Brown Dwarfs: 20 Years Later

Outline

- Major Themes
- List of Properties/Exotica
- Deuterium Burning and the "Edge"
- Molecular Compositions/Clouds
- Spectral Features of L and T Dwarfs
- Evolutionary Models

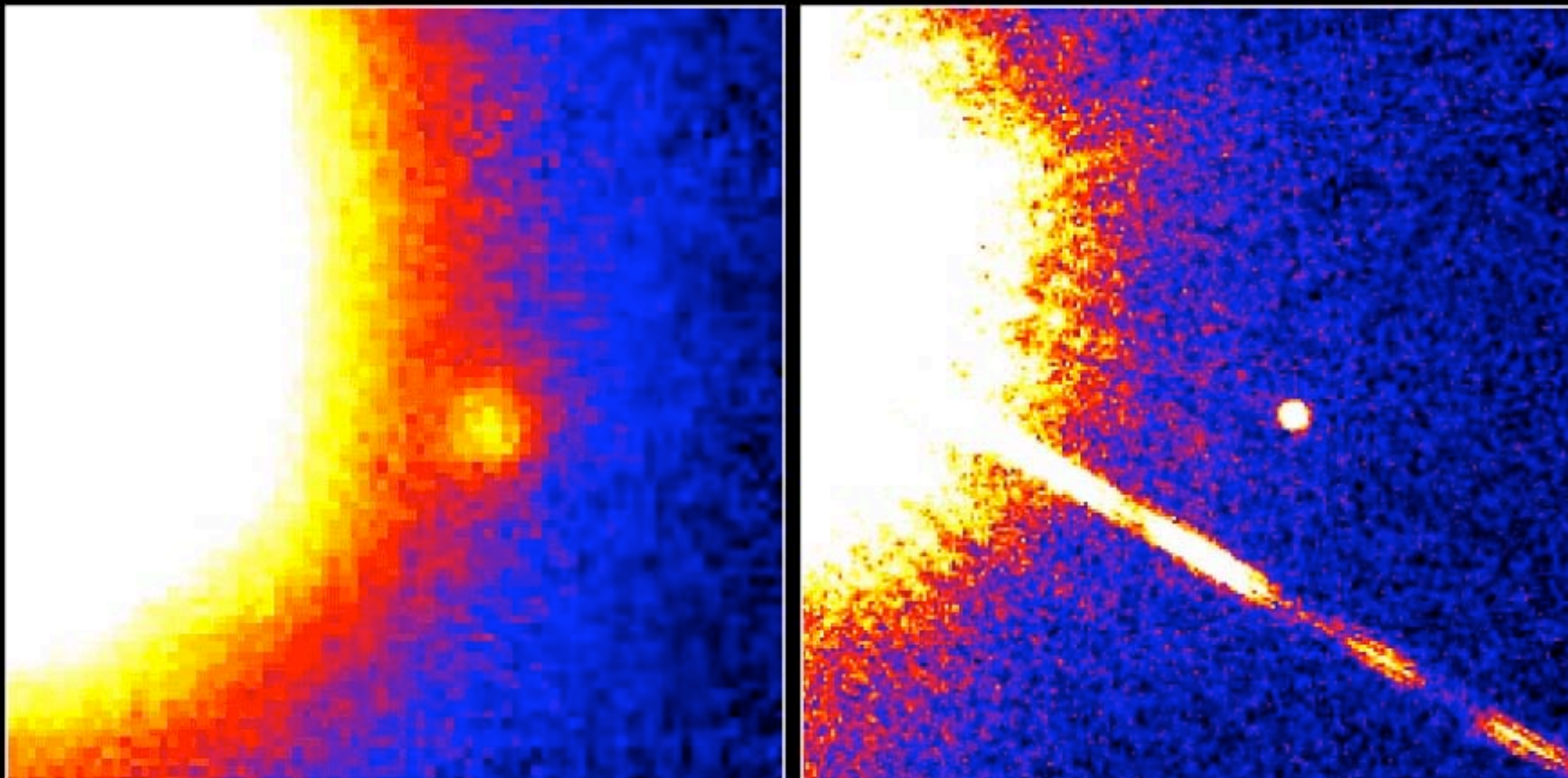
Brown Dwarf Exotica

- Deuterium Burning
- Metallic H/He cores
- Molecular Atmospheres
- H_2, H_2O, CH_4, CO, N_2, NH_3, FeH, CrH, Na, K, silicates, …..
- $L < 6 \times 10^{-5} L_O$
- $R \sim 0.1 R_O$ for "all" masses
- $T_e < 1800$ K
- $g \sim 1$ to 300 g's
- Infrared
- "Magenta"

- Silicate clouds (L dwarfs)
- Depleted atmospheres (rainout) in T dwarfs
- Broad alkali metal lines
- Mass function still rising at main-sequence edge
- *J, H, K* fluxes much higher that blackbody
- T dwarfs get <u>bluer</u> with decreasing T_e (in the IR)
- *J, Z* fluxes <u>increase</u> near L/T transition

L Dwarfs (2300 K - 1100 K), T Dwarfs (1100 K - 500 K), and Y Dwarfs (450 K - ??)

Brown Dwarf Gliese 229B



Palomar Observatory
Discovery Image
October 27, 1994

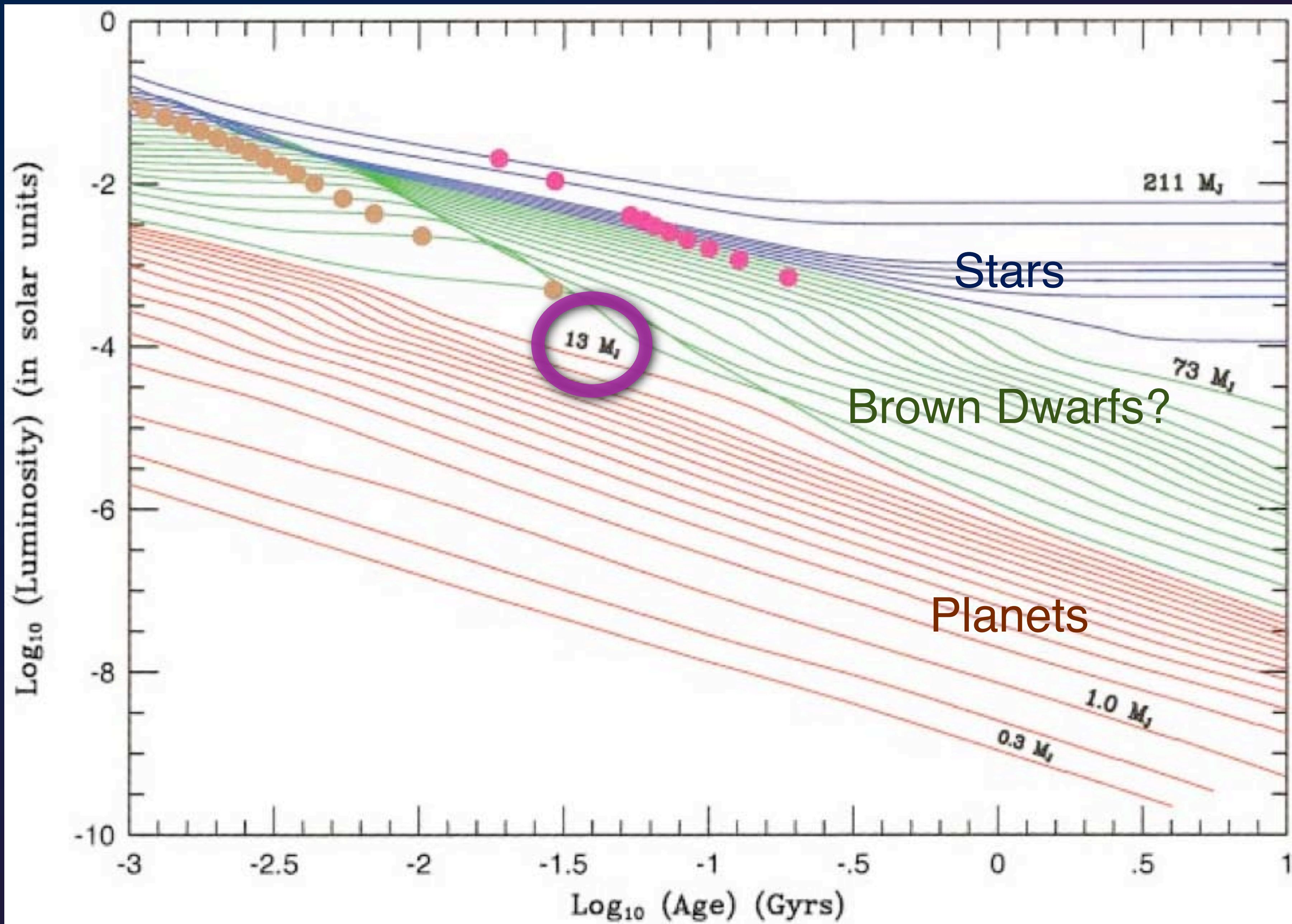
Hubble Space Telescope
Wide Field Planetary Camera
November 17, 1995

PRC95-48 • ST ScI OPO • November 29, 1995 • T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

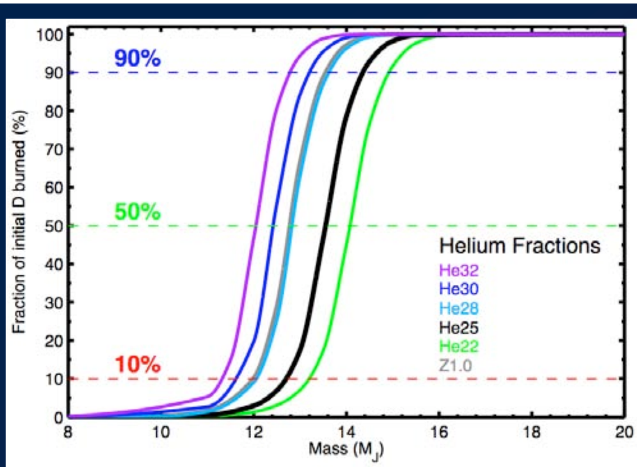
Deuterium-Burning Mass

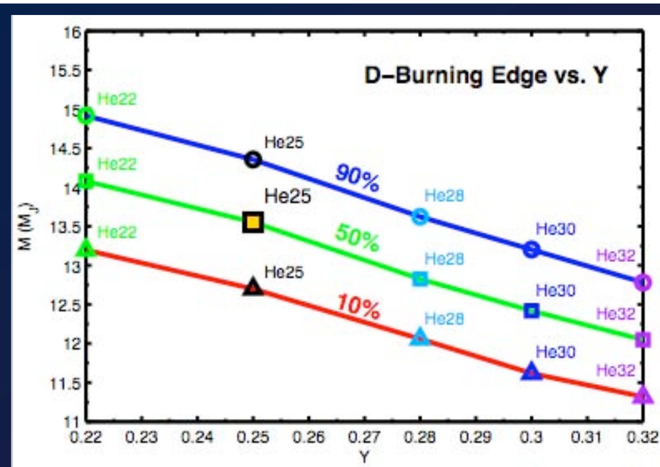
Spiegel, Burrows, and Milsom
2011

Evolution

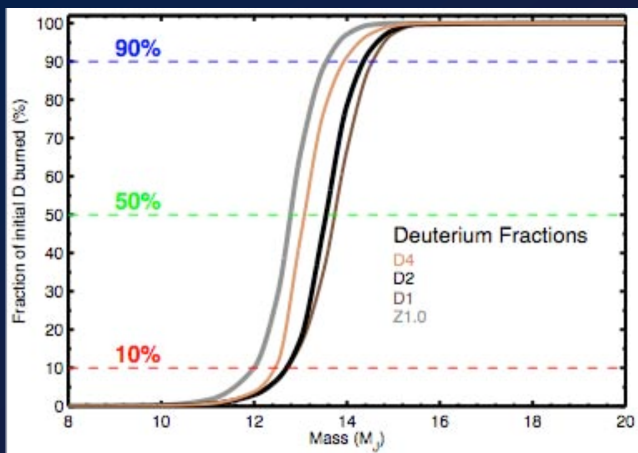


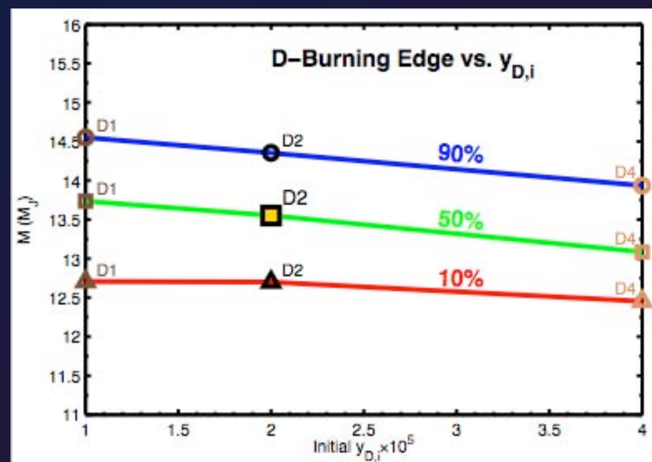
Stars
Brown Dwarfs?
Planets
211 M_J
73 M_J
13 M_J
1.0 M_J
0.3 M_J
Log_{10} (Luminosity) (in solar units)
Log_{10} (Age) (Gyrs)
0
-2
-4
-6
-8
-10
-3
-2.5
-2
-1.5
-1
-.5
0
.5
1



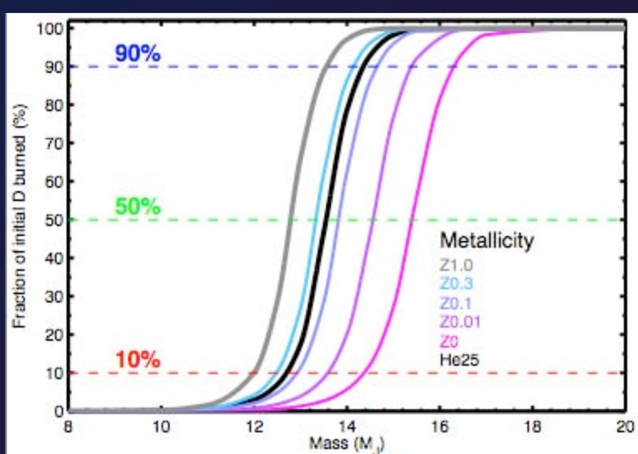


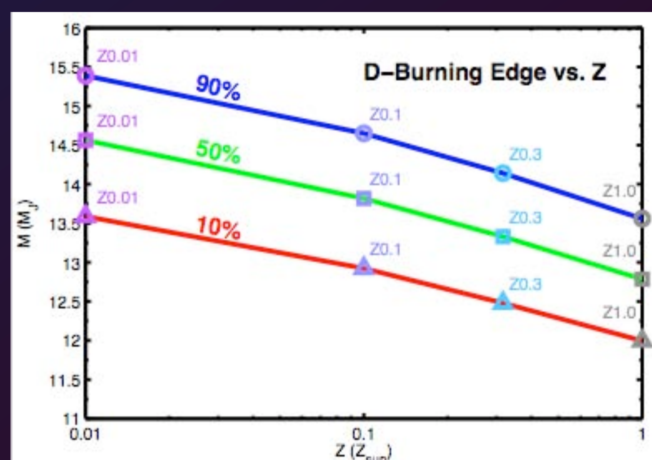
Roughly 13 M_J, but model-dependent.





More helium, more deuterium, and higher opacity result in lower D-burning mass.





What is meant by "deuterium burning"?

Changing the "deuterium-burning criterion" from 10% to 50%, and also from 50% to 90% changes the required mass by nearly 1 M_J!

Spiegel, Burrows, Milsom 2011

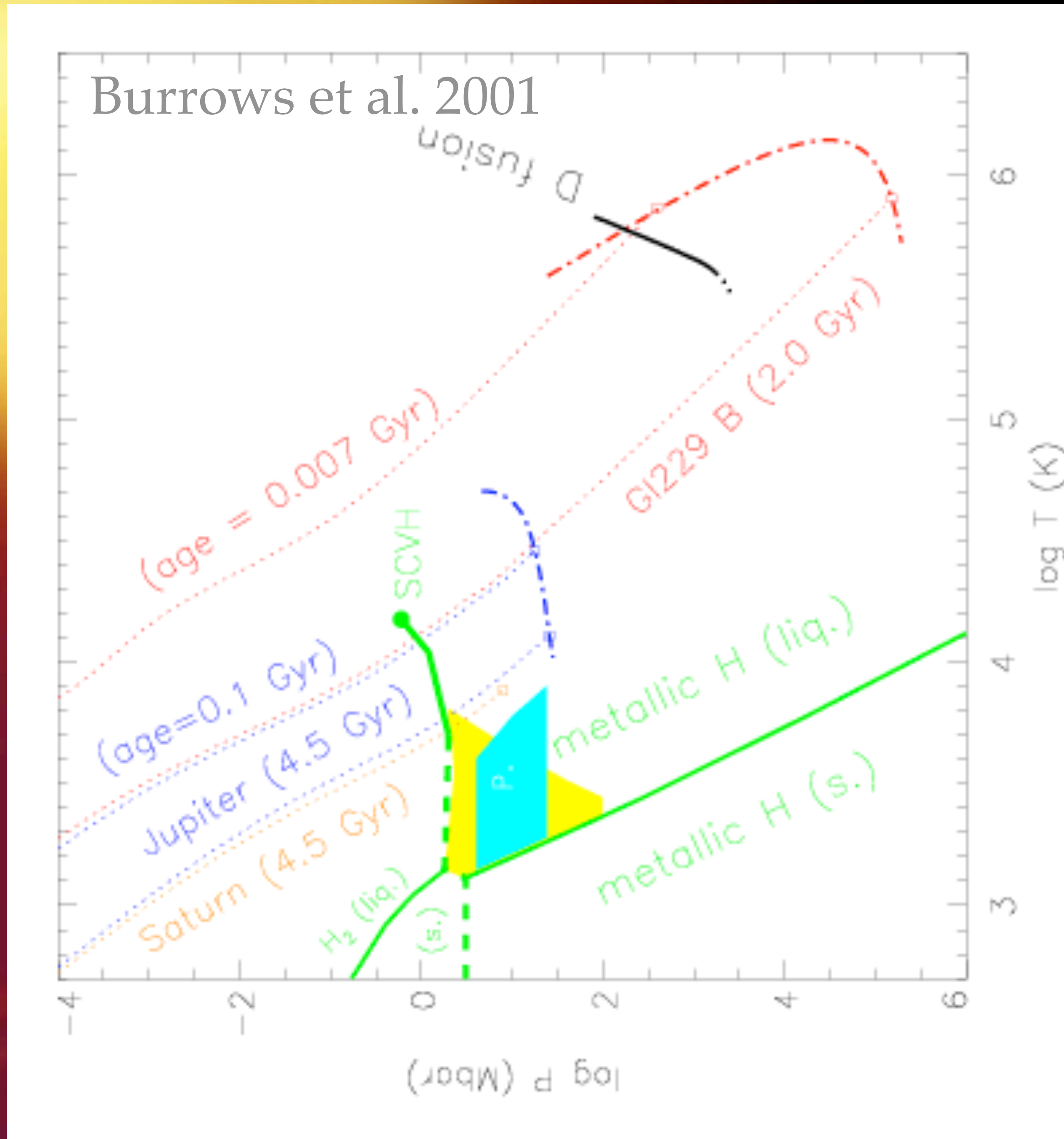
EOS of H_2 :

Coulomb interactions

vs.

