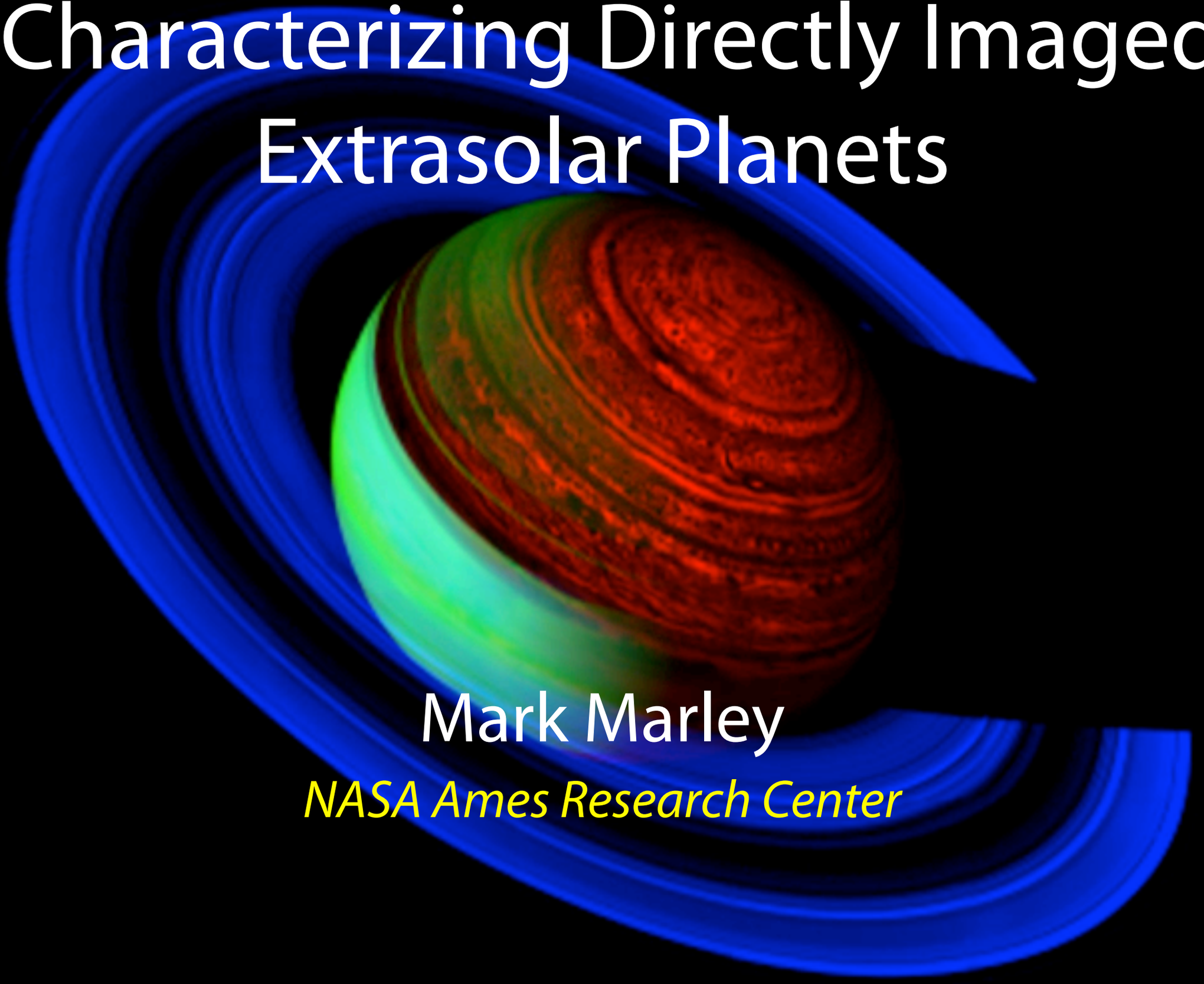
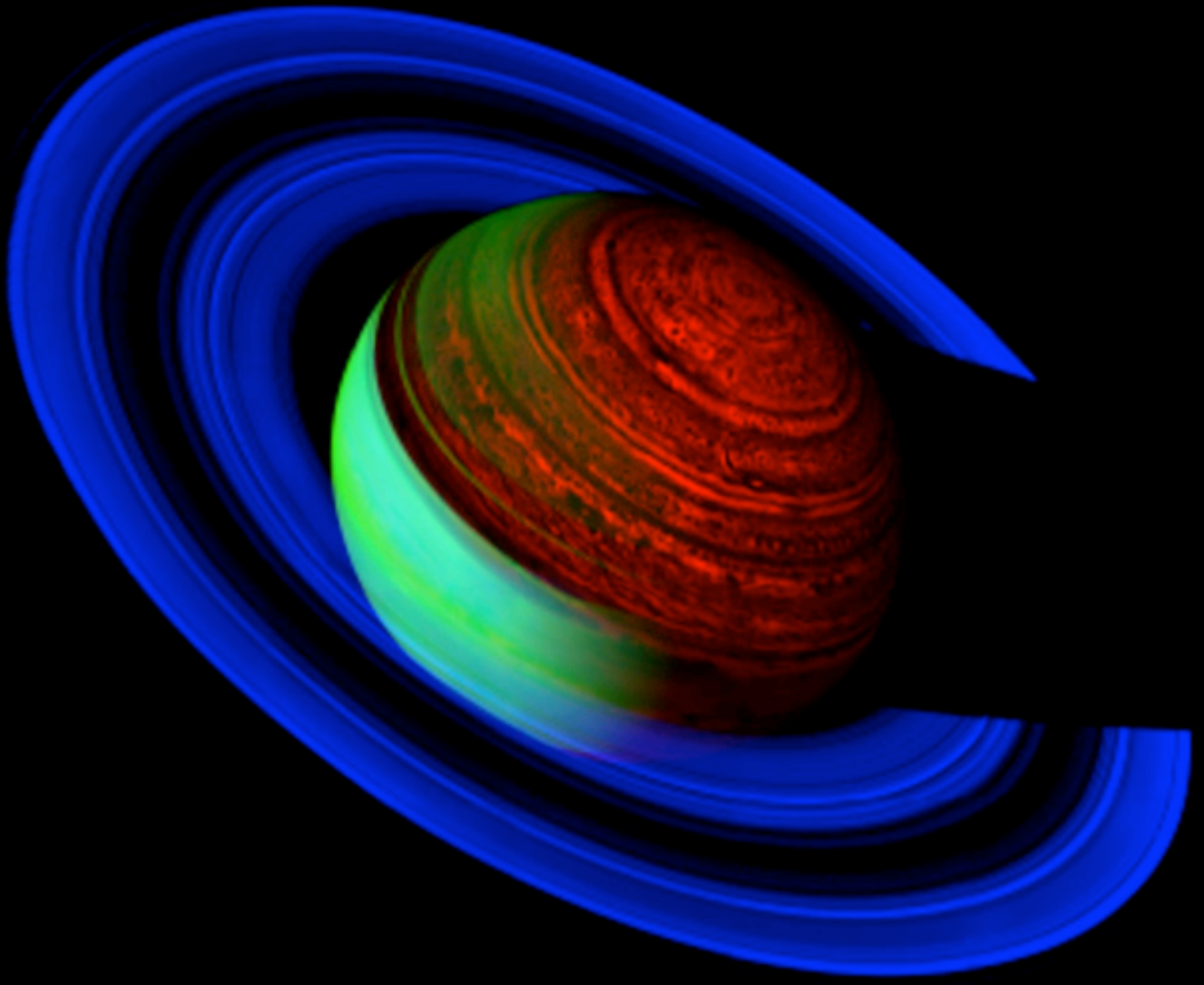
Characterizing Directly Imaged Extrasolar Planets



Mark Marley

NASA Ames Research Center

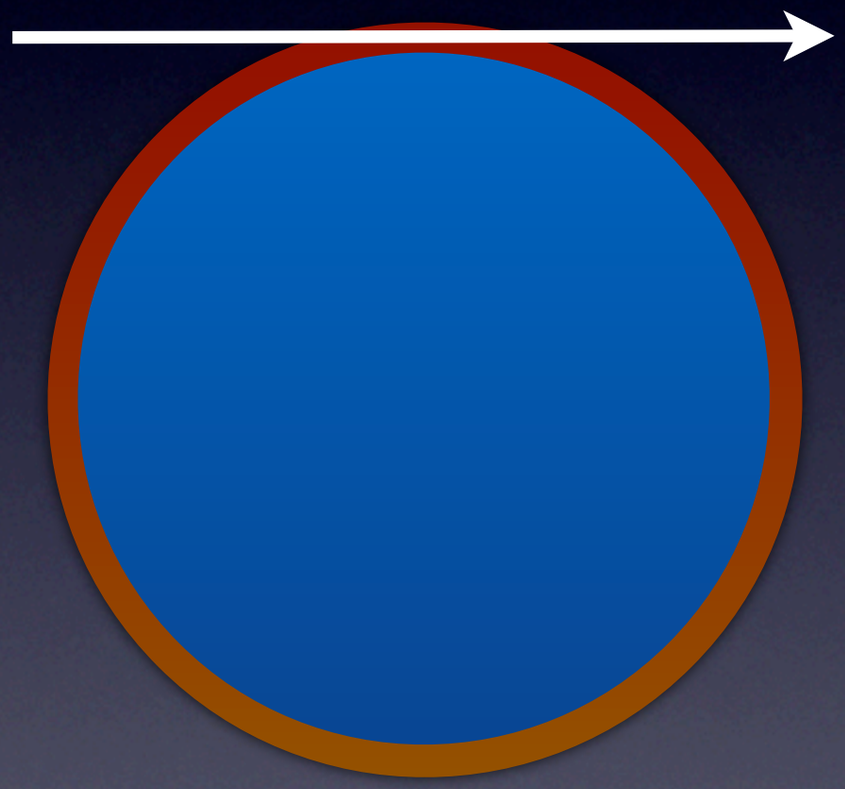


Charge from Scott: *What do we know about the atmospheres of exoplanets and what additional information do we need in order to address the things that we currently do not understand?*

My opinion (giant planets):

- The hot transiting planets are a special case of objects which provide more insight into specialized problems of photochemistry, escape, and winds than to the more general problem of exoplanet atmosphere composition.
- Going forward, the characterization of directly imaged gas and ice giants—*particularly determining composition*—has great promise to provide more "actionable" information on planetary architectures and formation processes.

Transits provide information primarily on stratospheric processes, highly influenced by photochemical processes

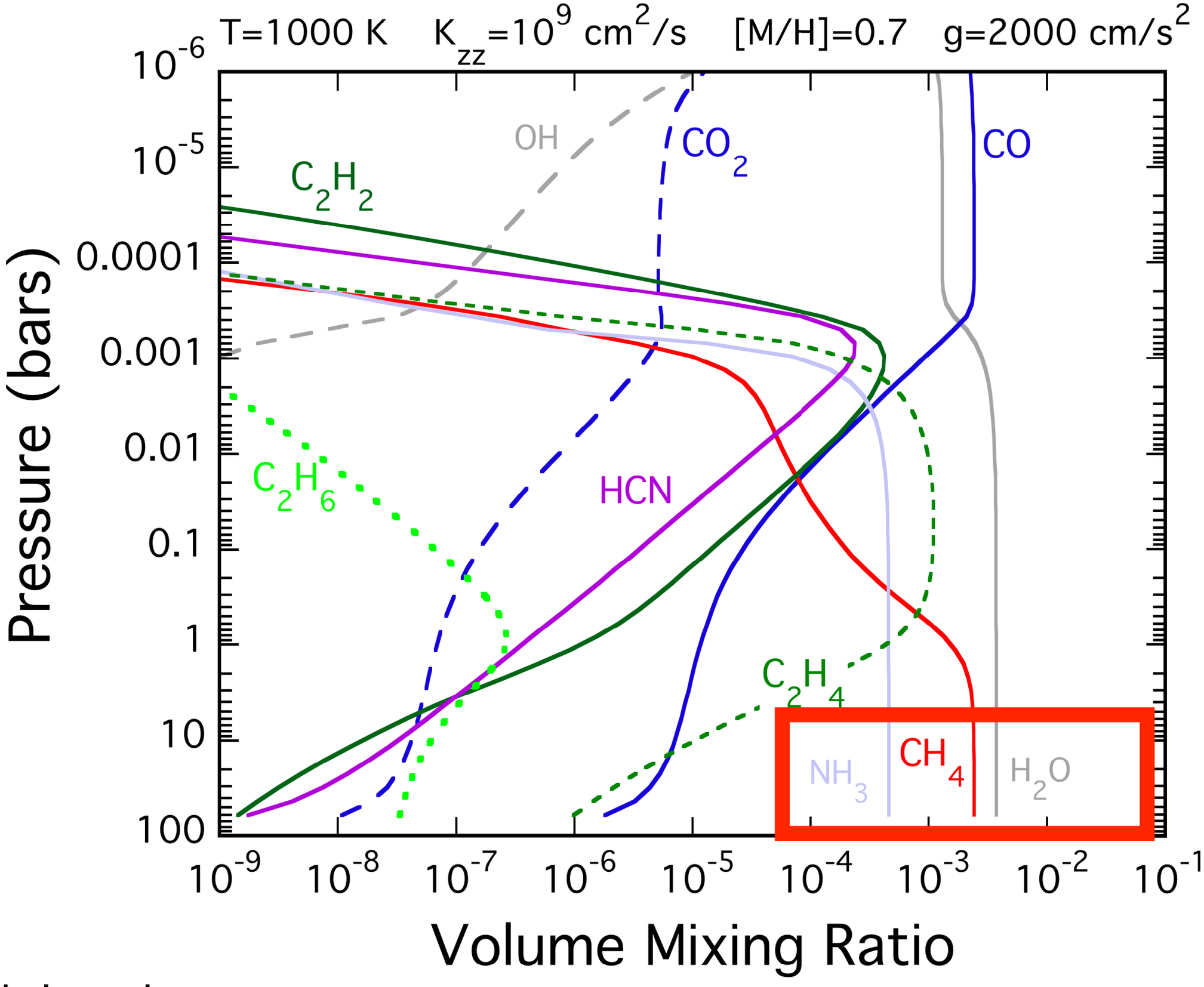


Slant optical depth for hazes can be 10 to 100x larger than normal optical depth (Fortney 2005)

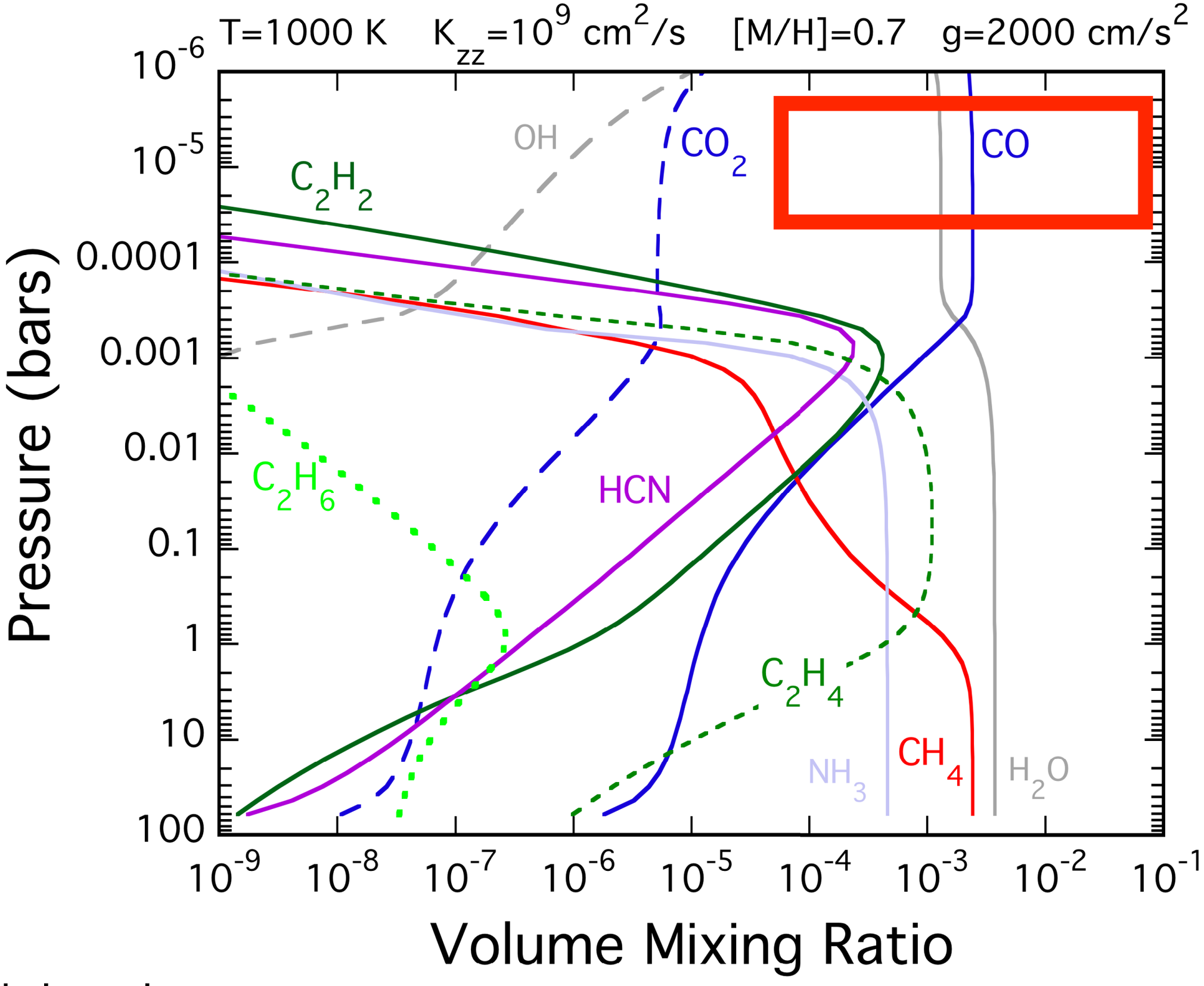
Hot Jupiters are Extreme Case

Jupiter at 0.05 AU

- 10,000x higher UV flux
- H, C, O, N, S, P chemistry
- Many complex chemical pathways


