Sand, Iron, and Ice: The Role of Clouds in Directly Imaged Exoplanet Spectra

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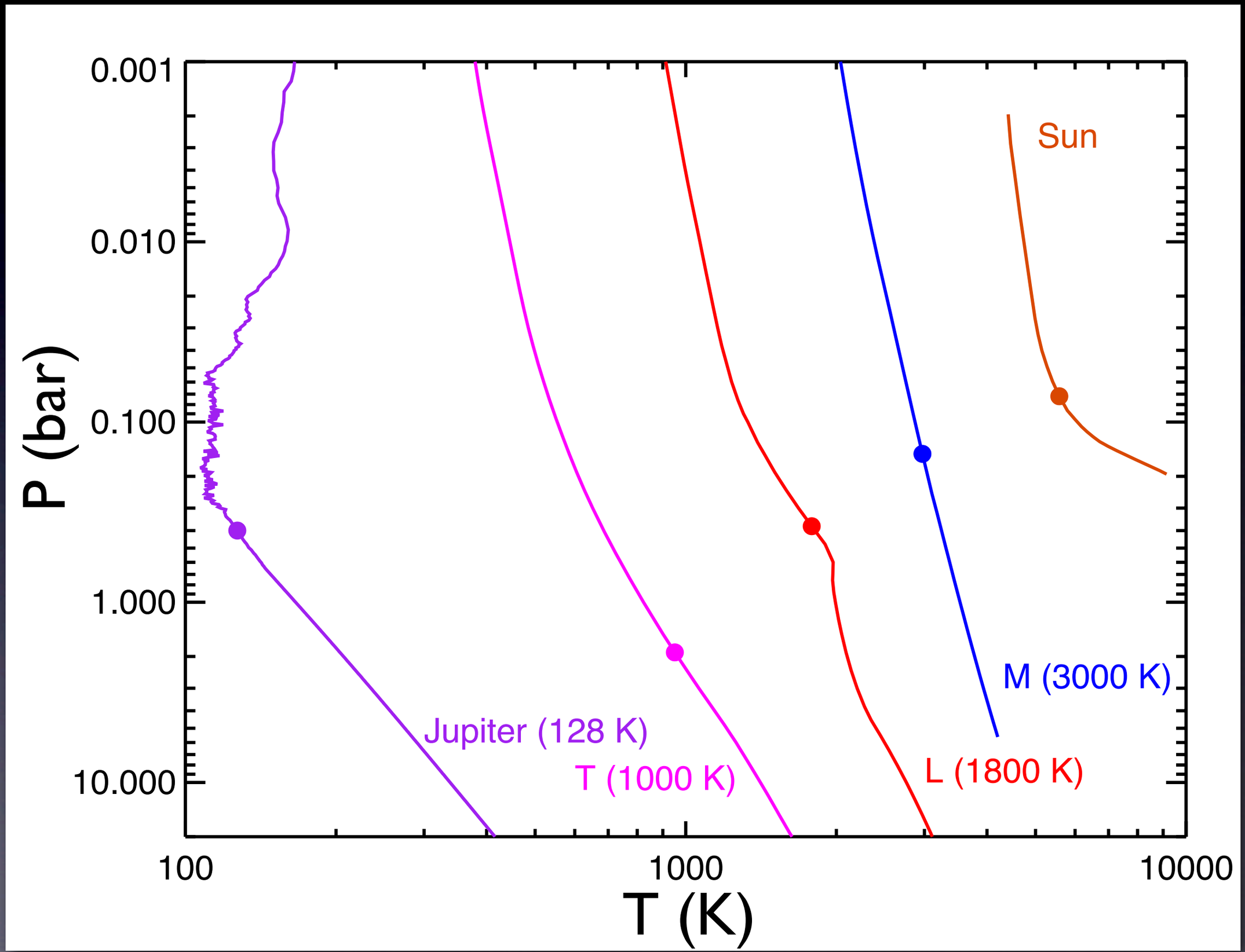
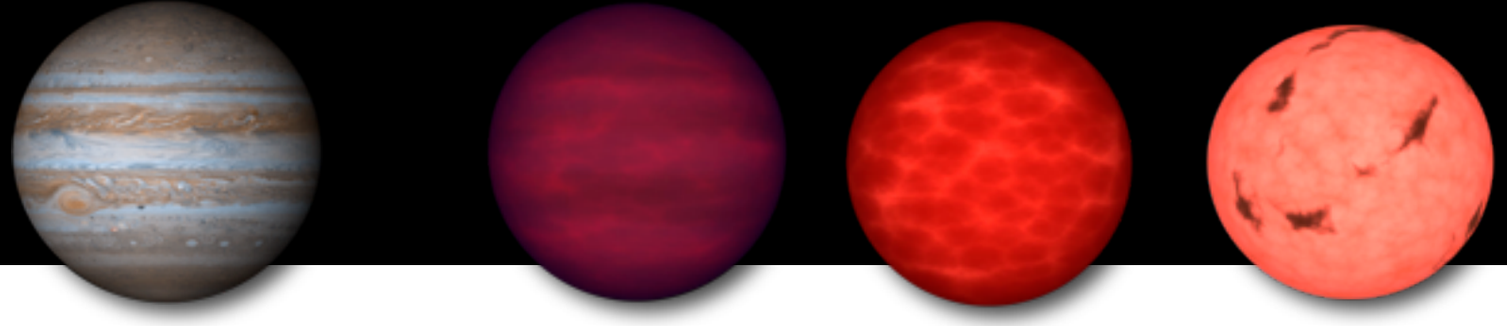
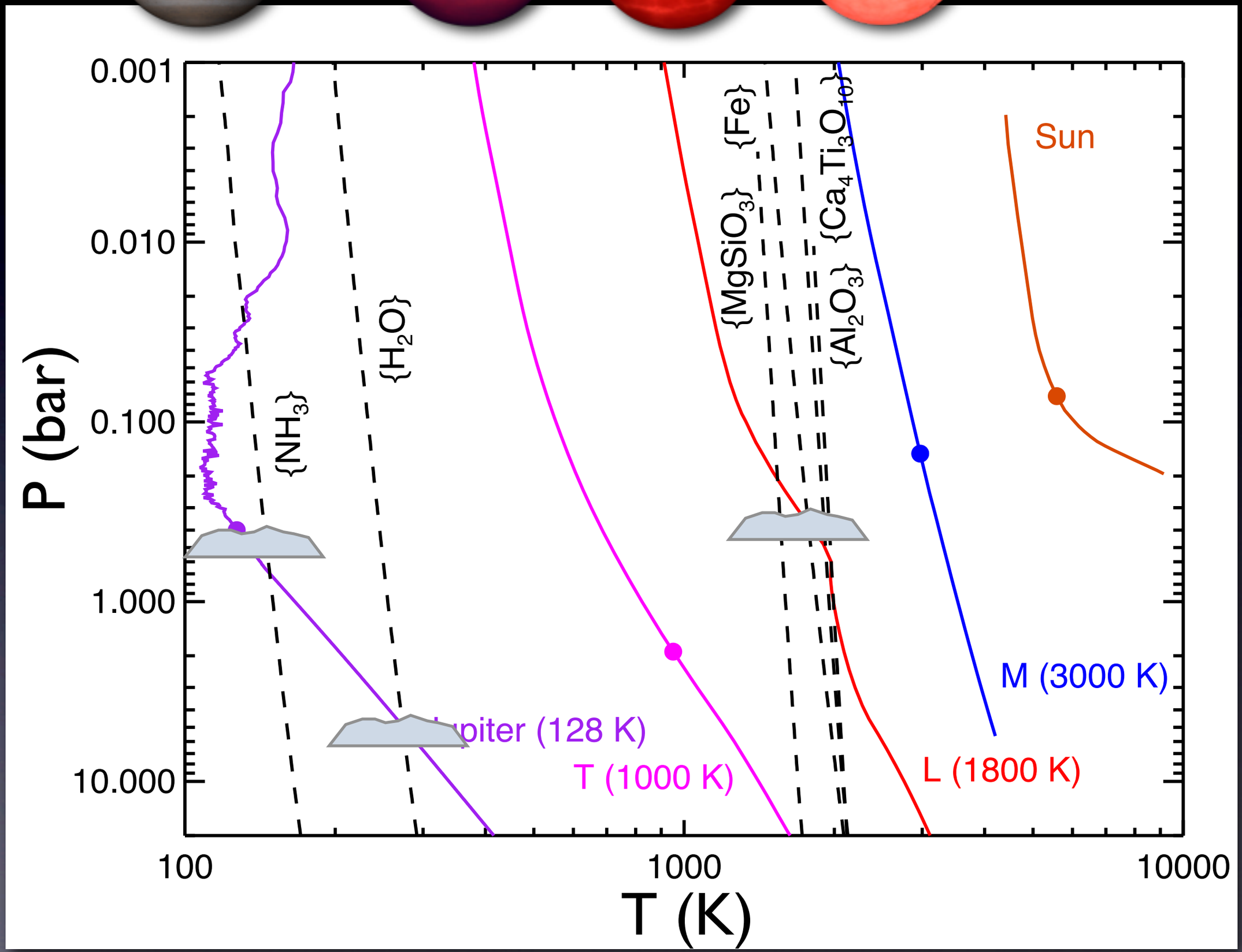
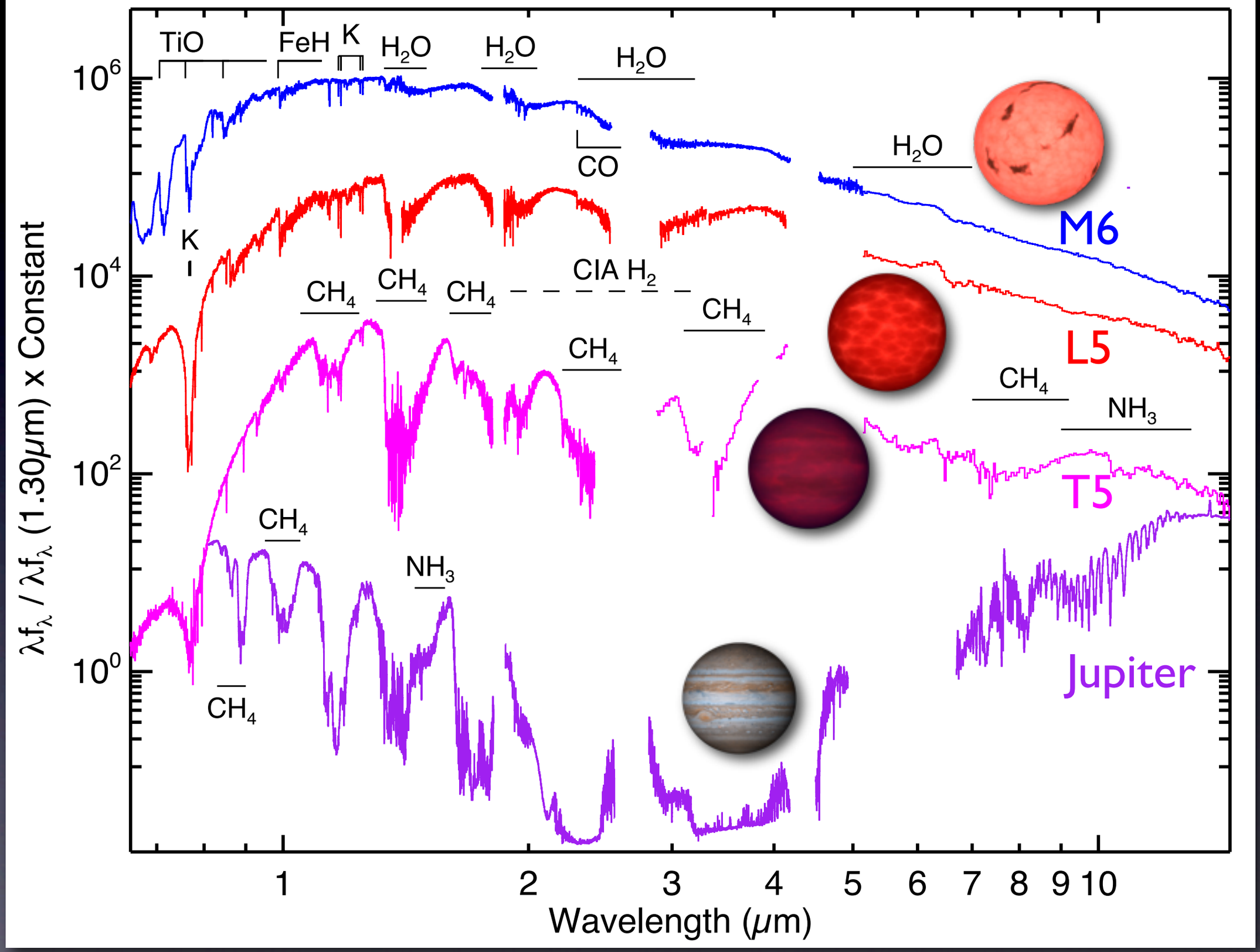
Directly Imaged Planets

- more than half a dozen now
- scores more expected soon from GPI, SPHERE, other programs
- goal is to self-consistently derive mass, Teff, composition, from photometry & low R spectra
- an understanding of clouds is central to this task

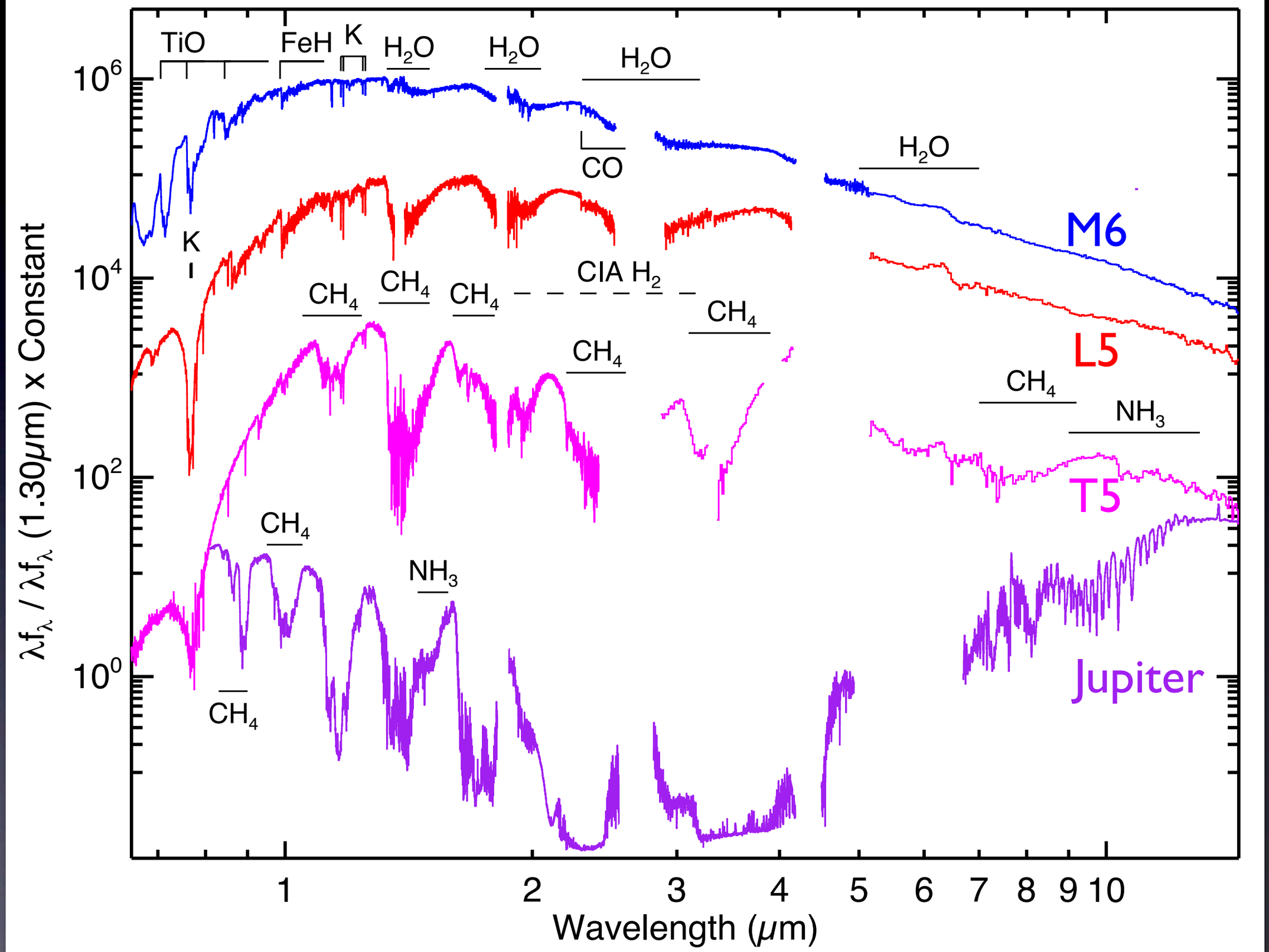

0.001
0.010
0.100
1.000
10.000
P (bar)
100
1000
10000
T (K)
Sun
M (3000 K)
L (1800 K)
T (1000 K)
Jupiter (128 K)



