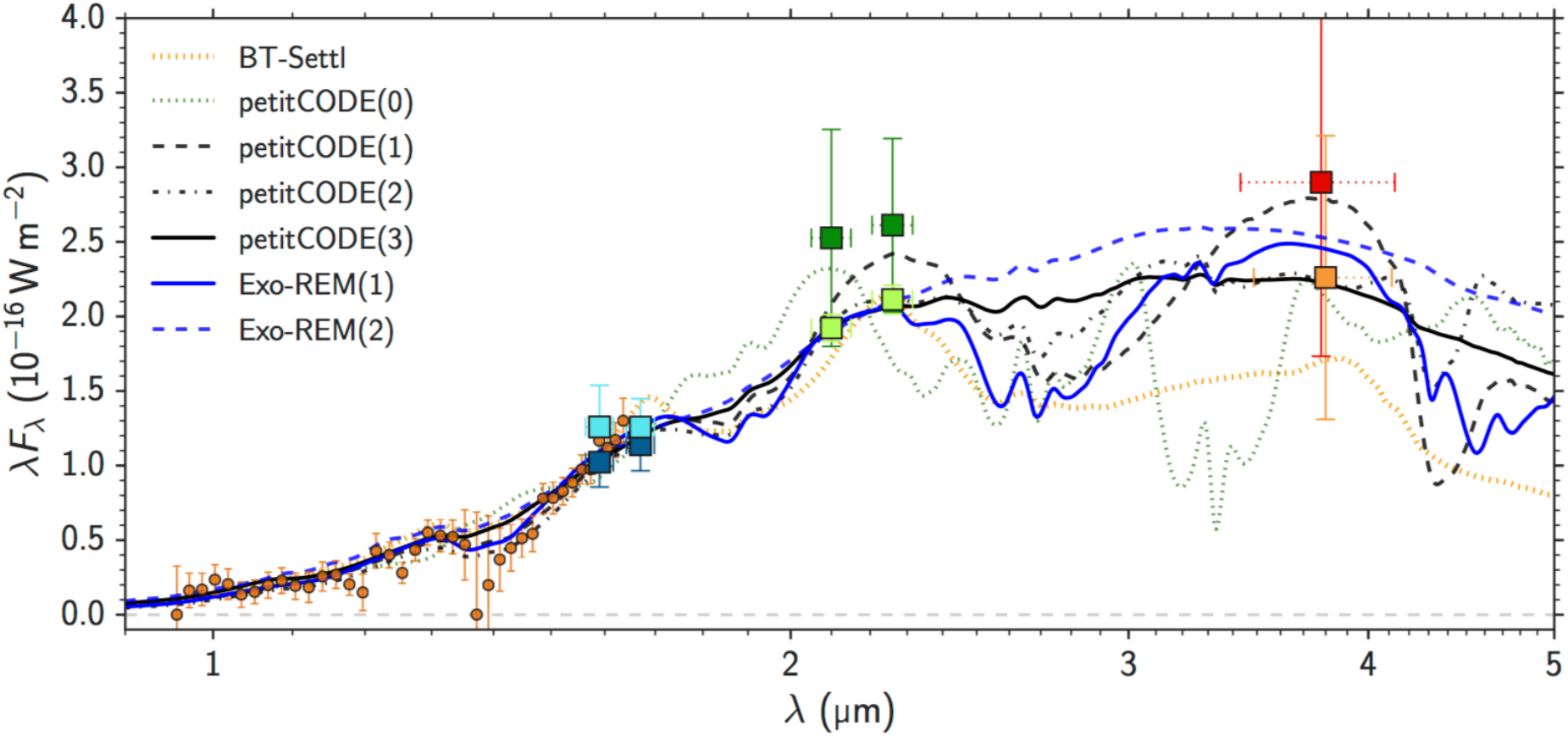
[Kepler et al. 2018]

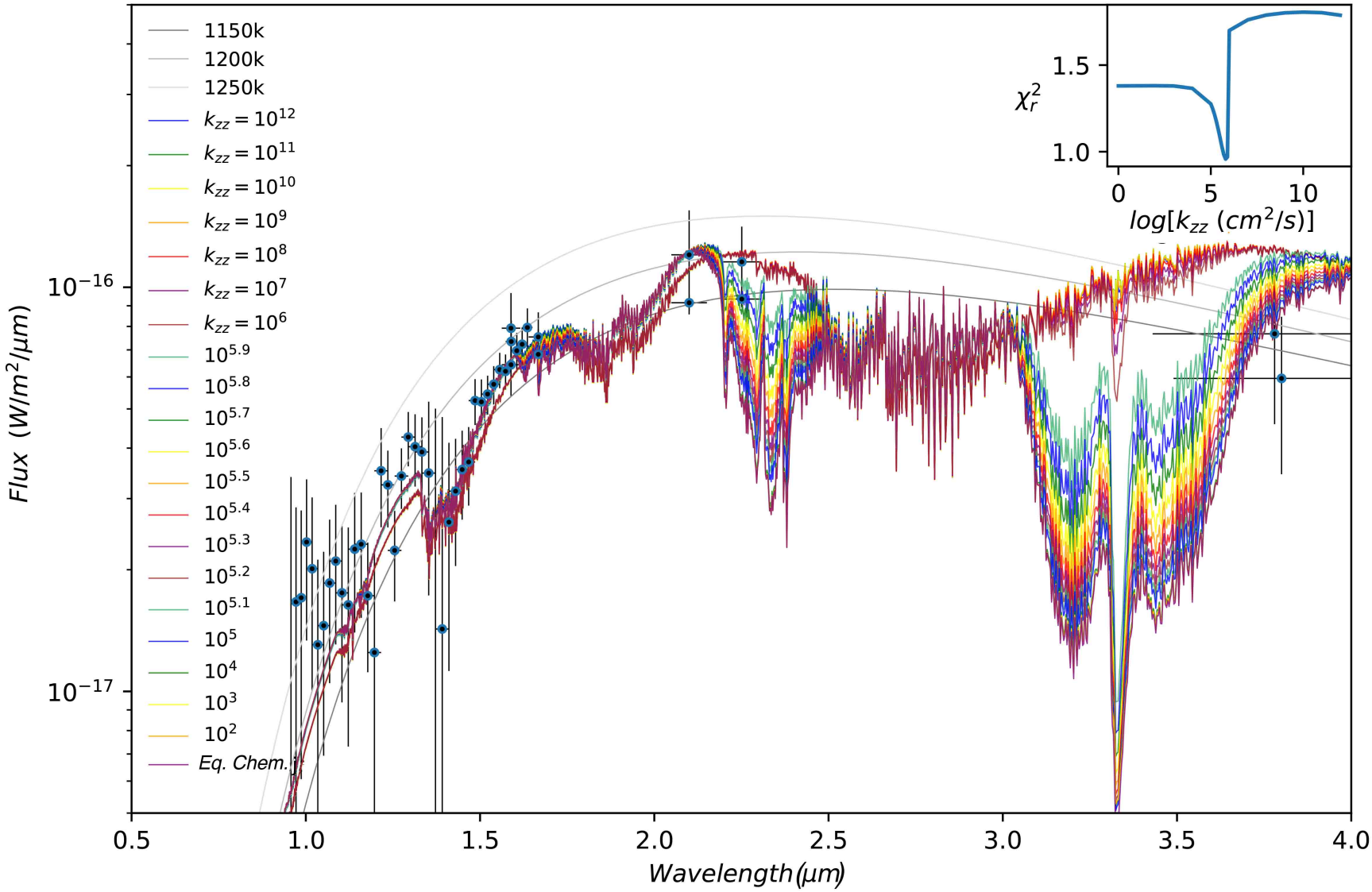
PDS70b spectrum: Clouds



H2 = 1.593 μm
H3 = 1.667 μm
K1 = 2.11 μm
K2 = 2.25 μm

[Muller et al. 2018]

PDS70b spectrum: **ChemKM**

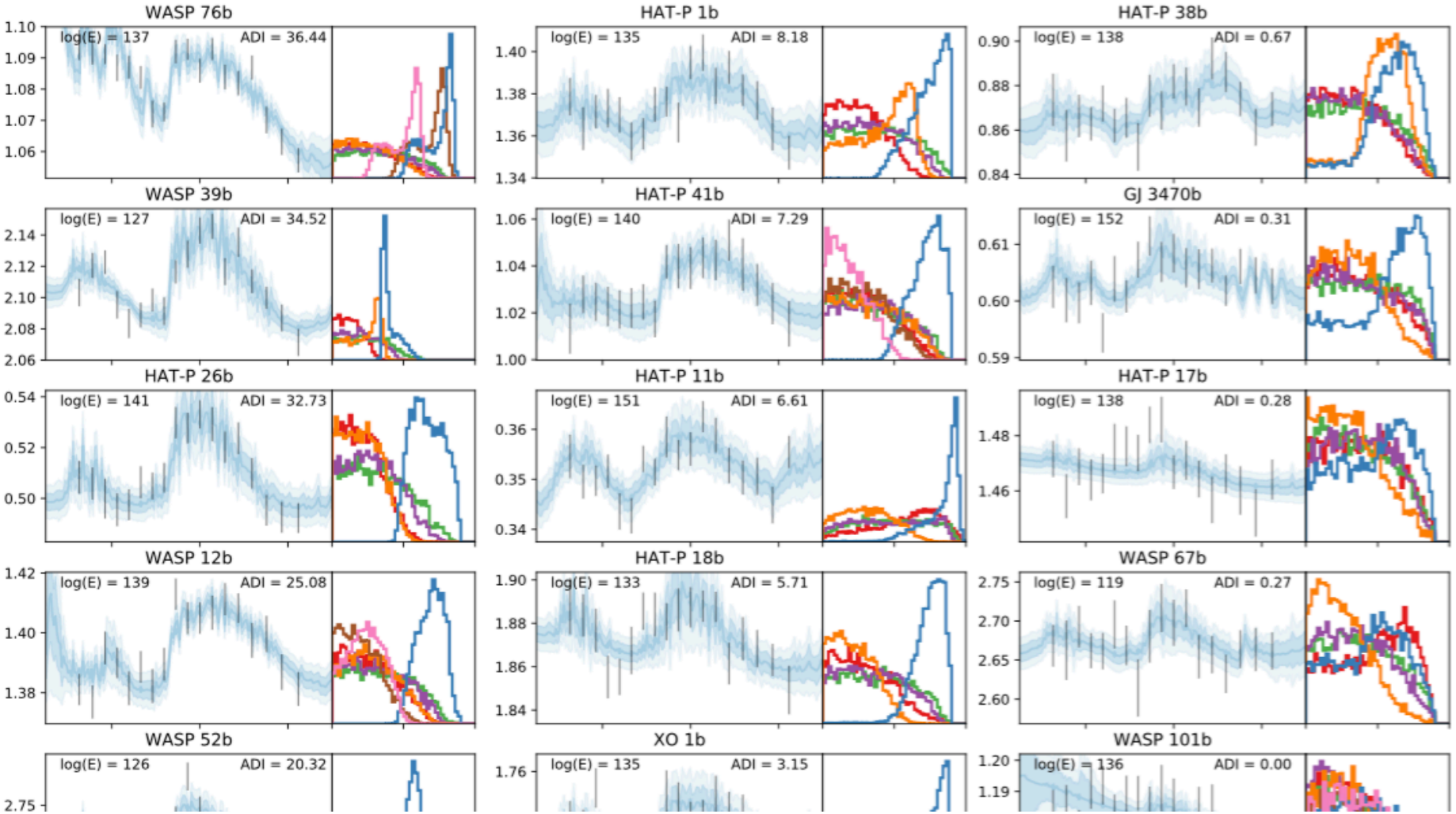


Q: CH_4: 2B|^2B

[Molaverdikhani et al 2018 in prep.]

How about irradiated planets?

Water is everywhere…



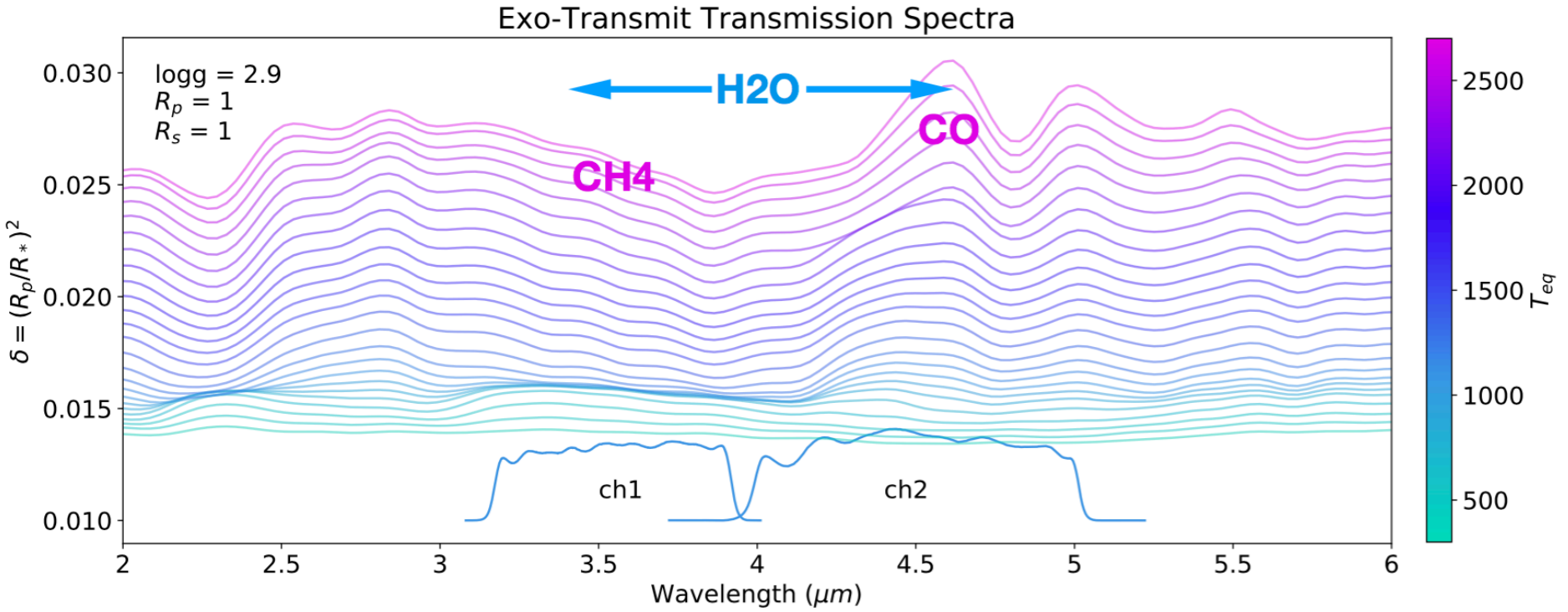
Q: CH_4: 2BI^2B

[Tsiaras et al. 2018]

Take the blue pill
That's water
Story ends

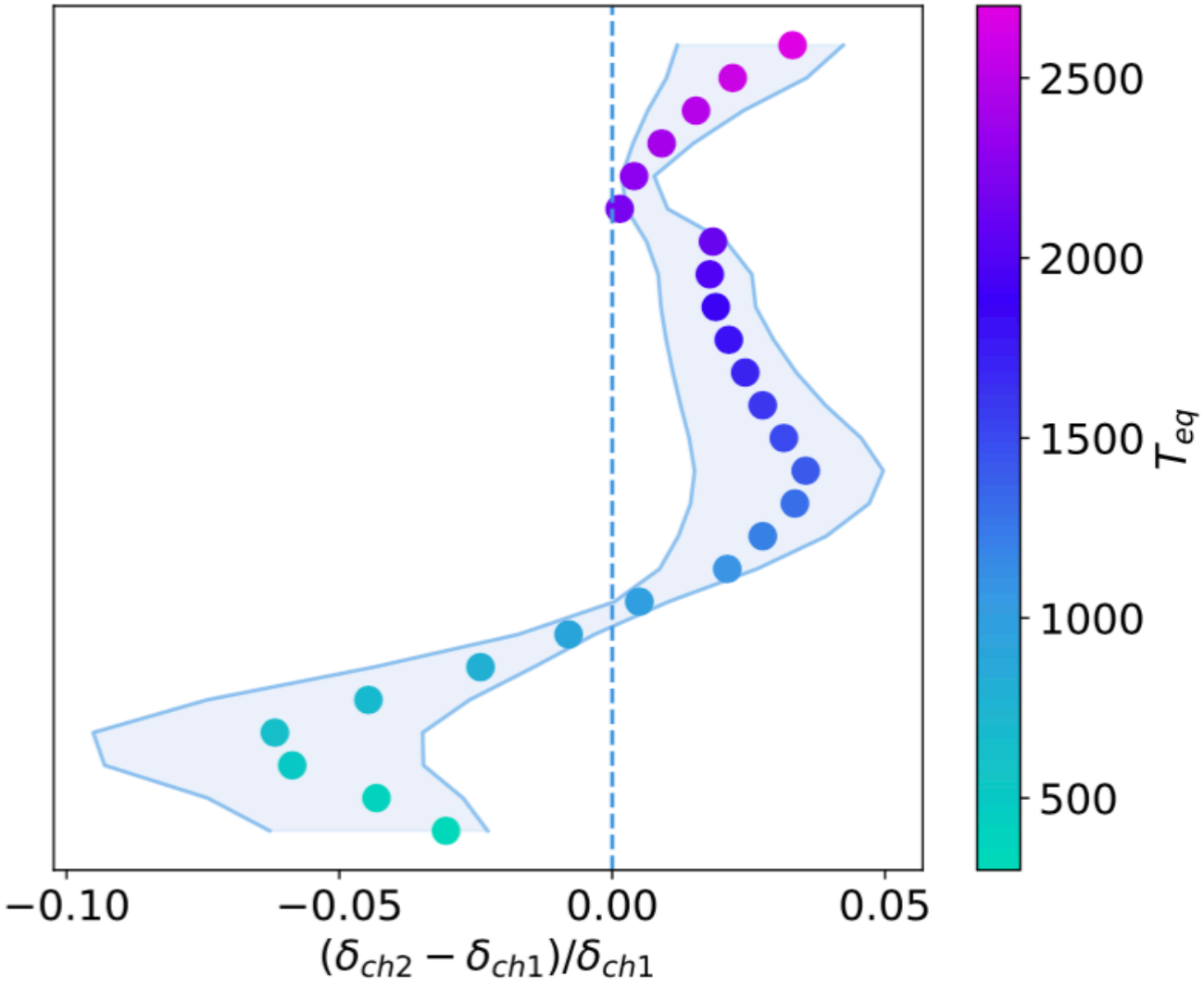
Take the red pill
That's methane
You stay in
Wonderland, and
I show you how
deep the rabbit
hole goes.