T=1000 K
K_zz=10^9 cm^2/s
[M/H]=0.7
g=2000 cm/s^2
Pressure (bars)
10^-6
10^-5
0.0001
0.001
0.01
0.1
1
10
100
OH
CO_2
CO
C_2H_2
C_2H_6
HCN
C_2H_4
NH_3
CH_4
H_2O
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Volume Mixing Ratio

Zahnle et al.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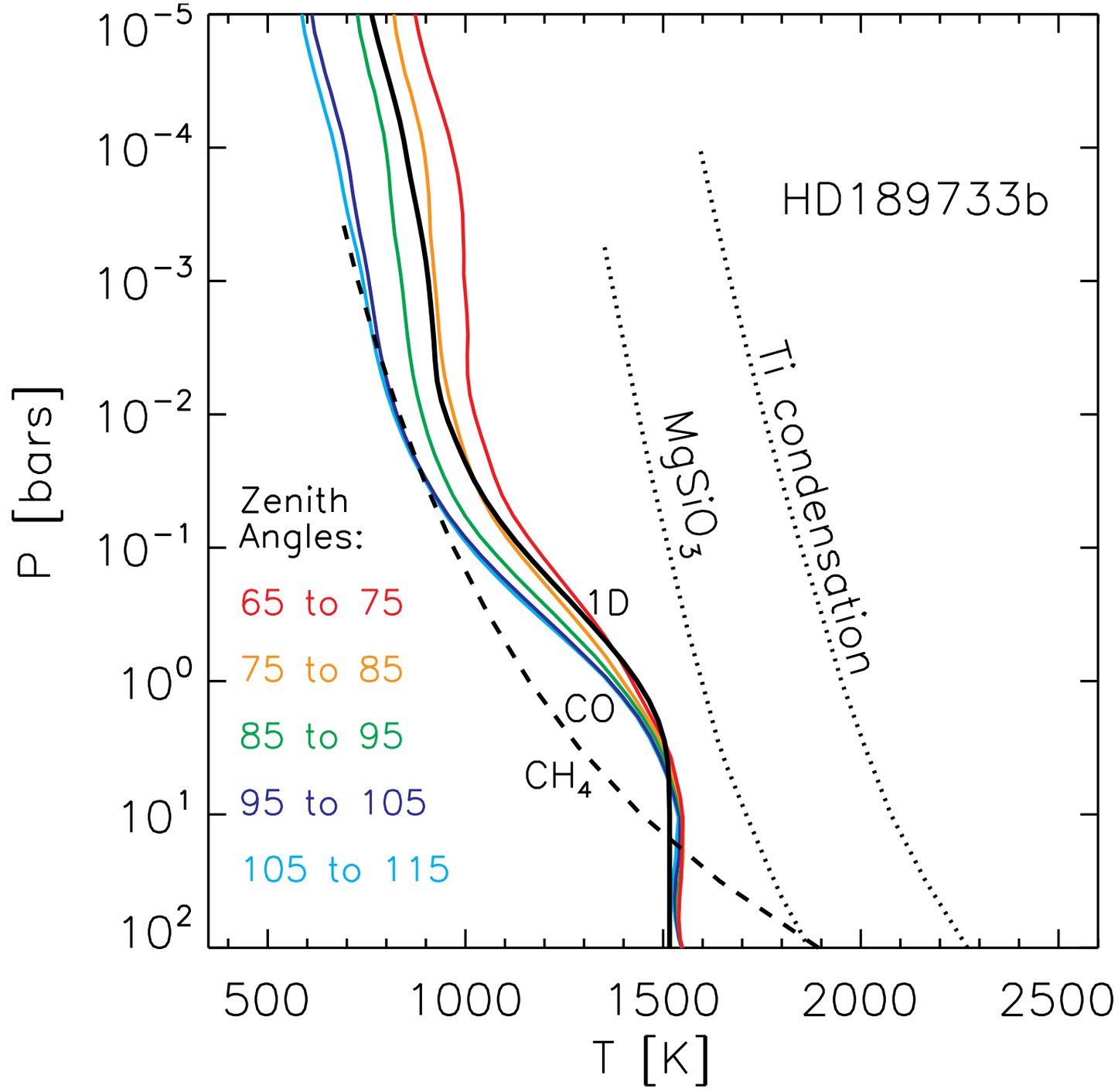
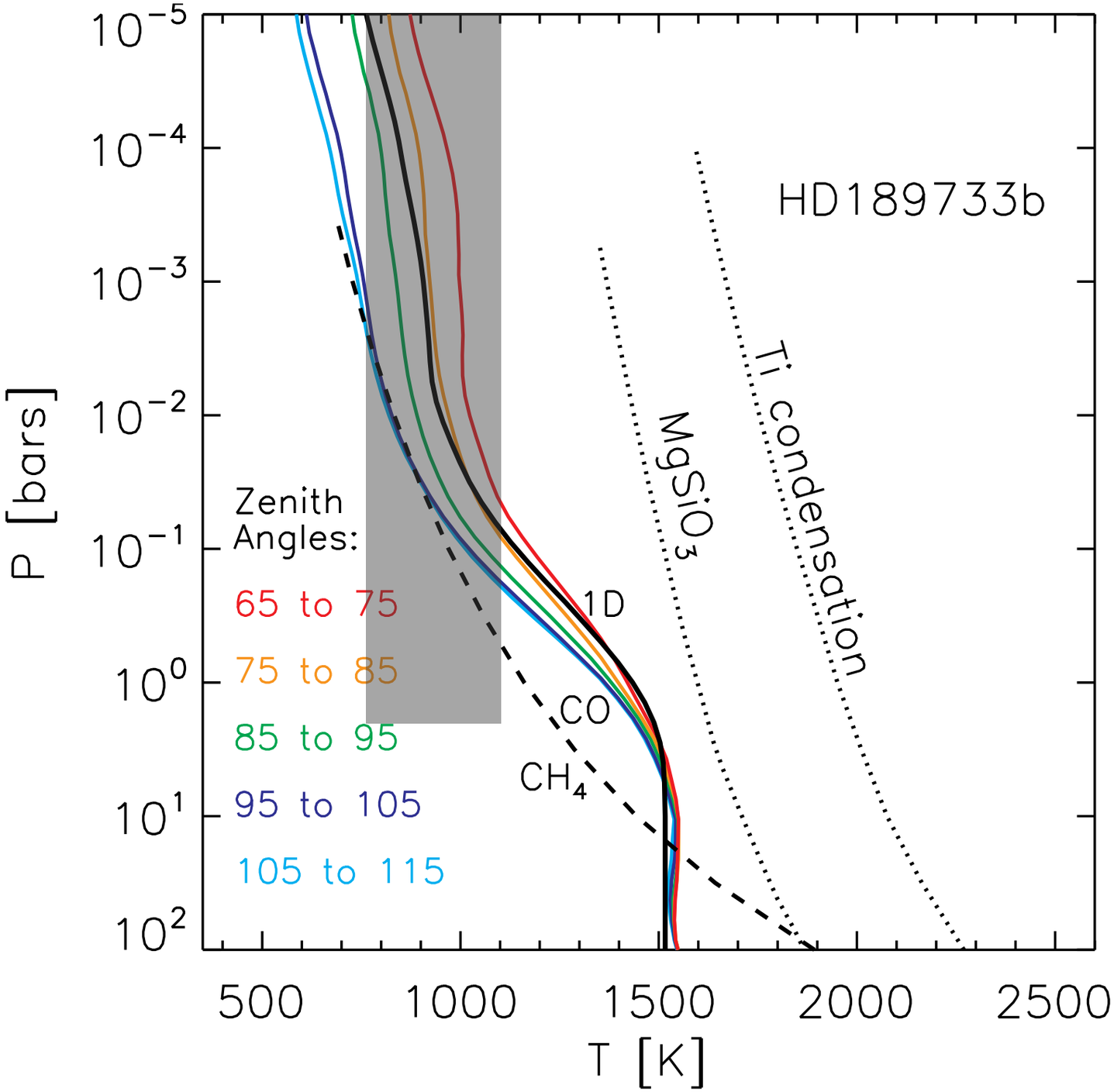
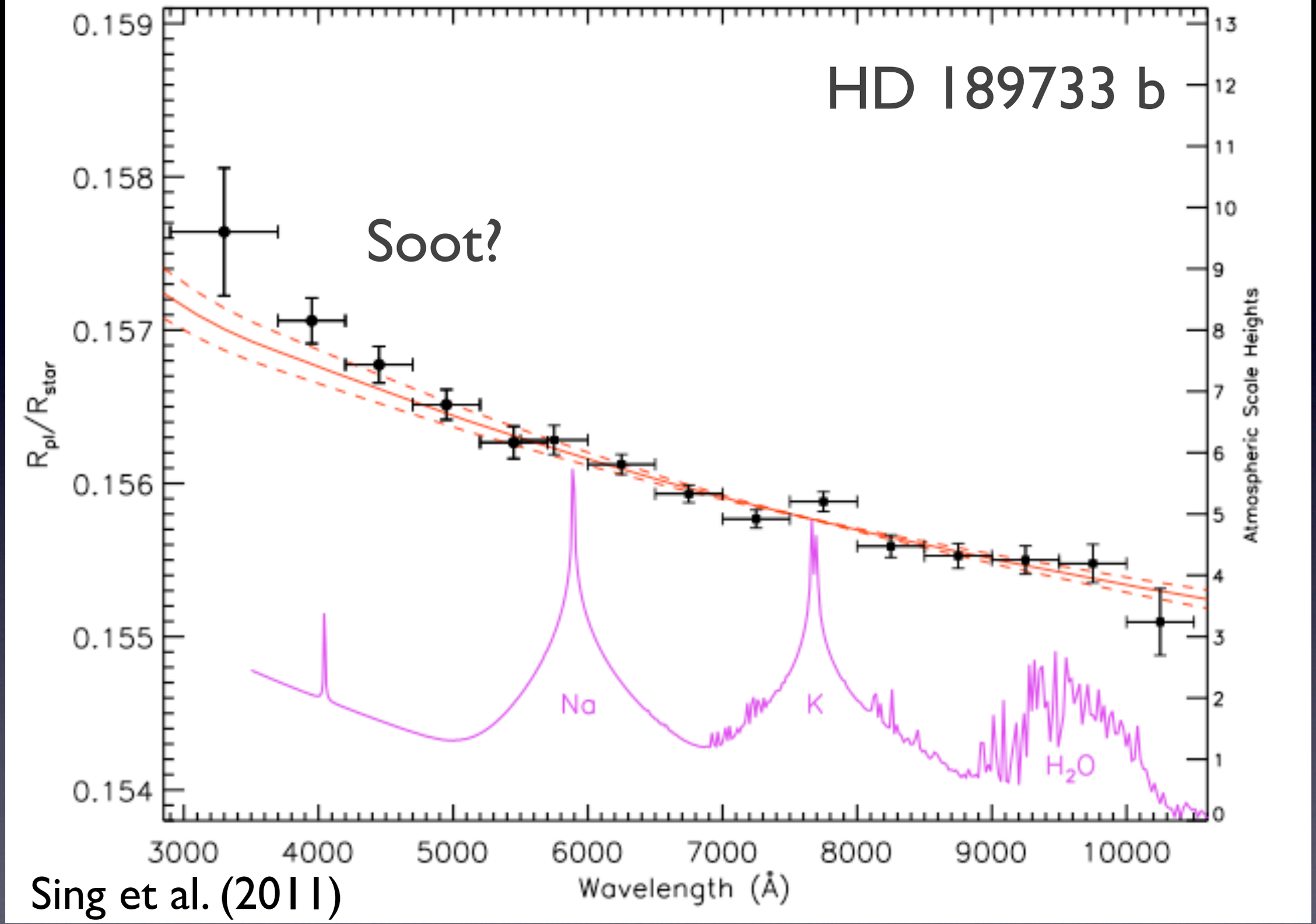
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Volume Mixing Ratio

Zahnle et al.

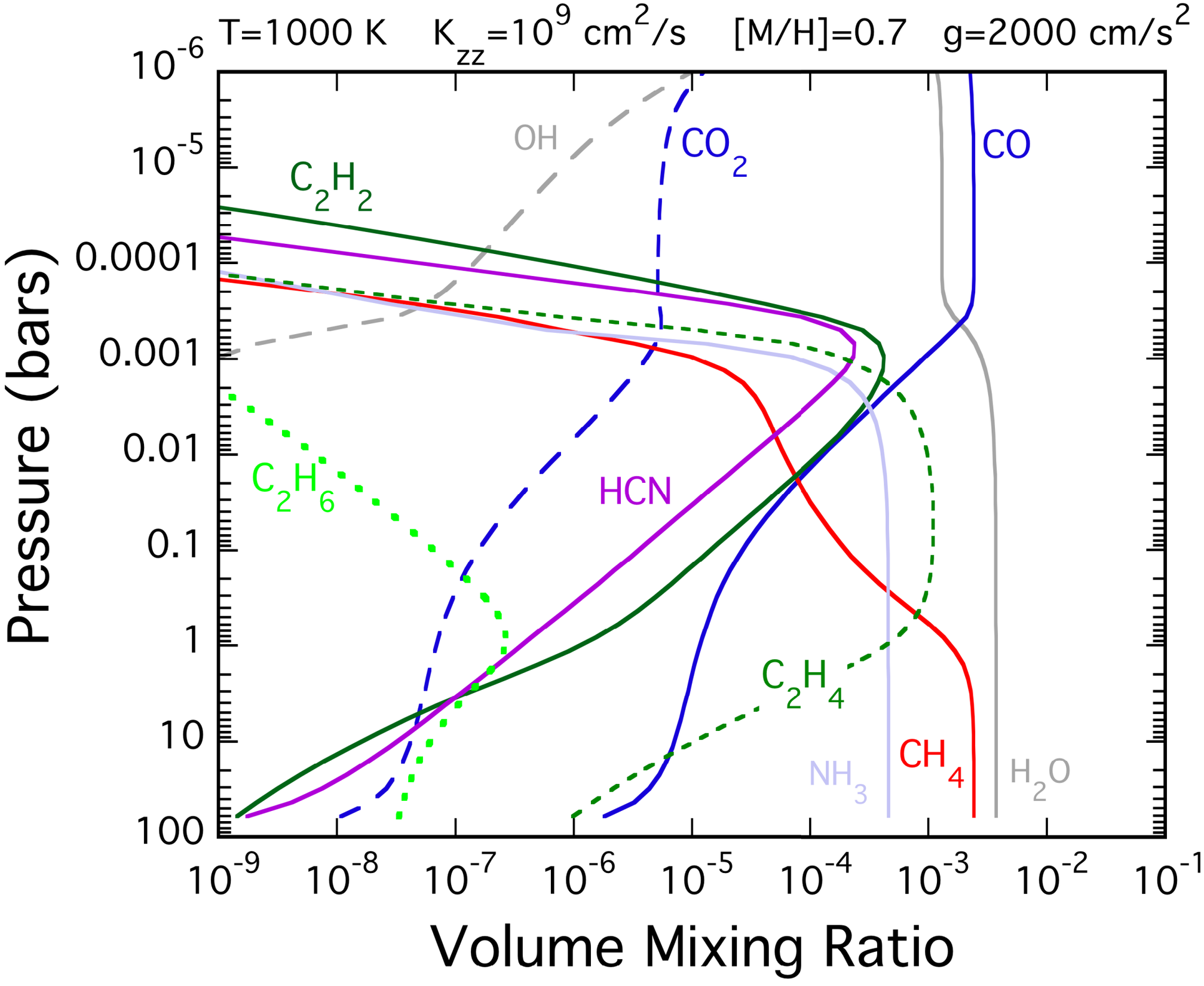

HD189733b
P [bars]
T [K]
Zenith Angles:
65 to 75
75 to 85
85 to 95
95 to 105
105 to 115
1D
CO
CH4
MgSiO3
Ti condensation
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
500
1000
1500
2000
2500

