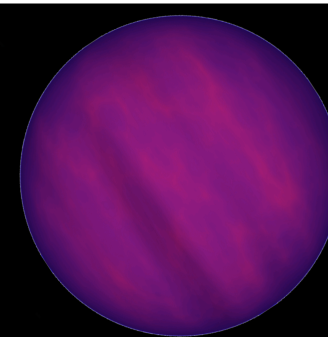
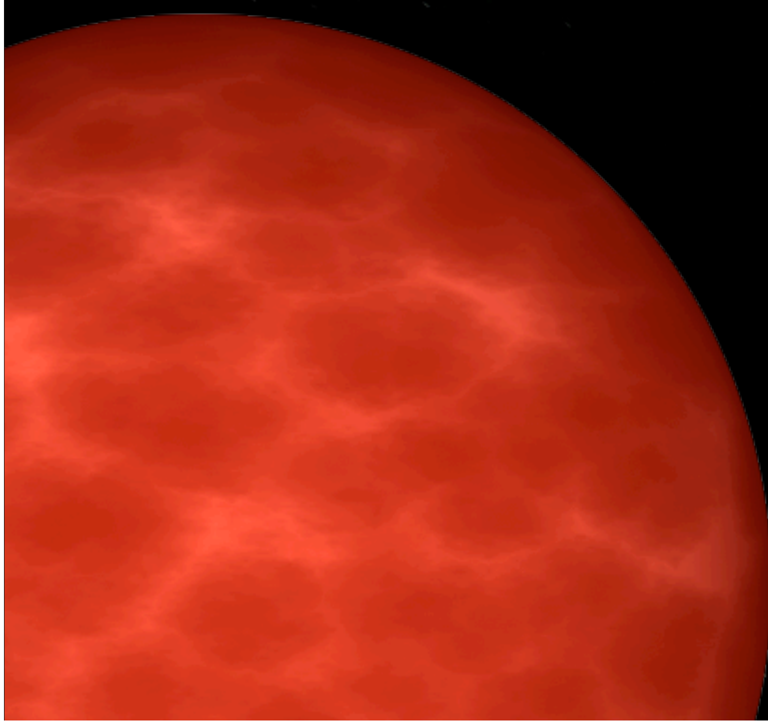


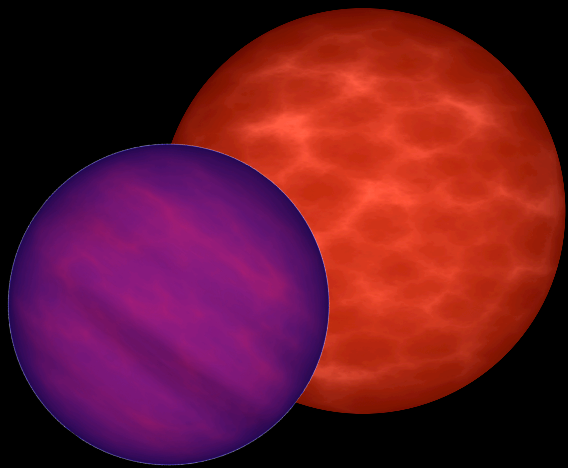
Brown Dwarfs

Planetary Guides and Galactic Standard Candles

Adam J. Burgasser

Massachusetts Institute of Technology





overview

What is a brown dwarf?

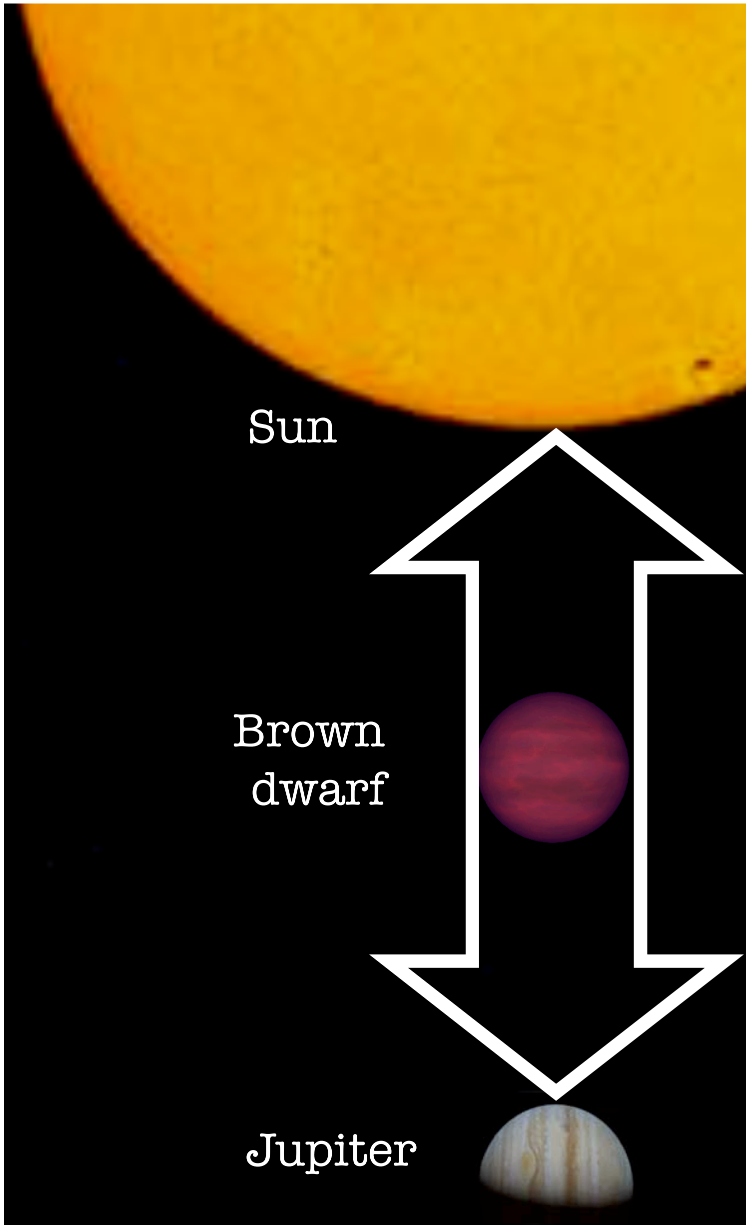
Definition, discovery, properties, spectral types

Brown dwarfs as planetary guides

cool atmospheres & clouds

Brown dwarfs as Galactic standard candles

tracer populations, age-dating (clocks)



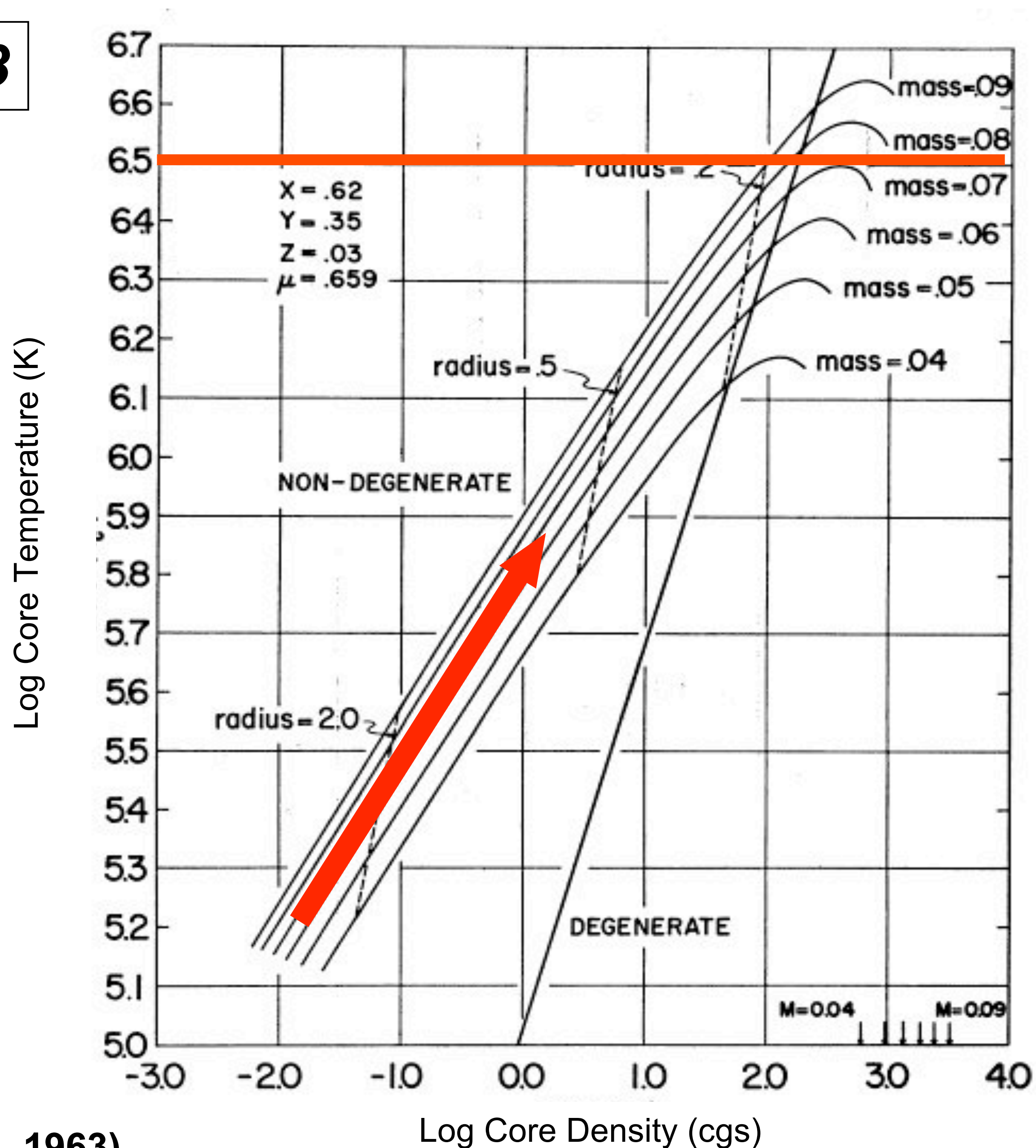
what is a ***brown dwarf*** ?

Objects with properties intermediate between stars and planets.

"Failed stars" - form like stars, found as isolated systems, can have their own planetary systems

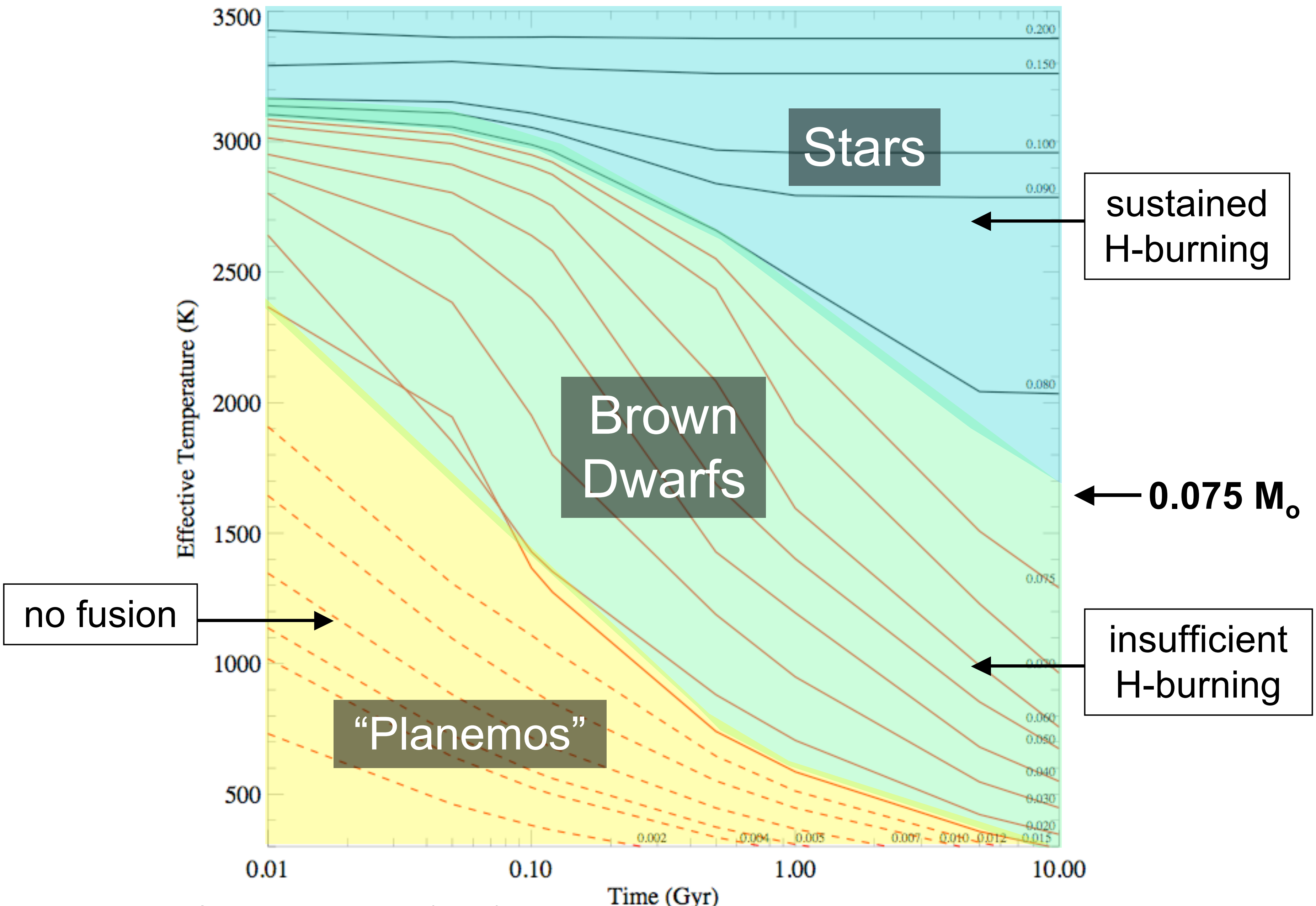
"Super-Jupiters" - do not fuse hydrogen, sizes comparable to Jupiter, planetary atmospheres

ca. 1963



H-burning threshold $\approx 3 \times 10^6$ K

Kumar (1962, 1963)
see also Hayashi & Nakano (1963)



models from Burrows et al. (2001)

Atmosphere:

$\rho \approx 10^{-4}$-10^{-6} g/cm^3 T < 2500 K

P ≈ 0.1-10 bar g ≈ 10^2-10^5 cm/s^2

$H_{scale} \approx 1$ km

Interior:

Strongly coupled, partially degenerate plasma - metallized H

Bulk composition (by mass): 73% H, 25% He, < 2% “metals”

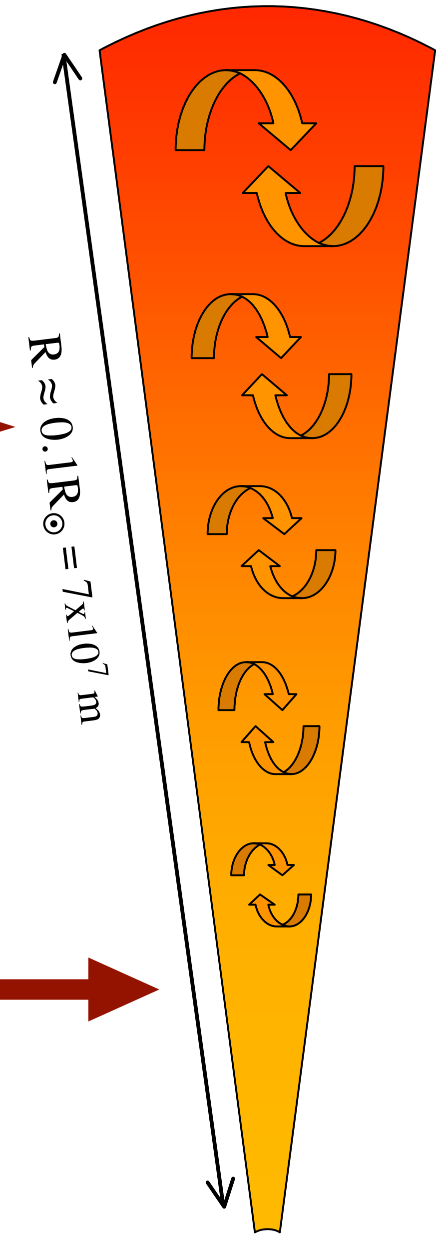
Energy transport: primarily convection (n=1.5 polytrope)

