Lessons from Brown Dwarfs

Mark Marley

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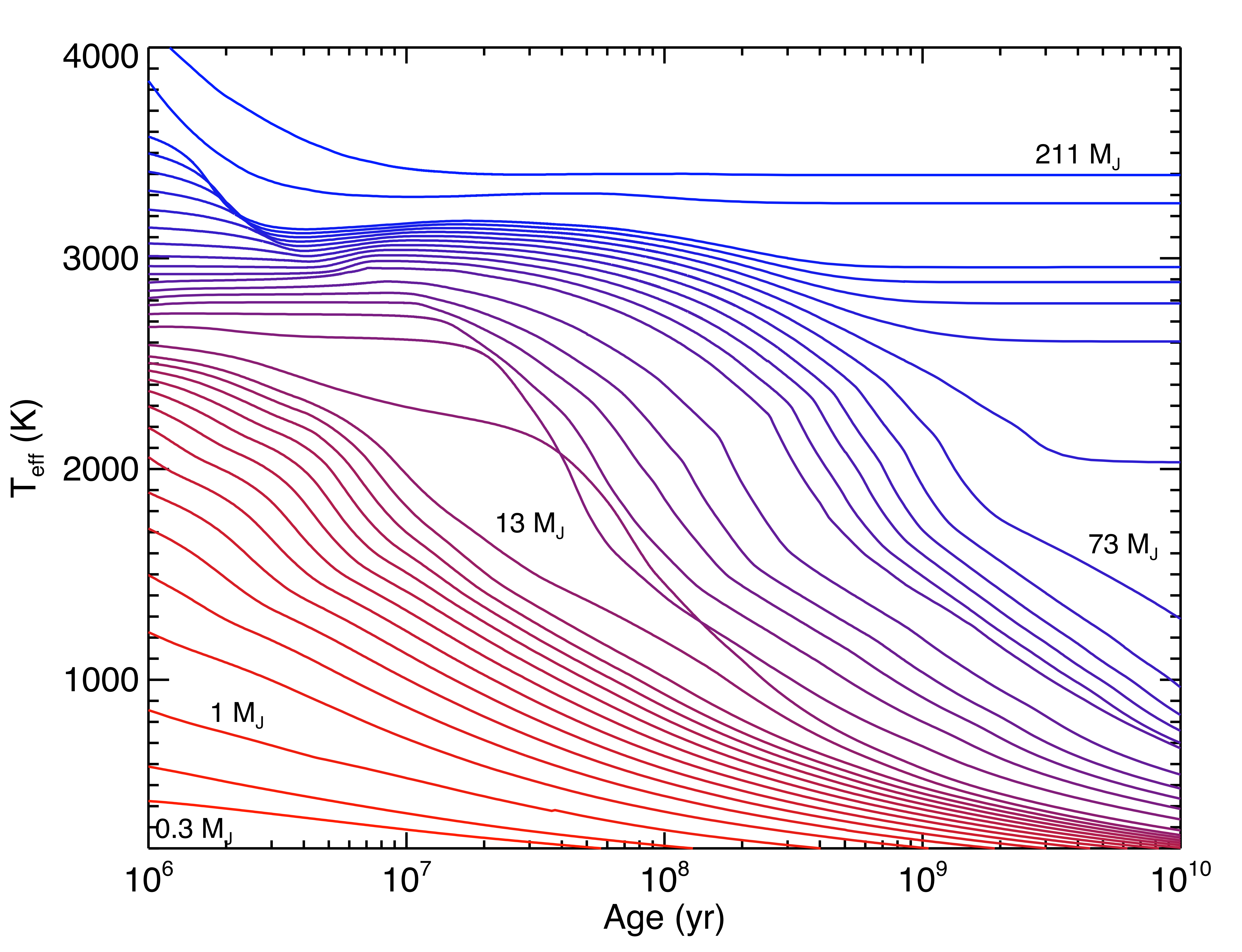
Why Brown Dwarfs?



adapted from Burrows, Marley+ (1997)

- H_2-He objects with masses below H fusion limit (~78M_J)
- Same T_{eff} range as exoplanets
- Atmospheric processes are all generally the same as planets
- Easier to observe & obtain spectra, provide learning and testing ground for exoplanets
- It happened "here" first

Why Me?

- I've been studying brown dwarfs since 1986, before their discovery
- First exoplanet paper in 1999. Seen both fields mature along somewhat different tracks
- Been involved in a lot of "lessons learned", including my own mistakes
- Have published on Solar Systems giants, exoplanets, and brown dwarfs

EVOLUTION AND INFRARED SPECTRA OF BROWN DWARFS

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Lunar and Planetary Laboratory, University of Arizona, Tucson
Received 1986 January 15; accepted 1986 April 8

Atmospheric, Evolutionary, and Spectral Models of the Brown Dwarf Gliese 229 B

M. S. Marley,* D. Saumon, T. Guillot, R. S. Freedman,
W. B. Hubbard, A. Burrows, J. I. Lunine

DETECTION OF ABUNDANT CARBON MONOXIDE IN THE BROWN DWARF GLIESE 229B

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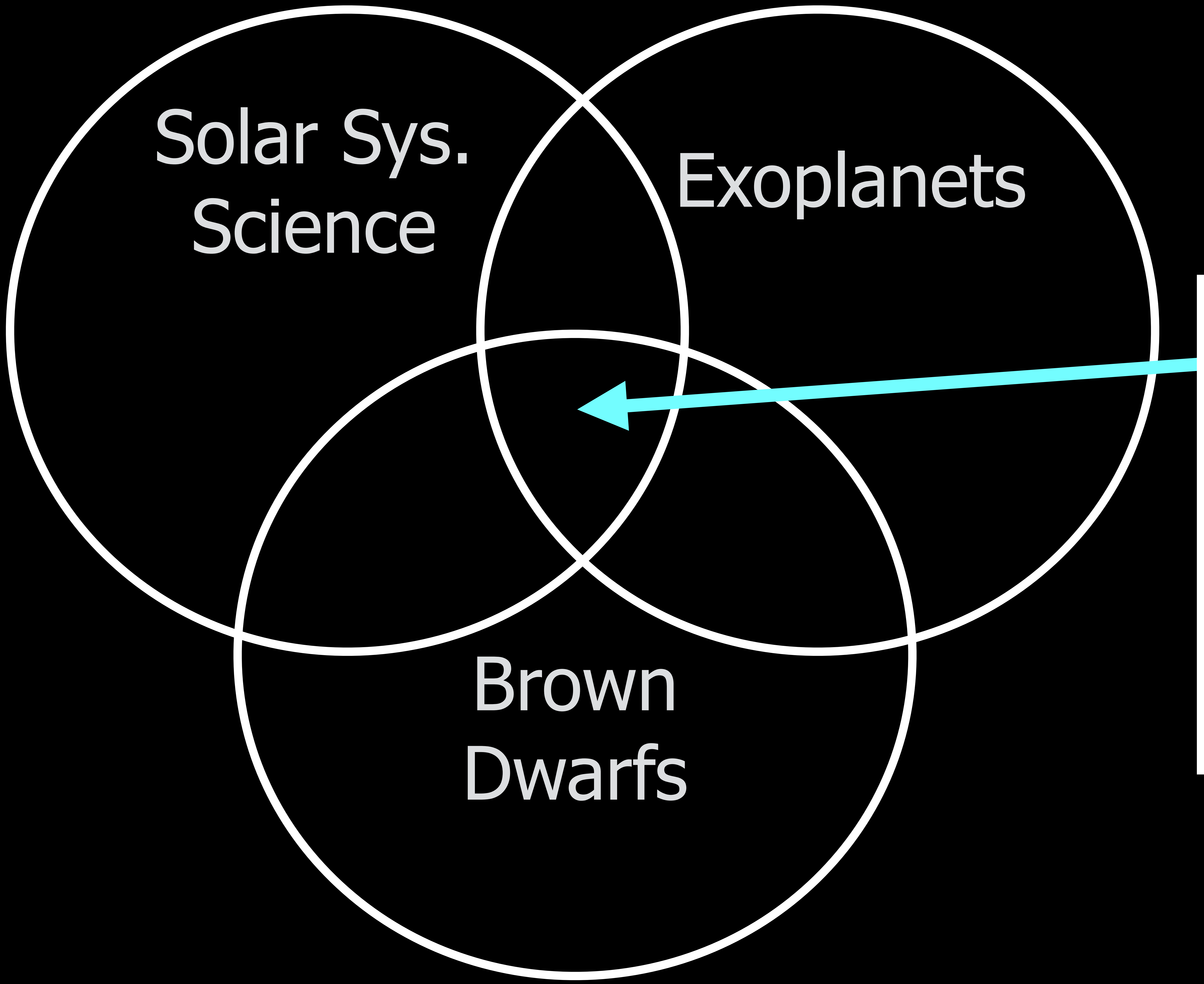
The Dusty Atmosphere of the Brown Dwarf Gliese 229B

Caitlin A. Griffith, Roger V. Yelle, Mark S. Marley



- Atmospheric Processes
  - Energy transport
  - Chemistry
  - Clouds
  - Photochemistry
  - Dynamics

Atmospheric Processes are Central

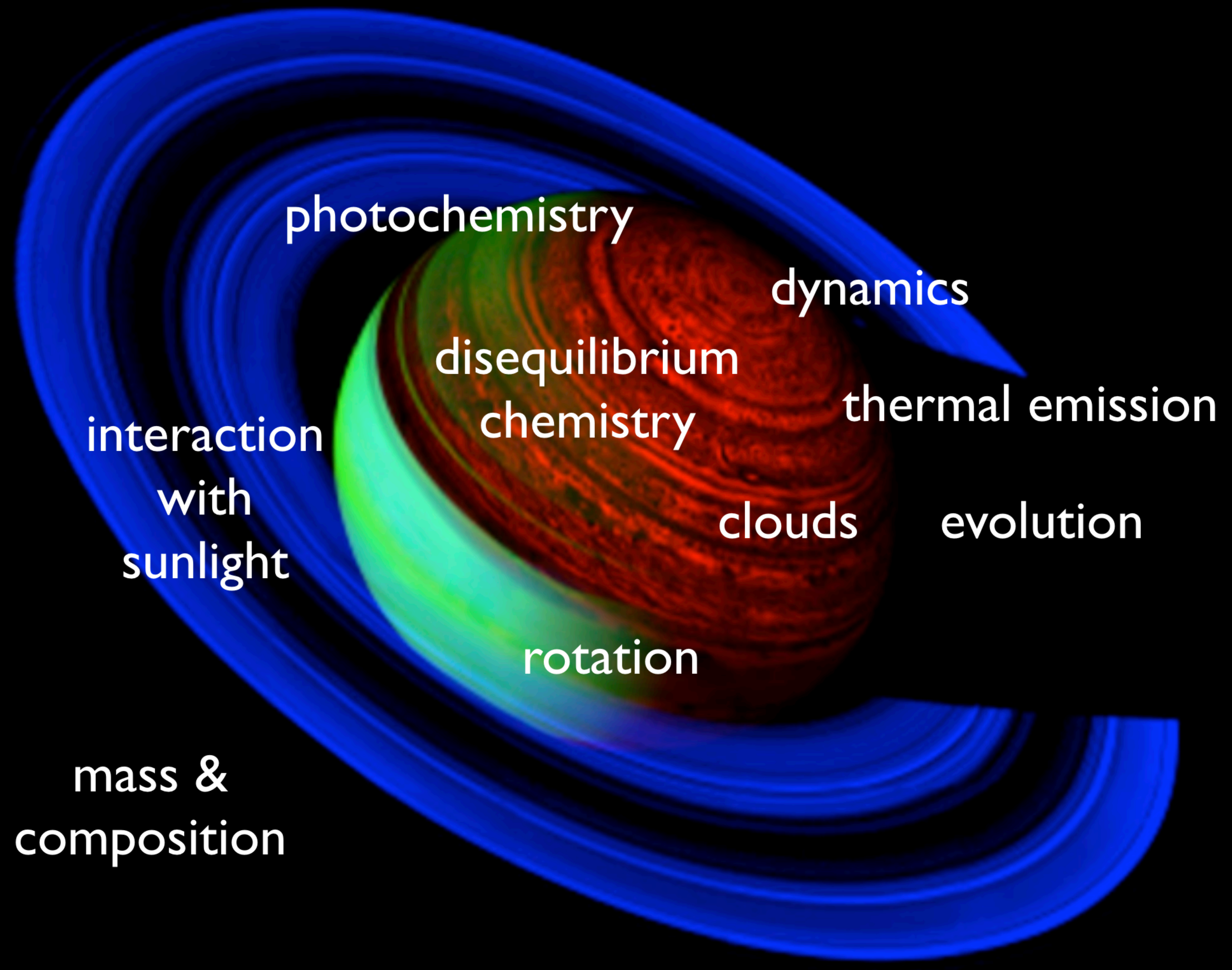
Energy is absorbed from incident starlight as well as transported up from interior and radiated away to space. The atmosphere is the gatekeeper for evolution, chemistry, clouds, and ultimately all observed spectra.

Brown dwarfs test our understanding of atmospheric processes and connect to solar system and extrasolar giant planets.

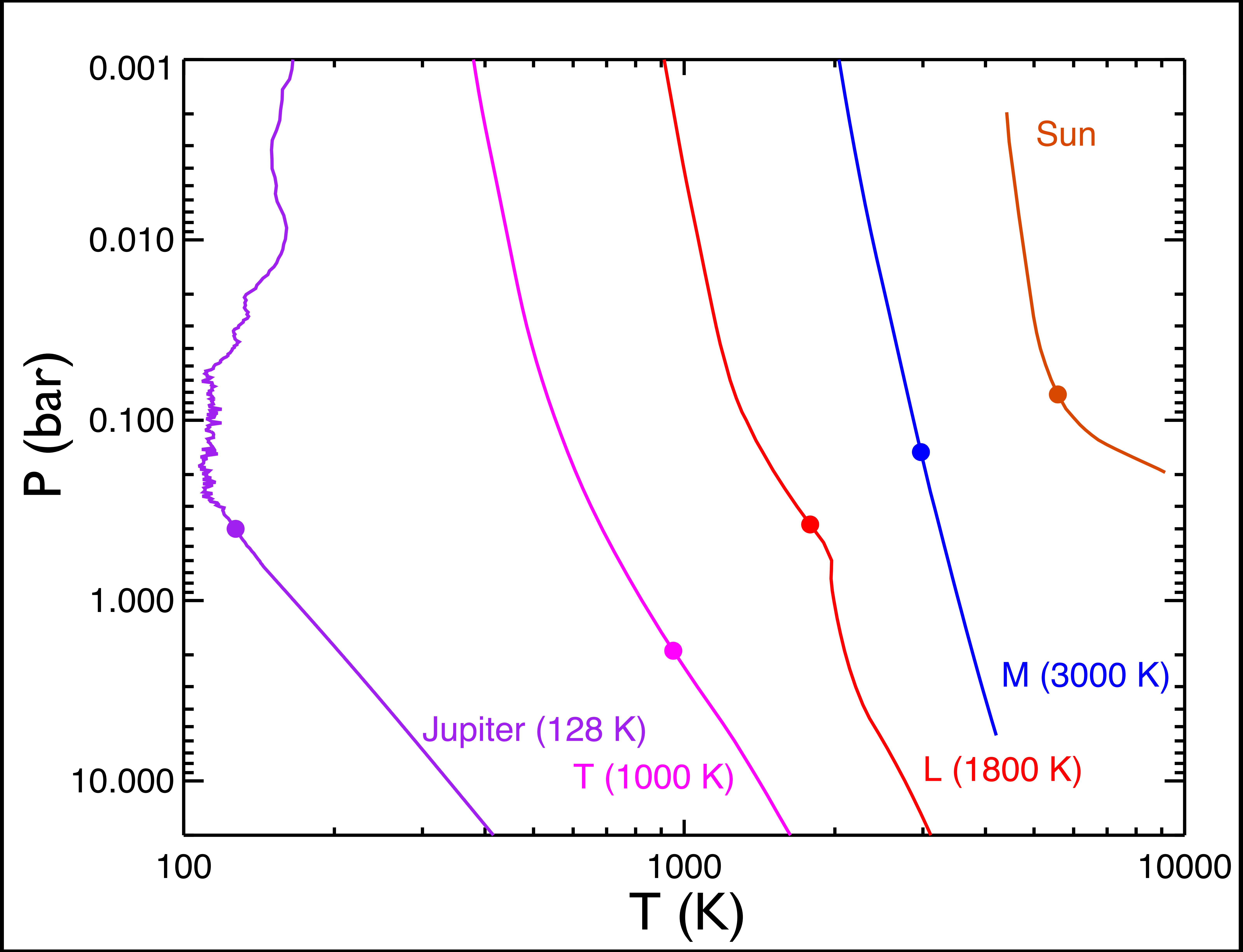
Goal is understanding of processes, not just reporting numbers.