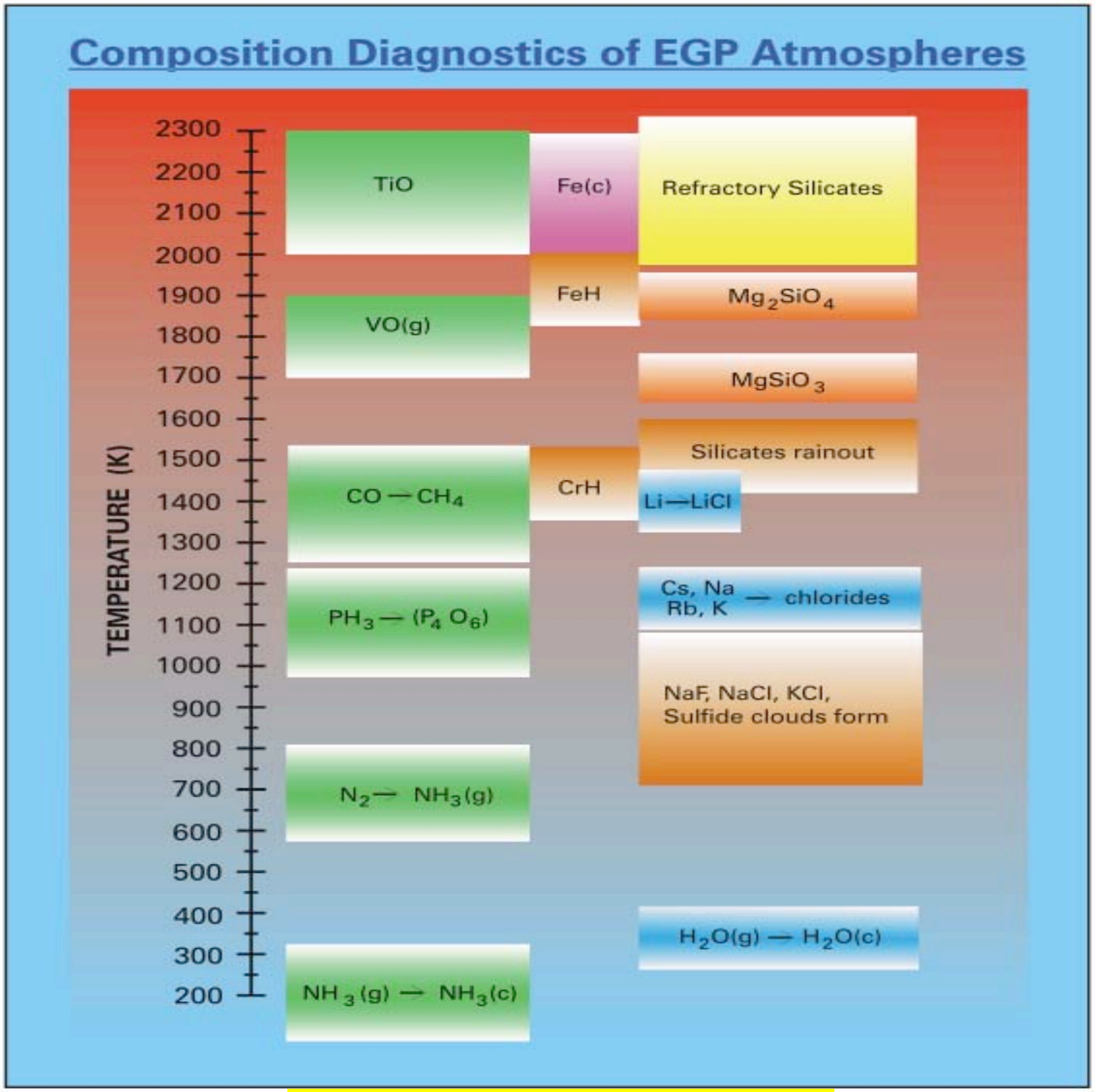
electron degeneracy

Wigner and Huntington (1935)