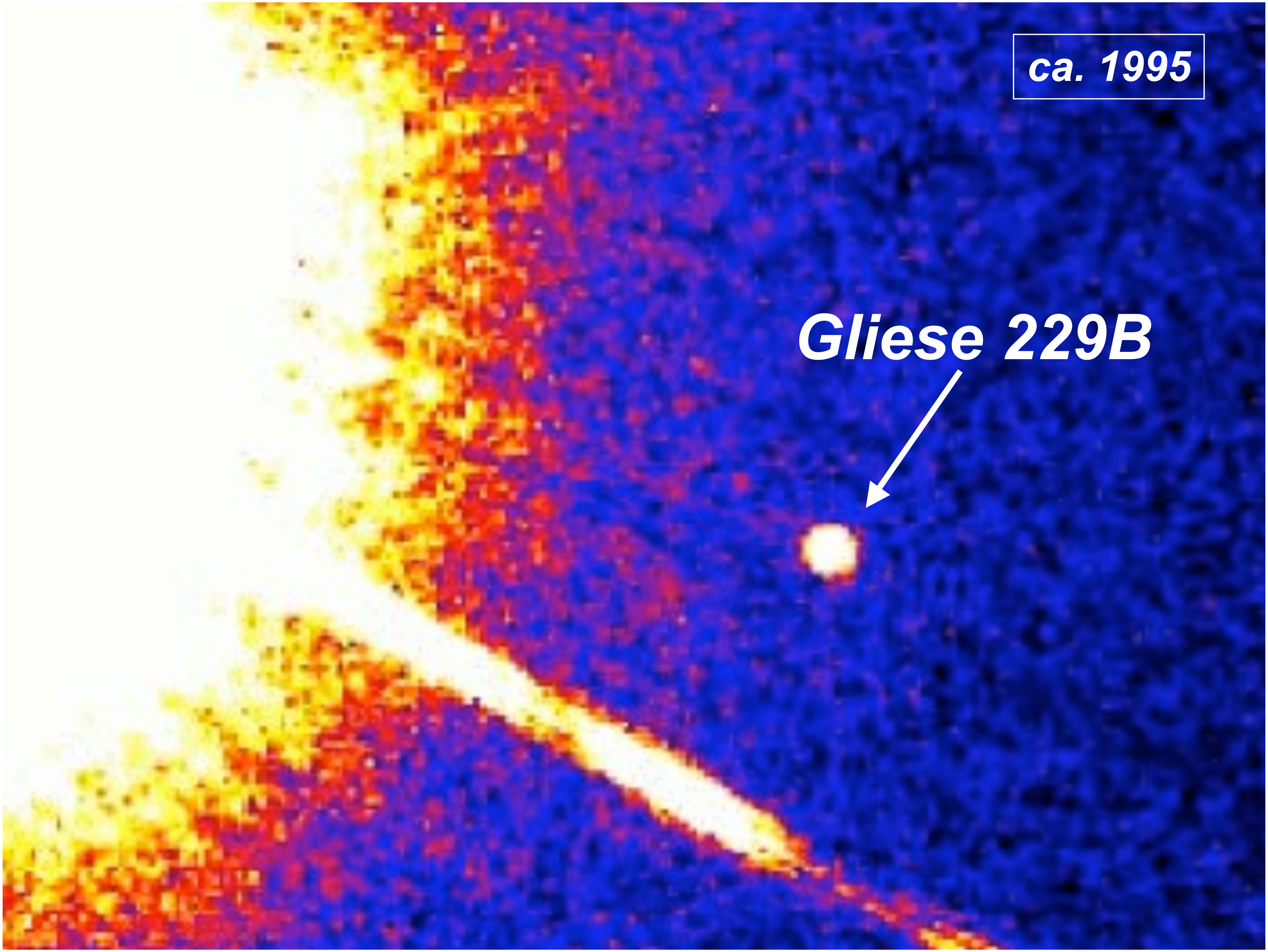
Core:

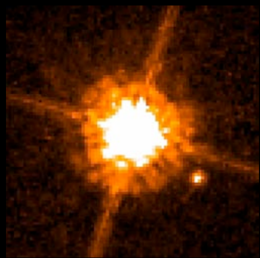
$\rho \approx 10$-10^3 g/cm^3

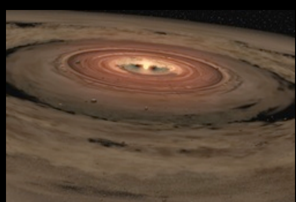
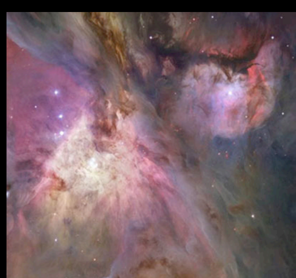
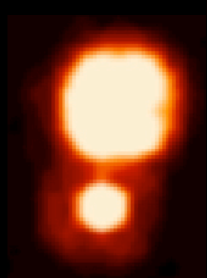
P ≈ 10^{11} bar

T < 3×10^6 K




ca. 1995
Gliese 229B



>500 Brown dwarfs have been found in nearly all Galactic environments

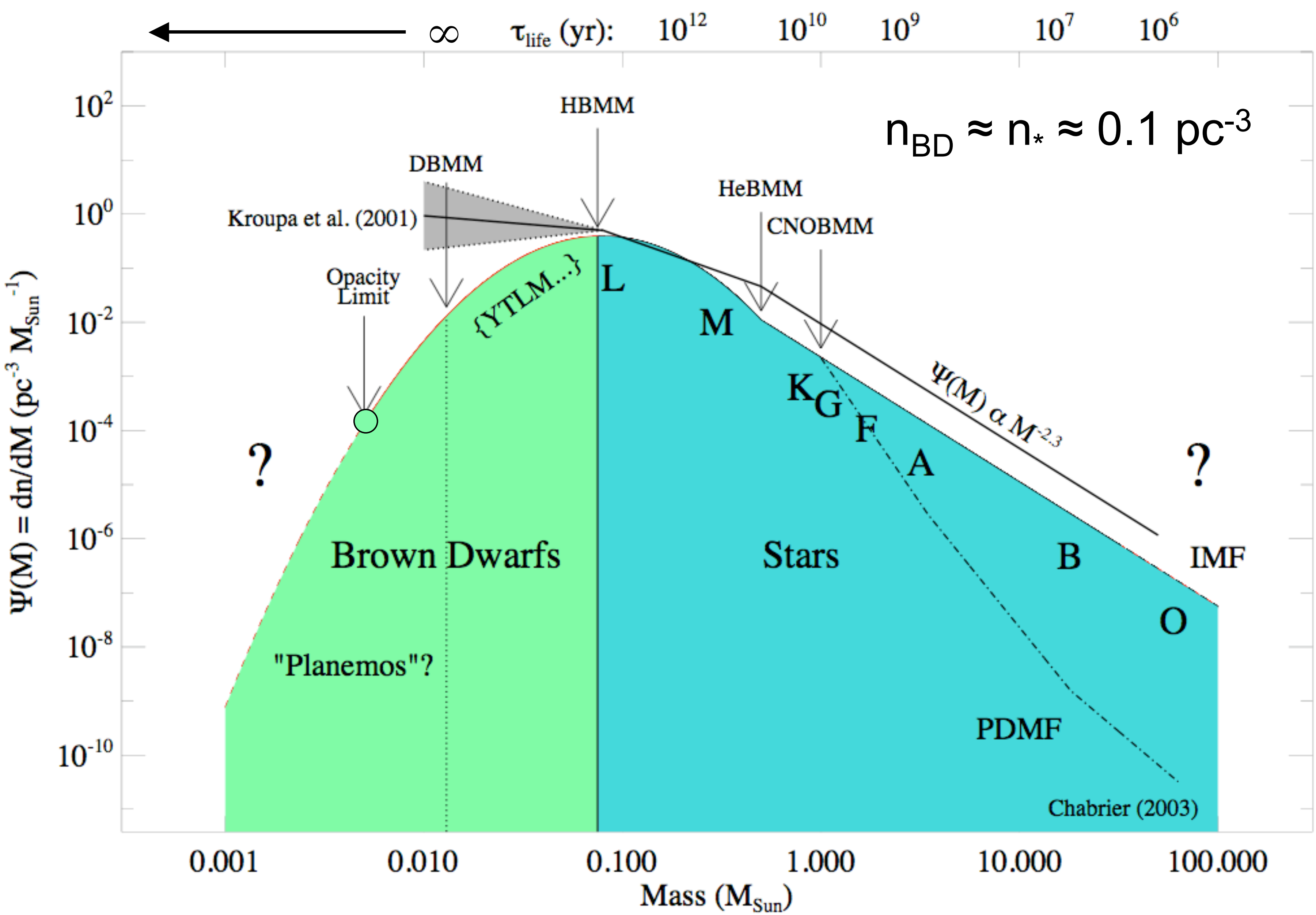
- Isolated field objects
- star forming regions
- binary/triple systems
- Companions
- CVs
- Galactic halo

Identified primarily in wide-field near-infrared surveys

2MASS, SDSS, DENIS → UKIDSS, CFHTLS

Extrema

- $T_{eff} \approx 650$ K
- $L \approx 10^{-6}$ L_o
- $M \approx 3$-8 $M_{Jupiter}$
- ages <1 Myr to > 10 Gyr

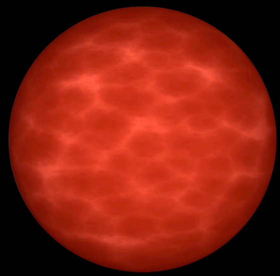


∞
τlife (yr): 10^12 10^10 10^9 10^7 10^6
nBD ≈ n* ≈ 0.1 pc-3
HBMM
DBMM
Kroupa et al. (2001)
HeBMM
CNOBMM
Opacity Limit
{YTLM...}
L
M
K
G
F
A
B
O
Ψ(M) α M-2.3
?
?
Brown Dwarfs
Stars
IMF
"Planemos"?
PDMF
Chabrier (2003)
Ψ(M) = dn/dM (pc-3 MSun-1)
Mass (MSun)
0.001
0.010
0.100
1.000
10.000
100.000

Spectral types

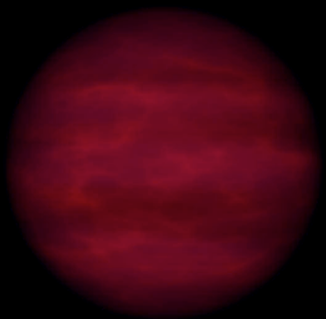
M dwarfs (3500-2100 K)

magnetically active, only the youngest brown dwarfs are classified M-type



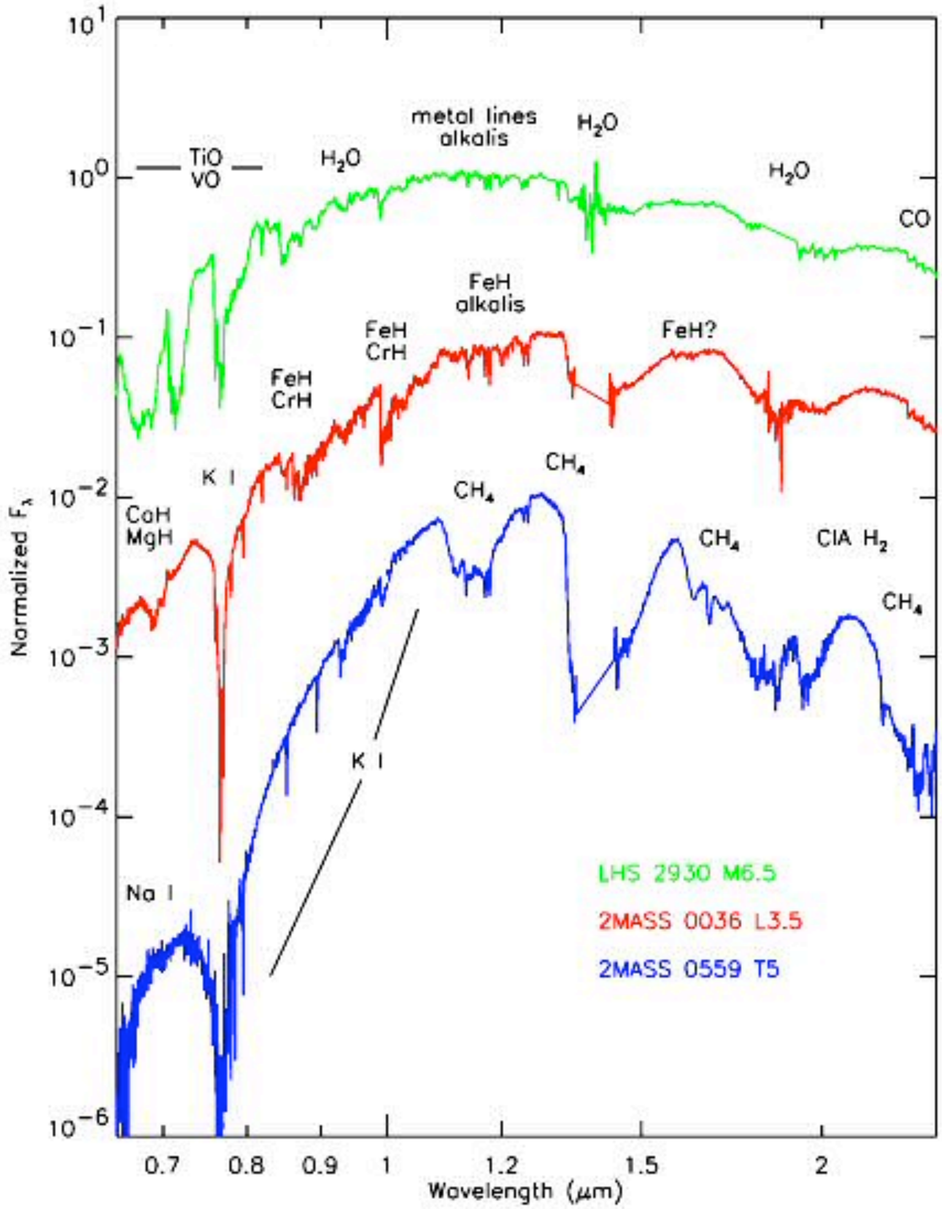
L dwarfs (2100-1300 K)

molecule-rich atmospheres contain clouds of “hot dirt” and other condensates



T dwarfs (1300-600? K)

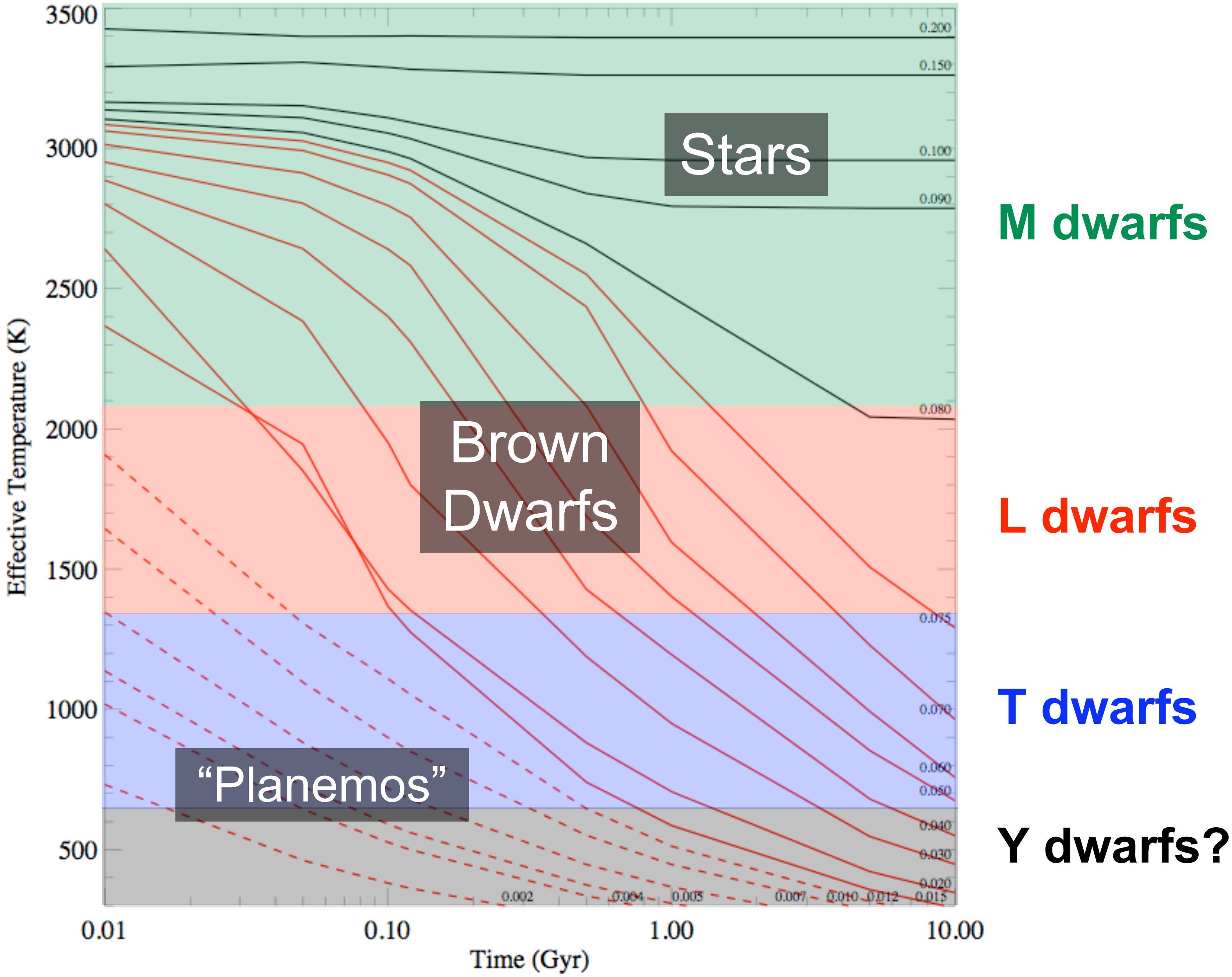
coldest known brown dwarfs, atmospheres contain CH_4 and NH_3 gases



M dwarfs are dominated by TiO, VO, H_2O, CO absorption plus metal/alkali lines.