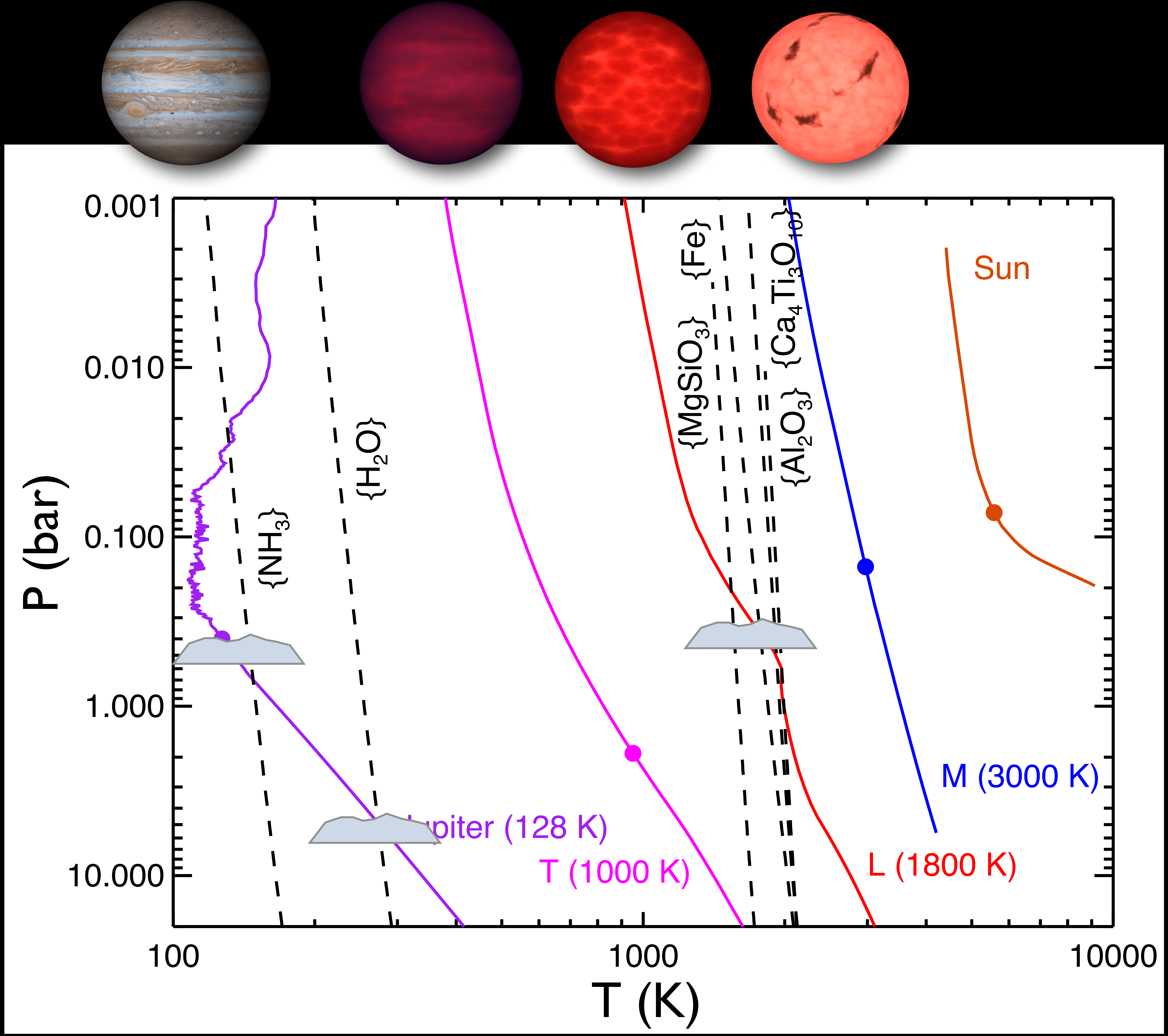
Today

- Short reminder on brown dwarf atmospheres and evolution
- A selection of lessons learned
  - Clouds
  - Hazes
  - Chemistry
    - Rainout
    - Disequilibrium chemistry
- Concluding thoughts and advice



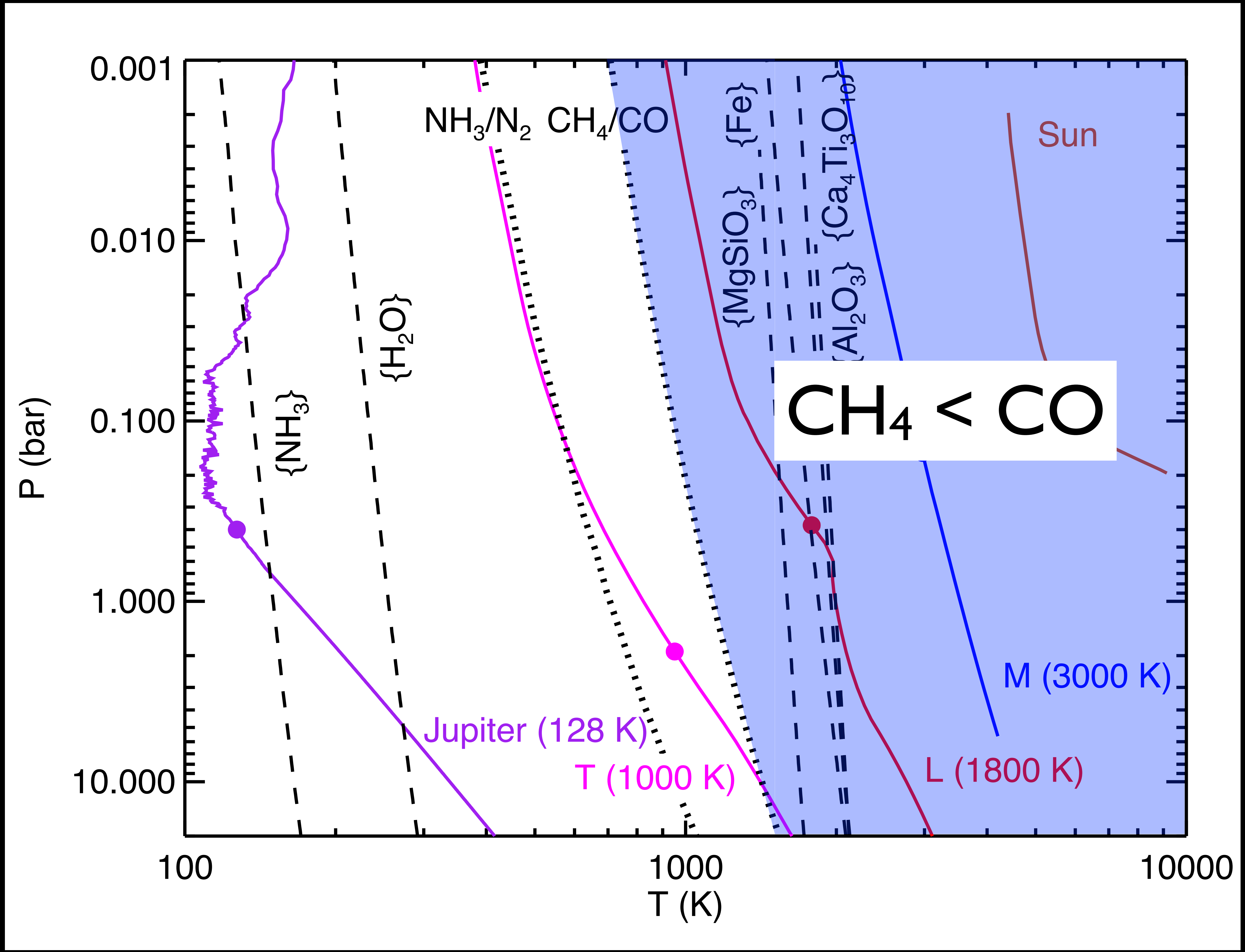
Atmospheres in Context



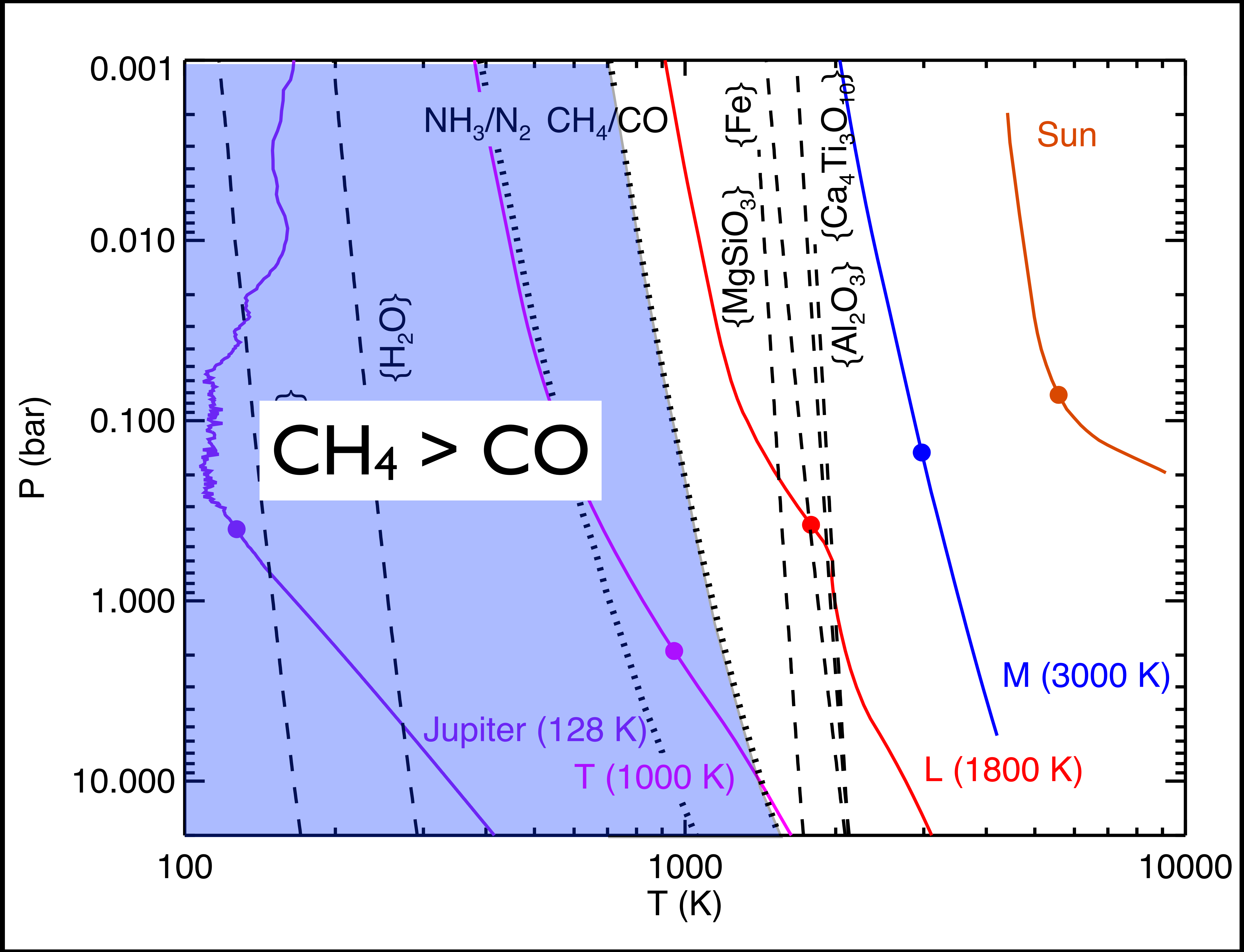


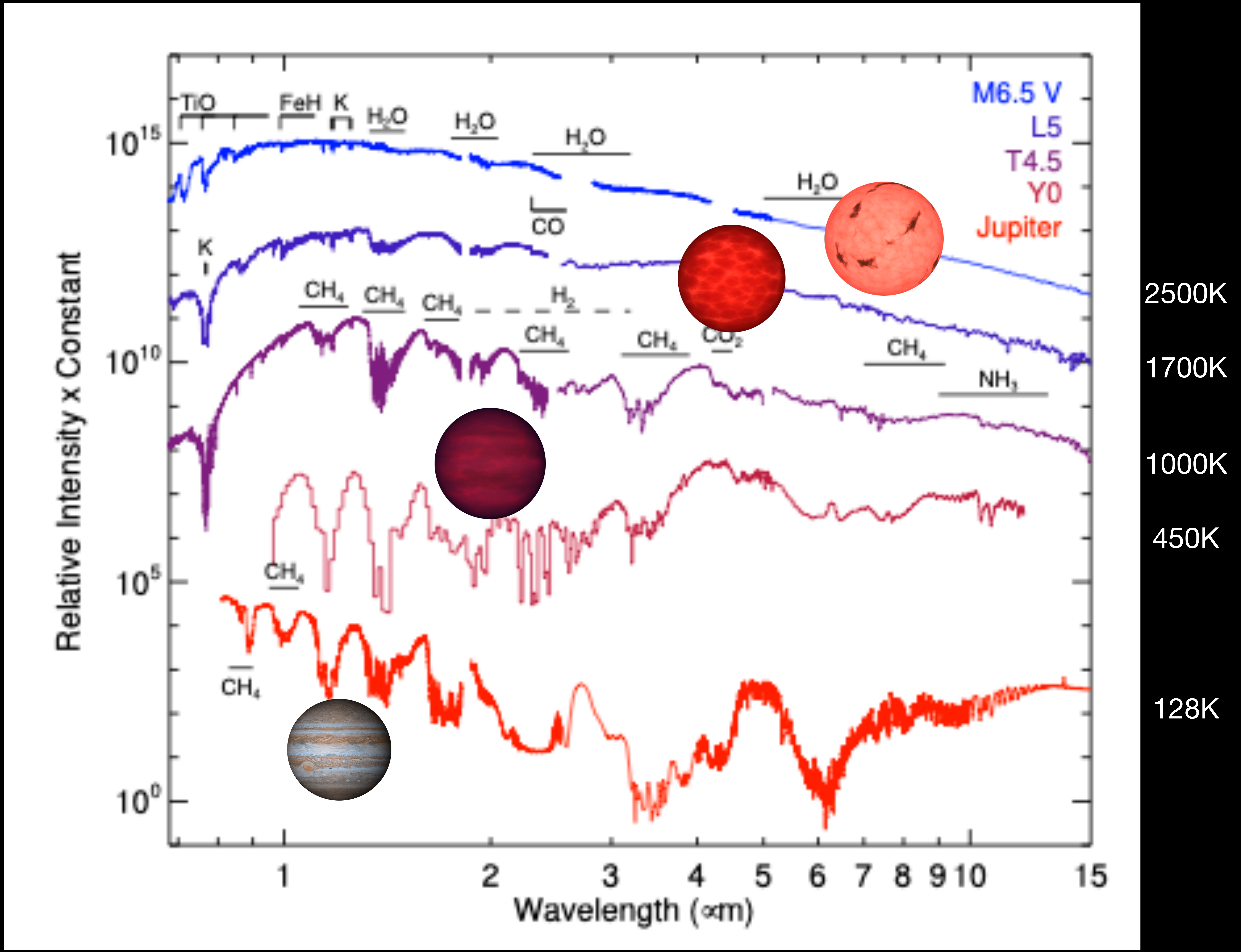
0.001
0.010
0.100
1.000
10.000
P (bar)
100
1000
10000
T (K)
{NH_3}
{H_2O}
{$MgSiO_3$}
{Fe}
{Al_2O_3}
{$Ca_4Ti_3O_{10}$}
Sun
M (3000 K)
L (1800 K)
T (1000 K)
upiter (128 K)

Chemical Equilibrium Transition



Chemical Transition




M6.5 V
L5
T4.5
Y0
Jupiter
TiO
FeH
K
H2O
CO
CH4
H2
CO2
NH3
Relative Intensity x Constant
Wavelength (∝m)
2500K
1700K
1000K
450K
128K

M. Cushing

Jupiter 130K
WISEJ2209+27 JWST - Beiler, Cushing+ 370K
Fν (mJy) Normalized
Wavelength (μm)
0
1
2
3
4
5
6
7
4
5
6
7
8
9
10
12

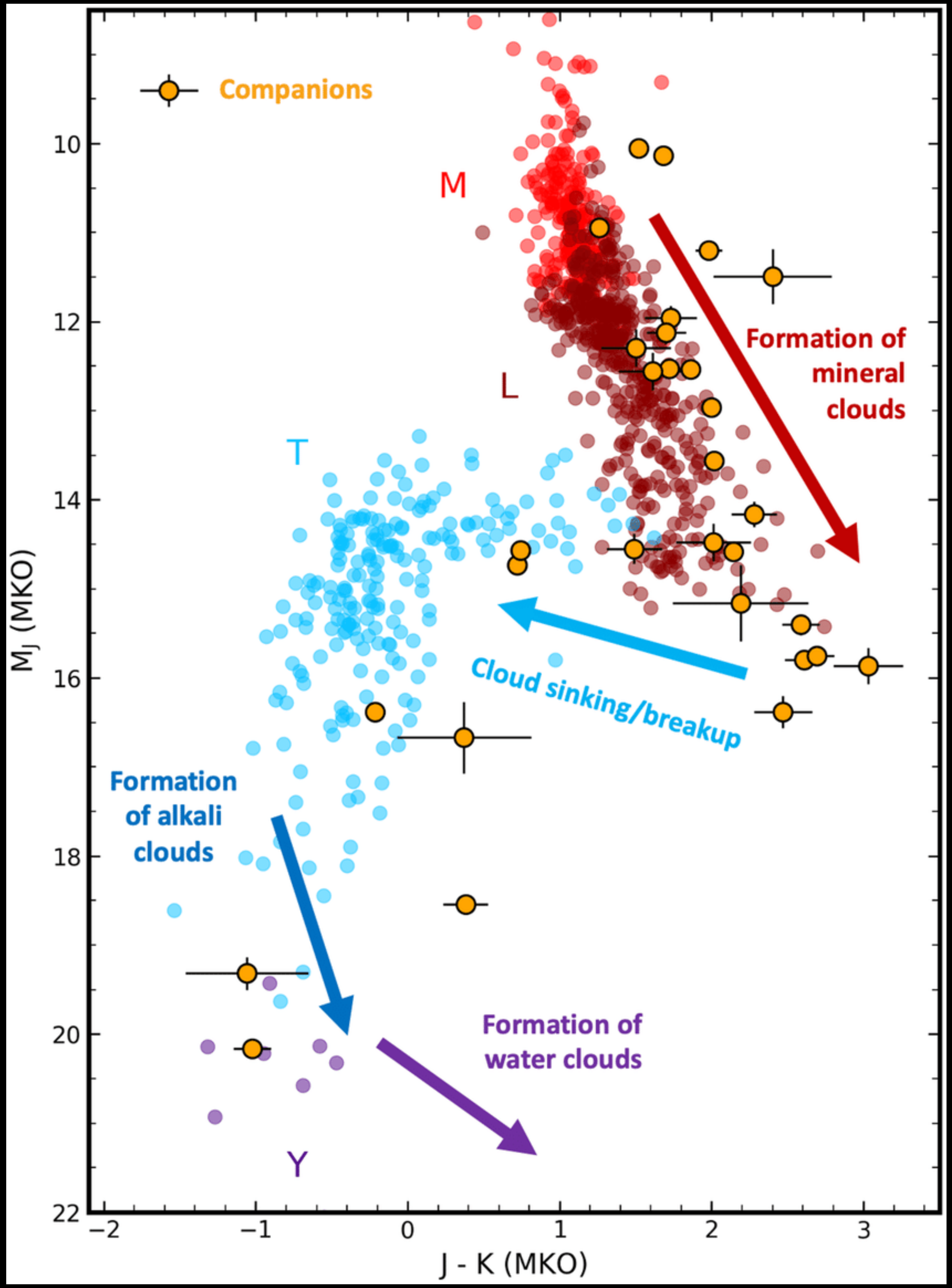
LESSONS


Clouds

Clouds

- Long been appreciated that clouds would condense (since 60s)
- Cloud behavior is fundamental aspect of brown dwarf spectra and photometry
- Clouds are intrinsically 3D but need to start with 1D to solve
  - Particle composition, size, distribution matter
  - Possible time variability
- Easy to see their effects but hard to fingerprint