Soot Precursors





Sing et al. (2011)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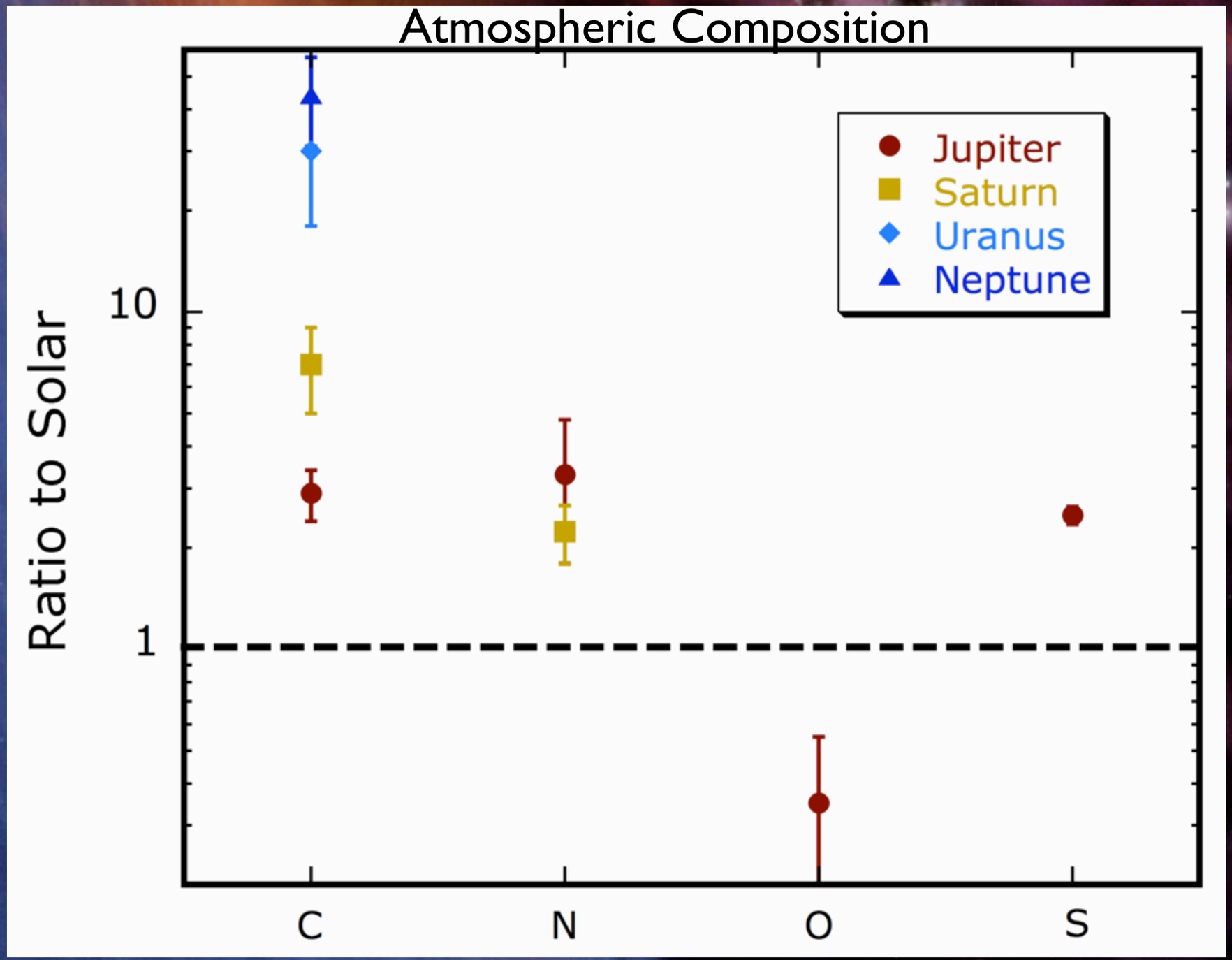
NH_3
H_2O
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Volume Mixing Ratio

This is an amazing and rich scientific field made possible by observations of unprecedented elegance and creativity. But...

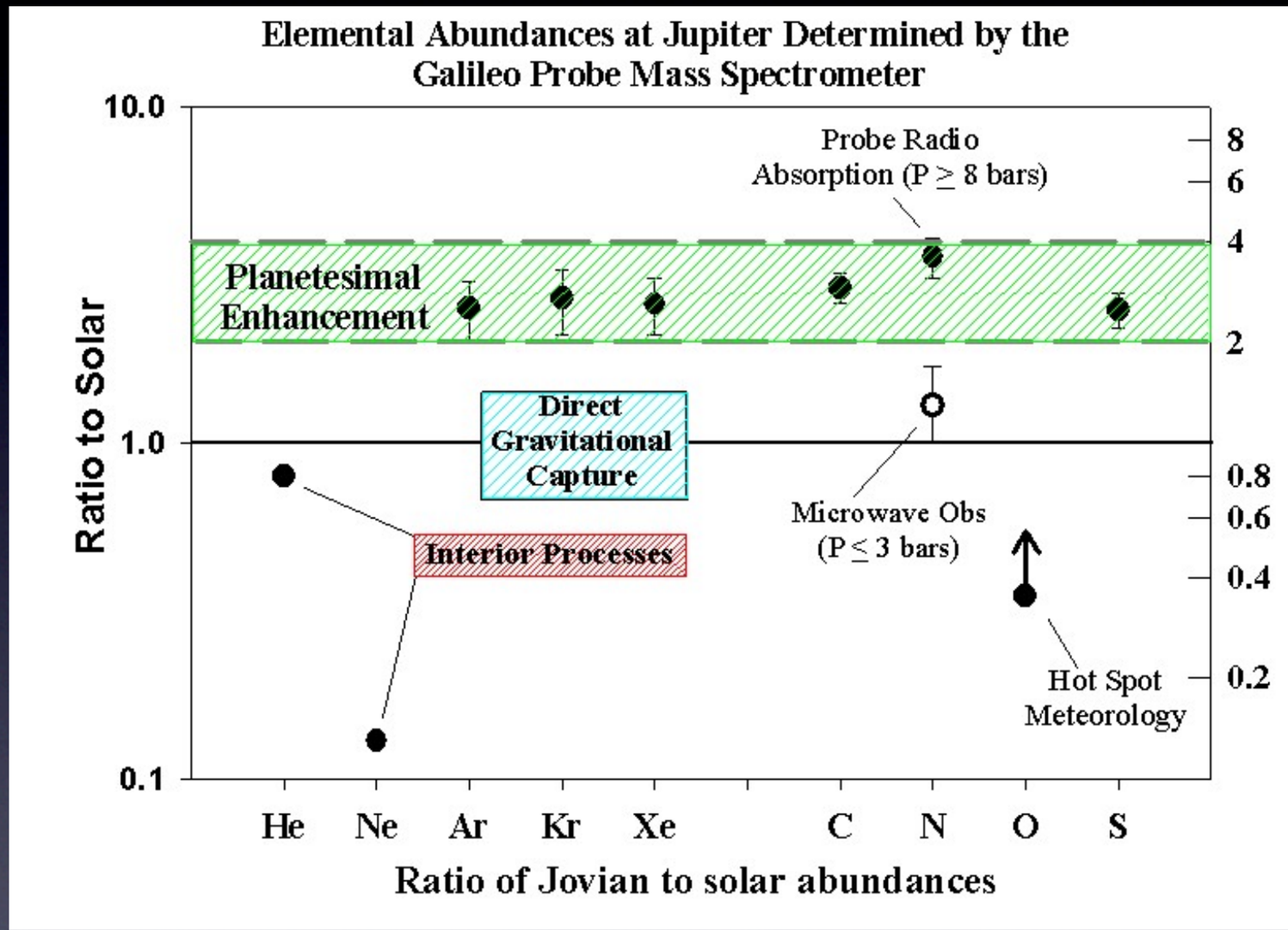
Bulk atmospheric composition measured over the full disk is a more useful constraint on interior and formation processes



Bulk atmospheric composition measured over the full disk is a more useful constraint on interior and formation processes

Atmospheric Composition

- Insight in to bulk planetary composition
- Key constraint on thermal structure, evolution
- Evidence for core accretion vs. gas instability debate



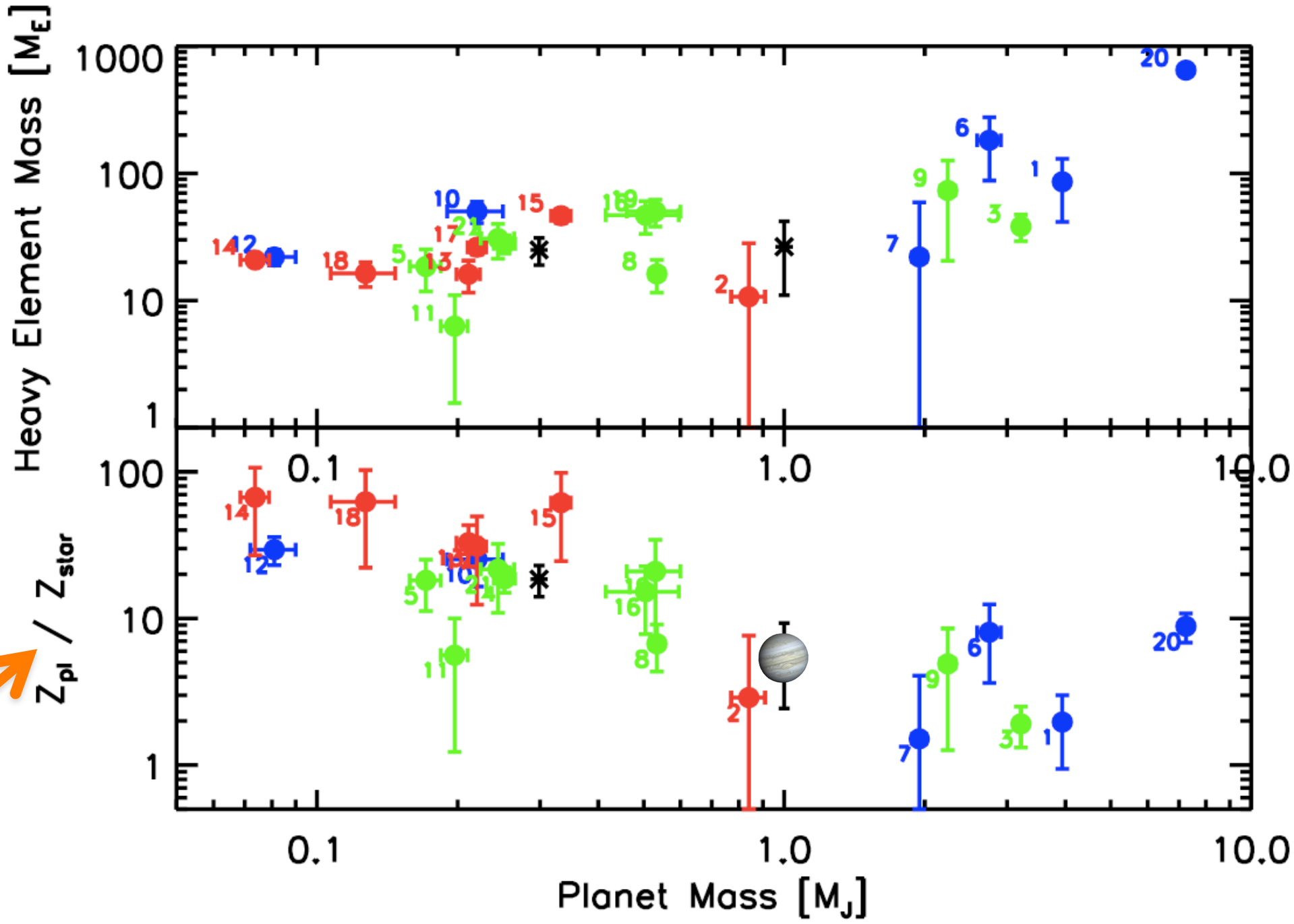
Owen et al. (1999)

How does composition vary with orbit, ice line, mass, etc?

- Exoplanetary Heavy Element Enrichment Fits Solar System Patterns
- A quasi-uniform super-solar enrichment above ~ 1 M_J

[Fe/H]<0.0
0.0≤[Fe/H]<0.2
0.2≤[Fe/H]<0.4

Enrichment Factor



Miller & Fortney (2011)

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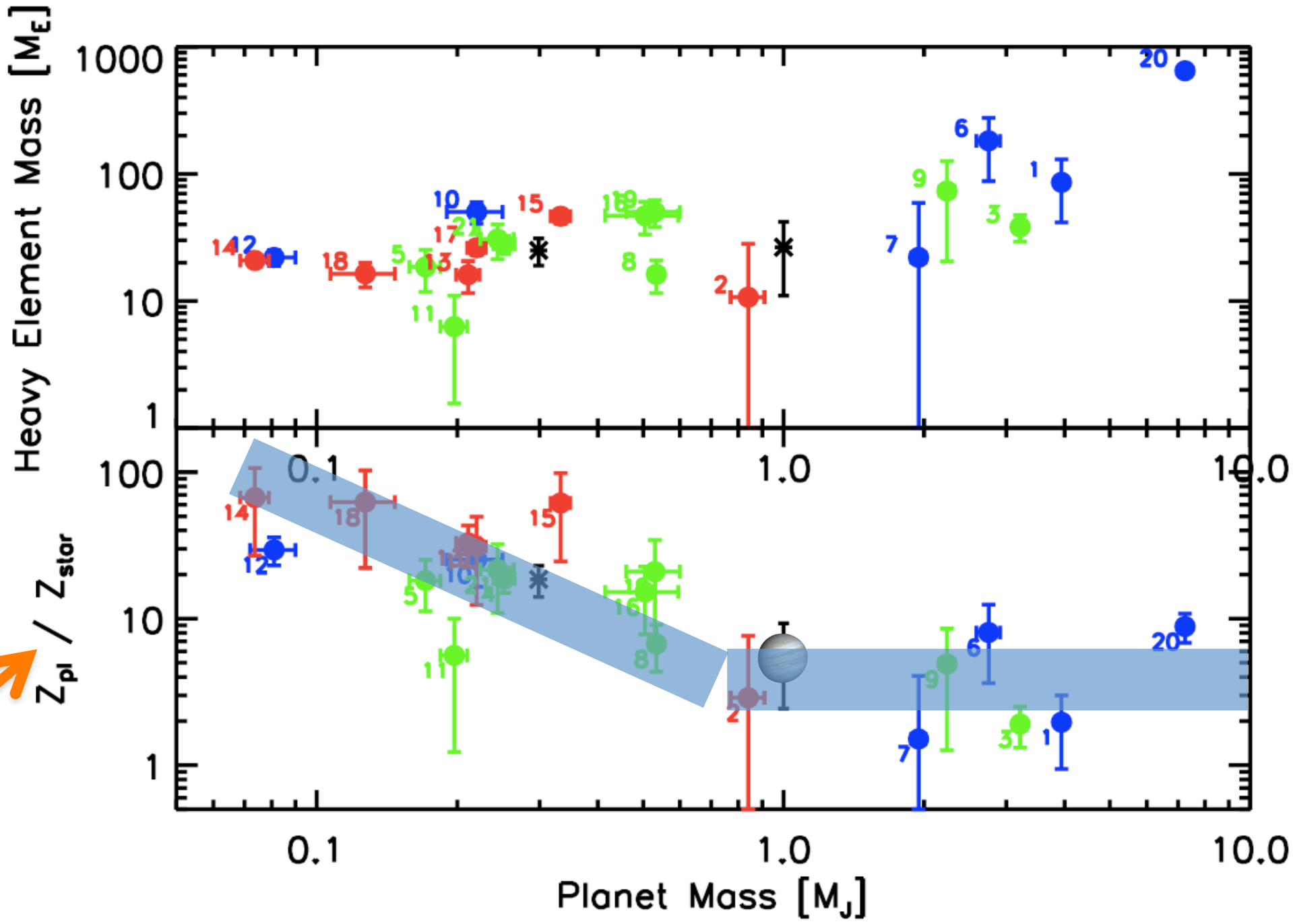
Enrichment Factor



Miller & Fortney (2011)

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Fingerprint of giant planet formation.