Spitzer – IRAC channels



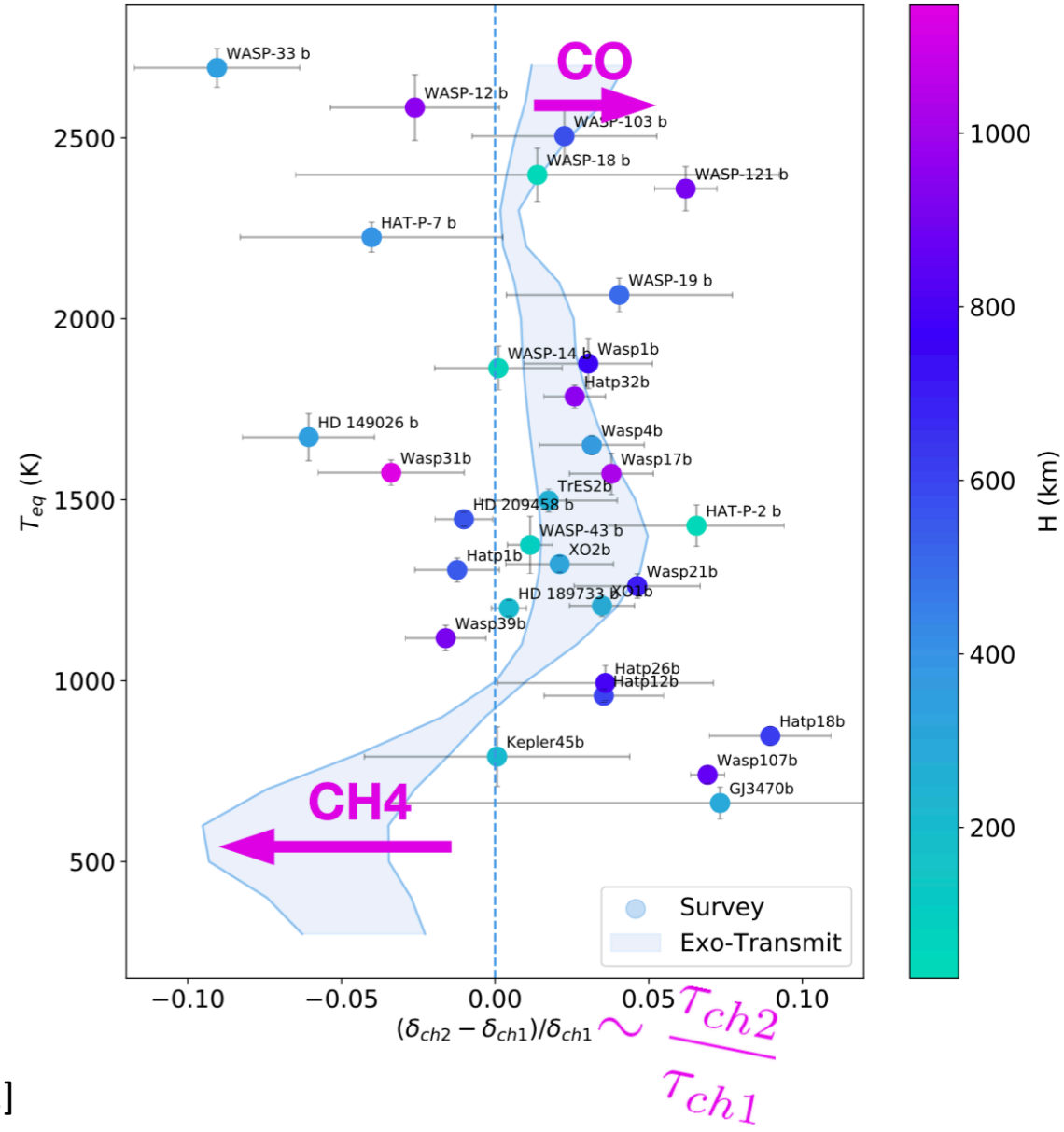
[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer – IRAC channels



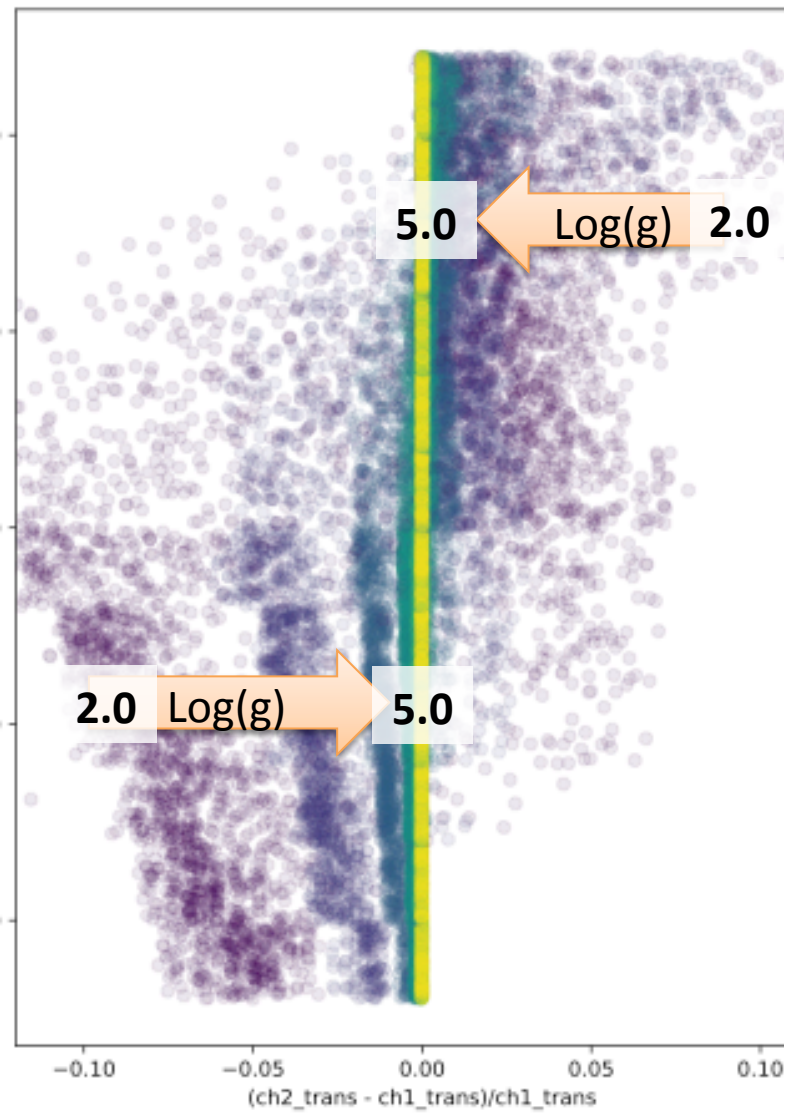
[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer – IRAC channels

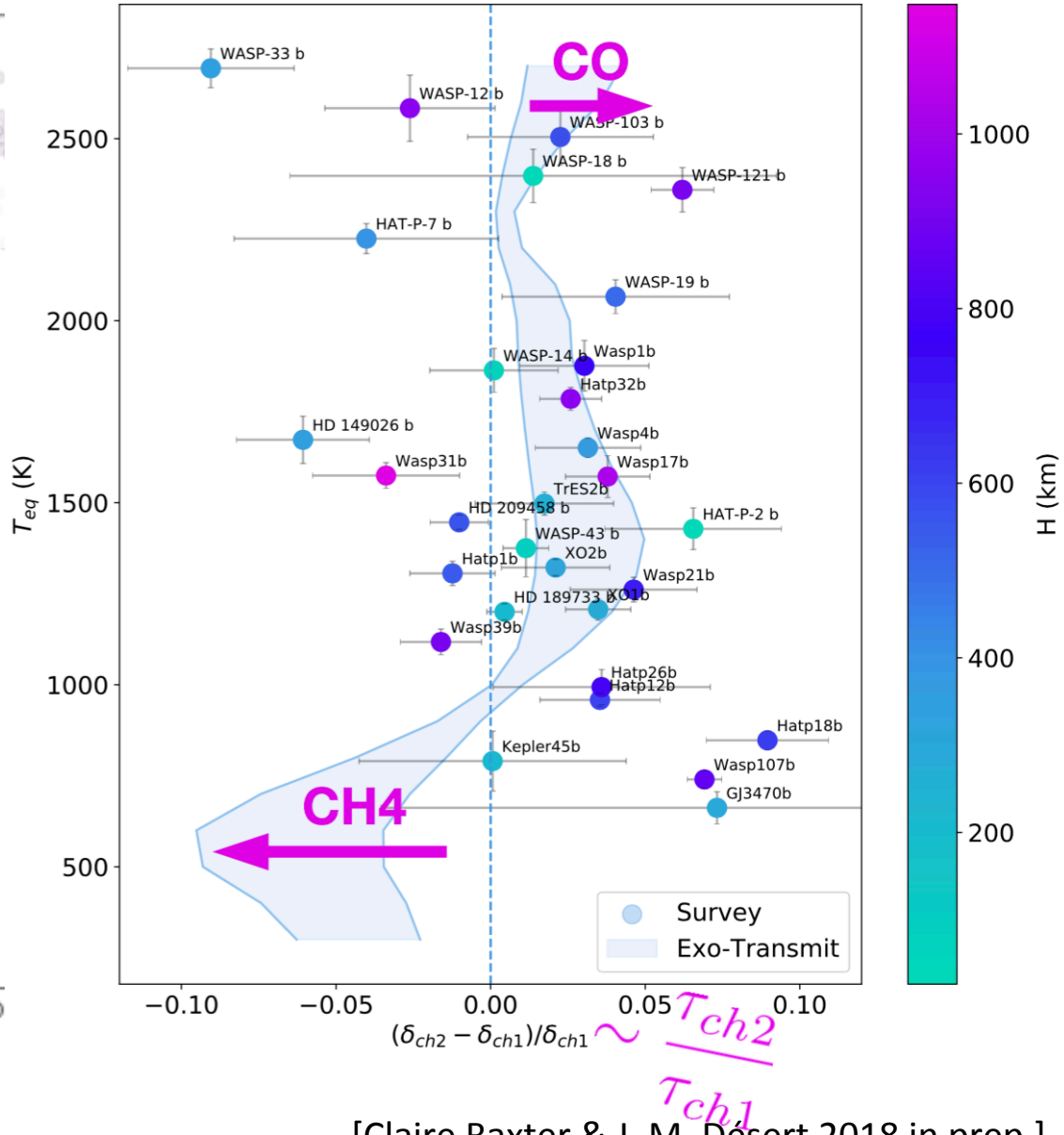


[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer – IRAC channels

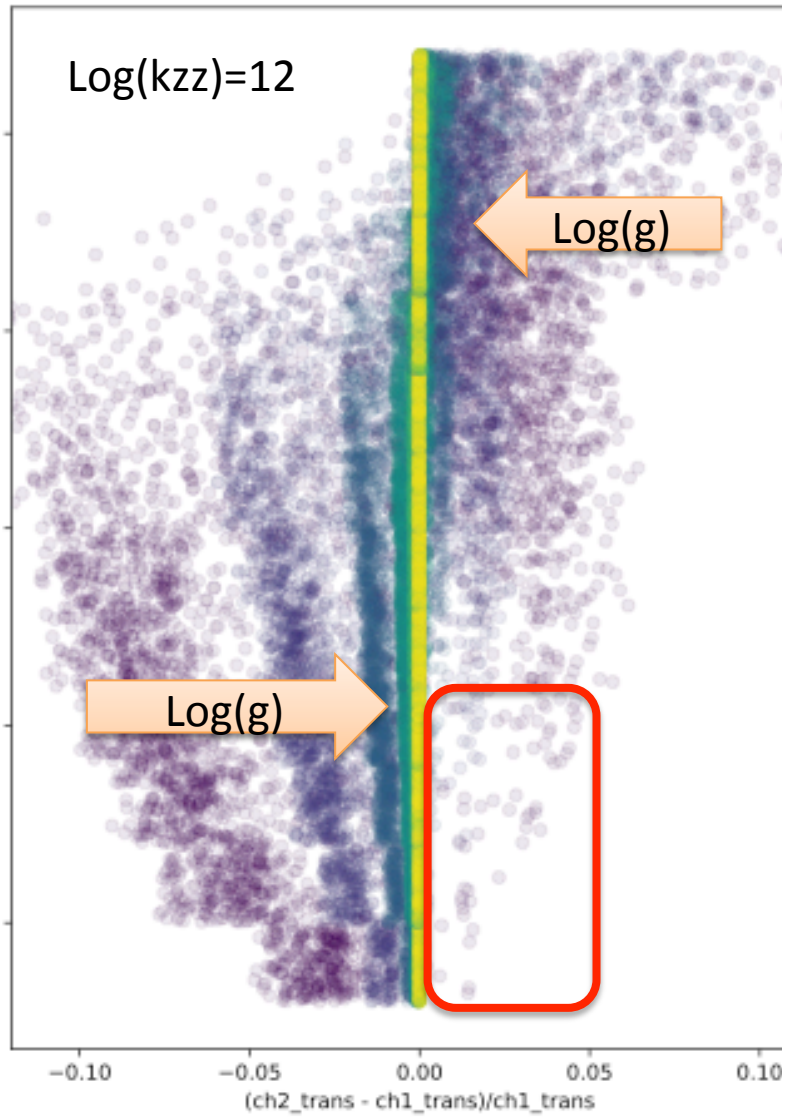


[Molaverdikhani et al. 2018 in prep]