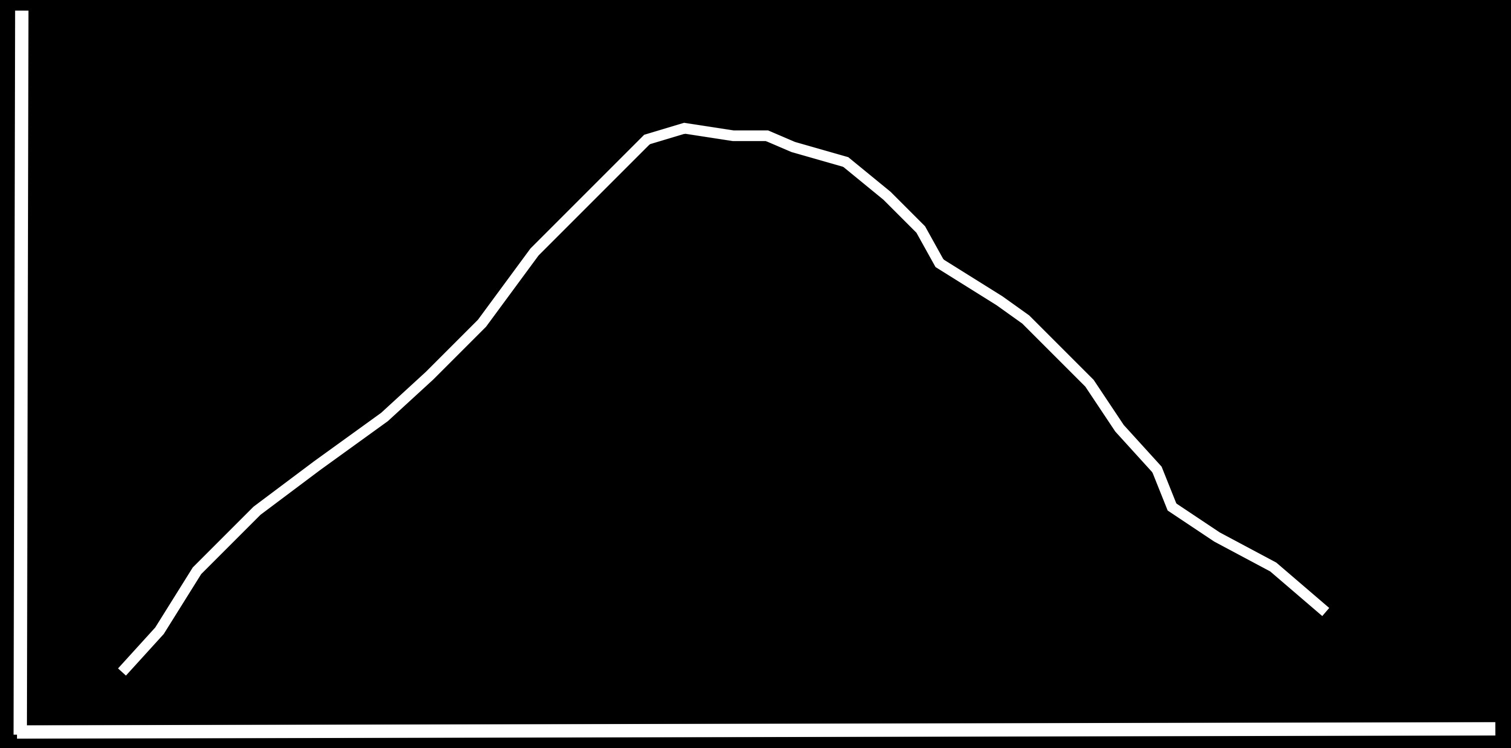
J



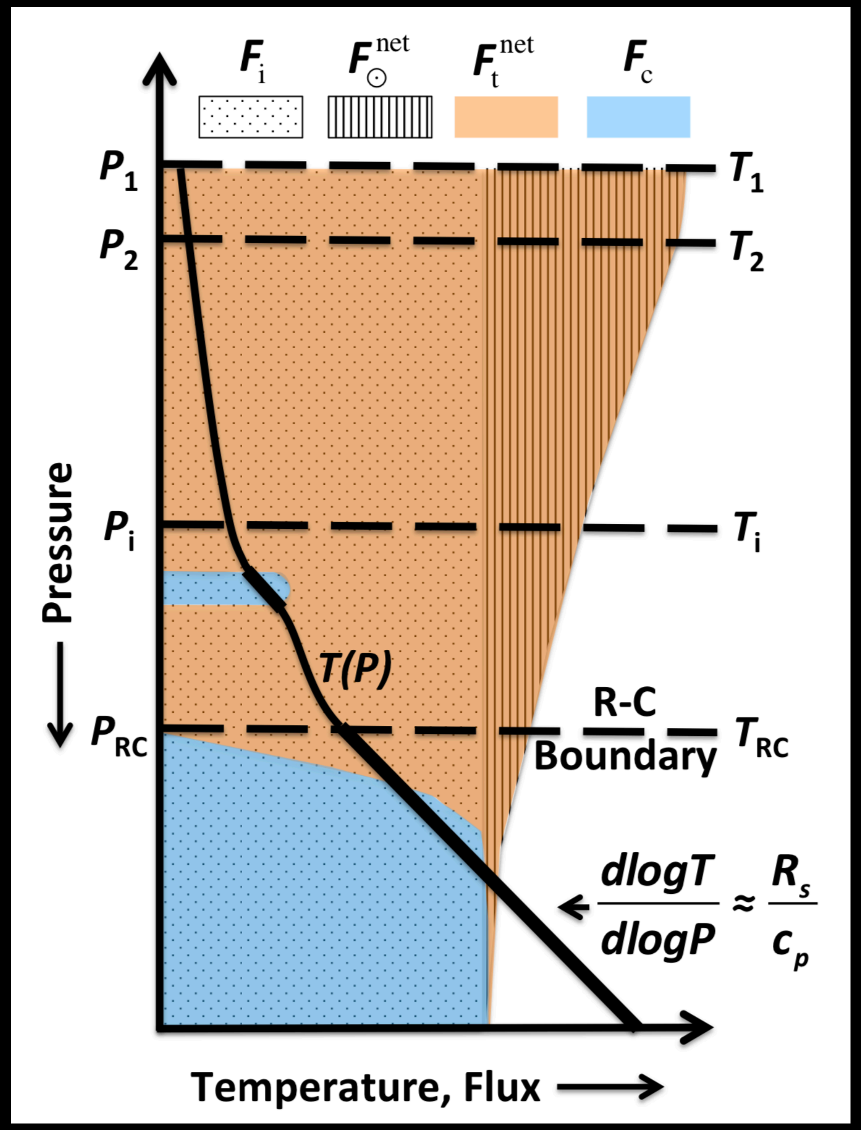
J-K

Gao+ (2021)

Thermal Emission



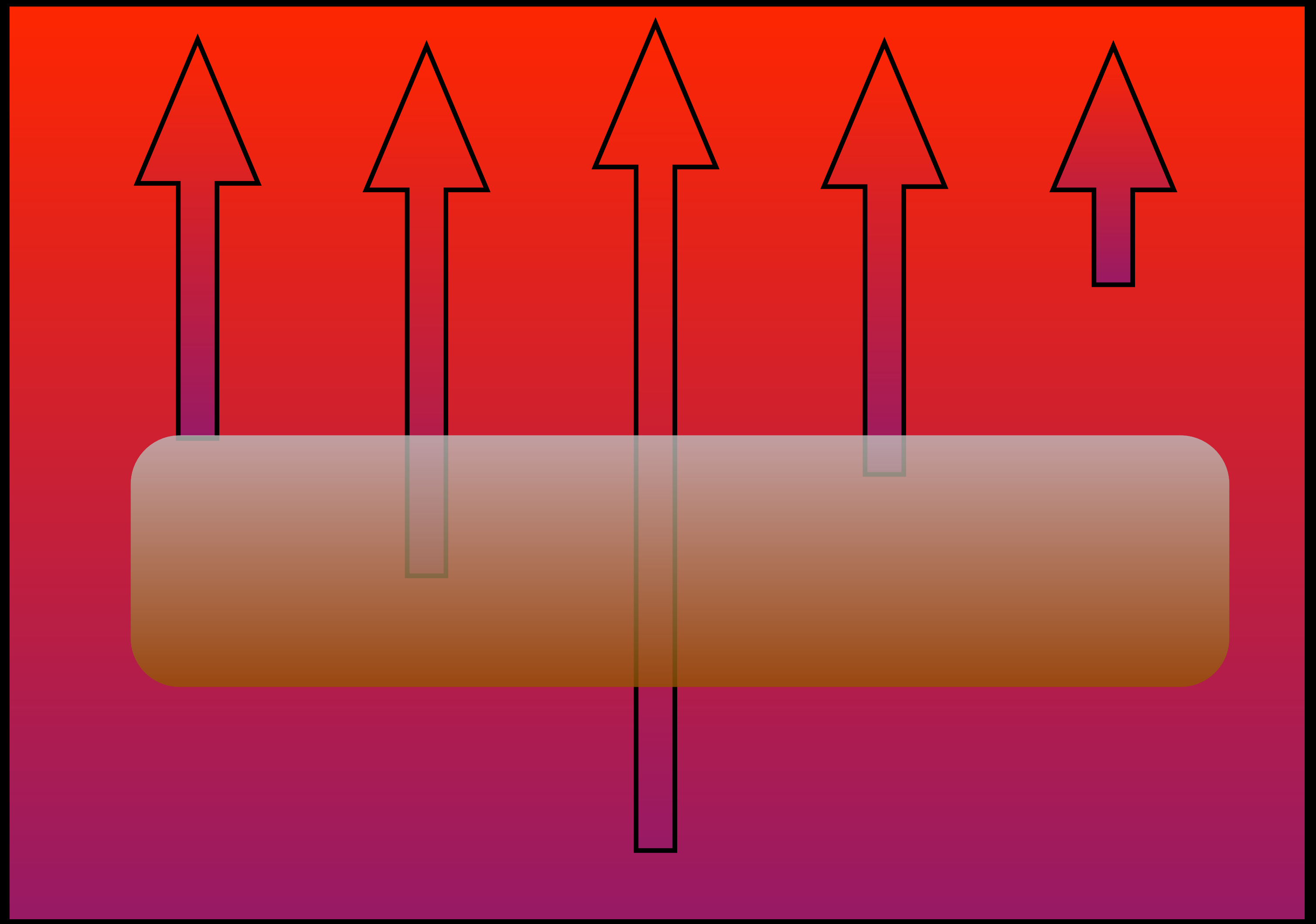
Cloudless

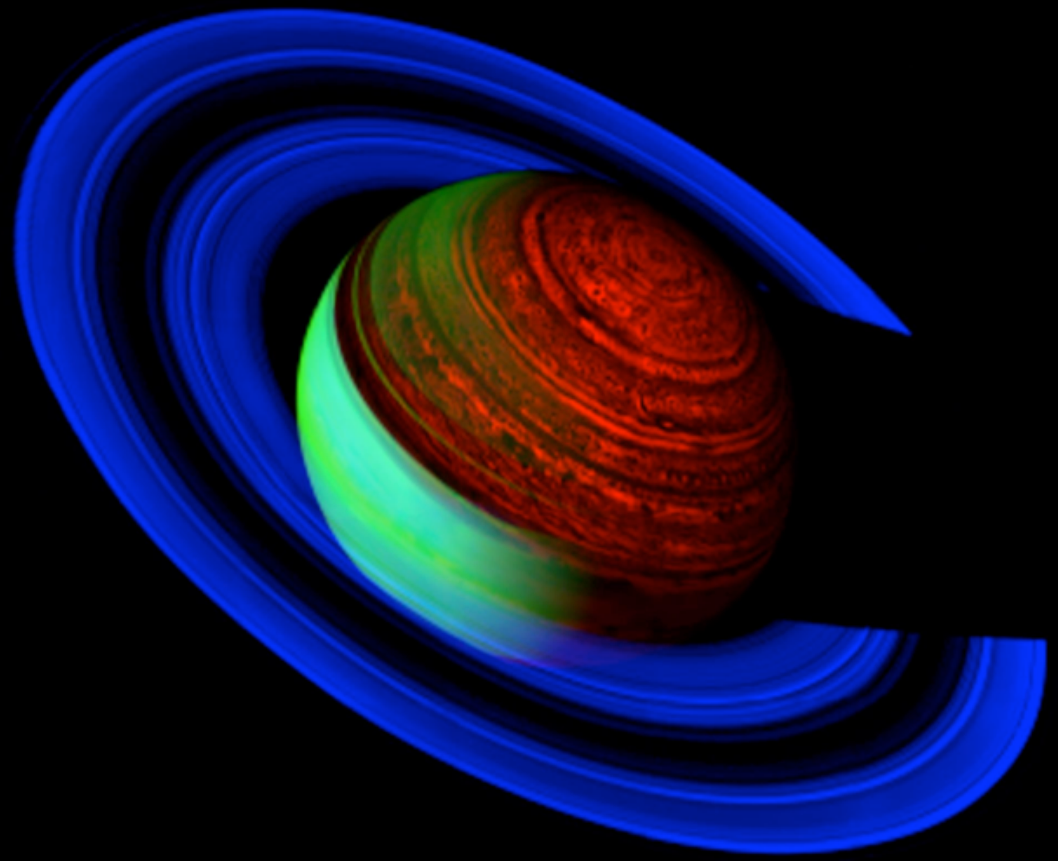


Marley & Robinson (2016)