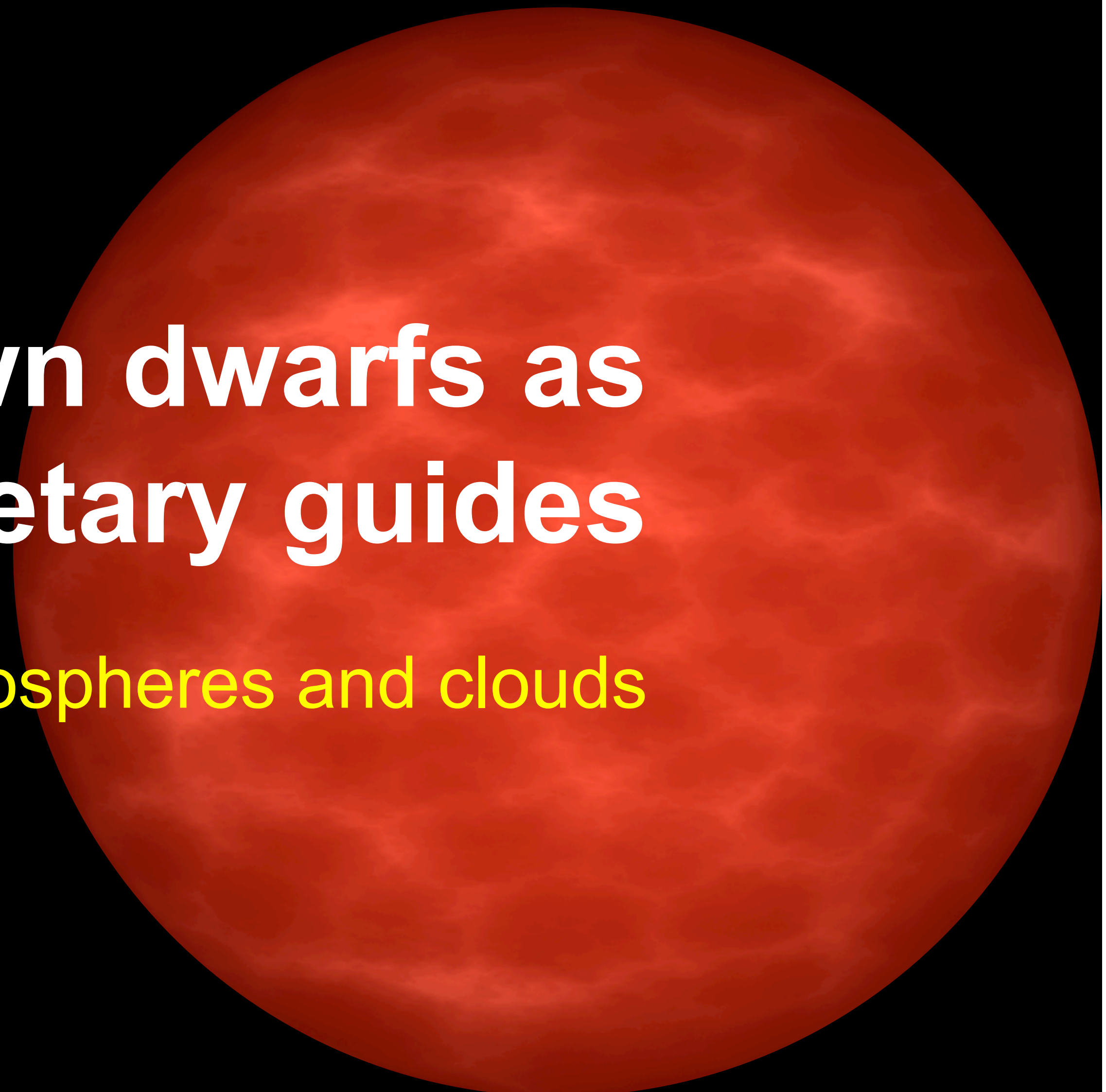
L dwarfs replace oxides with hydrides (FeH, CrH, MgH, CaH), alkalis are prominent, condensate clouds.

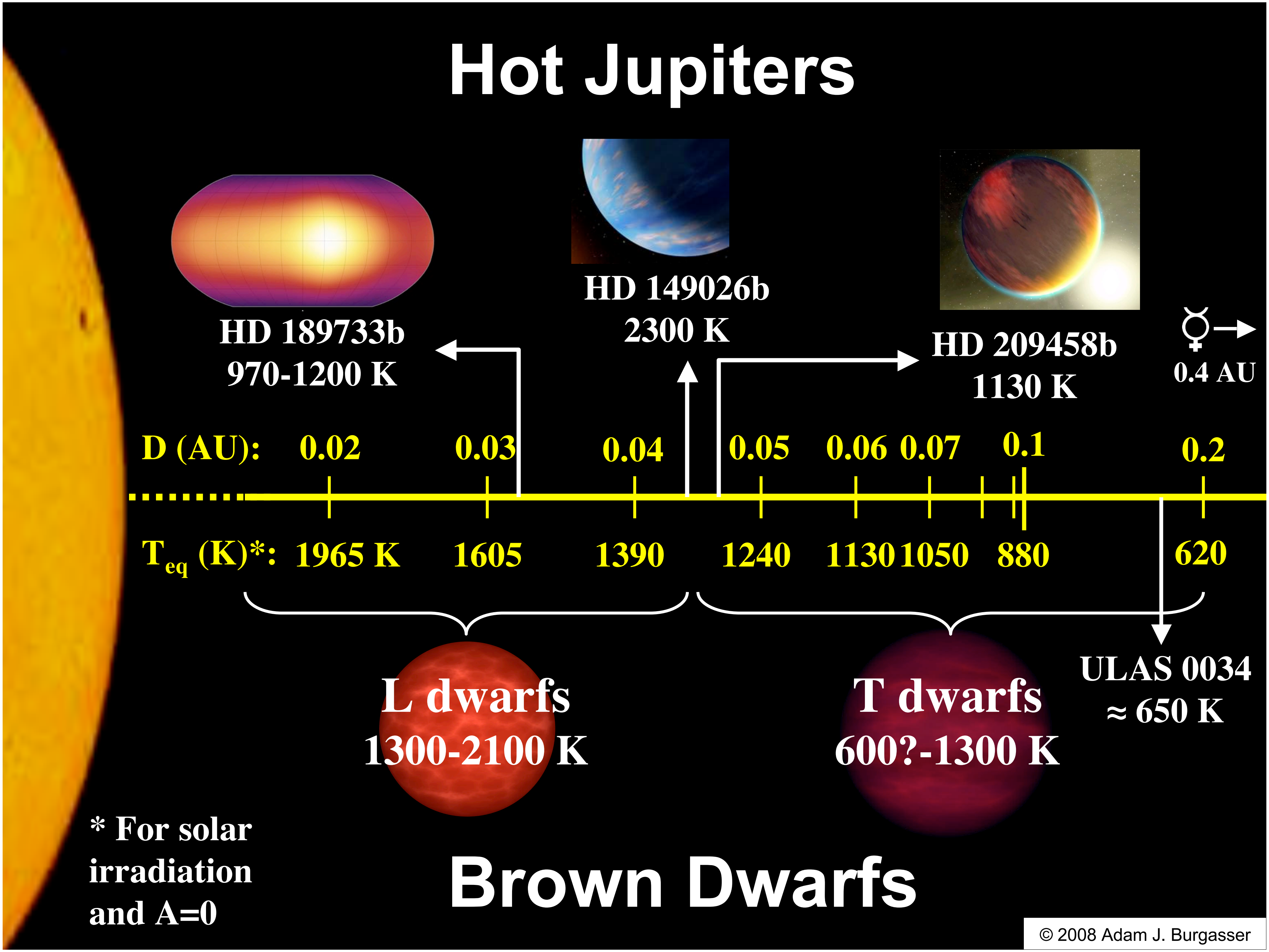
T dwarfs exhibit strong CH_4 and H_2O and extremely broadened Na I and K I.


Stars
Brown Dwarfs
“Planemos”
M dwarfs
L dwarfs
T dwarfs
Y dwarfs?
Effective Temperature (K)
Time (Gyr)
3500
3000
2500
2000
1500
1000
500
0.01
0.10
1.00
10.00
0.200
0.150
0.100
0.090
0.080
0.075
0.070
0.060
0.050
0.040
0.030
0.020
0.015
0.012
0.010
0.007
0.005
0.004
0.002

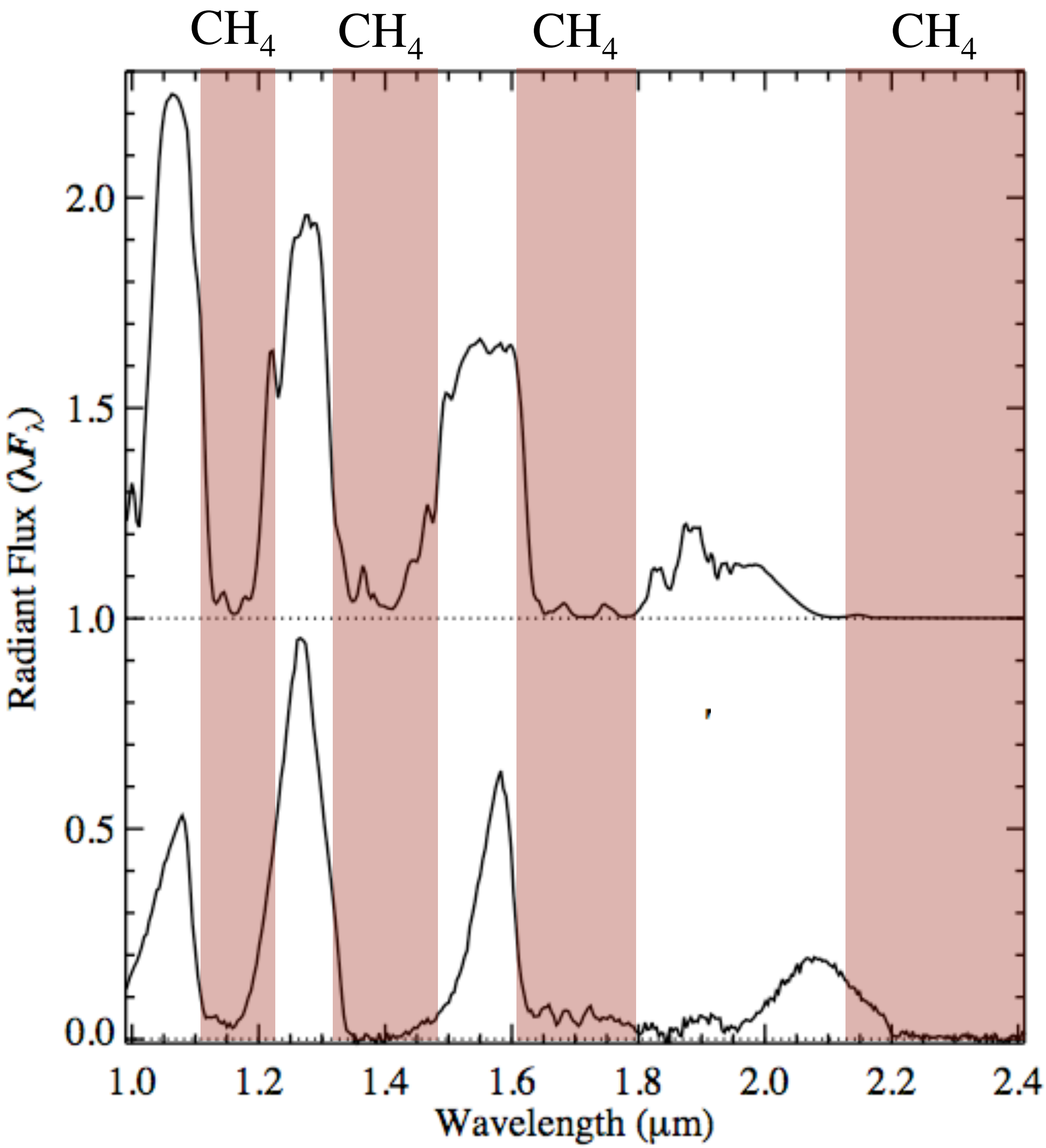
Brown dwarfs as planetary guides

Cool atmospheres and clouds

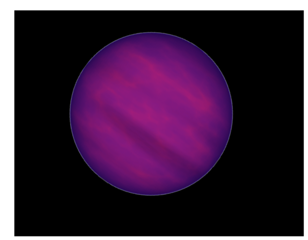




Hot Jupiters
HD 189733b
970-1200 K
HD 149026b
2300 K
HD 209458b
1130 K
☿→
0.4 AU
D (AU): 0.02 0.03 0.04 0.05 0.06 0.07 0.1 0.2
T$_{eq}$ (K)*: 1965 K 1605 1390 1240 1130 1050 880 620
L dwarfs
1300-2100 K
T dwarfs
600?-1300 K
ULAS 0034
≈ 650 K
* For solar irradiation and A=0
Brown Dwarfs
© 2008 Adam J. Burgasser



Saturn
90 K



T8 dwarf
700 K

Clouds

Jupiter

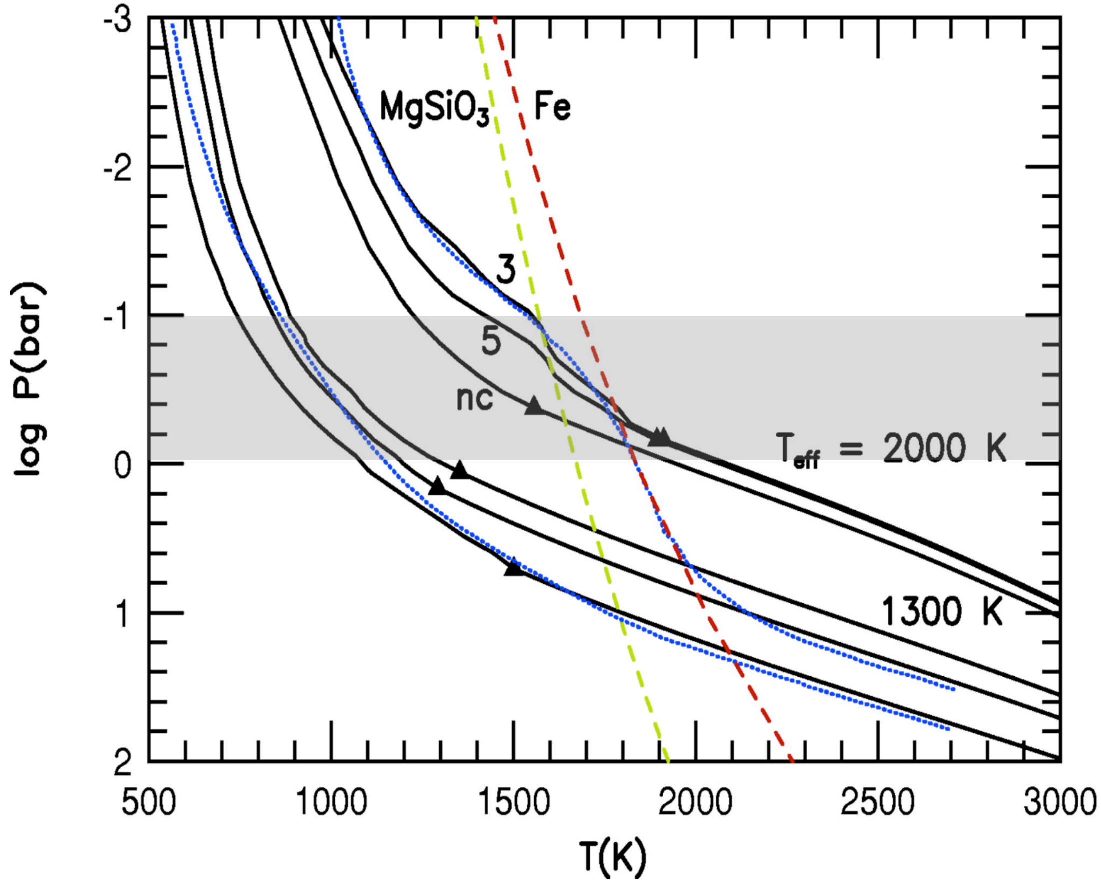
Condensate clouds direct consequence of low temperatures and chemistry - **present in planetary and brown dwarf atmospheres.**

For **Hot Jupiters**, clouds are critical for determining thermal balance (albedo) and energy transport (winds)