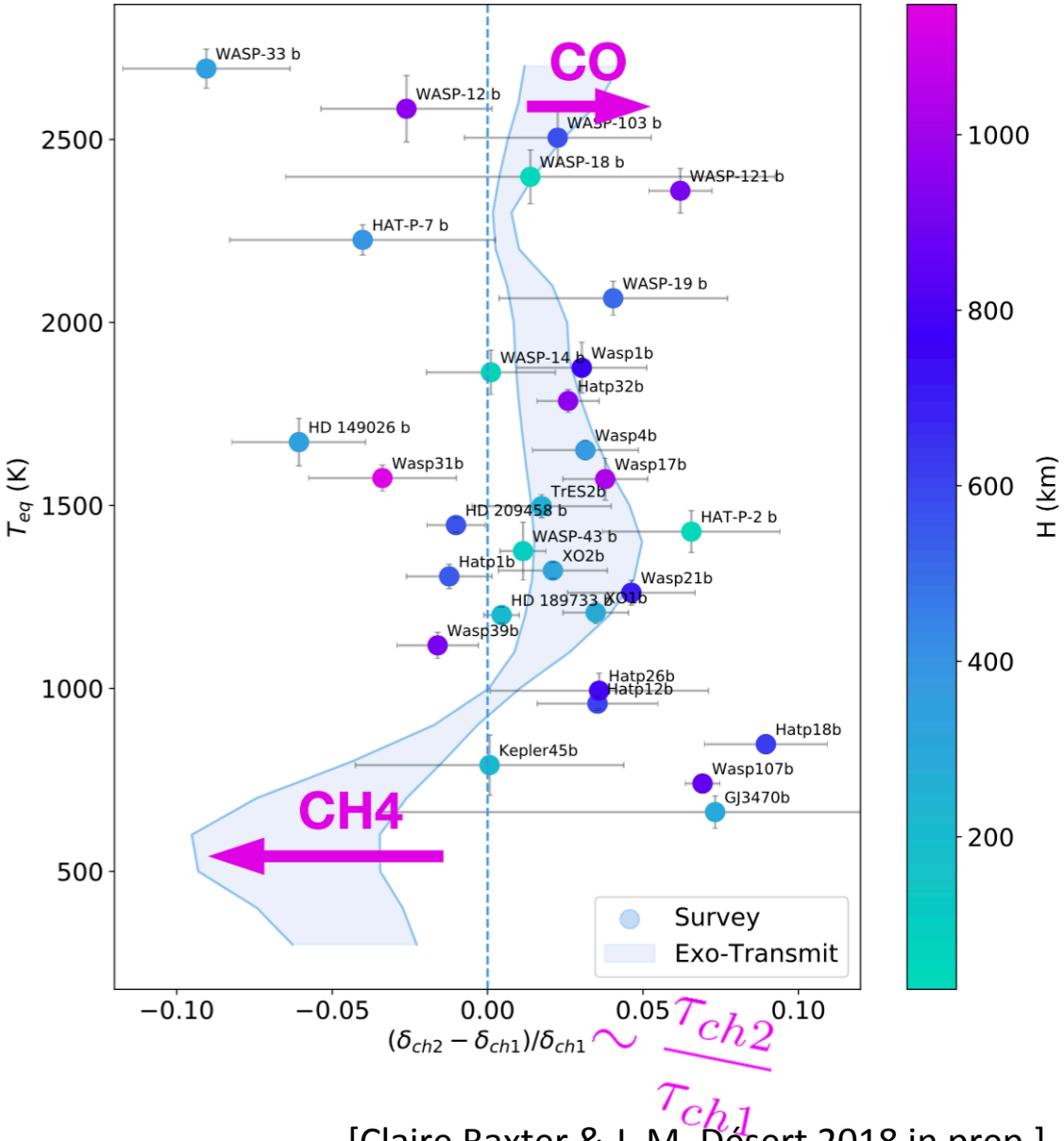


[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer – IRAC channels



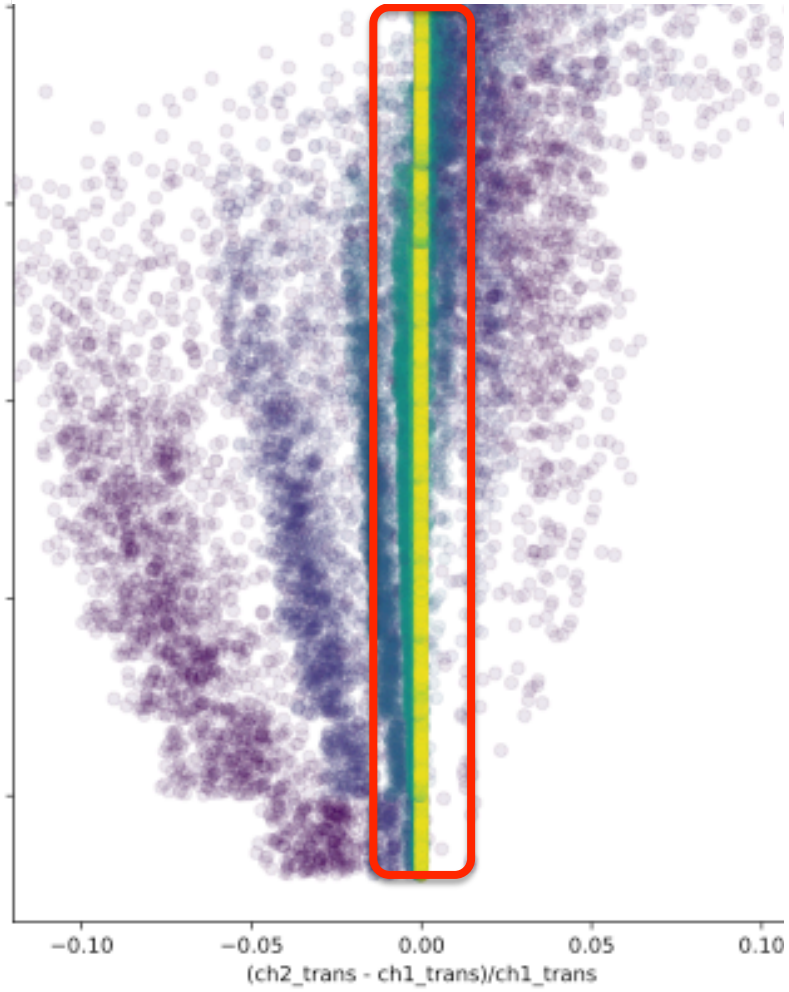
[Molaverdikhani et al. 2018 in prep]



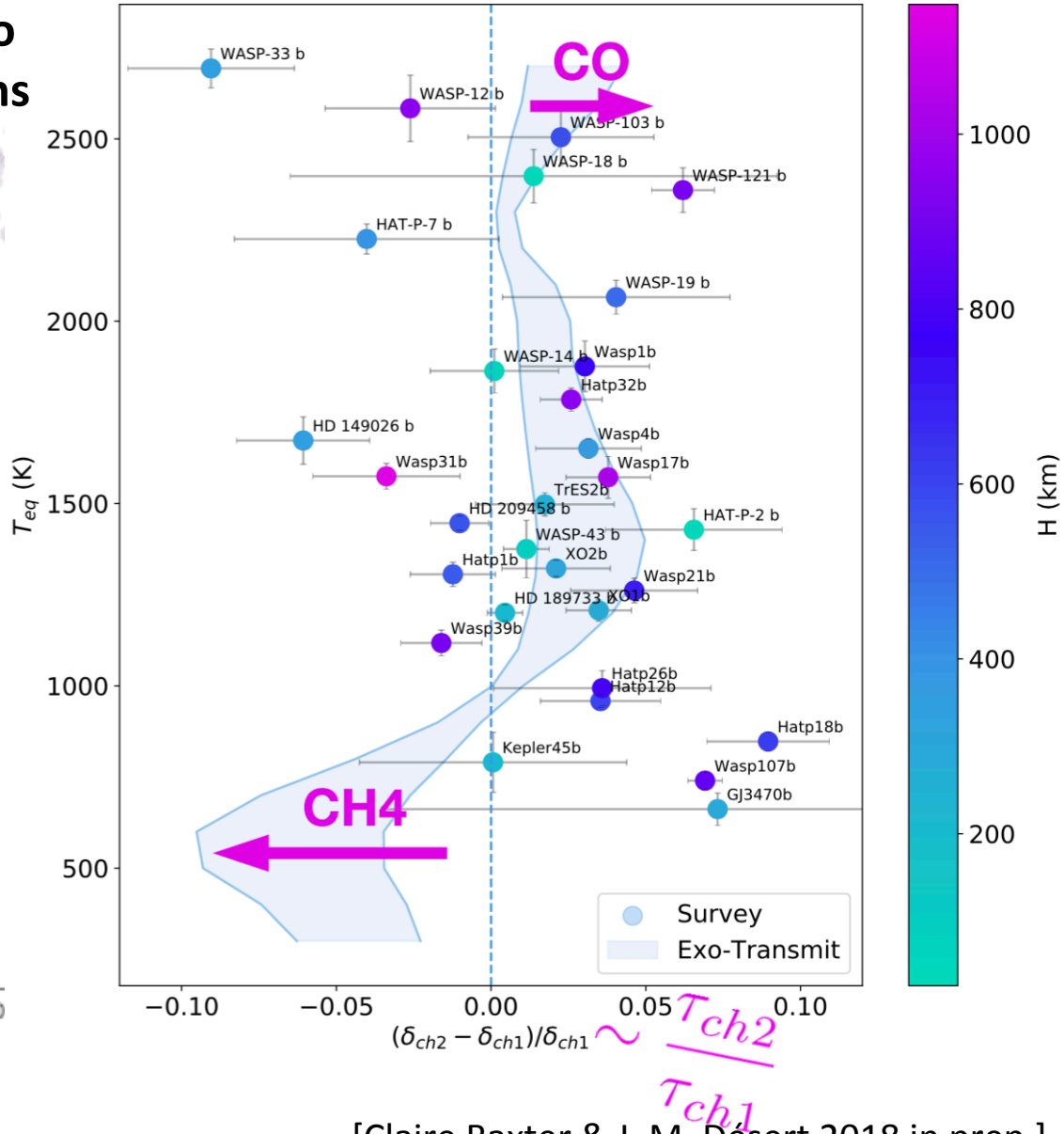
[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer – IRAC channels

Issues: models cluster around zero
Large uncertainties of observations



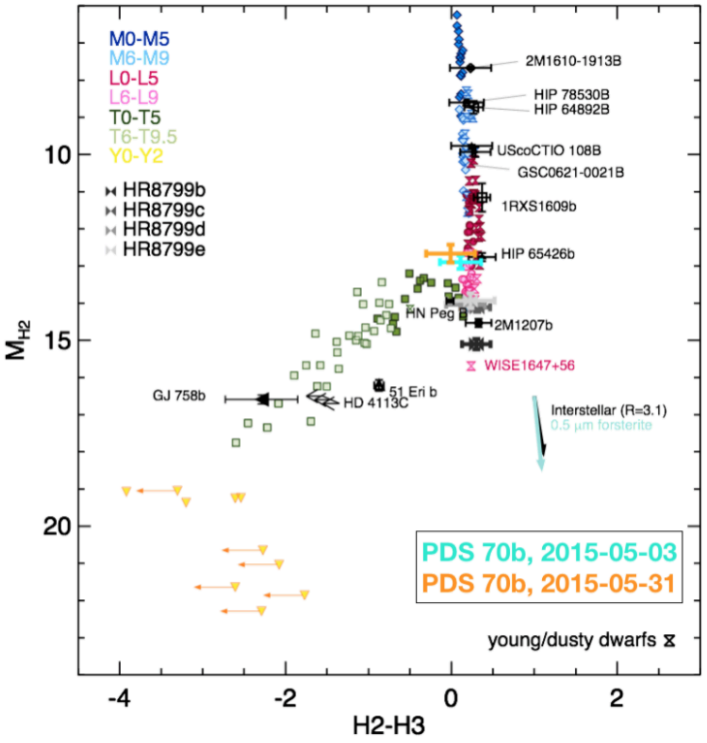
[Molaverdikhani et al. 2018 in prep]

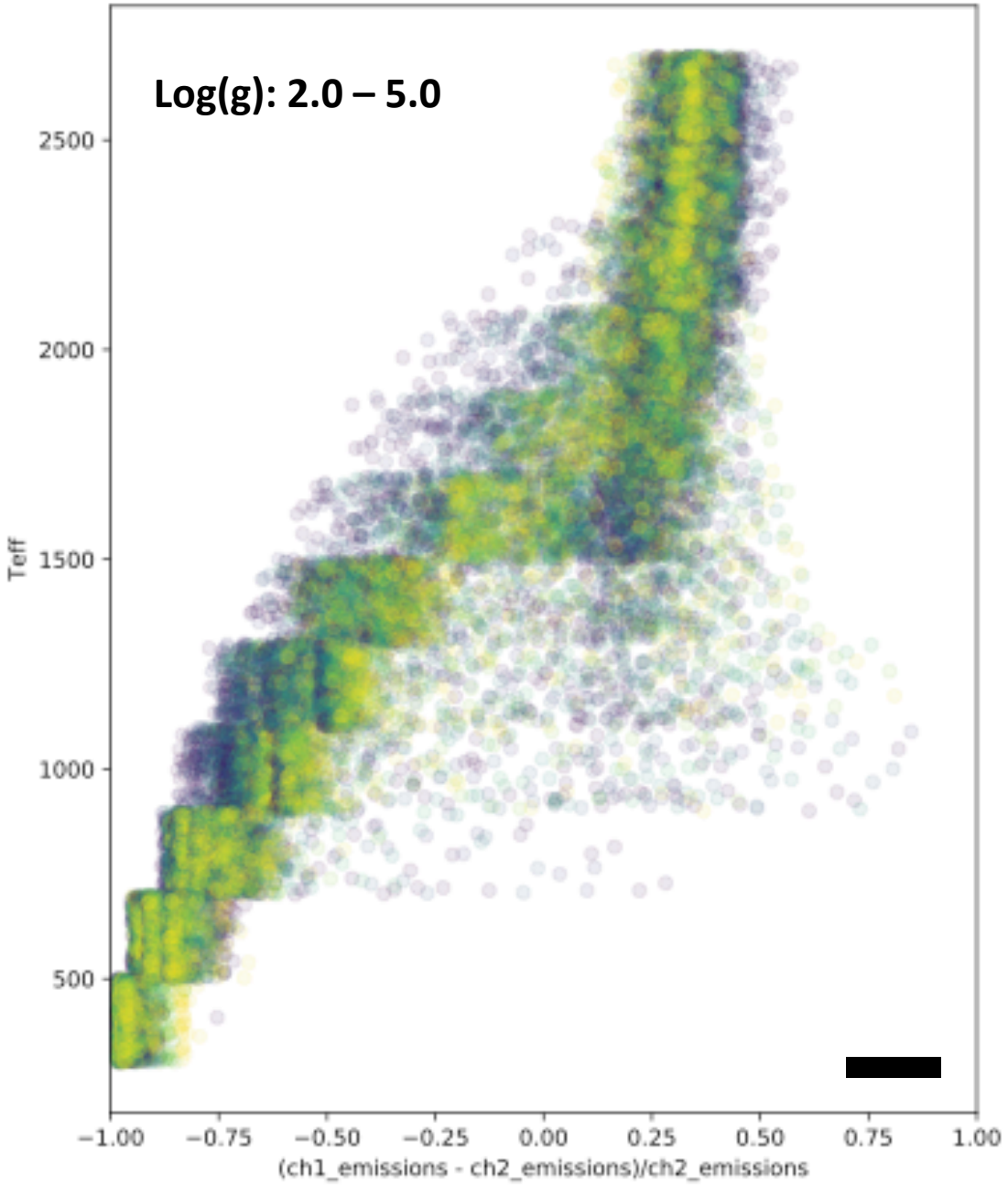


[Claire Baxter & J. M. Désert 2018 in prep.]

