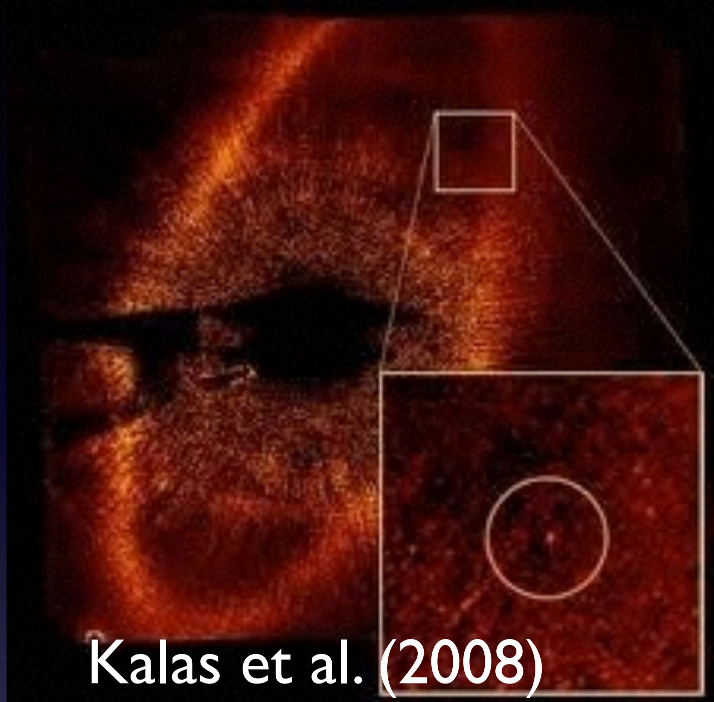
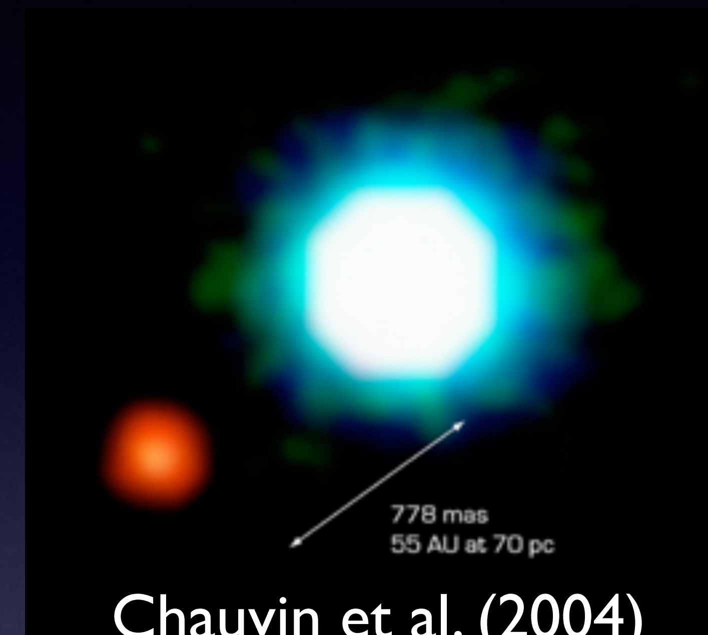
# Crown Jewels of Young Exoplanets

Travis Barman (University of Arizona)

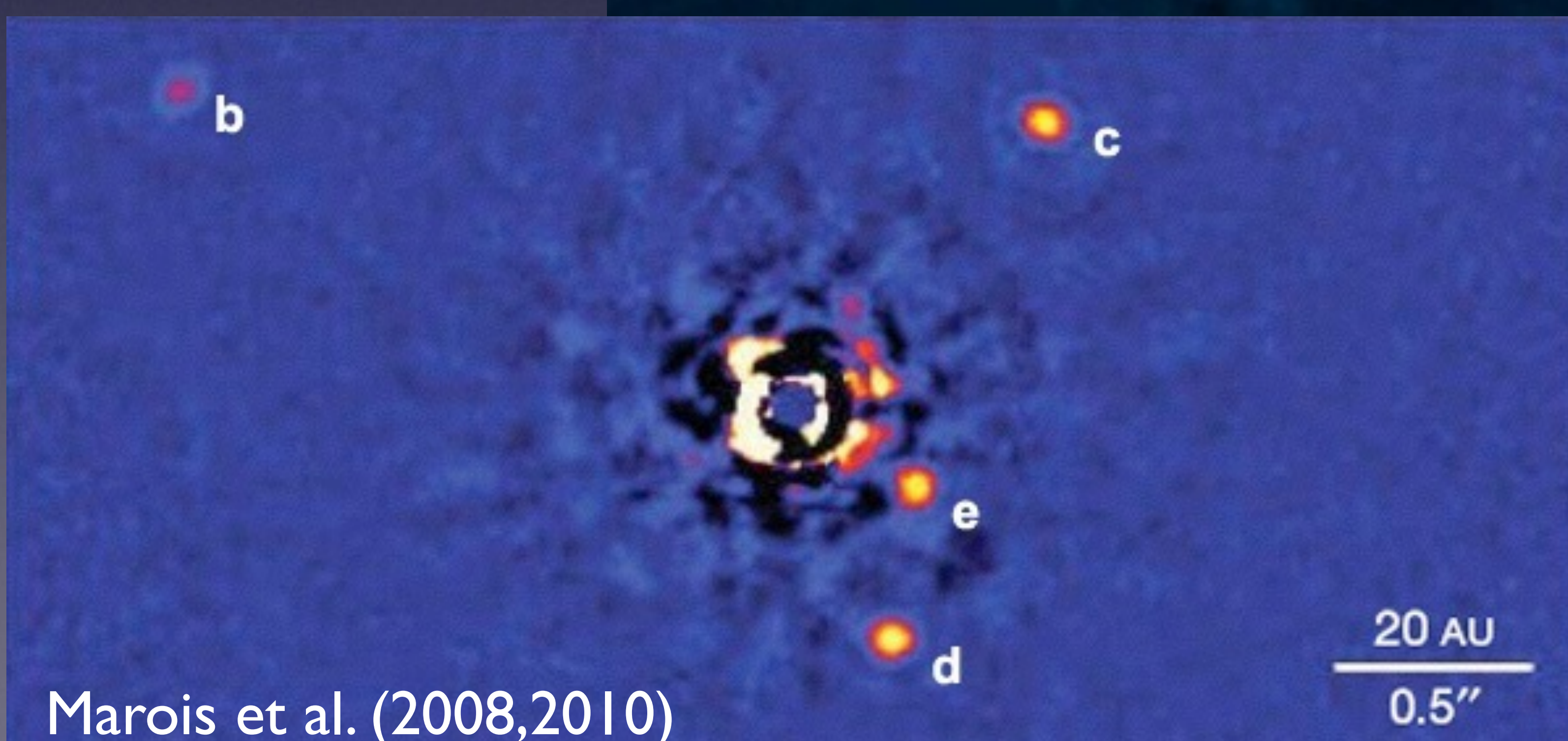


Kalas et al. (2008)

Lagrange et al. (2009)



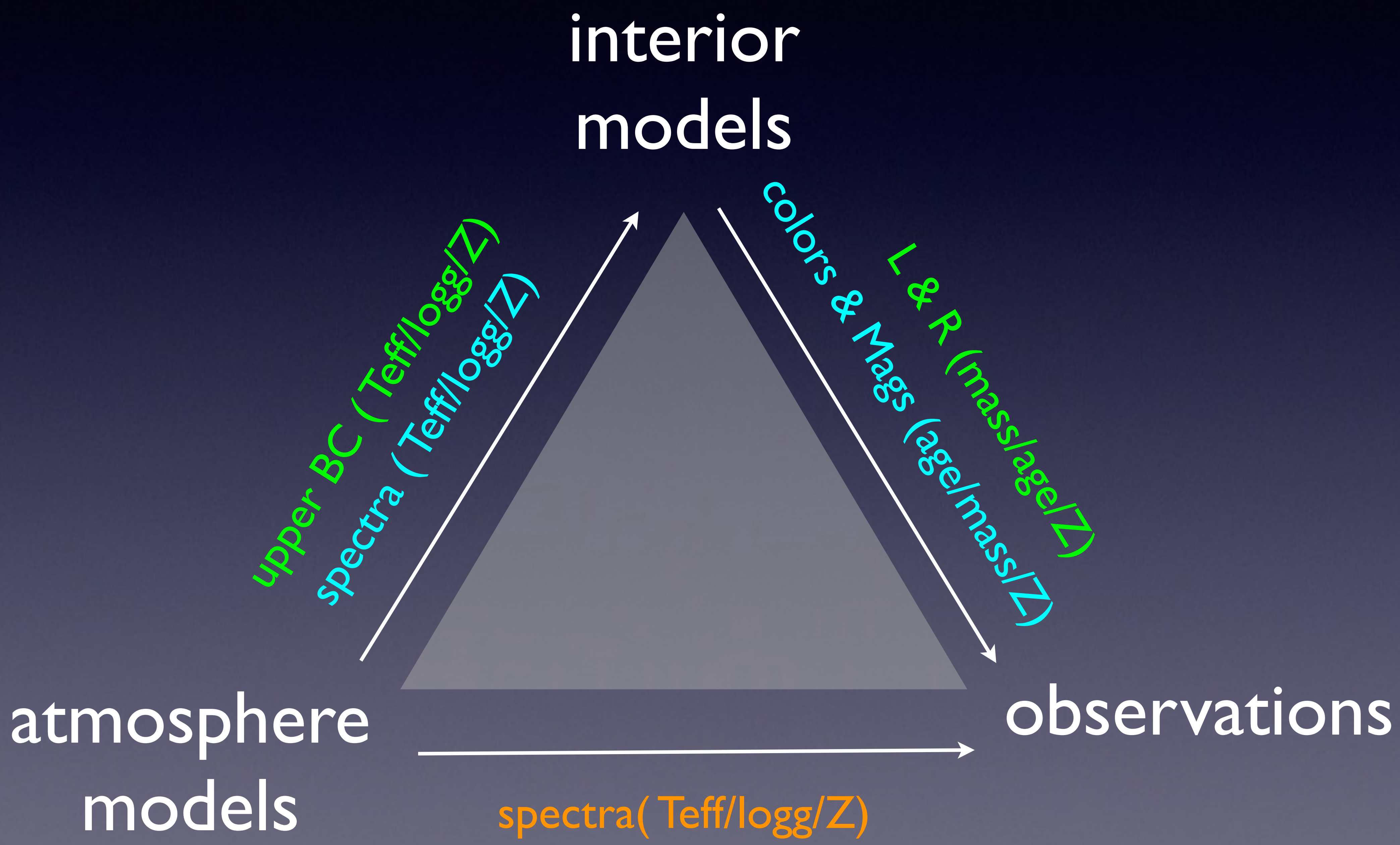

Chauvin et al. (2004)



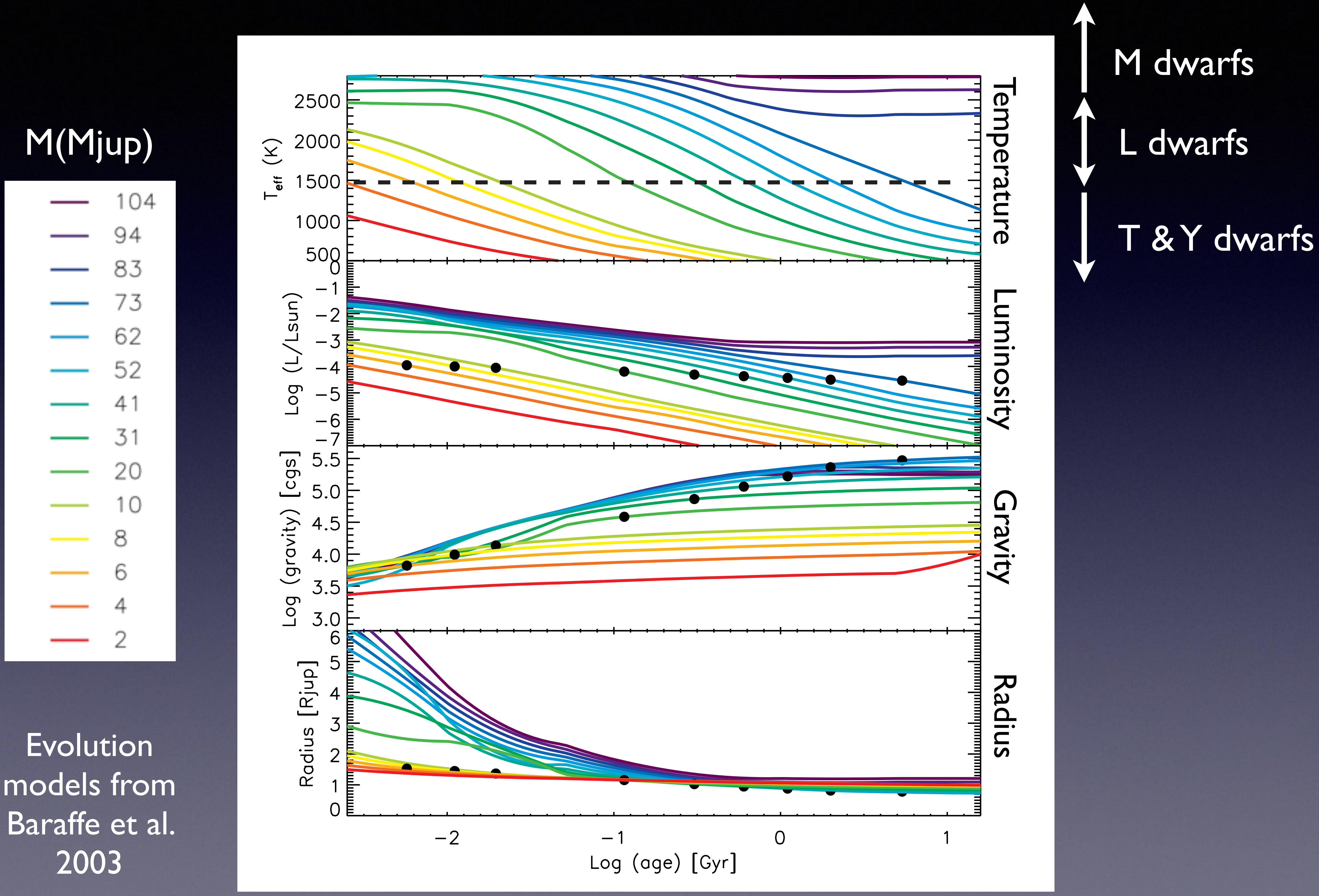

Marois et al. (2008,2010)


Lafrénière et al. (2010)

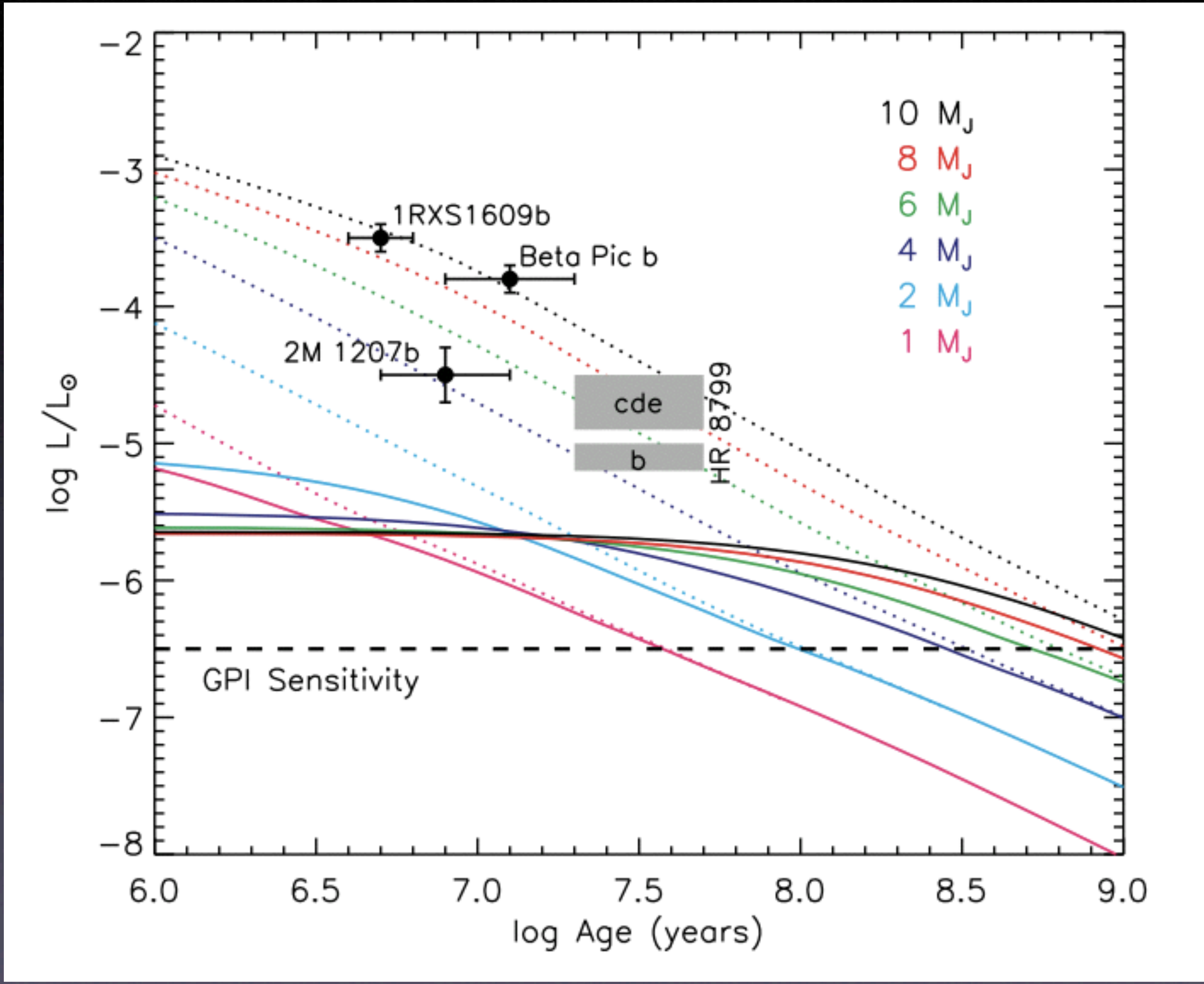
Atmosphere [noun]:
“a transition region between the stellar interior and the interstellar medium” (Grey 1992)