Earth

Titan

Condensation in BD Atmospheres

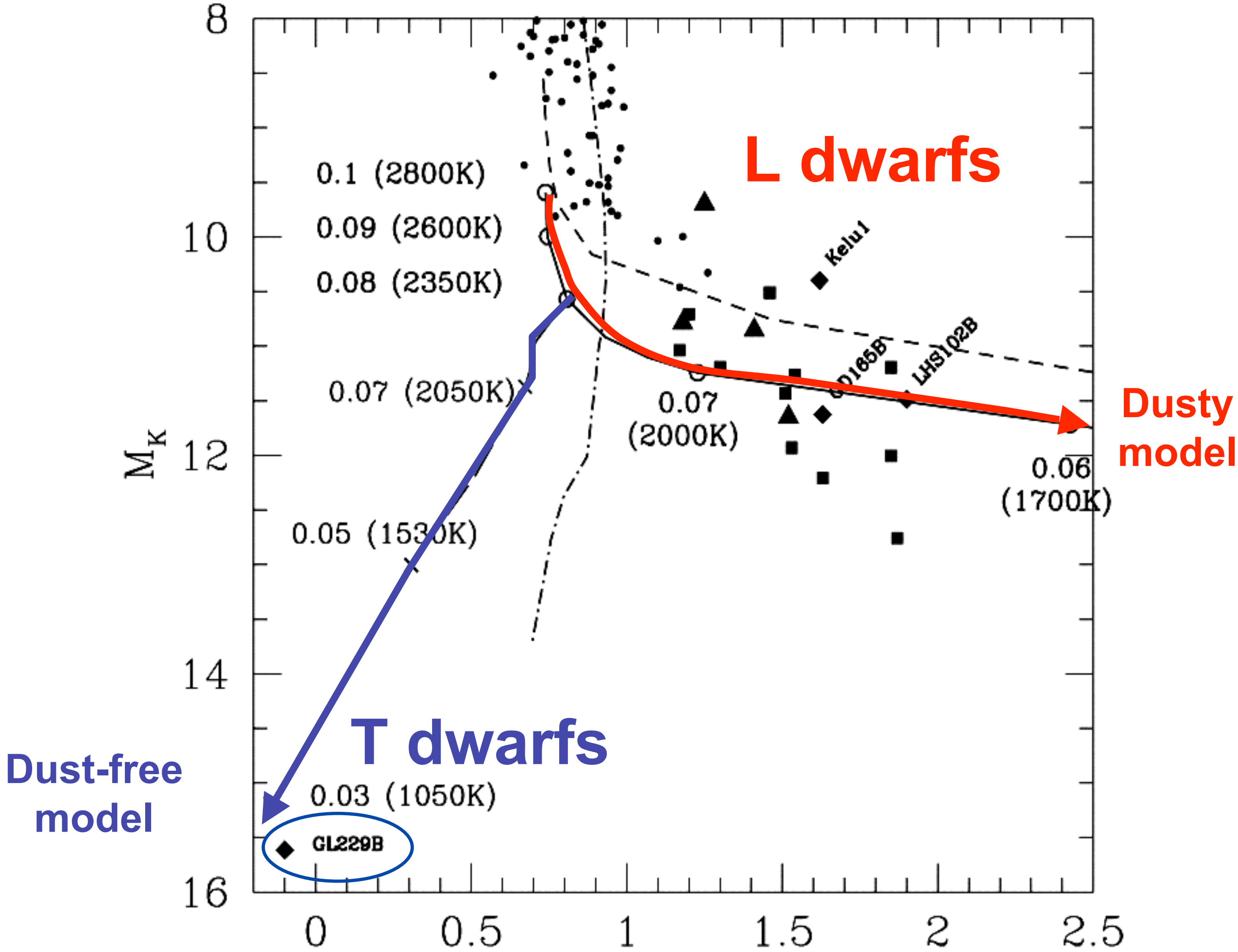


Marley et al. (2002)

At the atmospheric temperatures and pressures of late-M and L dwarfs, several gaseous species form condensates.

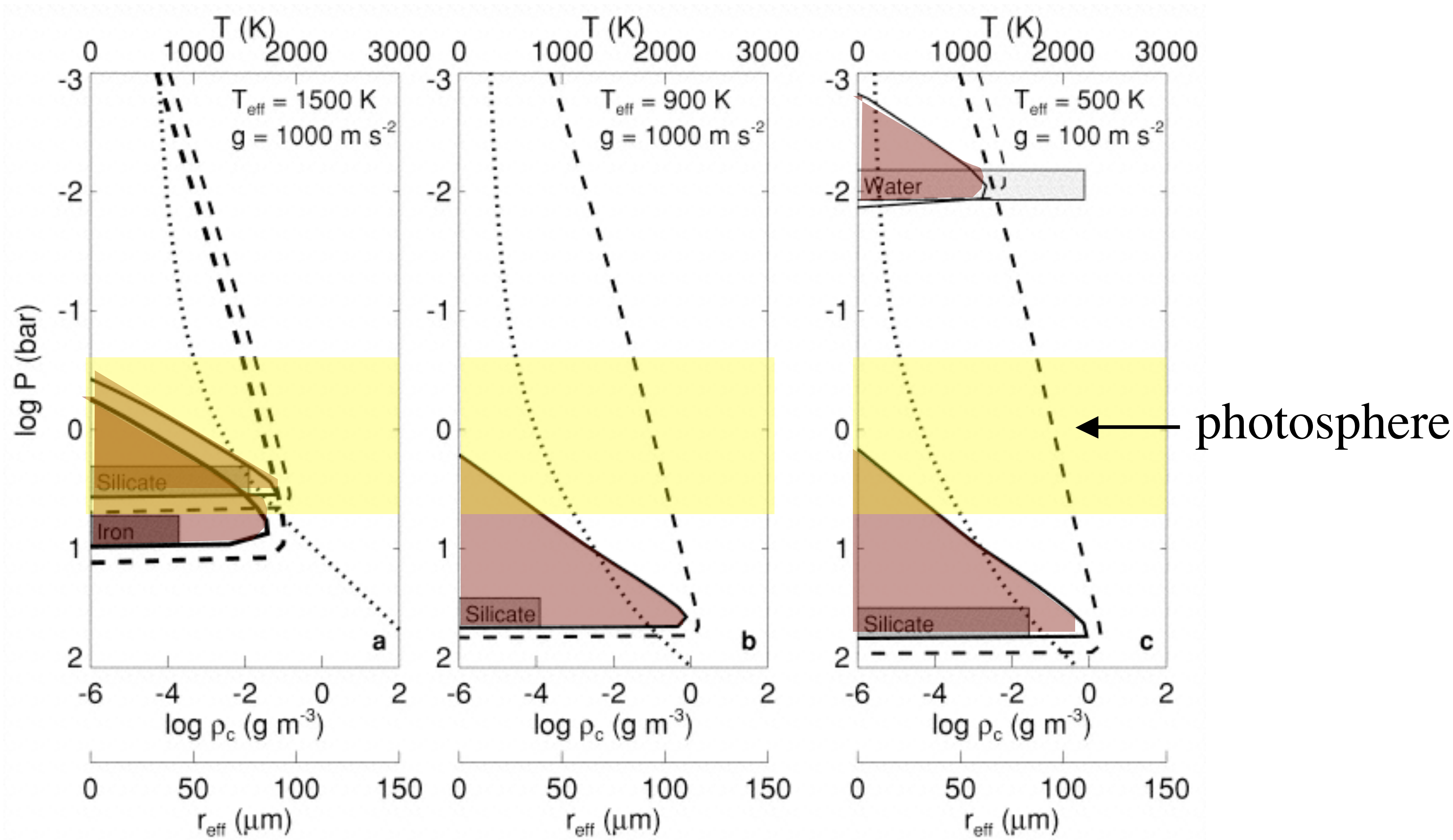
e.g.:

- TiO → TiO_2(s), $CaTiO_3$(s)
- VO → VO(s)
- Fe → Fe(l)
- SiO → SiO_2(s), $MgSiO_3$(s)

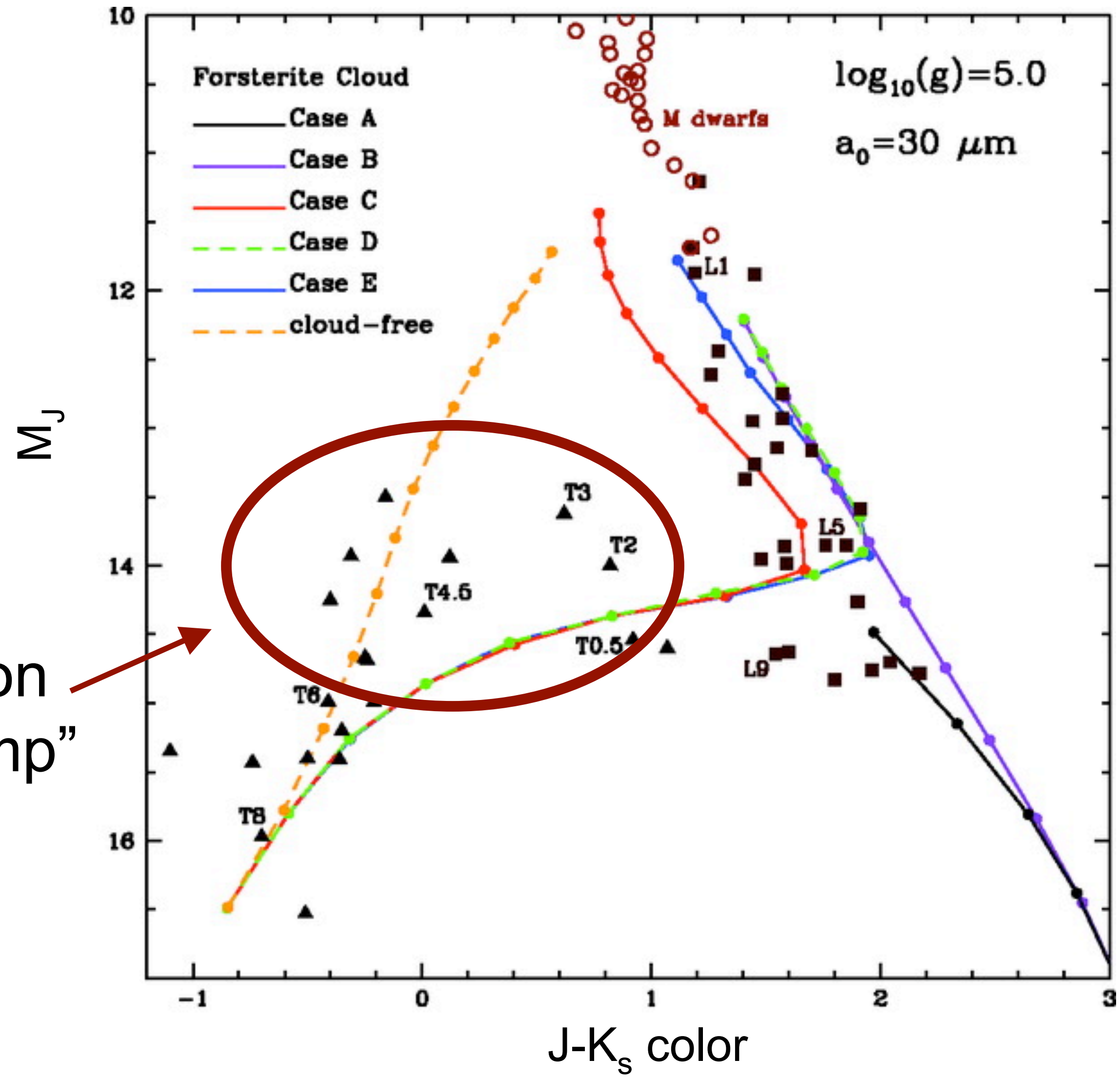


Chabrier et al. (2000)

Brown dwarf clouds



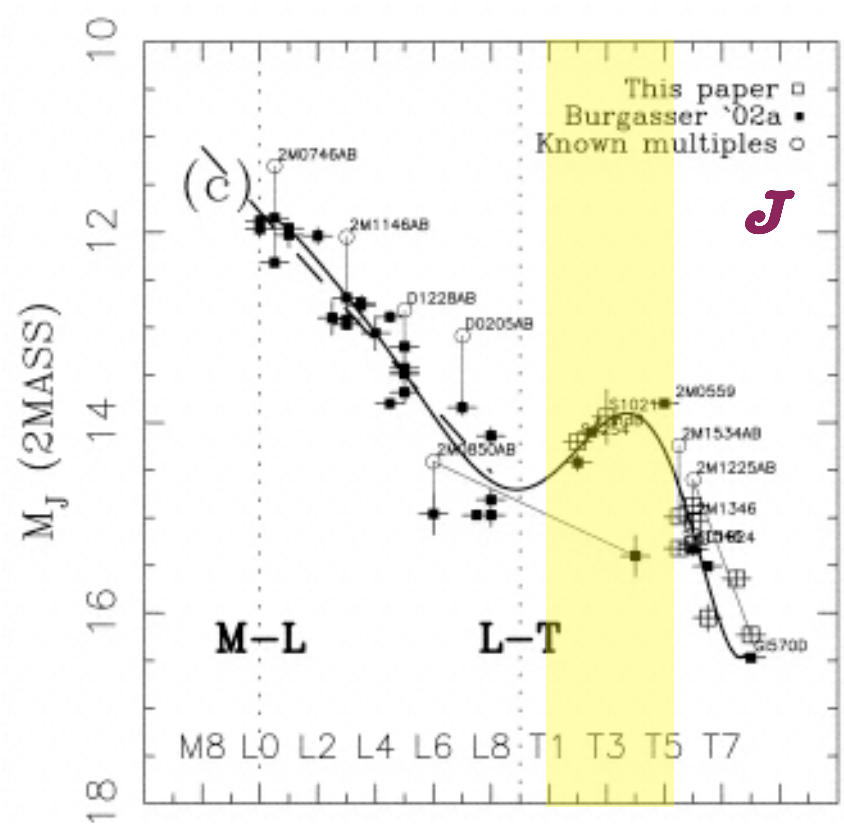
Ackerman & Marley (2001)

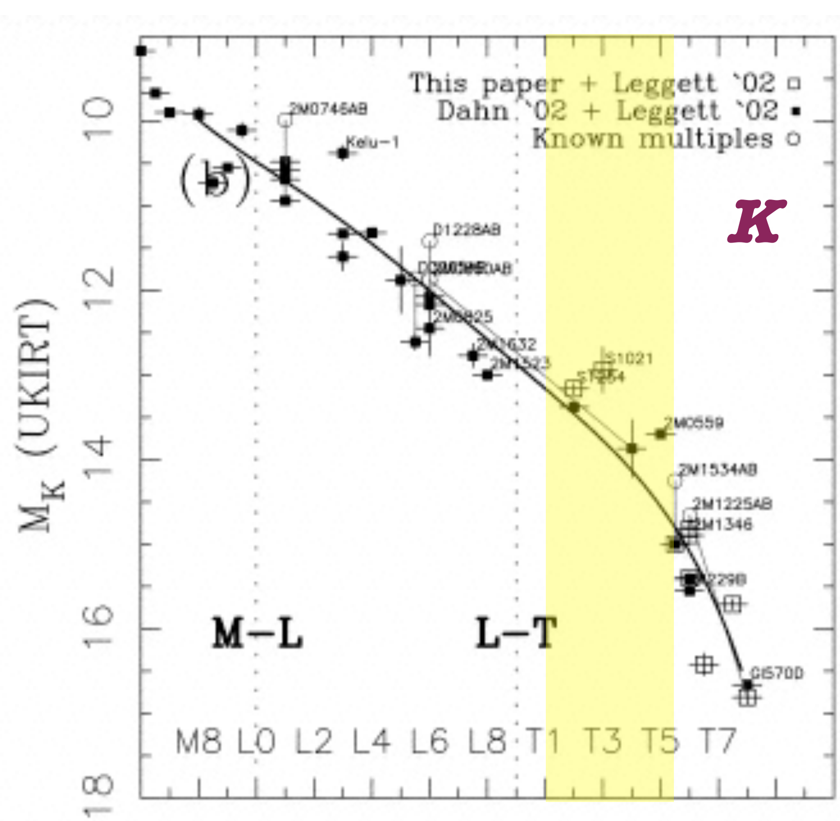


L/T transtion
"J-band bump"

Burrows et al. (2006)

The “J-band Bump”

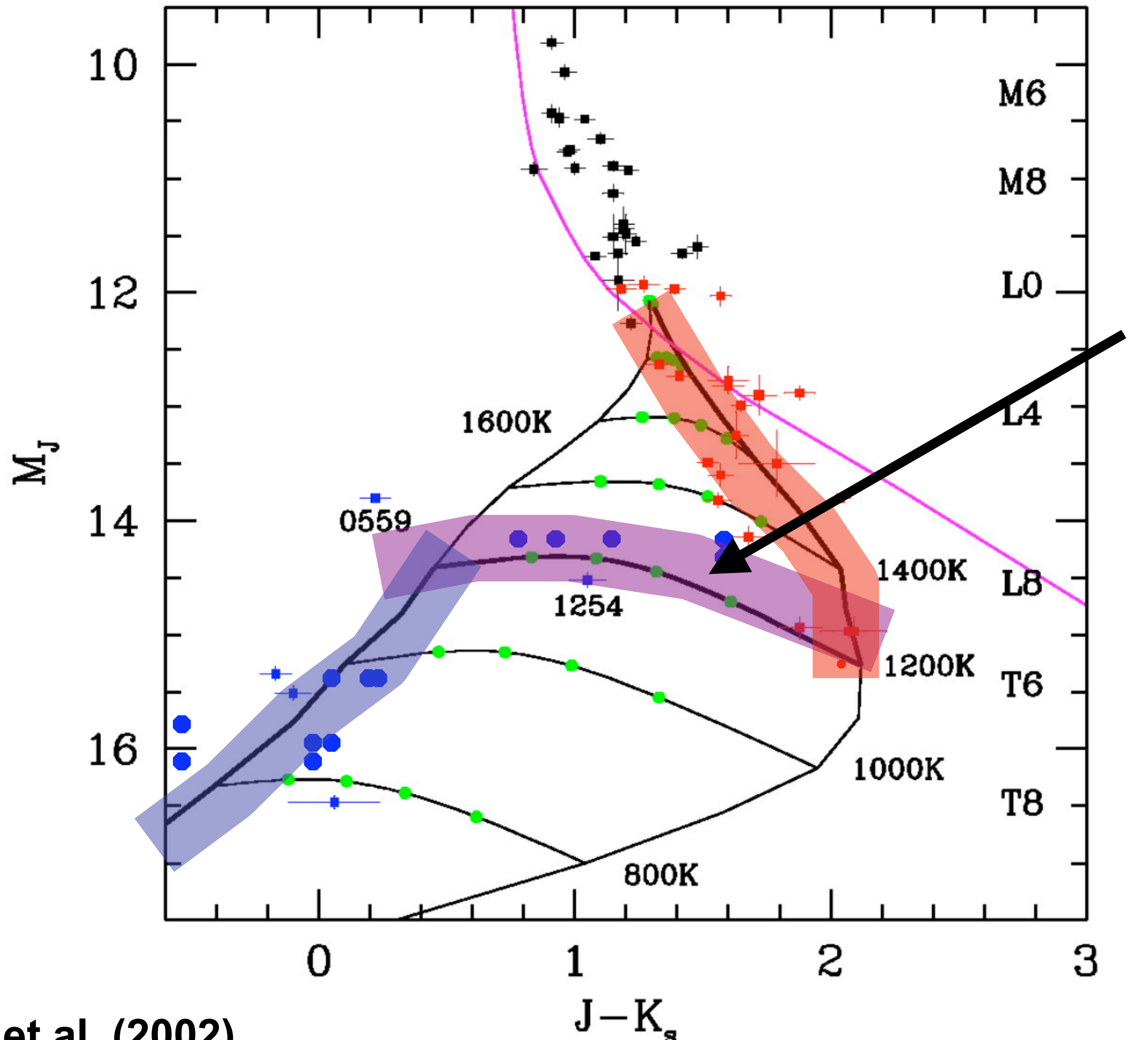


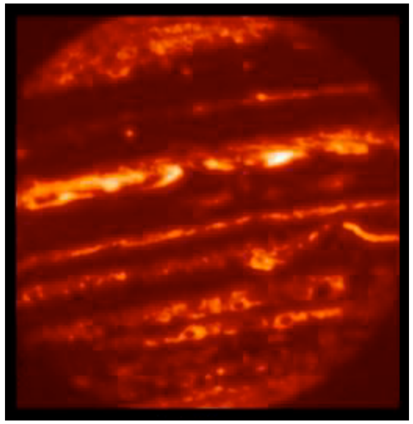


Tinney, Burgasser & Kirkpatrick (2003)

See also Dahn et al. (2002), Vrba et al. (2004)

Stormy Weather?