Cool

Hot

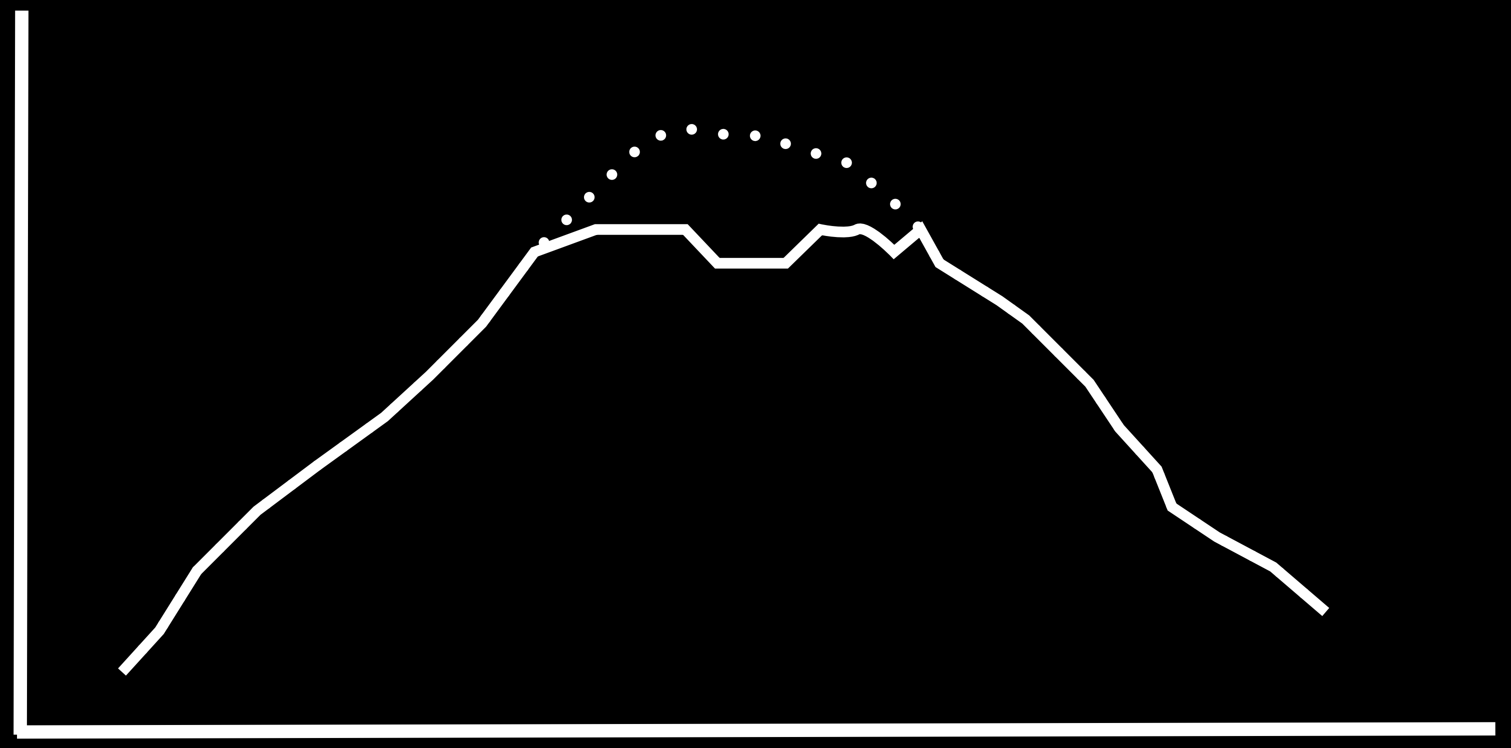




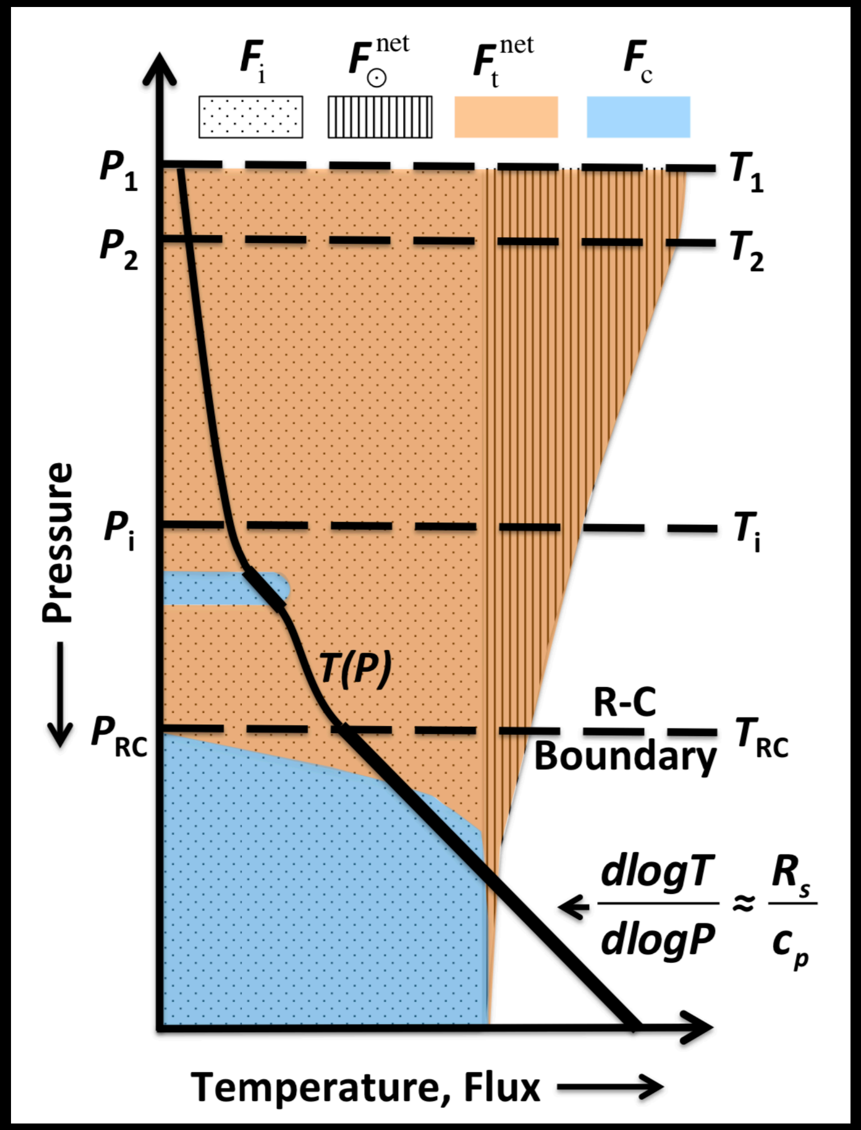
Wavelength →

Thermal Emission

T_{brt}
or
Flux



Cloudy



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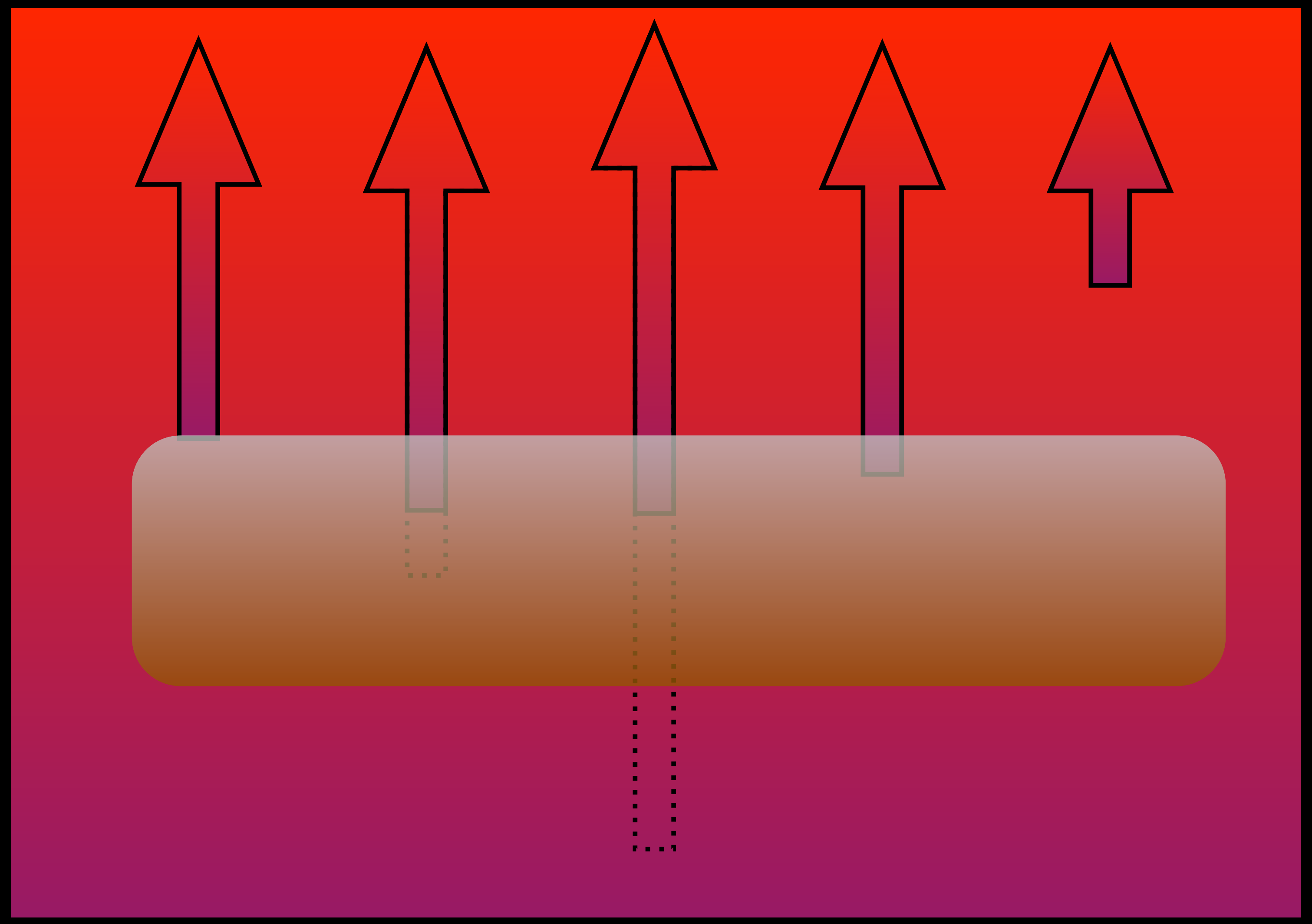
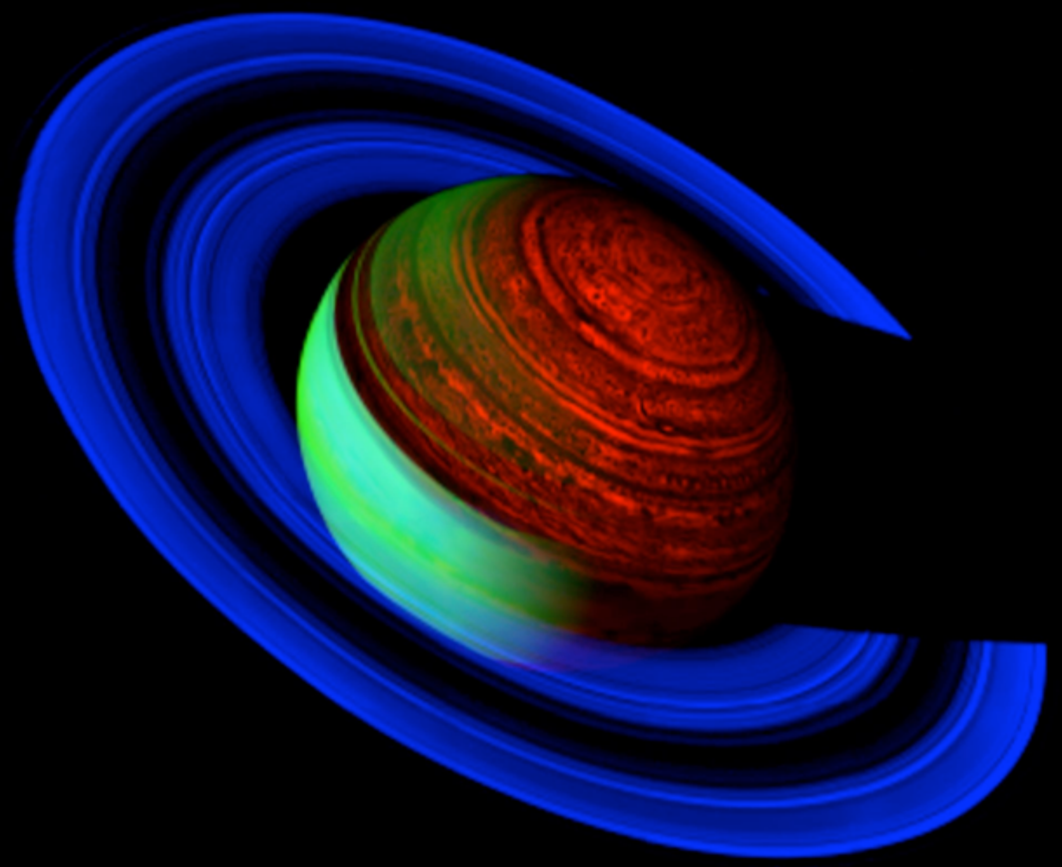
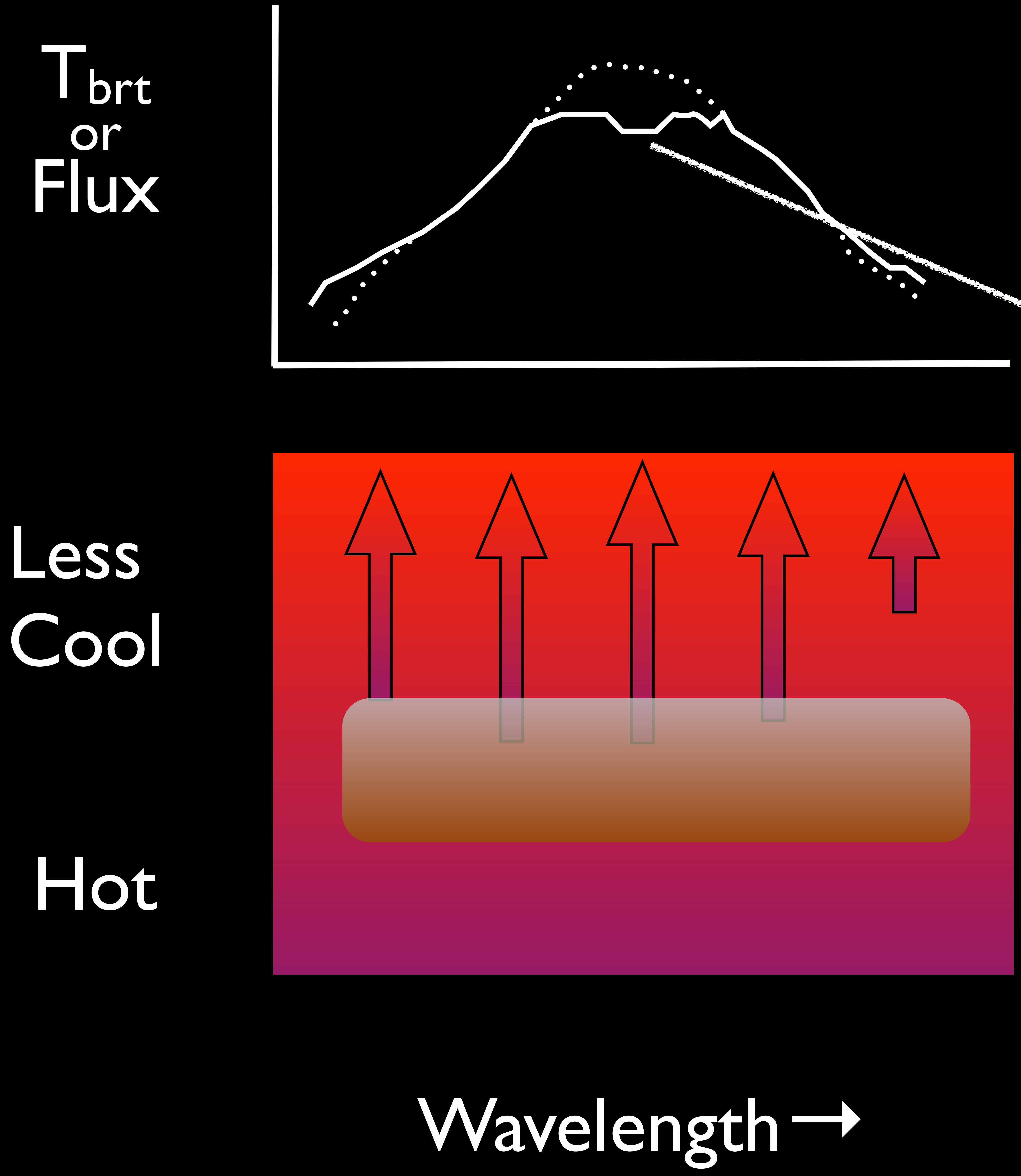
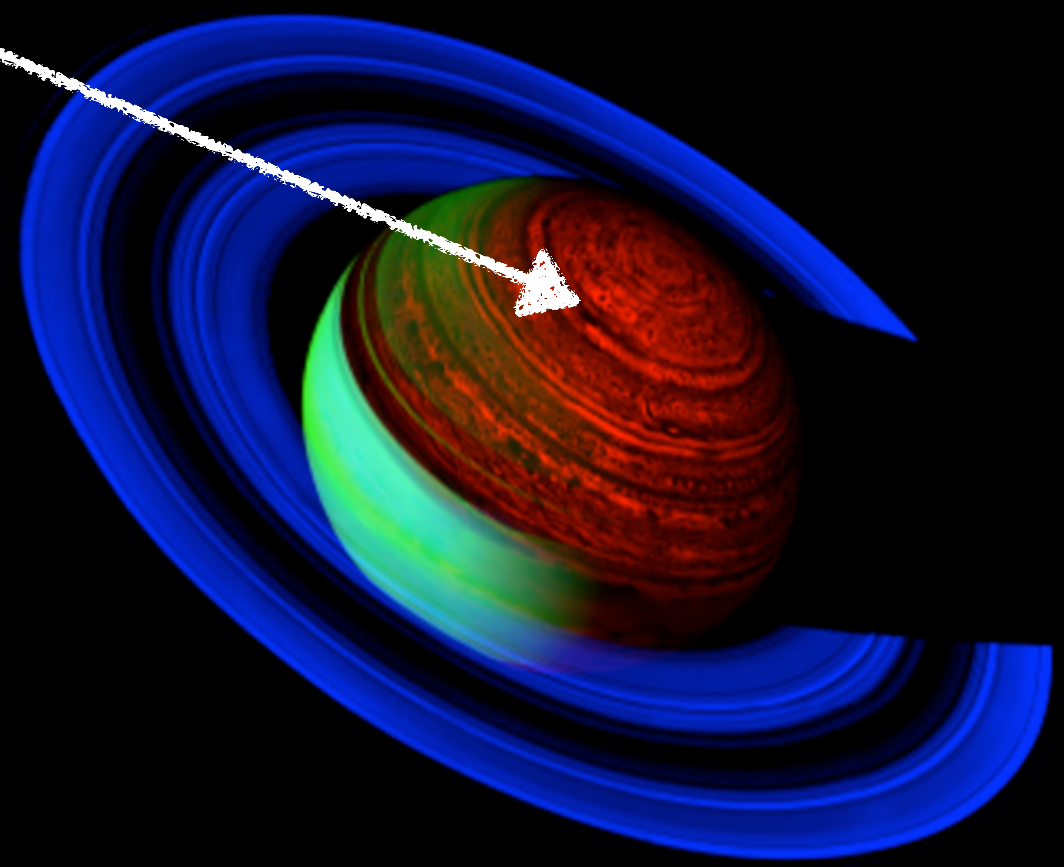


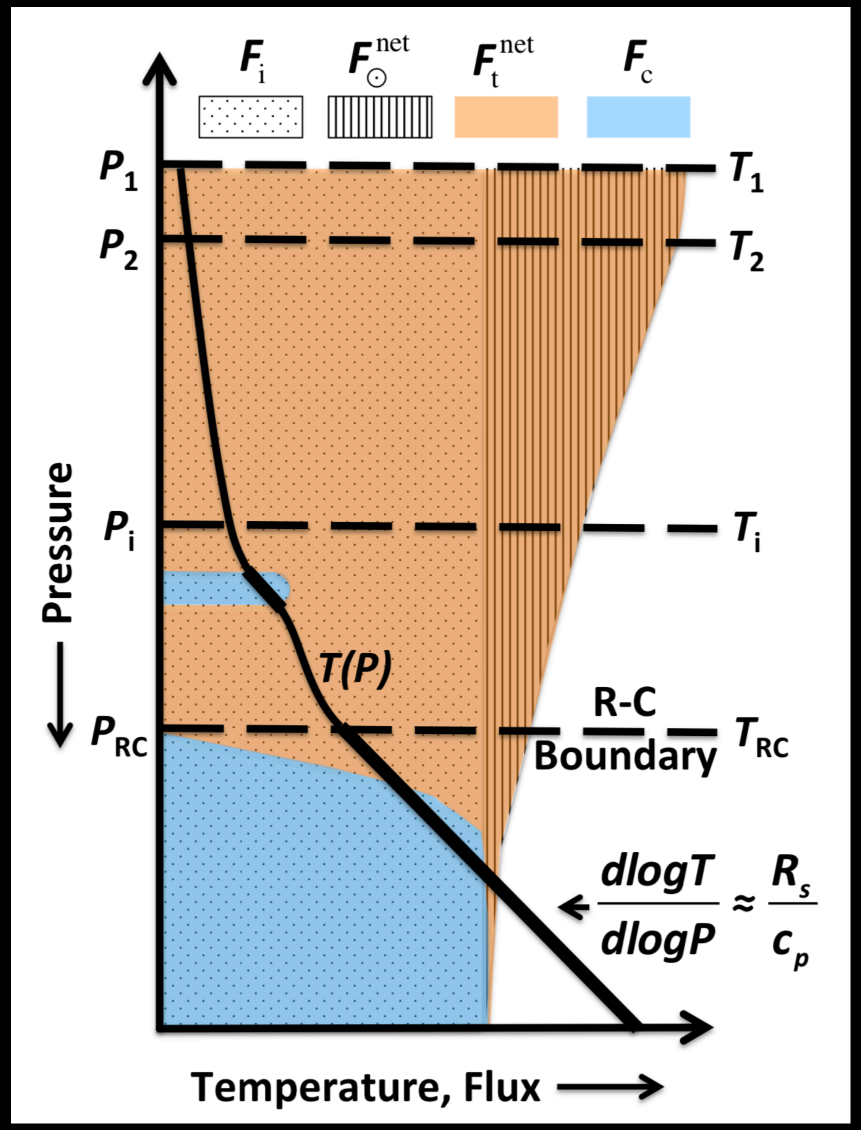


Wavelength →

Thermal Emission



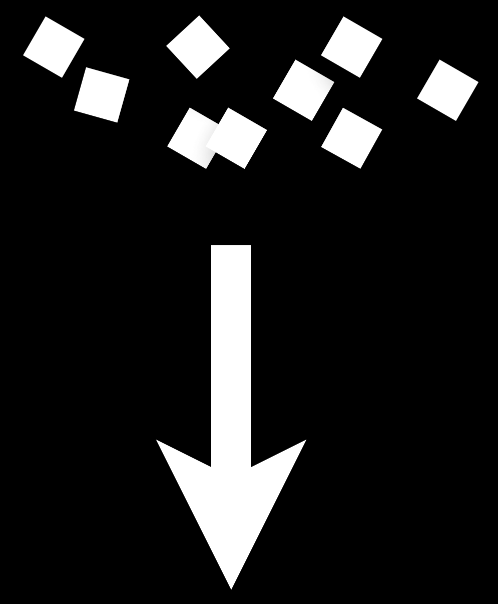




Marley & Robinson (2016)

Cloud Modeling Schools

Top - Down

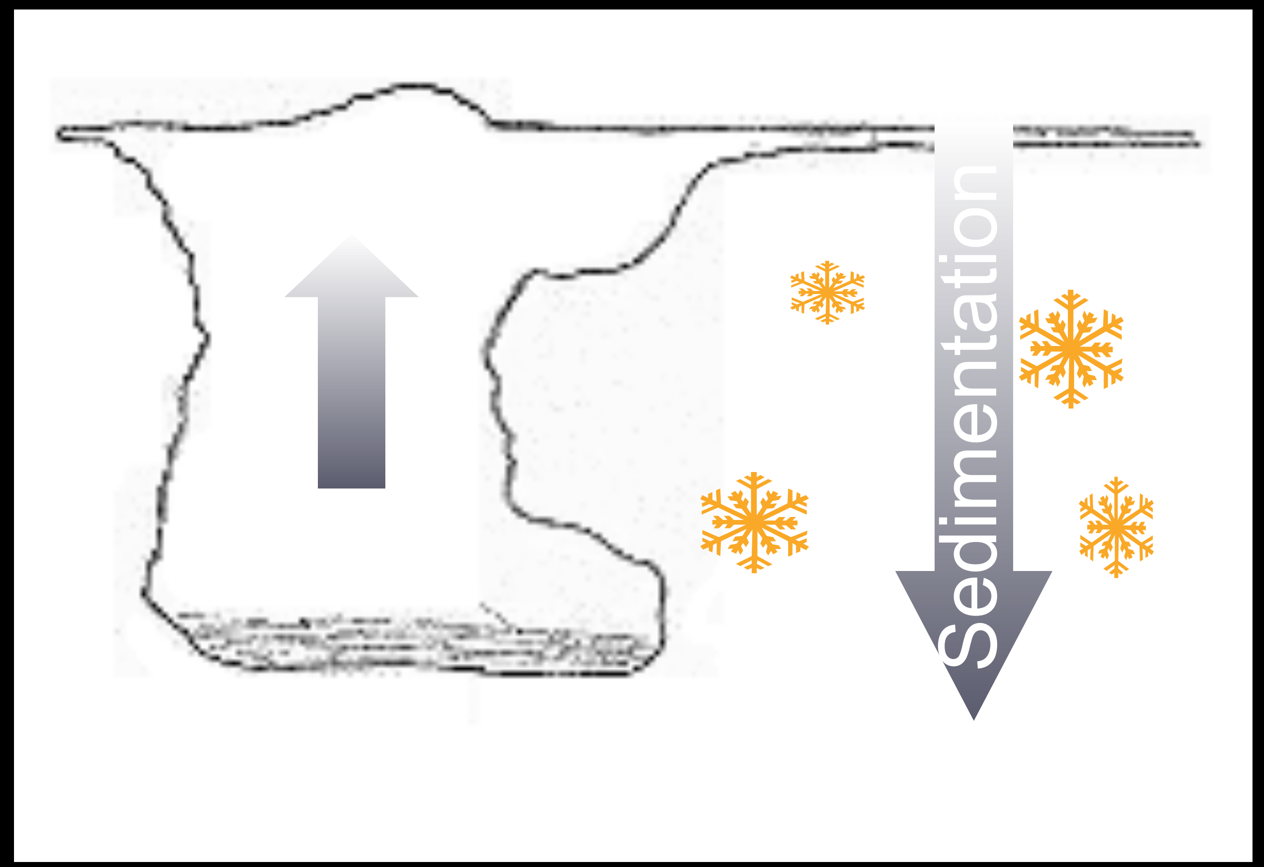


Helling et al.
CARMA

Fixed

Tsuji, Burrows

Bottom - Up



Ackerman & Marley,
PICASO
Exo-REM (Charnay et al.)