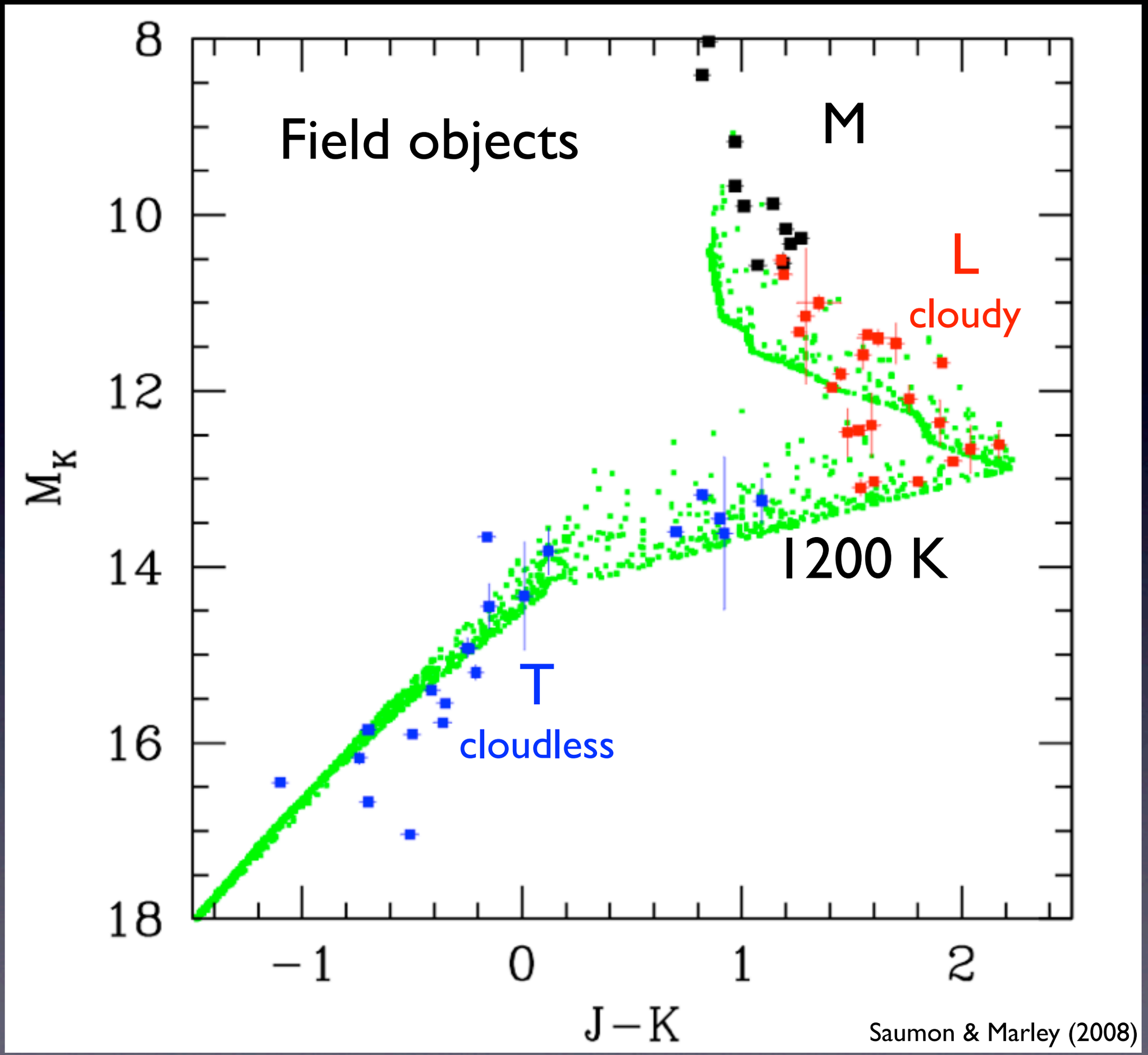

0.001
0.010
0.100
1.000
10.000
P (bar)
100
1000
10000
T (K)
{NH3}
{H2O}
{MgSiO3}
{Fe}
{Al2O3}
{Ca4Ti3O10}
Sun
Jupiter (128 K)
T (1000 K)
L (1800 K)
M (3000 K)



plot by Cushing in Marley & Leggett (2009)



plot by Cushing in Marley & Leggett (2009)



Saumon & Marley (2008)

Field objects

M

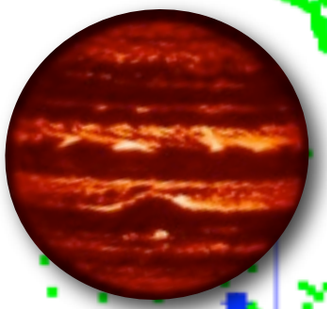
L

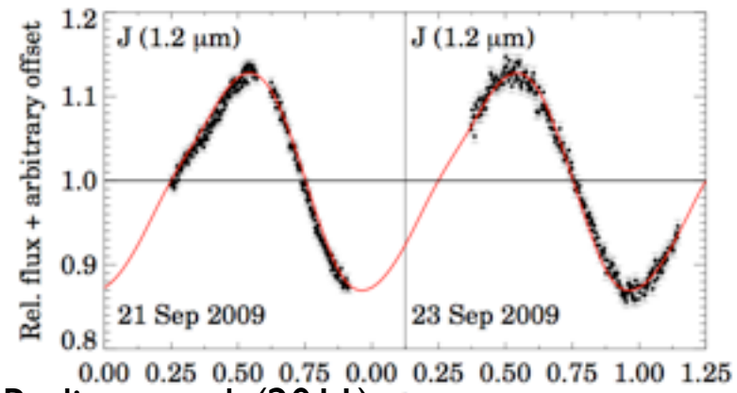
cloudy

1200 K

T

cloudless



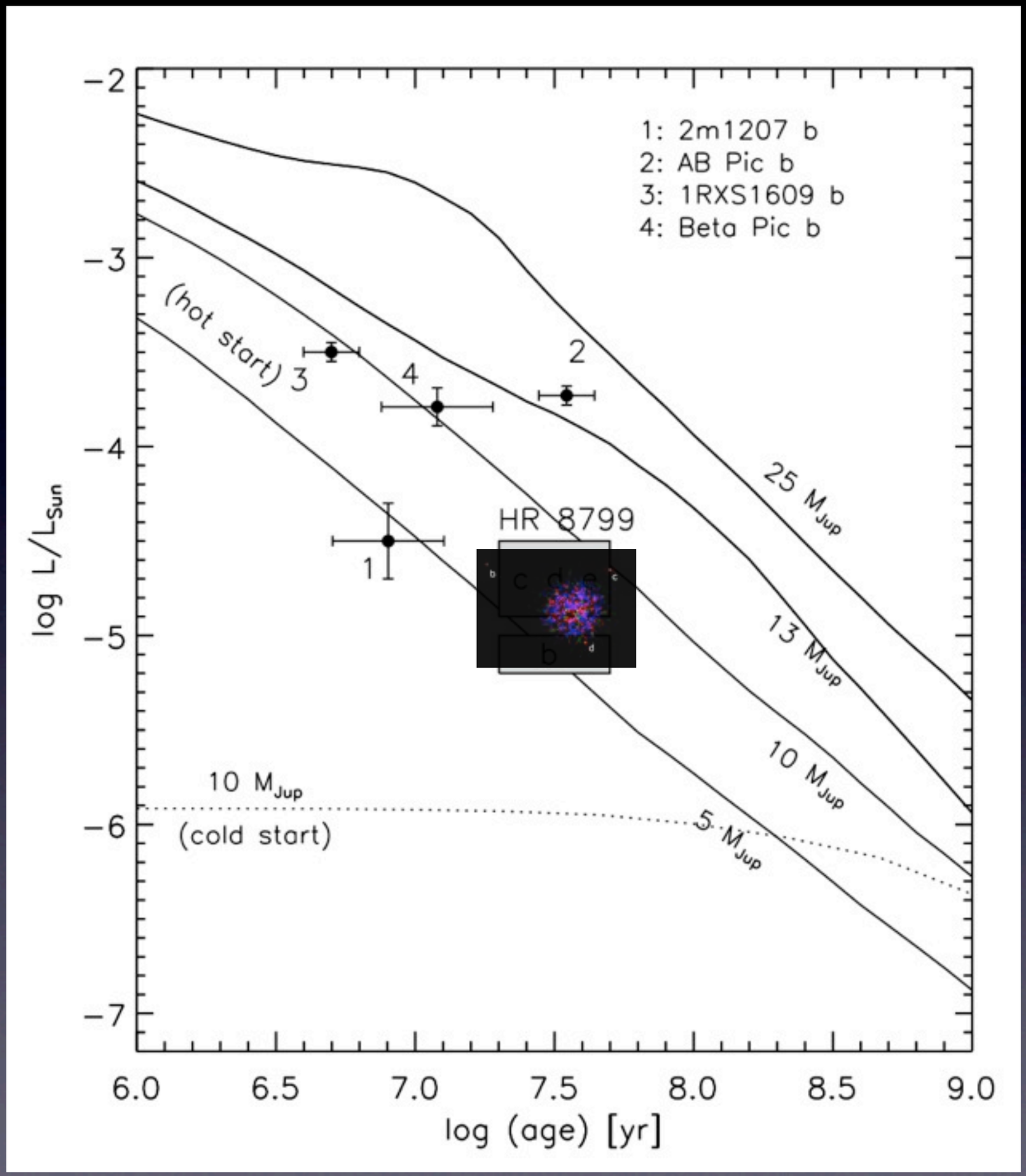


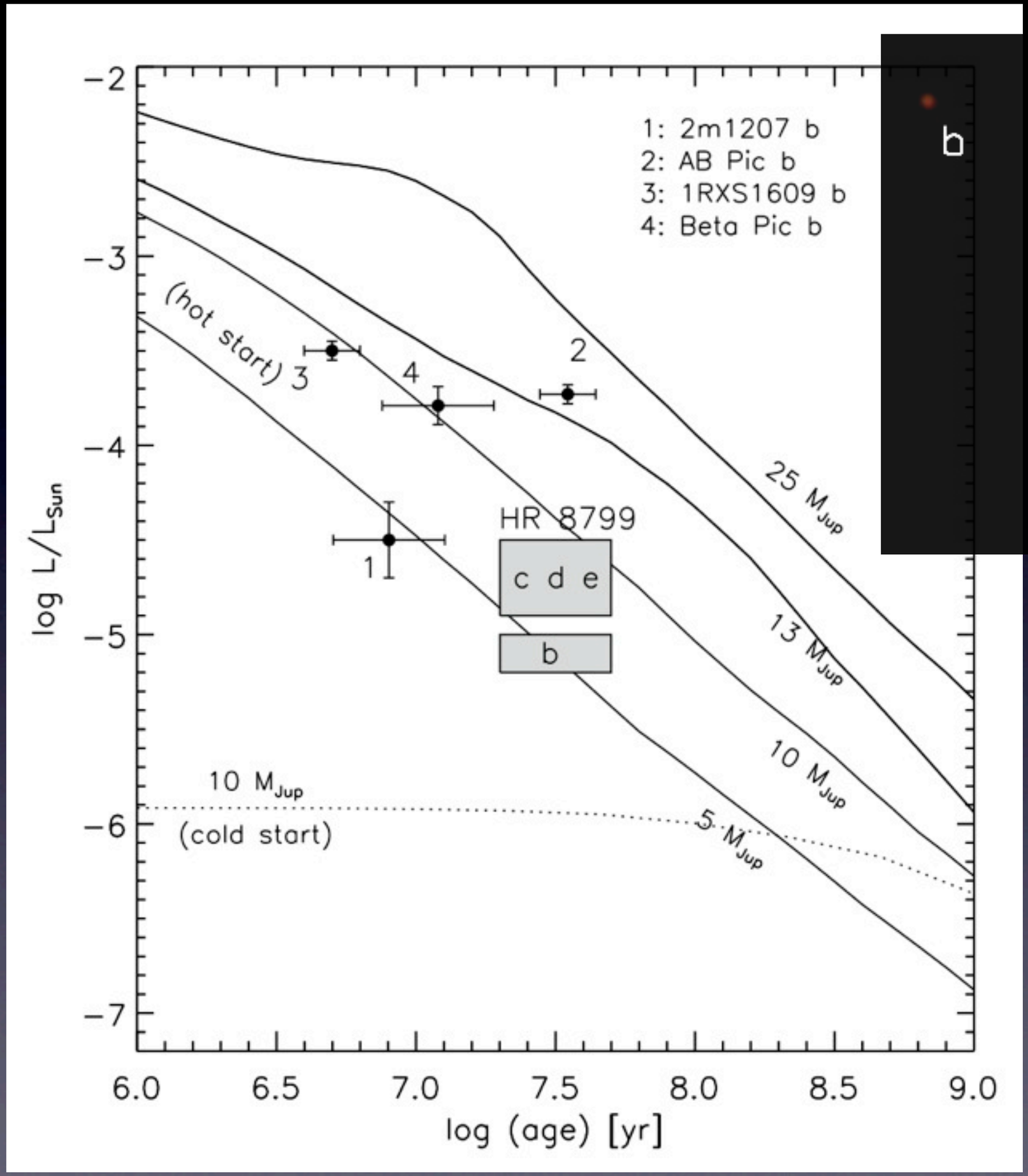
Radigan et al. (2011)

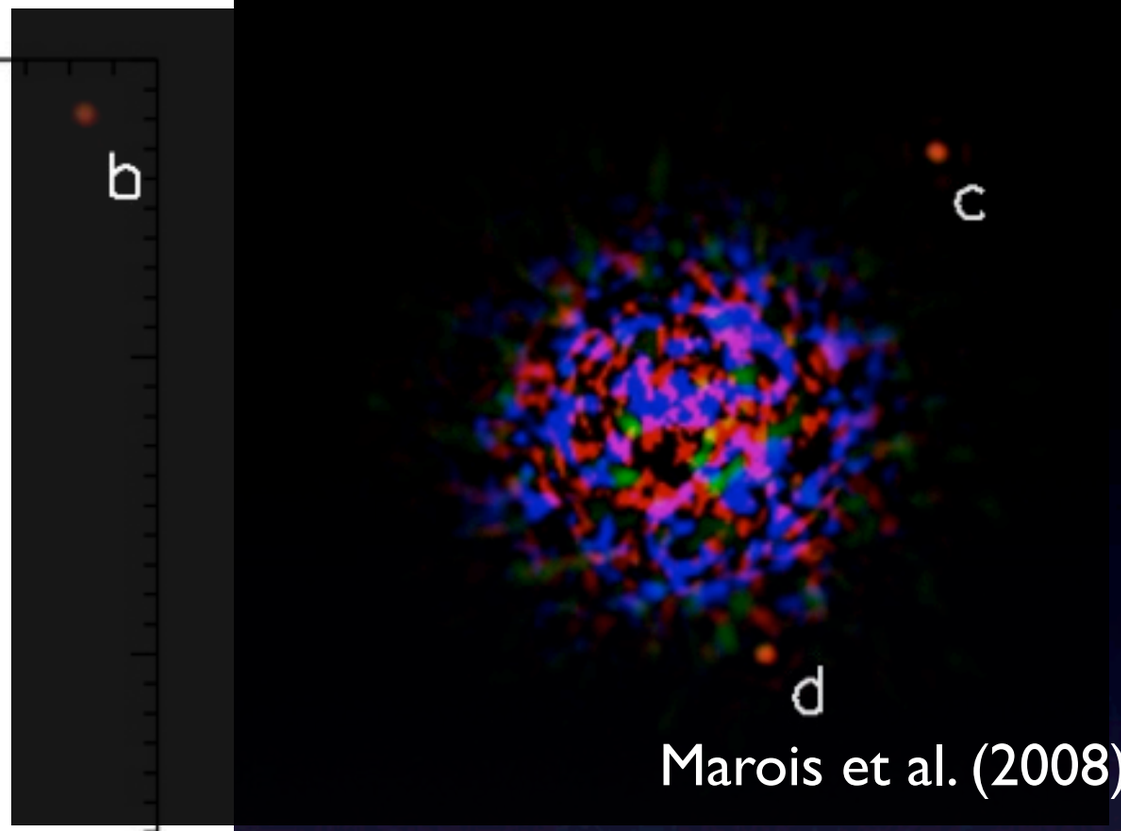
M_K

J−K

Saumon & Marley (2008)


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]
−2
−3
−4
−5
−6
−7
6.0
6.5
7.0
7.5
8.0
8.5
9.0

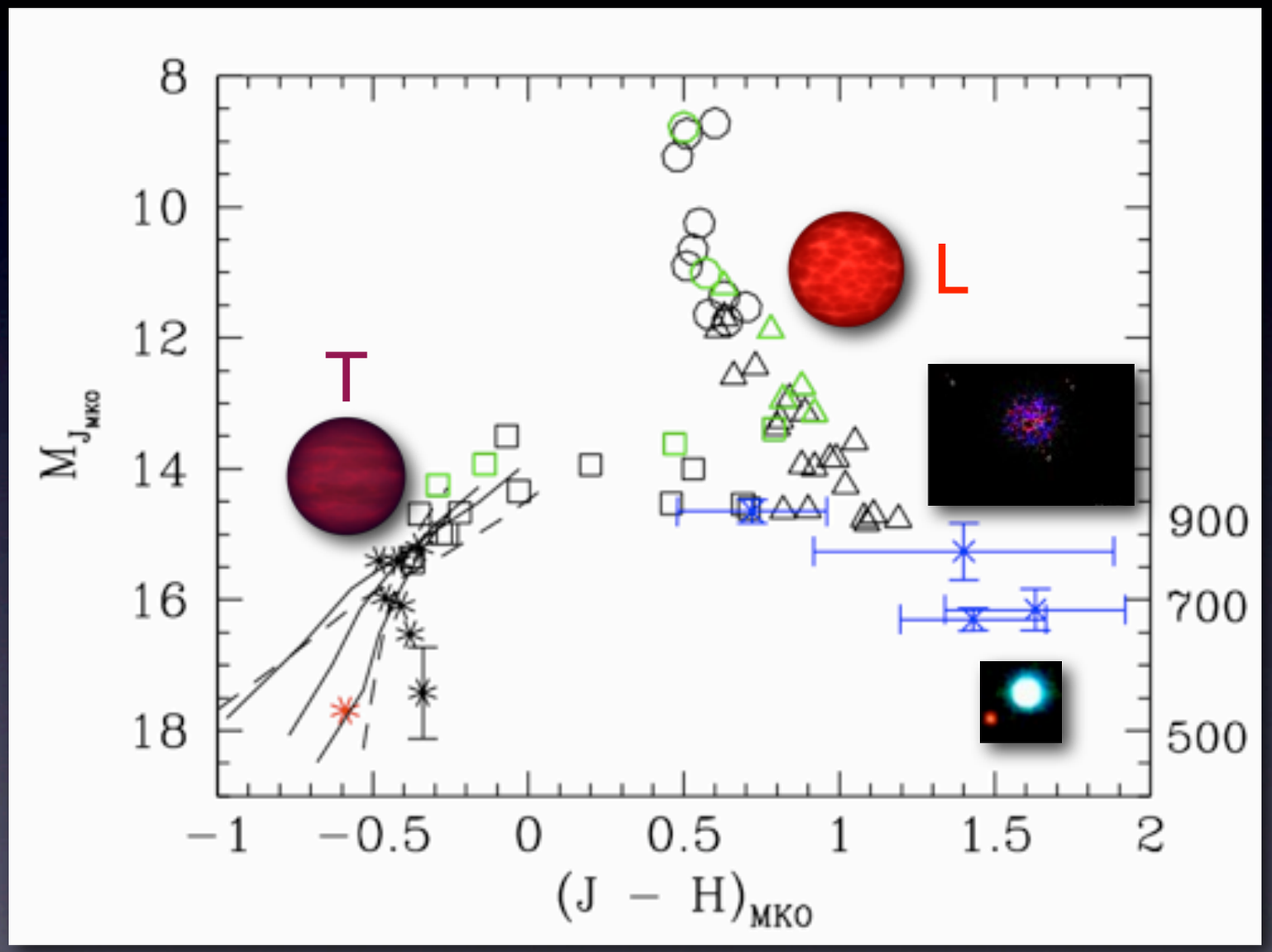




Marois et al. (2008)