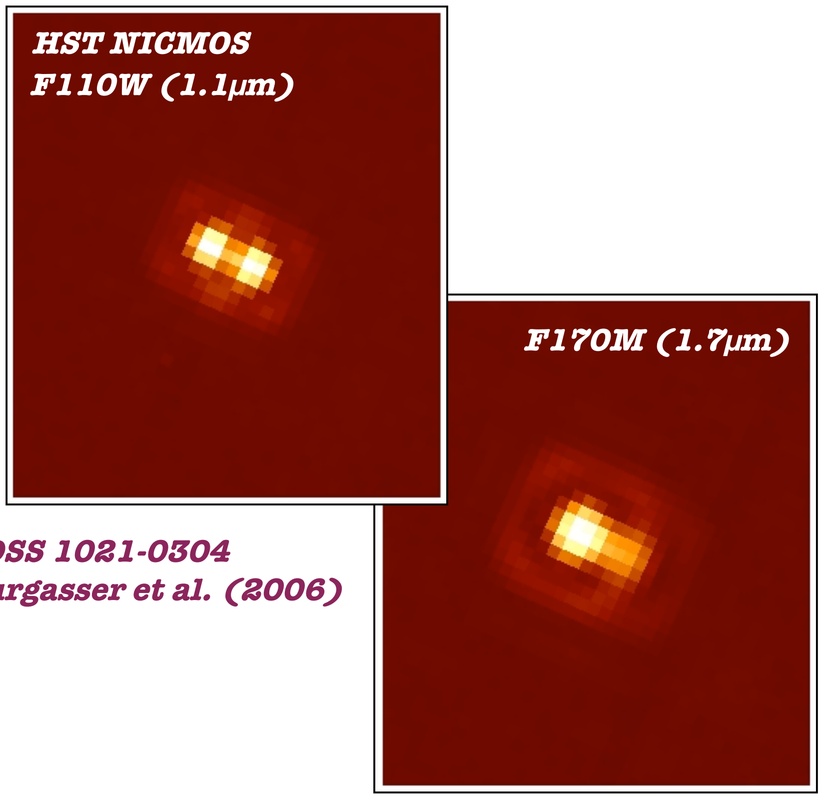




Jupiter at 5 μm "cloud holes"

Burgasser et al. (2002)
See also Knapp et al. (2004)

Binaries: Ideal Probes of the L/T Transition



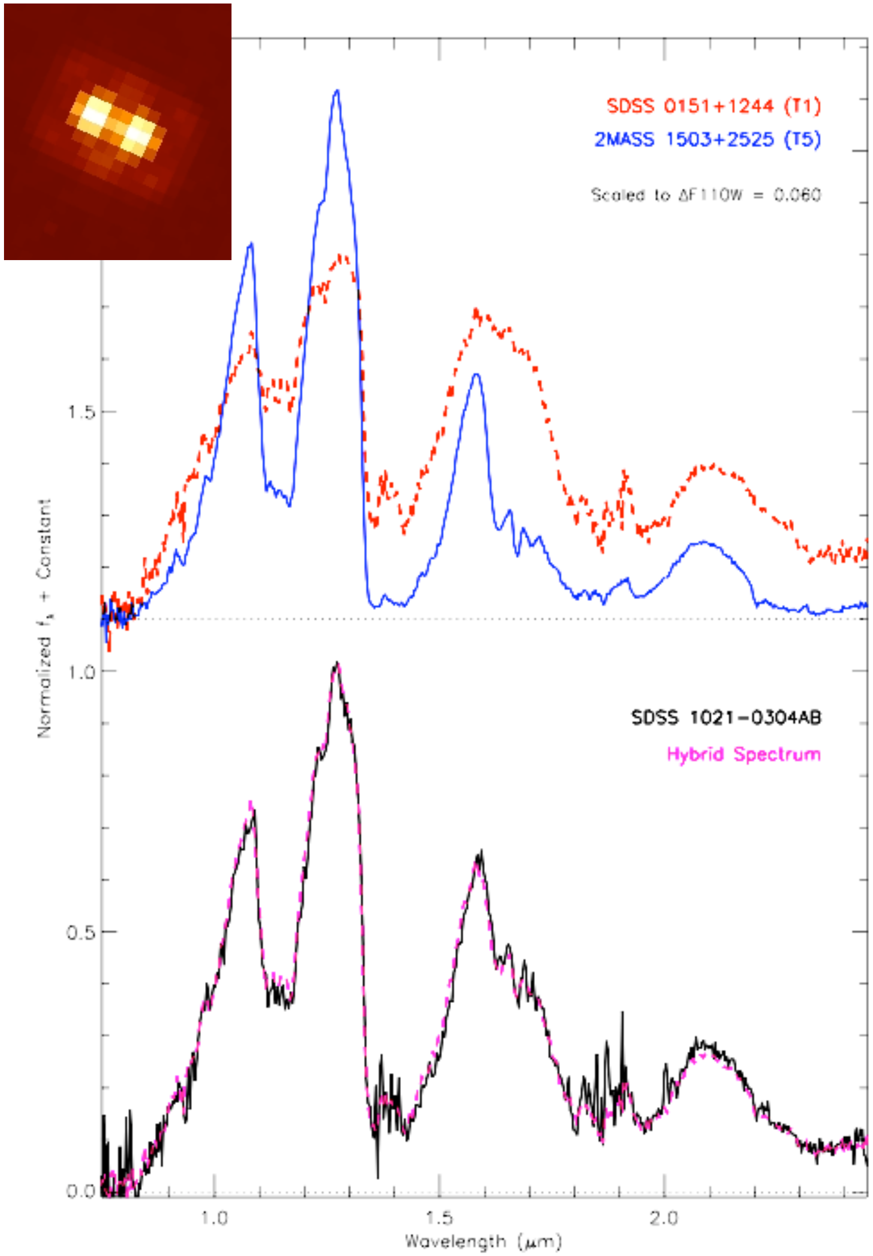
SDSS 1021-0304
Burgasser et al. (2006)

Cospatial: **Both components at same distances allows for accurate determination of relative fluxes**

Coeval: **Common age & composition ⇒ eliminate biases in heterogenous field samples**

Cooperative: **Close binaries are amenable to dynamical mass measurement**

(Lane et al. 2001; Bouy et al. 2004; Brandner et al. 2004; Zapatero Osorio 2004)



Burgasser et al. (2006)

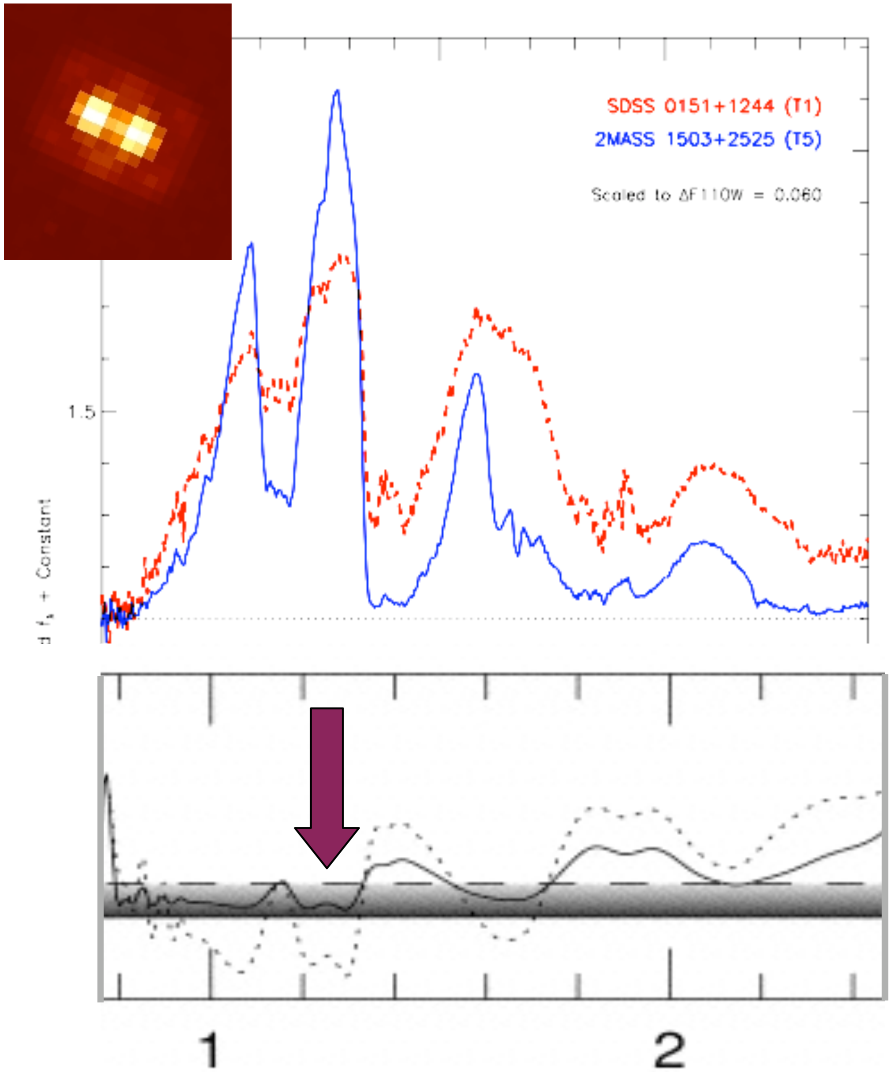
SDSS 1021-0304

Spectral synthesis: best match to composite spectrum based on scaling templates to relative photometry

Best match: T1+T5

Secondary is brighter at 1.05 and 1.25 µm, but less luminous overall ⇒ in same region where cloud opacity is important

SDSS 1021-0304



Ackerman & Marley (2001)

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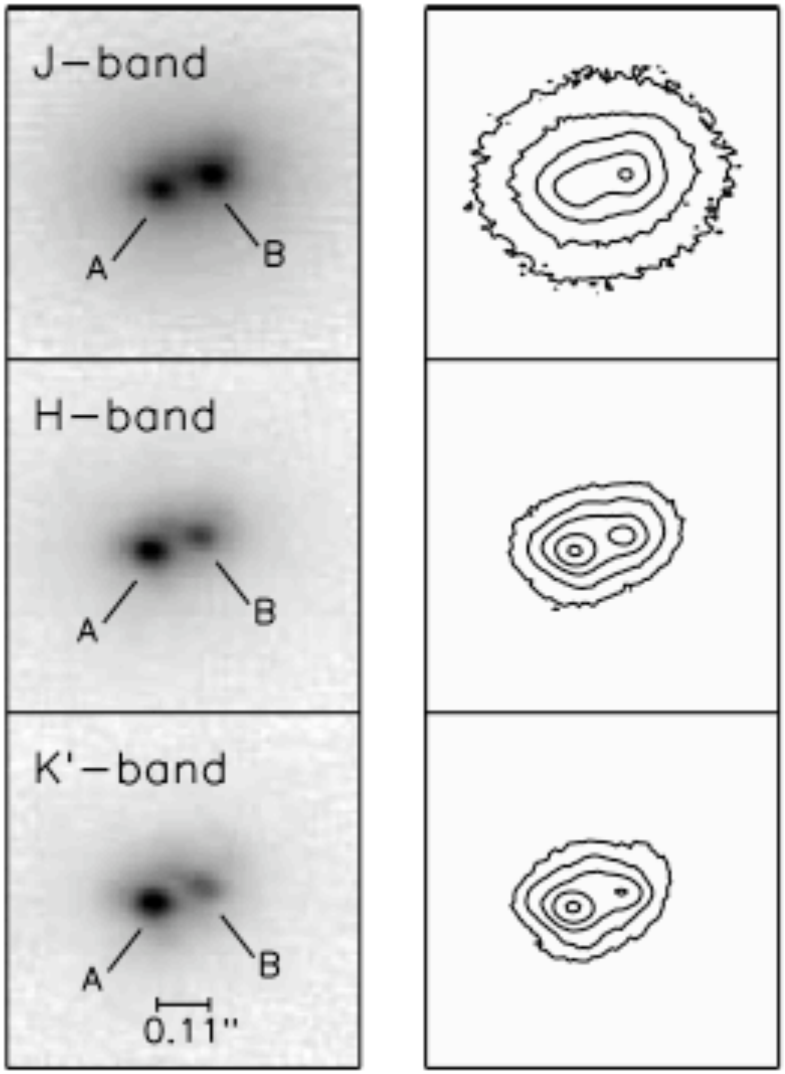


Liu et al. (2006)

SDSS 1534+1615

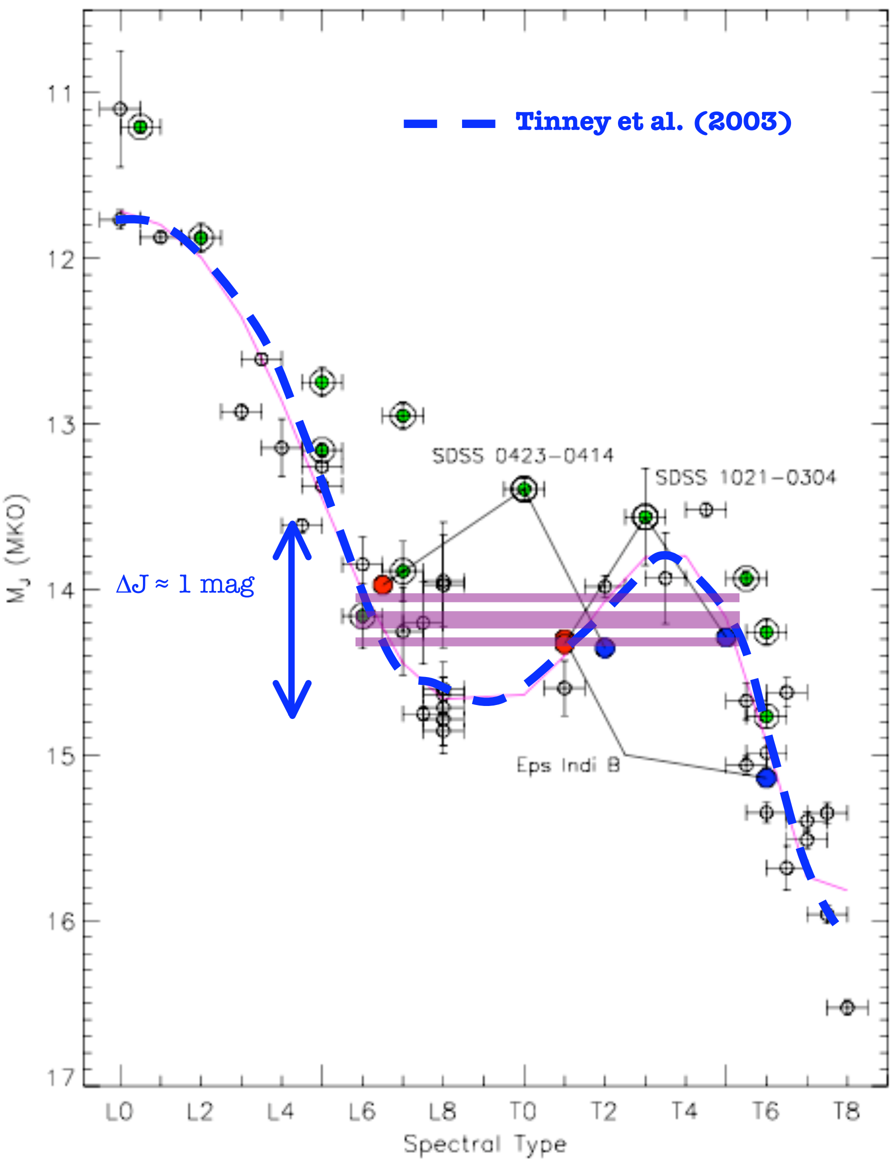
Resolved with Keck LGS AO

Flux reversal - one component brighter at J, the other at H & K

Spectral synthesis indicates T1.5 + T5.5, later-type object brighter at J

Similar behavior in other early-T binaries proves J-band brightening is an intrinsic feature of L/T transition

How Big of a Bump?