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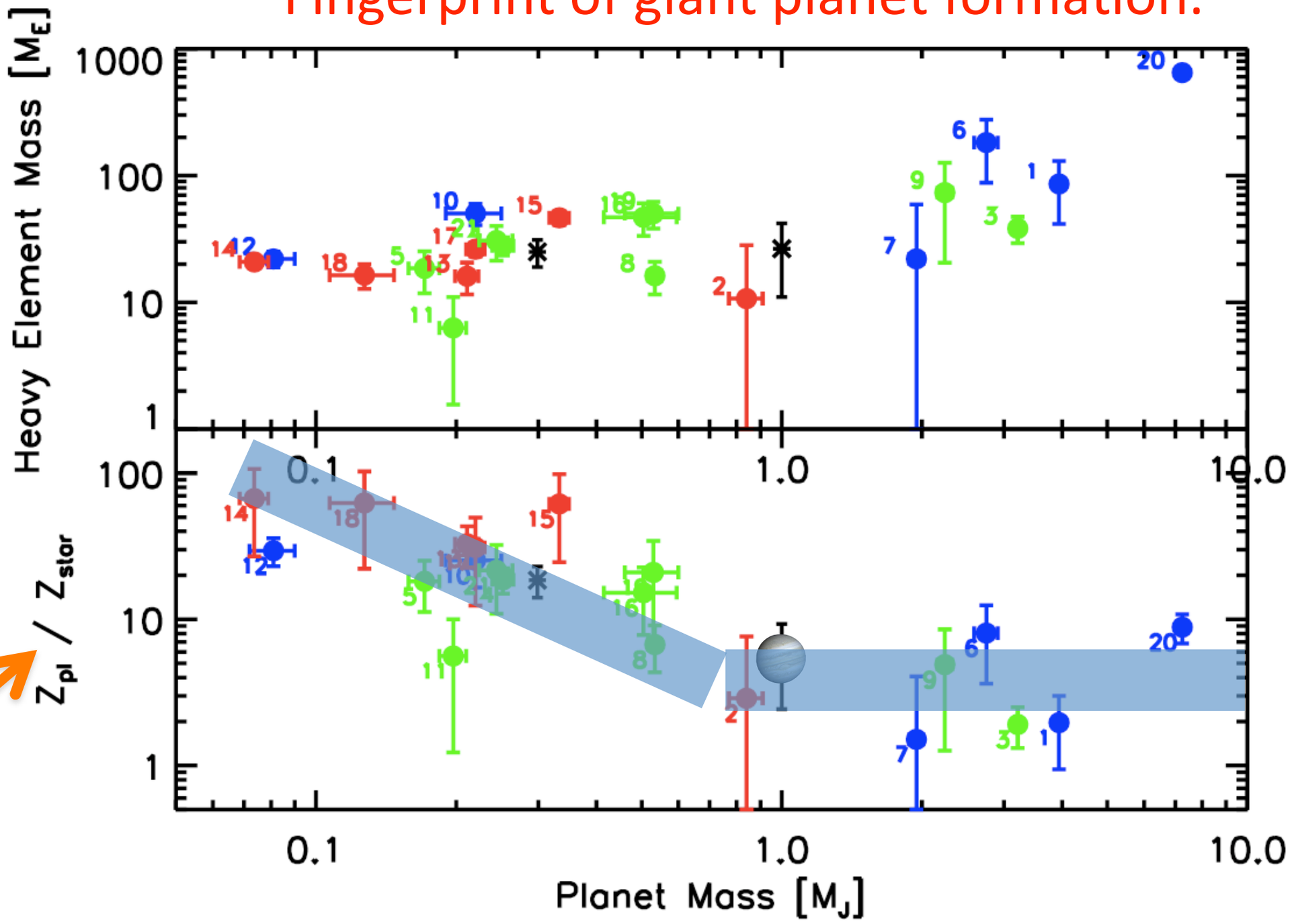
0.0≤[Fe/H]<0.2
0.2≤[Fe/H]<0.4



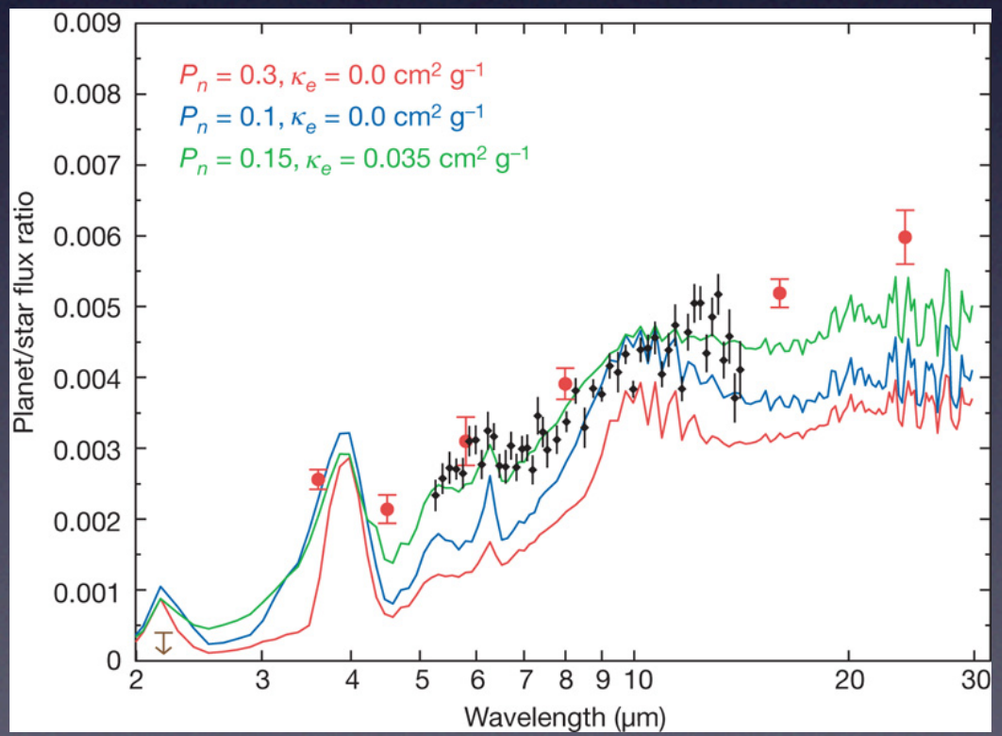
Enrichment Factor

Miller & Fortney (2011)

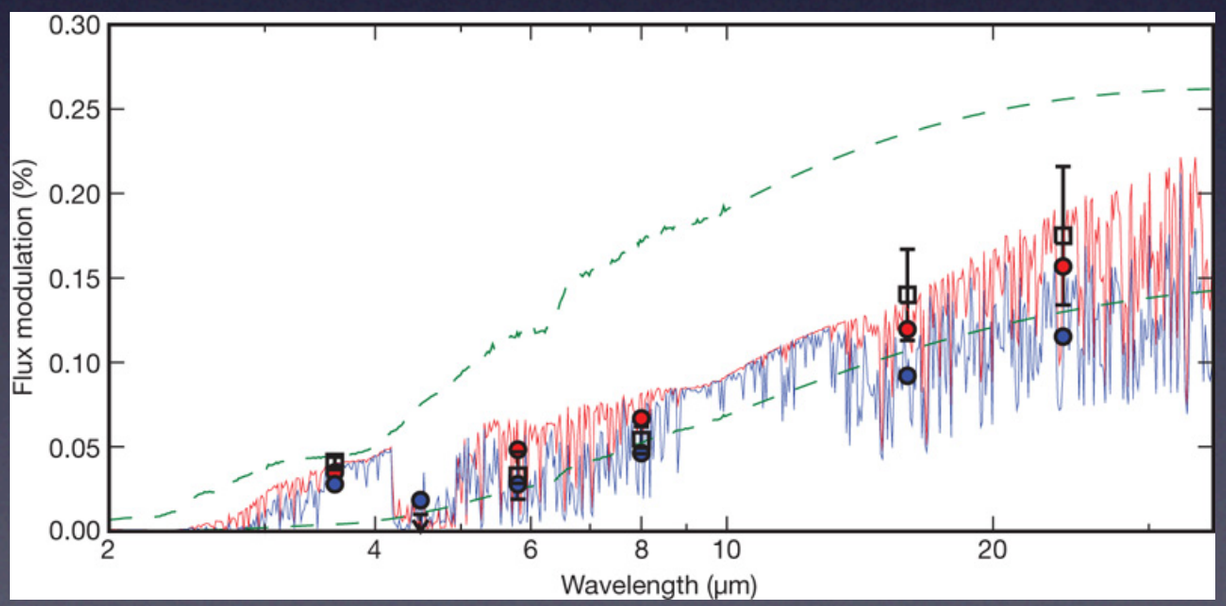
Eclipses

Most definitive molecular detections:

- HD 189733b: H_2O, CO_2 (Grillmair et al. 2008, Swain et al. 2009)
- GJ436b: CO, CO_2 (Stevenson et al. 2010)

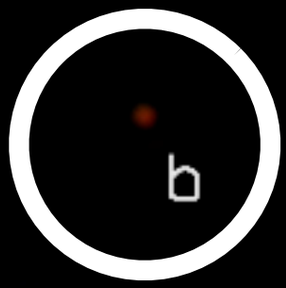


Grillmair et al. (2008)

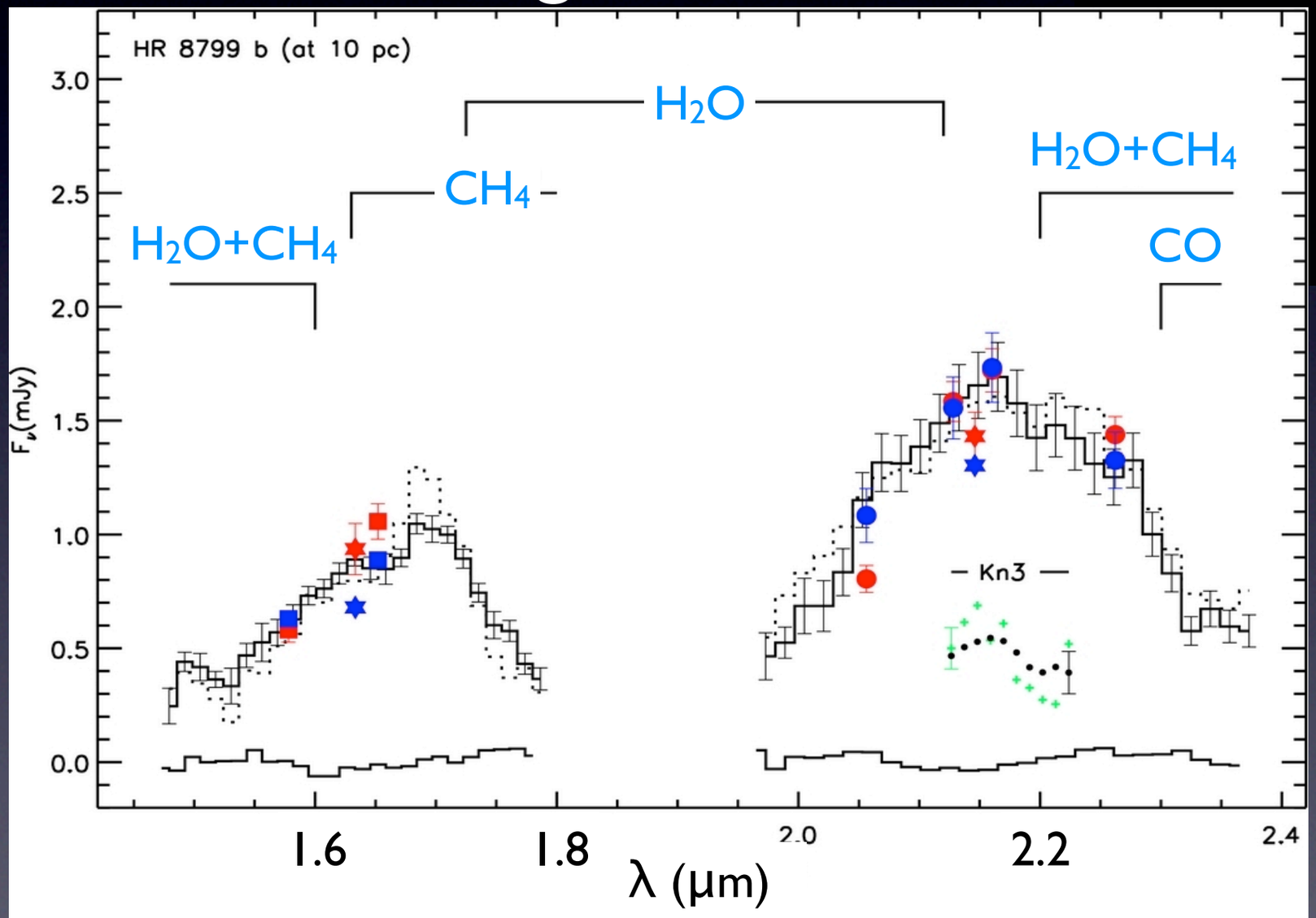


Stevenson et al. (2010)

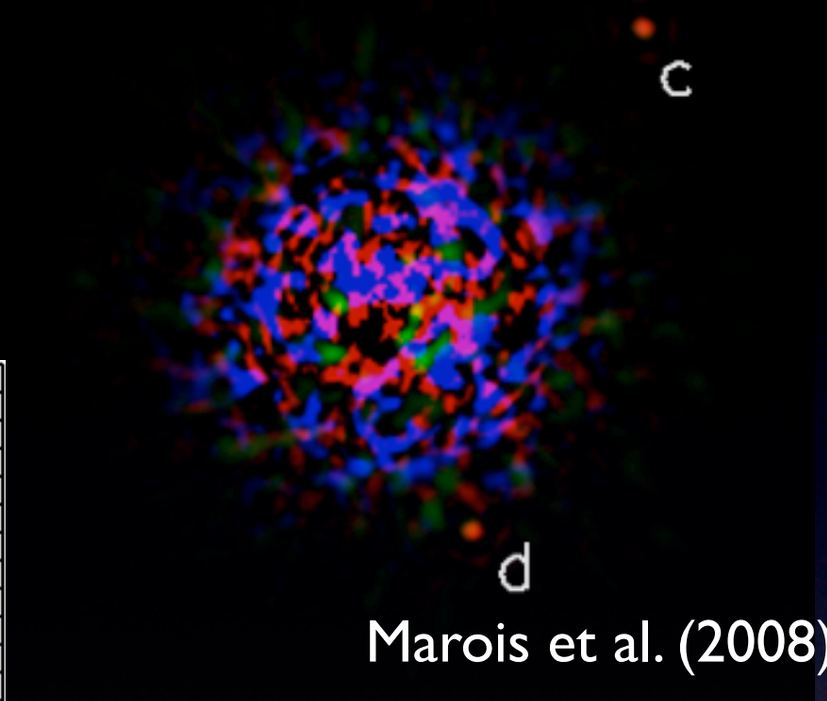
Direct imaging of one planet:



HR 8799b: CH_4, H_2O, CO
+ clouds, mixing



Barman et al. (2011)



Marois et al. (2008)

OSIRIS on Keck II

Direct Imaging

- Planets with variety of M, T_{eff}, [M/H], C/O, *a*
- Search for trends with stellar type, orbit
- Explore a greater phase space of orbits and planet characteristics than likely for transits
- Is there a core accretion or ice-line signature?
- Leverage expertise from solar system, brown dwarfs
- Photochemistry, winds, etc. less crucial to interpretation

Characterization

- Mass - spectra
- Radius - spectra
- Albedo
- Effective temperature
  - Equilibrium temperature - spectra
  - Internal luminosity
- ***Atmospheric Composition -*** spectra

