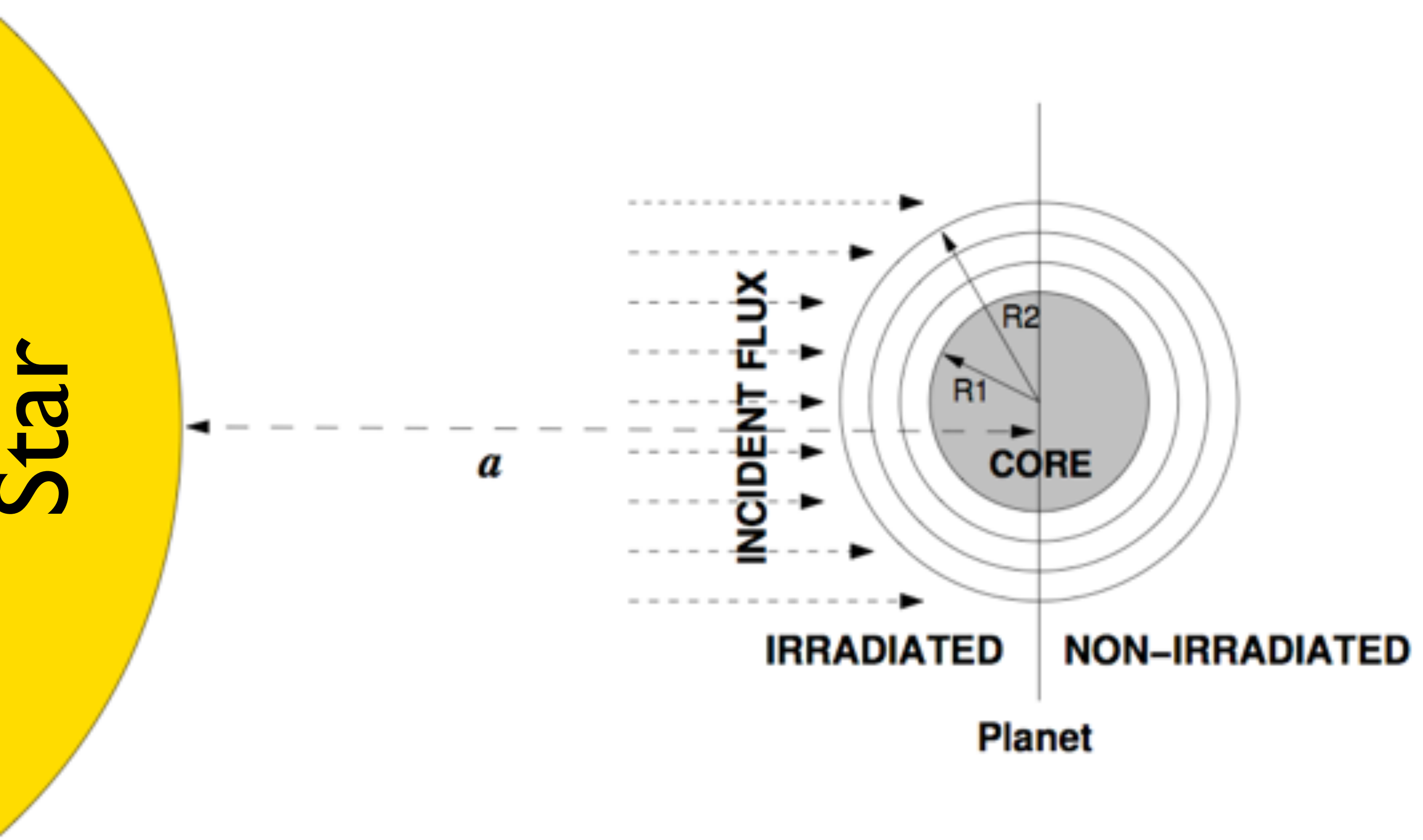
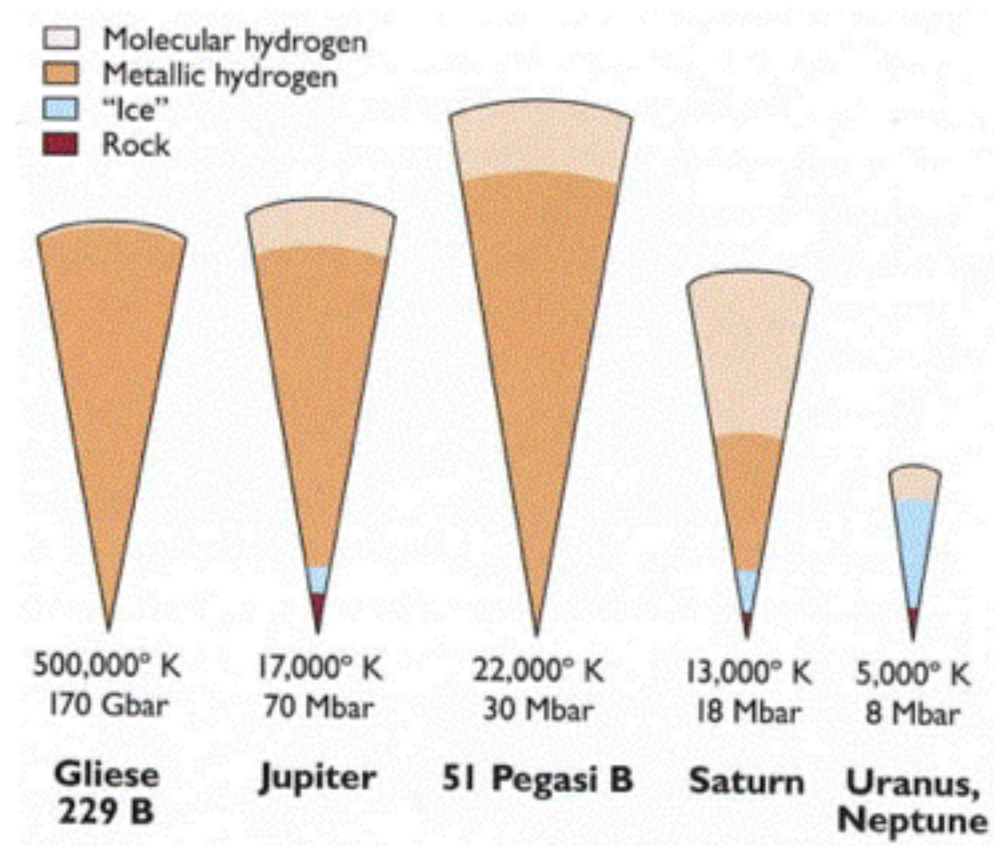
Exoplanet Atmospheres

- Motivation (brown dwarfs, observations ,etc.)
- equilibrium and non-equilibrium chemistry
- radiative transfer, opacities, and spectra
- simplified model atmosphere problems
- retrieval techniques

Atmosphere: Hydrogen & Helium, or other stuff.

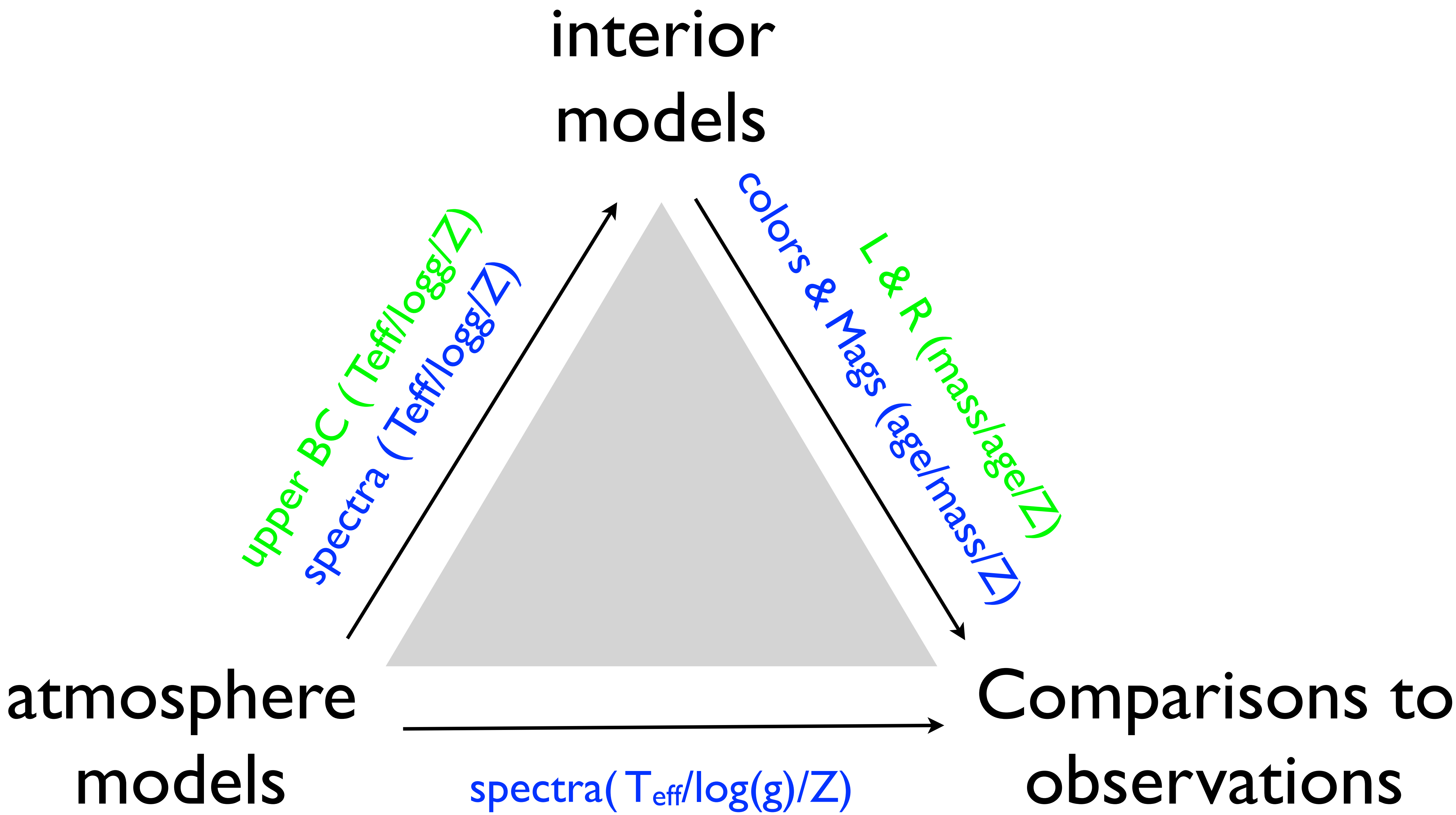
Interior: solid (rock, ice) or convective fluid (Hydrogen, Helium)



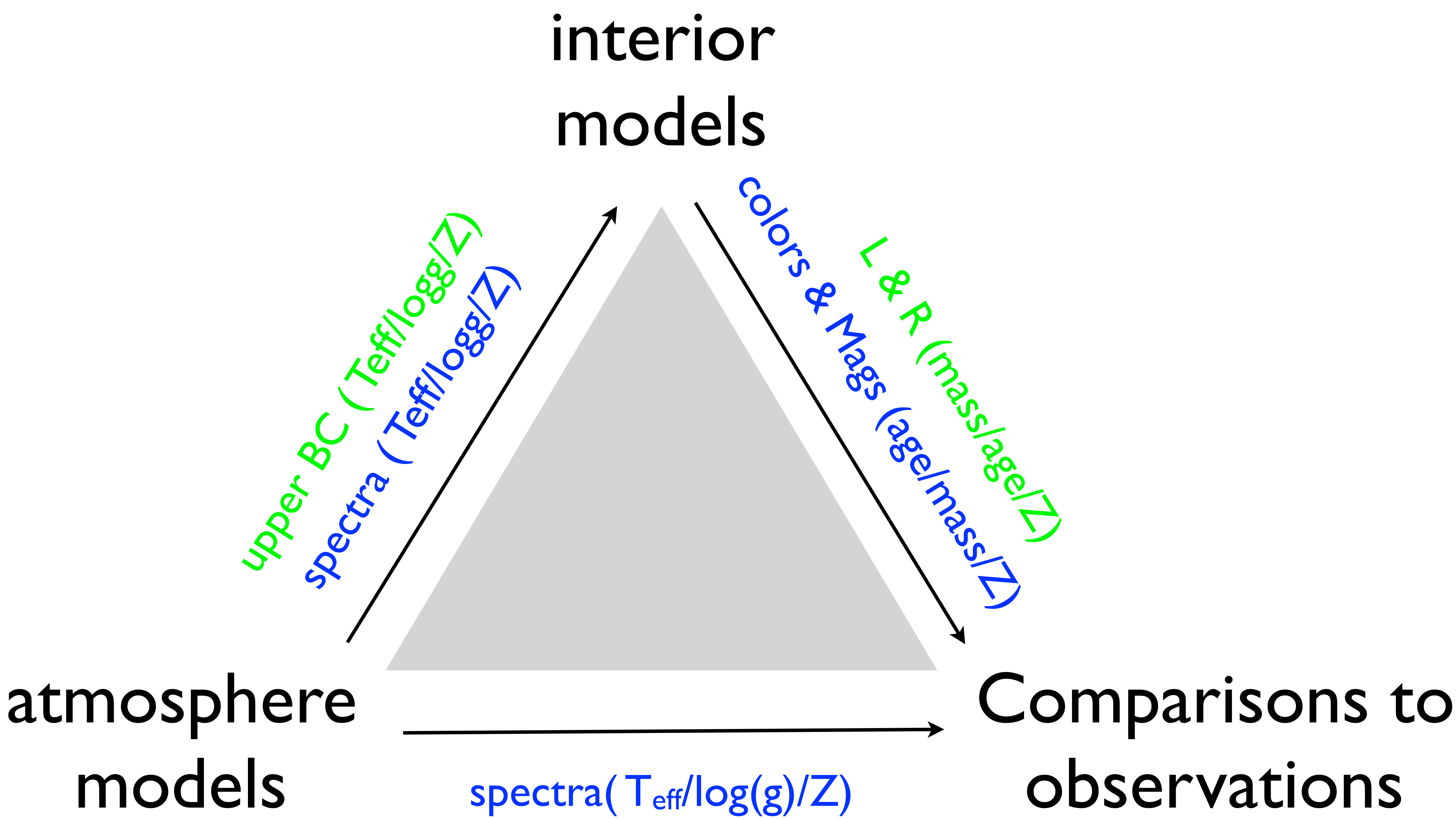


Bottom Layer: abrupt solid/liquid surface or deep continuous transition region.

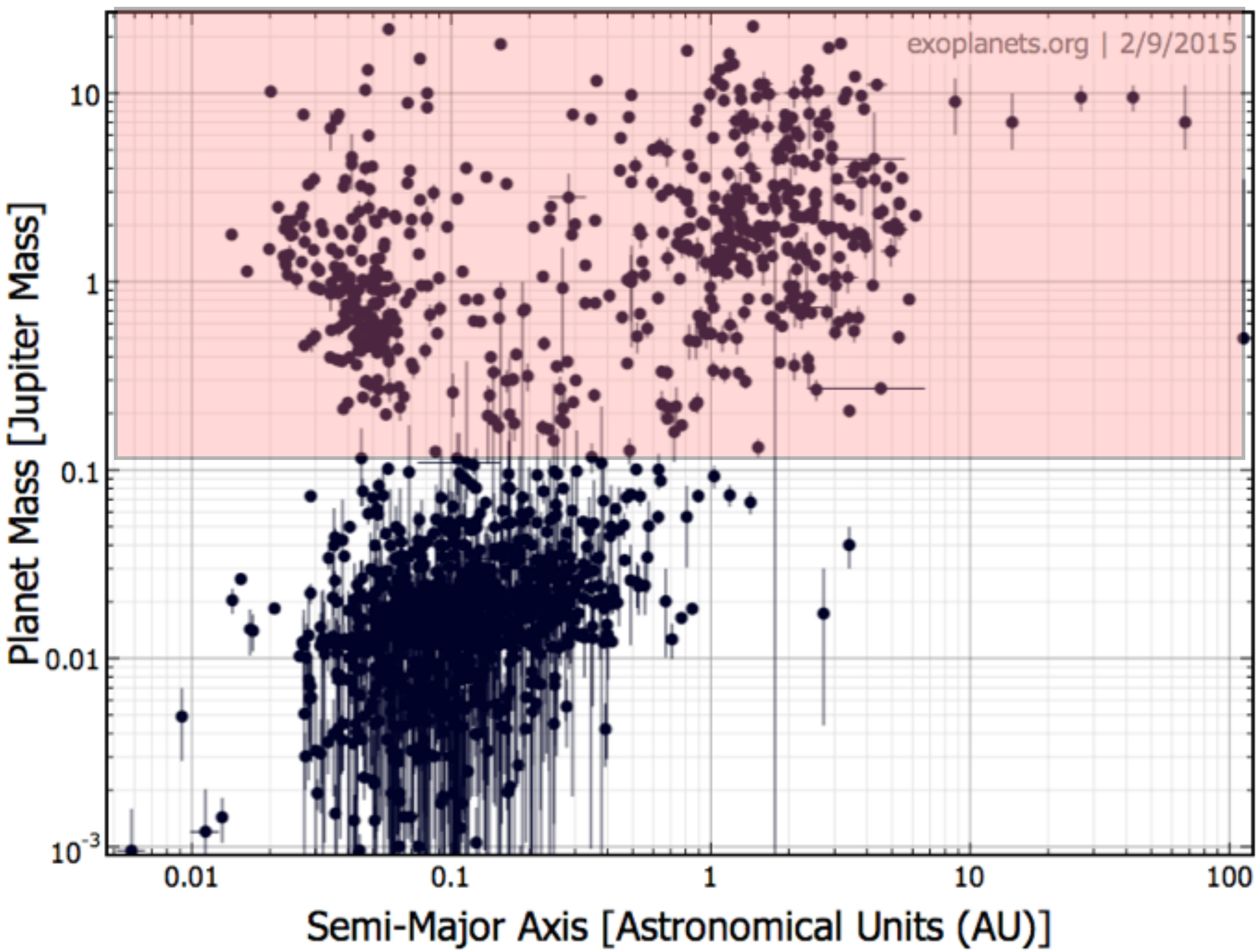
Atmosphere [noun]:
"a transition region between the stellar interior and the interstellar medium" (Grey 1992)



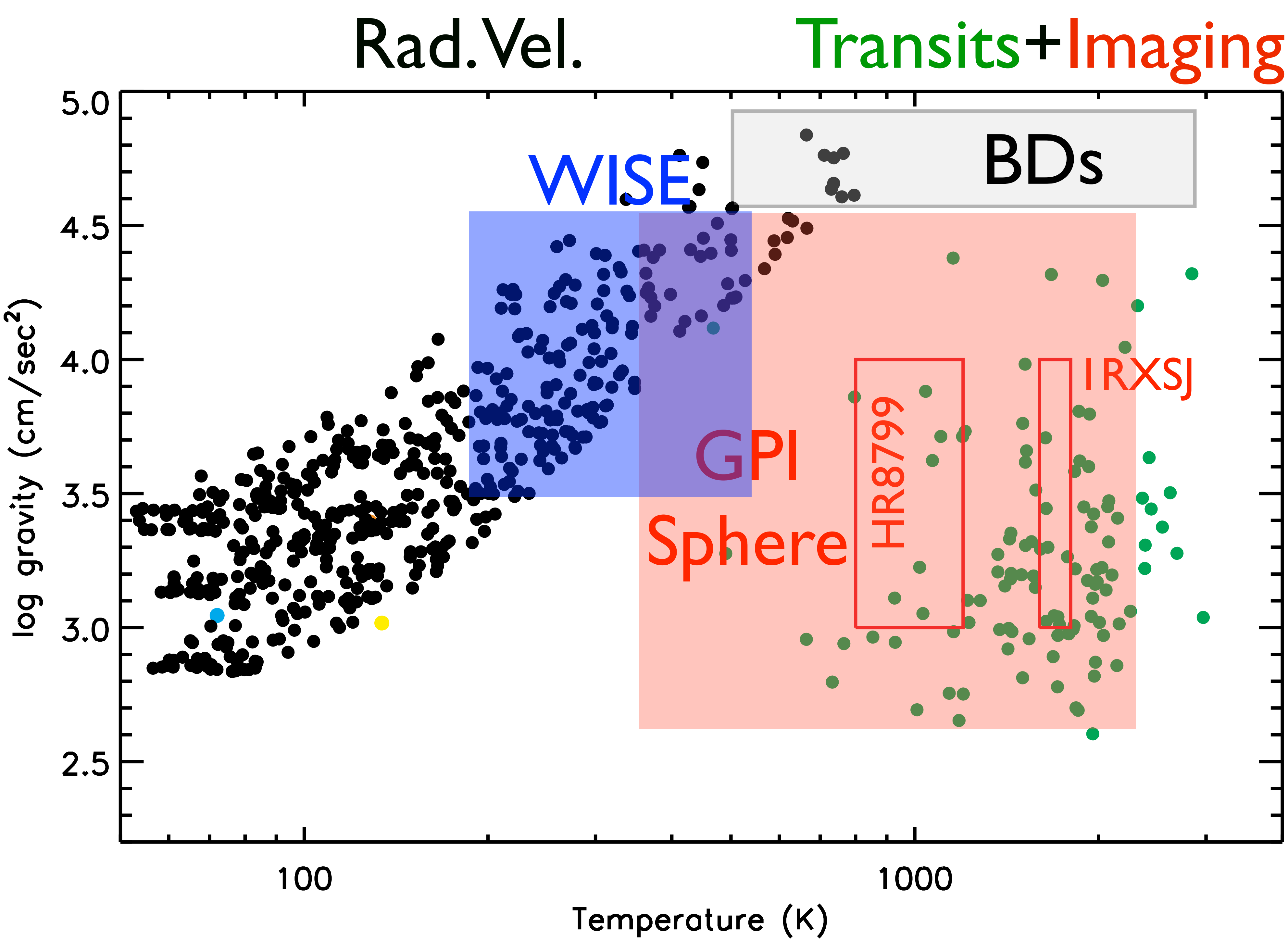
Atmosphere [noun]:
a transition region between the planet interior and the interplanetary medium



We will focus first on giants



The atmospheres we can study are generally warm to hot



$$\sigma T_{\rm eff}^4 = \int F_\nu d\nu$$

Lessons Learned from Brown Dwarfs
(~ 500K < T_{eff} < 2500K)

- $M/M_{Jup} > 80$ (Star)
- $13 < M/M_{Jup} < 80$ (Brown Dwarf)
- $M/M_{Jup} < 13$ (planet)

Lessons Learned from Brown Dwarfs
(~ 500K < T_{eff} < 2500K)

- observable atmosphere:
  Tgas ~ 1000K, Pgas ~ 0.1 to 1 bar.

- relatively thin atmospheres (Hp ~ 12 km)

- Major sources of opacity: Water, CIA, "dust", Alkali (Na, K) doublets

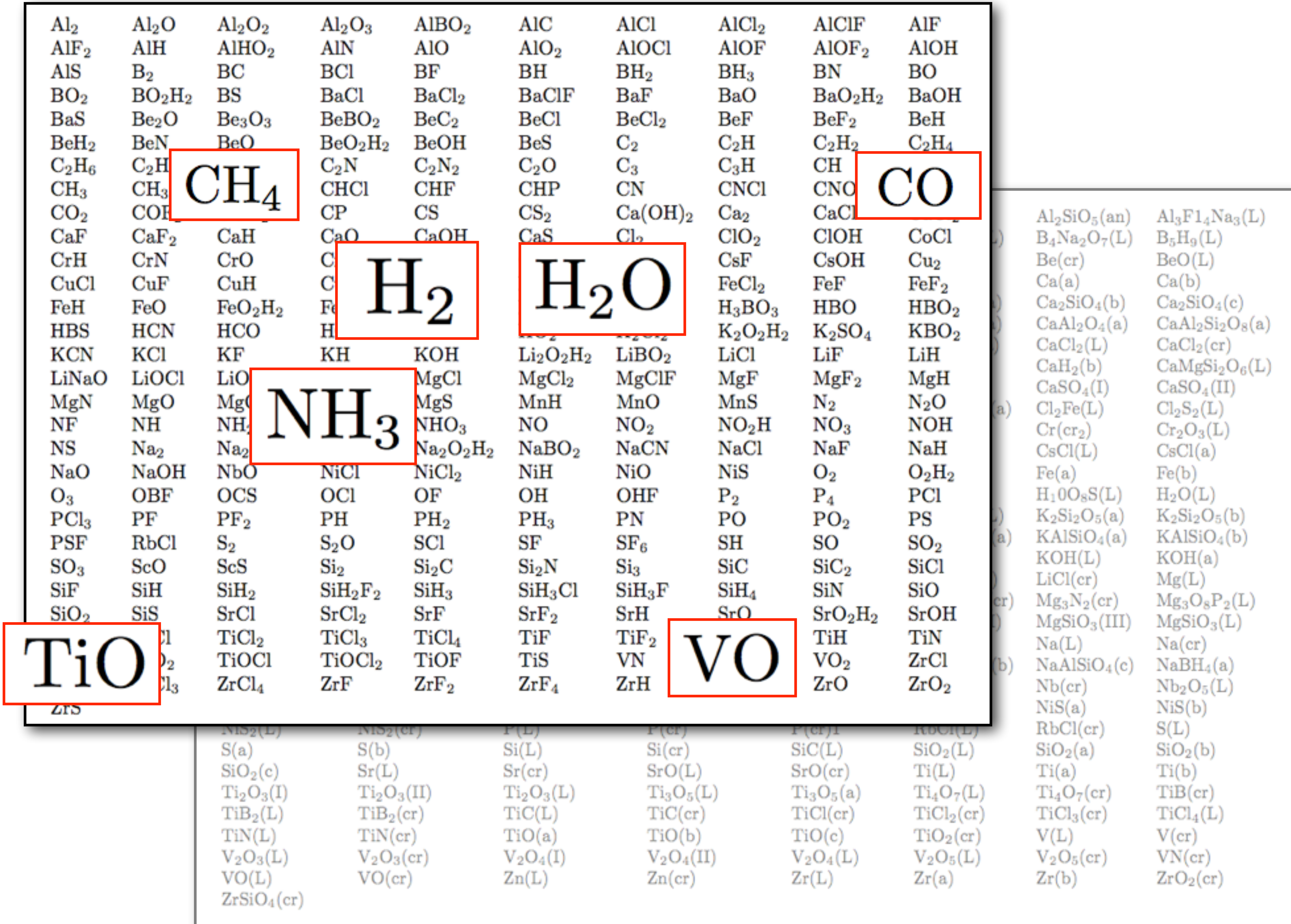
Giant Planet / Brown Dwarf overlap:

- mass: ~1 to < 80 x $M_{jupiter}$
- radius: ~ 1 to < 5 $R_{jupiter}$
- ages: ~ millions to billions of years old
- gravity: ~ 2 orders of magnitude
- effective temperature: ~ 100K to 2500K
- clouds: broad range of grains, ices (complex mixtures)
- non-equilibrium chemistry
- dynamics and "weather"
- BUT: different formation ... (composition & early evolution)

“Solar Abundances” (Asplund et al. 2009)

- solar abundances defines our baseline elemental composition
- solar C,N,O are often debated values (check the reference!)
- starting point for equilibrium chemistry calculations
- the relative values are “initial conditions” of atmosphere models (and usually conserved quantities).

