# Planetary Atmospheres: Models and Observations

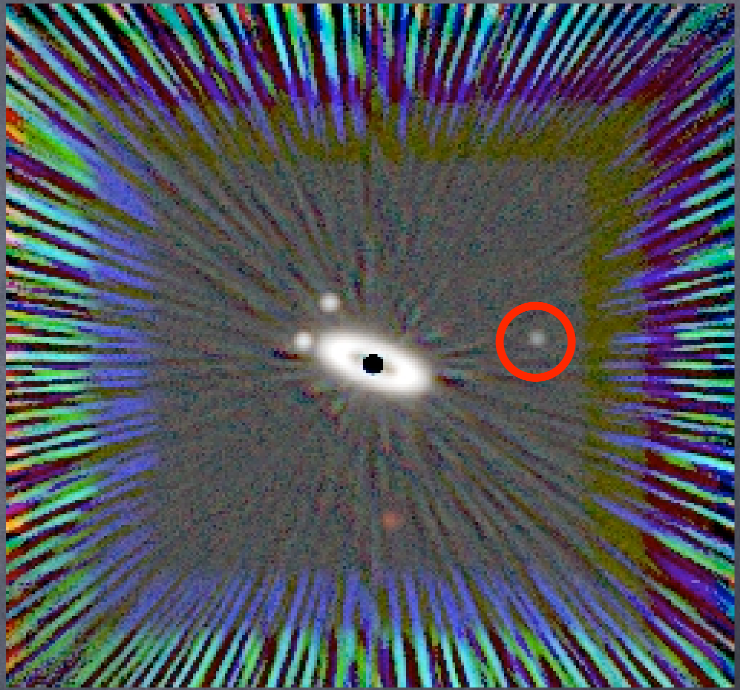
Mark Marley
(NASA Ames)
Collaborators:
Jonathan Fortney, Didier Saumon, Katharina Lodders, Richard Freedman

# Atmospheres

- Why?
- Structure
- Energetics
- Clouds
- Spectra
- Focus on processes more than results

# Why Study Atmospheres?

- Mediate all information (even transit radii)
- Regulate thermal evolution and radii
- Gravity, composition diagnostics
    - mass is not trivial for directly imaged planets
    - composition traces formation mechanism



# Radius: IR + Visible

$$L = 4\pi R^2 \sigma T_{\rm eff}^4 = (1-\Lambda)\pi R^2 (\pi \mathcal{F}_\star) + L_{\rm int}$$

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Mid-IR

Visible

$R$

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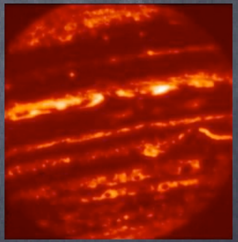
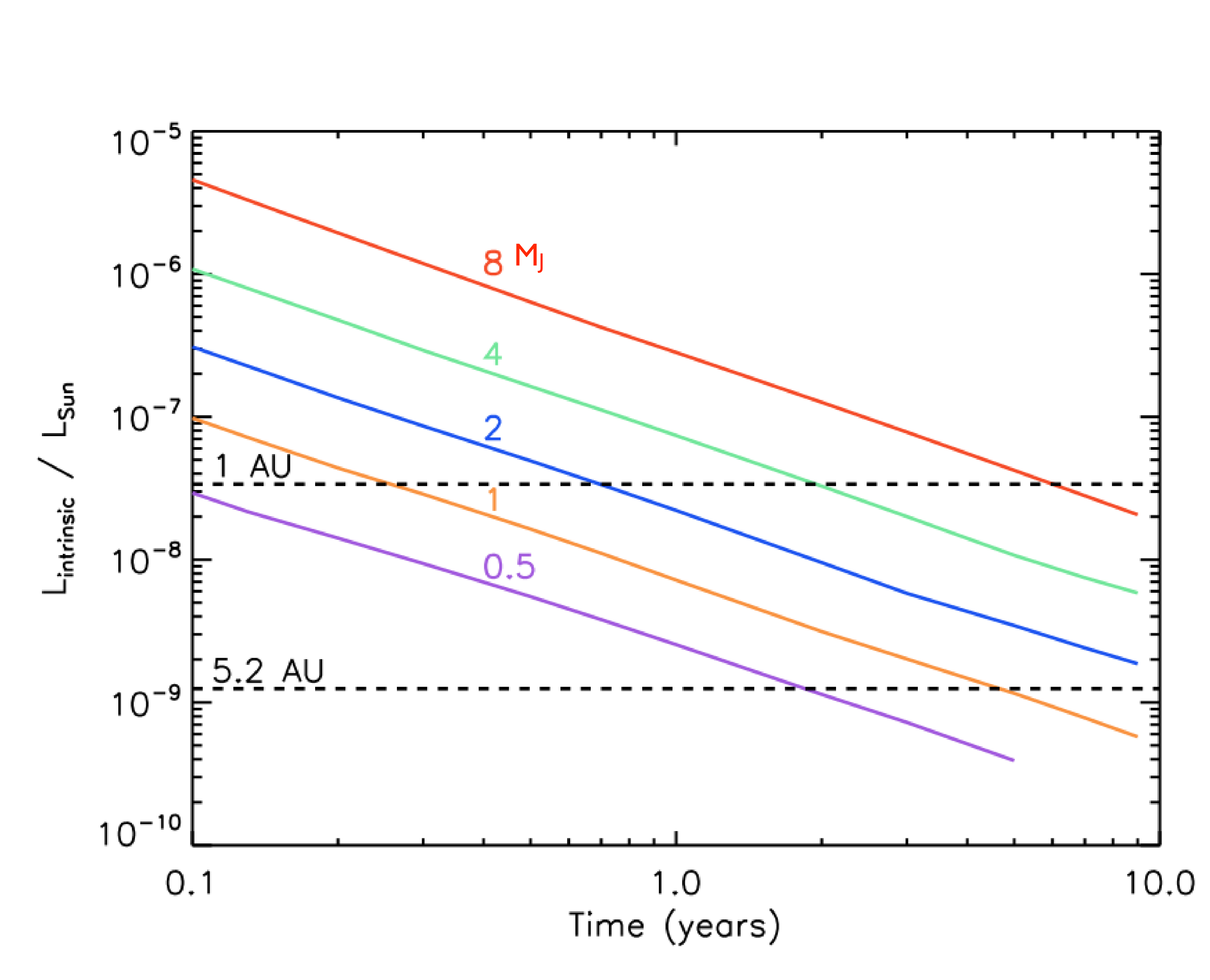
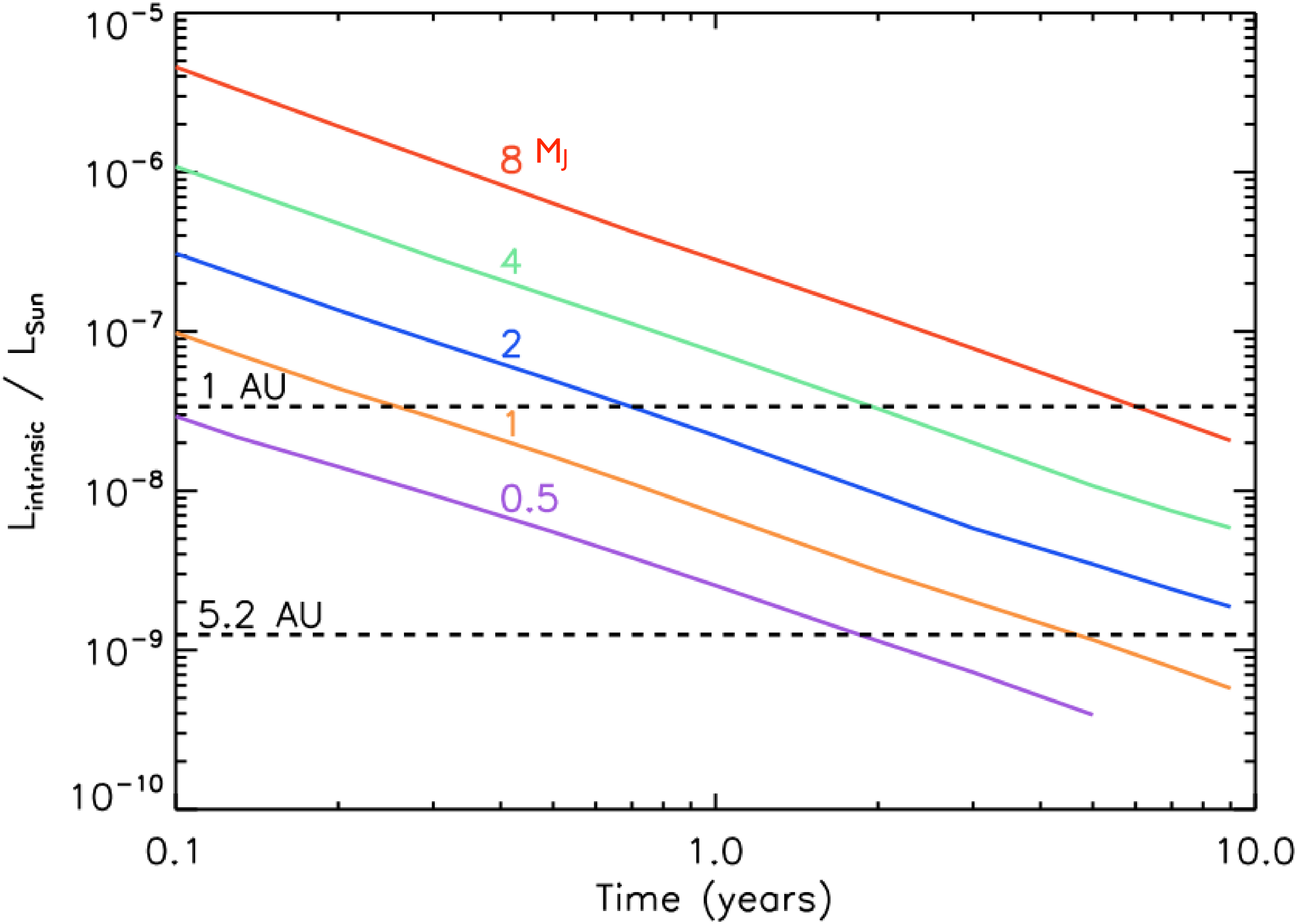


$R$

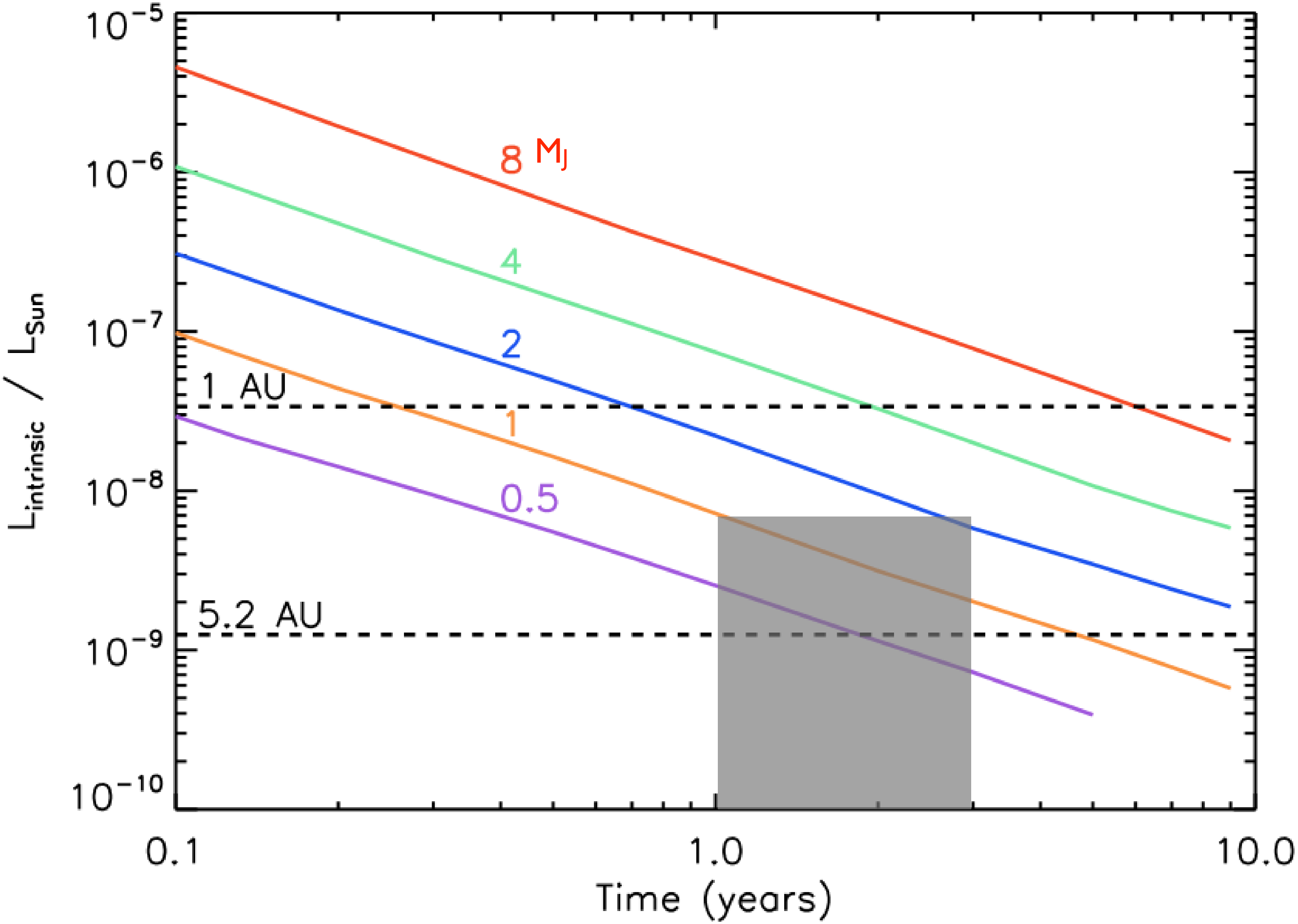


$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$L_{intrinsic} / L_{Sun}$
8 $M_J$
4
2
1
0.5
1 AU
5.2 AU
0.1
1.0
10.0
Time (years)

# M = 1 $M_J$; age = 1 - 3 Gyr



M = 1 $M_J$; age = 1 - 3 Gyr



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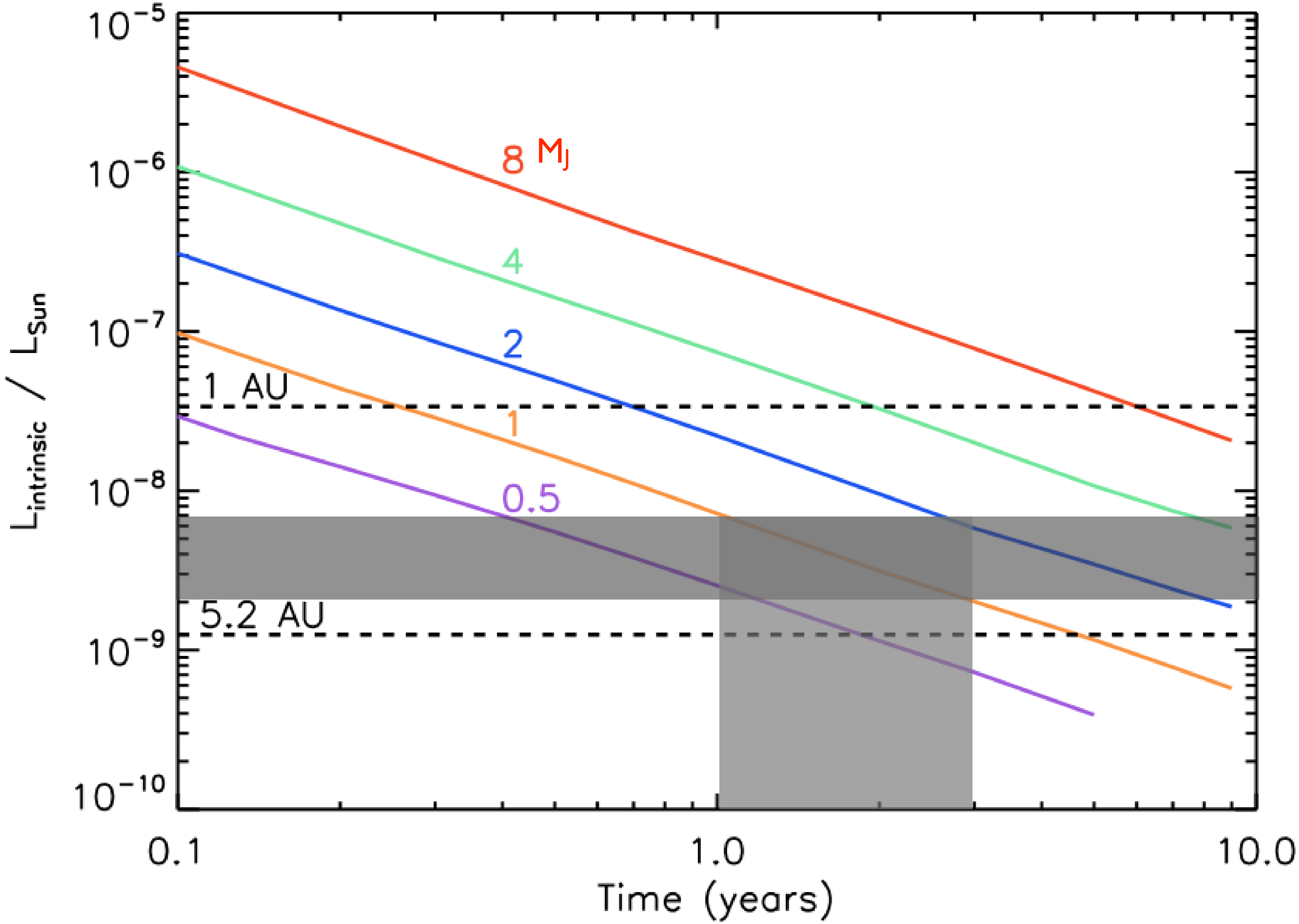
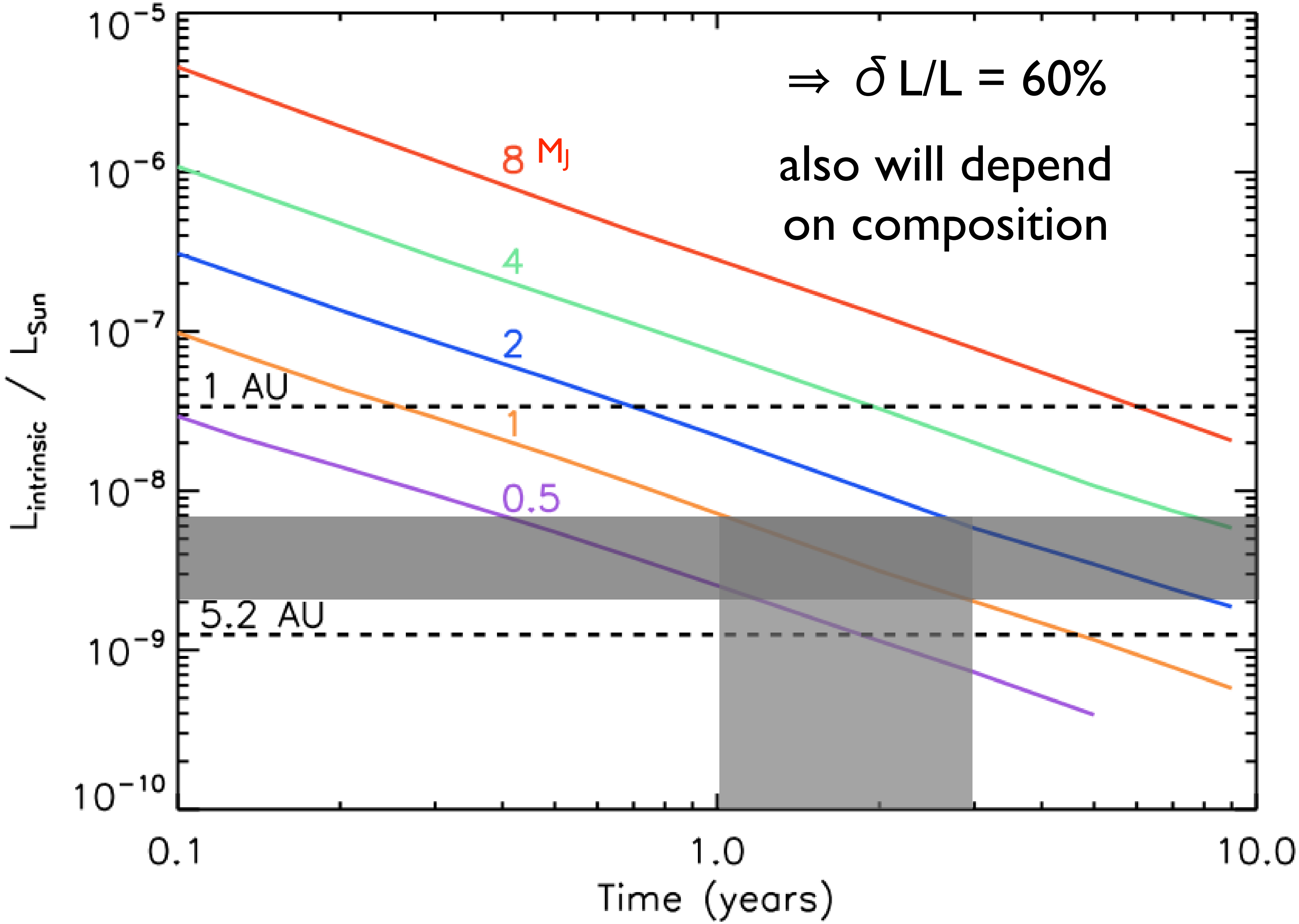


# $M = 1\ M_J$; age = 1 - 3 Gyr



# Constraining $R$

$$L = 4\pi R^2 \sigma T_{\rm eff}^4 = (1 - \Lambda)\pi R^2 (\pi \mathcal{F}_\star) + L_{\rm int}$$