Spitzer - emission

Colored by log(g)

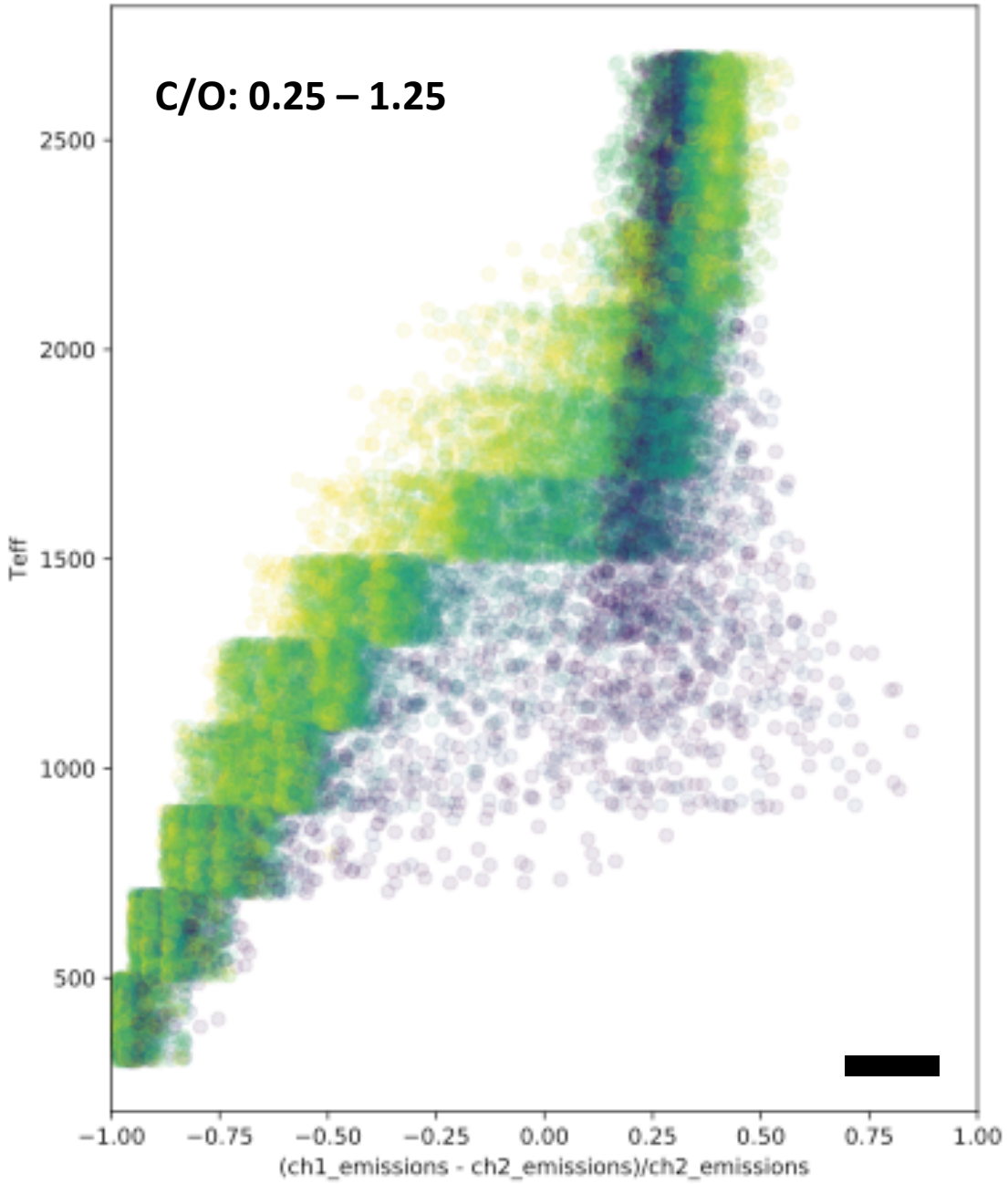




[Molaverdikhani et al. 2018 in prep]

Spitzer - emission

Colored by C/O

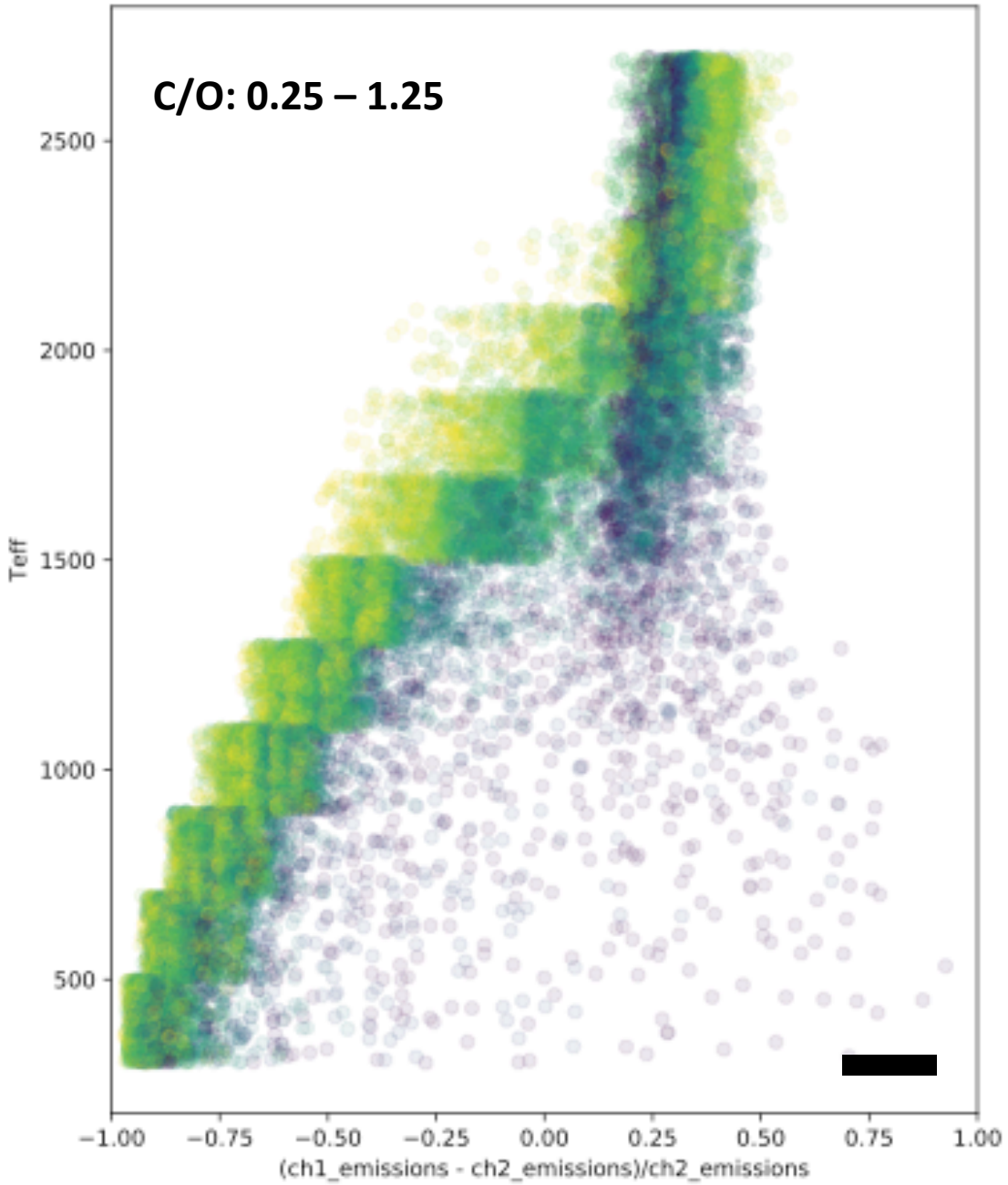


[Molaverdikhani et al. 2018 in prep]

Spitzer - emission

Colored by C/O

Log(kzz)=12

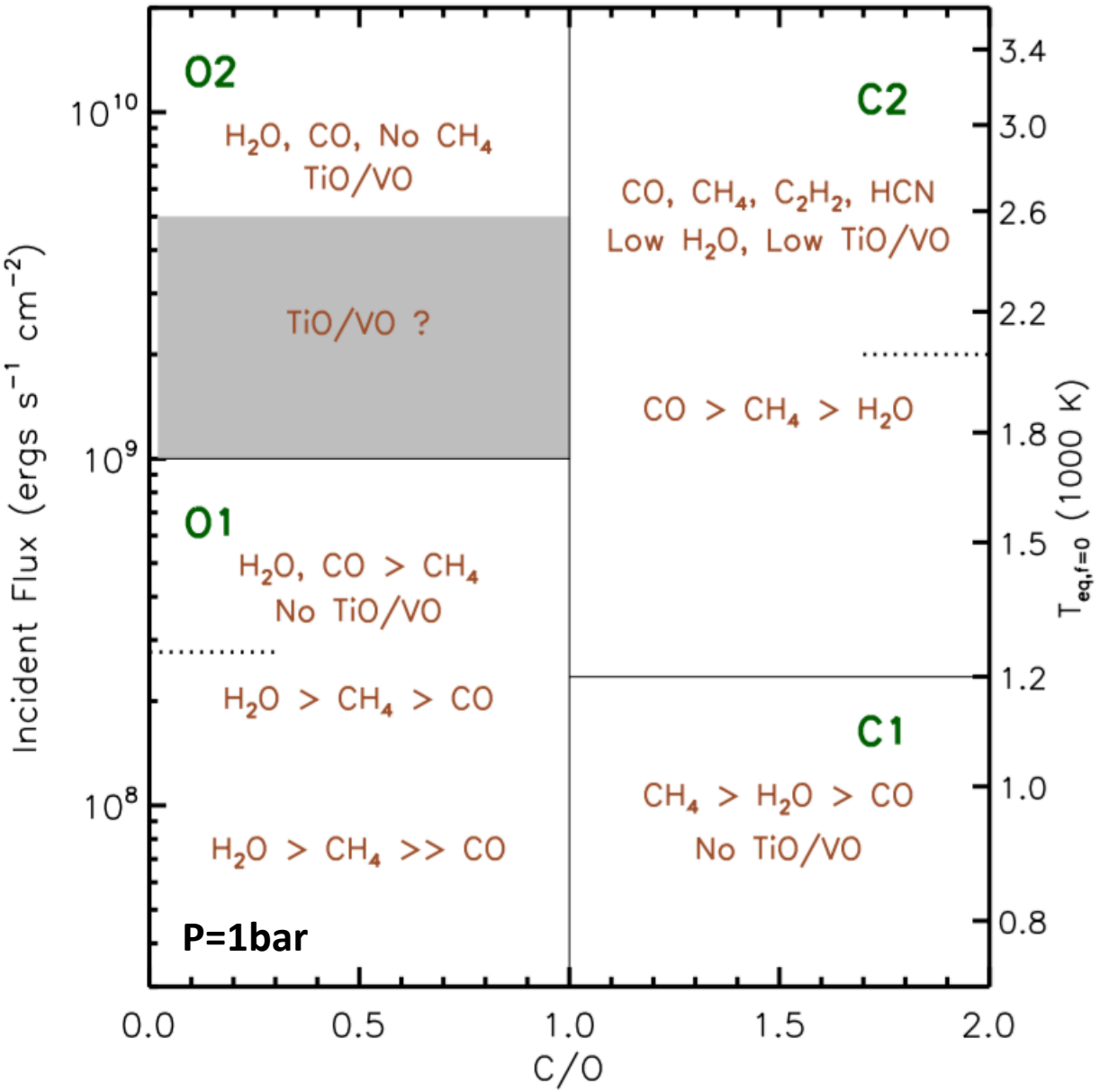


[Molaverdikhani et al. 2018 in prep]

C/O is important! And we knew it!

To name a few:

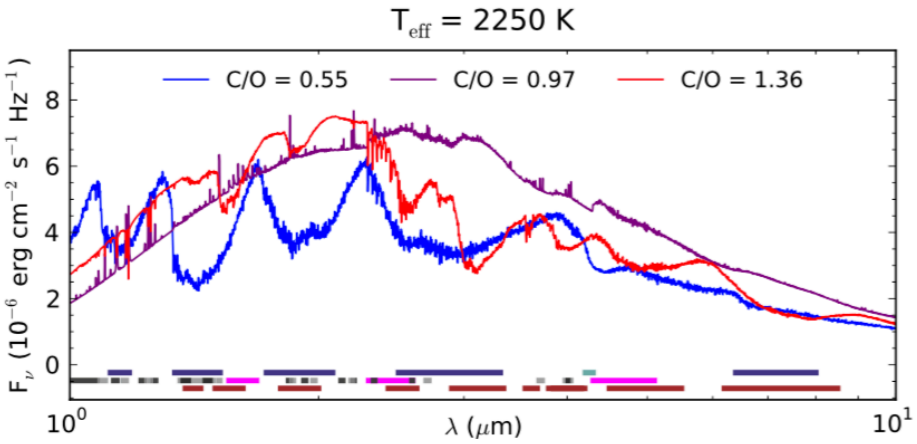
Fortney et al. 2005
Seager et al. 2005
Fortney et al. 2008



[Madhusudhan 2012]

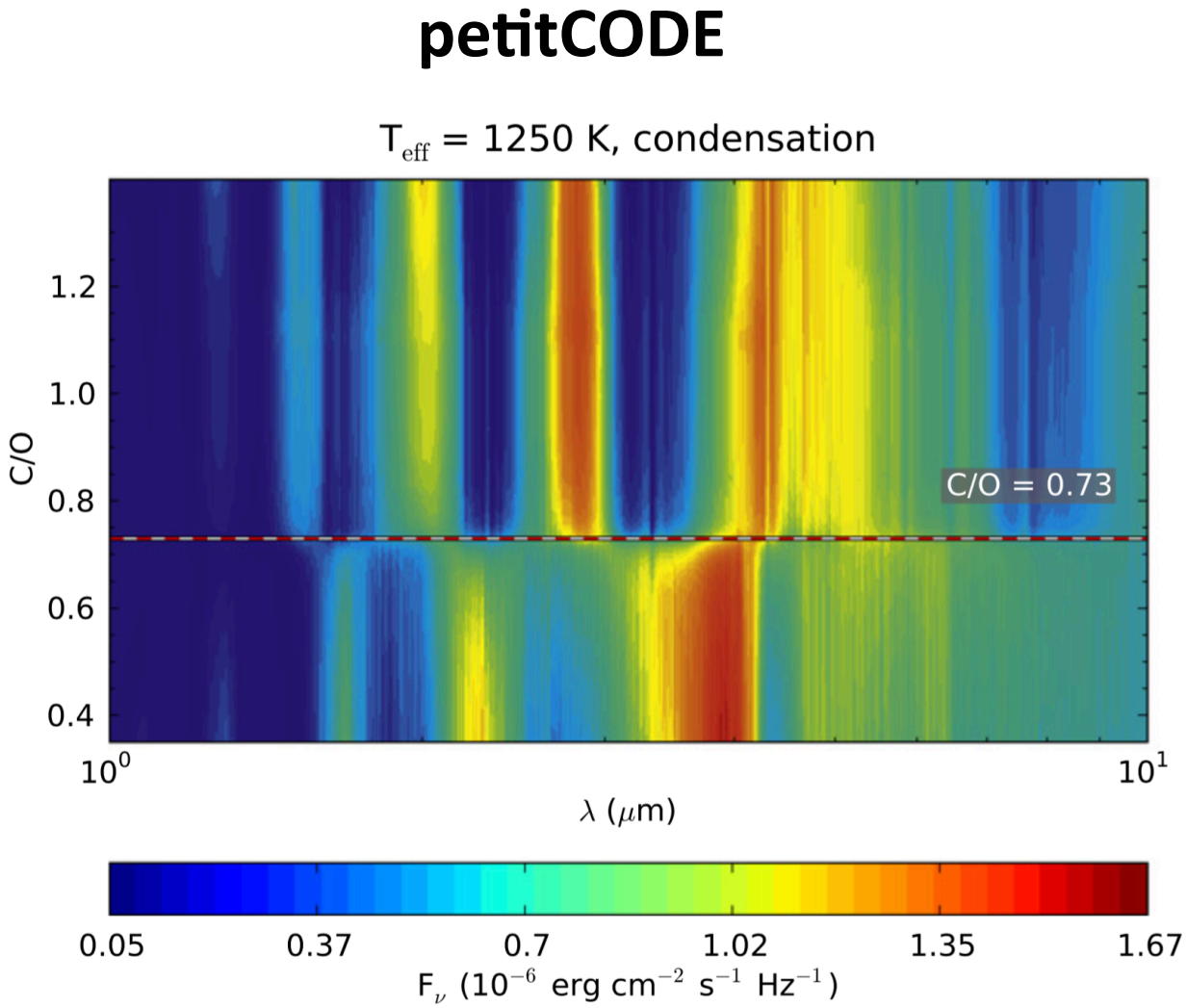
C/O is important! And we knew it!