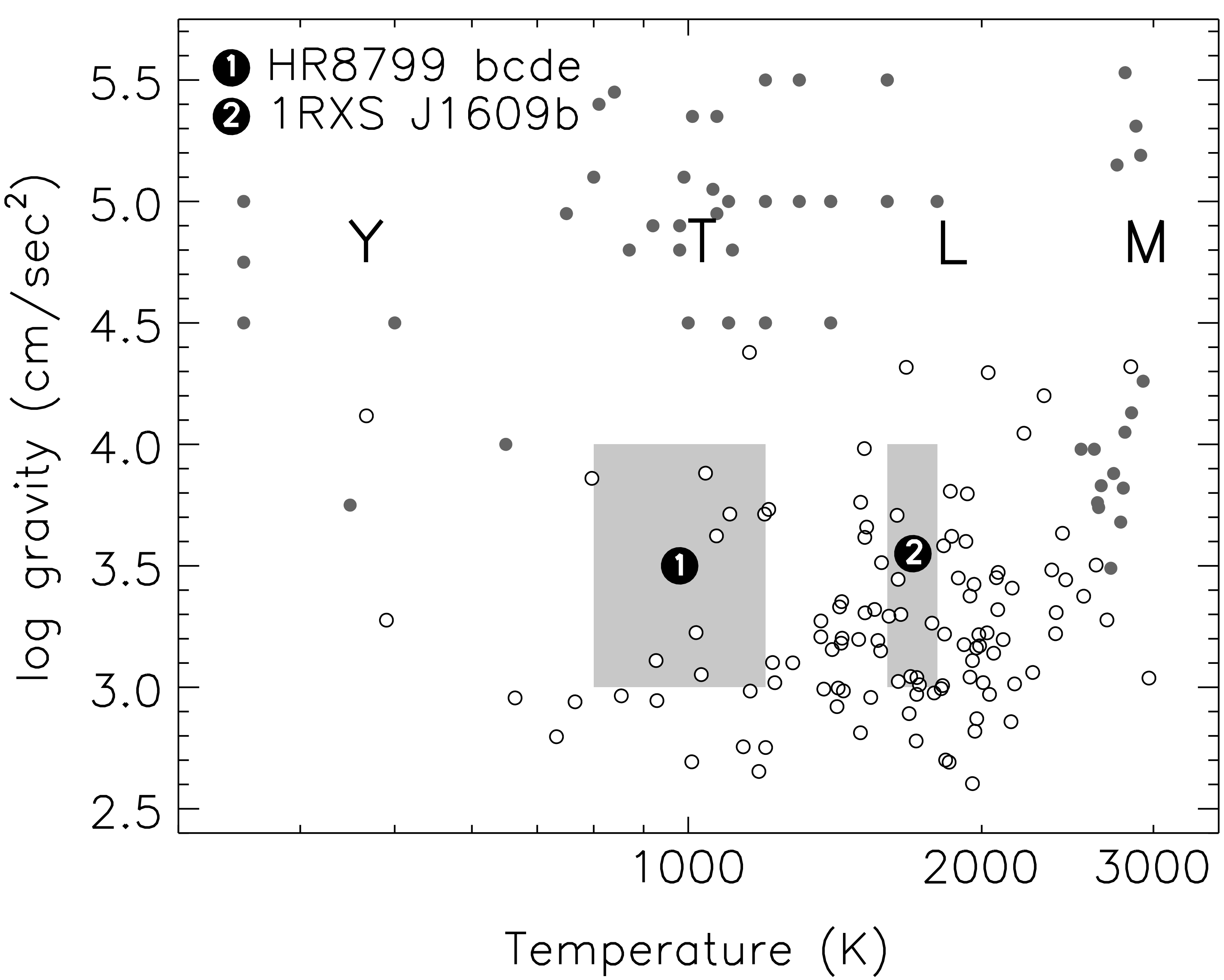
# Brown Dwarf / Giant Planet Evolution:



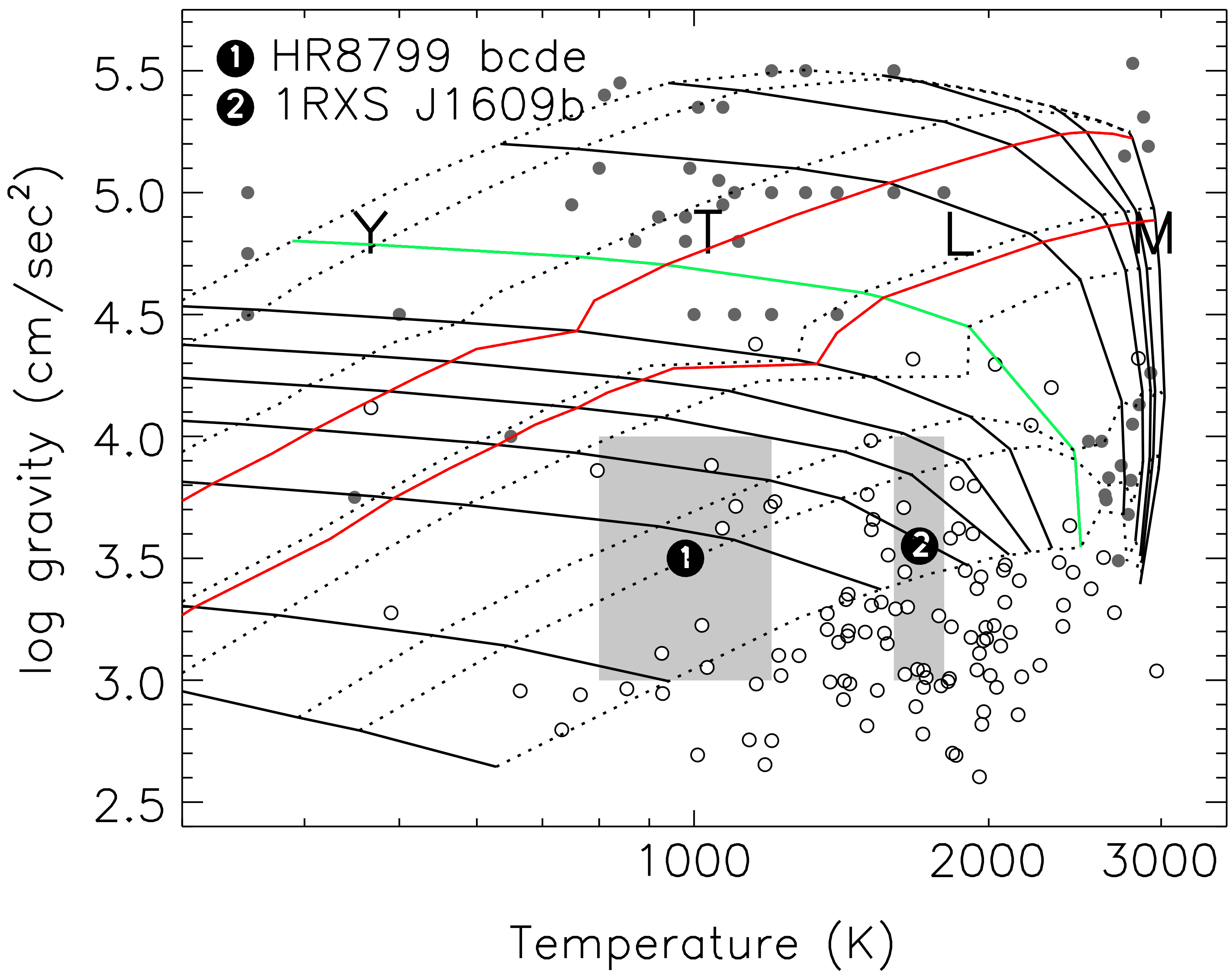

Evolution models from Baraffe et al. 2003




(see Marley et al. 2007; Fortney et al. 2008; Spiegel & Burrows 2012)



HR8799 bcde
1RXS J1609b
Y
T
L
M
log gravity (cm/sec$^2$)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1000
2000
3000
Temperature (K)



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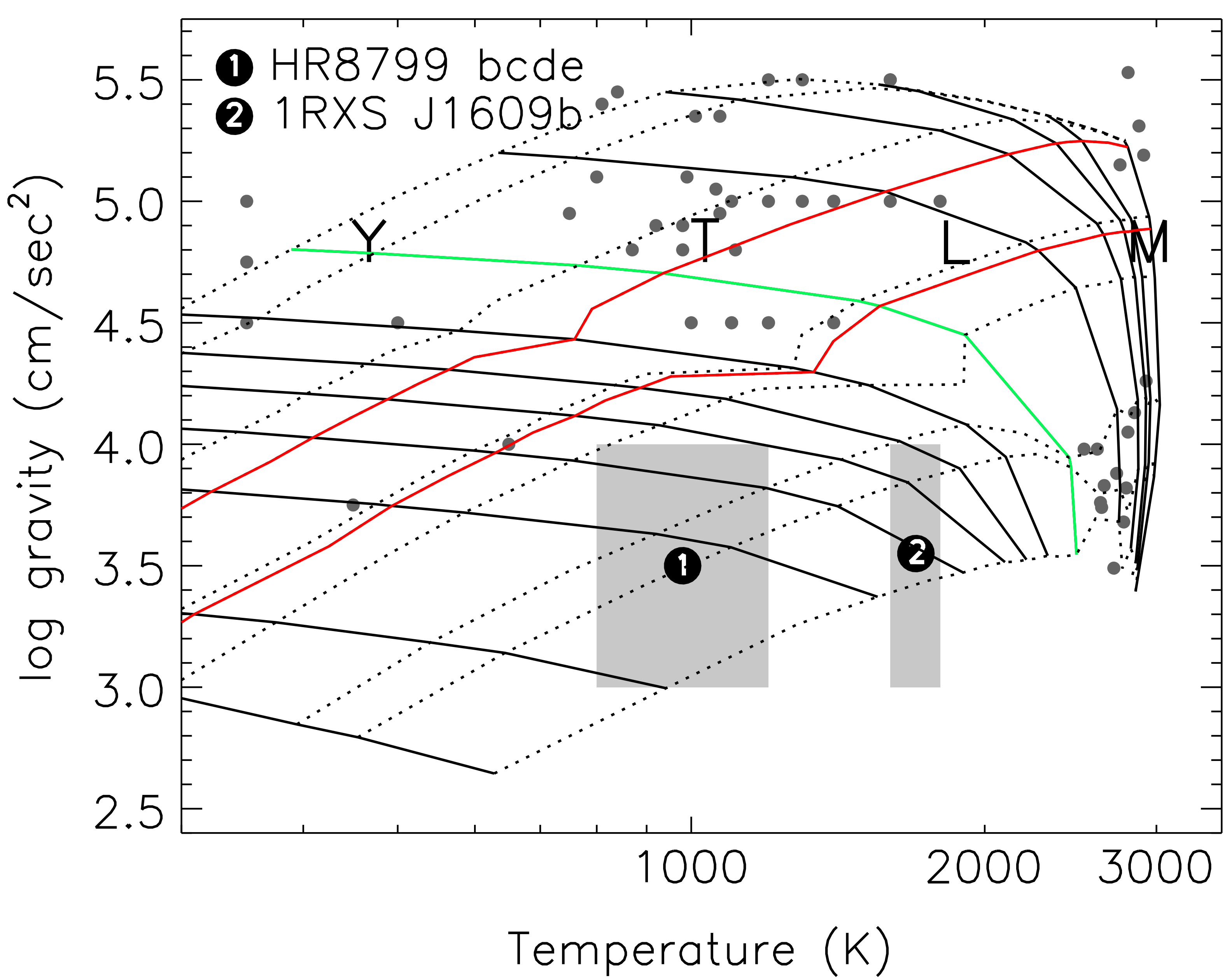
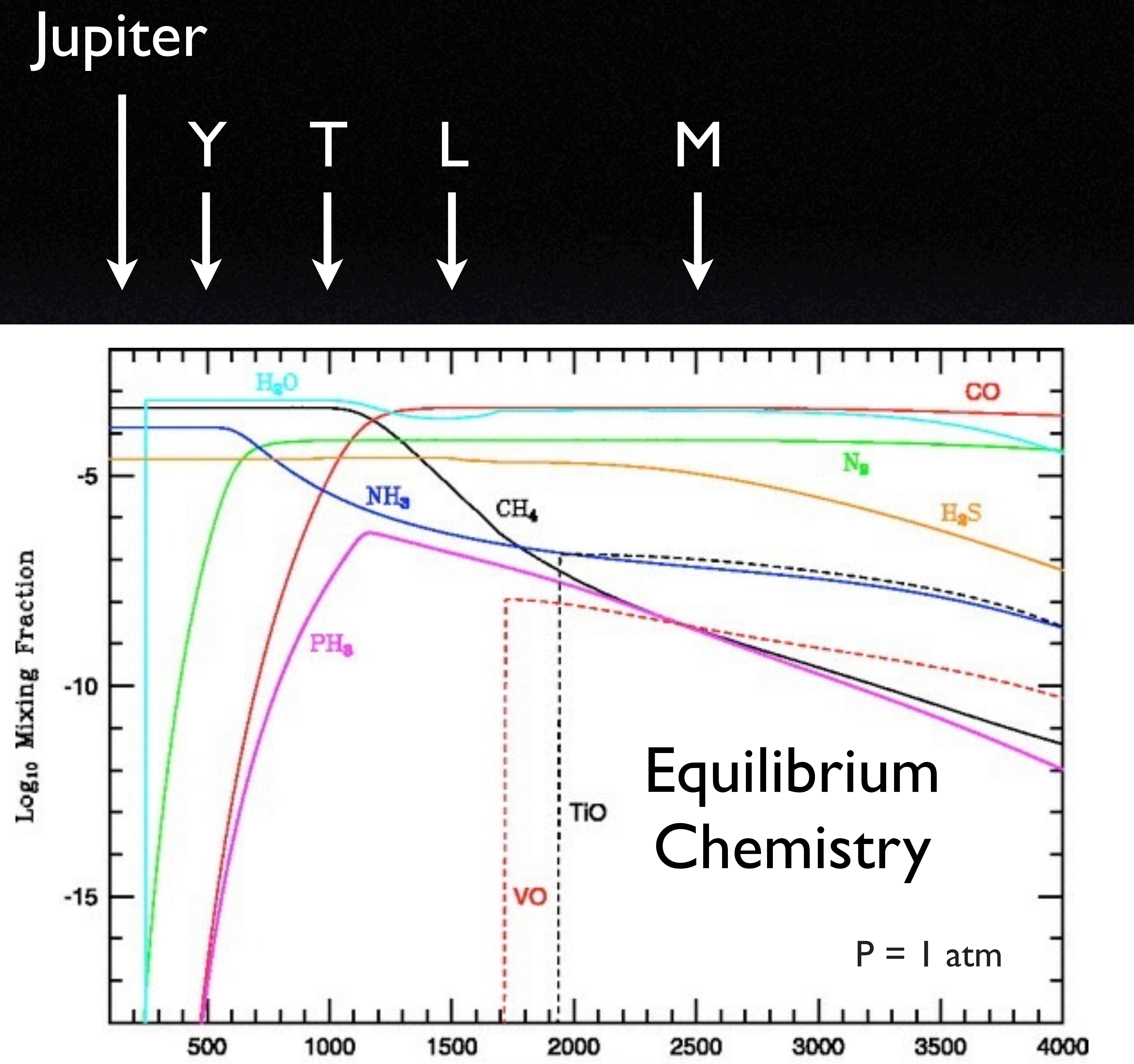


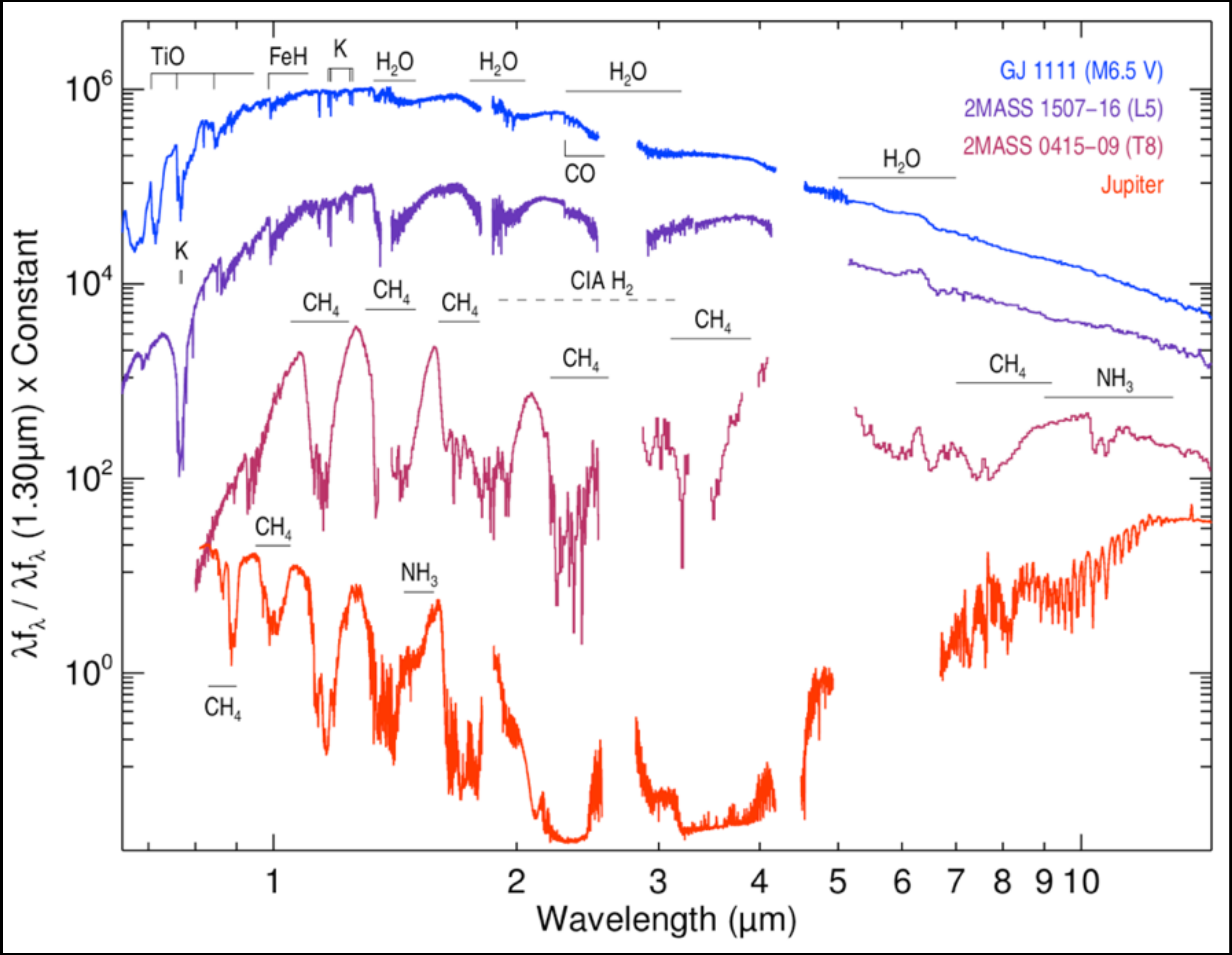
❶ HR8799 bcde
❷ 1RXS J1609b
Y
T
L
M
log gravity (cm/sec$^2$)
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1000
2000
3000
Temperature (K)

