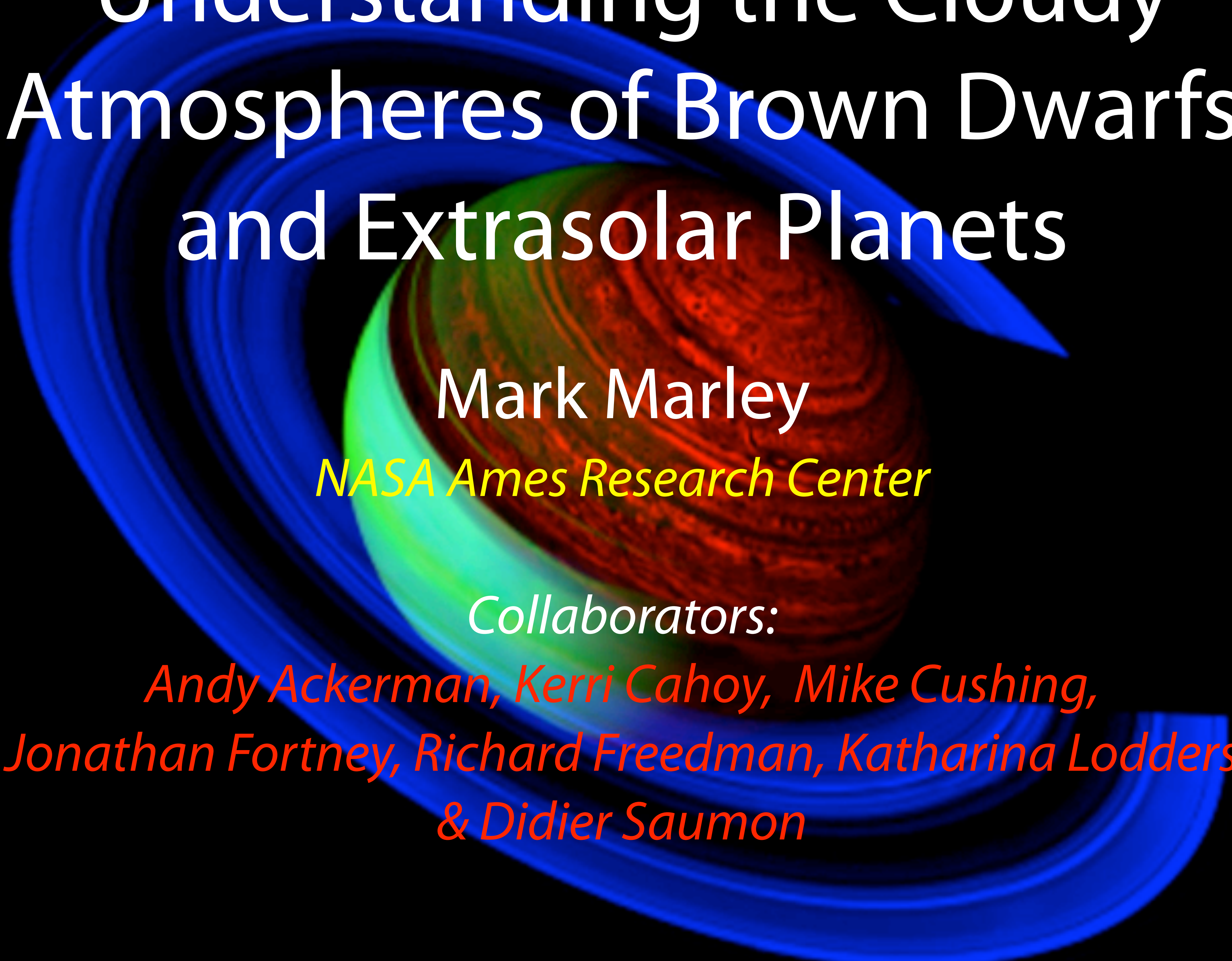
Understanding the Cloudy Atmospheres of Brown Dwarfs and Extrasolar Planets

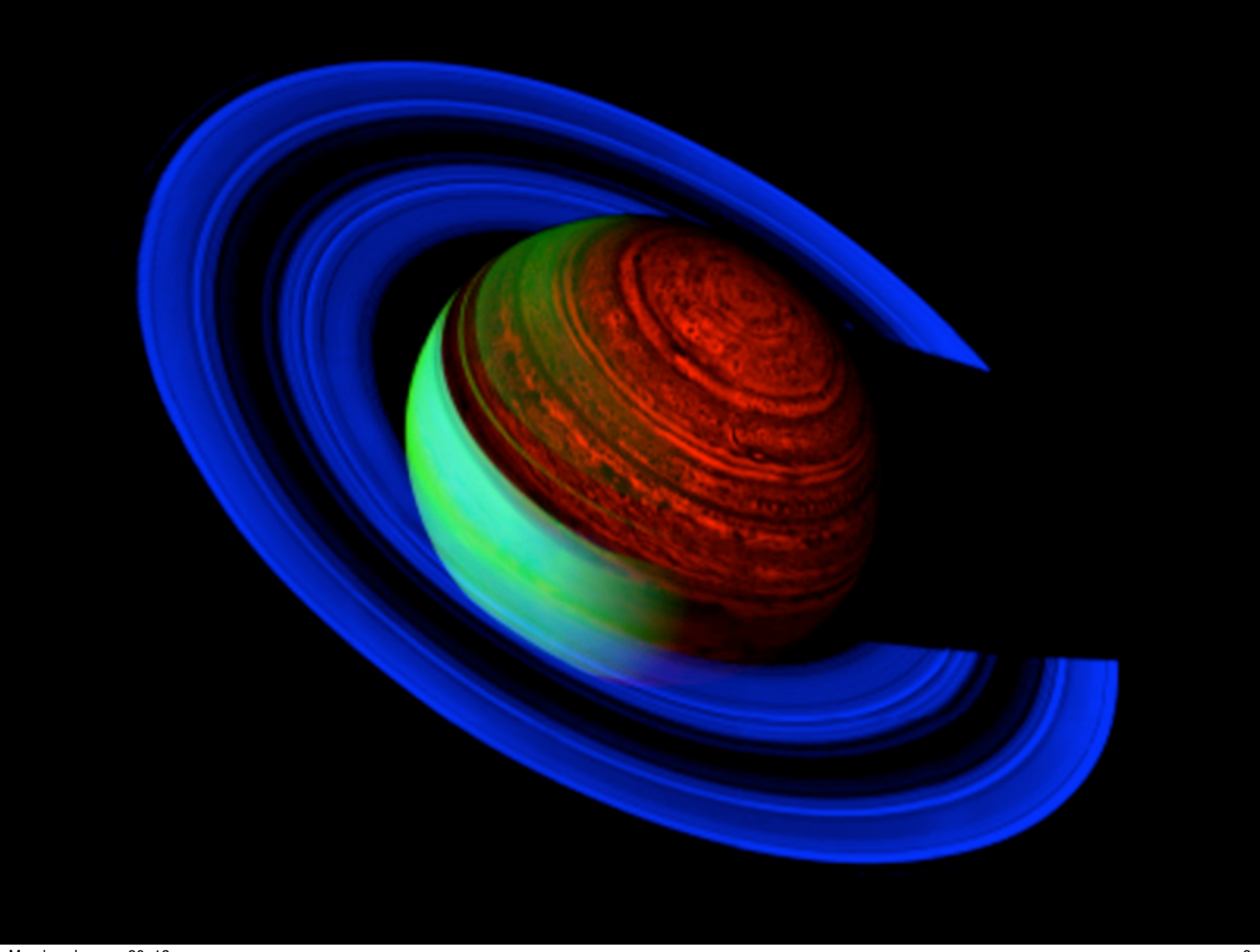


Mark Marley

NASA Ames Research Center

Collaborators:

Andy Ackerman, Kerri Cahoy, Mike Cushing, Jonathan Fortney, Richard Freedman, Katharina Lodders & Didier Saumon

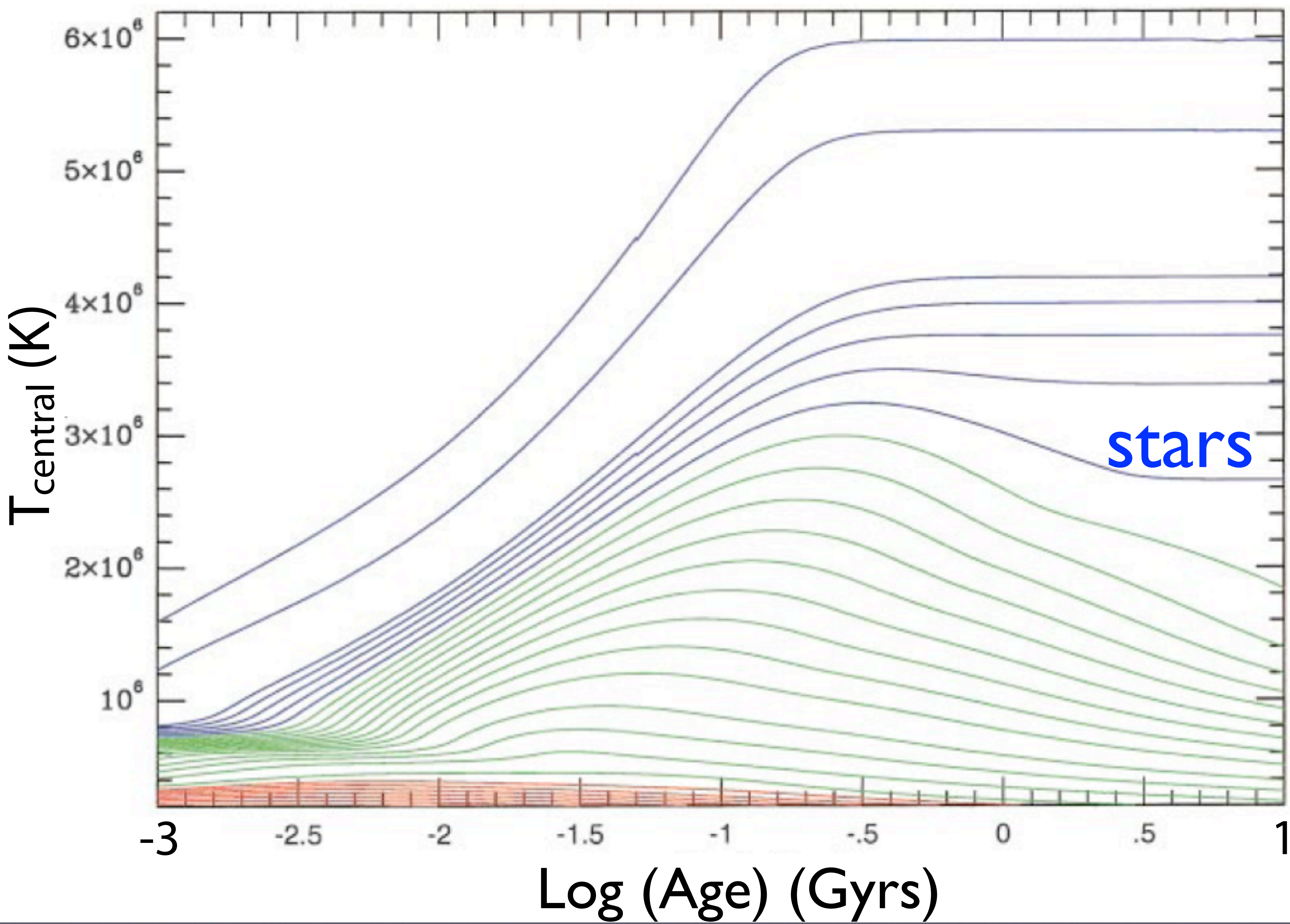


Today’s Message

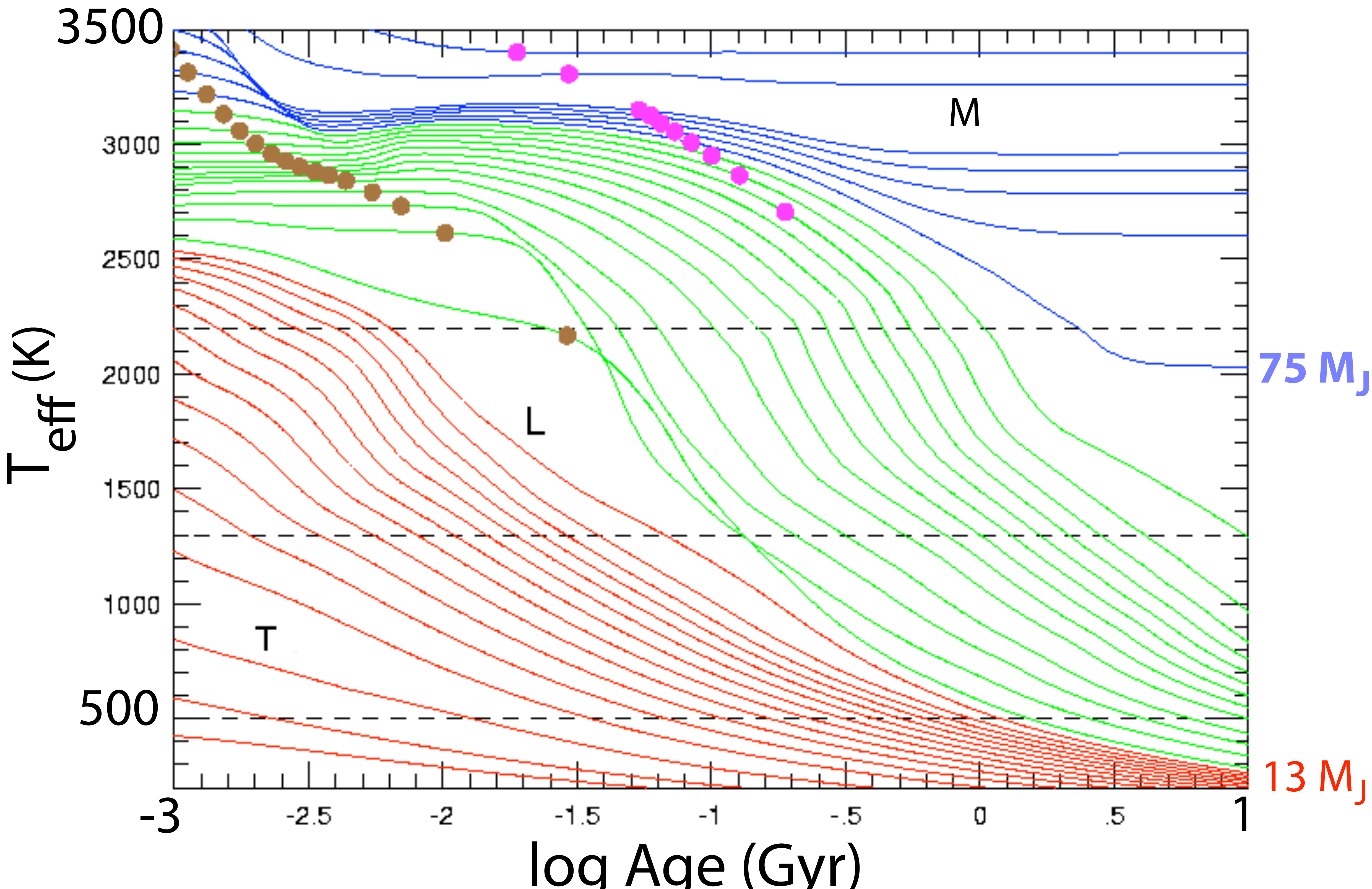
- Clouds are exceptionally important
- 3 main cloud modeling approaches to date, one of which is “make them up”
- Applications: properties of the HR 8799 planets & the L to T transition
- Photochemistry
- Lots of room for new ideas & new models

Today's Objects

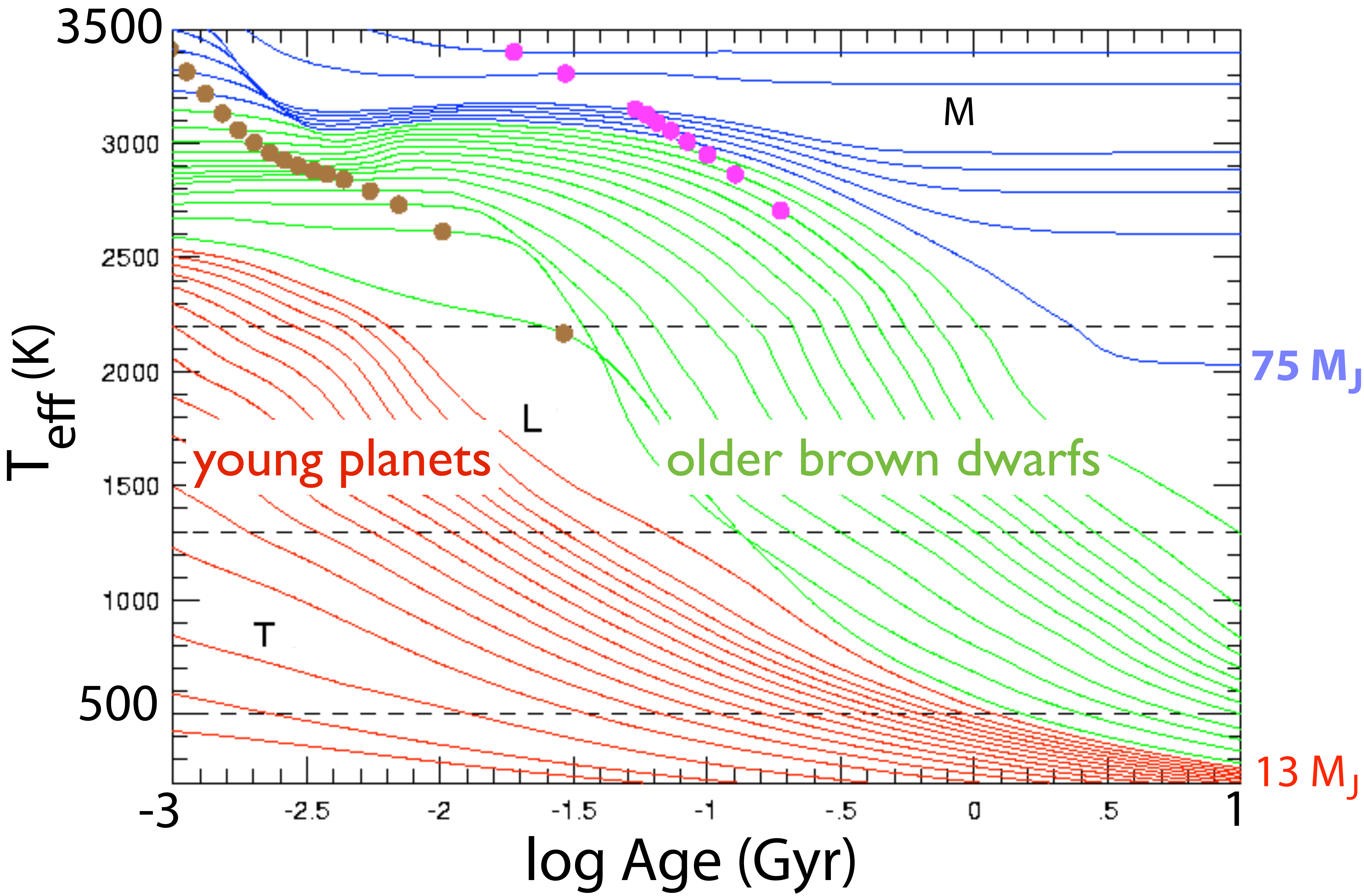
- Brown Dwarfs (L & T dwarfs)
    - objects with masses intermediate between planets and stars
    - composition similar to giant planets
    - vastly more & higher quality data than exoplanets
- Jovian mass exoplanets, young and old
- Issues broadly apply to terrestrial exoplanets



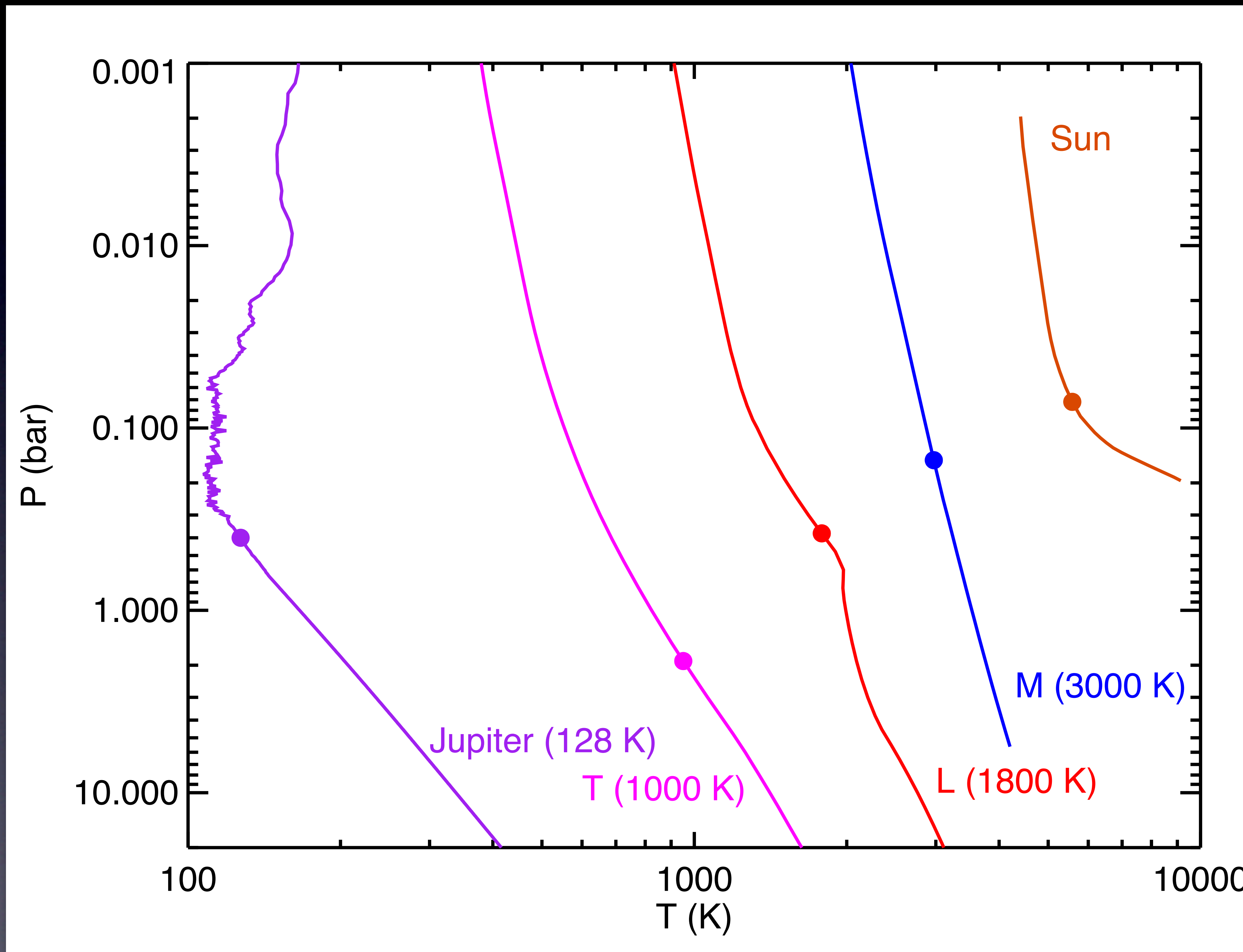
Burrows et al. (2001)



Burrows et al. 1997



Burrows et al. 1997


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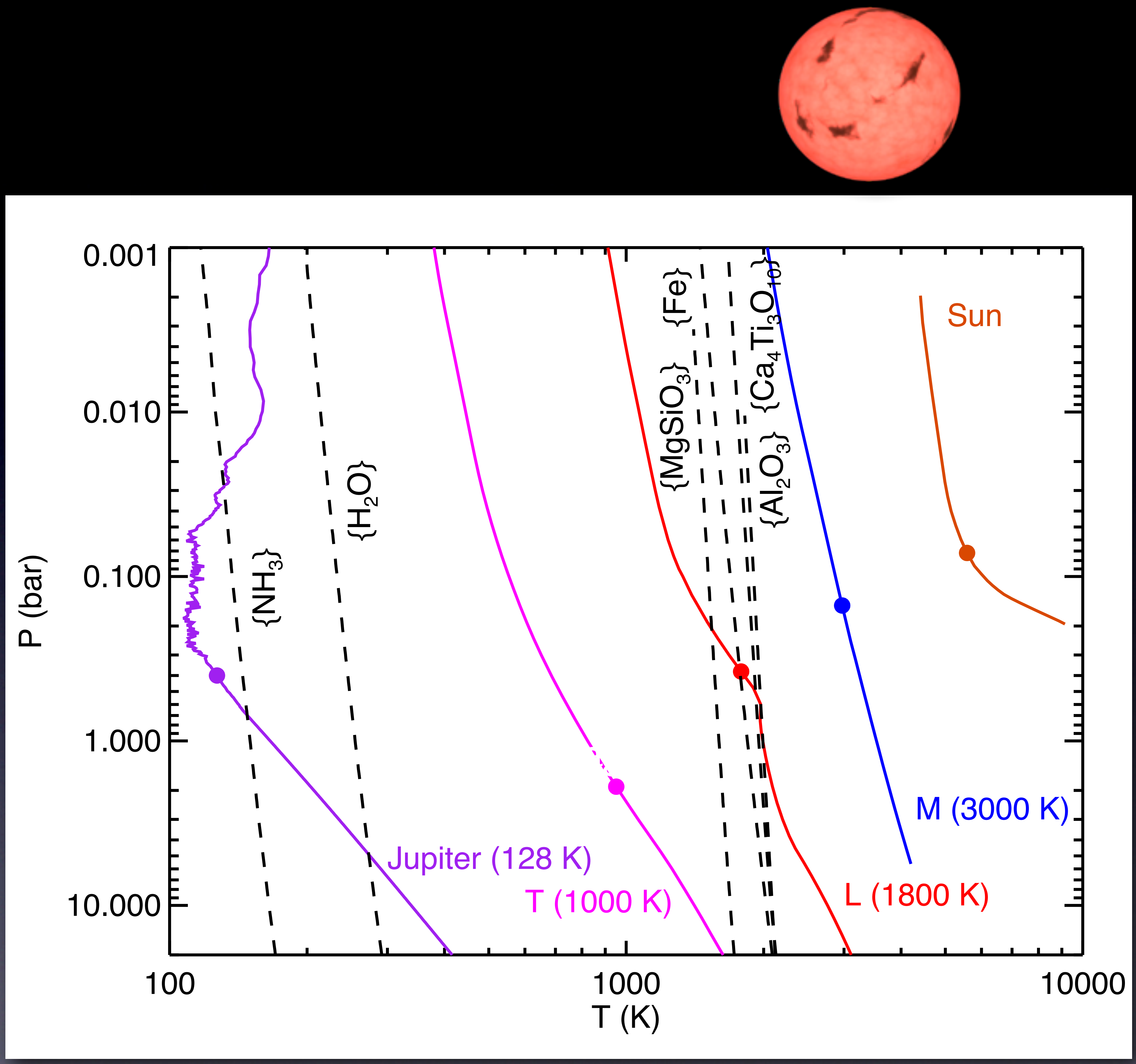
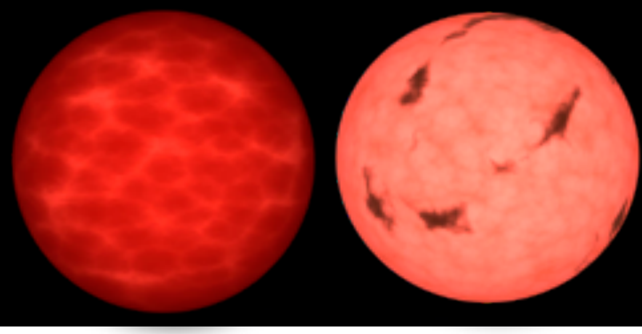
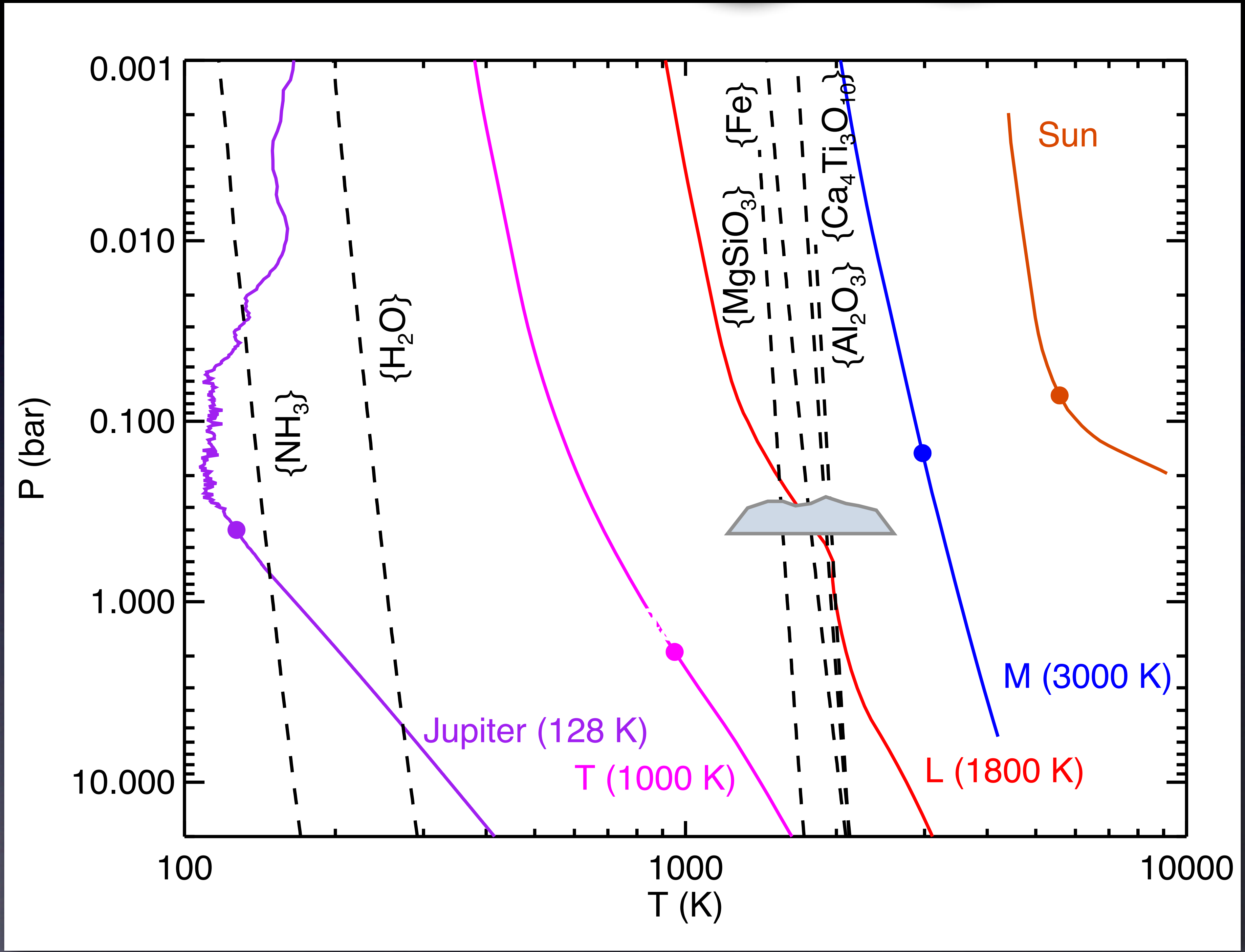
T (K)
Sun
M (3000 K)
L (1800 K)
T (1000 K)
Jupiter (128 K)



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

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T (K)
{NH$_3$}
{H$_2$O}
{MgSiO$_3$}
{Fe}
{Al$_2$O$_3$}
{Ca$_4$Ti$_3$O$_{10}$}
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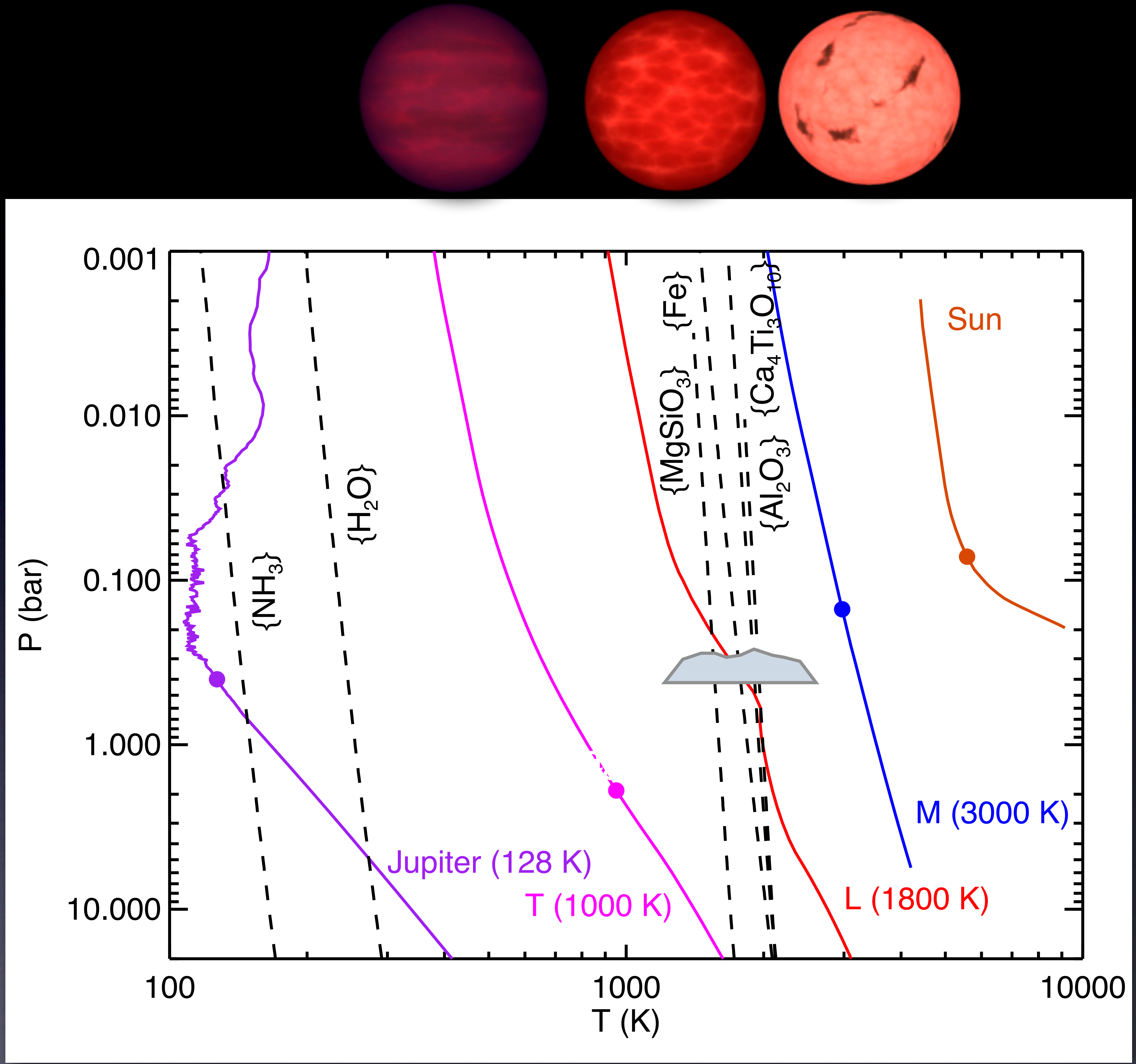

0.001
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P (bar)
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T (K)
{NH$_3$}
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Sun
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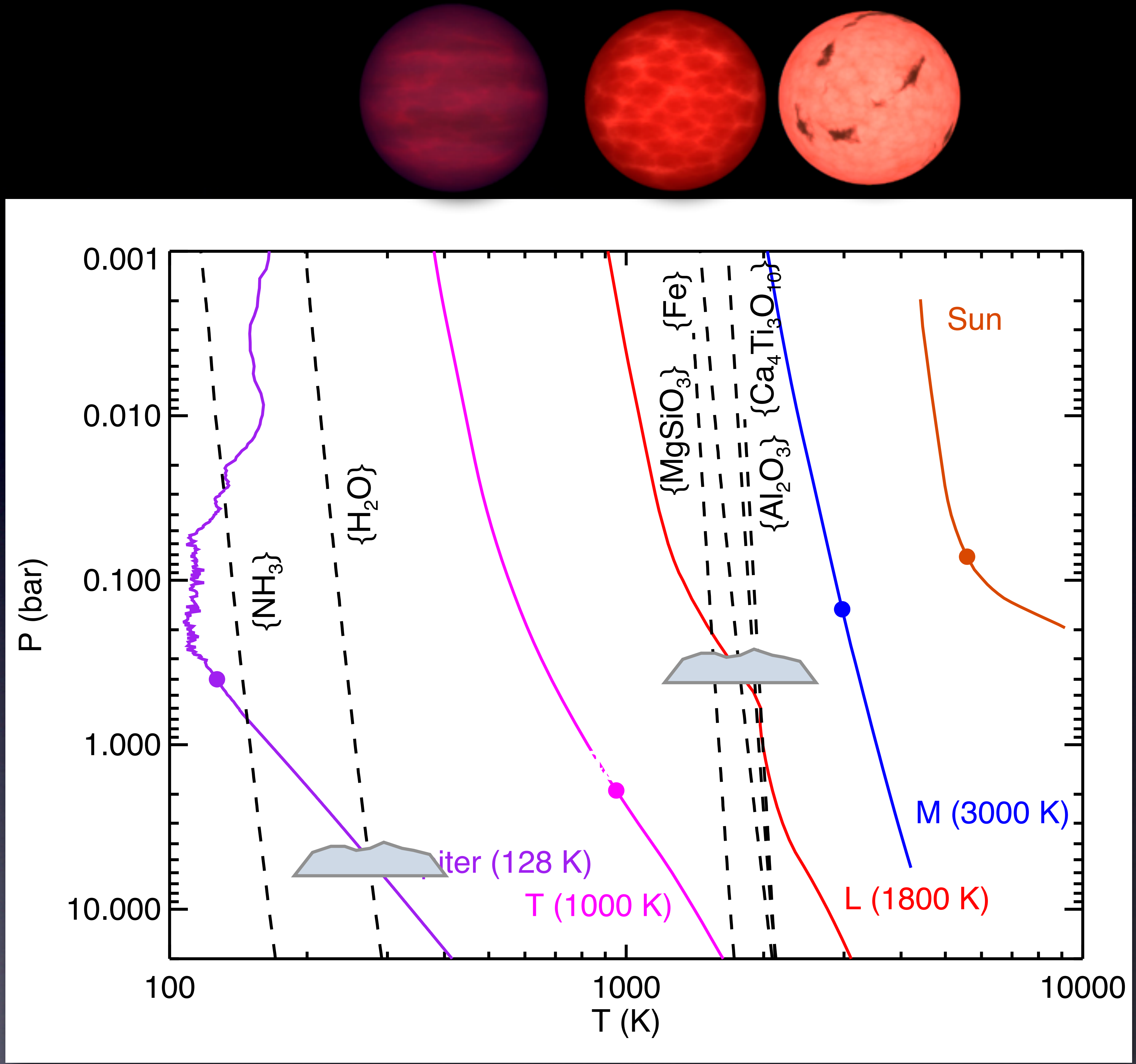