Goal: Characterize Architecture of Ice and Gas Giants in Multiple Systems

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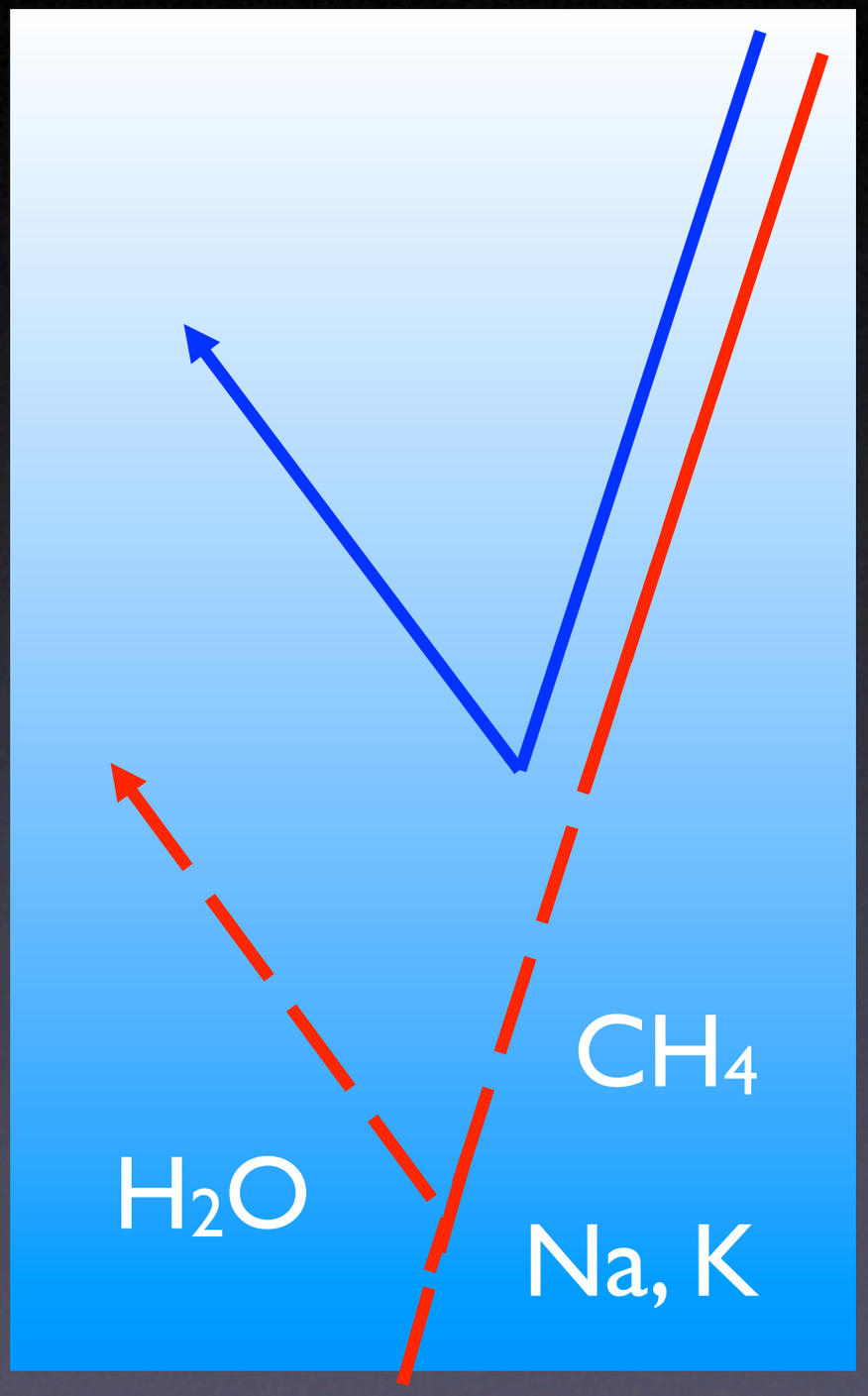
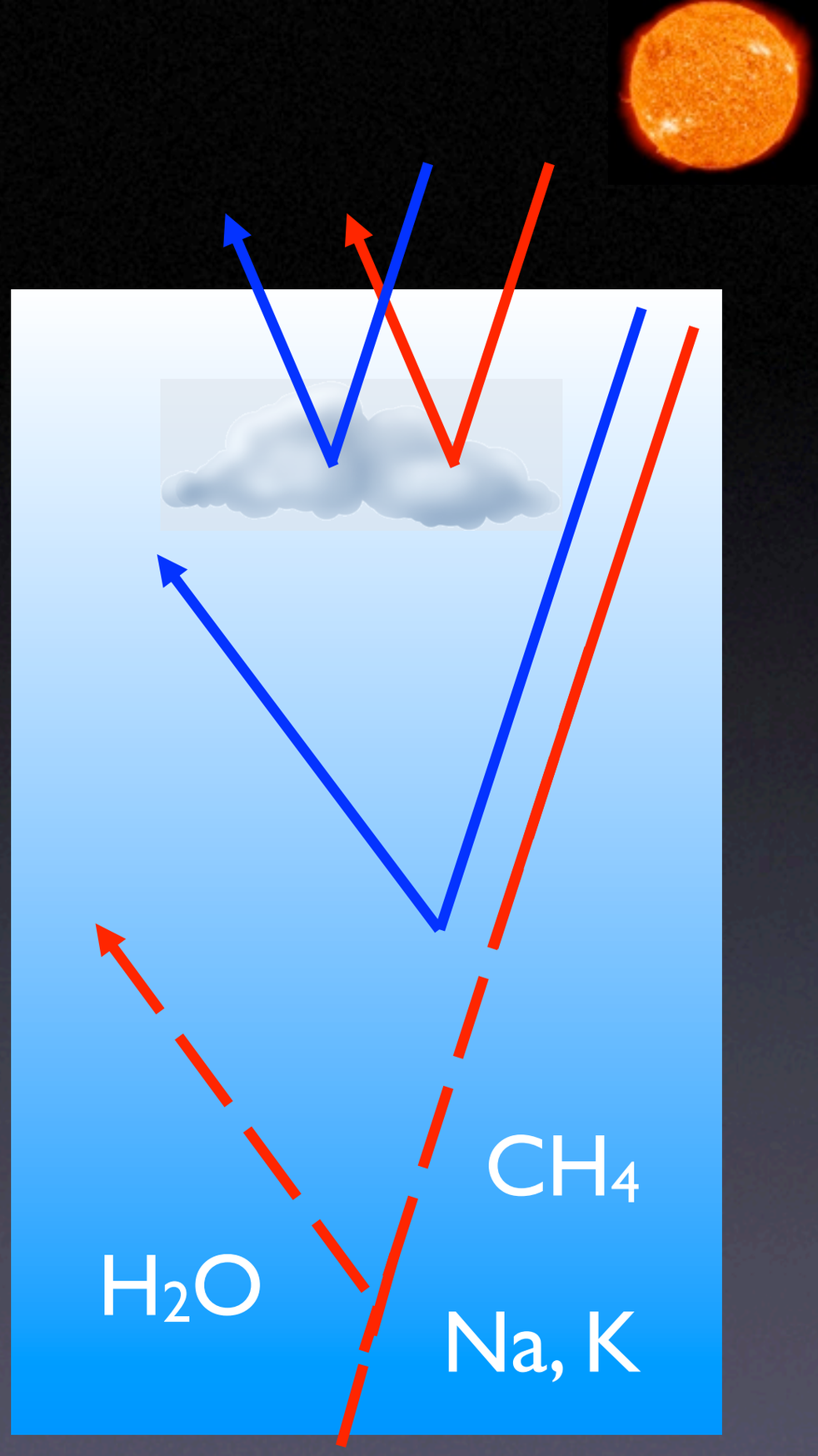
But... “all the cold giants look just like Jupiter”

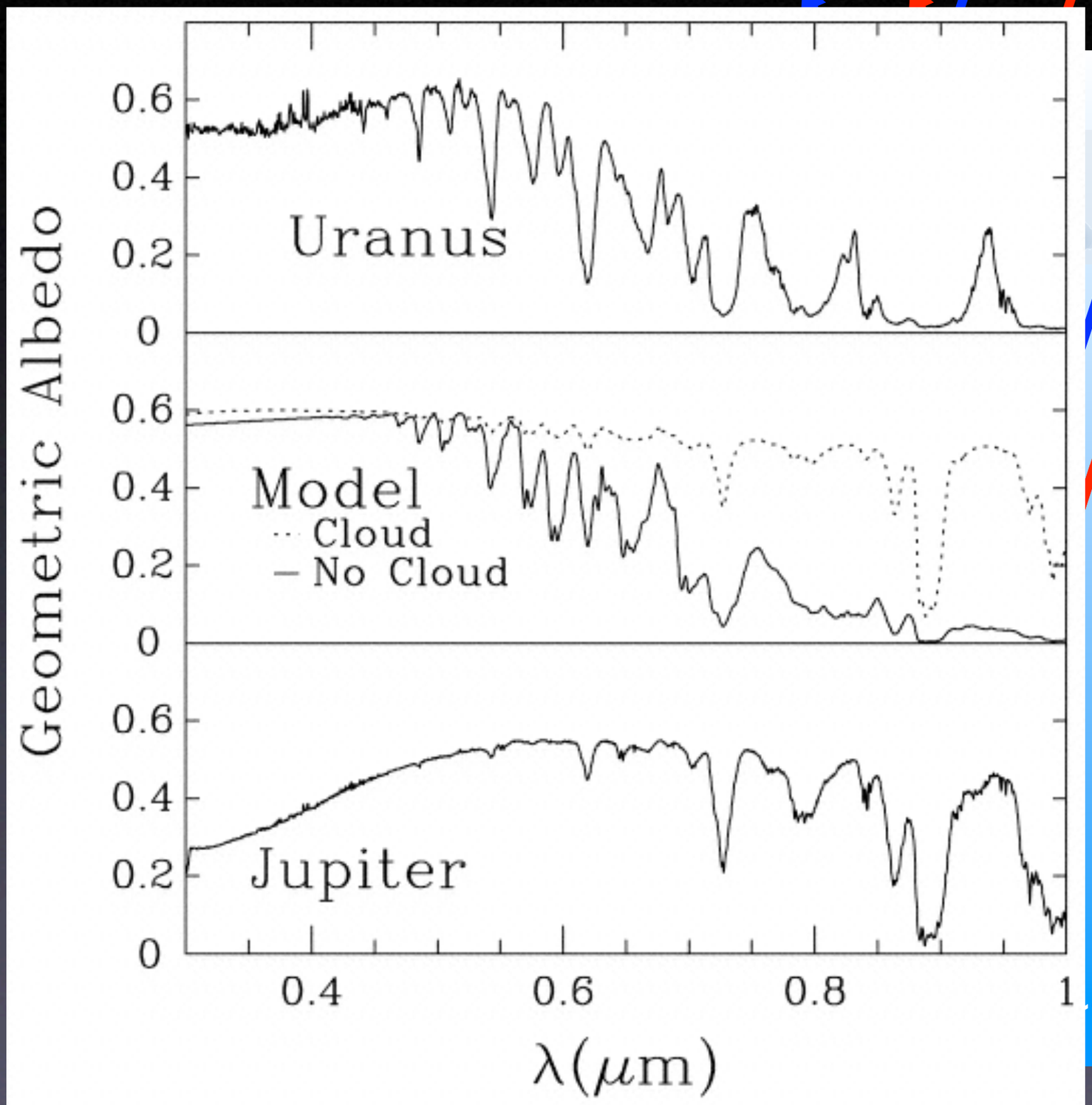
Goal: Characterize Architecture of Ice and Gas Giants in Multiple Systems

But... "all the cold giants look just like Jupiter"

False


CH_4
H_2O
Na, K


CH_4
H_2O
Na, K



Huge influence on Bond Albedo and T_{eq}

H_4

, K

Marley et al. (1999)

Thus Not all Jupiters are Jupiter

Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

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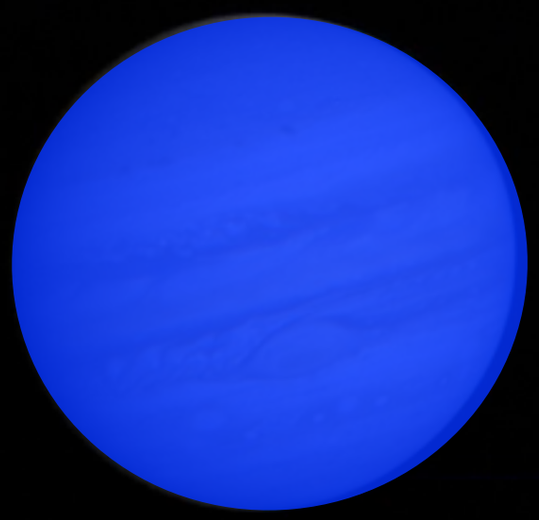