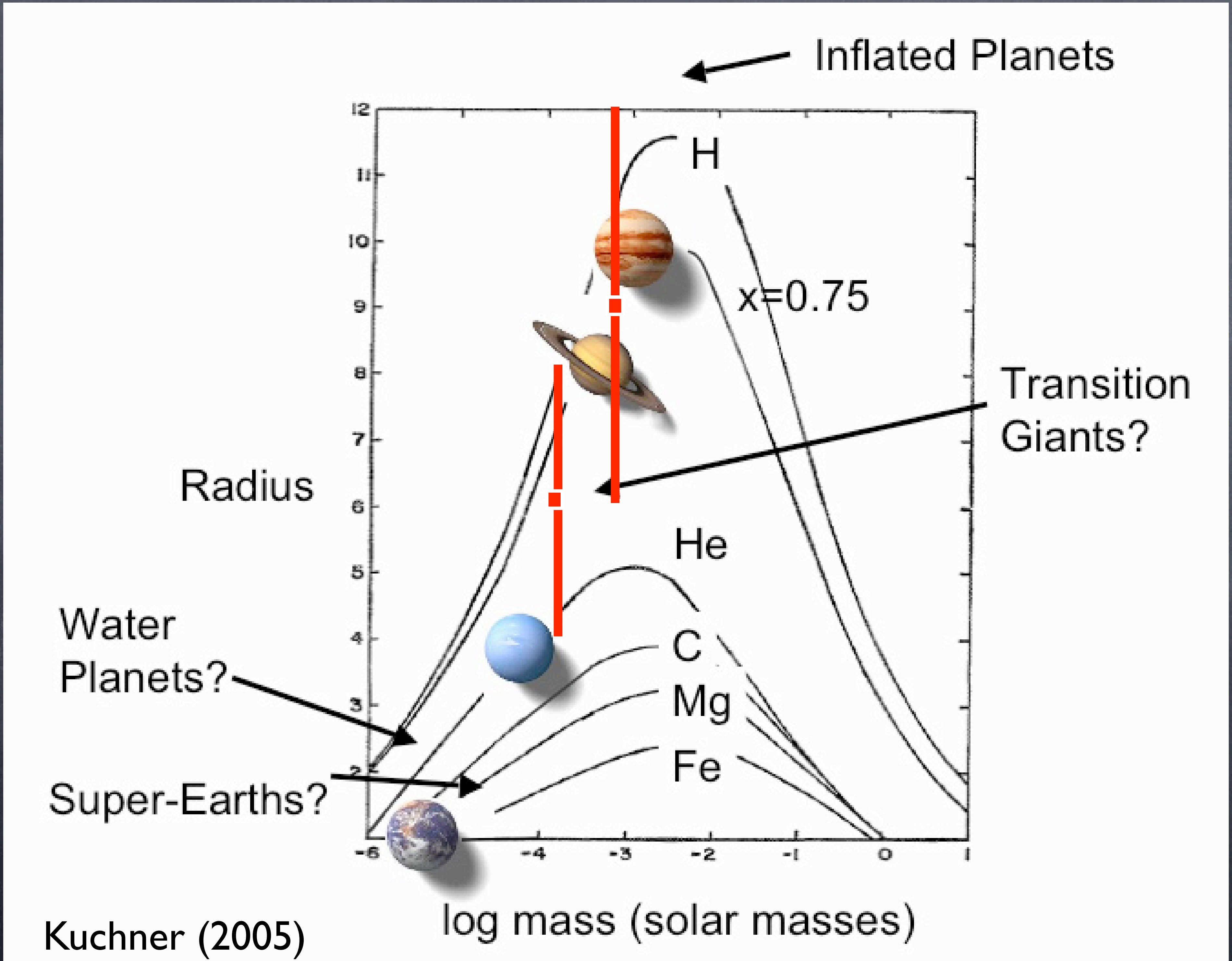
Mid-IR

Visible

$R$

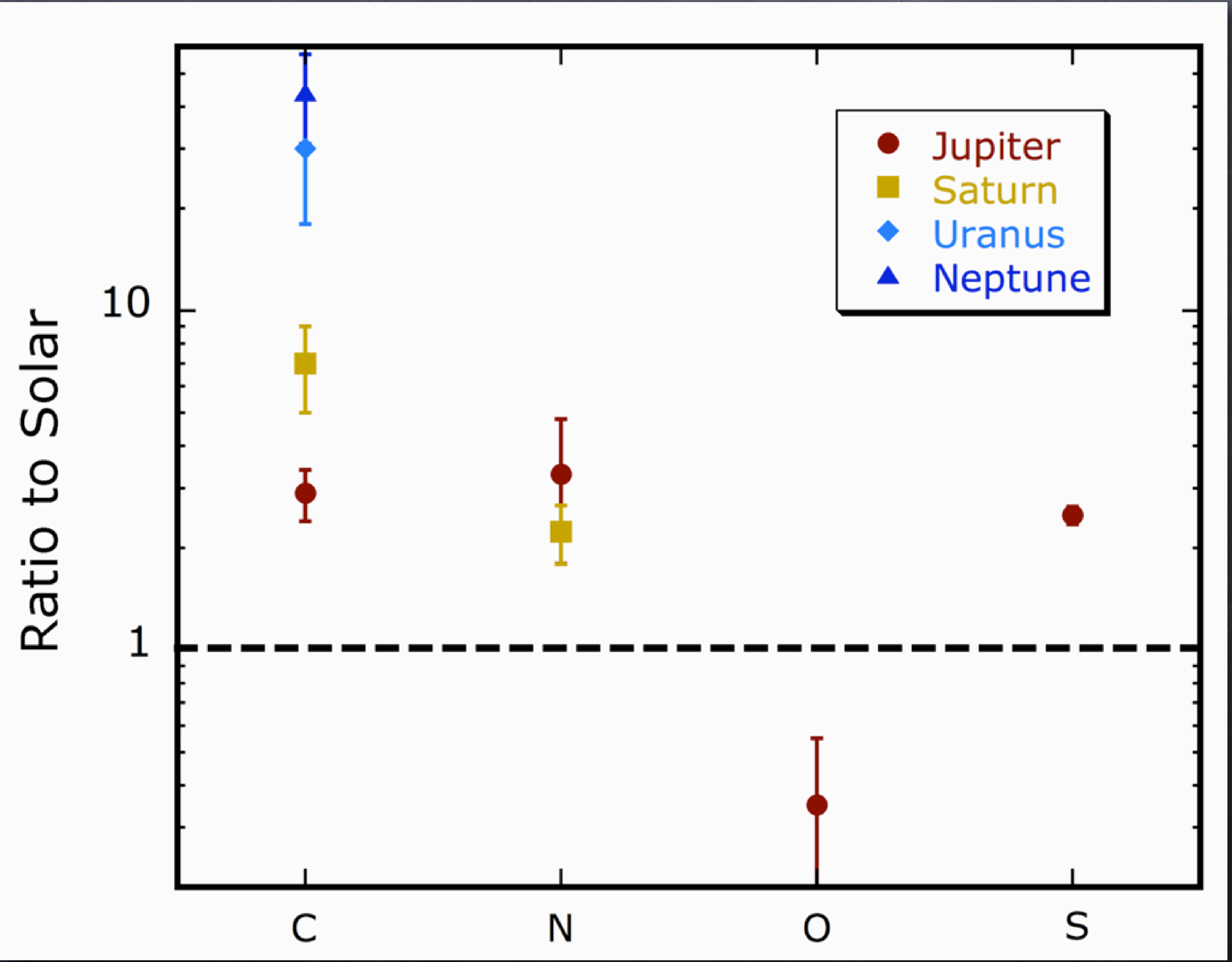
$$\frac{\delta R}{R} > \frac{1}{2}\frac{\delta L_{\rm int}}{L}$$

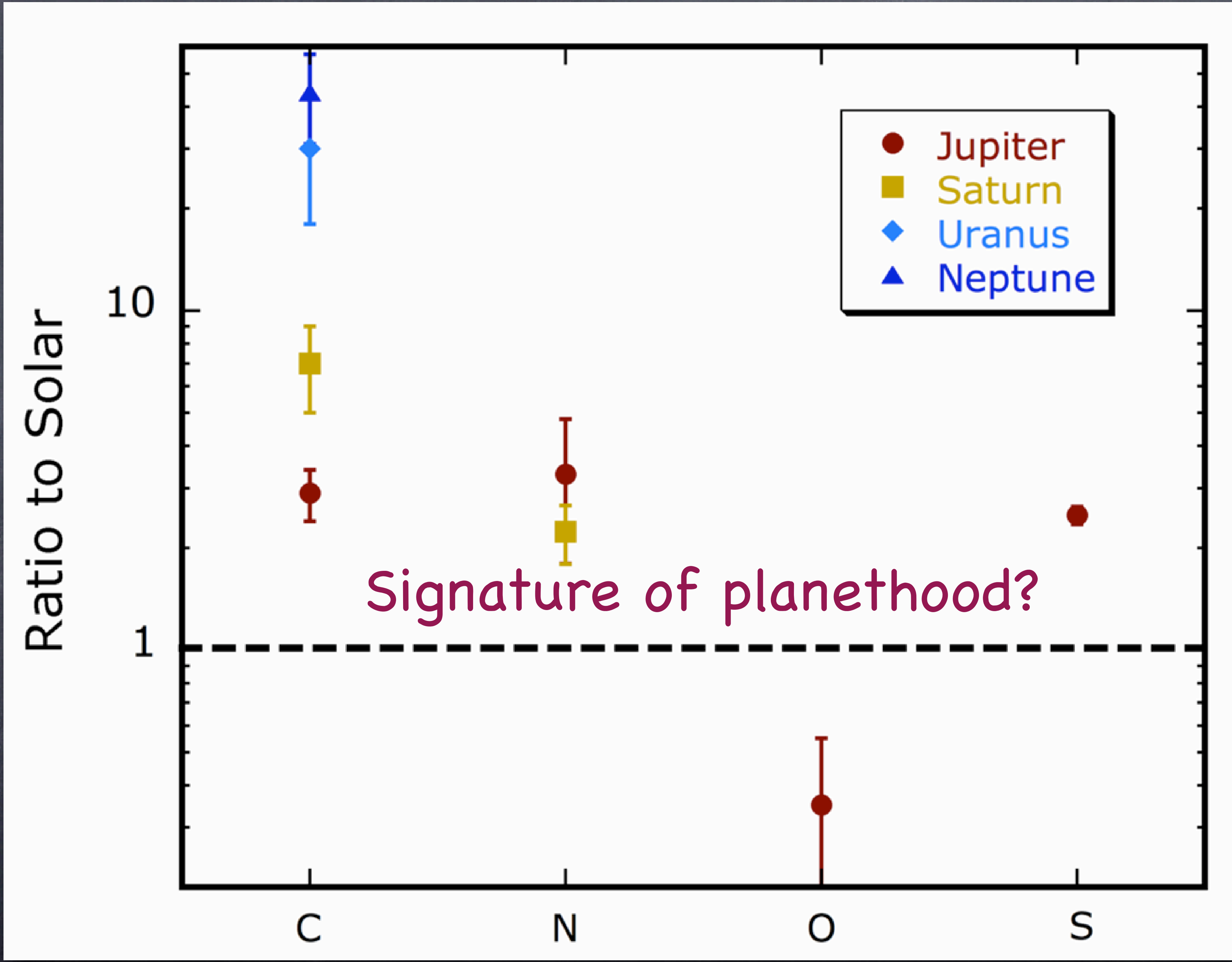
easily 30% or more



Inflated Planets
H
x=0.75
Transition
Giants?
Radius
He
Water
Planets?
C
Mg
Fe
Super-Earths?
12
11
10
9
8
7
6
5
4
3
2
-6
-4
-3
-2
-1
0
1
log mass (solar masses)
Kuchner (2005)

Need gravity diagnostics!
(spectra)


Jupiter
Saturn
Uranus
Neptune
Ratio to Solar
10
1
C
N
O
S

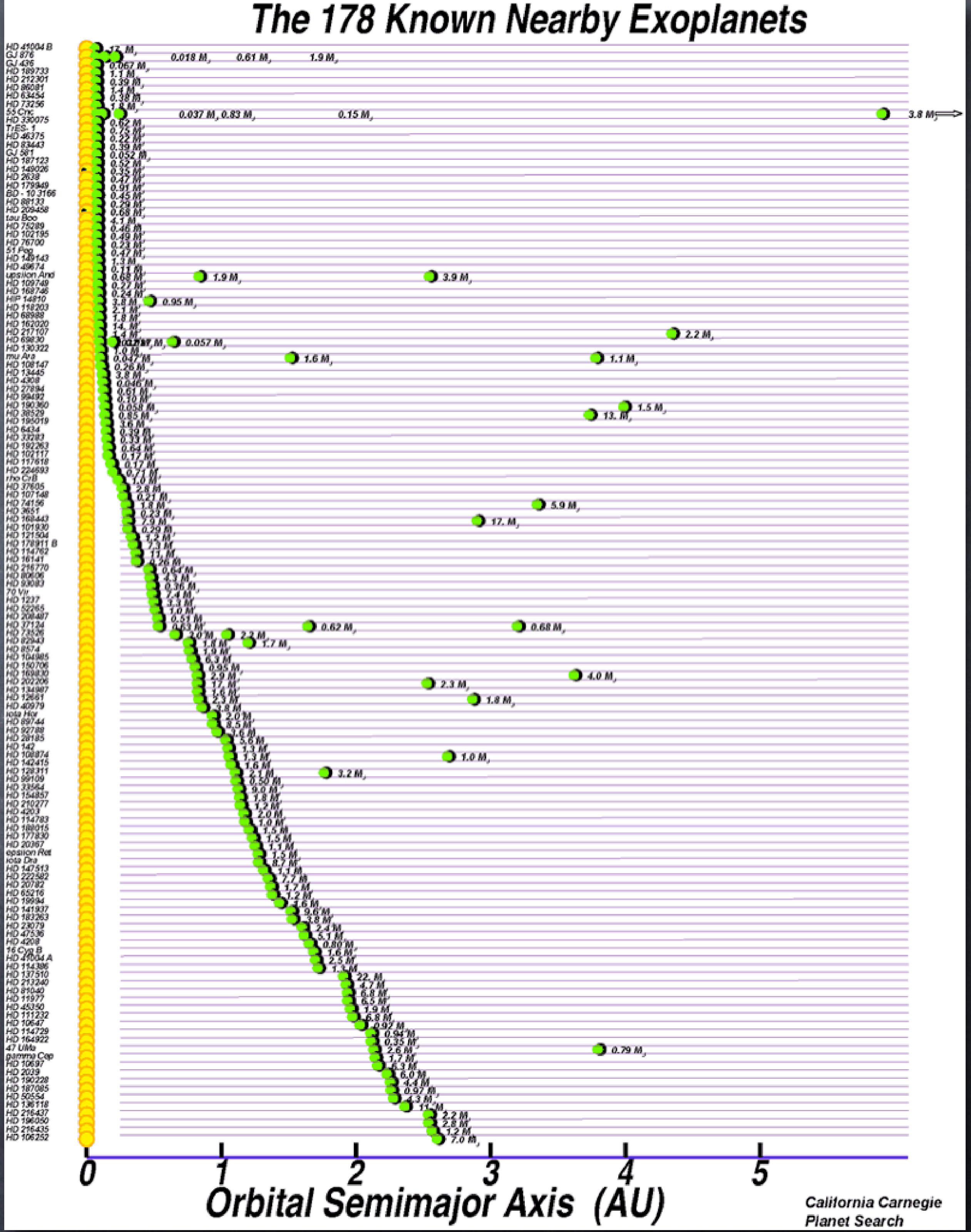


Ratio to Solar
10
1
Jupiter
Saturn
Uranus
Neptune
Signature of planethood?
C
N
O
S

# But...

Requiring compostion information turns most of the "Known Exoplanets" into "Known Exoplanet Candidates"

Known Exoplanets:
HD149026b
Gl 436b



Need composition diagnostics! (spectra)

# Need Models!

Composition

Chemistry

Opacities

Condensates

\+ Dynamics

---

Thermal Structure & Spectrum

Composition

Metallicity, C/O, ...

Chemistry

Opacities

Condensates

\+ Dynamics

---

Thermal Structure & Spectrum

Composition Metallicity, C/O, ...

Chemistry Sedimentation

Opacities

Condensates

\+ Dynamics

---

Thermal Structure & Spectrum

| | |
|---|---|
| Composition | Metallicity, C/O, ... |
| Chemistry | Sedimentation |
| Opacities | High $T$ $CH_4$ |
| Condensates | |
| + Dynamics | |

---

Thermal Structure & Spectrum

Composition — Metallicity, C/O, ...

Chemistry — Sedimentation

Opacities — High $T$ $CH_4$

Condensates — Cloud Physics

\+ Dynamics

---

Thermal Structure & Spectrum

| | |
|---|---|
| Composition | Metallicity, C/O, ... |
| Chemistry | Sedimentation |
| Opacities | High $T$ $CH_4$ |
| Condensates | Cloud Physics |
| + Dynamics | Circulation, $f$ |

Thermal Structure & Spectrum

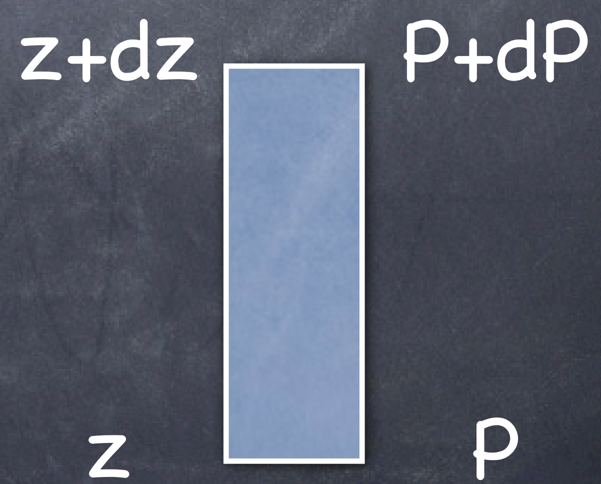
# Basics of Atmospheres

- Hydrostatic equilibrium
- Energy balance
- Breezing over details, see a basic atmospheric science text for derivations

# Hydrostatic Equilibrium

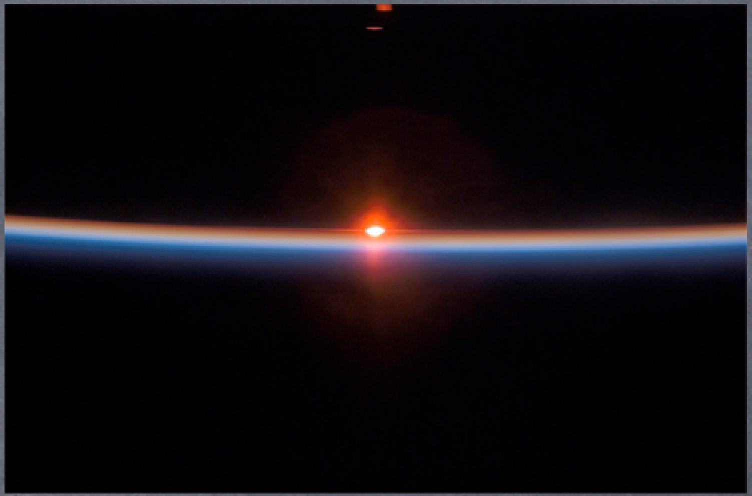
- Static atmosphere -> no net forces
- Weight of slab = $\rho g$
- Balanced by pressure differential = $dP/dz$
- $dP/dz + \rho g = 0$
- $dP/dz = -\rho g$
- Combine with ideal gas law

$$P = nkT = (\rho/m)kT$$



# Consequences

- $\boxed{P = P_o\, e^{-z/H}}$
- Scale Height: $H = kT/mg$
  - (m is mean molecular weight)
  - 9 km on Earth; scale for a hot Jupiter....
- Column number density $\mathcal{N} = n\, H = P/(mg)$
  - (n is local number density)
  - Note scaling with g (low g requires more molecules to compress air to given P)



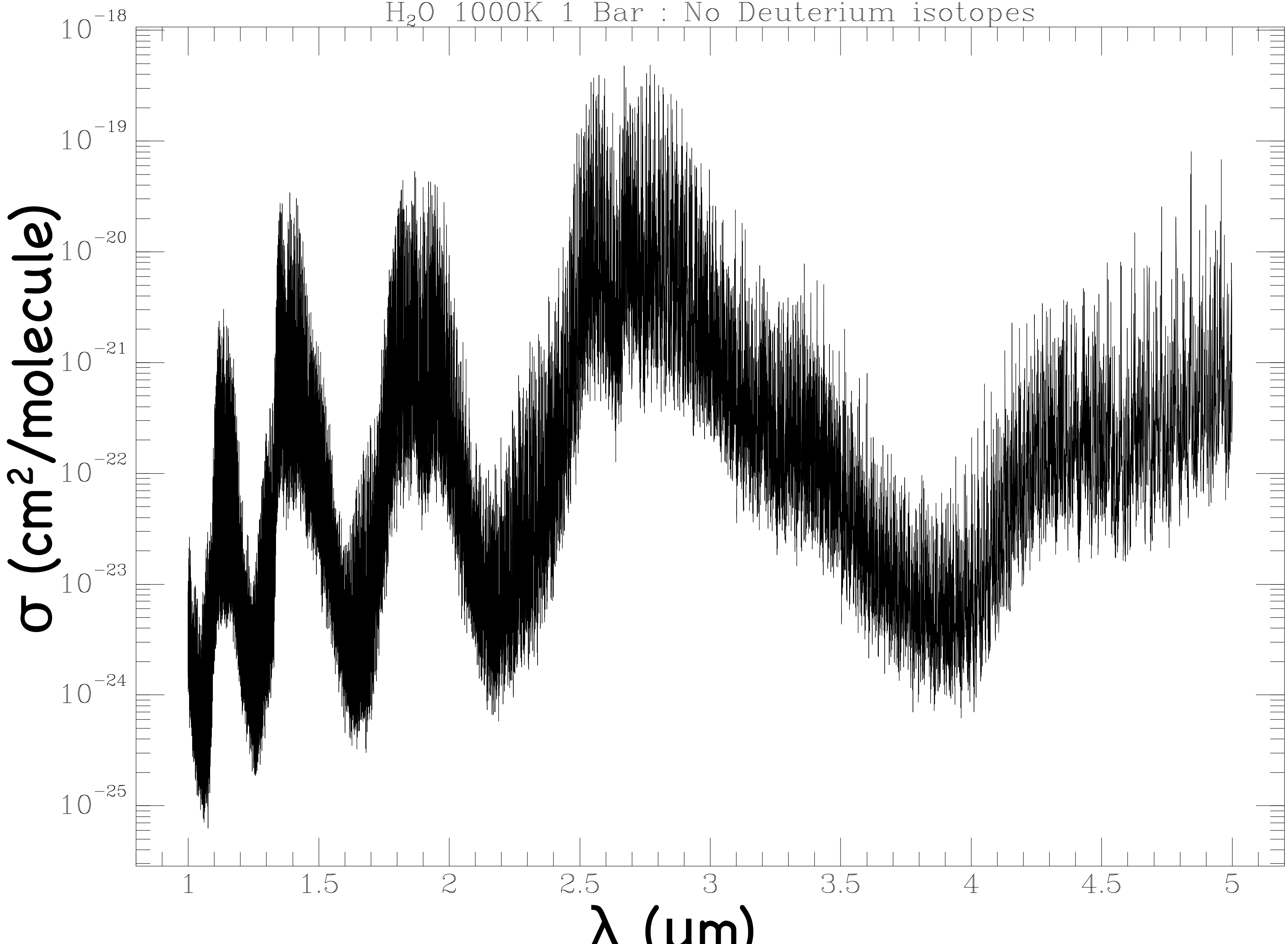
# Optical Depth

- Recall $\mathcal{N}$ (cm$^{-2}$) = n H
- Each species has a wavelength dependent cross section for interacting with a photon, $\sigma_\nu$ (cm$^2$)
- Optical depth above a given pressure level

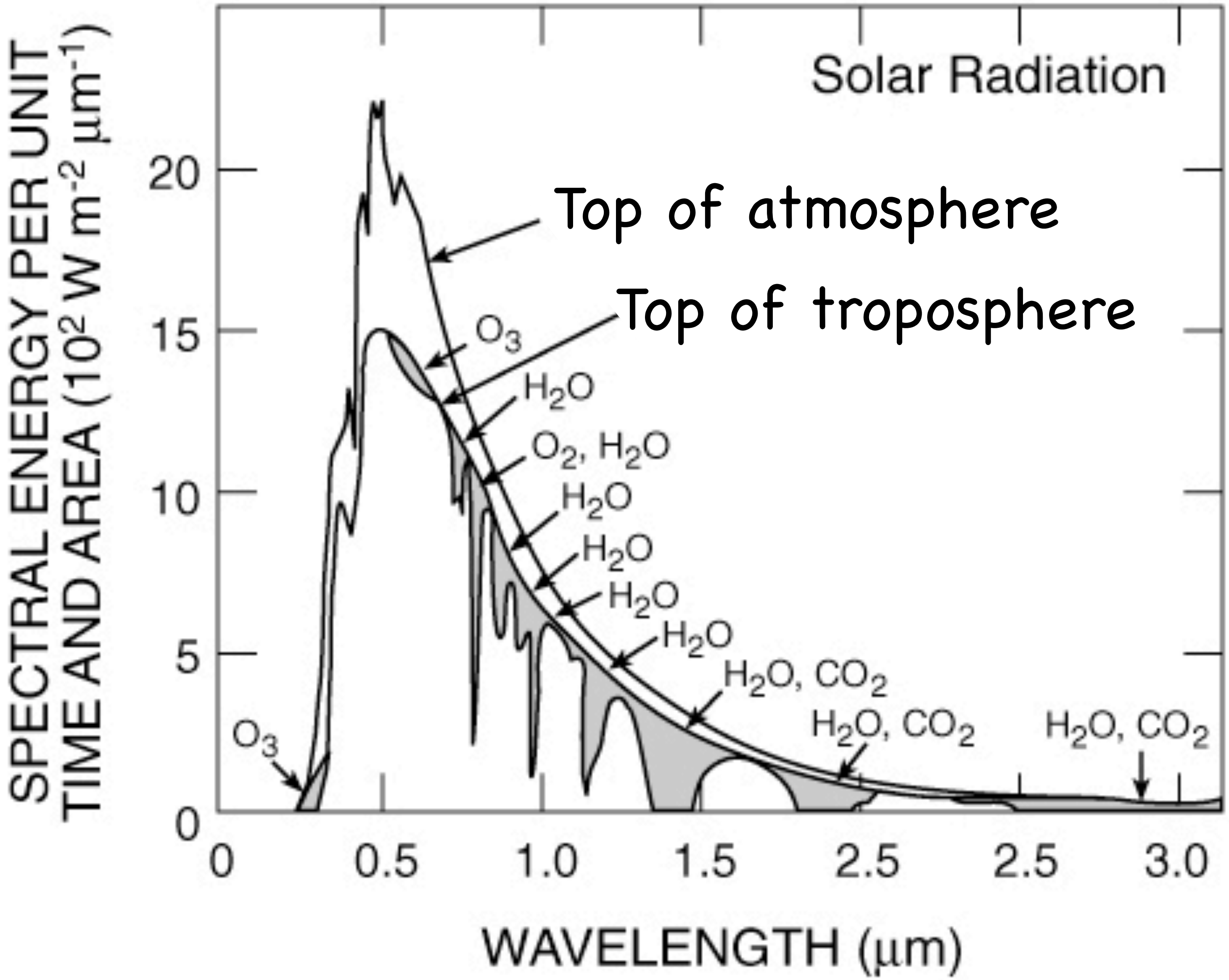
  $\tau = \sigma_\nu \mathcal{N}$

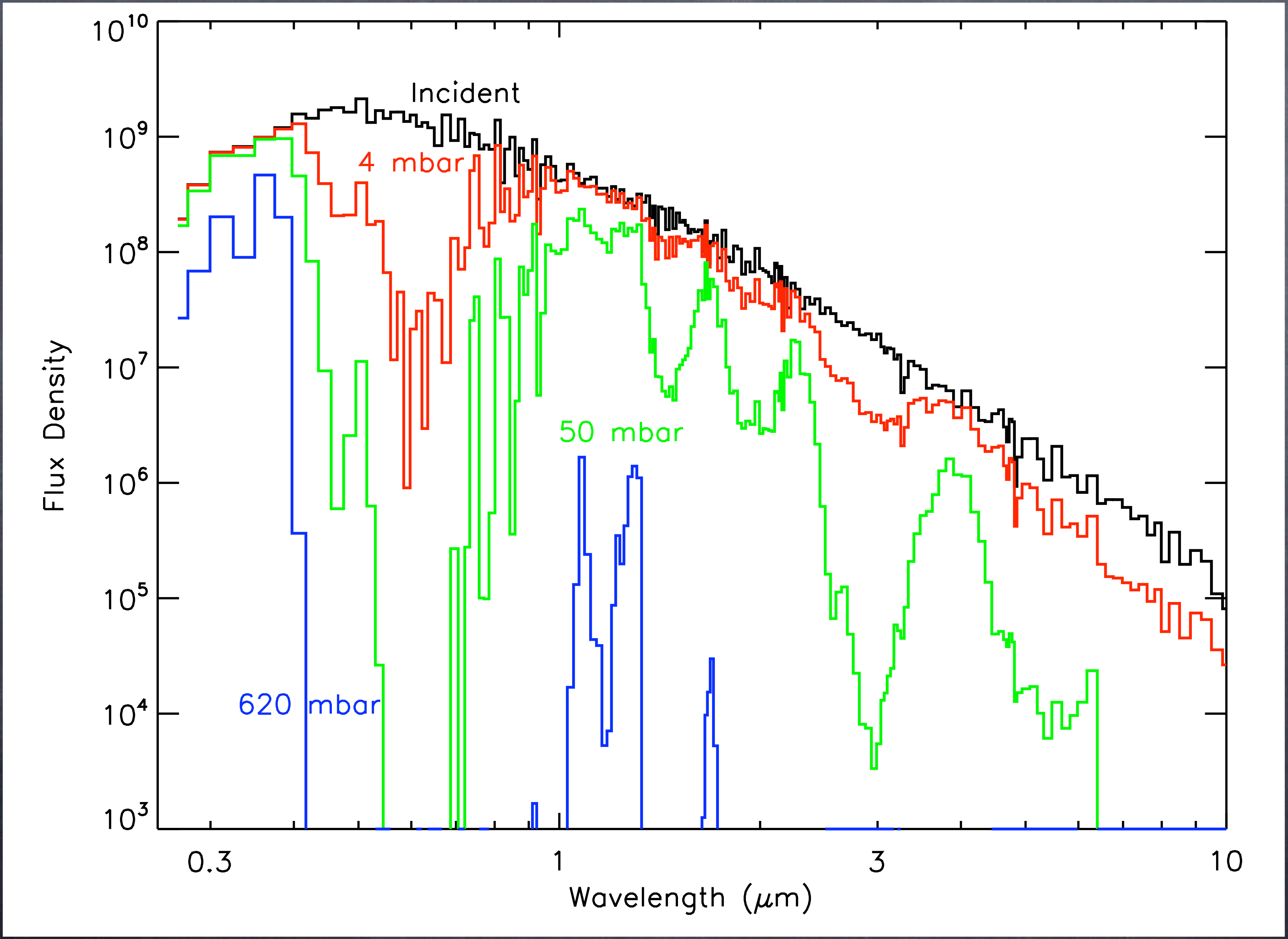
- Transmission from or to a given pressure level