Sun
M (3000 K)
L (1800 K)
T (1000 K)
iter (128 K)
{Fe}
{MgSiO3}
{Ca4Ti3O10}
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0.010
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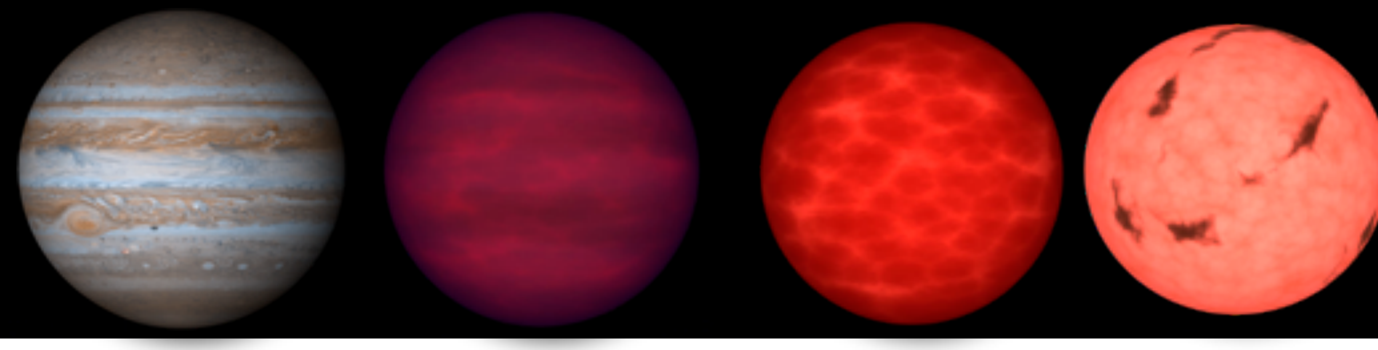
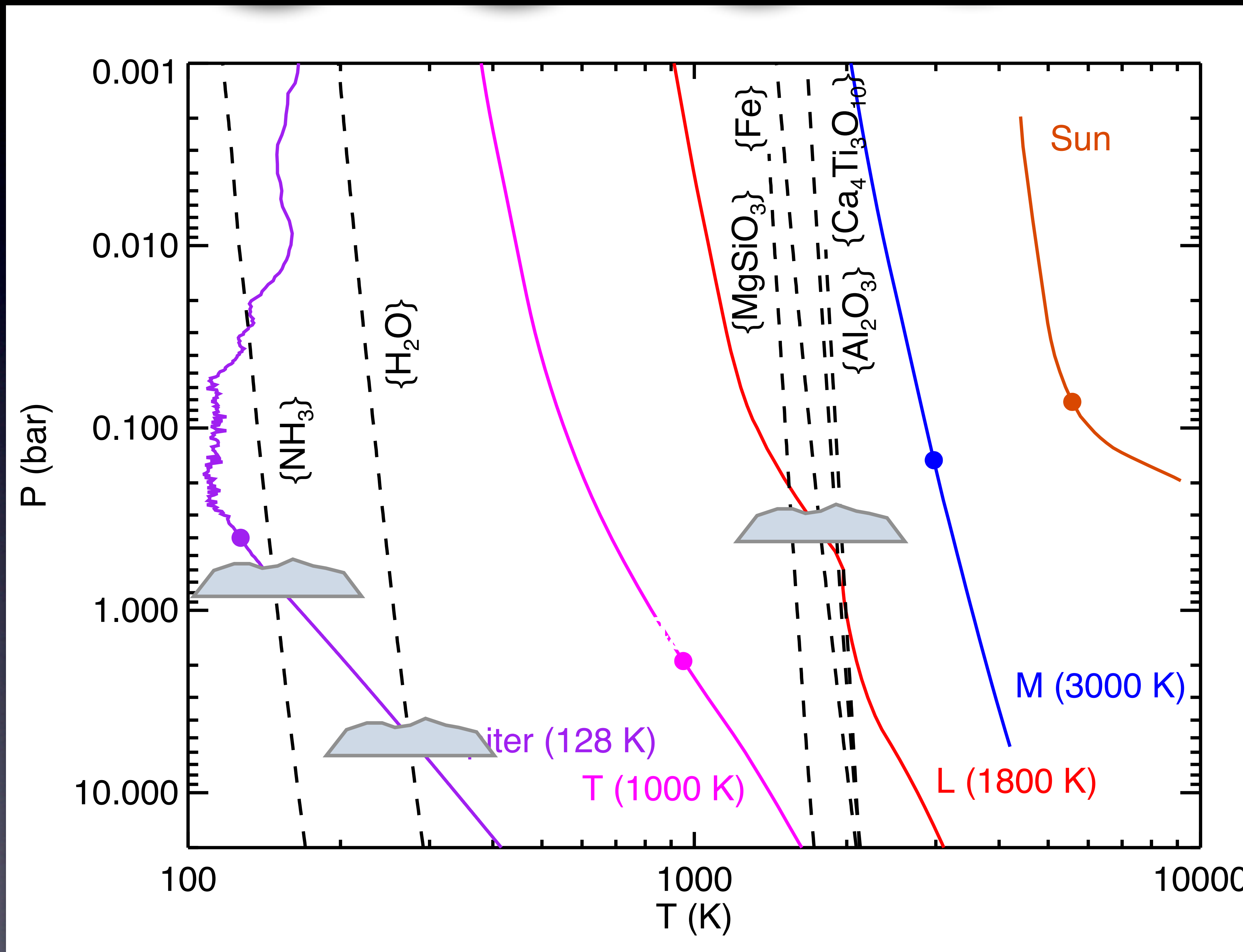
T (K)

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{NH_3}
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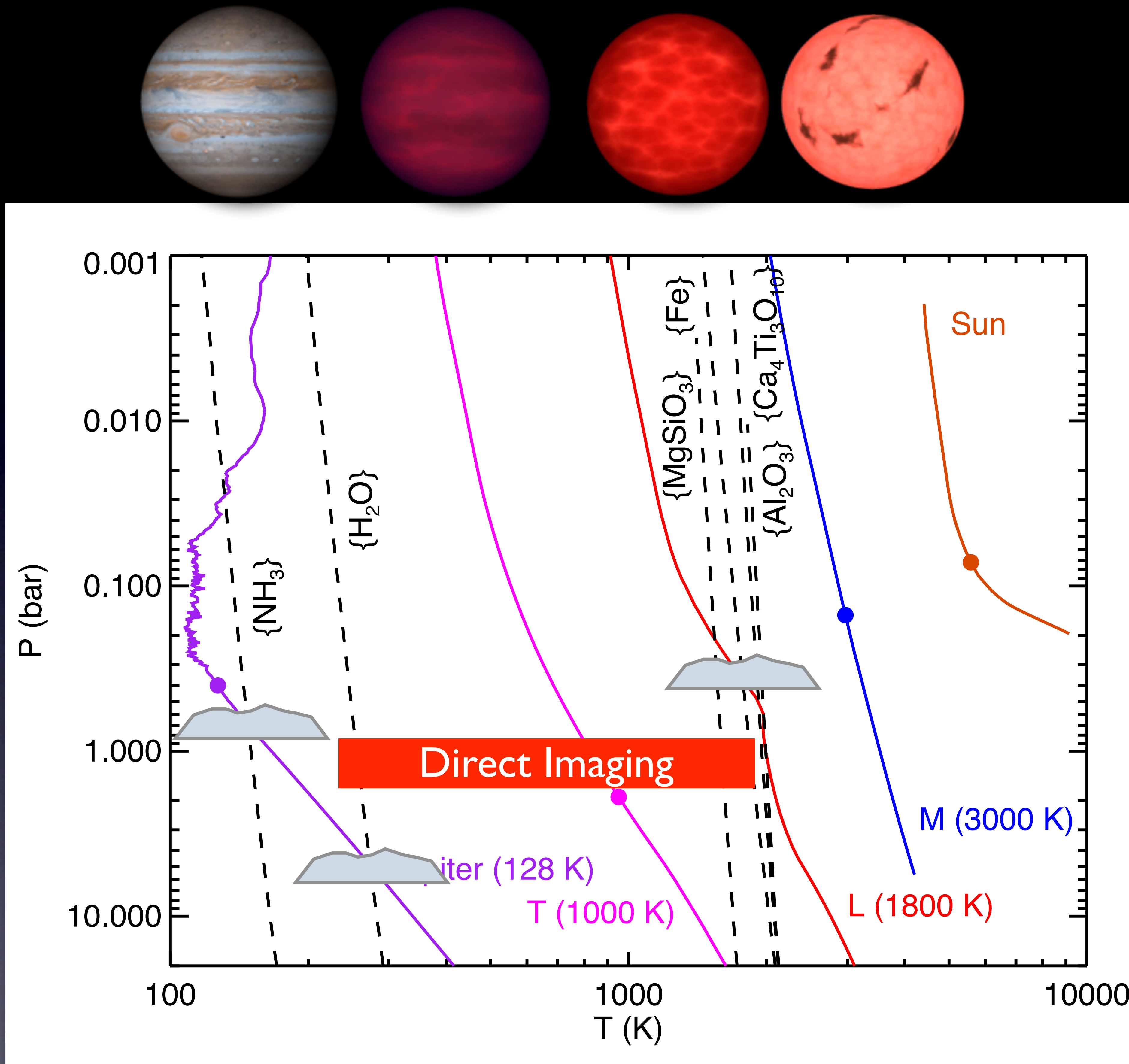
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P (bar)
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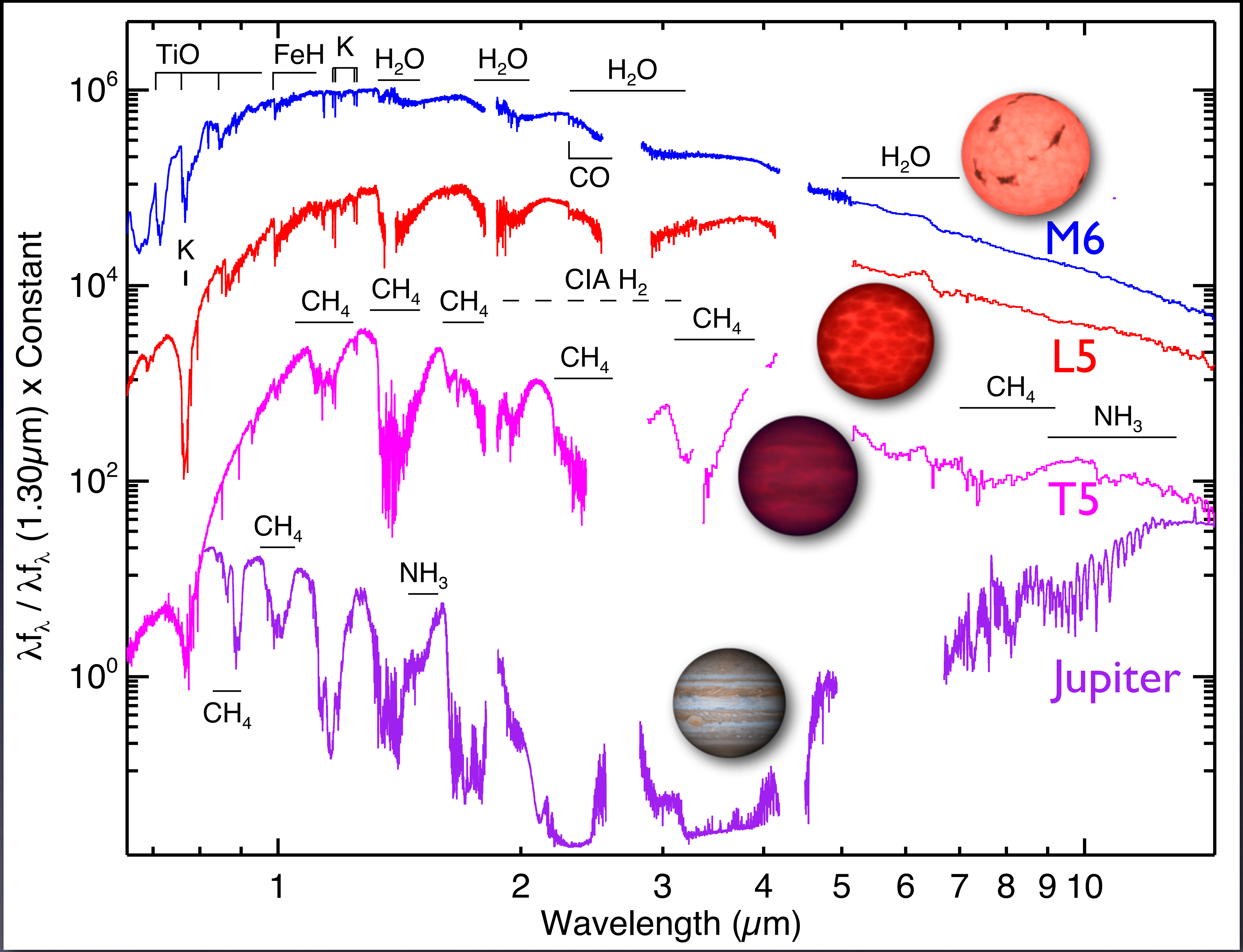
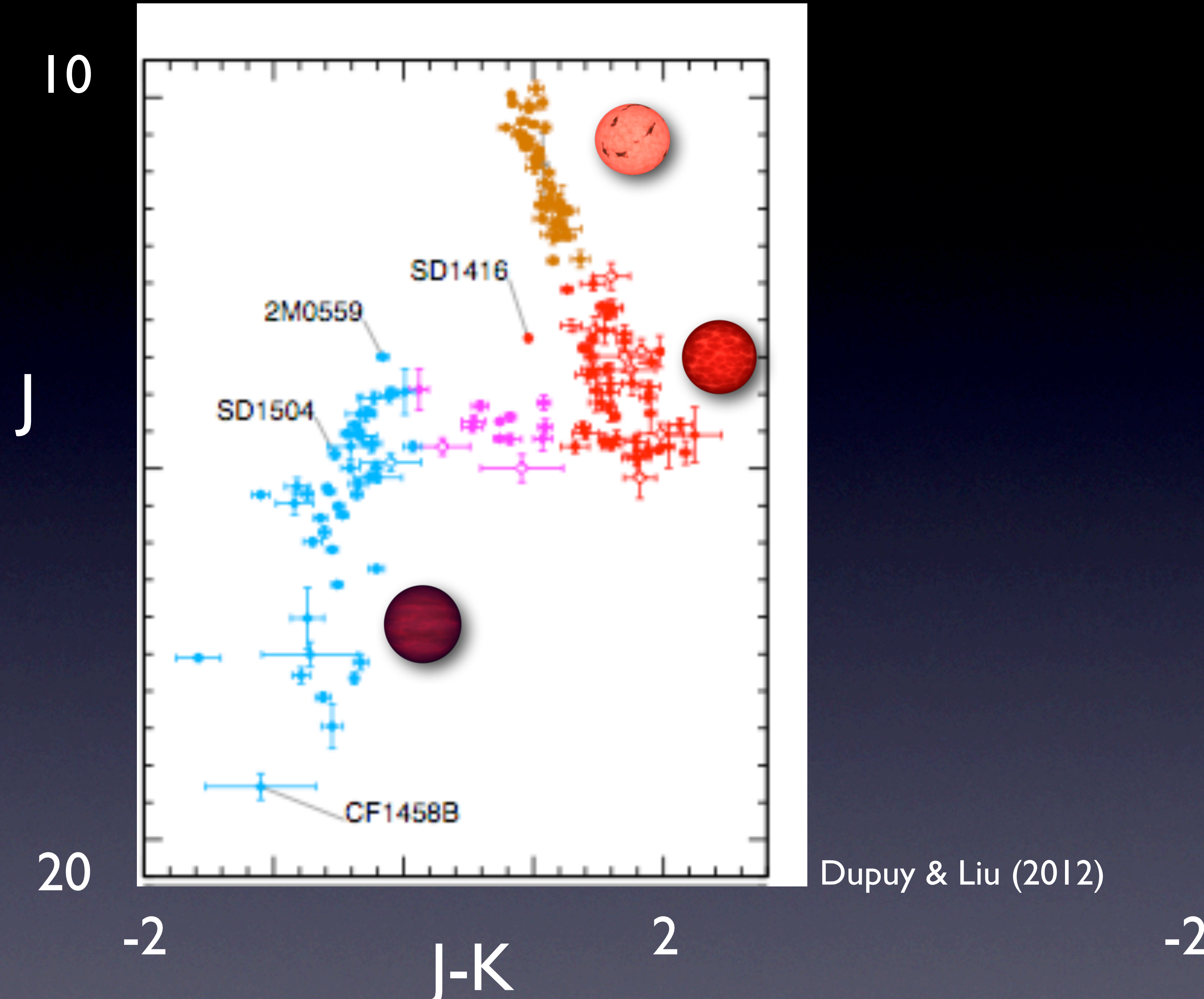
{Fe}
{Al_2O_3}
{$Ca_4Ti_3O_{10}$}
Sun
M (3000 K)
L (1800 K)
T (1000 K)
iter (128 K)
Direct Imaging

Thermal Emission

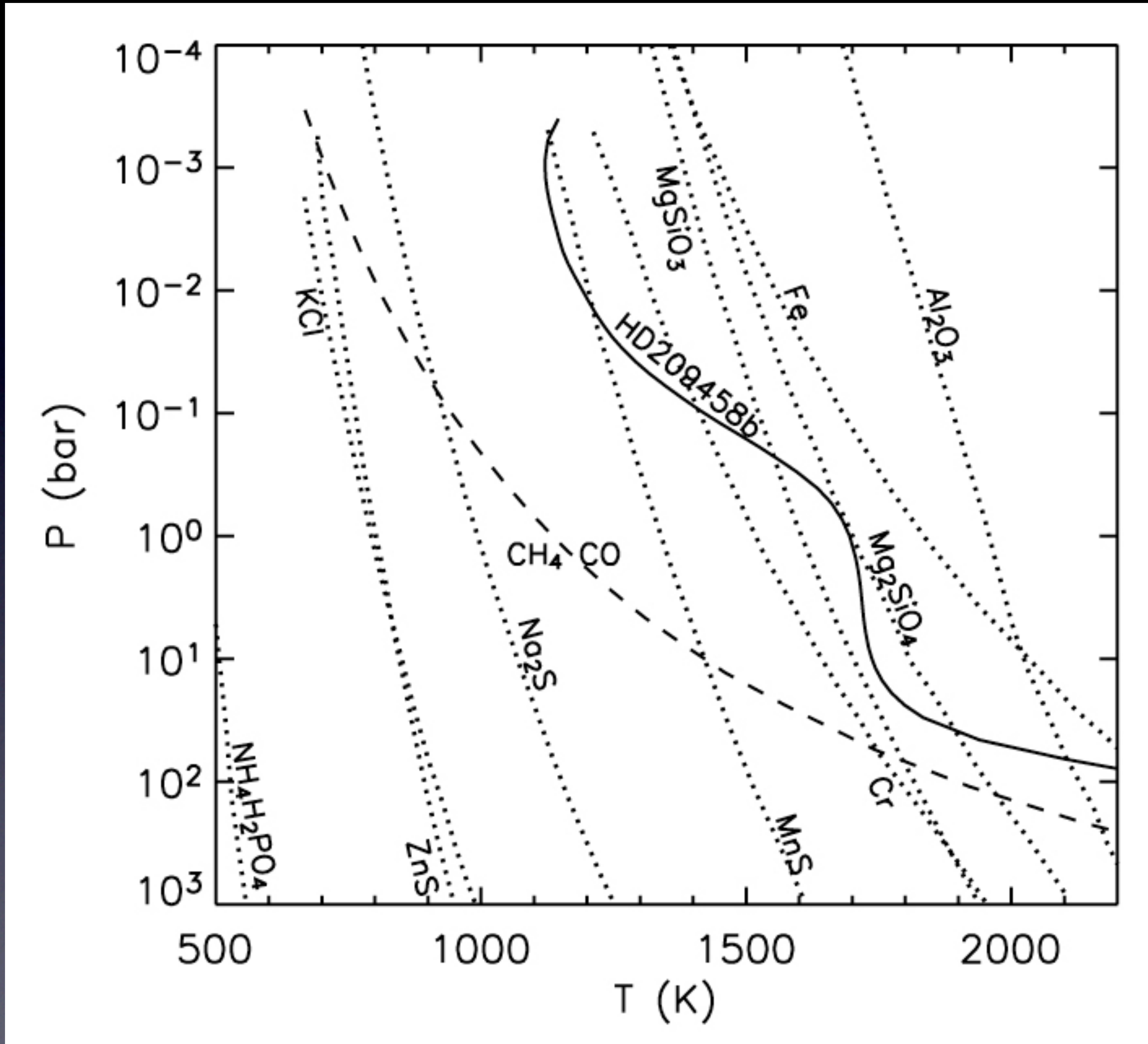


Marley & Leggett (2009)

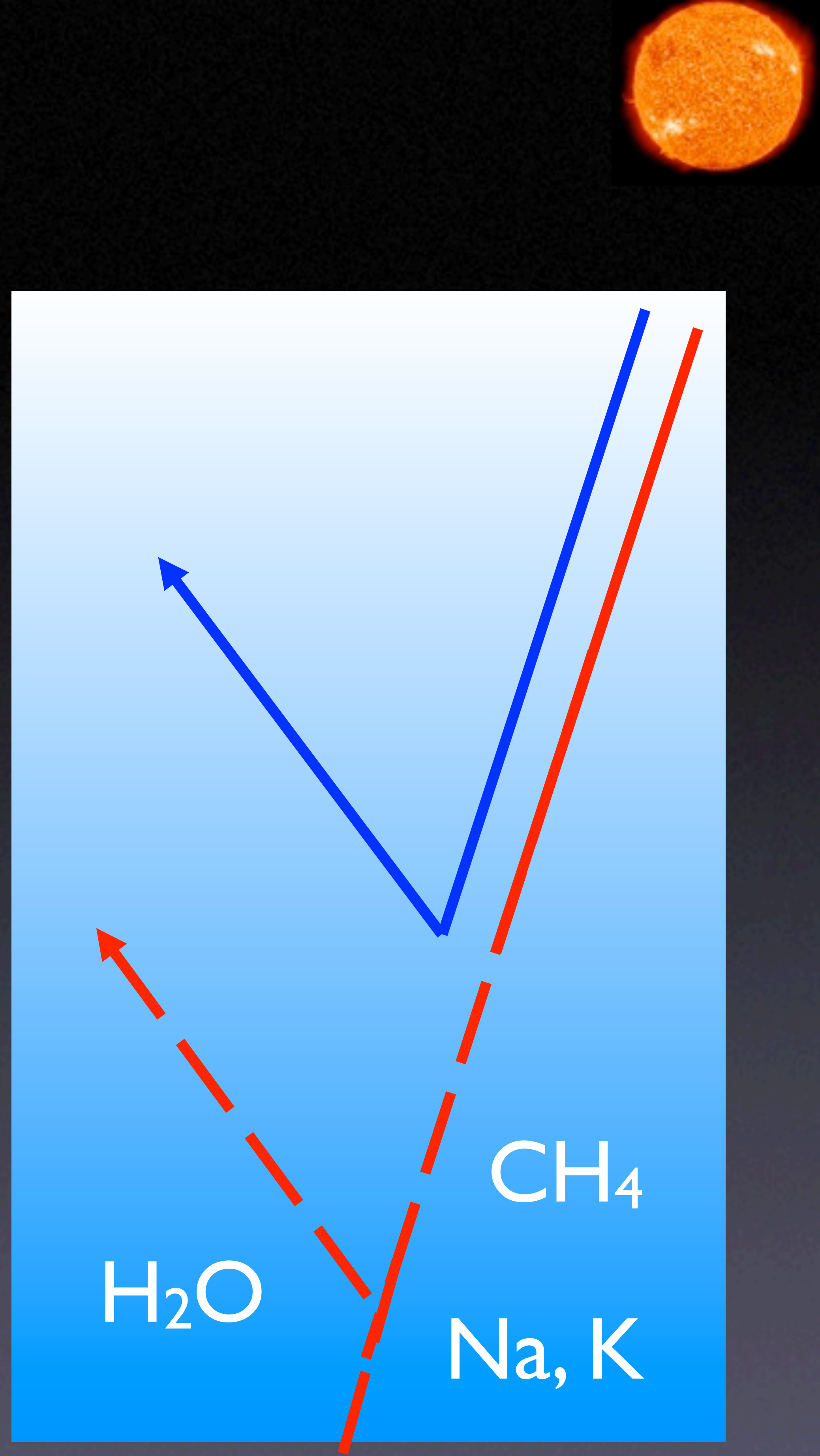


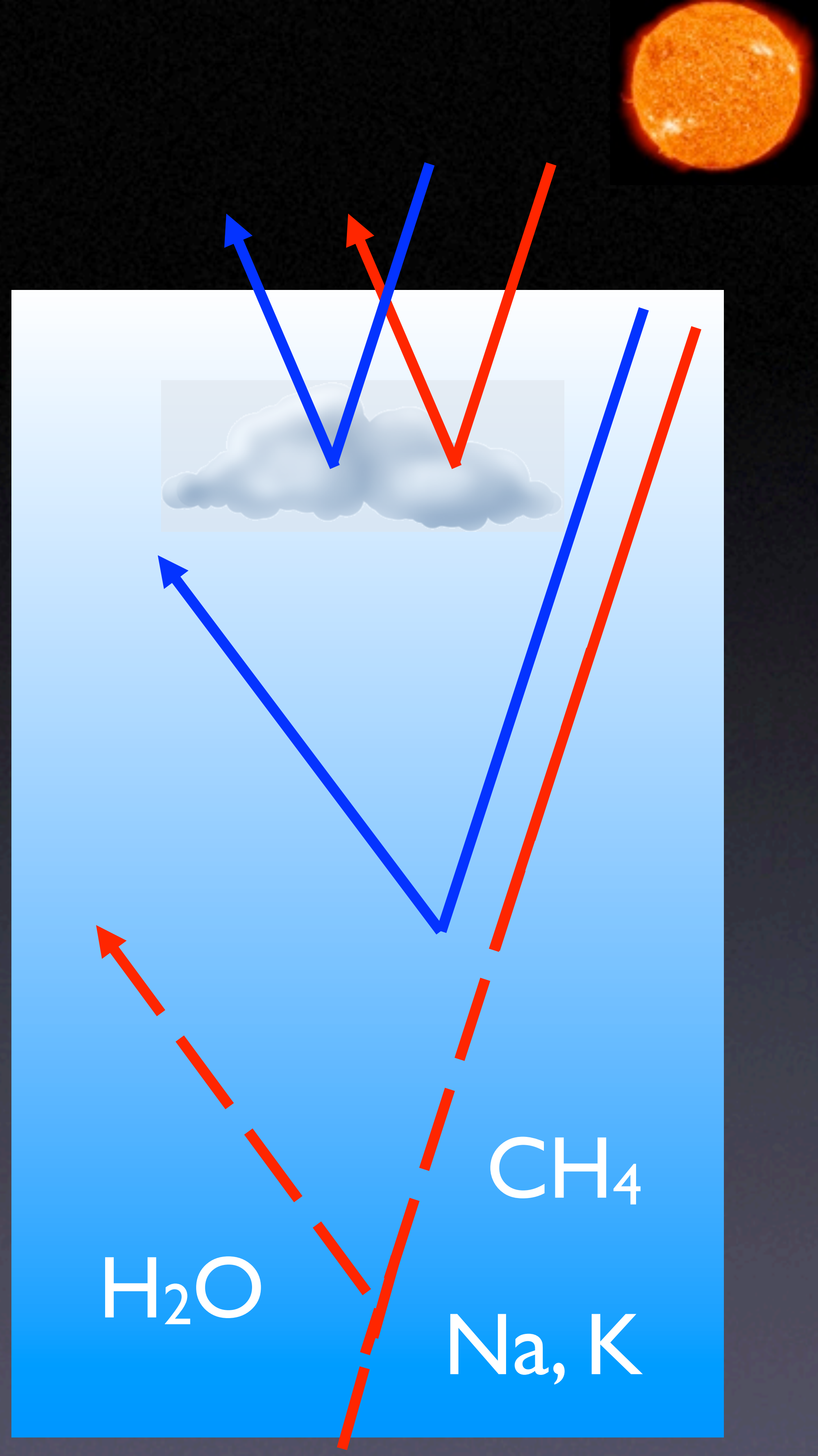
Dupuy & Liu (2012)

Hot Jupiters

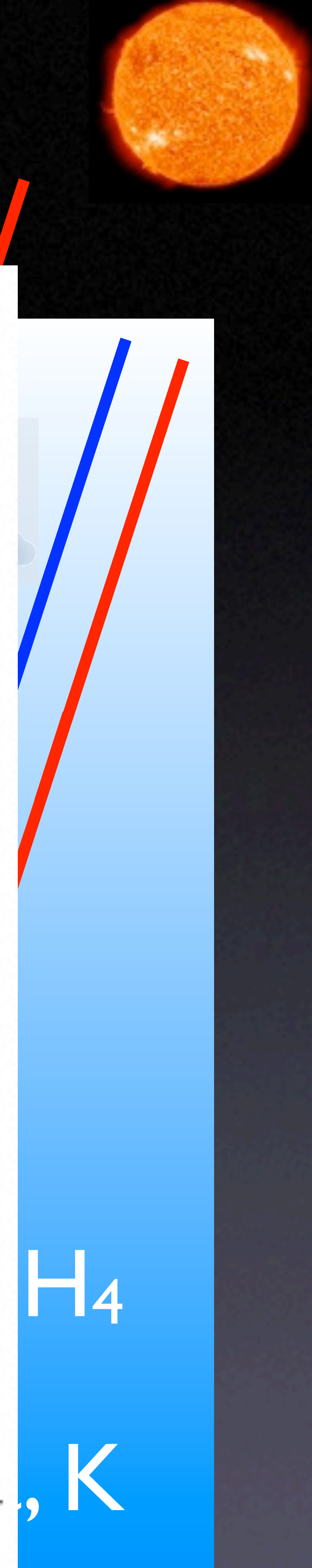


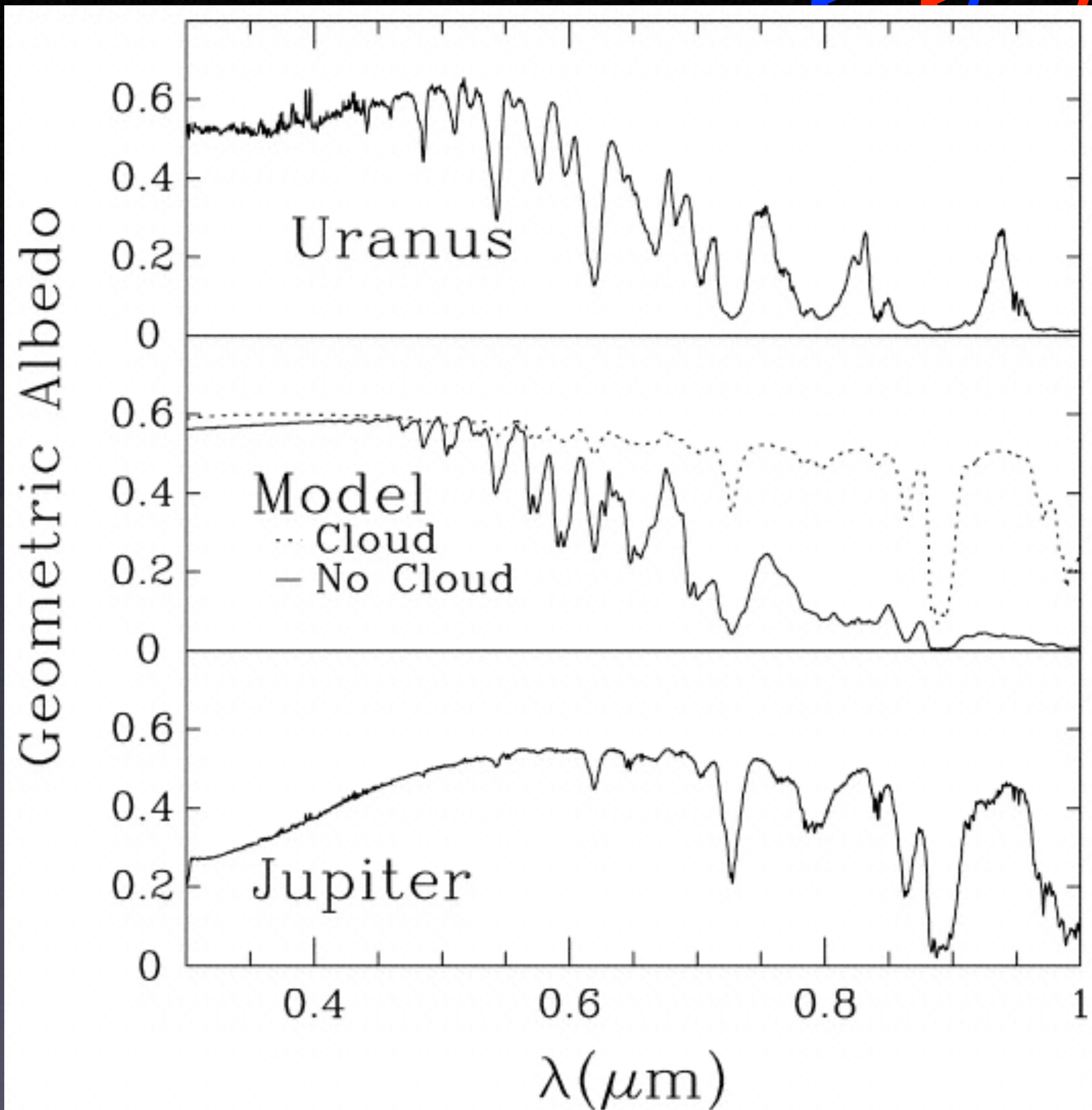
Importance of Clouds: Reflected Light


CH_4
H_2O
Na, K



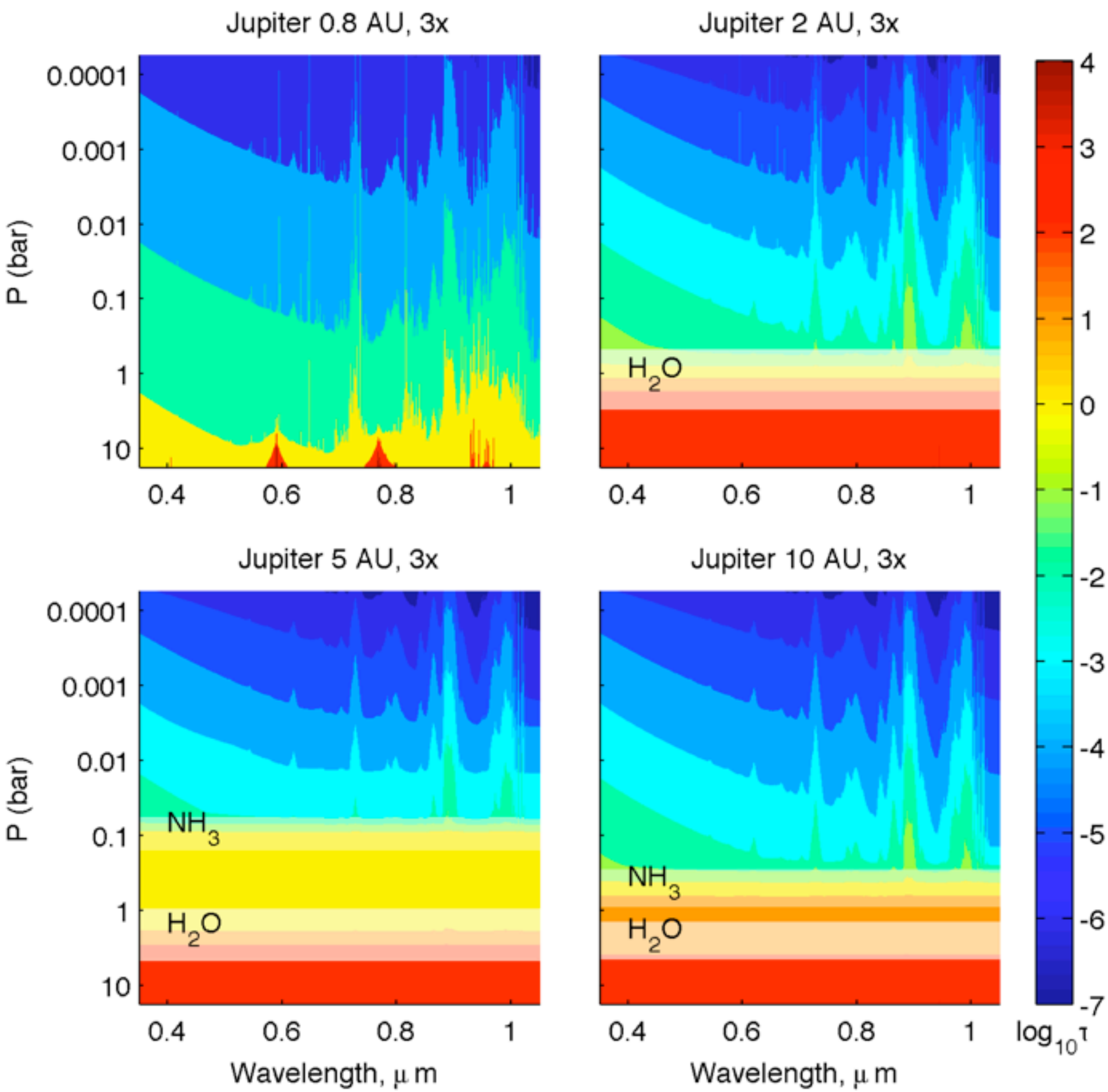
CH_4
H_2O
Na, K



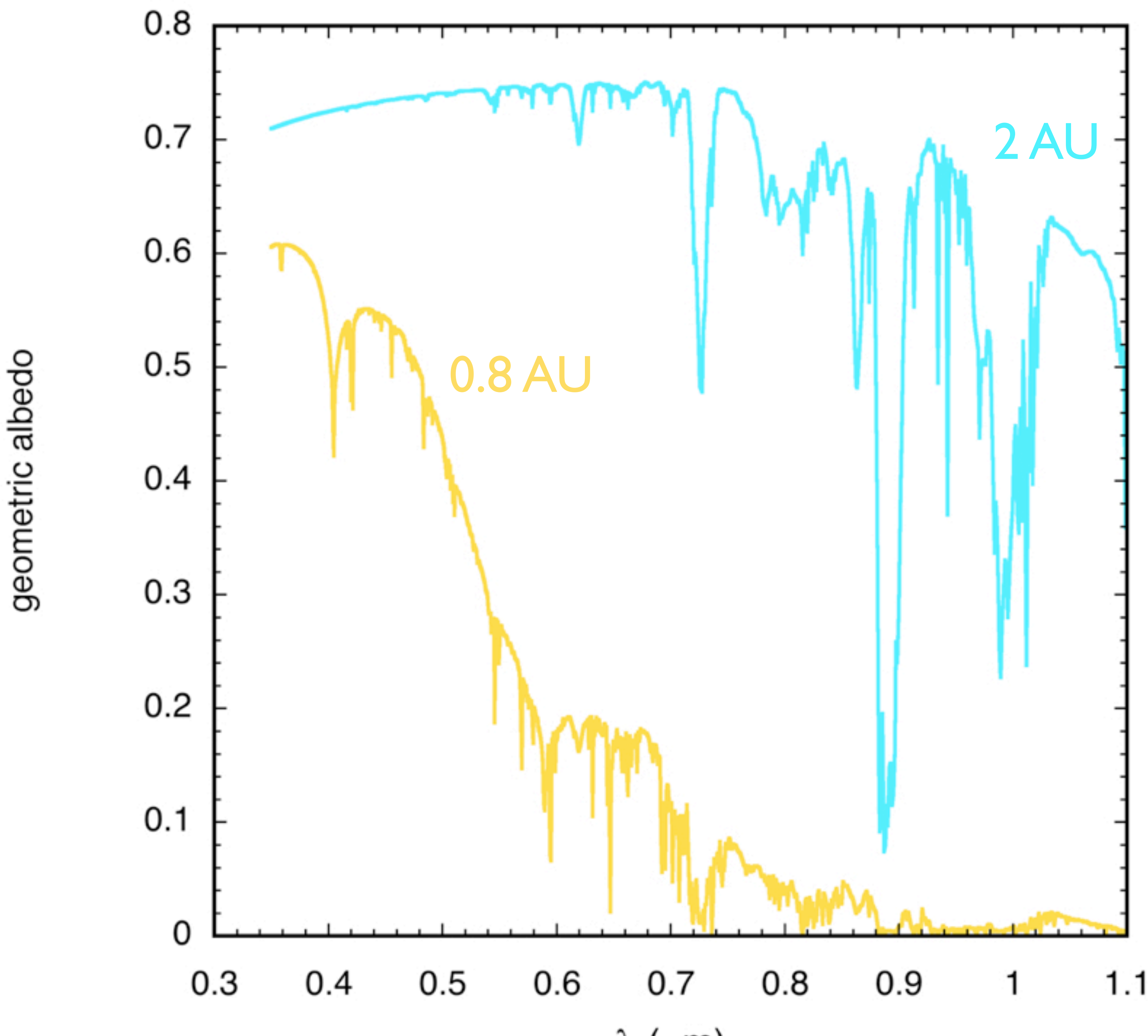


Huge influence on Bond Albedo and T_{eq}

Marley et al. (1999)



Cahoy et al. (2010)



Cahoy et al. (2010)

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.