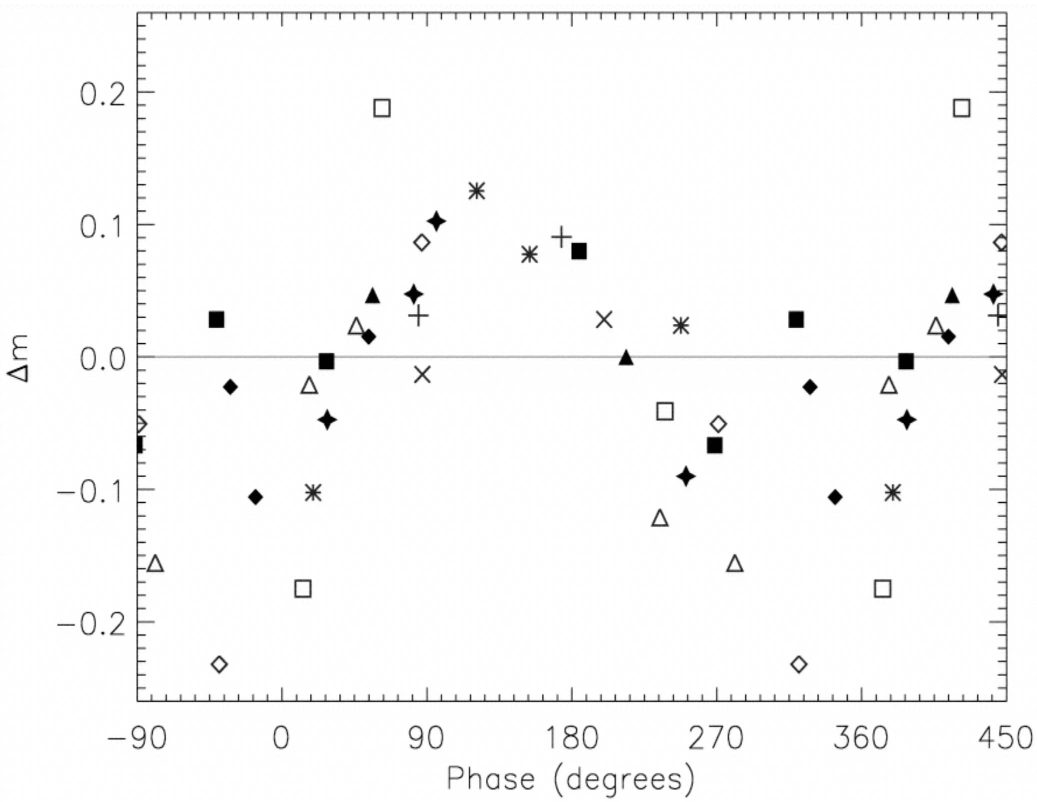
Burgasser et al. (2006)
see also Liu et al. (2006)

Component photometry suggests J-band bump not as extreme as previously surmised
⇒ binary contamination

However, binary fraction would need to be very high: >66% **amongst parallax field sample!**

Why are there so many binaries at the L/T transition?

Evidence for Cloud Disruption - Variability

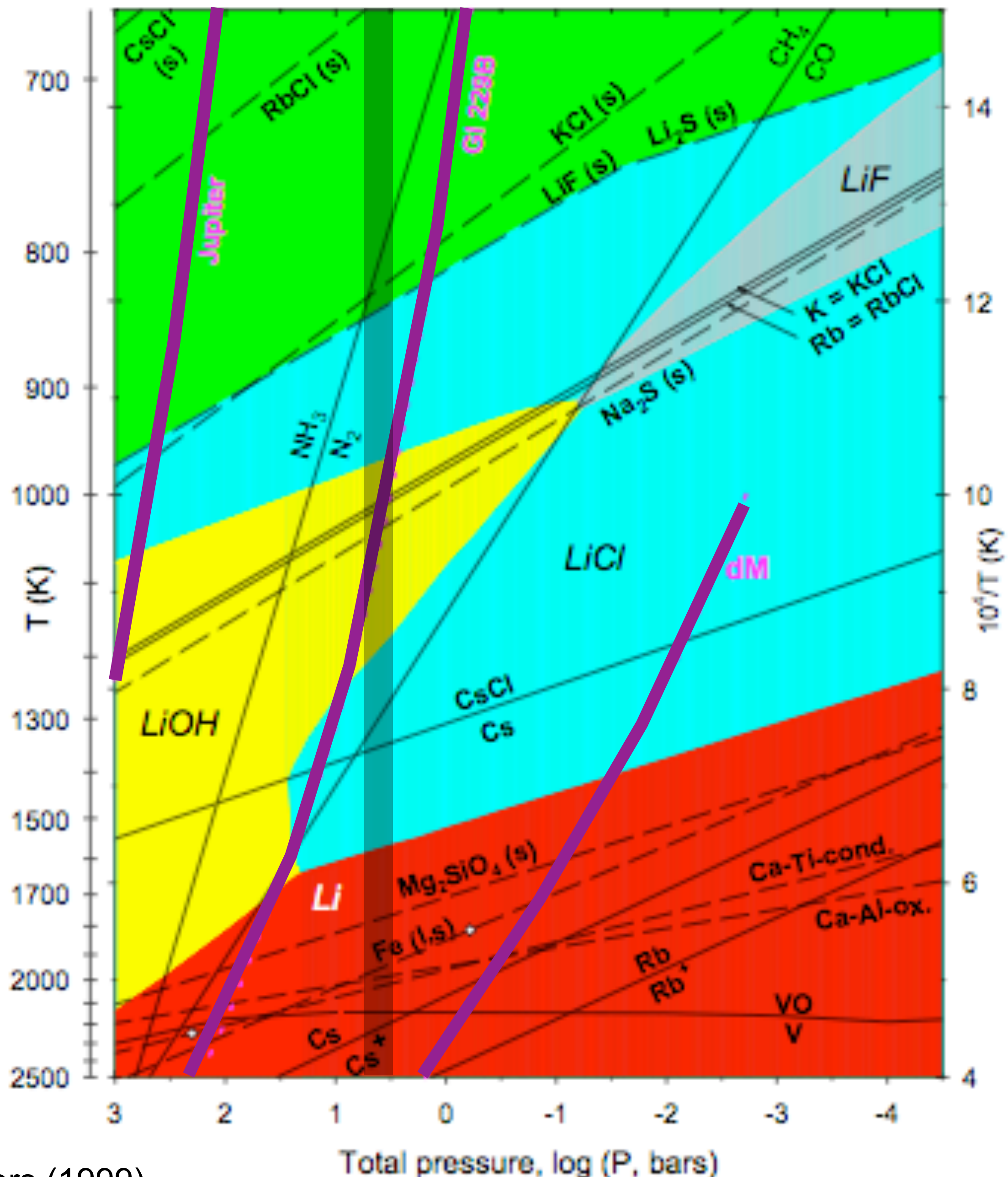


Enoch, Brown, & Burgasser (2003)

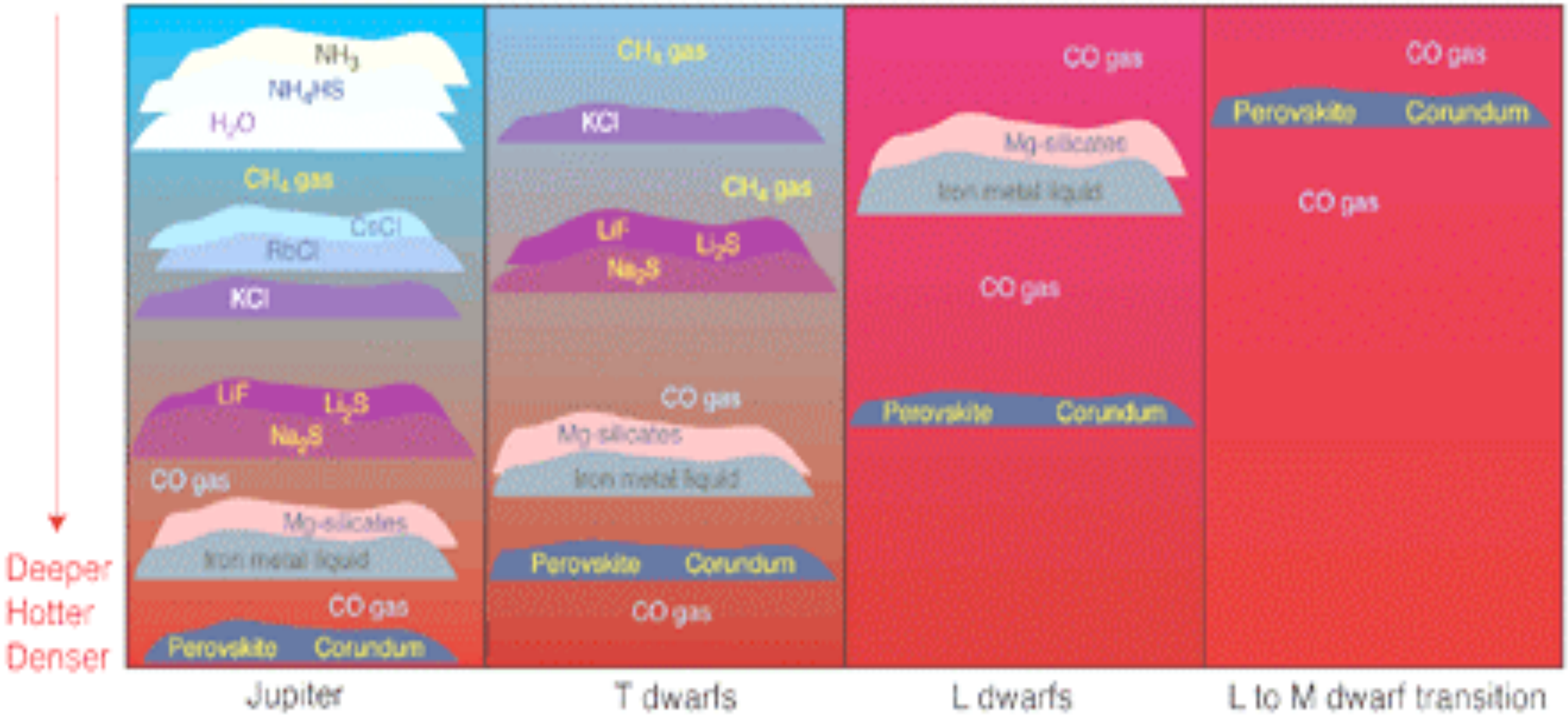
Many late-type L and T dwarfs are variable, **P ~ hours**, similar to dust formation rate.

Atmospheres too cold to maintain magnetic spots ⇒ **clouds likely**.

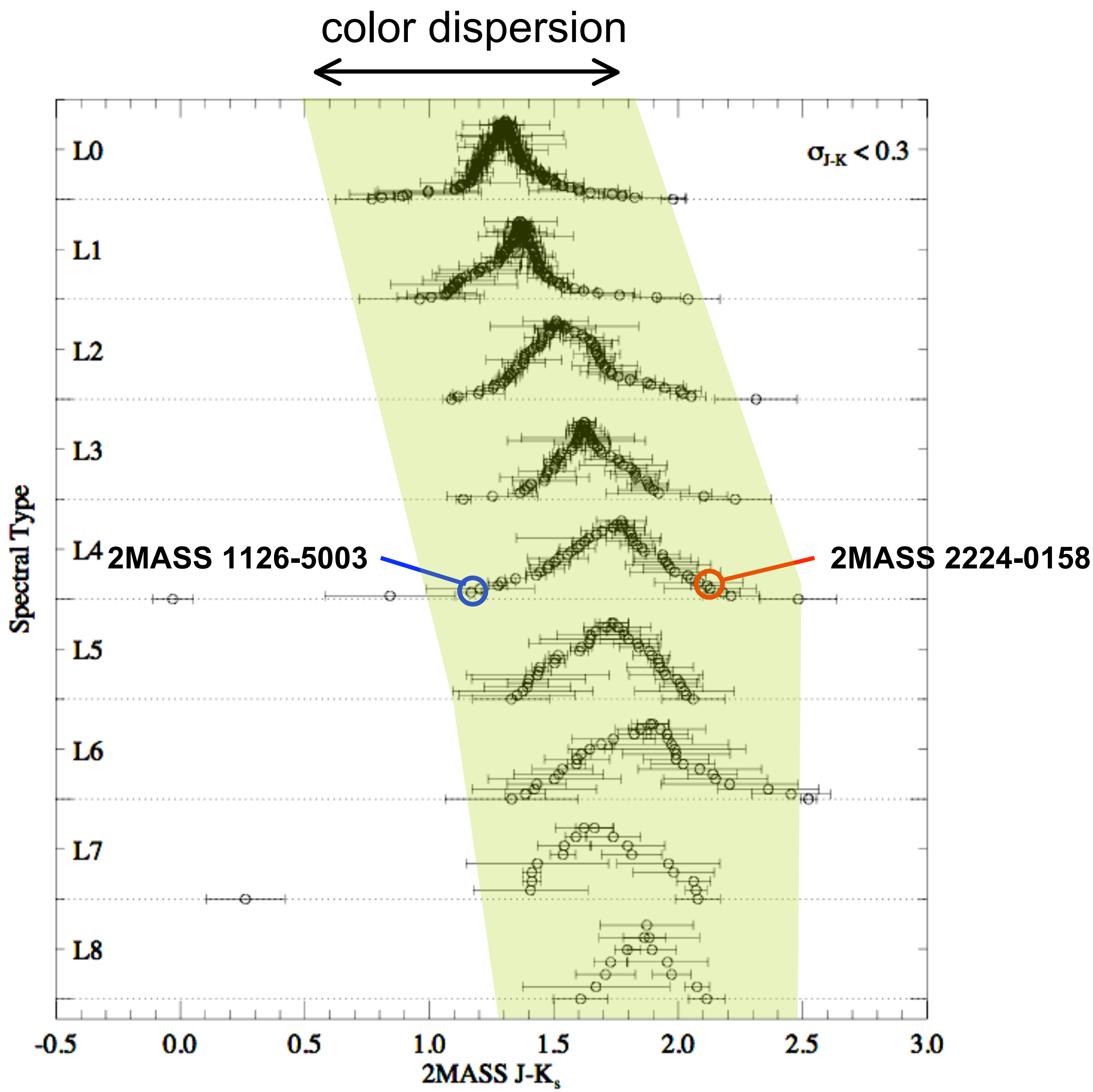
Periods are not generally stable ⇒ **rapid surface evolution**.