  $I = I_0 \, e^{-\tau}$



H2O 1000K 1 Bar : No Deuterium isotopes
σ (cm²/molecule)
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
1
1.5
2
2.5
3
3.5
4
4.5
5
λ (μm)

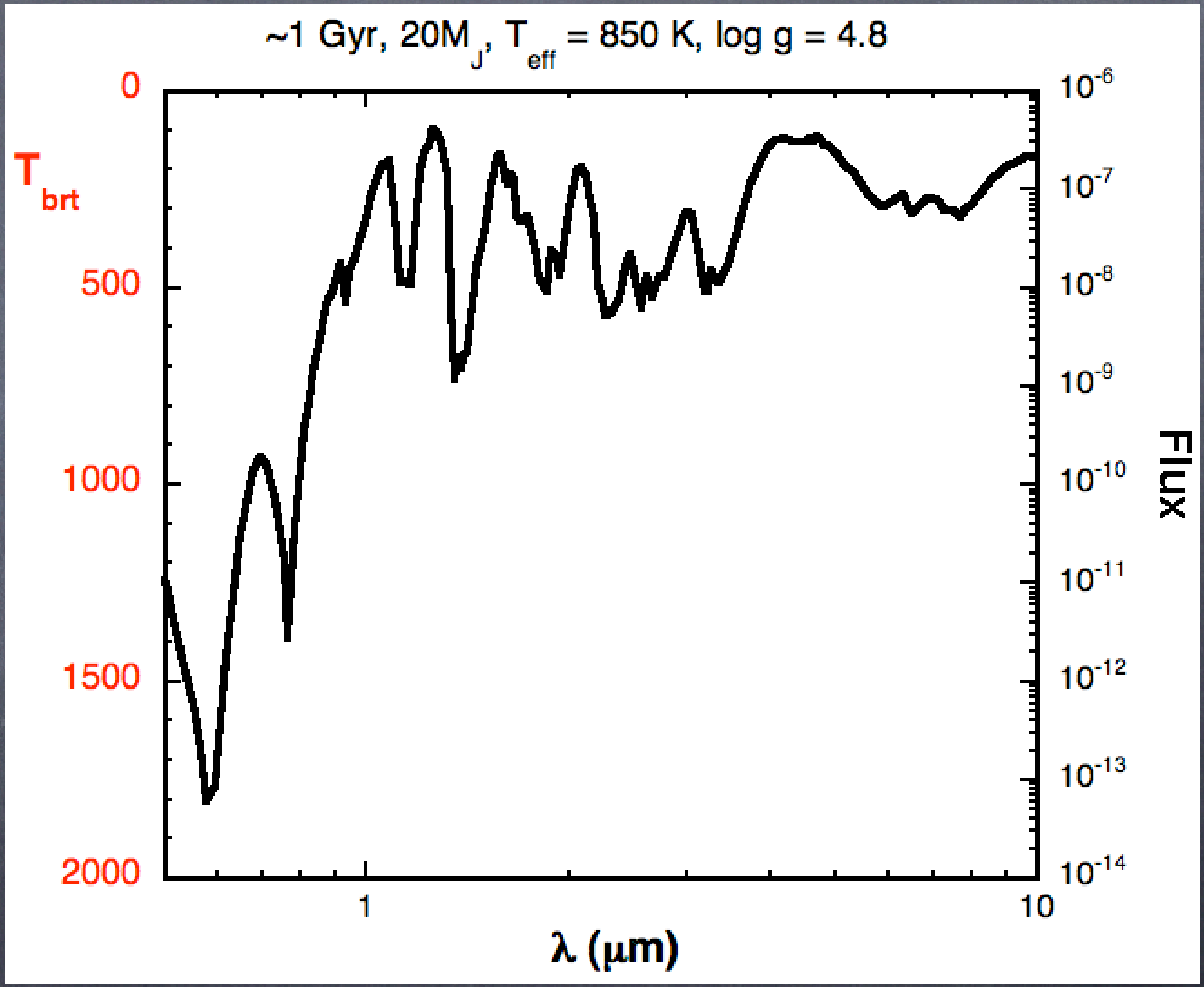

Solar Radiation
Top of atmosphere
Top of troposphere
$O_3$
$H_2O$
$O_2$, $H_2O$
$H_2O$
$H_2O$
$H_2O$
$H_2O$
$H_2O$, $CO_2$
$H_2O$, $CO_2$
$H_2O$, $CO_2$
$O_3$
SPECTRAL ENERGY PER UNIT TIME AND AREA ($10^2$ W m$^{-2}$ μm$^{-1}$)
20
15
10
5
0
0
0.5
1.0
1.5
2.5
2.5
3.0
WAVELENGTH (μm)



$10^{10}$
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
Flux Density
Incident
4 mbar
50 mbar
620 mbar
0.3
1
3
10
Wavelength ($\mu$m)

# Thermal Emission

- At each wavelength, see flux from $\tau \sim 1$
- If T(P) monotonic, strong absorption features are dark because the gas is cold, so viewing a fainter blackbody
- $T_{brt} \neq T_{eq}$



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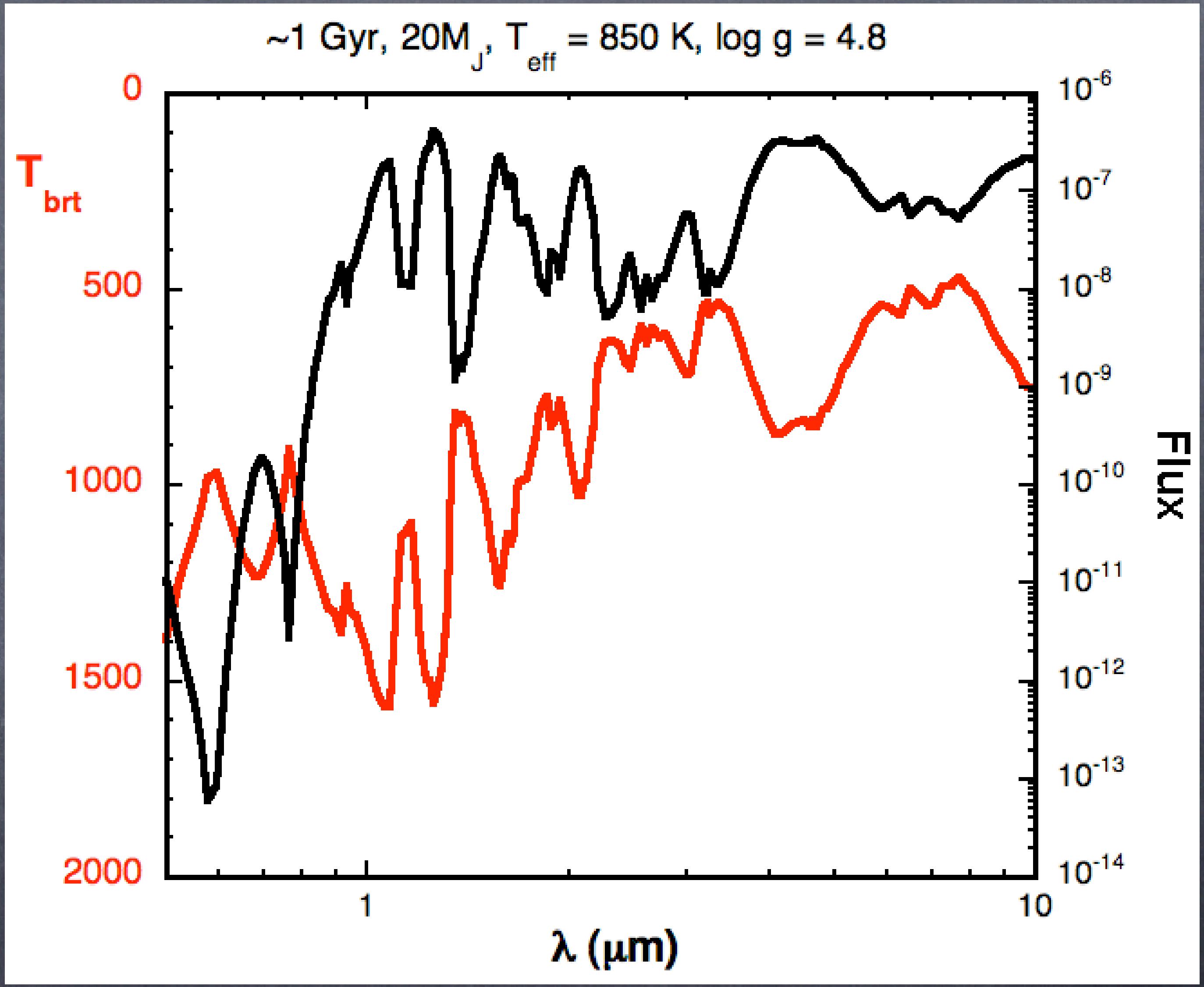
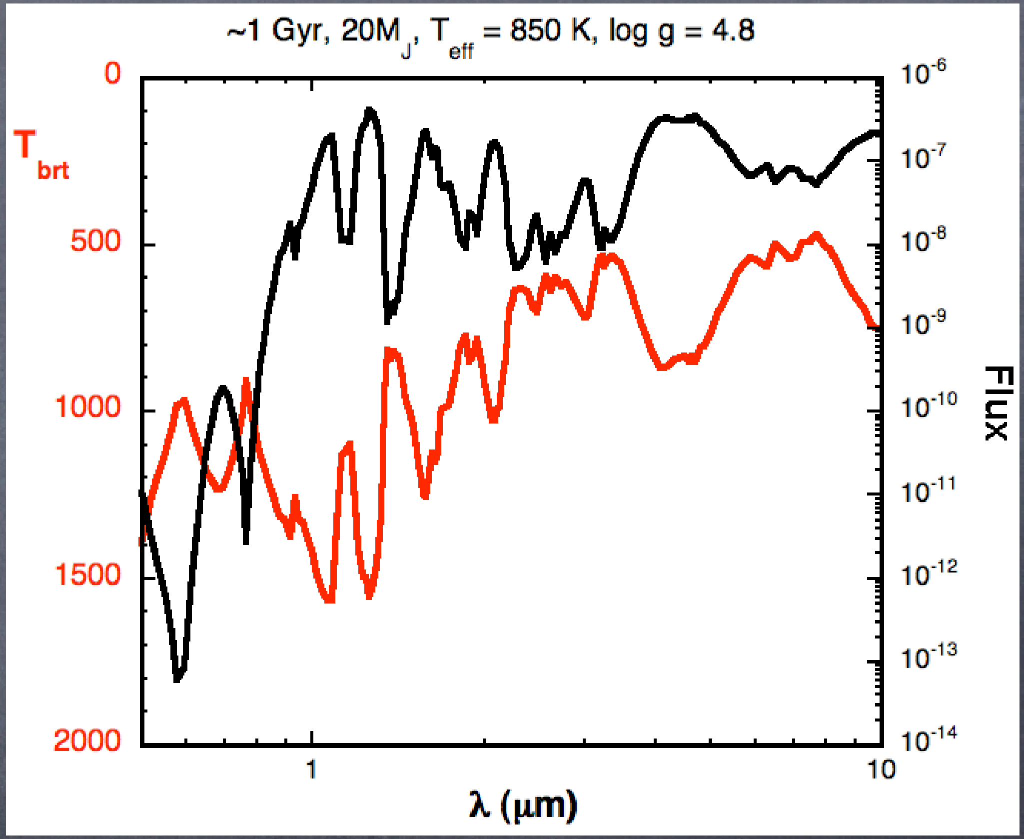
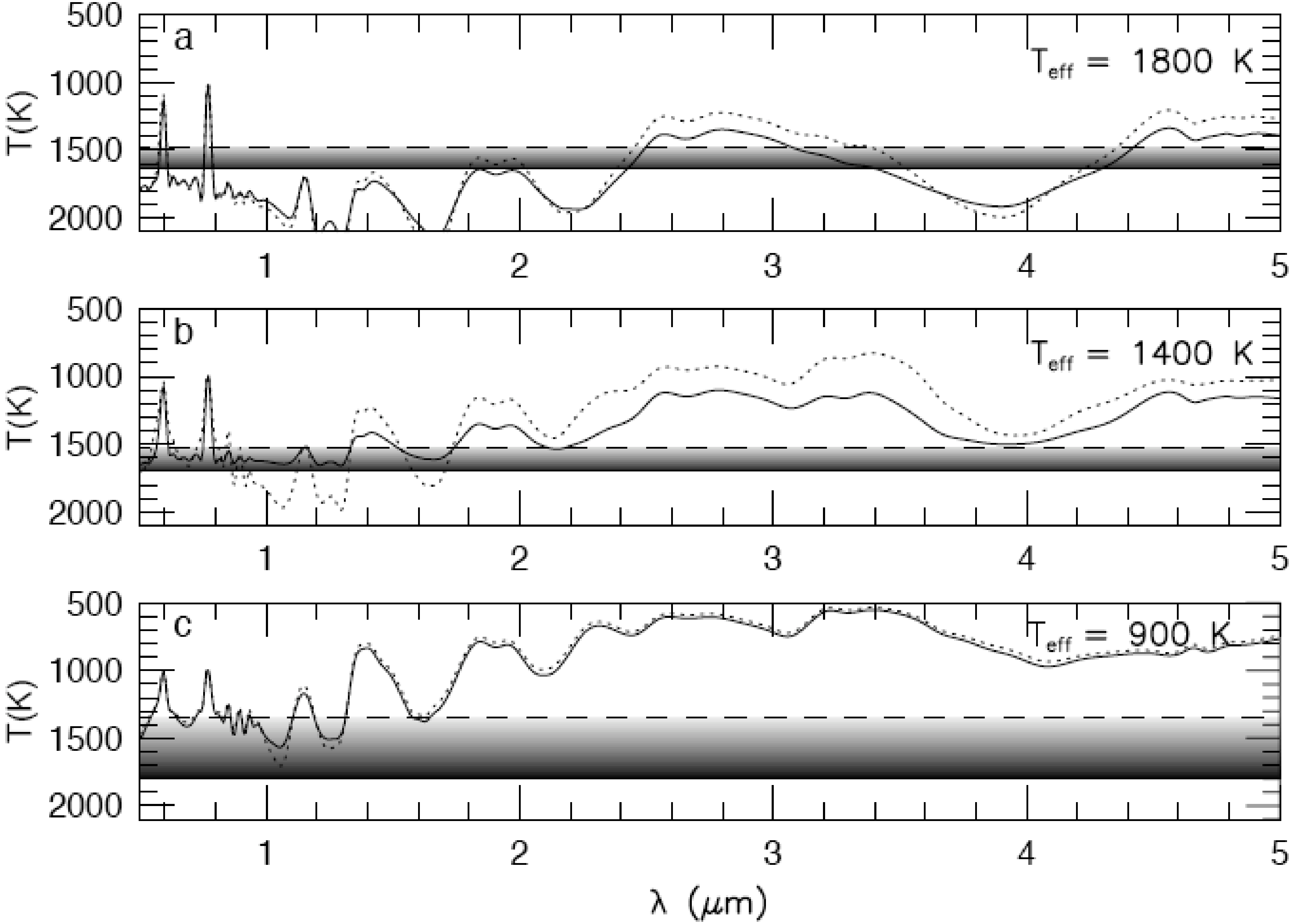


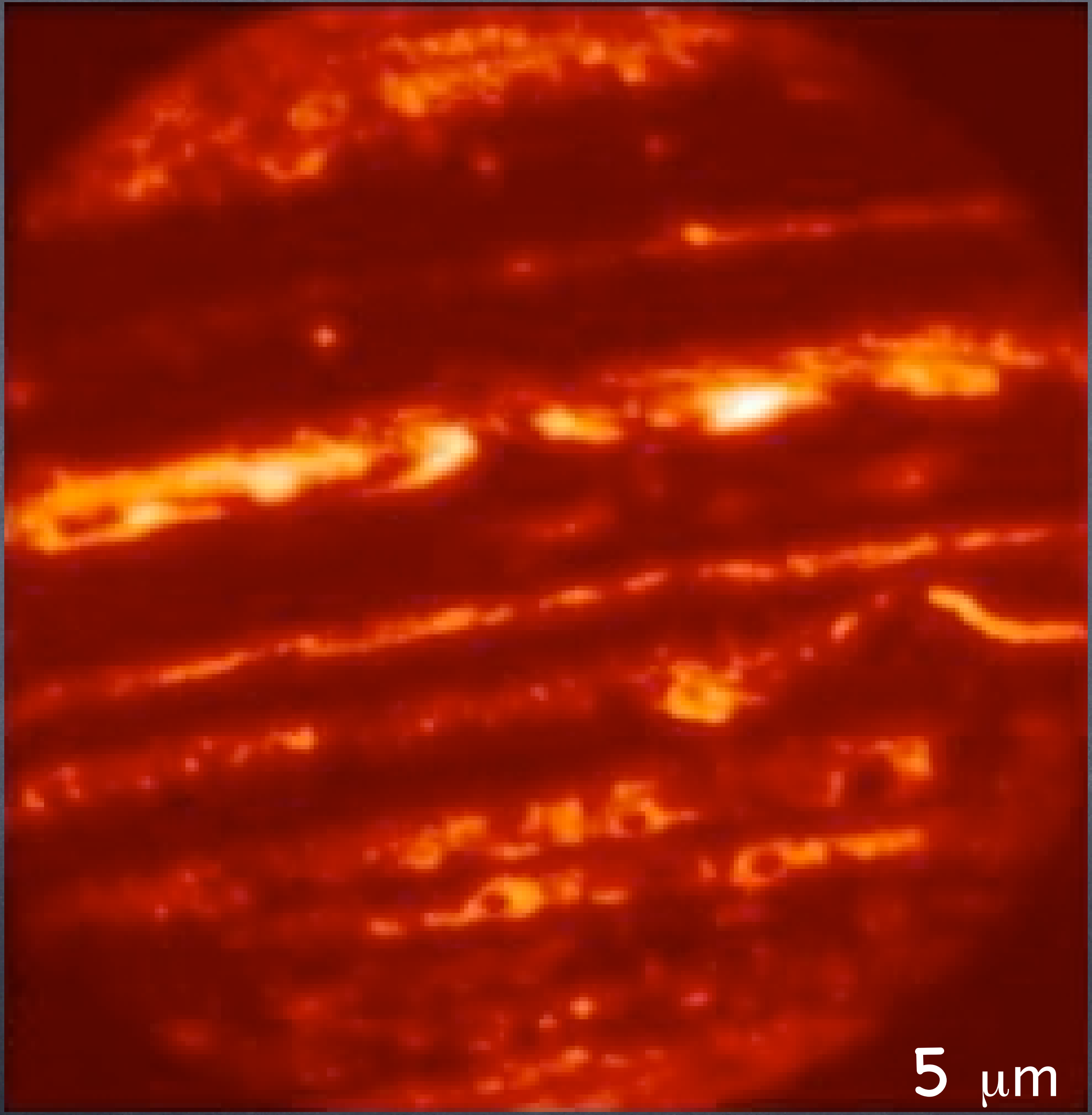
# Probing an Atmosphere

- $T_{min}$ ~ 500 K, $P_{min}$ ~ 0.1 bar
- $T_{max}$ ~1600 K, $P_{max}$ ~ 19 bar
- 5 scale heights!