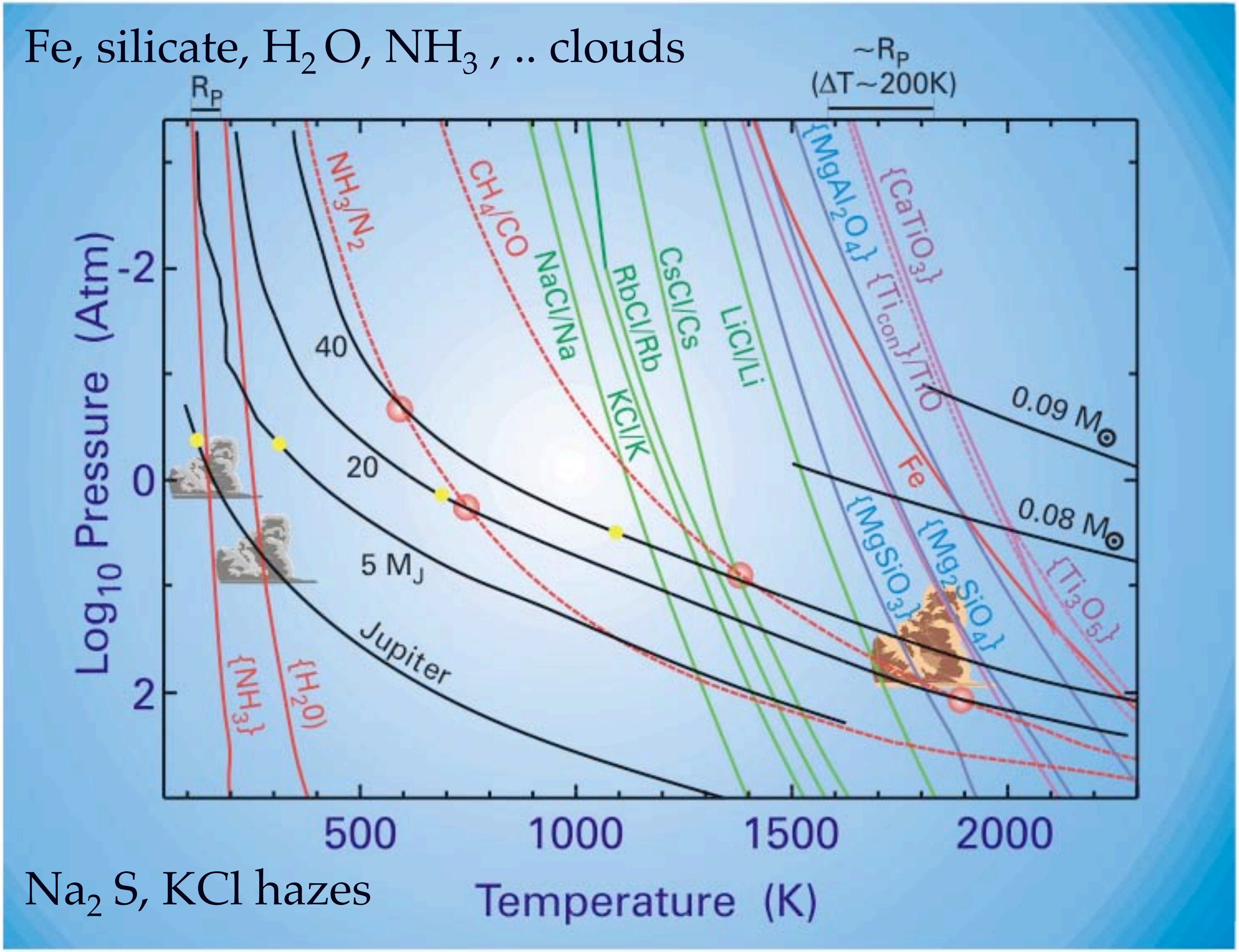
Compositions and Abundances

M Dwarfs → L Dwarfs → T Dwarfs → Jupiter

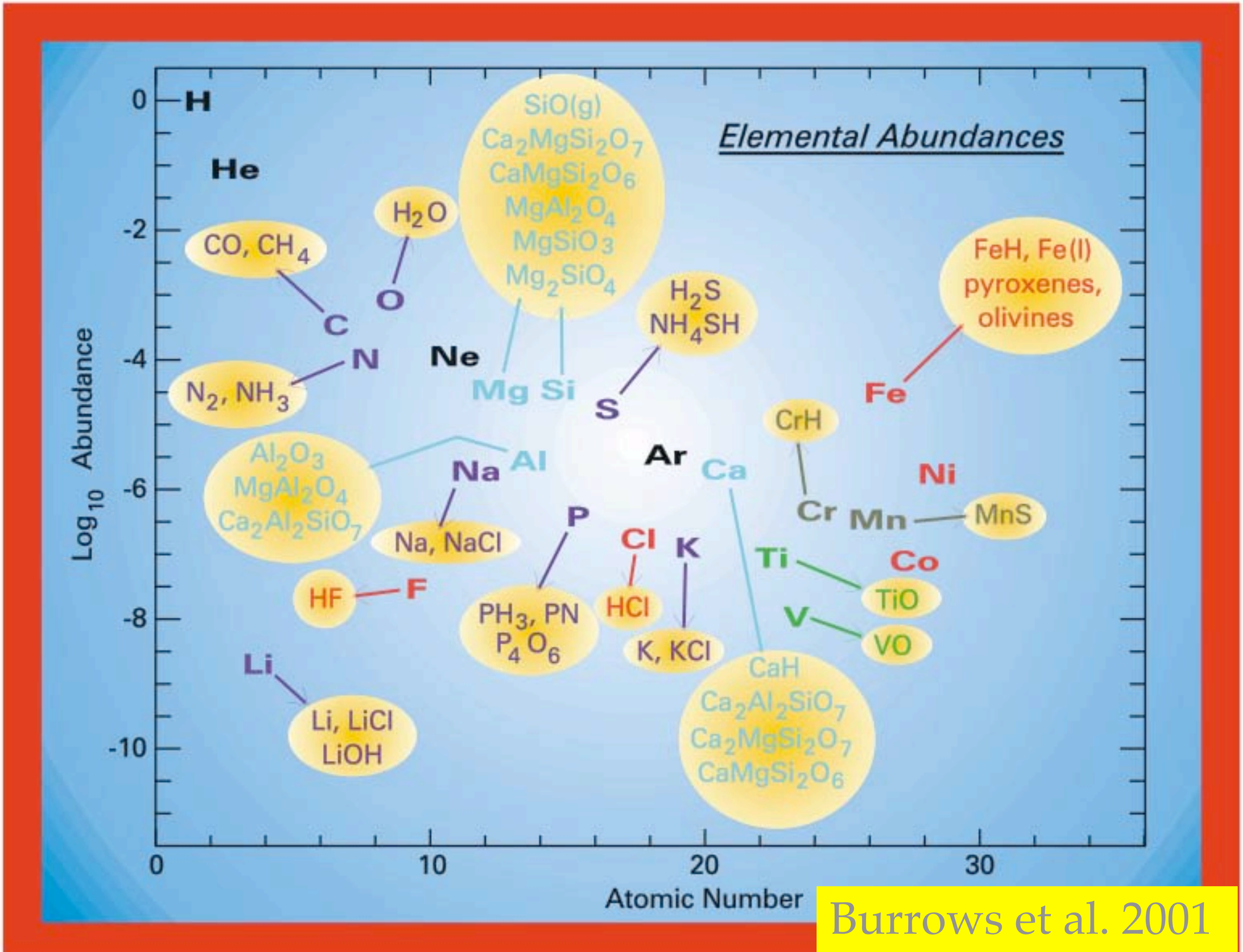


Burrows et al. 2001

Fe, silicate, H_2O, NH_3 , .. clouds

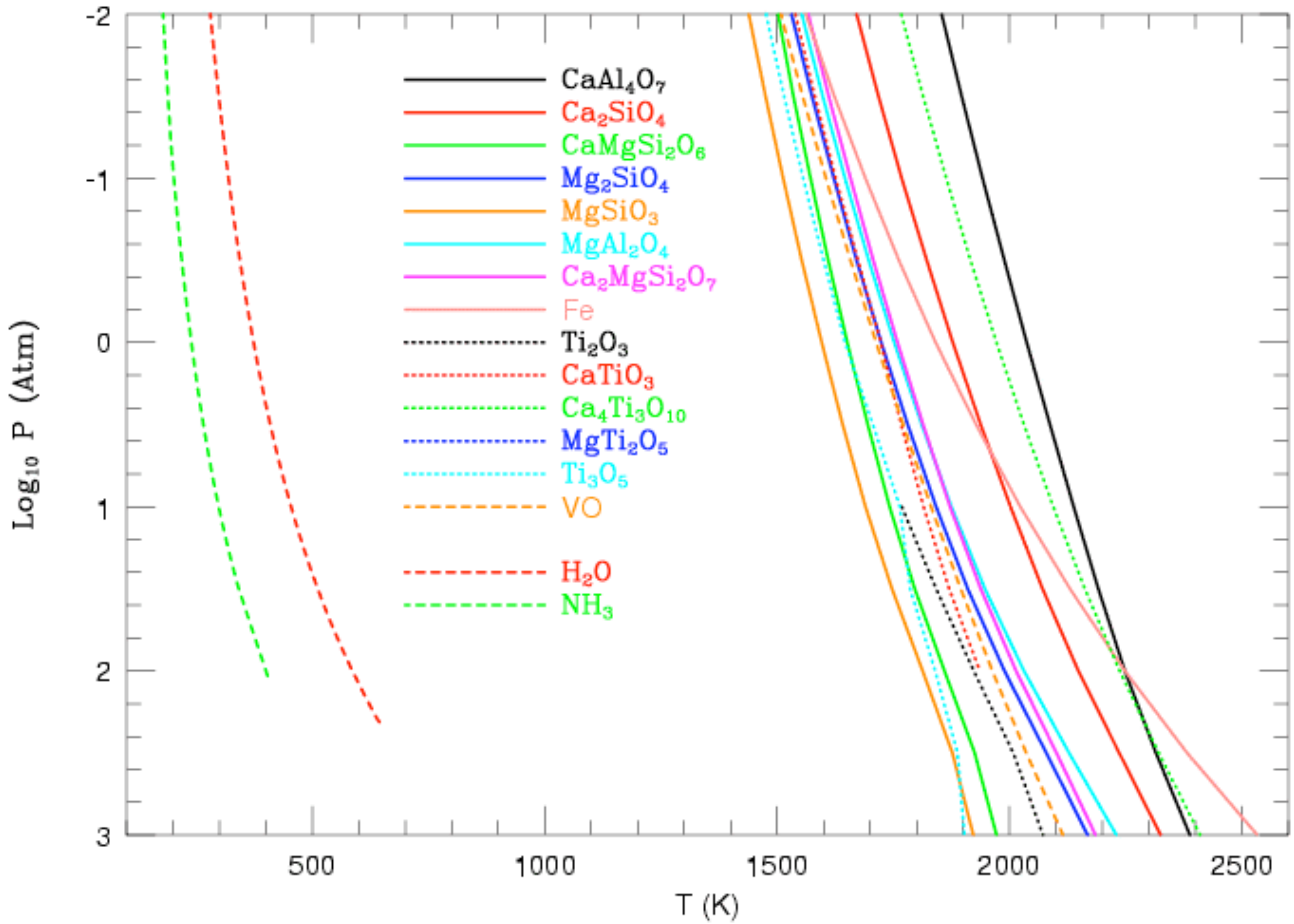


Na_2 S, KCl hazes



Burrows et al. 2001

Condensates in EGP and Brown Dwarf Atmospheres

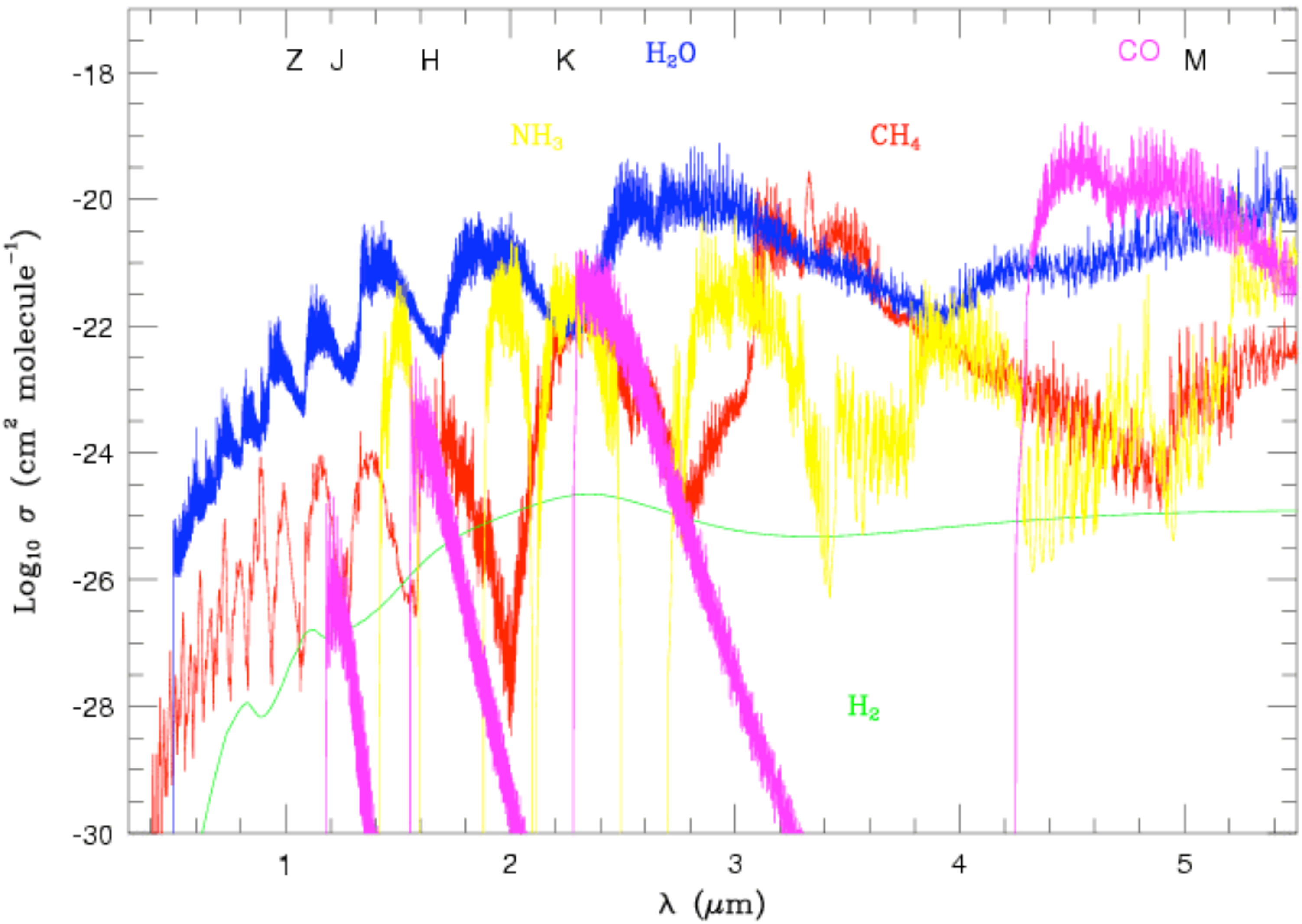


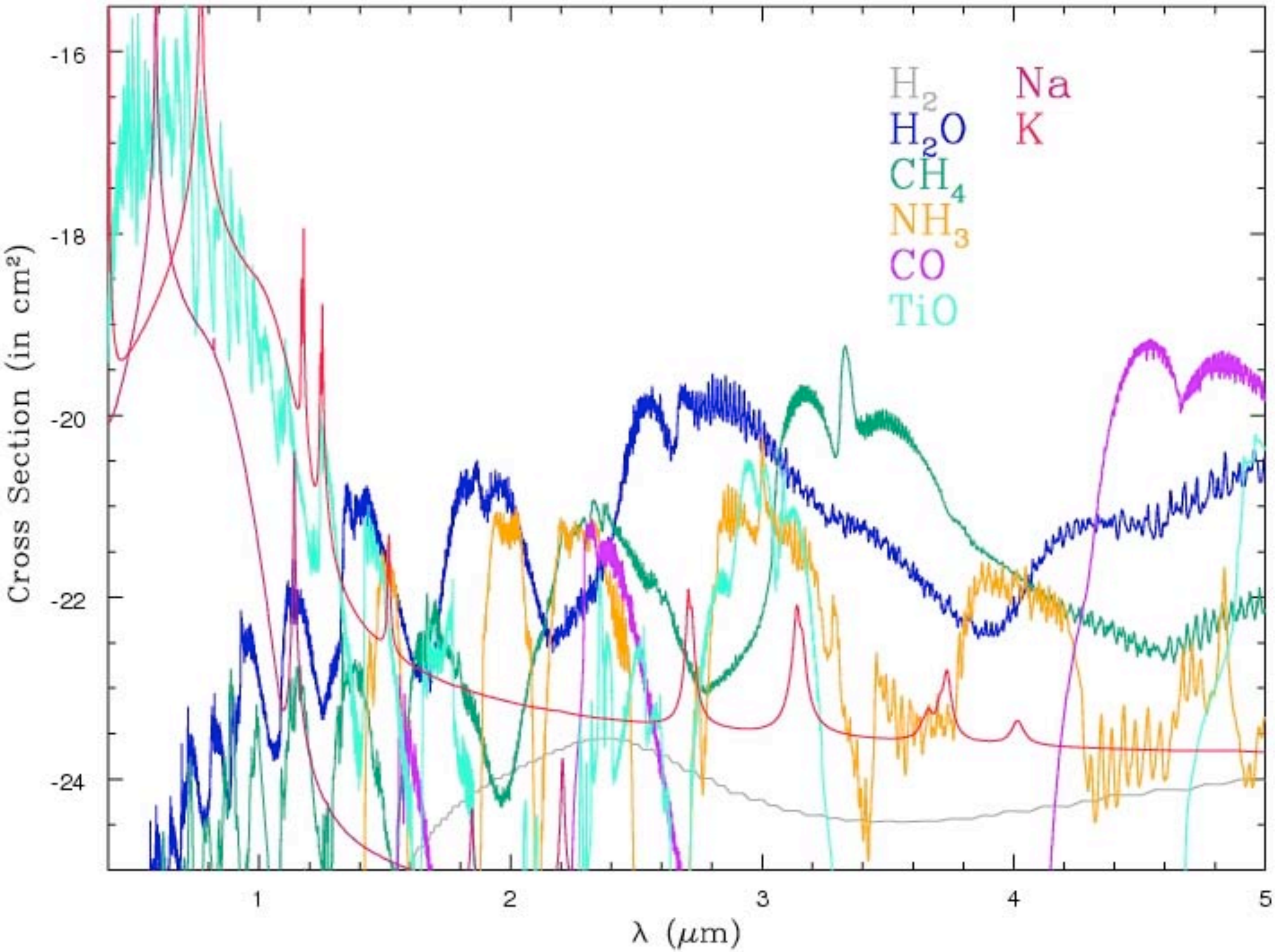
Fe, silicates, H_2O, NH_3

Molecular and Atomic Opacities

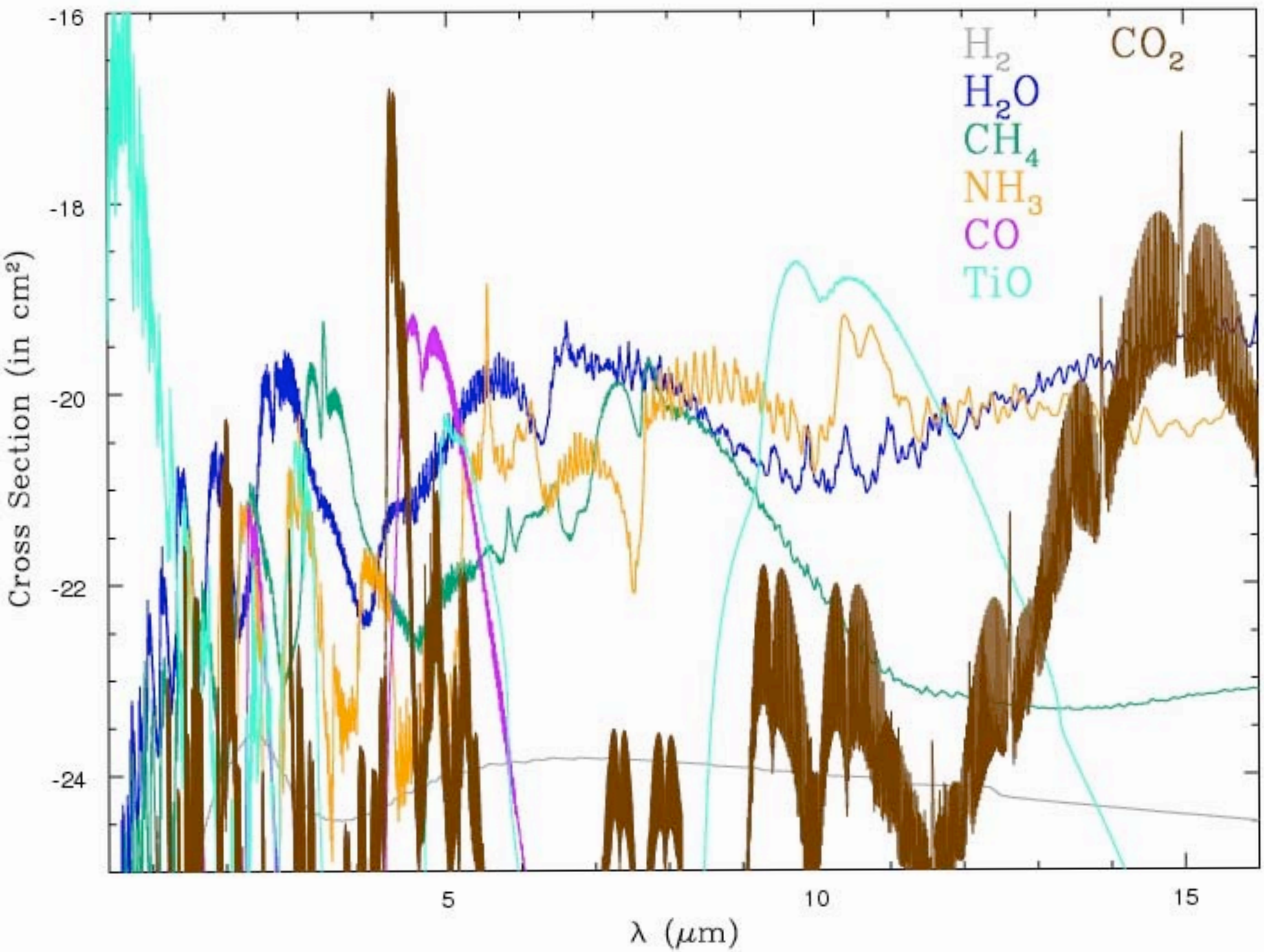
(critical tools)

Molecular Opacities

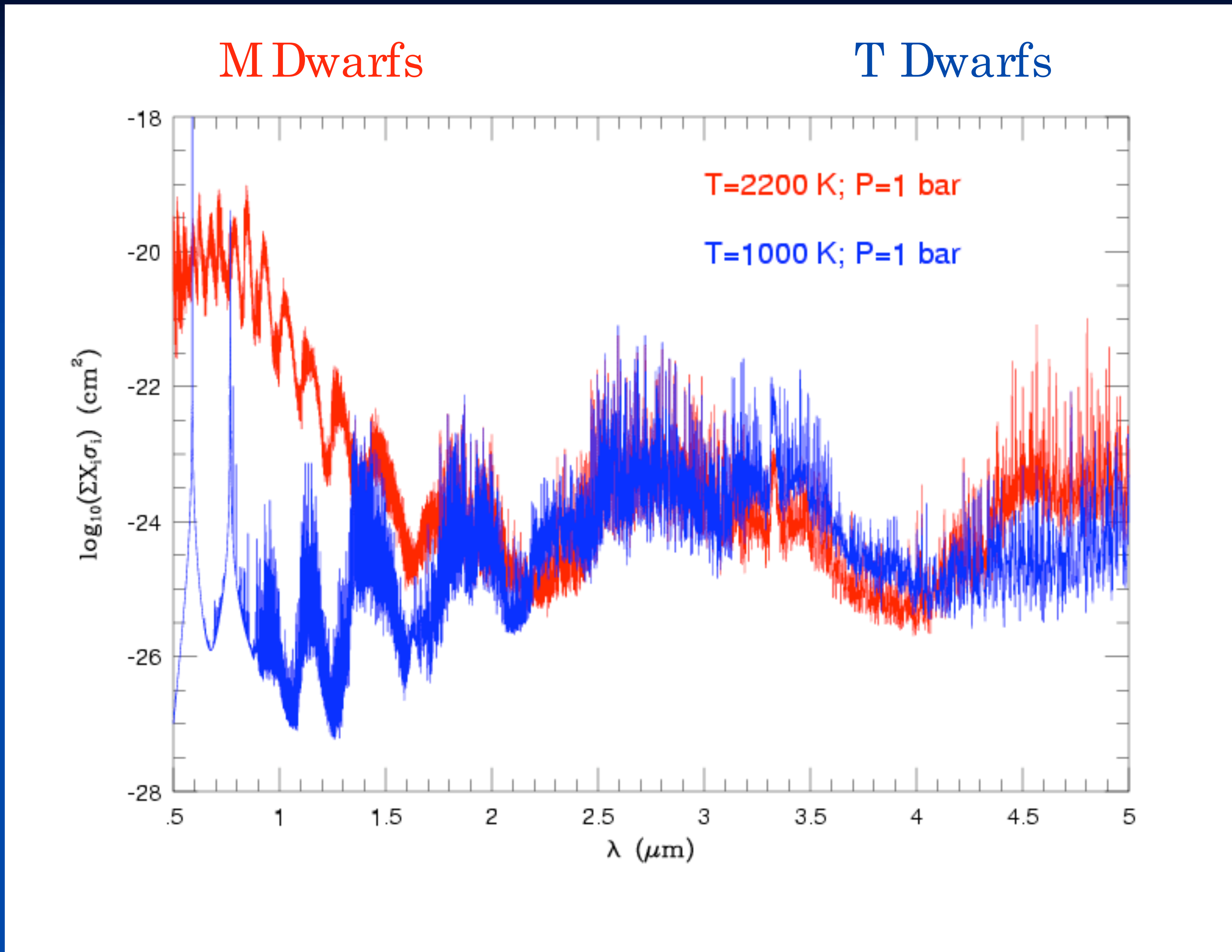




Cross Section (in cm²)
-16
-18
-20
-22
-24
1
2
3
4
5
λ (μm)
H2
H2O
CH4
NH3
CO
TiO
Na
K

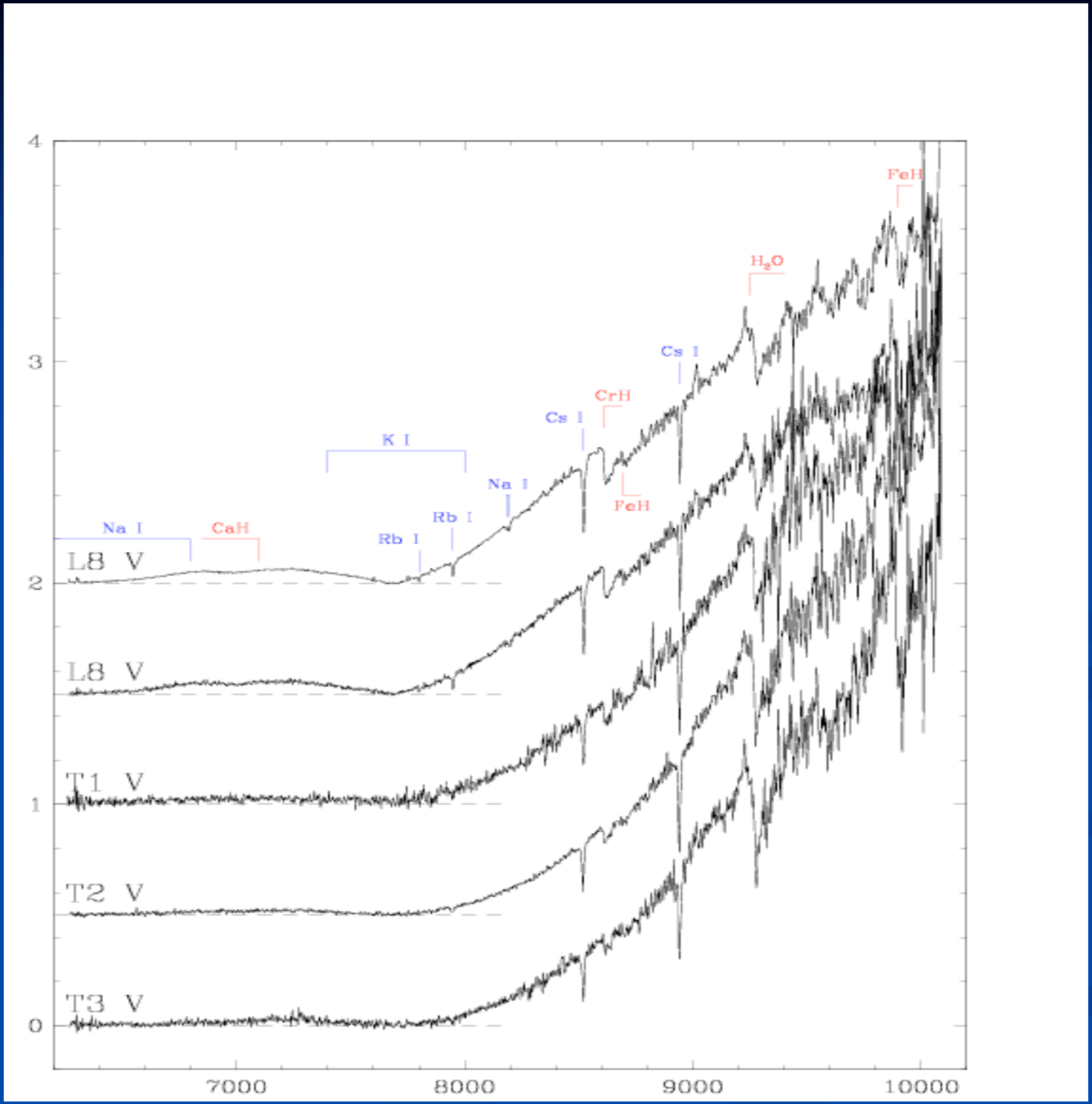


H2
CO2
H2O
CH4
NH3
CO
TiO
-16
-18
-20
-22
-24
Cross Section (in cm²)
5
10
15
λ (μm)

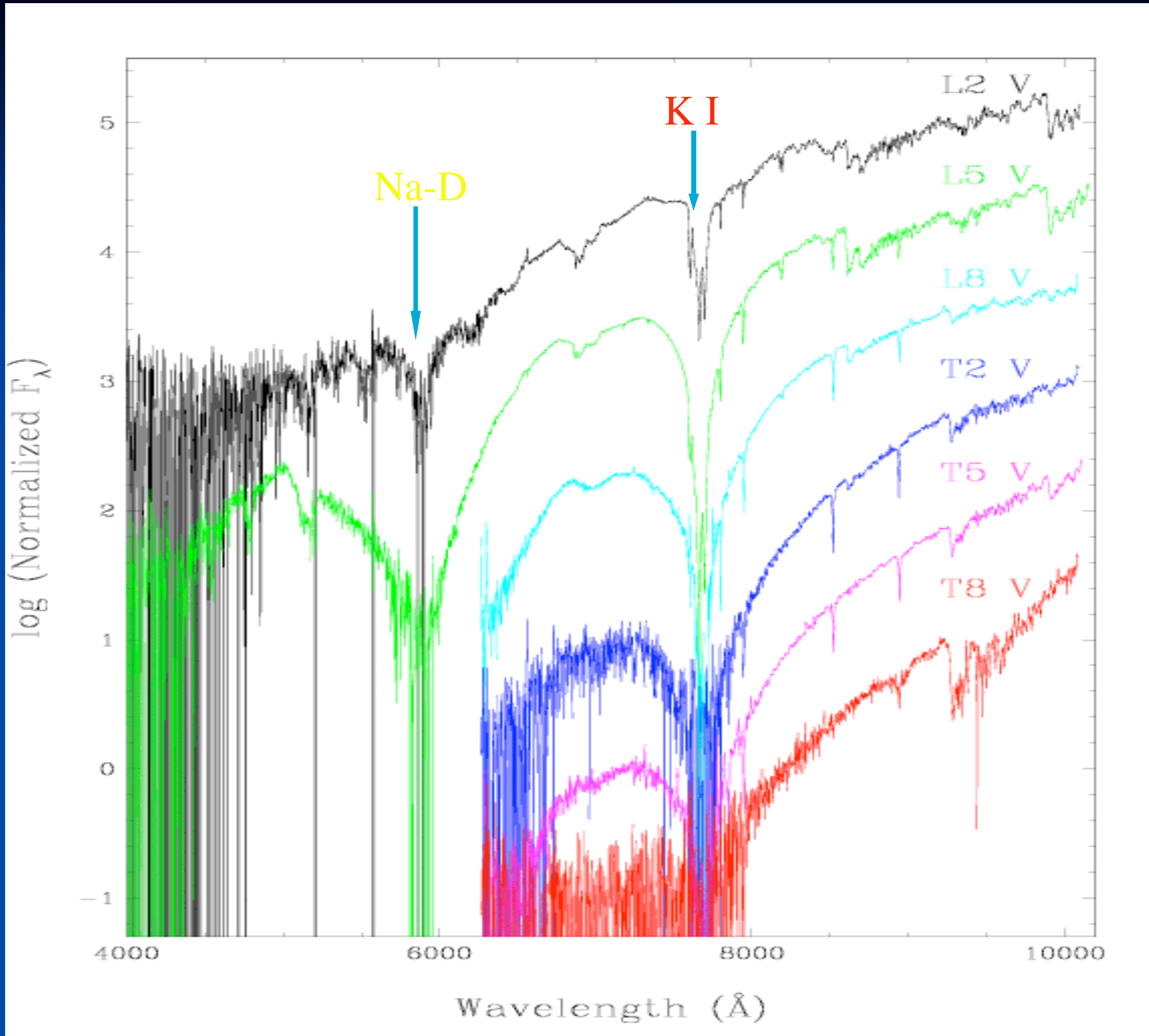

M Dwarfs
T Dwarfs
T=2200 K; P=1 bar
T=1000 K; P=1 bar
-18
-20
-22
-24
-26
-28
$\log_{10}(\Sigma X_i \sigma_i)$ (cm^2)
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
λ (μm)

Unique Spectral Features

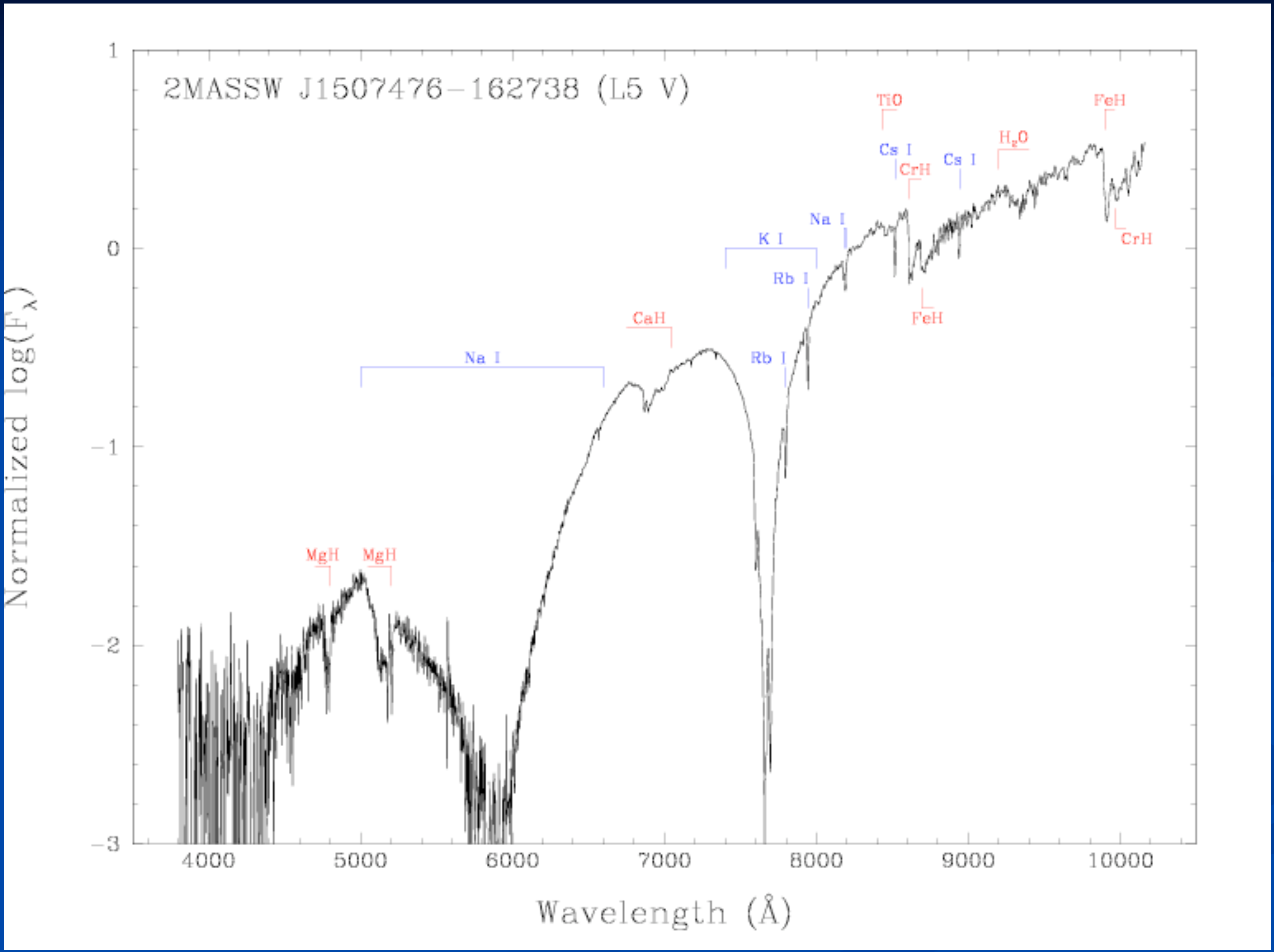
L Dwarfs (2300 K - 1100 K), T Dwarfs (1100 K - 500 K), and Y Dwarfs (450 K - ??)