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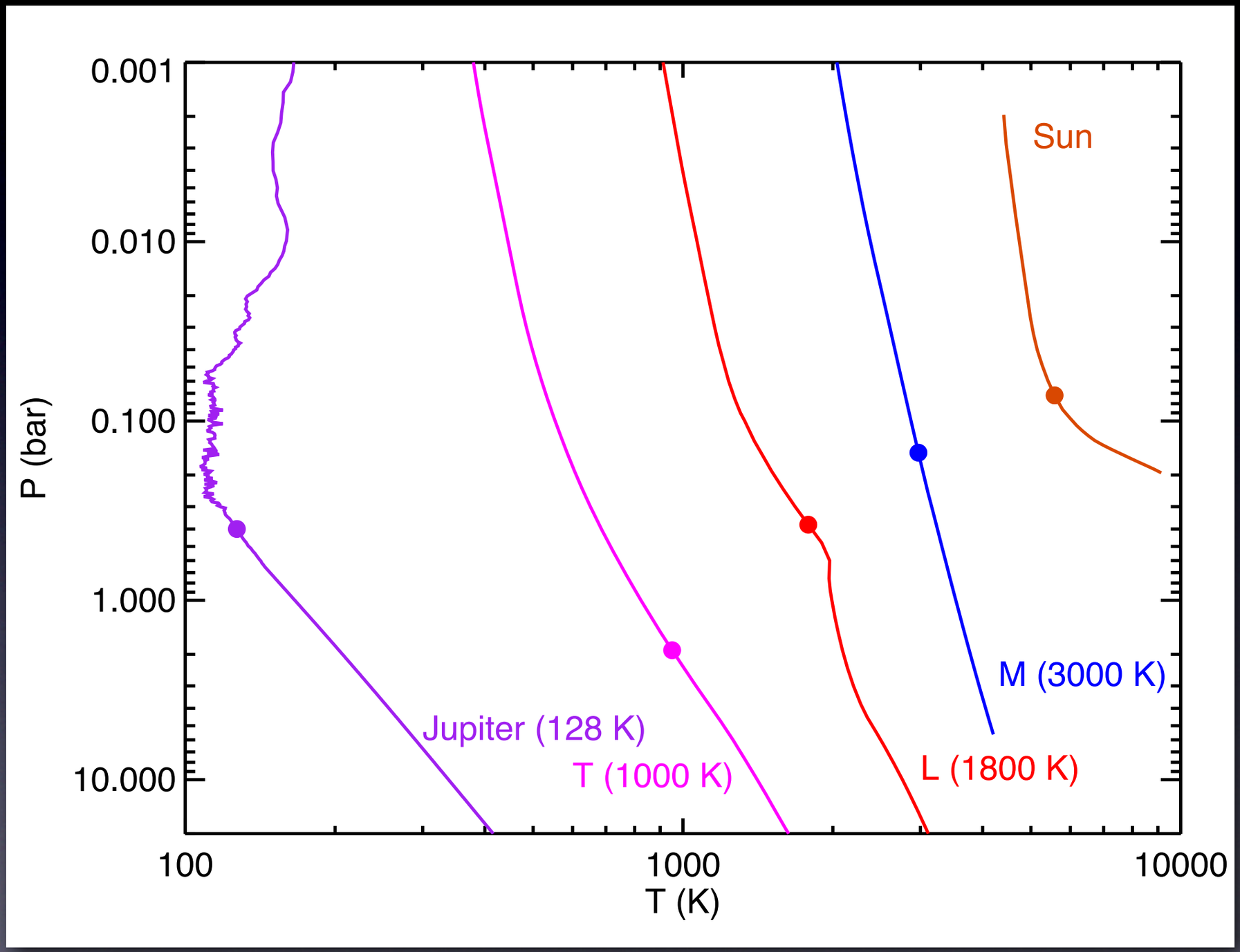
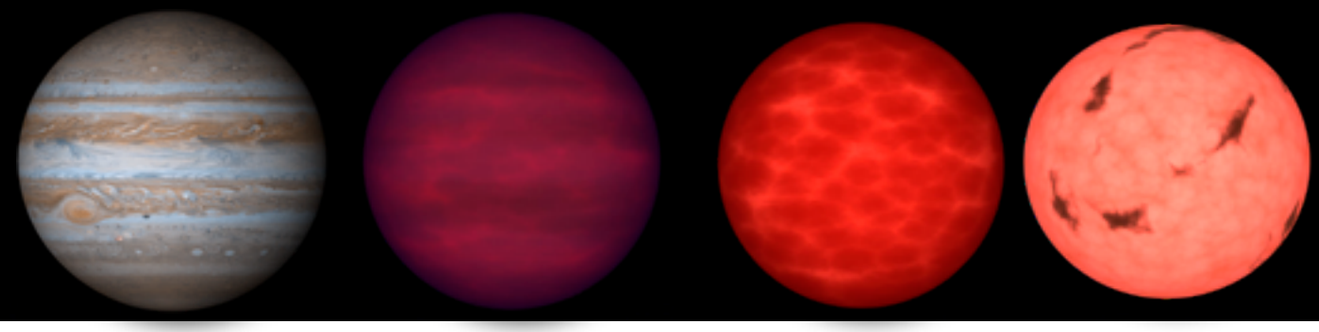
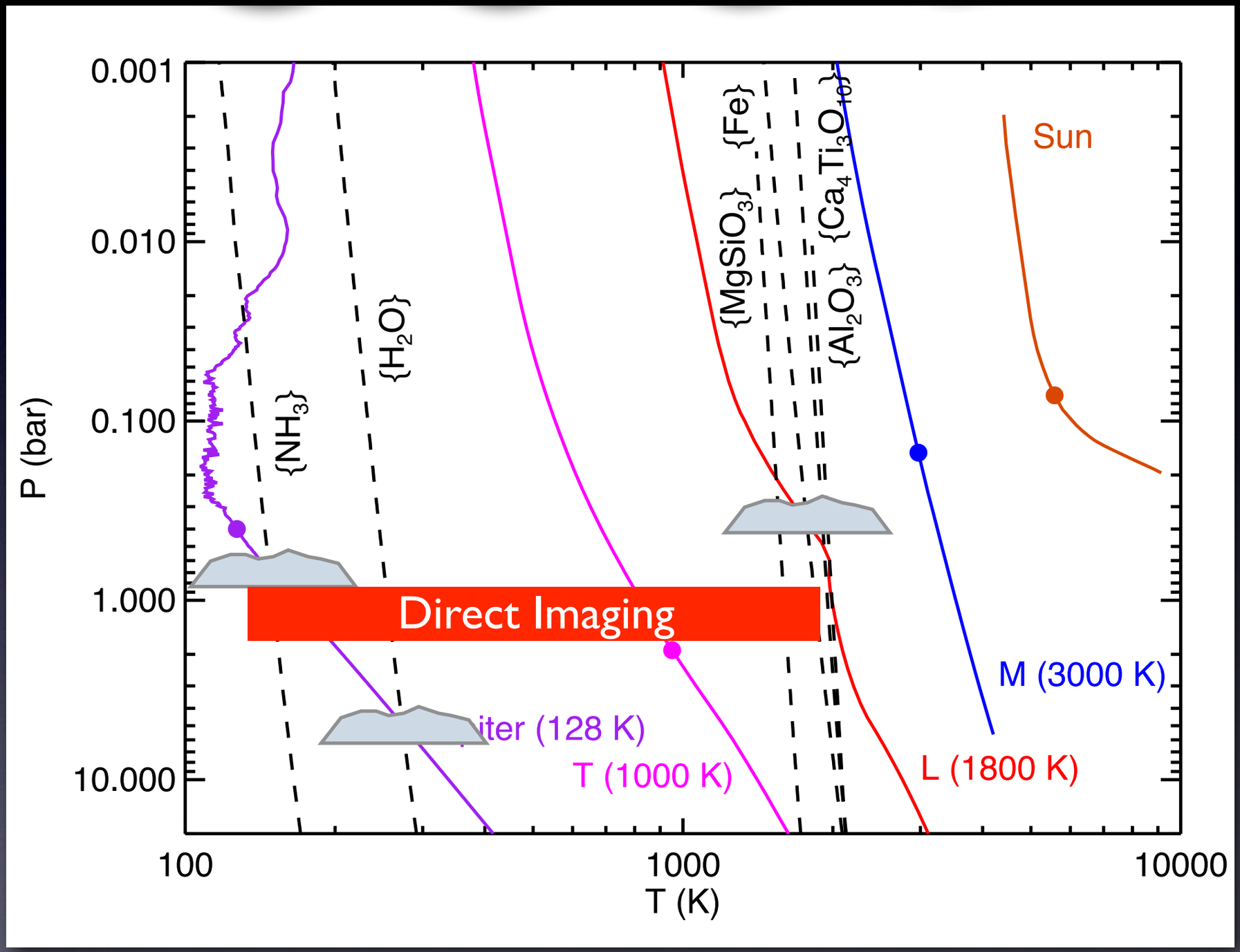
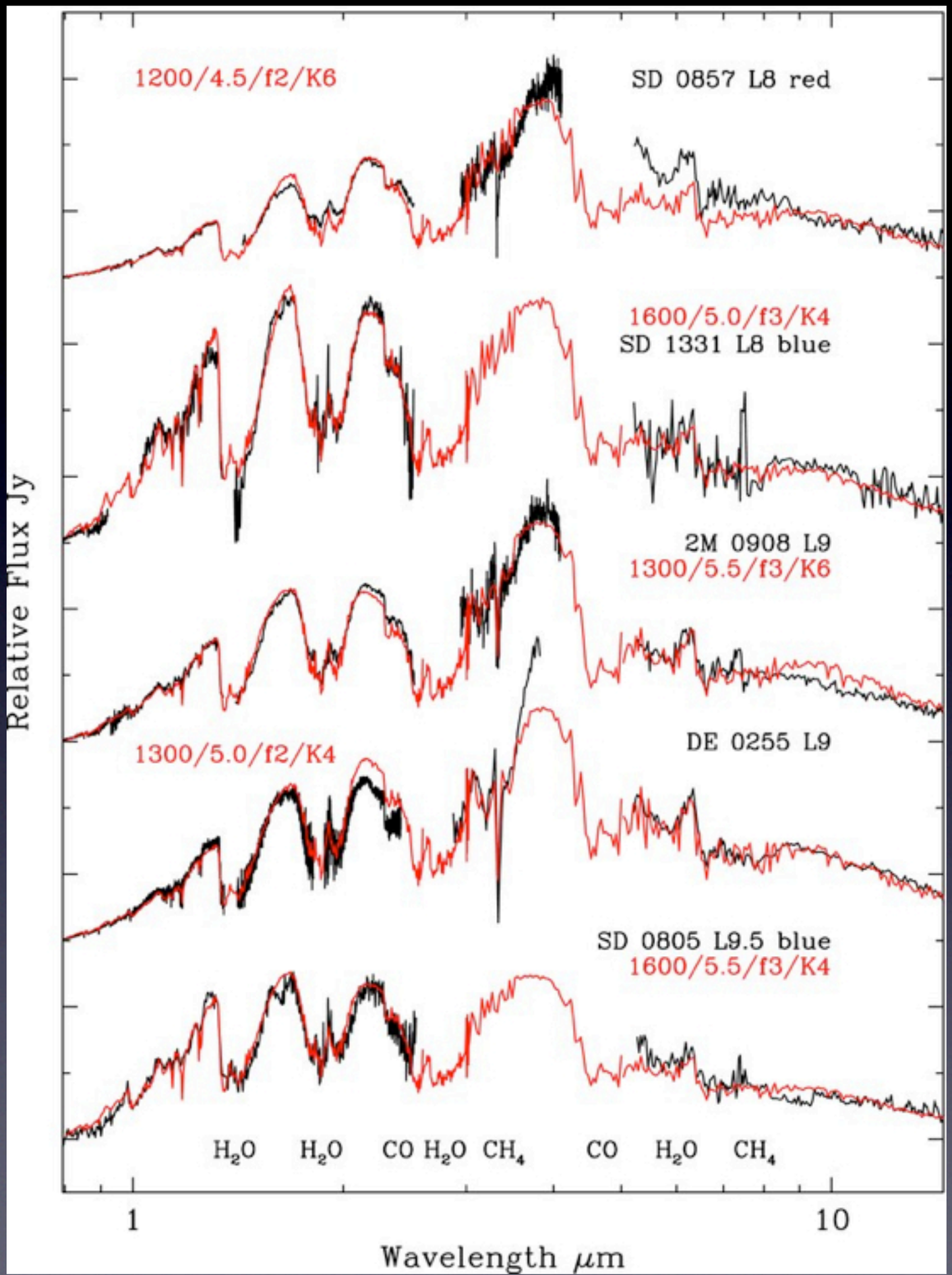
photochemistry


0.001
0.010
0.100
1.000
10.000
P (bar)
100
1000
10000
T (K)
Sun
M (3000 K)
L (1800 K)
T (1000 K)
Jupiter (128 K)



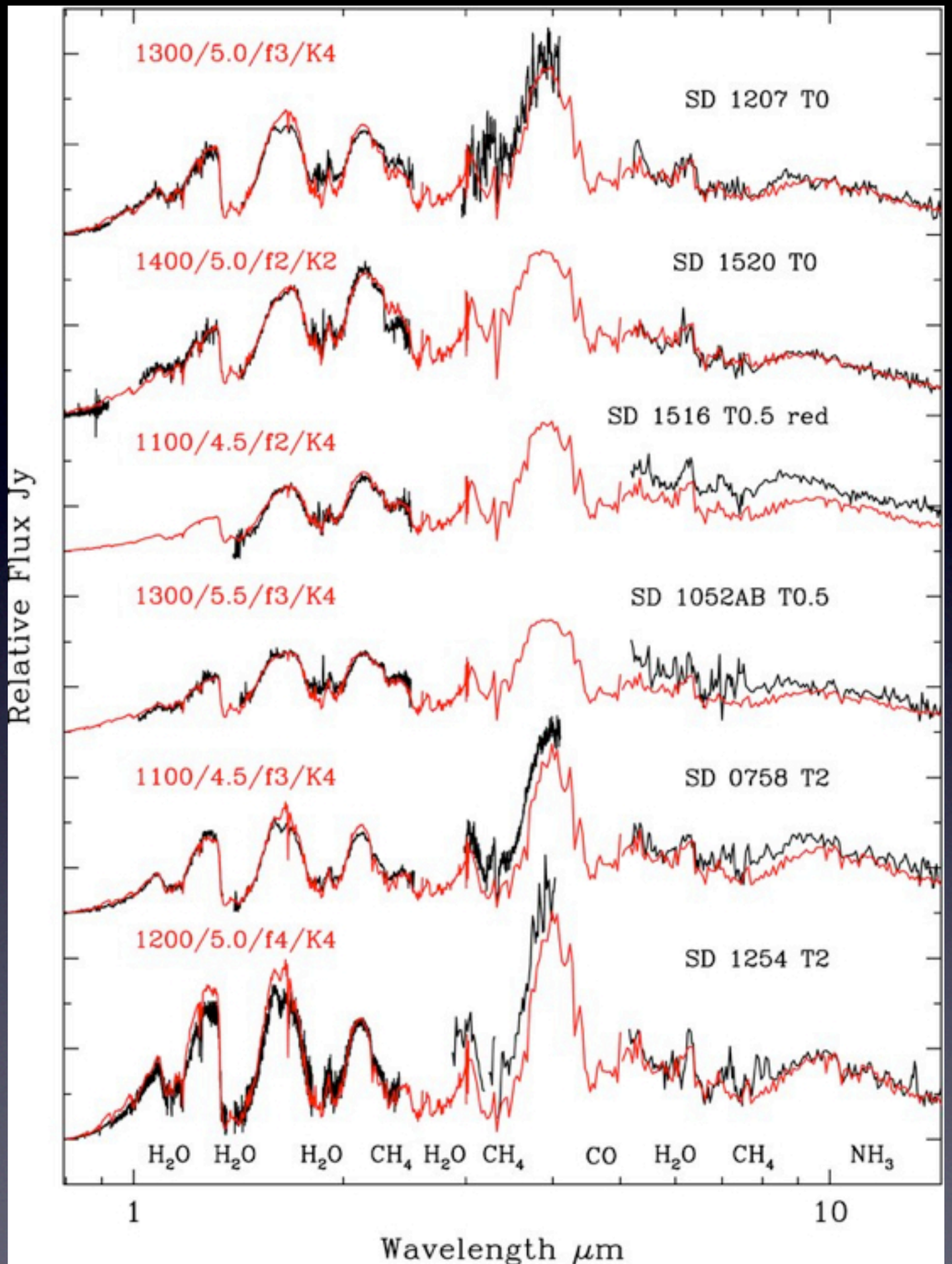

0.001
0.010
0.100
1.000
10.000
P (bar)
100
1000
10000
T (K)
{H2O}
{NH3}
{MgSiO3}
{Fe}
{Al2O3}
{Ca4Ti3O10}
Sun
Direct Imaging
iter (128 K)
T (1000 K)
L (1800 K)
M (3000 K)