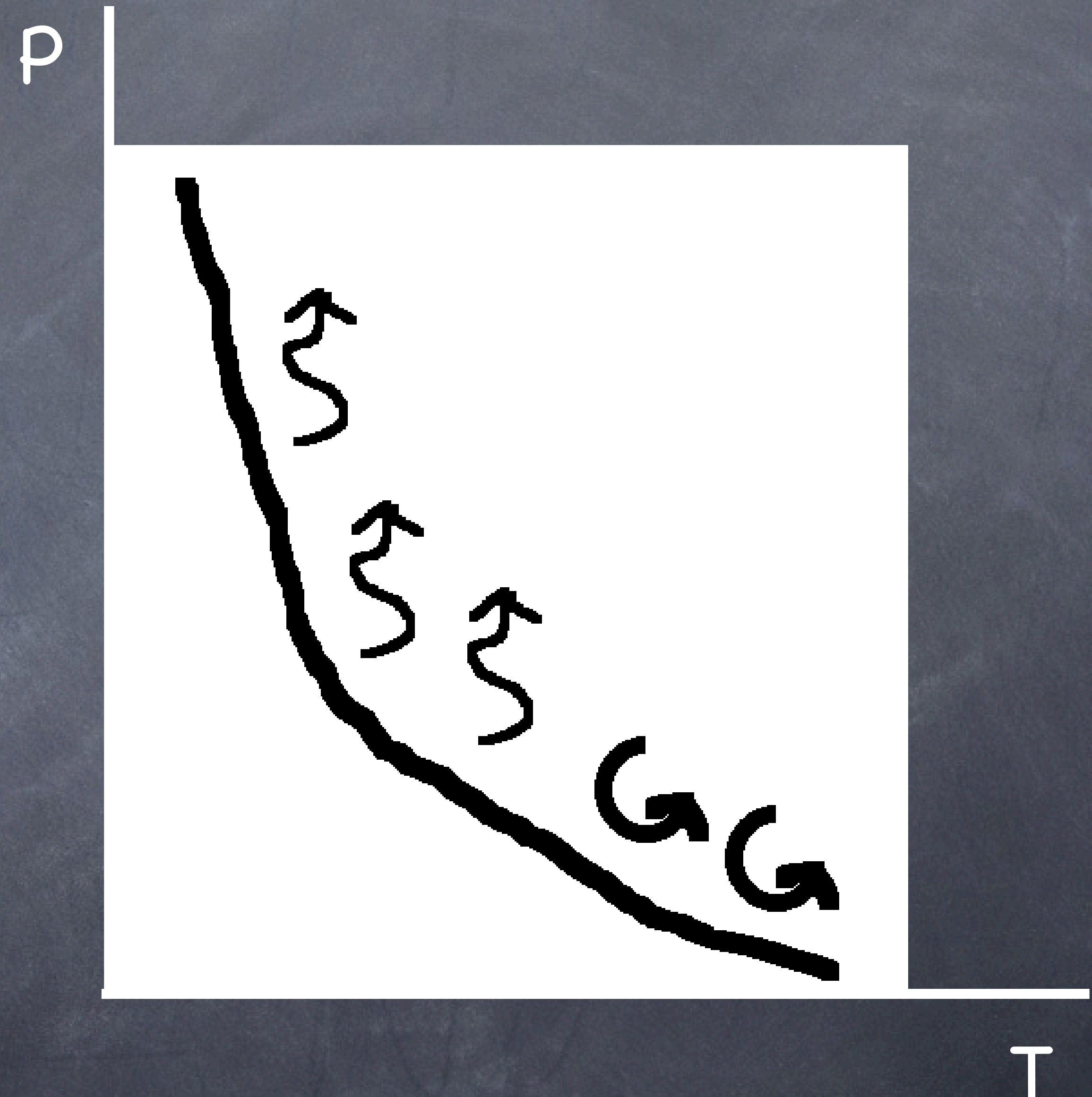


500
1000
1500
2000
T(K)
a
$T_{eff}$ = 1800 K
b
$T_{eff}$ = 1400 K
c
$T_{eff}$ = 900 K
1
2
3
4
5
λ (μm)


5 μm

# Energy Transport

- Deposited incident light heats atmosphere
- Atmosphere must transport upward all of the energy deposited below that point
  - convection
  - radiation
  - conduction
- Plus internal heat flux



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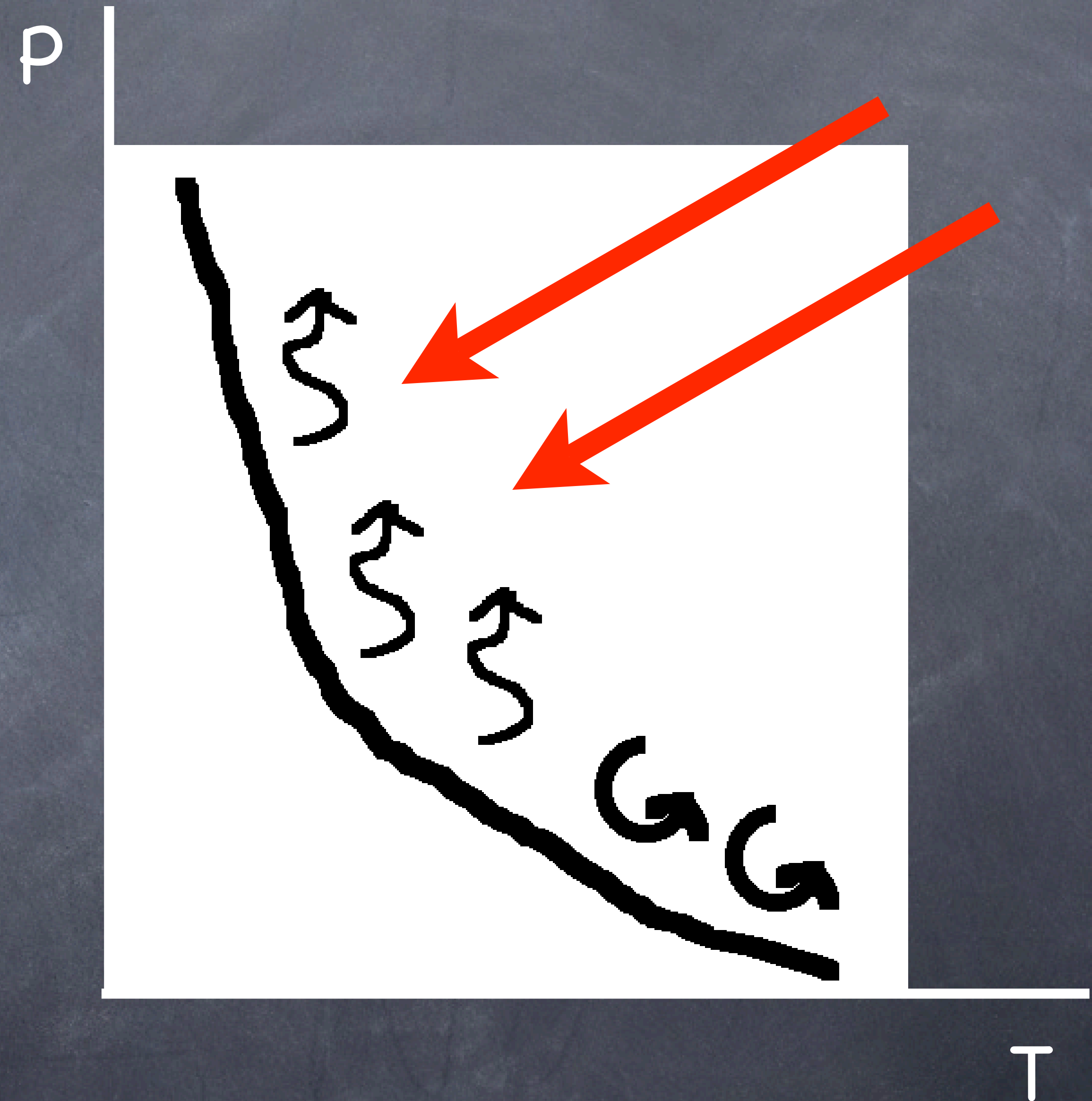

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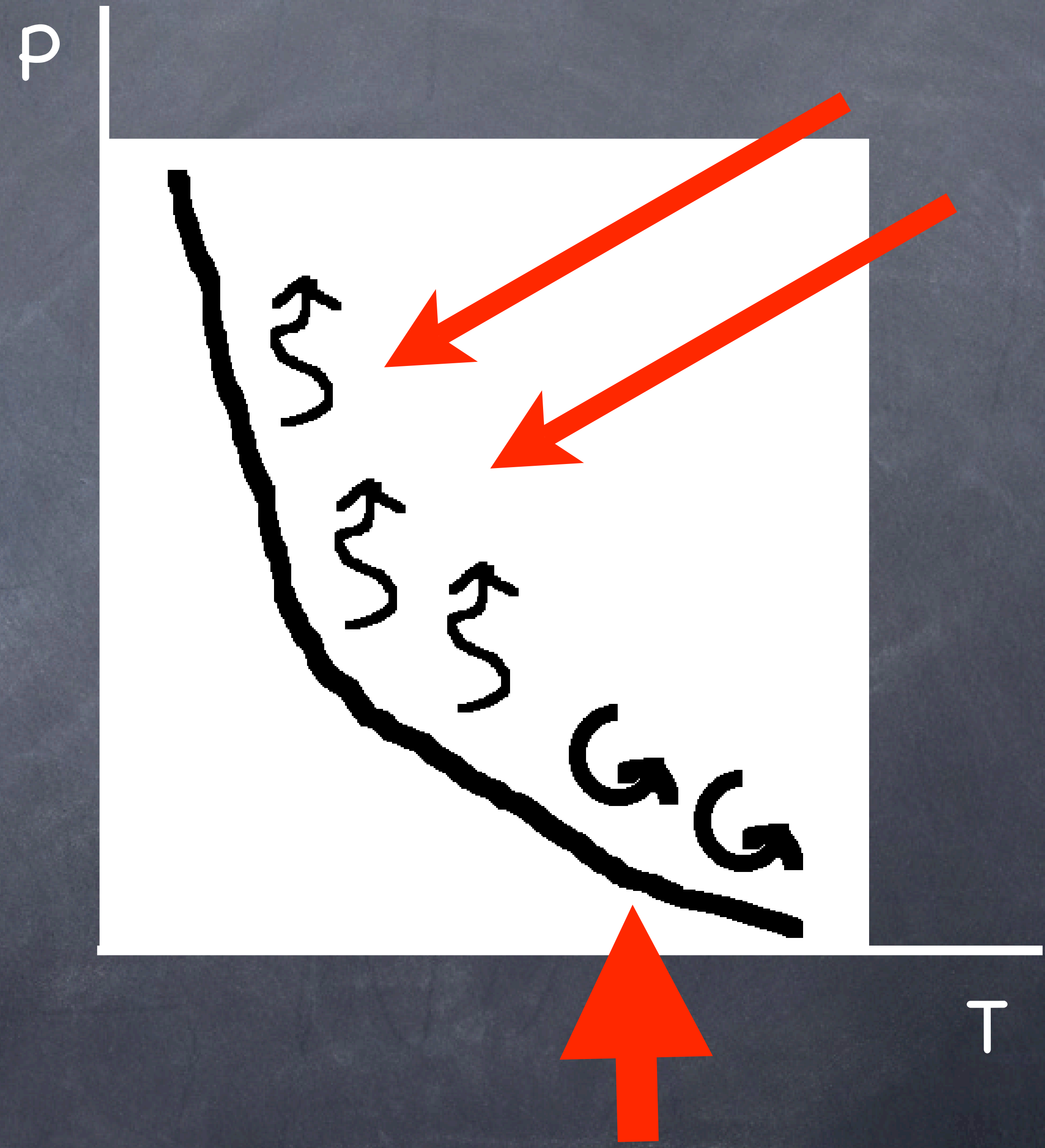
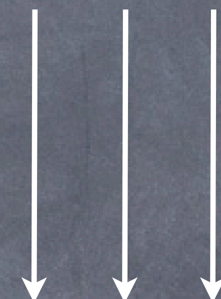


# How to Deposit Incident Light?

$$I = f(I_0/\mu)\, e^{-\tau/\mu}$$

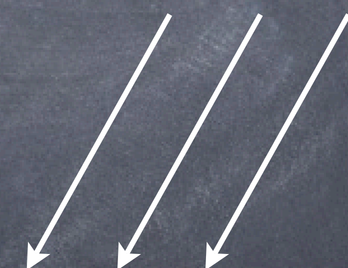
- stellar school: $f = 1/4$

$\mu=1$



- planetary school: $f = 1/2$

$\mu=1/2$



- Hot Jupiter school: $0 < f < 1$ $\mu=?$

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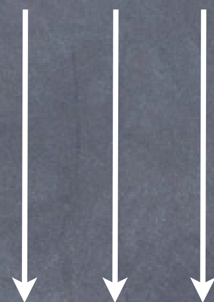
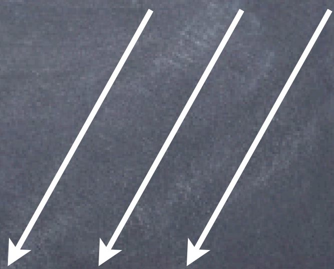
  $\mu$=1



- planetary school: $f$ = 1/2

  $\mu$=1/2

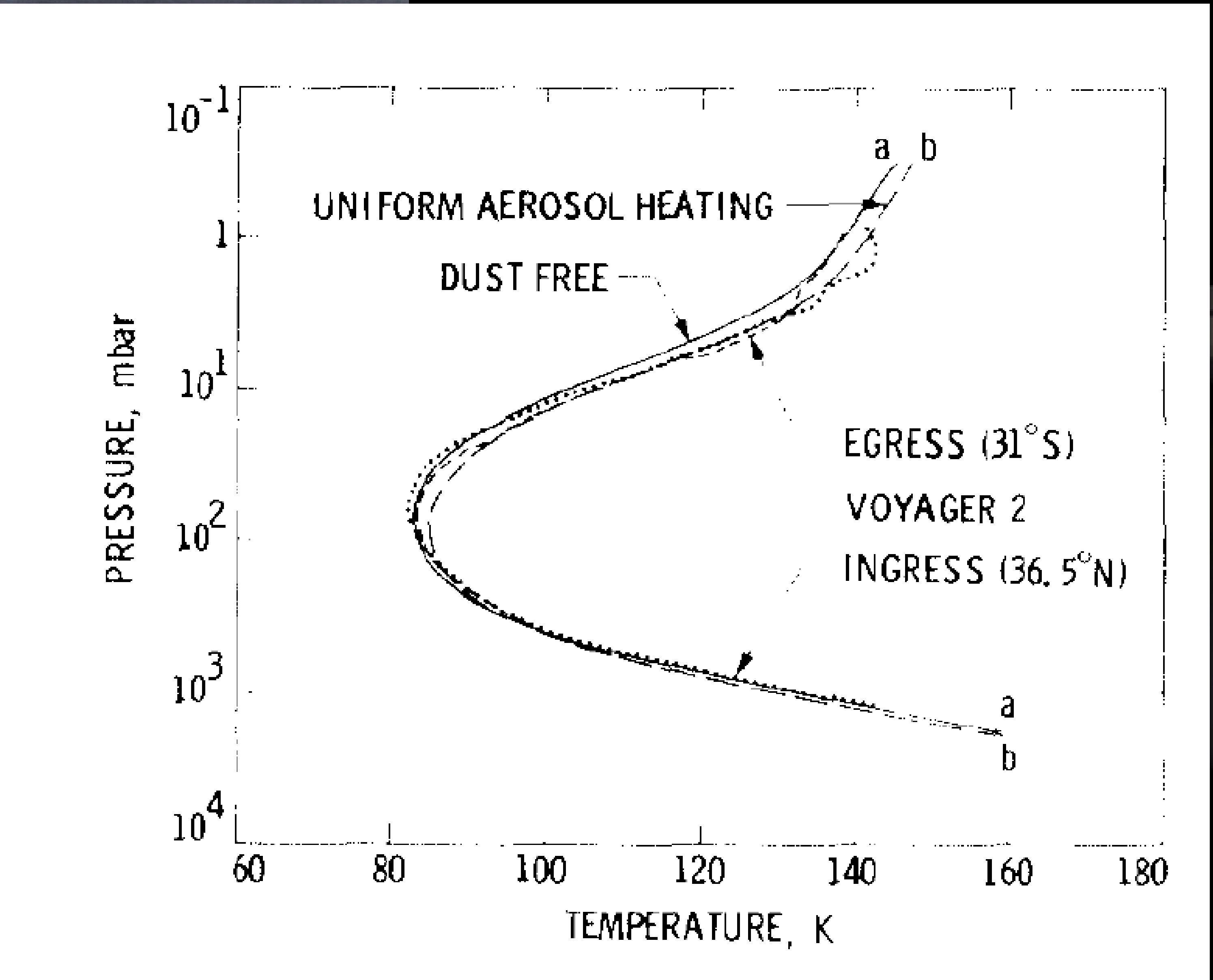


- Hot Jupiter school: 0 < $f$ < 1 $\mu$=?

# Ultimately Need a GCM

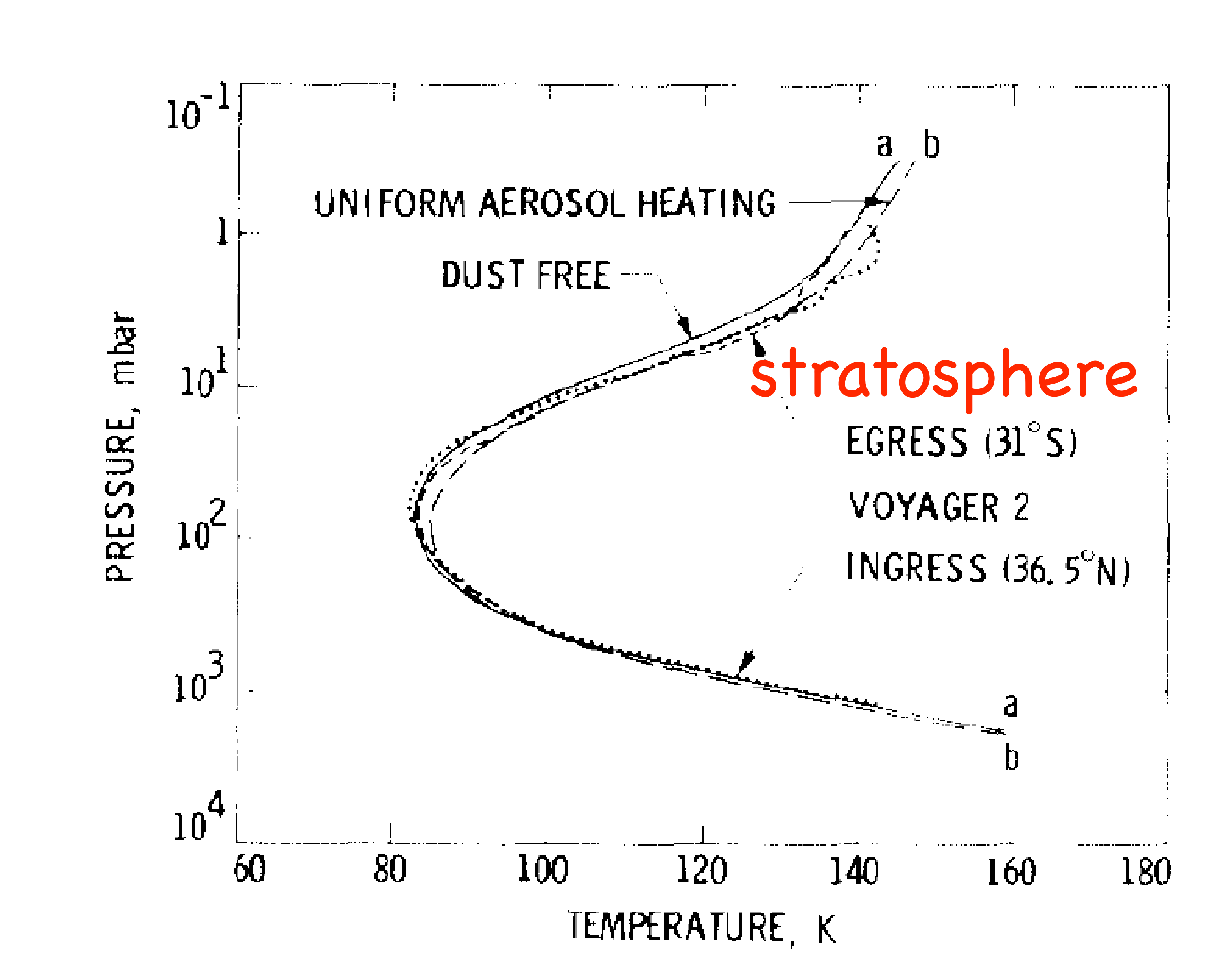
# 1D Models

# Saturn



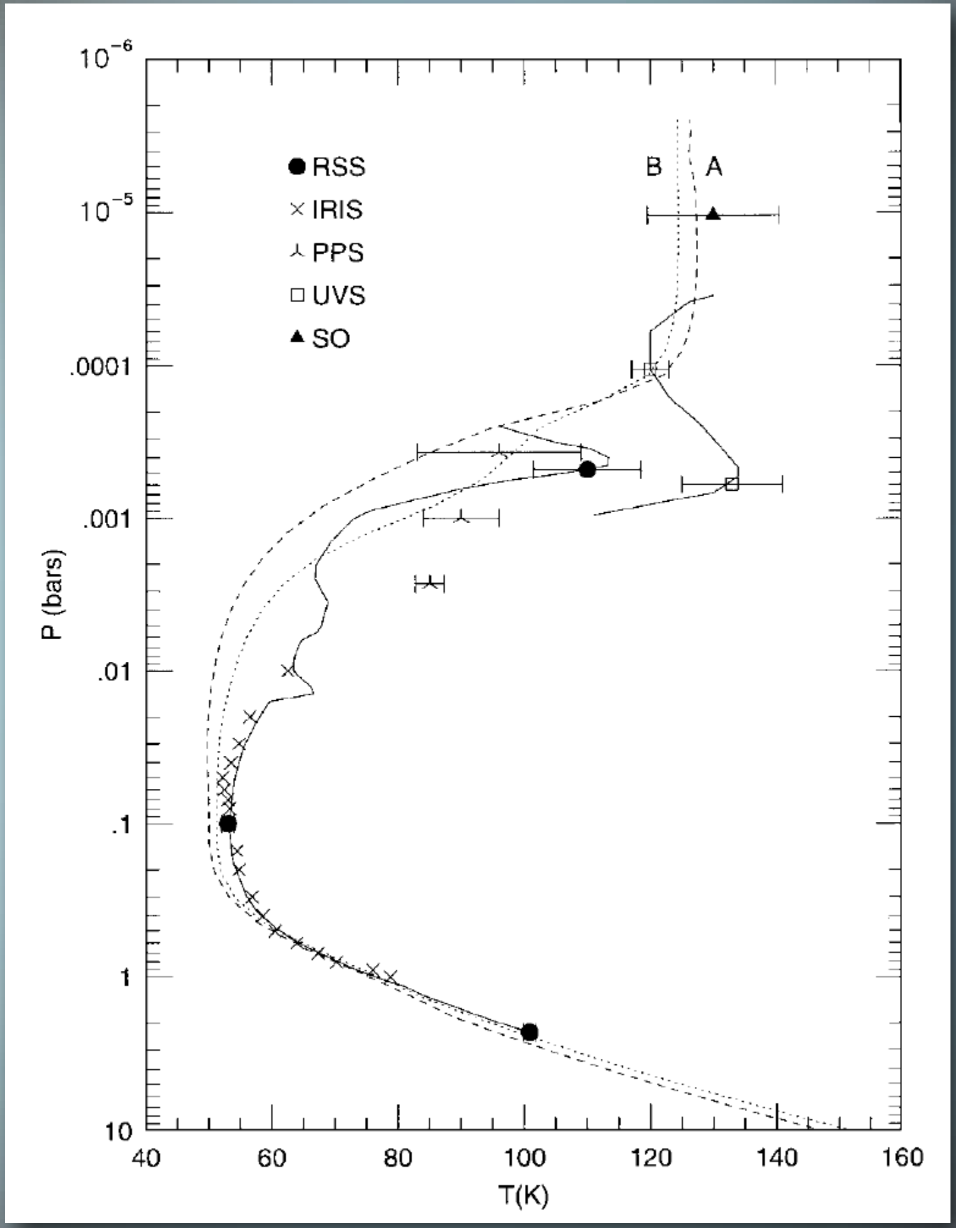

Appleby & Hogan (1984)

# Saturn



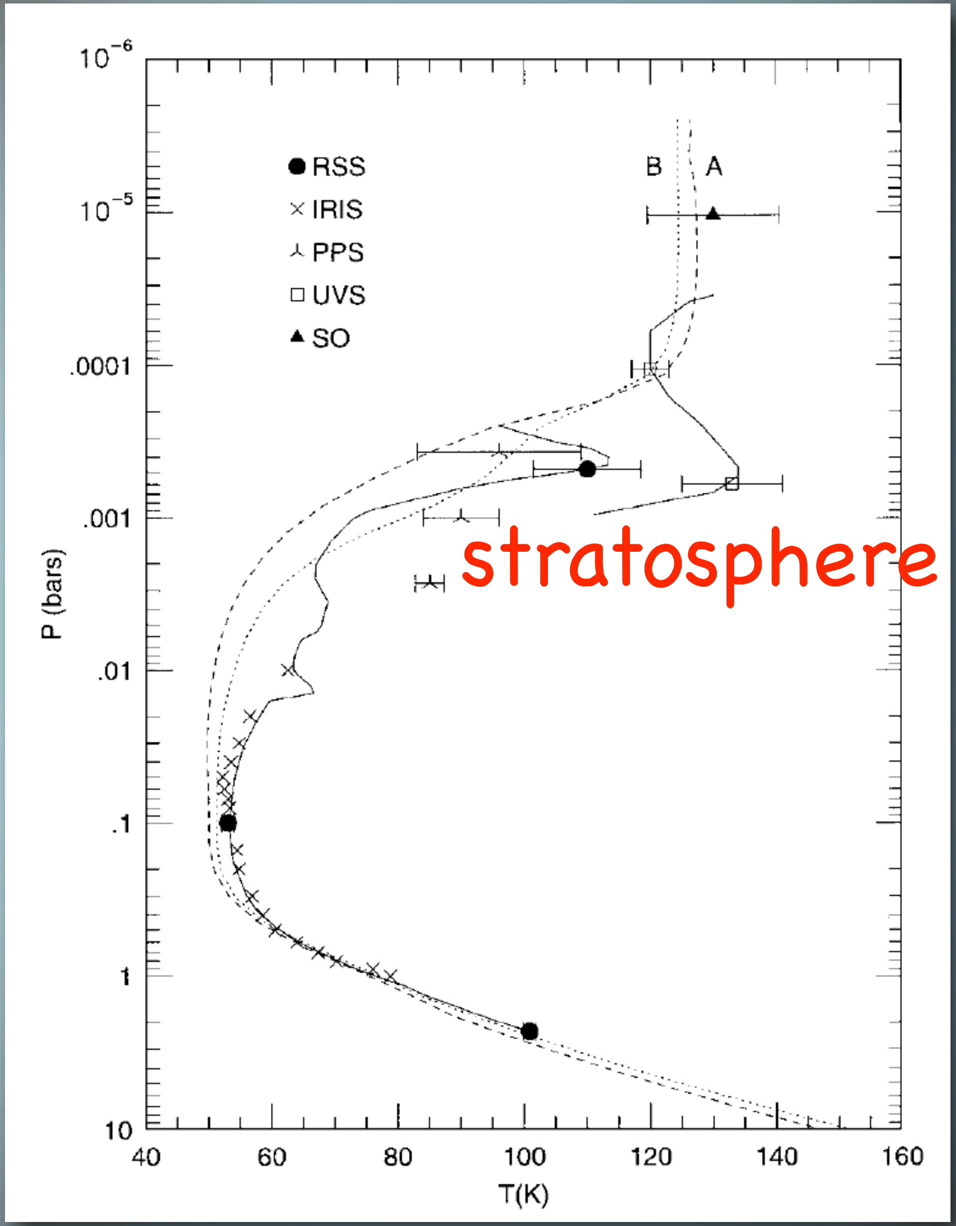

Appleby & Hogan (1984)