Kirkpatrick et al. 1999



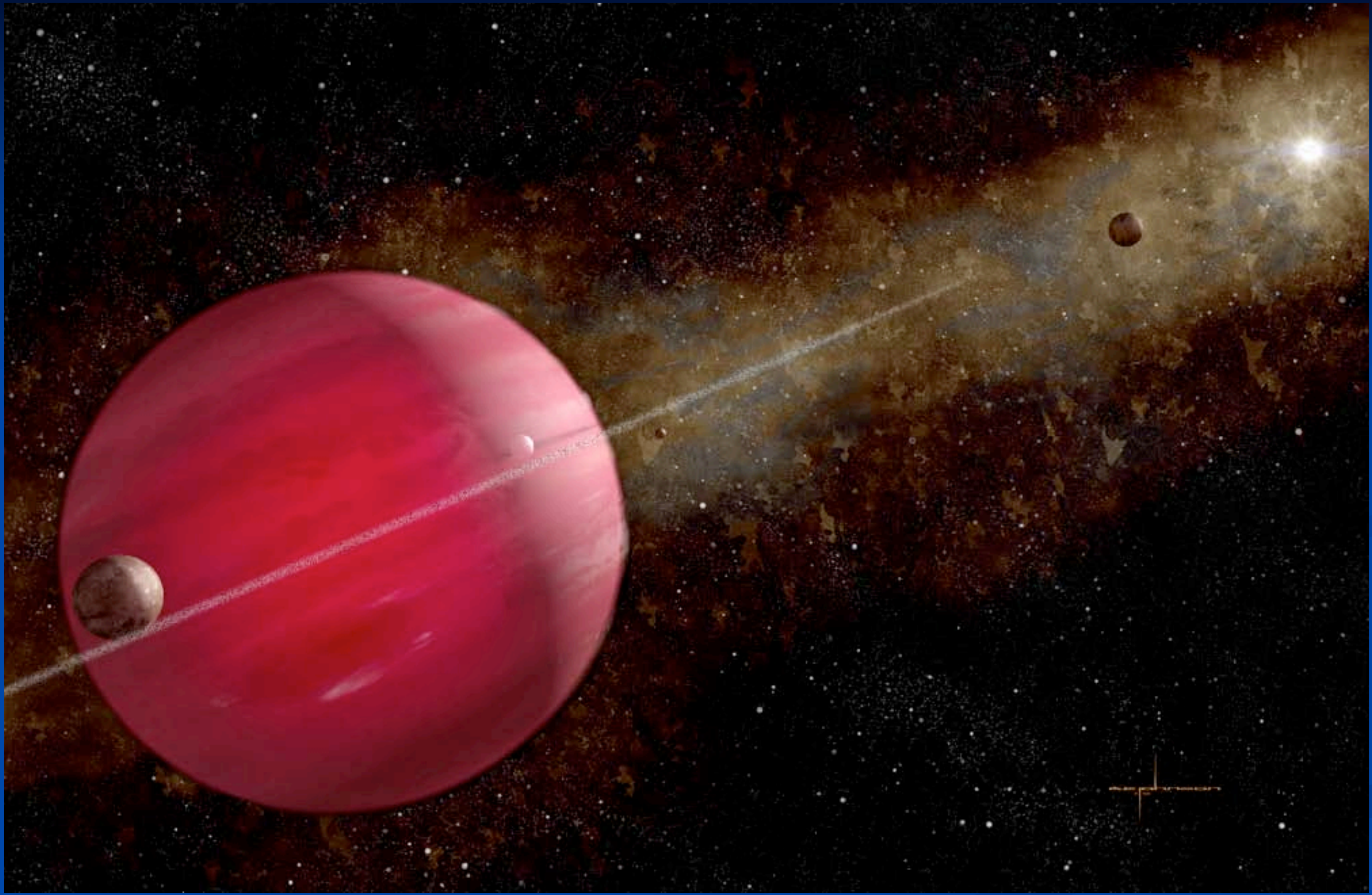
Burgasser et al. 2001

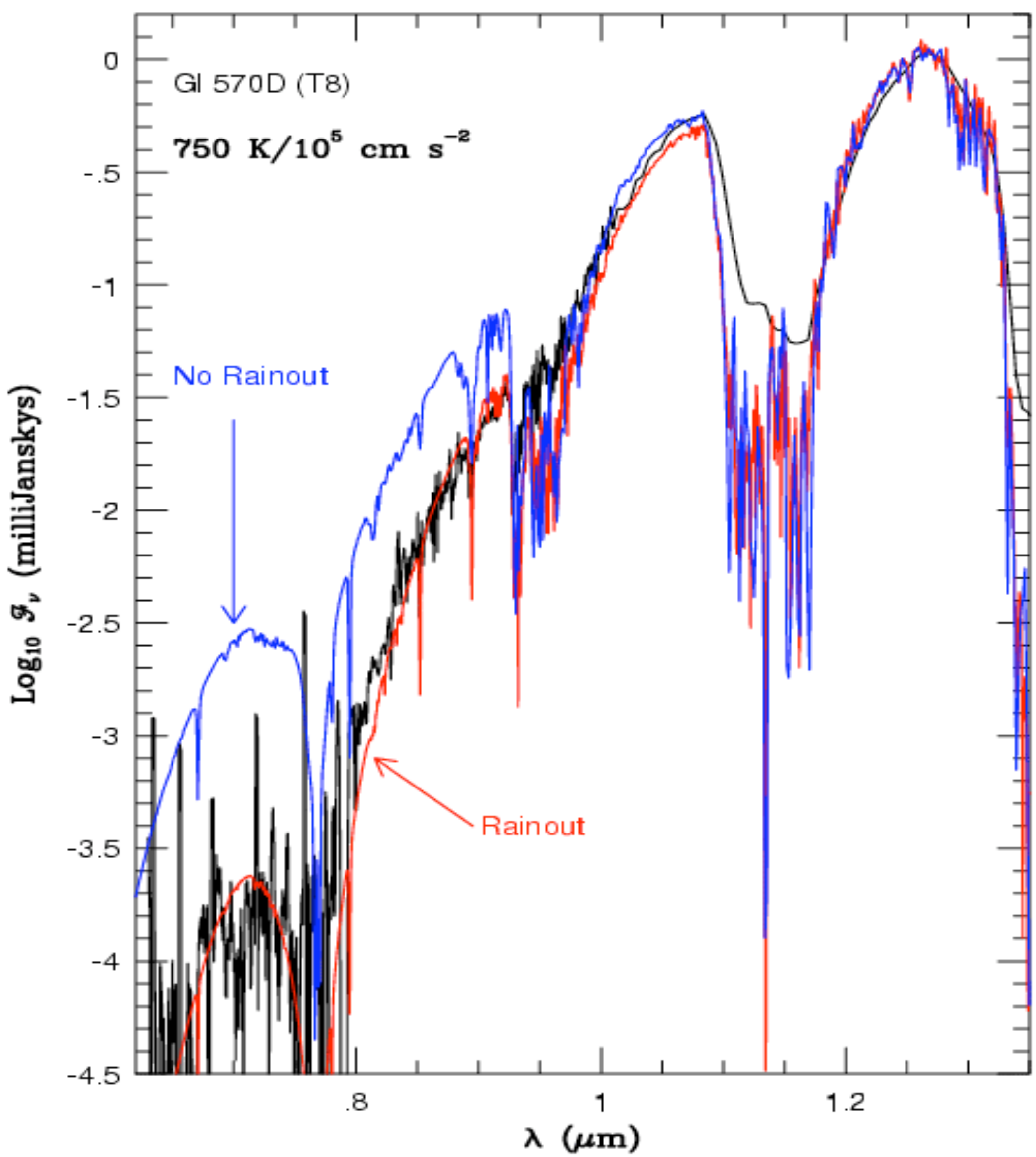


Reid et al. 2000

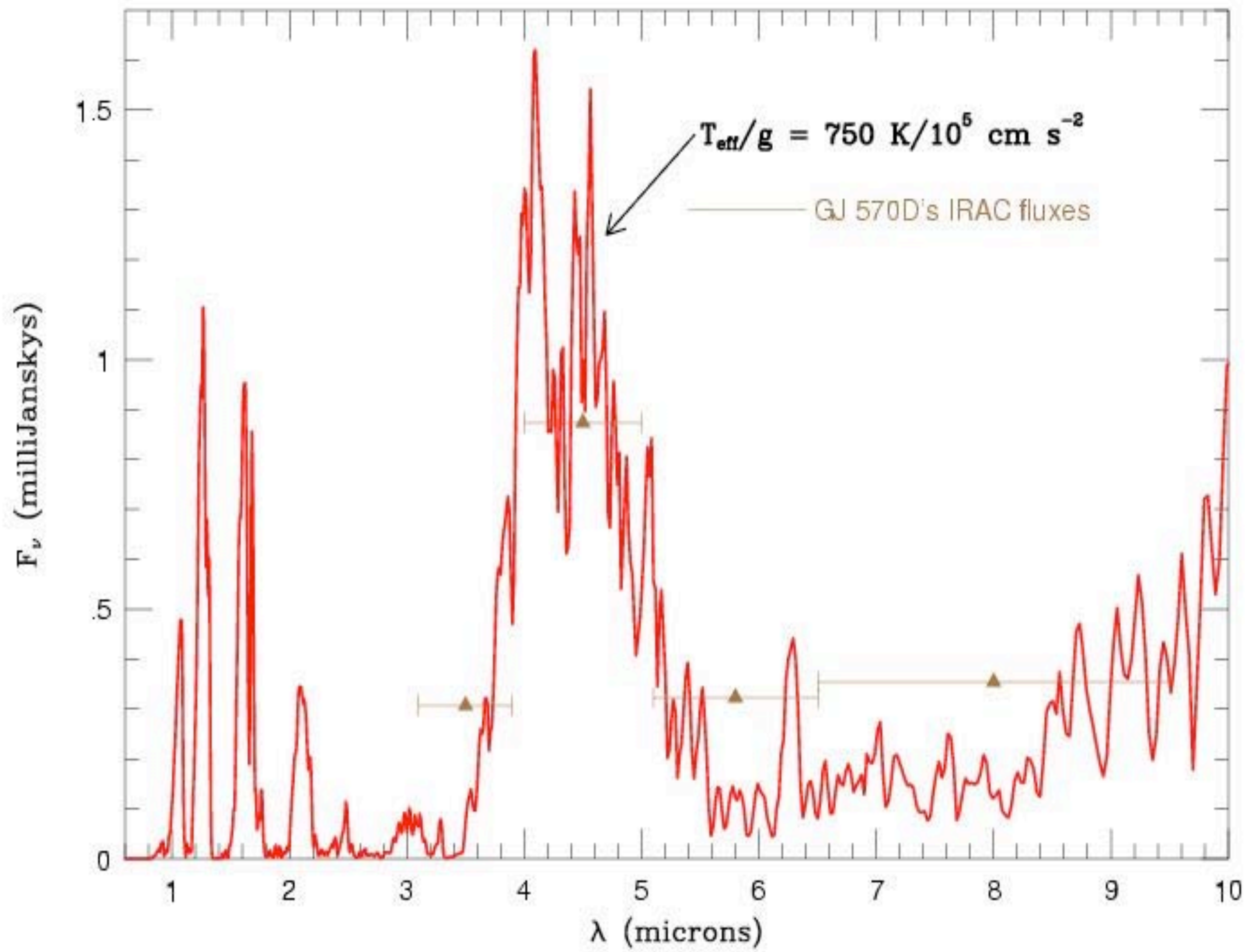
What is the Color of a Brown Dwarf?

MAGENTA



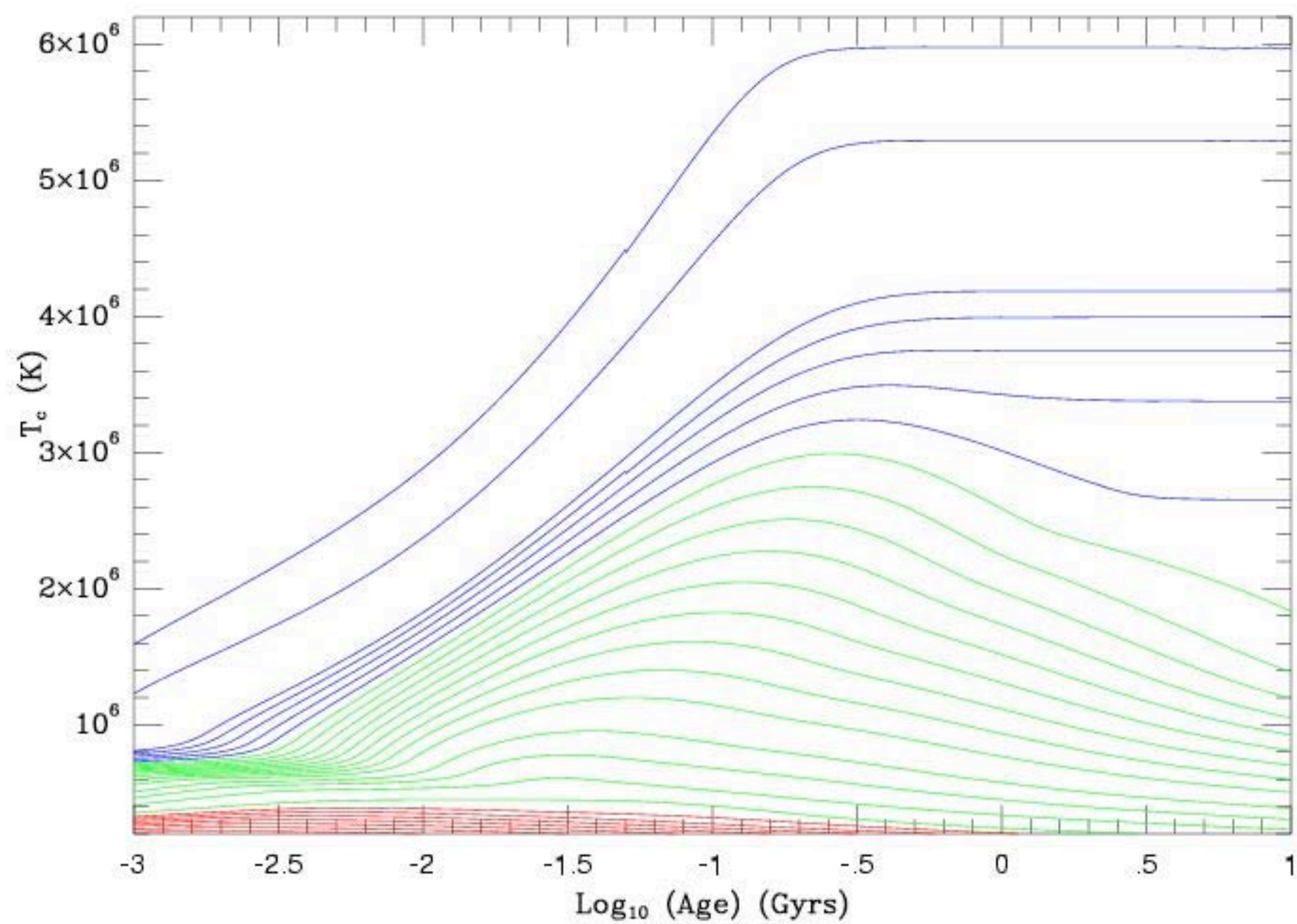


Gl 570D (T8)
750 K/10^5 cm s^-2
No Rainout
Rainout
Log10 Fν (milliJanskys)
λ (μm)
0
-.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
.8
1
1.2

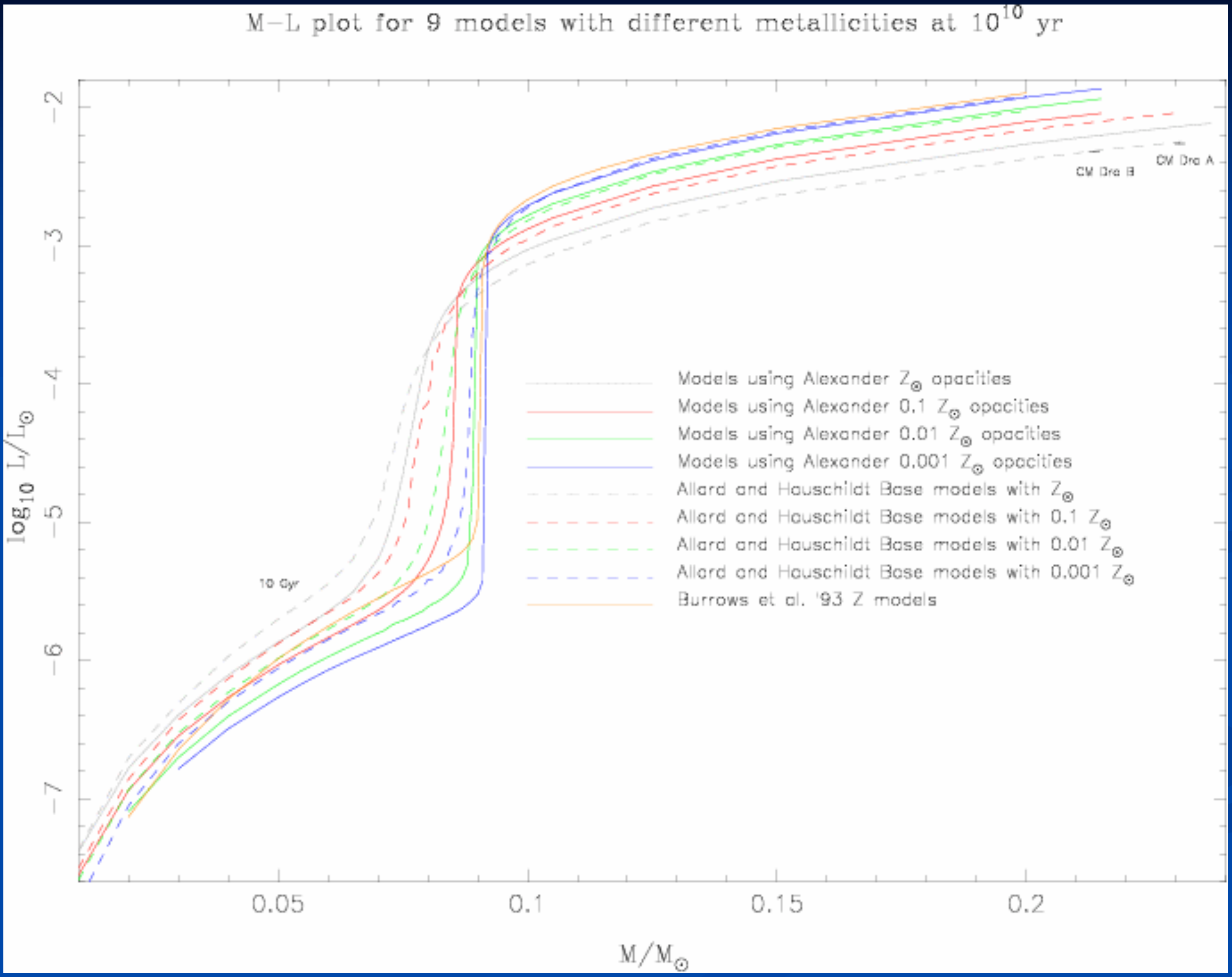


$T_{eff}/g = 750\ K/10^5\ cm\ s^{-2}$
GJ 570D's IRAC fluxes
F_ν (milliJanskys)
λ (microns)
0
.5
1
1.5
1
2
3
4
5
6
7
8
9
10