- Luminosities imply T_{eff} ~ 900 to 1000 K
- Stellar age range then implies 5 - 10 M_J

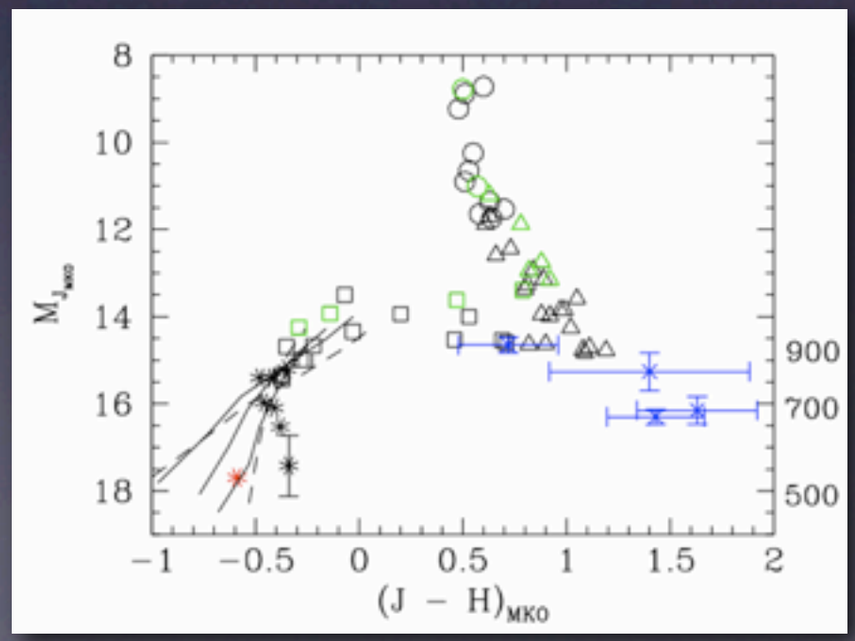
Directly Imaged Planets are Cloudy



- HR 8799 b,c,d and 2M1207B look like extensions of L sequence
- Early models agree: cloudy & low Teff
- Why do low g objects turn blue later?

Clouds

- Atmospheres are certainly cloudy to lower T_{eff} than field L dwarfs
- 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)
- But is this really true?



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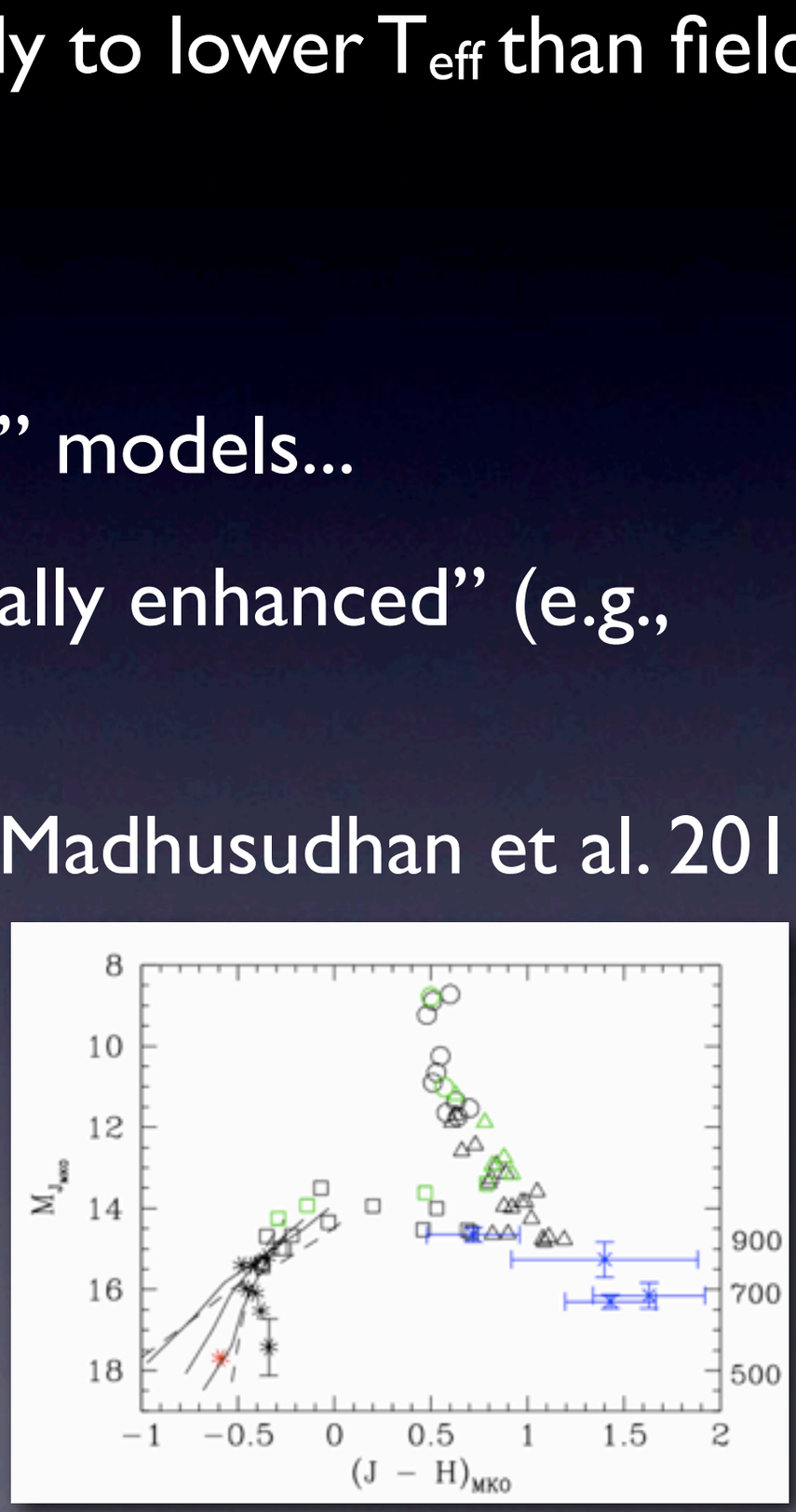
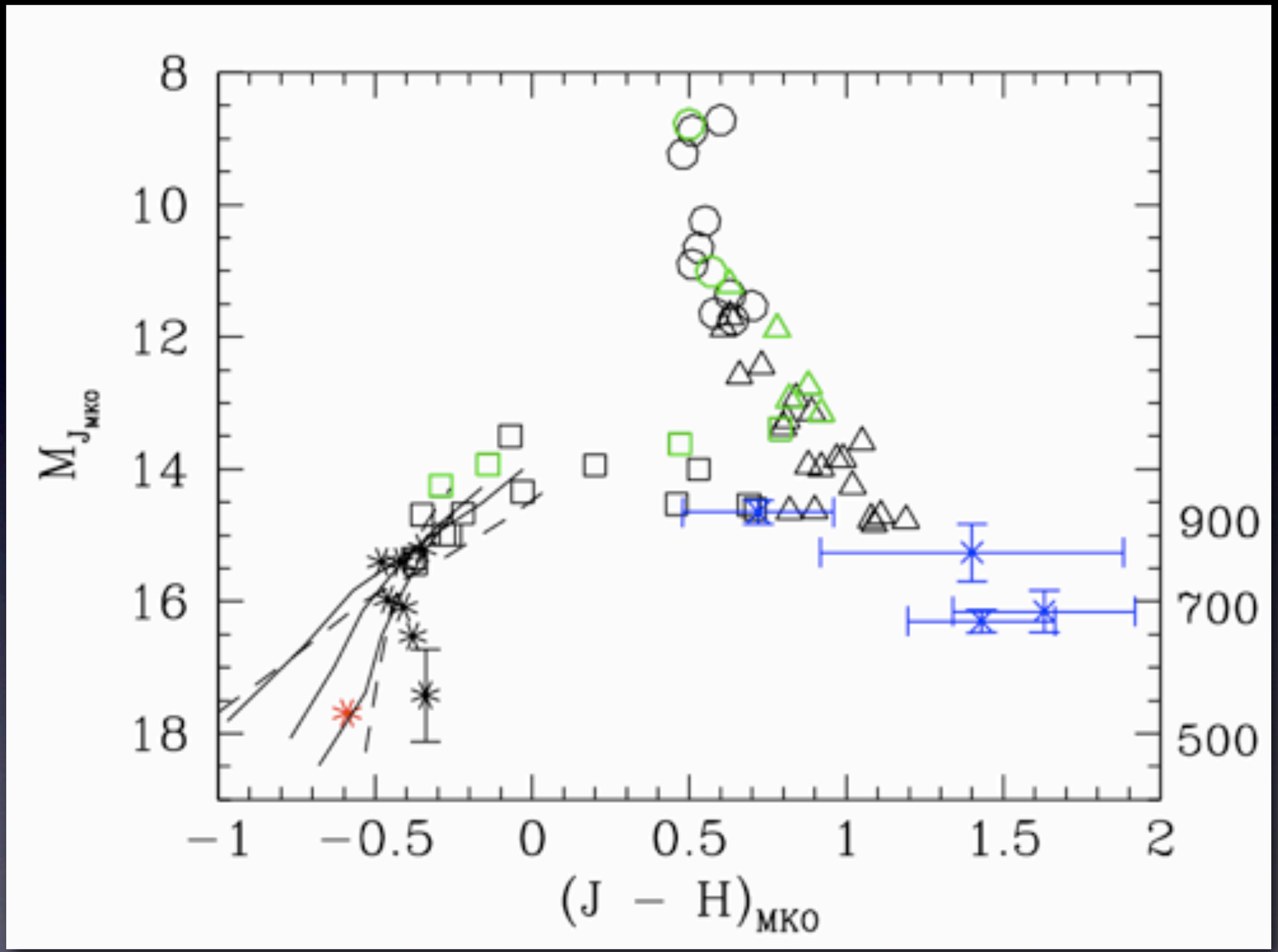
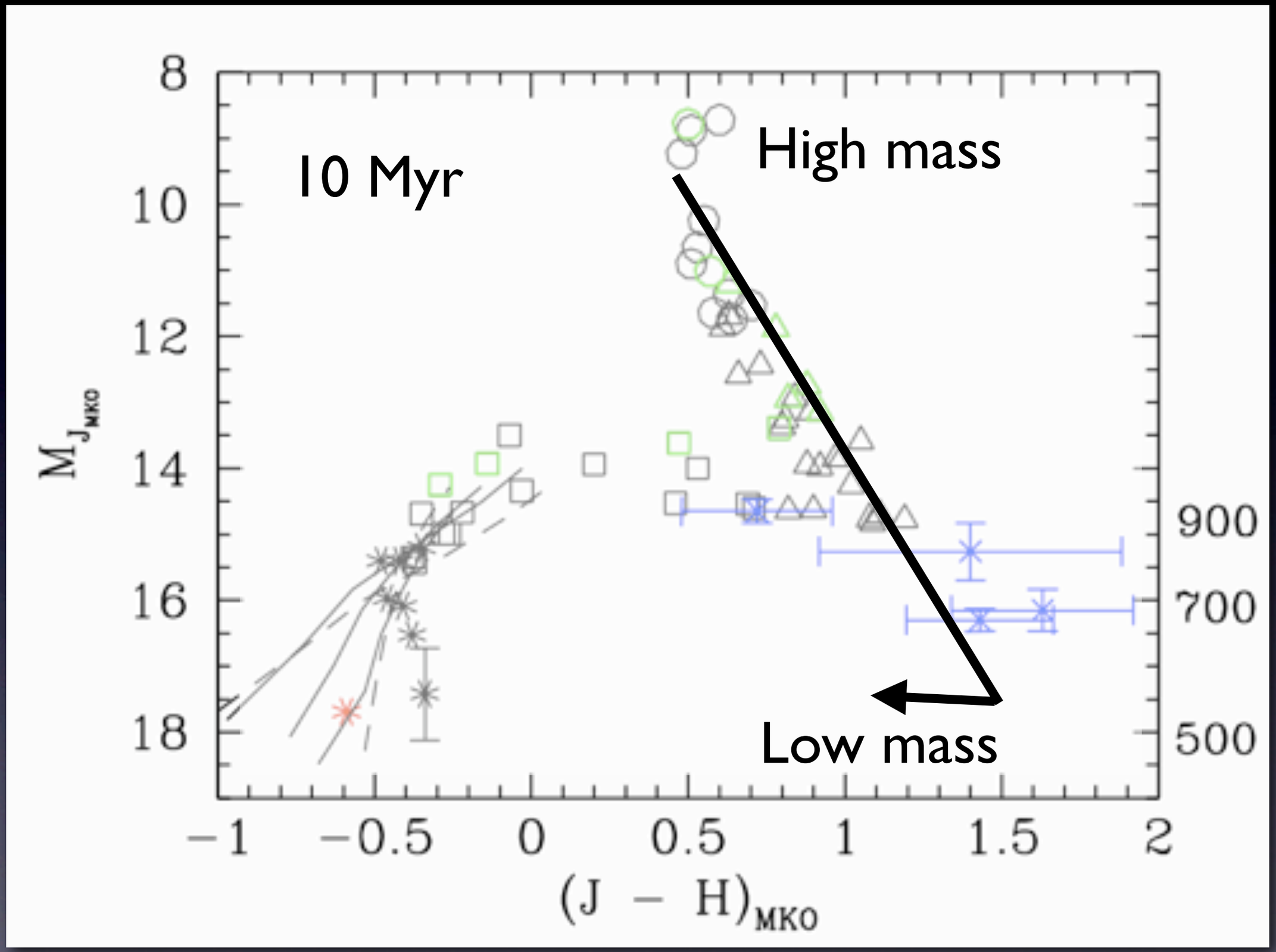
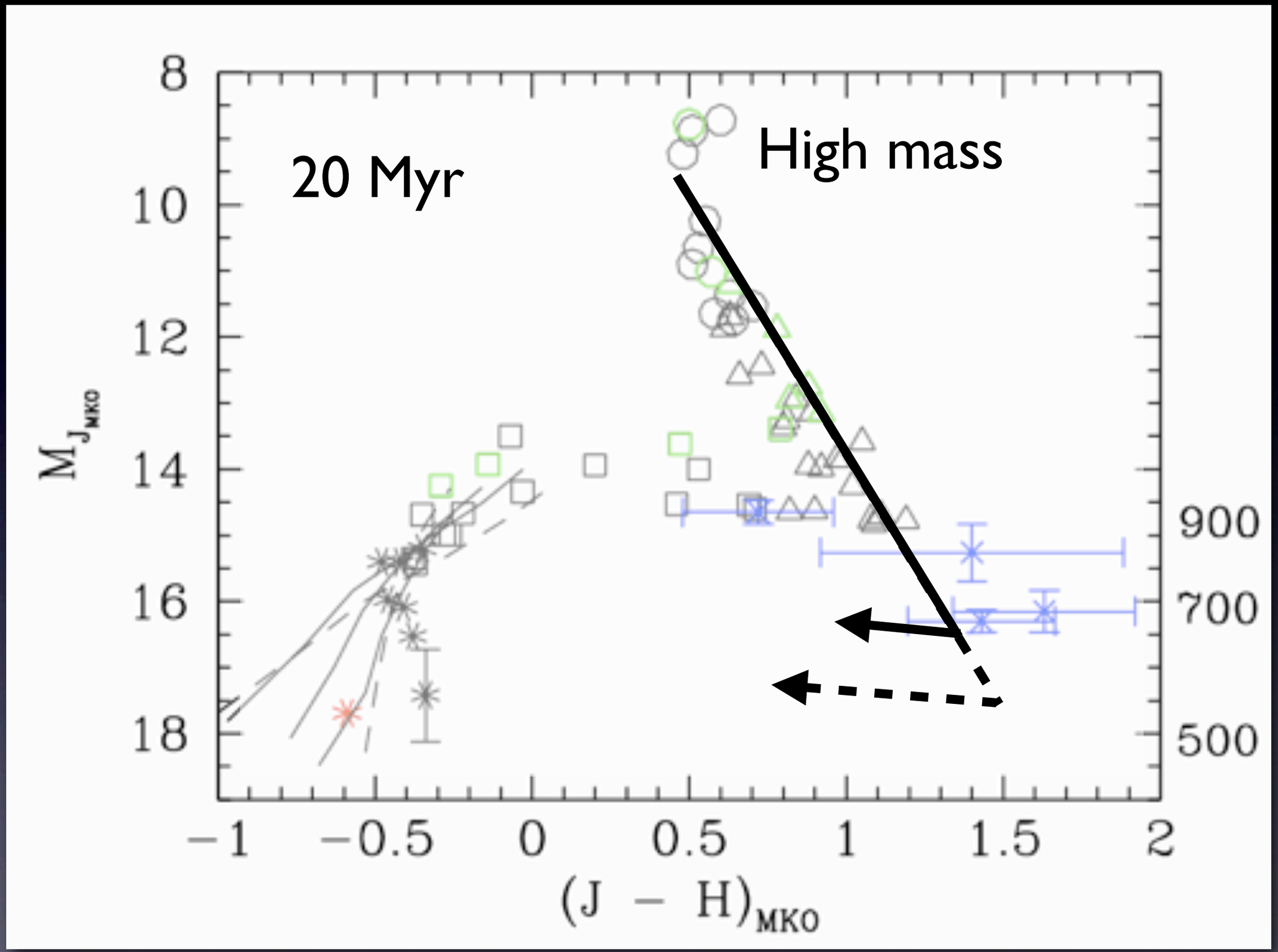
Alternative interpretation