Chemical Equilibrium

PHOENIX - DUSTY

Cloud Modeling Schools

Top - Down

Microphysics
Need seeds up here

Helling et al.
CARMA

Fixed

Tsuji, Burrows

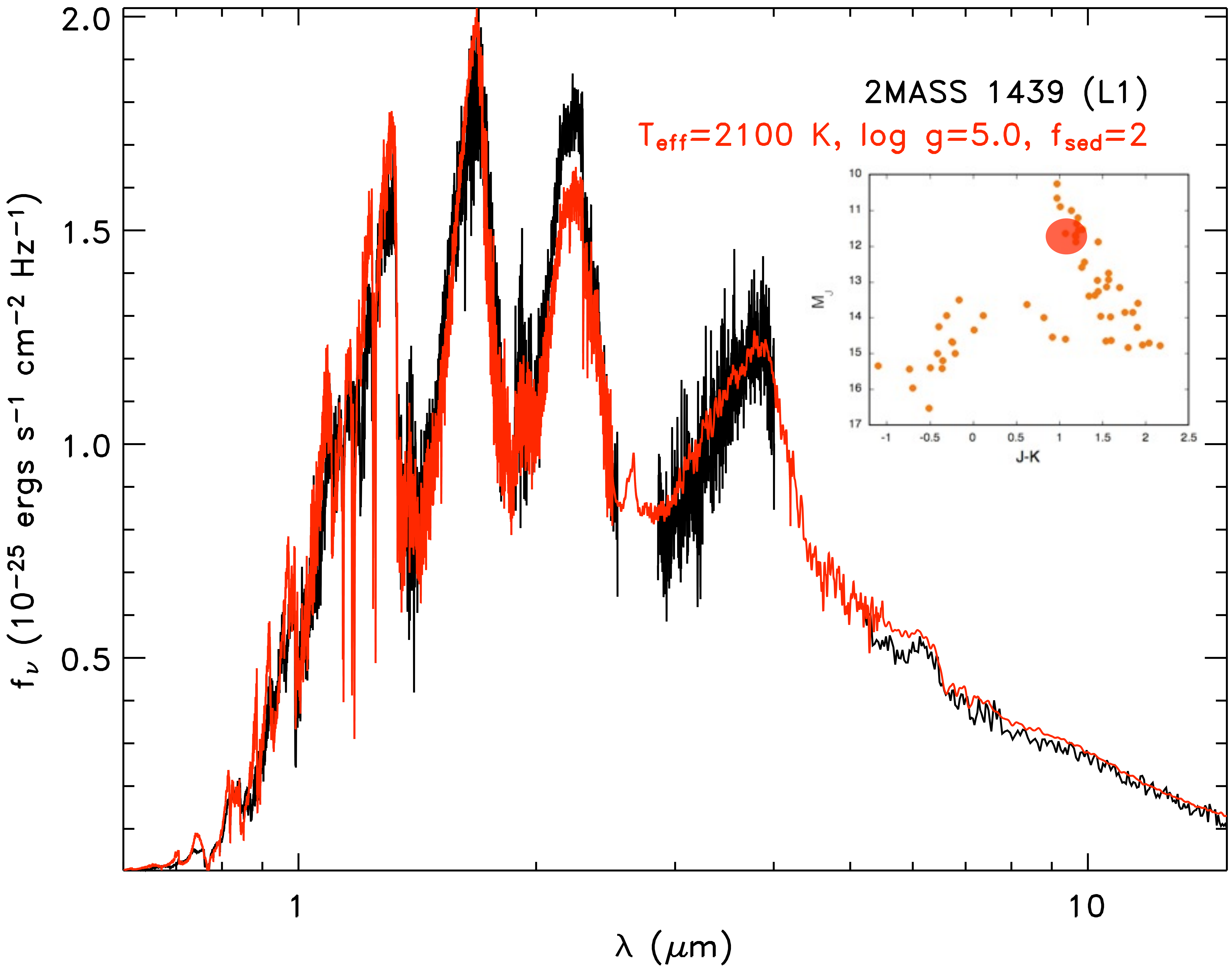
Bottom - Up

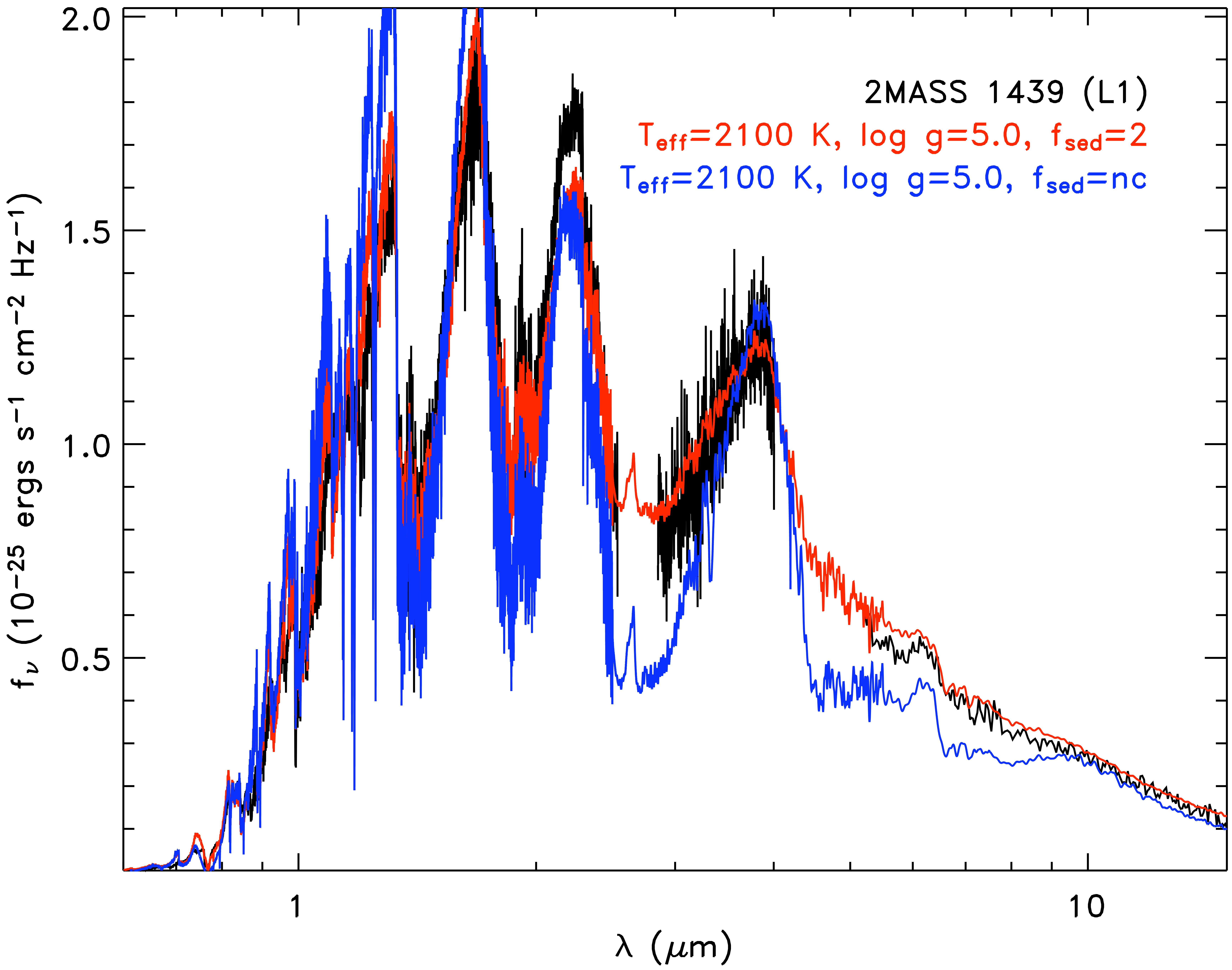
No microphysics
Not really 3D

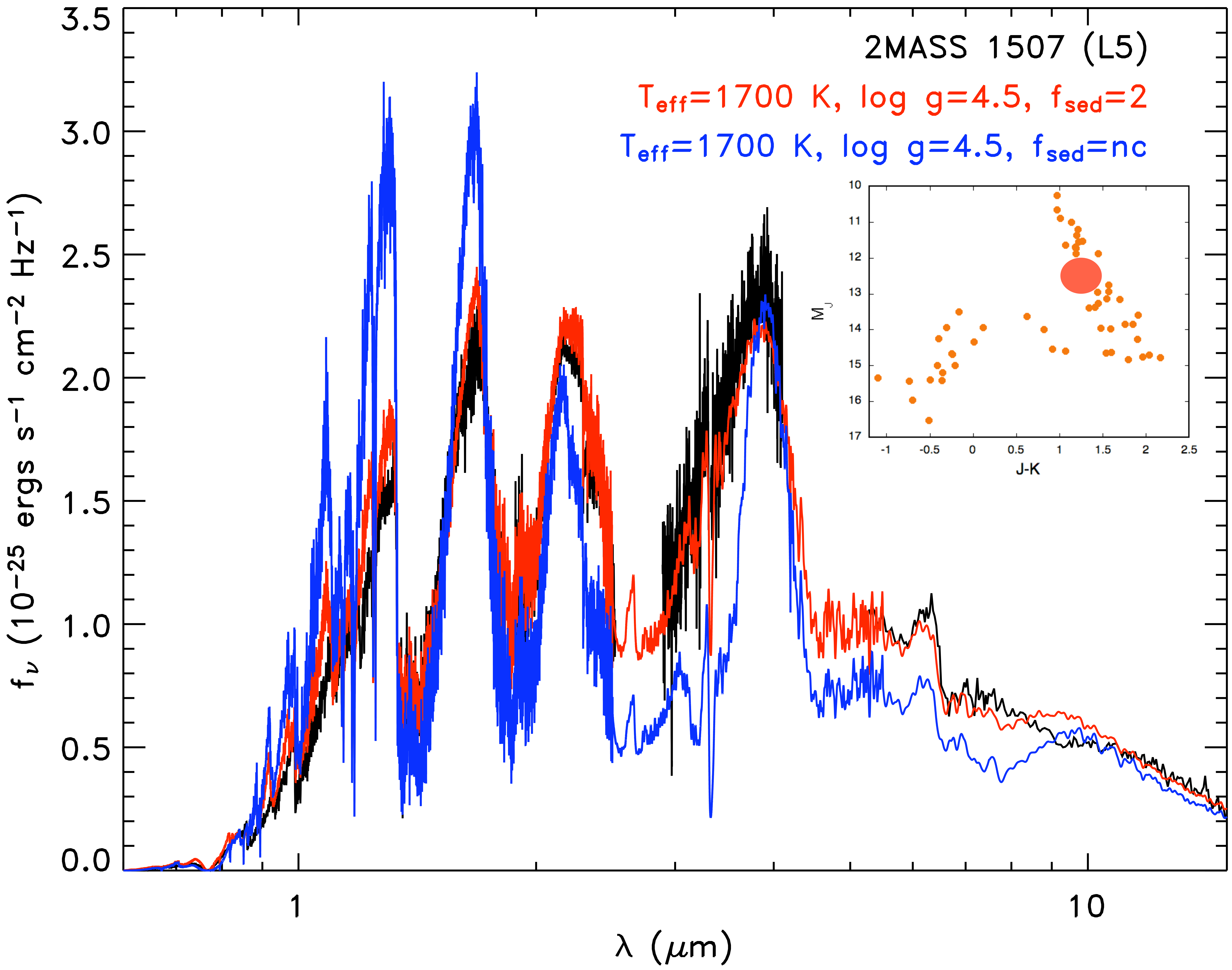
Ackerman & Marley,
Eddysed VIRGA
Exo-REM (Charnay et al.)

Chemical Equilibrium

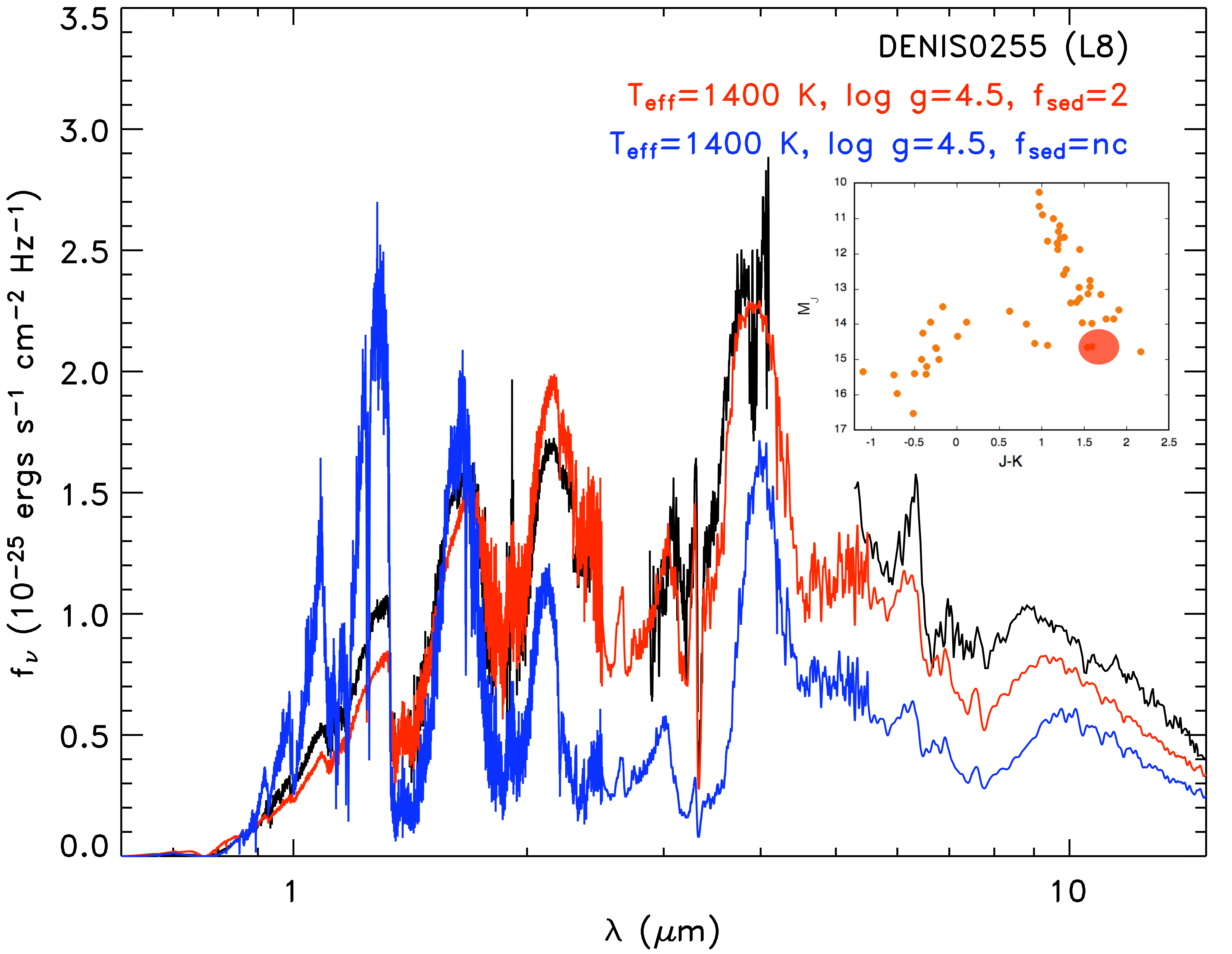
PHOENIX - DUSTY

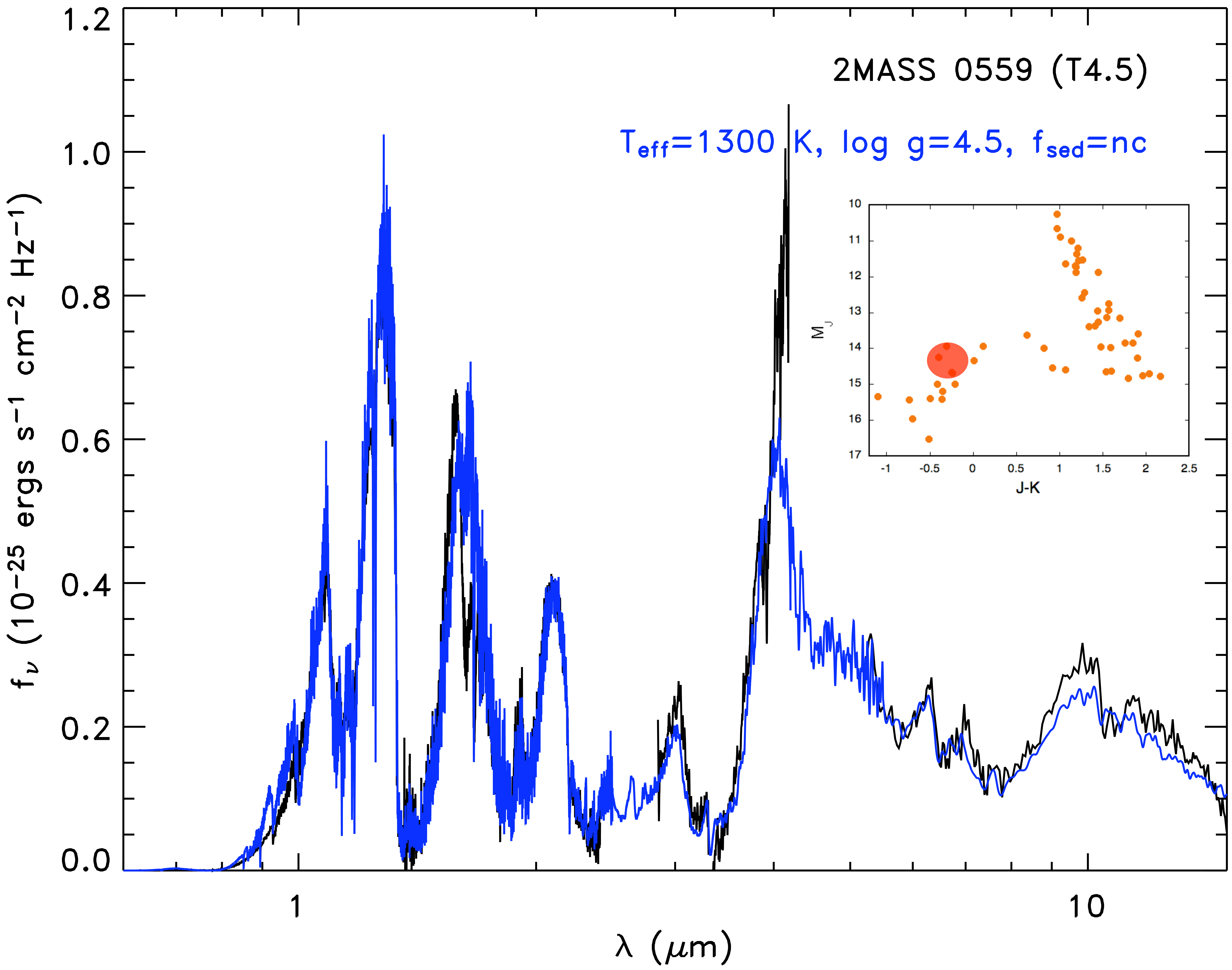

2MASS 1439 (L1)
T_eff=2100 K, log g=5.0, f_sed=2
f_ν (10^−25 ergs s^−1 cm^−2 Hz^−1)
2.0
1.5
1.0
0.5
1
10
λ (μm)
M_J
J-K
10
11
12
13
14
15
16
17
-1
-0.5
0
0.5
1
1.5
2
2.5