petitCODE



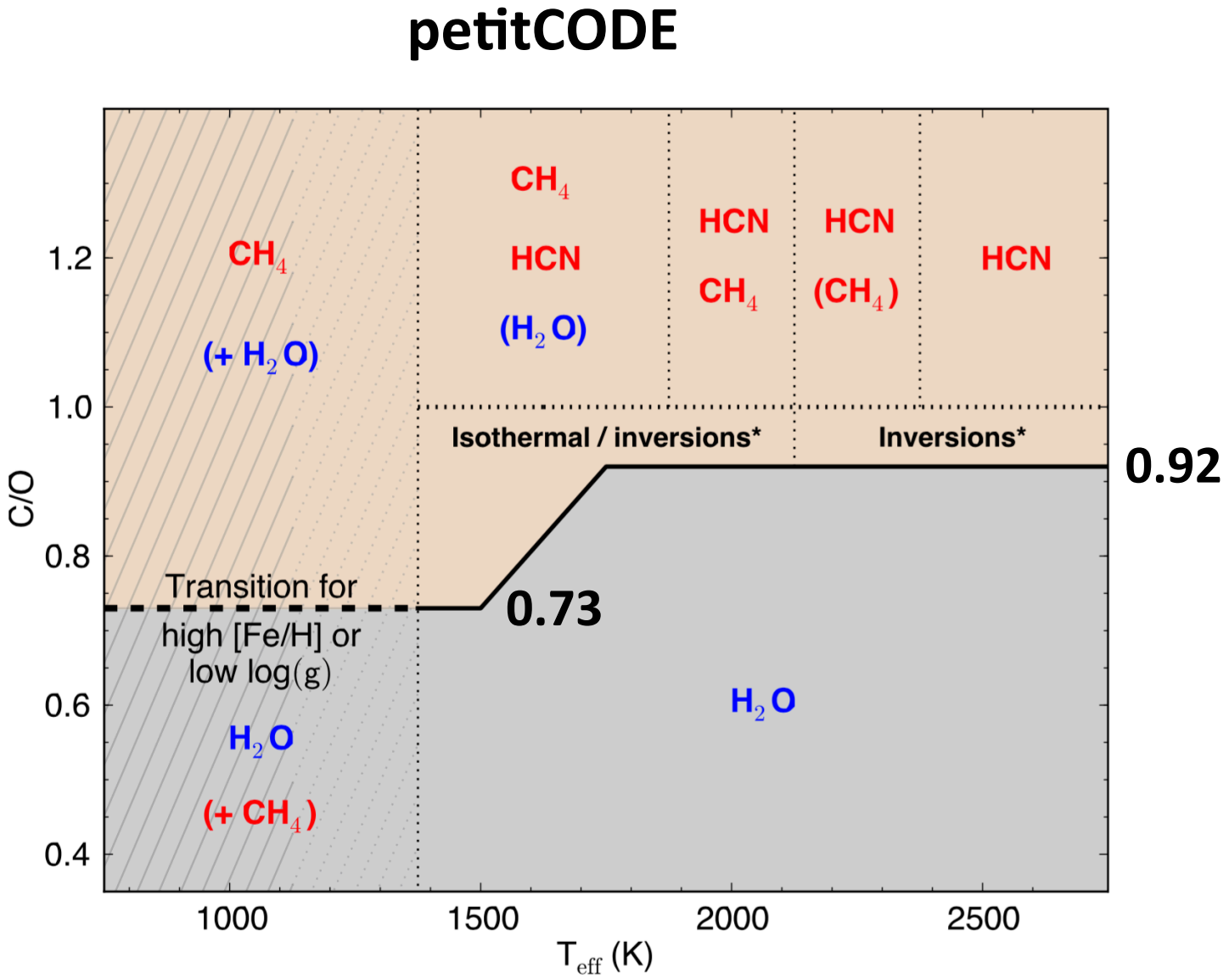
[Mollière et al. 2015]

C/O is important! And we knew it!



[Mollière et al. 2015]

C/O is important! And we knew it!



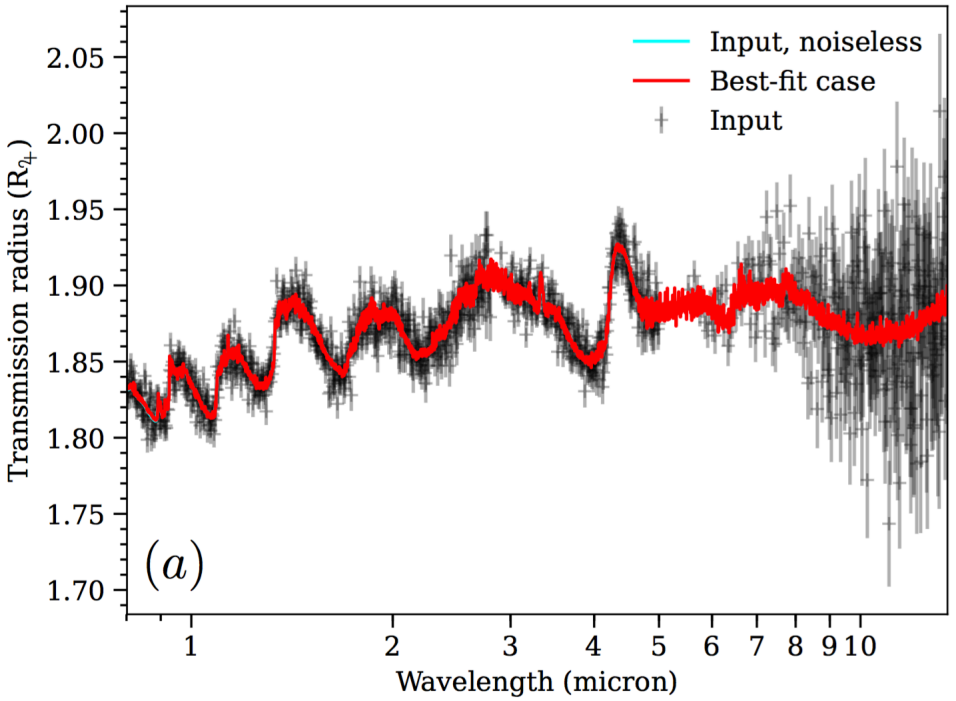
[Mollière et al. 2015]

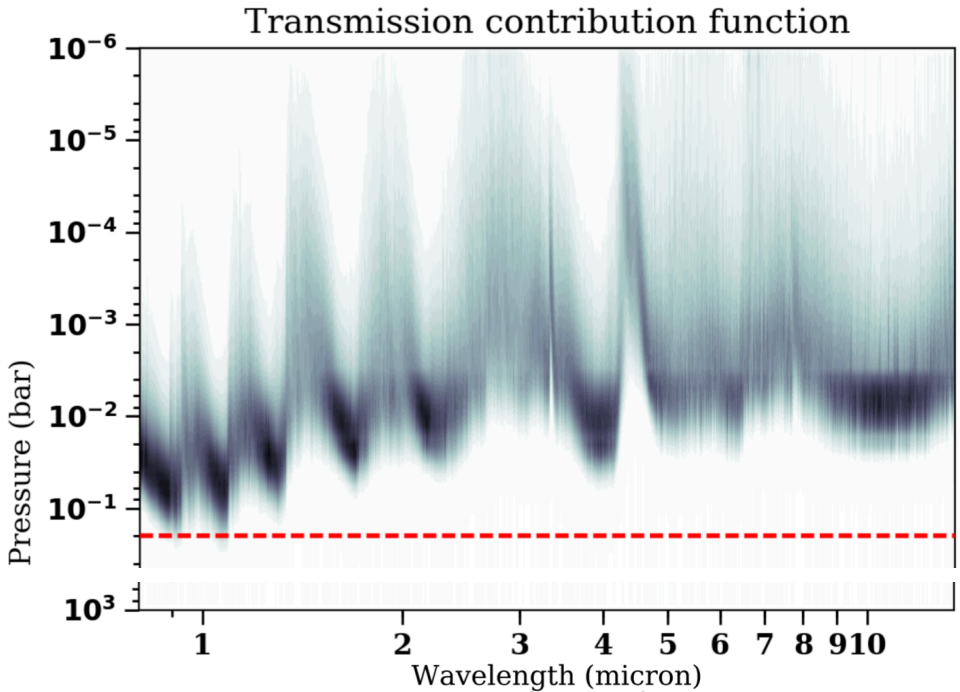
Let’s extract more info from the spectra!

Contribution Function

Connects the transmission to pressures at each wavelength

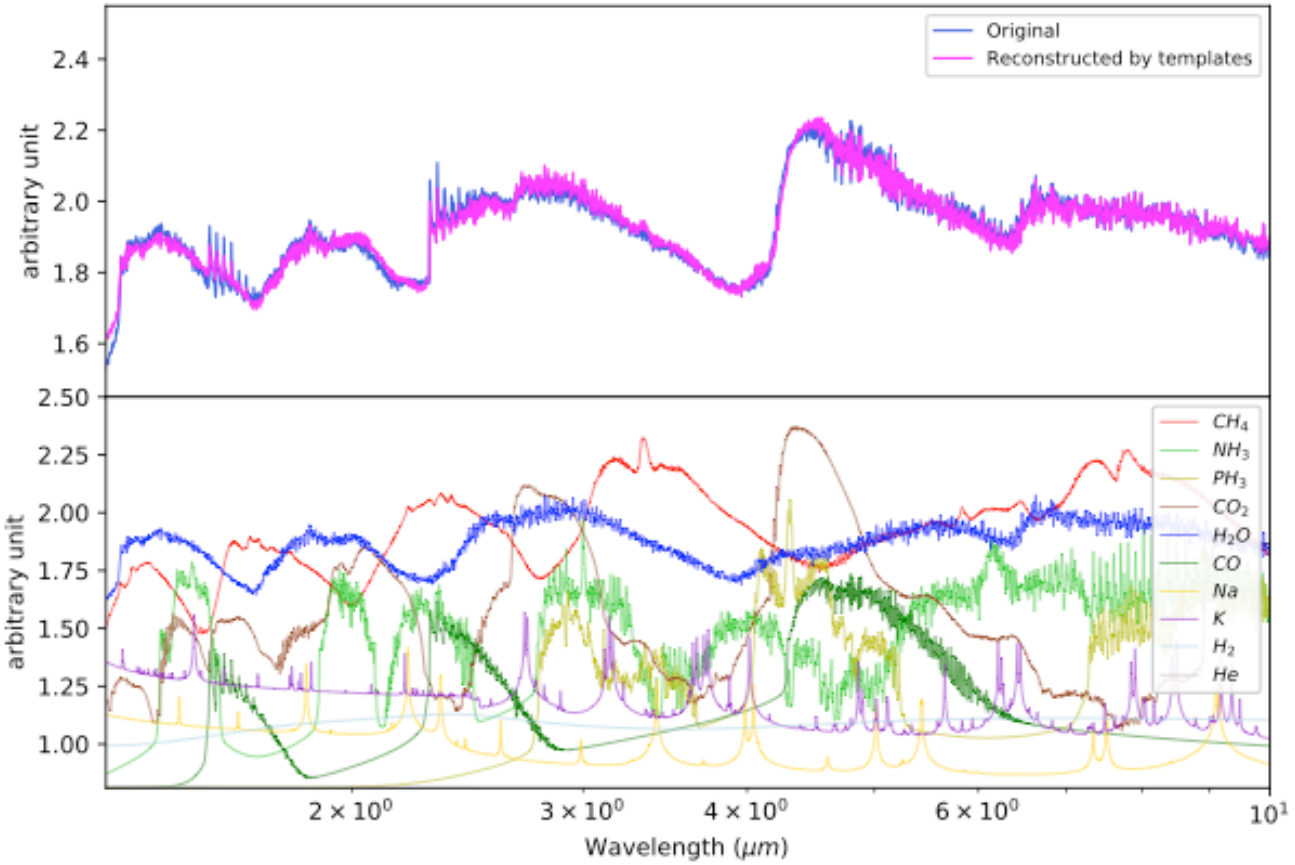
Information is integrated over all species





[Mollière et al. 2017]

Spectral Decomposition

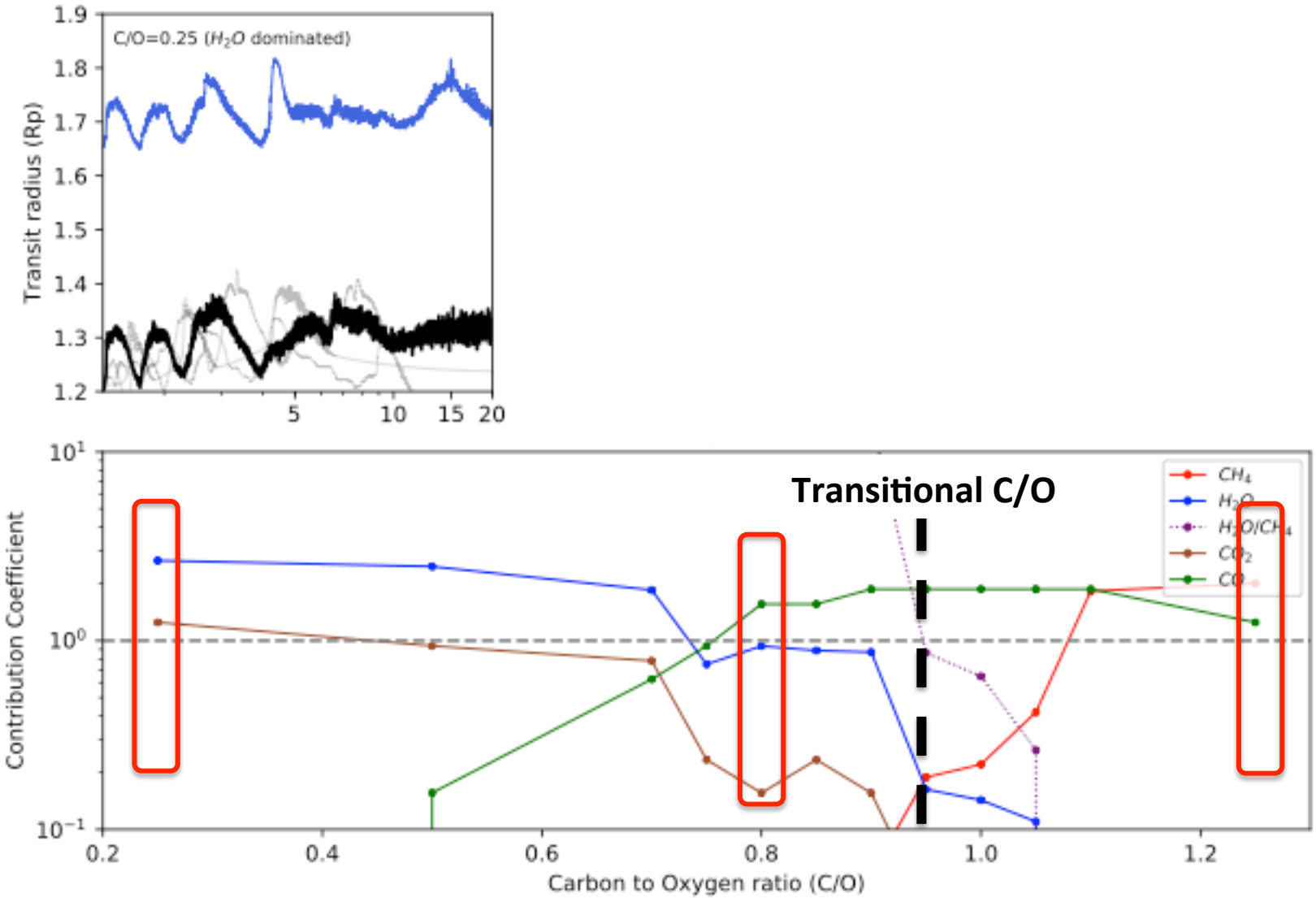


Connects the transmission to species

Information is integrated over all pressures and wavelengths

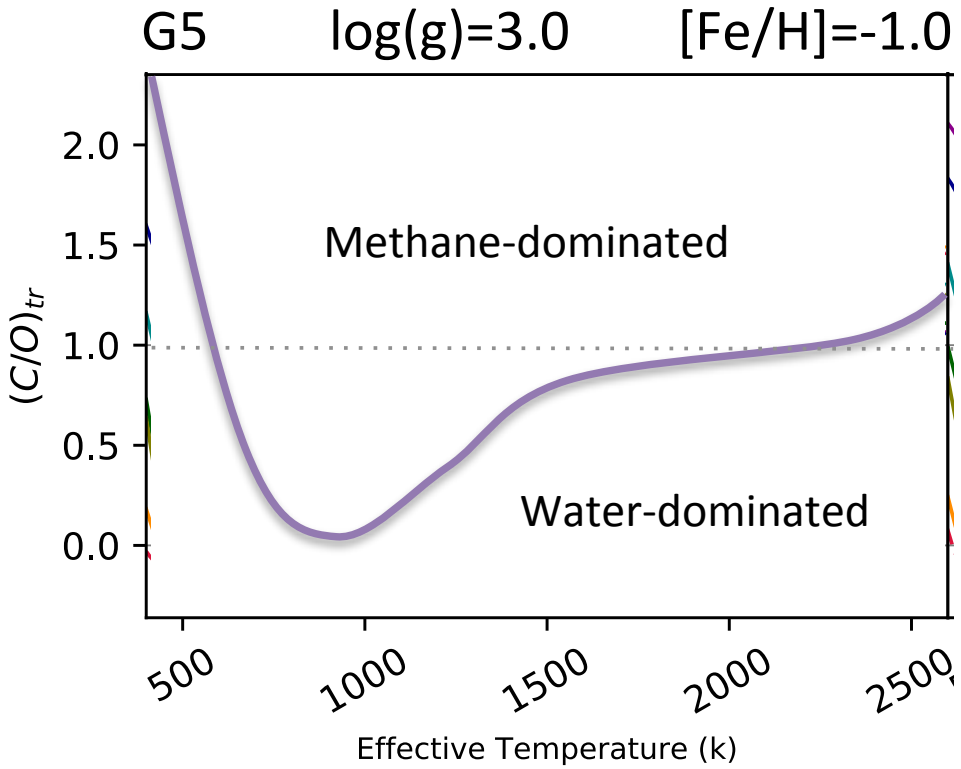
[Molaverdikhani et al. 2018, in prep.]