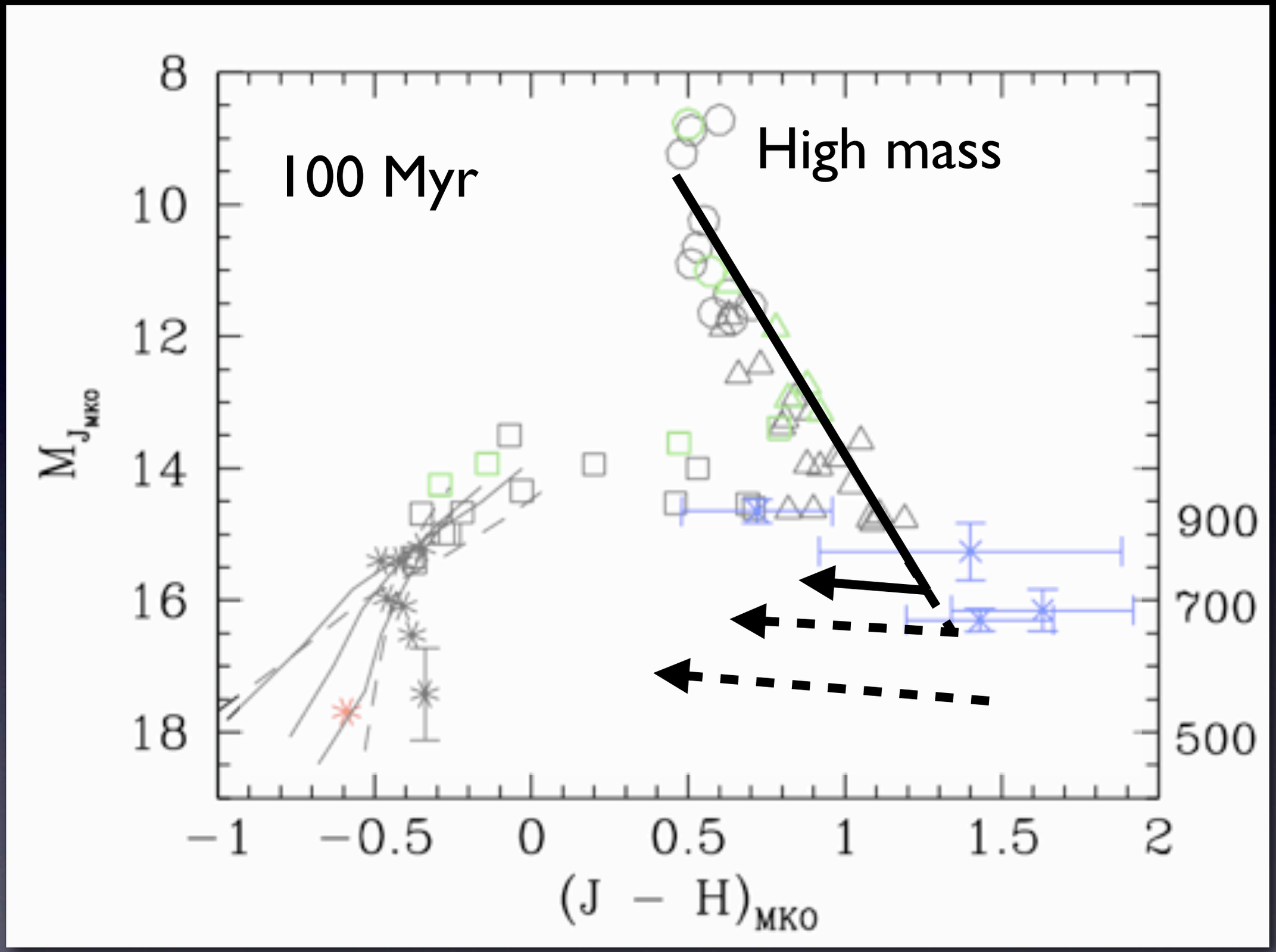
(also Barman)

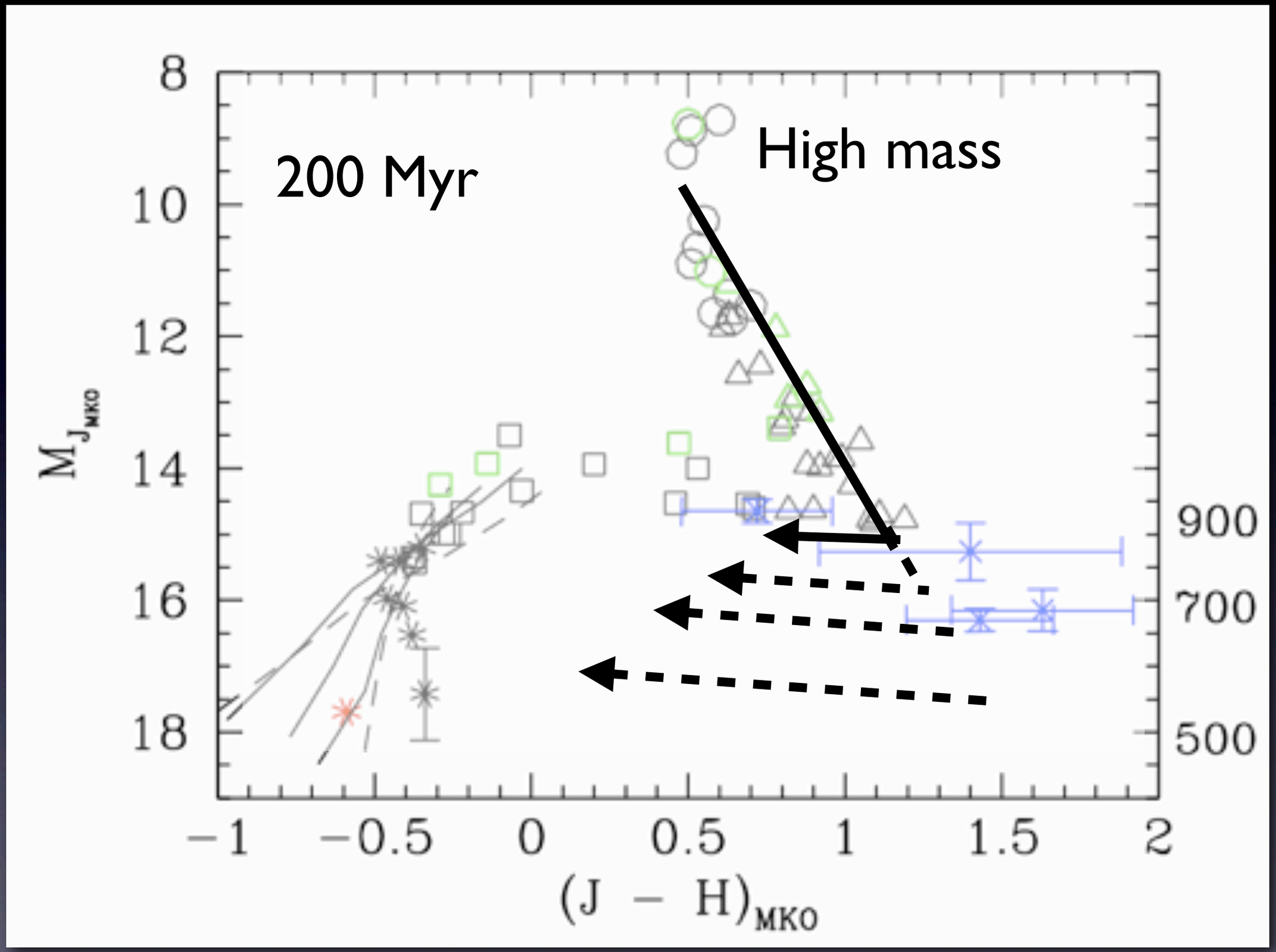


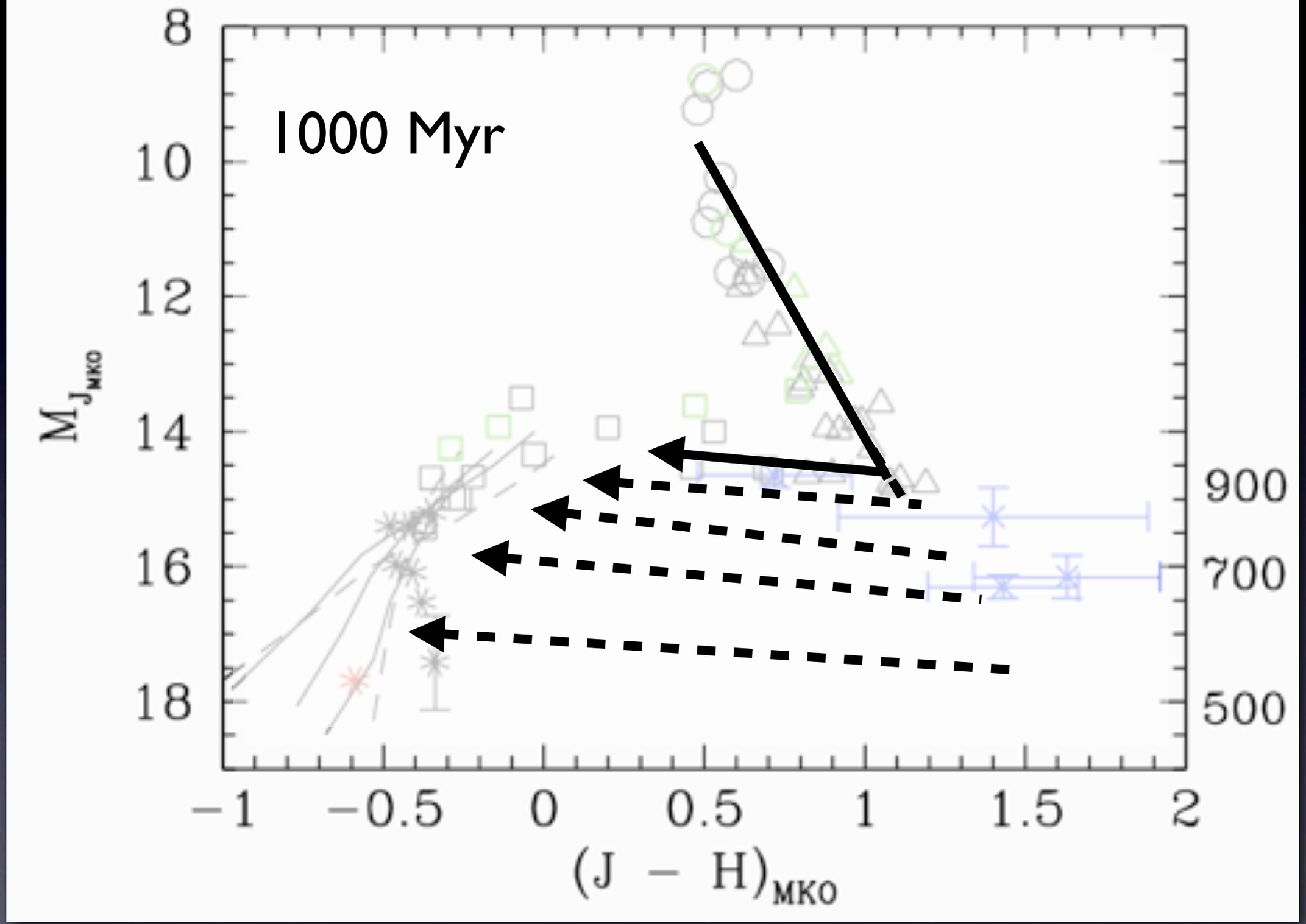

8
10
12
14
16
18
$M_{J_{МКО}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{МКО}$