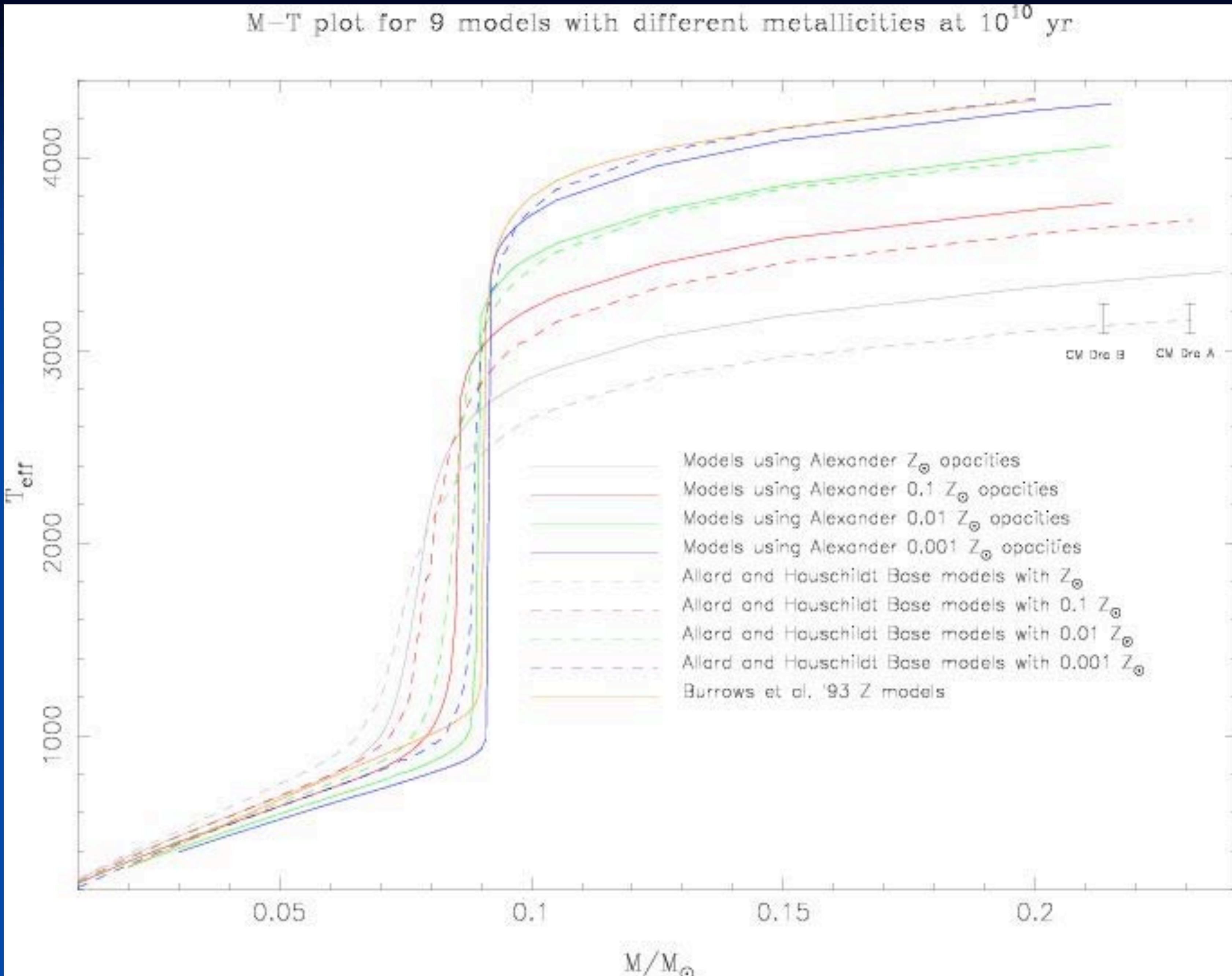
Evolutionary Models



6×10^6
5×10^6
4×10^6
3×10^6
2×10^6
10^6
T_c (K)
-3
-2.5
-2
-1.5
-1
-.5
0
.5
1
Log10 (Age) (Gyrs)

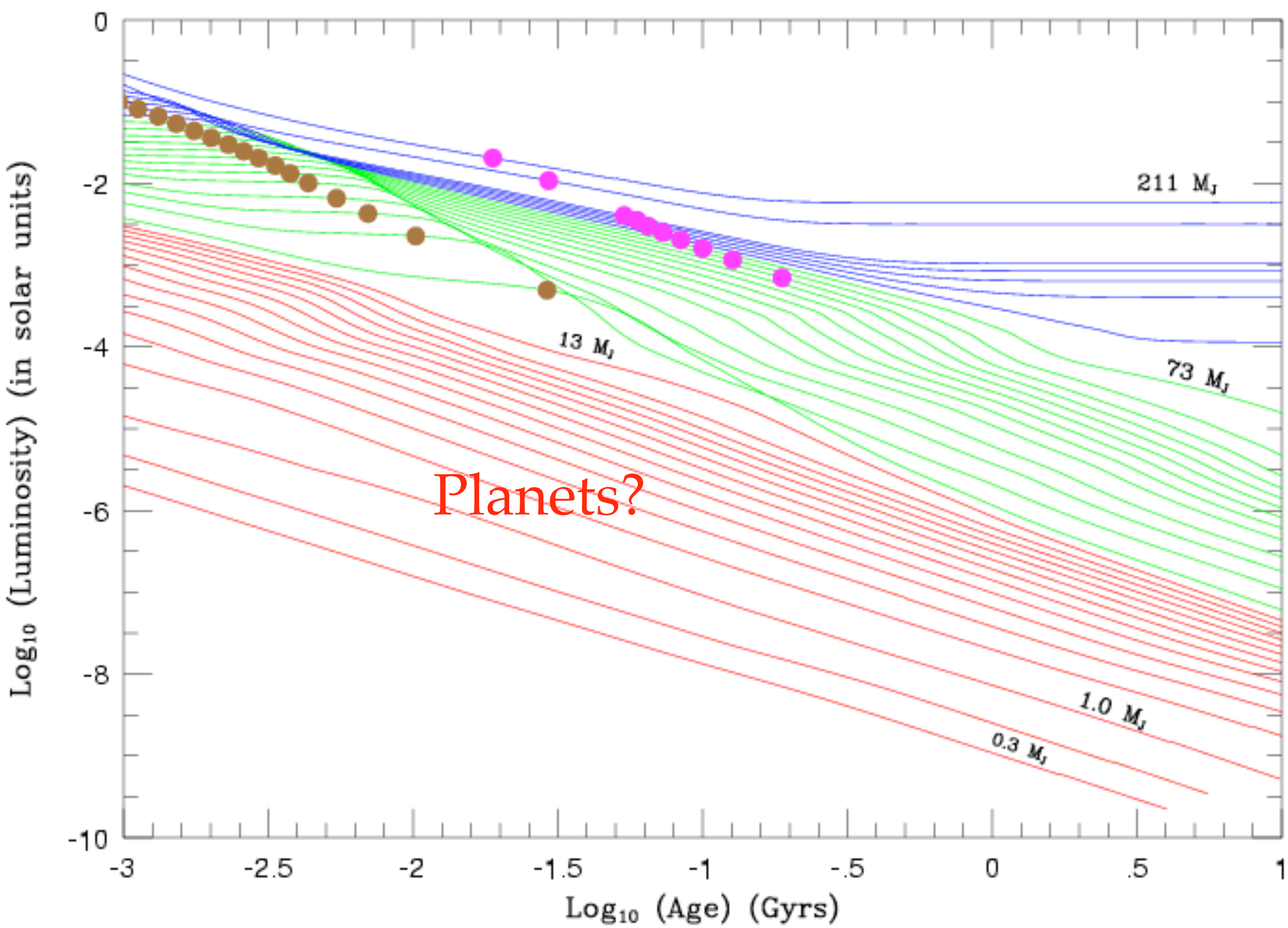


M–L plot for 9 models with different metallicities at 10^{10} yr
$\log_{10} L/L_\odot$
$M/M_\odot$
−2
−3
−4
−5
−6
−7
0.05
0.1
0.15
0.2
10 Gyr
CM Dra A
CM Dra B
Models using Alexander $Z_\odot$ opacities
Models using Alexander 0.1 $Z_\odot$ opacities
Models using Alexander 0.01 $Z_\odot$ opacities
Models using Alexander 0.001 $Z_\odot$ opacities
Allard and Hauschildt Base models with $Z_\odot$
Allard and Hauschildt Base models with 0.1 $Z_\odot$
Allard and Hauschildt Base models with 0.01 $Z_\odot$
Allard and Hauschildt Base models with 0.001 $Z_\odot$
Burrows et al. '93 Z models

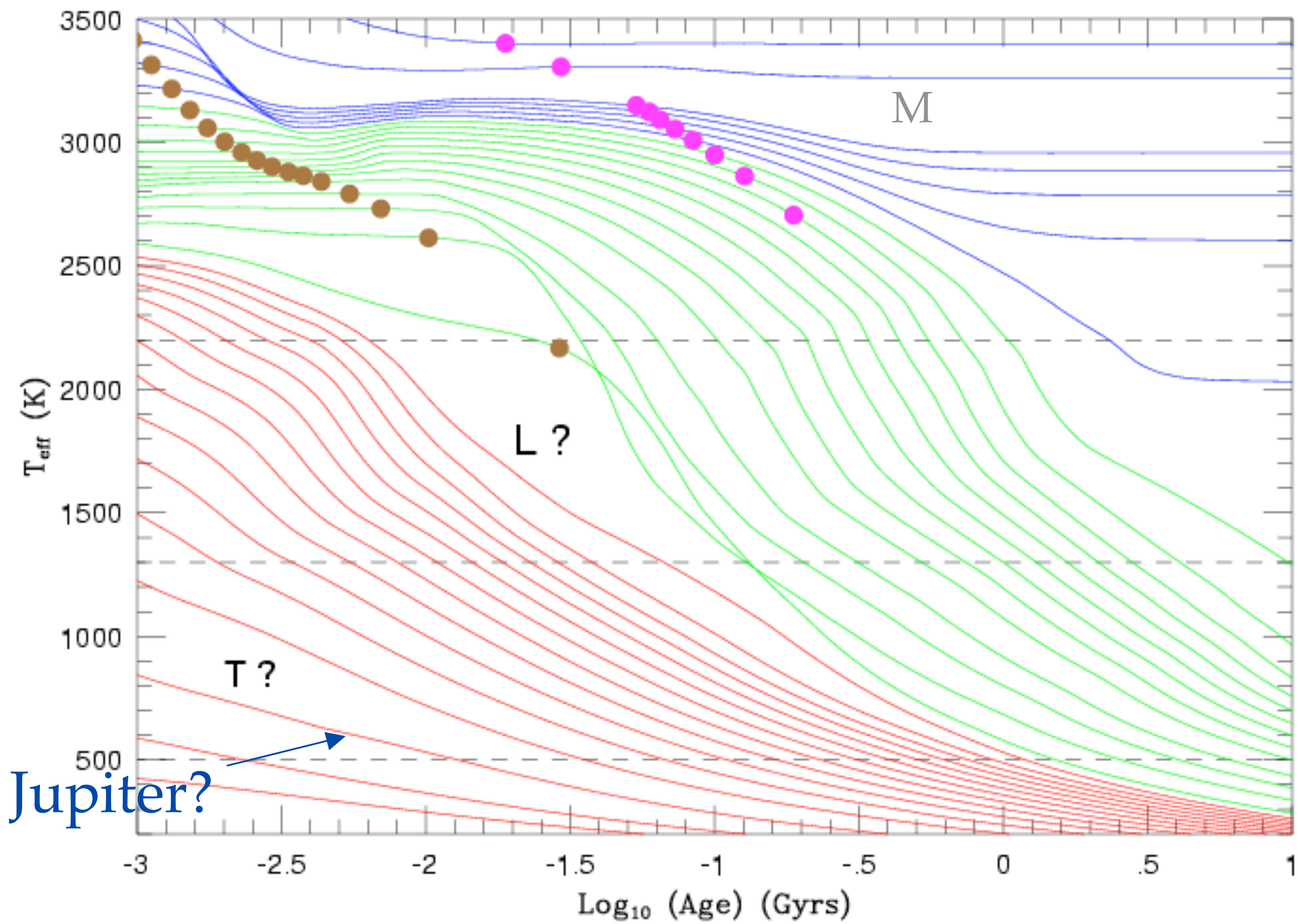


M–T plot for 9 models with different metallicities at 10^{10} yr
T_{eff}
1000
2000
3000
4000
0.05
0.1
0.15
0.2
$M/M_{\odot}$
CM Dra B
CM Dra A
Models using Alexander $Z_{\odot}$ opacities
Models using Alexander 0.1 $Z_{\odot}$ opacities
Models using Alexander 0.01 $Z_{\odot}$ opacities
Models using Alexander 0.001 $Z_{\odot}$ opacities
Allard and Hauschildt Base models with $Z_{\odot}$
Allard and Hauschildt Base models with 0.1 $Z_{\odot}$
Allard and Hauschildt Base models with 0.01 $Z_{\odot}$
Allard and Hauschildt Base models with 0.001 $Z_{\odot}$
Burrows et al. '93 Z models

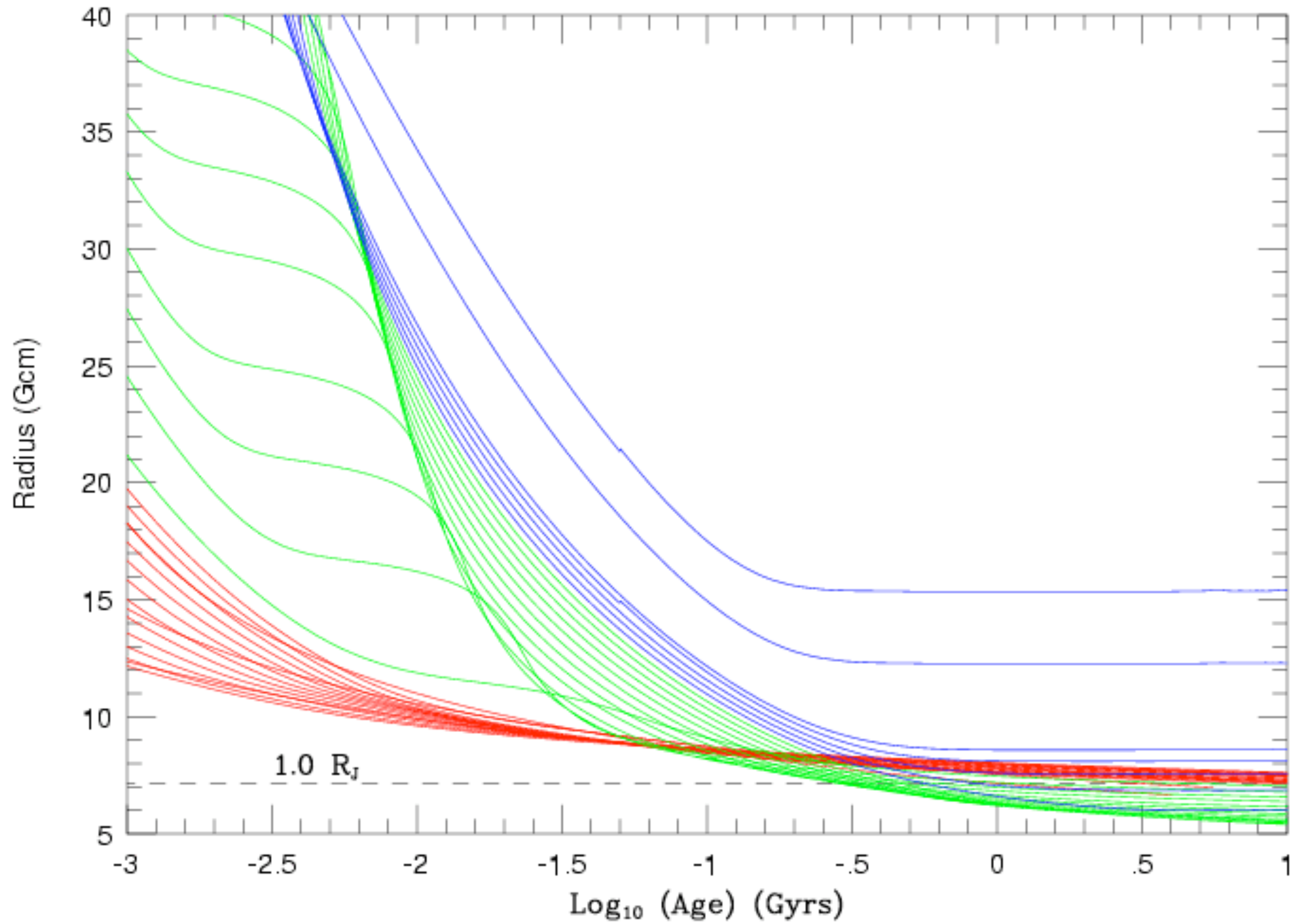
Luminosity vs. Age vs. Mass



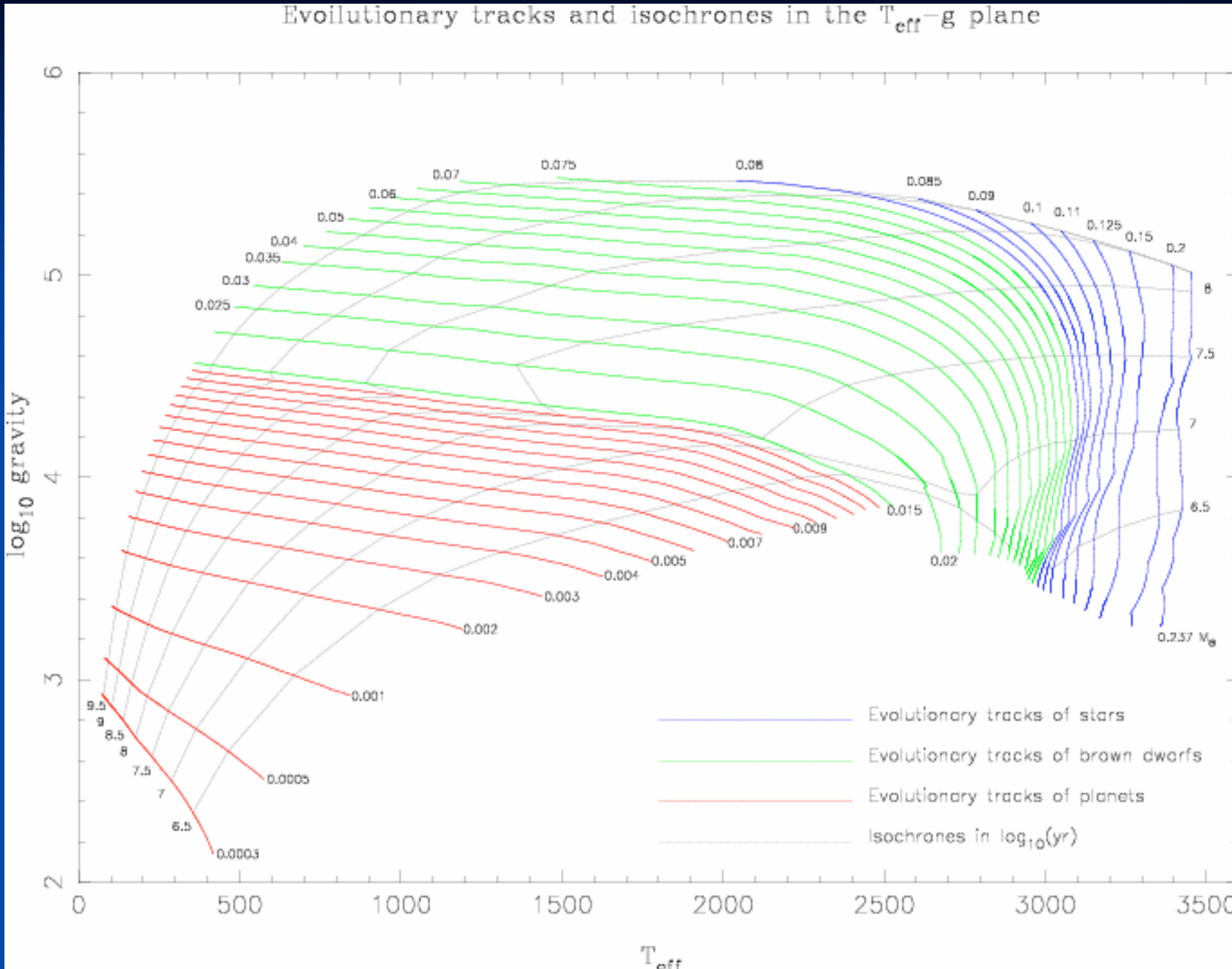
Burrows et al. 1997; Burrows et al. 2001