We Know How to Interpret Warm Giants

Brown Dwarf Legacy

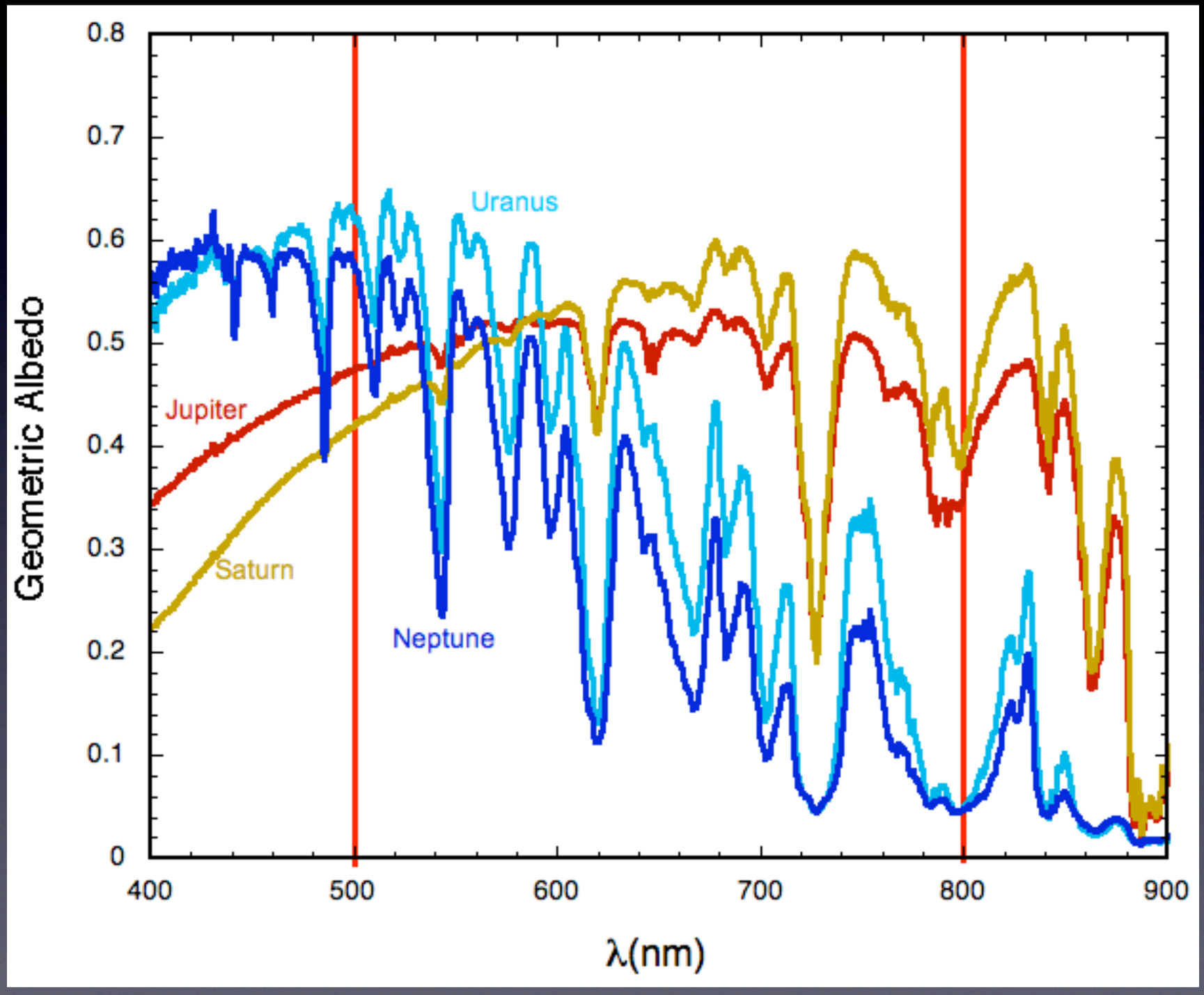
Early T Dwarfs



T0

T2

We Know How to Interpret Cool Giants



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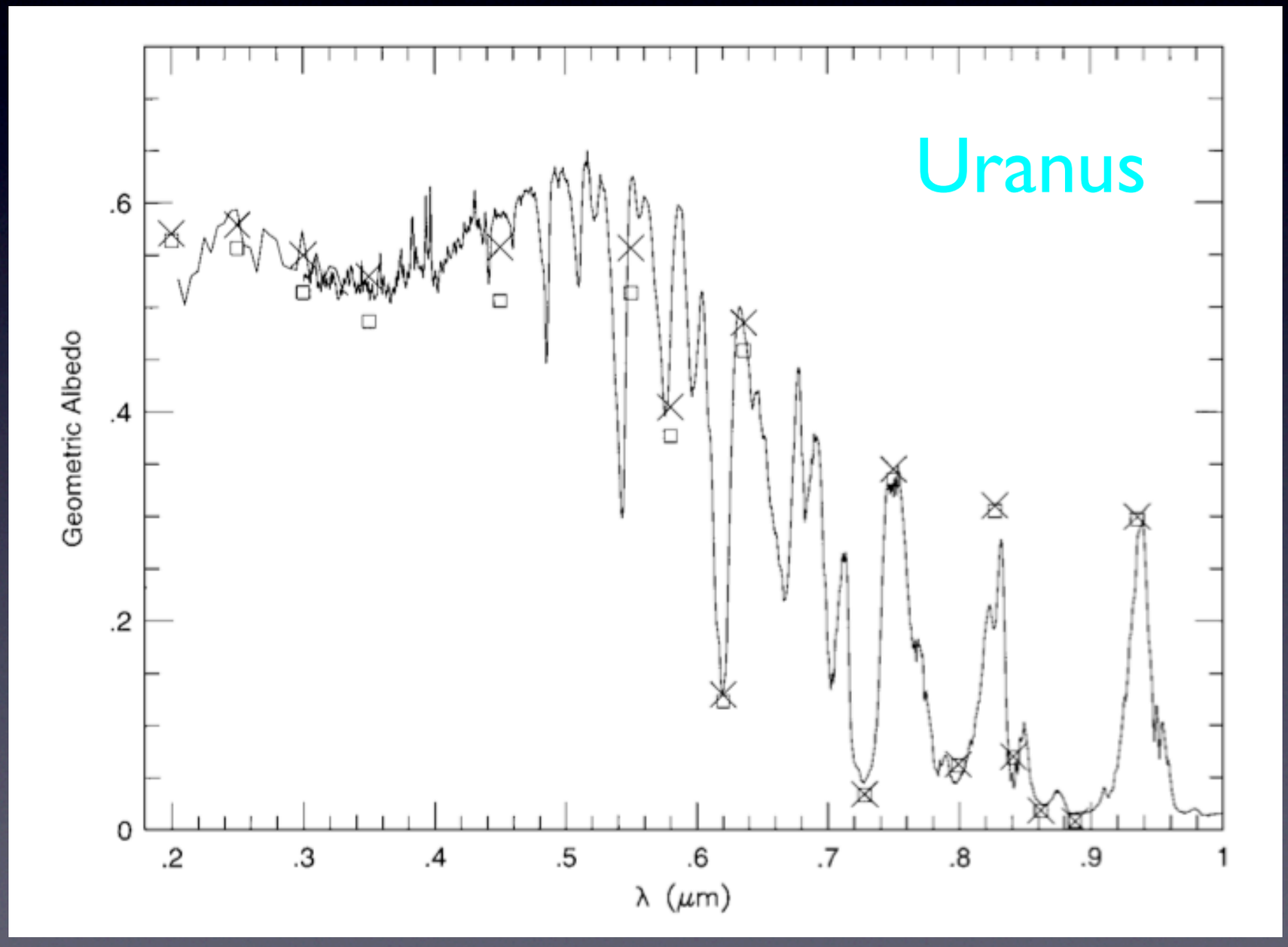
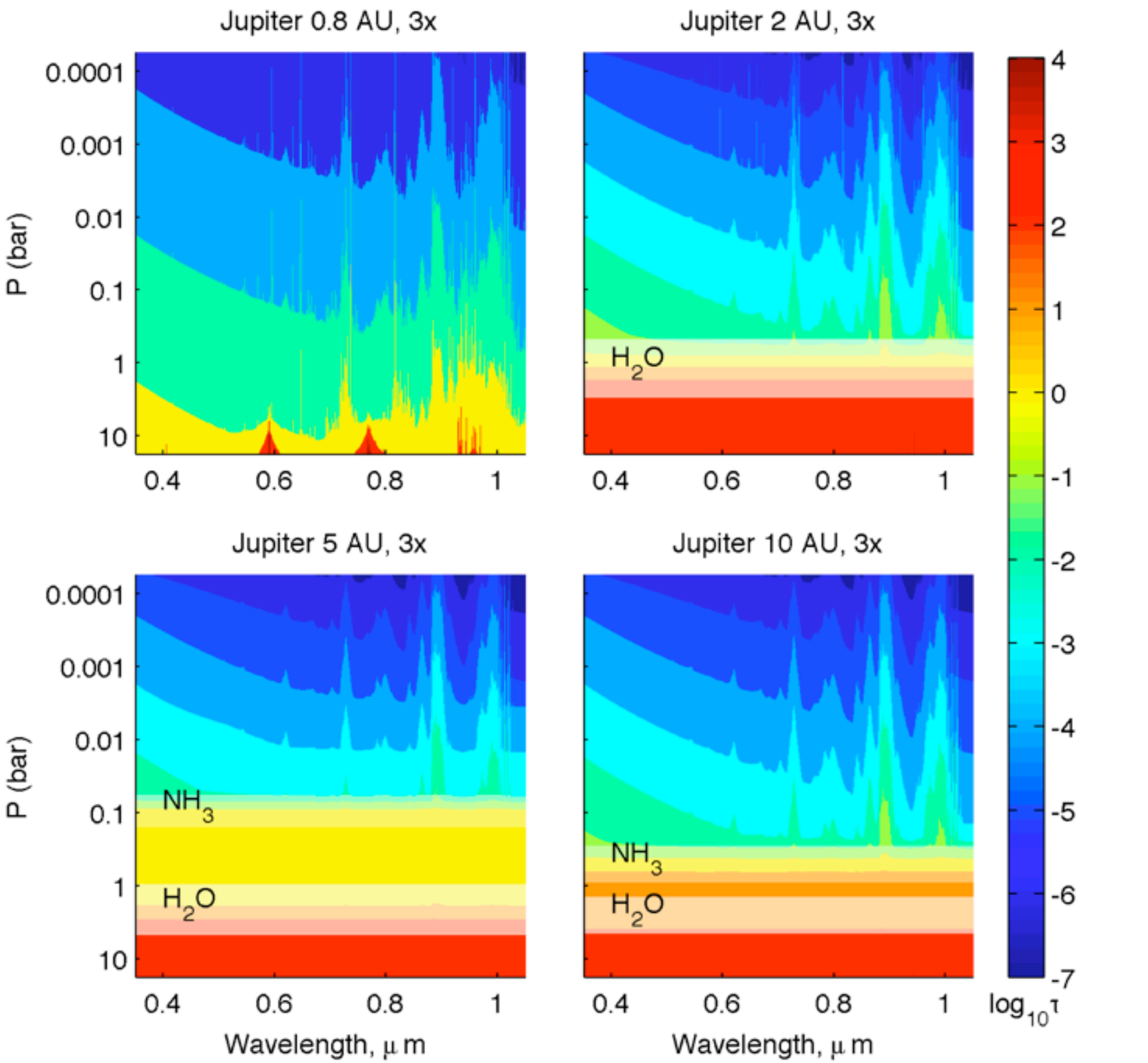
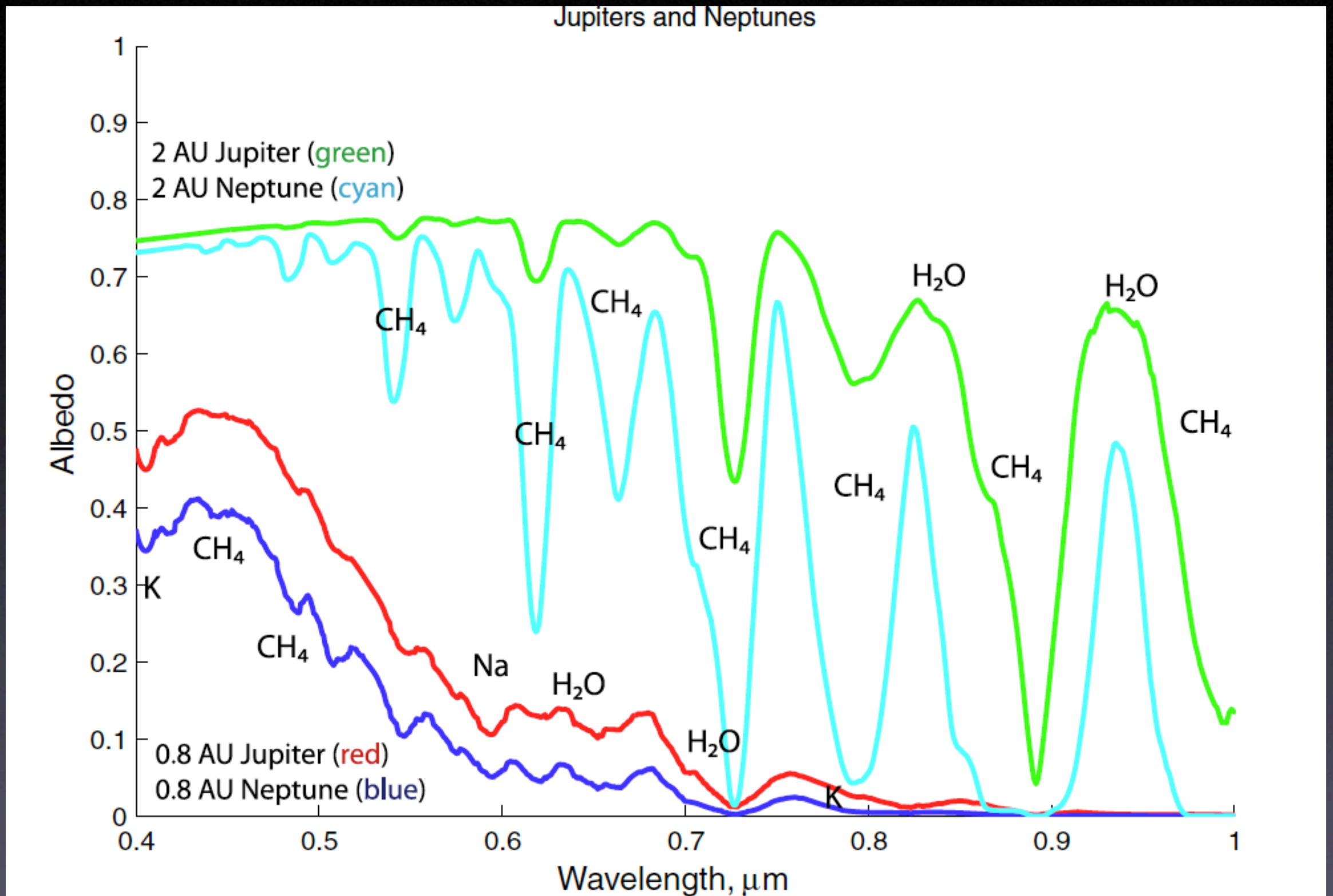


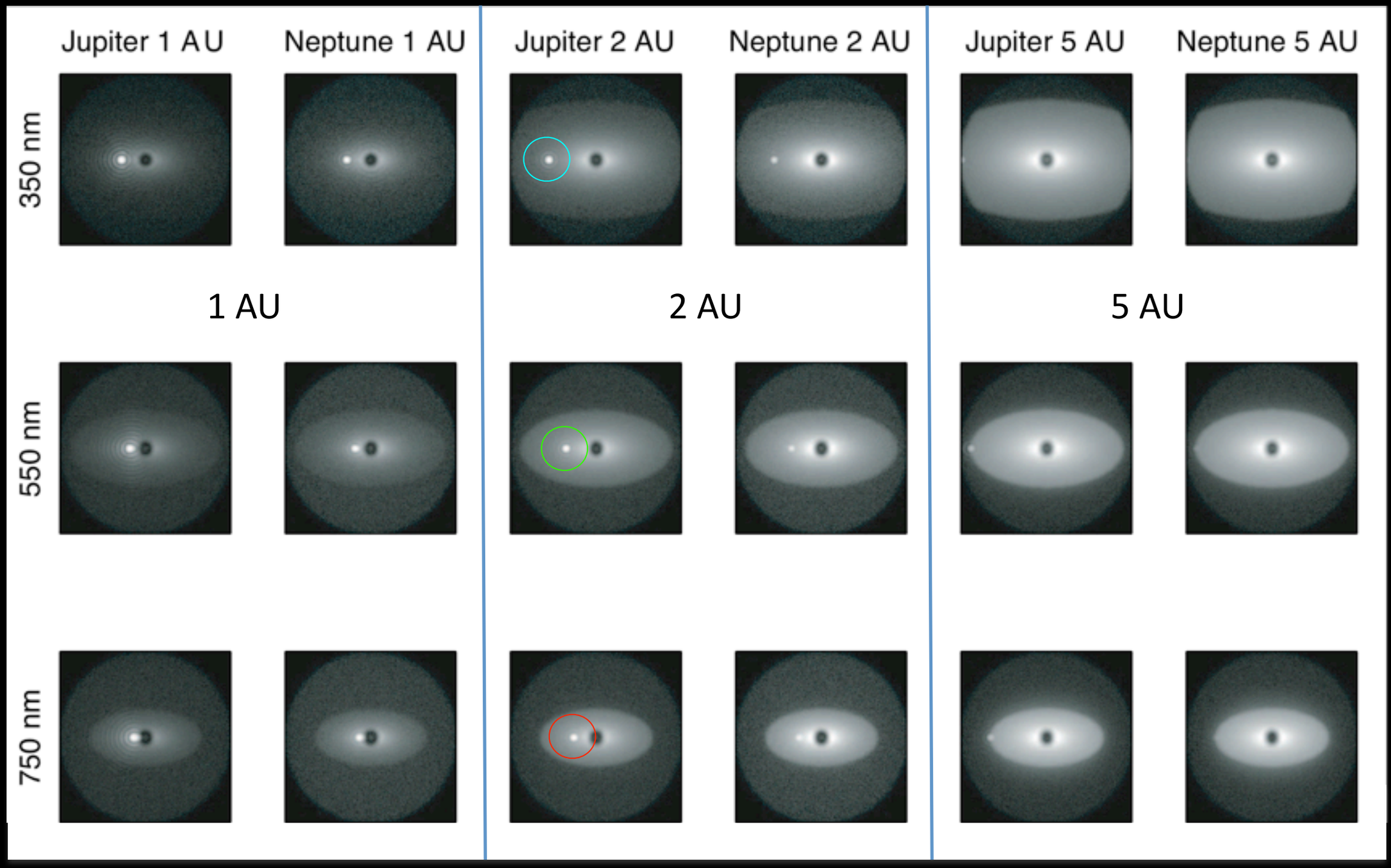
Example: Geometric albedo forward model vs data (Marley & McKay 1999)



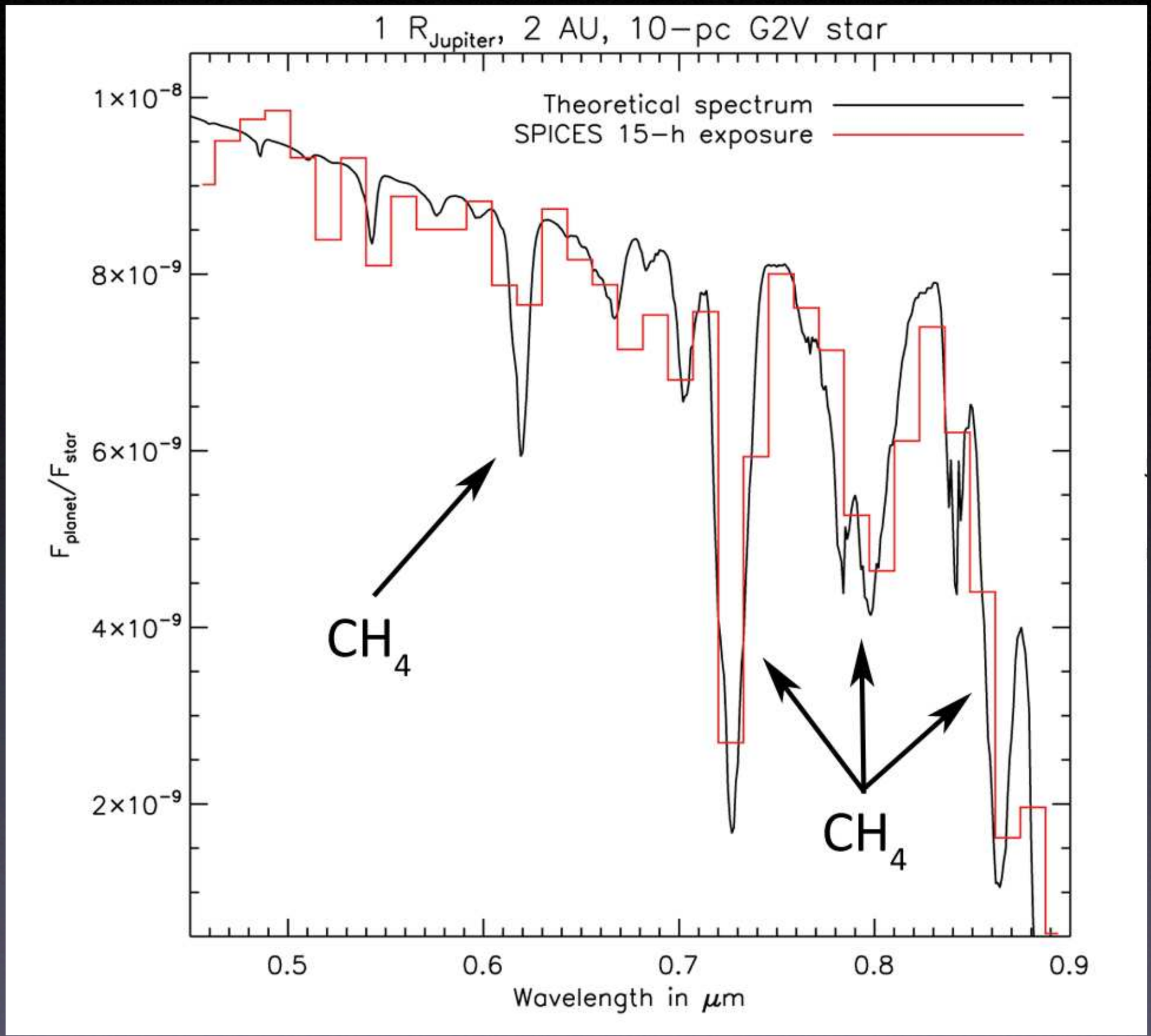
Cahoy et al. (2010)