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				



Al_2	Al_2O	Al_2O_2	Al_2O_3	$AlBO_2$	AlC	$AlCl$	$AlCl_2$	$AlClF$	AlF
AlF_2	AlH	$AlHO_2$	AlN	AlO	AlO_2	$AlOCl$	$AlOF$	$AlOF_2$	$AlOH$
AlS	B_2	BC	BCl	BF	BH	BH_2	BH_3	BN	BO
BO_2	BO_2H_2	BS	$BaCl$	$BaCl_2$	$BaClF$	BaF	BaO	BaO_2H_2	$BaOH$
BaS	Be_2O	Be_3O_3	$BeBO_2$	BeC_2	$BeCl$	$BeCl_2$	BeF	BeF_2	BeH
BeH_2	BeN	BeO	BeO_2H_2	$BeOH$	BeS	C_2	C_2H	C_2H_2	C_2H_4
C_2H_6			C_2N	C_2N_2	C_2O	C_3	C_3H	CH	
CH_3			$CHCl$	CHF	CHP	CN	$CNCl$		
CO_2			CP	CS	CS_2	$Ca(OH)_2$	Ca_2		
CaF	CaF_2	CaH	CaO	$CaOH$	CaS	Cl_2	ClO_2	$ClOH$	$CoCl$
CrH	CrN	CrO					CsF	$CsOH$	Cu_2
$CuCl$	CuF	CuH					$FeCl_2$	FeF	FeF_2
FeH	FeO	FeO_2H_2					H_3BO_3	HBO	HBO_2
HBS	HCN	HCO					$K_2O_2H_2$	K_2SO_4	KBO_2
KCN	KCl	KF	KH	KOH	$Li_2O_2H_2$	$LiBO_2$	$LiCl$	LiF	LiH
$LiNaO$	$LiOCl$			$MgCl$	$MgCl_2$	$MgClF$	MgF	MgF_2	MgH
MgN	MgO			MgS	MnH	MnO	MnS	N_2	N_2O
NF	NH			NHO_3	NO	NO_2	NO_2H	NO_3	NOH
NS	Na_2			$Na_2O_2H_2$	$NaBO_2$	$NaCN$	$NaCl$	NaF	NaH
NaO	$NaOH$	NbO	$NiCl$	$NiCl_2$	NiH	NiO	NiS	O_2	O_2H_2
O_3	OBF	OCS	OCl	OF	OH	OHF	P_2	P_4	PCl
PCl_3	PF	PF_2	PH	PH_2	PH_3	PN	PO	PO_2	PS
PSF	$RbCl$	S_2	S_2O	SCl	SF	SF_6	SH	SO	SO_2
SO_3	ScO	ScS	Si_2	Si_2C	Si_2N	Si_3	SiC	SiC_2	$SiCl$
SiF	SiH	SiH_2	SiH_2F_2	SiH_3	SiH_3Cl	SiH_3F	SiH_4	SiN	SiO
SiO_2	SiS	$SrCl$	$SrCl_2$	SrF	SrF_2	SrH		SrO_2H_2	$SrOH$
		$TiCl_2$	$TiCl_3$	$TiCl_4$	TiF	TiF_2		TiH	TiN
		$TiOCl$	$TiOCl_2$	$TiOF$	TiS	VN		VO_2	$ZrCl$
		$ZrCl_4$	ZrF	ZrF_2	ZrF_4	ZrH		ZrO	ZrO_2

Al_2SiO_5(an)	$Al_3F_{14}Na_3$(L)
$B_4Na_2O_7$(L)	B_5H_9(L)
Be(cr)	BeO(L)
Ca(a)	Ca(b)
Ca_2SiO_4(b)	Ca_2SiO_4(c)
$CaAl_2O_4$(a)	$CaAl_2Si_2O_8$(a)
$CaCl_2$(L)	$CaCl_2$(cr)
CaH_2(b)	$CaMgSi_2O_6$(L)
$CaSO_4$(I)	$CaSO_4$(II)
Cl_2Fe(L)	Cl_2S_2(L)
Cr(cr2)	Cr_2O_3(L)
CsCl(L)	CsCl(a)
Fe(a)	Fe(b)
$H_{10}O_8S$(L)	H_2O(L)
$K_2Si_2O_5$(a)	$K_2Si_2O_5$(b)
$KAlSiO_4$(a)	$KAlSiO_4$(b)
KOH(L)	KOH(a)
LiCl(cr)	Mg(L)
Mg_3N_2(cr)	$Mg_3O_8P_2$(L)
$MgSiO_3$(III)	$MgSiO_3$(L)
Na(L)	Na(cr)
$NaAlSiO_4$(c)	$NaBH_4$(a)
Nb(cr)	Nb_2O_5(L)
NiS(a)	NiS(b)
RbCl(cr)	S(L)

S(a)	S(b)	Si(L)	Si(cr)	SiC(L)	SiO_2(L)	SiO_2(a)	SiO_2(b)
SiO_2(c)	Sr(L)	Sr(cr)	SrO(L)	SrO(cr)	Ti(L)	Ti(a)	Ti(b)
Ti_2O_3(I)	Ti_2O_3(II)	Ti_2O_3(L)	Ti_3O_5(L)	Ti_3O_5(a)	Ti_4O_7(L)	Ti_4O_7(cr)	TiB(cr)
TiB_2(L)	TiB_2(cr)	TiC(L)	TiC(cr)	TiCl(cr)	$TiCl_2$(cr)	$TiCl_3$(cr)	$TiCl_4$(L)
TiN(L)	TiN(cr)	TiO(a)	TiO(b)	TiO(c)	TiO_2(cr)	V(L)	V(cr)
V_2O_3(L)	V_2O_3(cr)	V_2O_4(I)	V_2O_4(II)	V_2O_4(L)	V_2O_5(L)	V_2O_5(cr)	VN(cr)
VO(L)	VO(cr)	Zn(L)	Zn(cr)	Zr(L)	Zr(a)	Zr(b)	ZrO_2(cr)
$ZrSiO_4$(cr)							

Al_2	Al_2O	Al_2O_2	Al_2O_3	$AlBO_2$	AlC	AlCl	$AlCl_2$	AlClF	AlF
AlF_2	AlH	$AlHO_2$	AlN	AlO	AlO_2	AlOCl	AlOF	$AlOF_2$	AlOH
AlS	B_2	BC	BCl	BF	BH	BH_2	BH_3	BN	BO
BO_2	BO_2H_2	BS	BaCl	$BaCl_2$	BaClF	BaF	BaO	BaO_2H_2	BaOH
BaS	Be_2O	Be_3O_3	$BeBO_2$	BeC_2	BeCl	$BeCl_2$	BeF	BeF_2	BeH
BeH_2	BeN	BeO	BeO_2H_2	BeOH	BeS	C_2	C_2H	C_2H_2	C_2H_4
C_2H_6	C_2HCl	C_2HF	C_2N	C_2N_2	C_2O	C_3	C_3H	CH	CH_2
CH_3	CH_3Cl								
CO_2	COF_2								
CaF	CaF_2								
CrH	CrN								
CuCl	CuF								
FeH	FeO								
HBS	HCN								
KCN	KCl								
LiNaO	LiOCl								
MgN	MgO								
NF	NH								
NS	Na_2								
NaO	NaOH								
O_3	OBF								
PCl_3	PF								
PSF	RbCl								
SO_3	ScO								
SiF	SiH								
SiO_2	SiS								
SrS	TiCl								
TiO	TiO_2								
$ZrCl_2$	$ZrCl_3$								
ZrS									

Al(L)	Al(cr)	Al_2O_3(L)	A		Al_2S_3(b)	Al_2SiO_5(an)	$Al_3F_{14}Na_3$(L)
Al_4C_3(cr)	AlN(cr)	B(L)	B		$B_4Li_2O_7$(L)	$B_4Na_2O_7$(L)	B_5H_9(L)
$B_8K_2O_{13}$(L)	$BLiO_2$(L)	Ba(L)	Ba(cr)	$BaCl_2$(L)	Be(L)	Be(cr)	BeO(L)
$BeSO_4$(L)	$BeSO_4$(a)	$BeSO_4$(b)	$BeSO_4$(c)	C(gr)	Ca(L)	Ca(a)	Ca(b)
$Ca_2Al_2SiO_7$(a)	$Ca_2MgSi_2O_7$(L)	$Ca_2MgSi_2O_7$(a)	$Ca_2MgSi_2O_7$(b)	Ca_2SiO_4(L)	Ca_2SiO_4(a)	Ca_2SiO_4(b)	Ca_2SiO_4(c)
$Ca_3Al_2O_6$(a)	$Ca_3Al_2Si_3O_{12}$(	$Ca_3MgSi_2O_8$(a)	Ca_3N_2(a)	$Ca_3Si_2O_7$(a)	Ca_3SiO_5(a)	$CaAl_2O_4$(a)	$CaAl_2Si_2O_8$(a)
$CaAl_2SiO_6$(a)	$CaAl_4O_7$(a)	CaB_2O_4(L)	CaB_2O_4(a)	CaB_4O_7(L)	CaB_4O_7(a)	$CaCl_2$(L)	$CaCl_2$(cr)
CaF_2(L)	CaF_2(a)	CaF_2(b)	$CaFeSi_2O_6$(c)	CaH_2(L)	CaH_2(a)	CaH_2(b)	$CaMgSi_2O_6$(L)
$CaMgSi_2O_6$(a)	Ca			CaS(L)	CaS(cr)	$CaSO_4$(I)	$CaSO_4$(II)
$CaSO_4$(L)	Ca		(b)	$CaTiSiO_5$(L)	$CaTiSiO_5$(a)	Cl_2Fe(L)	Cl_2S_2(L)
Cl_2Sr(L)	Cl			Cr(L)	Cr(cr1)		Cr_2O_3(L)
Cr_2O_3(a)	Cr		)	Cs(L)	Cs(cr)		CsCl(a)
CsCl(b)	Cu(L)	Cu(cr)	Cu_2O(L)	CuO(cr)	Fe(L)		Fe(b)
Fe(c)	Fe_2O_3(cr)	Fe_3O_4(cr)	FeS(L)	FeS(a)	FeS_2(cr)		H_2O(L)
H_2O(cr)	K(L)	K_2SO_4(I)	K_2SO_4(II)	K_2SO_4(L)	$K_2Si_2O_5$(L)	$K_2Si_2O_5$(a)	$K_2Si_2O_5$(b)
$K_2Si_2O_5$(c)	K_2SiO_3(L)	K_2SiO_3(cr)	$KAlSi_2O_6$(a)	$KAlSi_2O_6$(b)	$KAlSi_3O_8$(a)	$KAlSiO_4$(a)	$KAlSiO_4$(b)
KBF_4(L)	KBF_4(a)	KBF_4(b)	KBH_4(a)	KBO_2(L)	KBO_2(cr)	KOH(L)	KOH(a)
KOH(b)	KOH(c)	Li(L)	Li_2O(L)	Li_2O_3			(L)
Mg			Mg_2SiO_4(cr)	Mg_2Ti			$_3O_8P_2$(L)
Mg			MgS(cr)	MgSi			SiO_3(L)
Mg			Mn(a)	Mn(c)			(cr)
Na			$NaAlSi_3O_8$(a)	$NaAlSiO_4$(a)	$NaAlSiO_4$(b)	$NaAlSiO_4$(c)	$NaBH_4$(a)
NaCl(L)	NaCl(cr)	$NaFeSi_2O_6$(a)	NaH(L)	NaH(cr)	Nb(L)	Nb(cr)	Nb_2O_5(L)
NbO(L)	Ni(L)	Ni(cr)	Ni_3S_2(L)	Ni_3S_2(a)	Ni_3S_2(b)	NiS(a)	NiS(b)
NiS_2(L)	NiS_2(cr)	P(L)	P(cr)	P(cr)1	RbCl(L)	RbCl(cr)	S(L)
S(a)	S(b)	Si(L)	Si(cr)	SiC(L)	SiO_2(L)	SiO_2(a)	SiO_2(b)
SiO_2(c)	Sr(L)	Sr(cr)	SrO(L)	SrO(cr)	Ti(L)	Ti(a)	Ti(b)
Ti_2O_3(I)	Ti_2O_3(II)	Ti_2O_3(L)	Ti_3O_5(L)	Ti_3O_5(a)	Ti_4O_7(L)	Ti_4O_7(cr)	TiB(cr)
TiB_2(L)	TiB_2(cr)	TiC(L)	TiC(cr)	TiCl(cr)	$TiCl_2$(cr)	$TiCl_3$(cr)	$TiCl_4$(L)
TiN(L)	TiN(cr)	TiO(a)	TiO(b)	TiO(c)	TiO_2(cr)	V(L)	V(cr)
V_2O_3(L)	V_2O_3(cr)	V_2O_4(I)	V_2O_4(II)	V_2O_4(L)	V_2O_5(L)	V_2O_5(cr)	VN(cr)
VO(L)	VO(cr)	Zn(L)	Zn(cr)	Zr(L)	Zr(a)	Zr(b)	ZrO_2(cr)
$ZrSiO_4$(cr)							

Al_2O_3(a)

$CaTiO_3$(a)

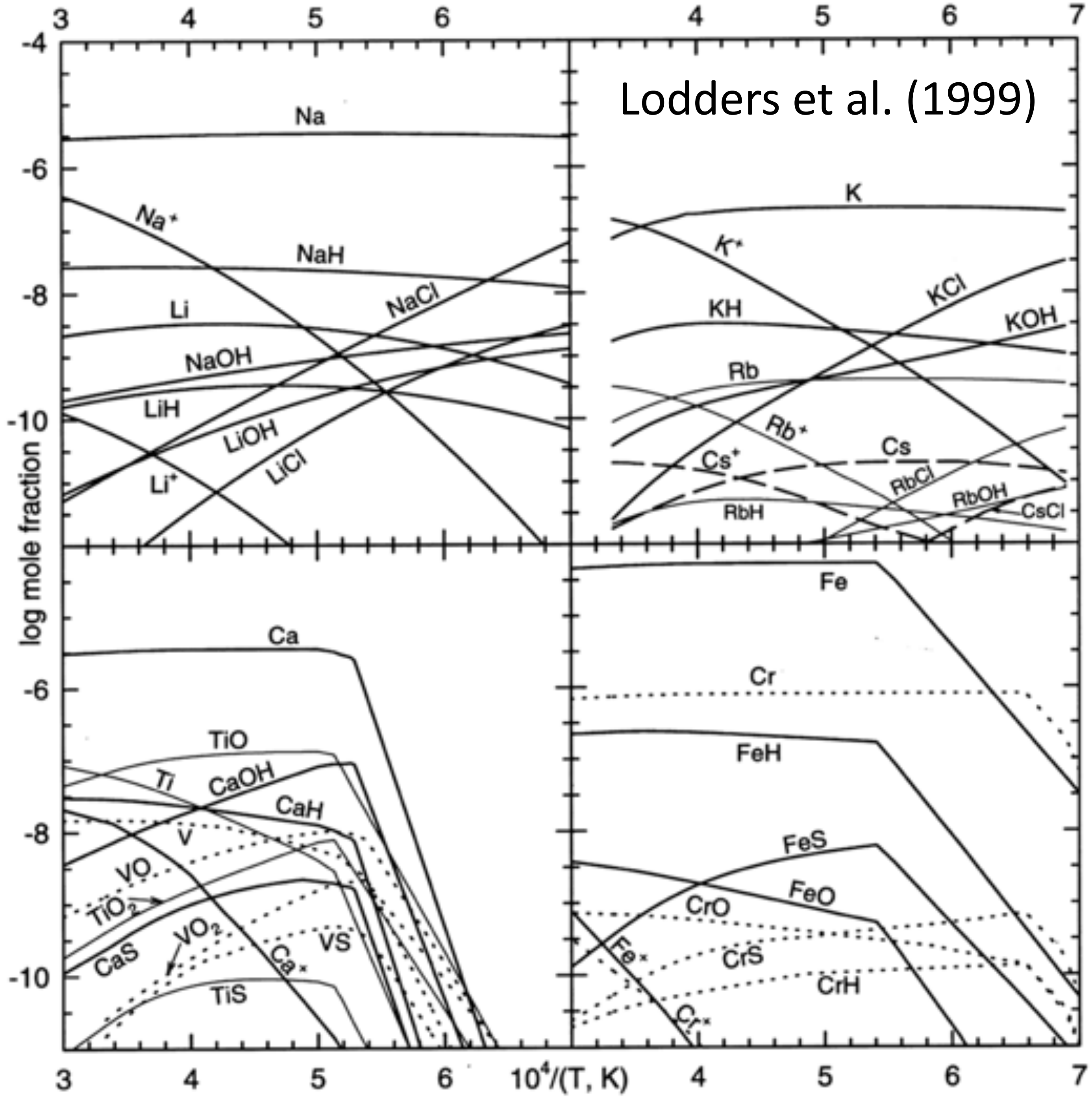
Fe(a)

Mg_2SiO_4(cr)

$MgSiO_3$(a)

Chemical Equilibrium (in a box)

- independent of time
- independent of box history
- all fluctuations are damped out
- independent of position in box
- $p_i = f(T, P, a_j)$ (partial pressure)



$$p_i = \left(\frac{n_i}{n_{tot}}\right) P_{gas} = x_i P_{gas}$$

x_i = mole fraction

Important references:
Fegley & Lodders (1994)
Burrows & Sharp (1999)

Equilibrium Chemistry (in a nutshell) More on this later ...

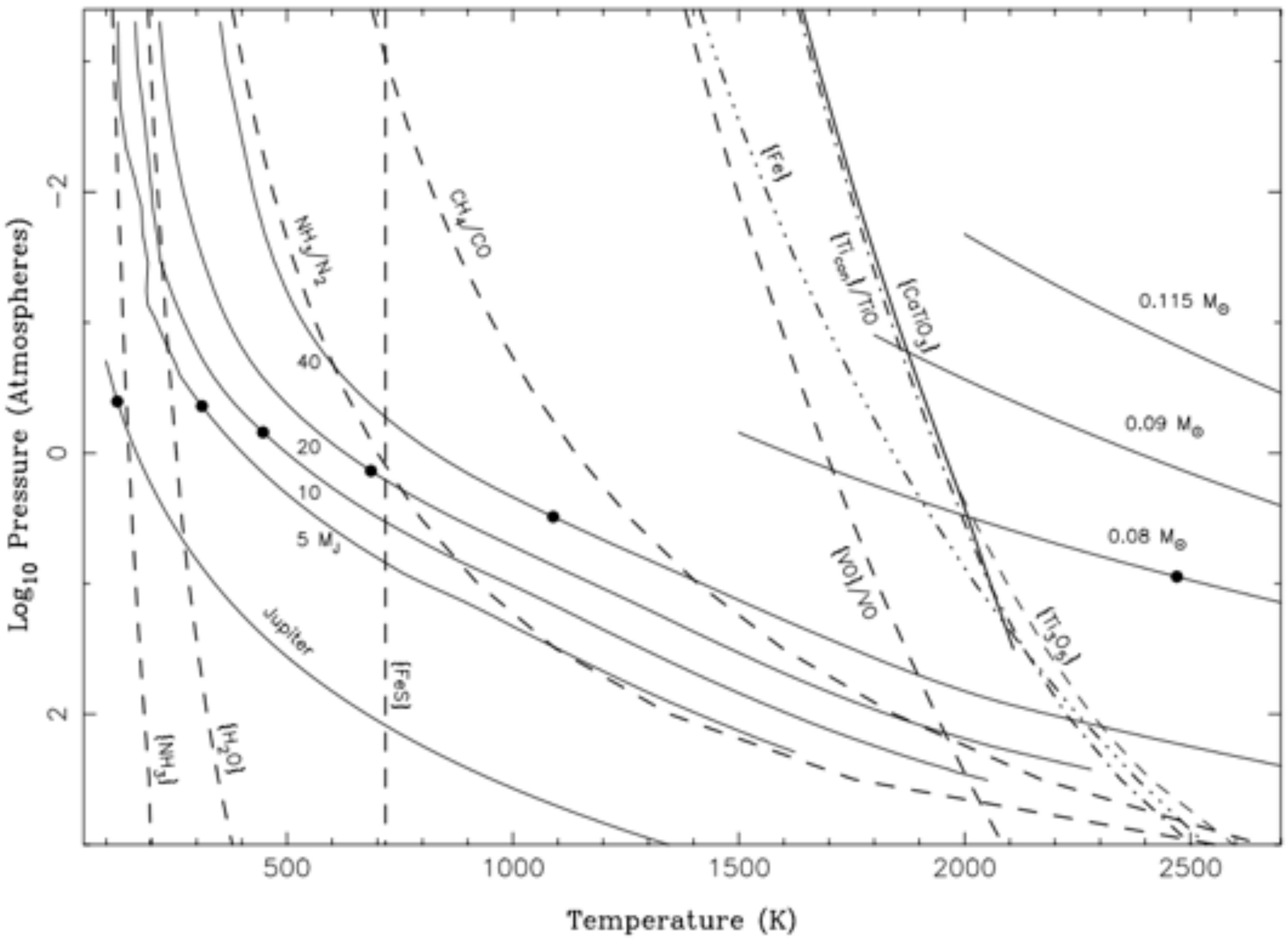
- Simplified example: Iron in Jupiter's atmosphere
- mass balance: $\sum \mathrm{Fe} = P_{\mathrm{Fe}} + P_{\mathrm{Fe(OH)_2}} + 2P_{\mathrm{Fe_2Cl_4}}$
- Expressed in terms of thermodynamic quantities:

$$\sum \mathrm{Fe} = a_{\mathrm{Fe}}\left[K_{\mathrm{Fe}} + K_{\mathrm{Fe(OH)2}}(f_{\mathrm{H_2}})(f_{\mathrm{O_2}}) + 2a_{\mathrm{Fe}}K_{\mathrm{Fe_2Cl_4}}(f_{\mathrm{Cl_2}})^2\right]$$

- system of equations for each element (each equation can be very long, e.g., hydrogen can have 100s of terms)
- solved for f, numerically, with some initial guesses and fixed element abundances. Equivalent to minimizing the Gibbs potential
- Alternative methods used (examples discussed later)

Results of model atmosphere calculations
(See also Allard et al. 2001)

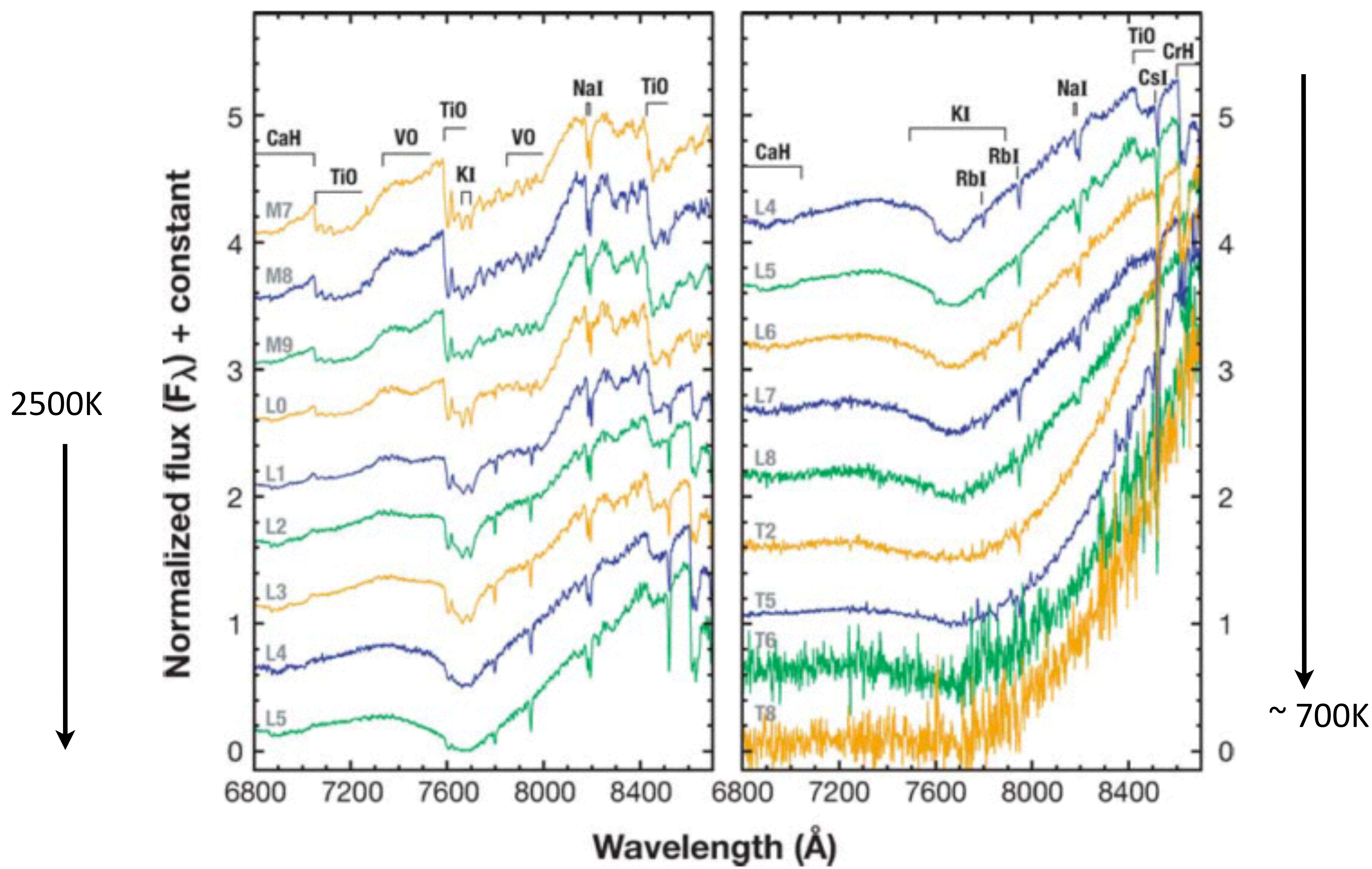
- chemical equilibrium
- hydrostatic equilibrium
- radiative+convective equilibrium
- one-dimension (radial)
- time-independent
- fixed abundances (e.g. “solar”)



Temperature Structures of sub-stellar mass objects:

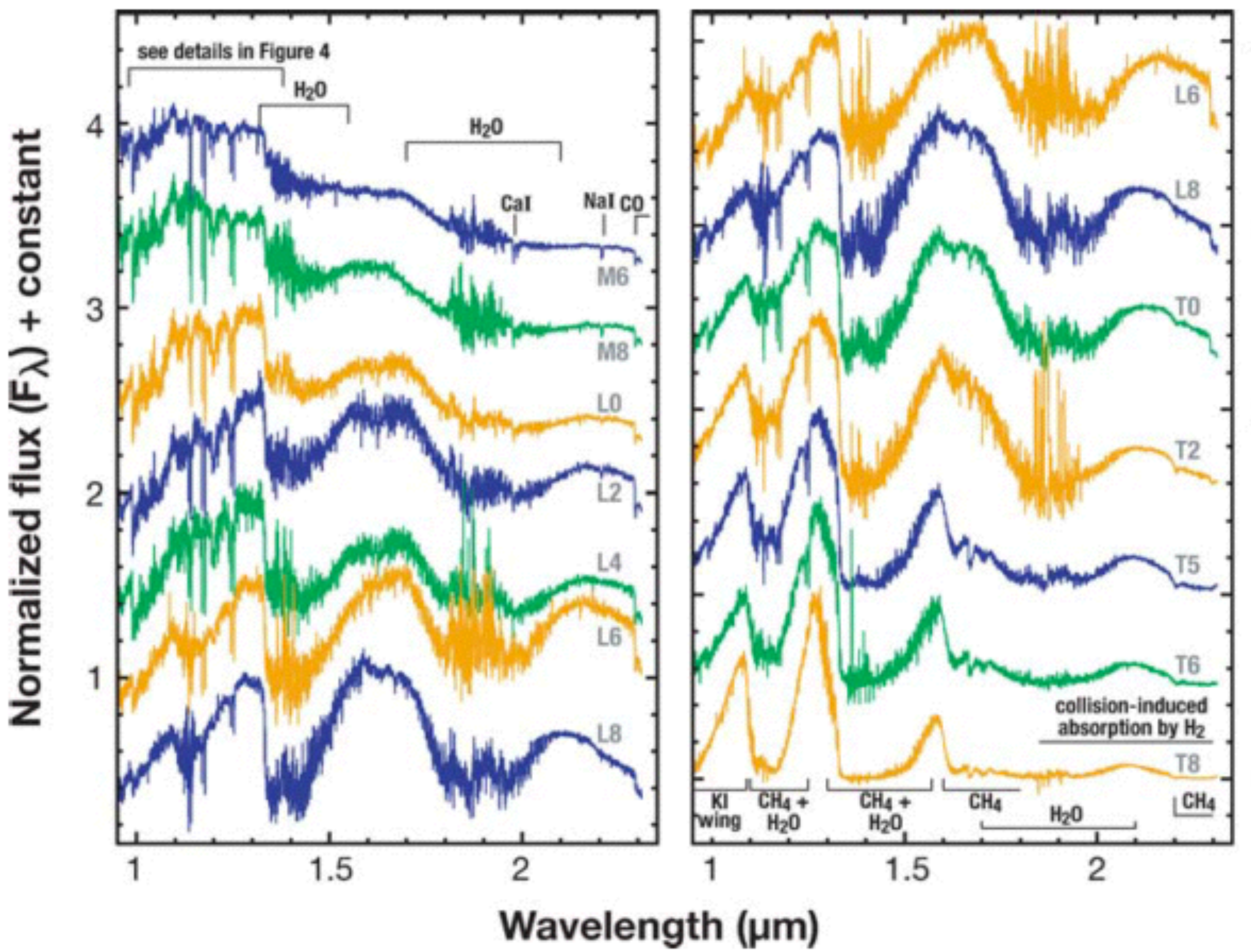
Burrows & Sharp (1996)