2MASS 1439 (L1)
T_eff=2100 K, log g=5.0, f_sed=2
T_eff=2100 K, log g=5.0, f_sed=nc
f_ν (10^-25 ergs s^-1 cm^-2 Hz^-1)
λ (μm)
2.0
1.5
1.0
0.5
1
10

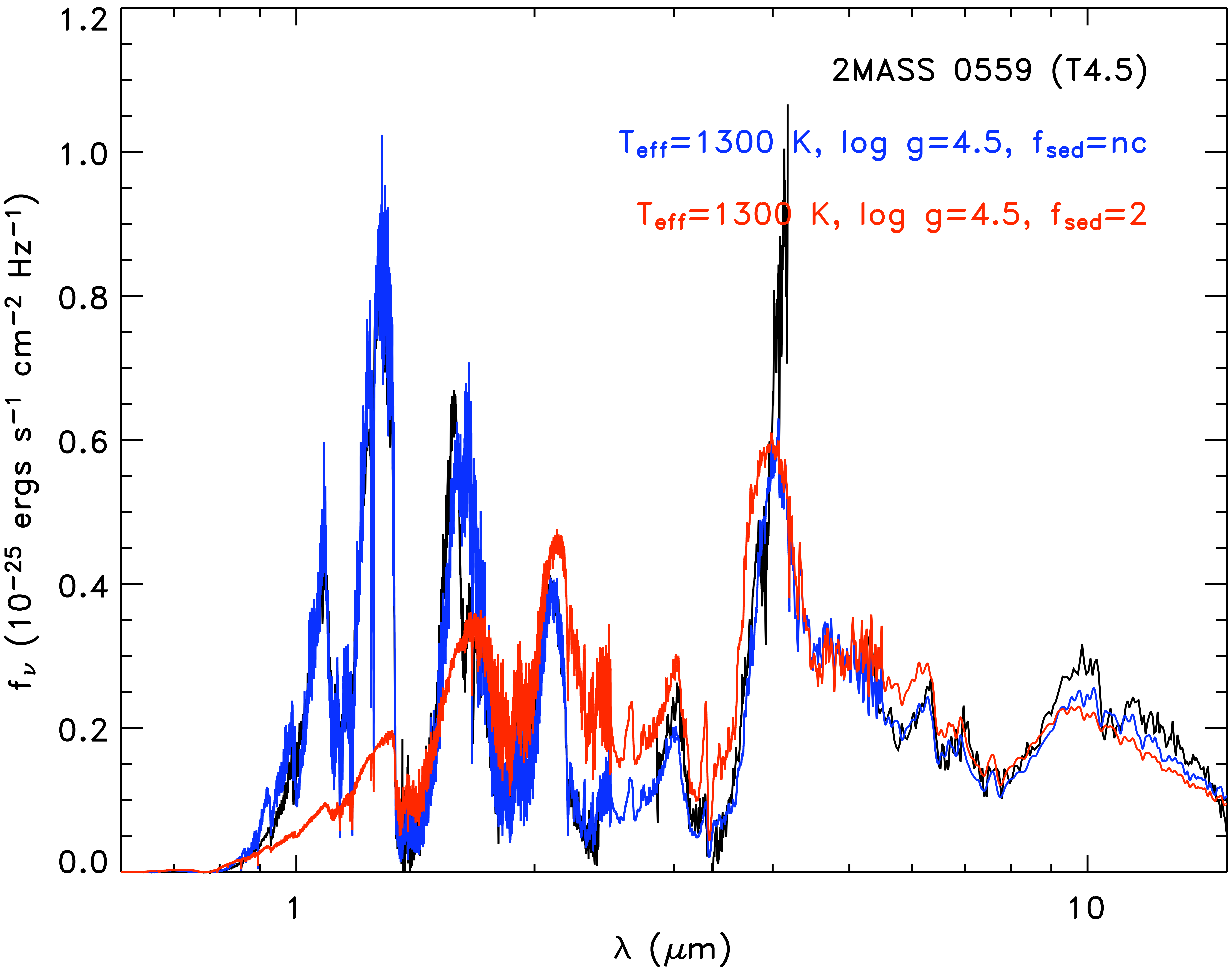


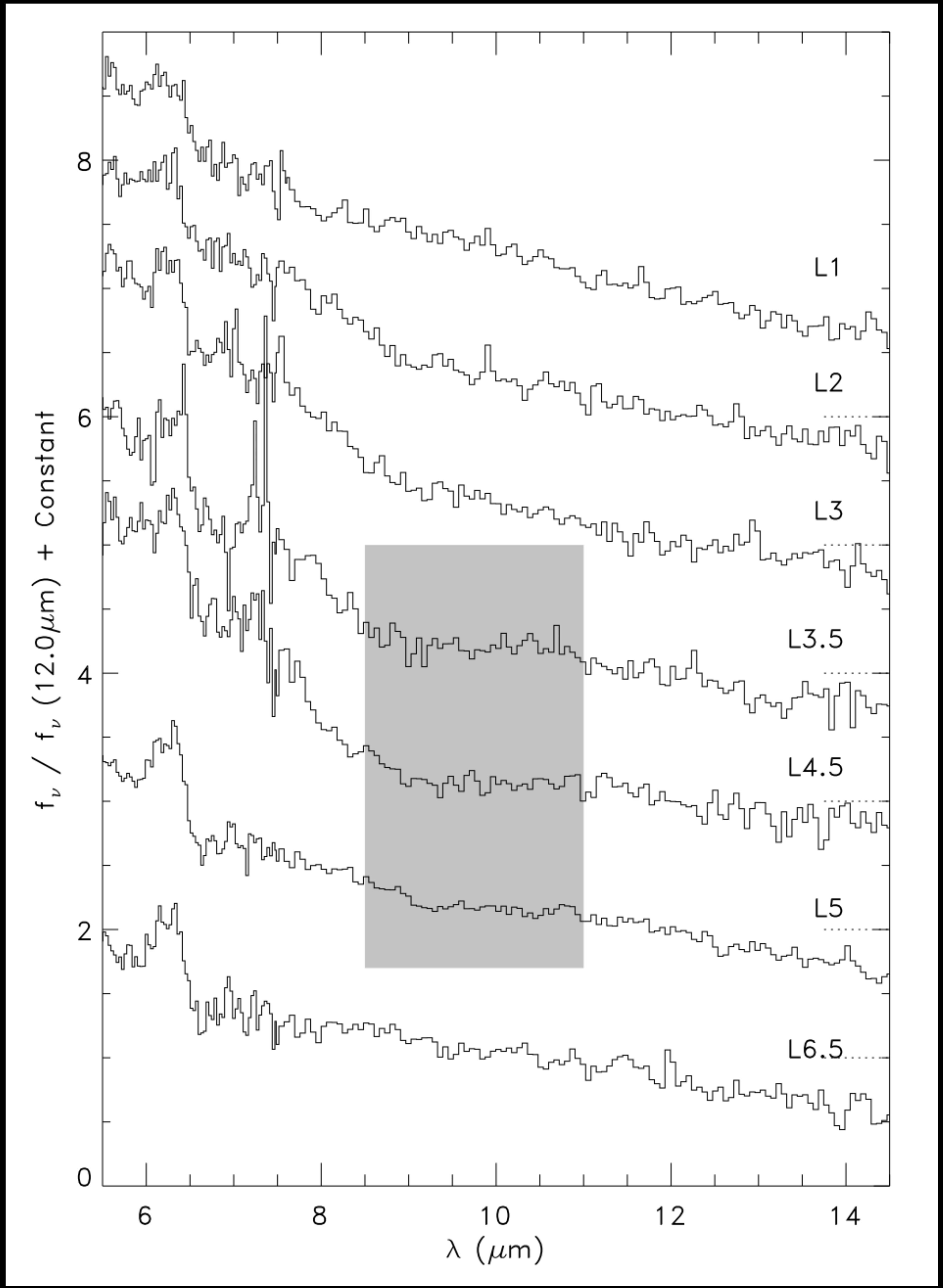
2MASS 1507 (L5)
T_{eff}=1700 K, log g=4.5, f_{sed}=2
T_{eff}=1700 K, log g=4.5, f_{sed}=nc
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
λ (μm)
M_J
J-K


DENIS0255 (L8)
T_eff=1400 K, log g=4.5, f_sed=2
T_eff=1400 K, log g=4.5, f_sed=nc
f_ν (10^-25 ergs s^-1 cm^-2 Hz^-1)
λ (μm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
10
M_J
J-K
10
11
12
13
14
15
16
17
-1
-0.5
0
0.5
1
1.5
2
2.5



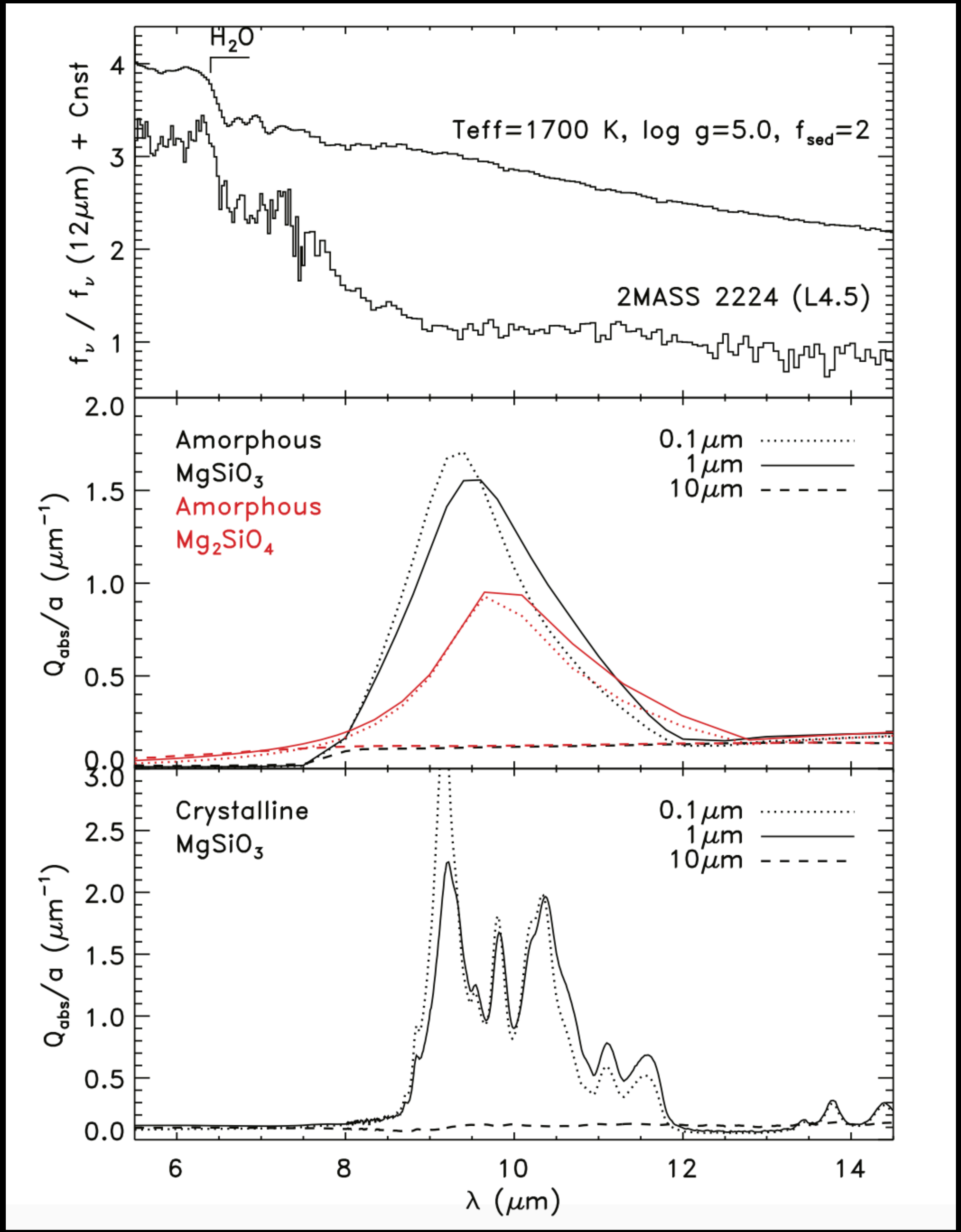
2MASS 0559 (T4.5)
T_{eff}=1300 K, log g=4.5, f_{sed}=nc
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
λ (μm)
M_J
J-K


2MASS 0559 (T4.5)
T_{eff}=1300 K, log g=4.5, f_{sed}=nc
T_{eff}=1300 K, log g=4.5, f_{sed}=2
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
λ (μm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1
10



Cushing+ (2006)

- Broadband signature is unmistakable
- Silicate absorption more subtle
- Easier with JWST
- Clouds can change dramatically in just 100K. Why?

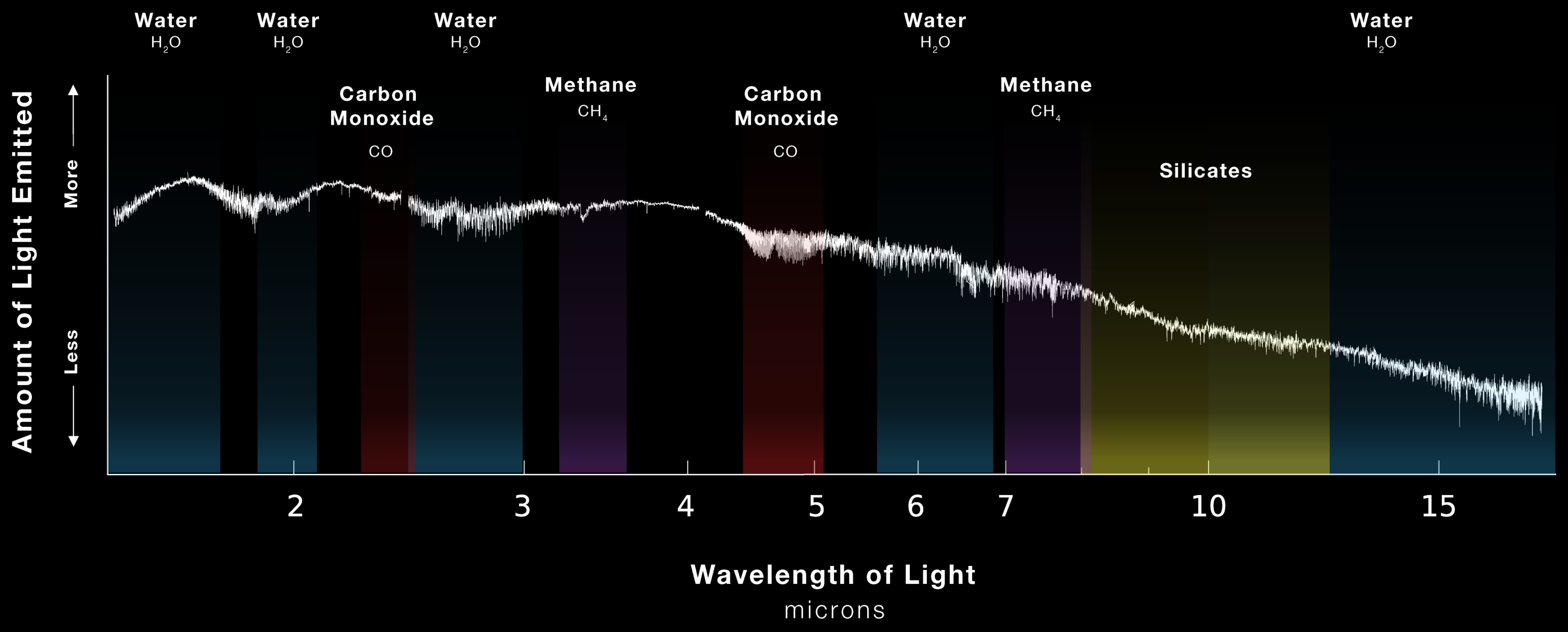


Cushing+ (2006)