Burrows et al. 2001

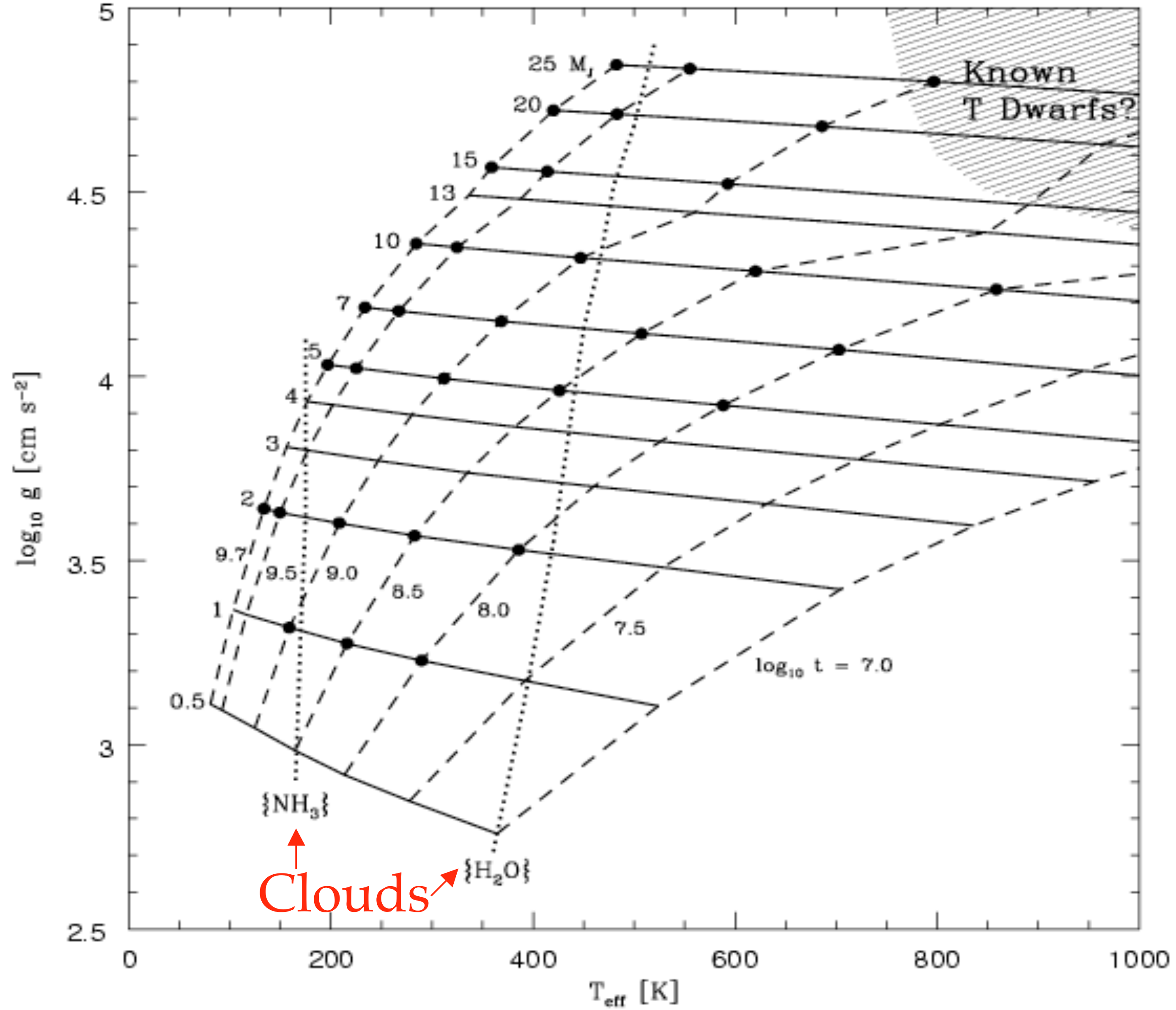


Radius (Gcm)
40
35
30
25
20
15
10
5
1.0 R_J
-3
-2.5
-2
-1.5
-1
-.5
0
.5
1
Log_{10} (Age) (Gyrs)



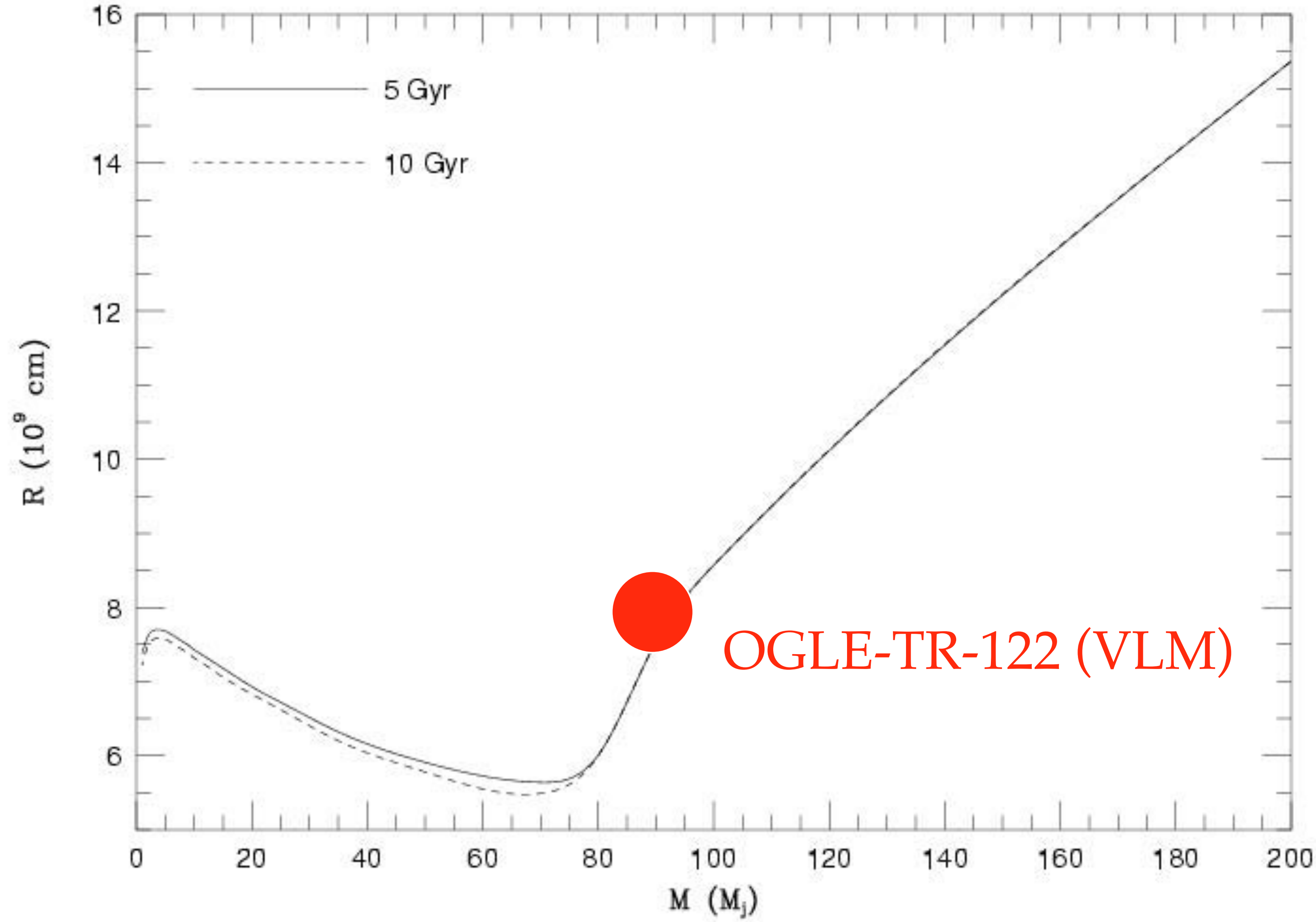
Evoilutionary tracks and isochrones in the T_{eff}–g plane
$\log_{10}$ gravity
T_{eff}
Evolutionary tracks of stars
Evolutionary tracks of brown dwarfs
Evolutionary tracks of planets
Isochrones in $\log_{10}$(yr)
0.237 $M_{\odot}$

Isolated EGPs and Y Dwarfs

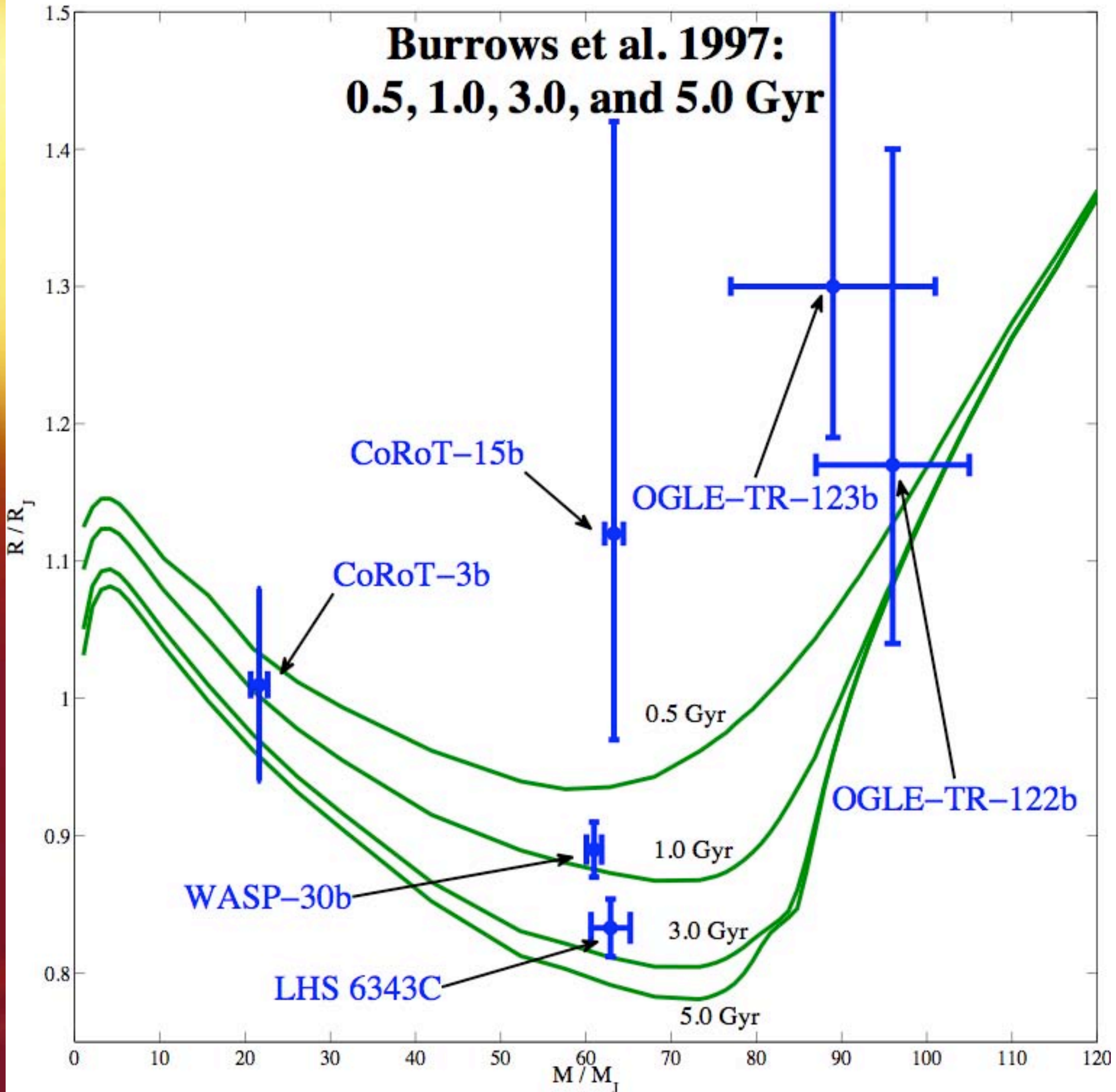


Burrows, Sudarsky, and Lunine 2003

Radius-Mass Relation



Brown dwarf Radii (when we know the Mass and have an estimate of the age (?)- ambiguous interpretations

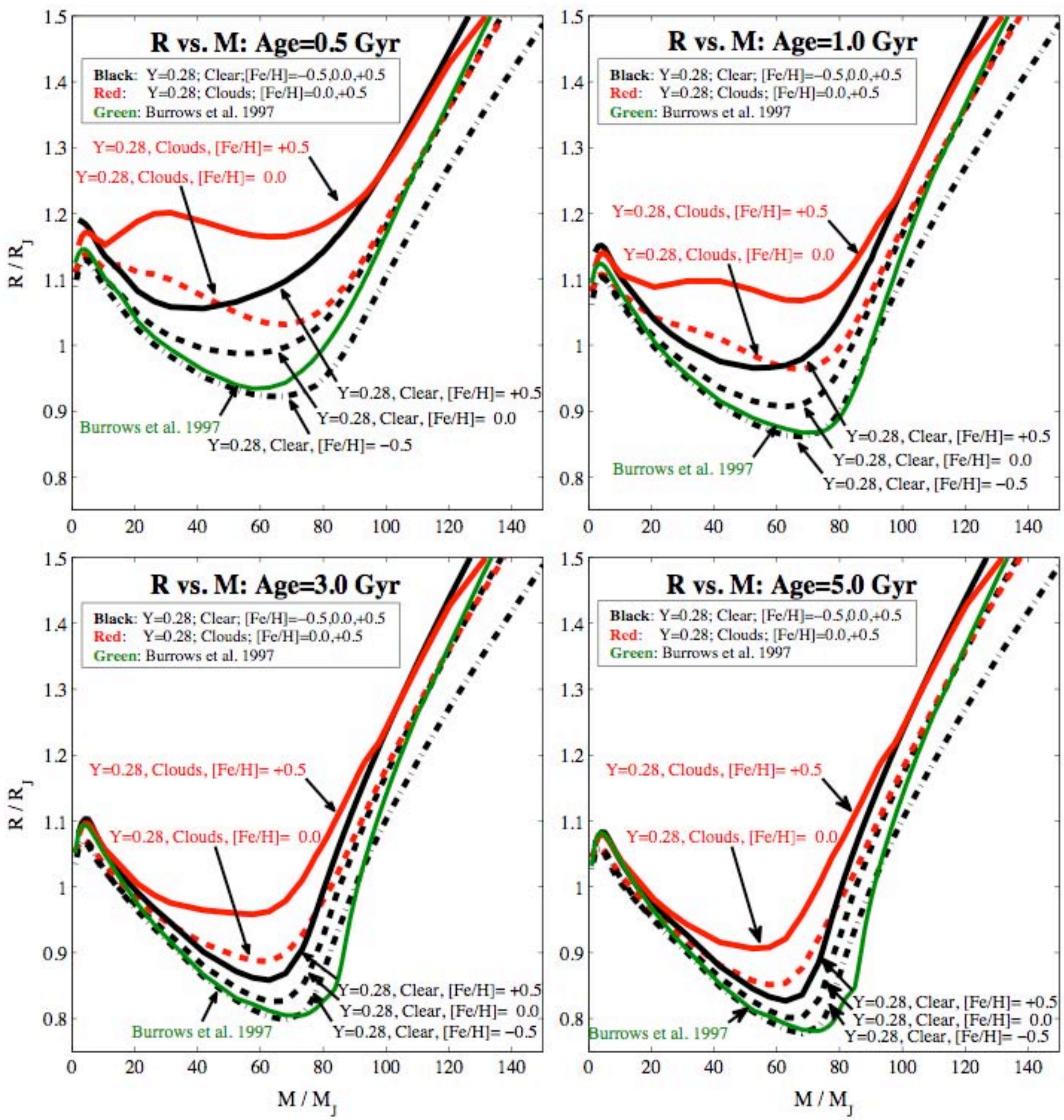


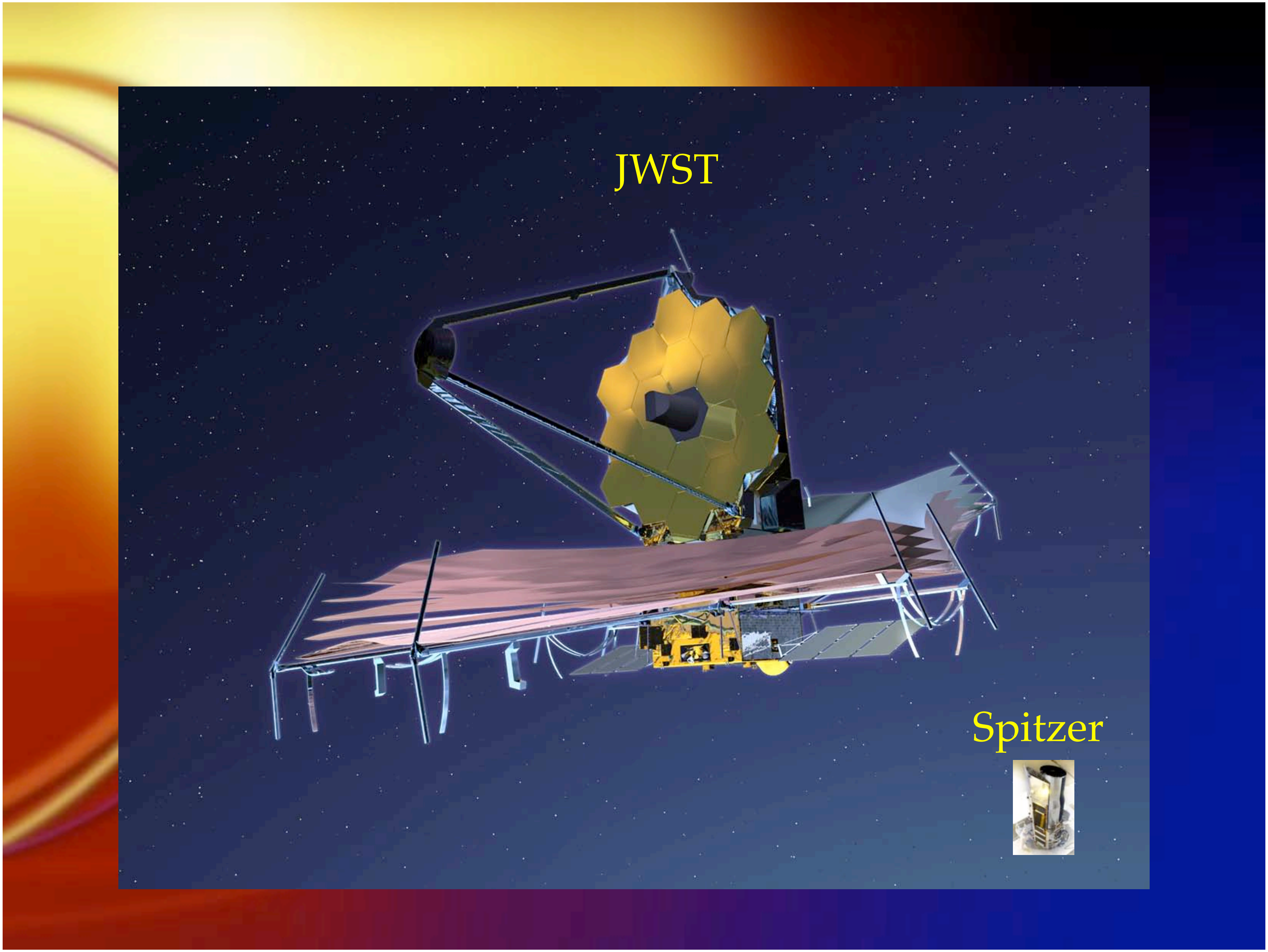
Burrows et al. 2011

Brown dwarf Radii - functions of metallicity, clouds, …: 5-30%

Brown dwarf Radii - Not just a test of the EOS!