A quick introduction to *spectral types* of brown dwarfs

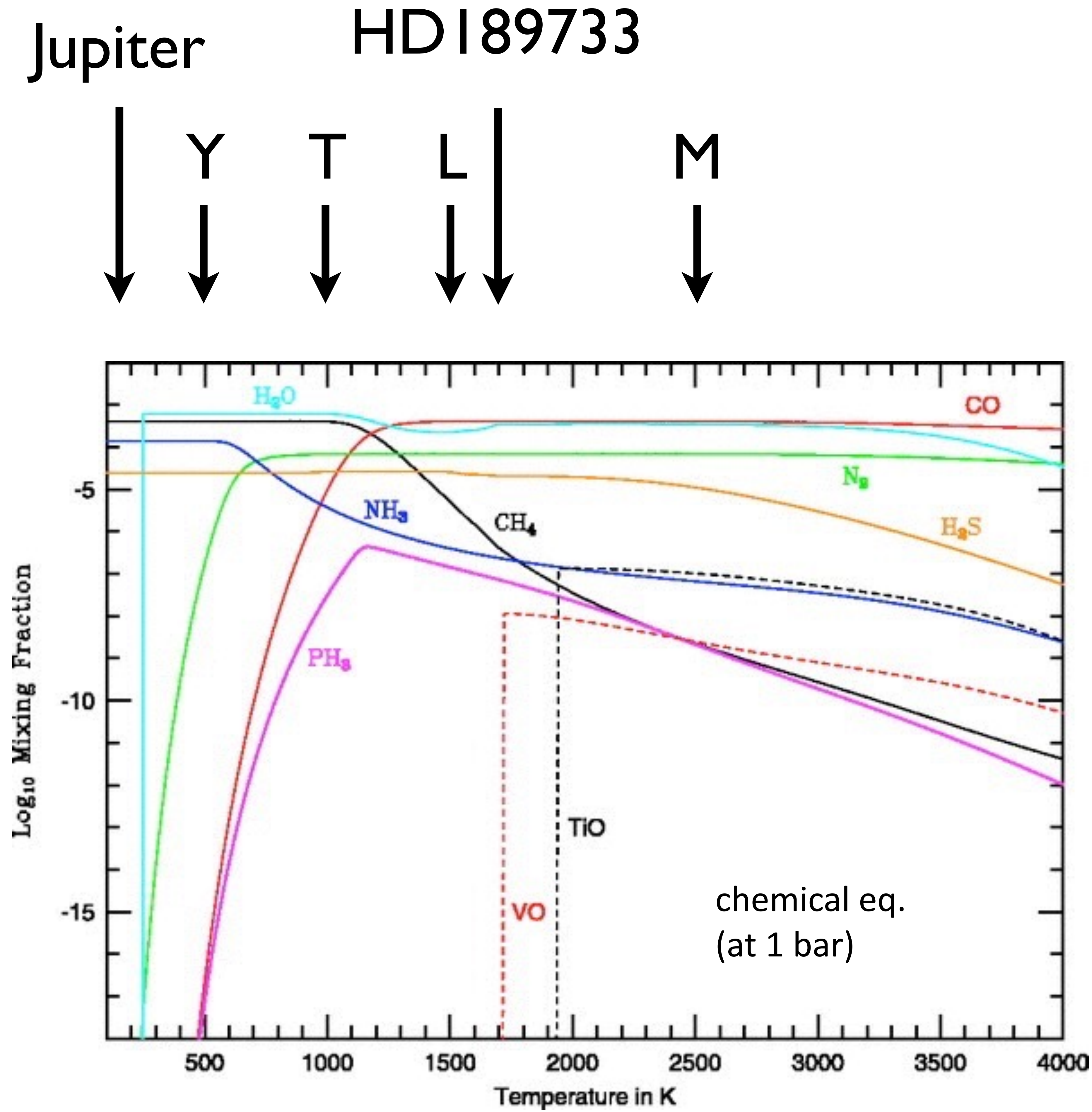


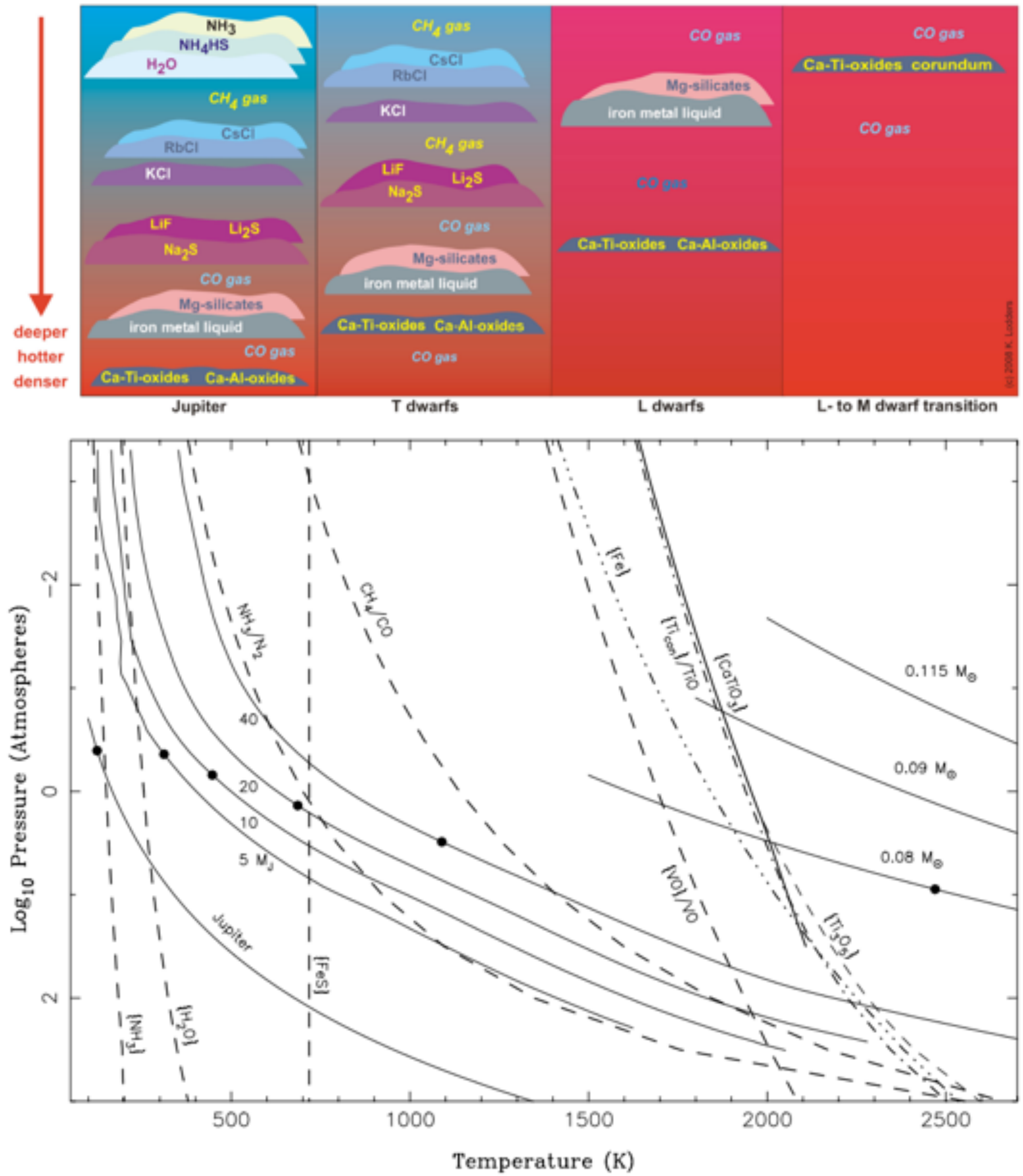
A quick introduction to *spectral types* of brown dwarfs

2500K



~ 700K


Jupiter
HD189733
Y
T
L
M
H2O
CO
N2
H2S
NH3
CH4
PH3
TiO
VO
-5
-10
-15
500
1000
1500
2000
2500
3000
3500
4000
Log10 Mixing Fraction
Temperature in K
chemical eq.
(at 1 bar)



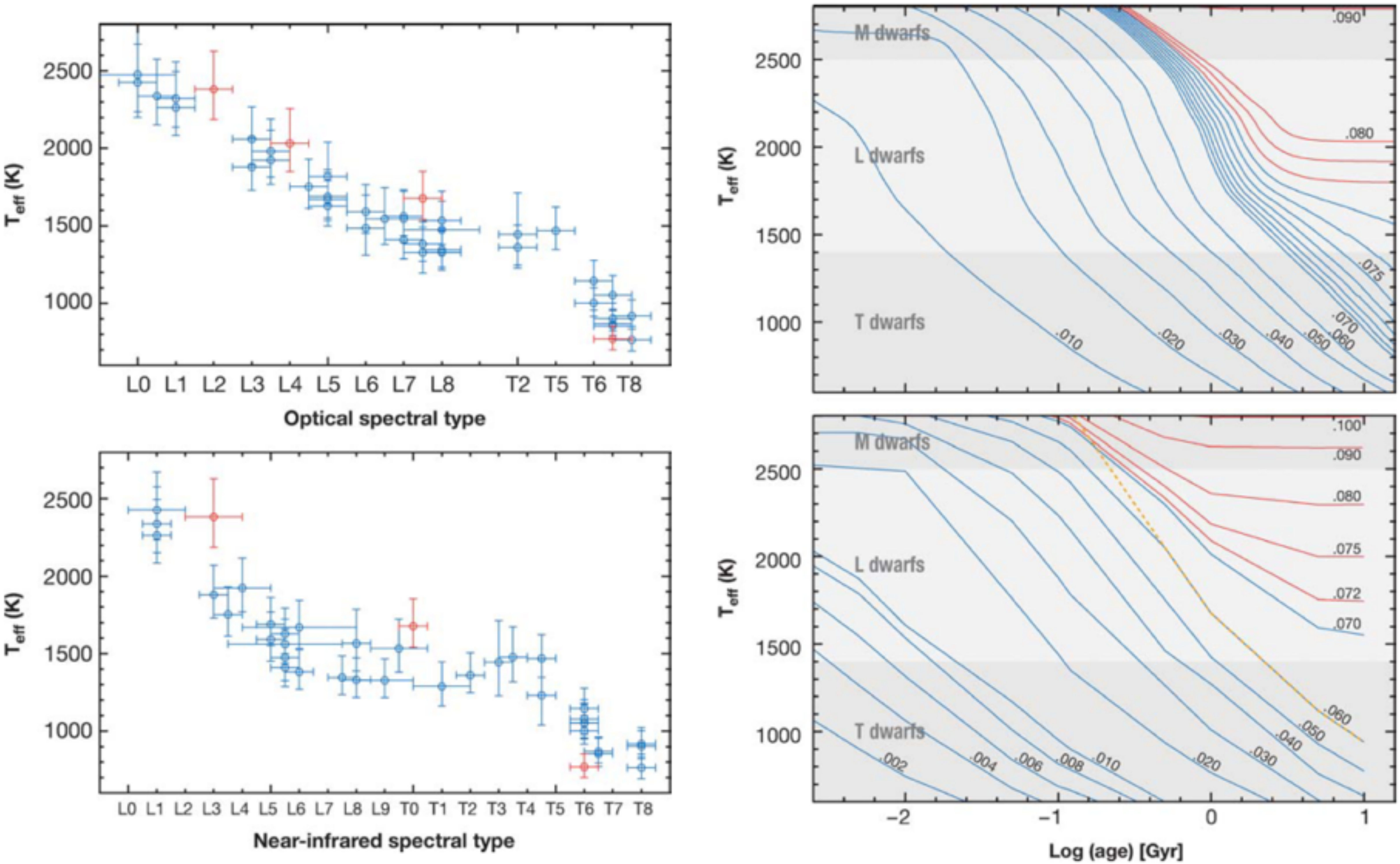
Temperature Structures of sub-stellar mass objects:

Results of model atmosphere calculations (See also Allard et al. 2001)

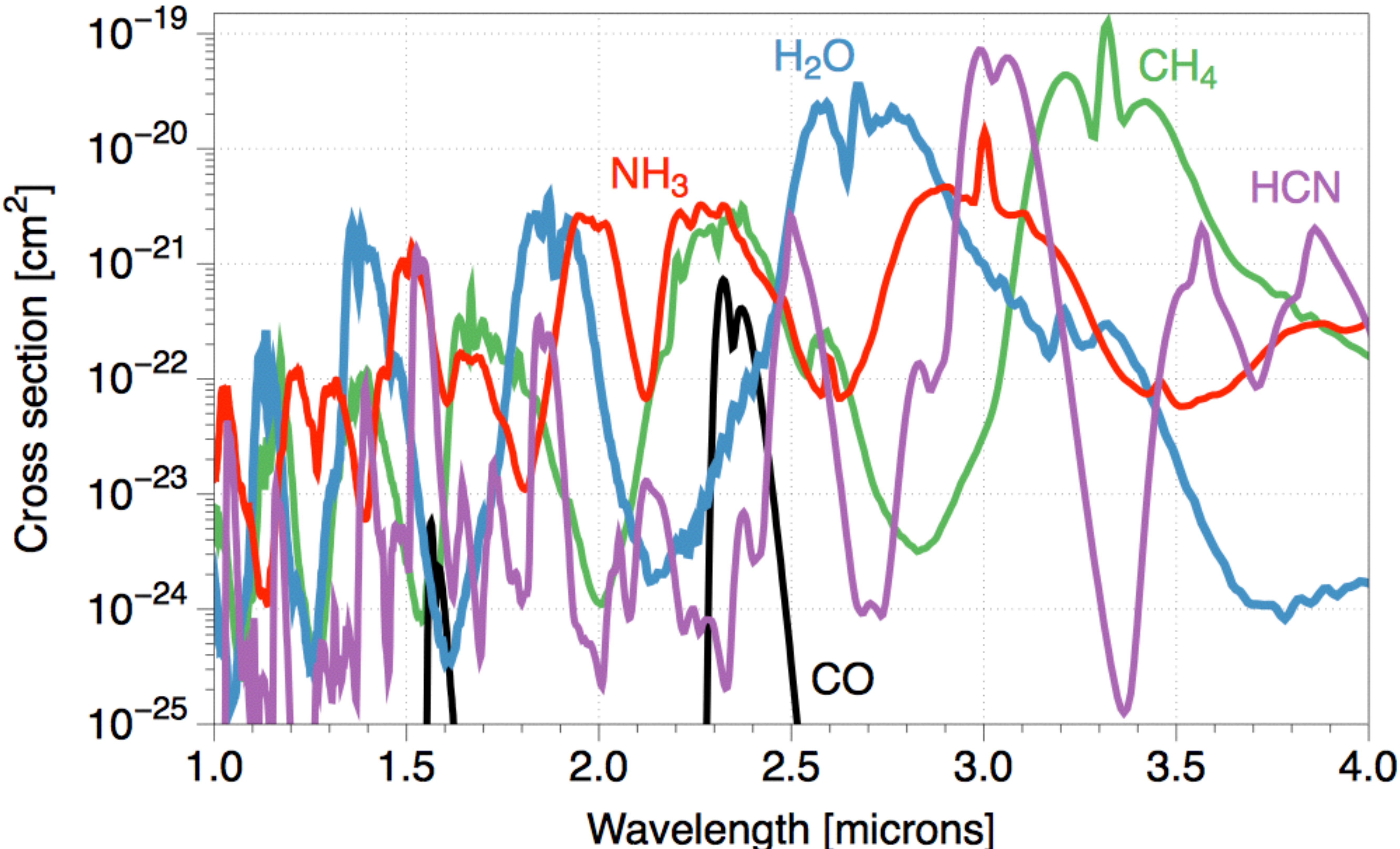
- chemical equilibrium
- hydrostatic equilibrium
- radiative+convective equilibrium
- one-dimension (radial)
- time-independent
- fixed abundances (e.g. "solar")

Burrows & Sharp (1996)

A single object evolves through the Spectral Type (SpT(Teff) also not exactly a unique function at low T)

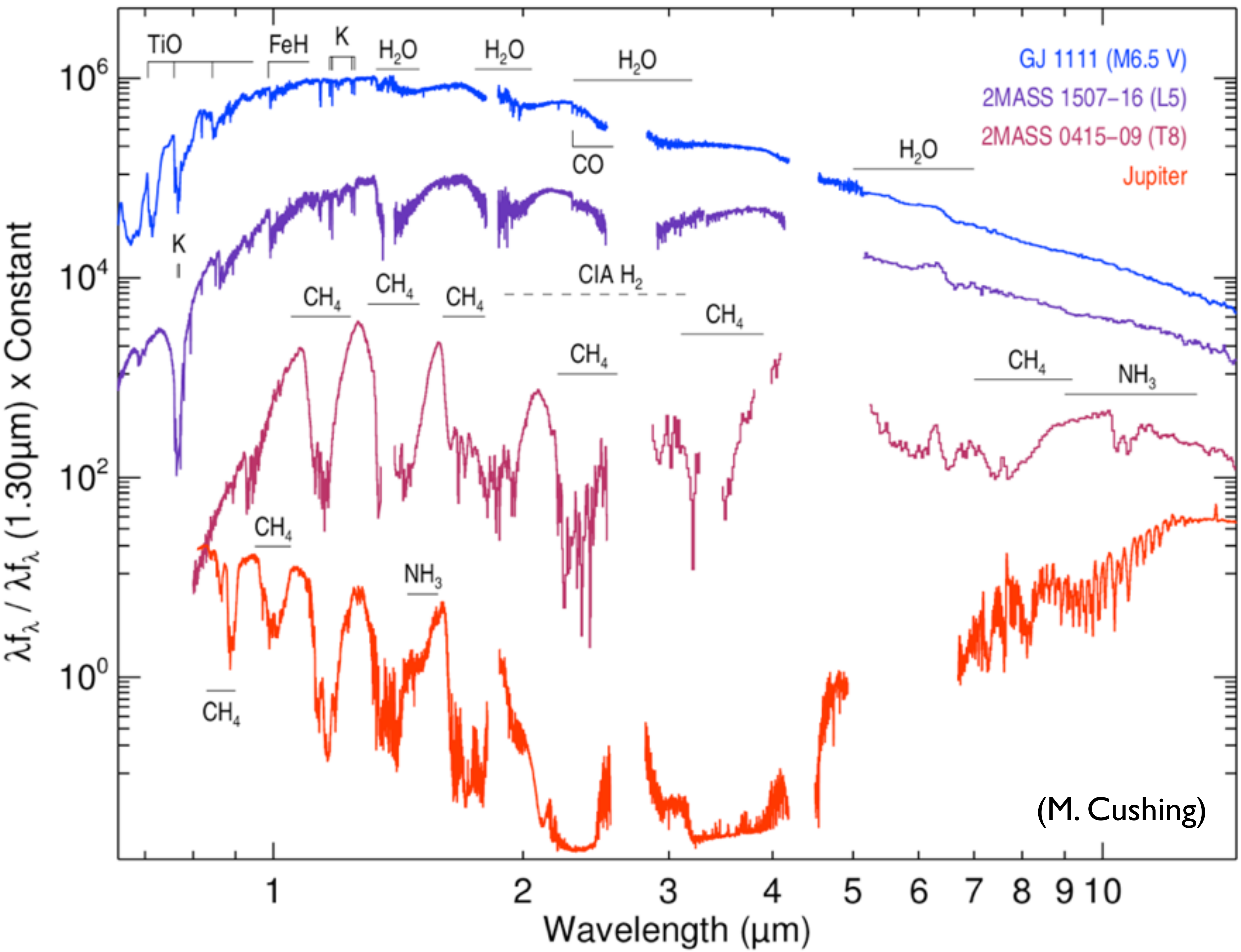


major molecular absorbers
(NOT “continuous” -- 100s of billions of lines)

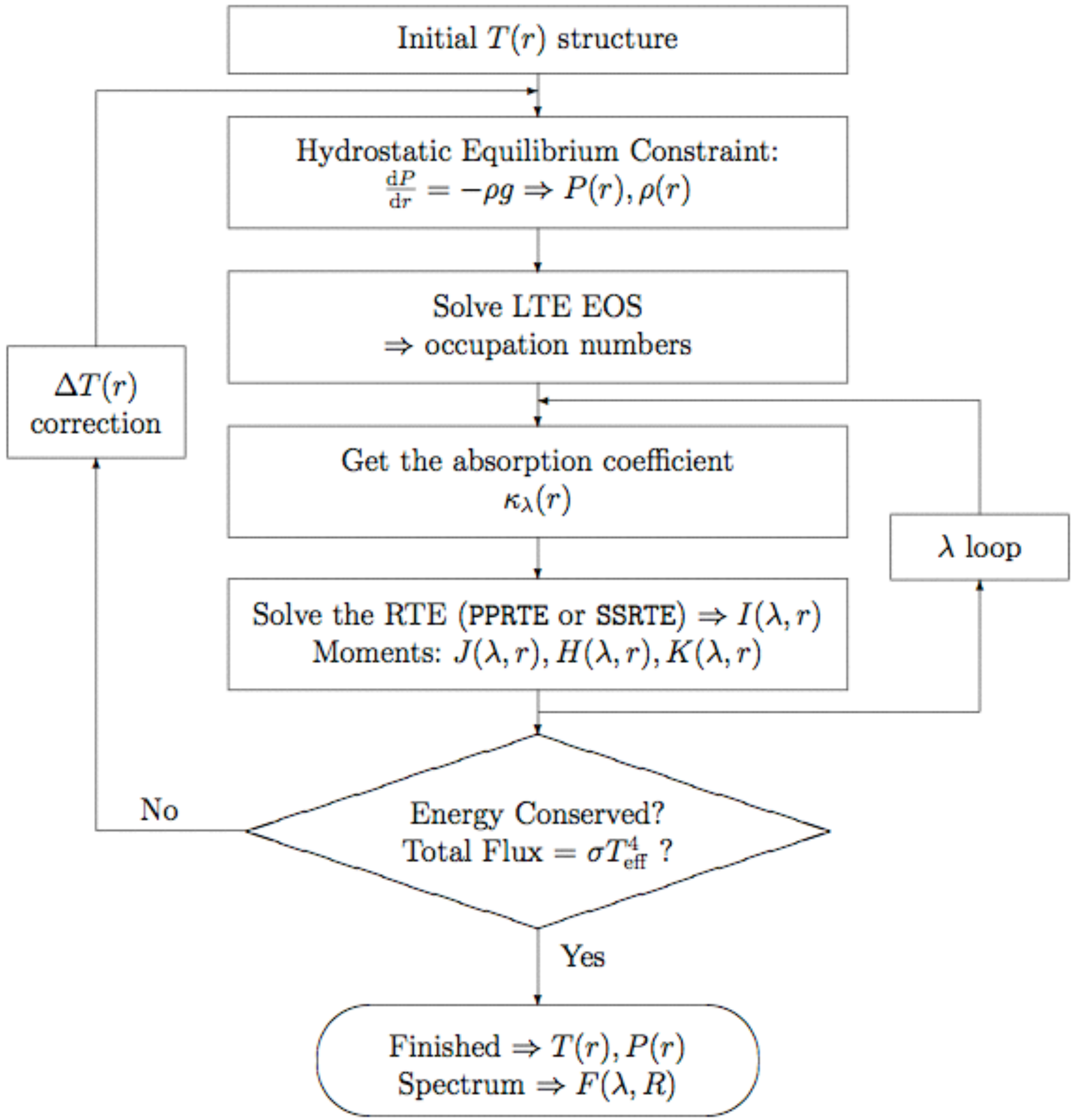


This is actually cm^2 / molecule

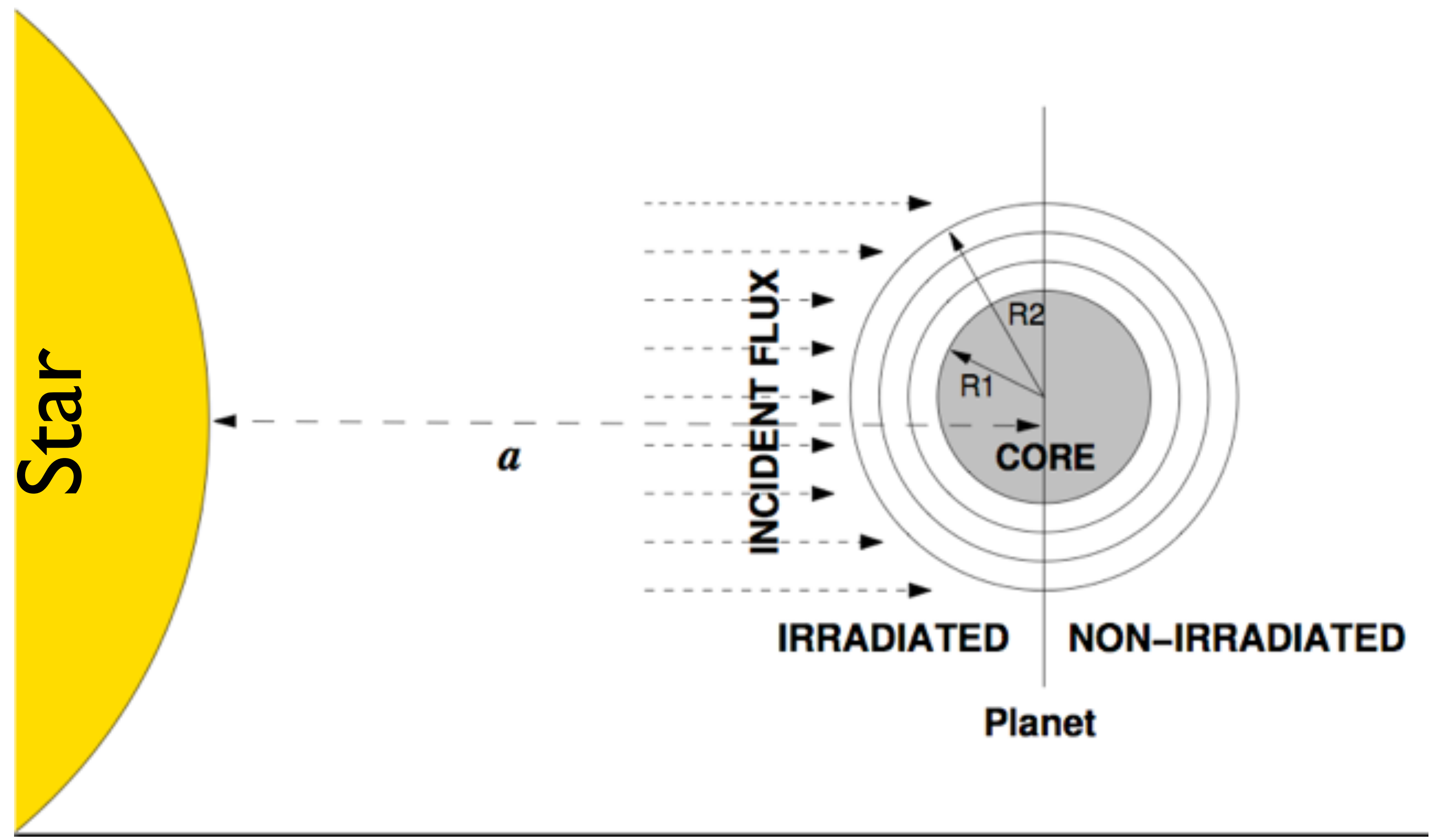
Zahnle & Marley (2014)

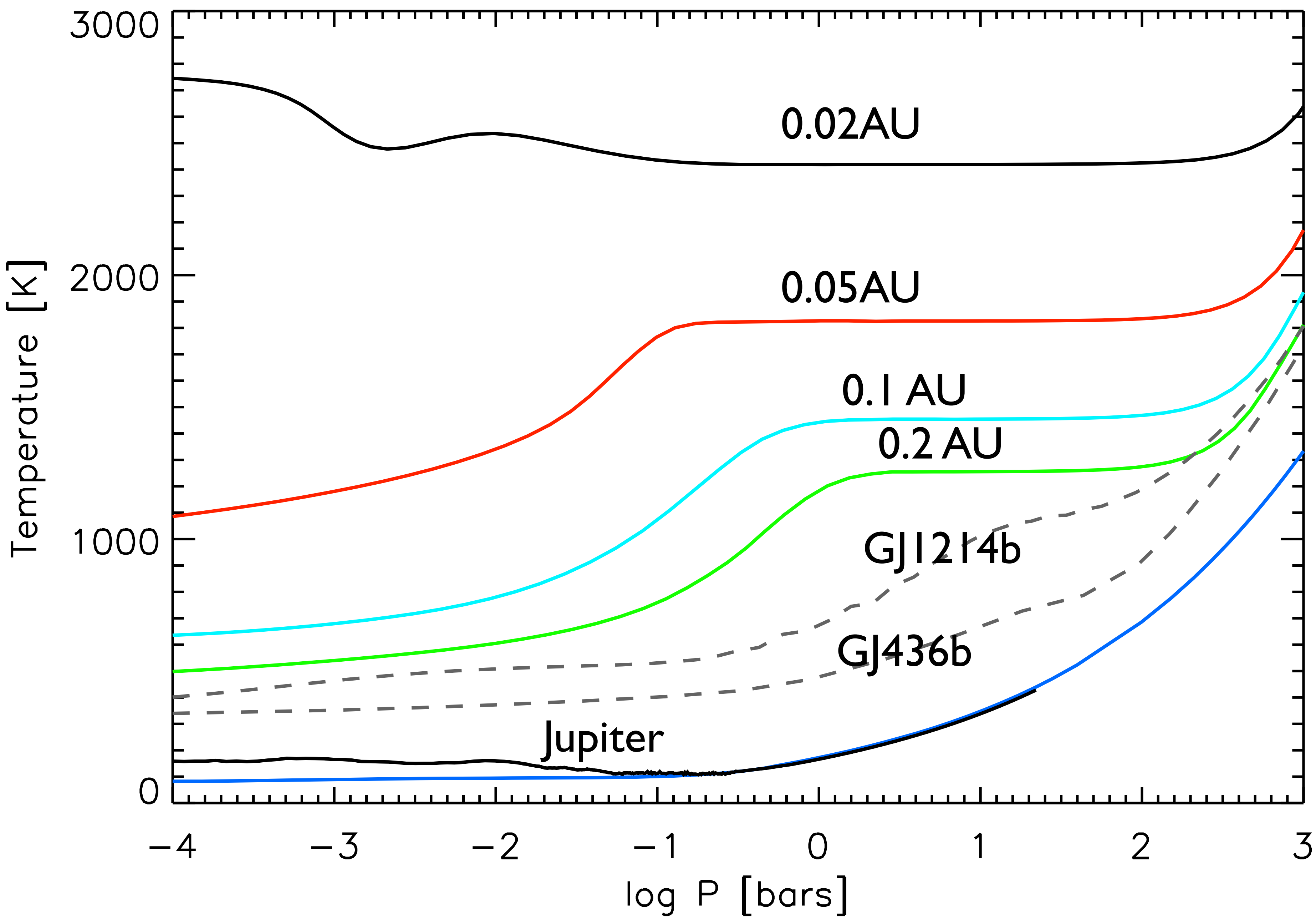

TiO
FeH
K
H2O
H2O
H2O
CO
H2O
K
CIA H2
CH4
CH4
CH4
CH4
CH4
CH4
NH3
CH4
NH3
CH4
GJ 1111 (M6.5 V)
2MASS 1507−16 (L5)
2MASS 0415−09 (T8)
Jupiter
10^6
10^4
10^2
10^0
λfλ / λfλ (1.30μm) x Constant
1
2
3
4
5
6
7
8
9
10
Wavelength (μm)
(M. Cushing)