Thus Not all Jupiters are Jupiter

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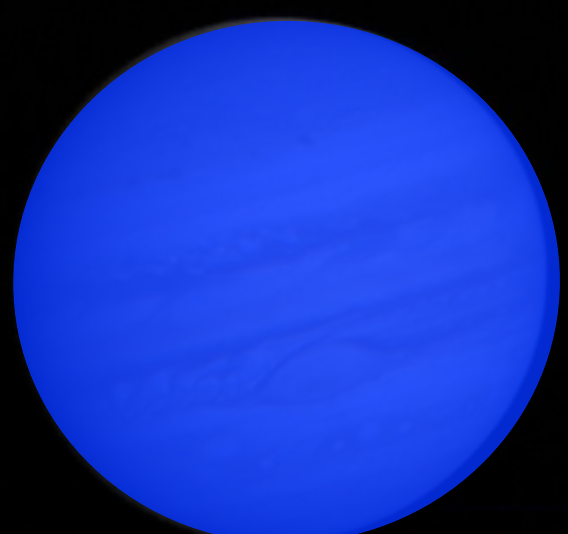


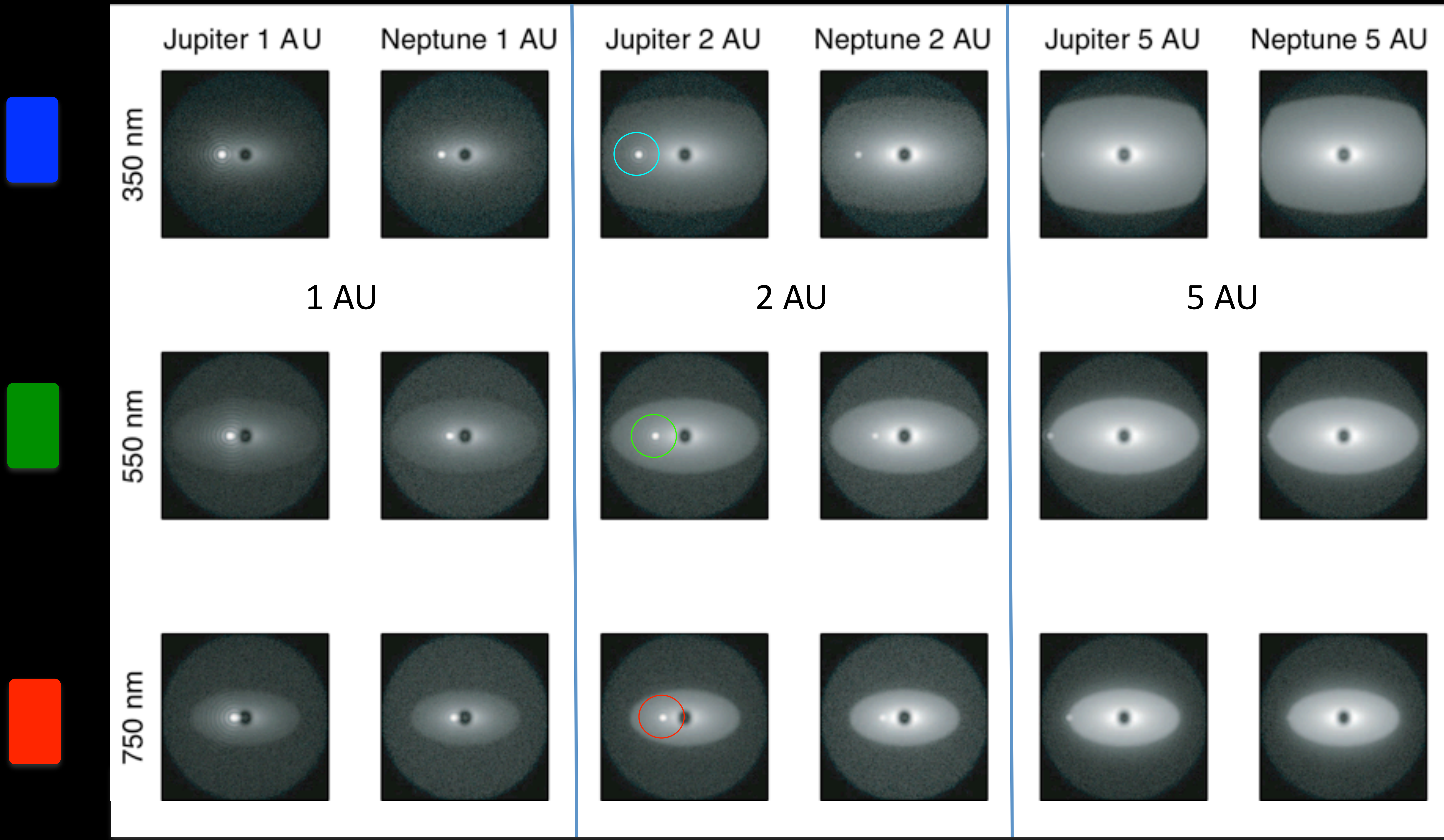
Thus Not all Jupiters are Jupiter

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

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

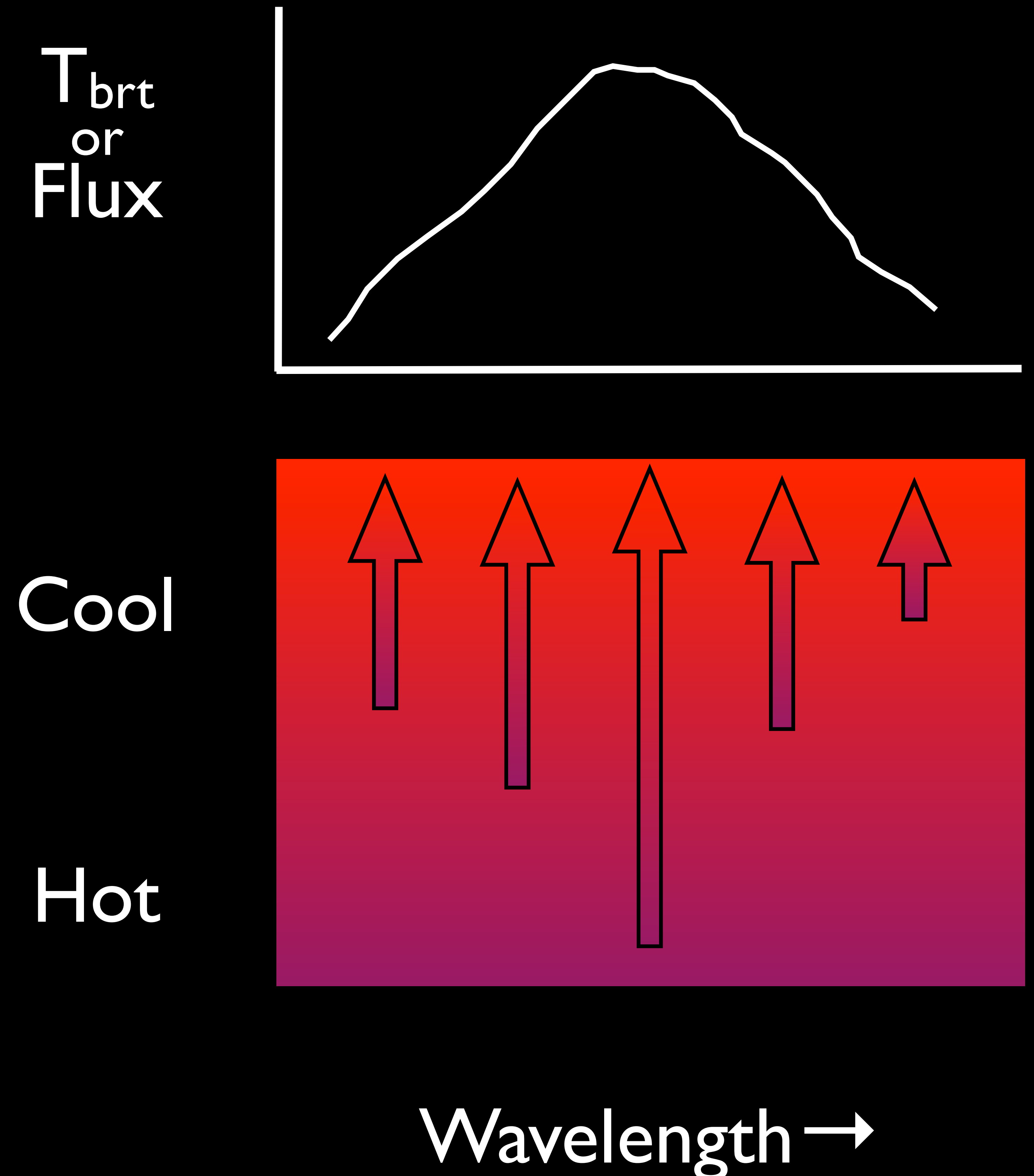
photochemistry

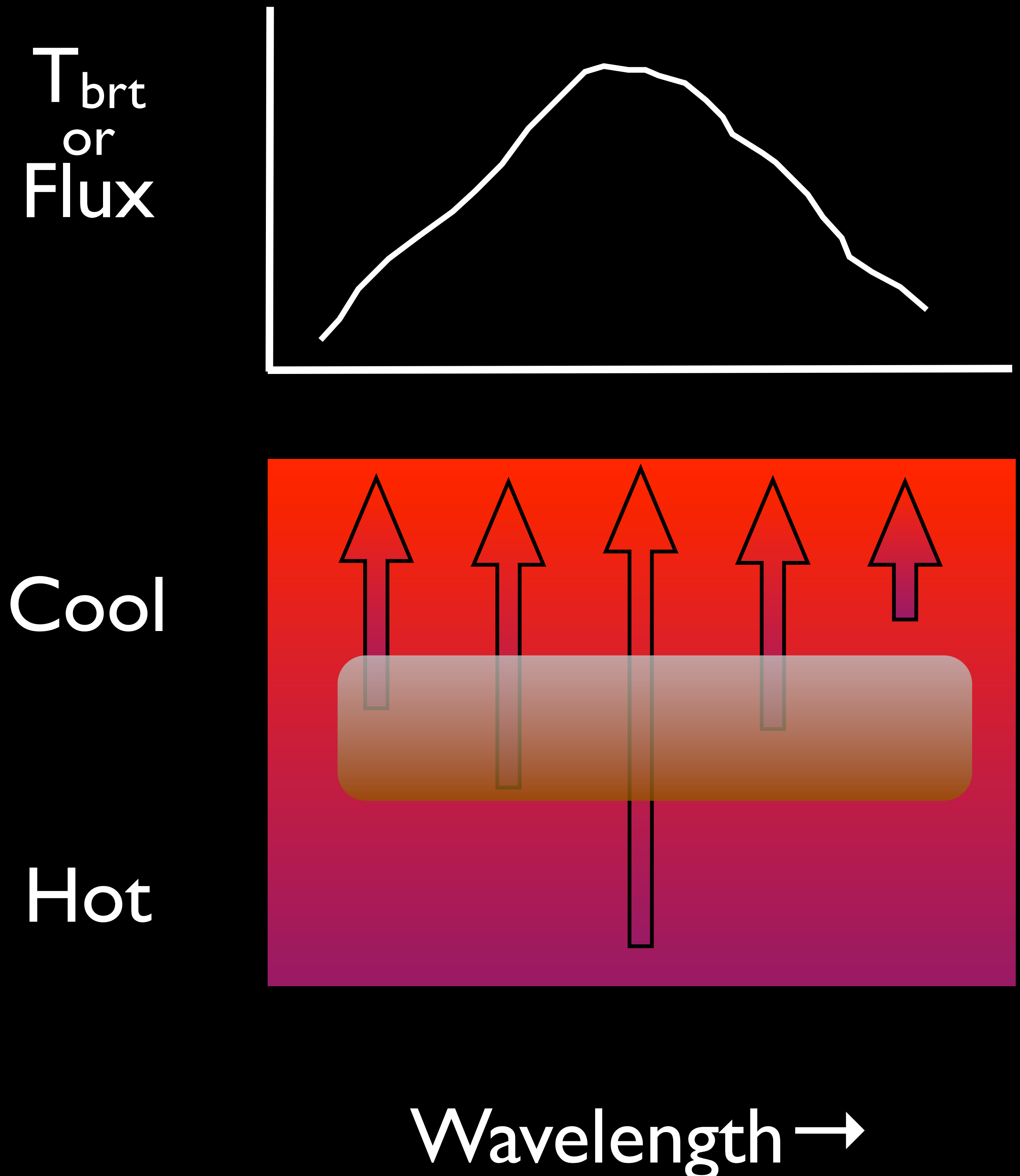
Scattered light
Simulated direct images



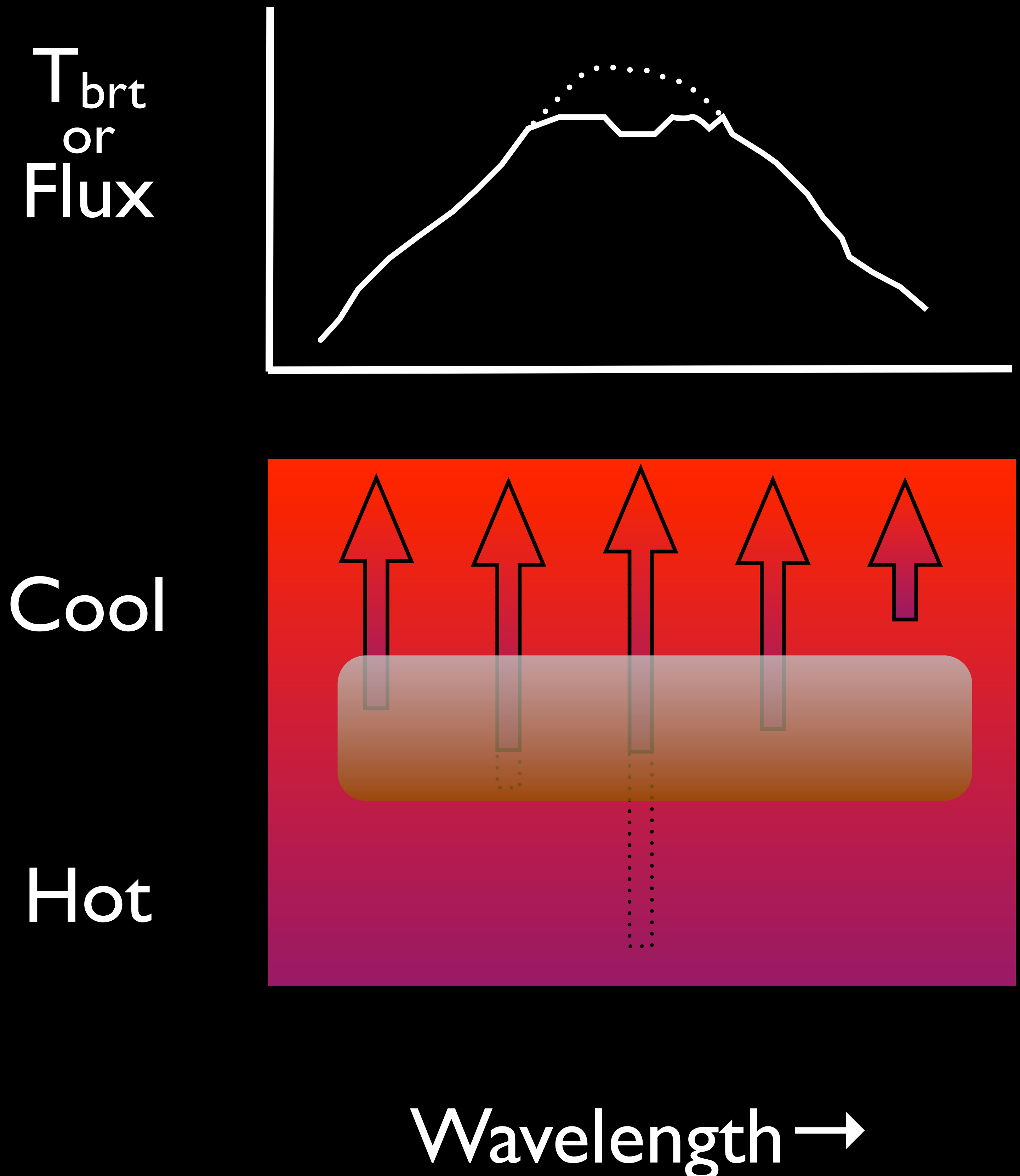
Cahoy et al. (2009)

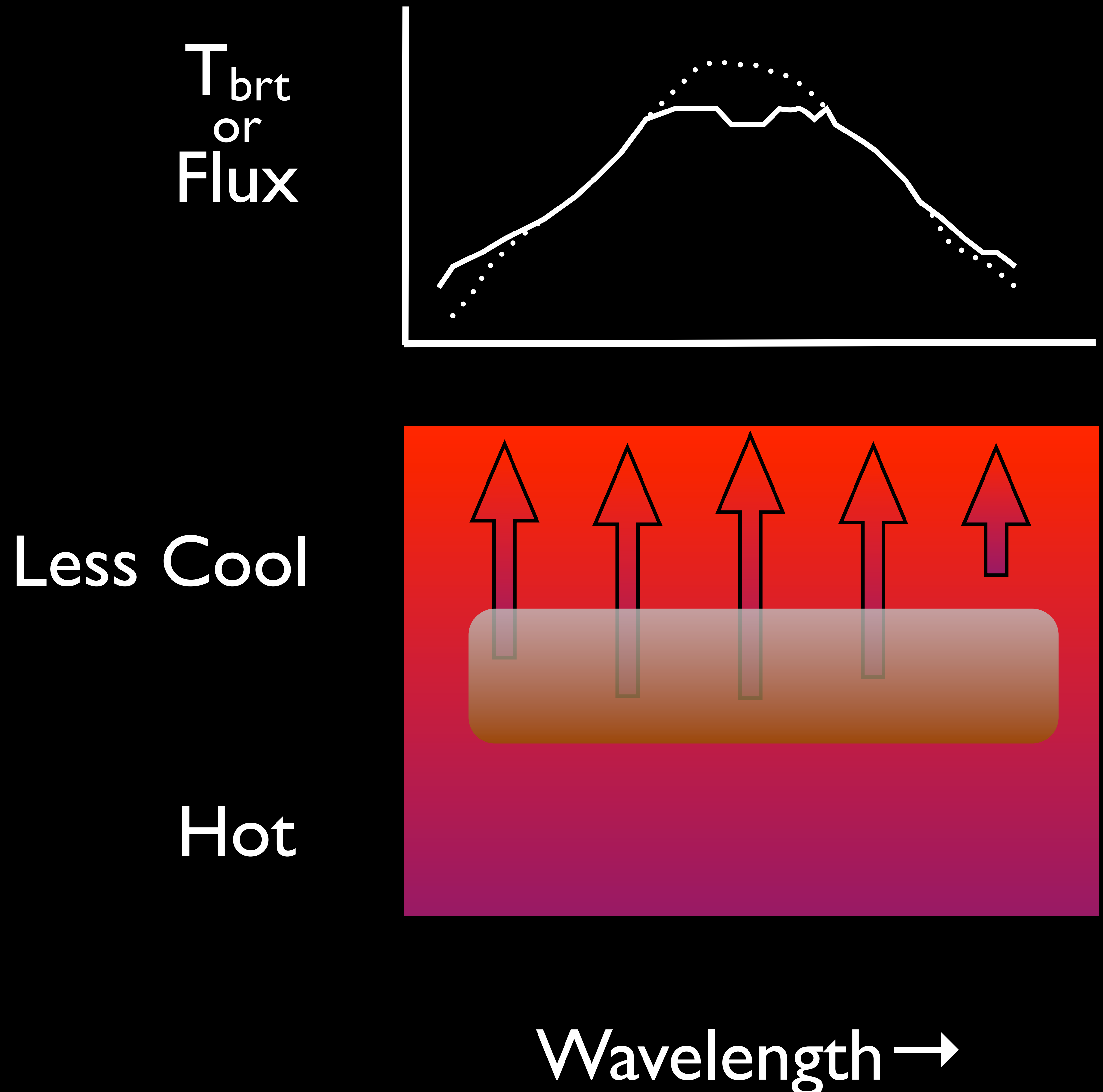
Importance of Clouds: Thermal Emission


T_{brt}
or
Flux
Cool
Hot
Wavelength →



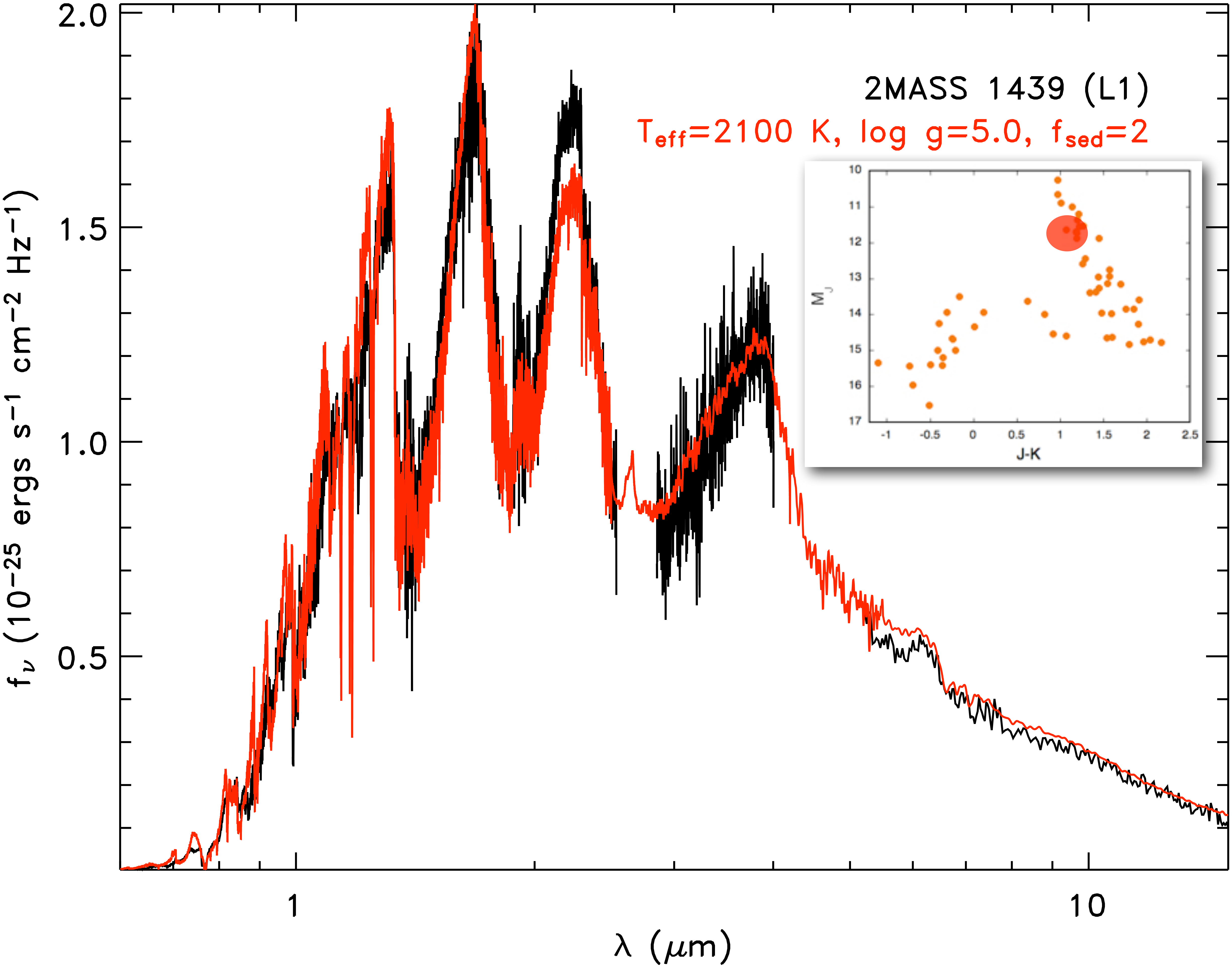
T_{brt}
or
Flux
Cool
Hot
Wavelength →


T_{brt}
or
Flux
Cool
Hot
Wavelength →

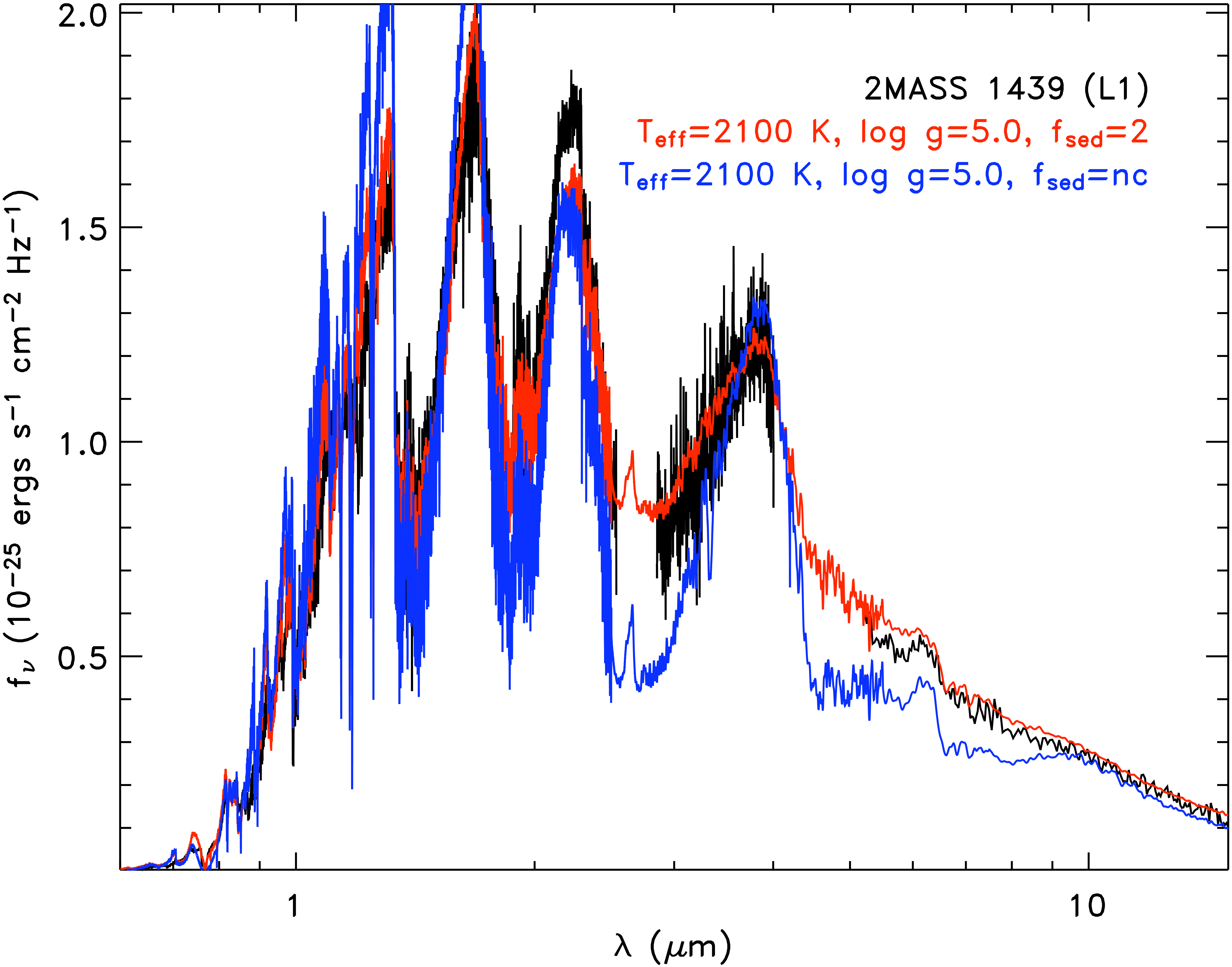


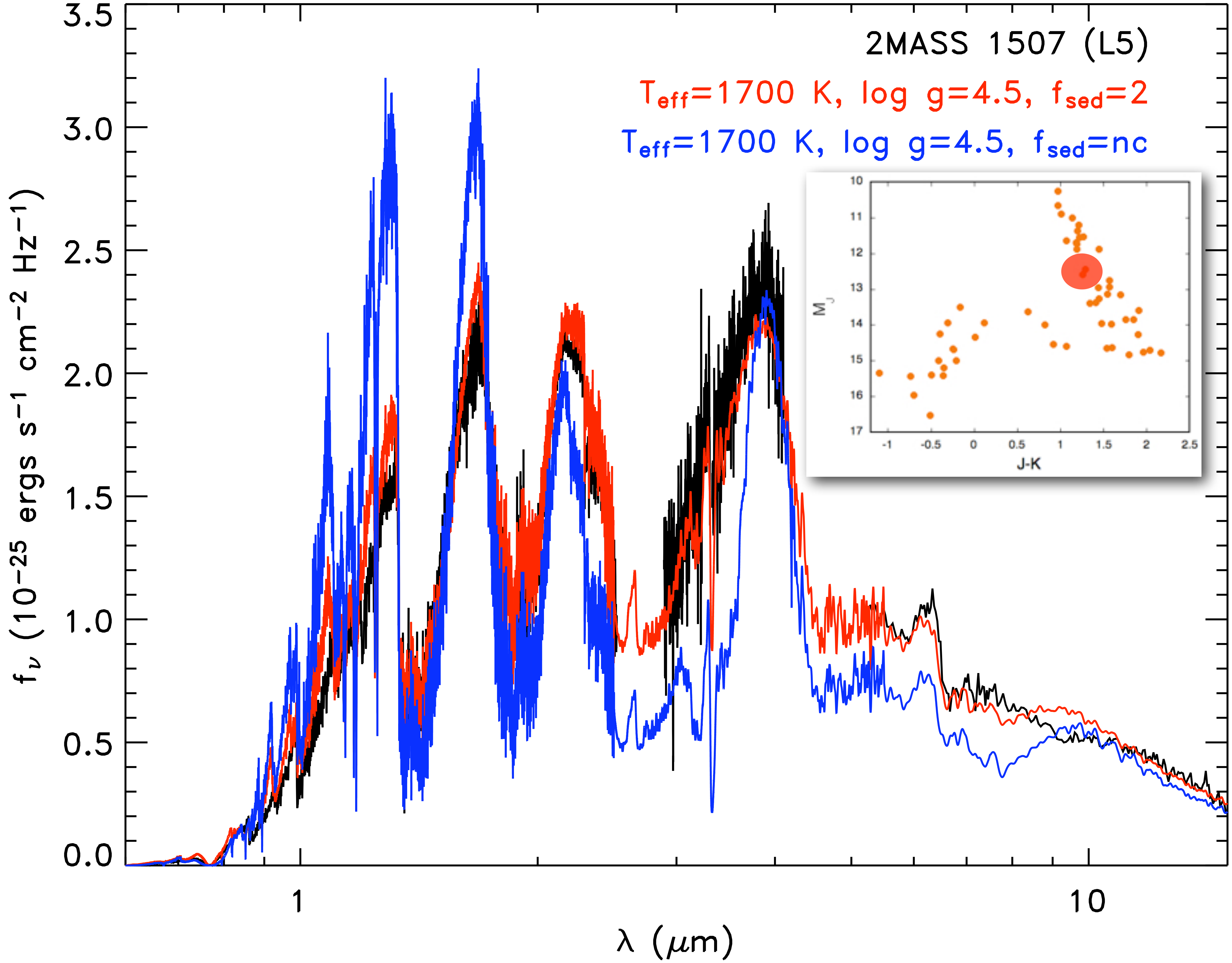
T_{brt}
or
Flux
Less Cool
Hot
Wavelength →

Brown Dwarf Examples



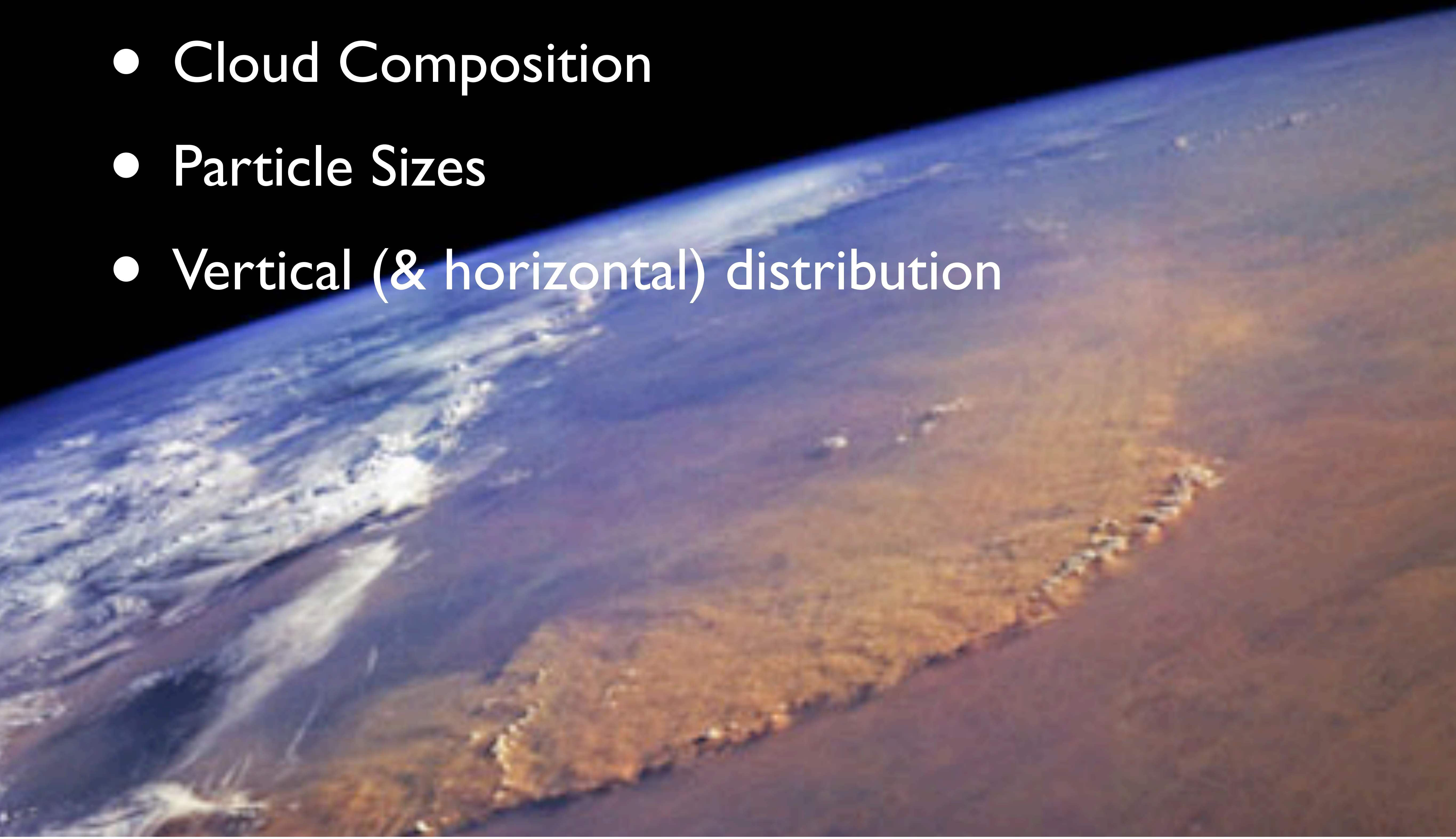
2MASS 1439 (L1)
Teff=2100 K, log g=5.0, fsed=2
fν (10−25 ergs s−1 cm−2 Hz−1)
λ (μm)
2.0
1.5
1.0
0.5
1
10
M_J
J-K

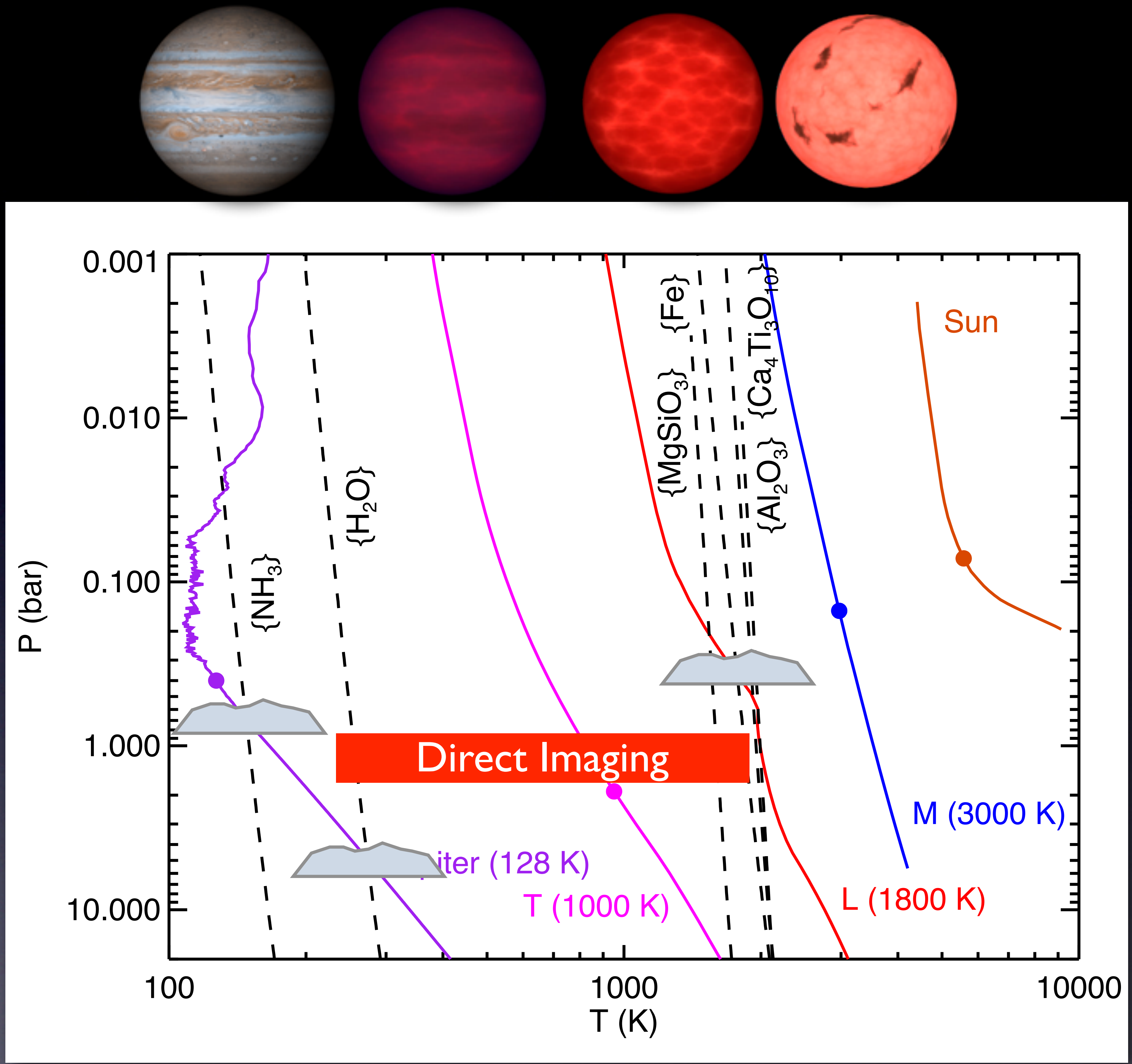

2MASS 1439 (L1)
T_{eff}=2100 K, log g=5.0, f_{sed}=2
T_{eff}=2100 K, log g=5.0, f_{sed}=nc
f_ν (10^{-25} ergs s^{-1} cm^{-2} Hz^{-1})
λ (μm)
2.0
1.5
1.0
0.5
1
10


2MASS 1507 (L5)
Teff=1700 K, log g=4.5, fsed=2
Teff=1700 K, log g=4.5, fsed=nc
fν (10−25 ergs s−1 cm−2 Hz−1)
λ (μm)
M_J
J-K

What do we need to know for atmosphere modeling?