EXOPLANET VHS 1256 b

EMISSION SPECTRUM

NIRSpec and MIRI | IFU Medium-Resolution Spectroscopy

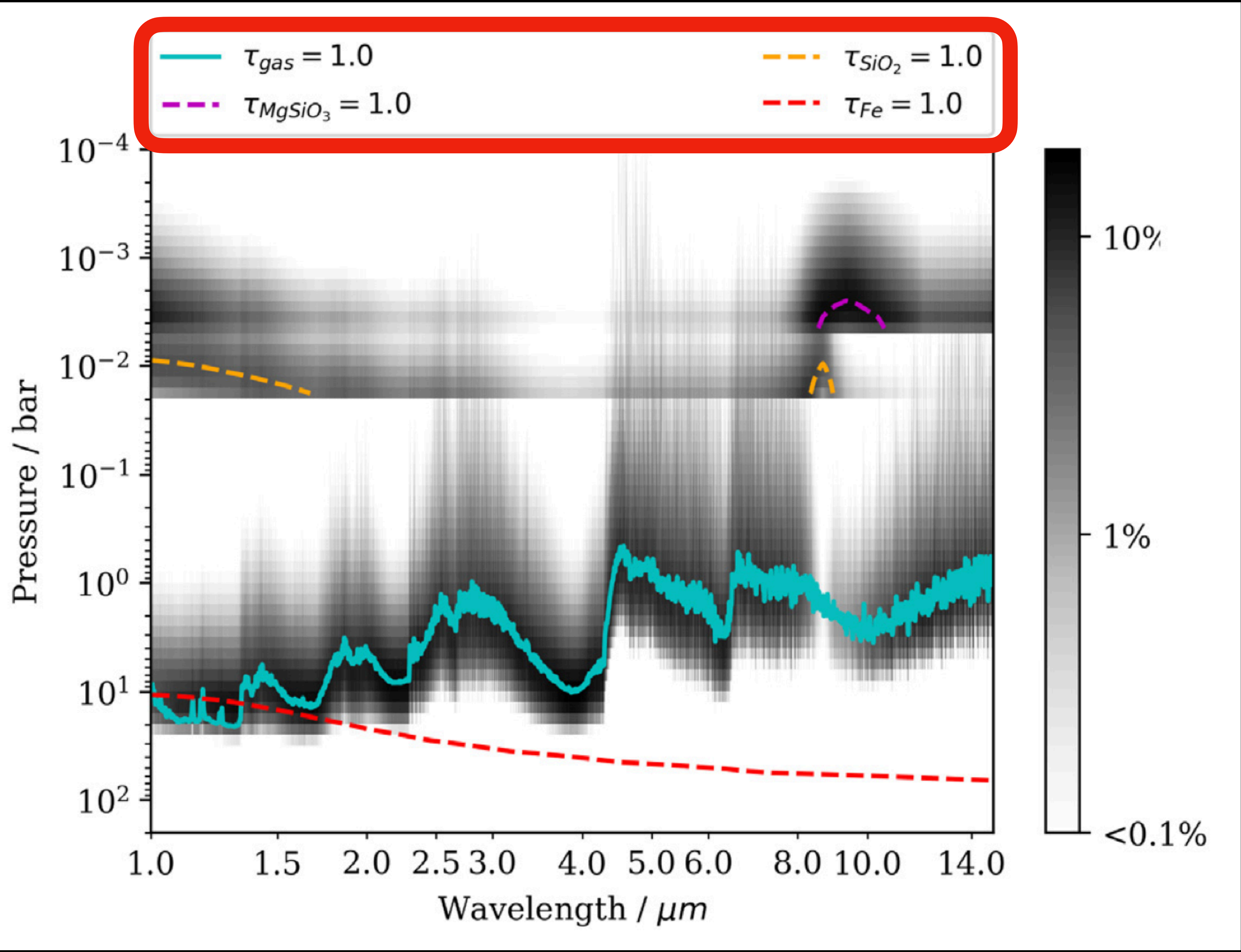


Miles+ 2023

WEBB SPACE TELESCOPE

Clouds

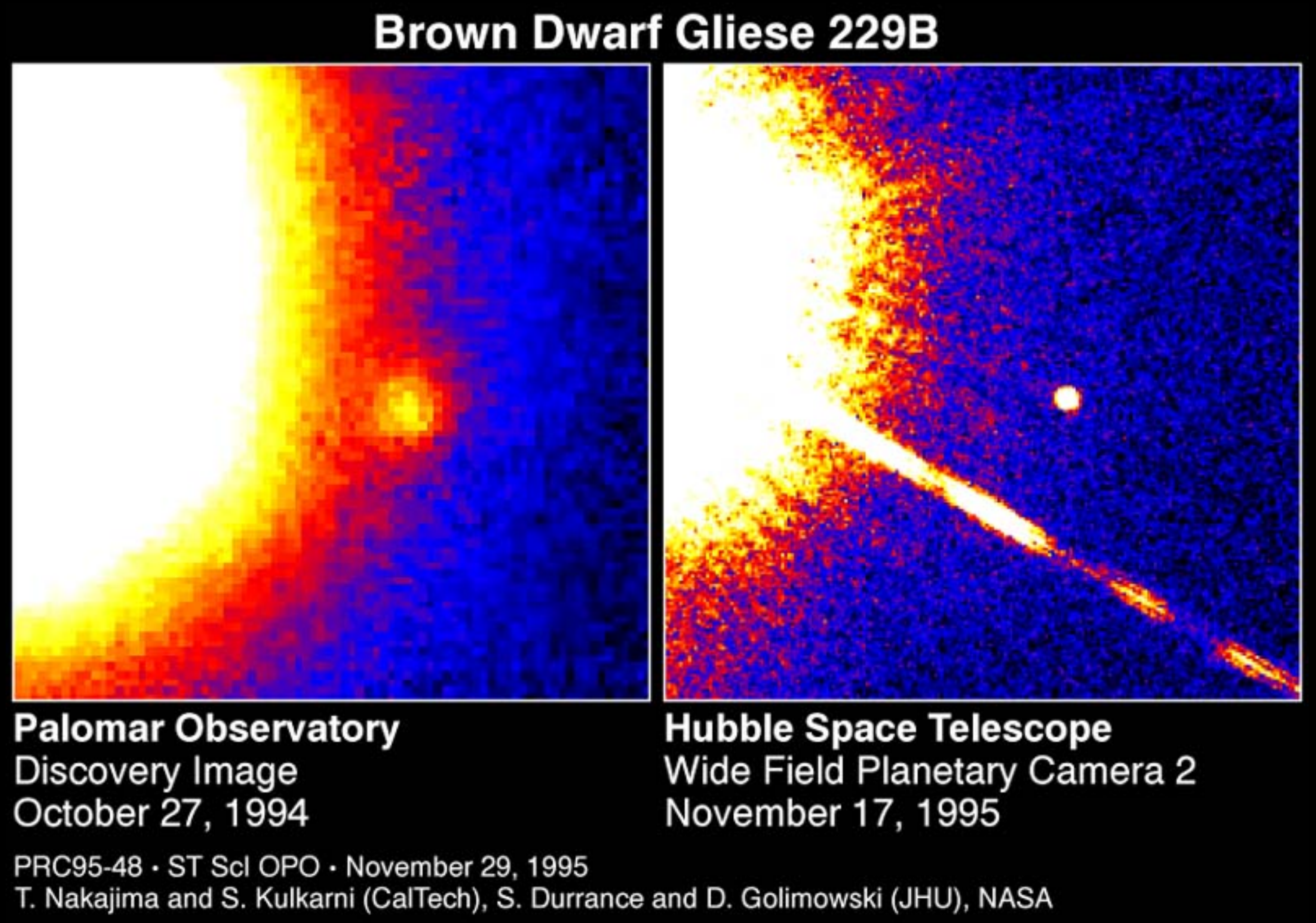
- Silicate spectral signature present in brown dwarfs…will be seeing for exoplanets
- Exactly which species and characteristics still unknown (SiO_2, $MgSiO_3$, Mg_2SiO_4…learn a little mineralogy!). Need to start considering:
    - Mg/Si ratio (when does SiO_2 form?)
    - Crystalline/amorphous
- Lots of room for improvement but remember clouds are hard even for Earth's atmosphere
- Need more powerful & flexible models
- ***Advice:*** Regardless of which model you use, ***aim for underlying physical understanding***, not just reporting parameters for a model (e.g., f_{sed}=2)

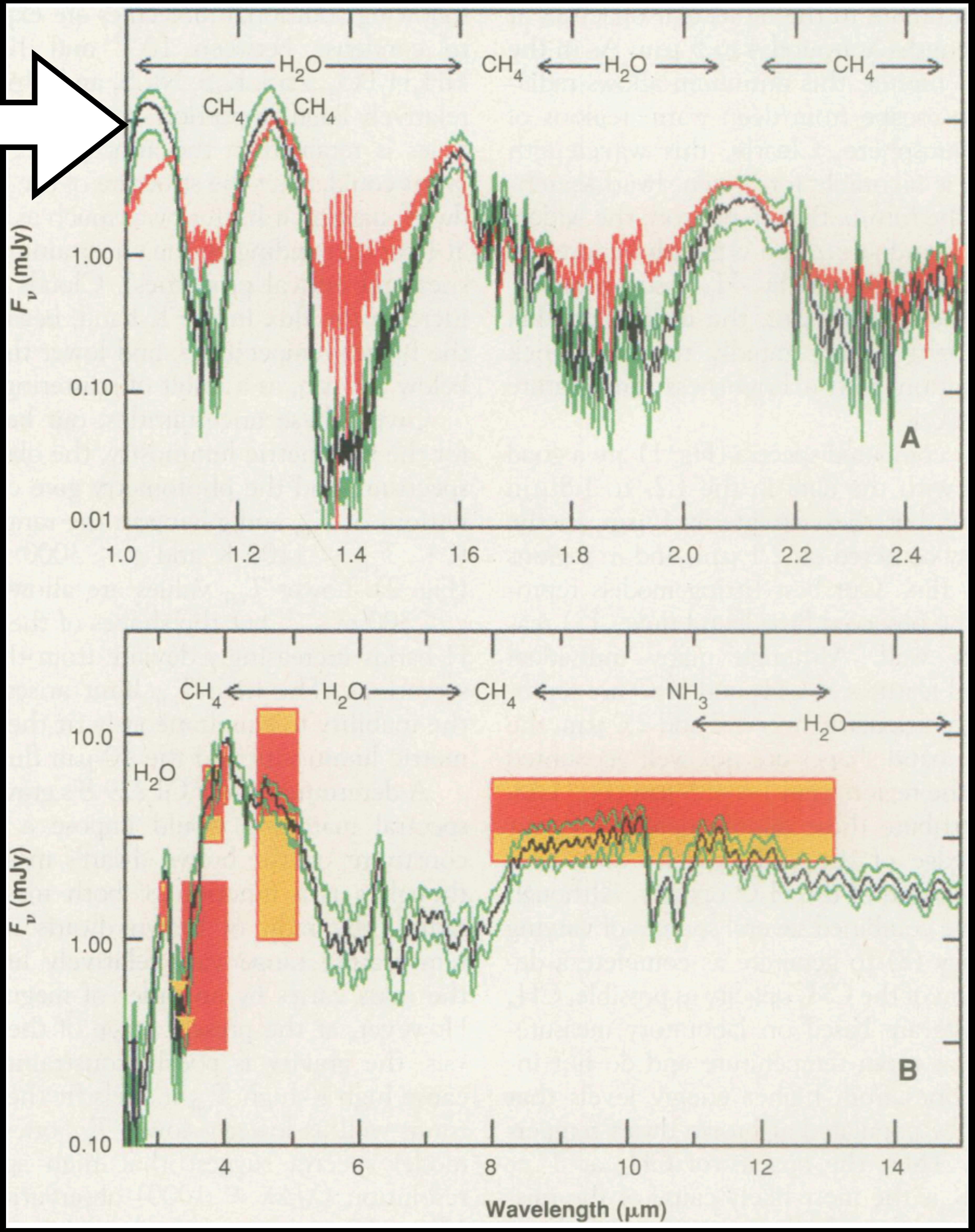


Burningham+ (2021)

Gl 229B the First Brown Dwarf and a Lesson Learned

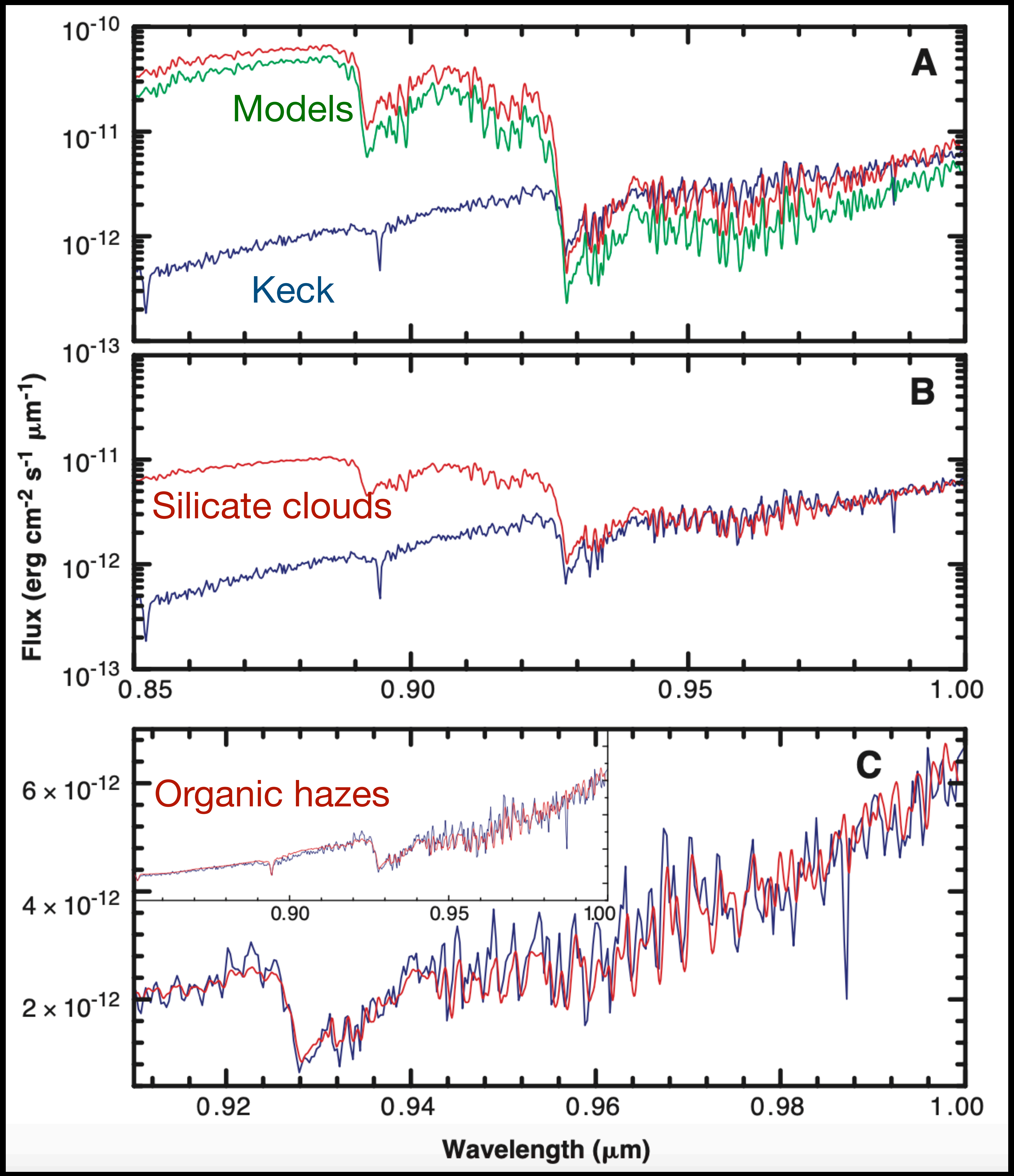
- H_2, He atmosphere w/CH_4, H_2O
- Jupiter size
- ~60x Jupiter mass
- ~900 K, like young Jupiter





Marley+ (1997)

Organic Hazes?

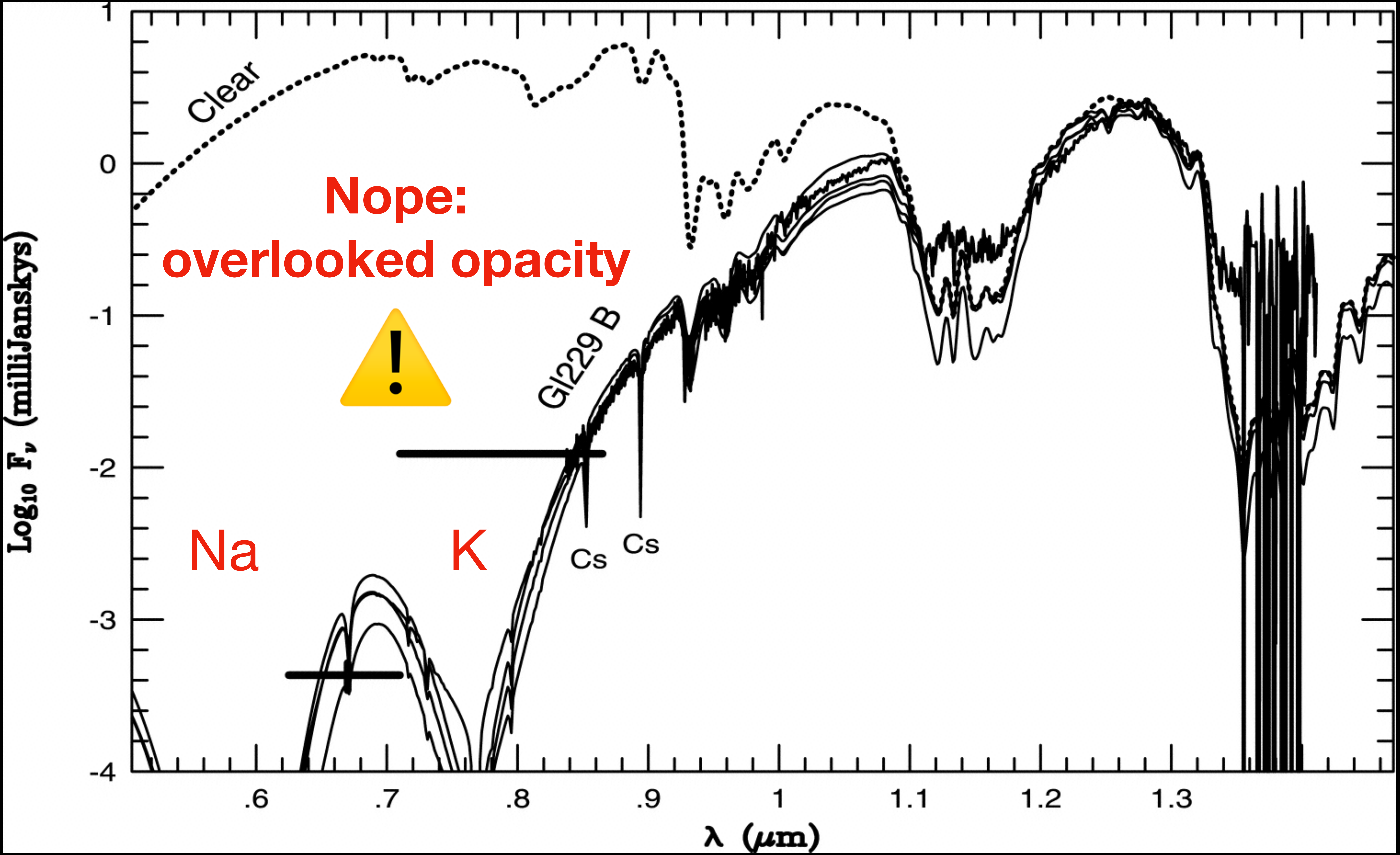


SCIENCE VOL 282 11 DECEMBER 1998

The Dusty Atmosphere of the Brown Dwarf Gliese 229B

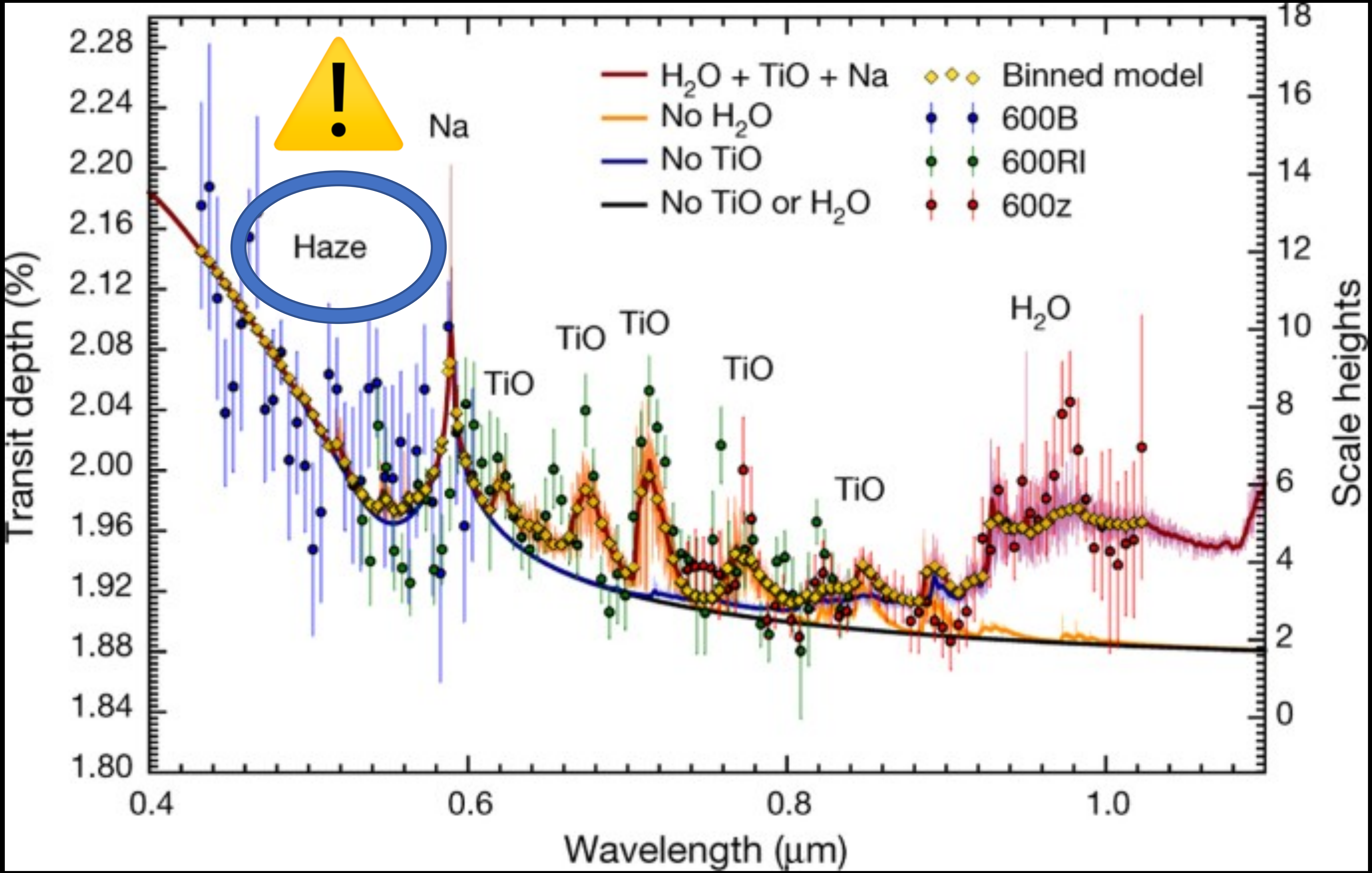
Caitlin A. Griffith, Roger V. Yelle, Mark S. Marley

The brown dwarf Gliese 229B has an observable atmosphere too warm to contain ice clouds like those on Jupiter and too cool to contain silicate clouds like those on low-mass stars. These unique conditions permit visibility to higher pressures than possible in cool stars or planets. Gliese 229B's 0.85- to 1.0-micrometer spectrum indicates particulates deep in the atmosphere (10 to 50 bars) having optical properties of neither ice nor silicates. Their reddish color suggests an organic composition characteristic of aerosols in planetary stratospheres. The particles' mass fraction (10^{-7}) agrees with a photochemical origin caused by incident radiation from the primary star and suggests the occurrence of processes native to planetary stratospheres.