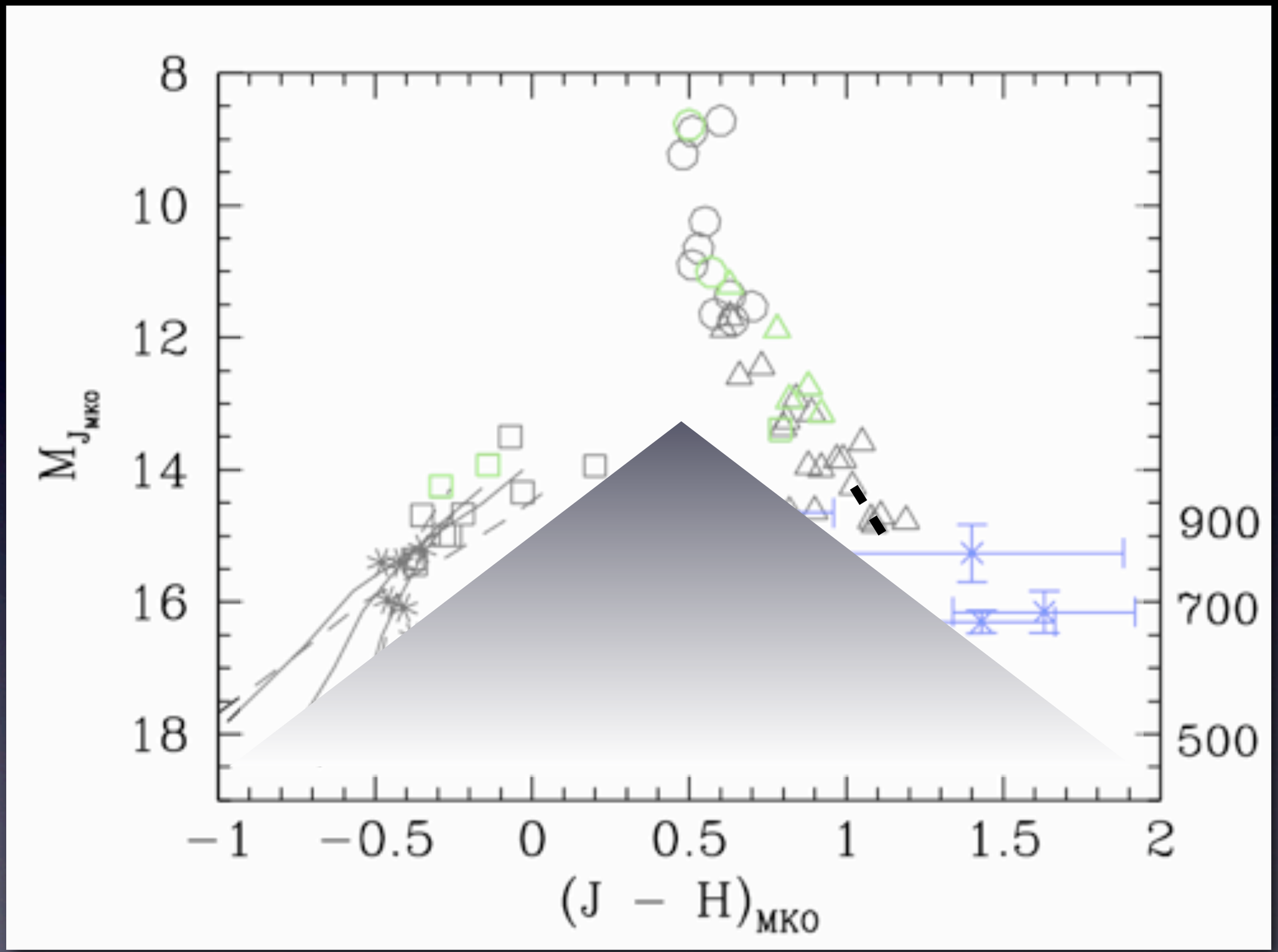

10 Myr
High mass
Low mass
8
10
12
14
16
18
$M_{J_{MKO}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{MKO}$


20 Myr
High mass
8
10
12
14
16
18
$M_{J_{MKO}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{MKO}$


100 Myr
High mass
8
10
12
14
16
18
$M_{J_{MKO}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{MKO}$


200 Myr
High mass
8
10
12
14
16
18
$M_{J_{MKO}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{MKO}$


1000 Myr
8
10
12
14
16
18
$M_{J_{MKO}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{MKO}$


8
10
12
14
16
18
$M_{J_{МКО}}$
900
700
500
−1
−0.5
0
0.5
1
1.5
2
$(J - H)_{МКО}$

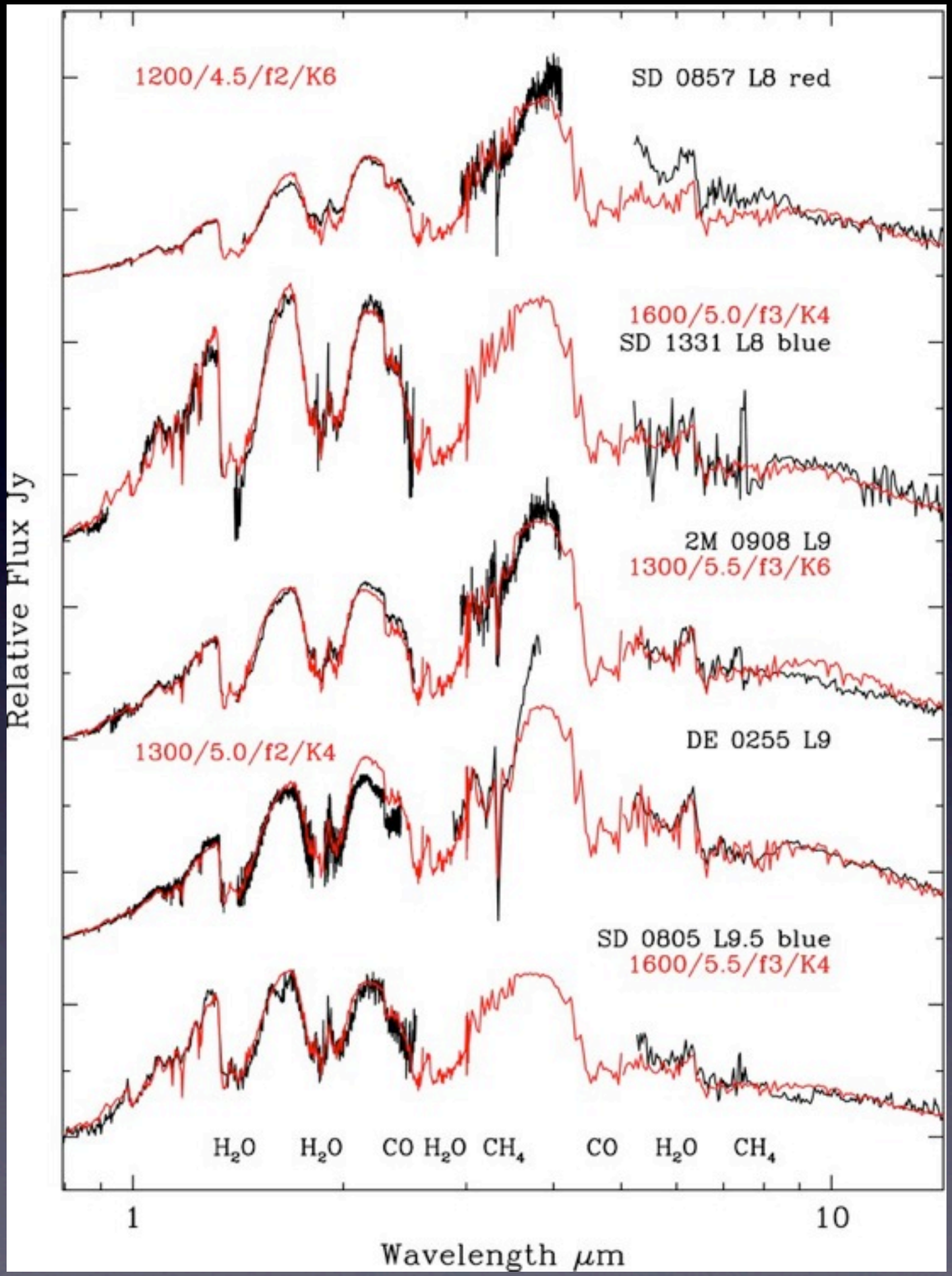
Gravity-dependent L to T turnoff

- Already hints of this in field L & T dwarfs
- Pleiades turnoff is ~200 K cooler than field
- Predicts many planets in between classical L and T sequences
- If true standard cloud models will describe cloudy planets

Test with Cloud Models

- Most in literature are simple parameterizations (specify cloud base, thickness, particle sizes)
- None of these reproduce spectra or colors of cloudiest L dwarfs
- Ackerman & Marley (2001) model *predicts* particle sizes and vertical distribution. Not perfect but step beyond parameterization.

Tested Cloud Model



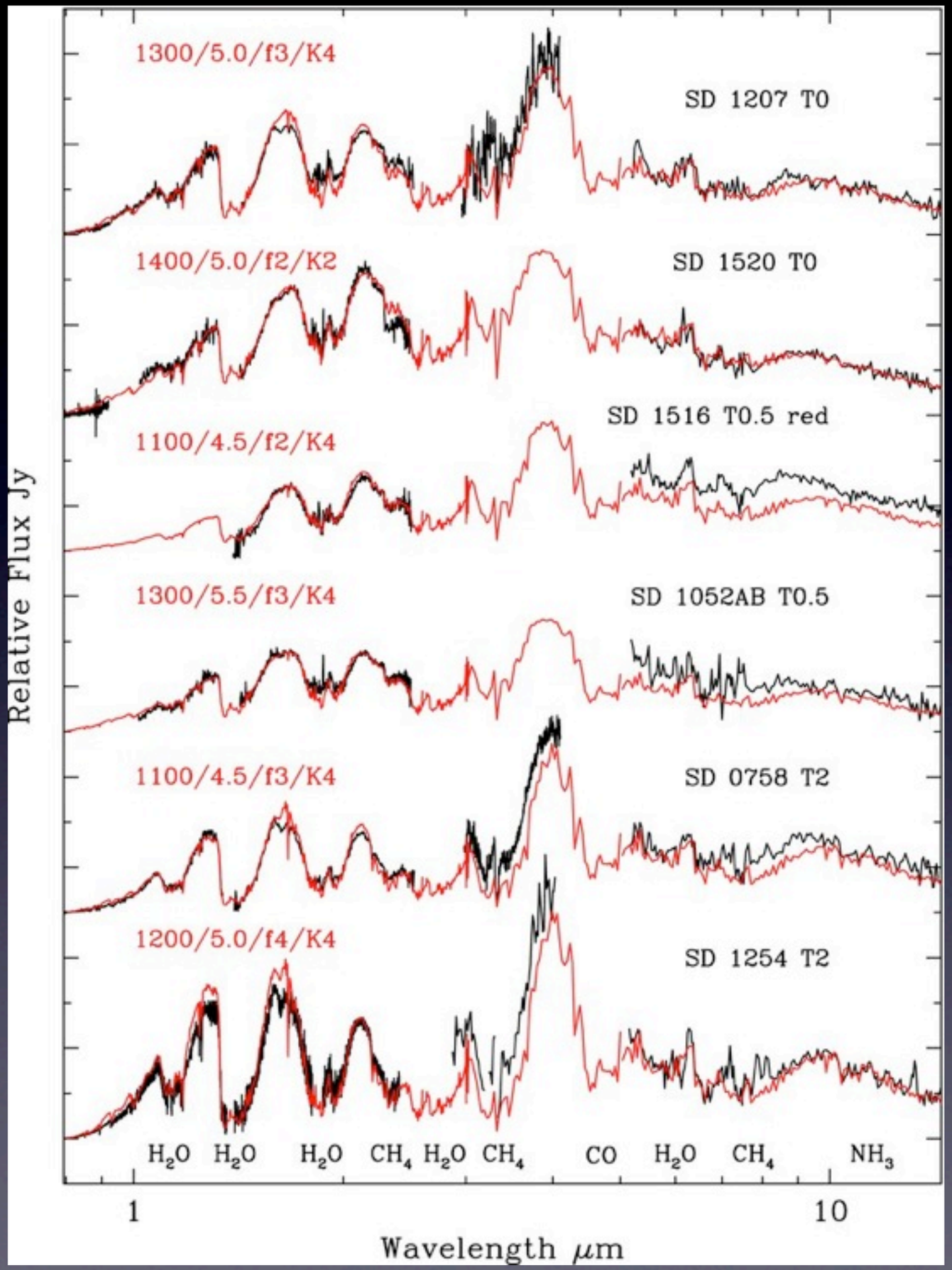
L8

blue L8

L9

L9

blue L9.5



T0

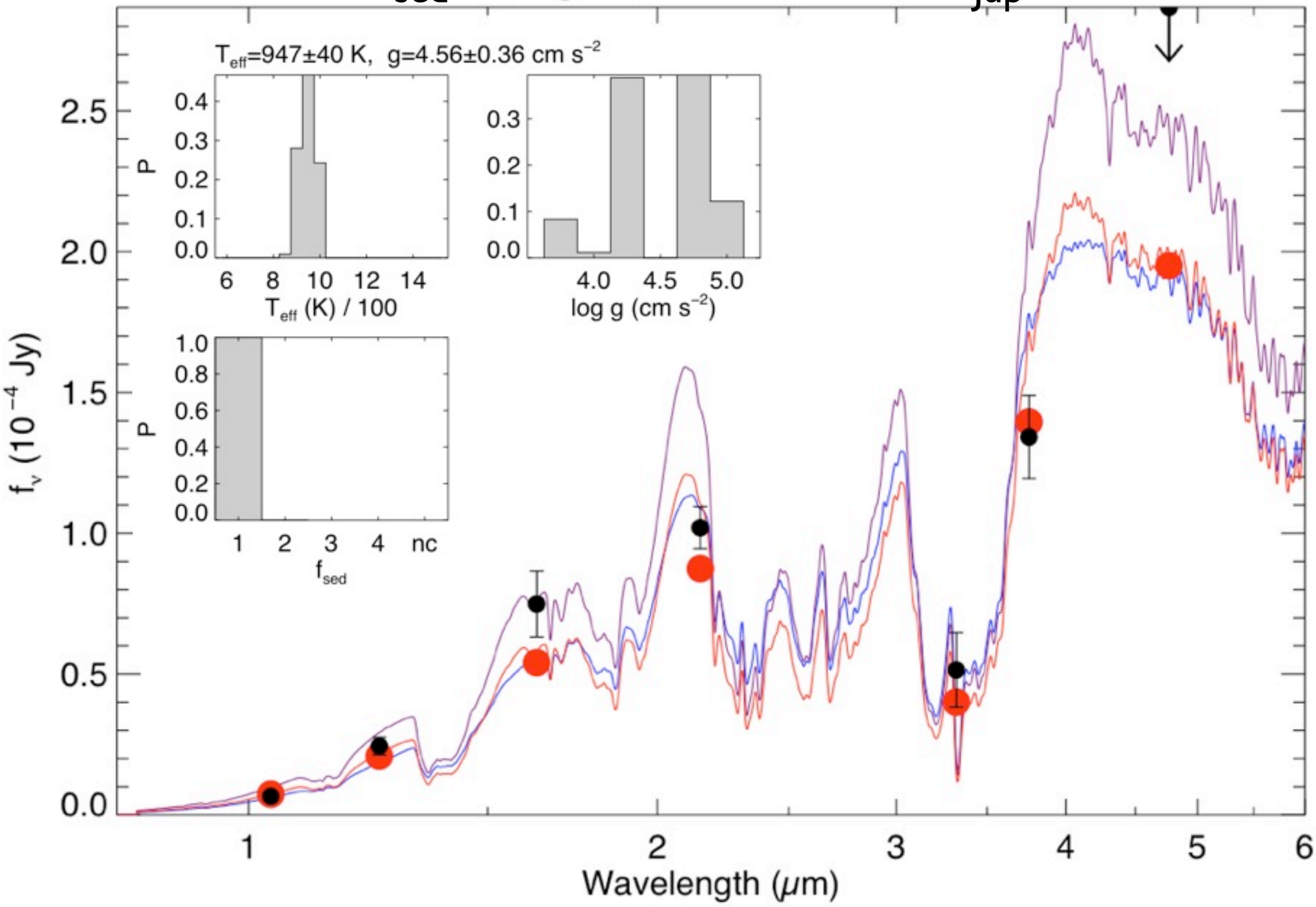
red T0.5
best HR 8799 b match

T2

HR 8799 b,c,d

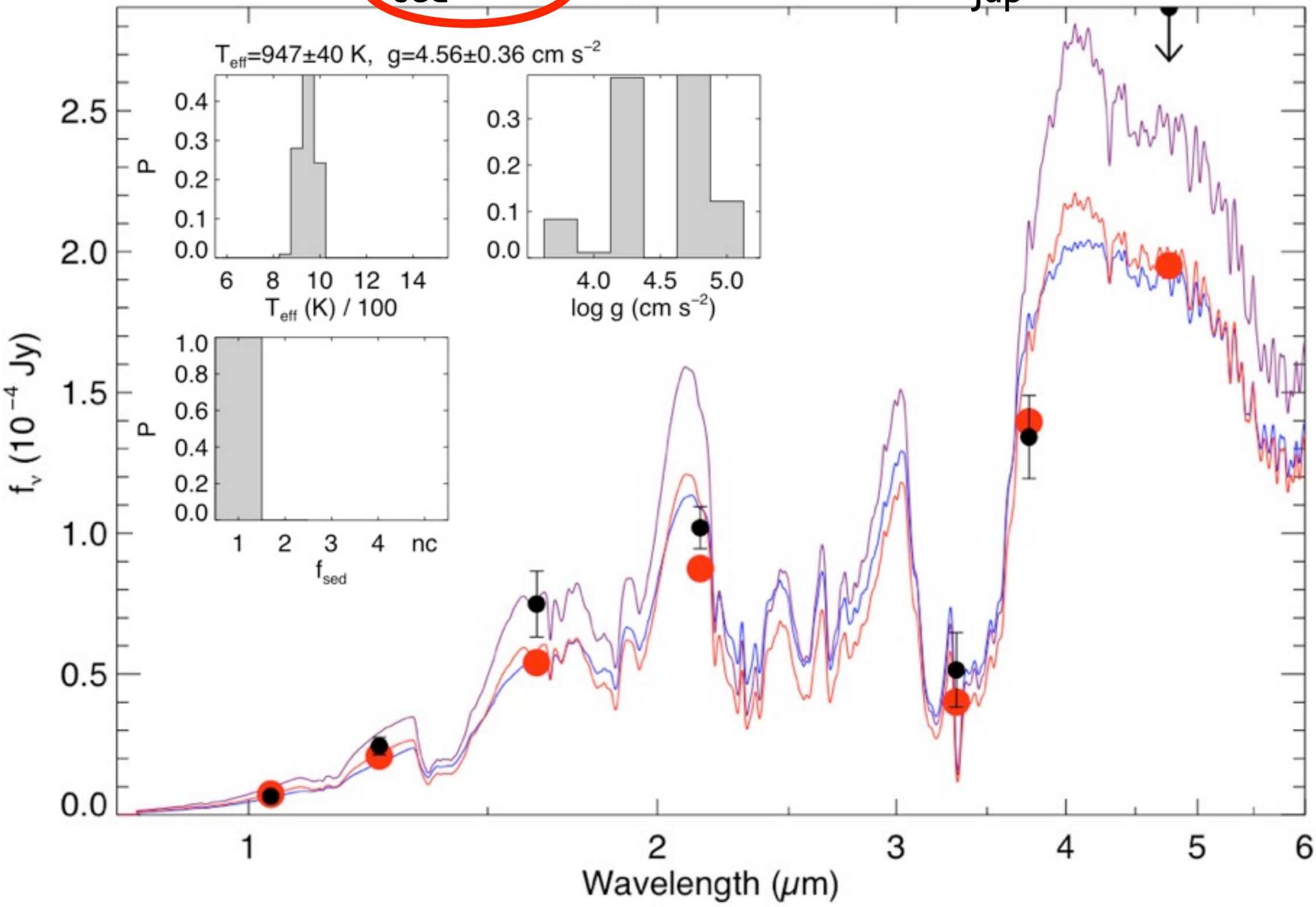
(self-consistent radii)

b: f_{sed} = 1 M ~ 10 to 40 M_{Jup}



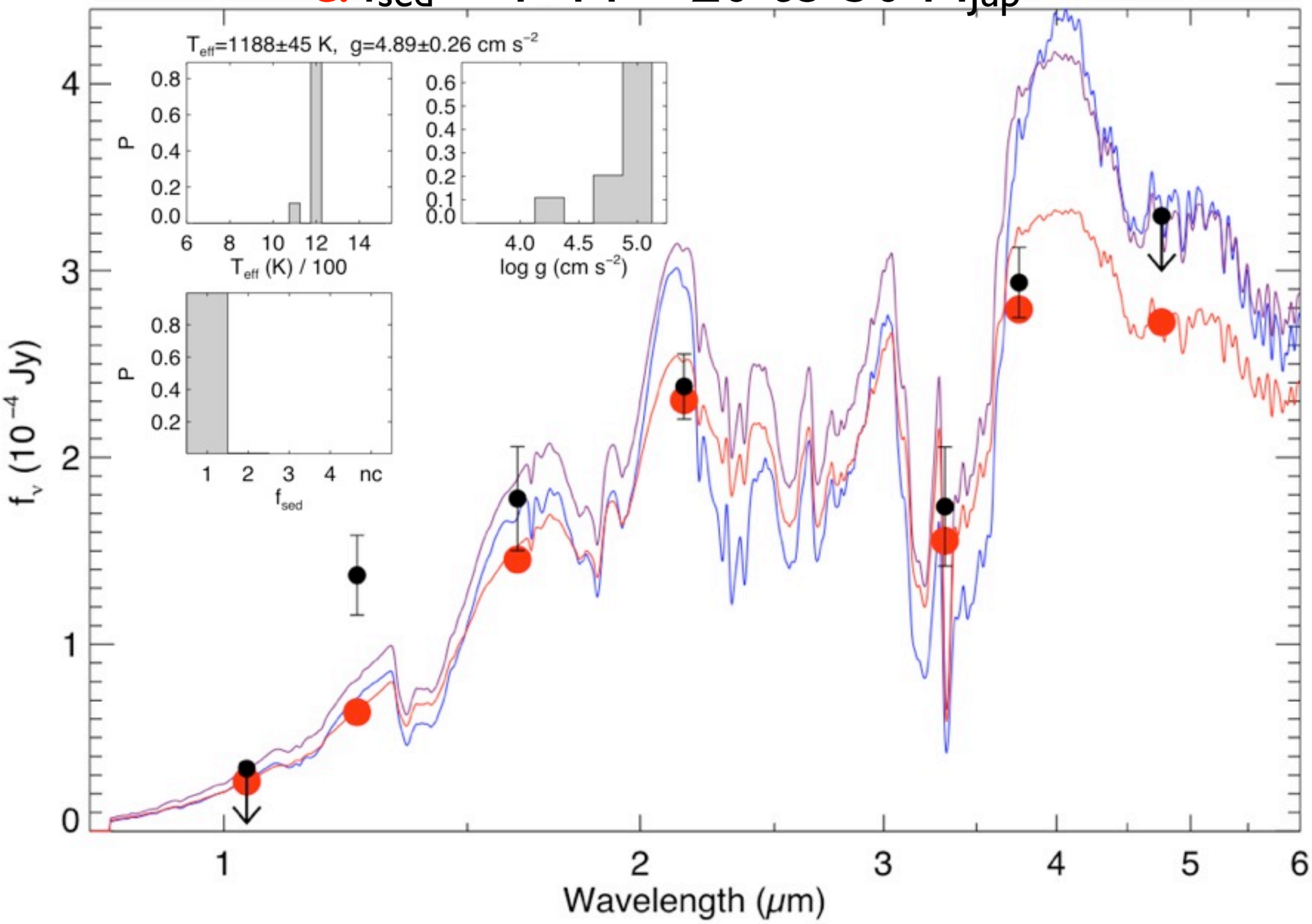
Marley et al. (in prep)