- Cloud Composition
- Particle Sizes
- Vertical (& horizontal) distribution





Sun
M (3000 K)
L (1800 K)
T (1000 K)
iter (128 K)
Direct Imaging
{NH$_3$}
{H$_2$O}
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{Fe}
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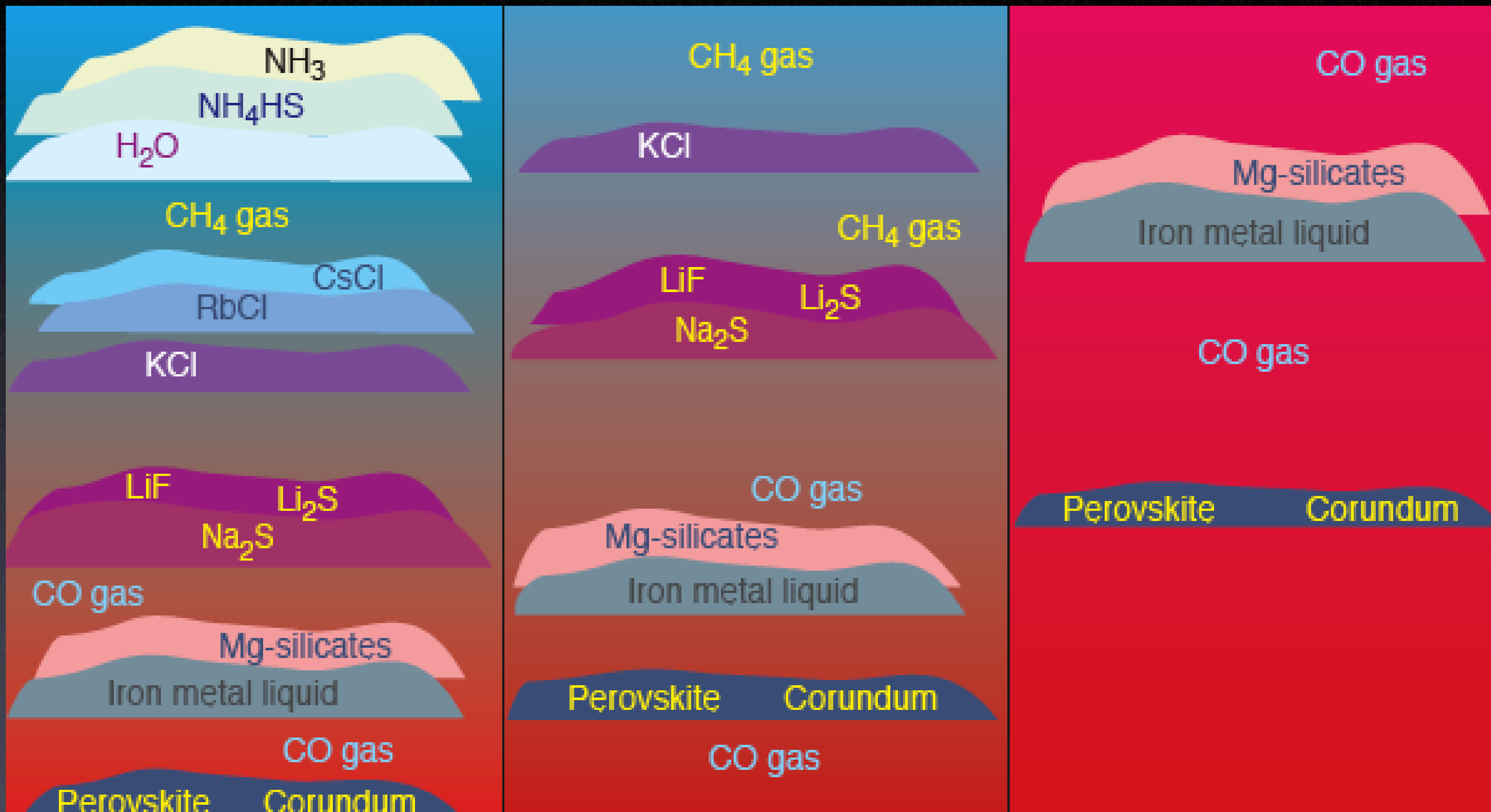
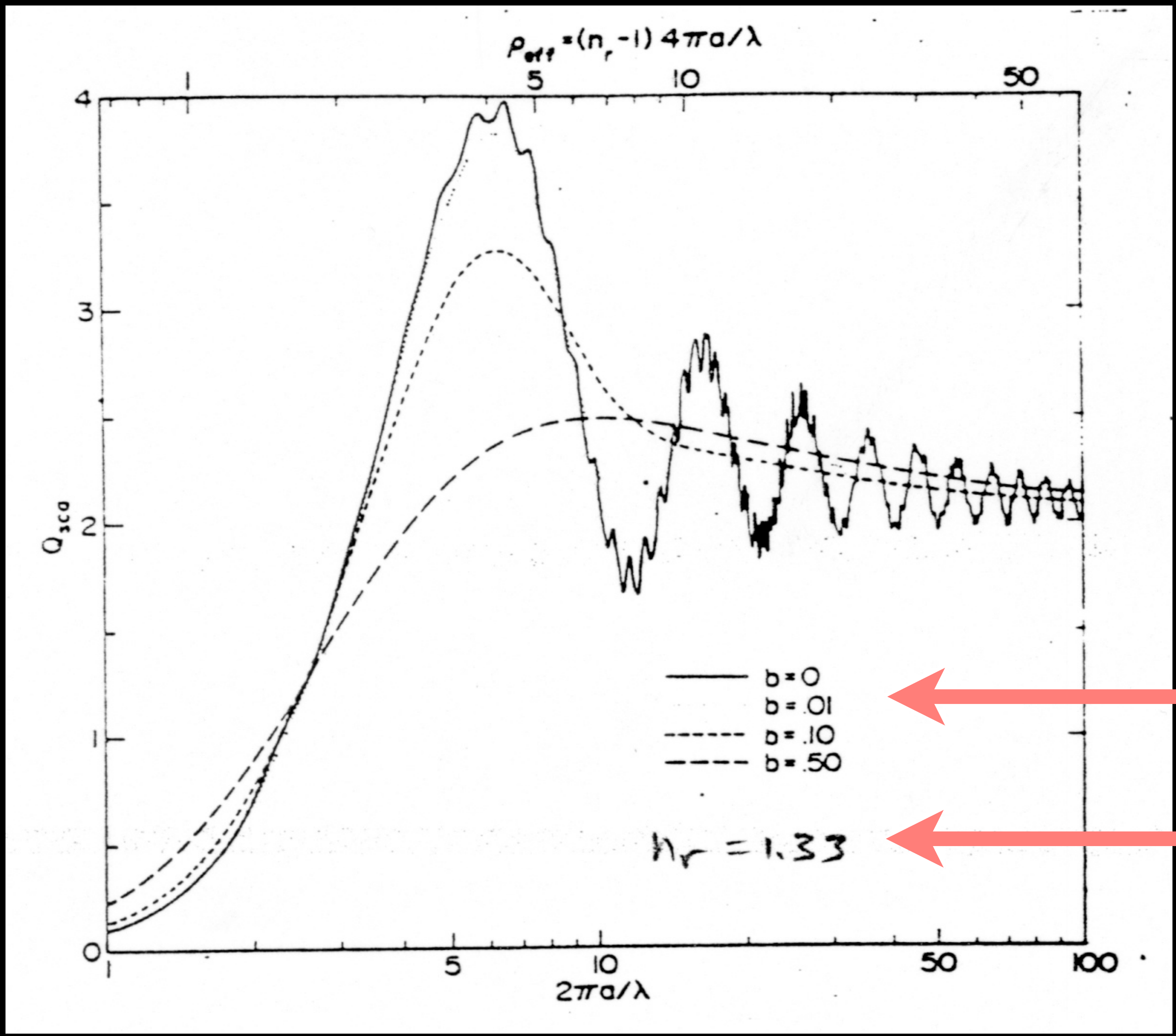
{Ca$_4$Ti$_3$O$_{10}$}
P (bar)
T (K)
0.001
0.010
0.100
1.000
10.000
100
1000
10000



Jupiter T dwarf L dwarf

Lodders (2005)

Size & composition controls the opacity



Q_{scat}

$2\pi a/\lambda$

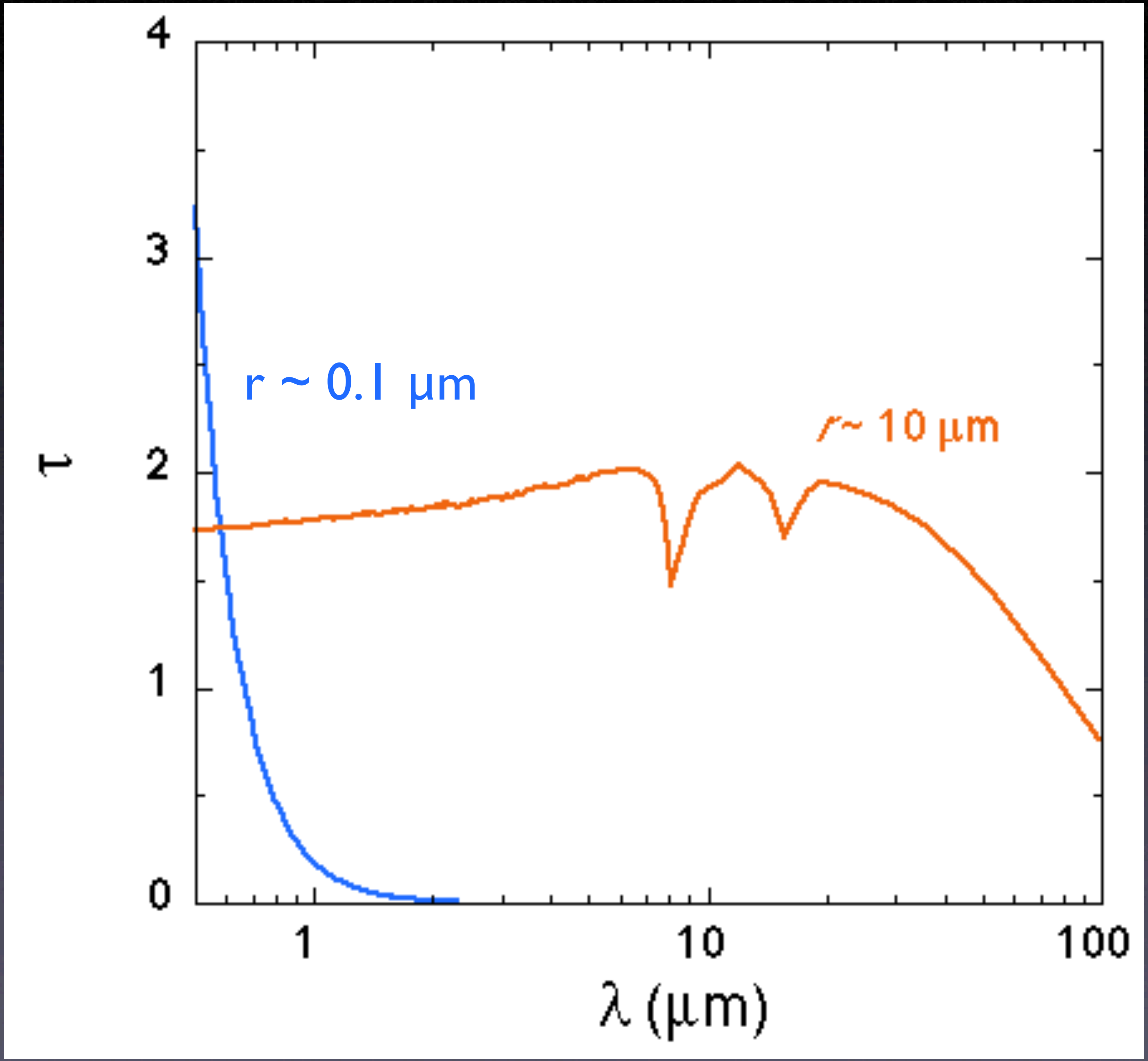
$\tau_{scat} = \mathcal{N} \pi a^2 Q_{scat}$

Need particle size, size distribution & column density

size distribution

real index

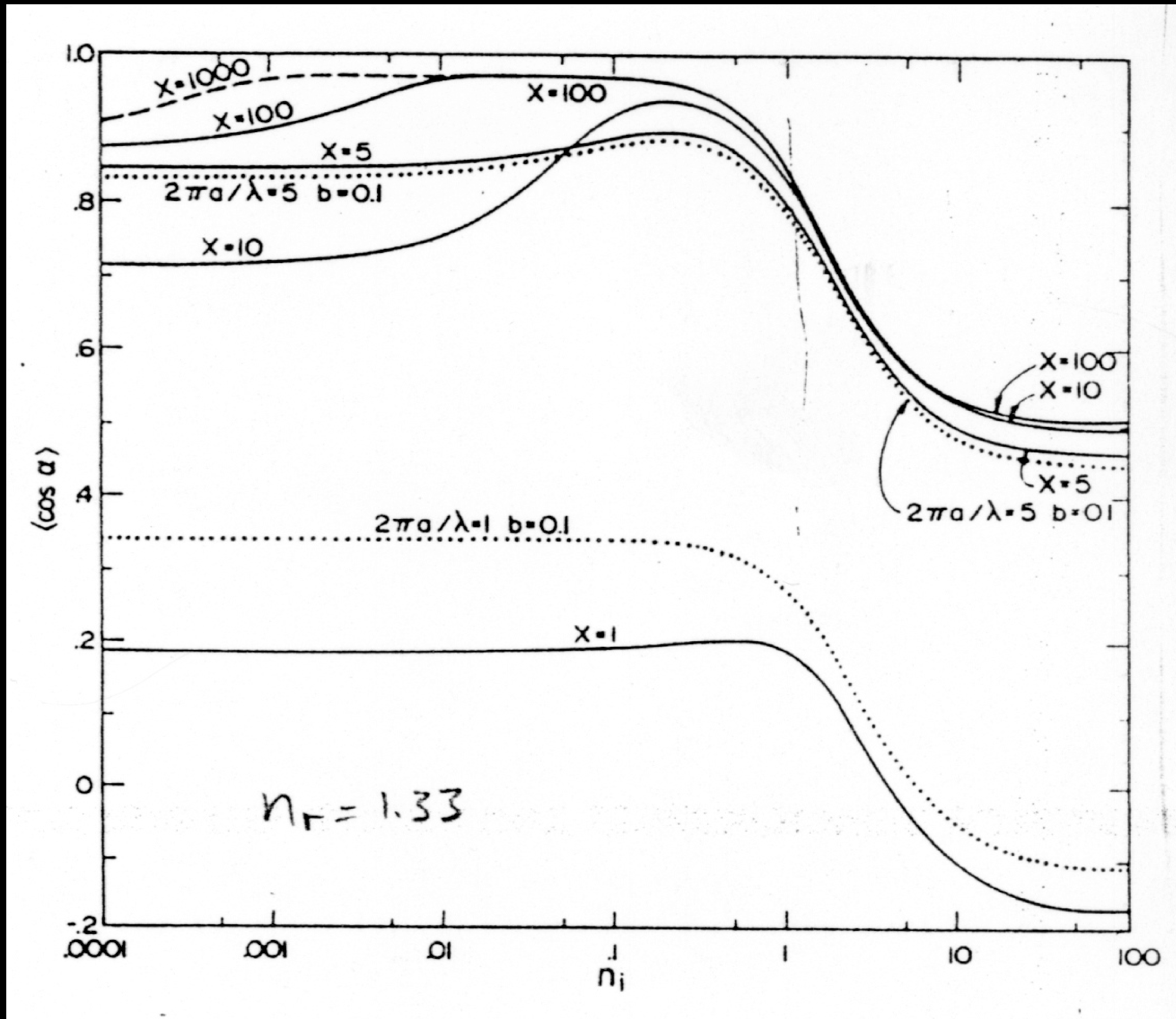
Example



- Big particles (~10 μm compared to < 1 μm)
- Mie vs. Rayleigh opacity

Scattering Angle

$\langle \cos \alpha \rangle$



n_i ← imaginary index

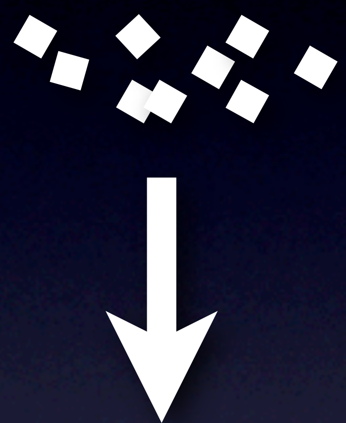
Simplest Model

$$\tau_\lambda = 75\epsilon Q_\lambda(r_c)\varphi\Big(\frac{P_{cl}}{1\,\mathrm{bar}}\Big)\Big(\frac{10^5\,\mathrm{cm\,s^{-2}}}{g}\Big)\Big(\frac{1\,\mu\mathrm{m}}{r_c}\Big)\Big(\frac{1.0\,\mathrm{g\,cm^{-3}}}{\rho_c}\Big).$$

- Can estimate cloud column mass
- Assume hydrostatic equilibrium
- Neglects dynamical effects
- How to compute sizes, vertical extent?
- Need a real model
- Or else guess and test

Cloud Modeling Schools

Top - Down



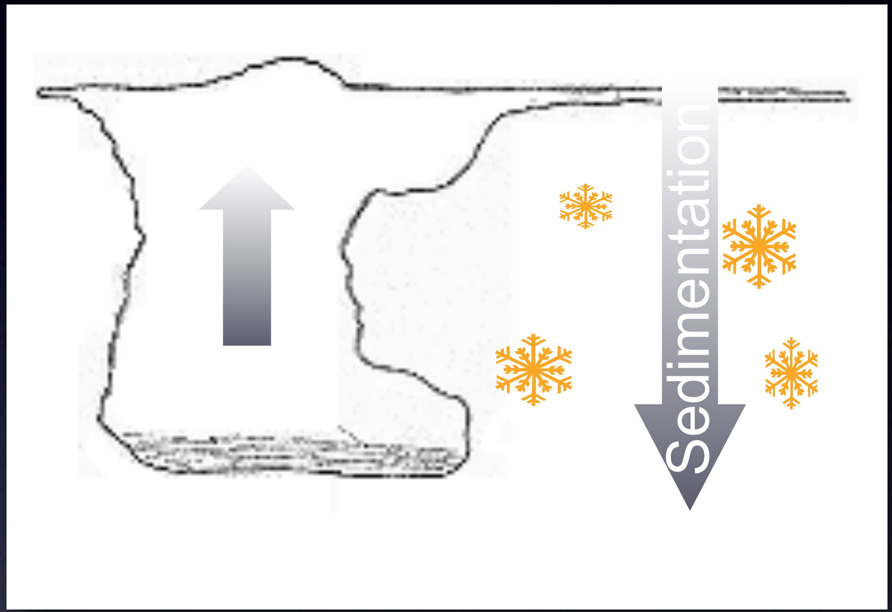
Helling et al.

Microphysics, nucleation, etc.

Fixed

Many examples

Bottom - Up



Ackerman & Marley

Chemical Equilibrium

PHOENIX - DUSTY

Cloud Modeling Schools

Top - Down

Helling et al.

Microphysics, nucleation, etc.

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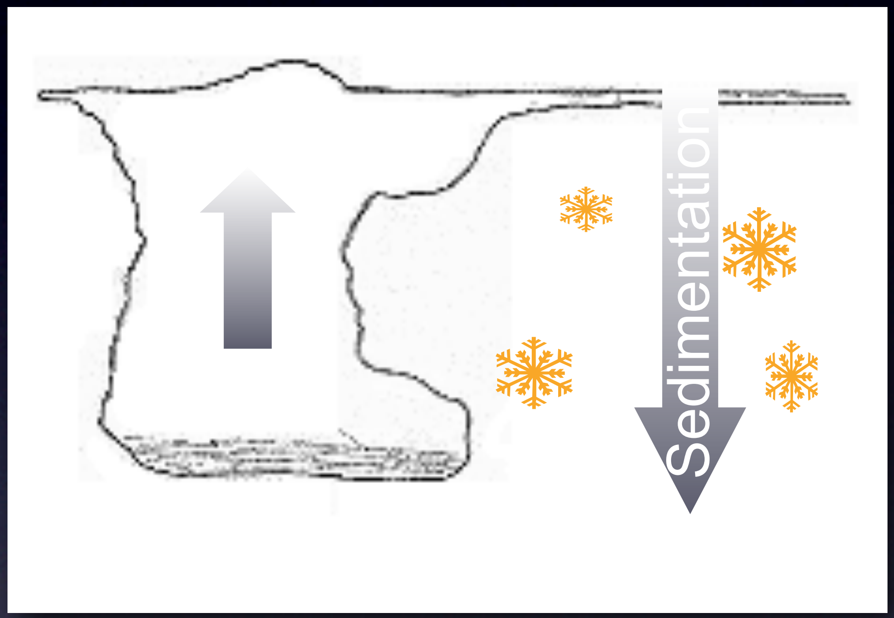


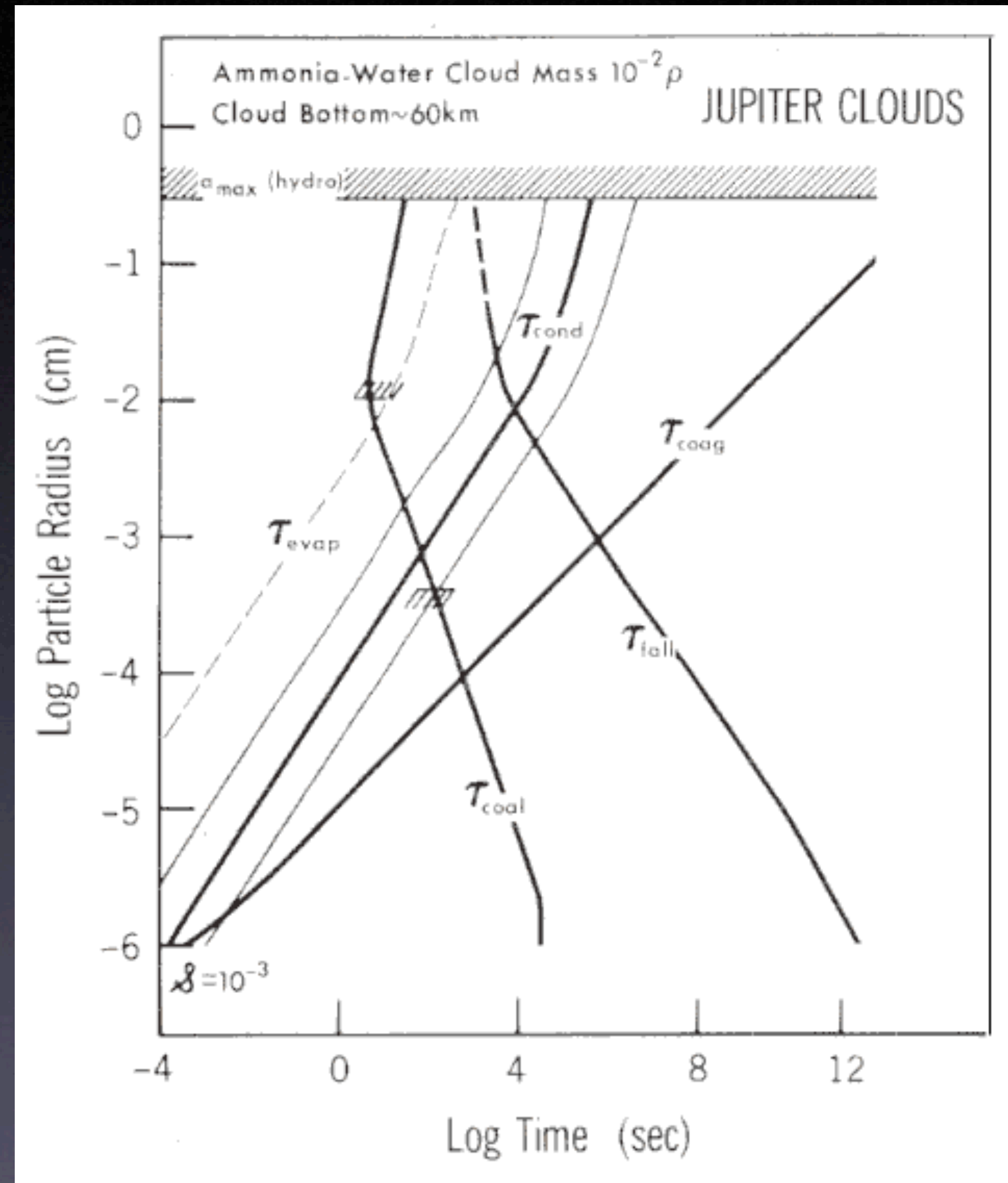
Ackerman & Marley

Chemical Equilibrium

PHOENIX - DUSTY

Why Not Rossow?

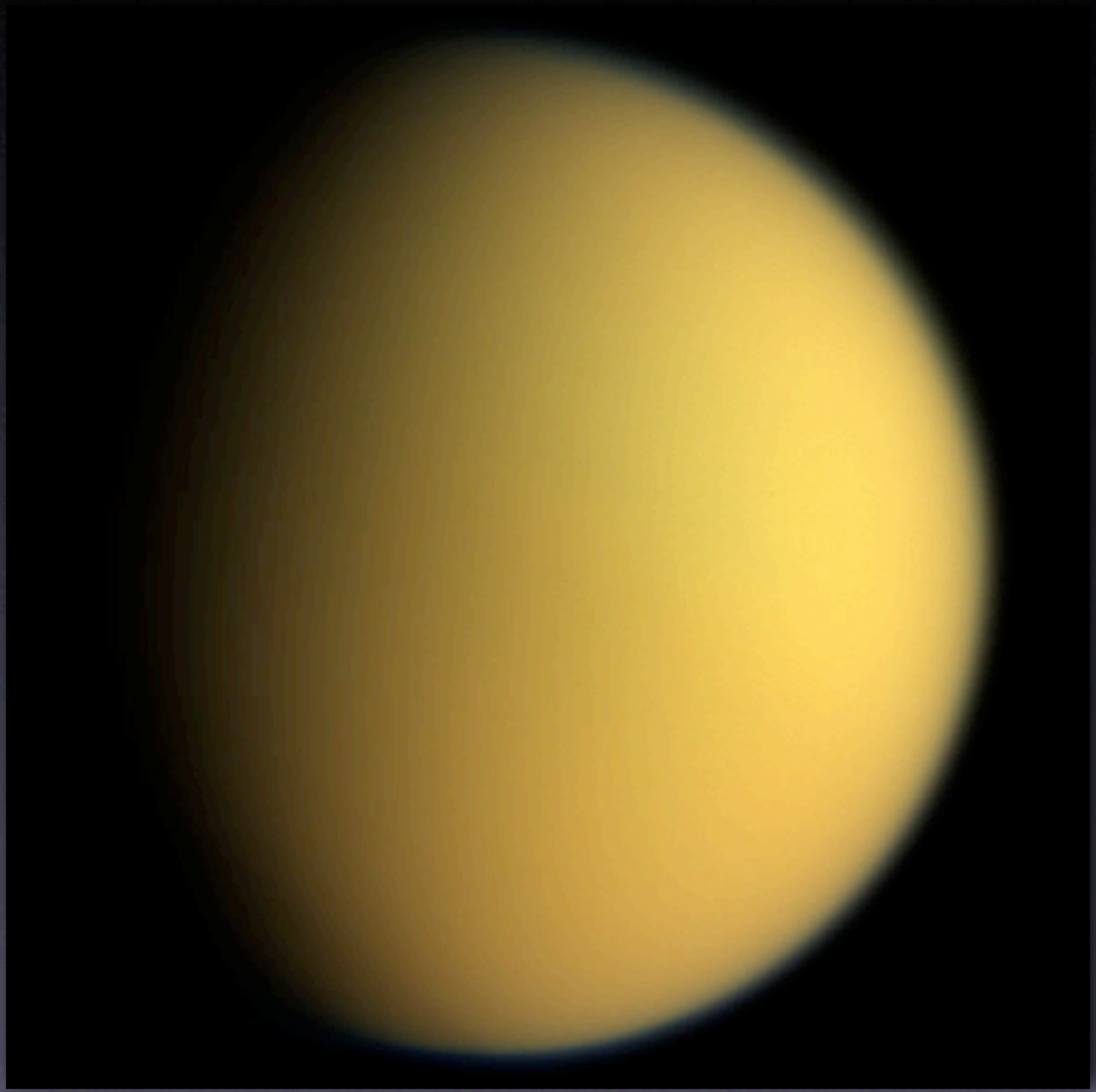
- Most extensive body of work on solar system clouds
  - Compute timescales, τ, for key cloud processes (nucleation, falling, coagulation, etc.)
  - Estimate sizes by comparing τ
  - Popular
- Computation of τ's introduces *many* assumptions
  - Surface tensions, supersaturation, coagulation efficiences, size distributions…
- Results very sensitive to unknowable quantities
- Does not constrain vertical condensate profile



Rossow 1978

Philosophy Behind Ackerman Model

- Needed a global 1D mean cloud model
- Initiated collaboration with Andy Ackerman
- Ackerman is highly skeptical any 1D cloud model is even possible



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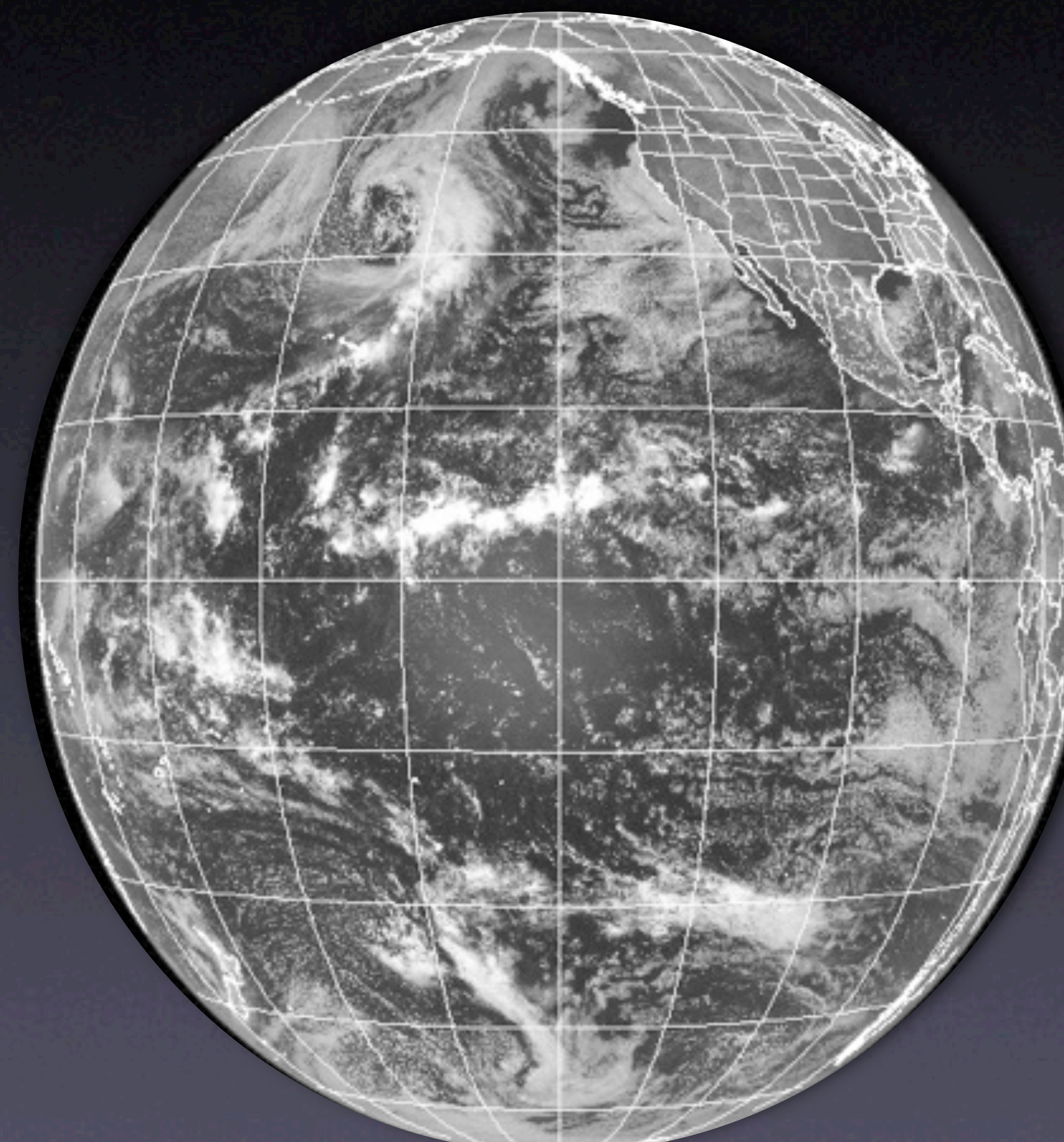