# Uranus

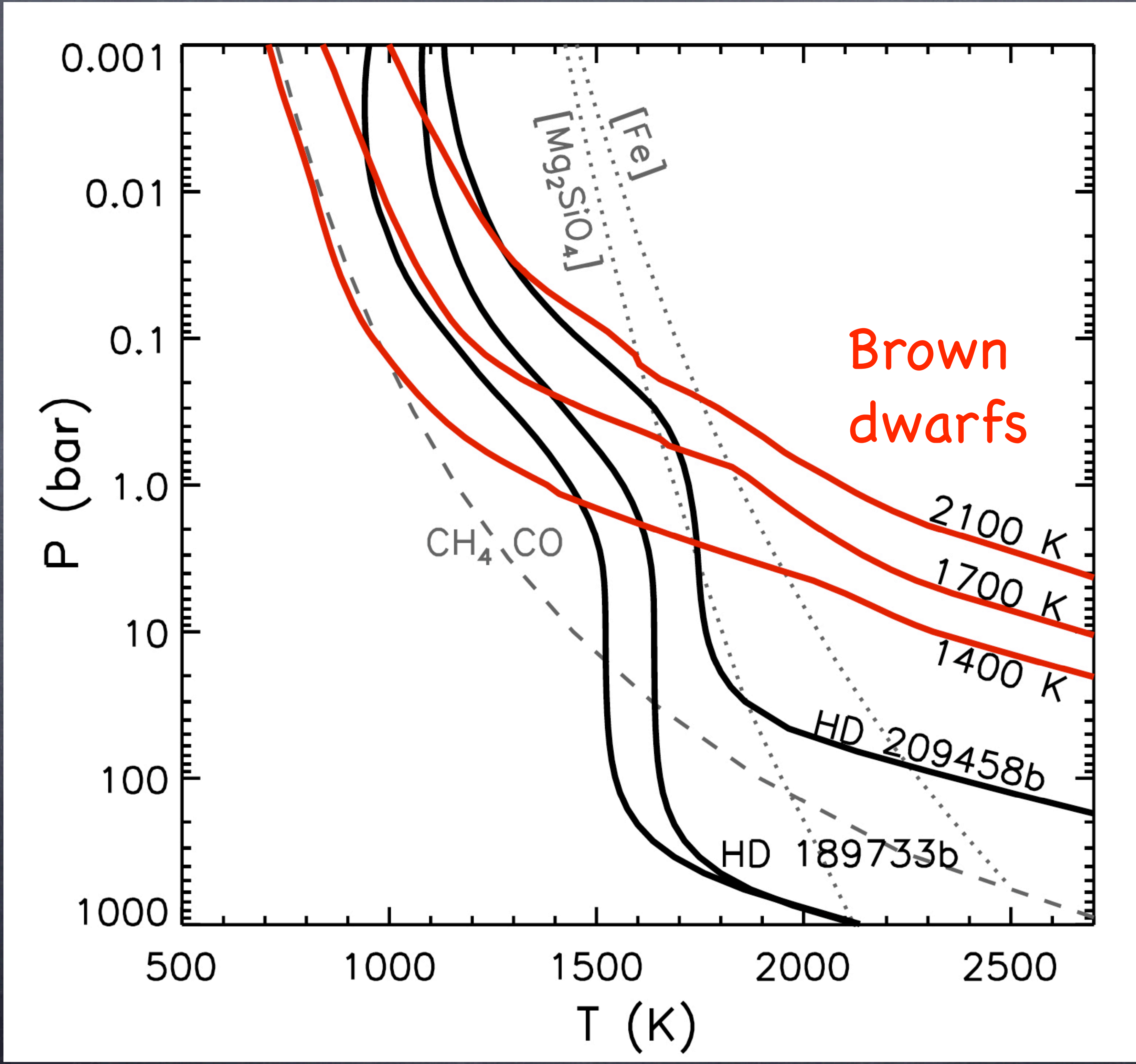



Marley & McKay (1999)

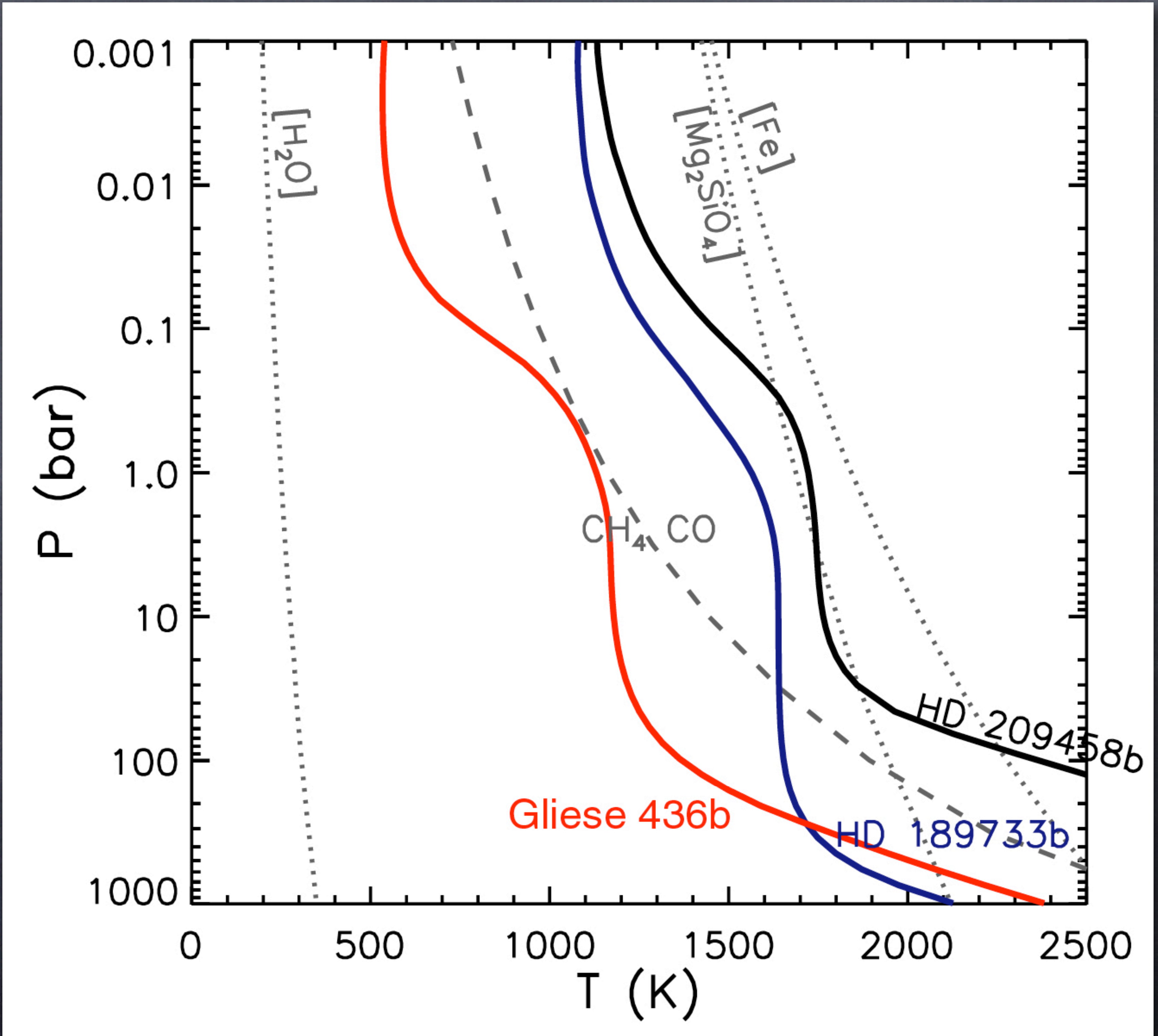
# Uranus



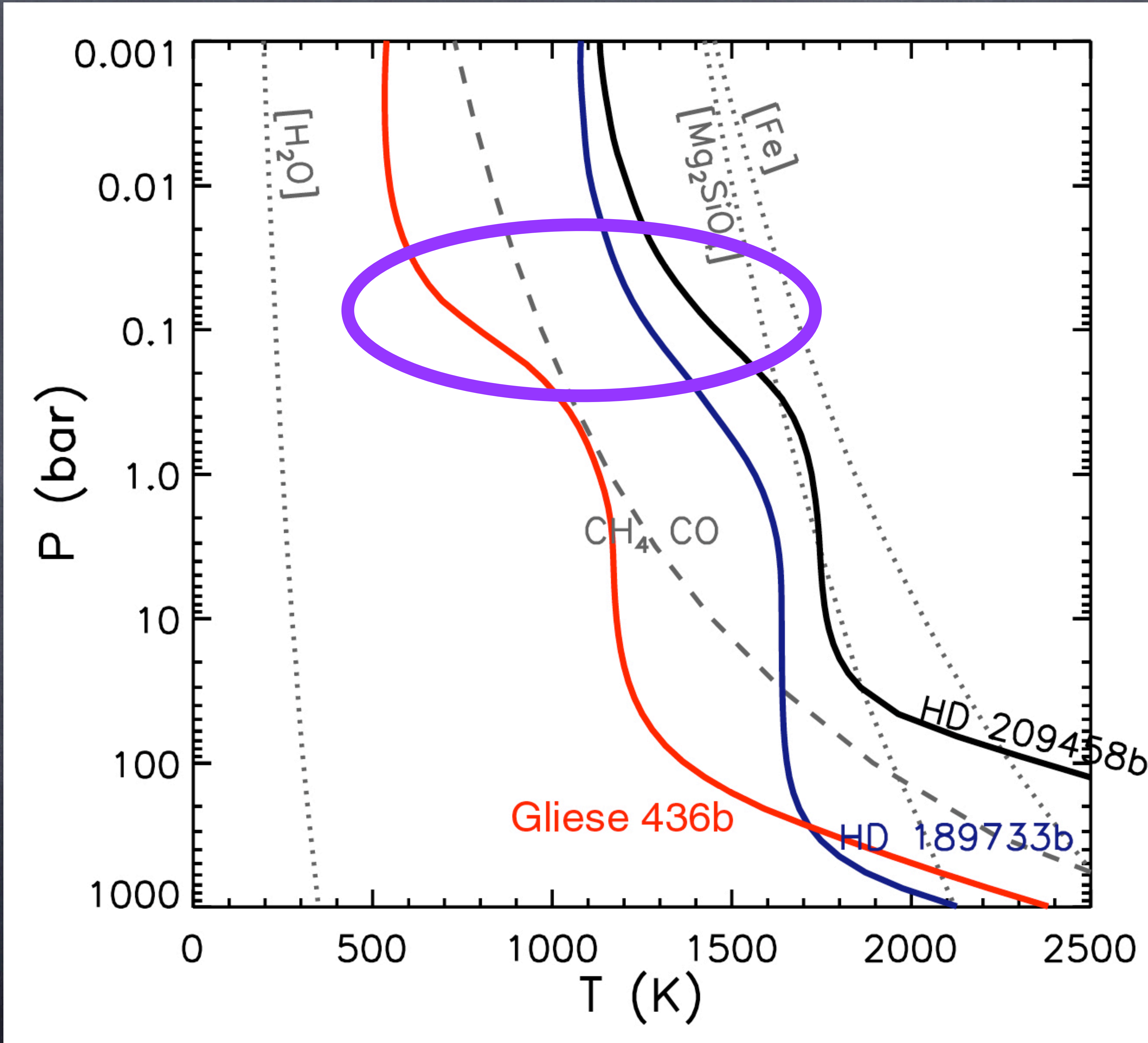

Marley & McKay (1999)



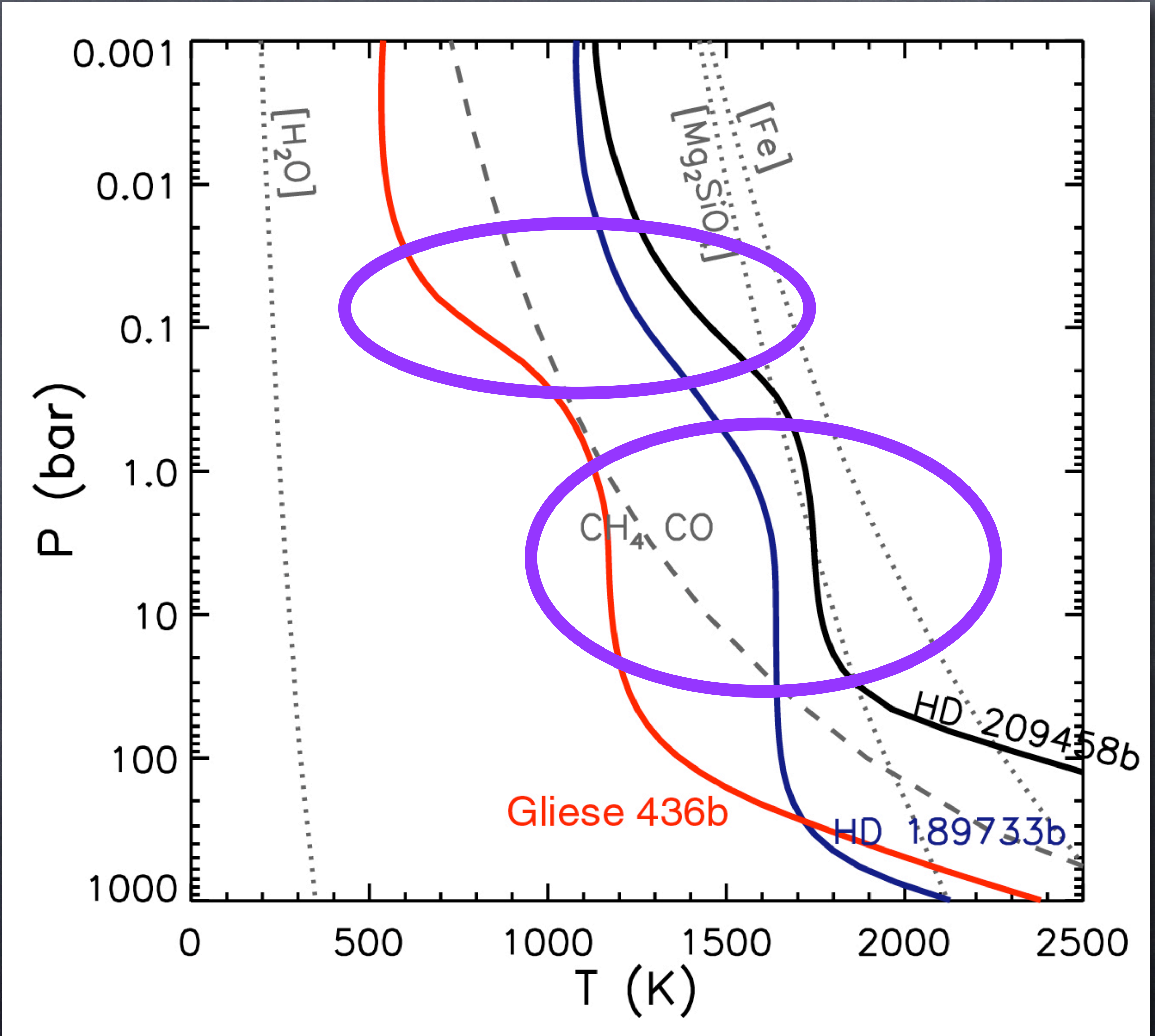
Brown dwarfs
2100 K
1700 K
1400 K
HD 209458b
HD 189733b
[Fe]
[$Mg_2SiO_4$]
$CH_4$ CO
0.001
0.01
0.1
1.0
10
100
1000
P (bar)
500
1000
1500
2000
2500
T (K)



P (bar)
T (K)
0.001
0.01
0.1
1.0
10
100
1000
0
500
1000
1500
2000
2500
[$H_2O$]
[$Mg_2SiO_4$]
[Fe]
$CH_4$ CO
HD 209458b
Gliese 436b
HD 189733b



P (bar)
T (K)
0.001
0.01
0.1
1.0
10
100
1000
0
500
1000
1500
2000
2500
[$H_2O$]
[$Mg_2SiO_4$]
[Fe]
$CH_4$ CO
Gliese 436b
HD 189733b
HD 209458b



0.001
0.01
0.1
1.0
10
100
1000
P (bar)
0
500
1000
1500
2000
2500
T (K)
[$H_2O$]
[$Mg_2SiO_4$]
[Fe]
$CH_4$ CO
HD 209458b
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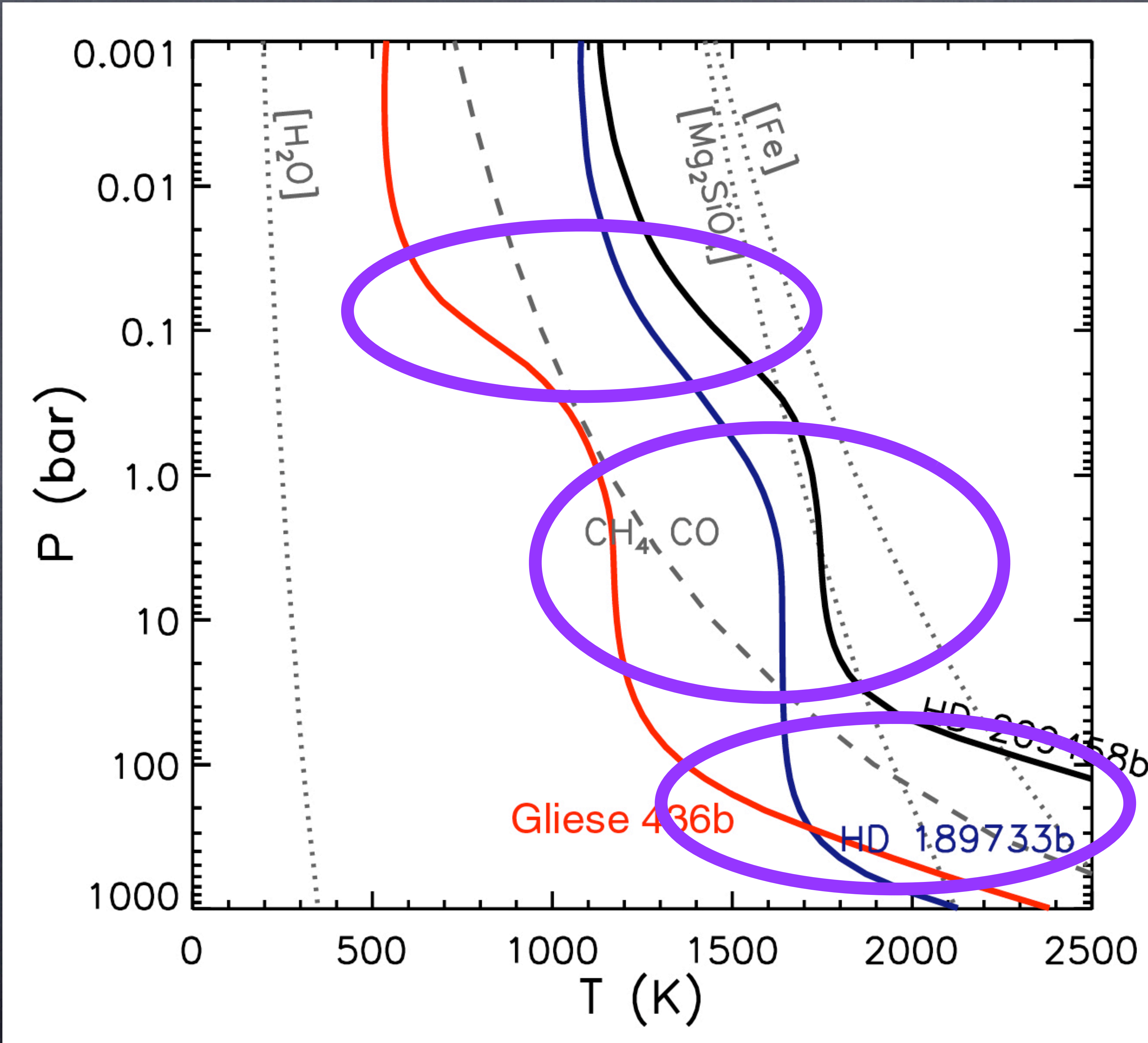
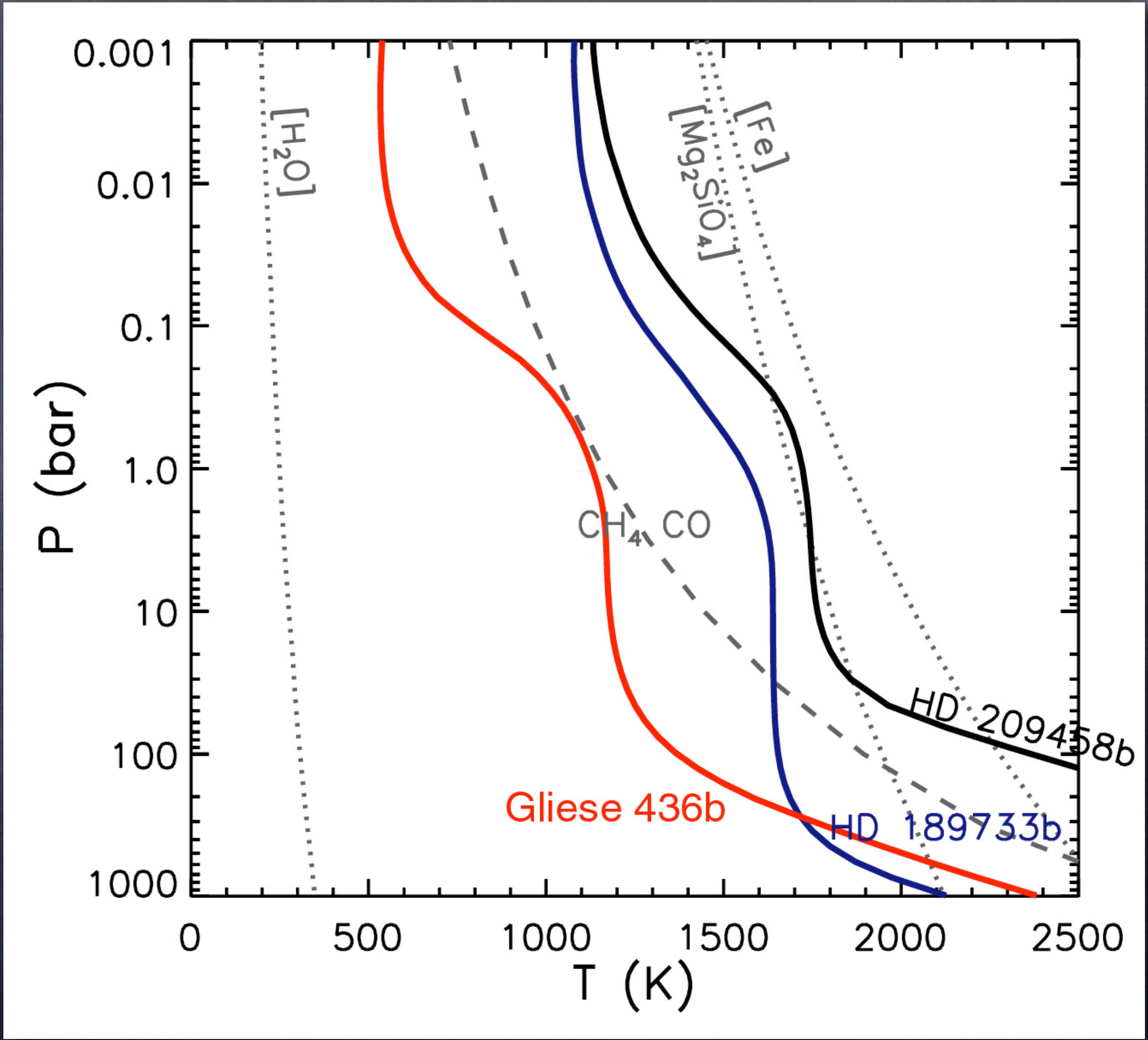
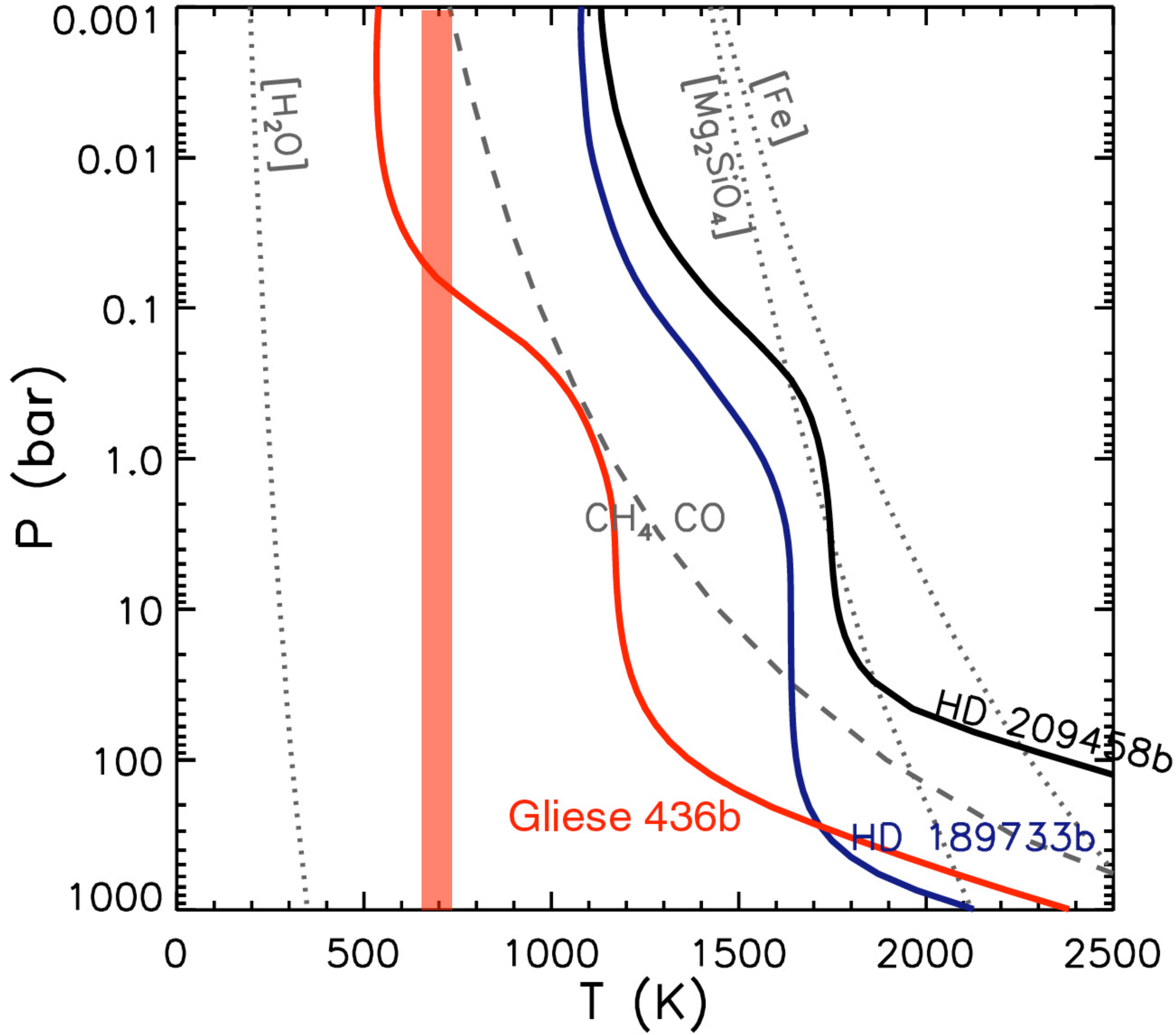
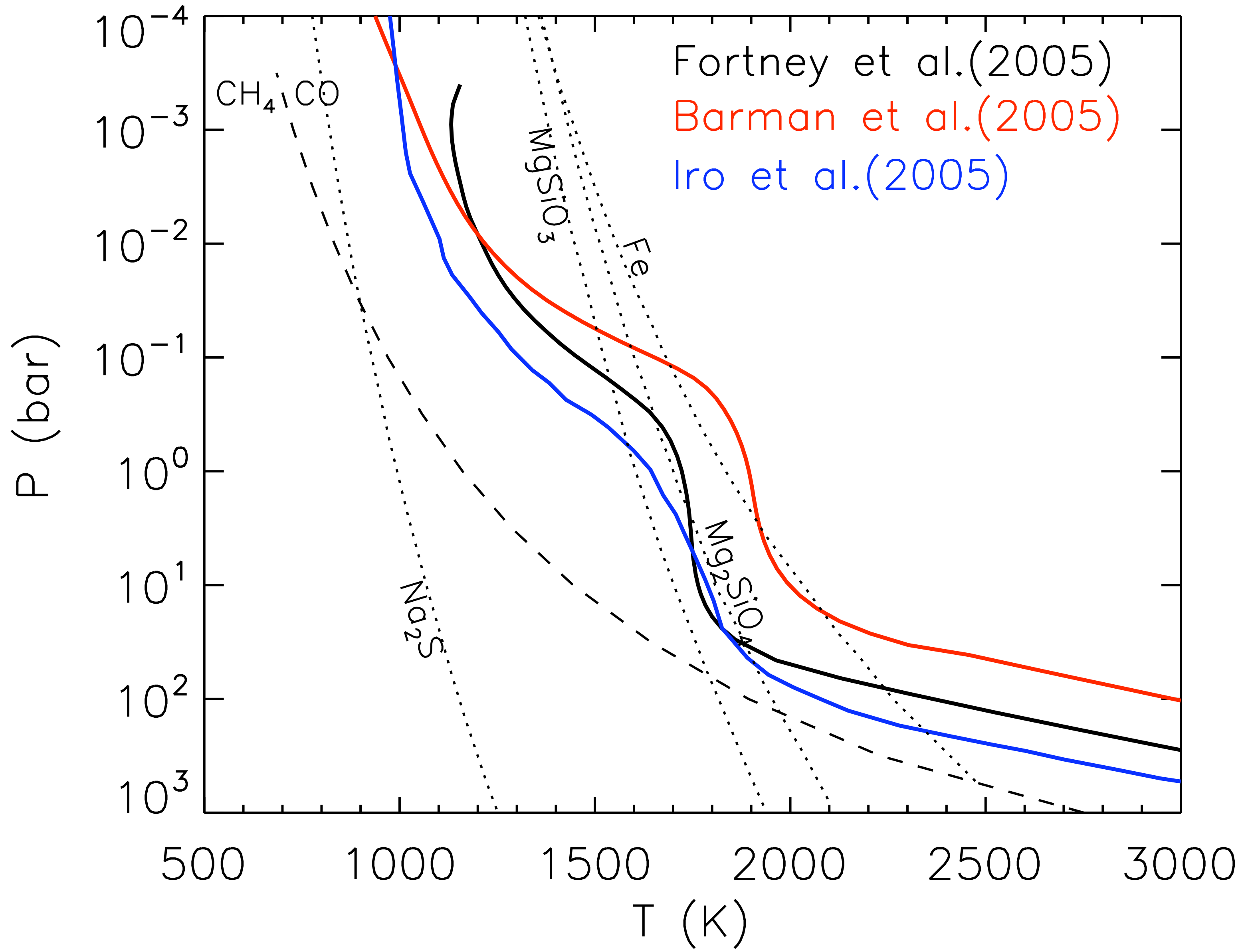