b: f_{sed} = 1 M ~ 10 to 40 M_{Jup}



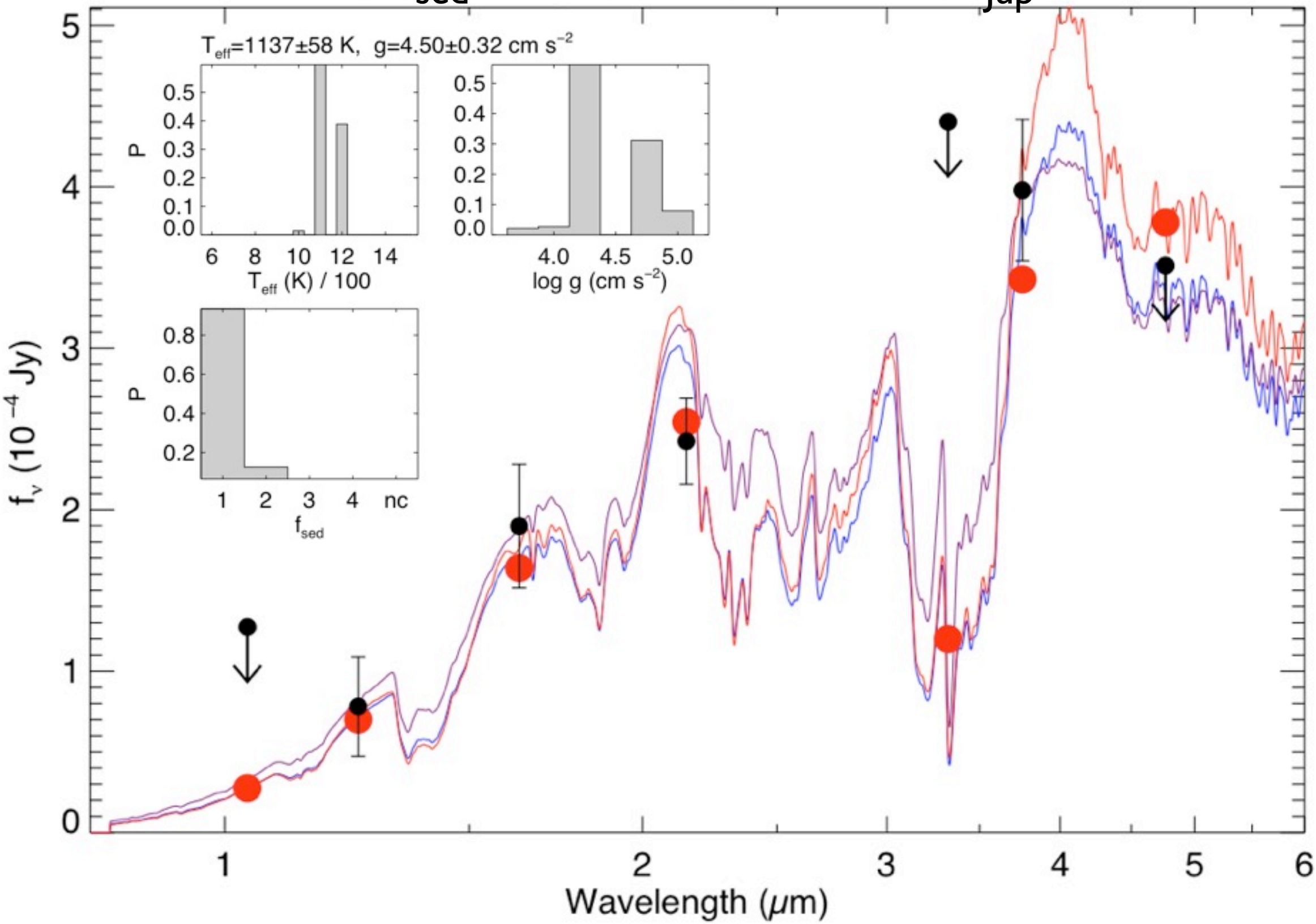
Marley et al. (in prep)

c: f_{sed} = 1 M ~ 20 to 50 M_{Jup}



Marley et al. (in prep)

d: f_{sed} = 1 M ~ 10 to 30 M_{Jup}

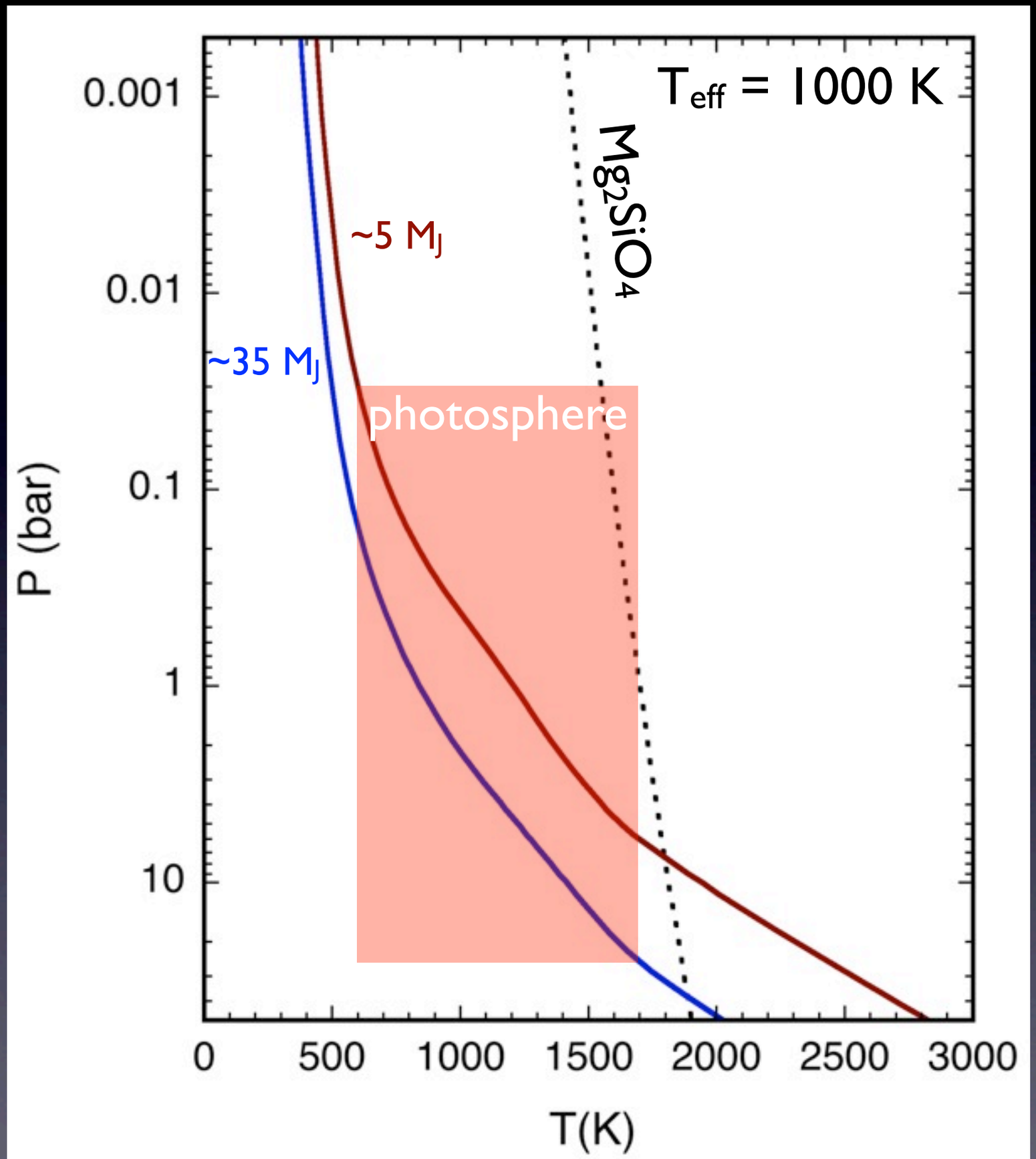


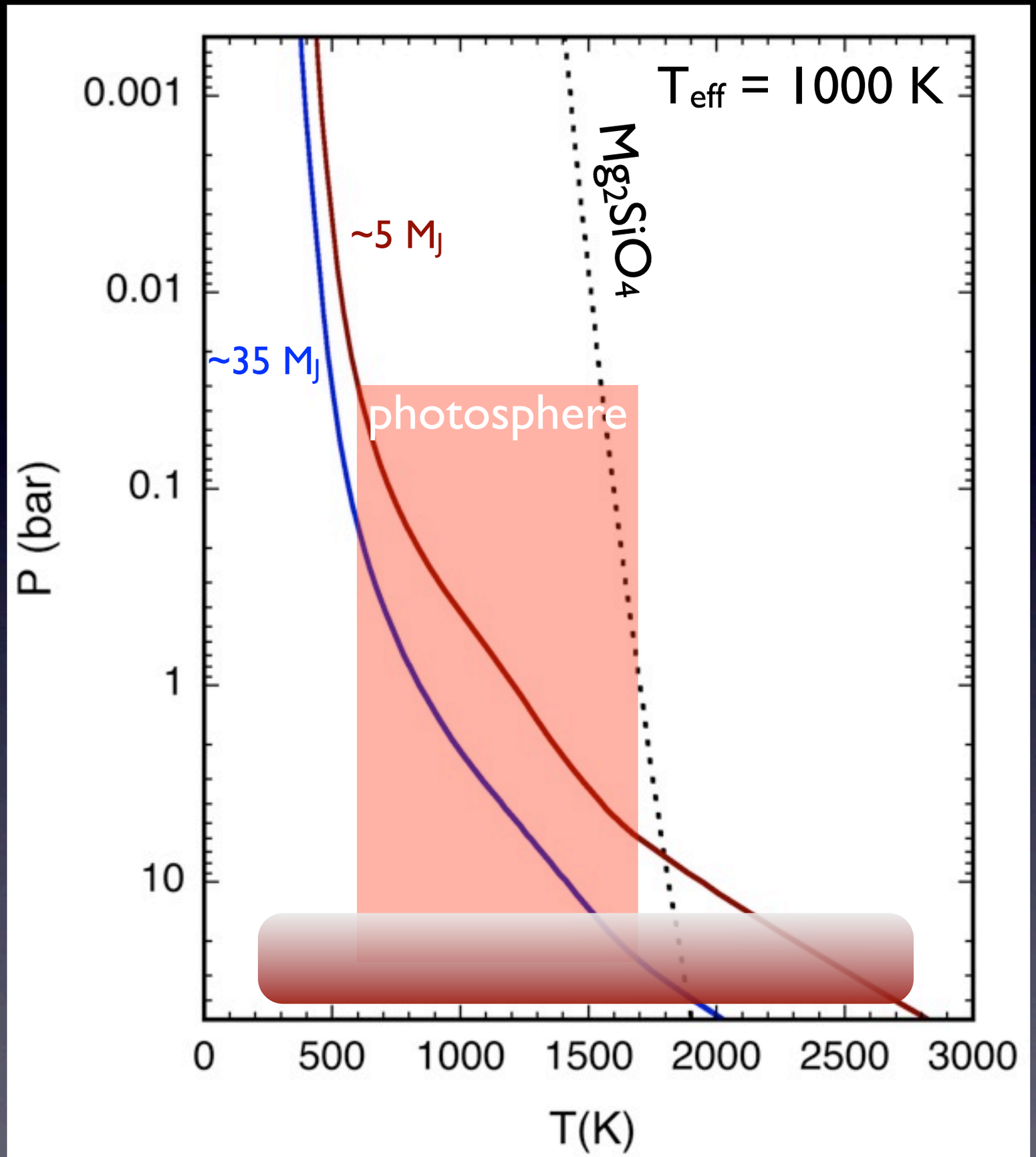
Marley et al. (in prep)

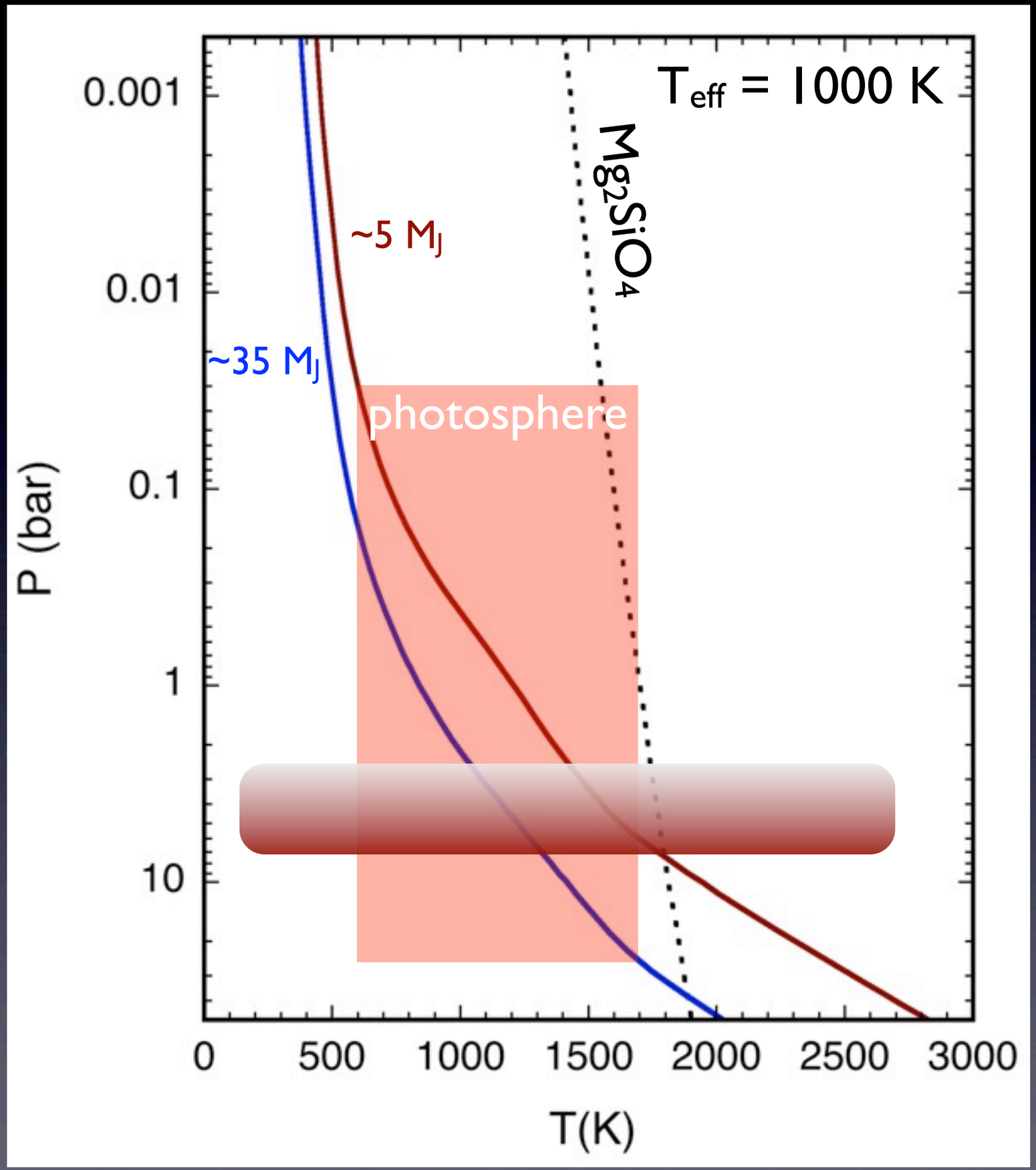
Standard L & T dwarf models using Ackerman & Marley (2001) cloud fits 19 of 21 photometric points