The basic model atmosphere recipe:

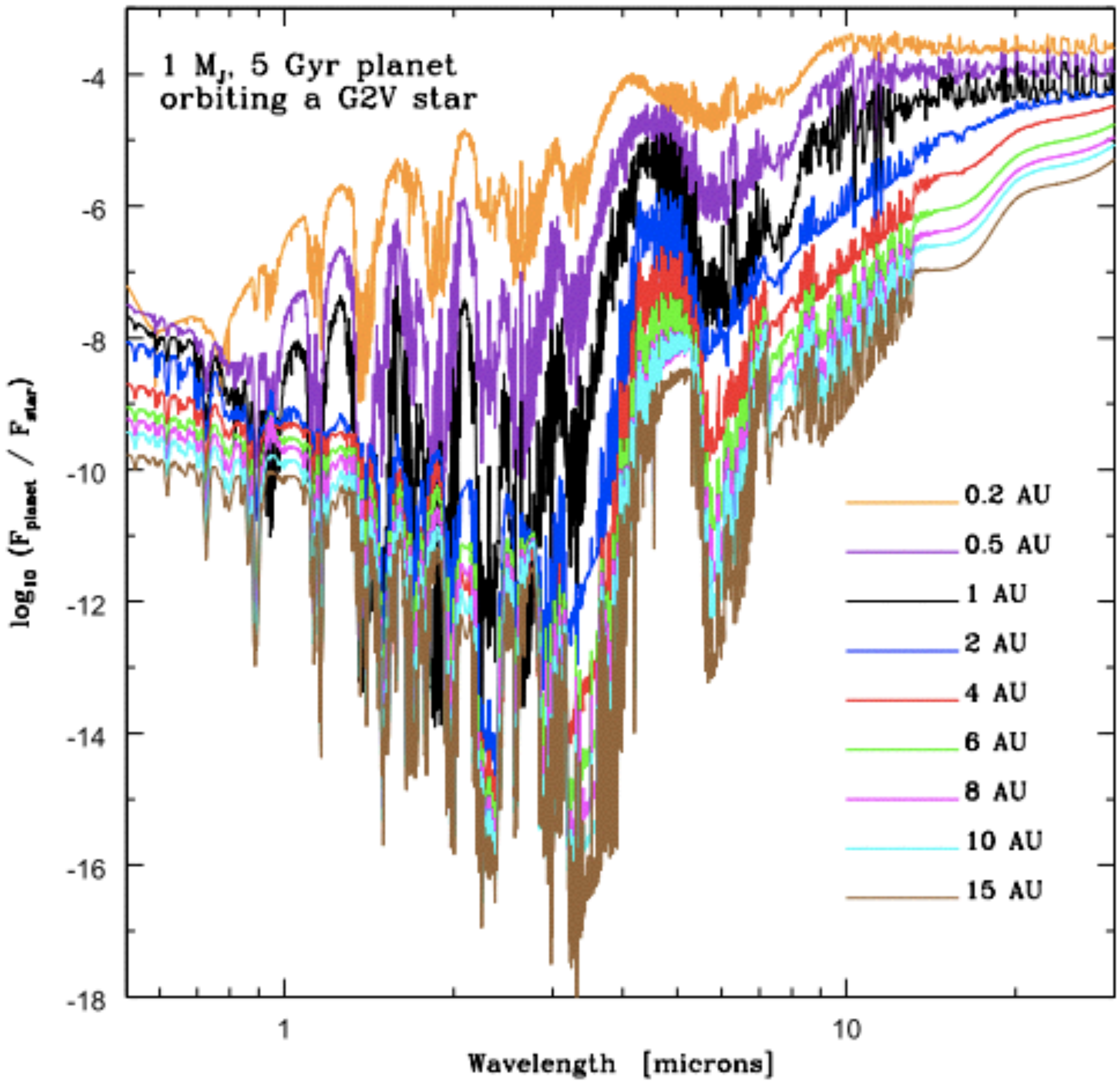


Major distinction between most brown dwarfs and giant planets -- incident stellar flux.



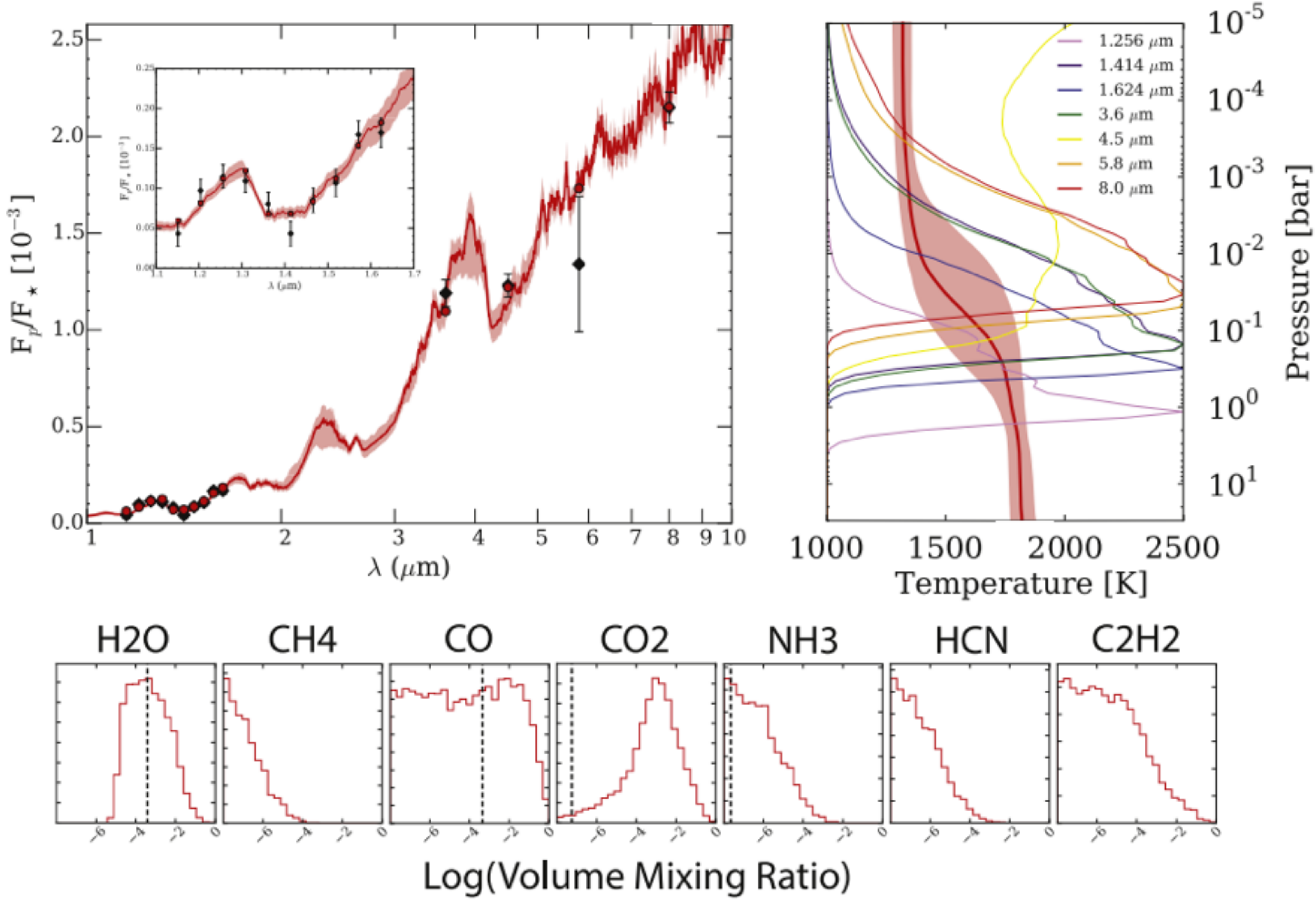

0.02AU
0.05AU
0.1 AU
0.2 AU
GJ1214b
GJ436b
Jupiter
Temperature [K]
log P [bars]
3000
2000
1000
0
−4
−3
−2
−1
0
1
2
3

“Synthetic” Exoplanet Spectra

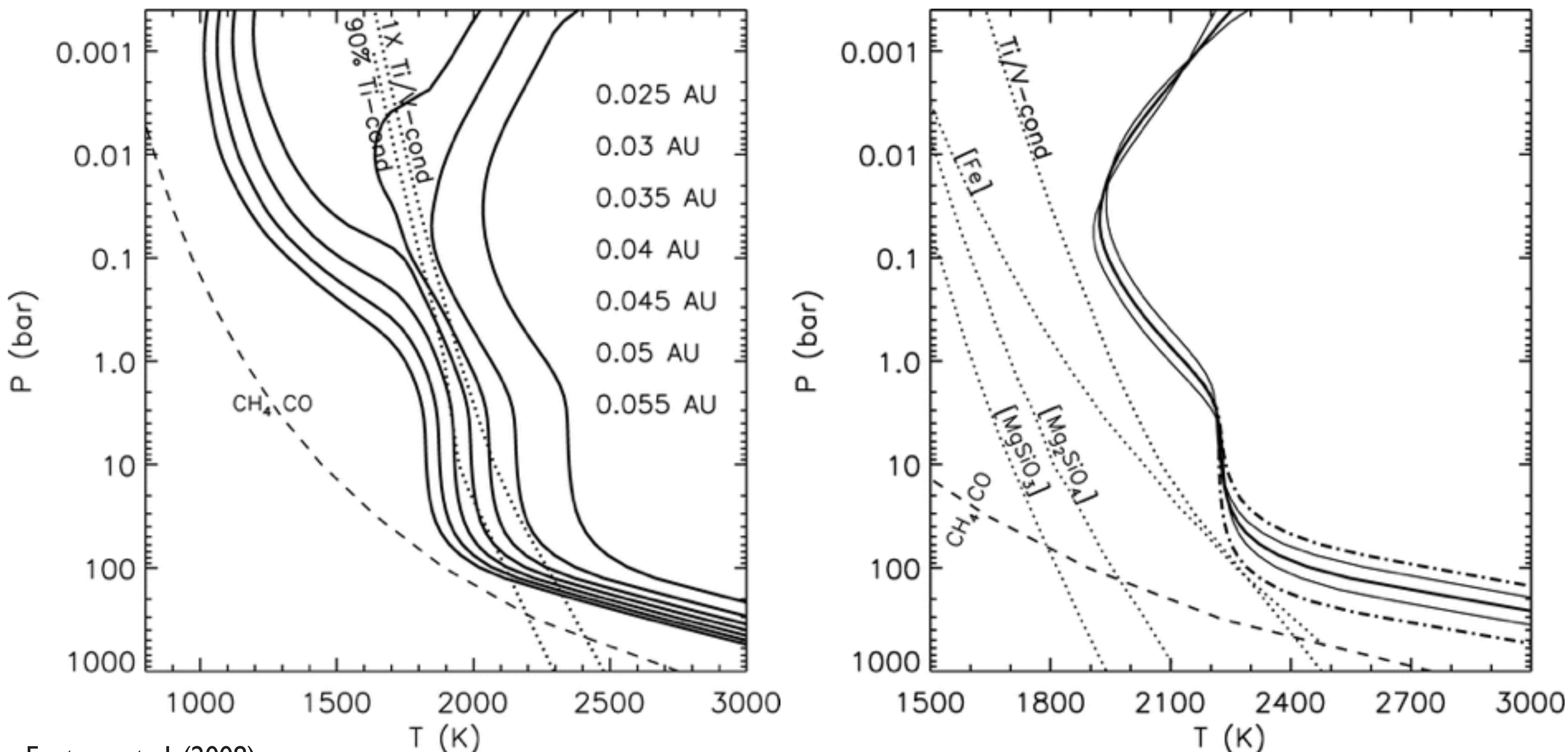


Burrows & Orton (2009)

HD209458b

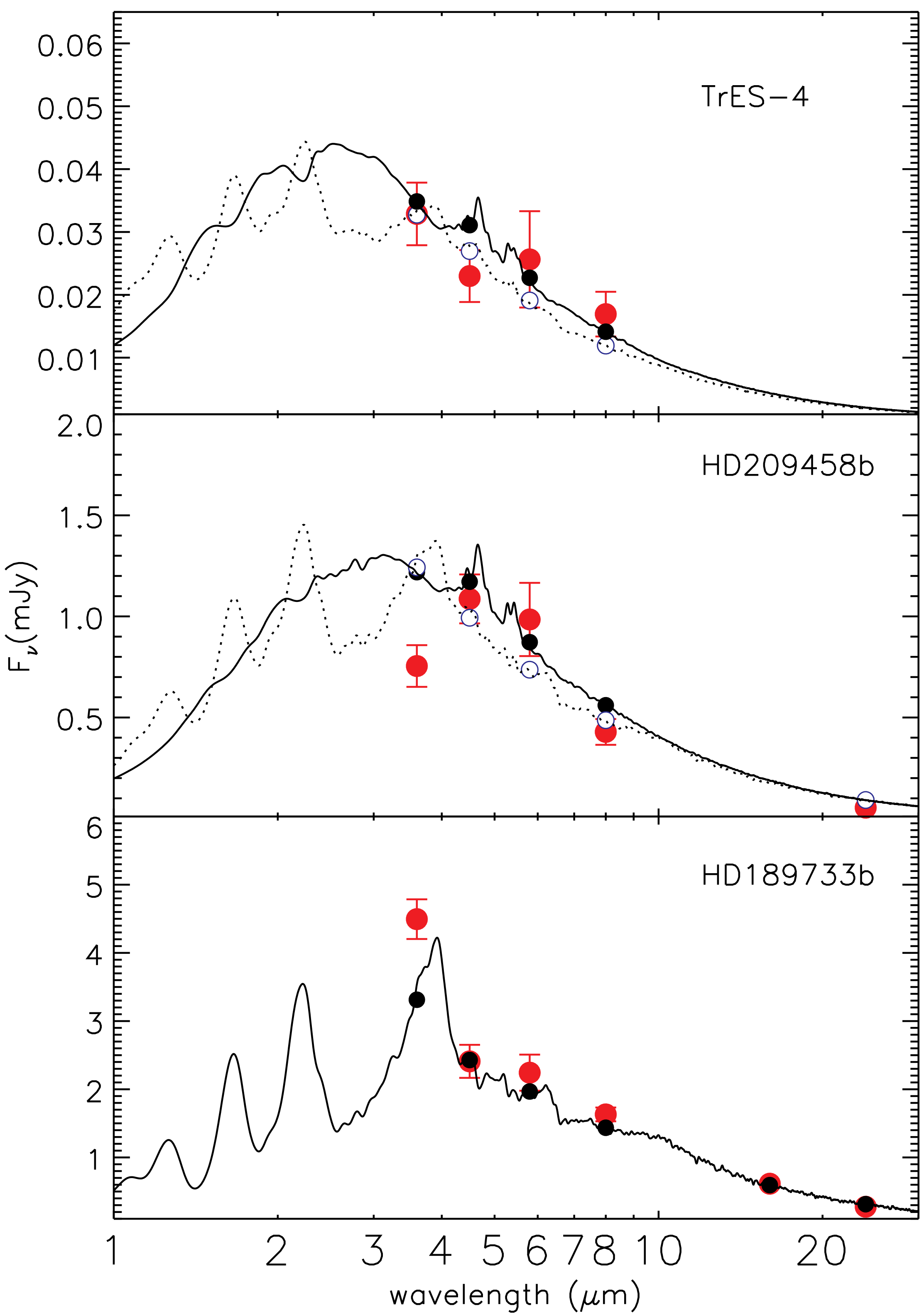


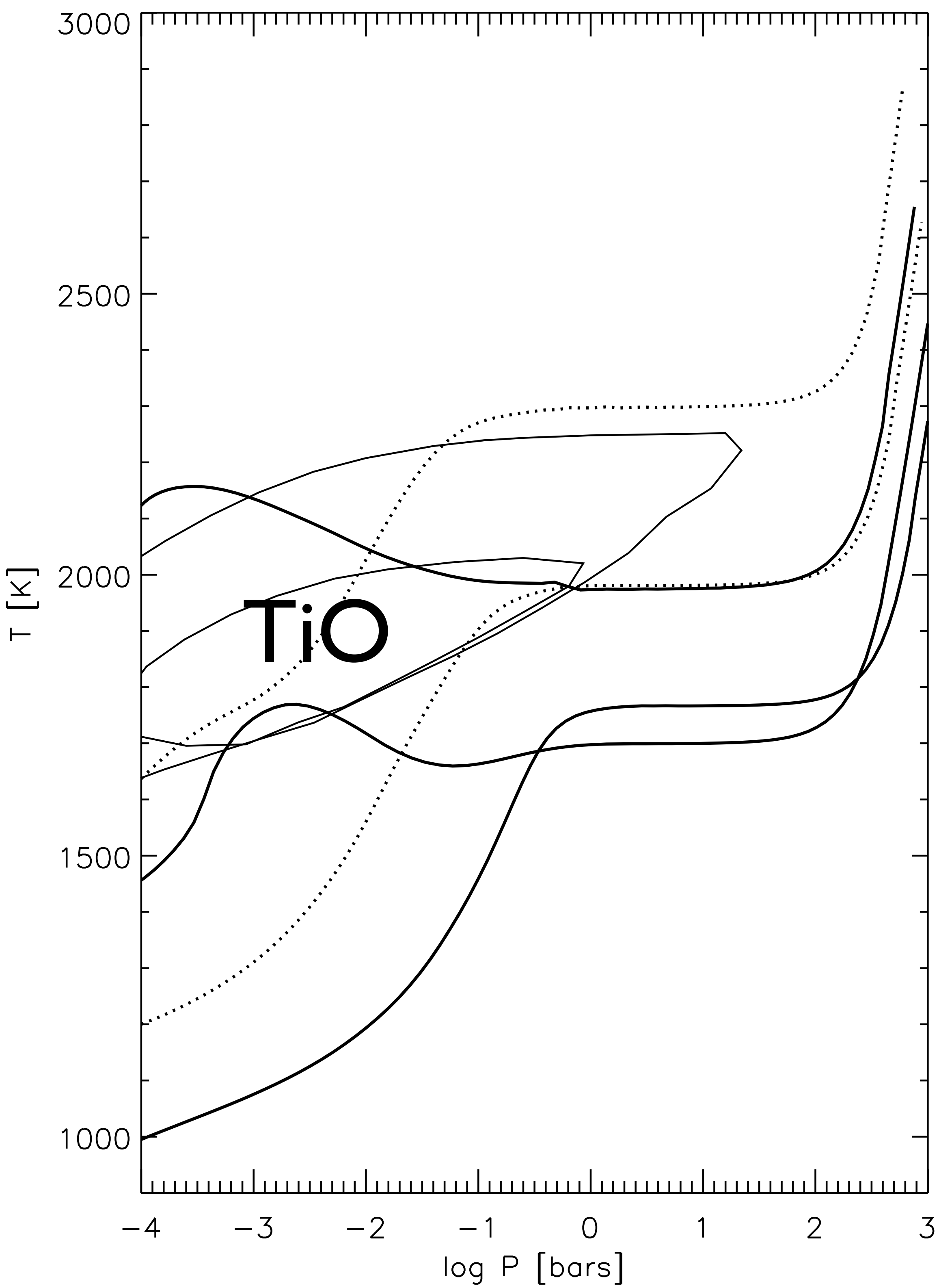
Line et al. (2016)



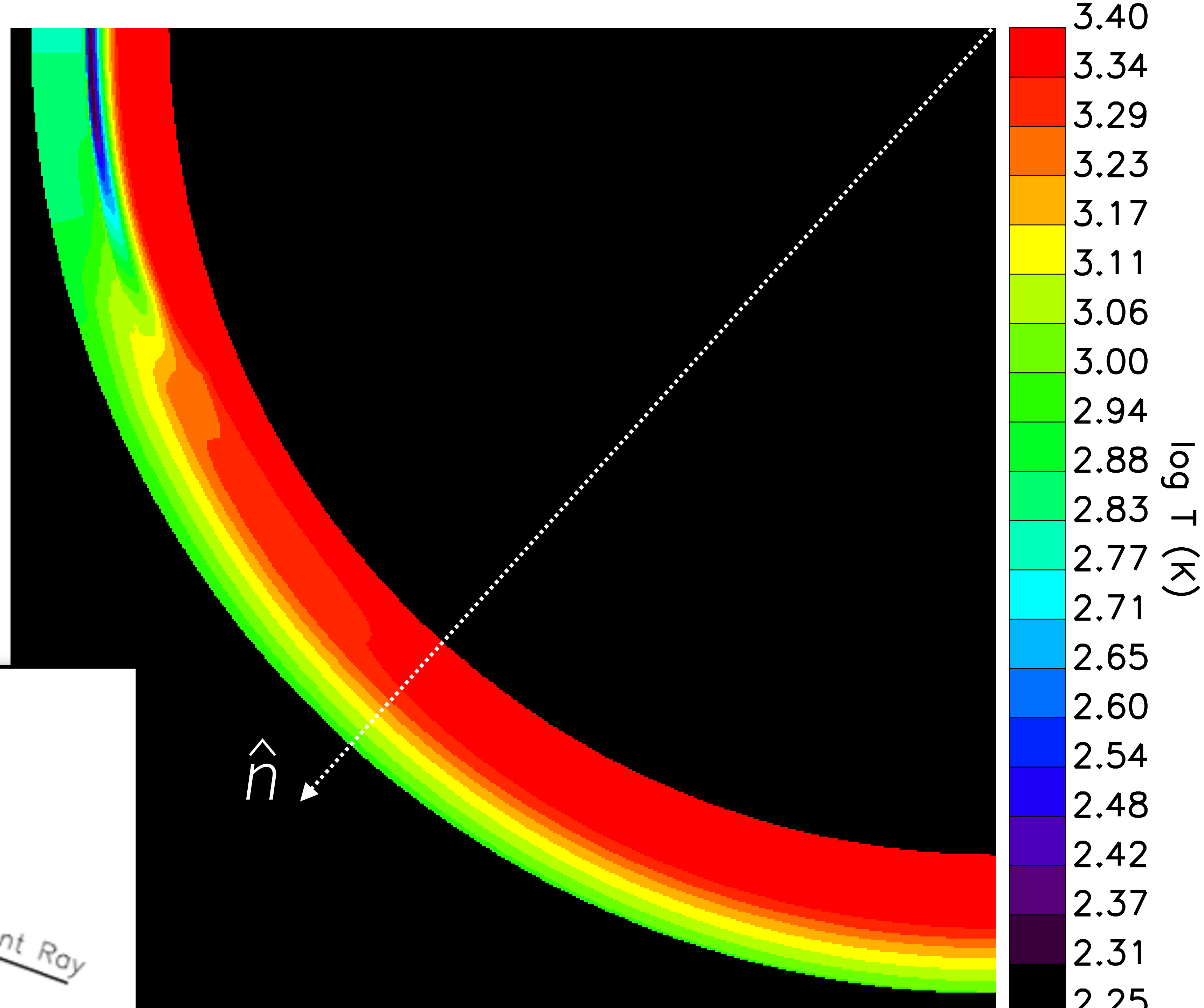
Fortney et al. (2008)