Burrows et al. 2011




JWST
Spitzer

The Beginning

"Non-Irradiated Giant Planets"

(free-floating, wide orbit)

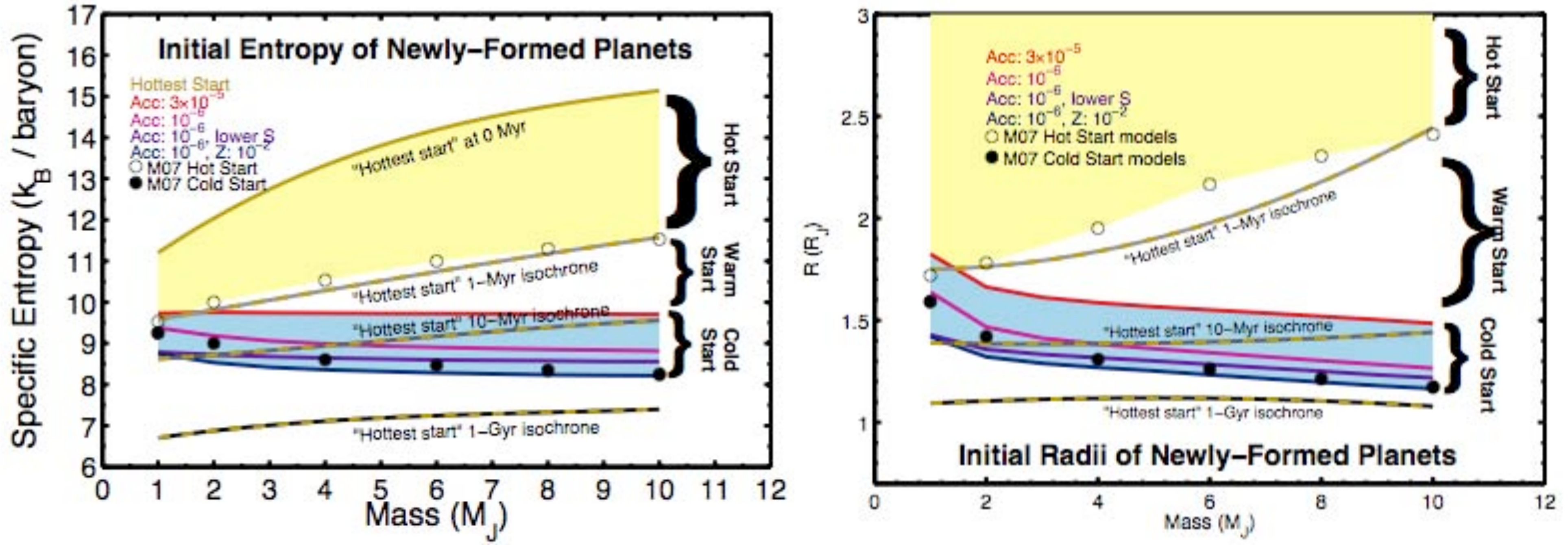
Spectroscopic and Photometric Discriminants of Giant Planet Formation Scenaros

D. Spiegel and A. Burrows

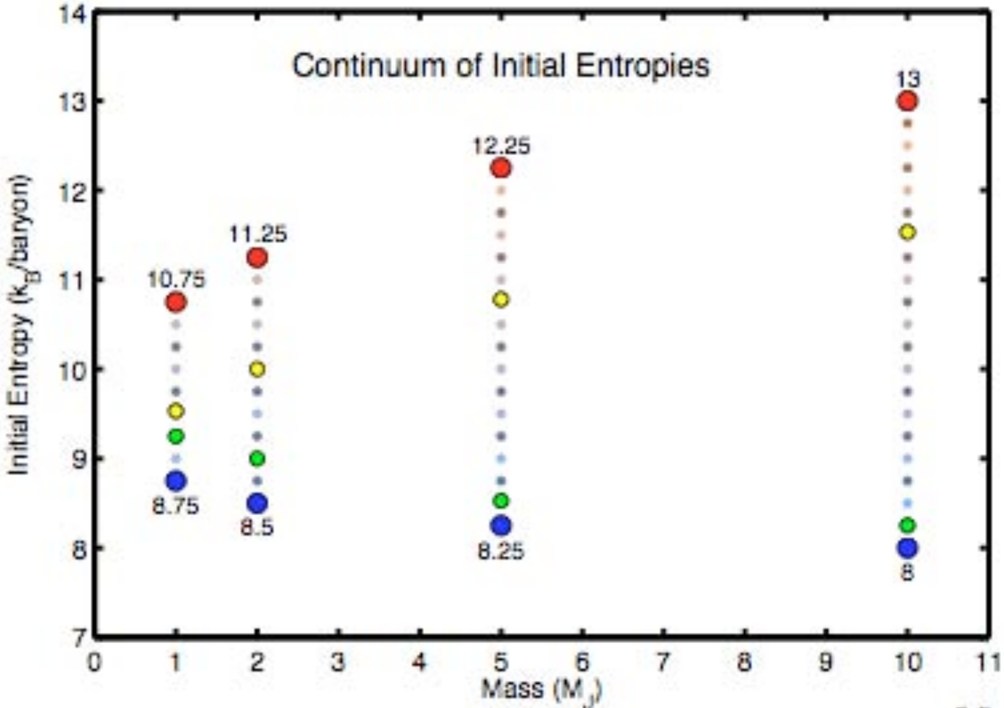
2011

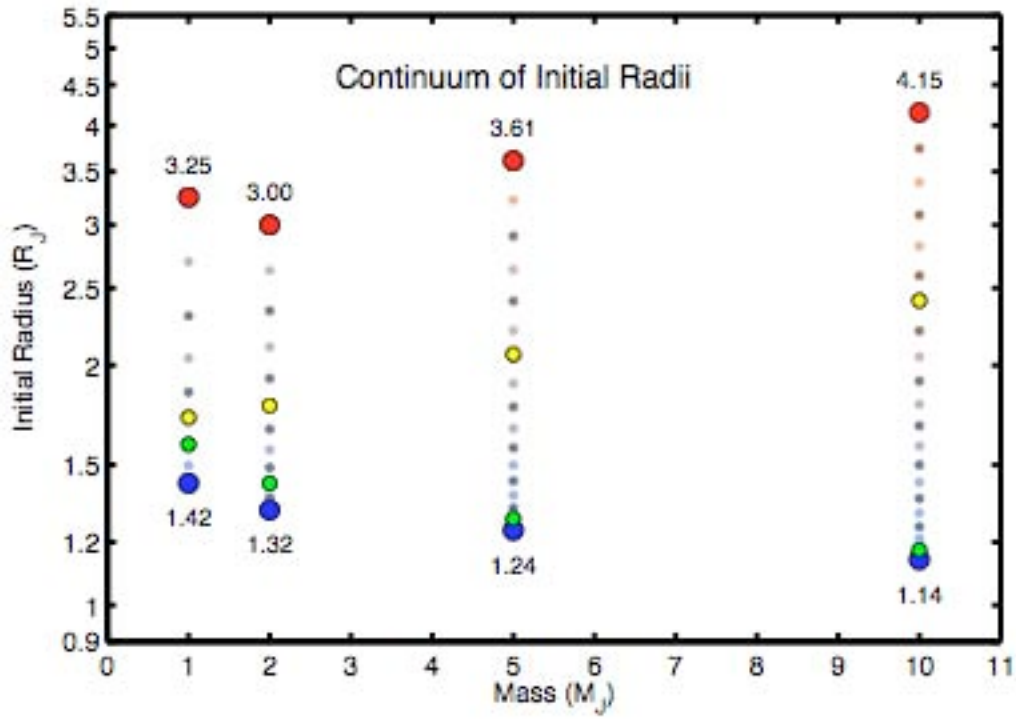
Initial BD/EGP Models are Quite Uncertain

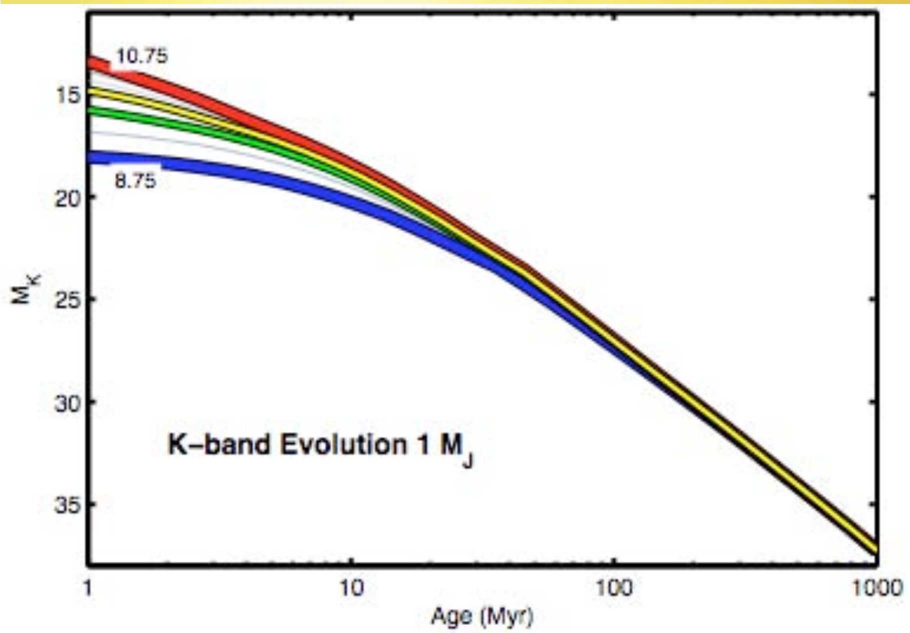
- Initial Radius, entropies determine flux evolution for quite some time
- Hot-start/cold-start/warm-start - Signatures of mode of formation

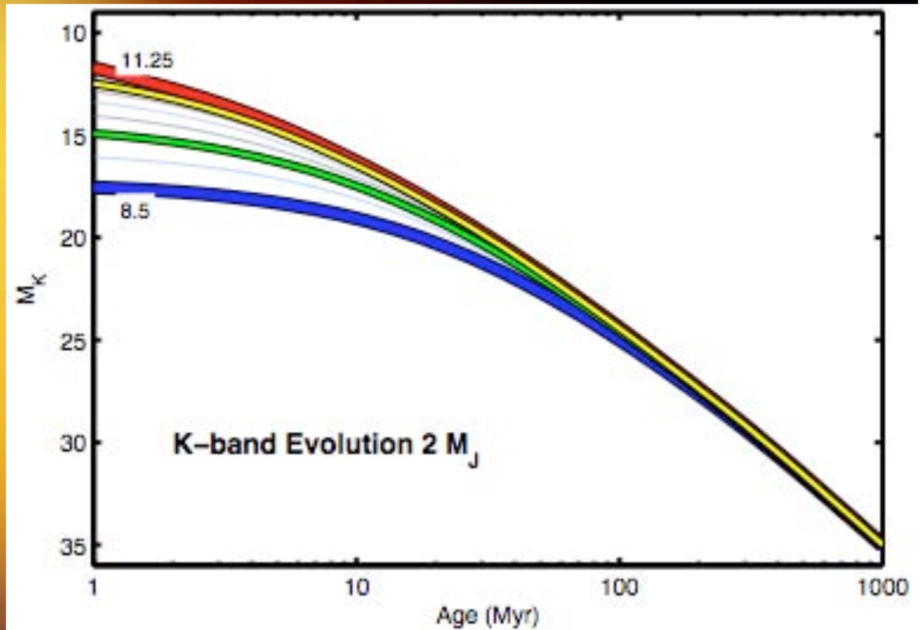


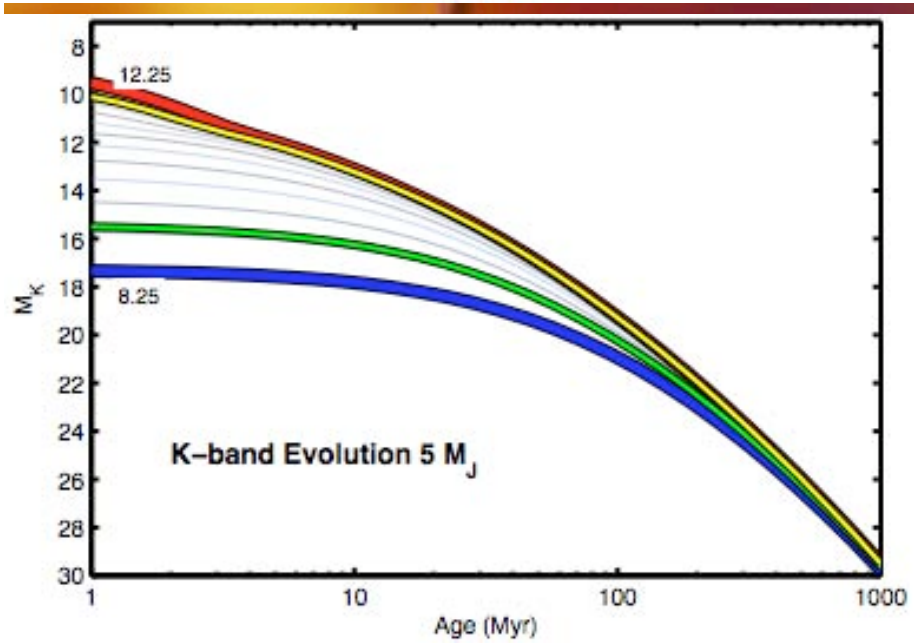
Initial Entropy of Newly–Formed Planets
Specific Entropy (k_B / baryon)
Mass (M_J)
Hottest Start
Acc: 3×10^-5
Acc: 10^-6
Acc: 10^-6, lower S
Acc: 10^-6, Z: 10^-2
M07 Hot Start
M07 Cold Start
"Hottest start" at 0 Myr
"Hottest start" 1–Myr isochrone
"Hottest start" 10–Myr isochrone
"Hottest start" 1–Gyr isochrone
Hot Start
Warm Start
Cold Start
Initial Radii of Newly–Formed Planets
R (R_J)
Mass (M_J)
Acc: 3×10^-5
Acc: 10^-6
Acc: 10^-6, lower S
Acc: 10^-6, Z: 10^-2
M07 Hot Start models
M07 Cold Start models
"Hottest start" 1–Myr isochrone
"Hottest start" 10–Myr isochrone
"Hottest start" 1–Gyr isochrone
Hot Start
Warm Start
Cold Start

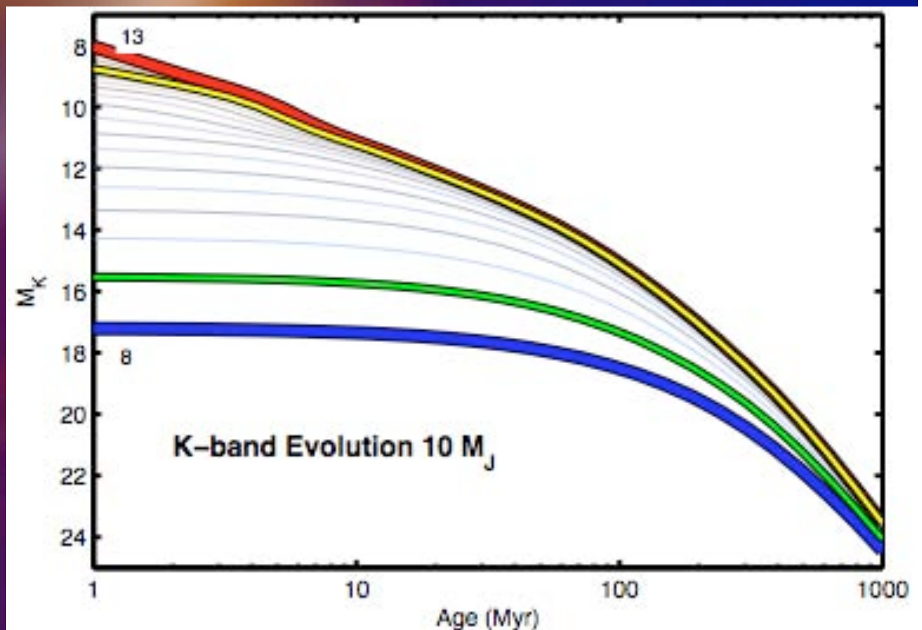

Continuum of Initial Entropies
Initial Entropy (k_B/baryon)
Mass (M_J)
10.75
11.25
12.25
13
8.75
8.5
8.25
8

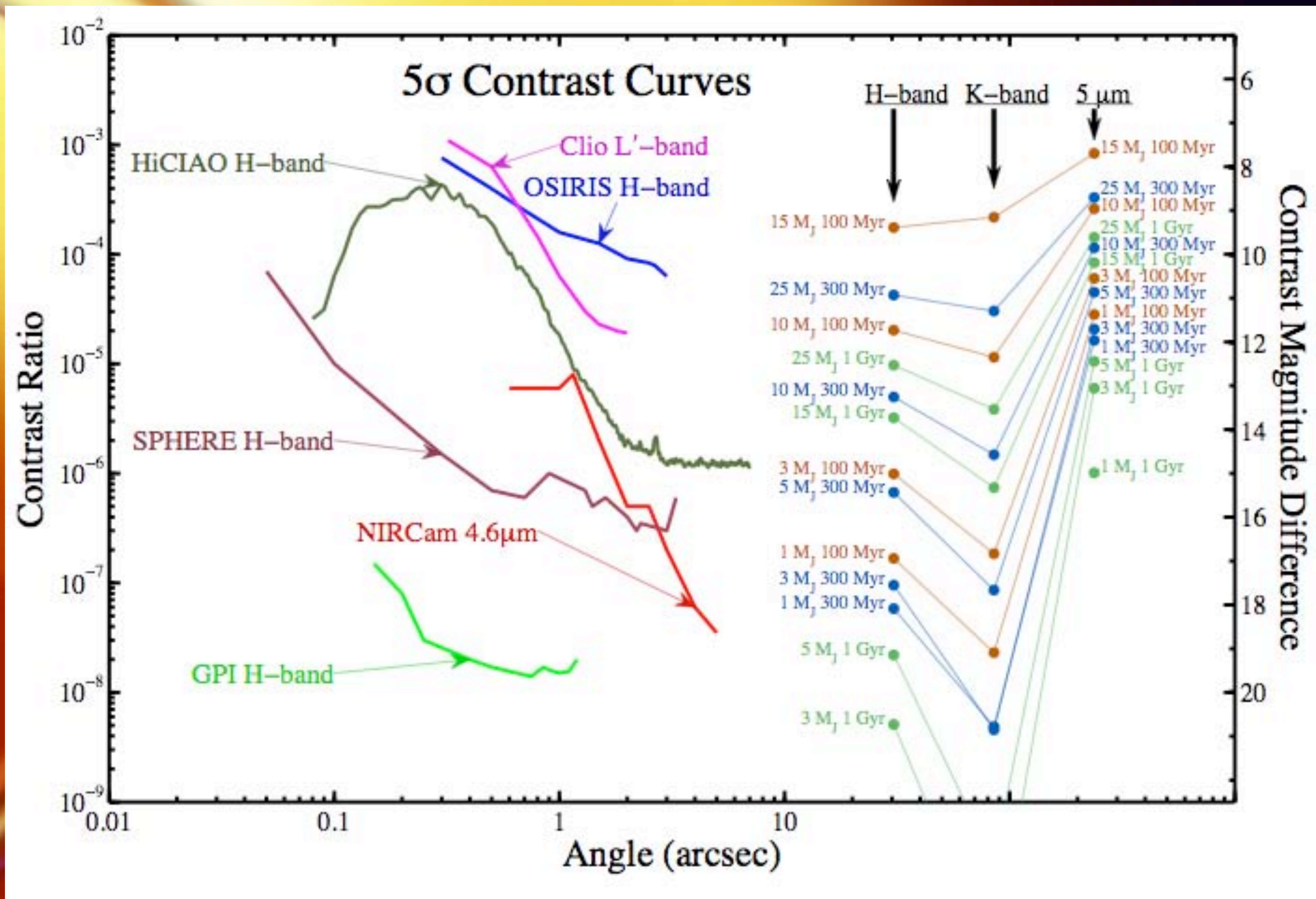

Continuum of Initial Radii
Initial Radius (R_J)
Mass (M_J)
3.25
3.00
3.61
4.15
1.42
1.32
1.24
1.14