# What shapes your spectrum, besides speckles?

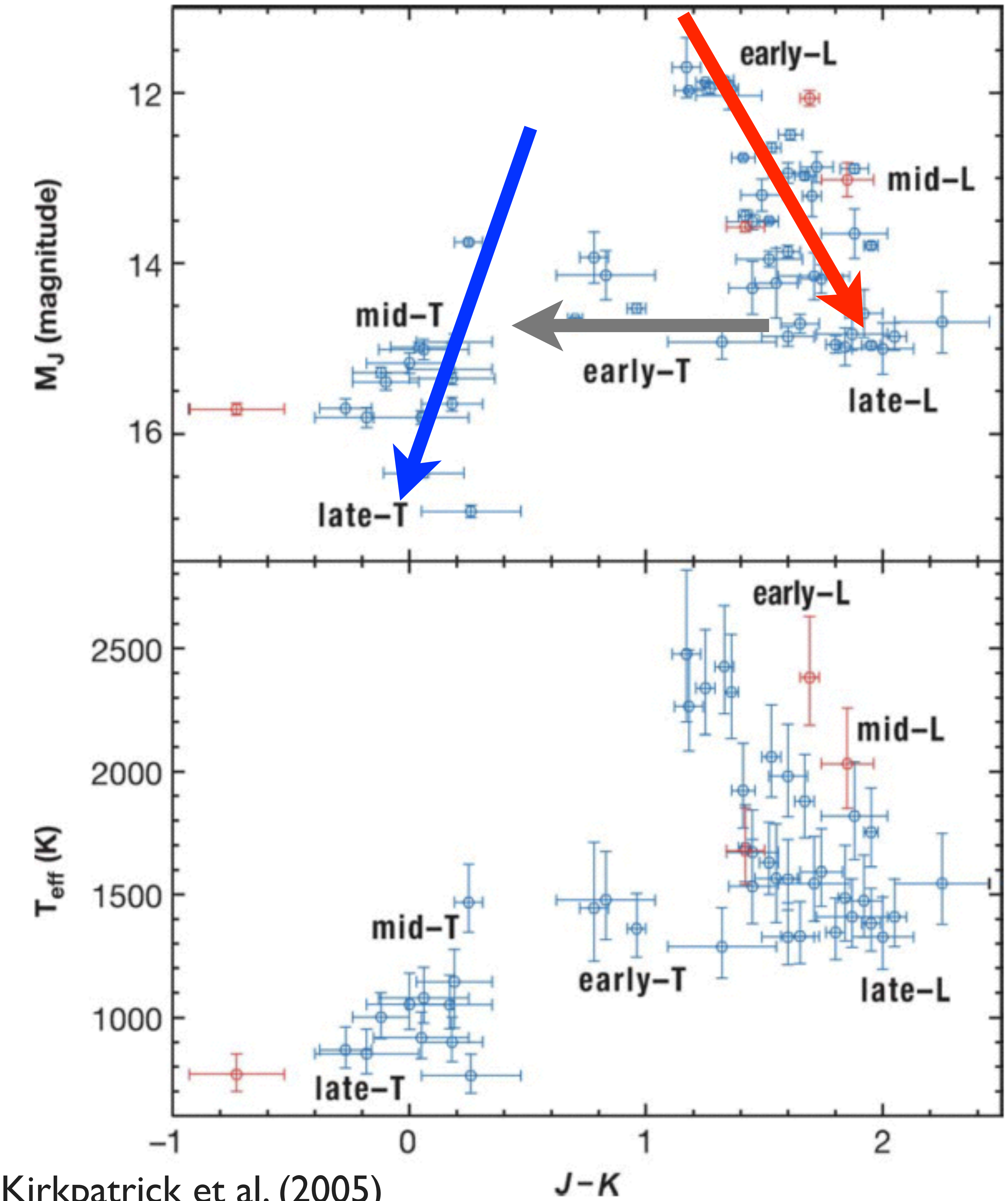
- Effective Temperature
- Gravity
- Clouds
- non-equilibrium chemistry
- metallicity




Sharp & Burrows (2007)

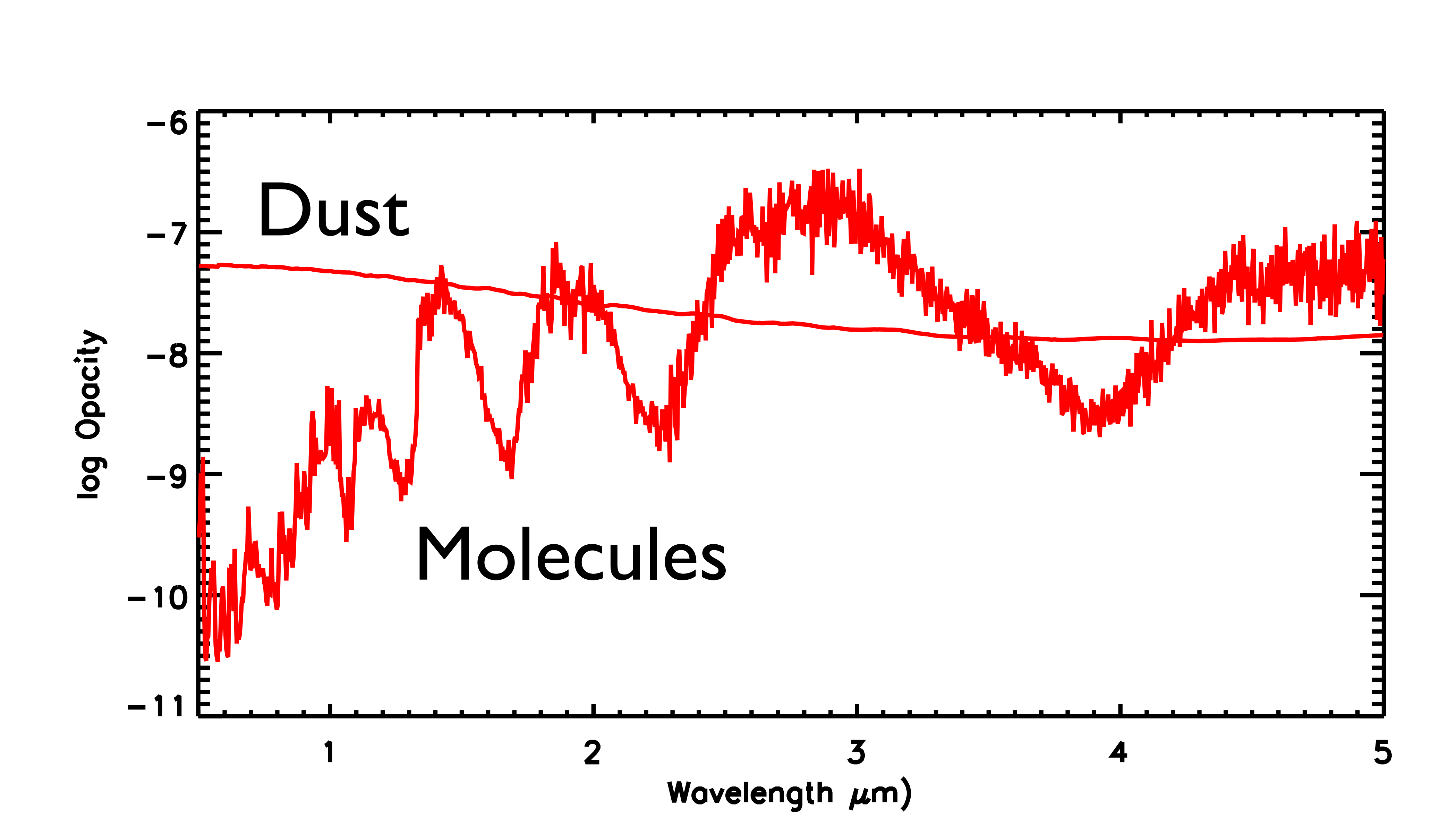



(From Mike Cushing)

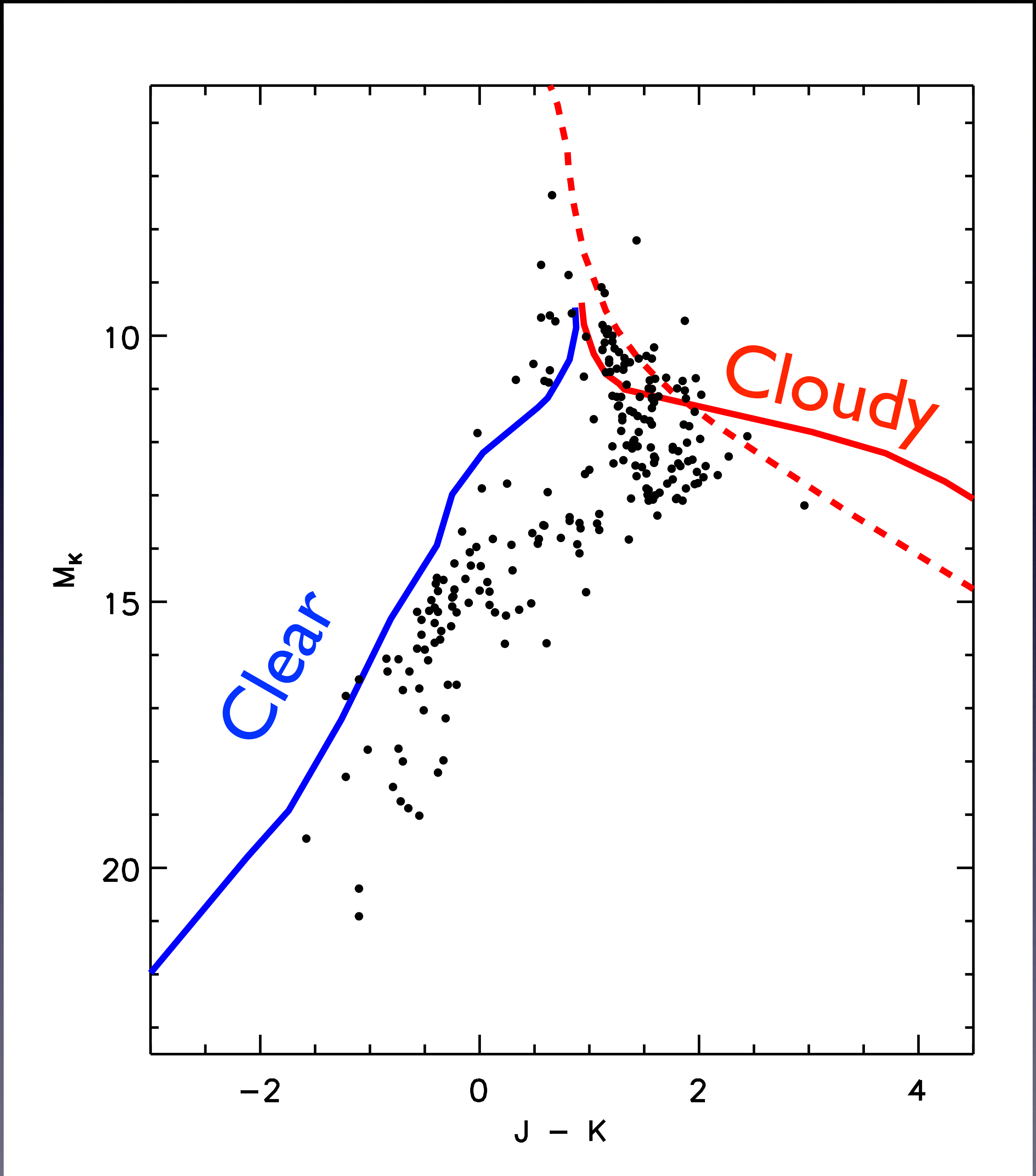


Kirkpatrick et al. (2005)

# Opacities:

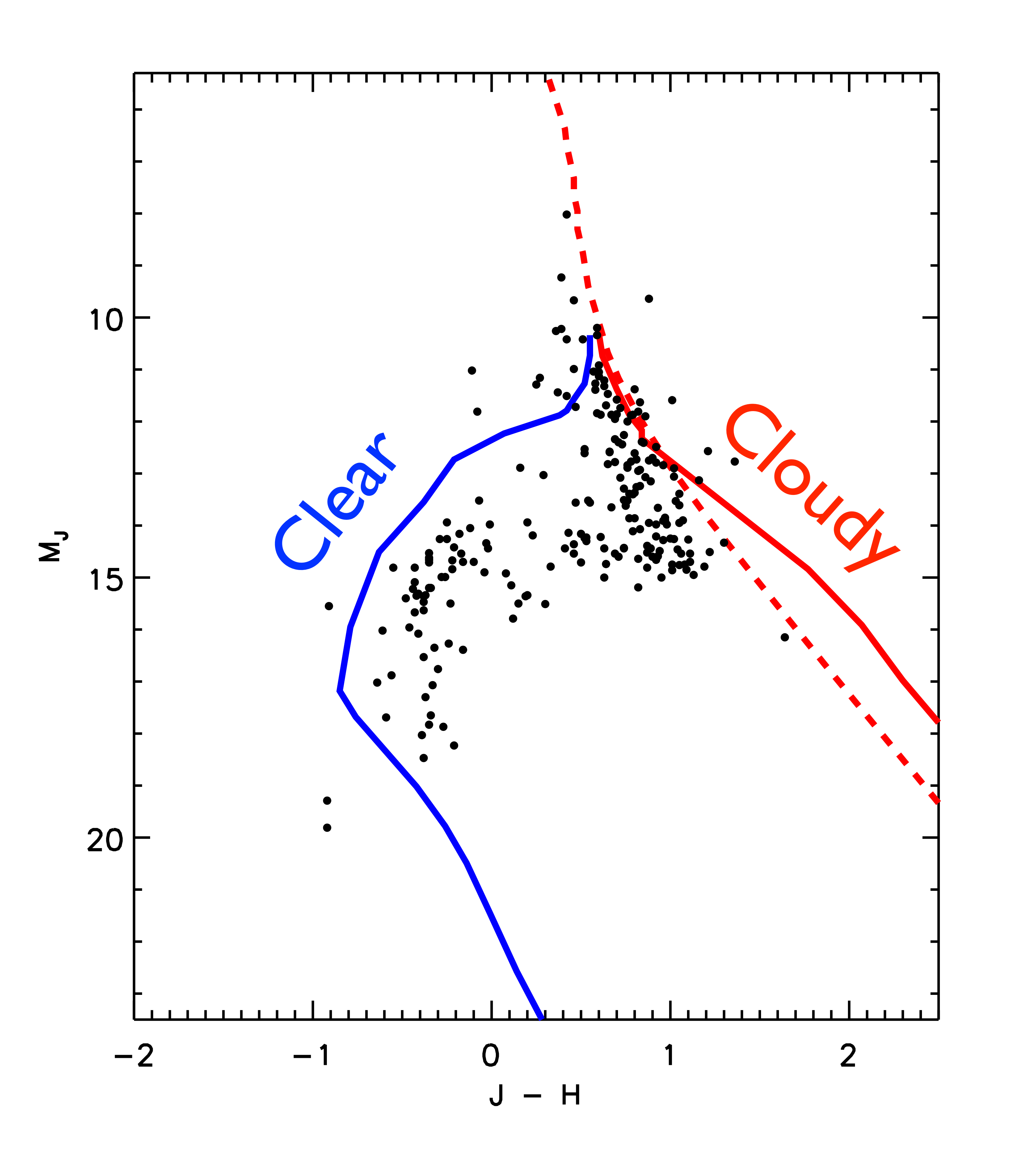


# Near-IR Color-Magnitude Diagrams



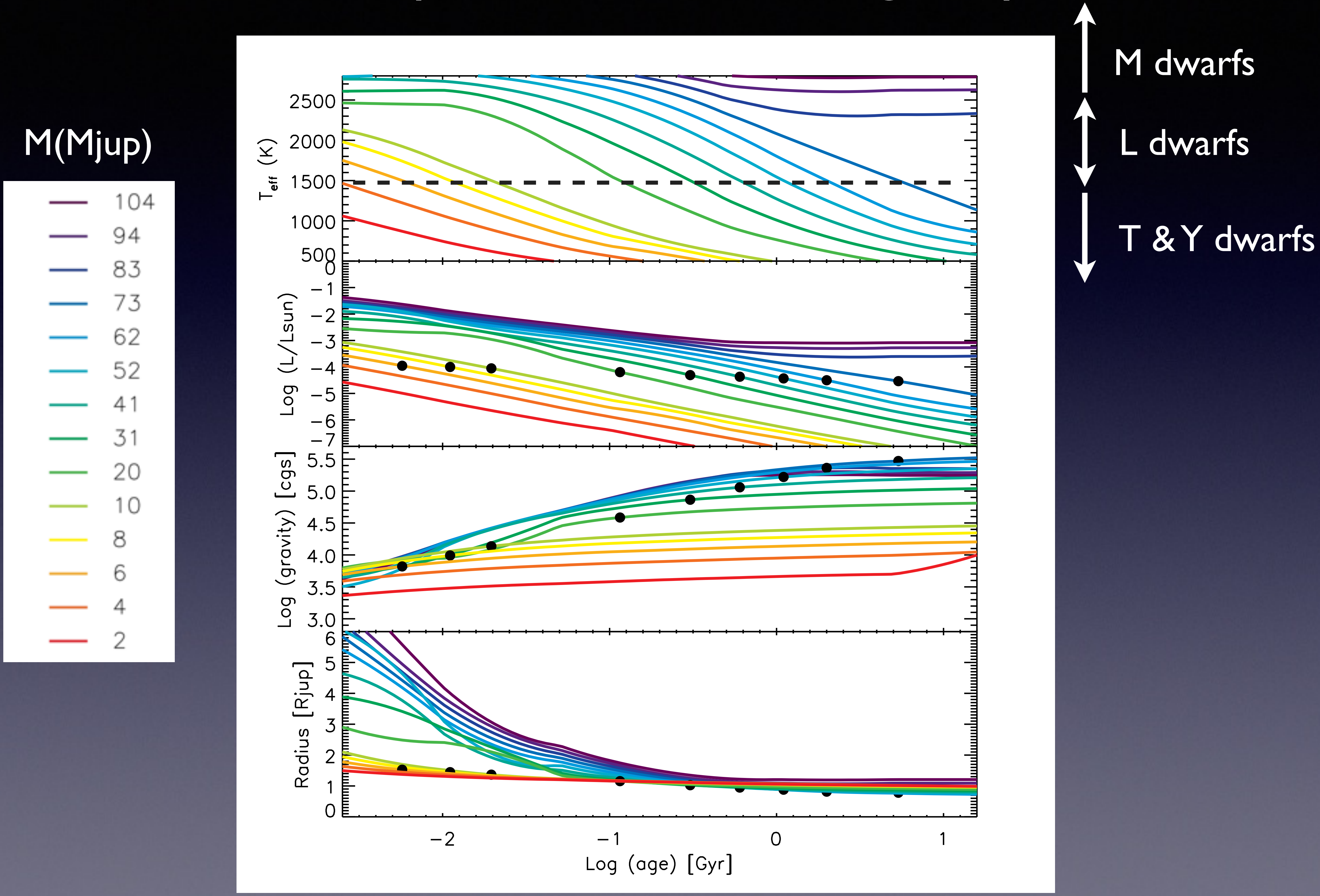

BD observations from Faherty et al. (2012) Dupuy &Kraus (2013) and Beichman et al. (2014)

# Near-IR Color-Magnitude Diagrams



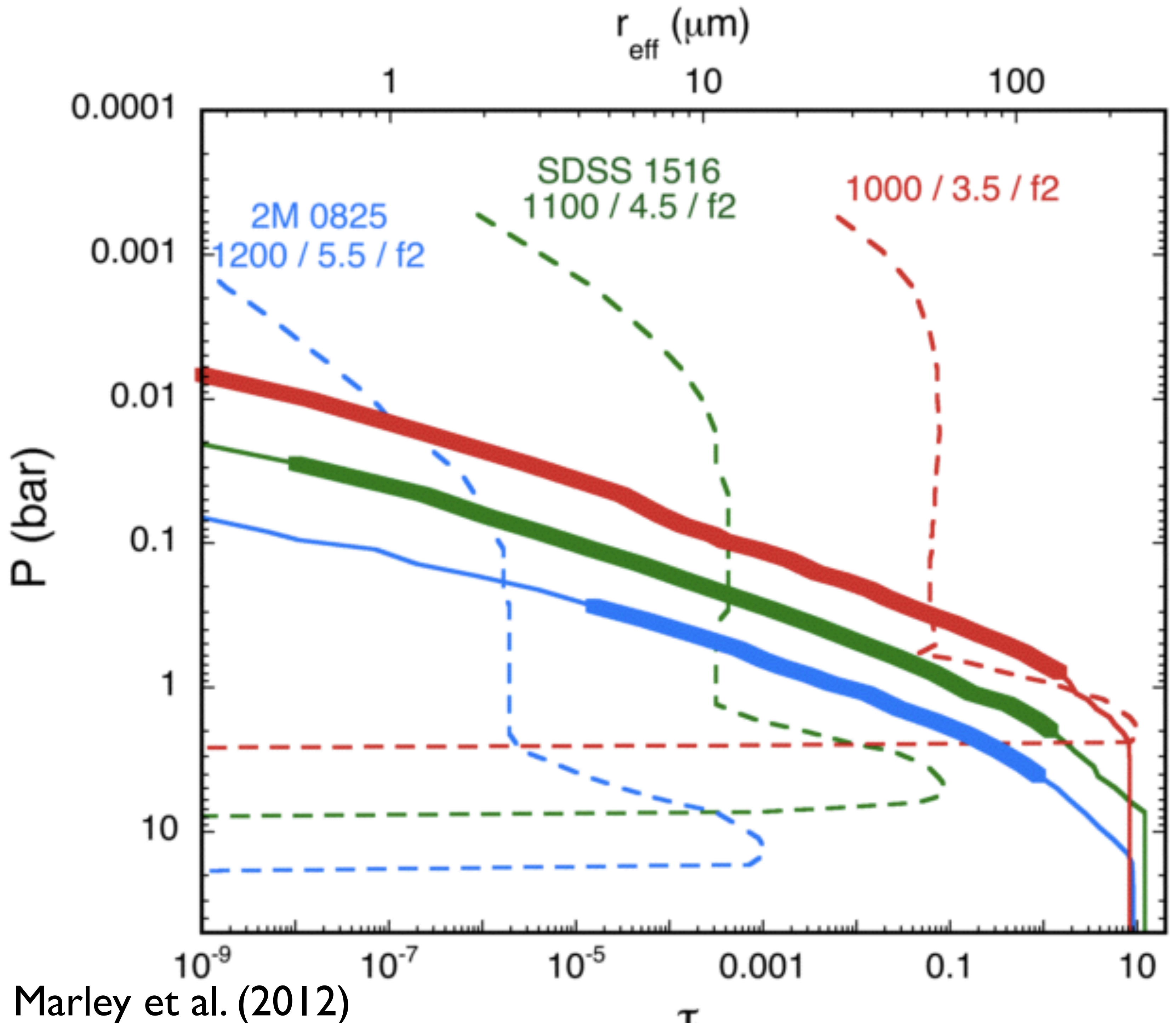

BD observations from Faherty et al. (2012) Dupuy &Kraus (2013) and Beichman et al. (2014)