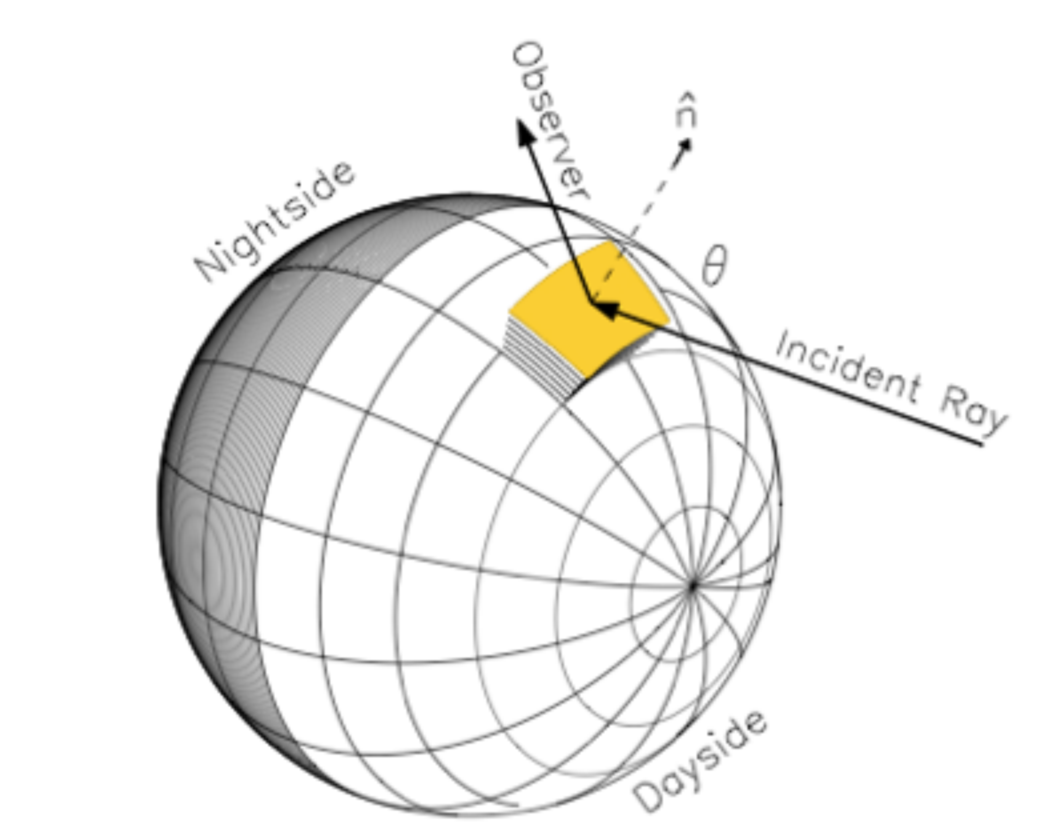
temperature inversions



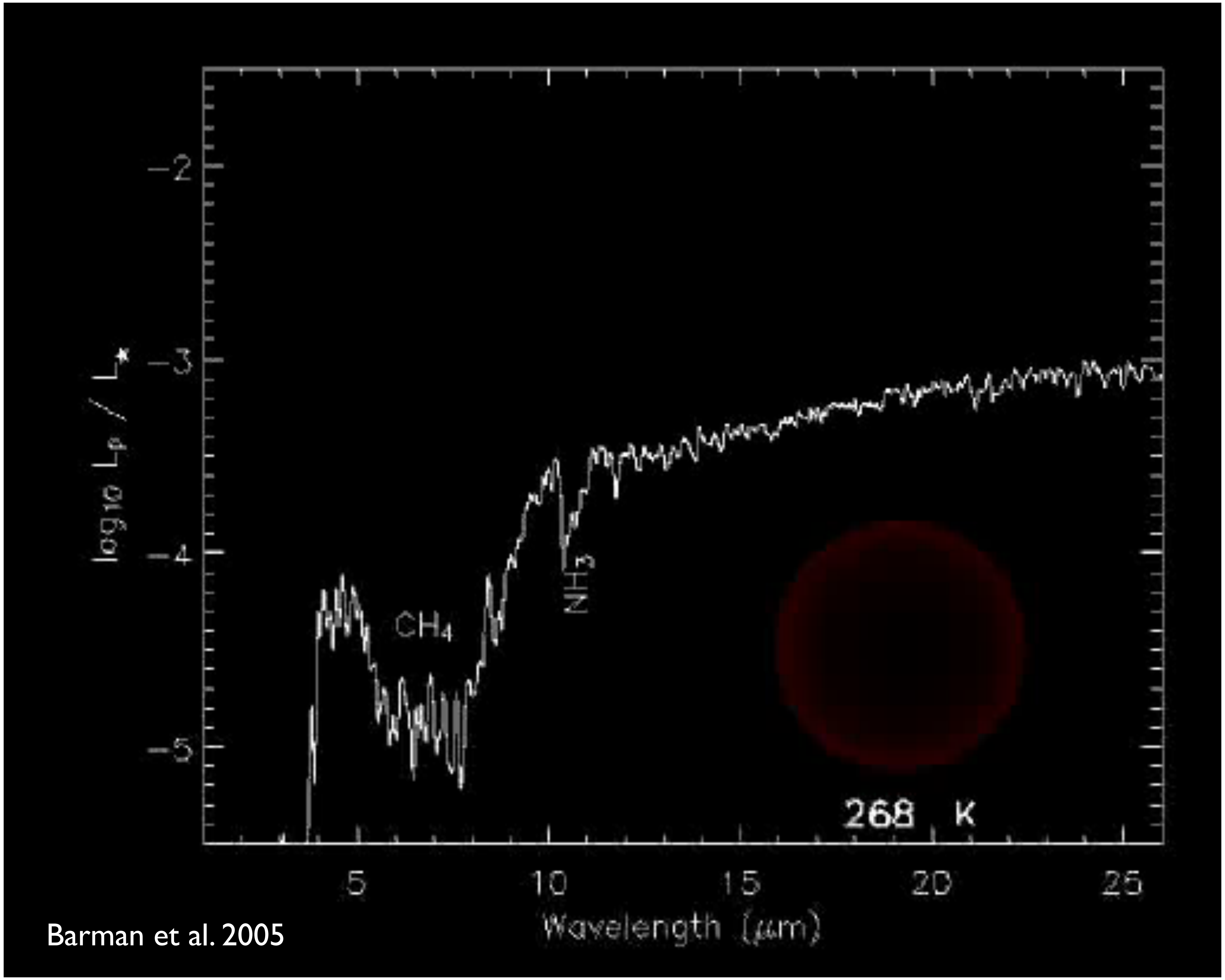


Phase-dependent Properties





Barman et al. 2005



Barman et al. 2005

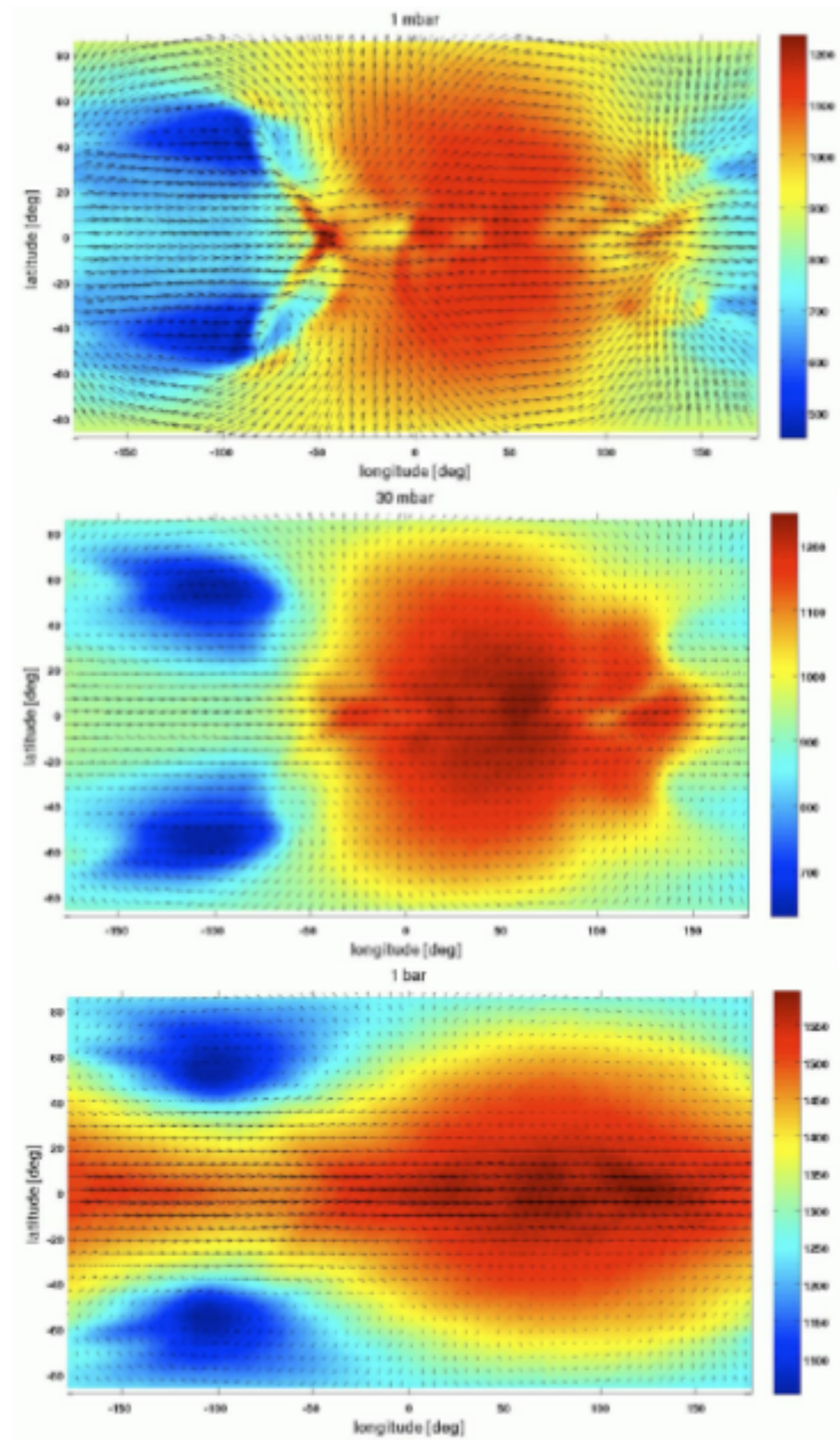
1200K

1000K

750K

450K

latitude



1 mbar

30 mbar

1 bar

longitude

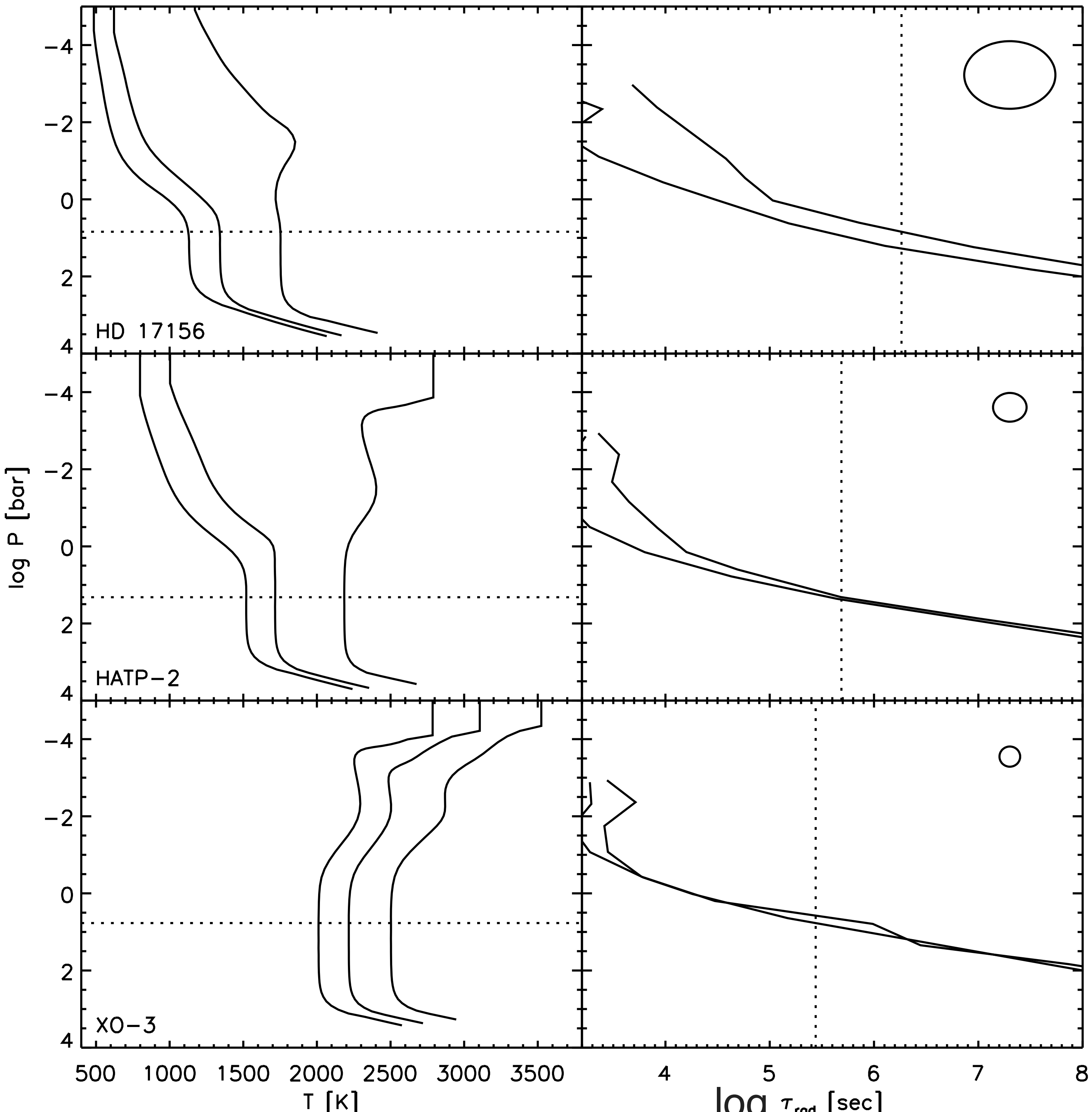
Showman et al. (2009)

eccentric planets

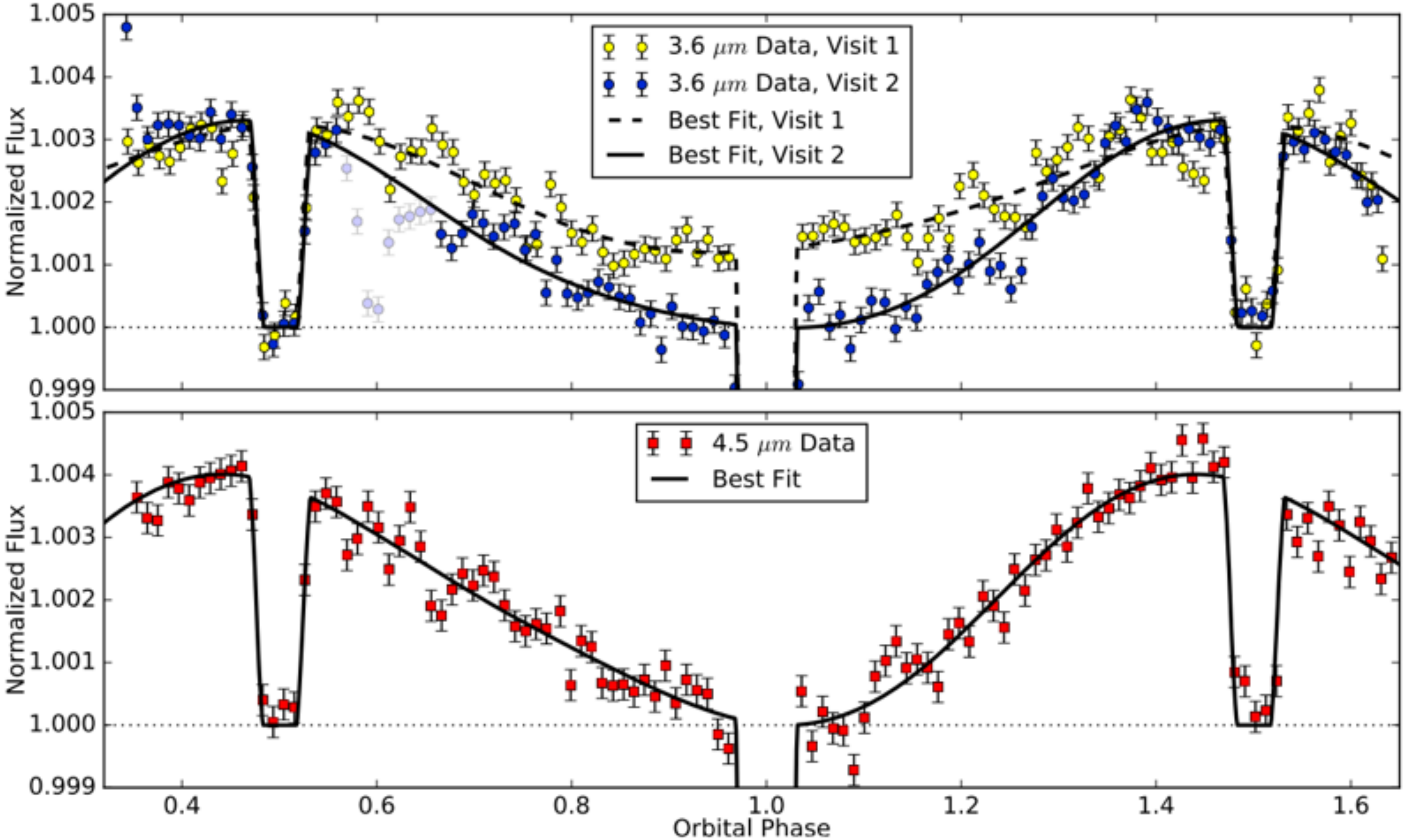
HD 17156b
e = 0.67

HAT-2
e= 0.52

XO-3
e = 0.26



WASP-43b

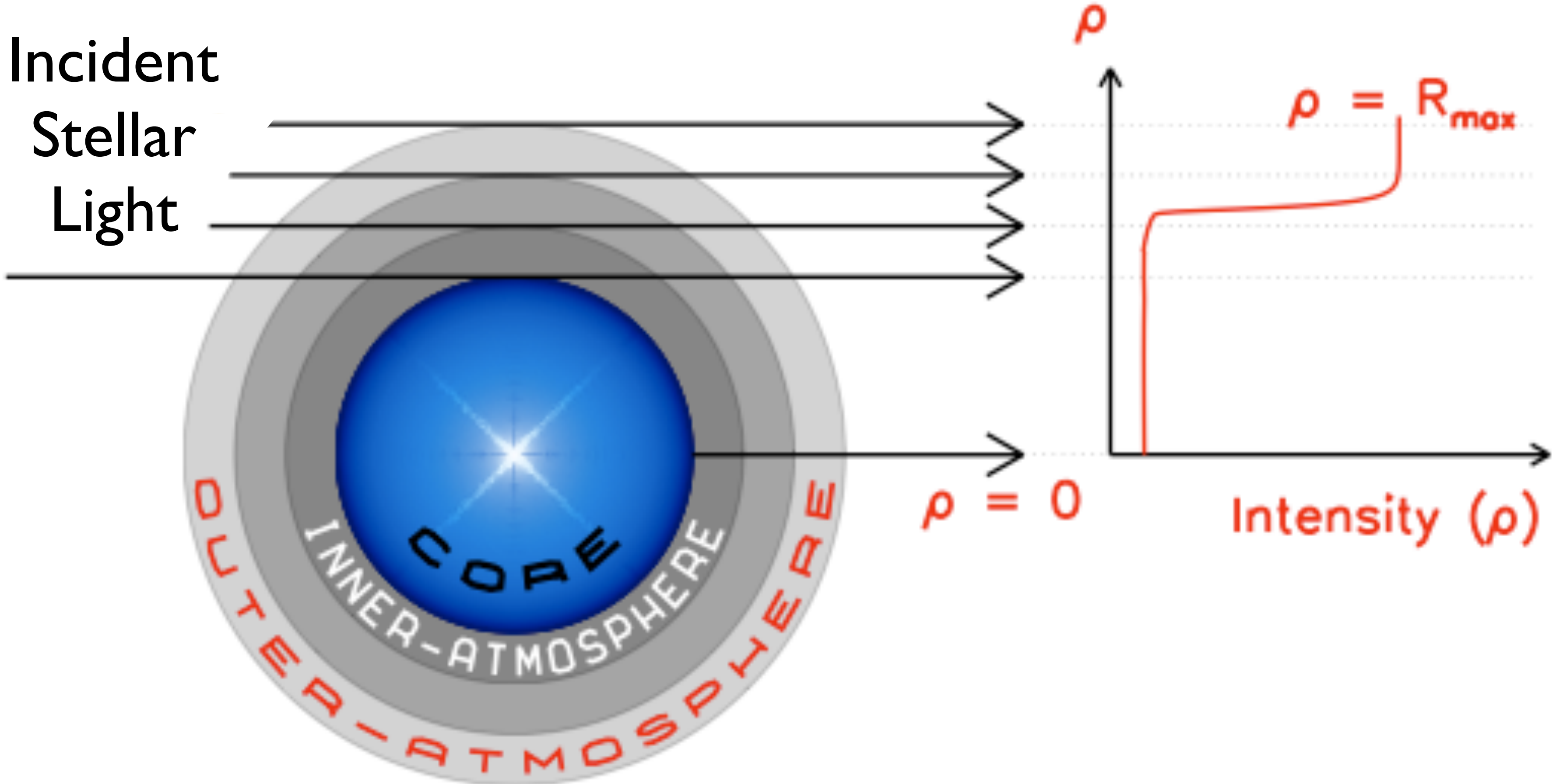


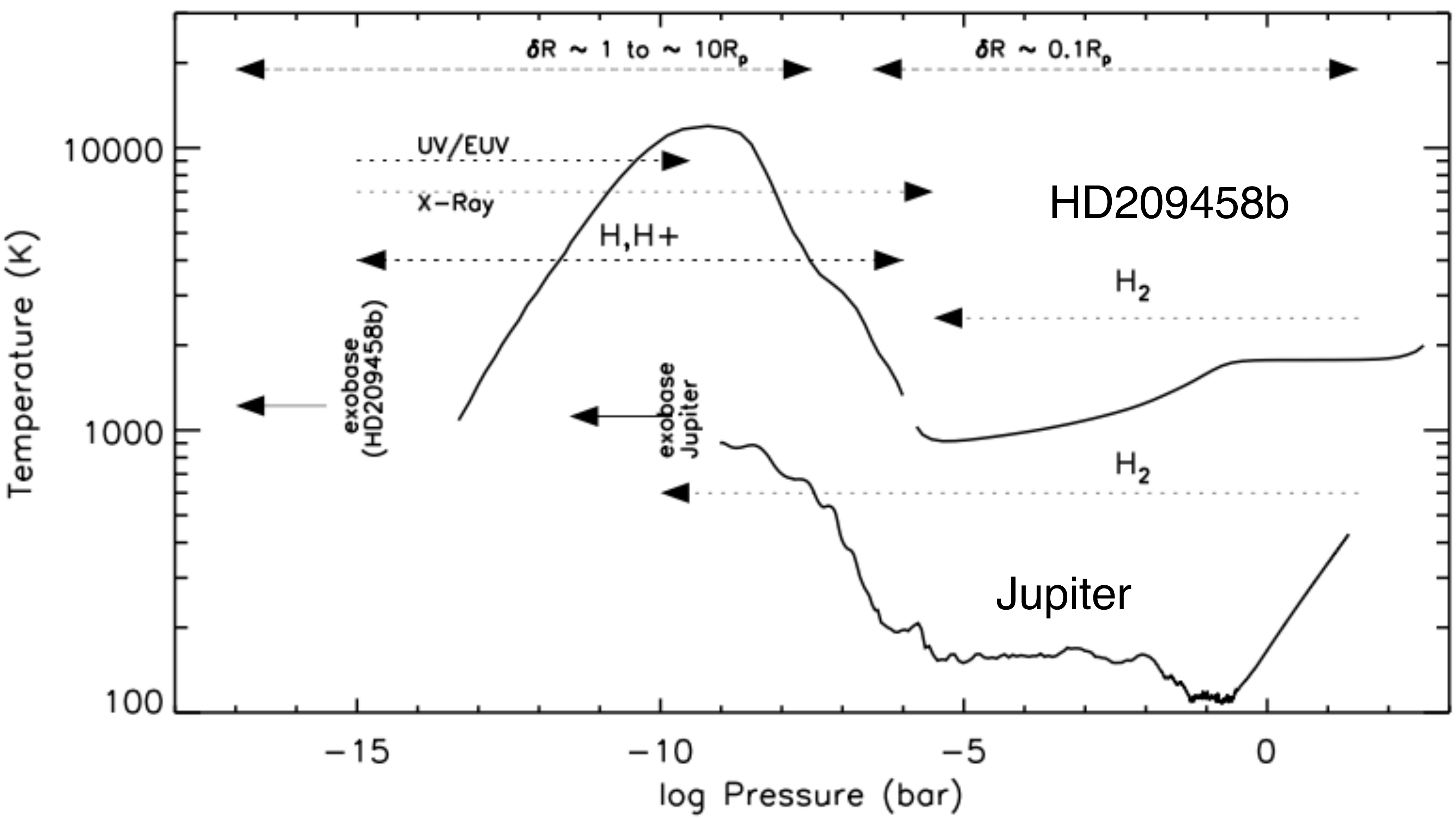
Stevenson et al. (2017)

Exoplanet Atmospheres

- Secondary Eclipses (e.g., HD 209458b)
- Phase-curves (e.g., HD 189733b)
- Transit spectroscopy (e.g., HD 189733b)
- Spatially Resolved ("directly" imaged) (e.g., 2m1207b, HR 8799 bcde)

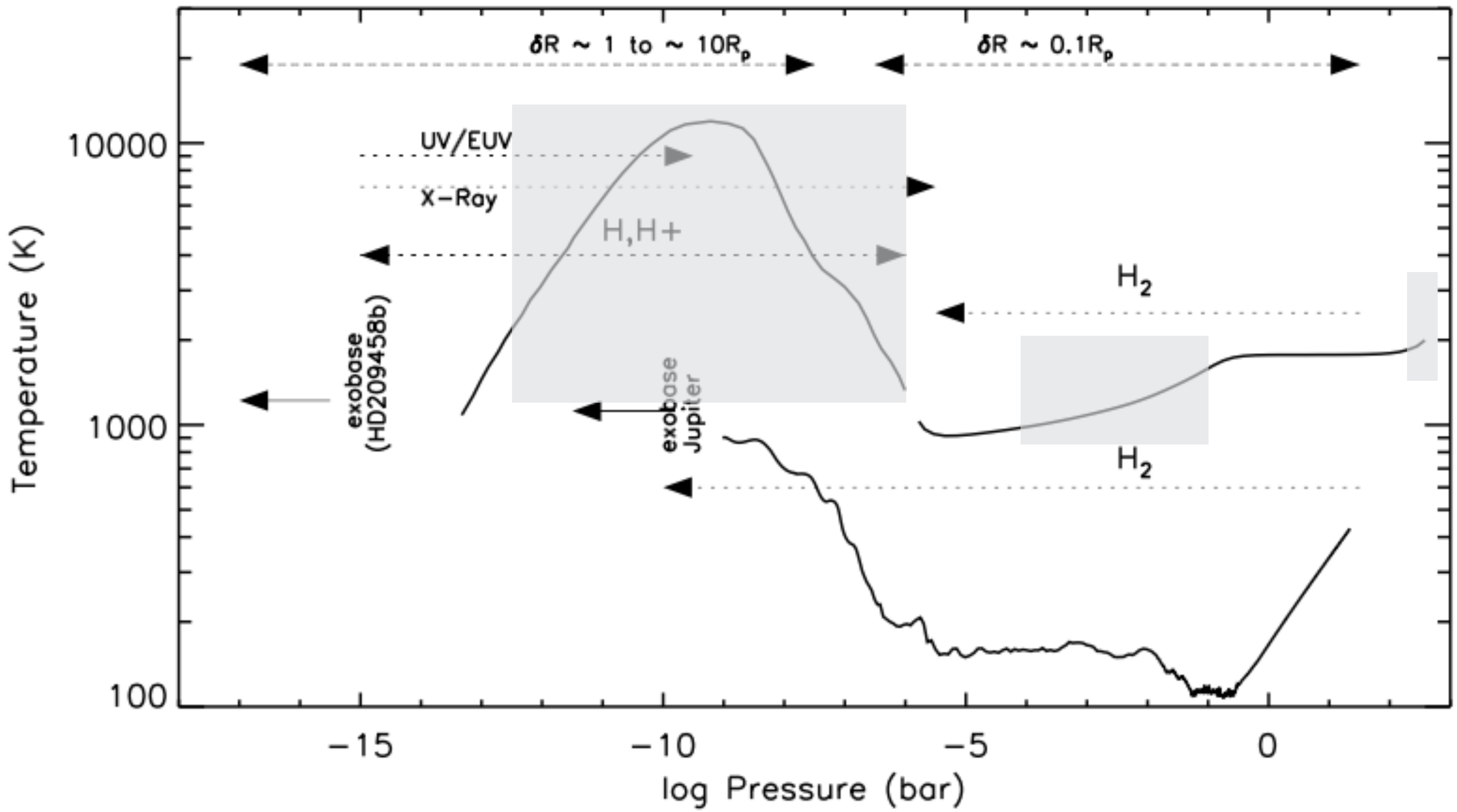
Transmission Spectrum
(primary eclipse)



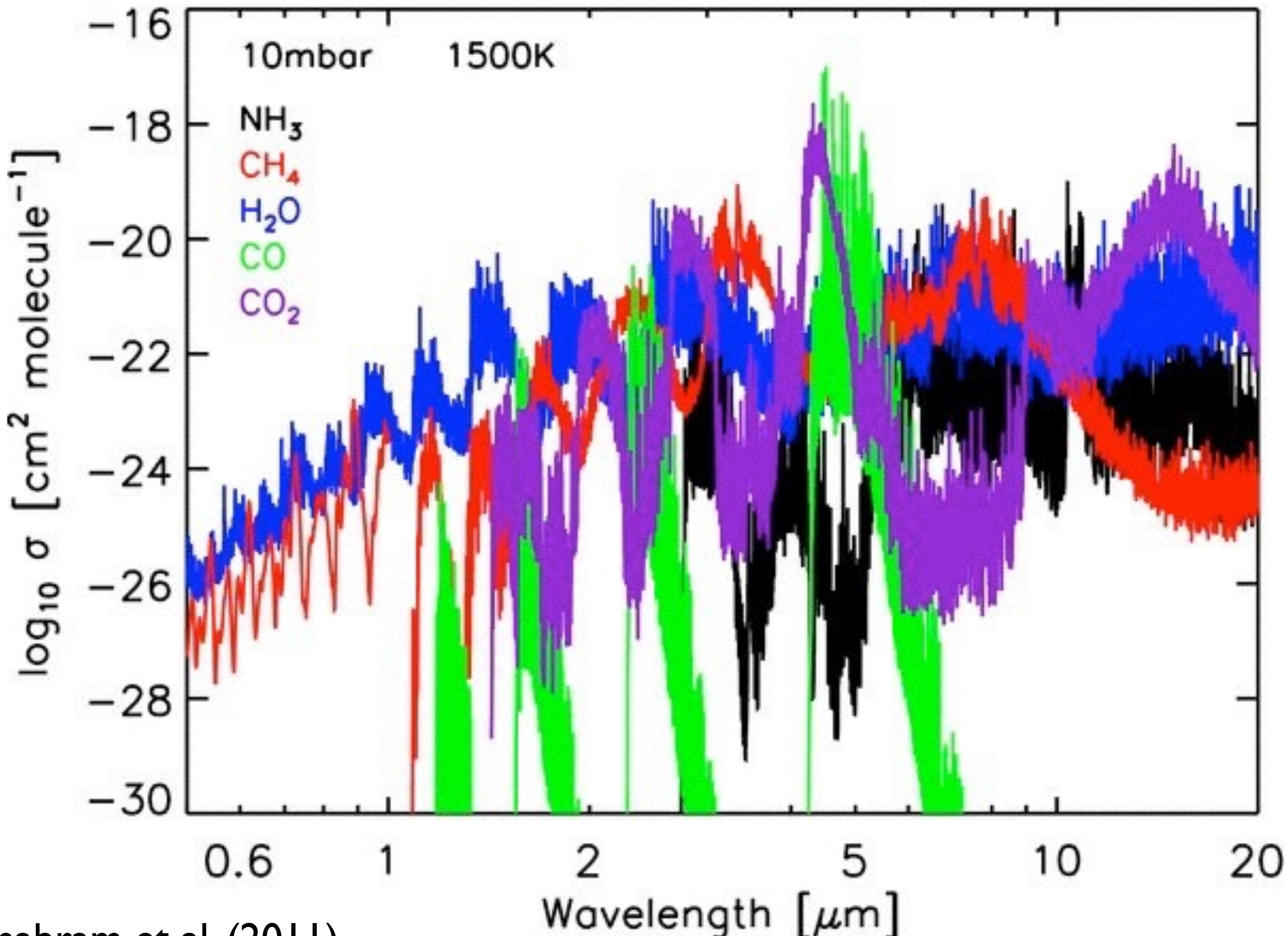


δR ~ 1 to ~ 10R$_p$
δR ~ 0.1R$_p$
UV/EUV
X-Ray
H,H+
HD209458b
H_2
exobase (HD209458b)
exobase Jupiter
H_2
Jupiter
Temperature (K)
10000
1000
100
−15
−10
−5
0
log Pressure (bar)

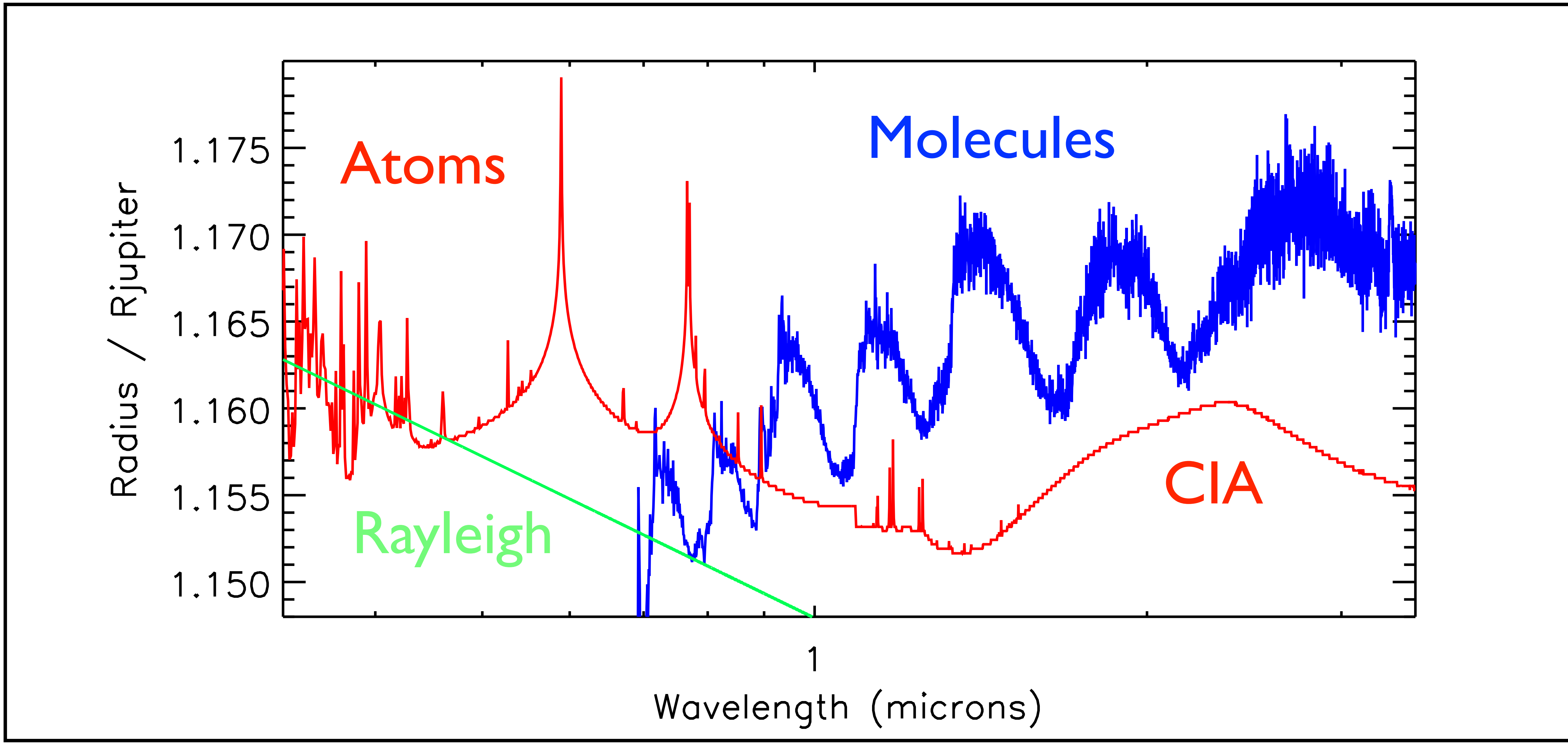
UV trans. Opt/IR trans.