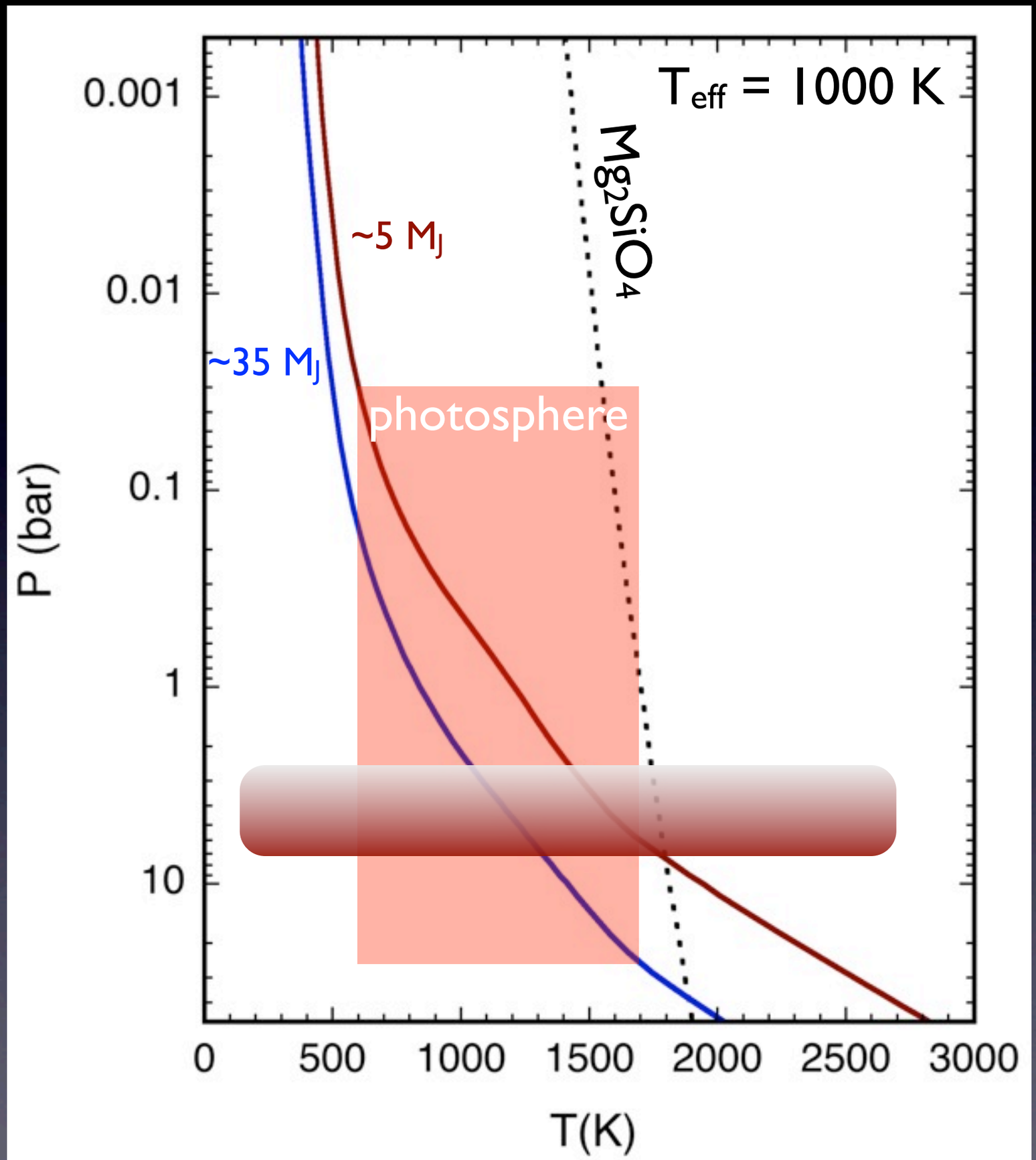
Not "radically enhanced" cloud or a "new class", just standard cloud present to lower T_{eff}

Why might this happen?


T_{eff} = 1000 K
Mg_2SiO_4
~5 M_J
~35 M_J
photosphere
0.001
0.01
0.1
1
10
P (bar)
0
500
1000
1500
2000
2500
3000
T(K)


T_{eff} = 1000 K
Mg_2SiO_4
~5 M_J
~35 M_J
photosphere
0.001
0.01
0.1
1
10
P (bar)
0
500
1000
1500
2000
2500
3000
T(K)


T_{eff} = 1000 K
Mg_2SiO_4
~5 M_J
~35 M_J
photosphere
0.001
0.01
0.1
1
10
P (bar)
0
500
1000
1500
2000
2500
3000
T(K)

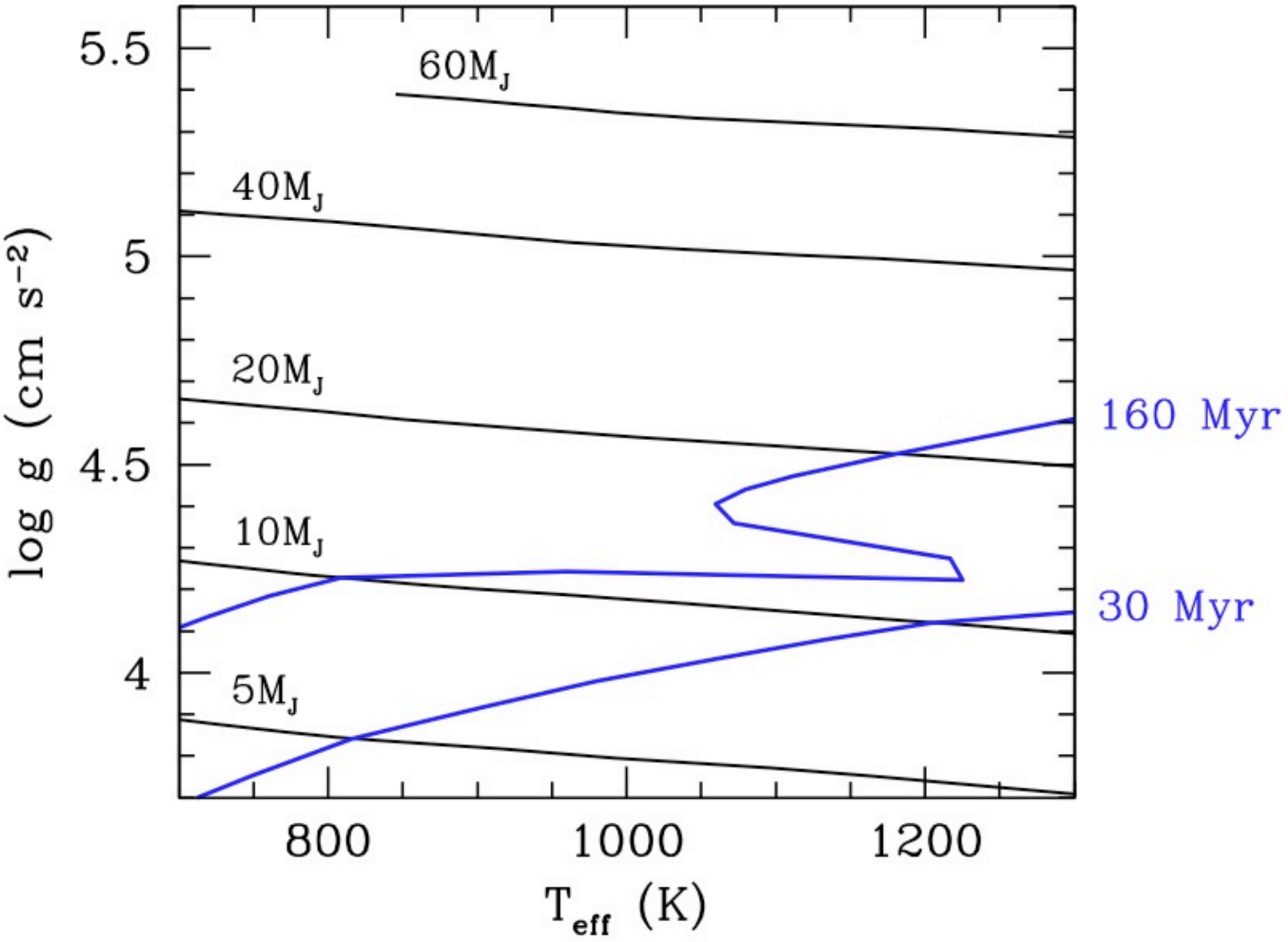


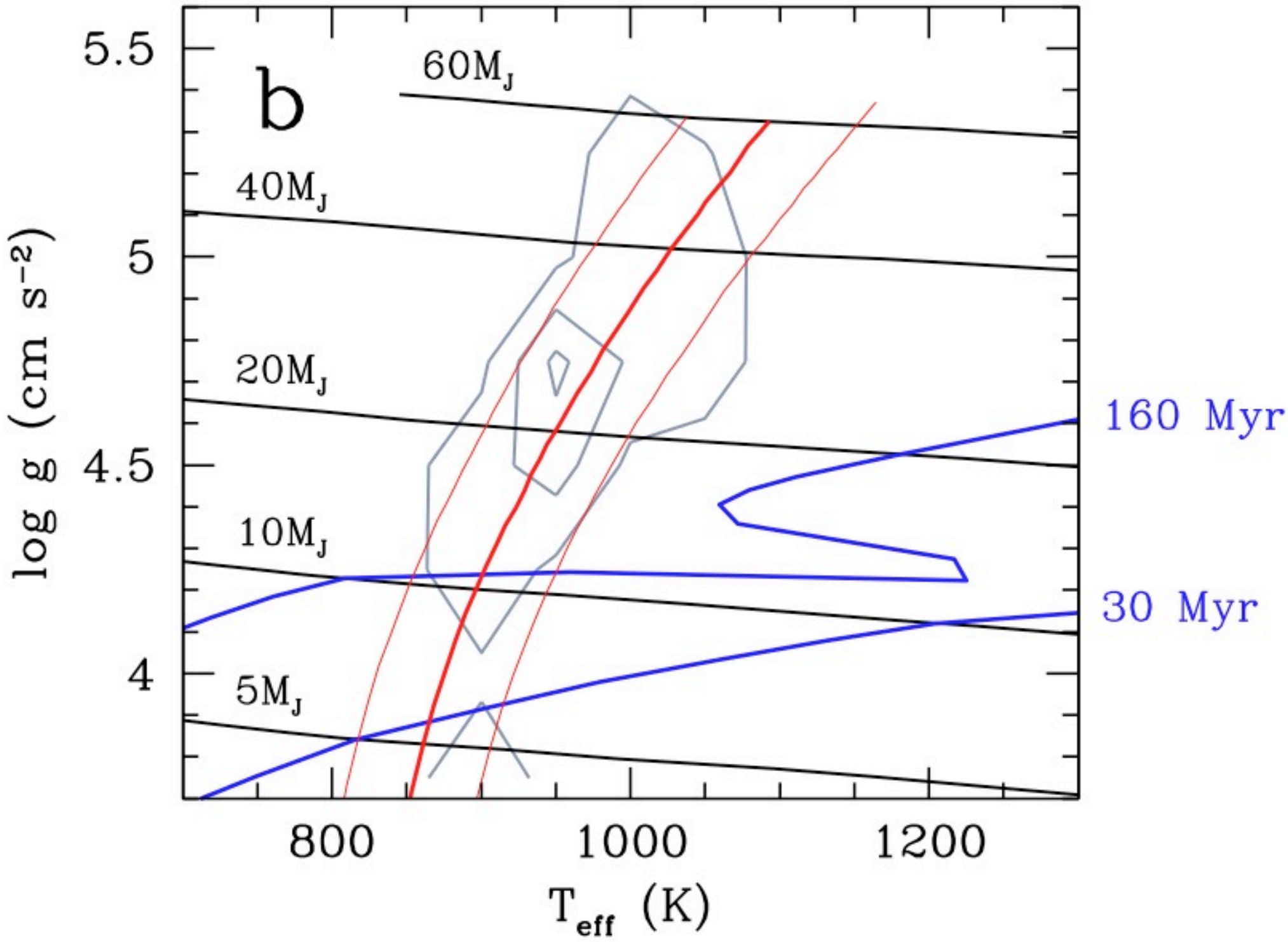
Also expect thicker clouds at lower gravity (Marley 2000)

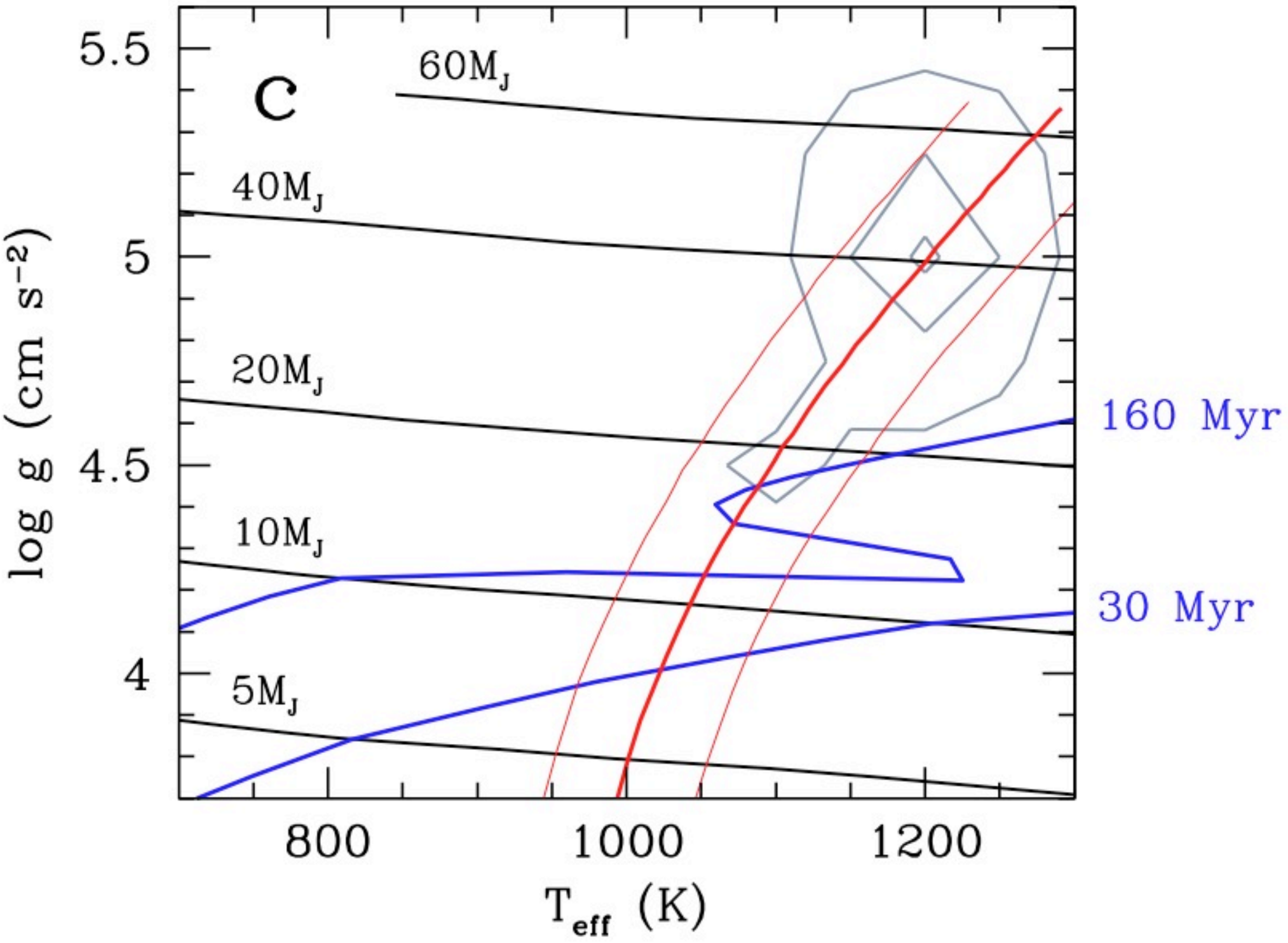
$$\tau \propto \frac{1}{g r_c}$$

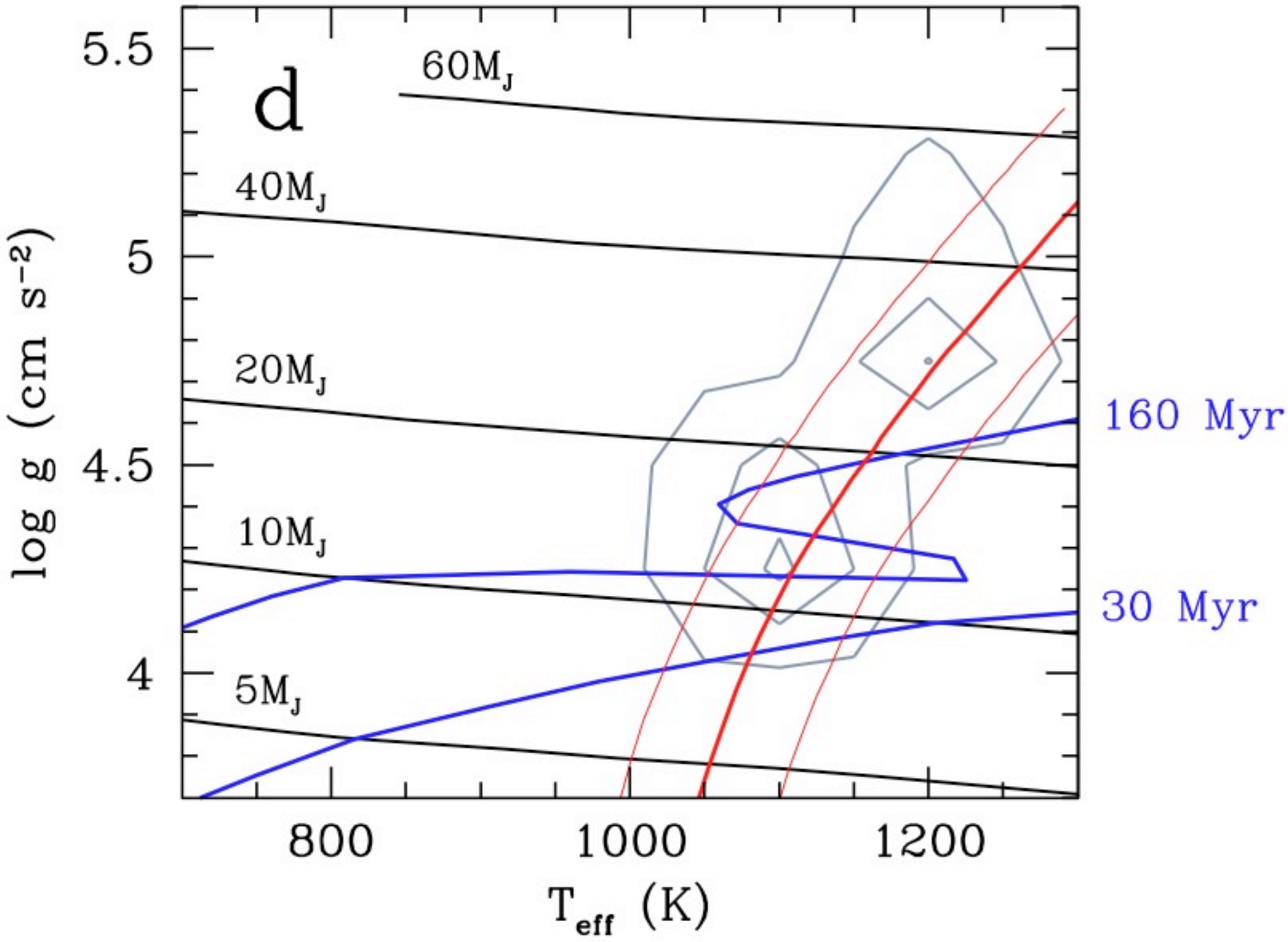
Not Yet Complete

- What about evolution?
- Spectra?