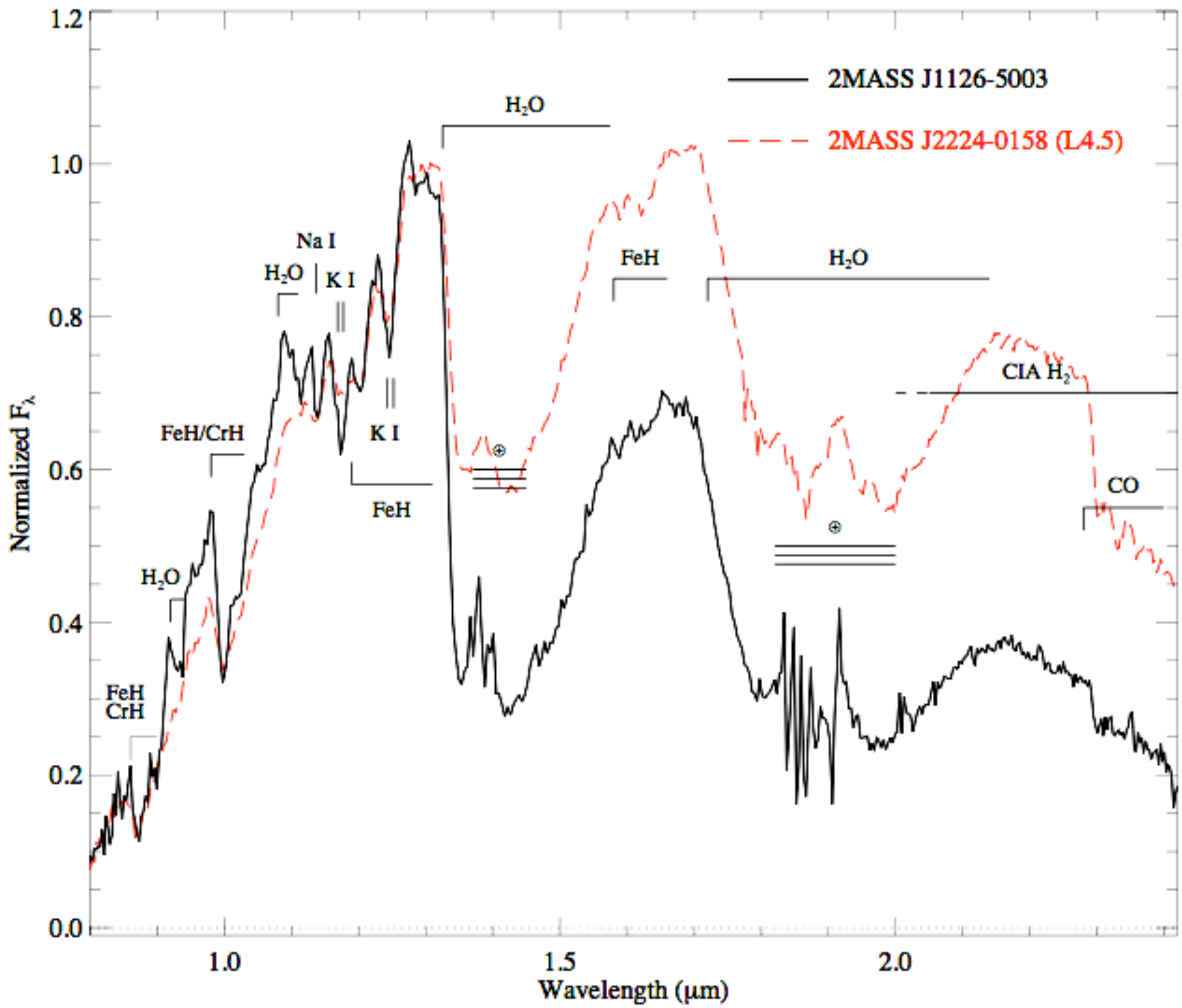


Lodders (1999)



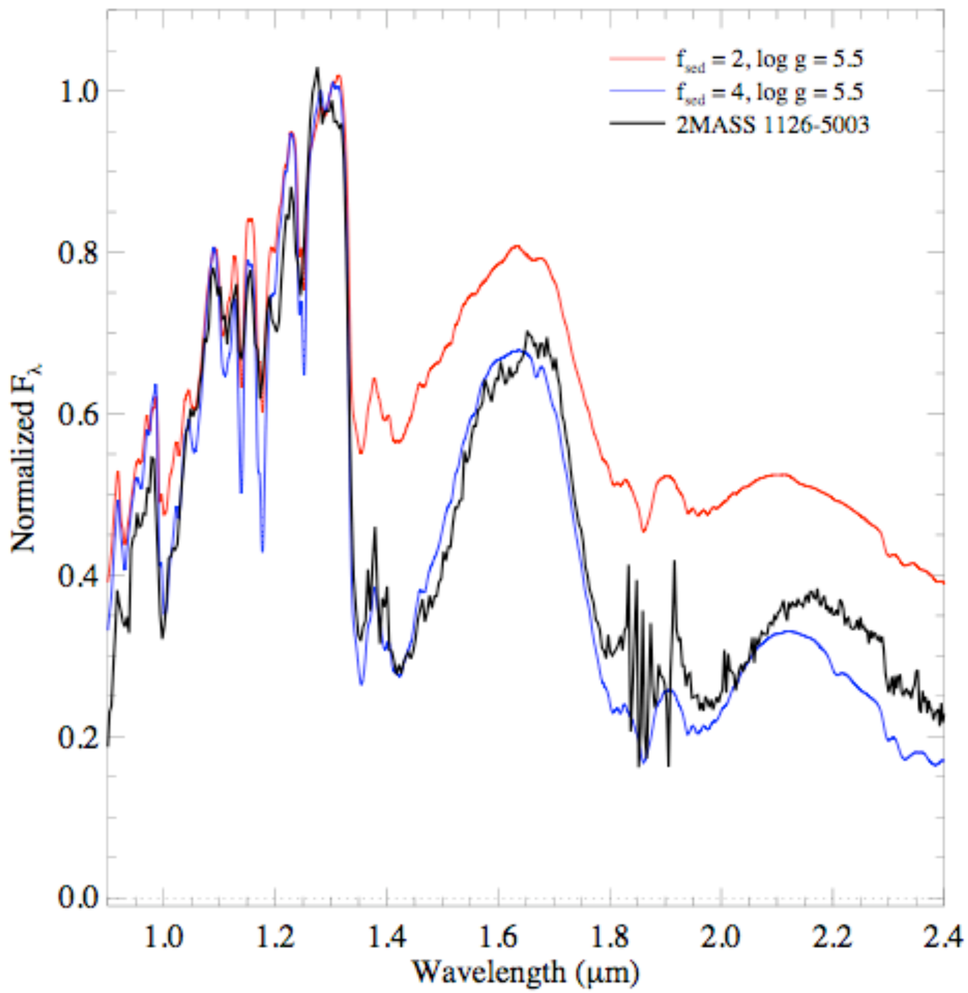
Lodders & Fegley (2006)


color dispersion
σJ-K < 0.3
L0
L1
L2
L3
L4
L5
L6
L7
L8
Spectral Type
2MASS 1126-5003
2MASS 2224-0158
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2MASS J-Ks



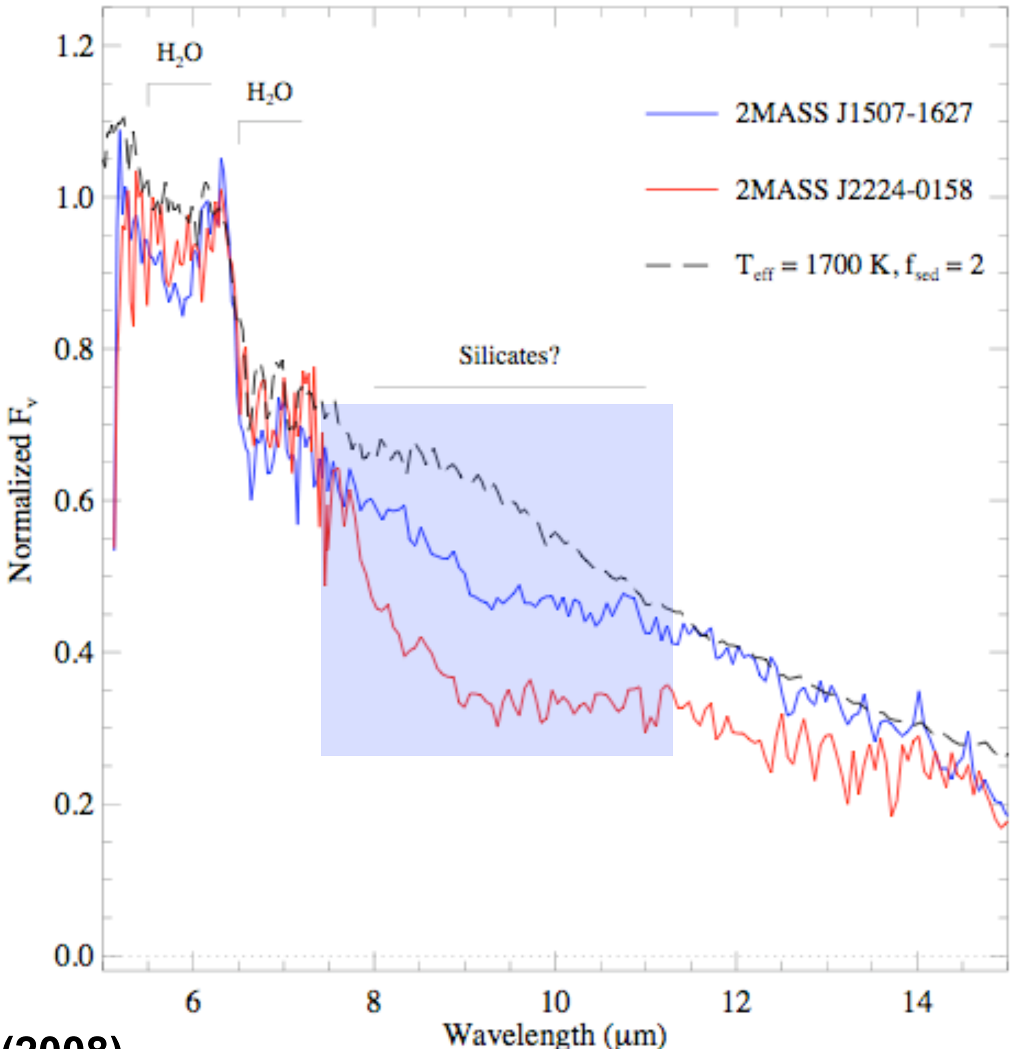
Burgasser et al. (2008)

blue dwarfs have thin clouds



Burgasser et al. (2008)
see also Knapp et al. (2004); Cruz et al. (2007); Cushing et al. (in prep.)

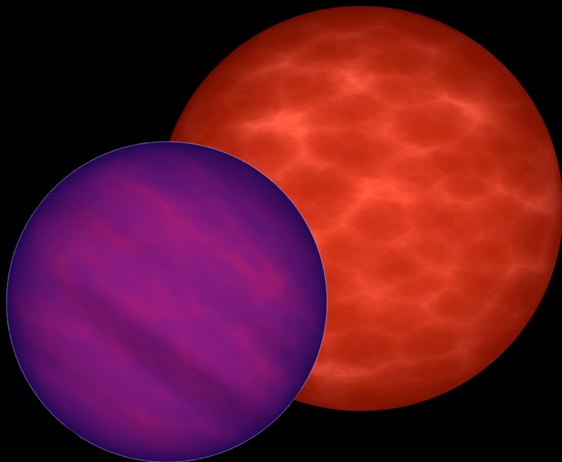
blue dwarfs have thin clouds
red dwarfs have thick clouds



Burgasser et al. (2008)
data from Cushing et al. (2006)

Brown dwarfs as Galactic standard candles

Why brown dwarfs may prove to be ideal probes of Galactic structure and evolution



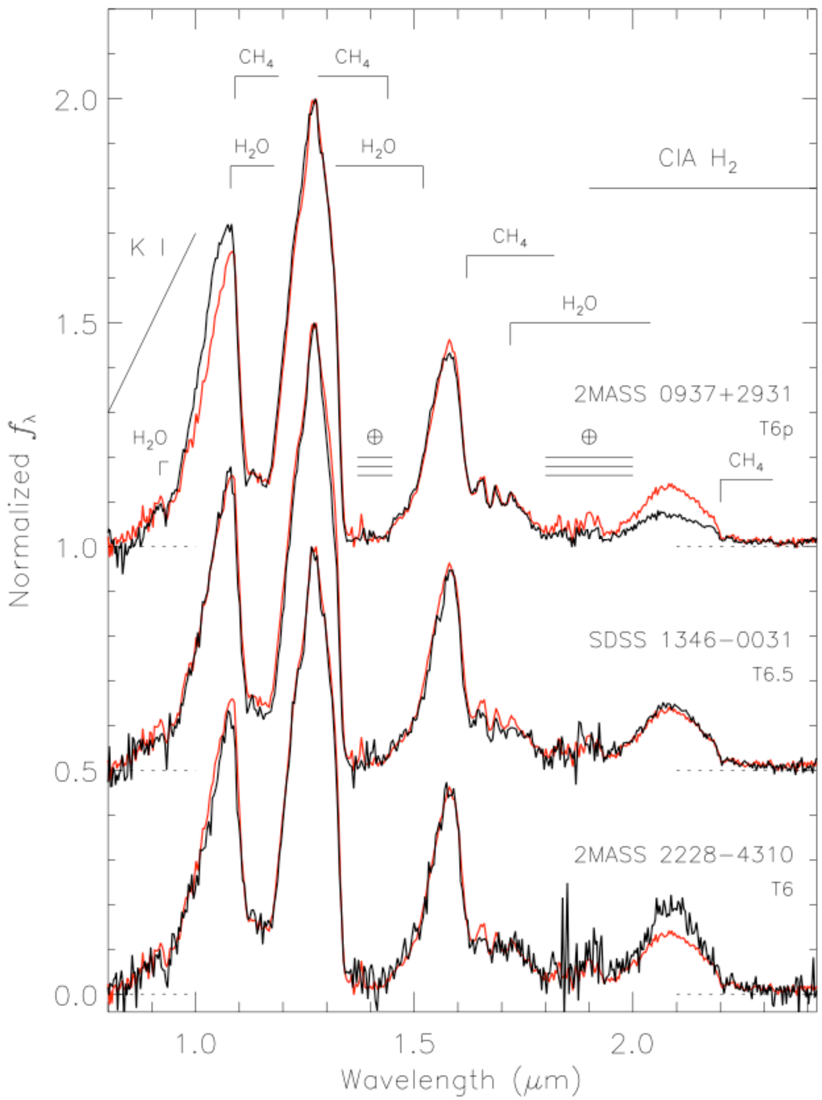
Why standard candles?

Large numbers and ubiquitous throughout Galaxy

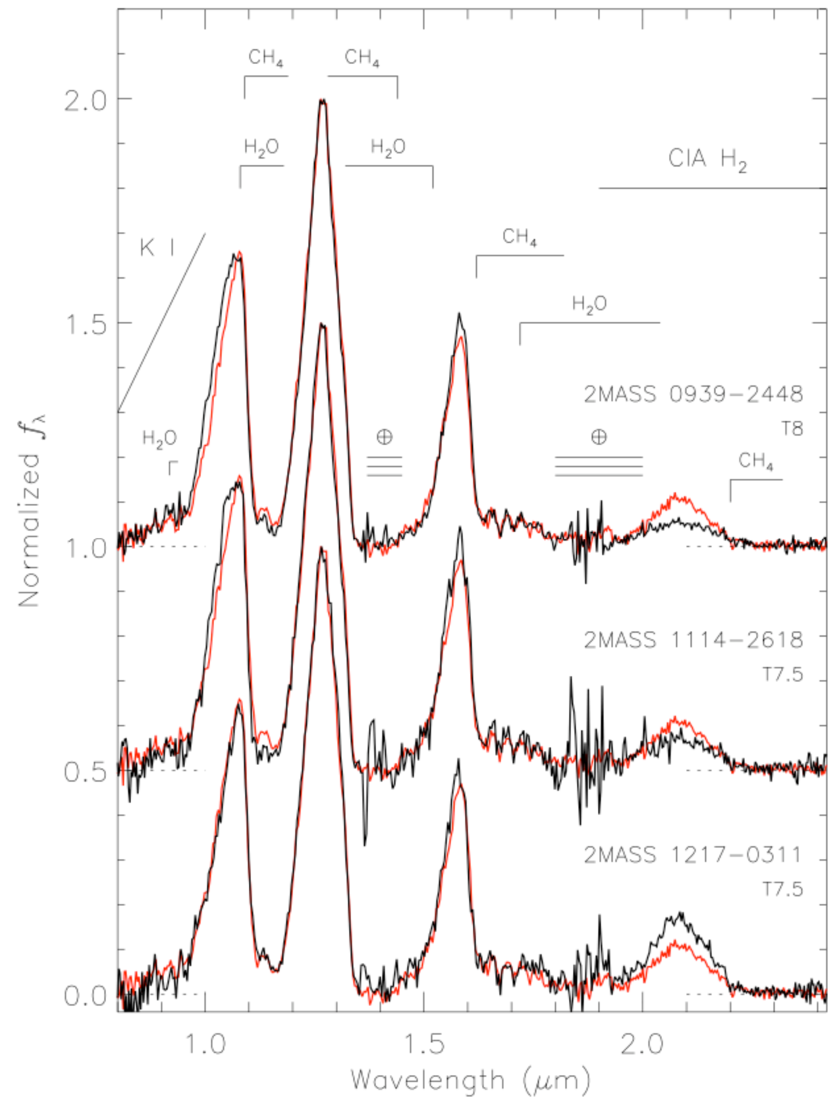
Spectral types are easily discerned and properties increasingly well-characterized

Evolutionary properties - “standard clocks”