Spectral Decomposition: Example



[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: Four spectral classes

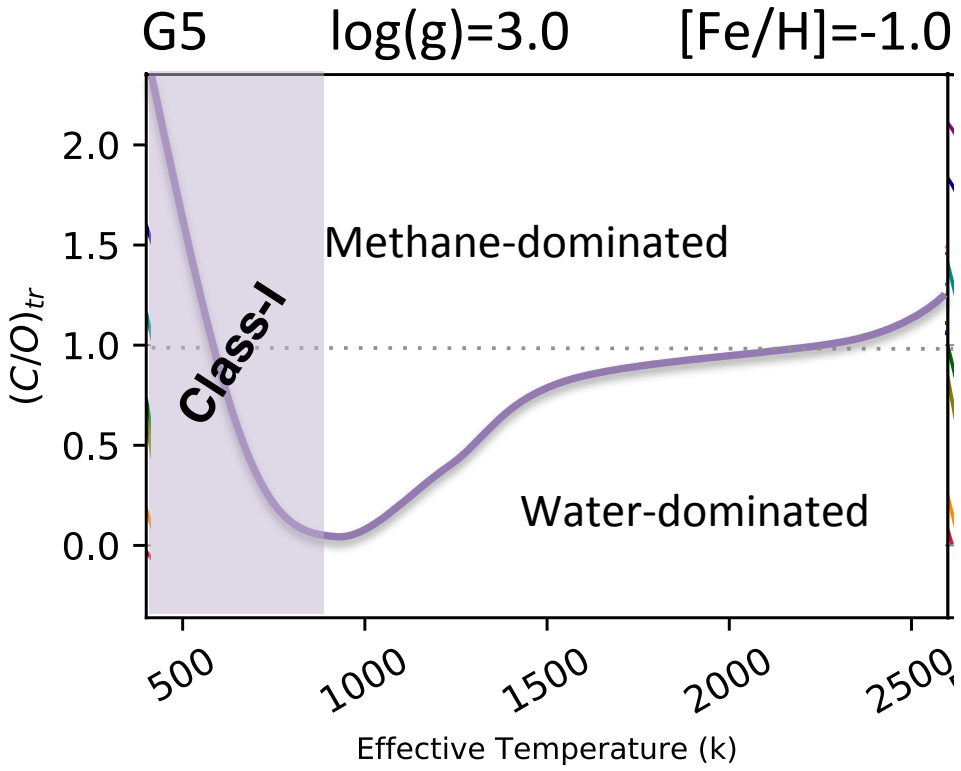


[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: Four spectral classes

~Full condensation

Oxygen removal by CO_2/ CO as Temp. increases



[Molaverdikhani et al. 2018, in prep.]

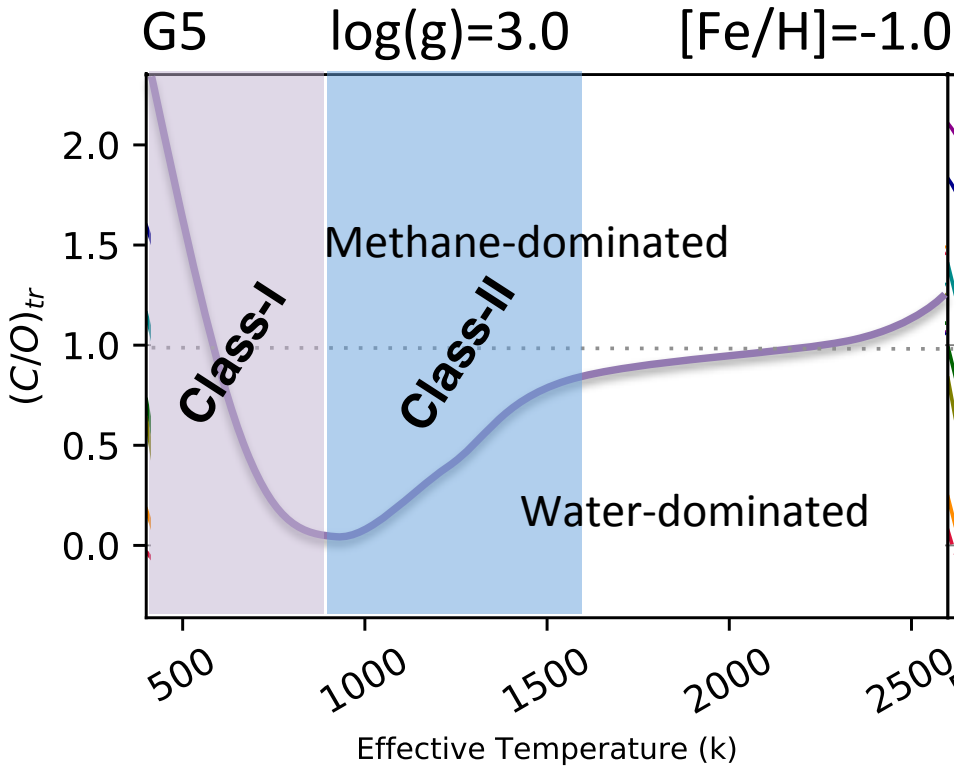
Transitional C/Os: Four spectral classes

~Full condensation

Oxygen removal by CO_2/ CO as Temp. increases

Partial evaporation

Oxygen abundance increases with Temp.



[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: Four spectral classes

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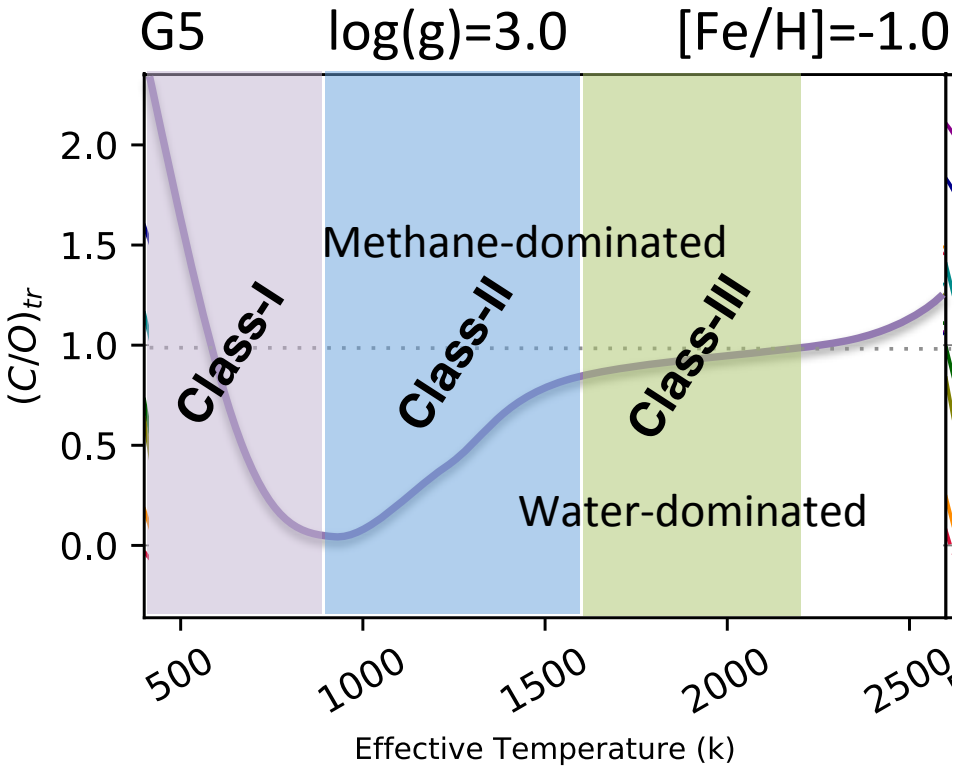
Oxygen removal by CO_2/ CO as Temp. increases

Partial evaporation

Oxygen abundance increases with Temp.

Full evaporation

Oxygen content remains constant



[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: Four spectral classes

~Full condensation

Oxygen removal by CO_2/ CO as Temp. increases

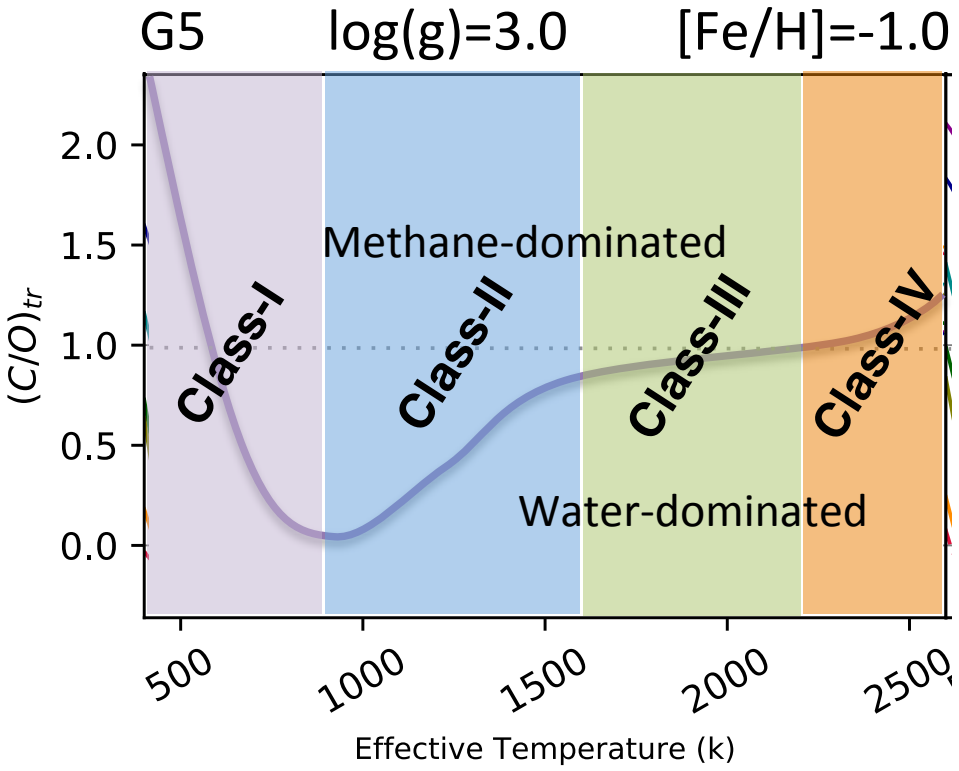
Partial evaporation

Oxygen abundance increases with Temp.

Full evaporation

Oxygen content remains constant

CH_4 destruction by HCN and water dissociation

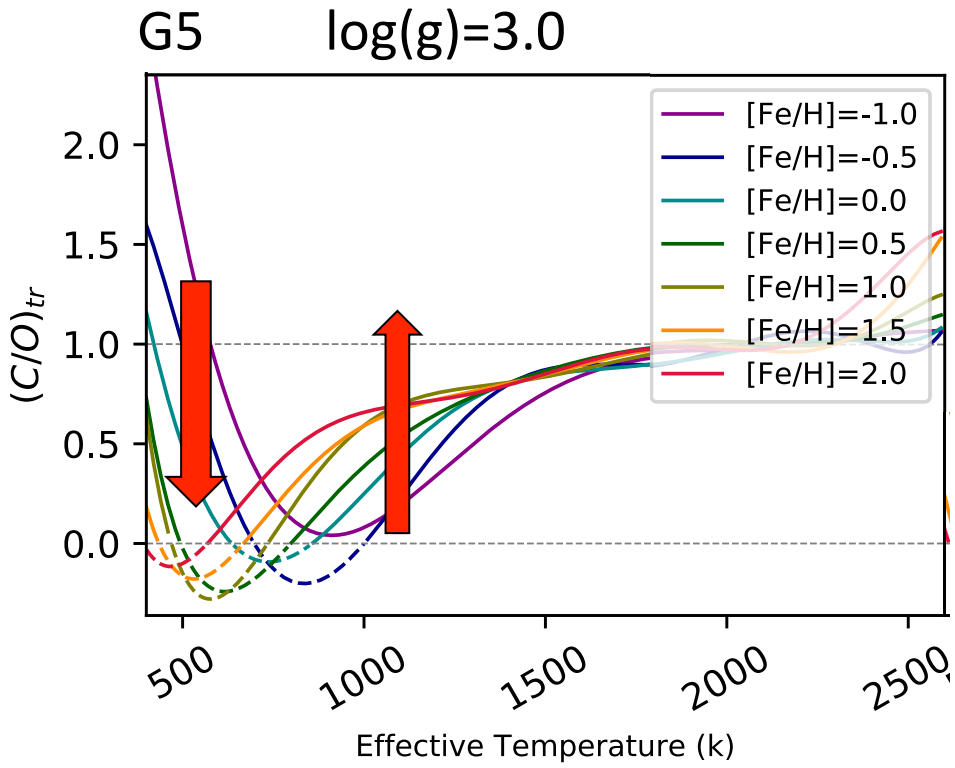


[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: The beta factor

At higher metallicity Oxygen lock-in CO_2

At higher metallicity more Oxygen is released by partial evaporation of condensates



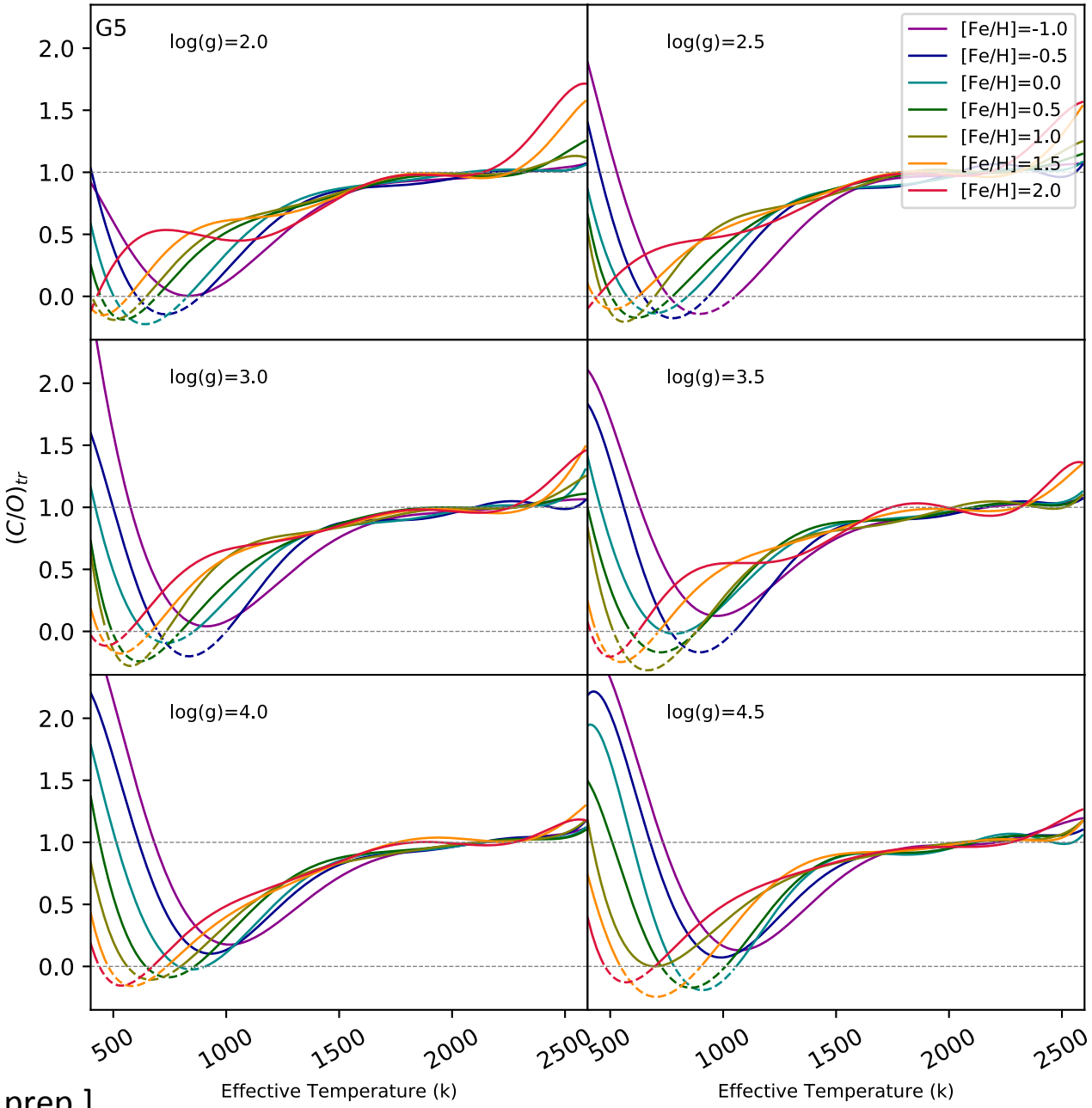
[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: The beta factor