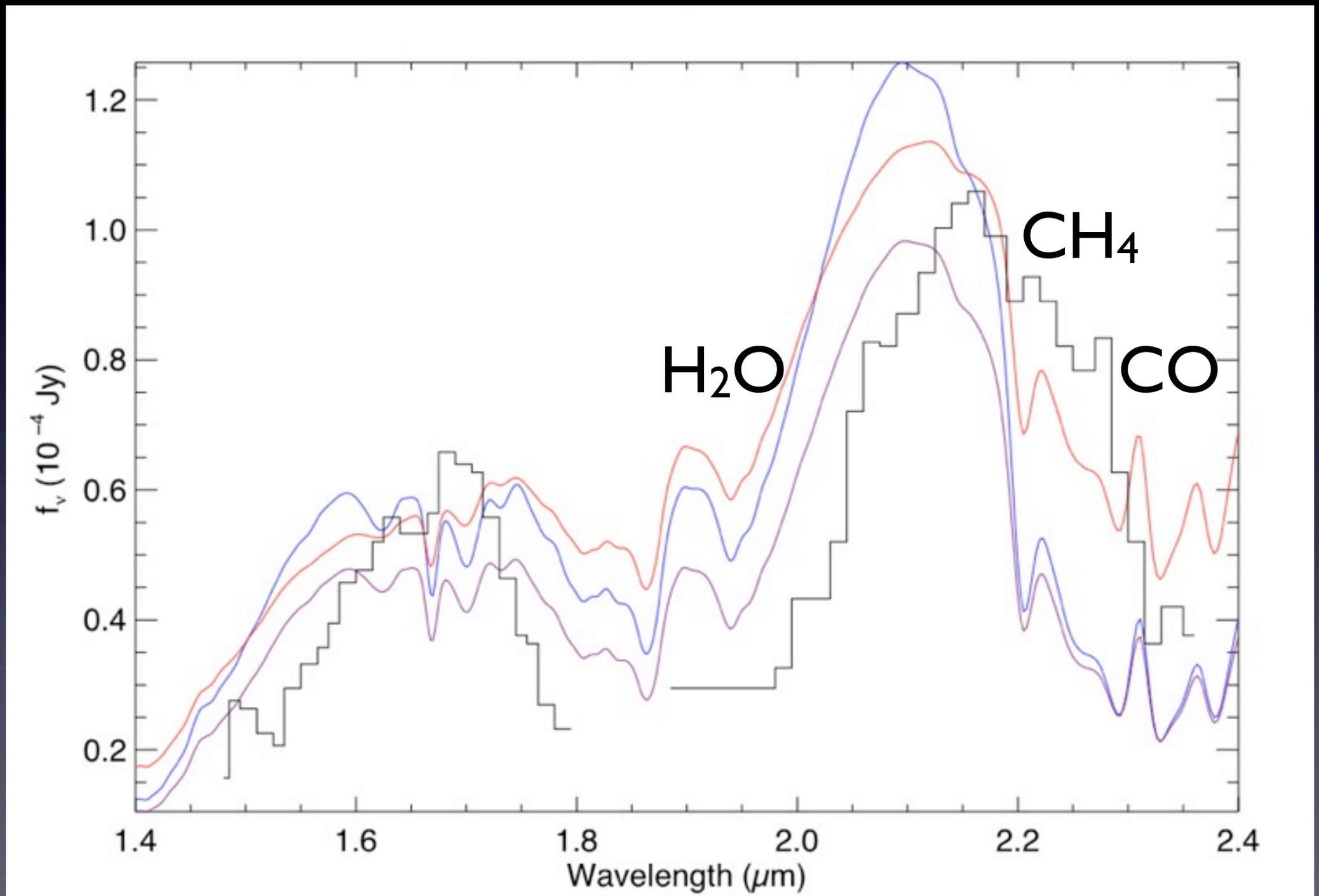

5.5
5
4.5
4
log g (cm s^{-2})
60M$_J$
40M$_J$
20M$_J$
10M$_J$
5M$_J$
160 Myr
30 Myr
800
1000
1200
T$_{eff}$ (K)

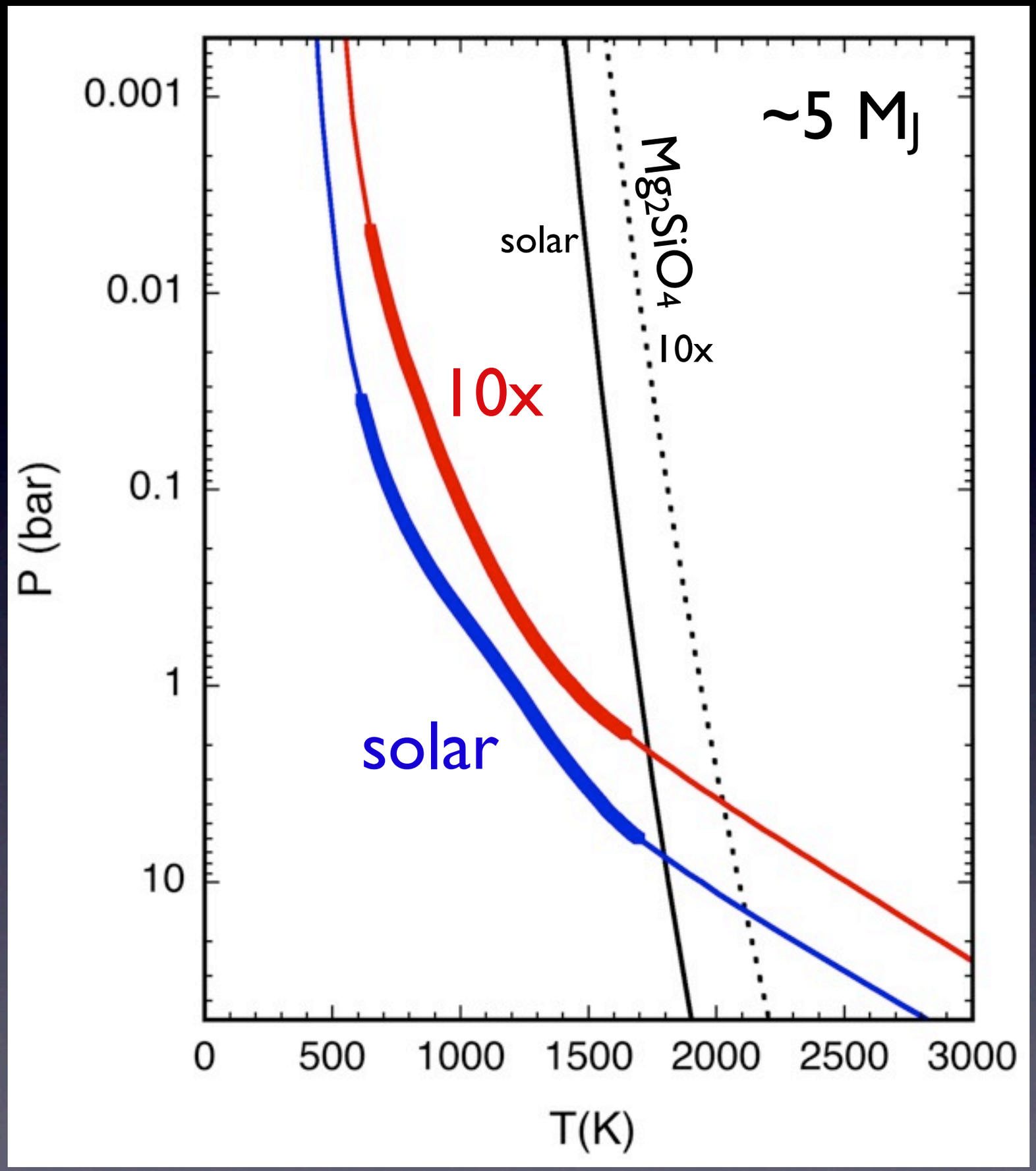

b
60M$_J$
40M$_J$
20M$_J$
10M$_J$
5M$_J$
160 Myr
30 Myr
5.5
5
4.5
4
log g (cm s^{-2})
800
1000
1200
T$_{eff}$ (K)


C
60M$_J$
40M$_J$
20M$_J$
10M$_J$
5M$_J$
160 Myr
30 Myr
5.5
5
4.5
4
log g (cm s^{-2})
800
1000
1200
T$_{eff}$ (K)


d
60M$_J$
40M$_J$
20M$_J$
10M$_J$
5M$_J$
160 Myr
30 Myr
5.5
5
4.5
4
log g (cm s^{-2})
800
1000
1200
T$_{eff}$ (K)

H & K Spectra May Imply High Metallicity





But... Cloud is farther from photosphere at high metallicity

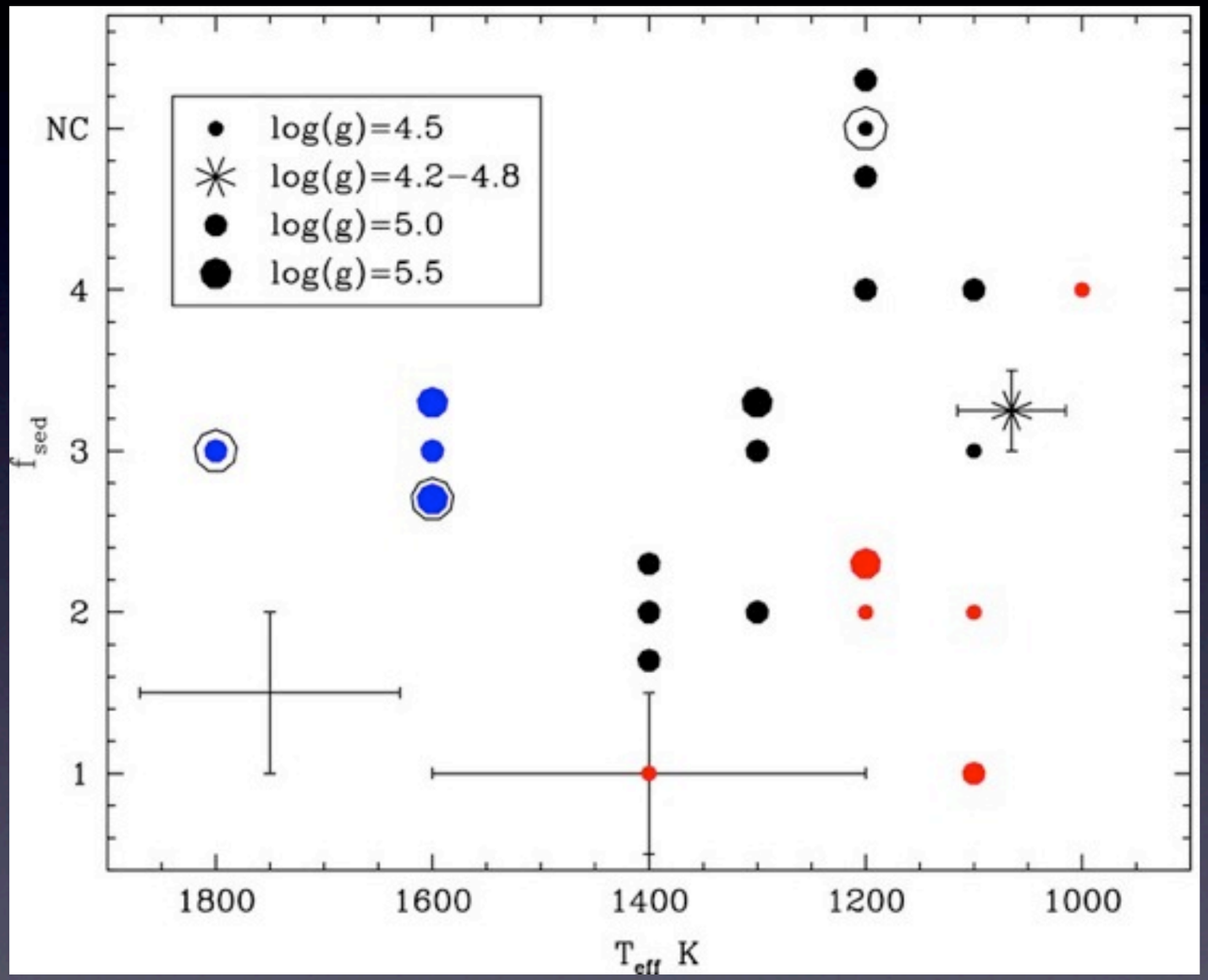
Conclusions

- Thick clouds at lower gravity is not a huge surprise
- Standard cloudy models **can** fit HR 8799bcd spectra with gravity-dependent transition T_{eff}
- Need to understand cloud structure, global dynamics as a function of gravity
- Evolution & spectra not yet fully in agreement
- Signs of other effects, including non-equilibrium chemistry and high metallicity

Why Later Transition T_{eff}?

- Gravity ?
- Metallicity ?

Thinner clouds ↑



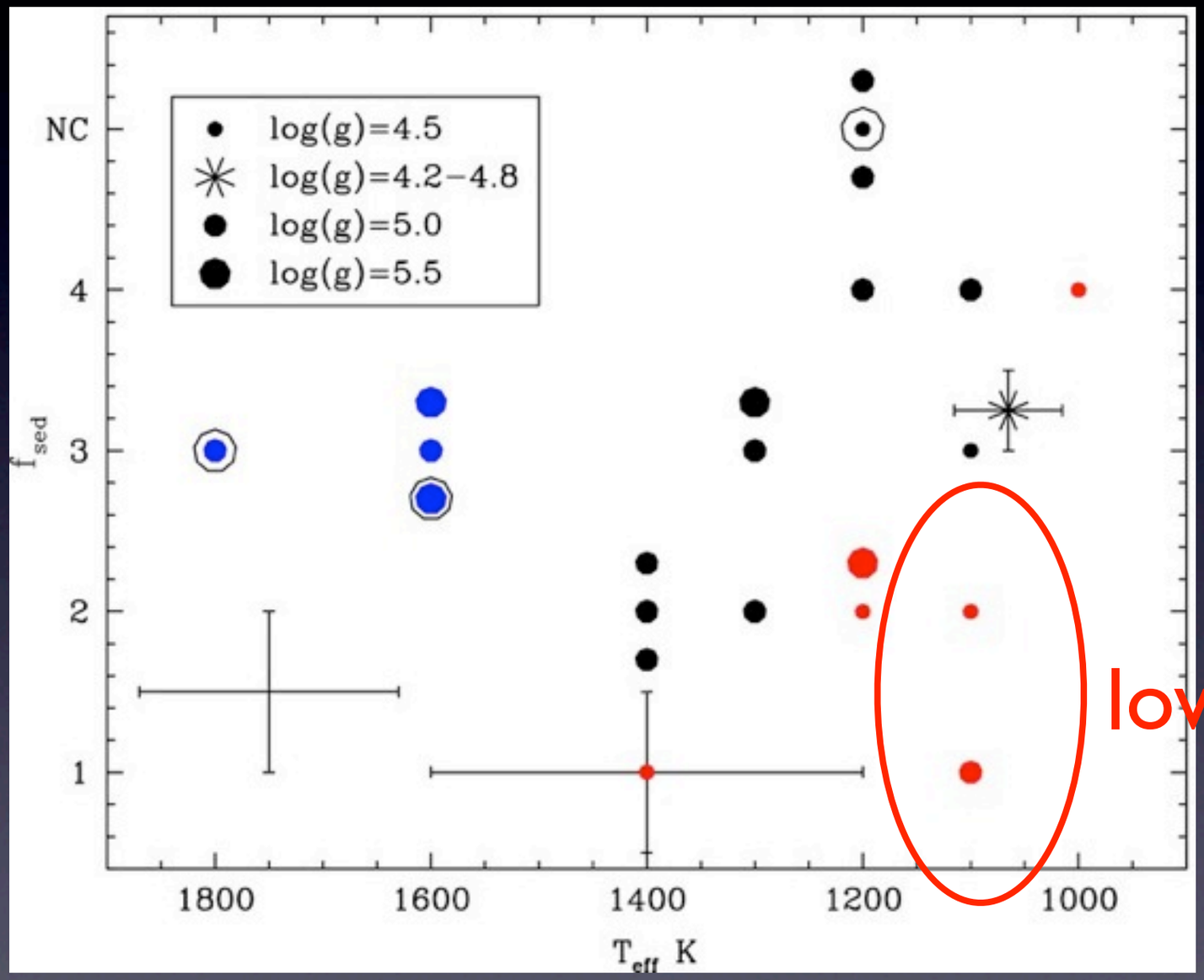
Stephens et al. (2010)

Cooler Temps →

Why Later Transition T_{eff}?

- Gravity ?
- Metallicity ?

Thinner clouds ↑



Stephens et al. (2010)

Cooler Temps →