# The importance of surface gravity:



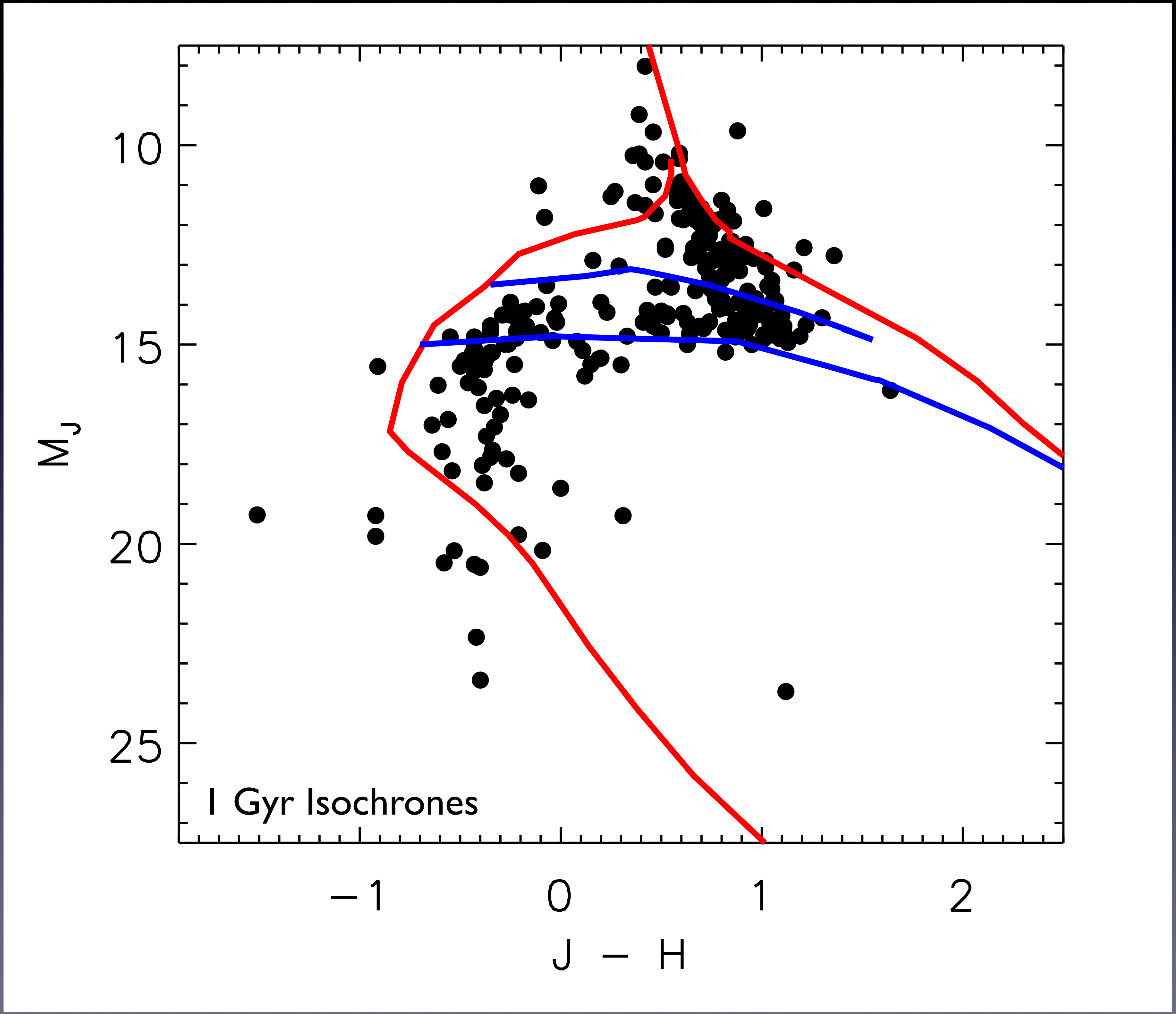

Baraffe et al. 2003

# The importance of surface gravity: clouds




Marley et al. (2012)

# The importance of surface gravity: clouds

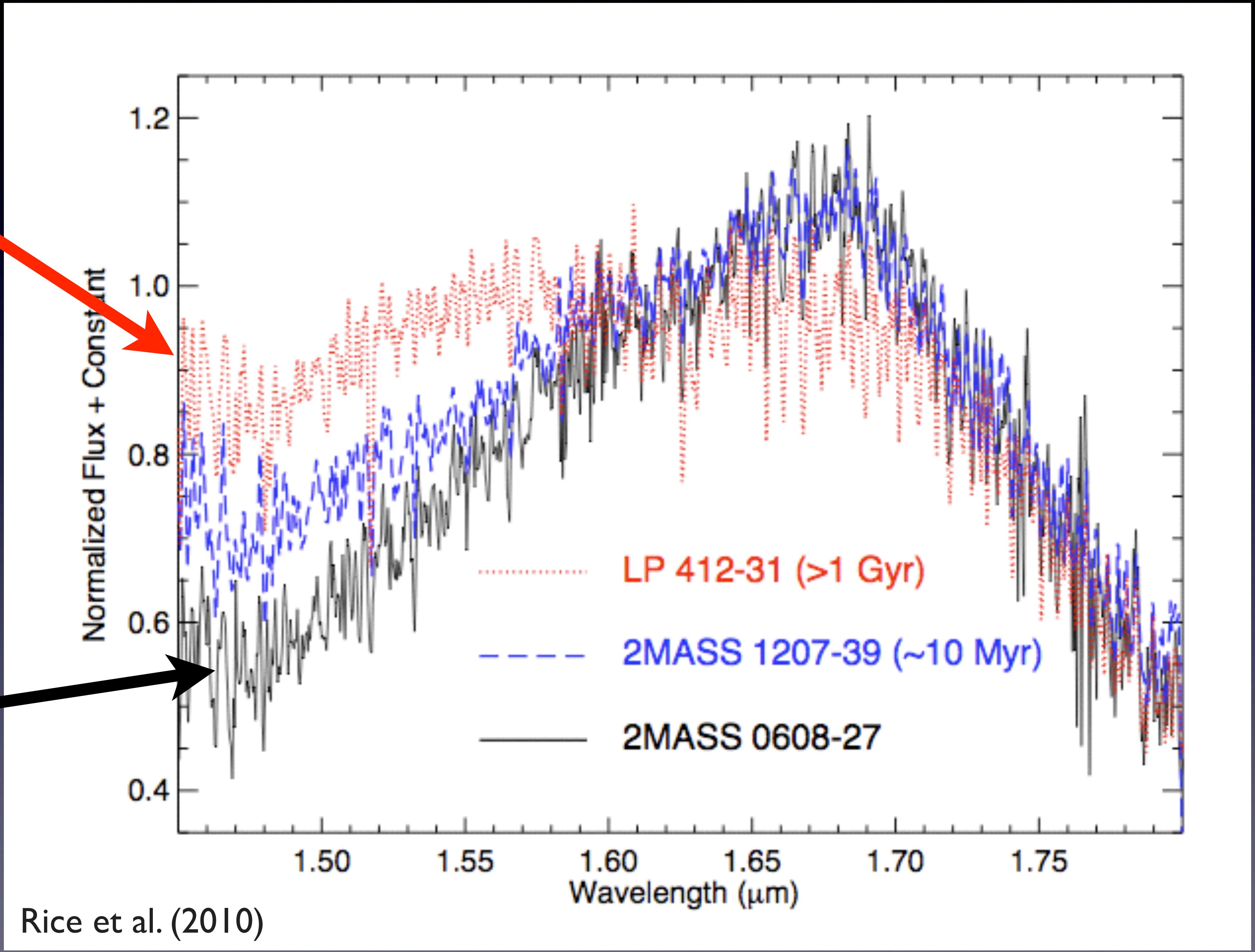



See also the work by Allard et al., Burrows et al., Helling et al. Marley et al., Morley et al., and Tsuji et al.

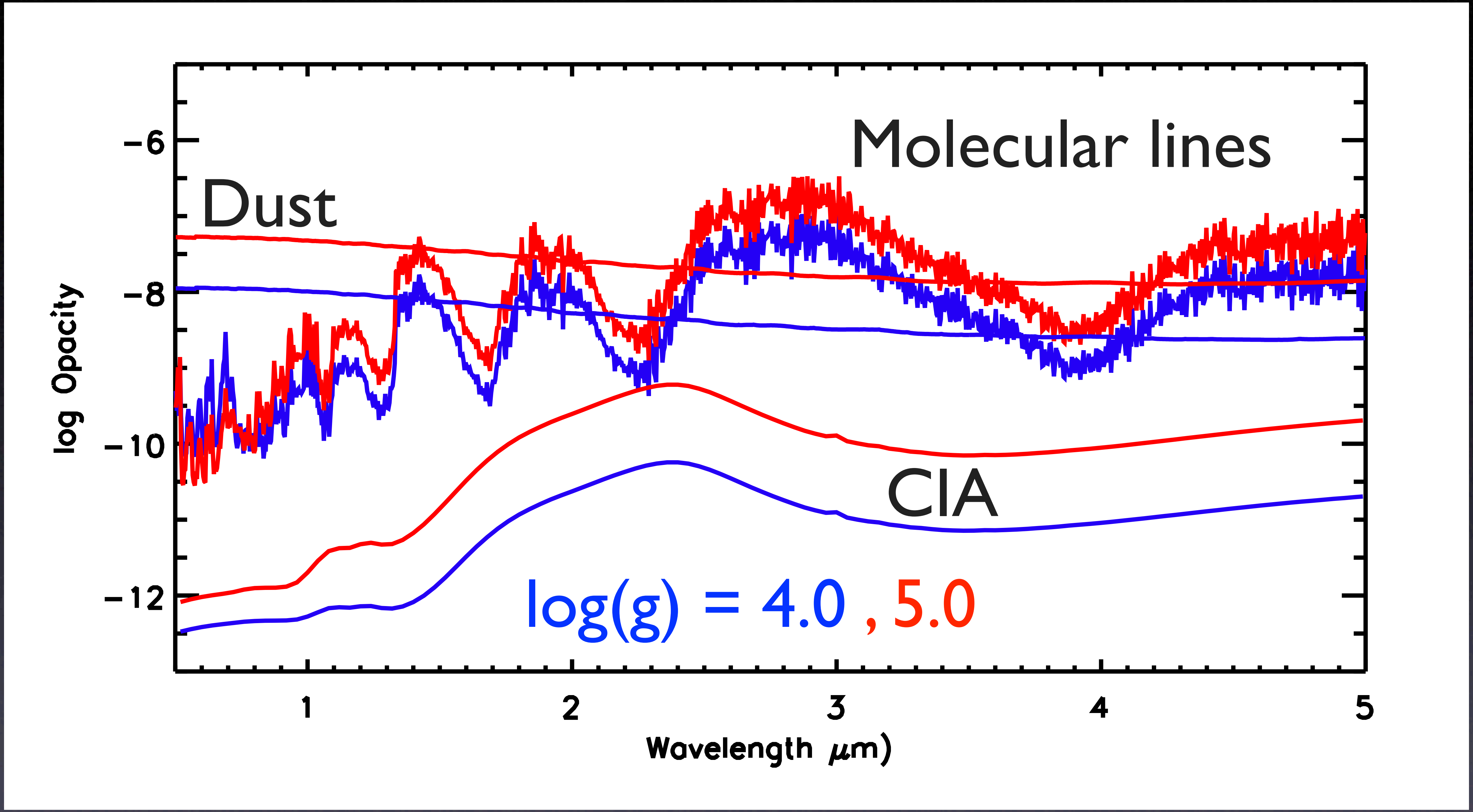
# H-band (triangular shape)

high gravity

low gravity



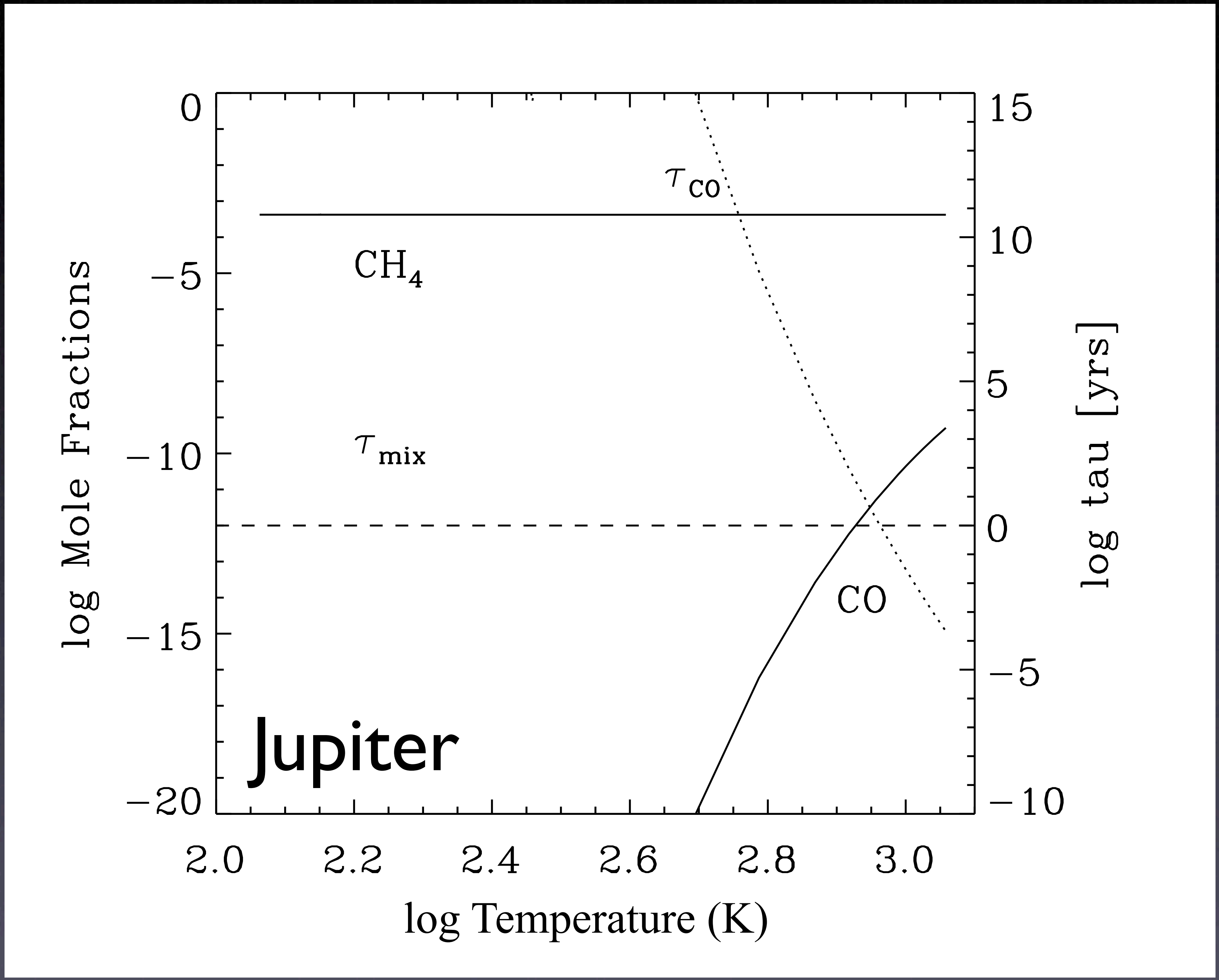

See also Allers et al. (2007), Allers & Lieu (2013), and refs for more examples.