Jupiters and Neptunes
2 AU Jupiter (green)
2 AU Neptune (cyan)
0.8 AU Jupiter (red)
0.8 AU Neptune (blue)
Albedo
Wavelength, μm
CH4
H2O
Na
K
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1

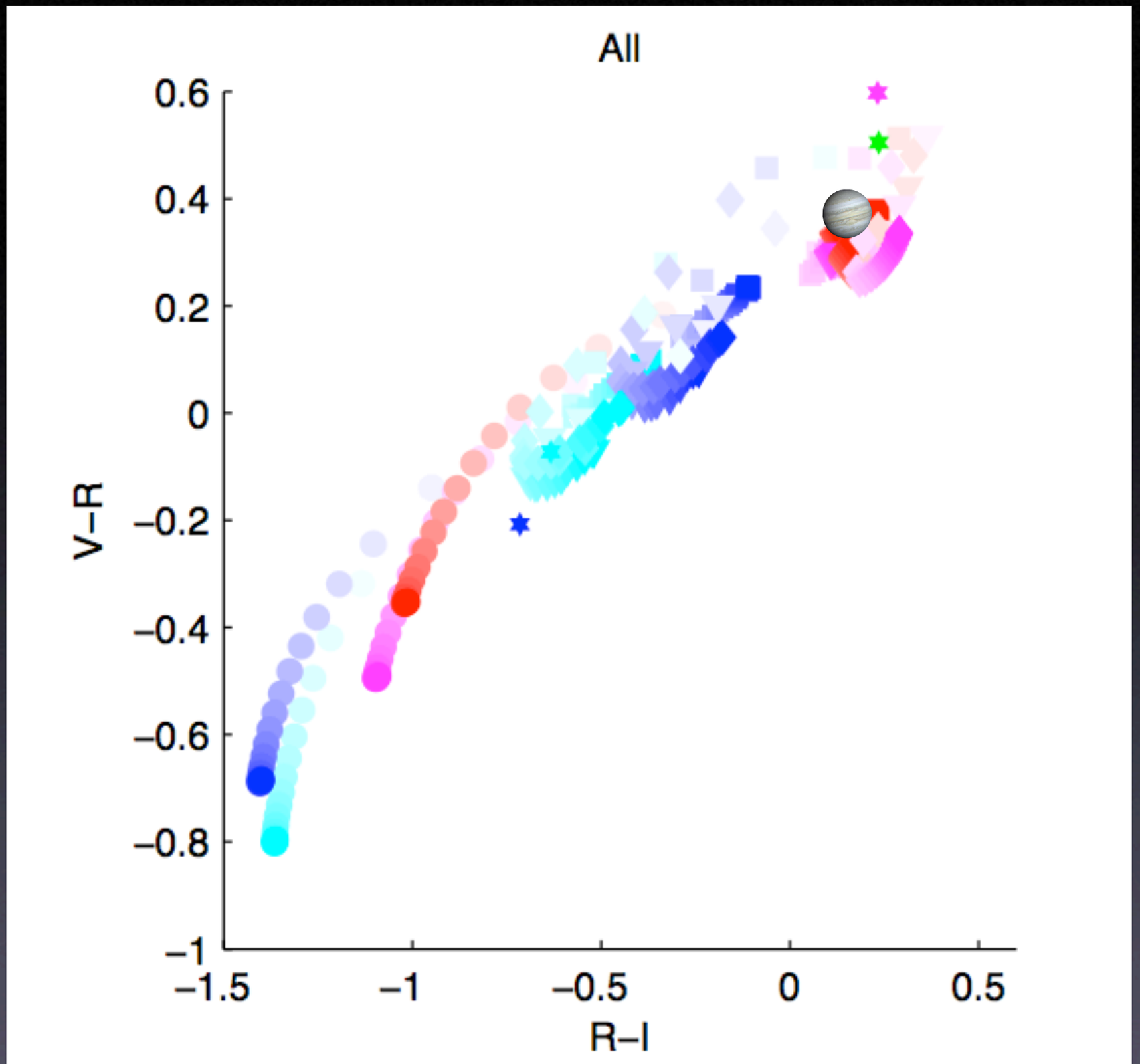
Scattered light
Simulated direct images



Cahoy et al. (2009)

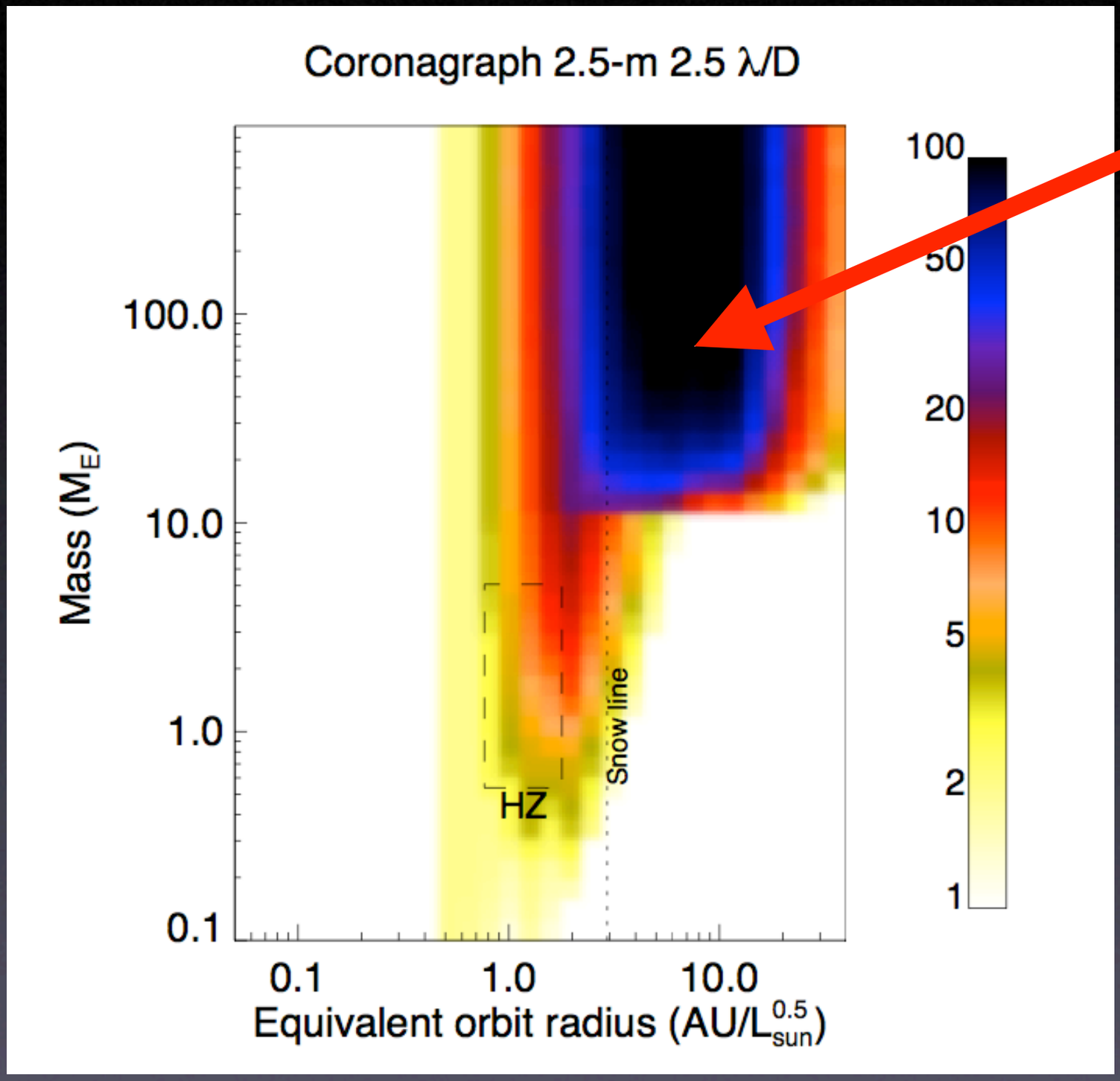


Boccaletti et al. (2012)



Cahoy et al. (2010)

Small Space Based Coronagraph

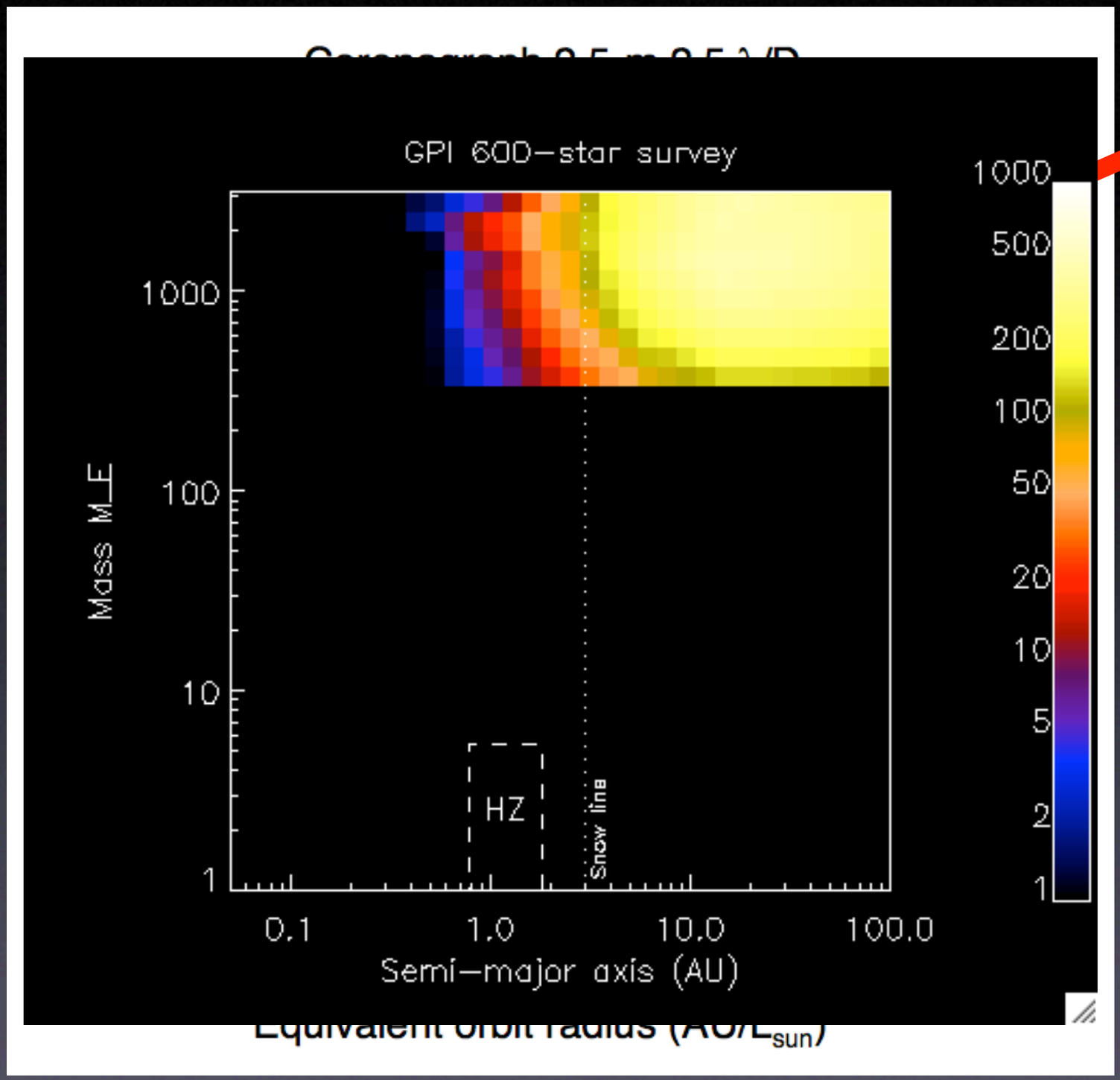


ExoPTF (2008-corrected)

Planetary system architectures, g, T_{eff}, composition

- gas giants
- ice giants
- super Earths
- GPI/SPHERE will not have a large sample inside the snow line and are sensitive to initial conditions

Small Space Based Coronagraph



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- ice giants
- super Earths
- GPI/SPHERE will not have a large sample inside the snow line and are sensitive to initial conditions

ExoPTF (2008-corrected)

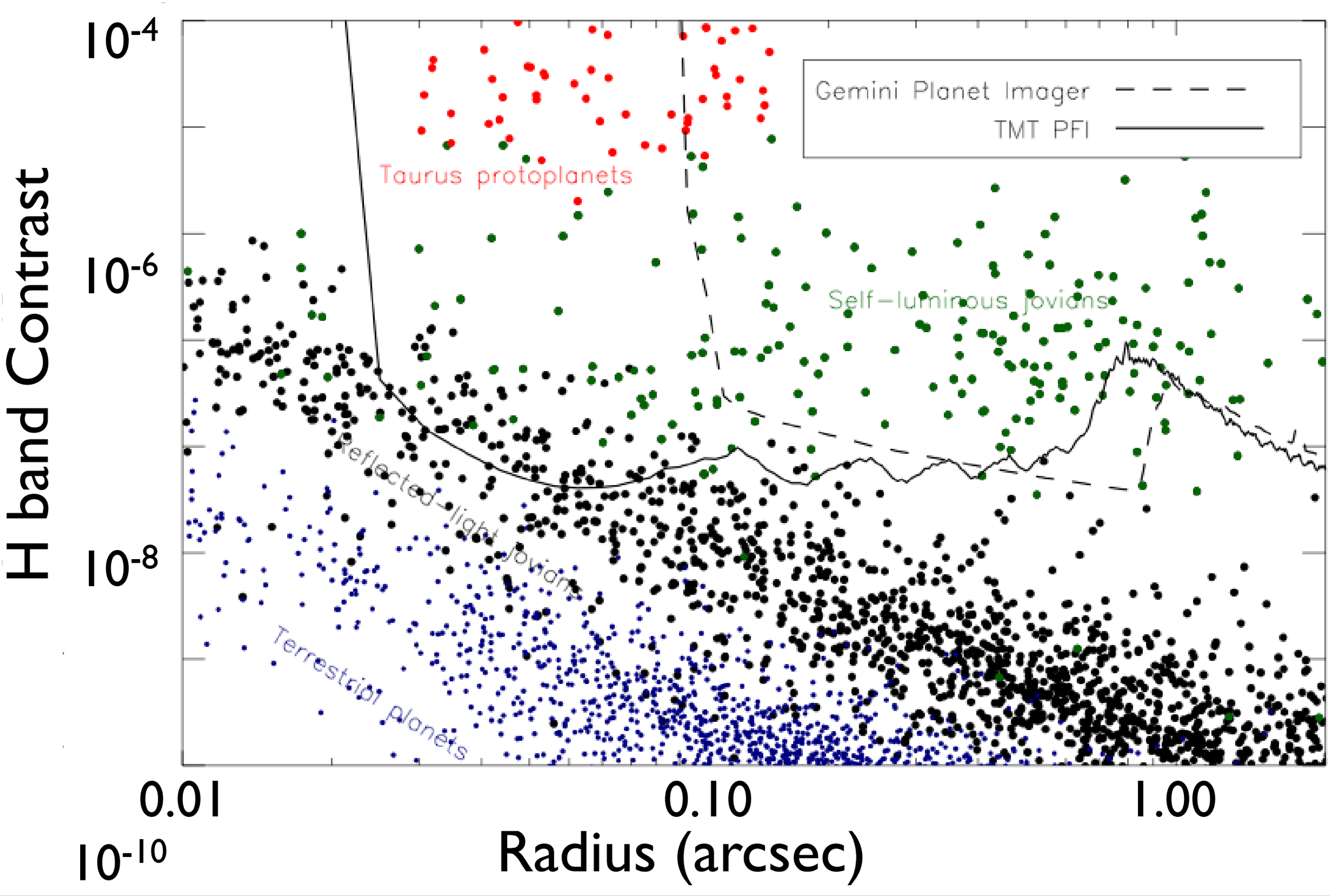
Advantages of Directly Imaged Cool Giants

- Good synergy with solar system planets
- Know how to interpret spectra
- Photochemistry and winds less crucial to interpretation (no massive external forcing)
- Derive composition, internal heat flow as function of planetary mass, orbit, insolation, stellar properties
- Brown dwarf legacy

Charge from Scott: *What do we know about the atmospheres of exoplanets and what additional information do we need in order to address the things that we currently do not understand?*

My opinion (giant planets):

- Composition as a function of planetary mass, orbit, stellar type
- Directly imaged cool gas and ice giants are best suited to obtaining this
- Constrains conditions in protoplanetary nebula, the mechanism of planet formation and evolution and provides boundary condition for terrestrial planet formation.



Courtesy B. Macintosh & J. Graham