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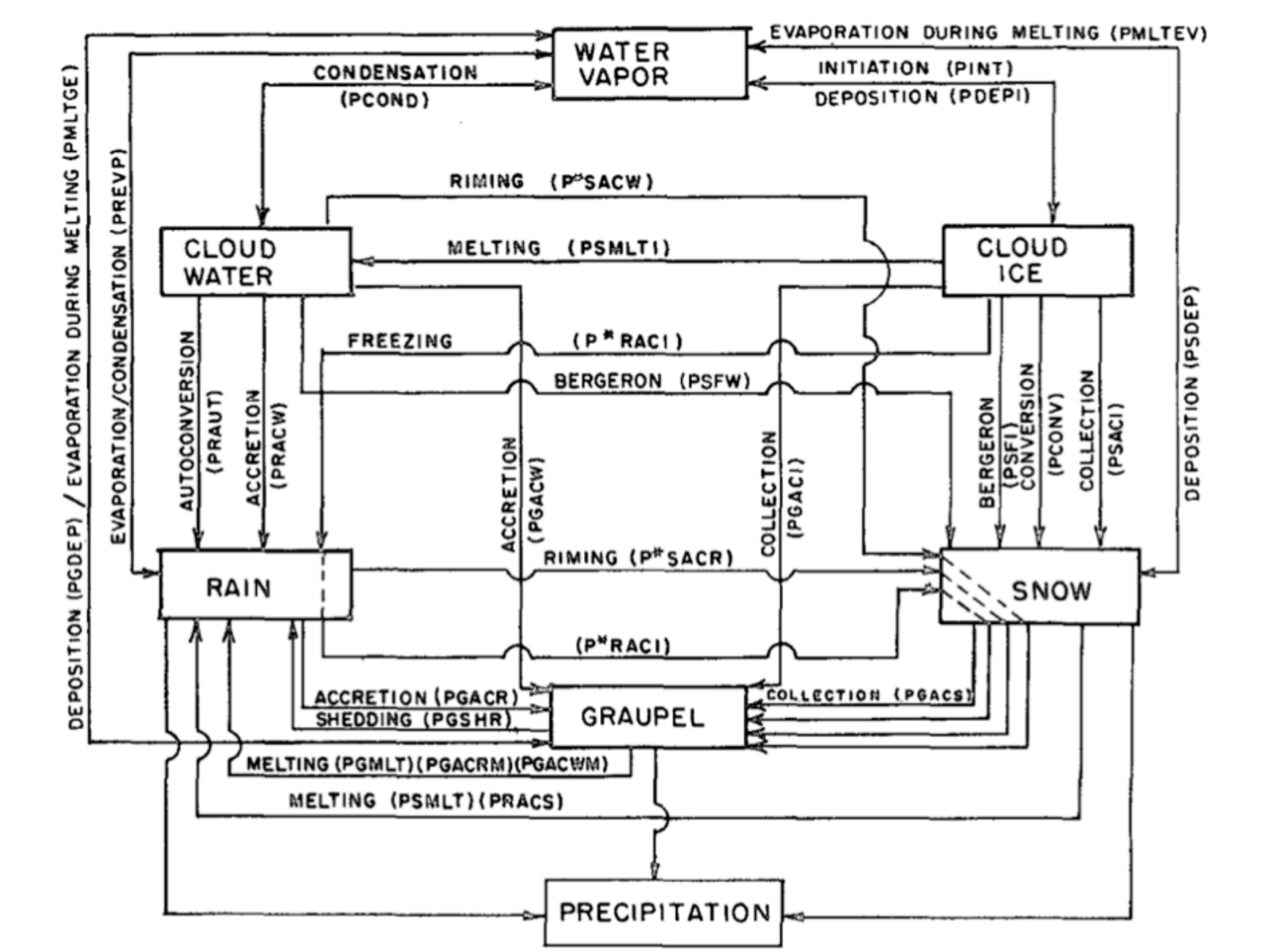
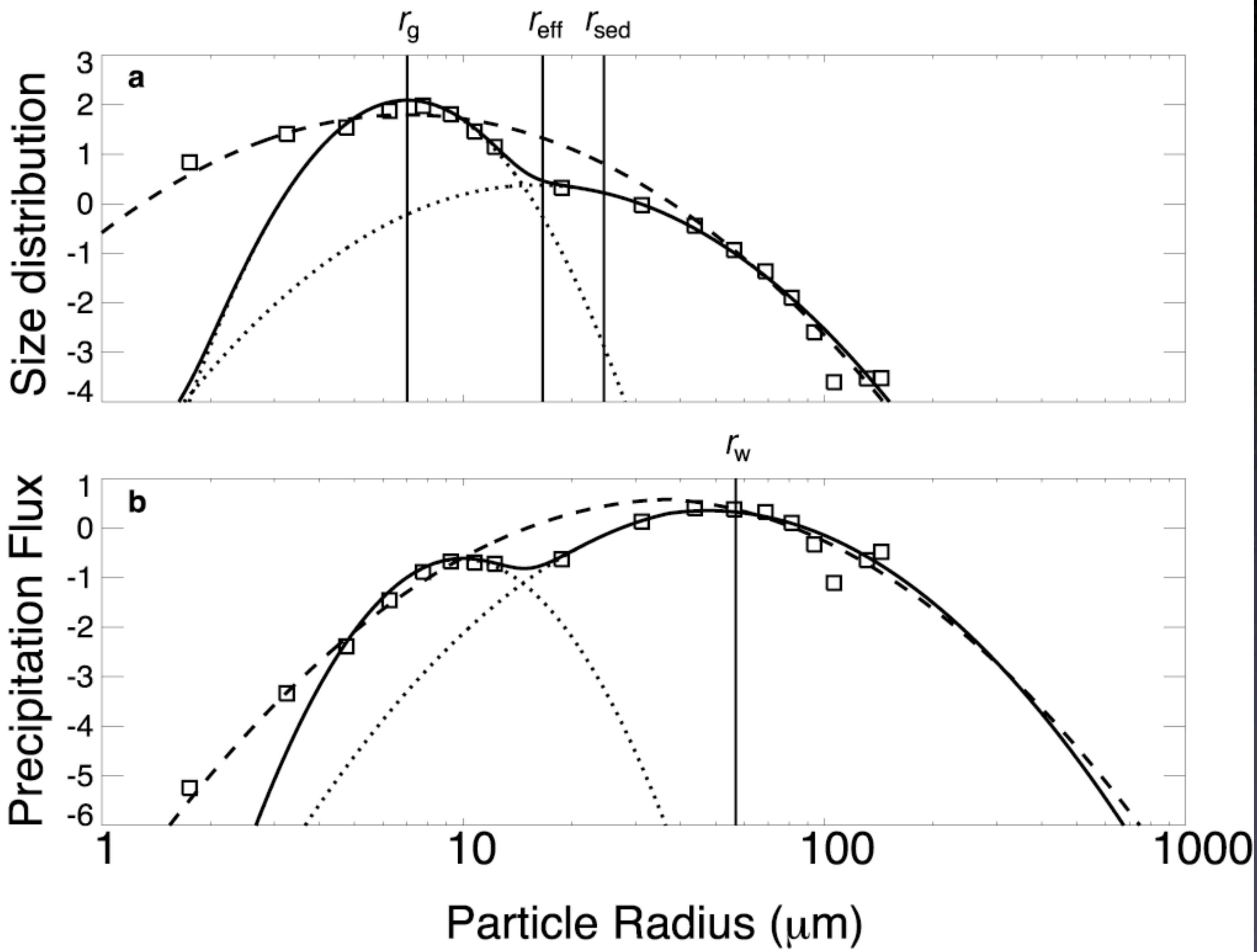

WATER VAPOR
EVAPORATION DURING MELTING (PMLTEV)
INITIATION (PINT)
DEPOSITION (PDEPI)
CONDENSATION
(PCOND)
DEPOSITION (PGDEP) / EVAPORATION DURING MELTING (PMLTGE)
EVAPORATION/CONDENSATION (PREVP)
RIMING (P*SACW)
CLOUD WATER
MELTING (PSMLTI)
CLOUD ICE
FREEZING
(P* RACI)
BERGERON (PSFW)
AUTOCONVERSION (PRAUT)
ACCRETION (PRACW)
ACCRETION (PGACW)
COLLECTION (PGACI)
BERGERON (PSFI)
CONVERSION (PCONV)
COLLECTION (PSACI)
DEPOSITION (PSDEP)
RIMING (P*SACR)
RAIN
SNOW
(P*RACI)
ACCRETION (PGACR)
SHEDDING (PGSHR)
GRAUPEL
COLLECTION (PGACS)
MELTING (PGMLT)(PGACRM)(PGACWM)
MELTING (PSMLT)(PRACS)
PRECIPITATION

Crucial to properly account for sedimentation flux



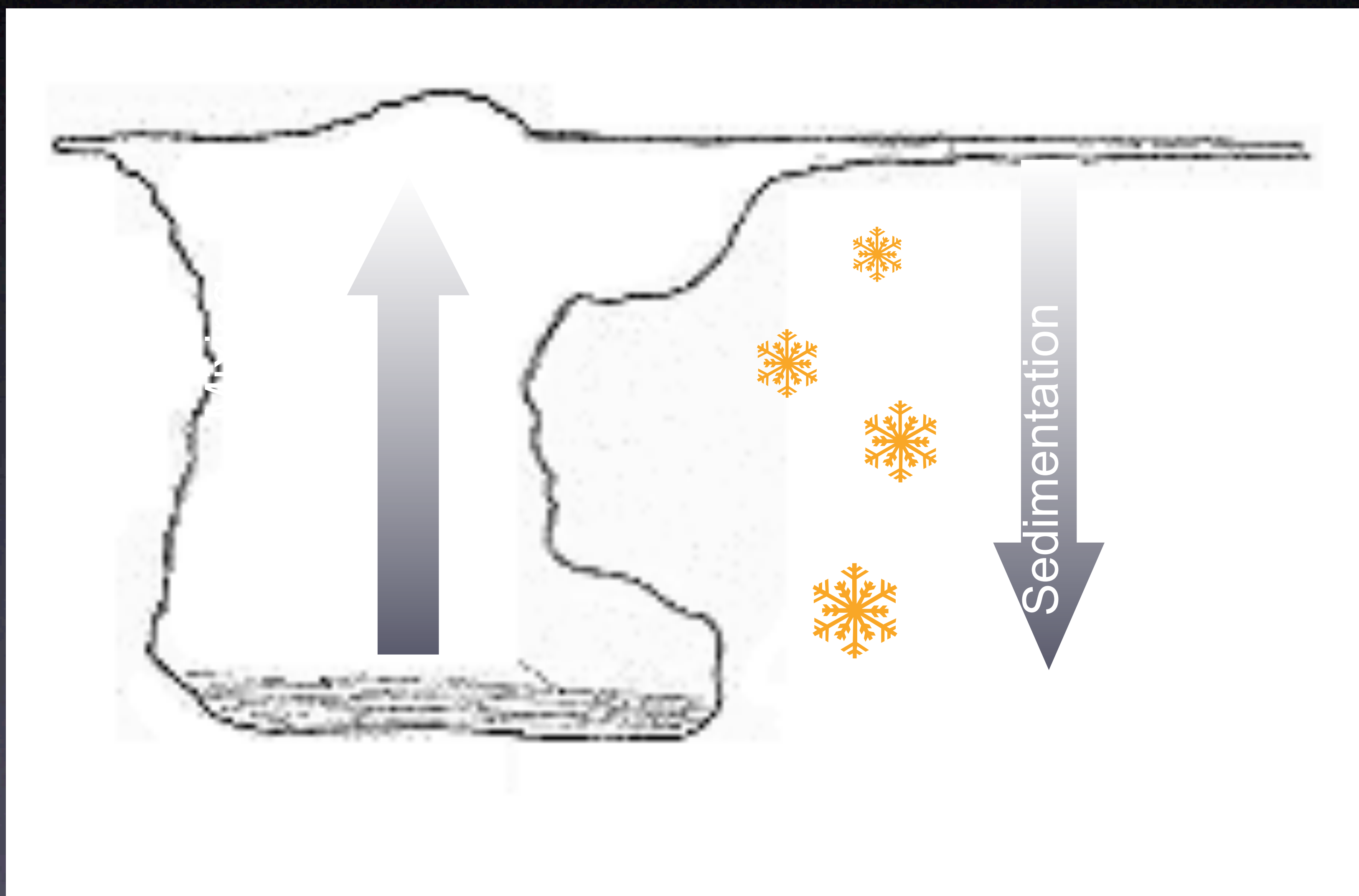
California stratocumulus; Ackerman & Marley (2001)

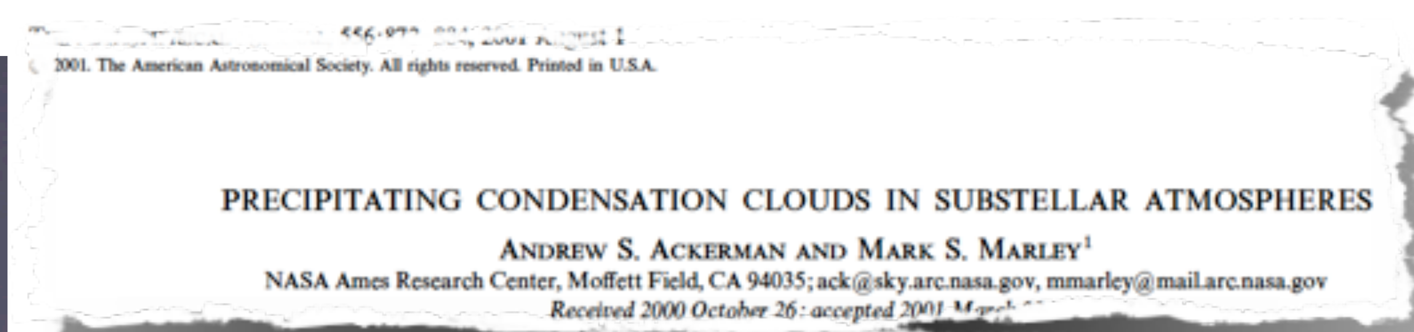
In terrestrial clouds, large particles transport most of the mass, resulting in thinner and less optically thick cloud decks.

Ackerman Cloud Model

$$-K \frac{\partial q_t}{\partial z} - f_{\rm sed}\, w_*\, q_c = 0$$

$f_{\rm sed}$ parameterizes efficiency of sedimentation relative to turbulent mixing (Jupiter $f_{\rm sed}$ ~ 3)





PRECIPITATING CONDENSATION CLOUDS IN SUBSTELLAR ATMOSPHERES

Andrew S. Ackerman and Mark S. Marley[1]
NASA Ames Research Center, Moffett Field, CA 94035; ack@sky.arc.nasa.gov, mmarley@mail.arc.nasa.gov

Received 2000 October 26; accepted 2001

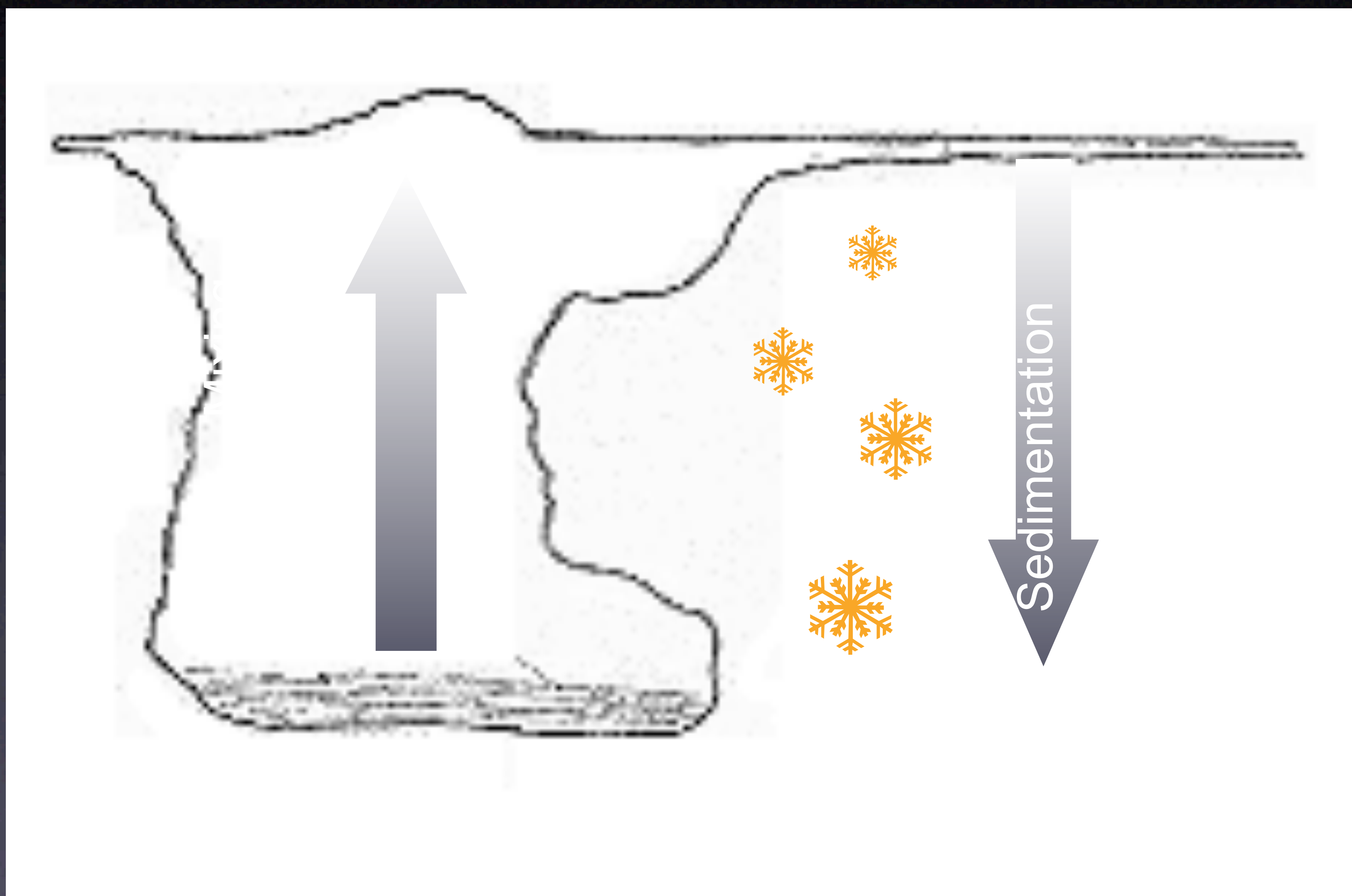
$f_{\rm sed} w^*$ = average sedimentation velocity of condensate

Model skips over microphysics to give a physically meaningful vertical profile of condensate sizes given assumed growth efficiency.

Ackerman Cloud Model

$$-K \frac{\partial q_t}{\partial z} - f_{\text{sed}} w_* q_c = 0$$

f_{sed} parameterizes efficiency of sedimentation relative to turbulent mixing (Jupiter f_{sed} ~ 3)



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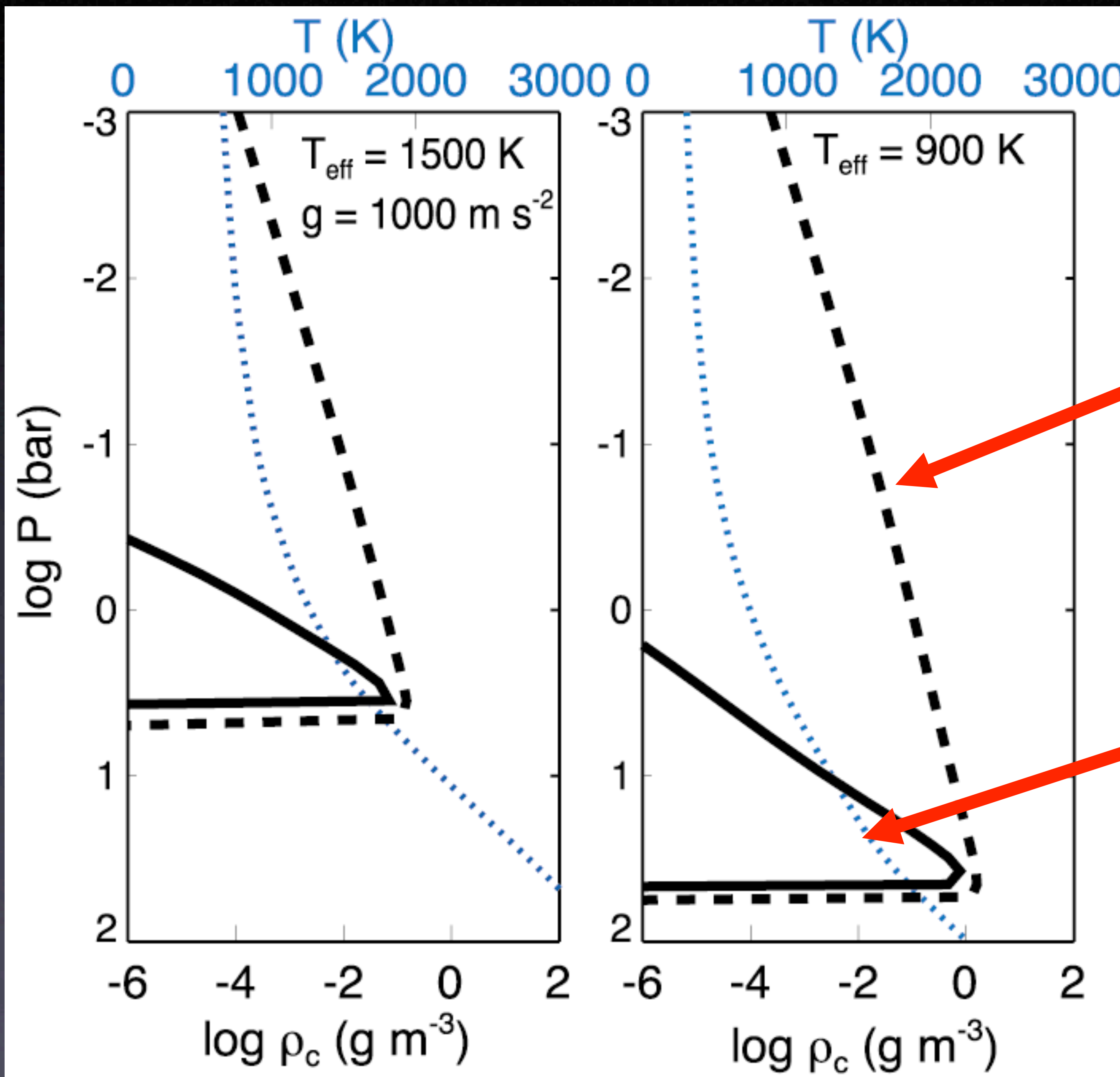
Model skips over microphysics to give a physically meaningful vertical profile of condensate sizes given assumed growth efficiency.

Example: Silicate Cloud



Well-mixed cloud, no precipitation

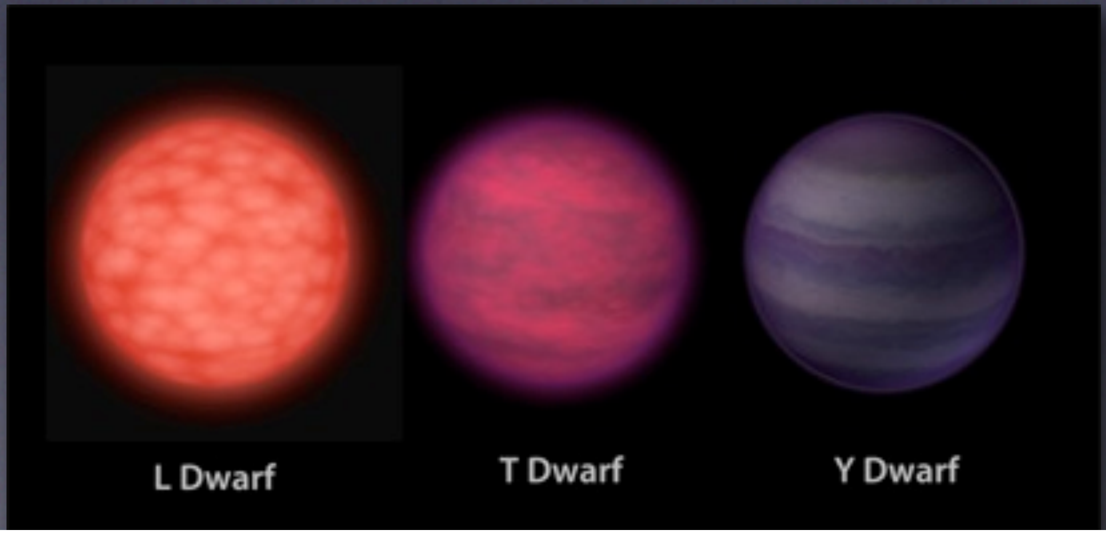
Steady state, precipitating cloud

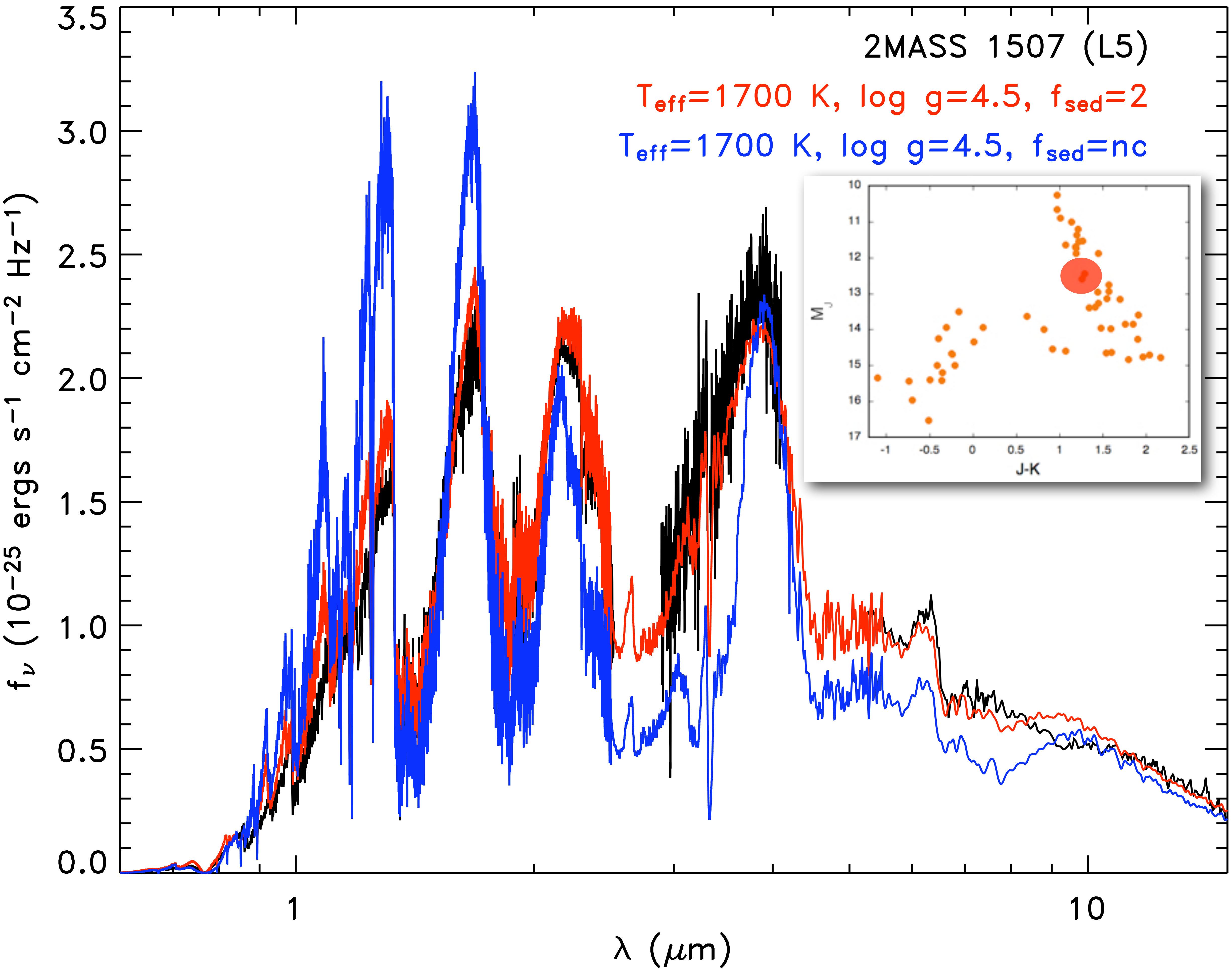
f_{sed} = 3

After Ackerman & Marley (2001)

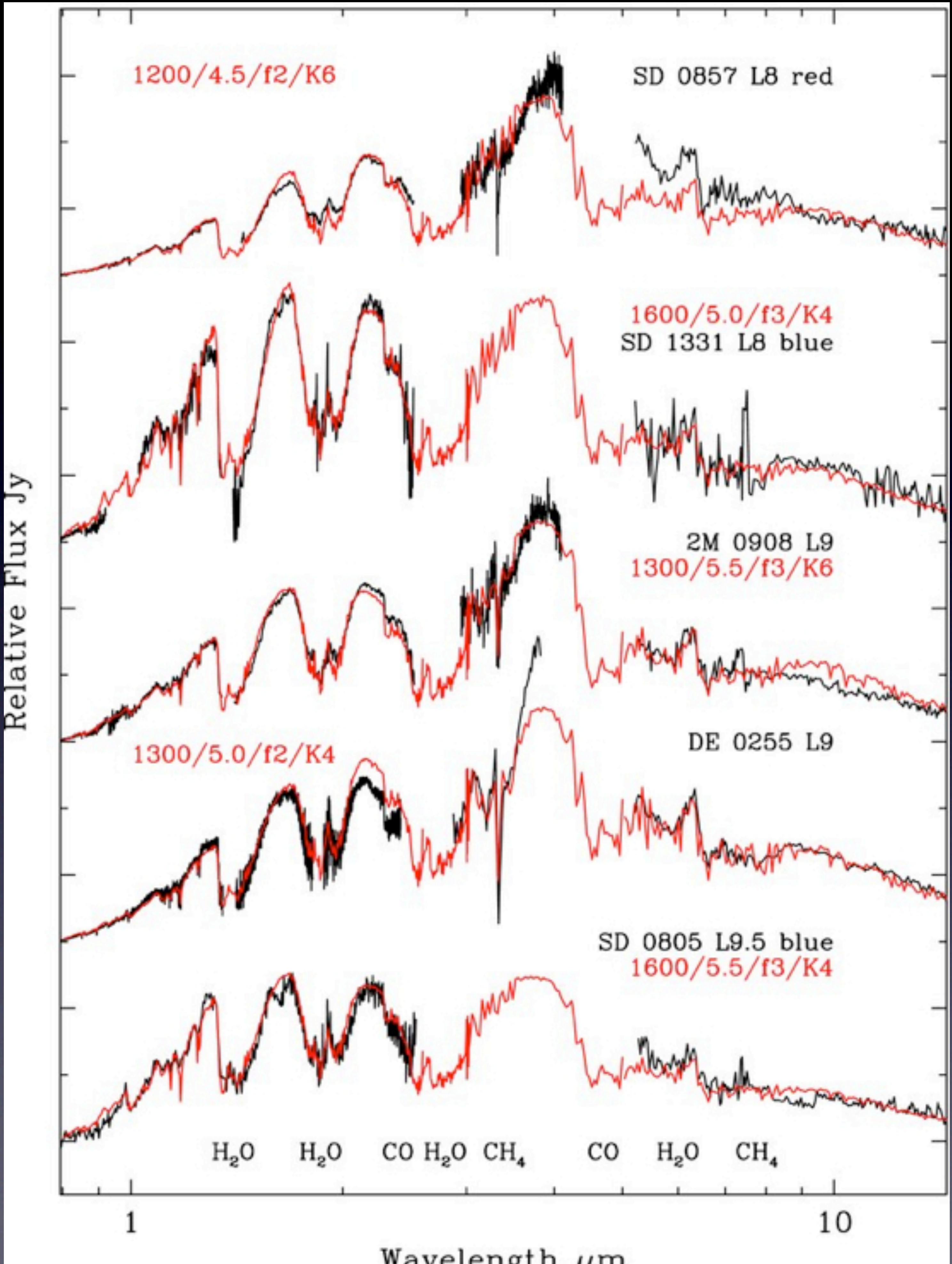
Other Ingredients

- Chemistry (Katharina Lodders)
- Molecular opacities (Richard Freedman)
- Atmospheric structure (Marley, following McKay)
- Thermal evolution (Didier Saumon)
- With cloud model can predict emergent spectra
- Spectra obtained by collaborators




2MASS 1507 (L5)
Teff=1700 K, log g=4.5, fsed=2
Teff=1700 K, log g=4.5, fsed=nc
fν (10−25 ergs s−1 cm−2 Hz−1)
λ (μm)
MJ
J-K

Tuning Parameters to fit the Cloudiest L dwarfs



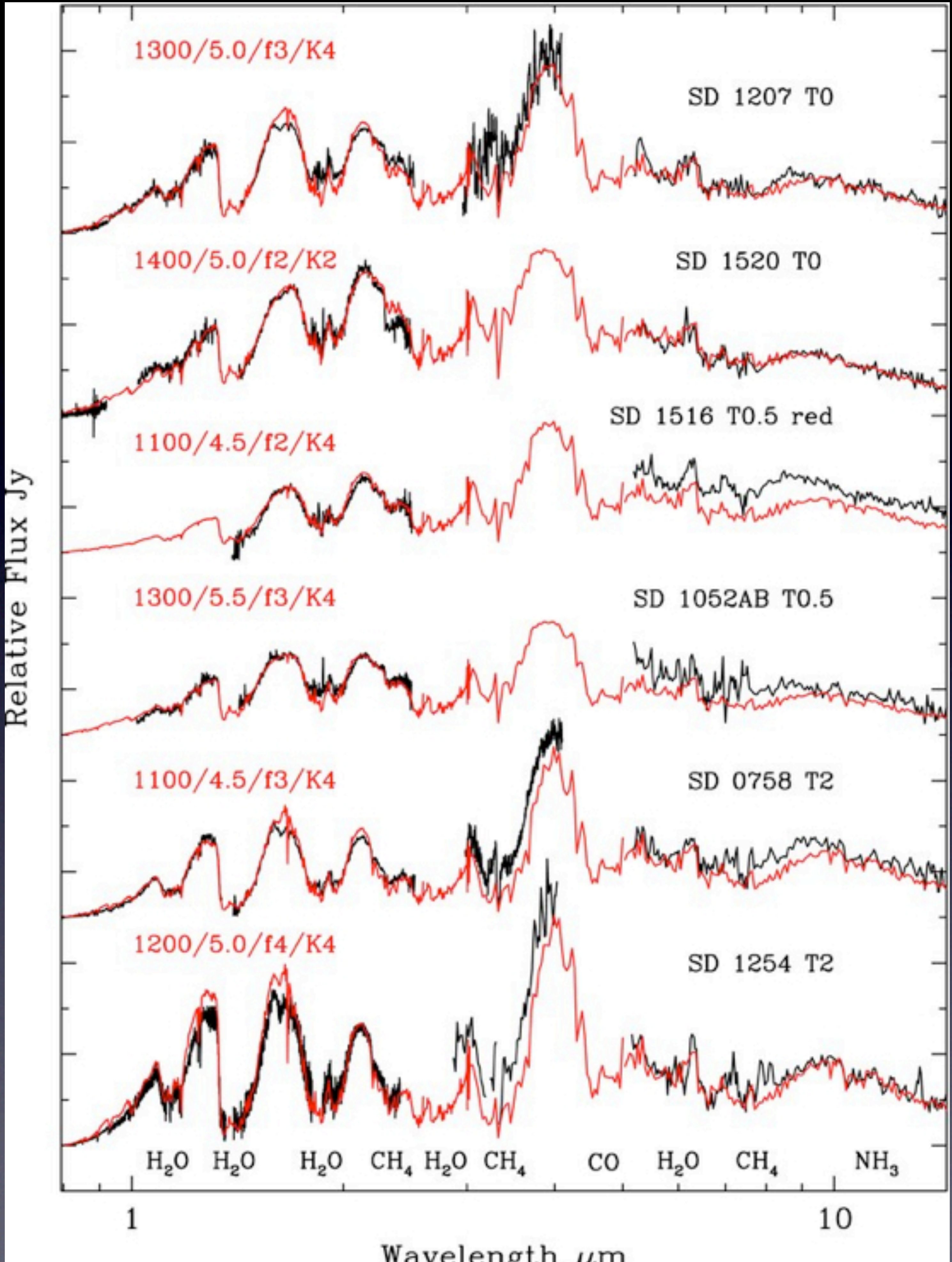
L8

blue L8

L9

L9

blue L9.5



Early T Dwarfs

T0

Approach clearly works well, but not perfectly. Does not explain why f_{sed} varies.

How well does this tool work with the directly imaged planets?