CIA: lower gravity changes H and K bands, also makes spectrum redder

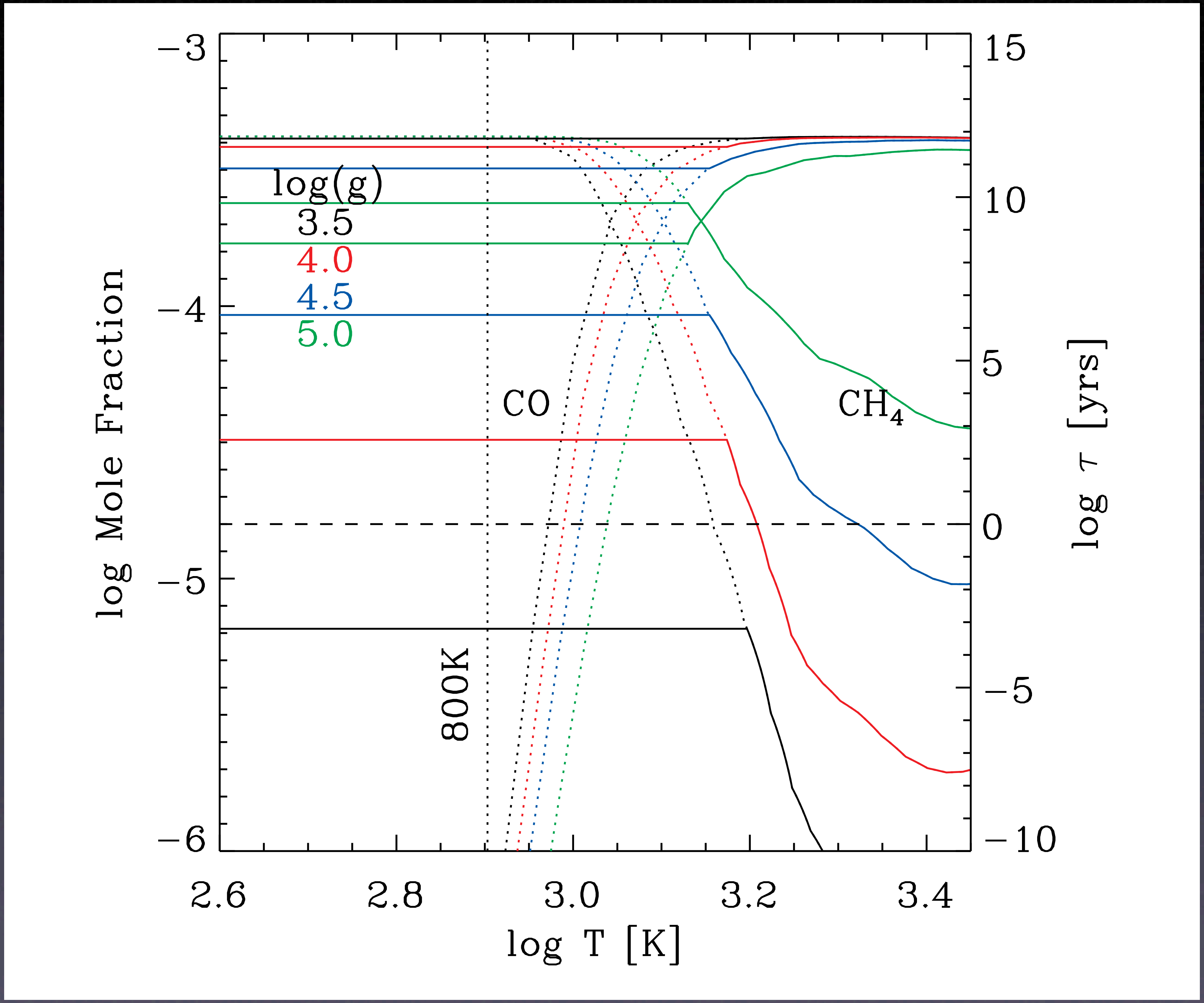
(see Borysow et al. 1997, Kirkpatrick et al. 2006)

# Departures from chemical equilibrium by vertical mixing:




See also: Noll et al. 1997; Griffith & Yelle, 1999; Saumon et al. 2000, 2006; Hubeny et al. 2007

# Departures from chemical equilibrium by vertical mixing:

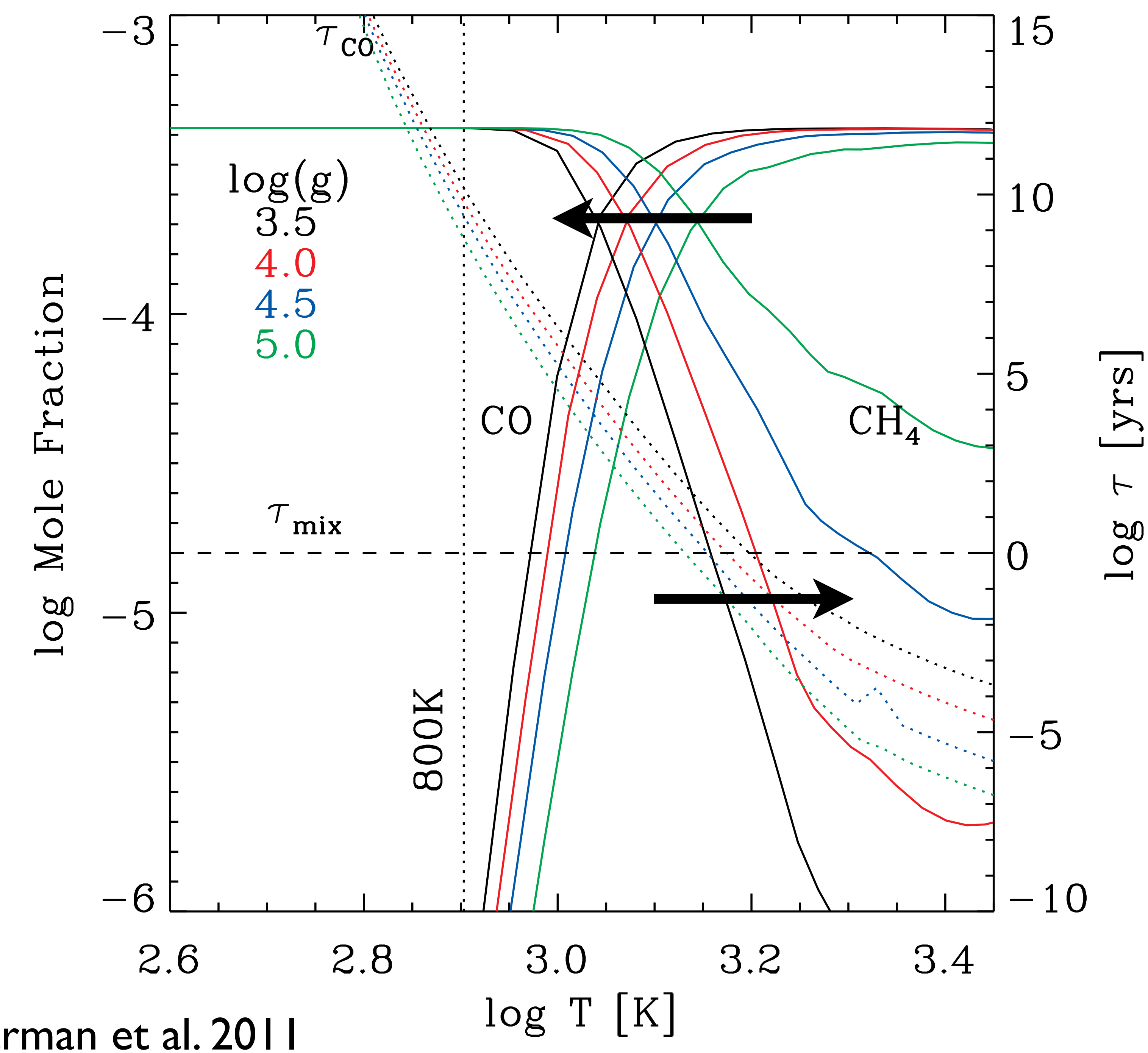



see, e.g., Hubeny & Burrows (2007)

$$t_{\rm dyn} = \frac{L^2}{K_{\rm eddy}}.$$

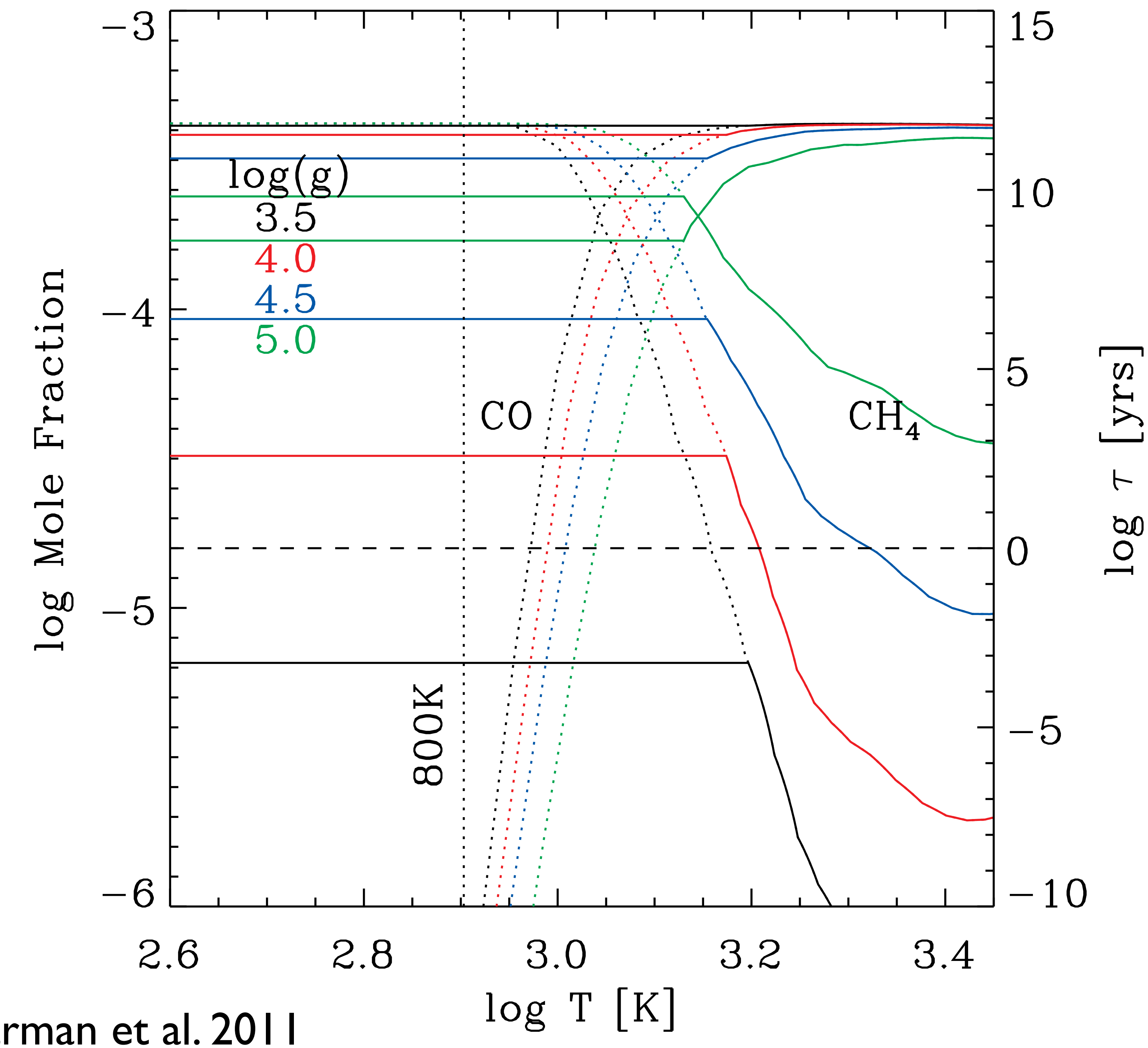
$$t_{\rm chem}({\rm CO}) = \frac{1}{2.3 \times 10^{-10} K_a \exp(-36200/T)[{\rm H_2}]^2}\ {\rm s},$$

# Departures from chemical equilibrium by vertical mixing:




Barman et al. 2011

# Departures from chemical equilibrium by vertical mixing:



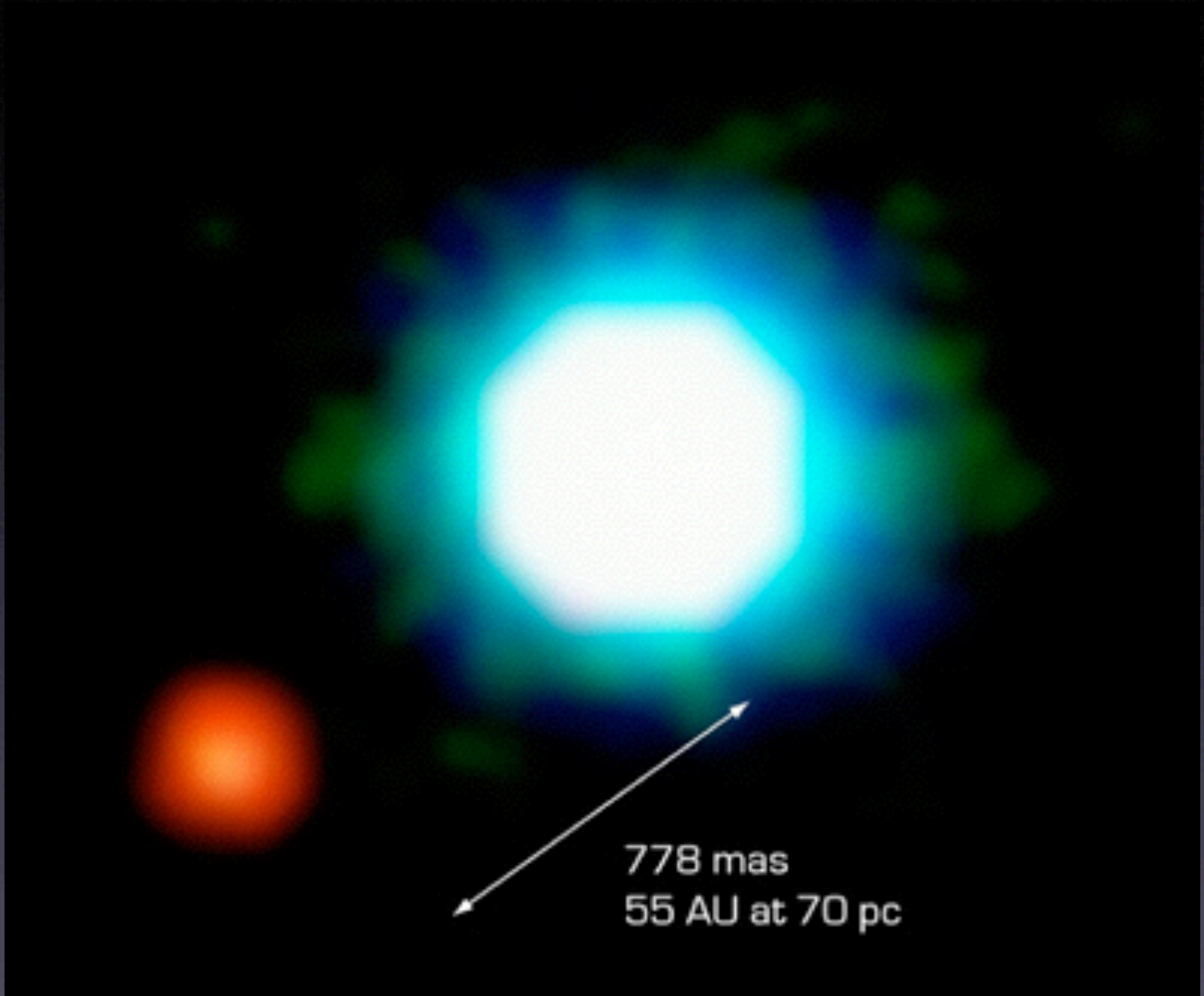

Barman et al. 2011

mixing ratios of $H_2O$, CO, and $CH_4$
are depth-independent (in this simple model)

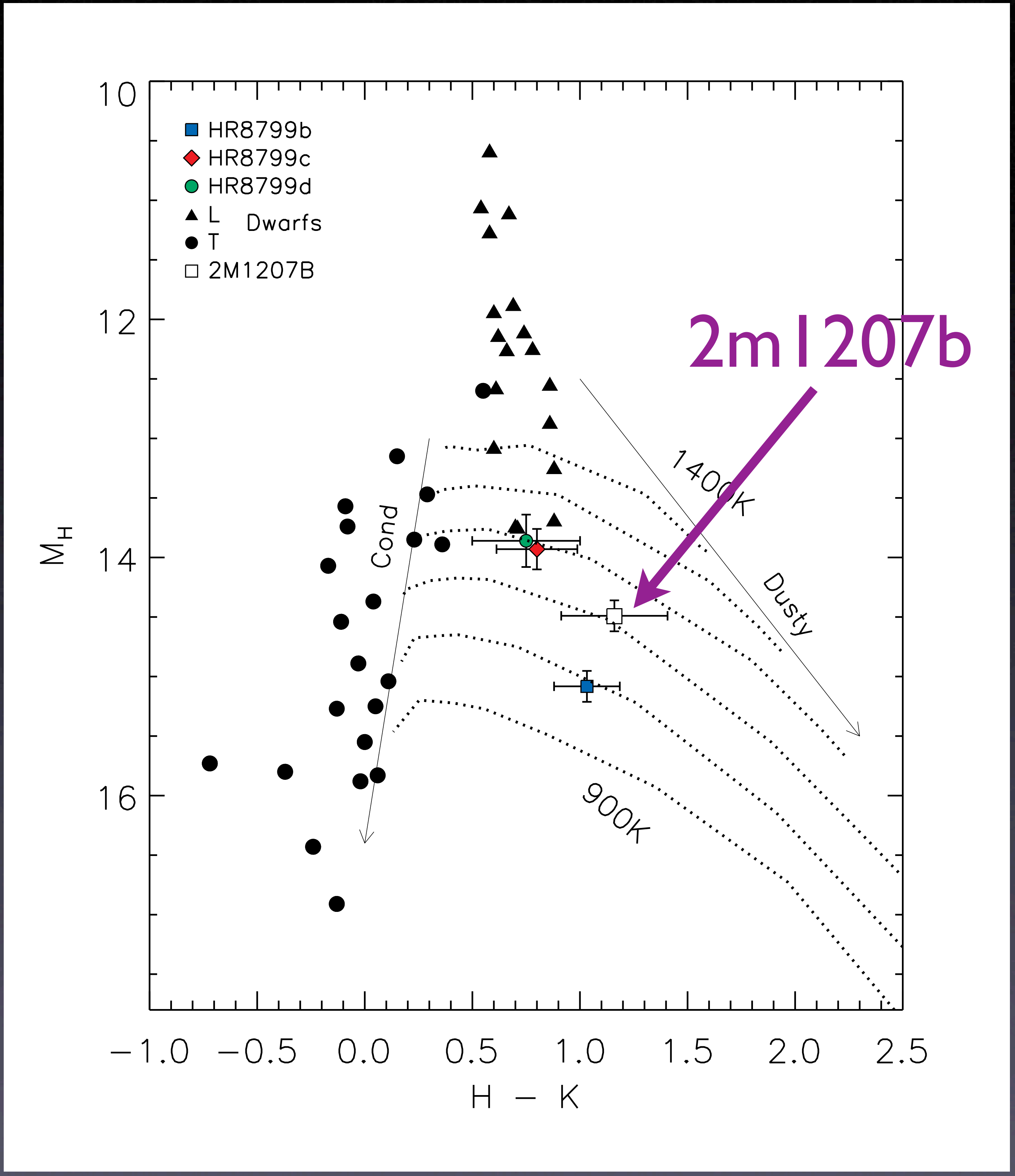
# 2m1207B

2M1207A:
~ 8 Myr Brown Dwarf
(TW Hya member)
d = 52 pc

2M1207B:
M ~ 5 to 10 Mjup
P > 1000 yrs

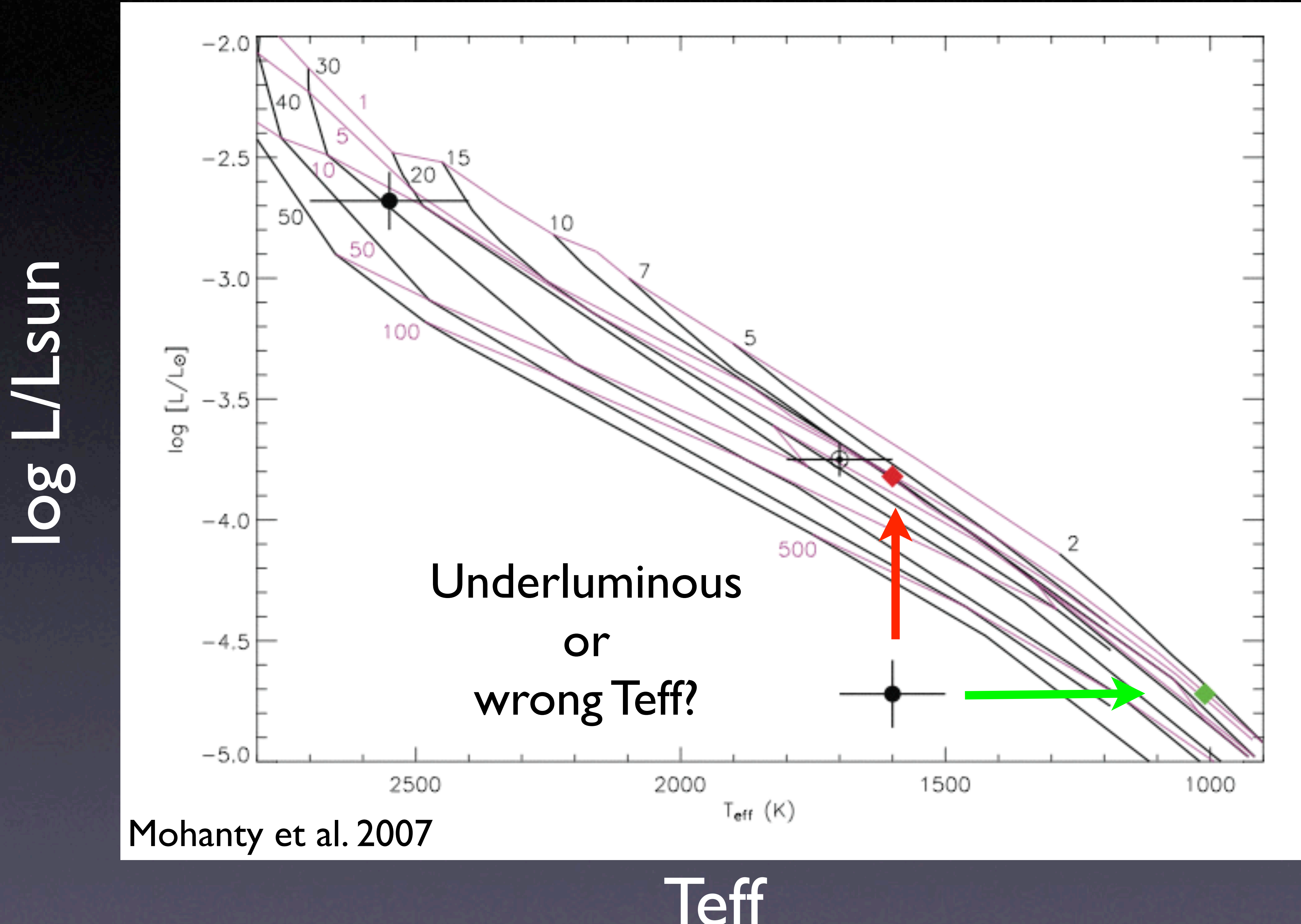



Chauvin et al. (2004)