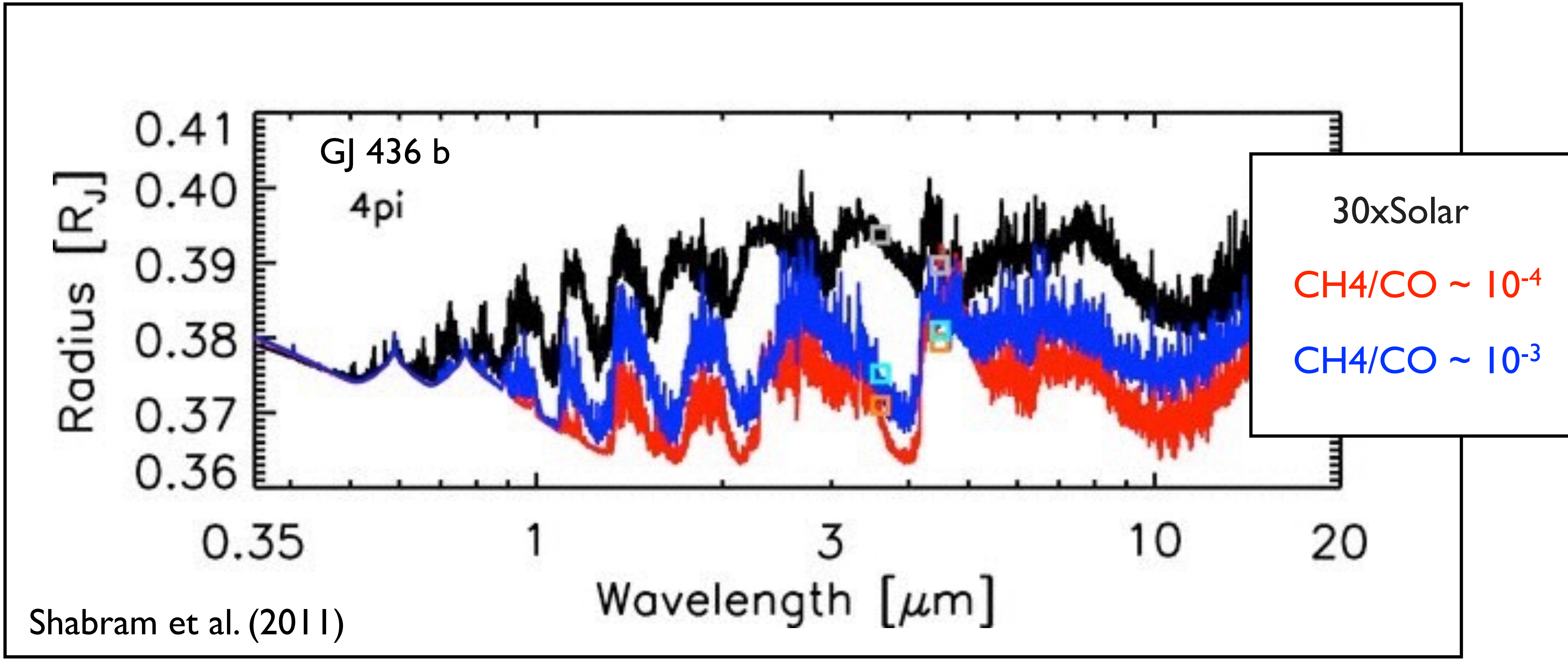


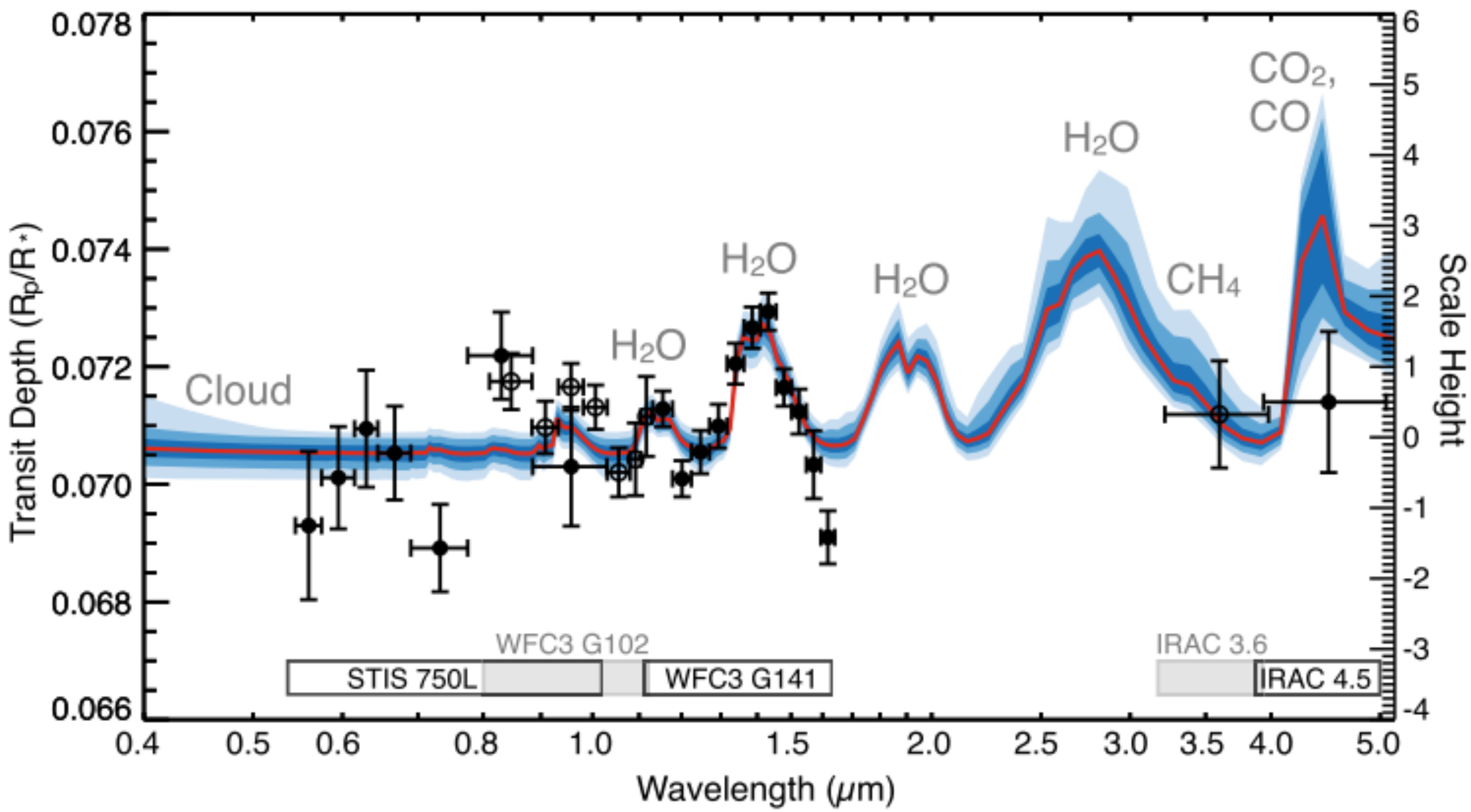
Interior



Shabram et al. (2011)

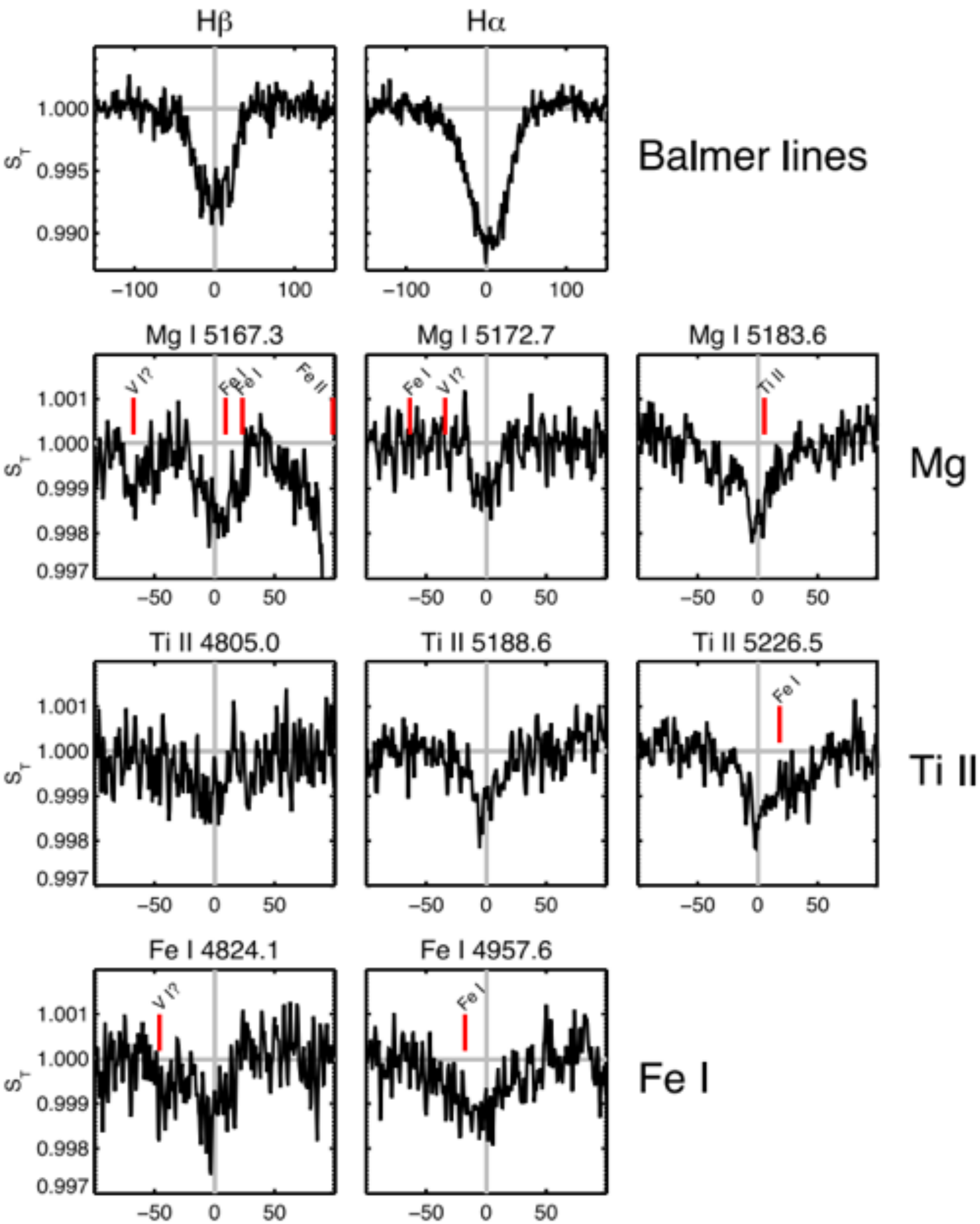

Atoms
Molecules
Rayleigh
CIA
1.175
1.170
1.165
1.160
1.155
1.150
Radius / Rjupiter
1
Wavelength (microns)

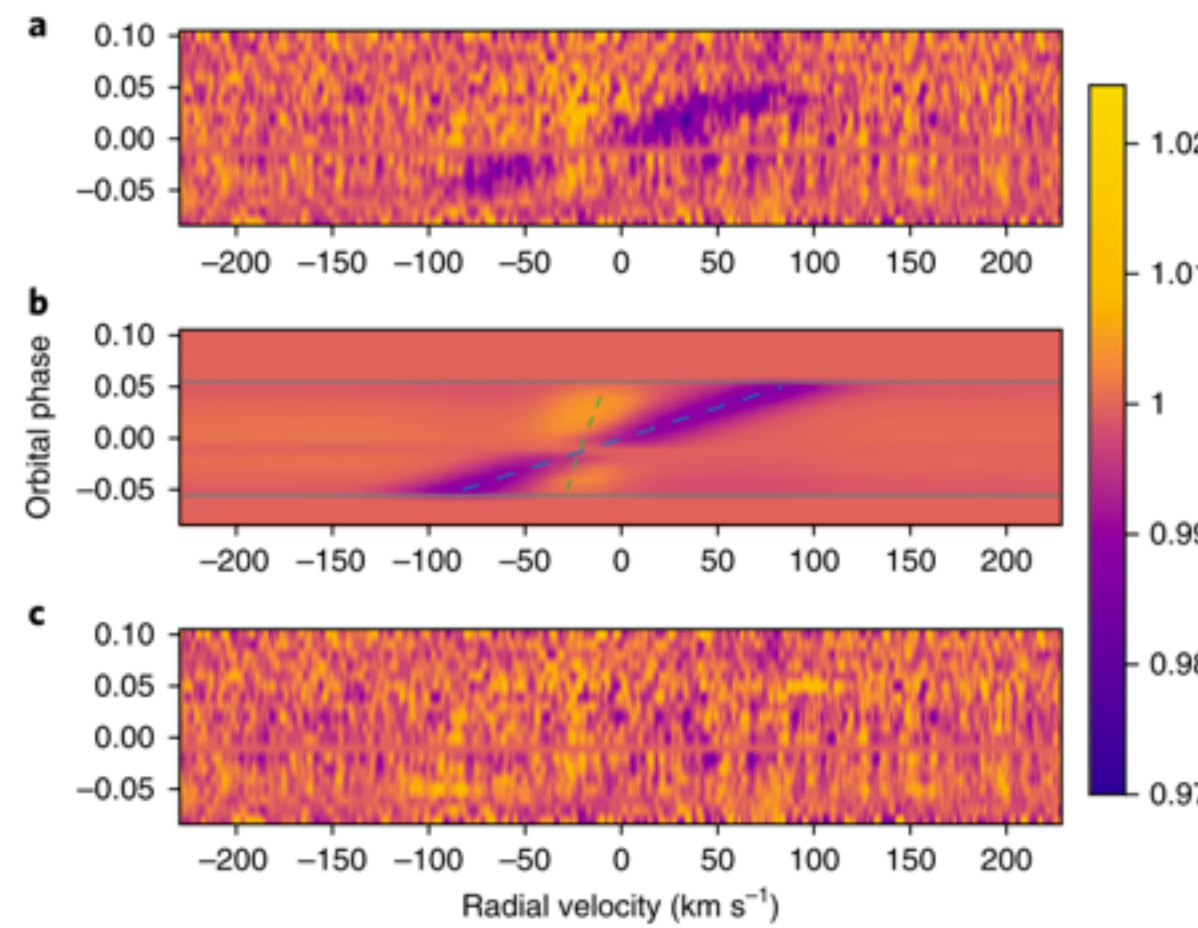

GJ 436 b
4pi
0.41
0.40
0.39
0.38
0.37
0.36
Radius [R_J]
0.35
1
3
10
20
Wavelength [μm]
30xSolar
CH4/CO ~ 10-4
CH4/CO ~ 10-3
Shabram et al. (2011)



Transit Depth (R_p/R_*)
0.078
0.076
0.074
0.072
0.070
0.068
0.066
Scale Height
6
5
4
3
2
1
0
-1
-2
-3
-4
Cloud
H_2O
H_2O
H_2O
H_2O
CH_4
CO_2,
CO
WFC3 G102
STIS 750L
WFC3 G141
IRAC 3.6
IRAC 4.5
0.4
0.5
0.6
0.8
1.0
1.5
2.0
2.5
3.0
3.5
4.0
5.0
Wavelength (μm)

Kelt9-b, high-resolution transition spectroscopy

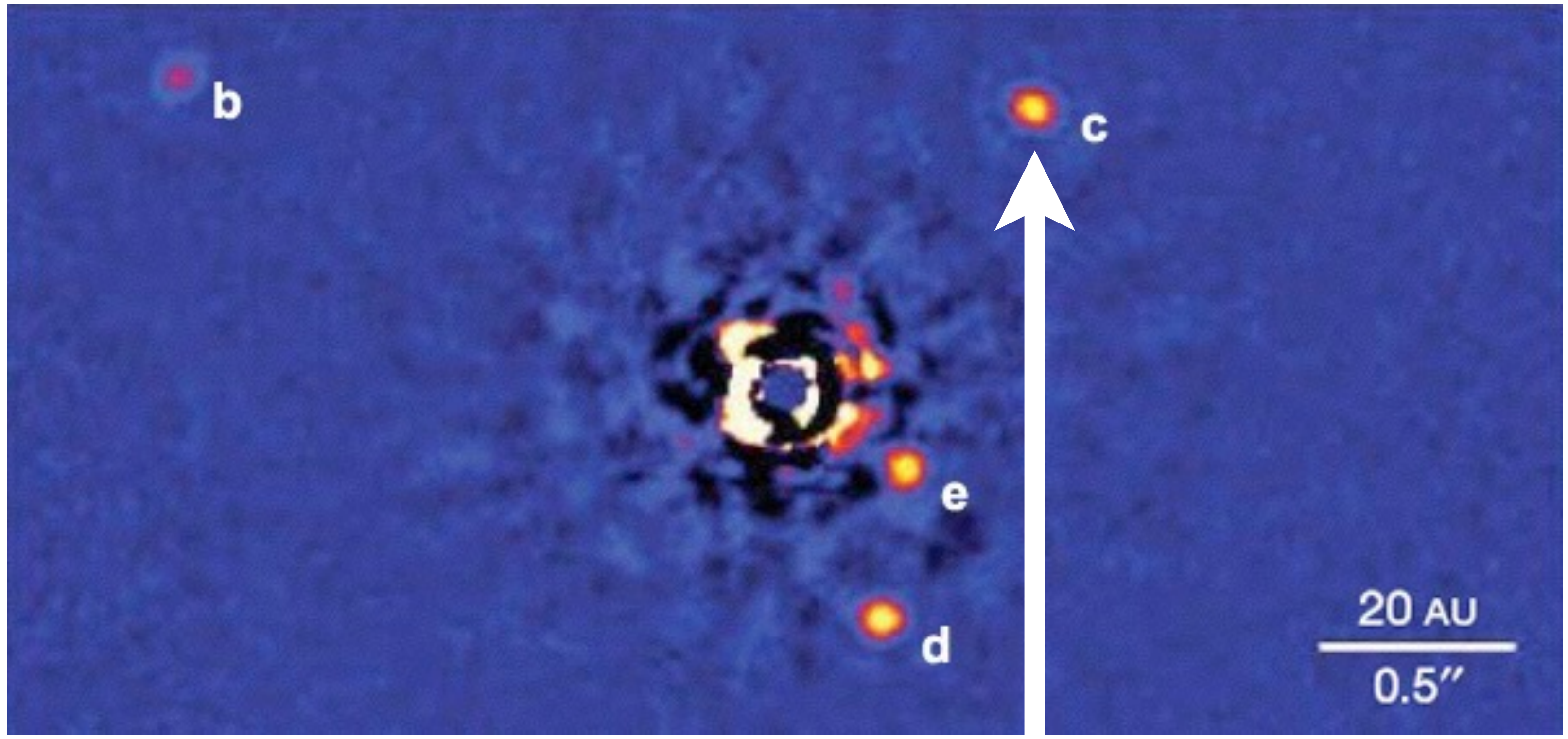


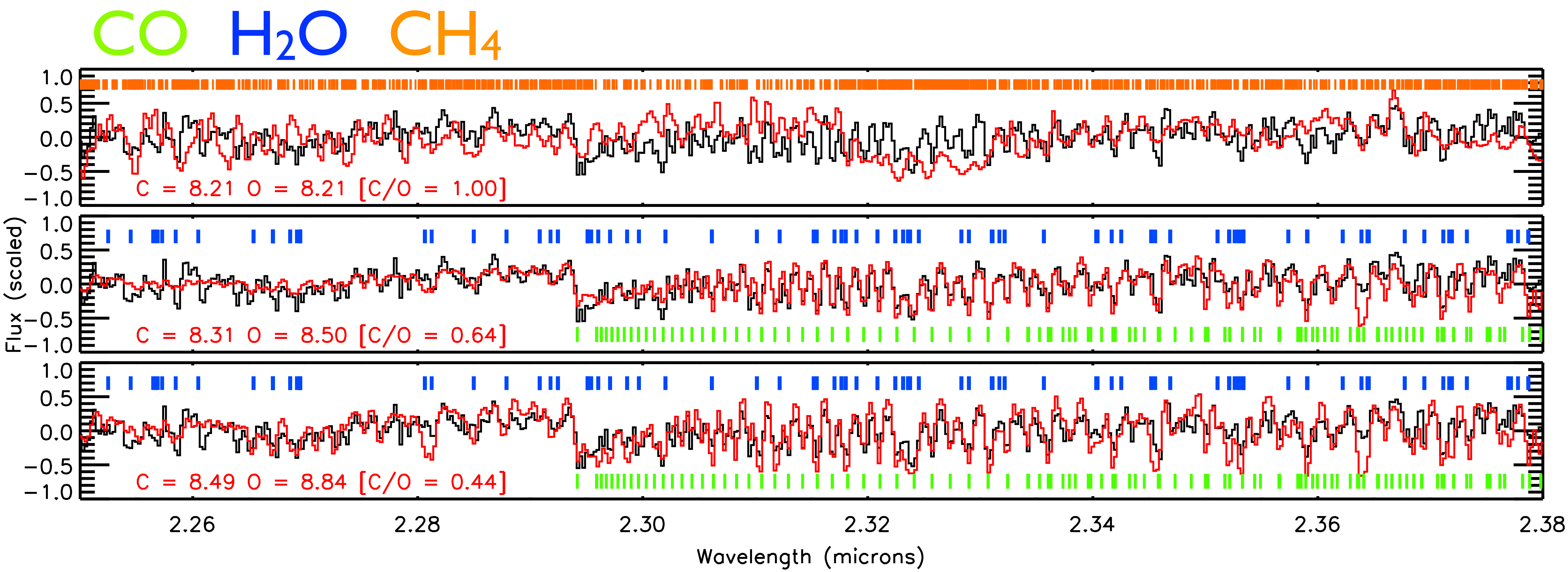


Cauley et al. (2018); Yan et al. 2018

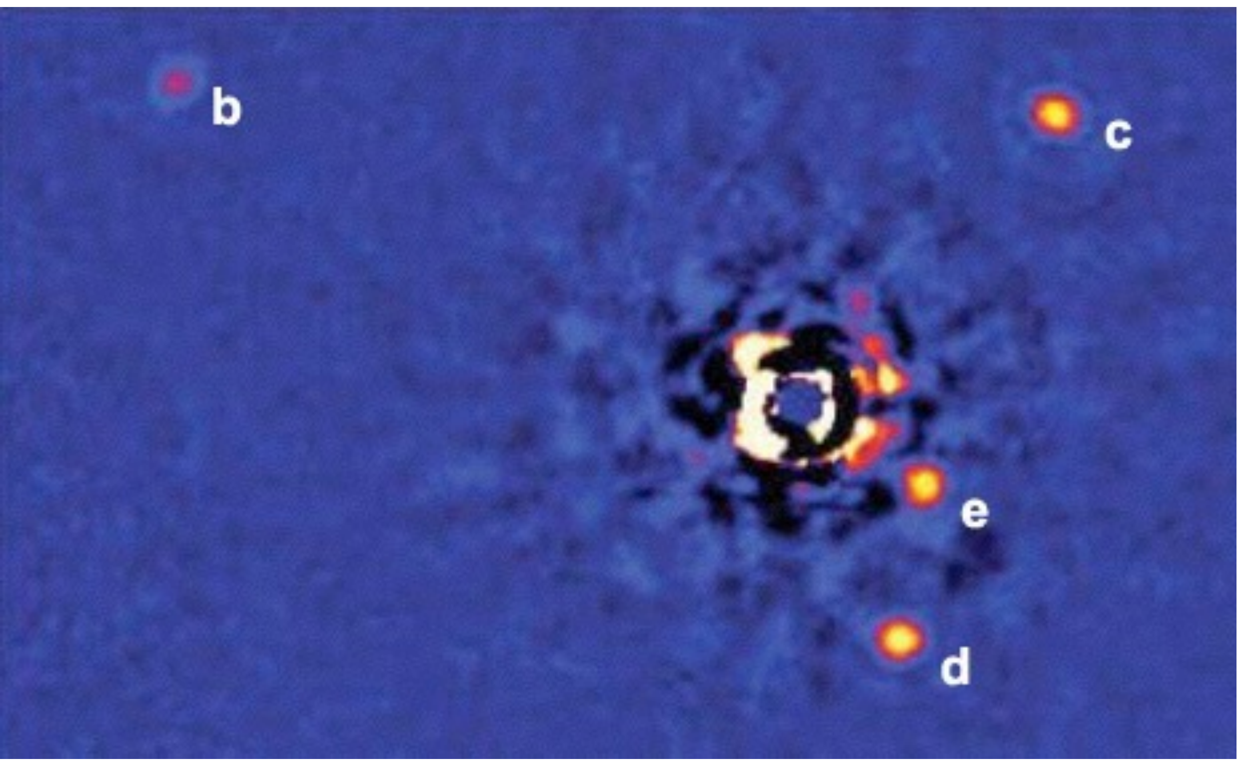
Exoplanet Atmospheres

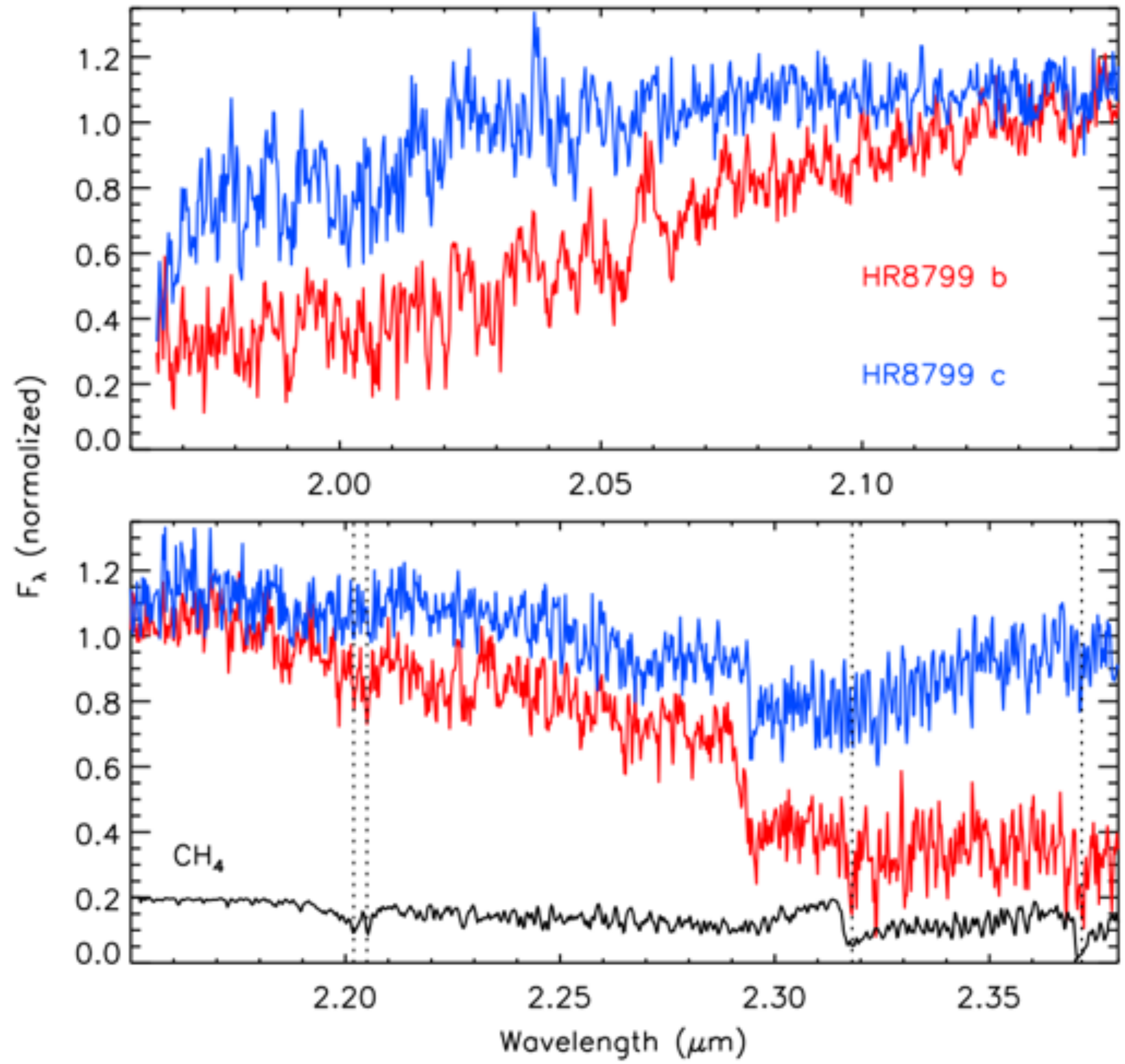
- Secondary Eclipses (e.g., HD 209458b)
- Phase-curves (e.g., HD 189733b)
- Transit spectroscopy (e.g., HD 189733b)
- Spatially Resolved ("directly" imaged) (e.g., 2m1207b, HR 8799 b, c, & d)