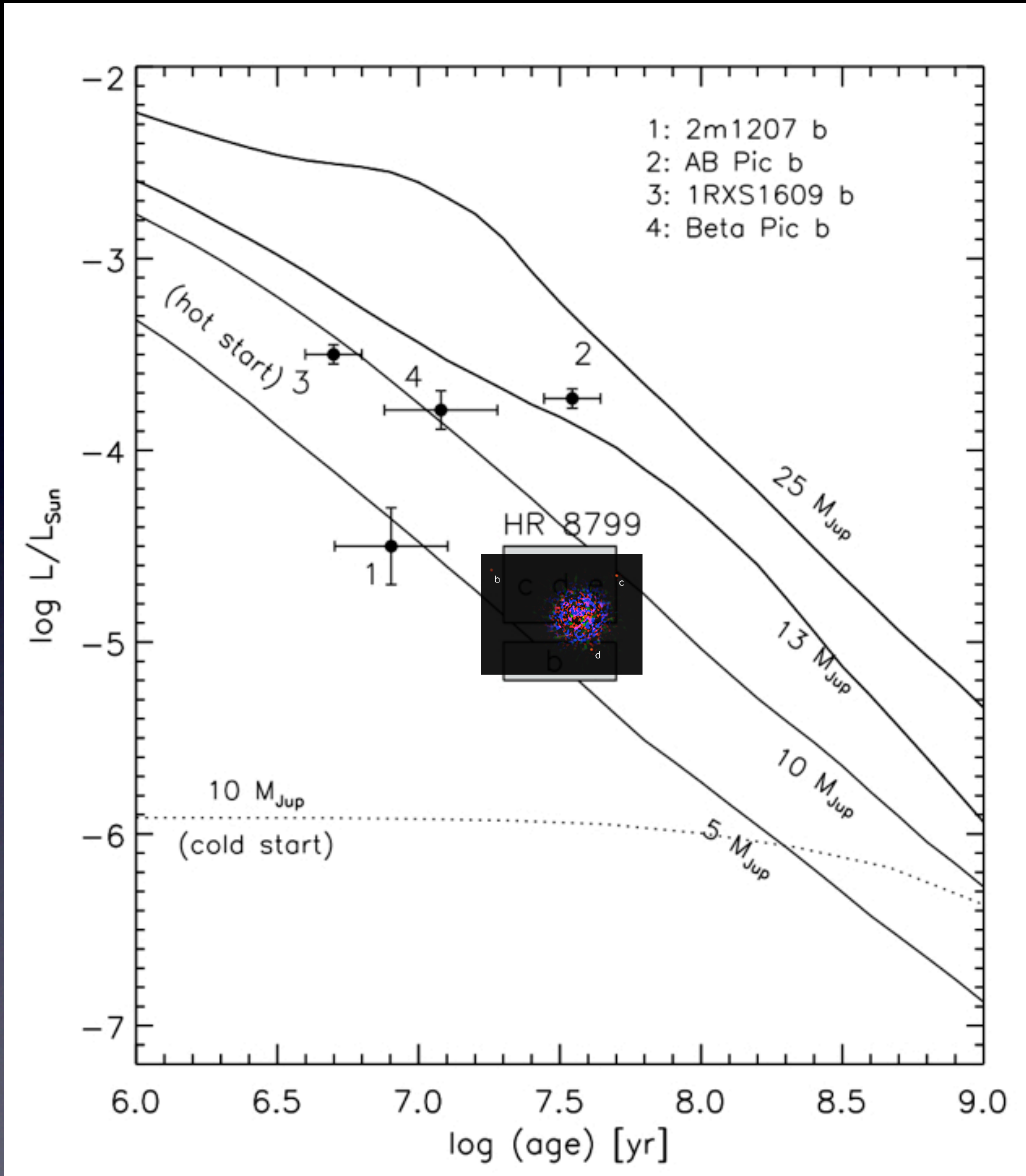
T2

Understanding Clouds & the Directly Imaged Planets

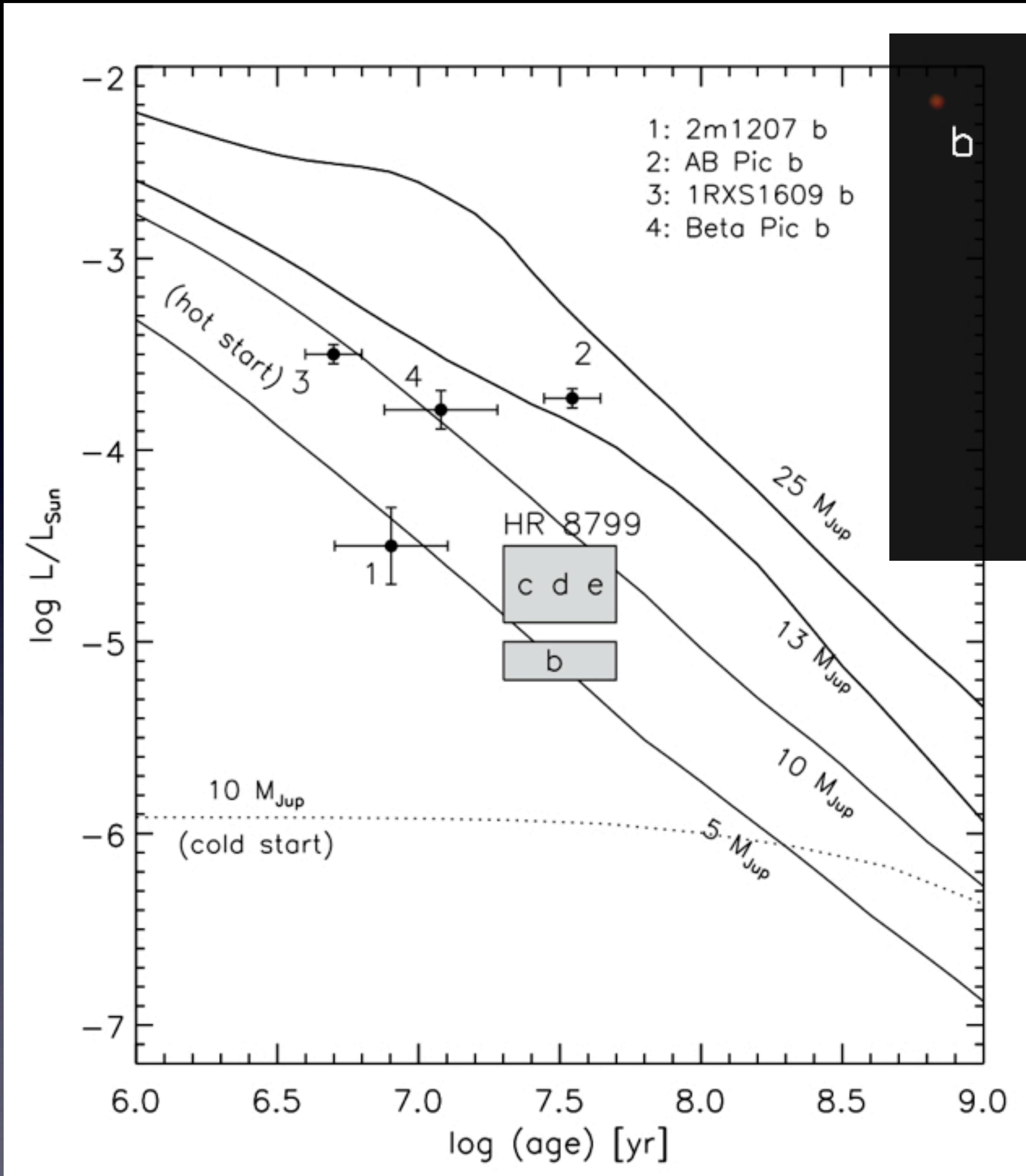
(in five years there will be far more data for these objects than the hot Jupiters)

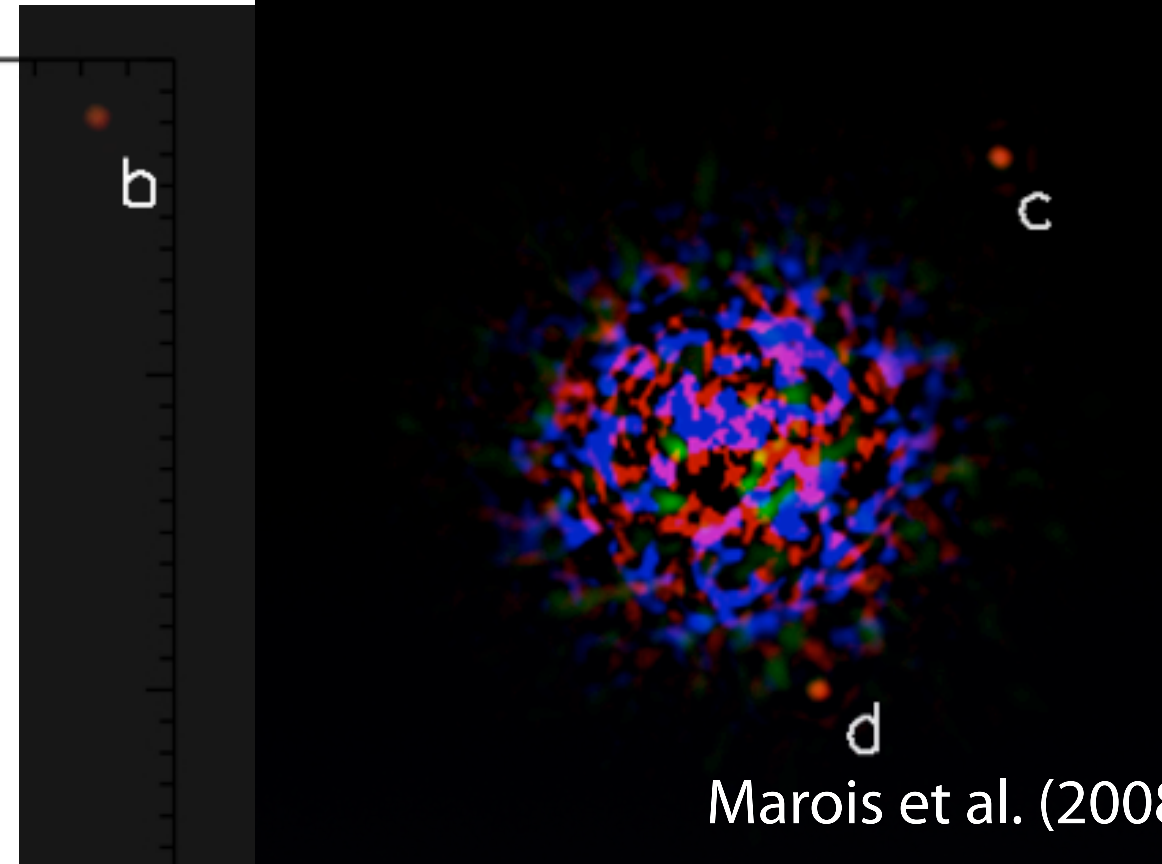
Understanding Clouds & the Directly Imaged Planets

(in five years there will be far more data for these objects than the hot Jupiters)



1: 2m1207 b
2: AB Pic b
3: 1RXS1609 b
4: Beta Pic b
(hot start)
HR 8799
25 M_{Jup}
13 M_{Jup}
10 M_{Jup}
5 M_{Jup}
10 M_{Jup}
(cold start)
log L/L_{Sun}
log (age) [yr]

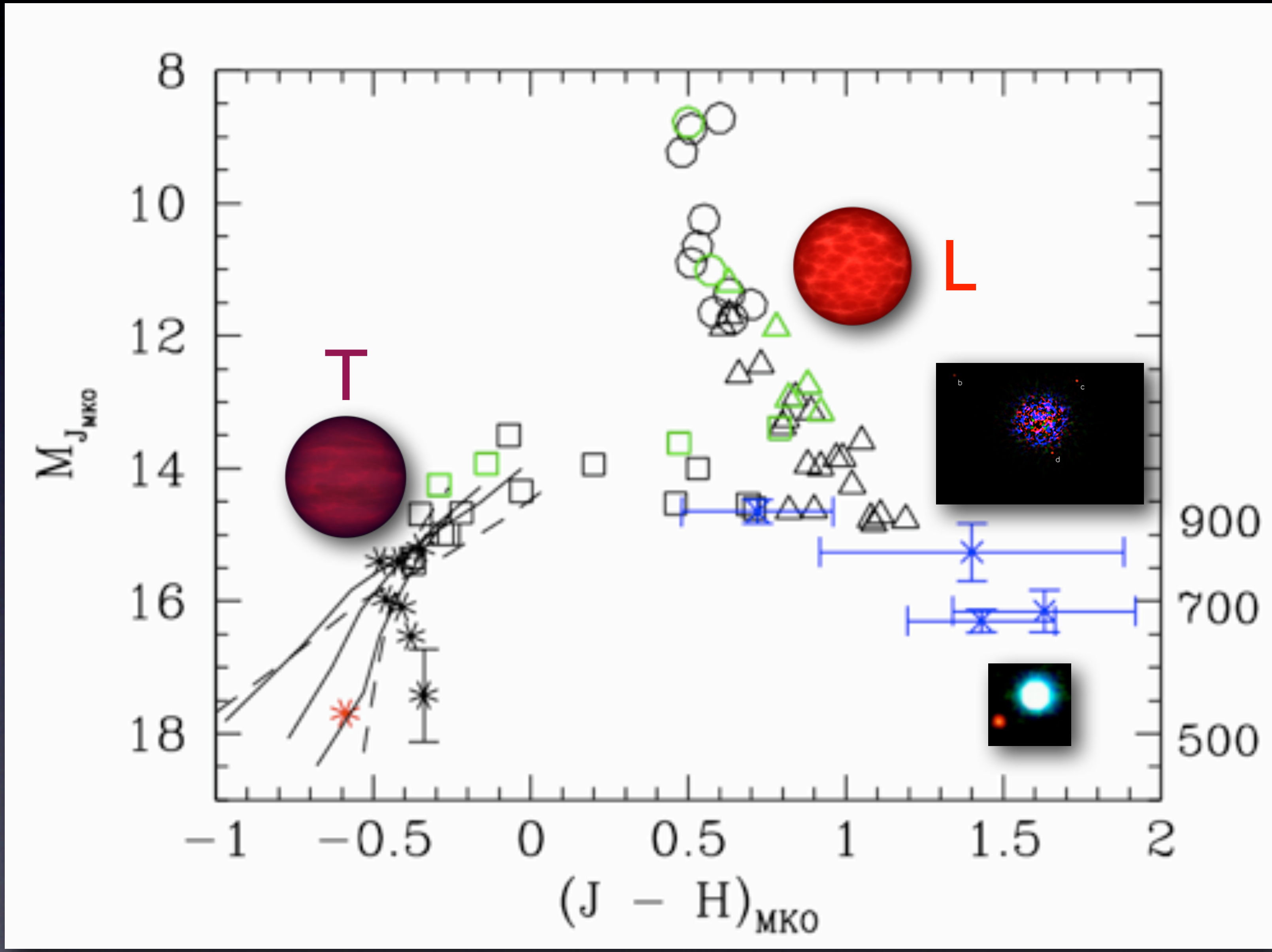




Marois et al. (2008)

- Luminosities imply T_{eff} ~ 900 to 1000 K
- But photometry looks like hotter L dwarfs

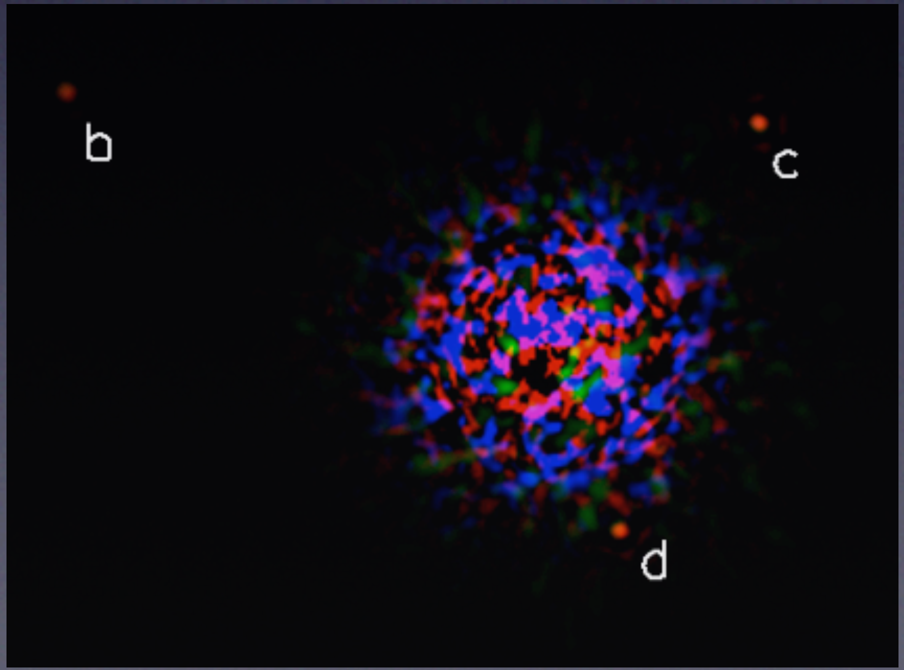
Directly Imaged Planets Are Very Cloudy



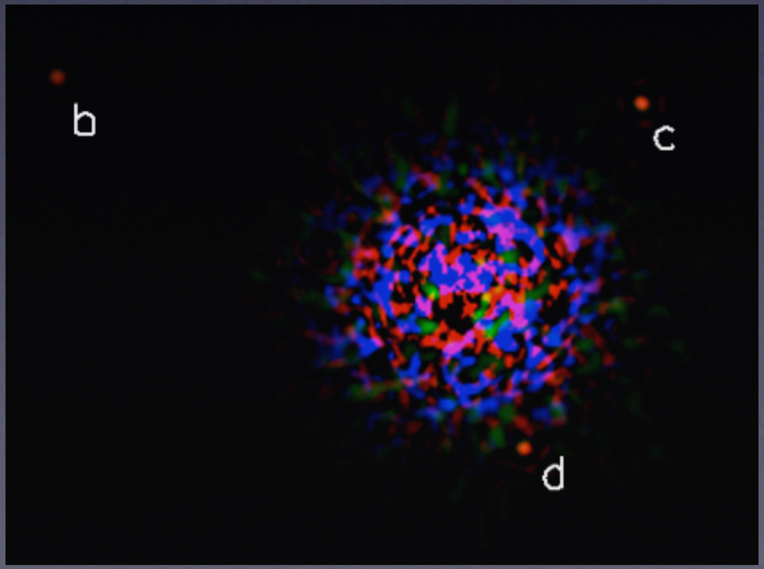
- HR 8799 b,c,d and 2M1207B look like extensions of L sequence
- Why do low g objects turn blue later?

How Cloudy?

- Emerging conventional wisdom:
  - When compared to “standard” models...
  - HR 8799bcd clouds are “radically enhanced” (e.g., Bowler et al. 2010)
  - Entire “new class” of objects (Madhusudhan et al. 2011)
  - Fits require unusual object radii



Planet	Reference	Mass ($M_{\rm Jup}$)	log g	$T_{\rm eff}$ (K)	$R(R_{\rm J})$	age (Myr)
b[1]	Barman et al. (2011a)	$0.1 - 3.3$	3.5 ± 0.5	1100 ± 100	0.63 - 0.92	$30 - 300$
	Currie et al. (2011)	$5 - 15$	$4 - 4.5$	$800 - 1000$	···	$30 - 300$
	Galicher et al. (2011)	1.8	4	1100	0.69	···
	Mad. et al. (2011)	$2 - 12$	$3.5 - 4.3$	$750 - 850$	···	$10 - 150$
c	Currie et al. (2011)	$7 - 17.5$	$4 - 4.5$	$1000 - 1200$	···	$30 - 300$
	Galicher et al. (2011)	1.1	3.5	1200	0.97	···
	Mad. et al. (2011)	$7 - 13$	$4 - 4.3$	$950 - 1025$	···	$30 - 100$
	This work		4.7 ± 0.3	1070 ± 100		
d	Currie et al. (2011)	$5 - 17.5$	$3.75 - 4.5$	$1000 - 1200$	···	$30 - 300$
	Galicher et al. (2011)	6	4.0	1100	1.25	···
	Mad. et al. (2011)	$3 - 11$	$3.5 - 4.2$	$850 - 1000$	···	$10 - 70$
	This work		4.5 ± 0.3	1060 ± 110		



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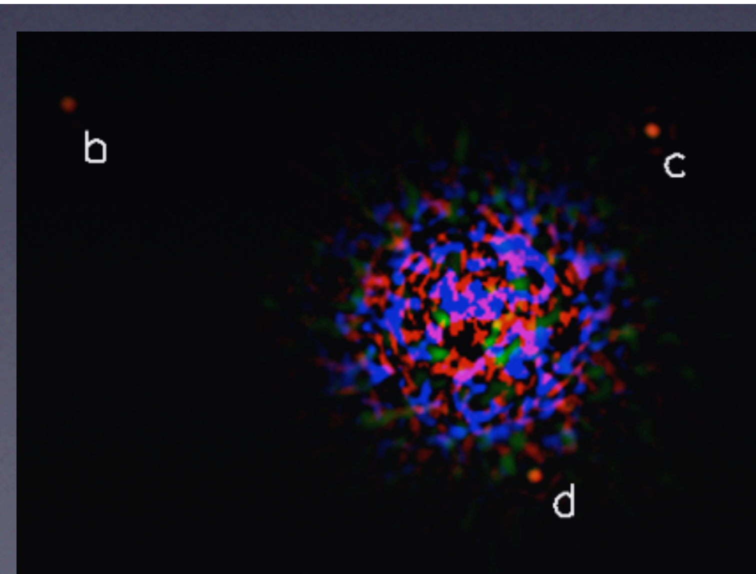
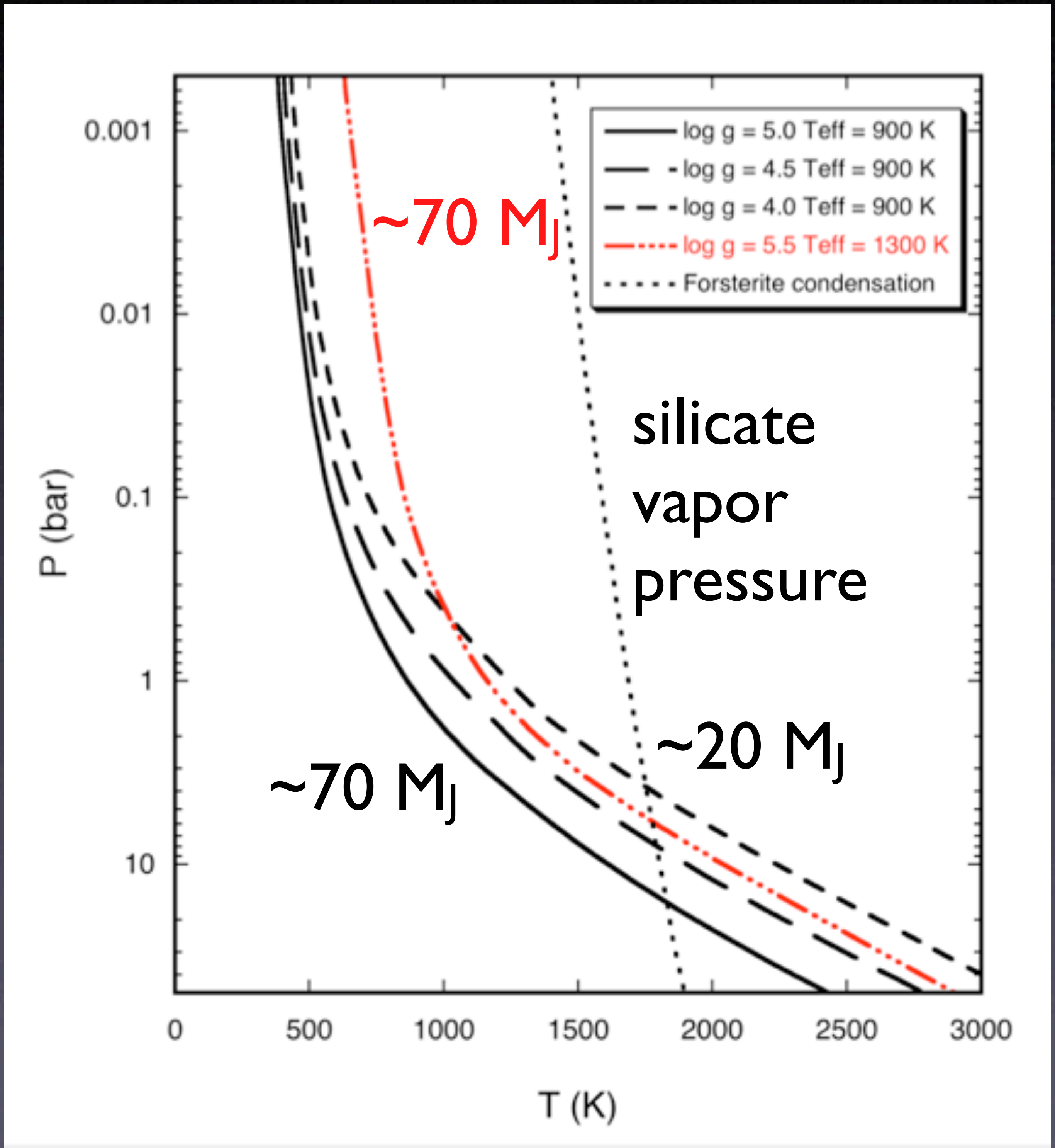
33% volume

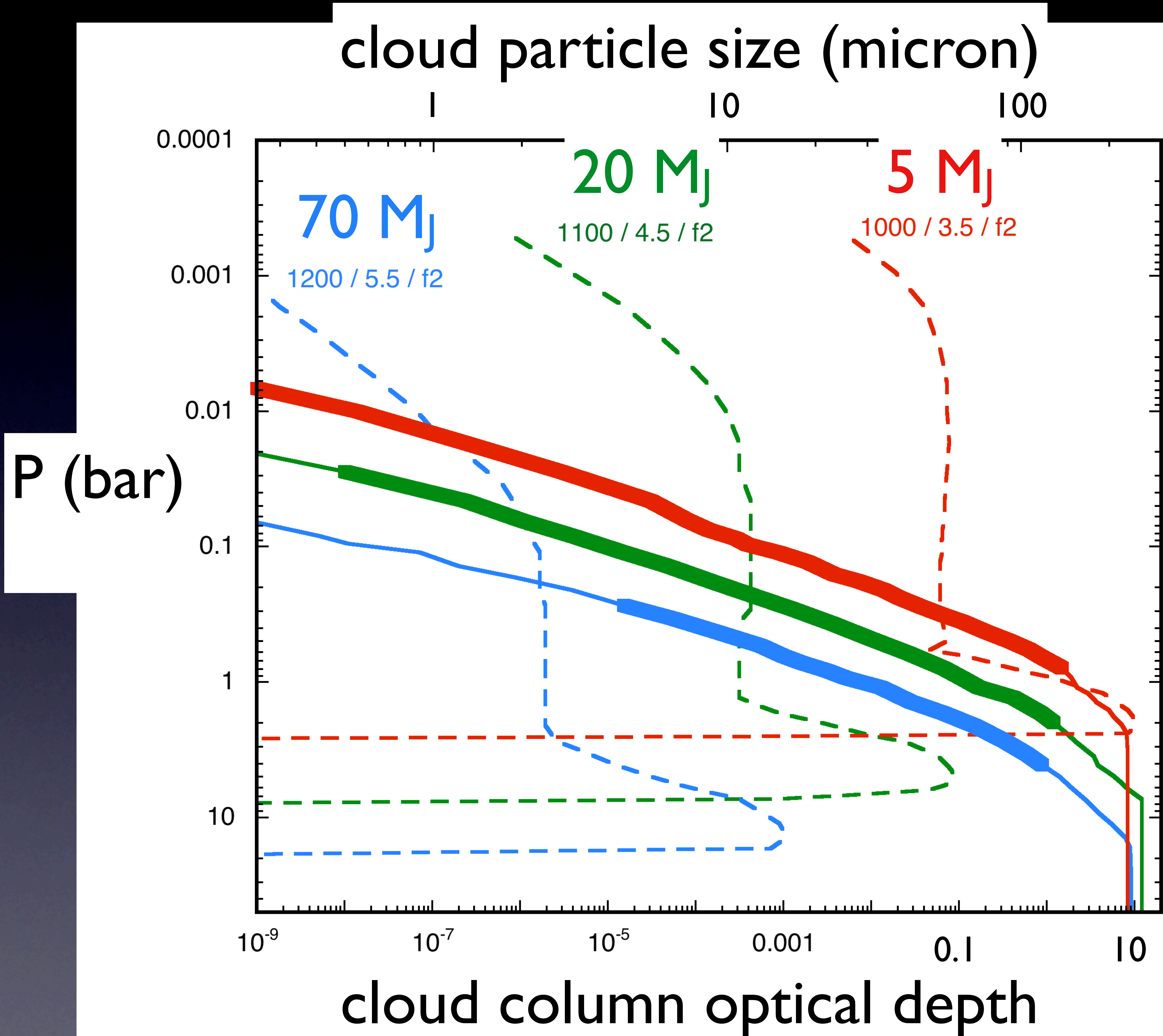


Clouds at Low Gravity

$$\tau_\lambda = 75\epsilon Q_\lambda(r_c)\varphi\left(\frac{P_{cl}}{1\,\mathrm{bar}}\right)\left(\frac{10^5\,\mathrm{cm\,s^{-2}}}{g}\right)\left(\frac{1\,\mu\mathrm{m}}{r_c}\right)\left(\frac{1.0\,\mathrm{g\,cm^{-3}}}{\rho_c}\right).$$



At lower gravity:
cloud base at lower P so less mass to condense but higher in atmosphere

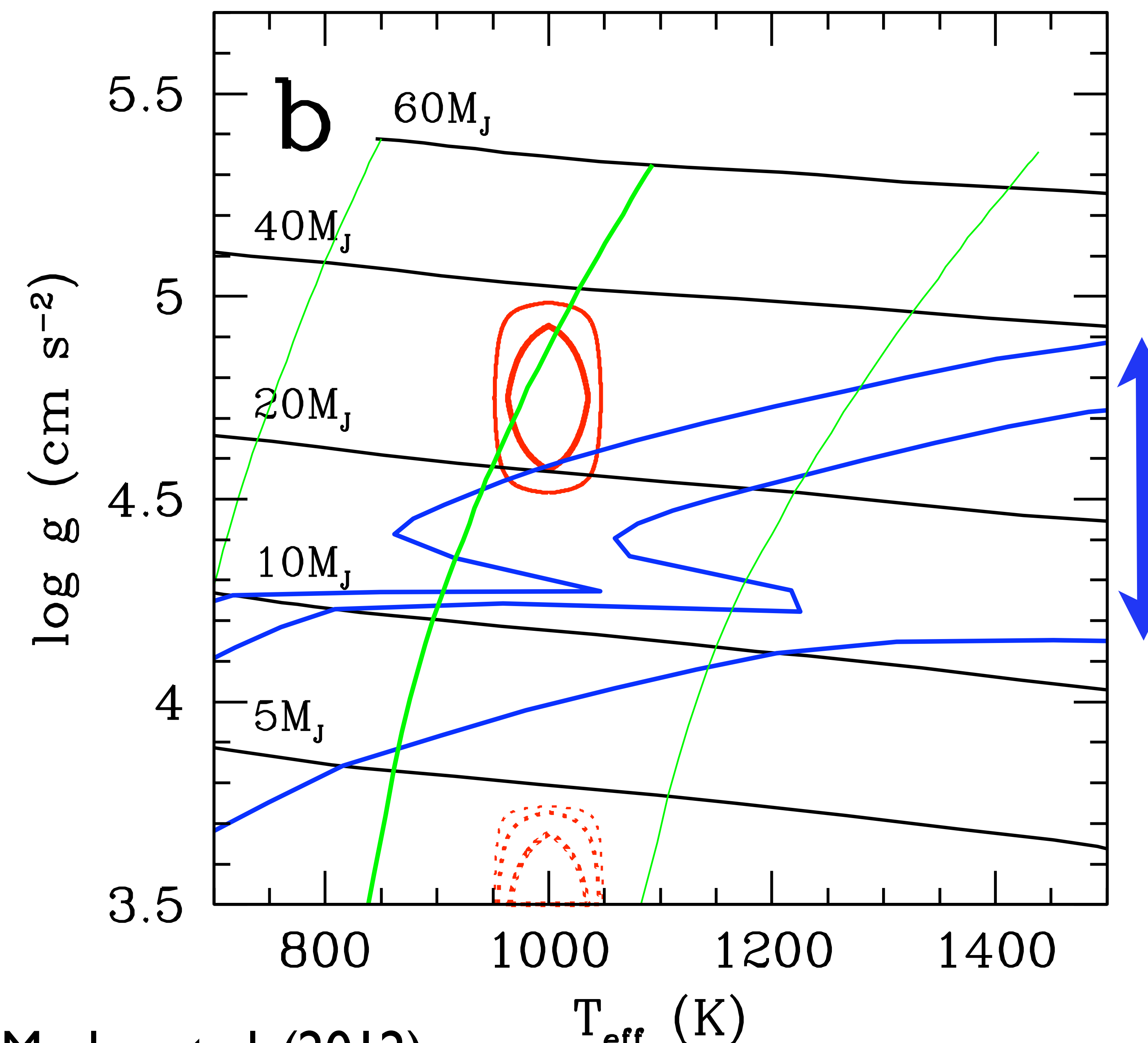


At lower gravity: cloud base at higher & larger radii but similar column tau

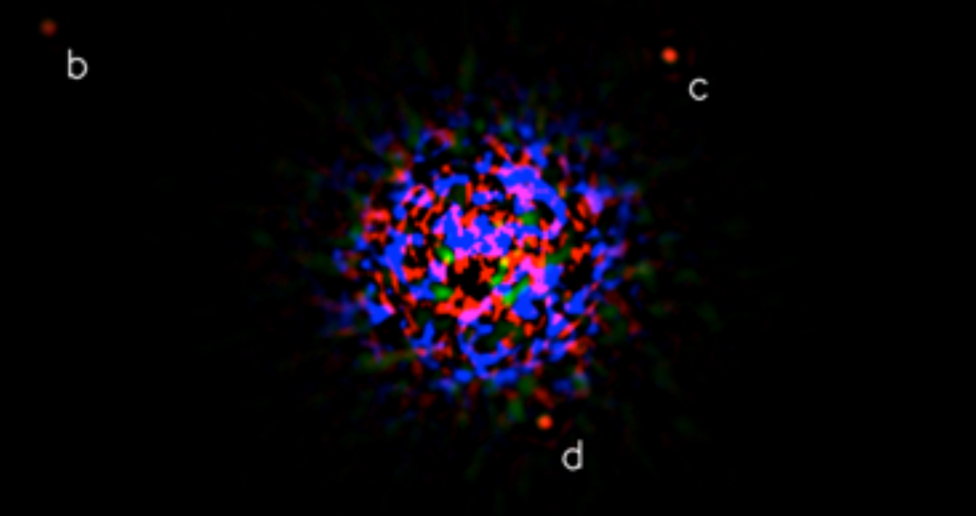
low gravity, cool planet has similar cloud to hotter L dwarf

Combining Everything

planets cool with time

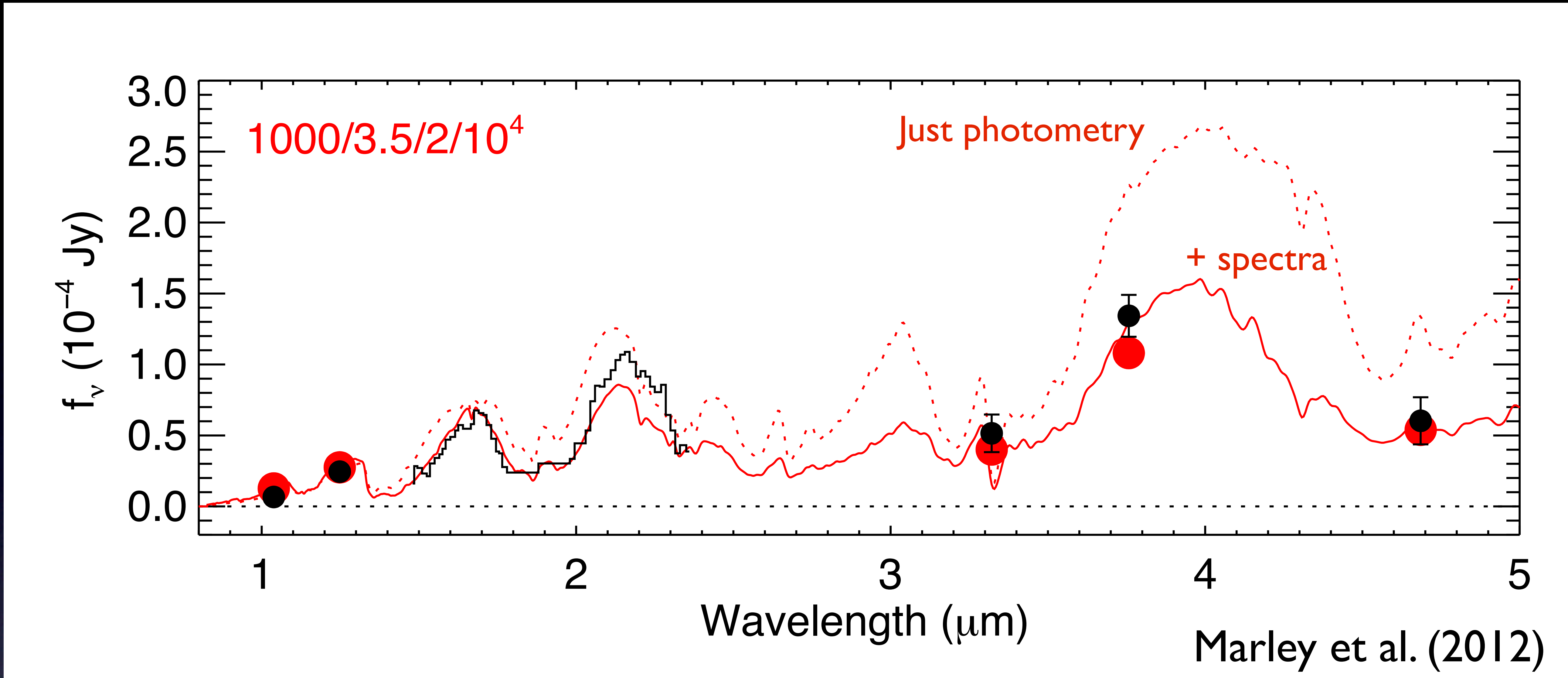


Marley et al. (2012)