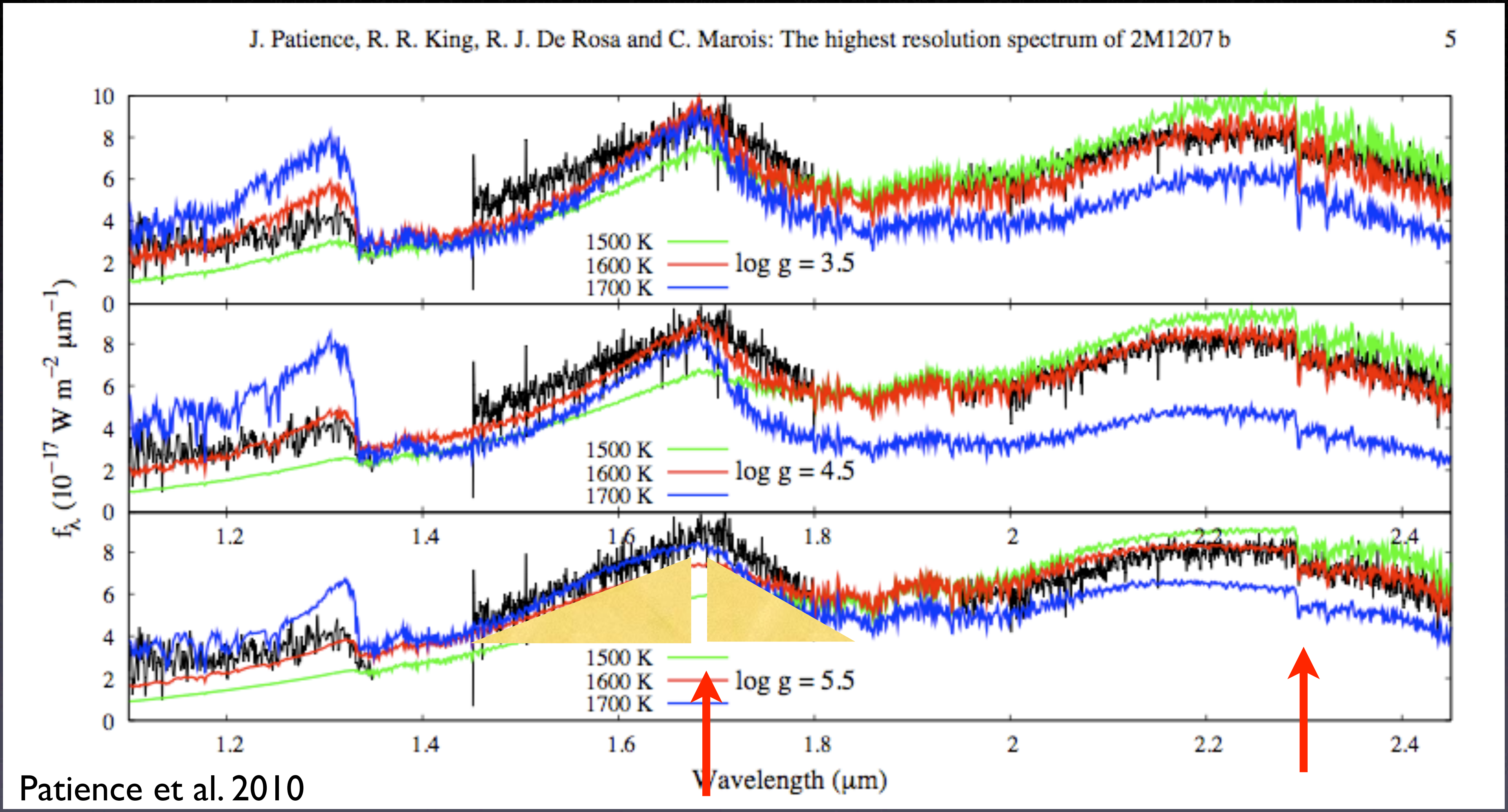
2m1207b
HR8799b
HR8799c
HR8799d
L
T
Dwarfs
2M1207B
10
12
14
16
$M_H$
−1.0 −0.5 0.0 0.5 1.0 1.5 2.0 2.5
H − K
Cond
1400K
Dusty
900K

# Expected range in Teff & L for 1 -- 500 Myr & 2 -- 50 Mjup objects




Mohanty et al. 2007

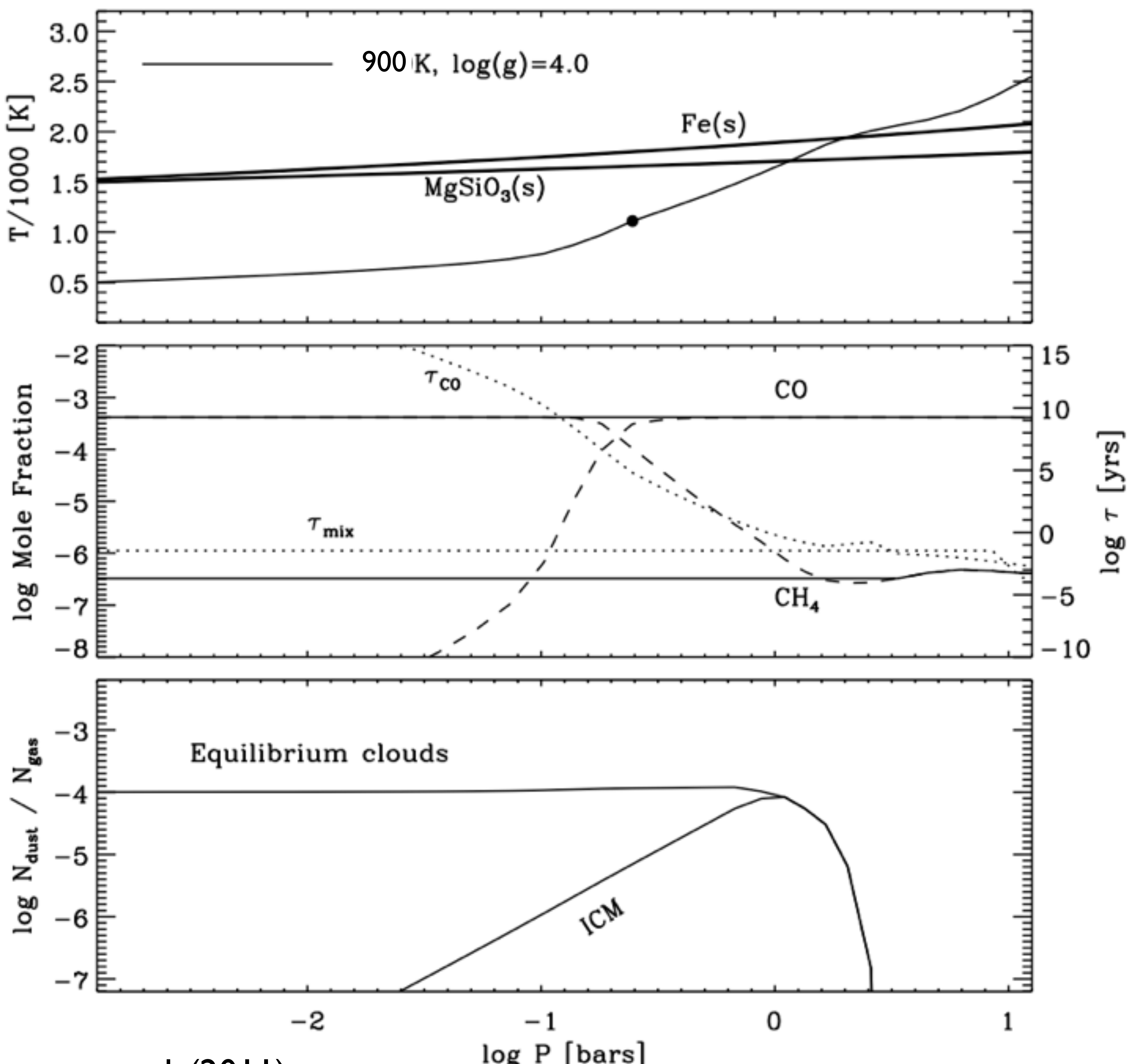
# New SINFONI spectra:




Patience et al. 2010

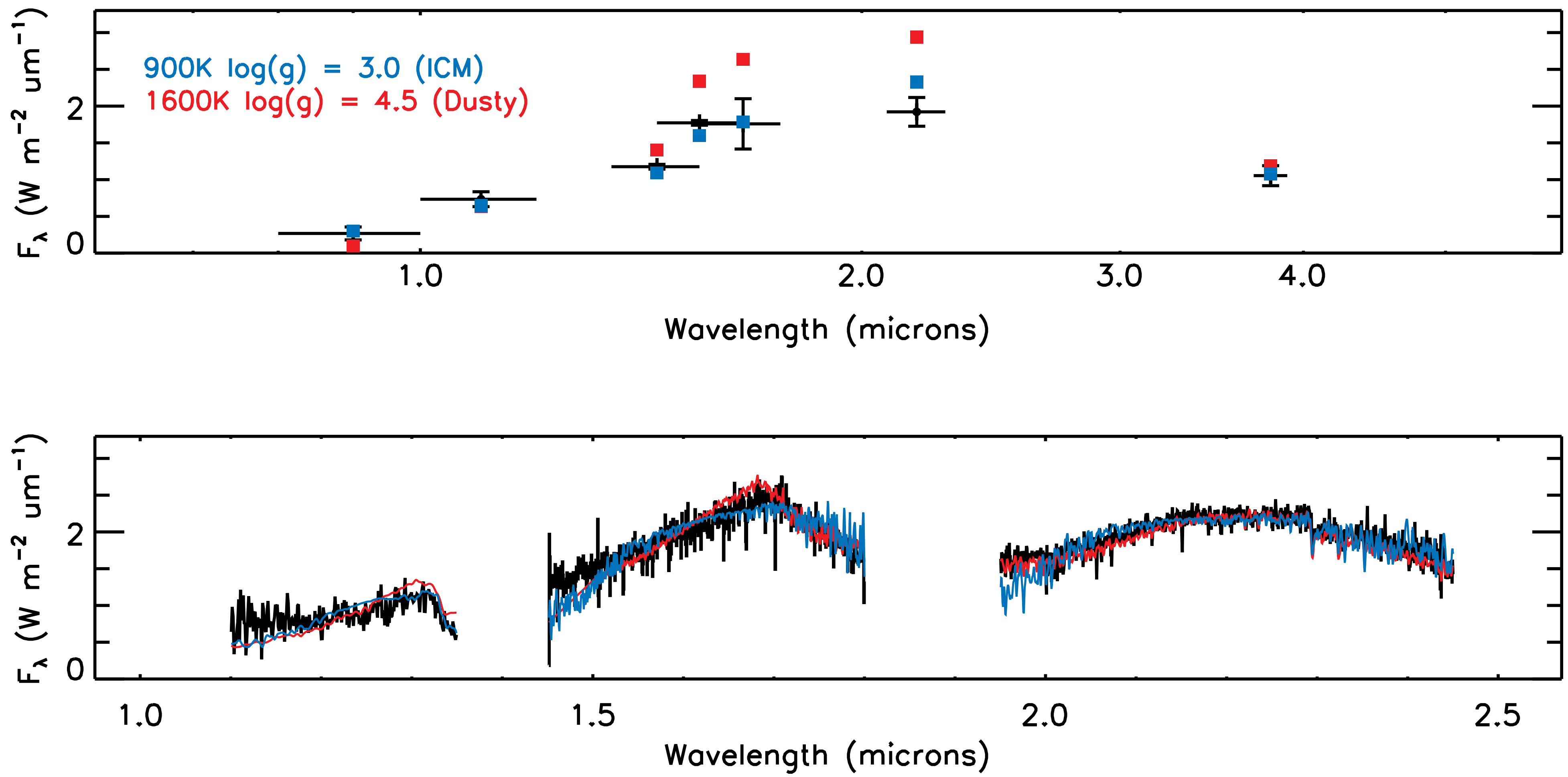
triangular shaped H-band

CO



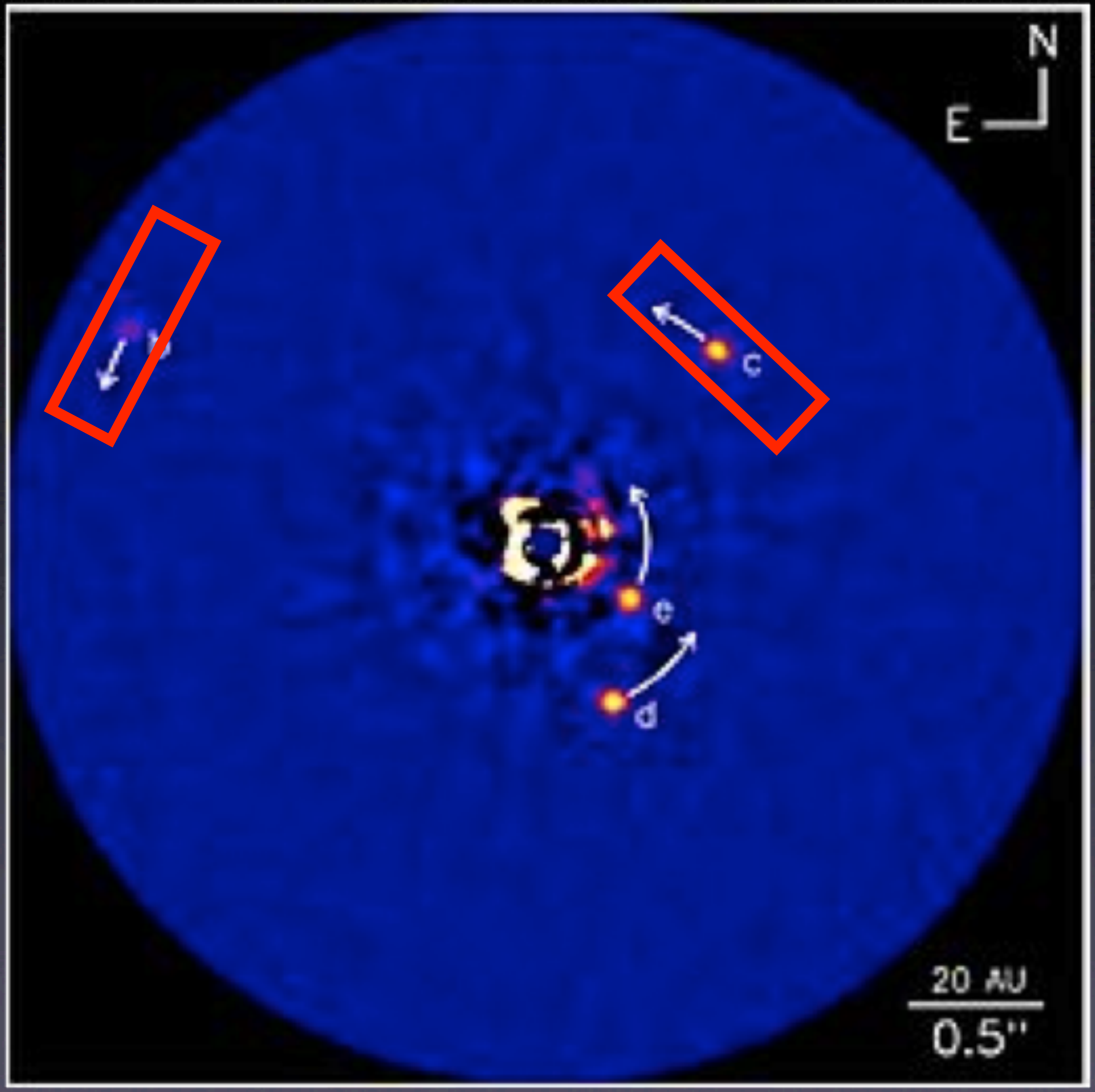

Barman et al. (2011)

# 2M1207b, 900K and Methane-poor!

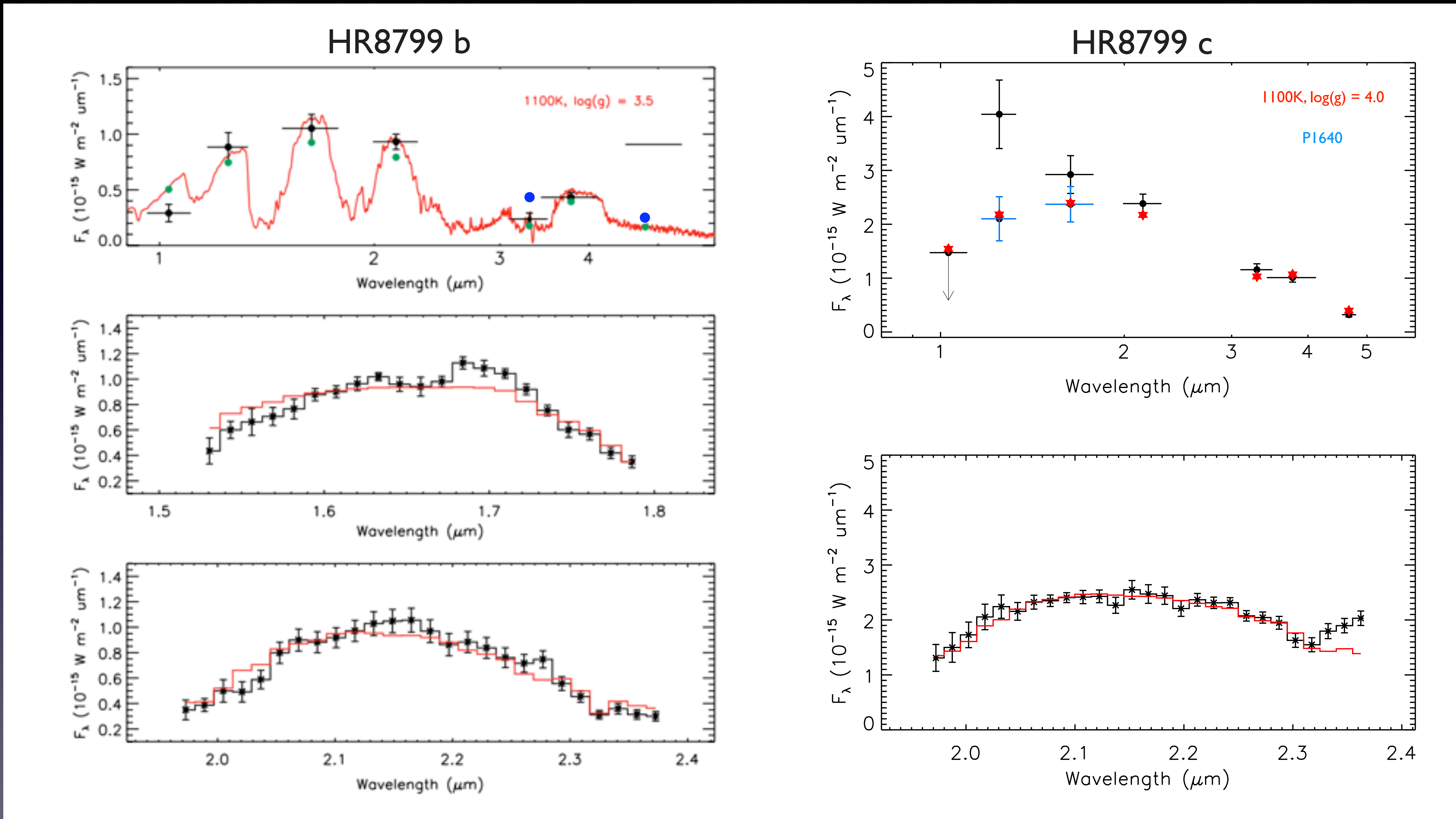



Barman et al. (2011)