Lower metallicity
&
Higher log(g)
Result in similar trends

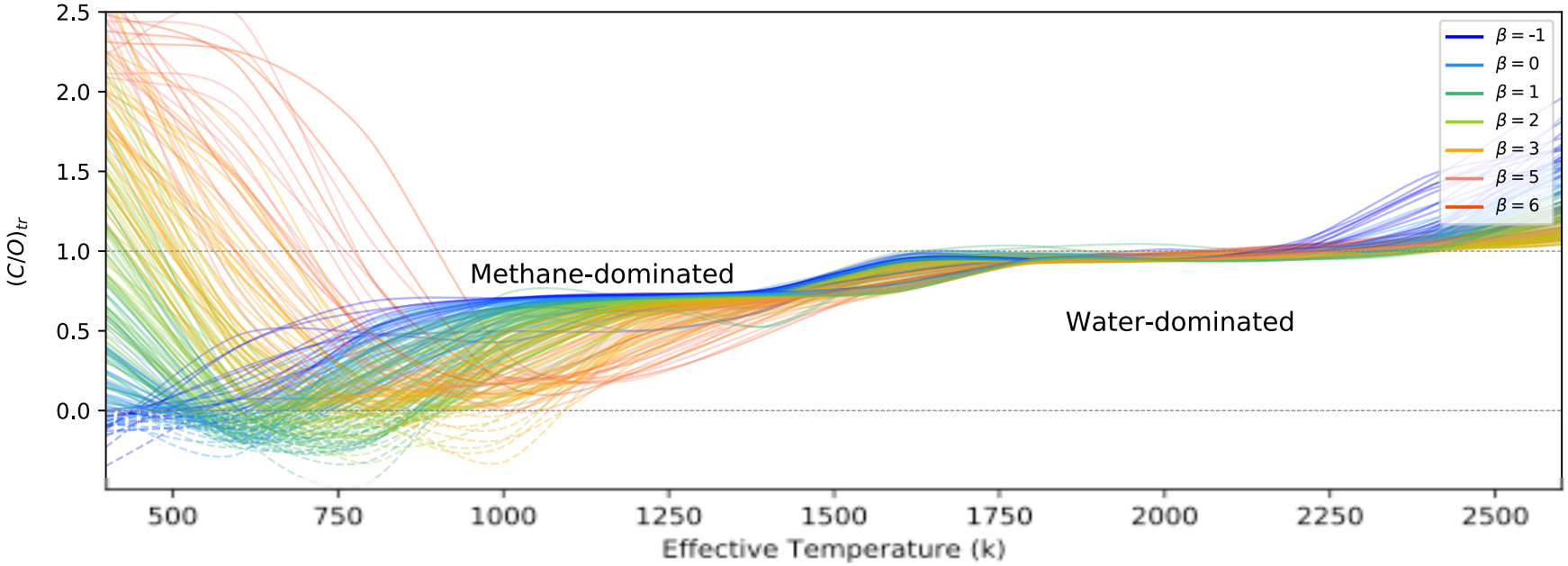
The beta factor:

$$\beta = log(g) - c_\beta [Fe/H]$$



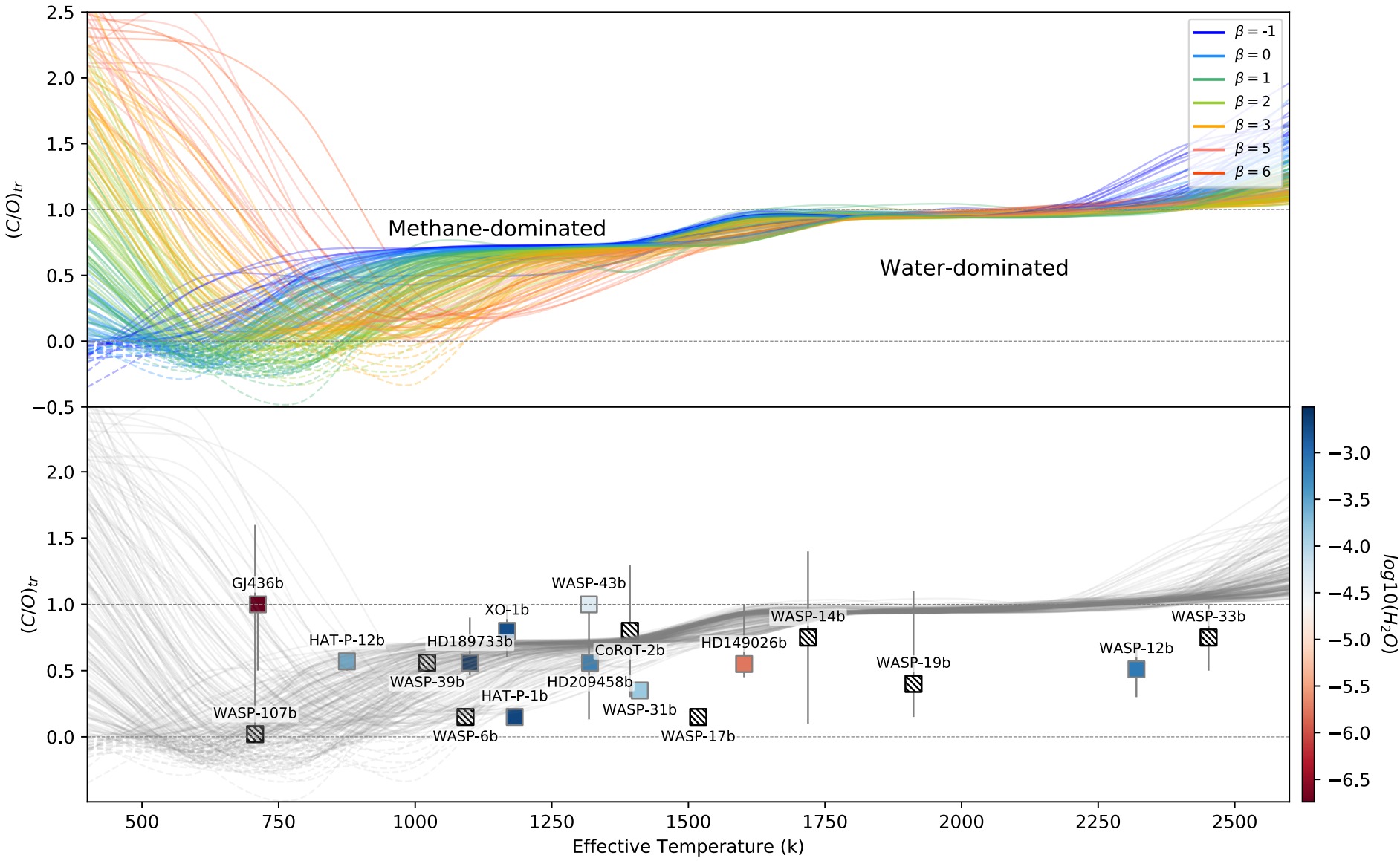
[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: all

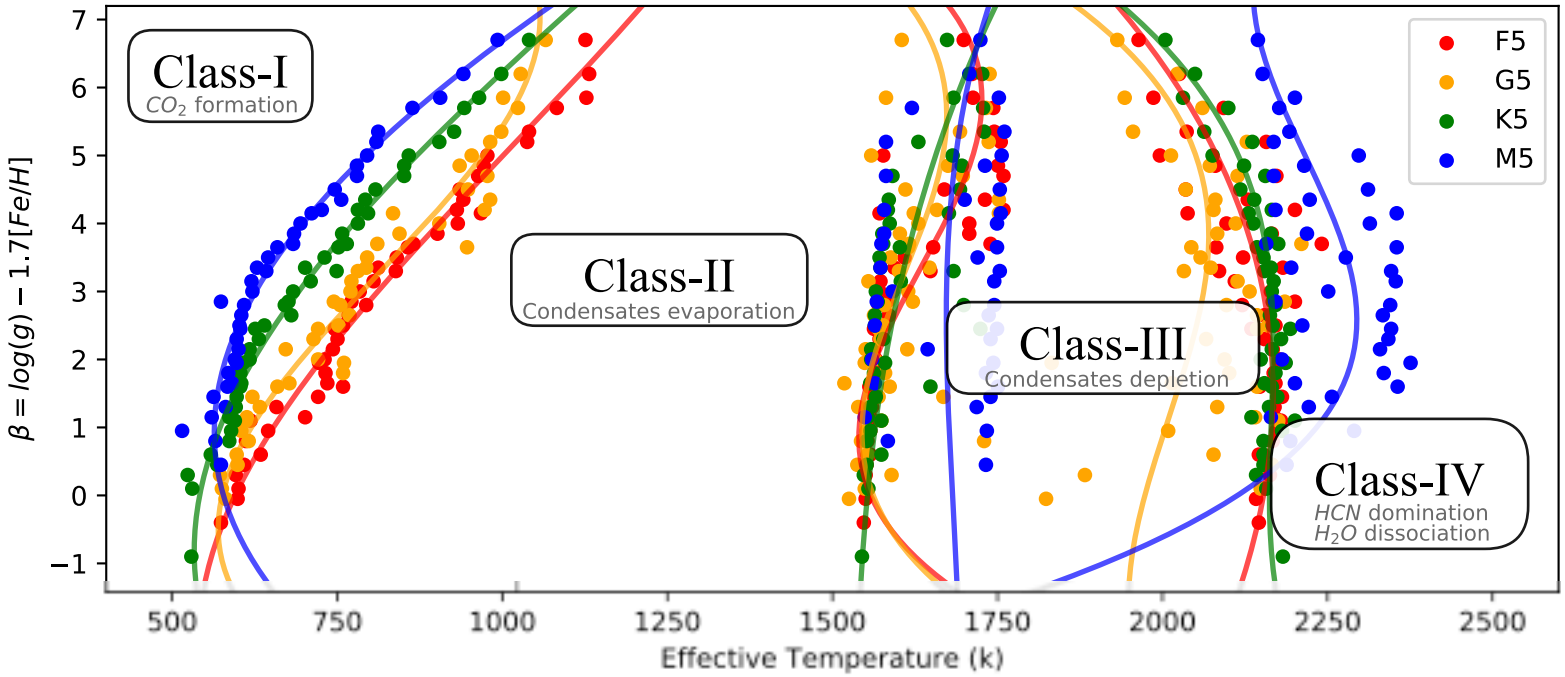


[Molaverdikhani et al. 2018, in prep.]

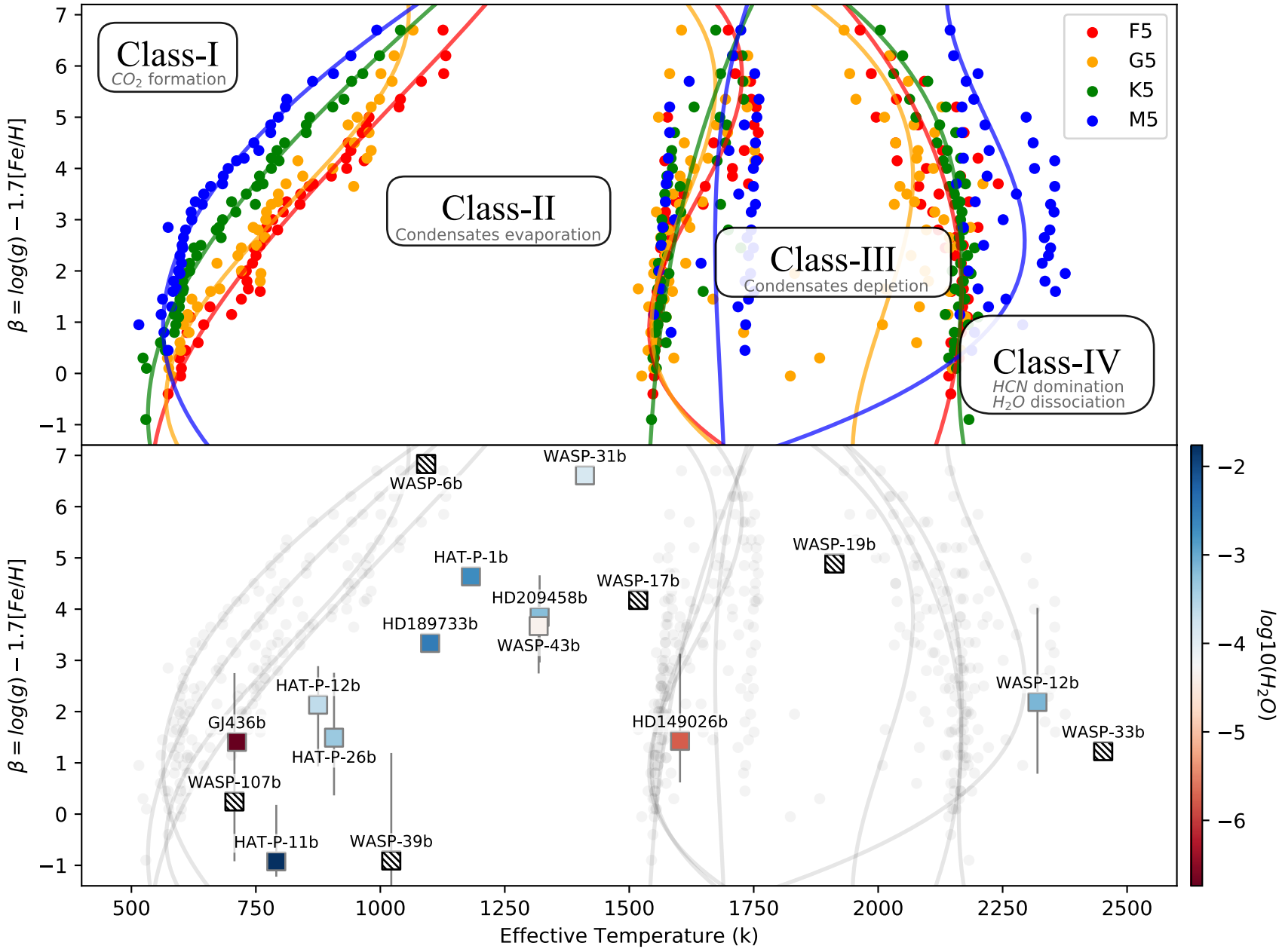
Transitional C/Os: all



[Molaverdikhani et al. 2018, in prep.]