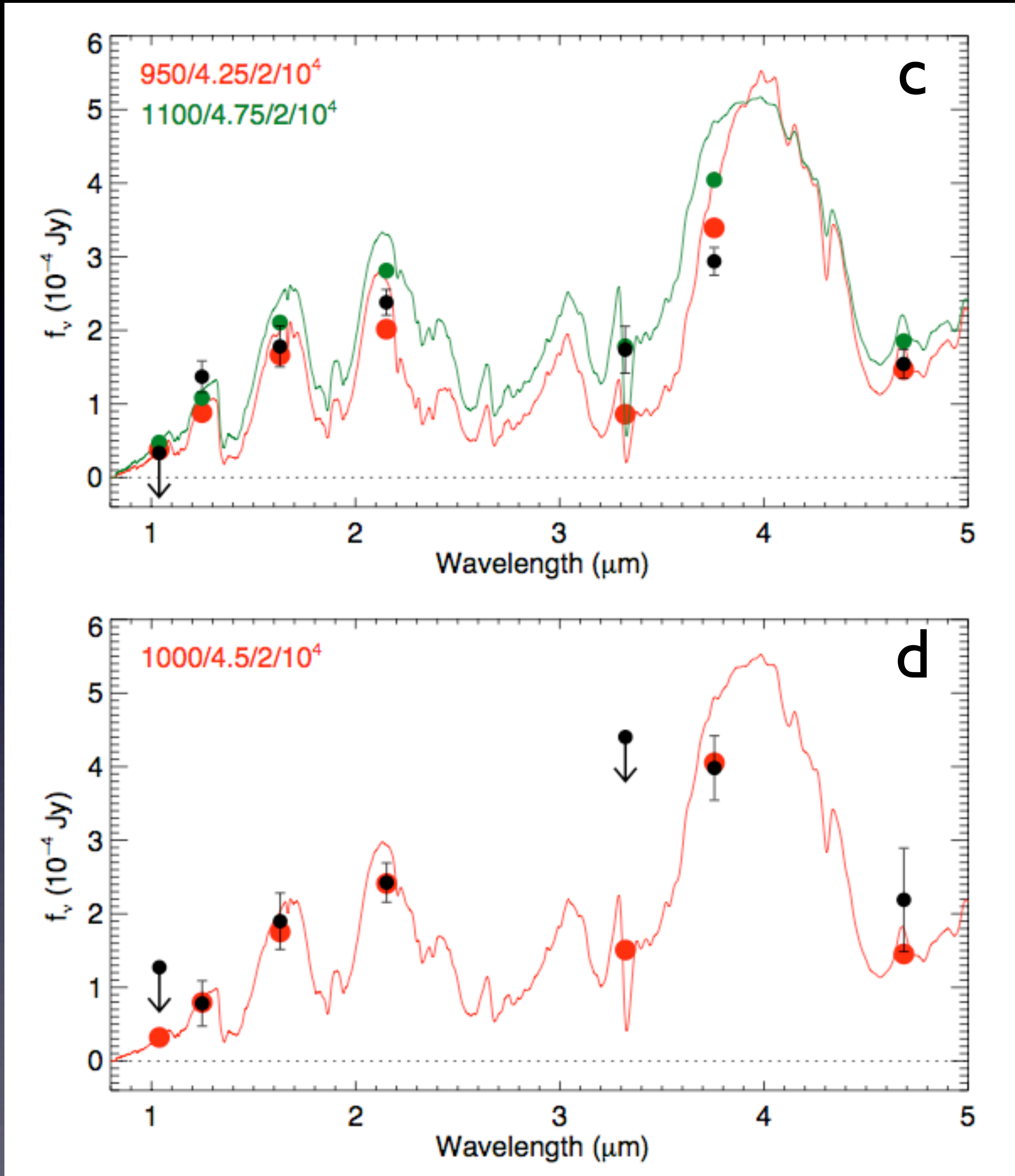


Marois et al. (2008)

likely age range of star



- Mass ~ 5 M_{Jup}, T_{eff} = 1000 K, f_{sed} = 2
- "Normal" clouds, similar to warmer L dwarfs
- "Normal" planetary radius as predicted by evolution

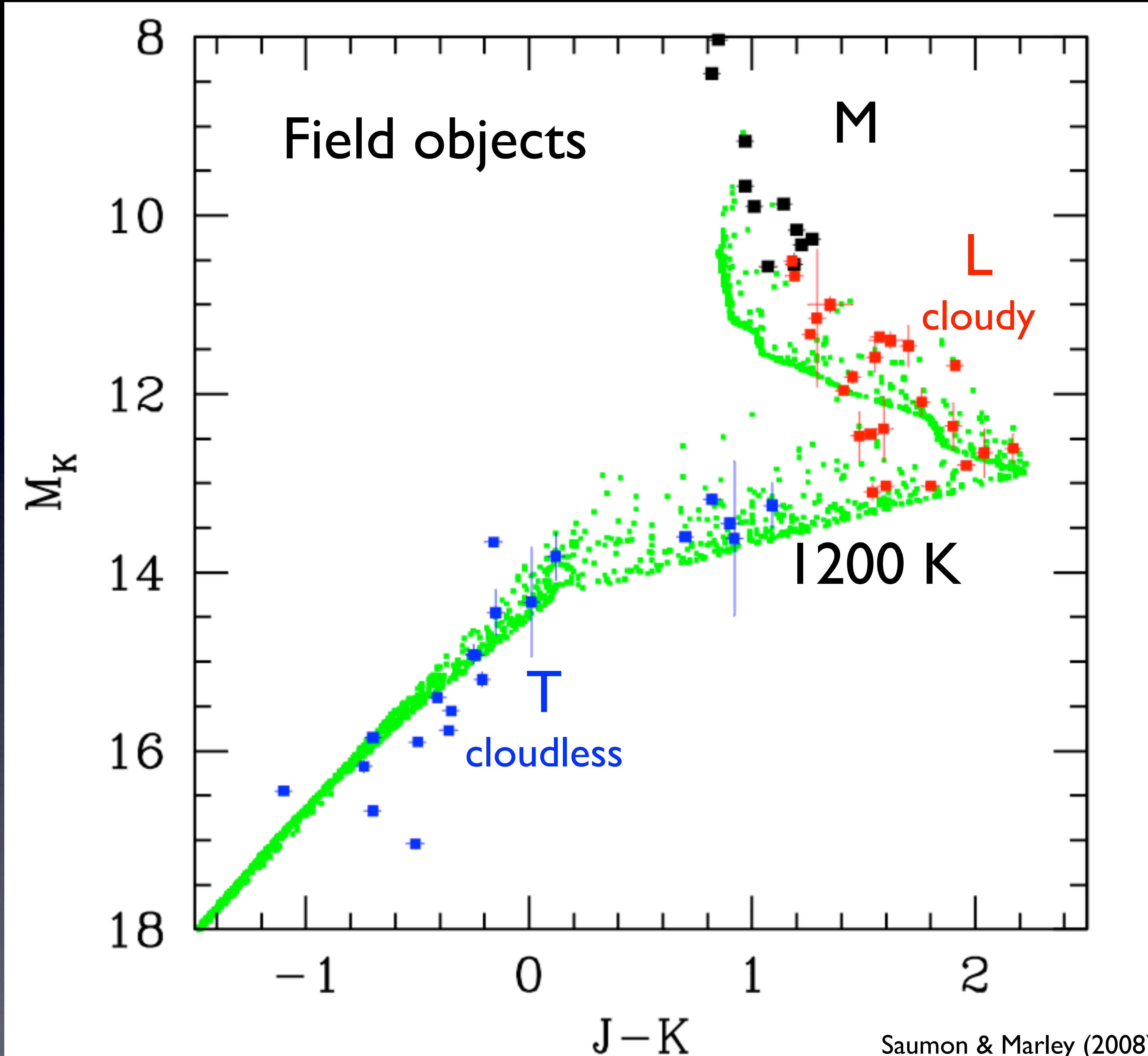


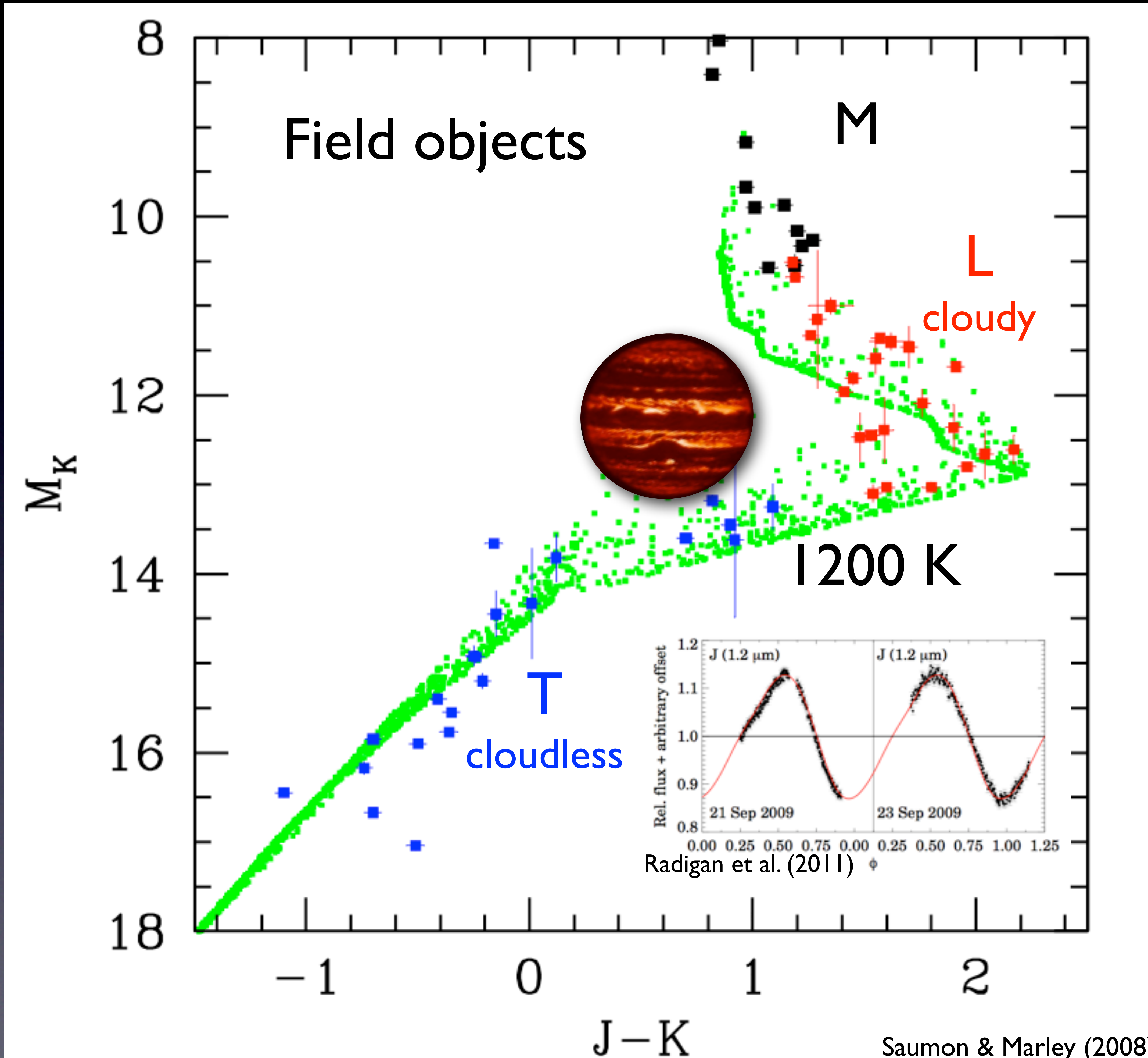
Both ~ 10 M_J and fit with normal clouds and self-consistent radii

Moral: cloud model is crucial for data interpretation. Guess and test not adequate.

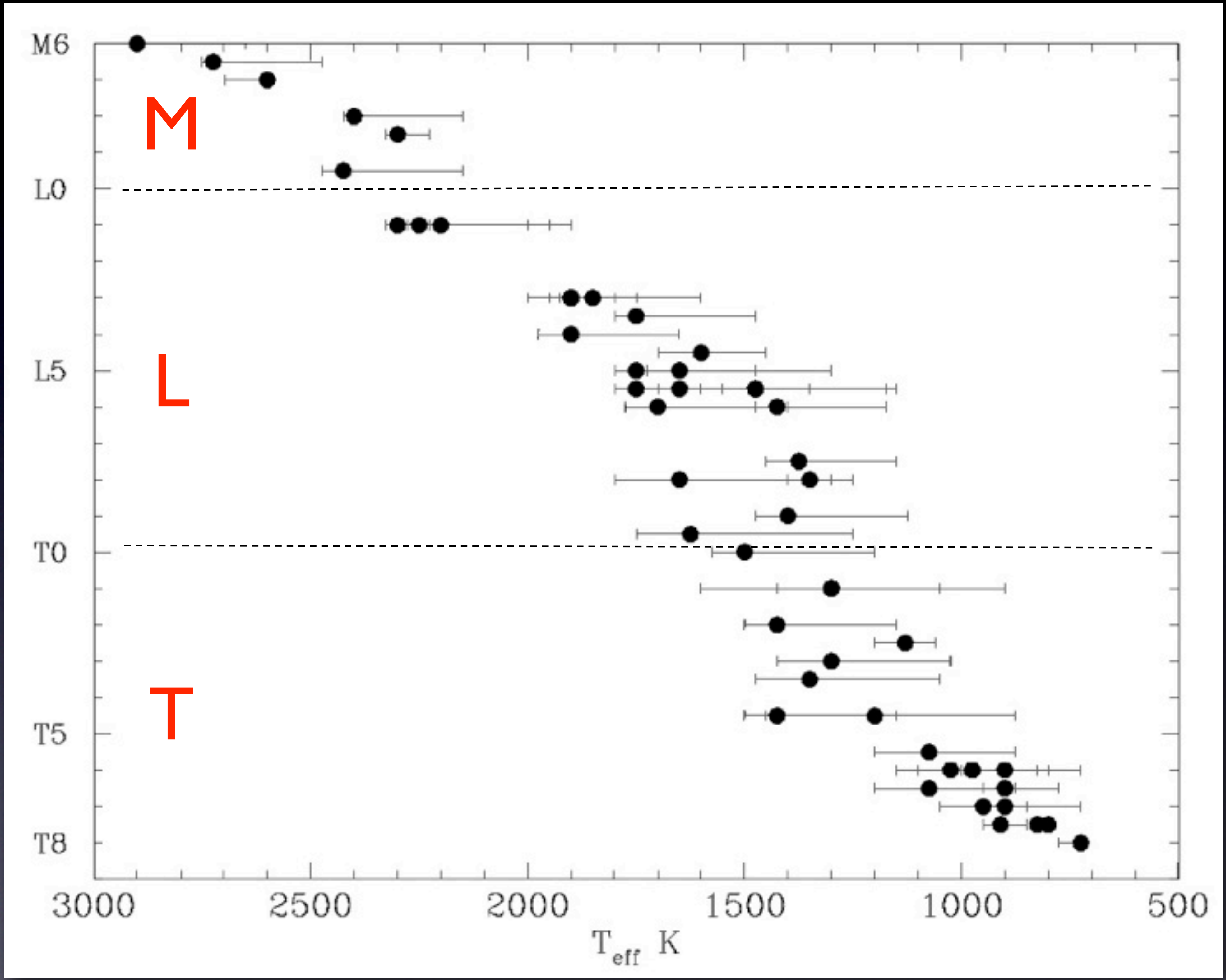
Marley et al. (2012)

What About the Transition?


Field objects
M
L
cloudy
1200 K
T
cloudless
M_K
J−K
8
10
12
14
16
18
−1
0
1
2
Saumon & Marley (2008)


Field objects
M
L
cloudy
1200 K
T
cloudless
M_K
J−K
8
10
12
14
16
18
−1
0
1
2
J (1.2 μm)
J (1.2 μm)
Rel. flux + arbitrary offset
21 Sep 2009
23 Sep 2009
Radigan et al. (2011)
Saumon & Marley (2008)

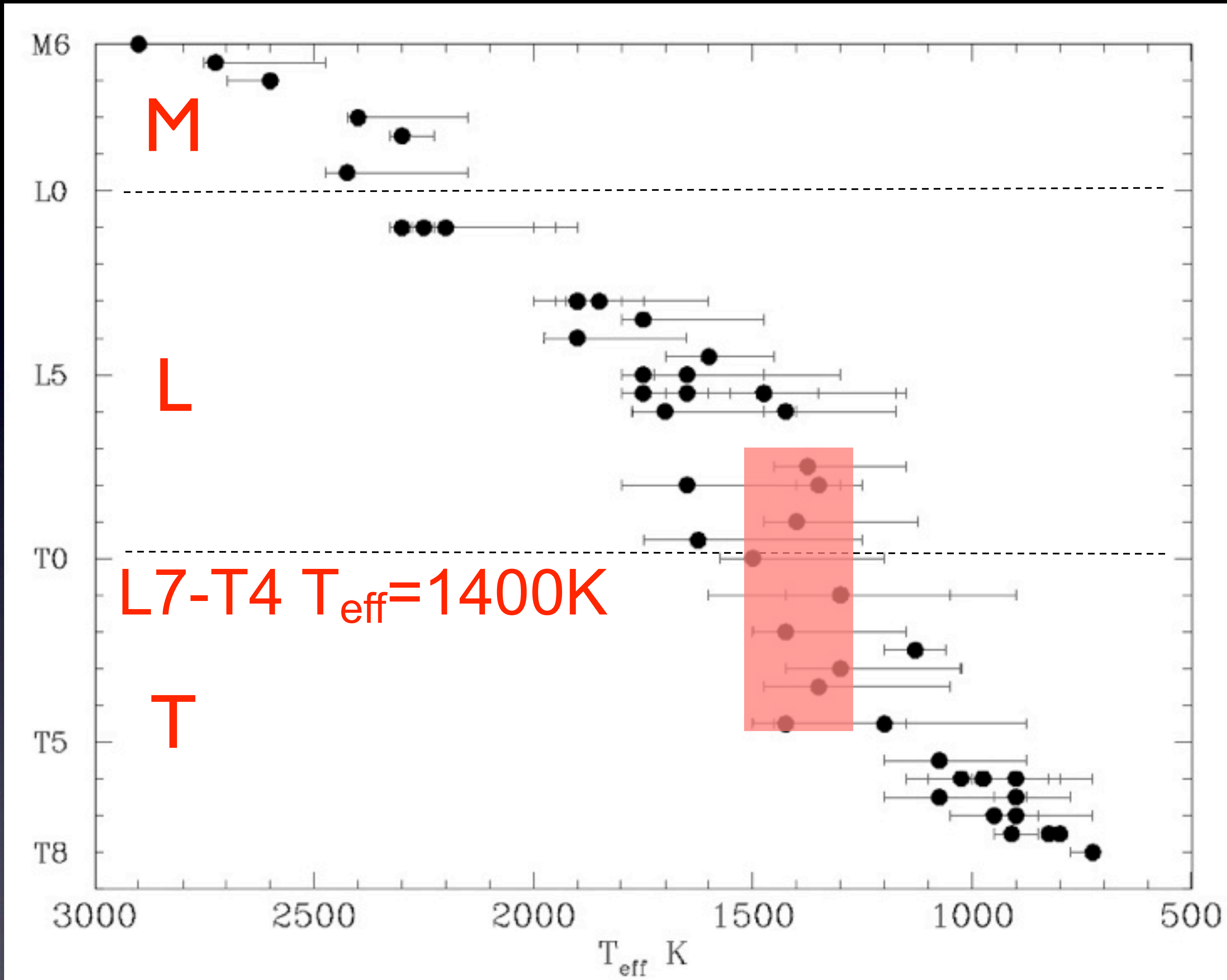
In Field Transition is at ~constant T_{eff}



T_{eff} and (infrared) spectral type adjusted for recently confirmed binaries and newer objects Error bars reflect unknown ages. The coldest object in the plot is the T8 2MASS J0415-09.

data from Golimowski et al. (2004) & Luhman et al. (2007)

In Field Transition is at ~constant T_{eff}



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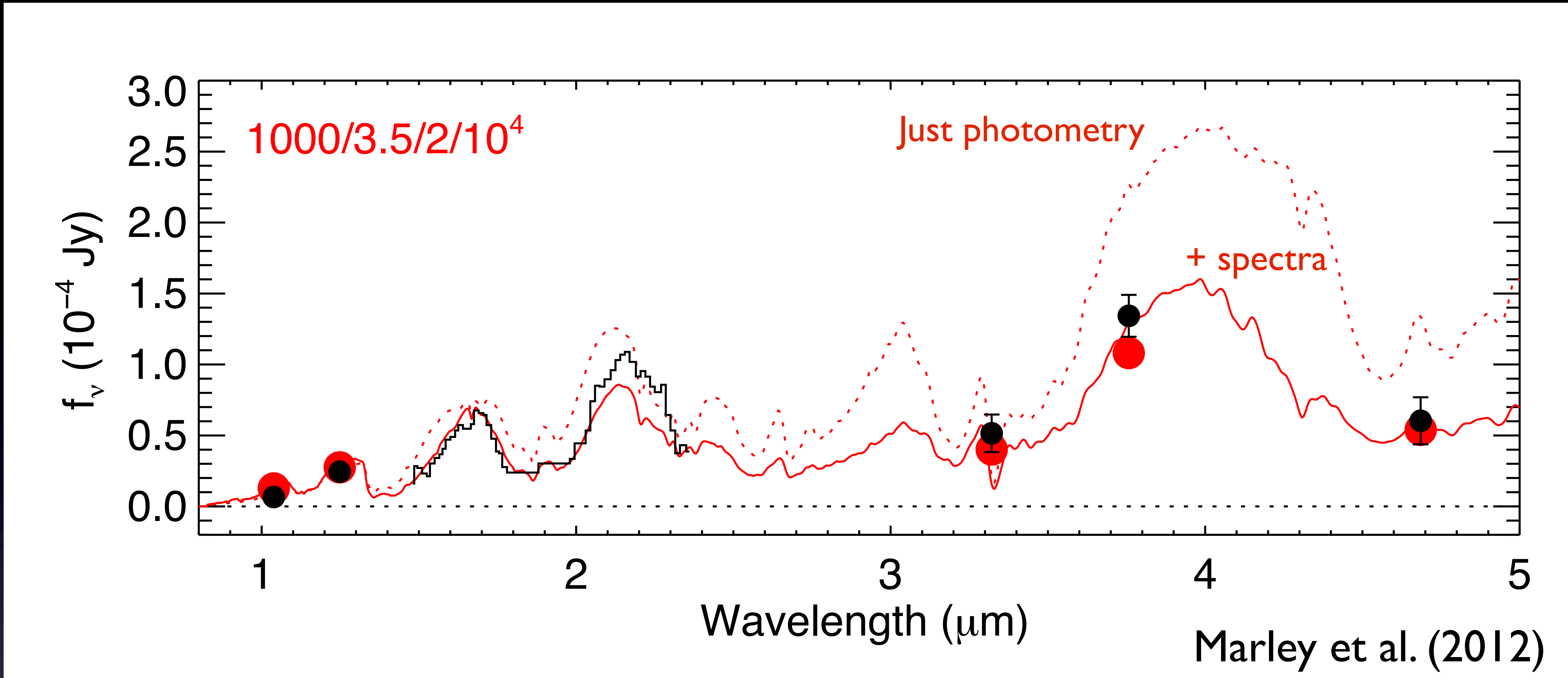
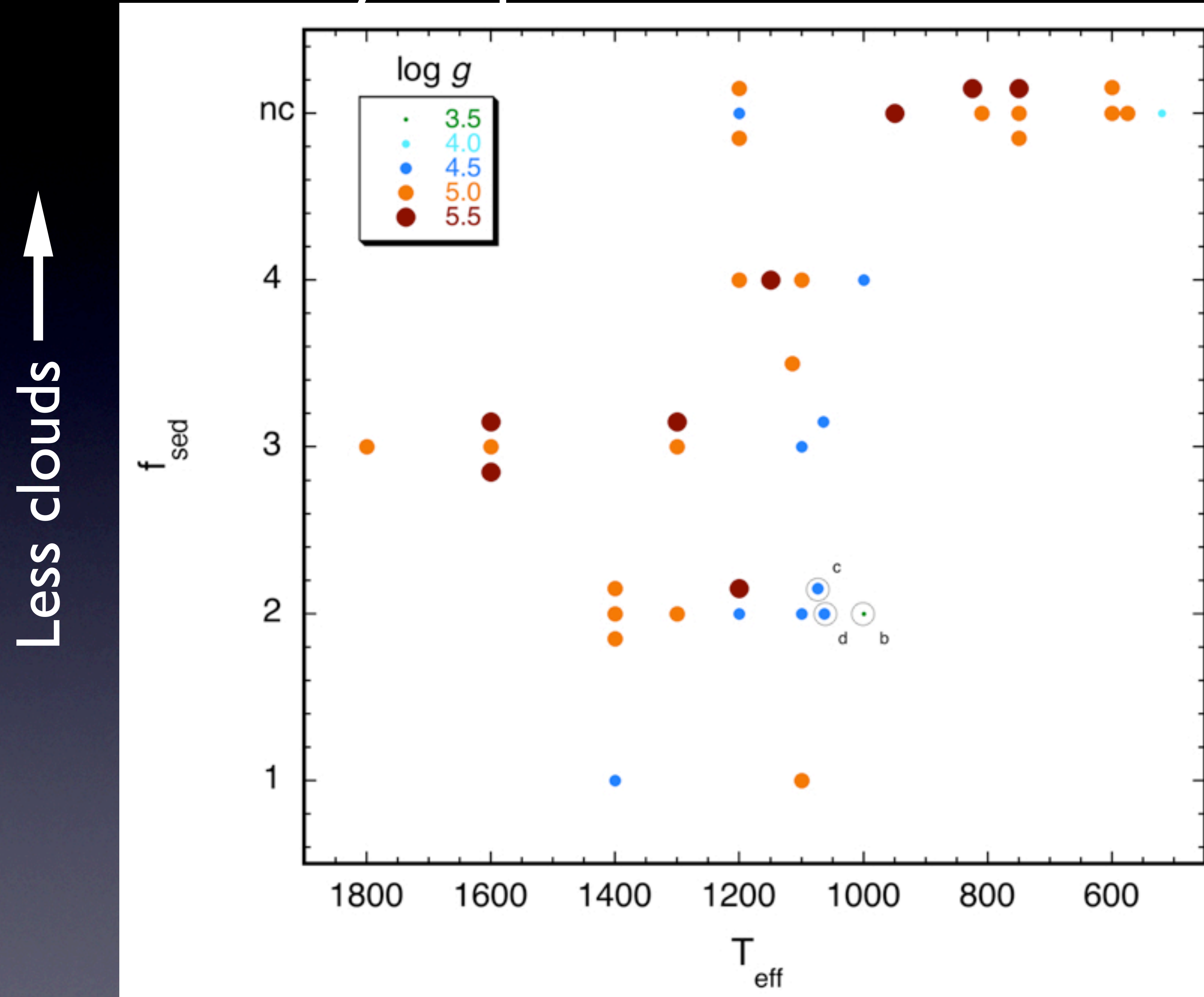
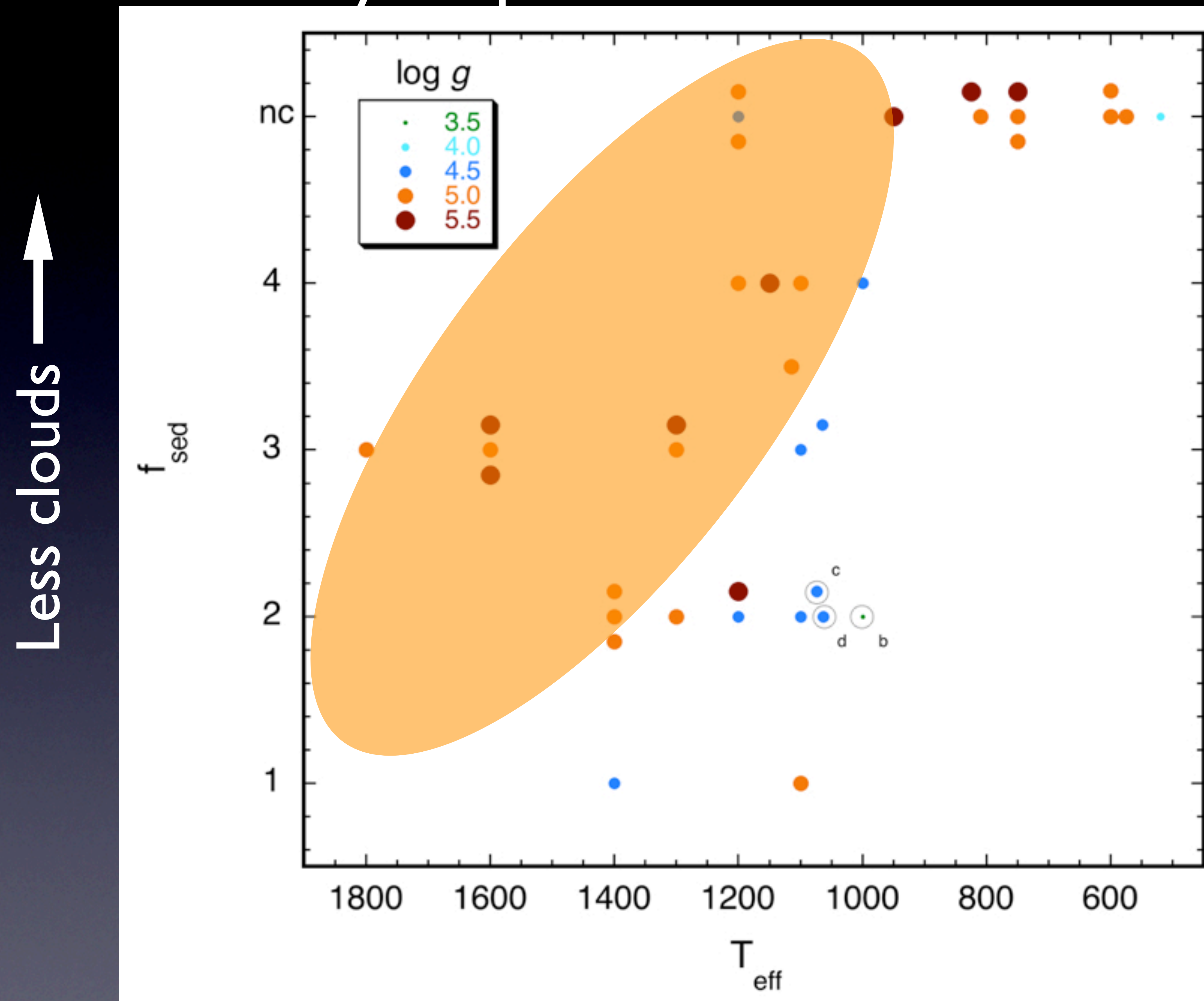