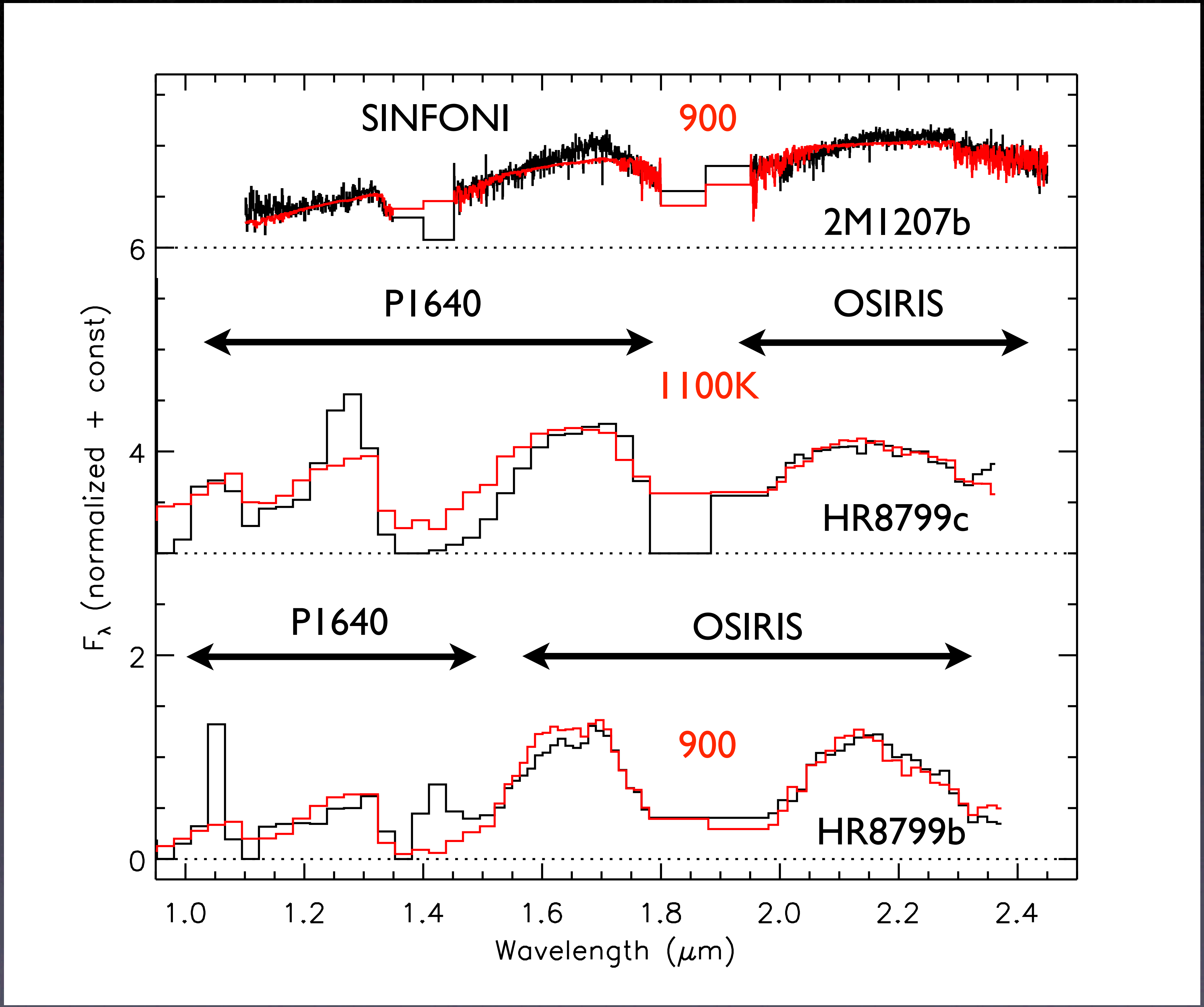
# The HR8799 Planets




heavily processed Keck/NIRC2 image

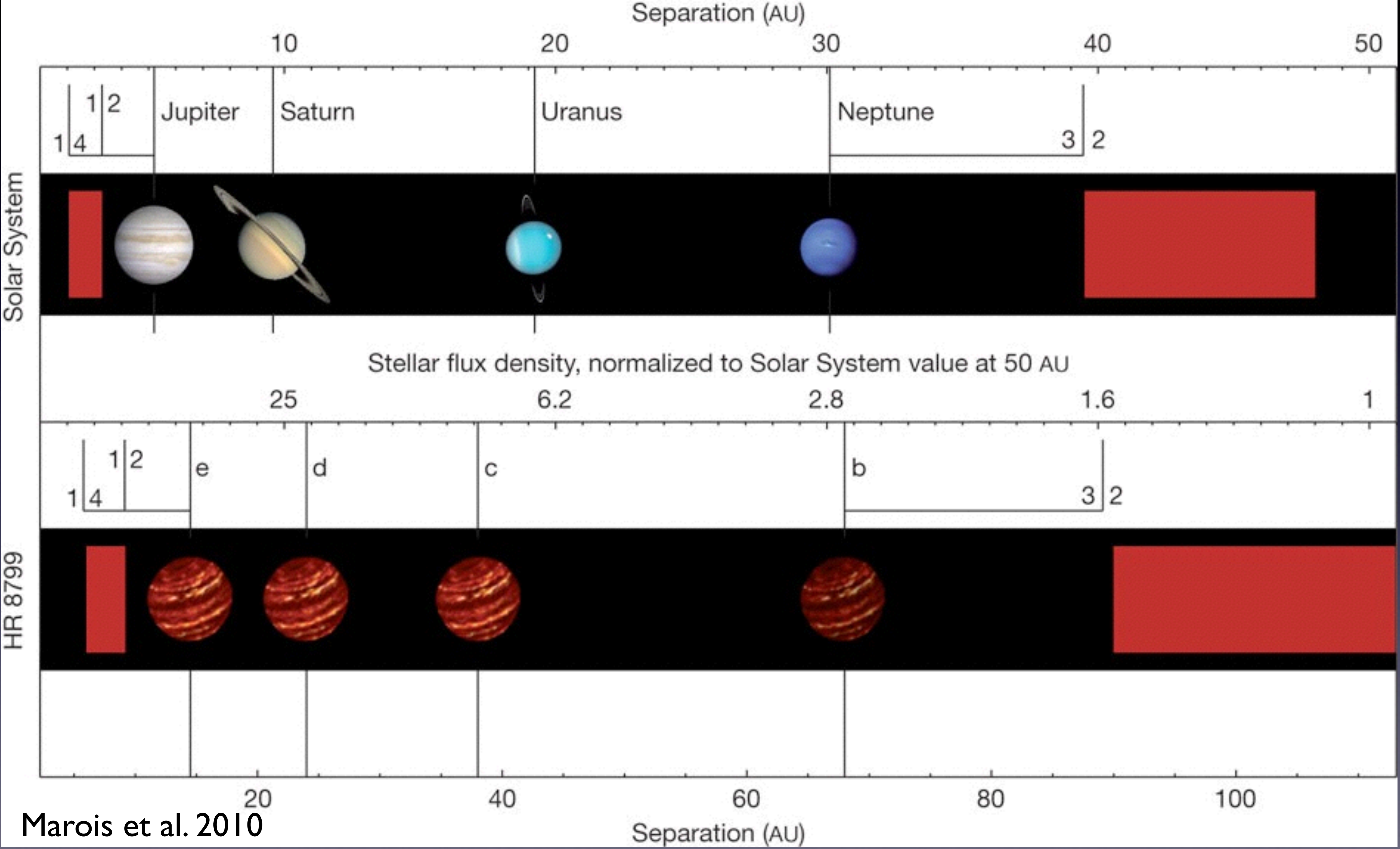



Barman et al. (2011), Konopacky et al. (2013),
Currie et al. (2012), Skemer et al. (2012), Galicher et al. (2012)



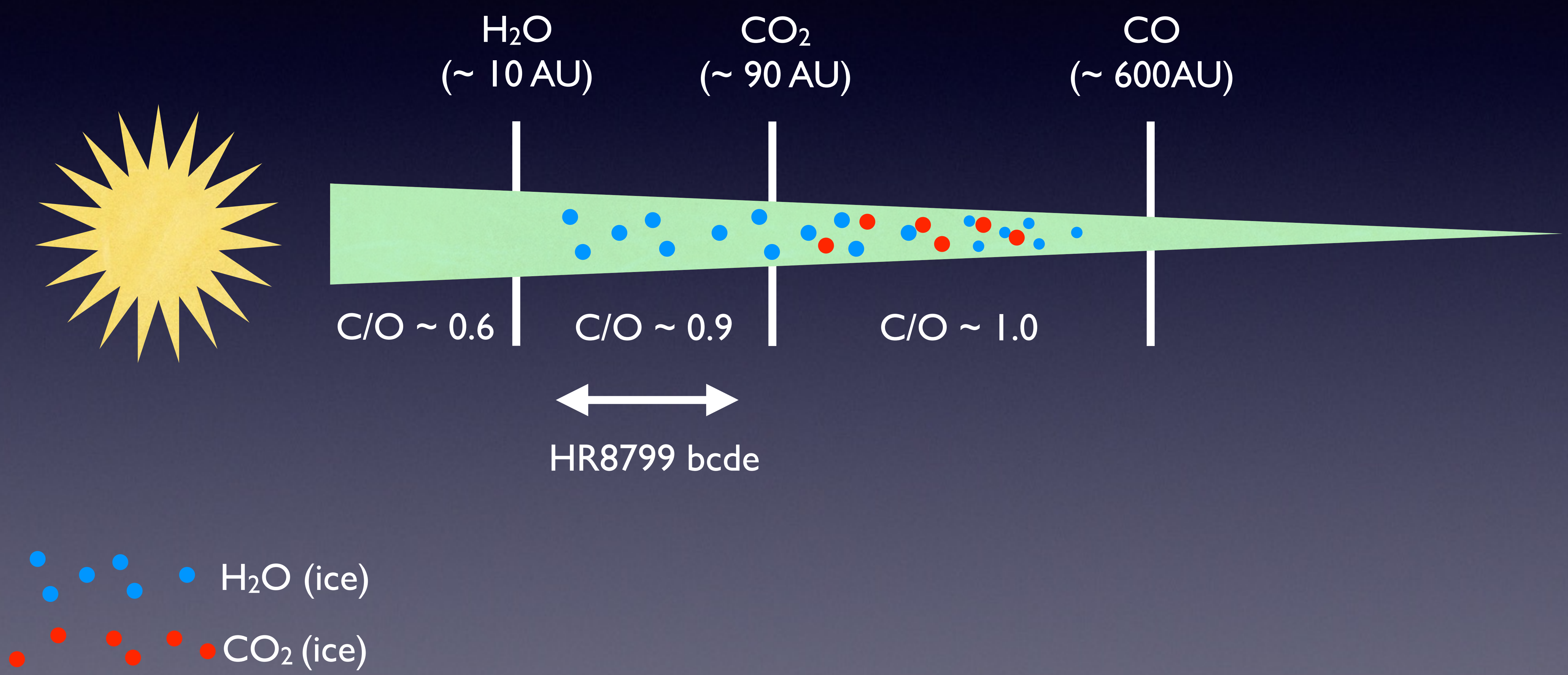

P1640: Oppenheimer et al. 2013; OSIRIS: Barman et al. 2011a, Konopacky et al. 2013; 2M1207b: Patience et al. 2011, Barman et al. 2011b

# The HR8799 Planetary System:




Marois et al. 2010

# core-accretion:

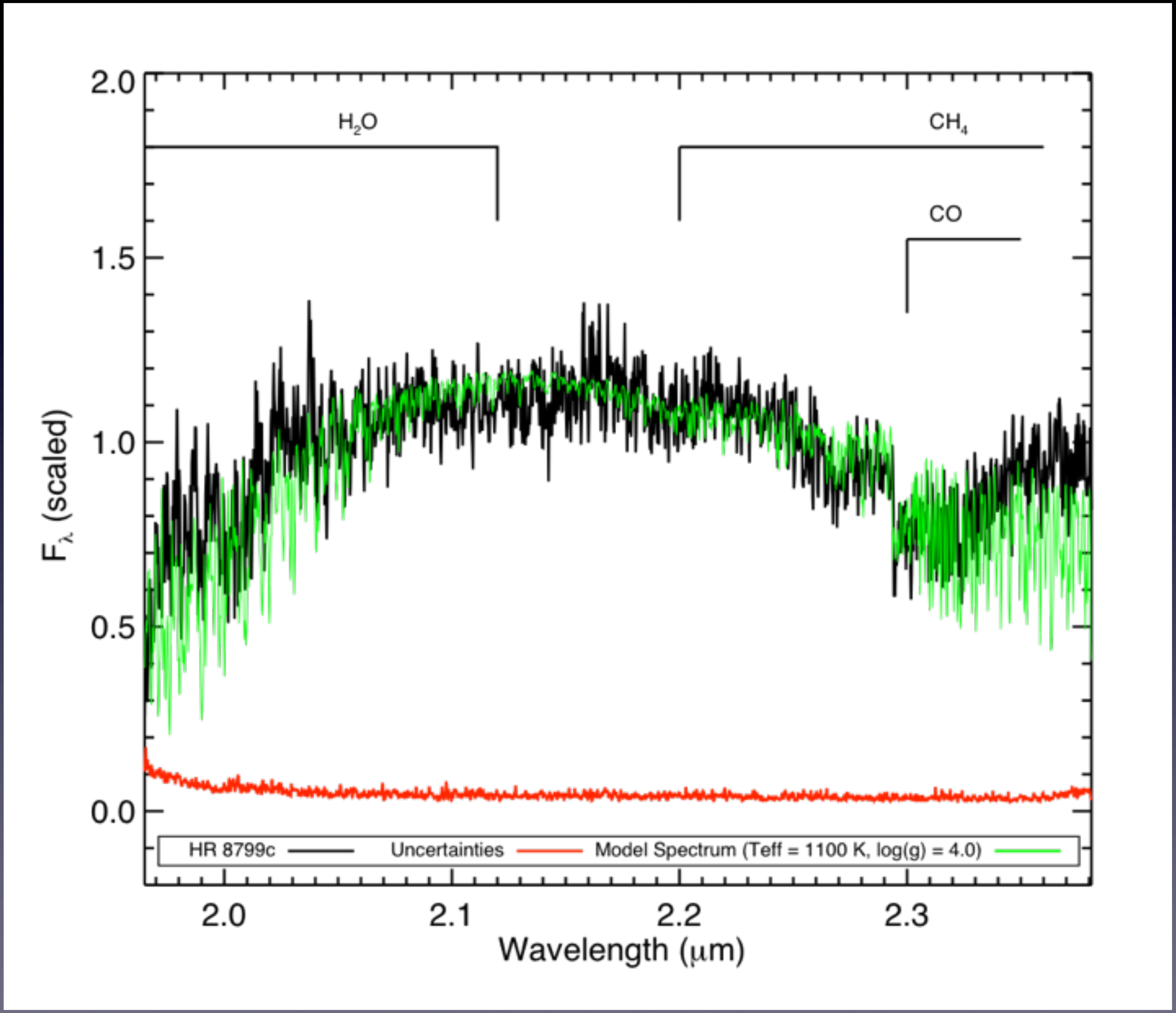



(see Oberg et al. 2011)

- A range of C/O values, including stellar, are possible in the core-accretion scenario (Oberg et al. 2011).

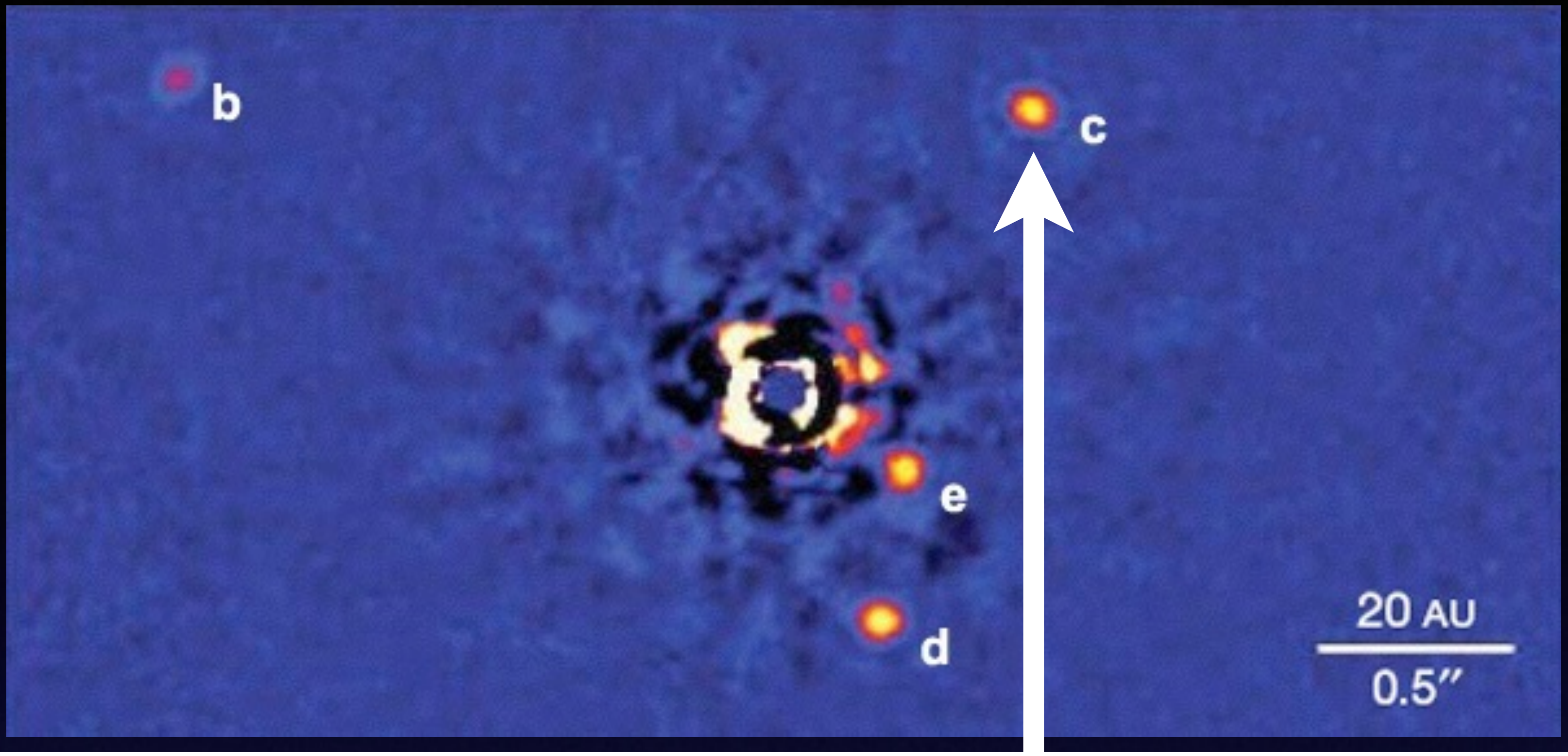
- Stellar C/O is expected if HR8799bcde formed by gravitational instability (Helled & Bodenheimer 2010).