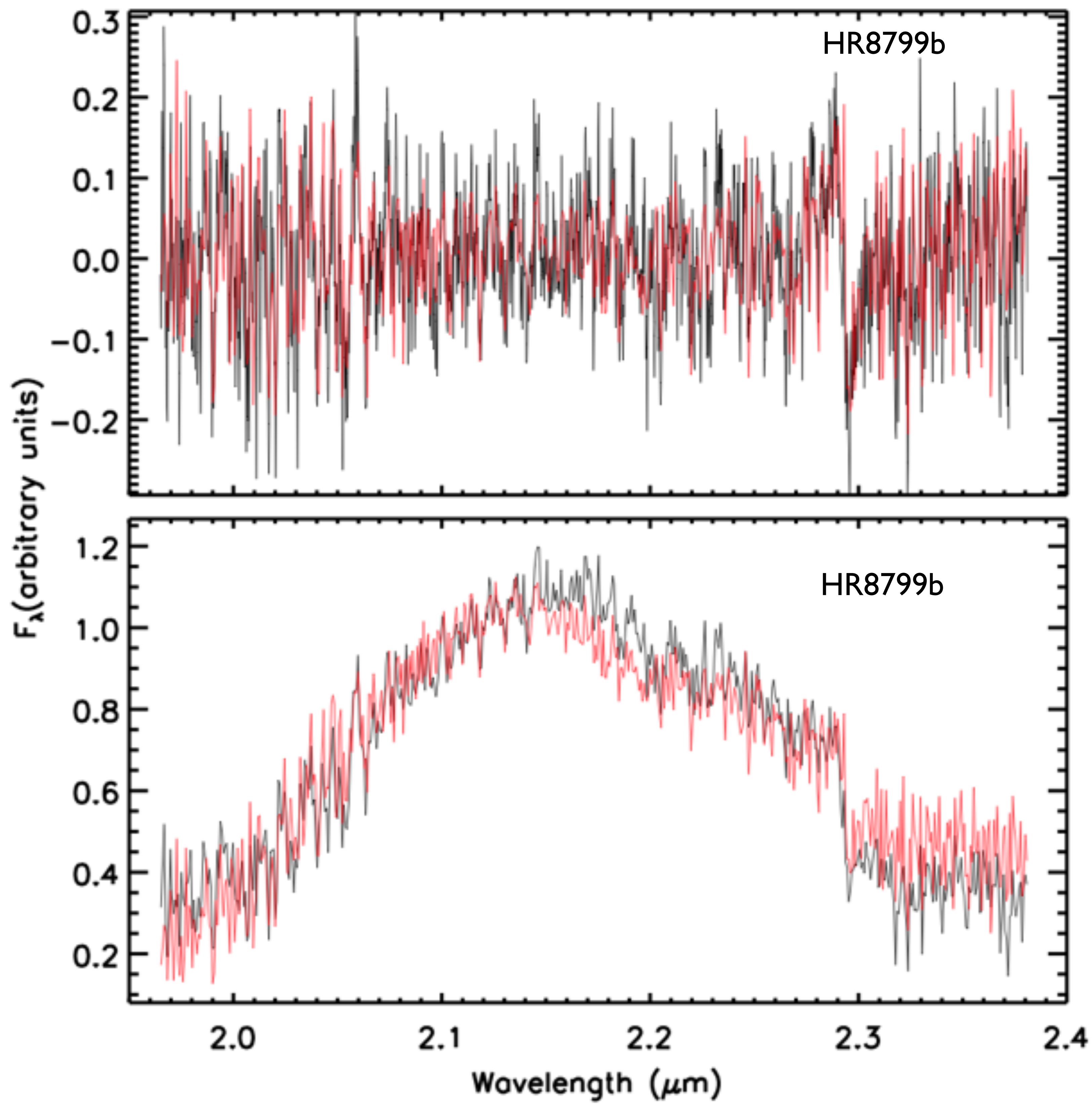




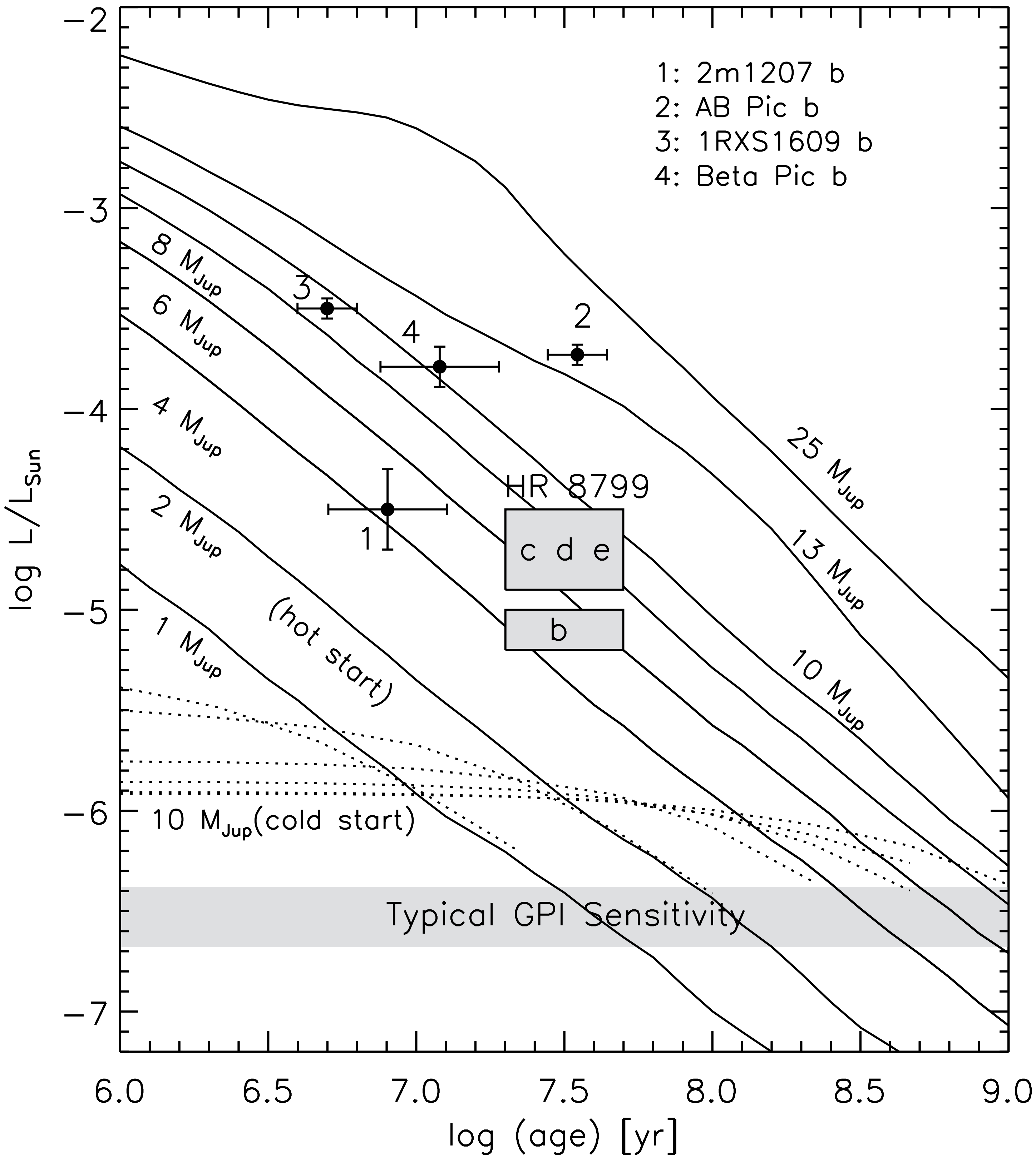
Konopacky, Barman, Macintosh & Marois (2013)


b
c
e
d


HR8799 b
HR8799 c
CH4
Fλ (normalized)
Wavelength (μm)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2.00
2.05
2.10
2.20
2.25
2.30
2.35

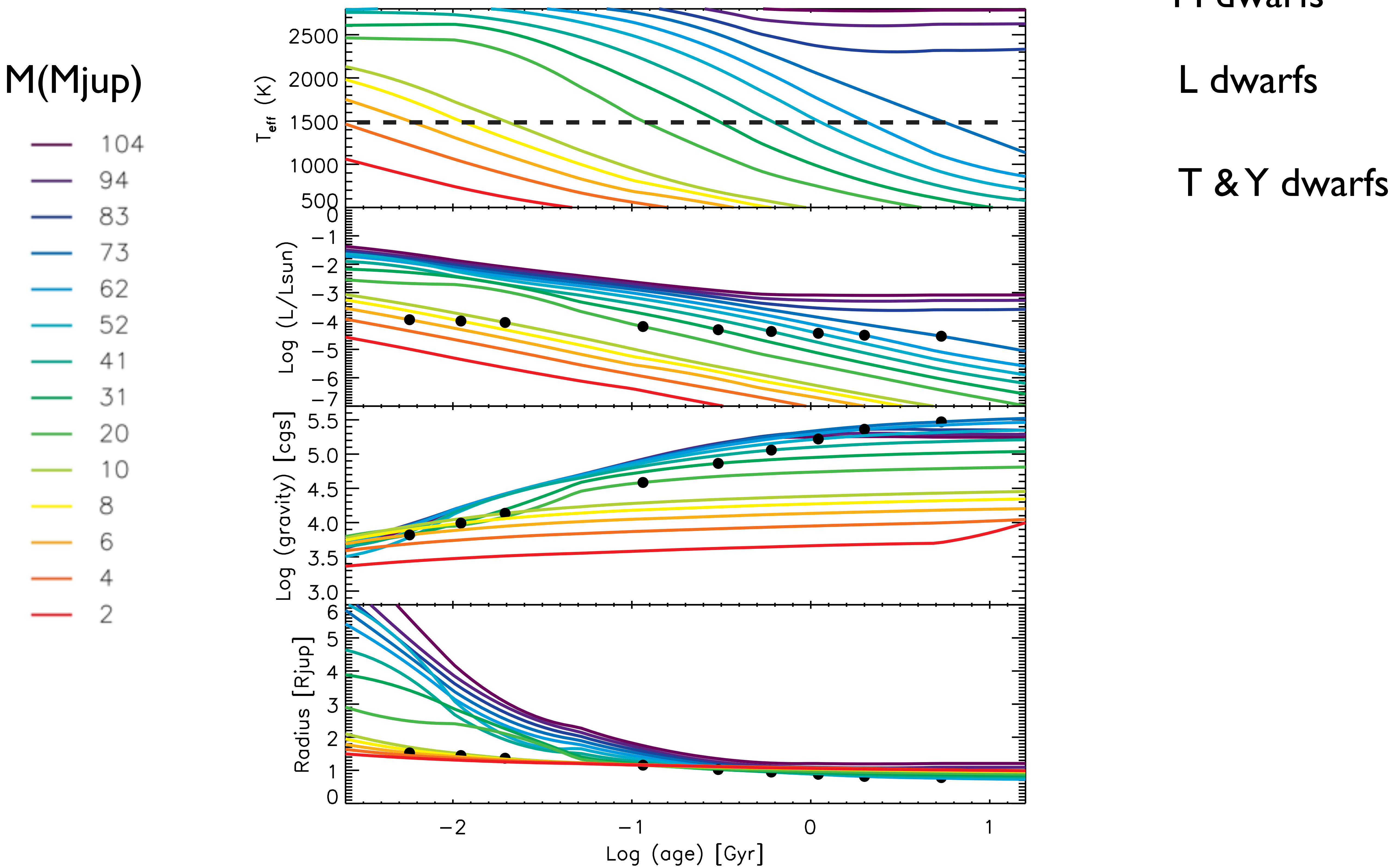


HR8799b
HR8799b
0.3
0.2
0.1
0.0
−0.1
−0.2
1.2
1.0
0.8
0.6
0.4
0.2
2.0
2.1
2.2
2.3
2.4
Wavelength (μm)
Fλ(arbitrary units)



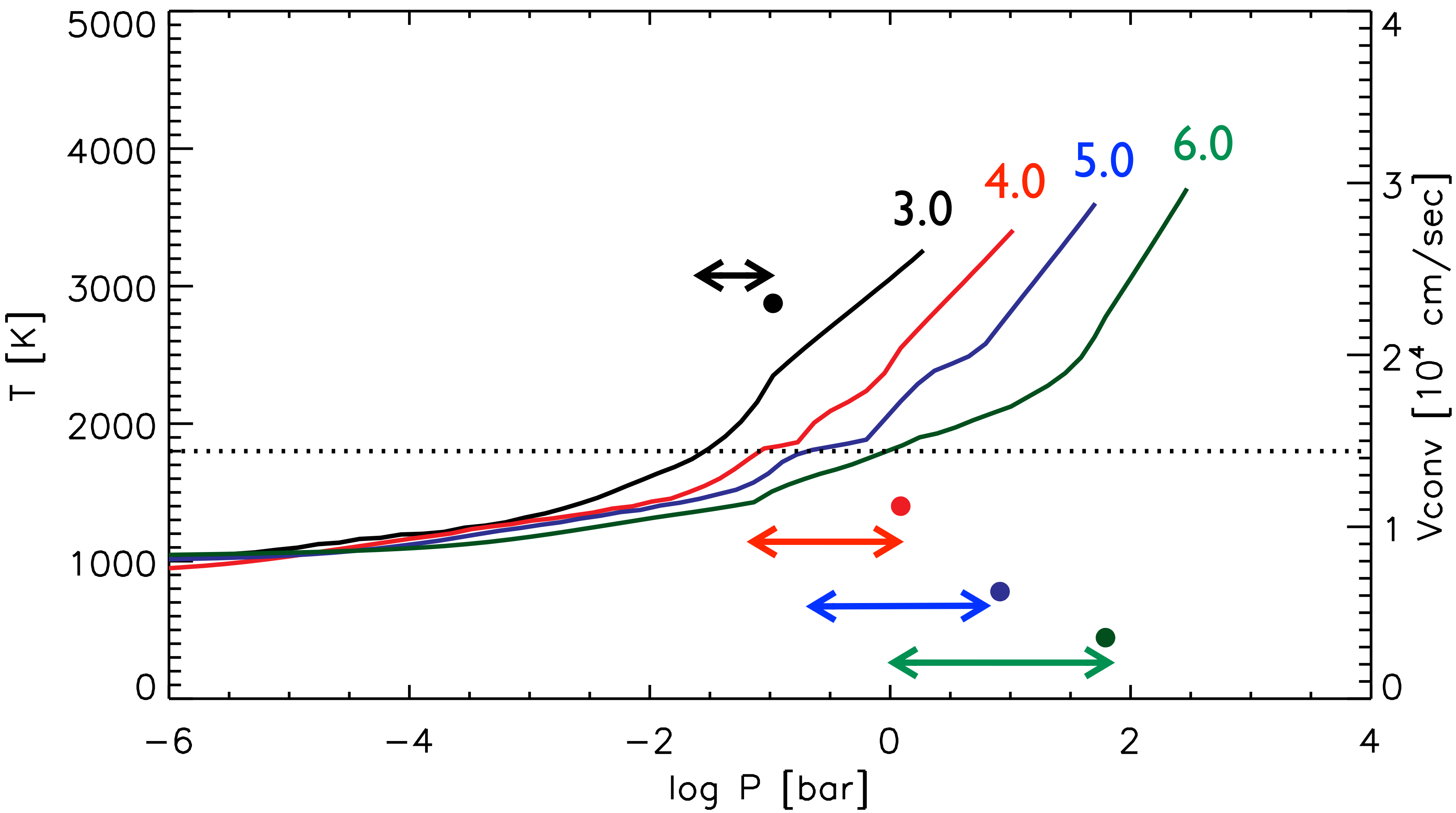
1: 2m1207 b
2: AB Pic b
3: 1RXS1609 b
4: Beta Pic b
25 M_{Jup}
13 M_{Jup}
10 M_{Jup}
8 M_{Jup}
6 M_{Jup}
4 M_{Jup}
2 M_{Jup}
1 M_{Jup}
(hot start)
10 M_{Jup}(cold start)
HR 8799
c d e
b
Typical GPI Sensitivity
log L/L$_{Sun}$
log (age) [yr]
−2
−3
−4
−5
−6
−7
6.0
6.5
7.0
7.5
8.0
8.5
9.0

The importance of surface gravity:



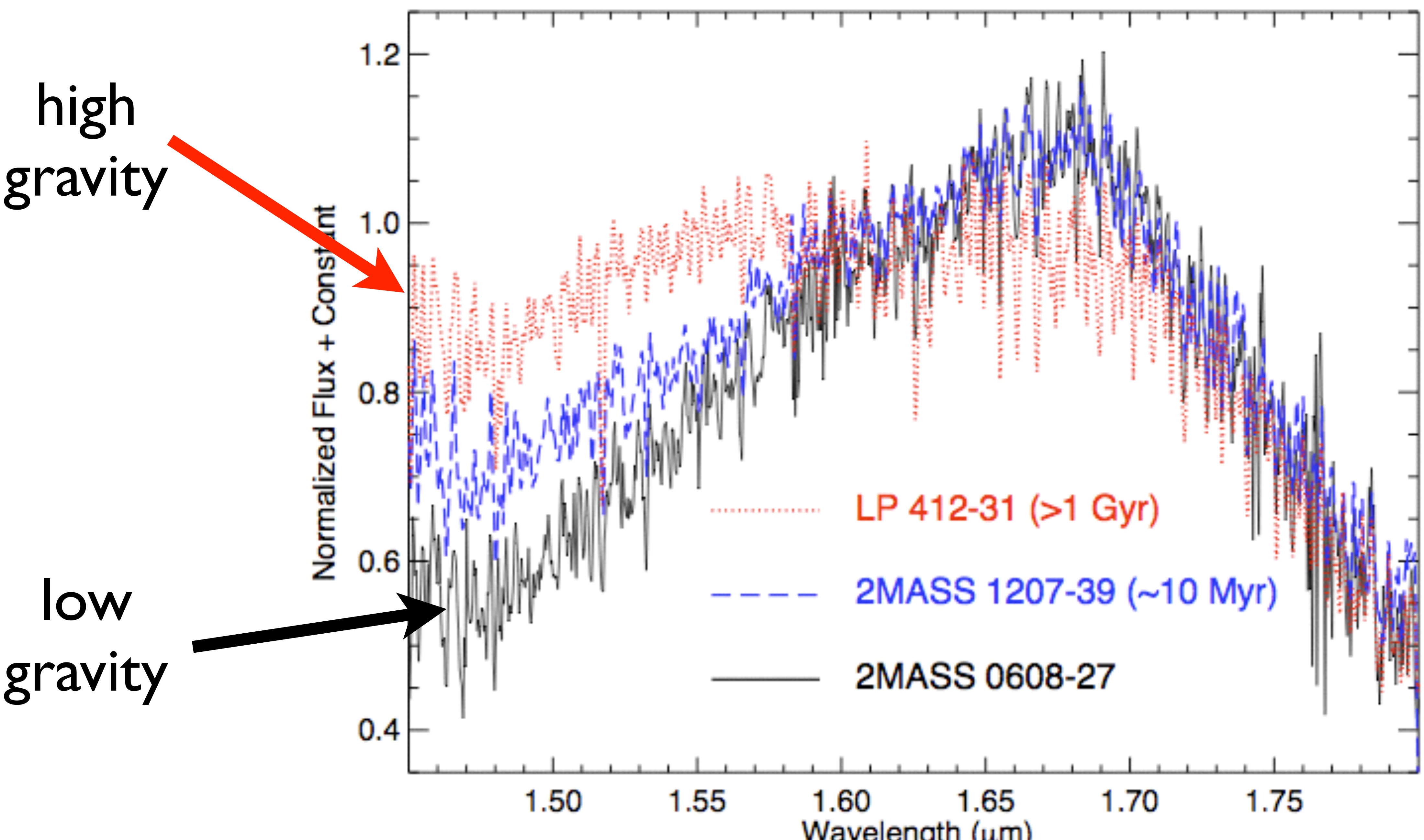
Baraffe et al. 2003

Convection and Gravity



Relative positions of photosphere and top of convection zone (cz). Vertical position indicates convective velocities at top of cz.

H-band (triangular shape)

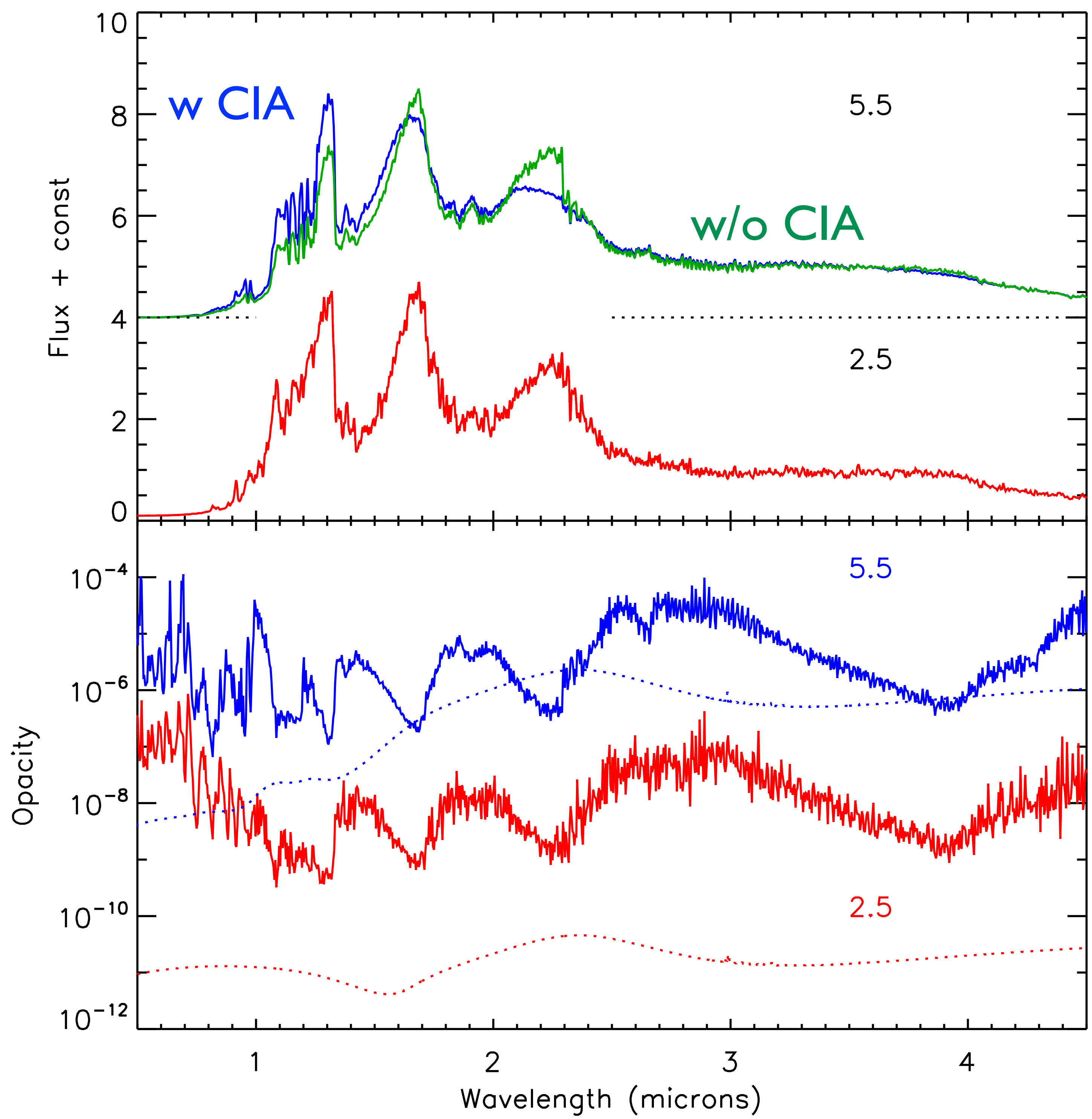


Rice et al. (2010)

See also Allers et al. (2007) and refs for more examples.