Mass ~ 5 M_{Jup}, T_{eff} = 1000 K, f_{sed} = 2

Gravity Dependence to Transition

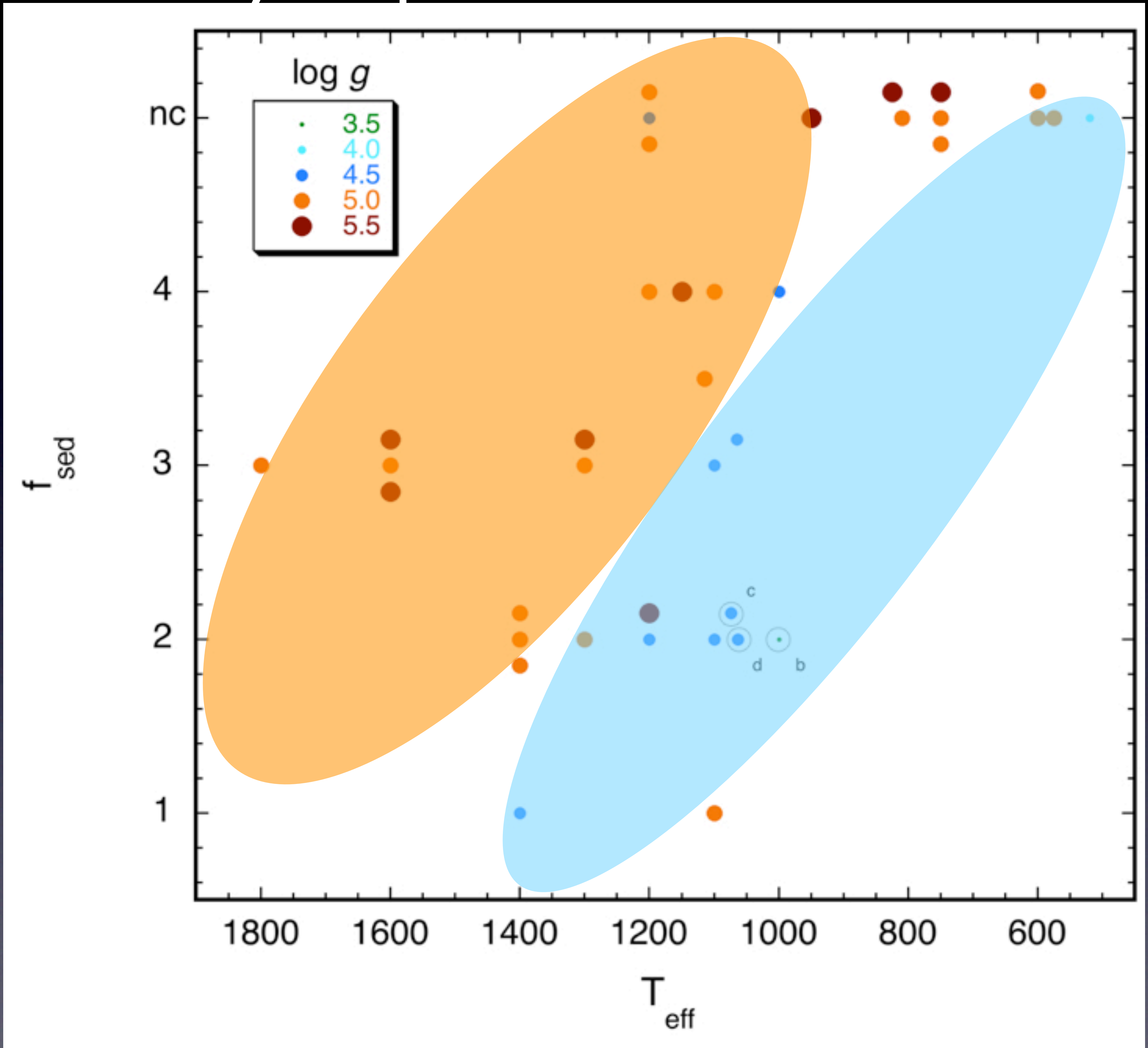


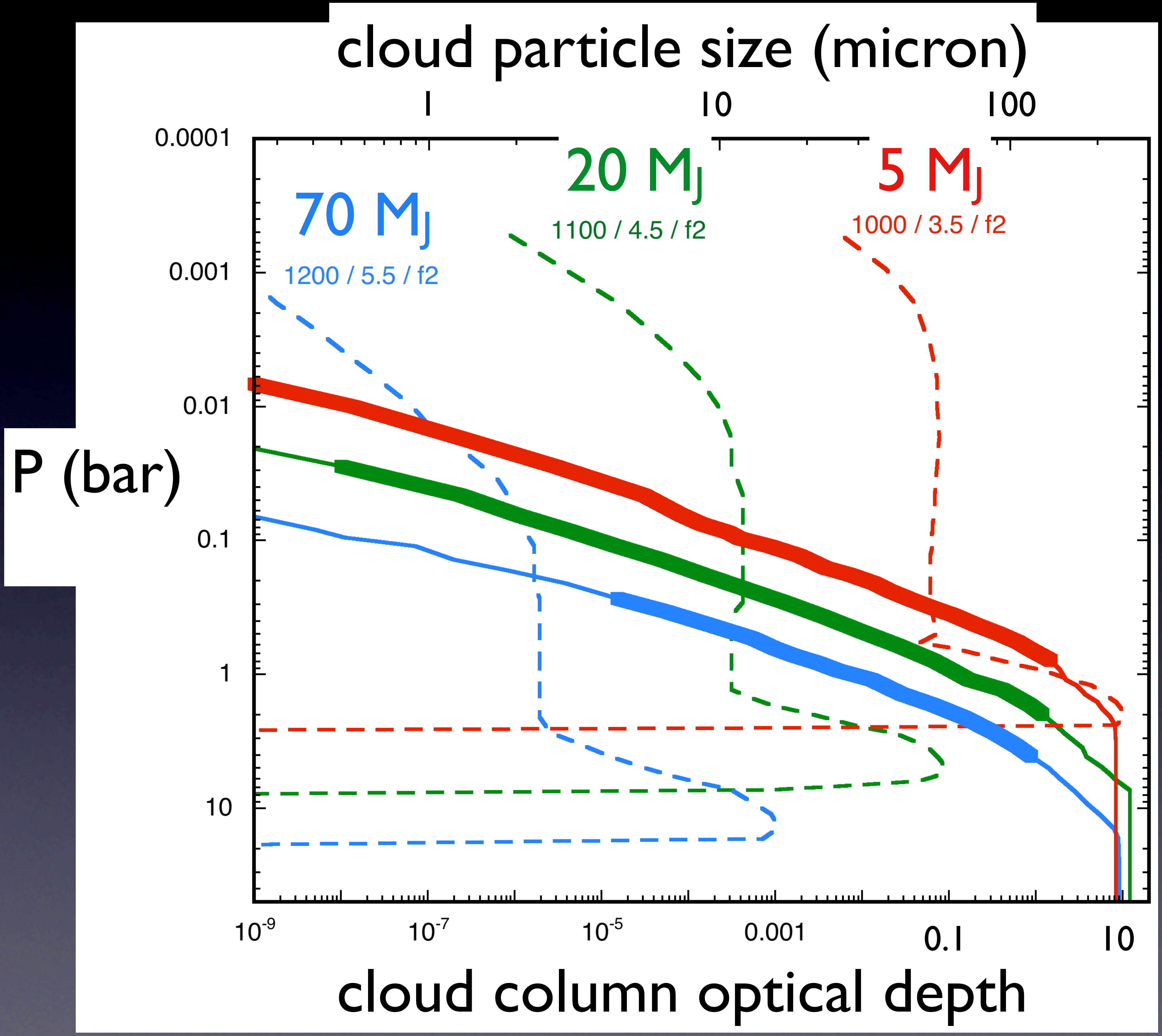
Gravity Dependence to Transition



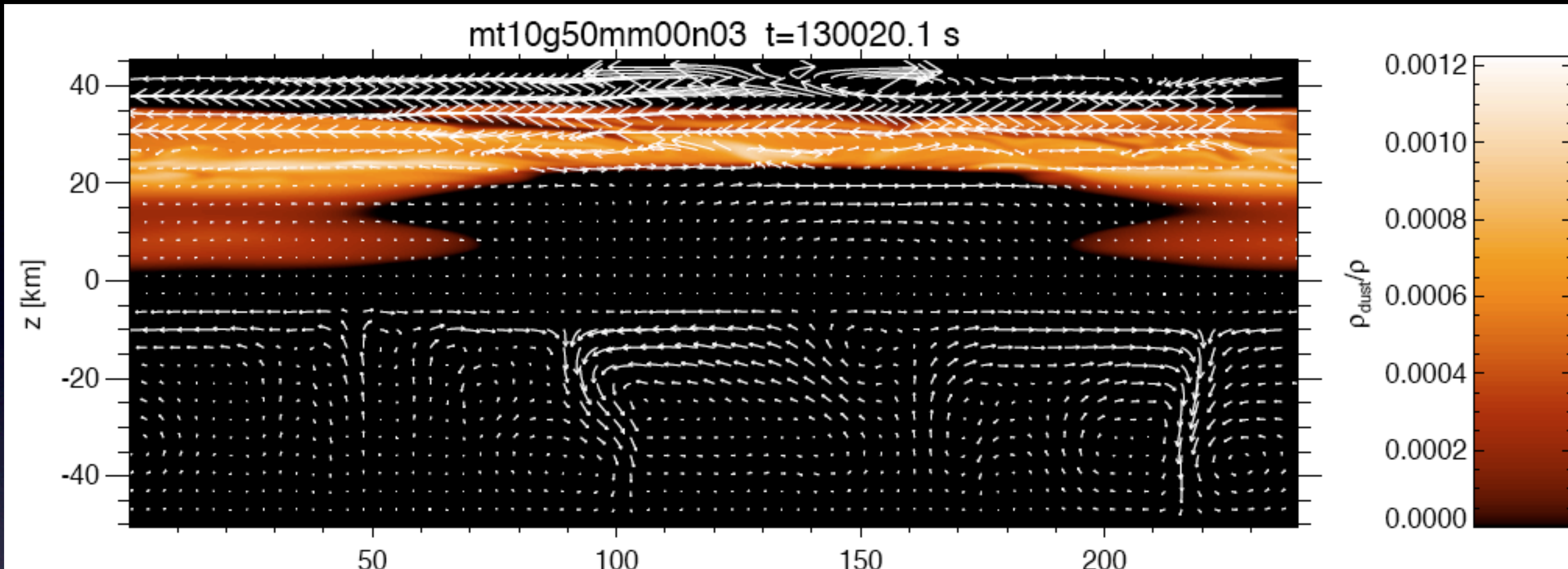
Gravity Dependence to Transition

Less clouds →



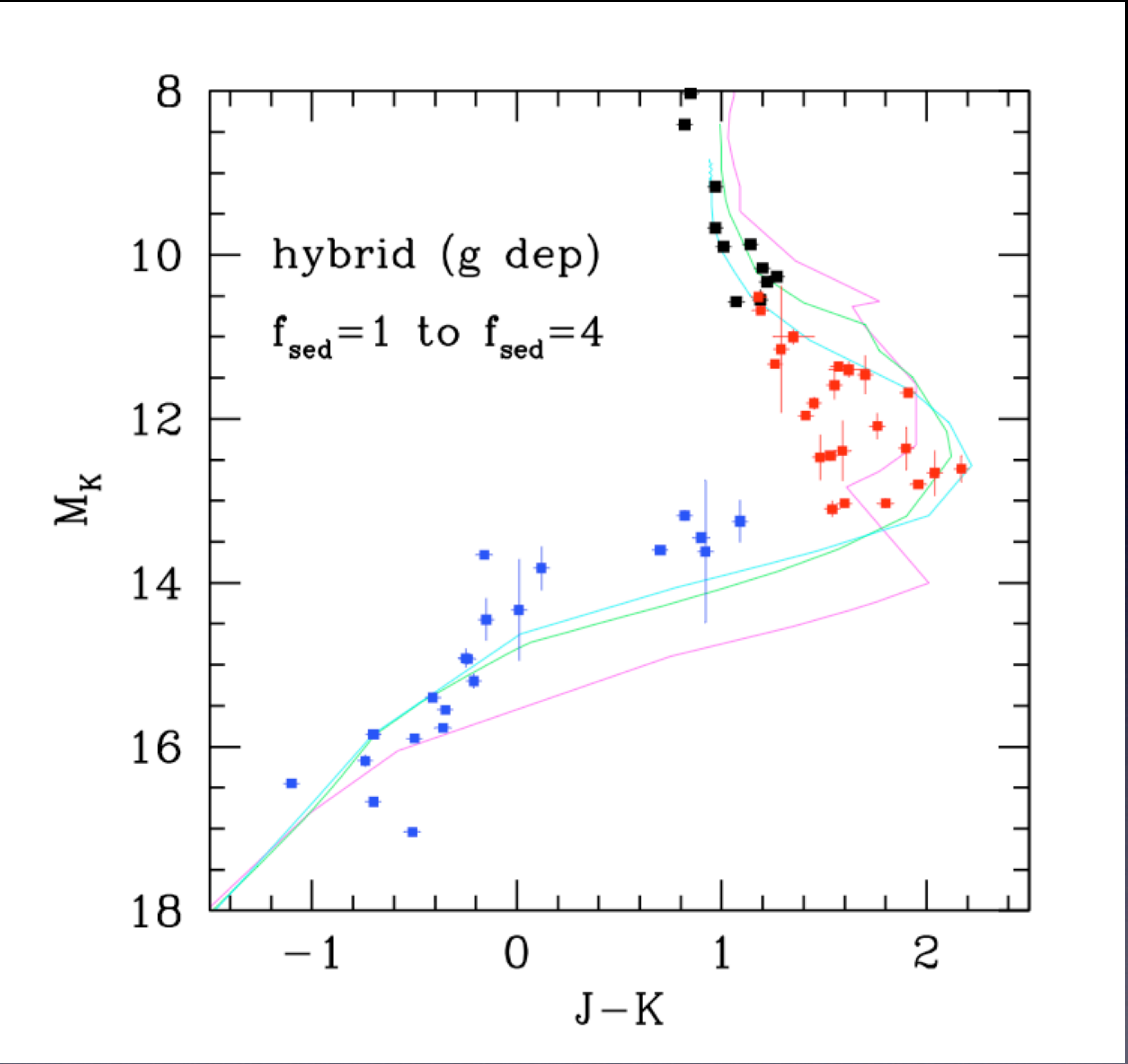

cloud particle size (micron)
1
10
100
0.0001
0.001
0.01
0.1
1
10
P (bar)
70 M_J
1200 / 5.5 / f2
20 M_J
1100 / 4.5 / f2
5 M_J
1000 / 3.5 / f2
10^{-9}
10^{-7}
10^{-5}
0.001
0.1
10
cloud column optical depth

May need 3D Simulations to Understand



Freytag et al. (2010)

- Waves may be important mechanism that keeps dust aloft
- Interplay of dynamics and clouds only beginning to be explored



hybrid (g dep)
f_{sed}=1 to f_{sed}=4
M_K
J−K
8
10
12
14
16
18
−1
0
1
2

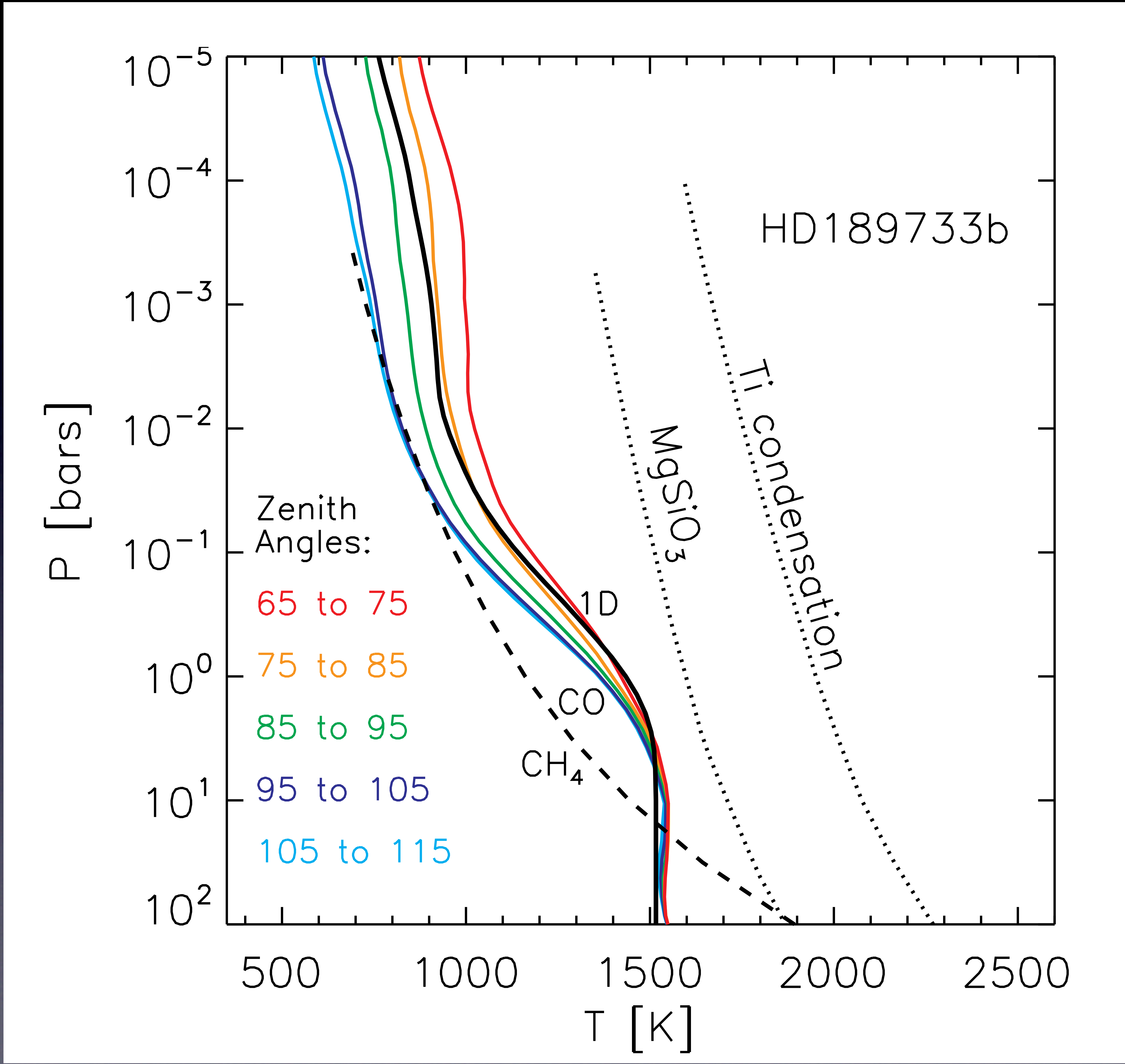
Photochemistry

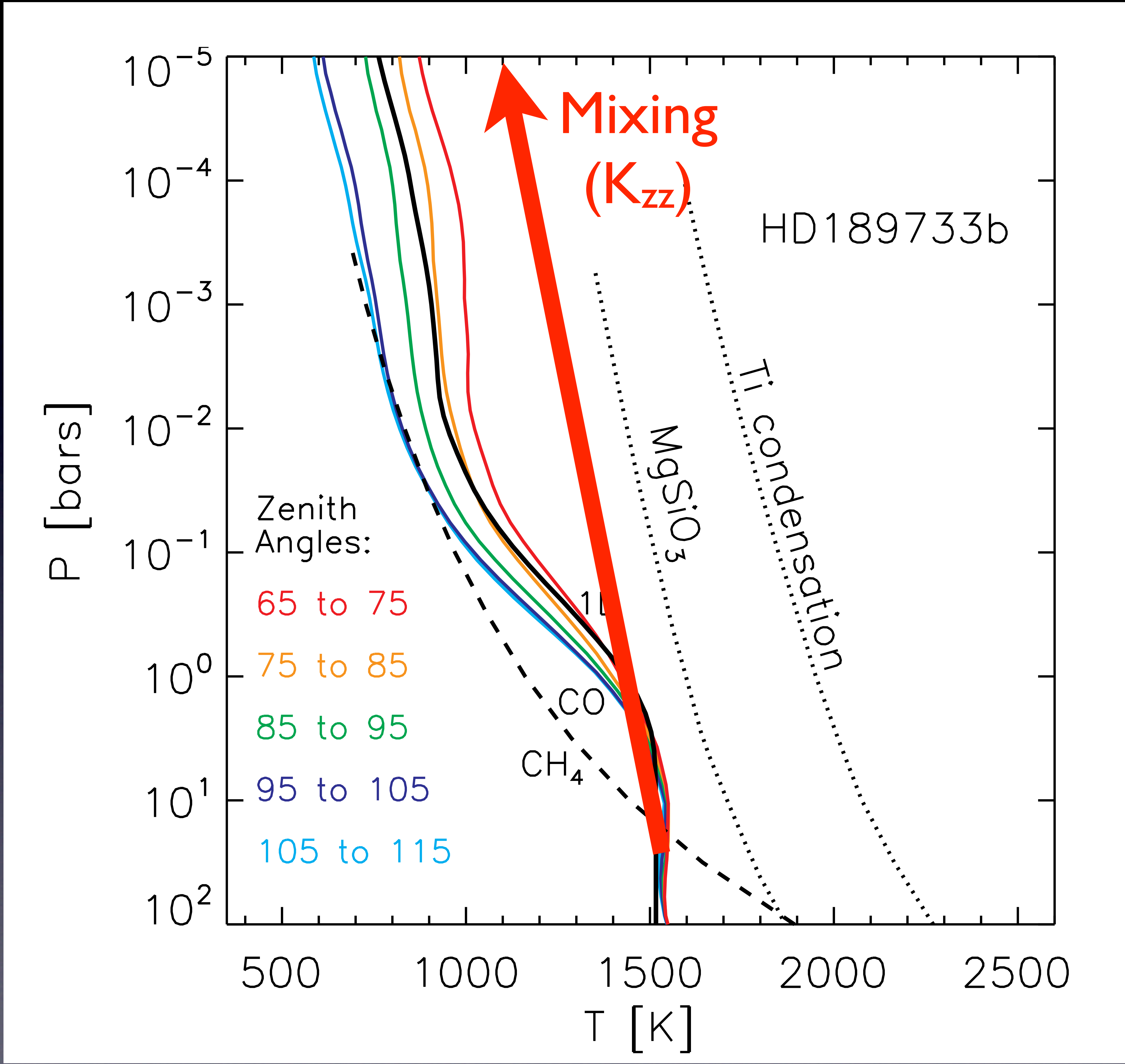
Photochemistry at higher insolation?

Hot Jupiters are Extreme Case

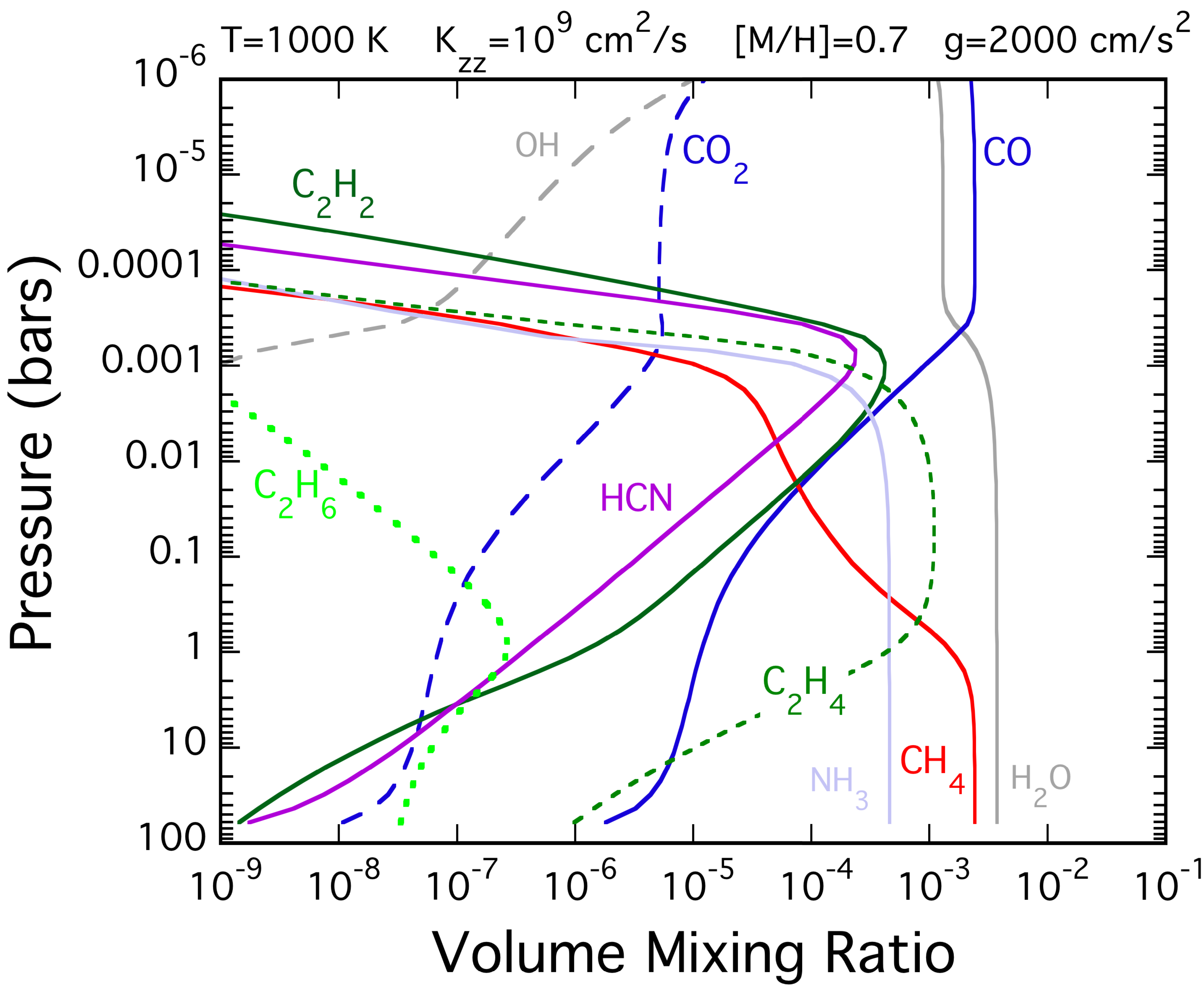
Jupiter at 0.05 AU

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


HD189733b
Zenith Angles:
65 to 75
75 to 85
85 to 95
95 to 105
105 to 115
1D
CO
CH_4
$MgSiO_3$
Ti condensation
P [bars]
T [K]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
500
1000
1500
2000
2500



Mixing
(Kzz)
HD189733b
Ti condensation
MgSiO3
Zenith
Angles:
65 to 75
75 to 85
85 to 95
95 to 105
105 to 115
CO
CH4
P [bars]
T [K]
500
1000
1500
2000
2500

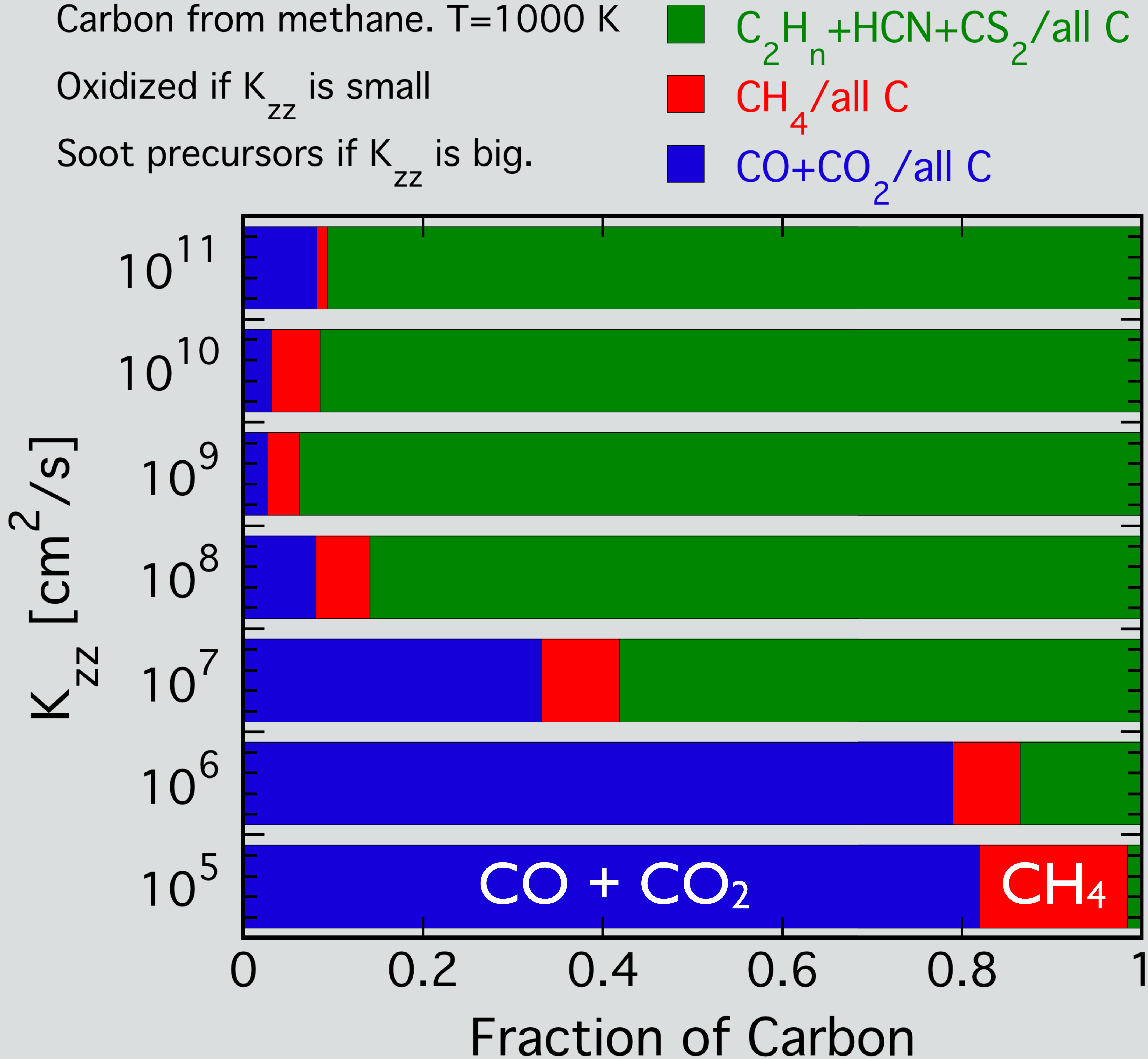


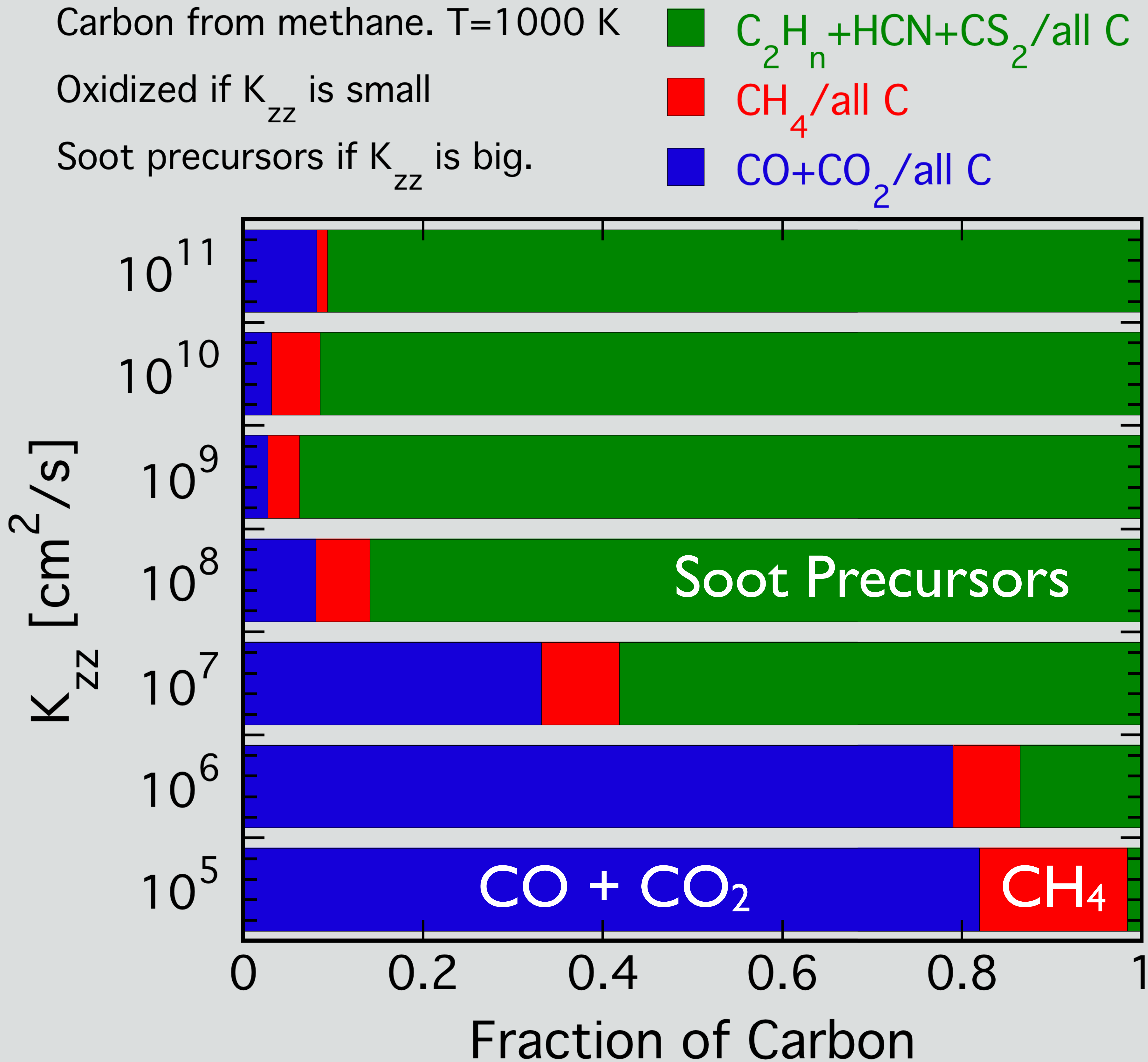
T=1000 K K_zz=10^9 cm^2/s [M/H]=0.7 g=2000 cm/s^2
Pressure (bars)
10^-6
10^-5
0.0001
0.001
0.01
0.1
1
10
100
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1
Volume Mixing Ratio
OH
CO2
CO
C2H2
C2H6
HCN
C2H4
NH3
CH4
H2O

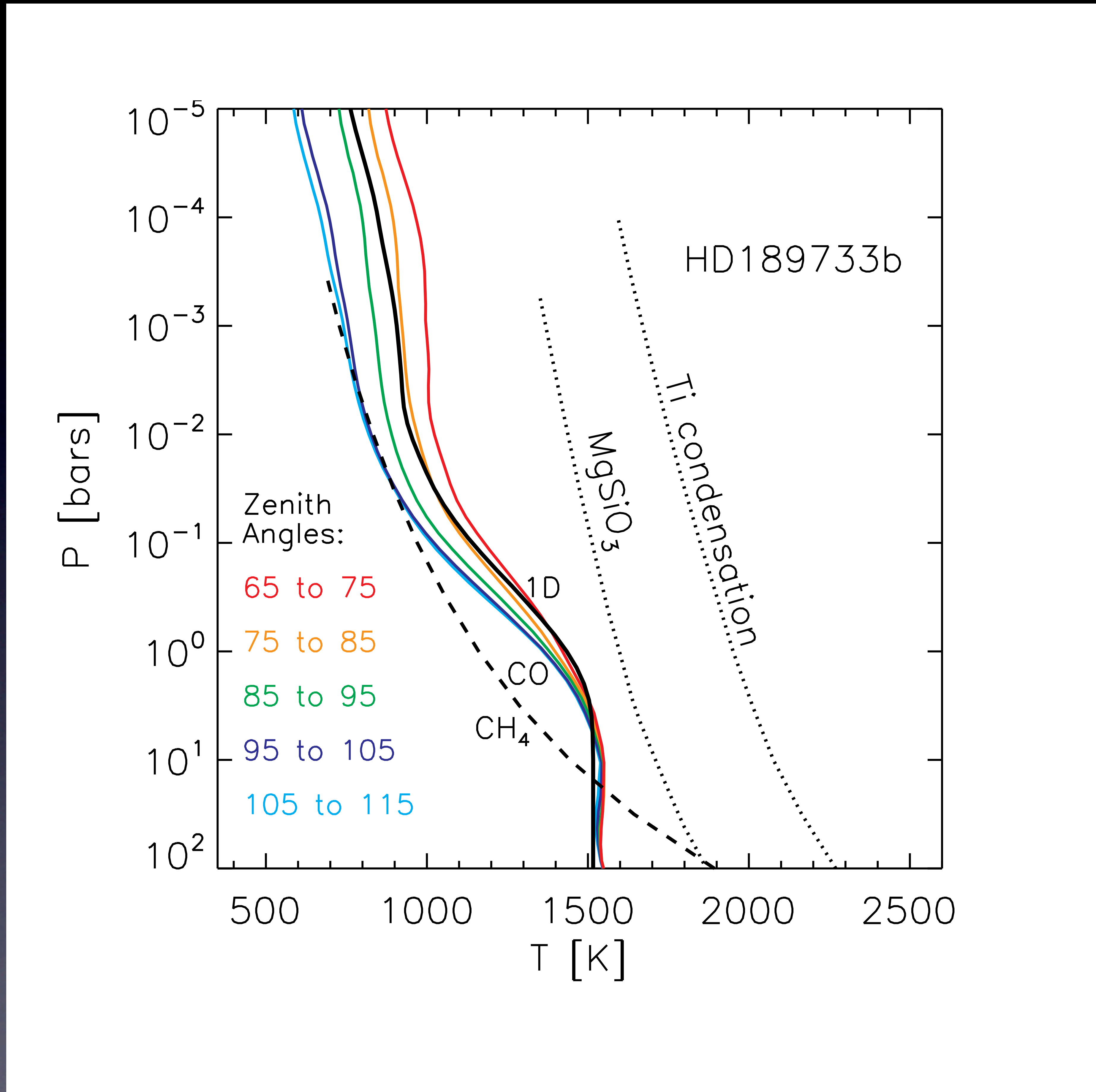
Carbon from methane. T=1000 K

Oxidized if K_{zz} is small

Soot precursors if K_{zz} is big.

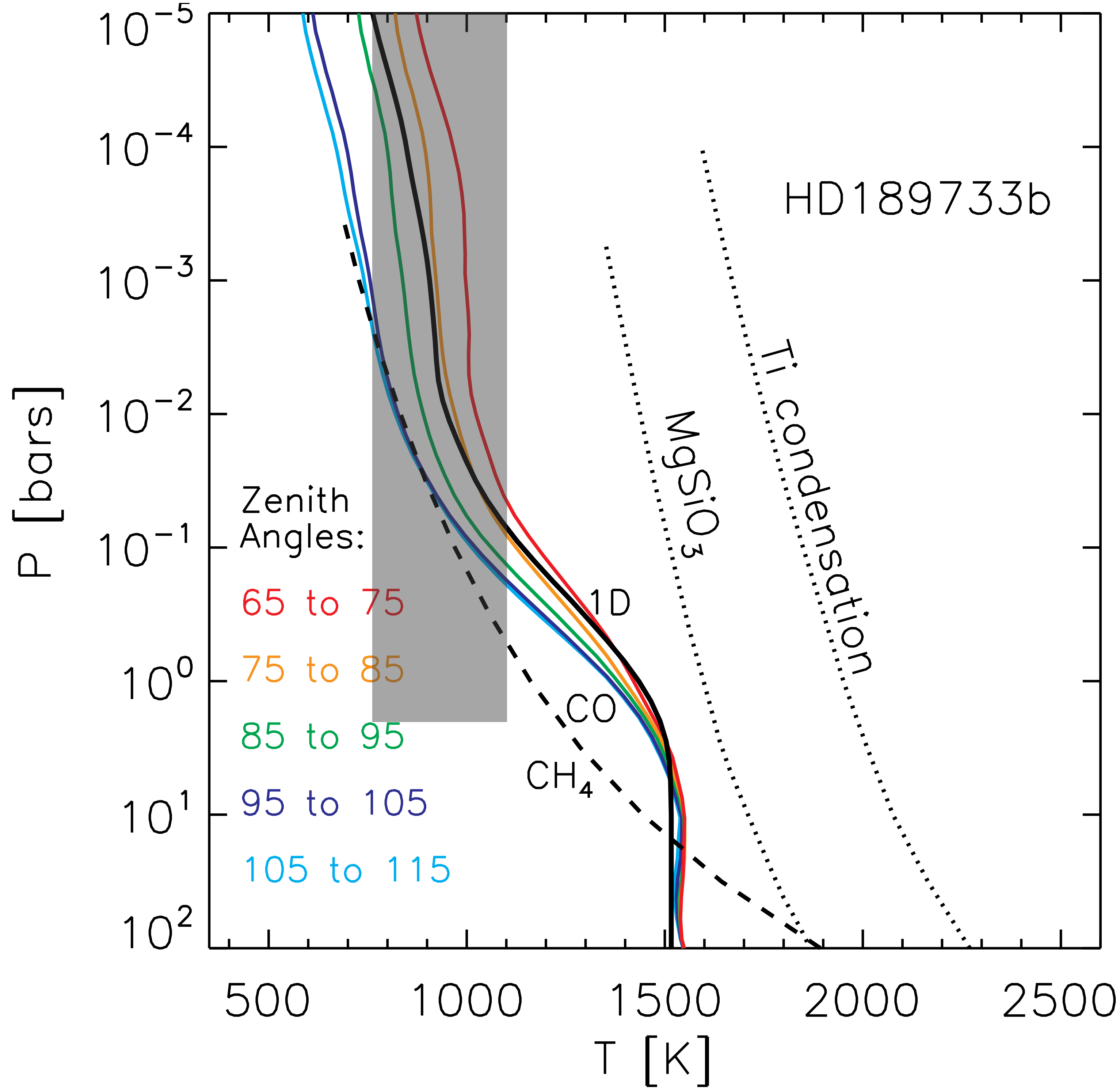


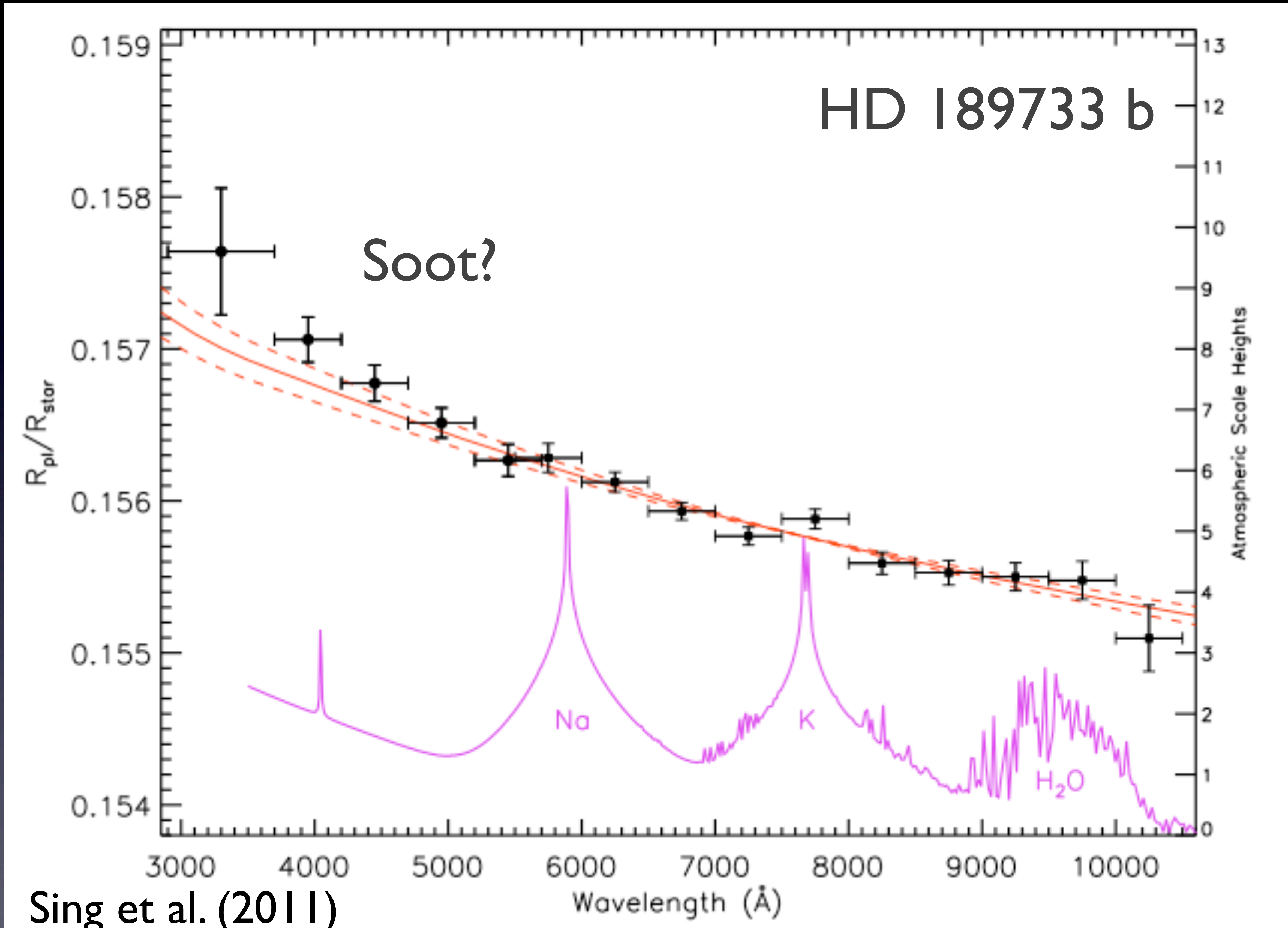

Carbon from methane. T=1000 K
Oxidized if K_{zz} is small
Soot precursors if K_{zz} is big.
$C_2H_n+HCN+CS_2$/all C
CH_4/all C
$CO+CO_2$/all C
K_{zz} [cm^2/s]
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
Soot Precursors
$CO + CO_2$
CH_4
0
0.2
0.4
0.6
0.8
1
Fraction of Carbon



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
500
1000
1500
2000
2500

Soot Precursors





HD 189733 b
Soot?
0.159
0.158
0.157
0.156
0.155
0.154
R_{pl}/R_{star}
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength (Å)
Atmospheric Scale Heights
Na
K
H_2O
Sing et al. (2011)

Conclusions

- Clouds are very important
- Existing models are adequate but there is much room for improvement (talk by Helling)
- Brown dwarfs provide imporant tests
- HR 8799 planets are not strange but rather are consistent with known cloud physics
- Need cloud models to properly interpret data
- Photochemical products also may provide an important source of particulate opacity