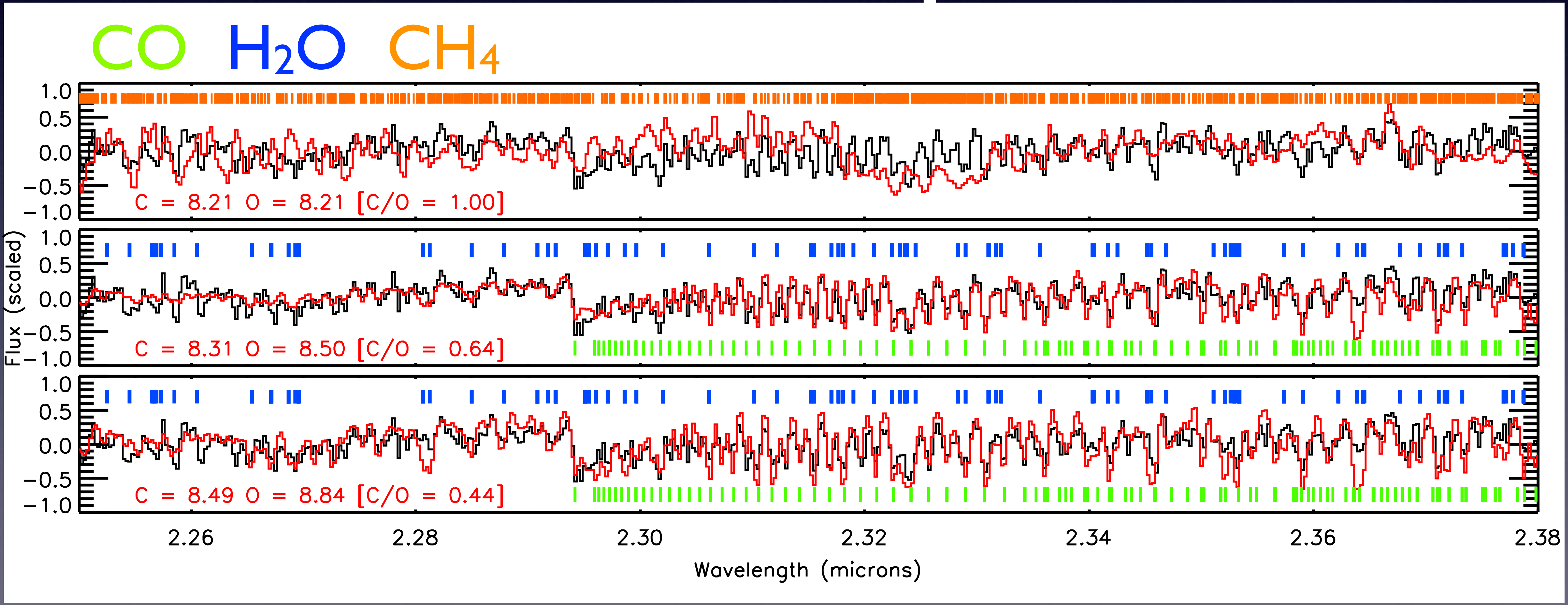
# HR8799c (full resolution, R ~ 4000)




Konopacky, Barman, Macintosh & Marois (2013)

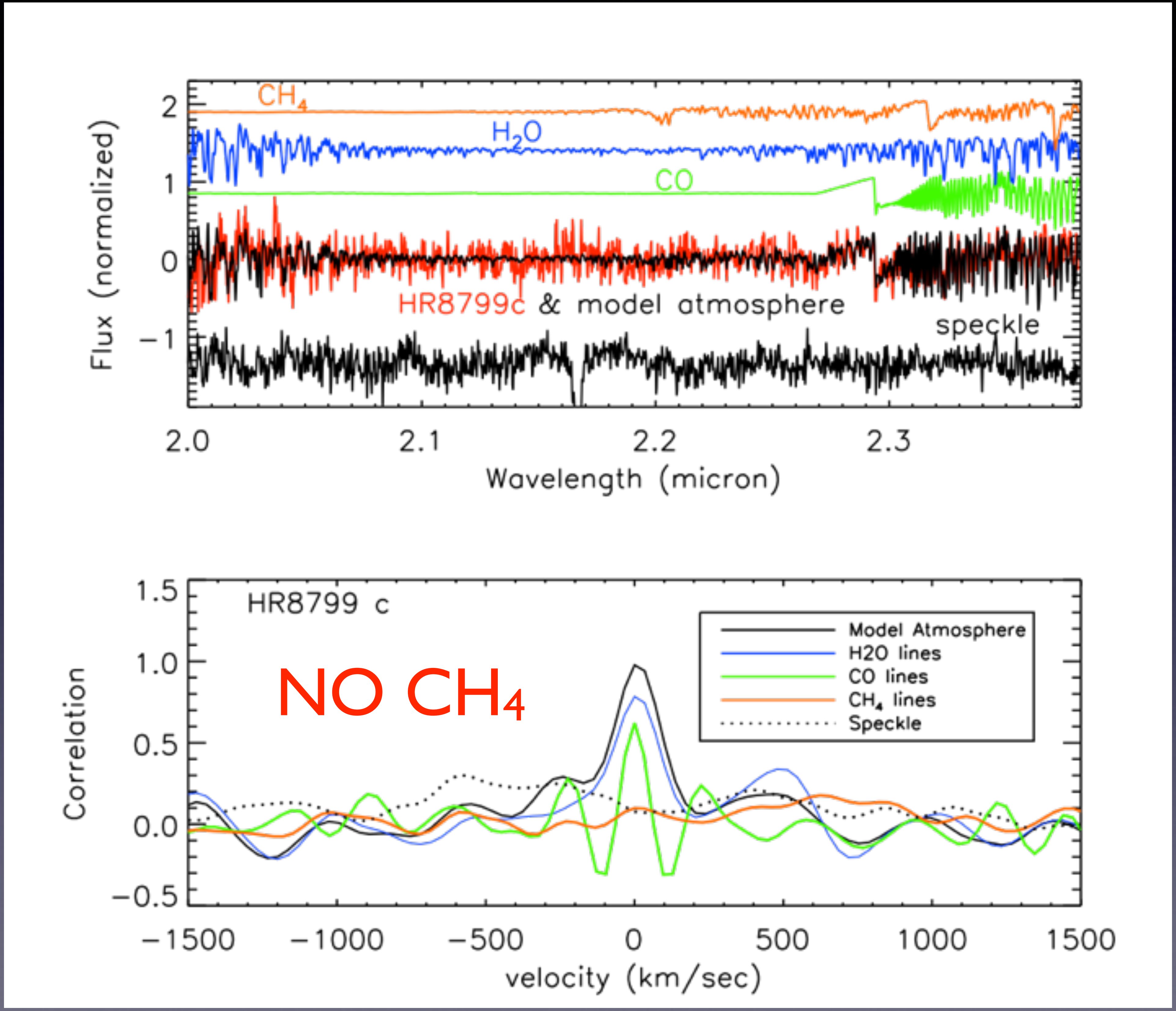
# HR8799c



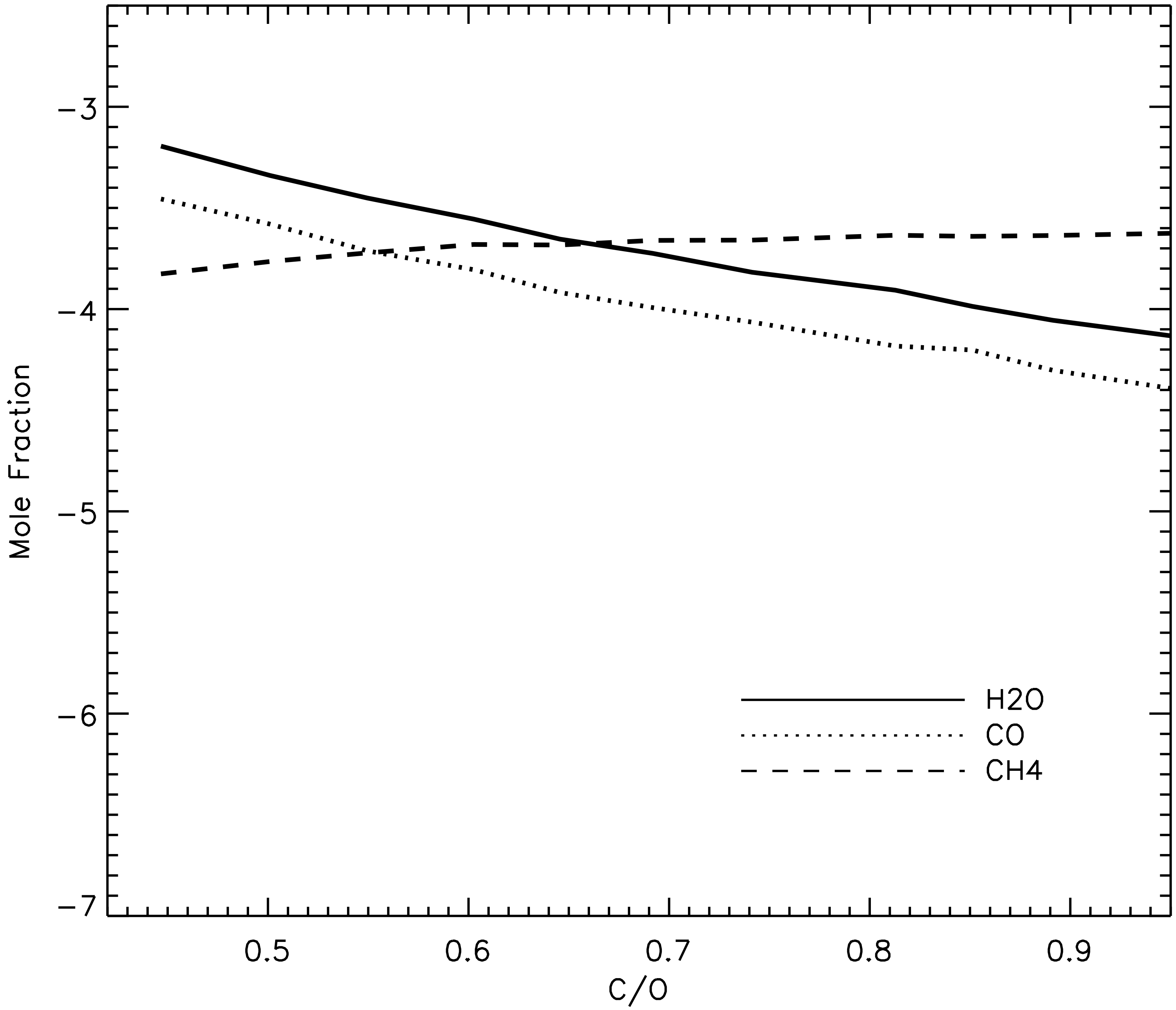

Konopacky, Barman, Macintosh & Marois (2013)

# HR8799c Cross-correlation analysis:

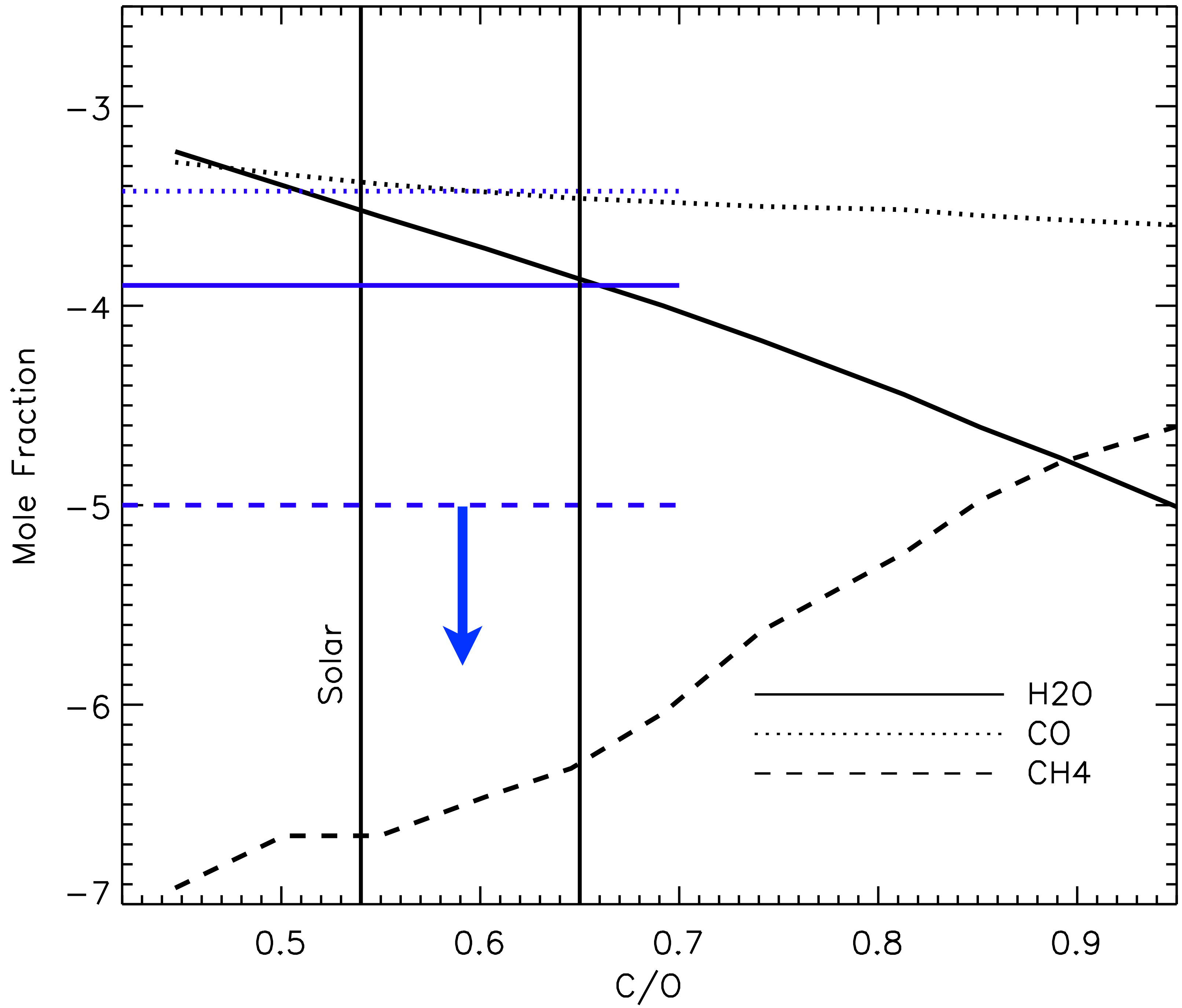



Konopacky, Barman, Macintosh & Marois (2013)

# Equilibrium Chemistry



# Non-Equilibrium Chemistry



# Young Planet H-band Sequence

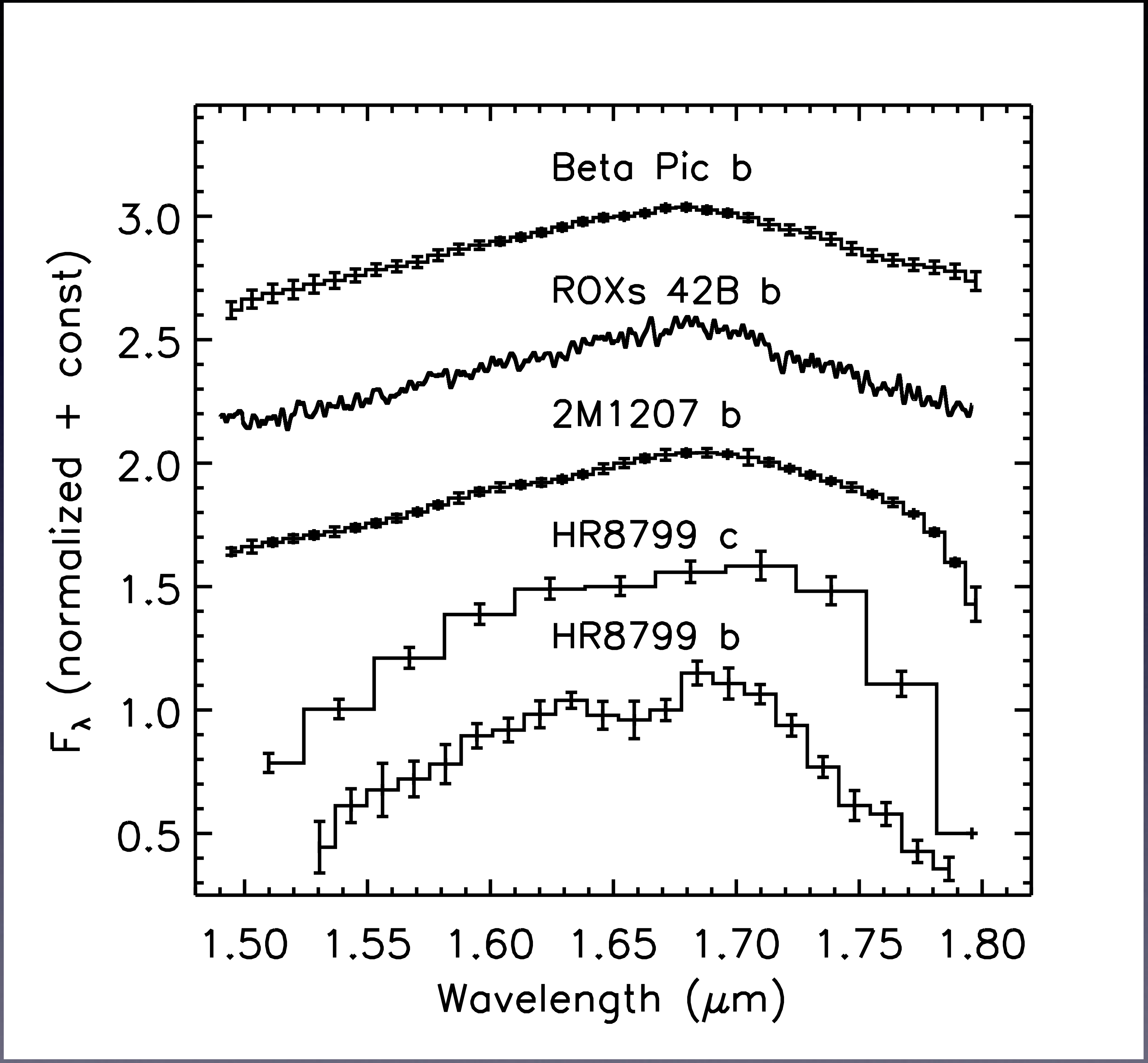
GPI
(Chilcote et al. 2014)

OSIRIS
(Bowler et al. 2014)

SINFONI
(Patience et al. 2010)

P1640
(Oppenheimer et al. 2013)

OSIRIS
(Barman et al. 2011)



# Giant Planet ⟷ Brown Dwarf

- mass: ~1 to < 80 x Mjupiter
- radius: ~ 1 to < 5 Rjupiter
- ages: ~ millions to billions of years old
- gravity: ~ 2 orders of magnitude
- effective temperature: ~ 100K to 2500K
- clouds: broad range of grains and ices
- non-equilibrium chemistry ($CO/CH_4$, $N_2/NH_3$, $CO_2$ ... )
- dynamics and “weather”
- BUT: different formation .... (composition & early evolution)

## What can we learn from direct imaging?

- Determine the frequency of planets at large orbital separations.
- Calibrate giant planet evolution models and establish the efficiency of various planet formation mechanisms.
- Map out the spectral evolution of giant planets.
- Provide new insight into the cloudy-to-clear atmosphere transition.