0.001
0.01
0.1
1.0
10
100
1000
P (bar)
0
500
1000
1500
2000
2500
T (K)
[$H_2O$]
[$Mg_2SiO_4$]
[Fe]
$CH_4$ CO
HD 209458b
Gliese 436b
HD 189733b

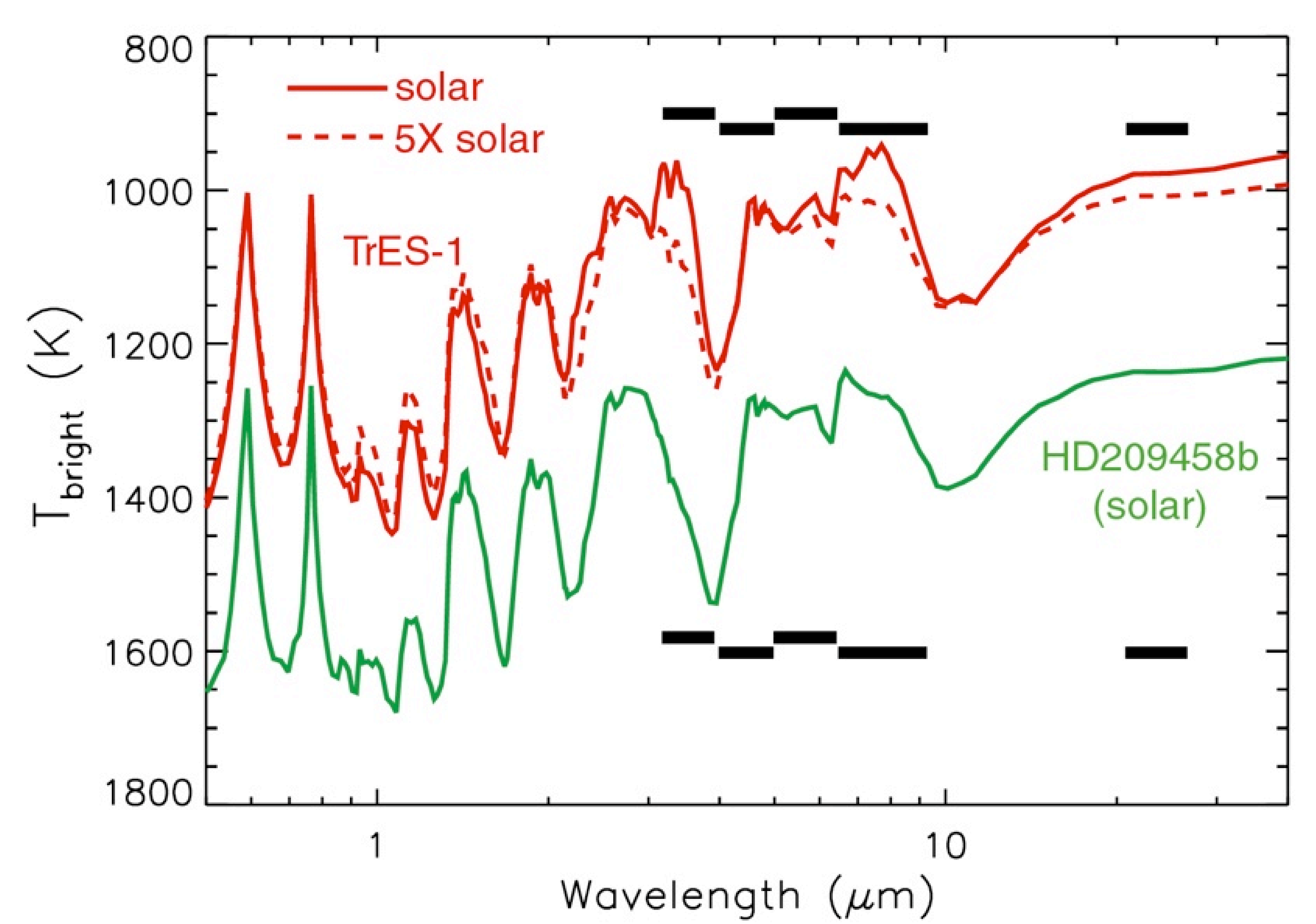

0.001
0.01
0.1
1.0
10
100
1000
P (bar)
0
500
1000
1500
2000
2500
T (K)
[H2O]
[Mg2SiO4]
[Fe]
CH4 CO
HD 209458b
HD 189733b
Gliese 436b



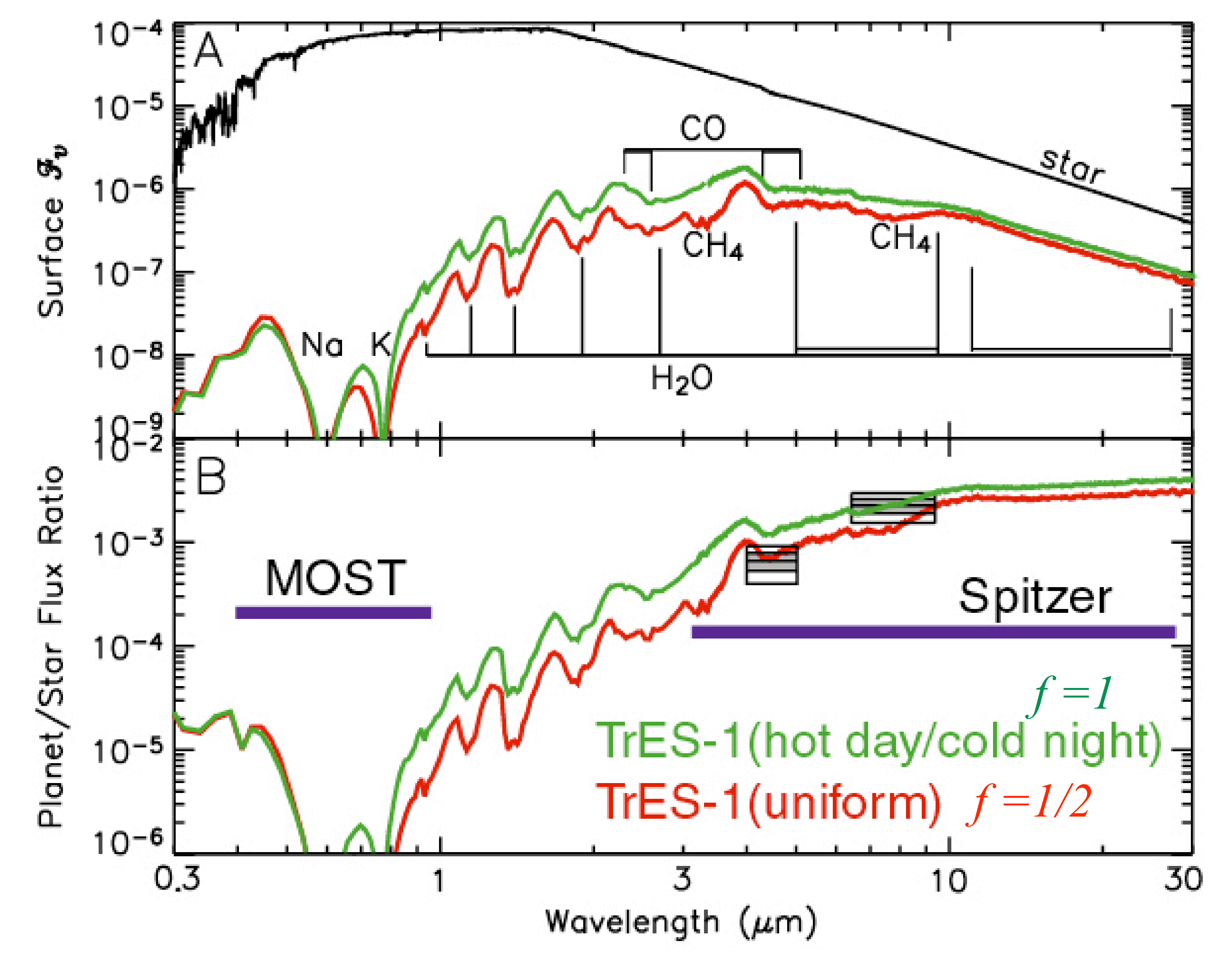
0.001
0.01
0.1
1.0
10
100
1000
P (bar)
0
500
1000
1500
2000
2500
T (K)
[H2O]
[Mg2SiO4]
[Fe]
CH4 CO
HD 209458b
HD 189733b
Gliese 436b



Fortney et al.(2005)
Barman et al.(2005)
Iro et al.(2005)
CH4
CO
MgSiO3
Fe
Mg2SiO4
Na2S
P (bar)
T (K)
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
500
1000
1500
2000
2500
3000

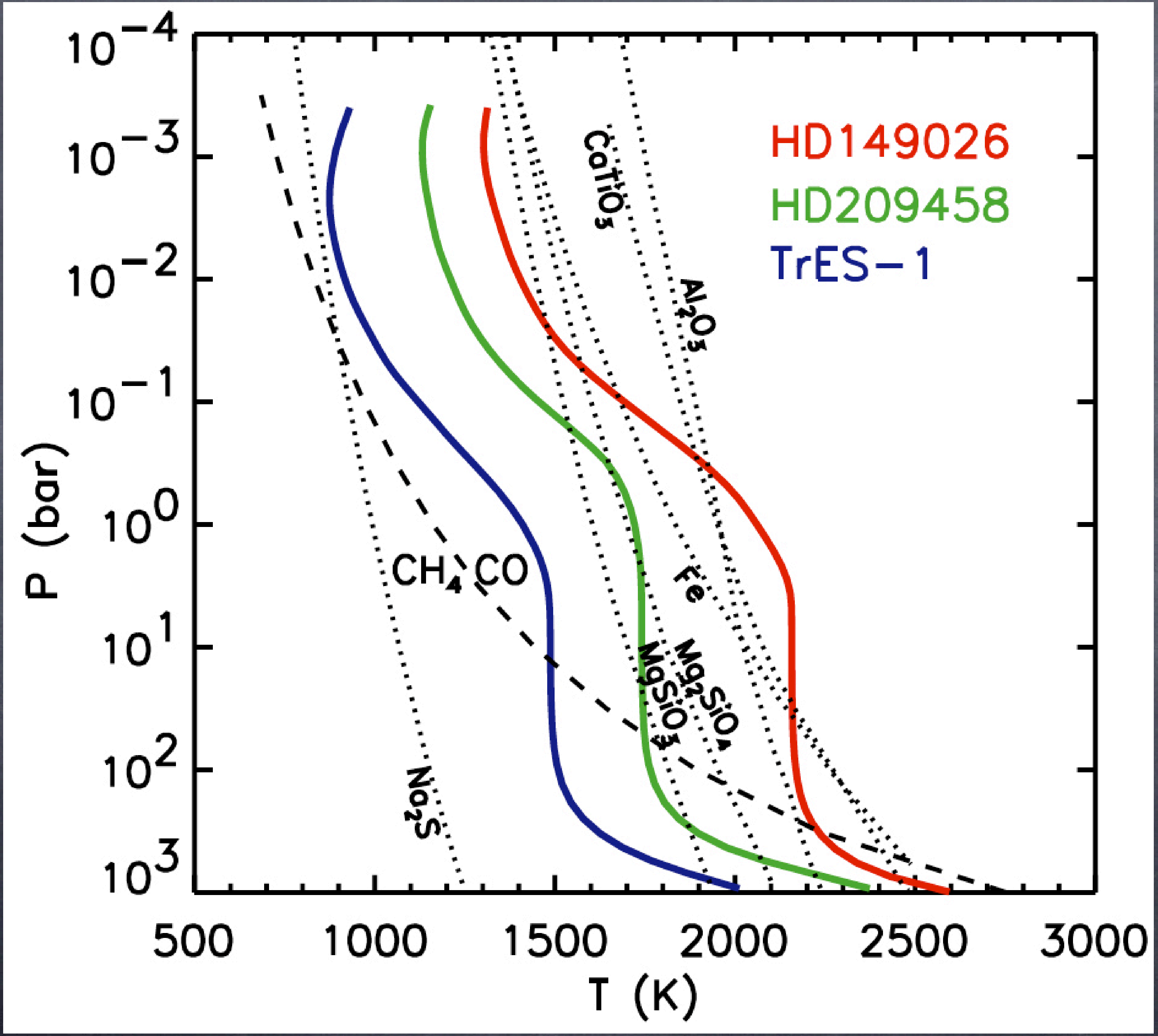


solar
5X solar
TrES-1
HD209458b (solar)
$T_{bright}$ (K)
Wavelength ($\mu$m)
800
1000
1200
1400
1600
1800
1
10

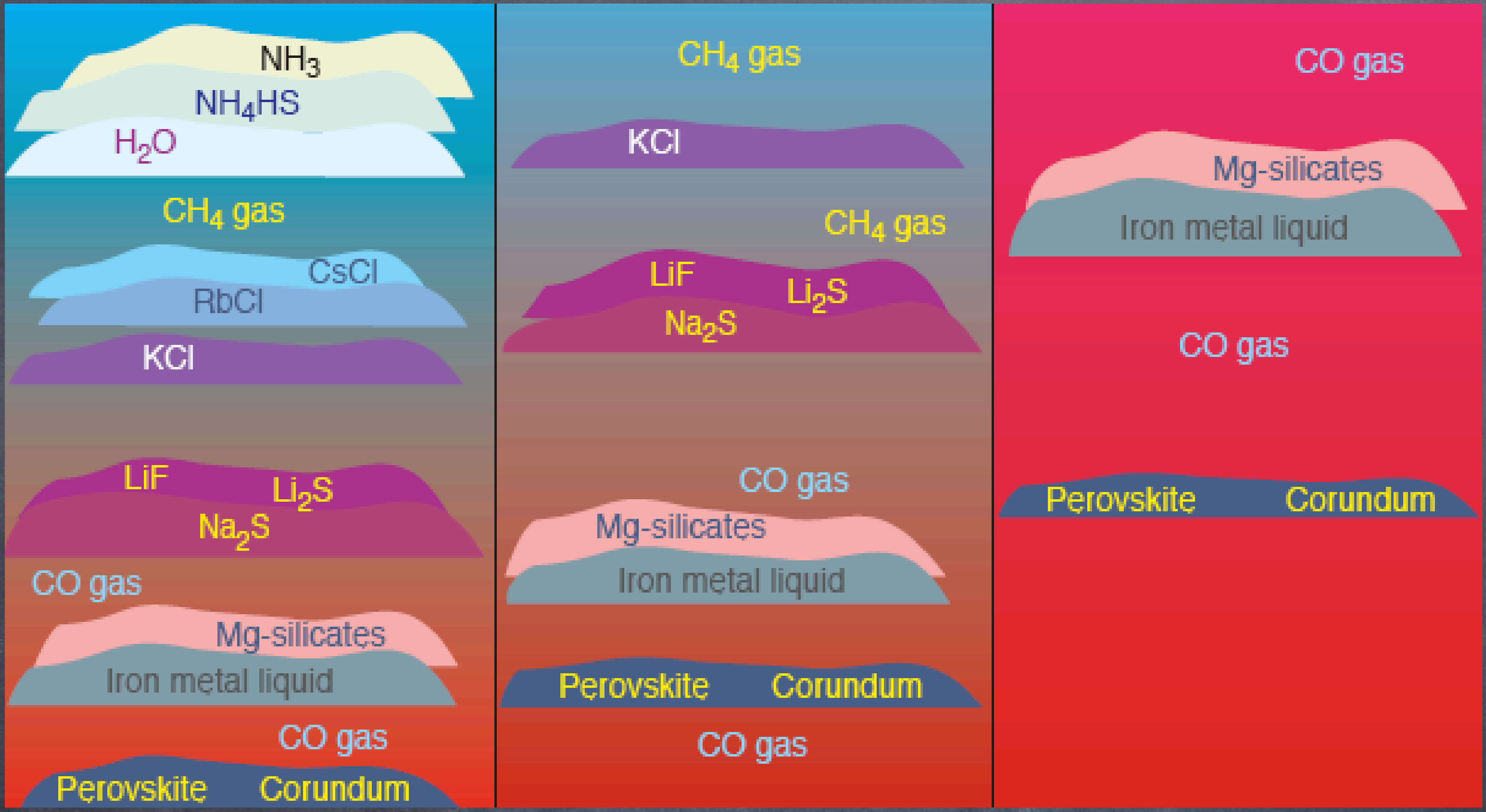


A
B
star
CO
$CH_4$
$CH_4$
Na
K
$H_2O$
MOST
Spitzer
$f = 1$
TrES-1(hot day/cold night)
TrES-1(uniform)
$f = 1/2$
Surface $\mathcal{F}_\nu$
Planet/Star Flux Ratio
Wavelength ($\mu$m)
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.3
1
3
10
30

# Clouds

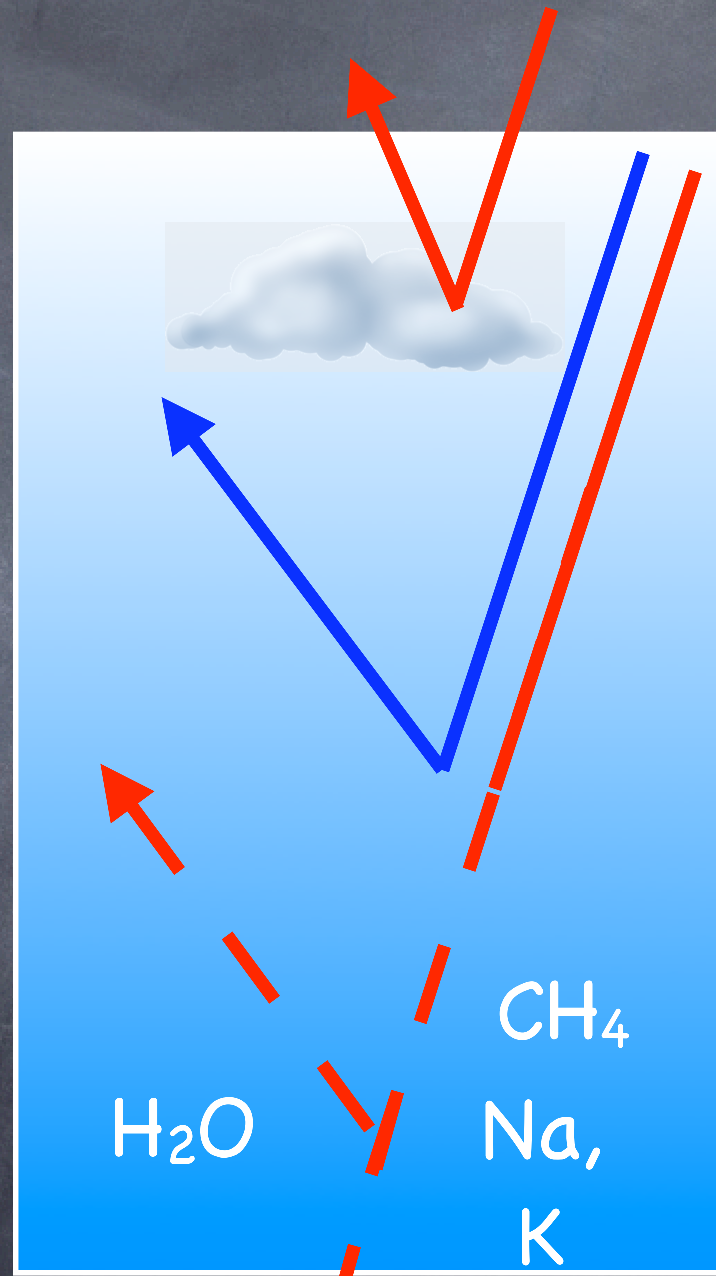


HD149026
HD209458
TrES−1
P (bar)
T (K)
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
500
1000
1500
2000
2500
3000
CaTiO₃
Al₂O₃
Fe
Mg₂SiO₄
MgSiO₃
CH₄ CO
Na₂S