Burrows, Marley, Sharp (2000)

“Haze” is often invoked to explain NUV-Visible slopes of exoplanets
Be careful!

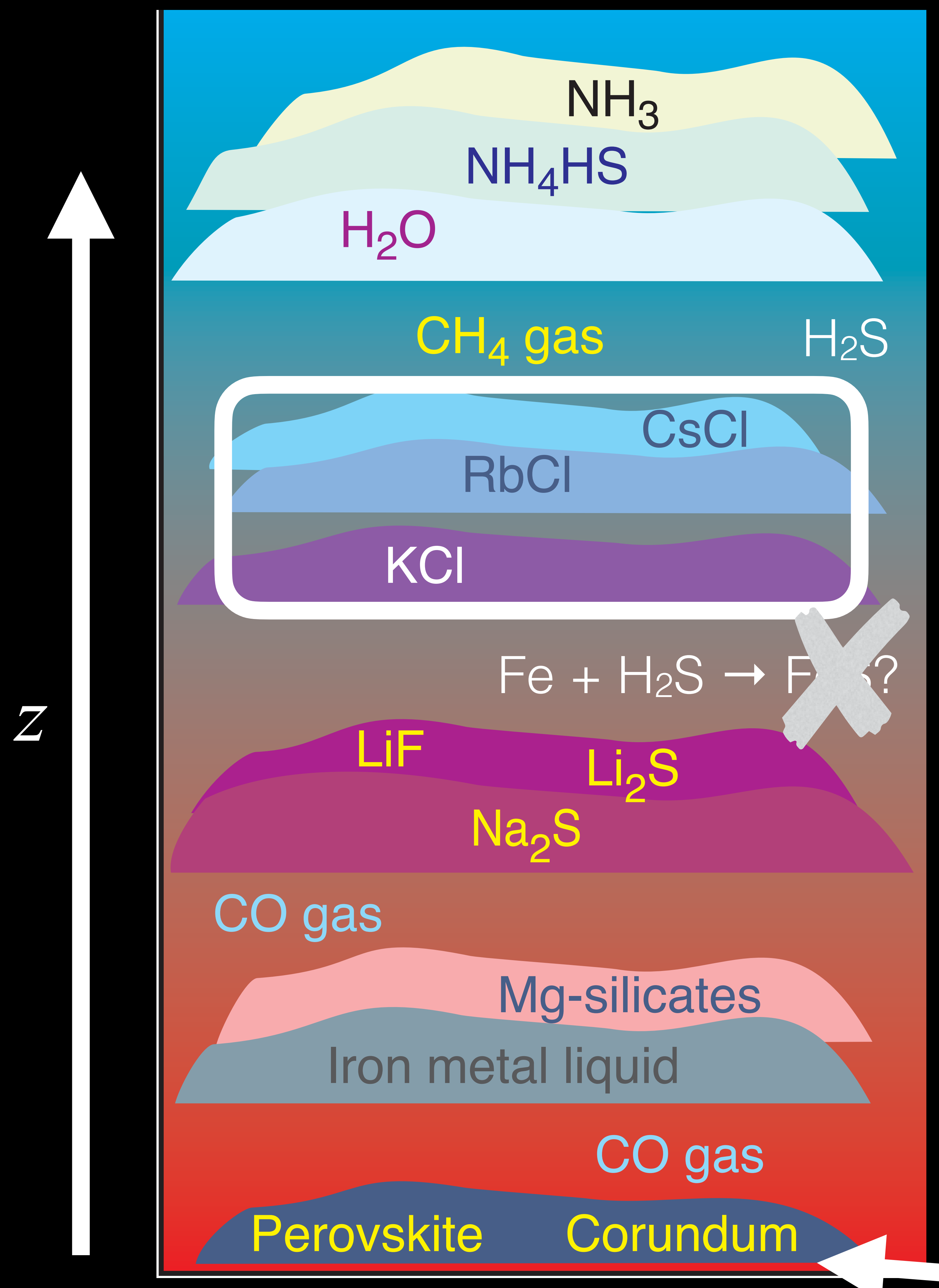


Sedaghati et al., 2017

see also Sing et al., 2015, etc., etc., etc.

Rainout

Rainout Chemistry

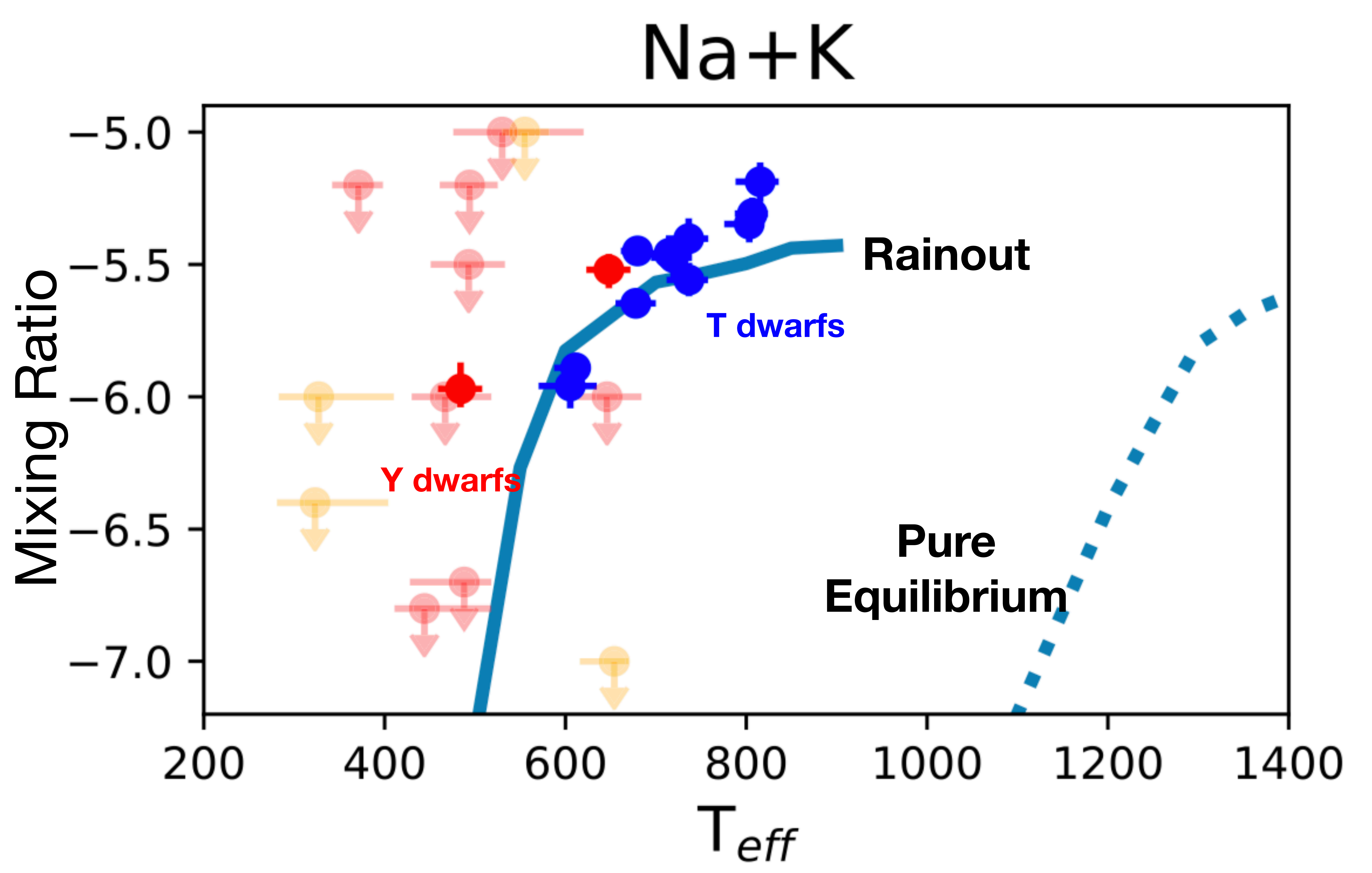


K. Lodders

Are condensed species really removed from equilibrium with the gas phase? Lewis termed this “rainout chemistry”. Canonical example is Fe and H_2S in Jupiter.

We test by seeing when Na, K are lost from the atmosphere. KCl vs. albite $NaAlSi_3O_8$.
Does Al_2O_3 sequester Al?

What Happens to Condensed Species?



Zalesky+ 2019

Retrieval methods test tens of thousands atmospheric composition to find the best fitting abundances.

Lesson Learned:

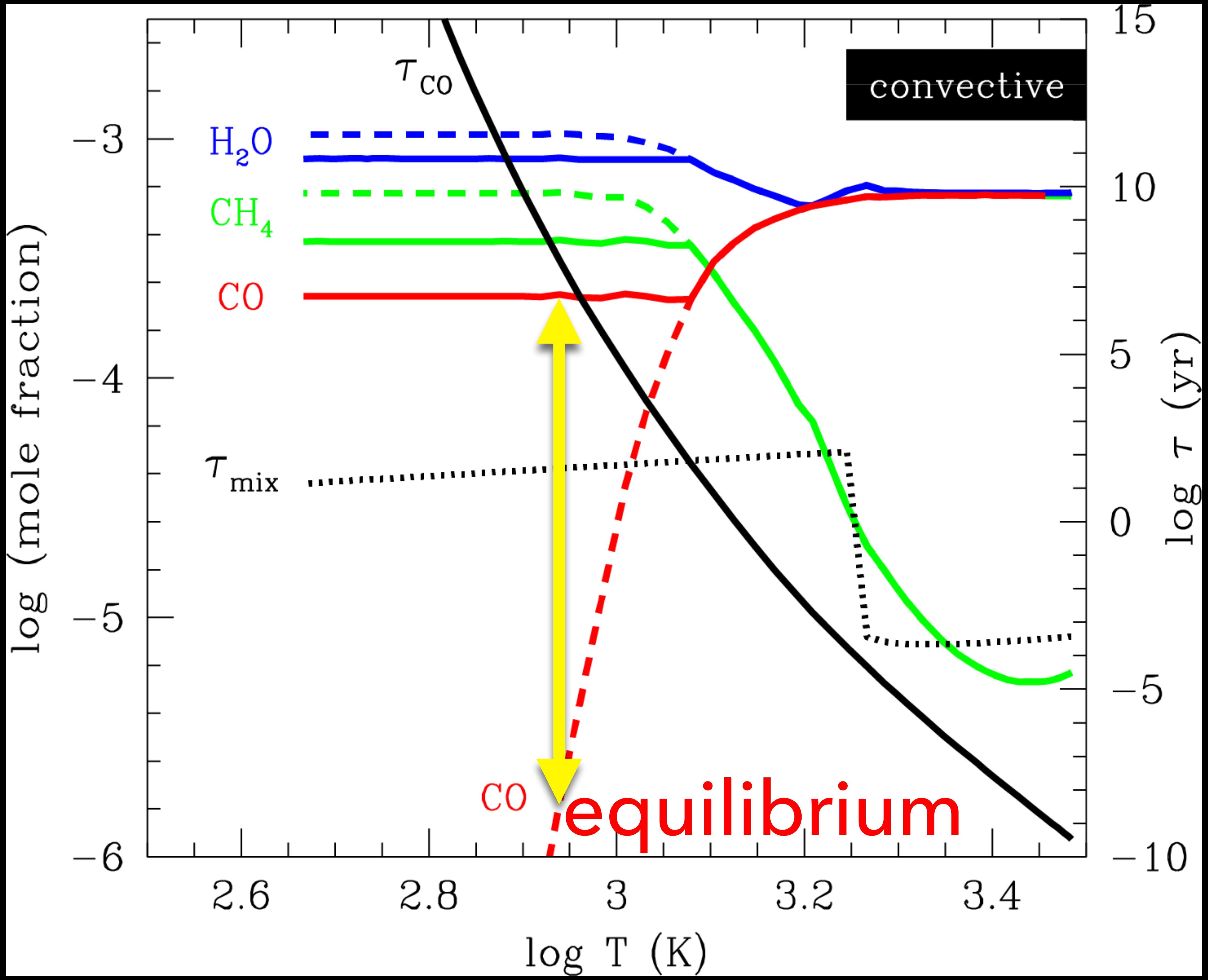
Rainout – not equilibirum – chemistry is the correct choice. **Exemplifies the type of understanding we should be aiming for, trend & process are important not the raw abundances.**

Alos an example of the brown dwarf-planetary connection


Disequilibrium Chemistry

Disequilibrium Chemistry

- Observed chemical composition departs from that expected in chemical equilibrium
- Vertical and horizontal transport vs. chemical equilibrium timescales
- 200+ papers on exoplanet disequilibrium chemistry in ADS



Saumon+ 2003

But “Disequilibrium Chemistry” Has a Long History

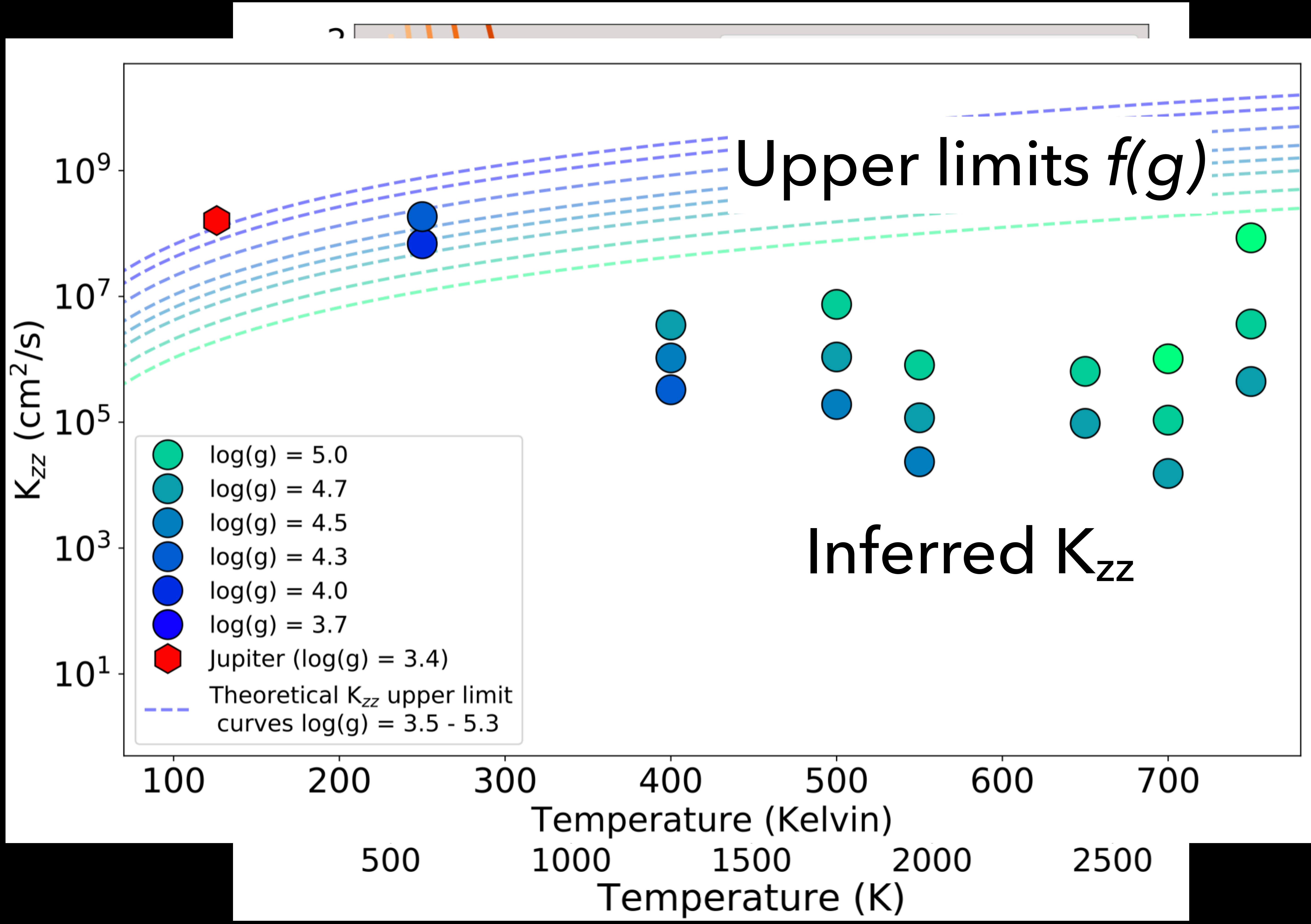
- Understood since 1970s in Jupiter’s atmosphere
- Fegley & Lodders (1996) predicted for brown dwarfs; Noll et al. (1997) confirmed CO-CH_4 disequilibrium
- Tends to be a focus of BD & exoplanet literature
- But not that surprising for giant exoplanets
  - Both vertical and wind driven expected
- ***Lesson Learned:*** *We don’t need any more simple examples of CO-CH_4 disequilibrium*
- Too often used as a crutch for “abundances are not what we expect” or “proposed observations will search for disequilibrium chemistry”

> (Lodders & Fegley 1994). However, as noted by Fegley & Lodders, CO in Gl 229B’s upper atmosphere could be present in abundances greater than predicted by thermochemical equilibrium if convective transport is sufficiently rapid compared with the CO-CH_4 equilibrium reaction timescales. This effect is observed in Jupiter’s atmosphere (Prinn & Barshay 1977; Noll et al. 1988). The CO abundance we derive is consistent with equilibrium at $T \geq 1250$ K according to Fegley & Lodder’s (1996) models. The presence of CO at qCO > 50 ppm at $T \leq 800$ K indicates that some mechanism like convective quenching must be at work in the atmosphere of Gl 229B.

Noll, Geballe, Marley (1997)

Lesson: BDs Point to Better Disequilibrium

- What can we ***do*** with it?
- Measure mixing timescales
- Relate to atmospheric structure
- Can we infer *Kzz* (z) ?
- Does it make sense?
- Feedbacks to structure, spectra?



Miles+ 2020

Some Lessons from Brown Dwarfs

- Most all exoplanet atmosphere topics were studied in brown dwarfs first
- Worthwhile to take time to look at the literature and see where the BD science went and what it focused on
- Some specific lessons:
    - Clouds are hard, we are not there yet (don't trust any models).
        - Don't focus on model parameters too much yet.
    - Don't blame clouds and hazes for every shortcoming.
    - Take rainout chemistry seriously.
    - Time to move on with disequilibrium chemistry. What is driving *Kzz*?
- ***Focus on understanding trends and physical processes***