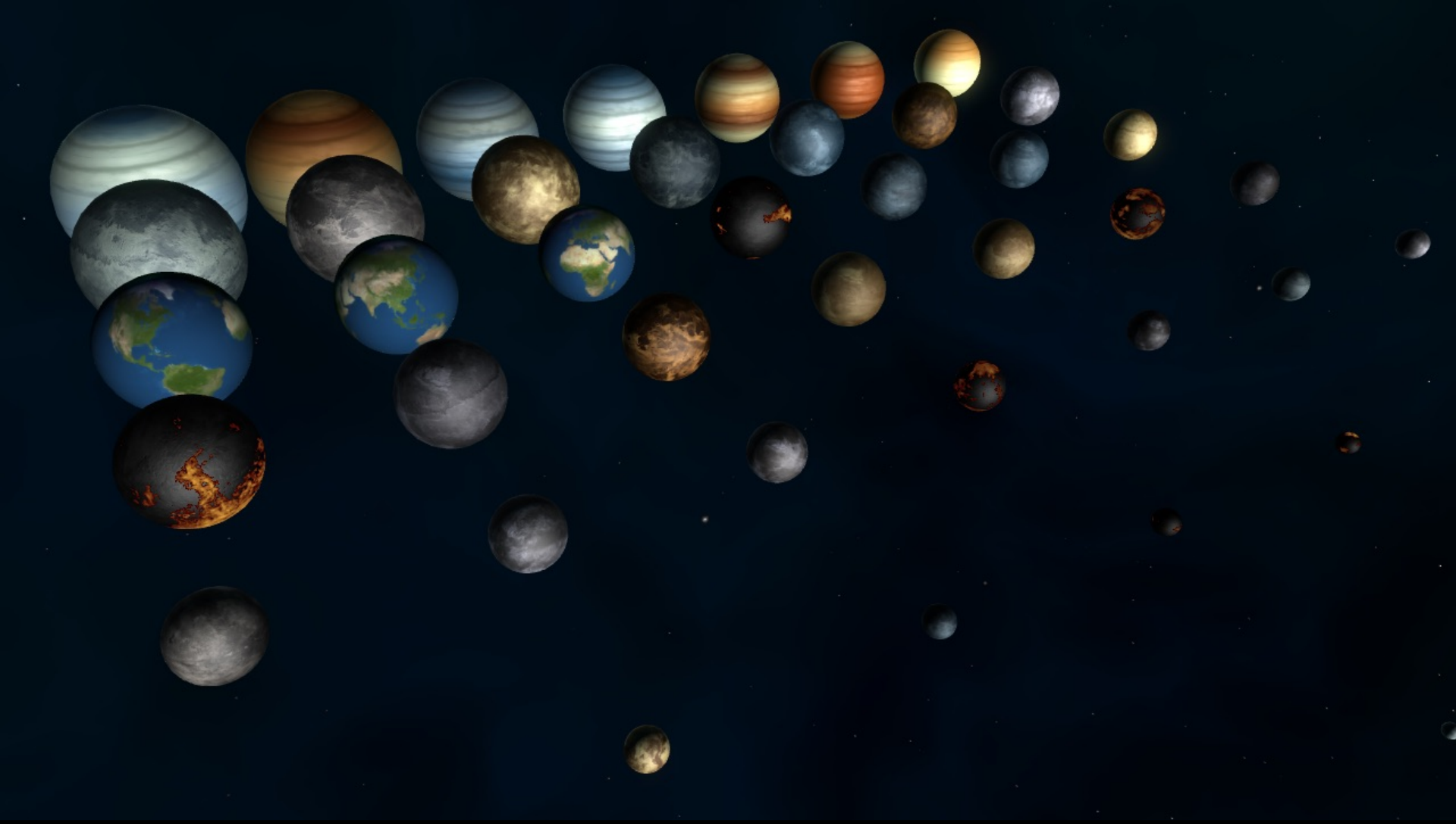
[Molaverdikhani et al. 2018, in prep.]



[Molaverdikhani et al. 2018, in prep.]

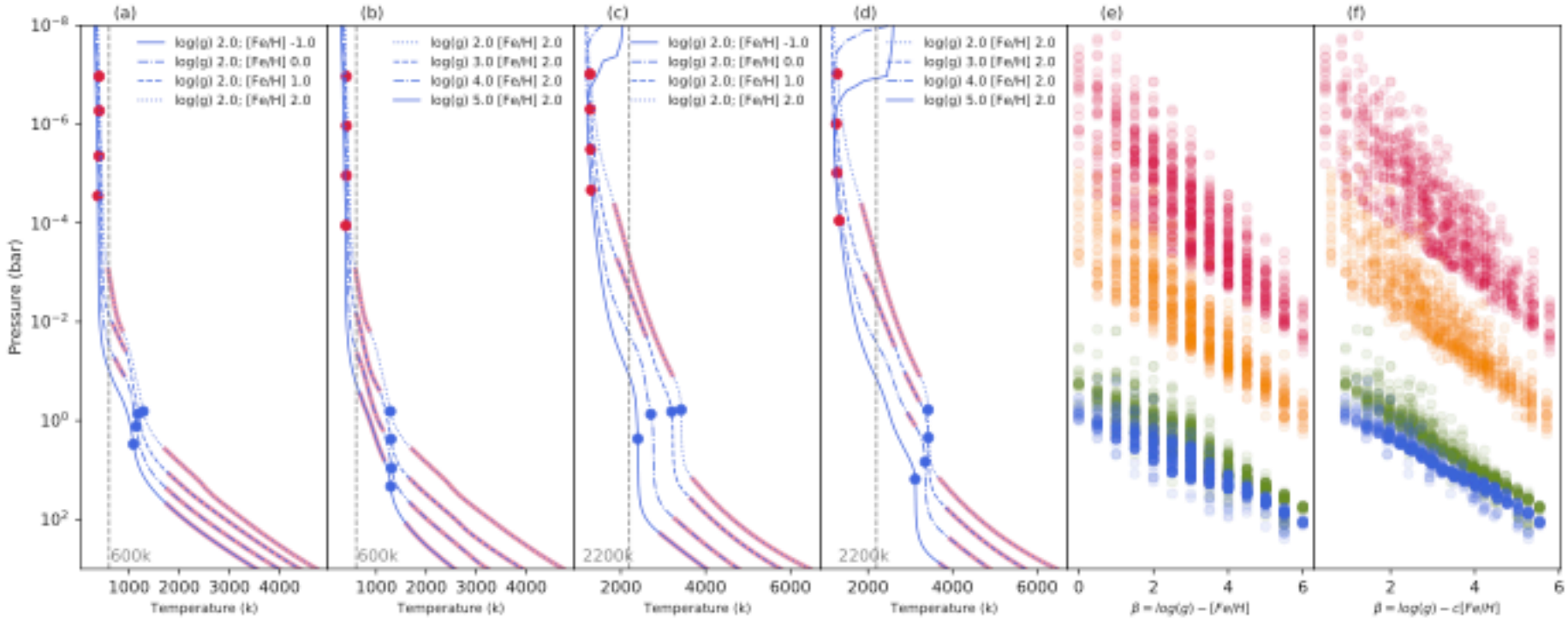
~Summary

- Four classes of irradiated planets
- C/O<1 != water-dominated atmosphere
  - C/O>~1 != methane-dominated atmosphere
- Methane: 800k-1500k with C/O>0.7
  - Madhusudhan's prediction: C/O>0.8 for more than 50% of hot-Jupiters

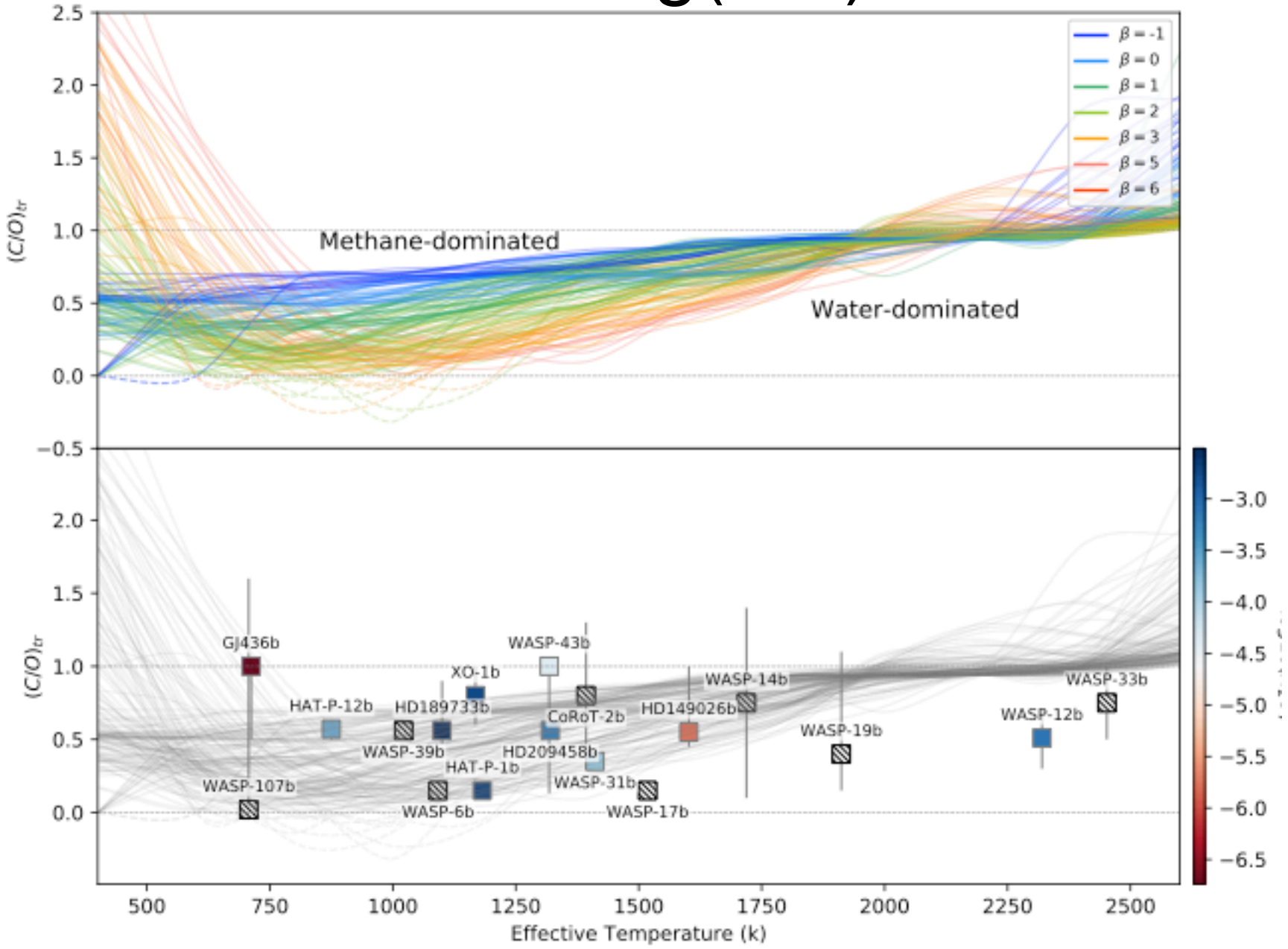


Extras

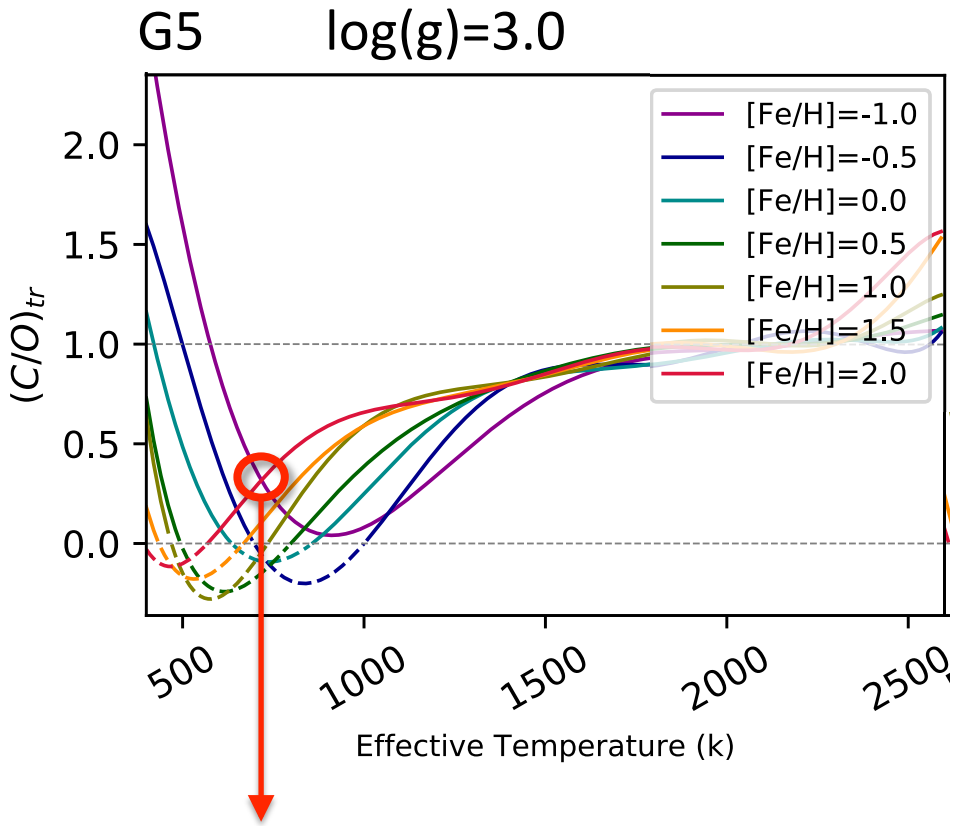
Beta factor


(a)
(b)
(c)
(d)
(e)
(f)
Pressure (bar)
Temperature (k)
log(g) 2.0; [Fe/H] -1.0
log(g) 2.0; [Fe/H] 0.0
log(g) 2.0; [Fe/H] 1.0
log(g) 2.0; [Fe/H] 2.0
log(g) 3.0 [Fe/H] 2.0
log(g) 4.0 [Fe/H] 2.0
log(g) 5.0 [Fe/H] 2.0
600k
2200k
β = log(g) − [Fe/H]
β = log(g) − c[Fe/H]

Transitional C/Os: log(kzz)=12



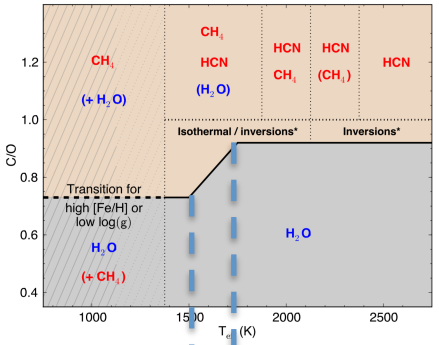
Transitional C/Os: Example

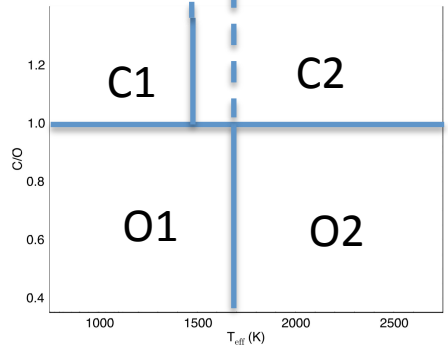


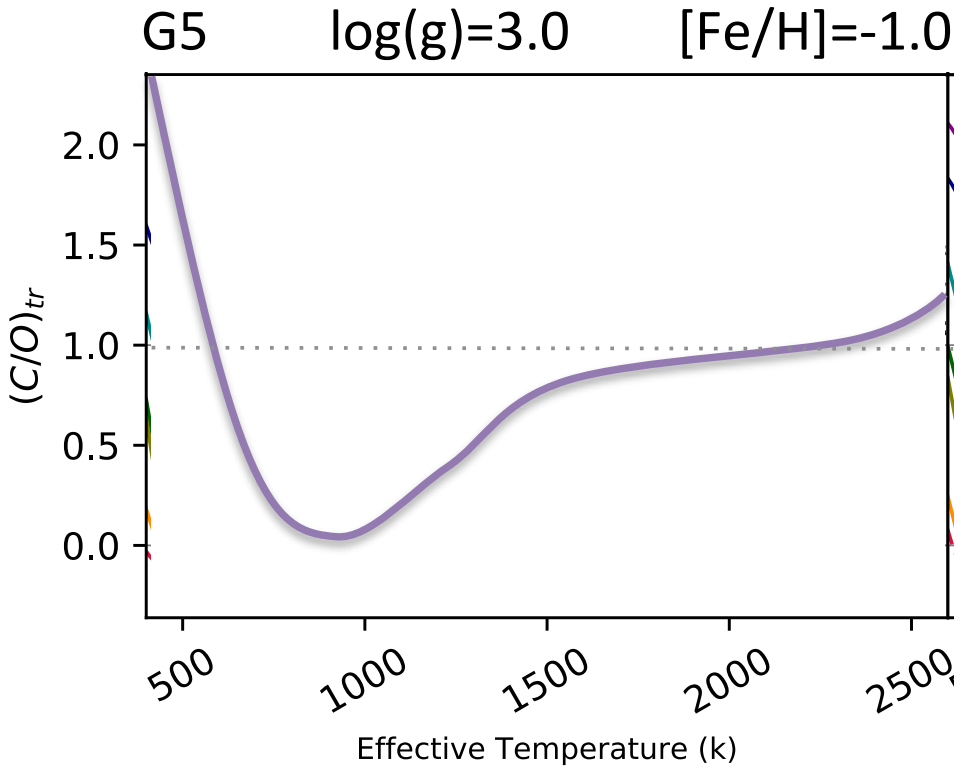
Same transitional C/O ratios but different Classes

[Molaverdikhani et al. 2018, in prep.]

Transitional C/Os: Example







[Molaverdikhani et al. 2018, in prep.]