10.75
8.75
K–band Evolution 1 M_J
M_K
Age (Myr)


11.25
8.5
K–band Evolution 2 M_J
M_K
Age (Myr)

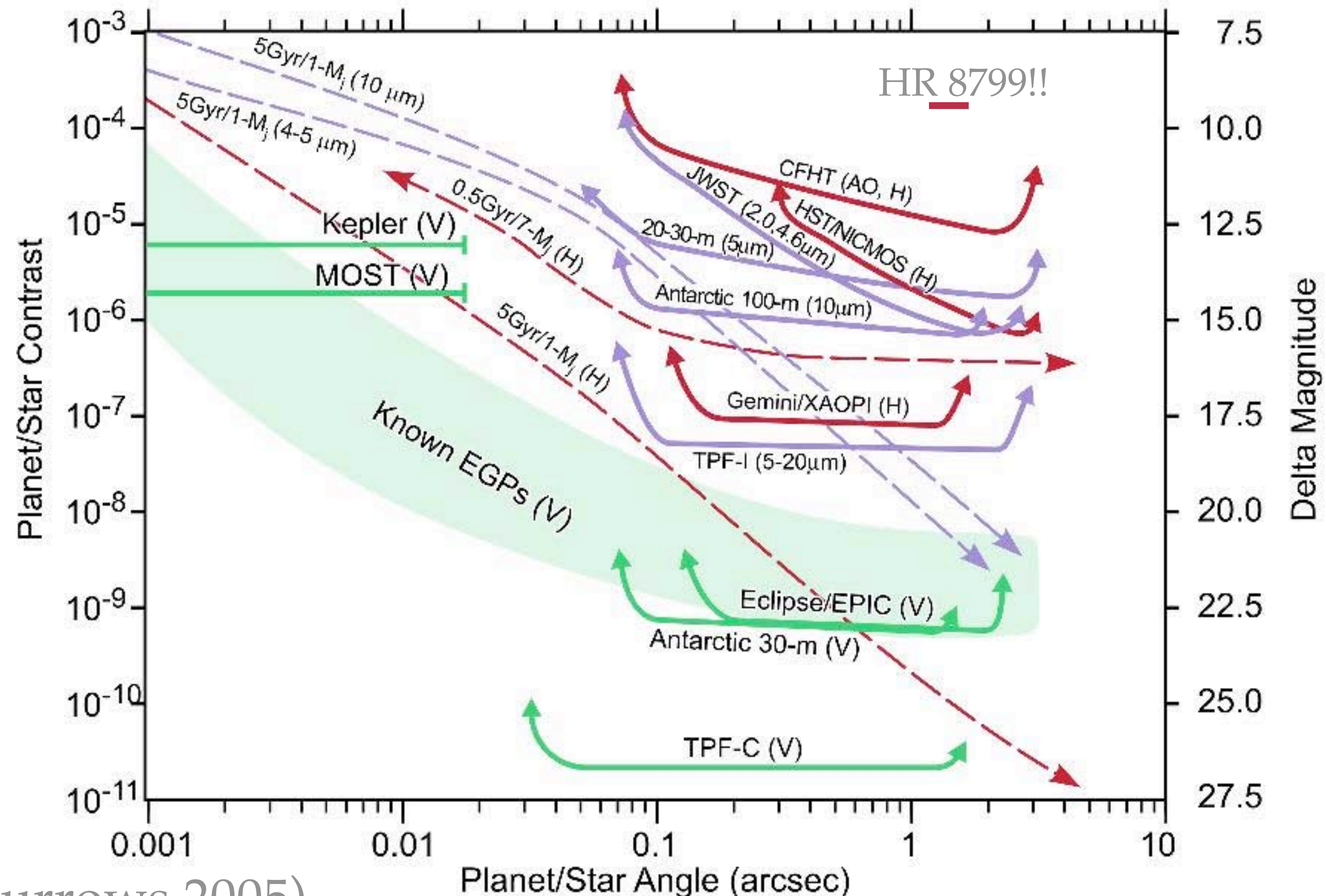

12.25
8.25
K–band Evolution 5 M_J
M_K
Age (Myr)


13
8
K–band Evolution 10 M_J
M_K
Age (Myr)



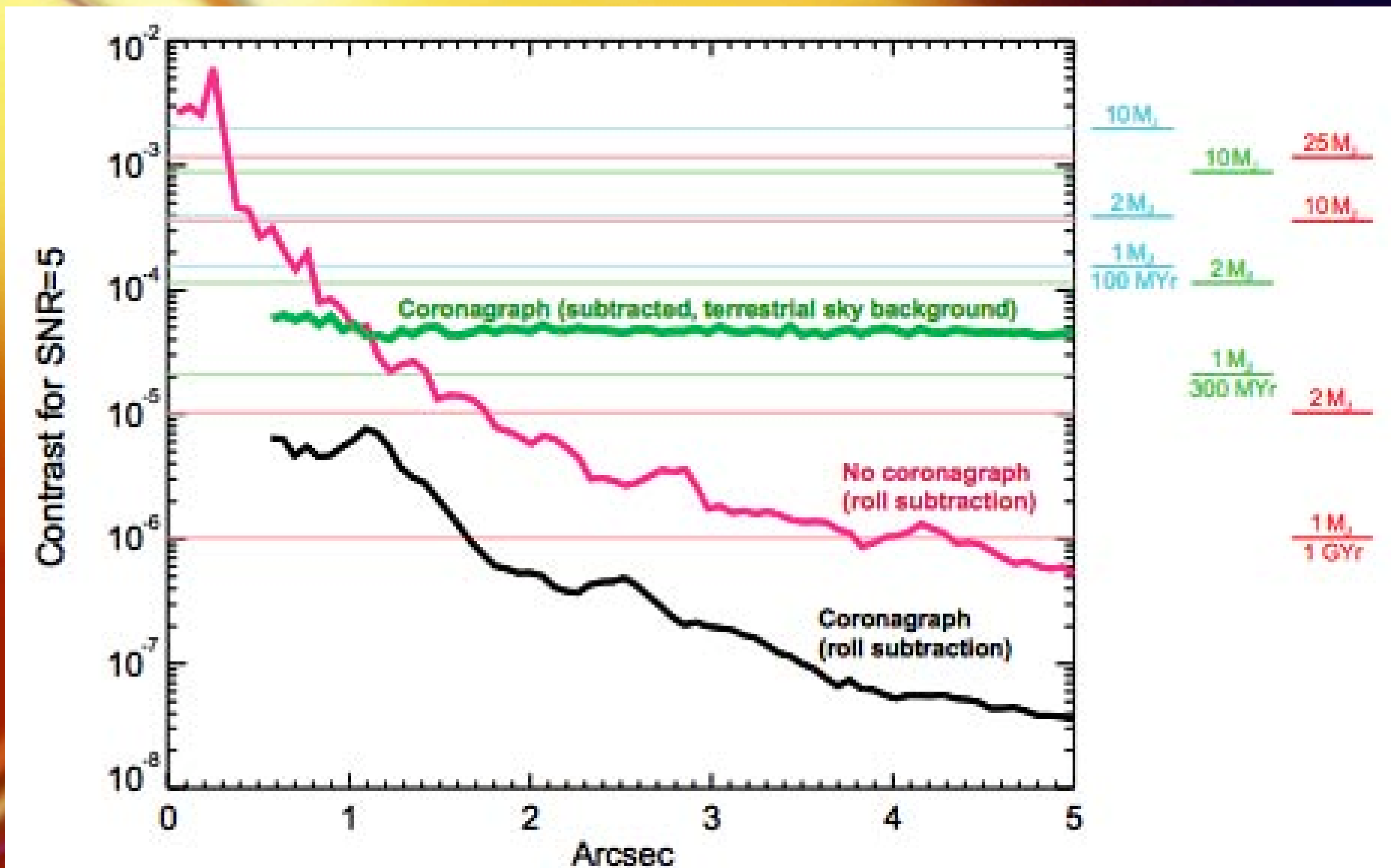
5σ Contrast Curves
Contrast Ratio
Angle (arcsec)
Contrast Magnitude Difference
HiCIAO H–band
Clio L′–band
OSIRIS H–band
SPHERE H–band
NIRCam 4.6μm
GPI H–band
H–band
K–band
5 μm
15 M_J 100 Myr
25 M_J 300 Myr
10 M_J 100 Myr
25 M_J 1 Gyr
10 M_J 300 Myr
15 M_J 1 Gyr
3 M_J 100 Myr
5 M_J 300 Myr
1 M_J 100 Myr
3 M_J 300 Myr
1 M_J 300 Myr
5 M_J 1 Gyr
3 M_J 1 Gyr
1 M_J 1 Gyr

Planet/Star *Contrast*: Theory (dashed) versus Capability



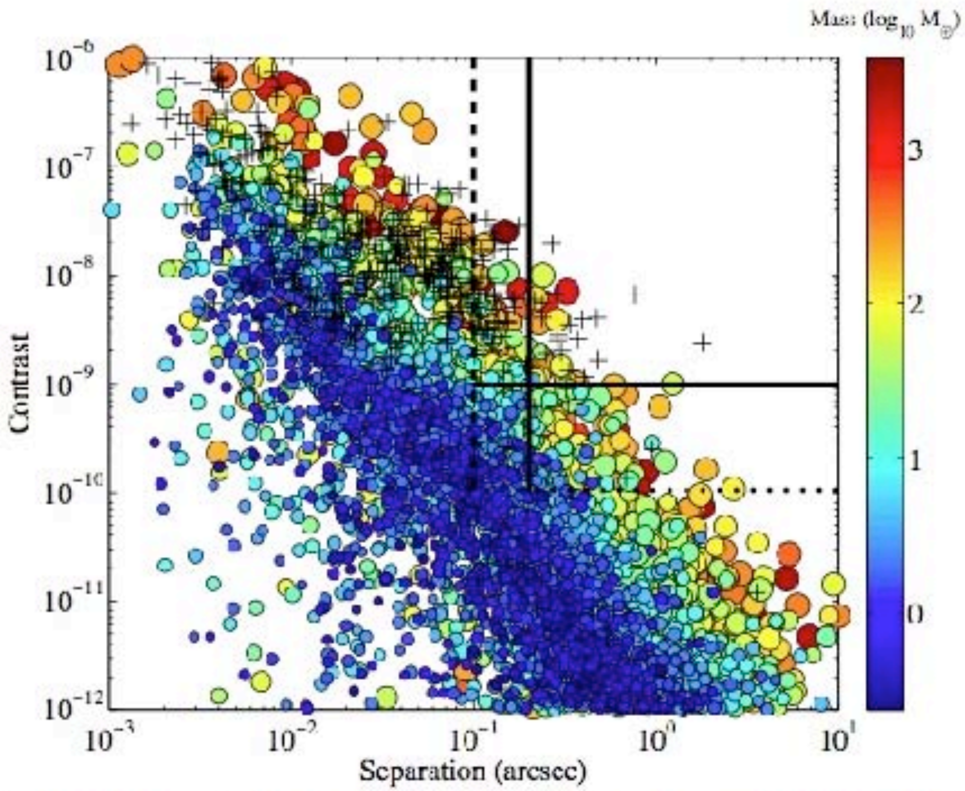
(Burrows 2005)

Red: H band (1.6 microns); Purple: Mid-IR; Green: Optical



Contrast for SNR=5
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
1
2
3
4
5
Arcsec
Coronagraph (subtracted, terrestrial sky background)
No coronagraph
(roll subtraction)
Coronagraph
(roll subtraction)
10M
2M
1M
100 MYr
10M
2M
1M
300 MYr
25M
10M
2M
1M
1 GYr

WFIRST-2.4 Exoplanet Imaging Sensitivity

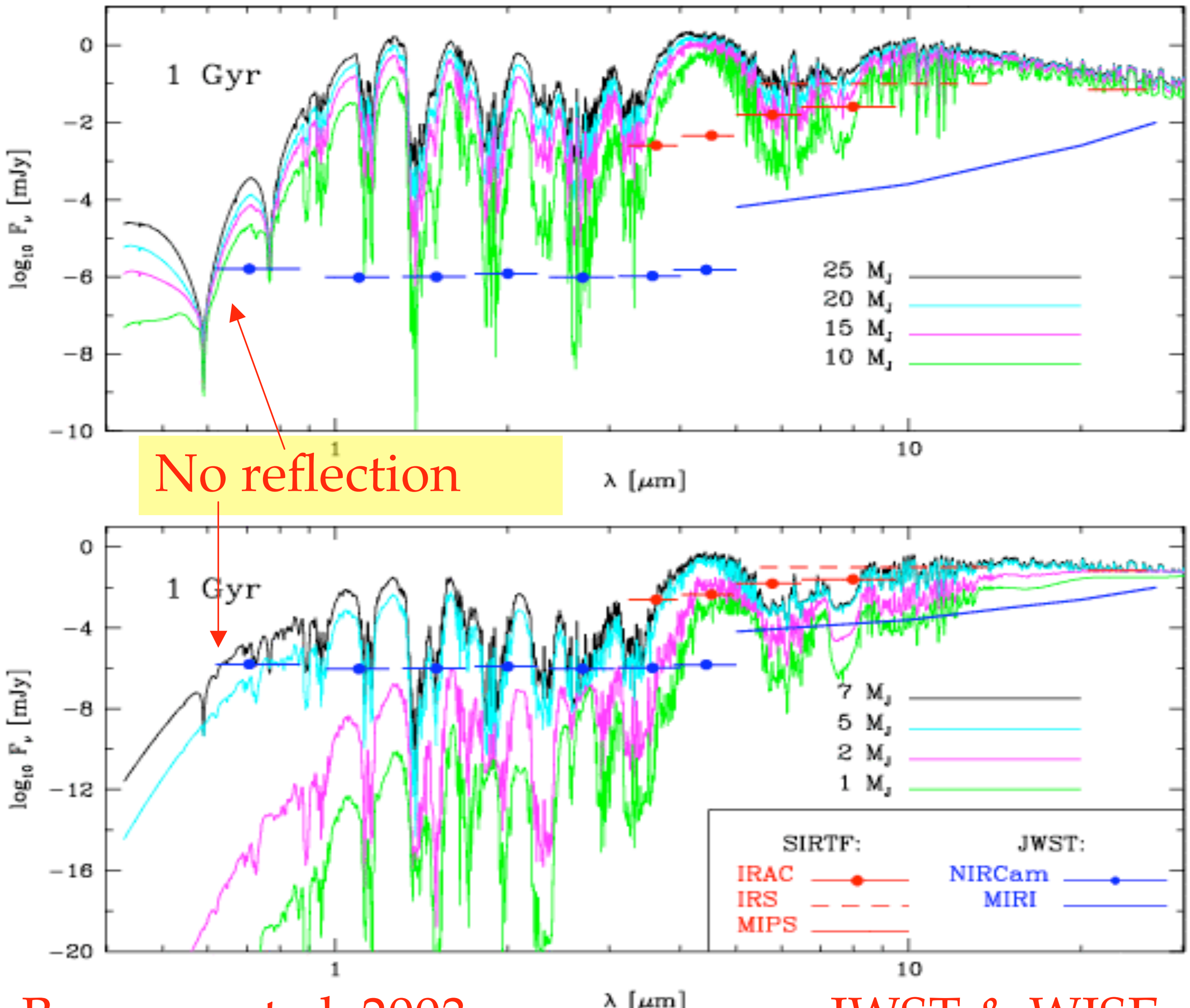


- Very sensitive to contrast limit (& IWA)

AFTA SDT report

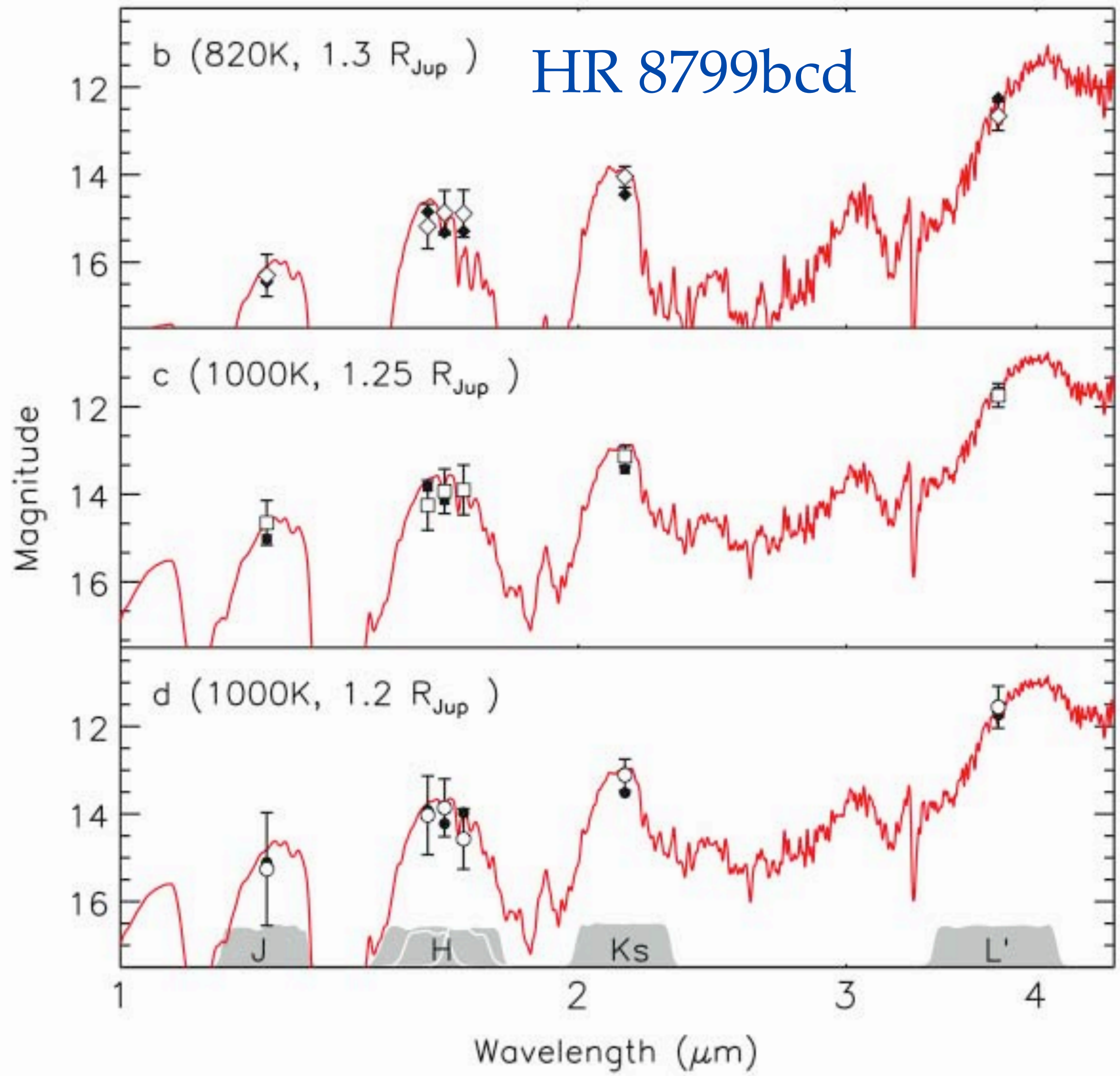
Figure 2-21: This figure is a snapshot in time of contrast and separation for model planets, ranging in size from Mars-like to several times the radius of Jupiter, for about 200 of the nearest stars within 30 pc. Color indicates planet mass while size indicates planet radius. Crosses represent known radial velocity planets. Solid black lines mark the baseline technical goal of 1 ppb contrast and 0.2 arcsec IWA, while the dotted lines show the more aggressive goals of 0.1 ppb and 0.1 arcsec IWA.

Isolated BDs/EGPs



Burrows et al. 2003

JWST & WISE


HR 8799bcd
b (820K, 1.3 R_{Jup})
c (1000K, 1.25 R_{Jup})
d (1000K, 1.2 R_{Jup})
Magnitude
12
14
16
J
H
Ks
L'
1
2
3
4
Wavelength (μm)