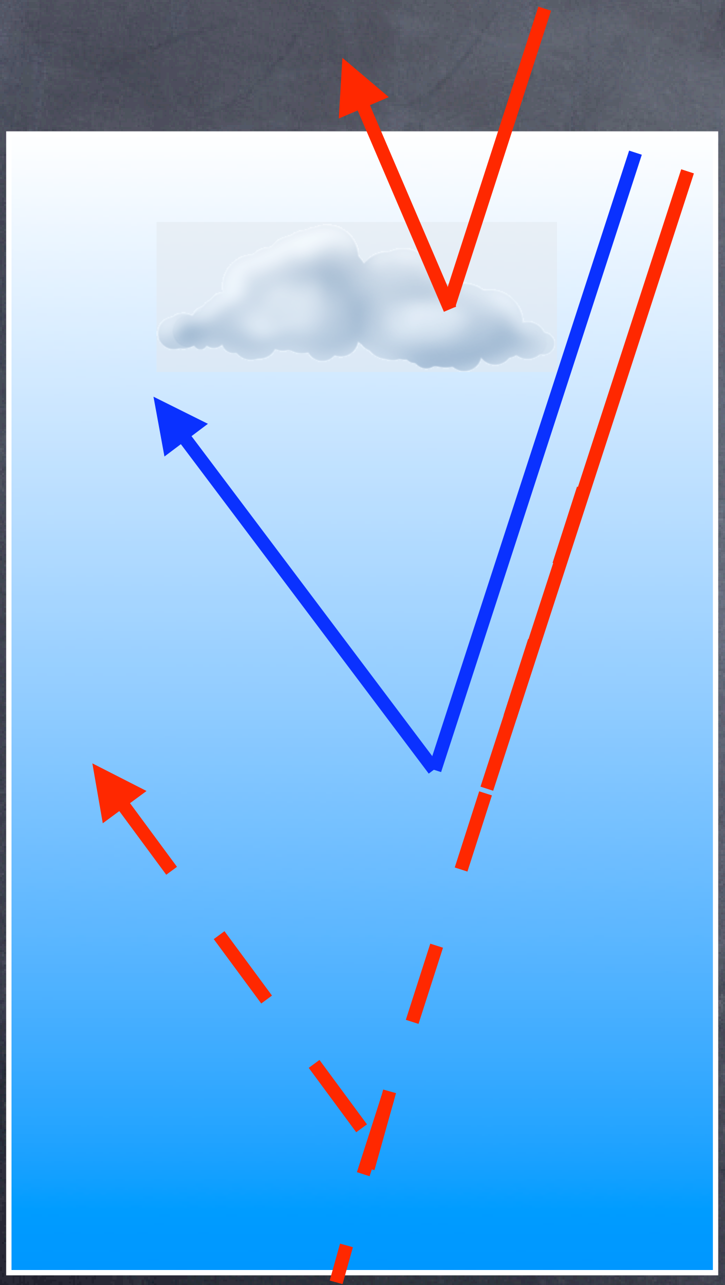


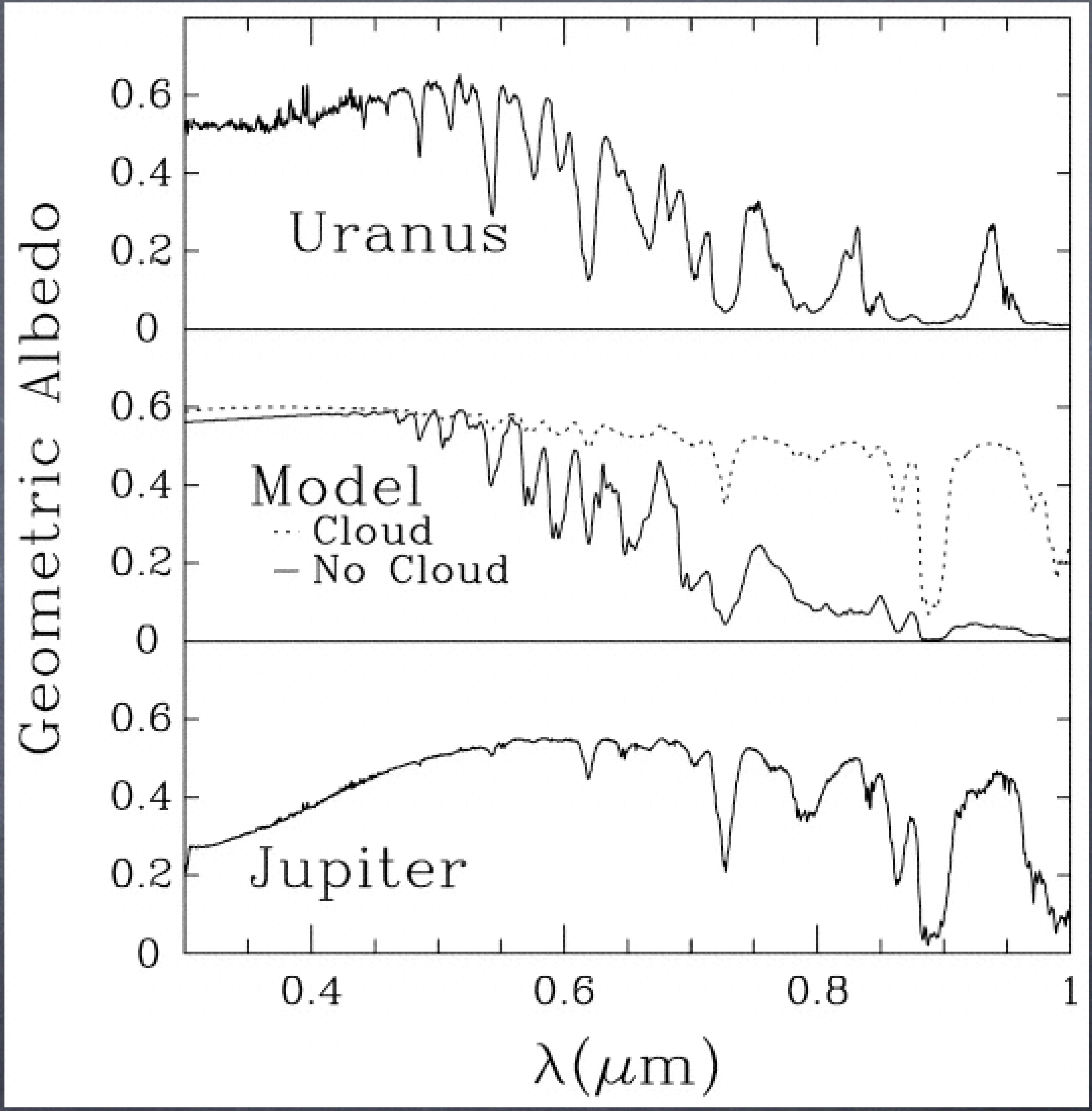

Jupiter Cloudless Hot Jupiter

Lodders (2005)

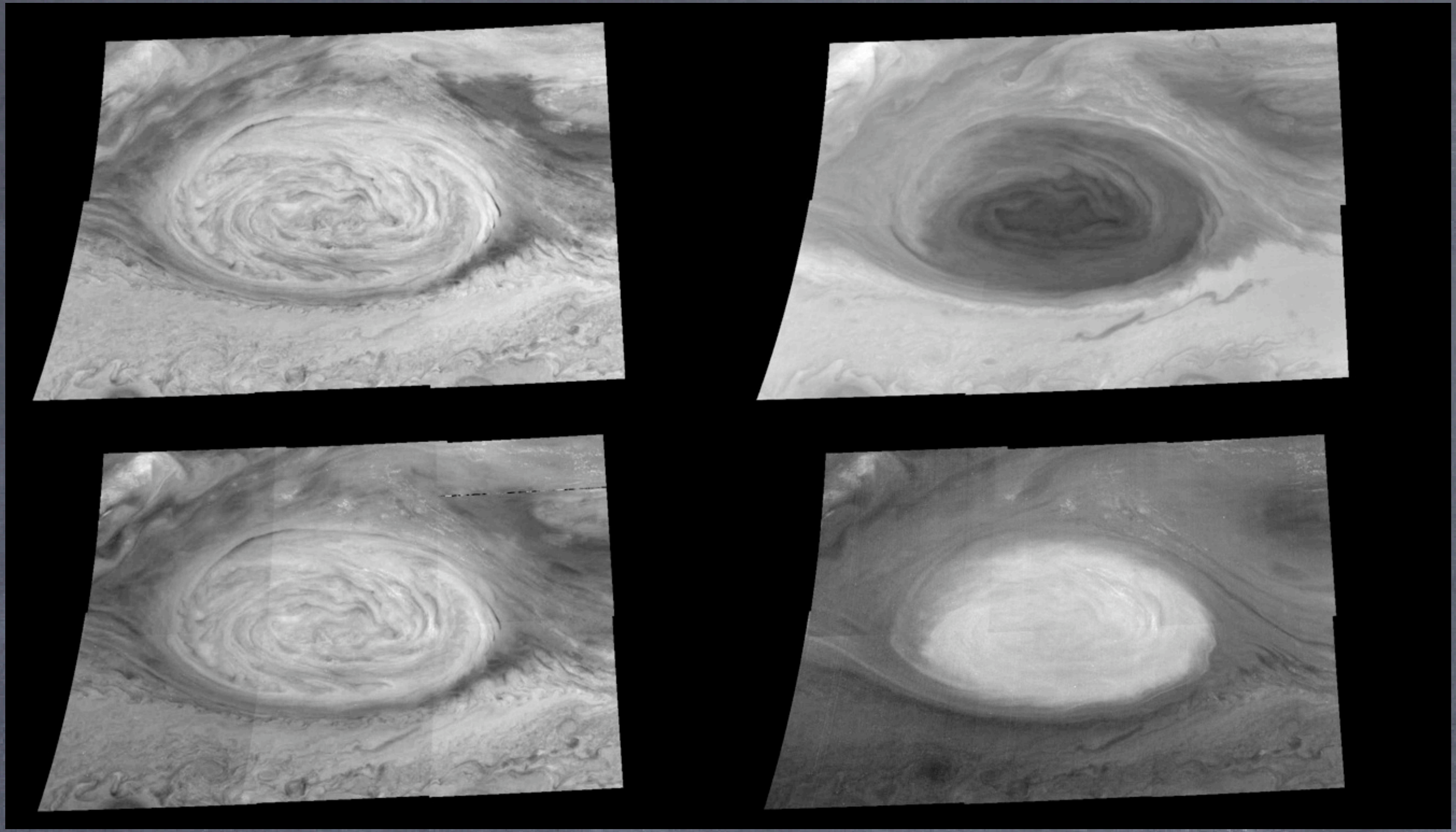


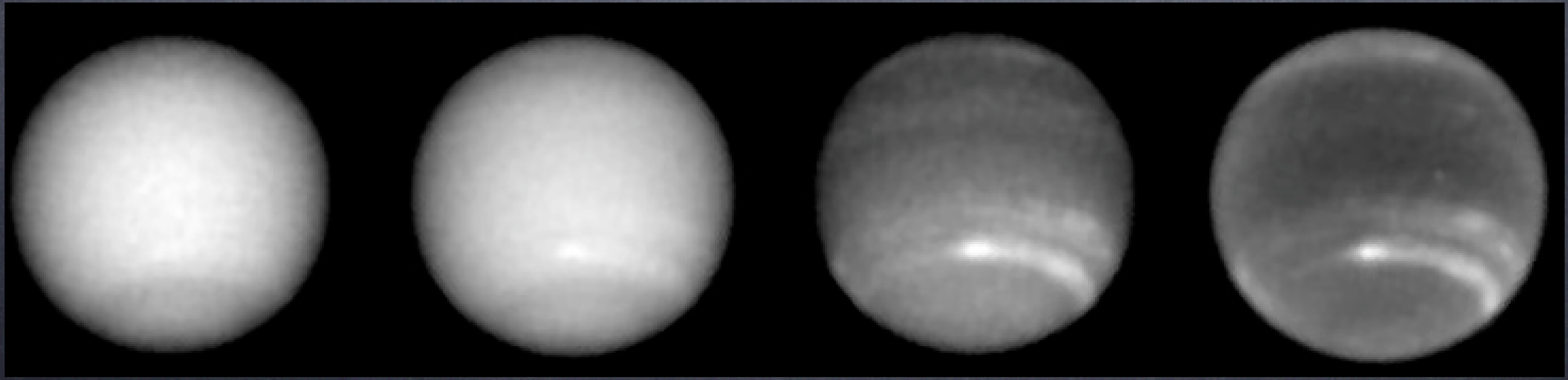
CH4
H2O
Na,
K






Marley et al. (1999)





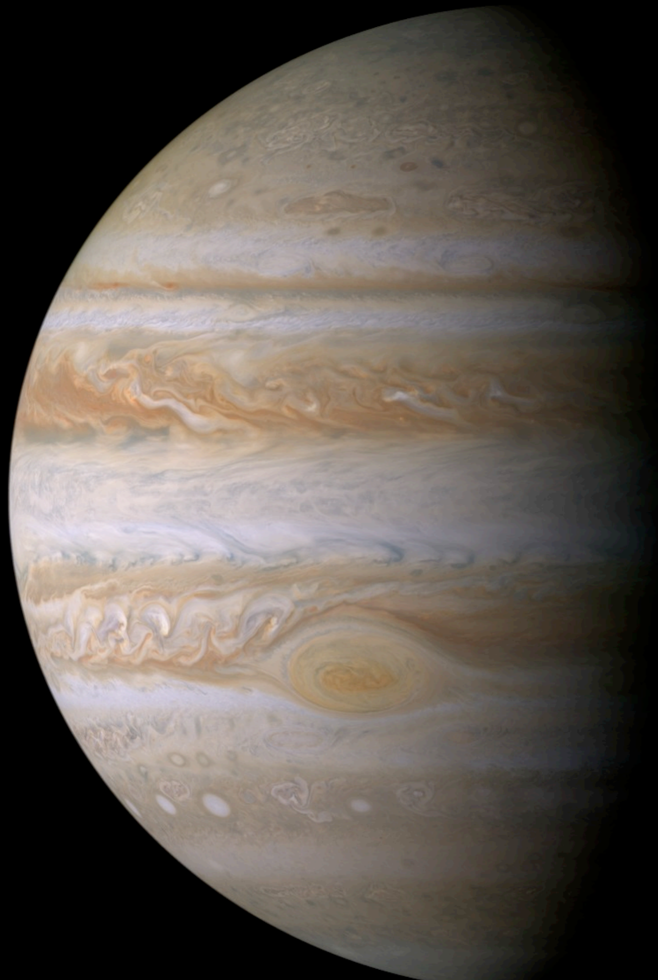
# Clouds

- No definitive detection yet in EGPs
- Very difficult to model, but play a crucial role in the spectra
- Phase variation as a function of wavelength can reveal sizes and vertical distribution

# Photochemistry

## Jupiter at 1 AU

- 25x higher UV flux
- H, C, O, N, S, P chemistry
- Many pathways to hazes
- But...Liang et al. (2004) find no hazes in hot Jupiters



# Haze Production

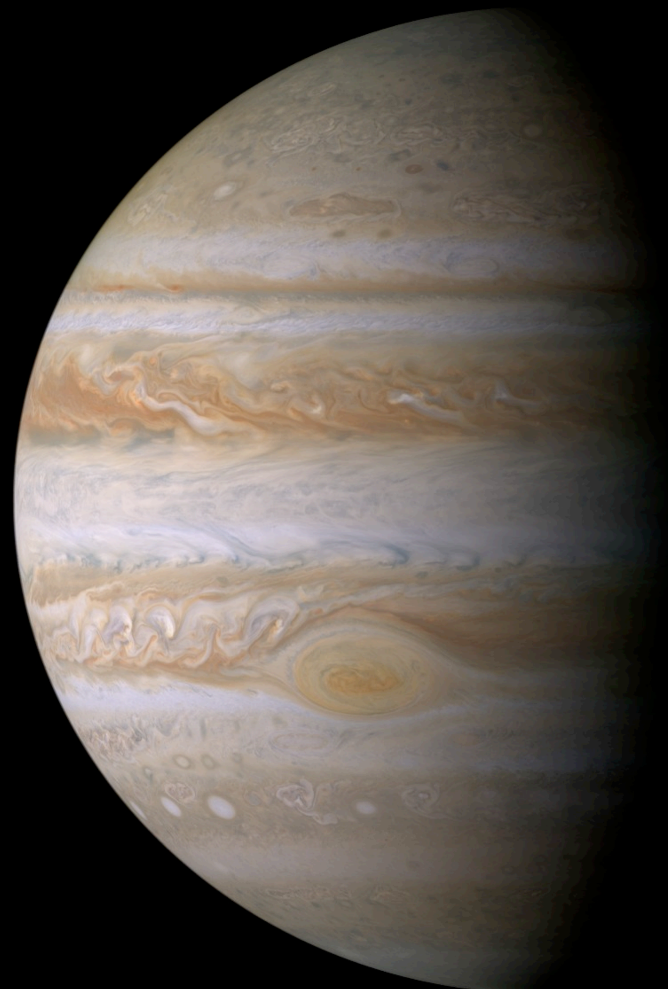
$CH_4$ + UV

$C_2H_2$ ↓ $C_6H_6$ ↓ Soot

New Paradigm?

$C_2H_6$ ↓ $C_3H_8$ ↓ parafin

Old School

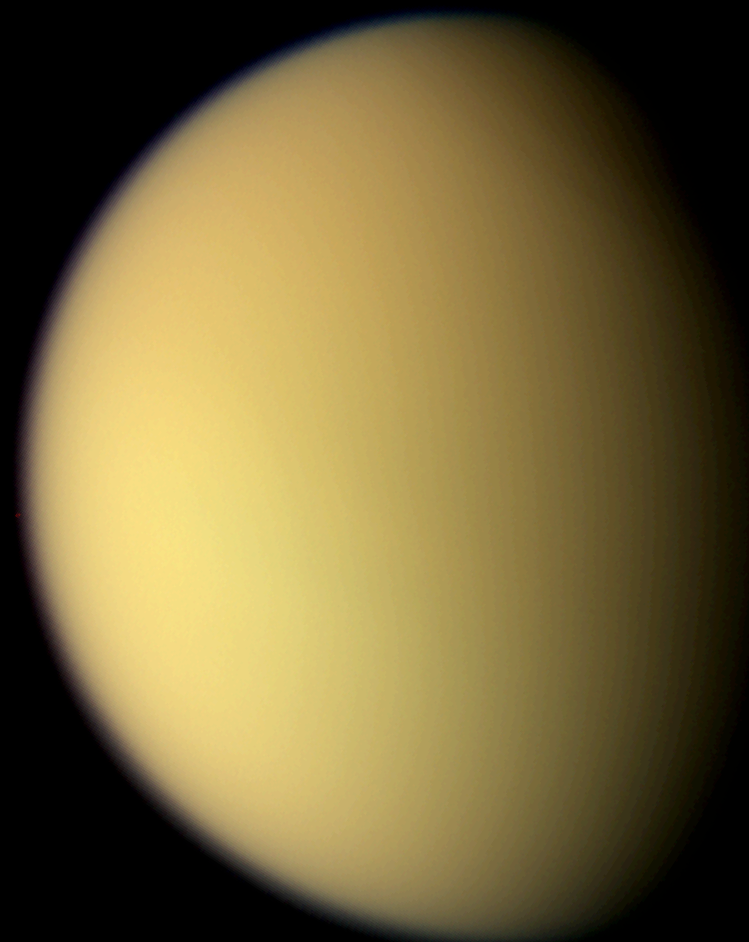


# Haze Production

$CH_4$ + UV

| | |
|---|---|
| $C_2H_2$ | $C_2H_6$ |
| ↓ | ↓ |
| $C_6H_6$ | $C_3H_8$ |
| ↓ | ↓ |
| Soot | parafin |
| New Paradigm? | Old School |

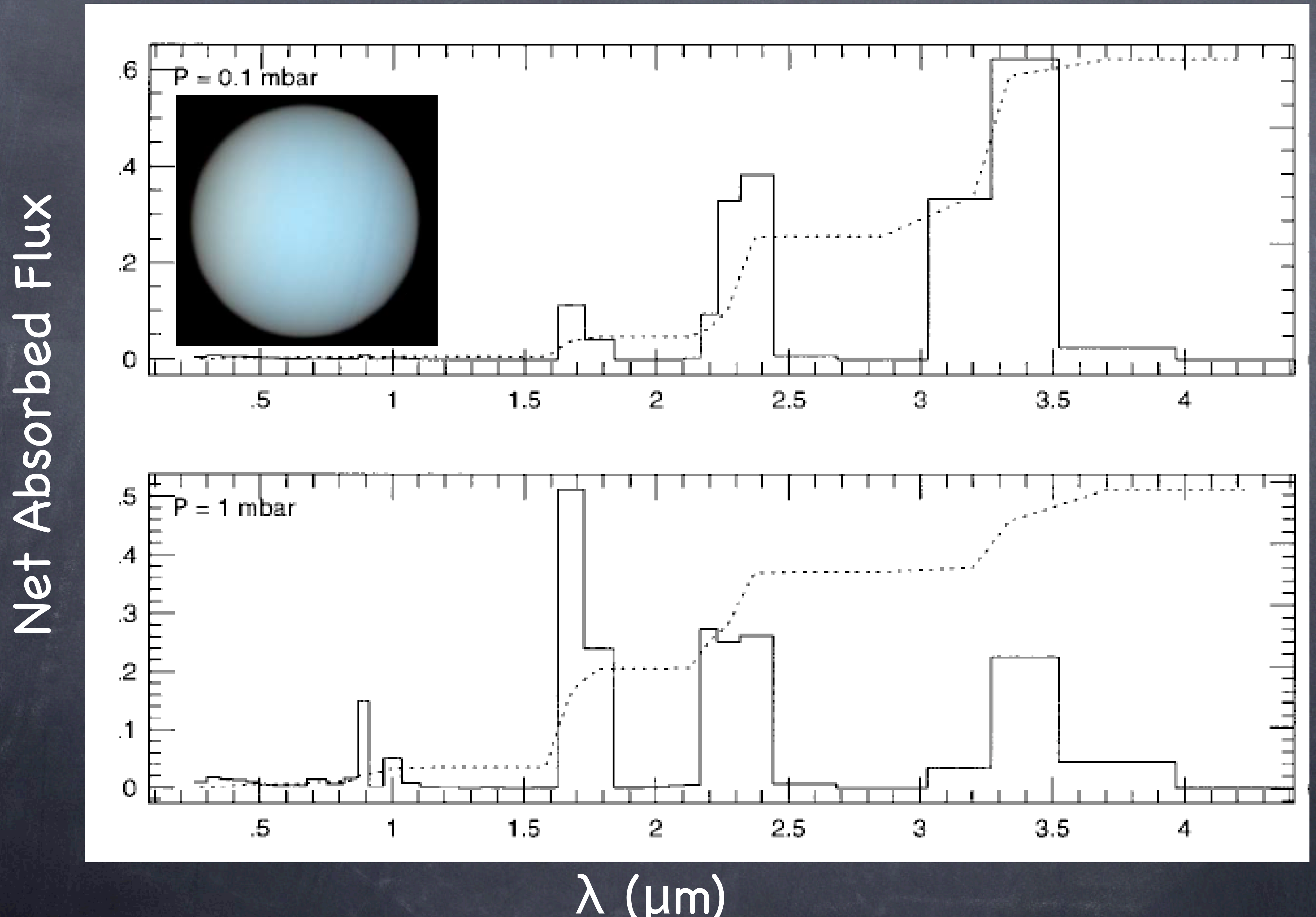
*Substantially* alter spectra and colors of canonical haze-free models

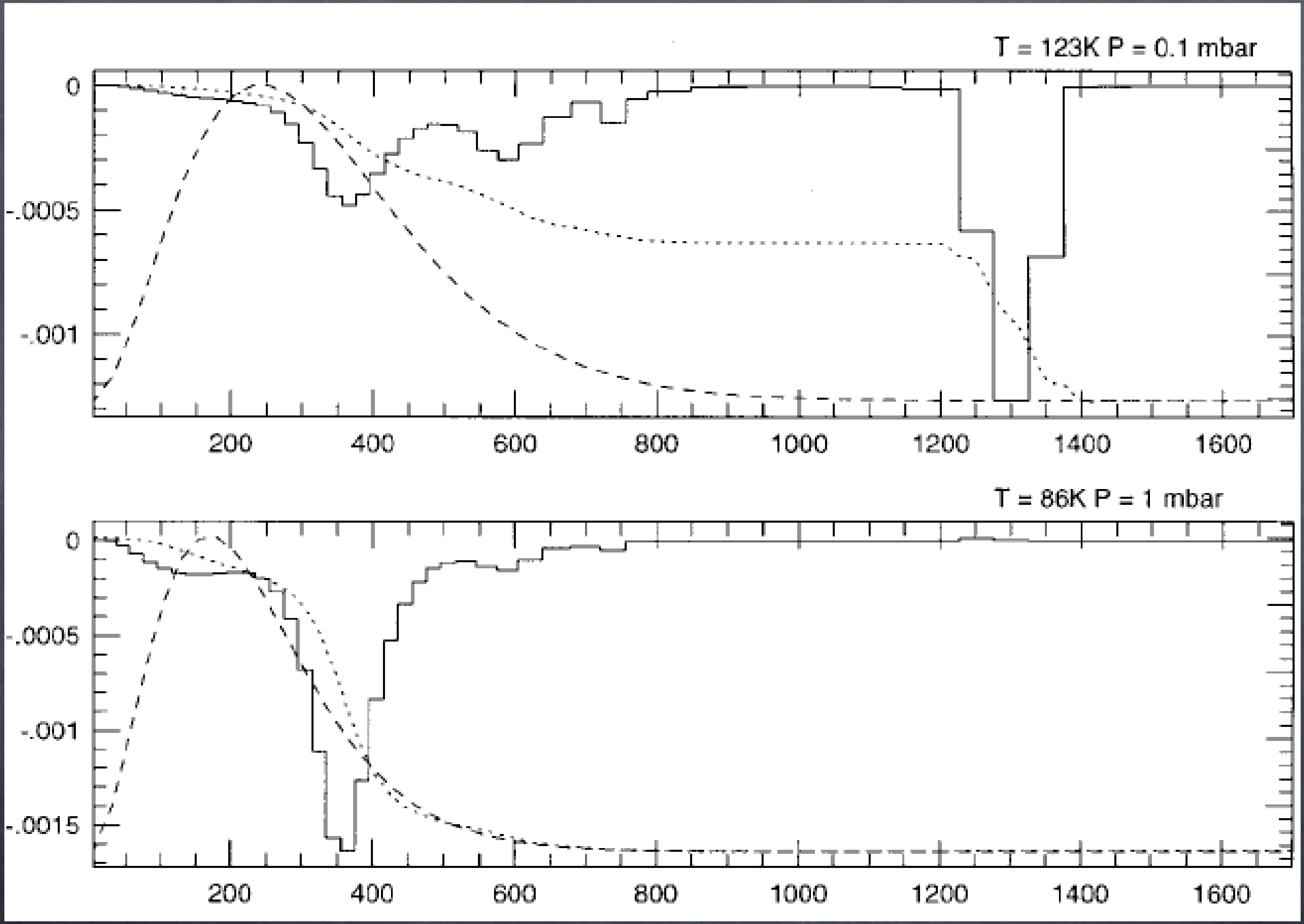


# At Low Spectral Resolution

- Clouds trump
- Hazes are a concern
- Metallicity
- C/O
- Non-equilibrium chemistry