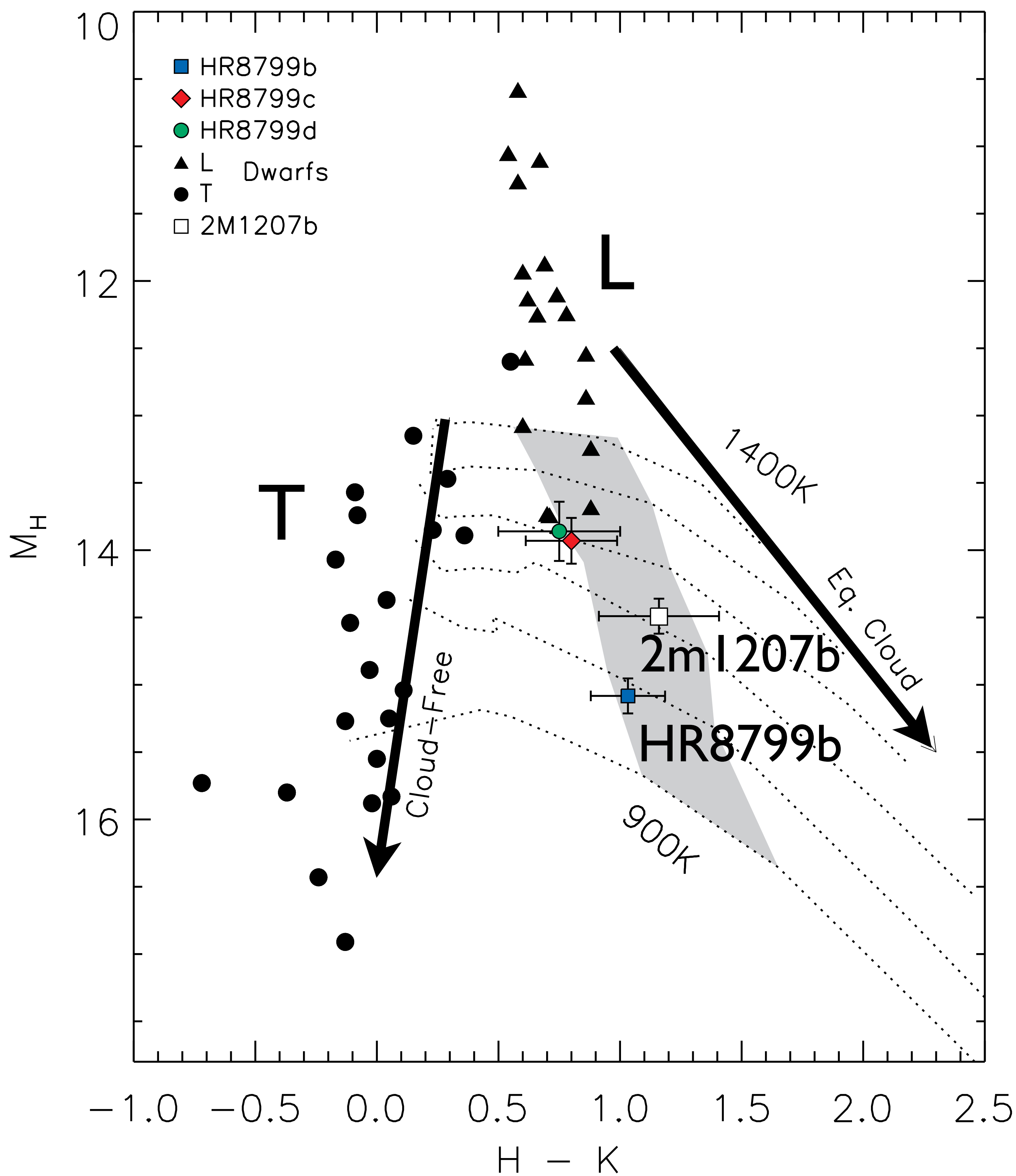
H-band (triangular shape)

CIA:
lower gravity changes H and K bands, also makes spectrum redder



(see Borysow et al. 1997, Kirkpatrick et al. 2006)

(temperature)

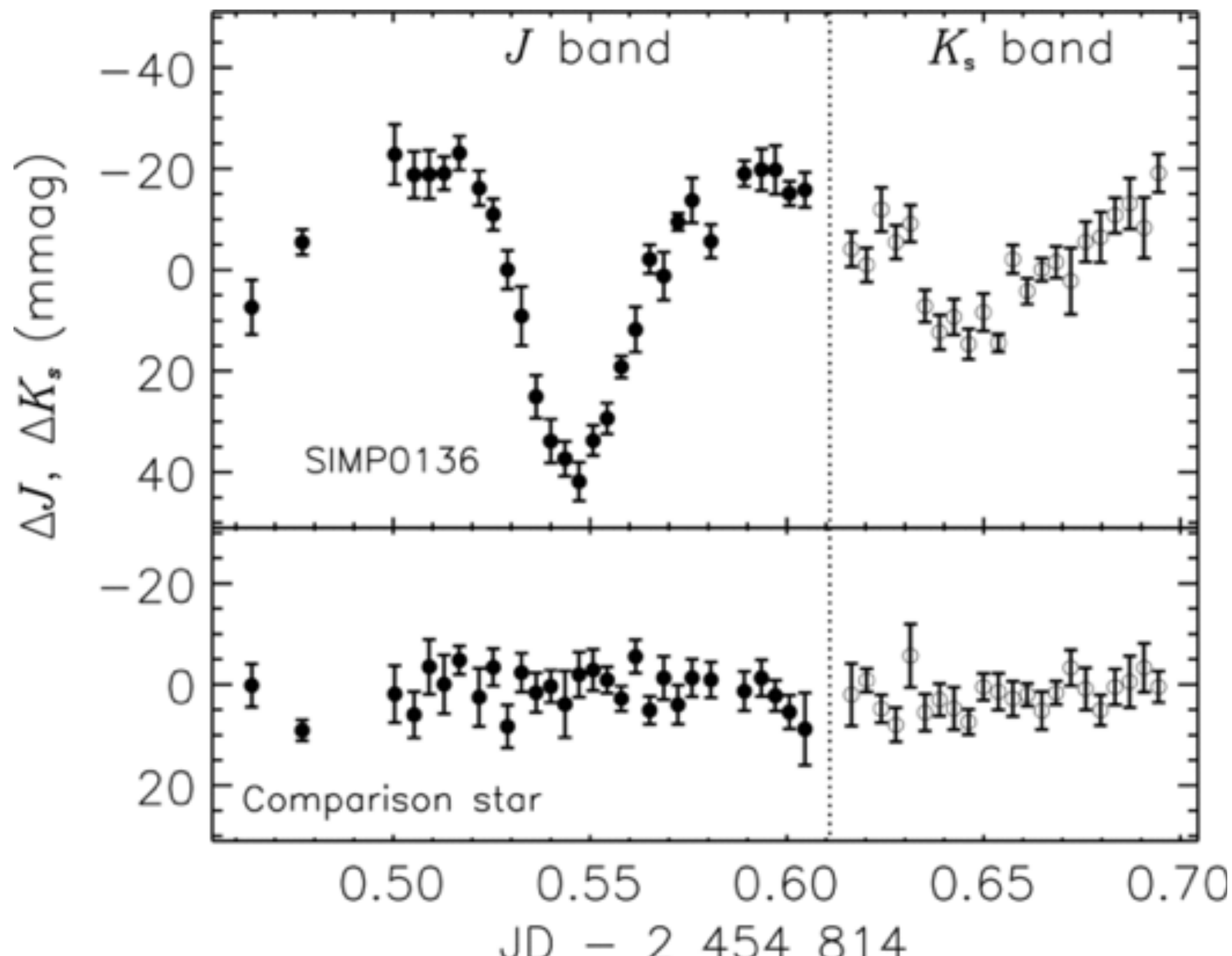


(clouds)

ext. of L sequence?

Barman et al. (2011)

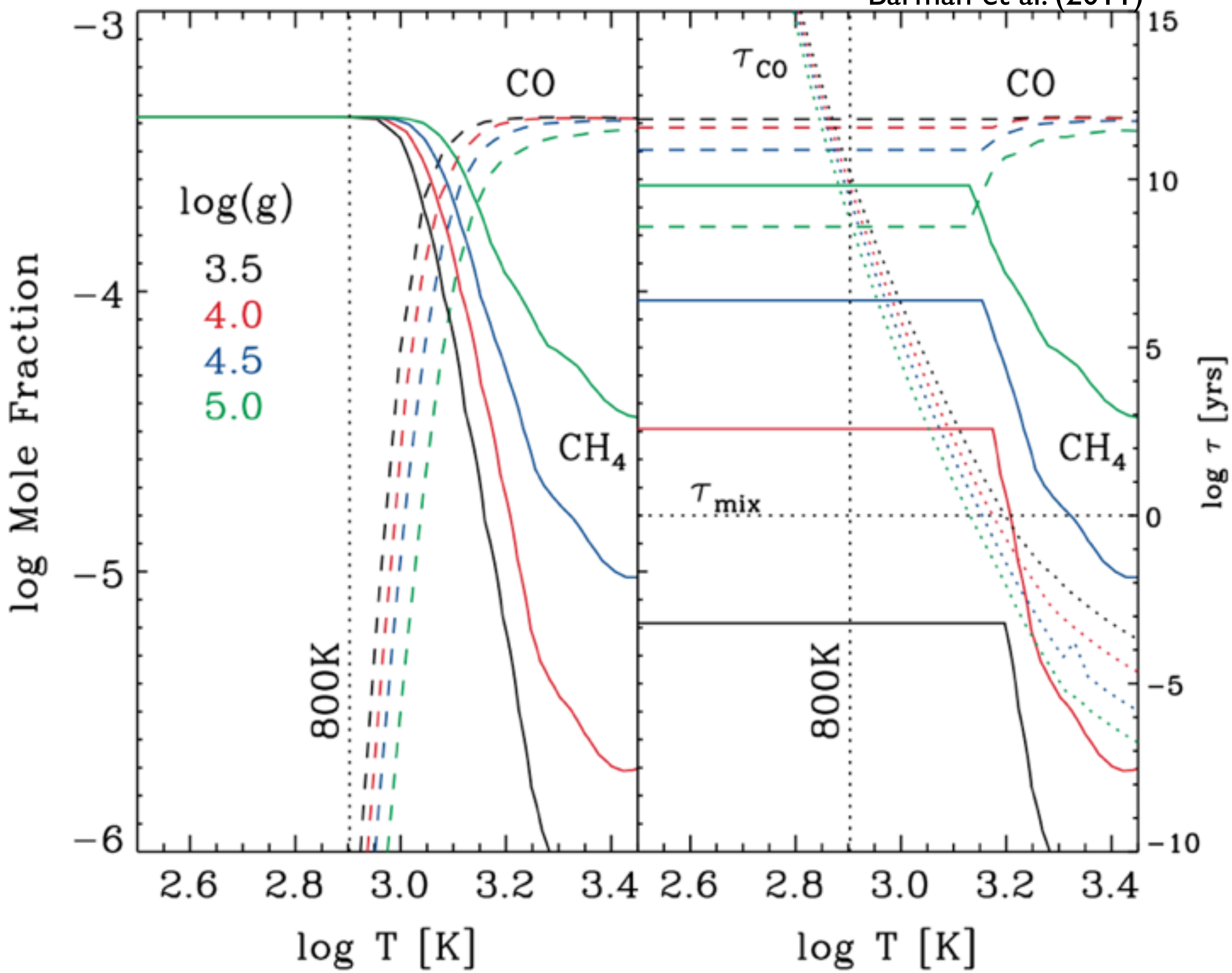
“Weather” in a T-type brown dwarf:



Artigau et al. (2009)

disequilibrium chemistry (by mixing)

Barman et al. (2011)

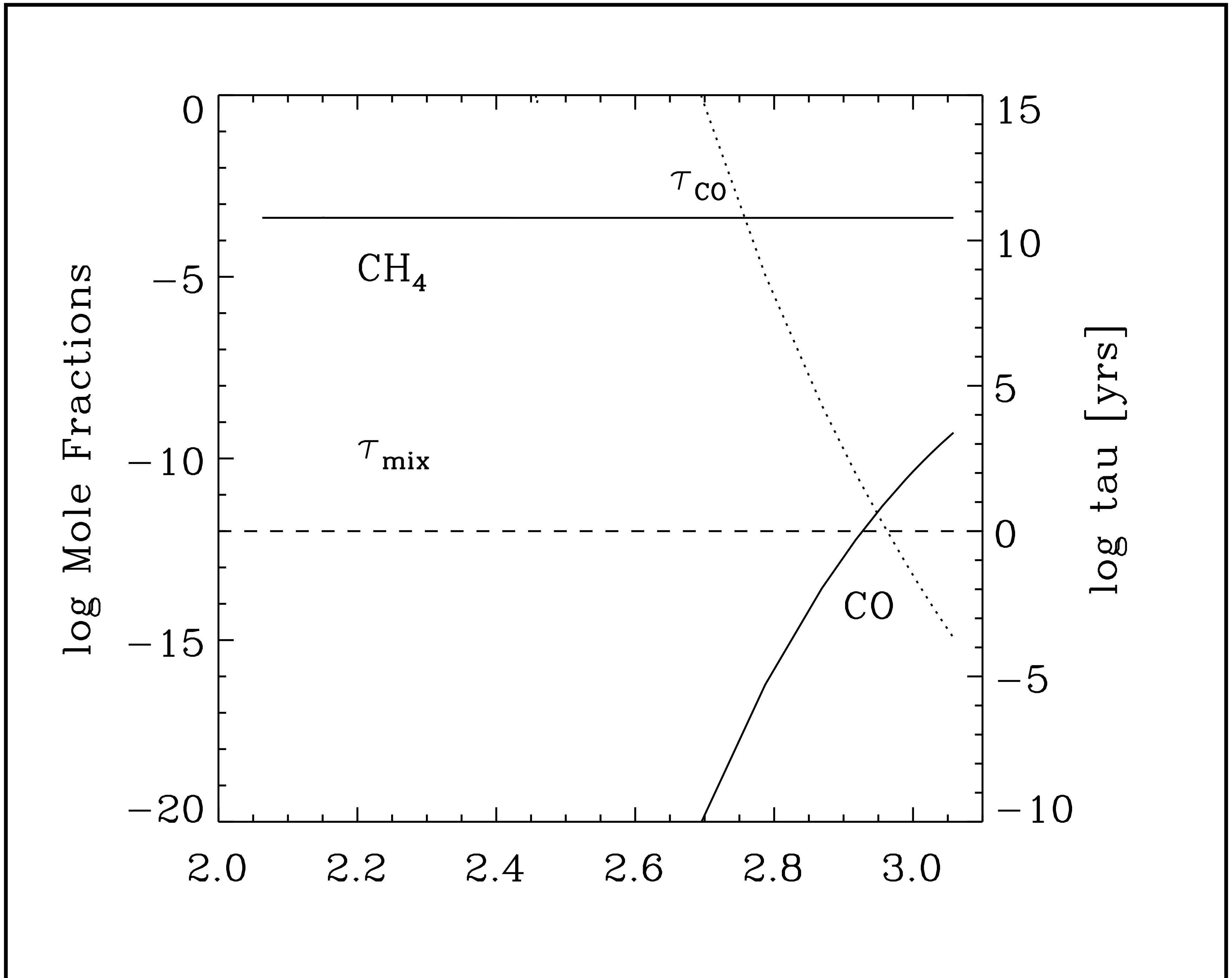


Zahnle & Marley (2014)
Hubeny & Burrows (2007);
Moses et al. (2011)

$$t_{dyn} = \frac{L^2}{K_{eddy}}.$$

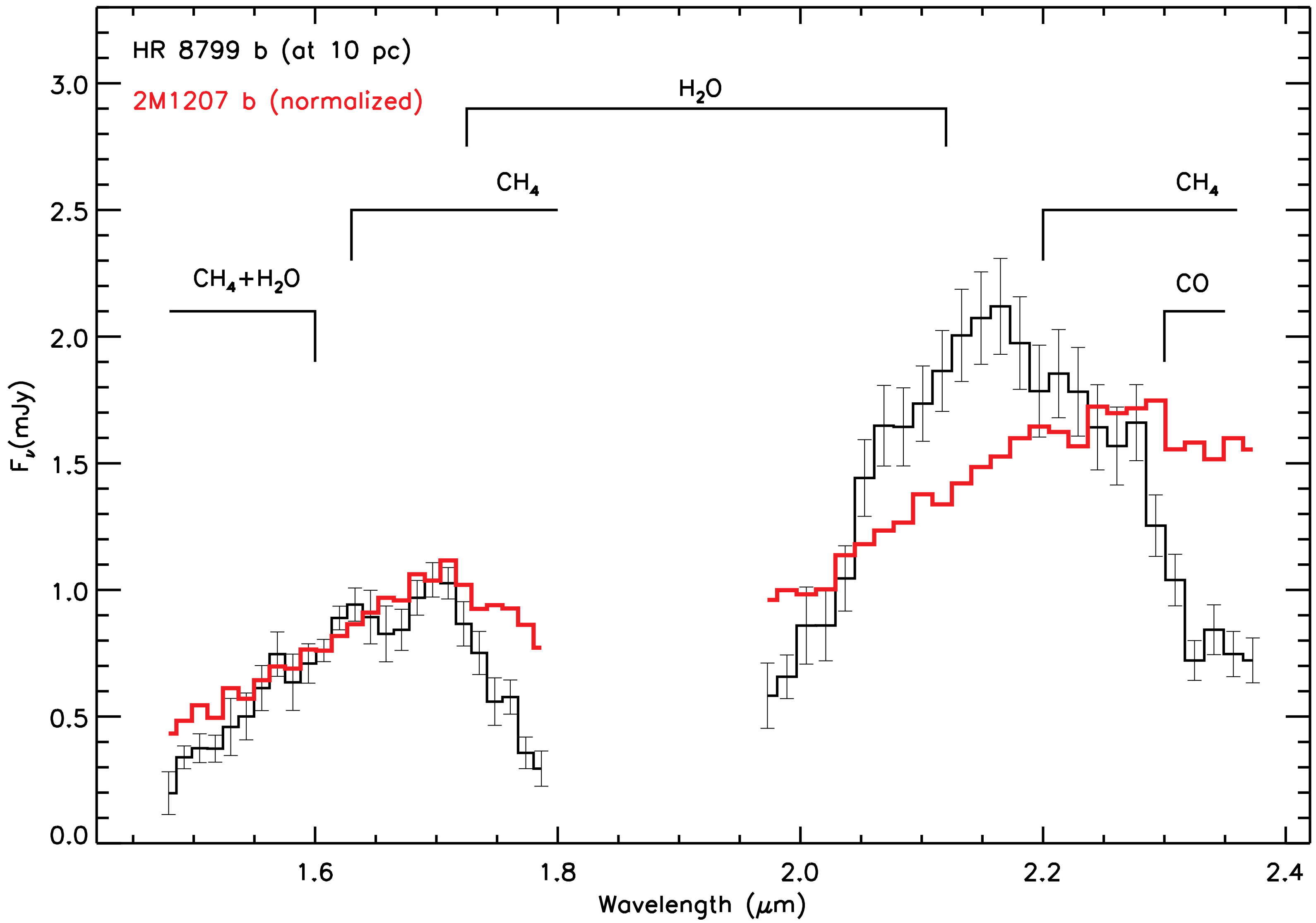
$$t_{chem}(CO) = \frac{1}{2.3 \times 10^{-10} K_a \exp(-36200/T)[H_2]^2} \text{ s},$$

Jupiter ...



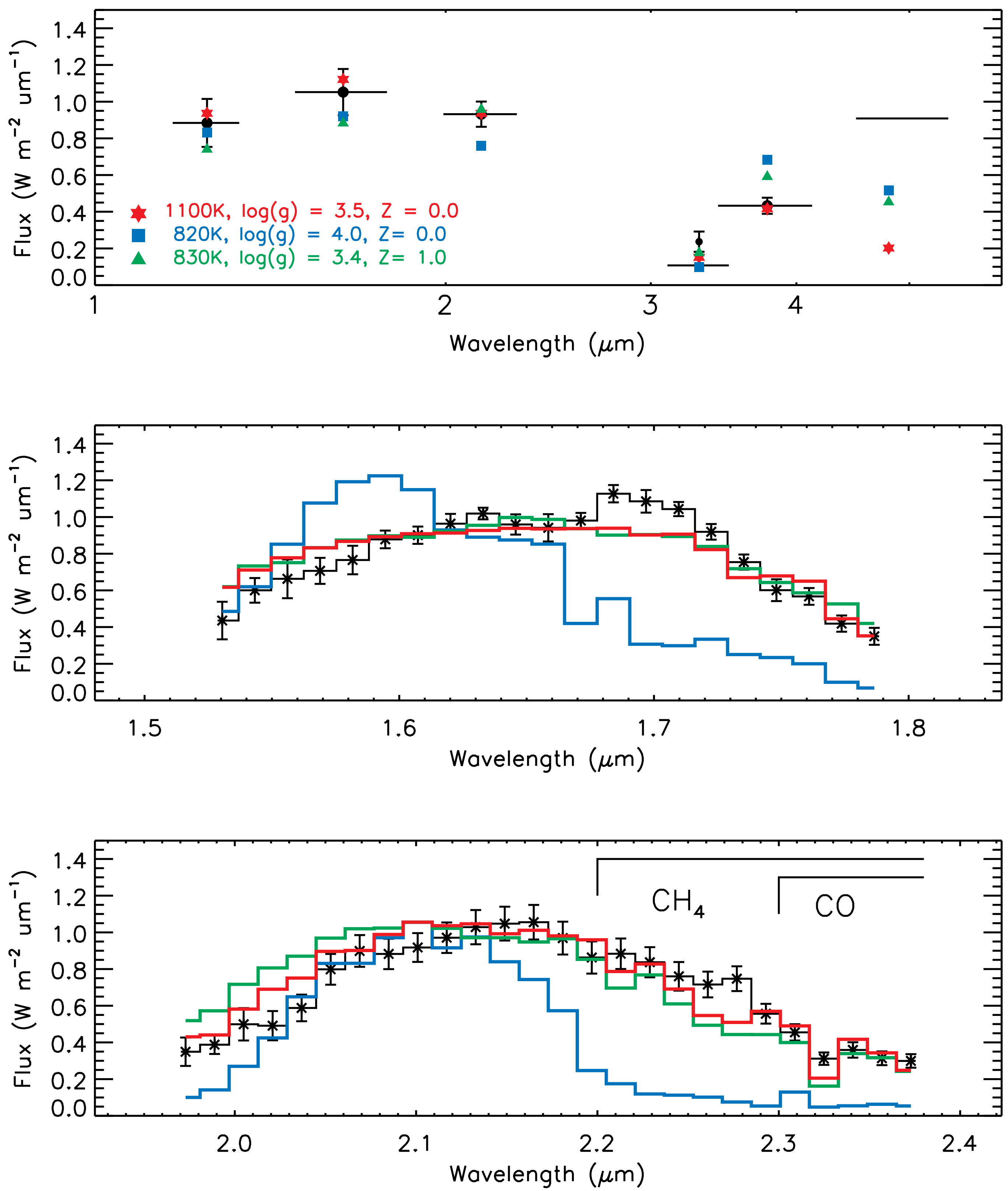
see Visshcer et al. (2010)

Direct Spectroscopy of planets: 2M1207b, HR 8799 b



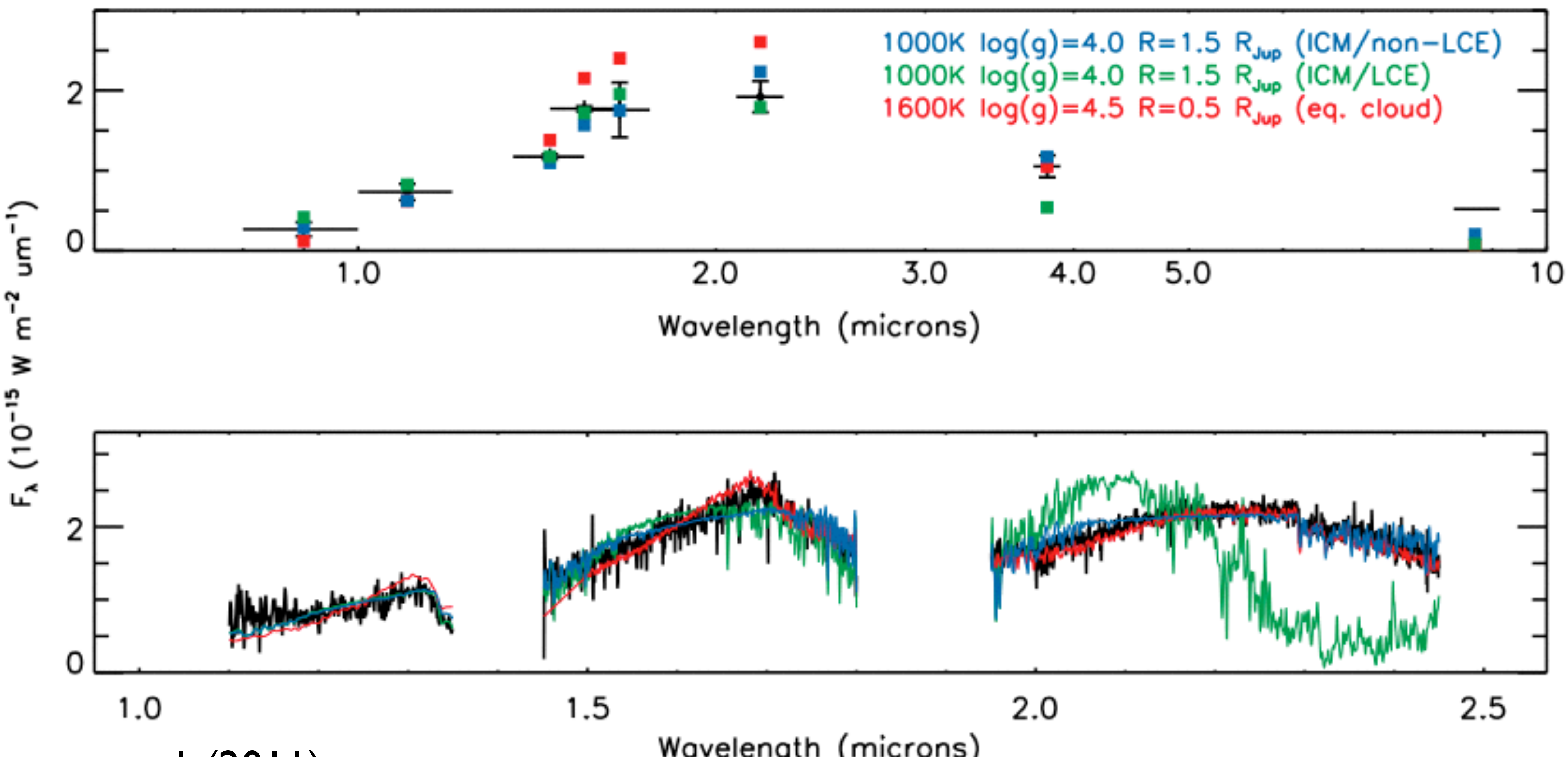
Patience et al. (2010)
Barman et al. (2011)

HR8799 b



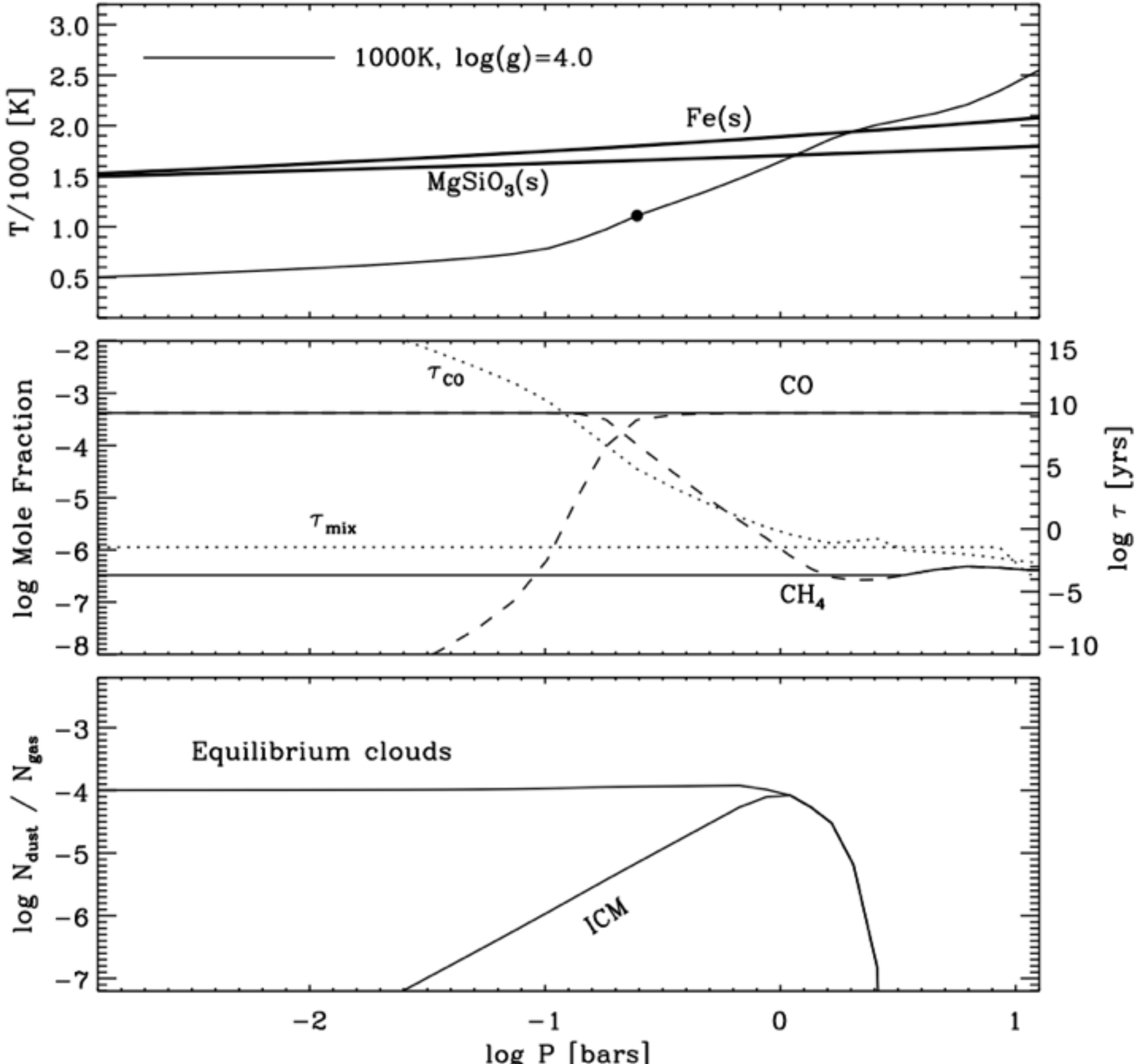
Barman et al. (2011)

2M1207b, 1000K and Methane-poor (non-eq CO/CH4 & clouds)



Barman et al. (2011)

2M1207 b



Barman et al. (2011)