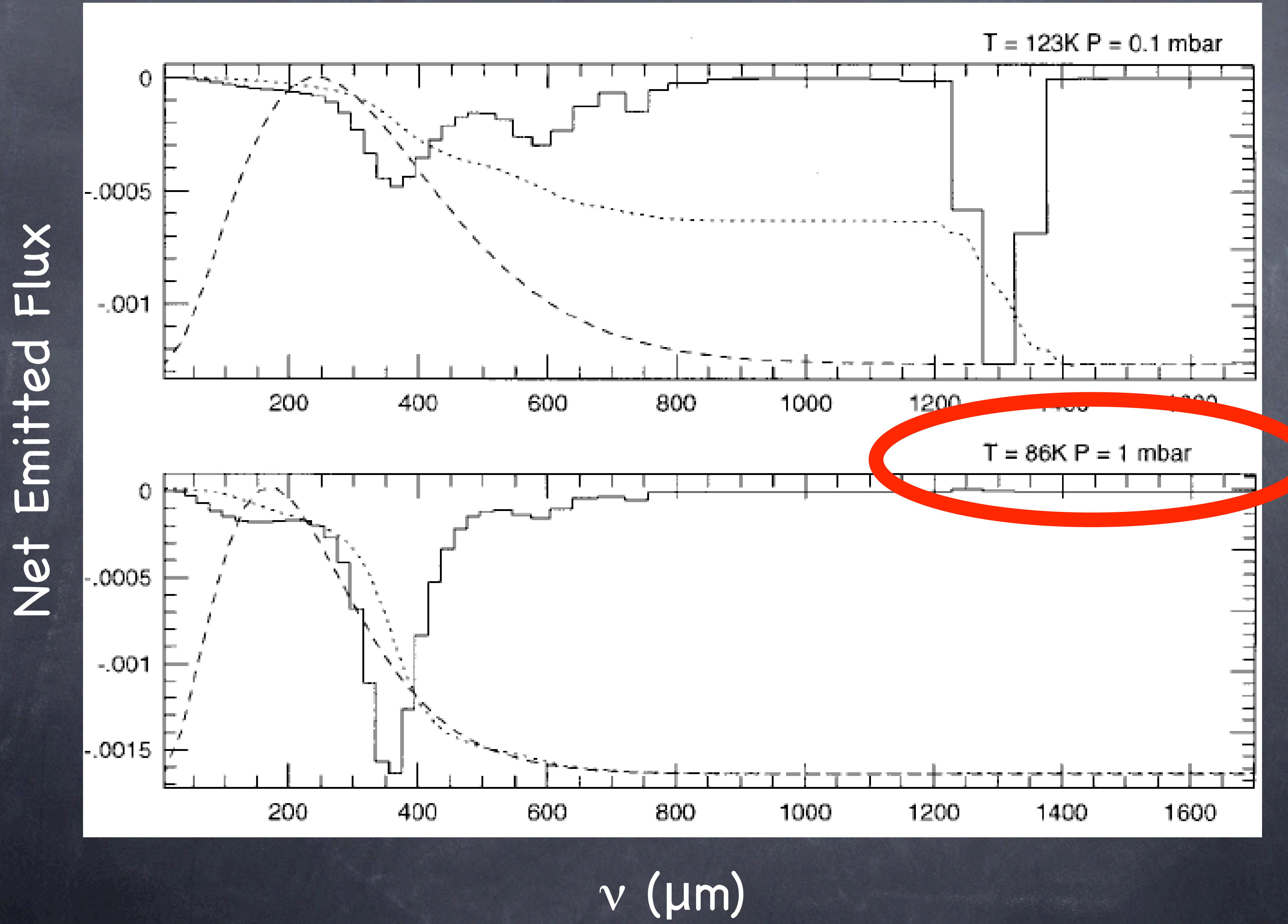
# Stratospheres


Net Absorbed Flux
P = 0.1 mbar
P = 1 mbar
.6
.4
.2
0
.5
.4
.3
.2
.1
0
.5
1
1.5
2
2.5
3
3.5
4
λ (μm)

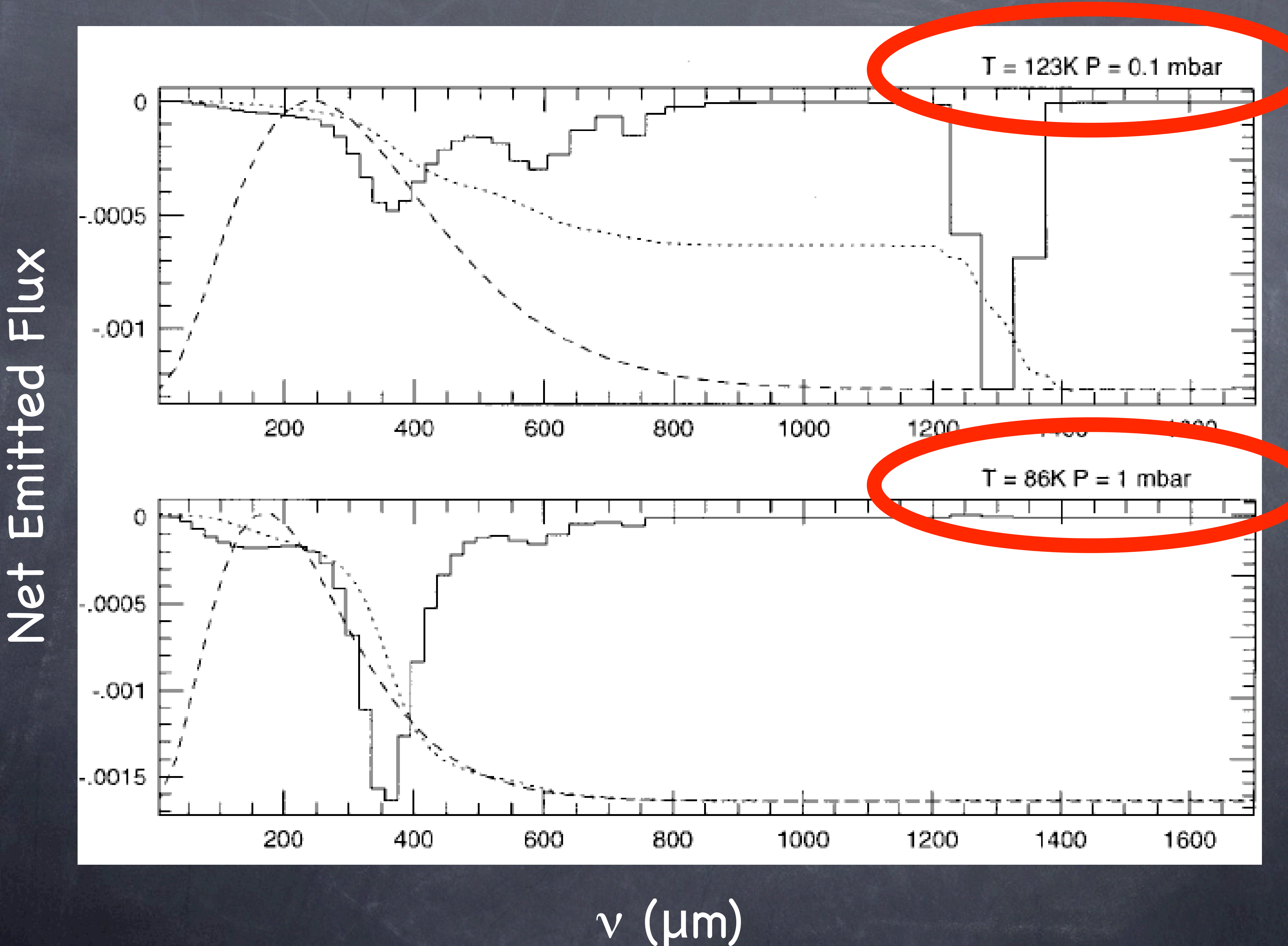



Net Emitted Flux

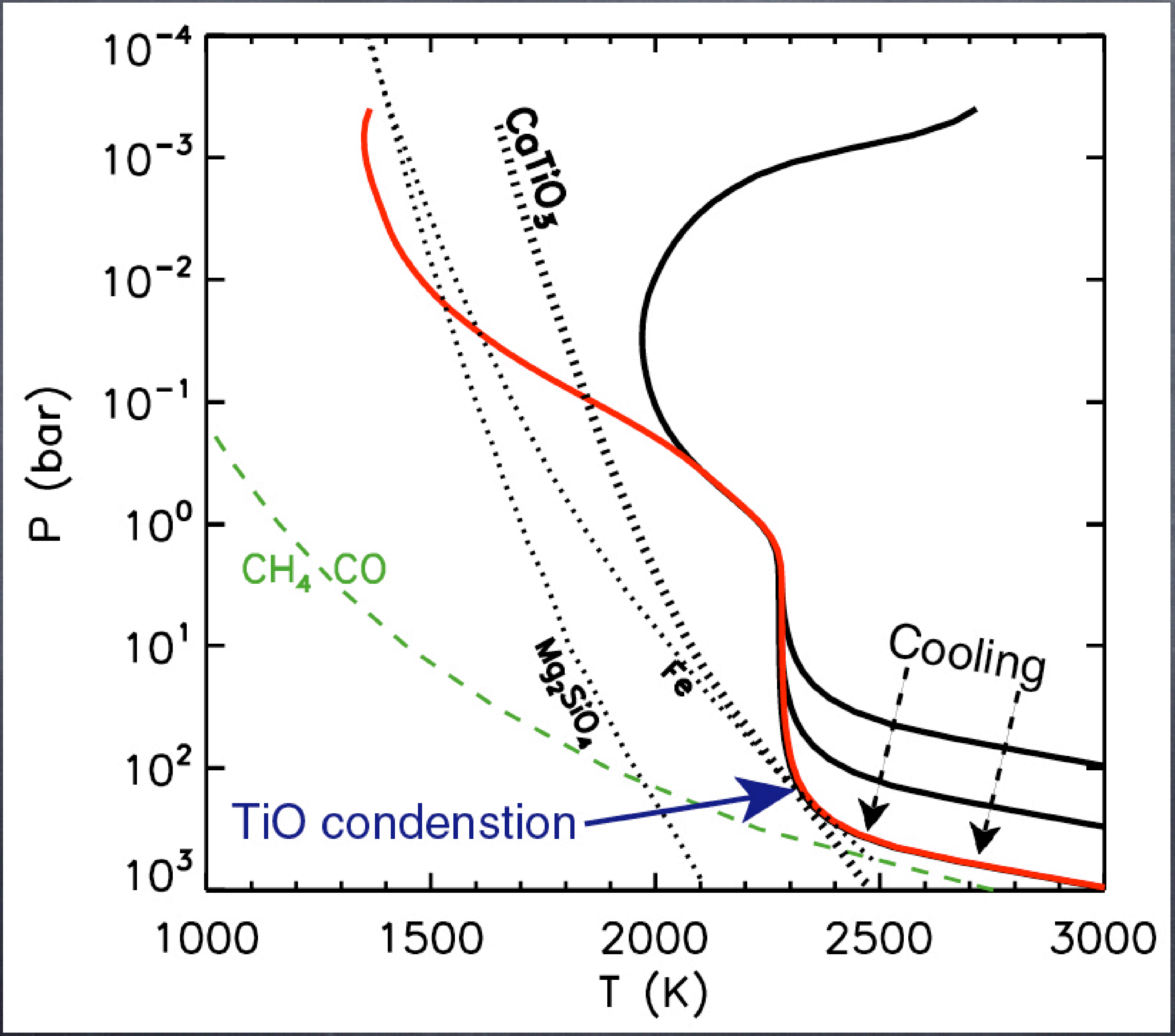
ν (μm)

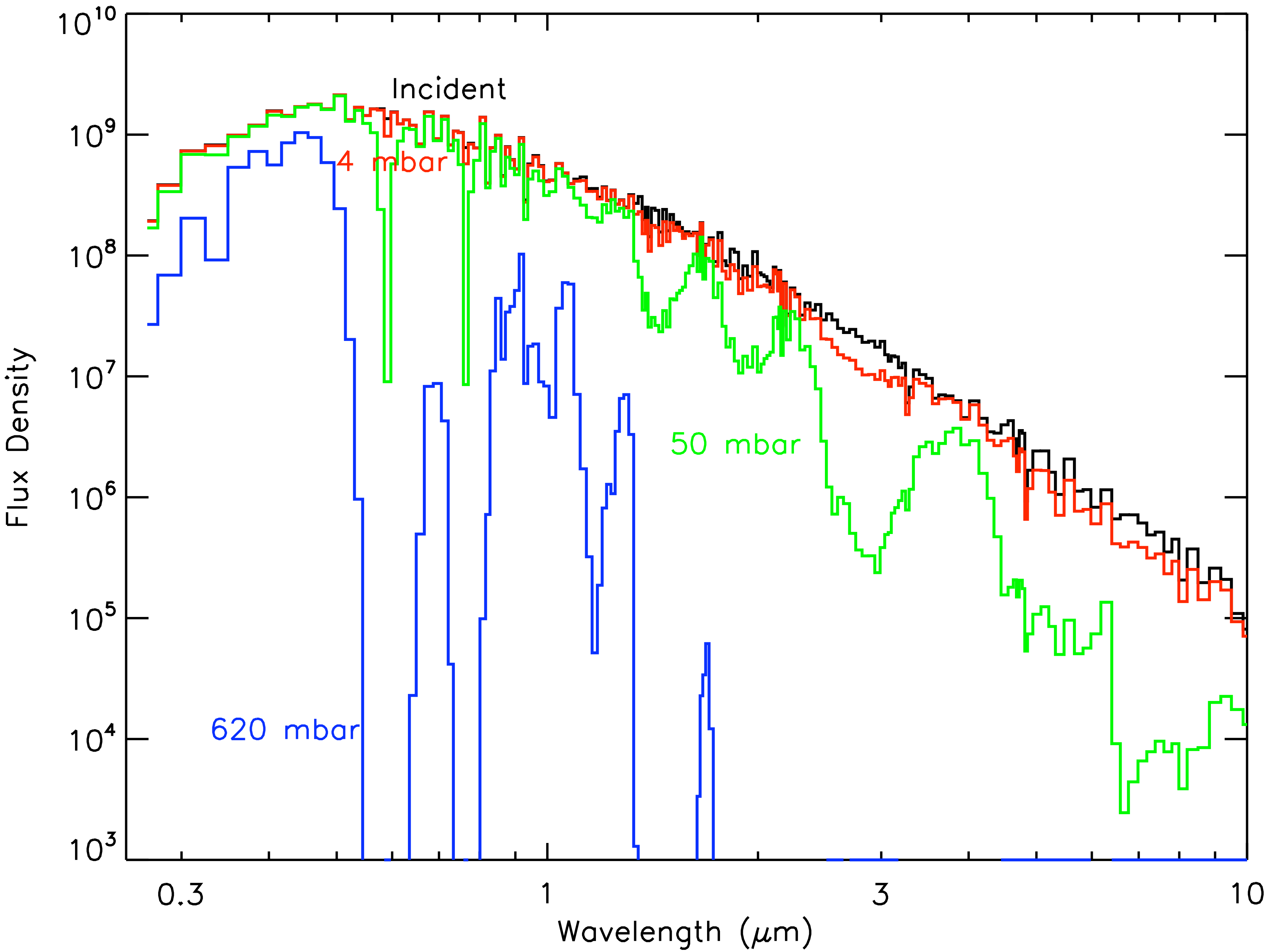


T = 123K P = 0.1 mbar
T = 86K P = 1 mbar
0
-.0005
-.001
-.0015
200
400
600
800
1000
1200
1400
1600
Net Emitted Flux
ν (μm)

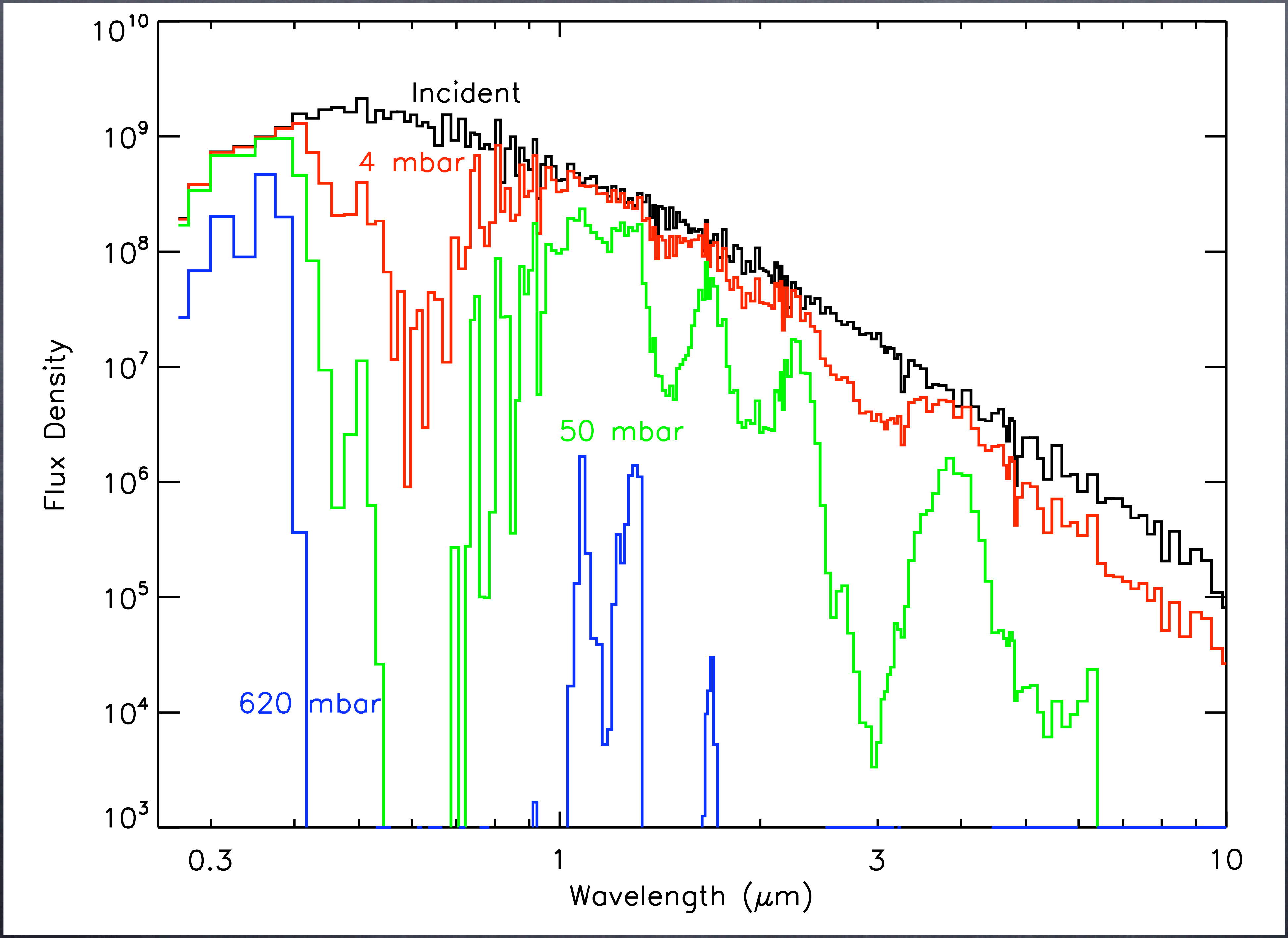

T = 123K P = 0.1 mbar
0
-.0005
-.001
200
400
600
800
1000
1200
T = 86K P = 1 mbar
0
-.0005
-.001
-.0015
200
400
600
800
1000
1200
1400
1600
Net Emitted Flux
ν (μm)

# TiO Stratospheres





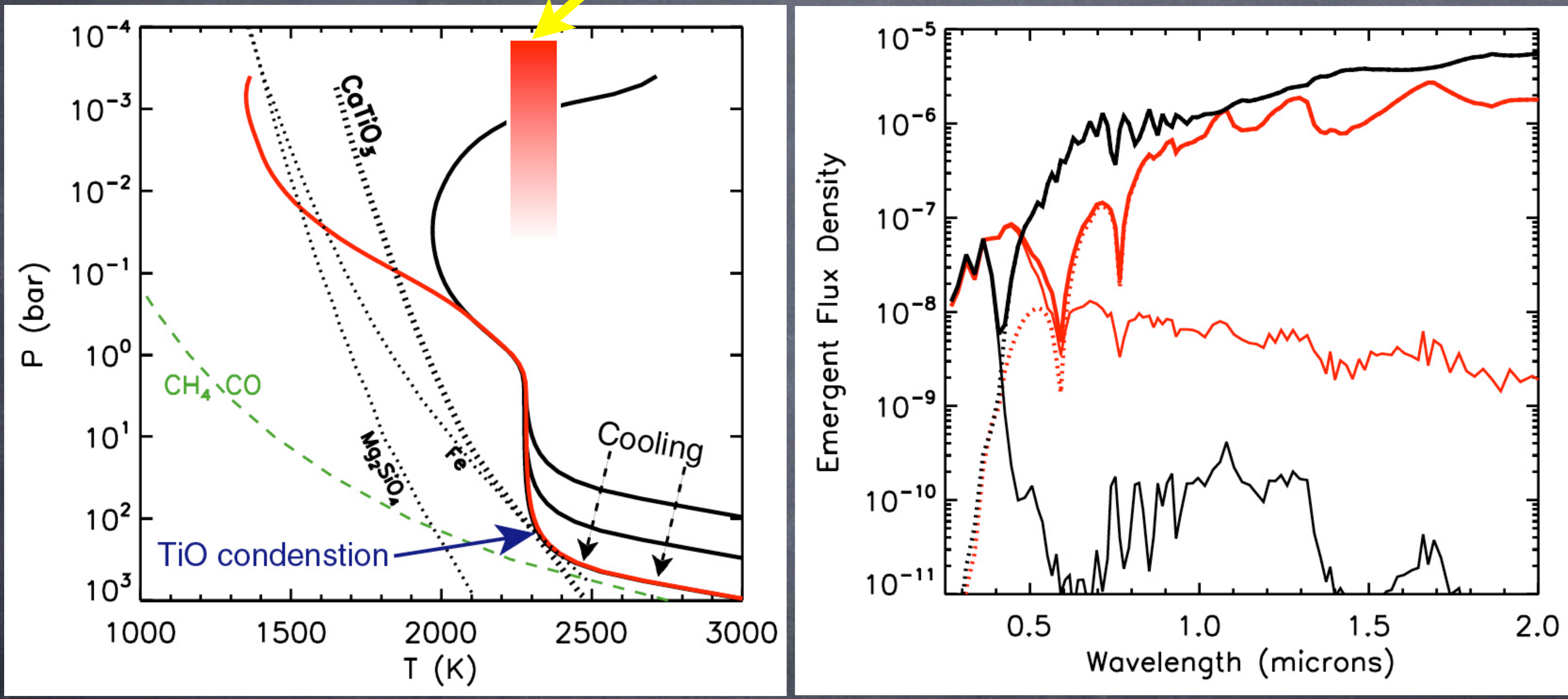
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$10^{5}$
$10^{4}$
$10^{3}$
Flux Density
Incident
4 mbar
50 mbar
620 mbar
0.3
1
3
10
Wavelength ($\mu$m)



Incident
4 mbar
50 mbar
620 mbar
Flux Density
Wavelength (μm)
$10^{10}$
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
0.3
1
3
10

# TiO Stratospheres

Harrington et al. (2007), for HD 149026b



# Planetary Atmospheres

- Structure and spectra dependent on interplay of chemistry, radiative transfer, cloud and molecular opacities, photochemistry, dynamics...
- Solar system planets are complex
- Beware simplistic analyses
- Planetary spectra are highly non-Planckian

# Hot Jupiter Observations

- Models grossly validated
- Many indications that global dynamics are important (day/night contrasts, maps)
- Prediction and detection of hot TiO stratospheres
- Transit spectroscopy
- Much more to come from Spitzer & JWST