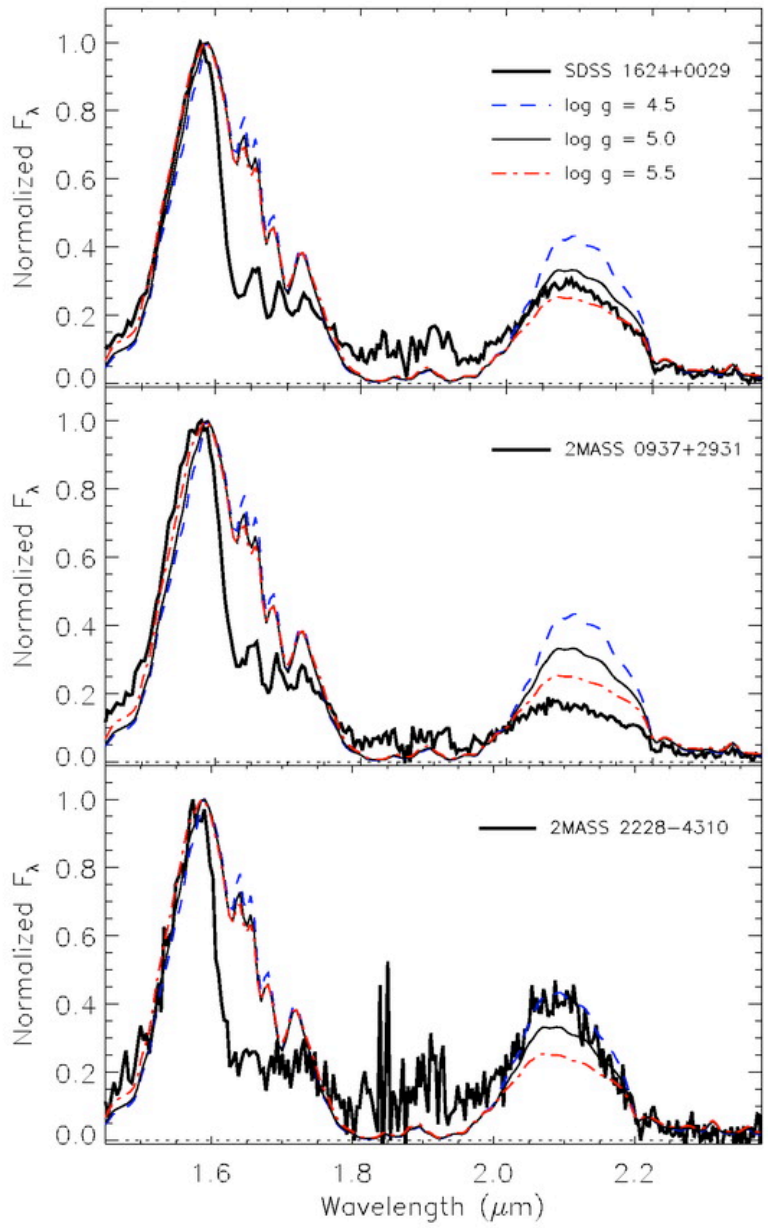
T6-T6.5



T7.5-T8



Burgasser, Burrows & Kirkpatrick (2006)

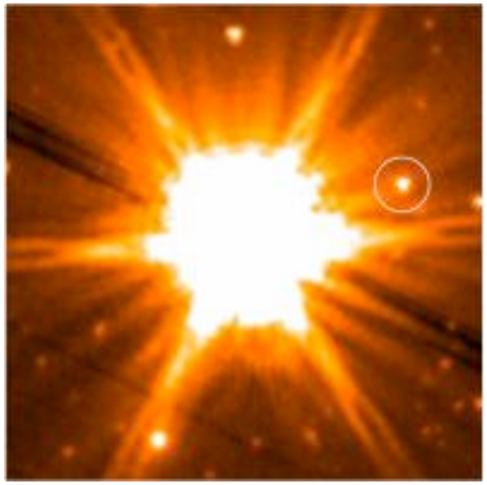


Burgasser, Burrows & Kirkpatrick (2006)

moderate gravity

high gravity

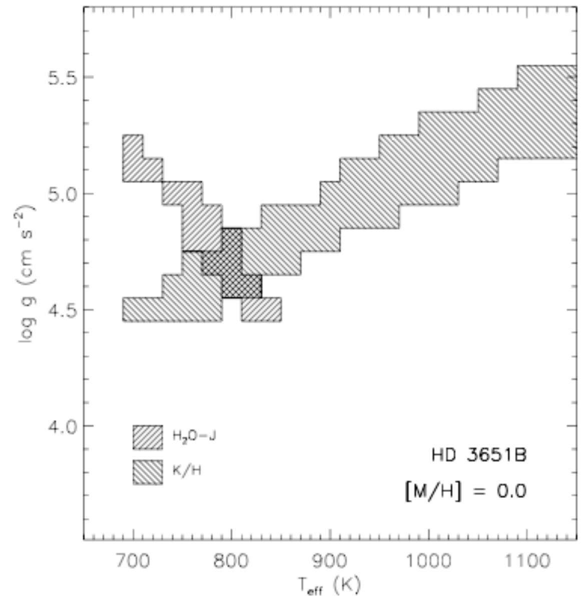
low gravity

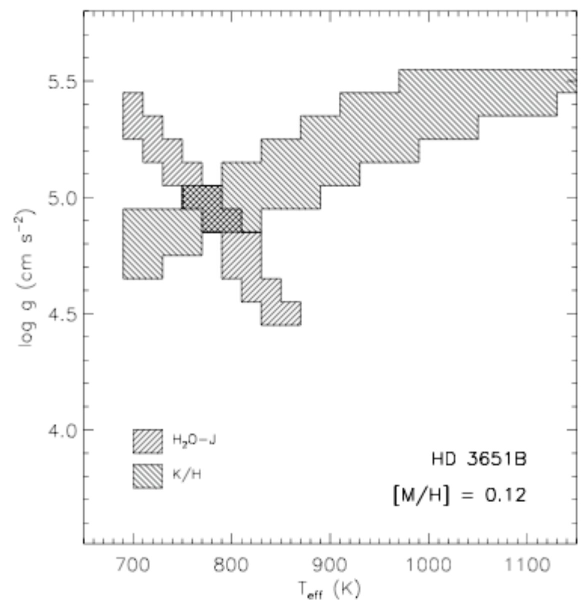


HD 3651B

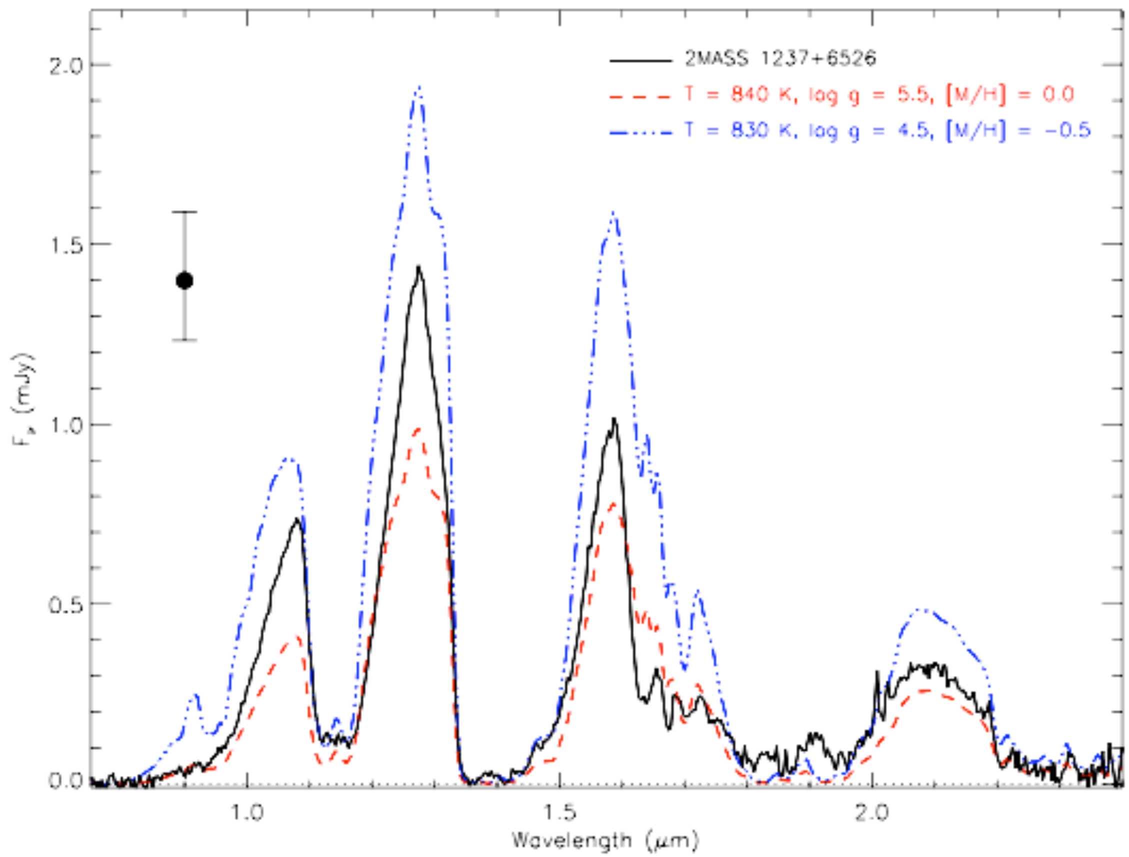
Luhman et al. (2006)
Mugrauer et al. (2006)

T8 companion
T_{eff} = 790±30 K
log g = 5.0±0.03
[M/H] = 0.12±0.04
age = 0.7-4.7 Gyr
mass = 33±13 M_{Jup}





Burgasser (2007)
see also Liu et al. (2007)



Liebert & Burgasser (2007)

2MASS 1237+6526

Burgasser et al. (2000,2002)

T6.5e

T_{eff} = 800-850 K

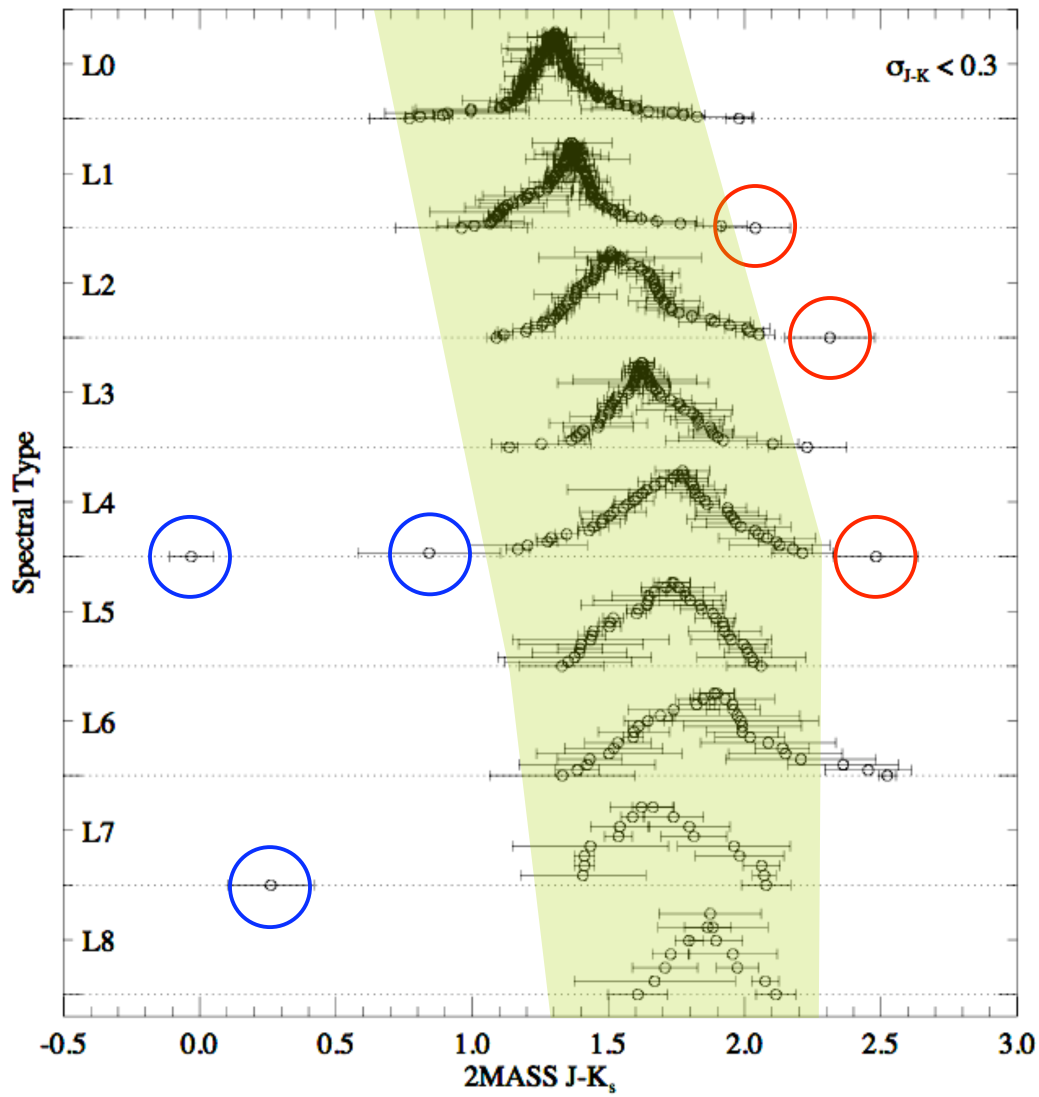
log g ≈ 5.0

[M/H] ≈ -0.2

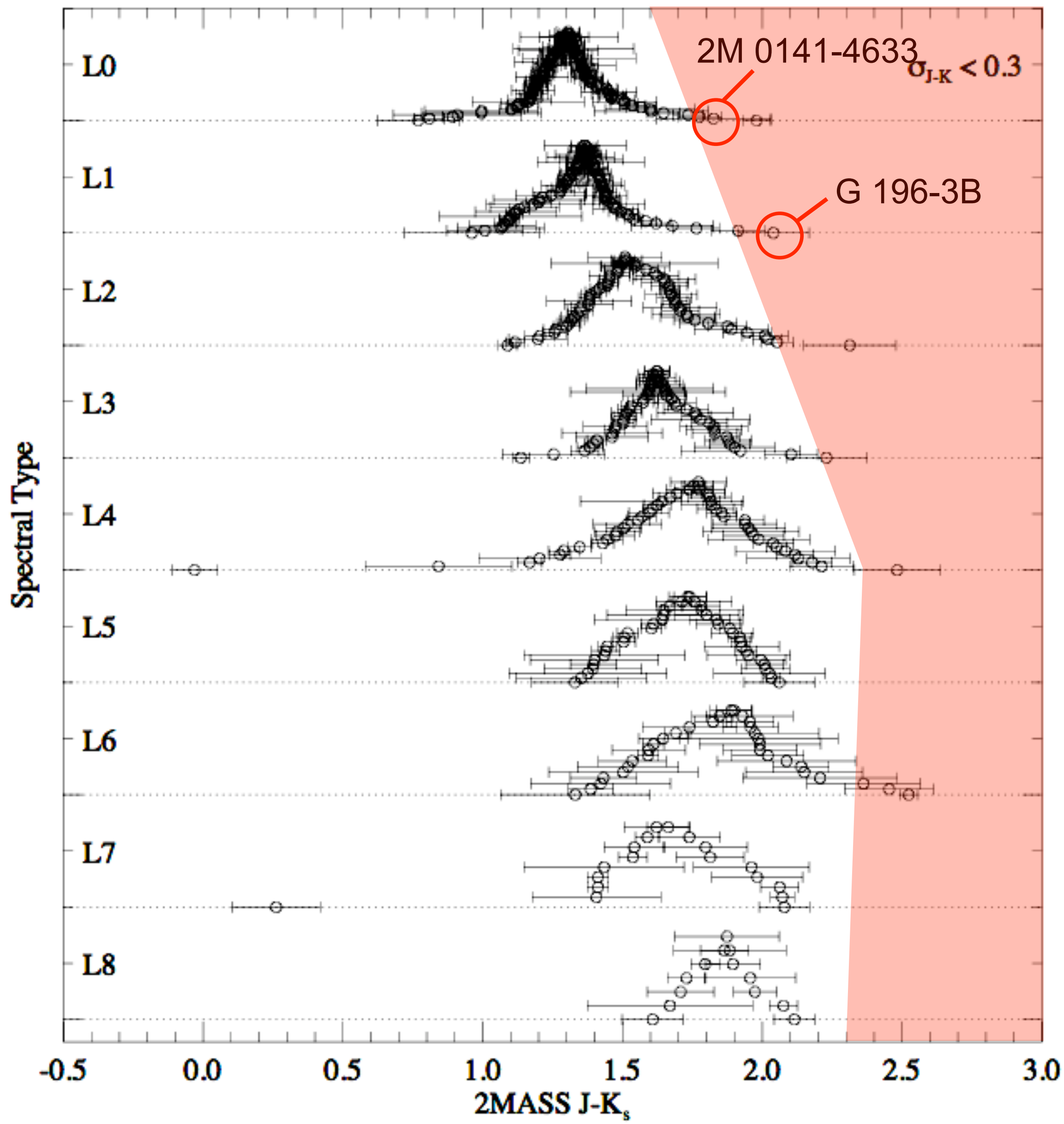
age > 2 Gyr

mass > 35 M_{Jup}

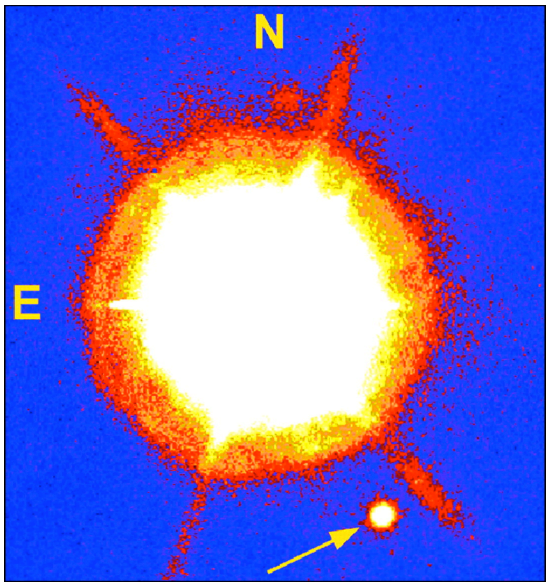
the “shrimp plot”



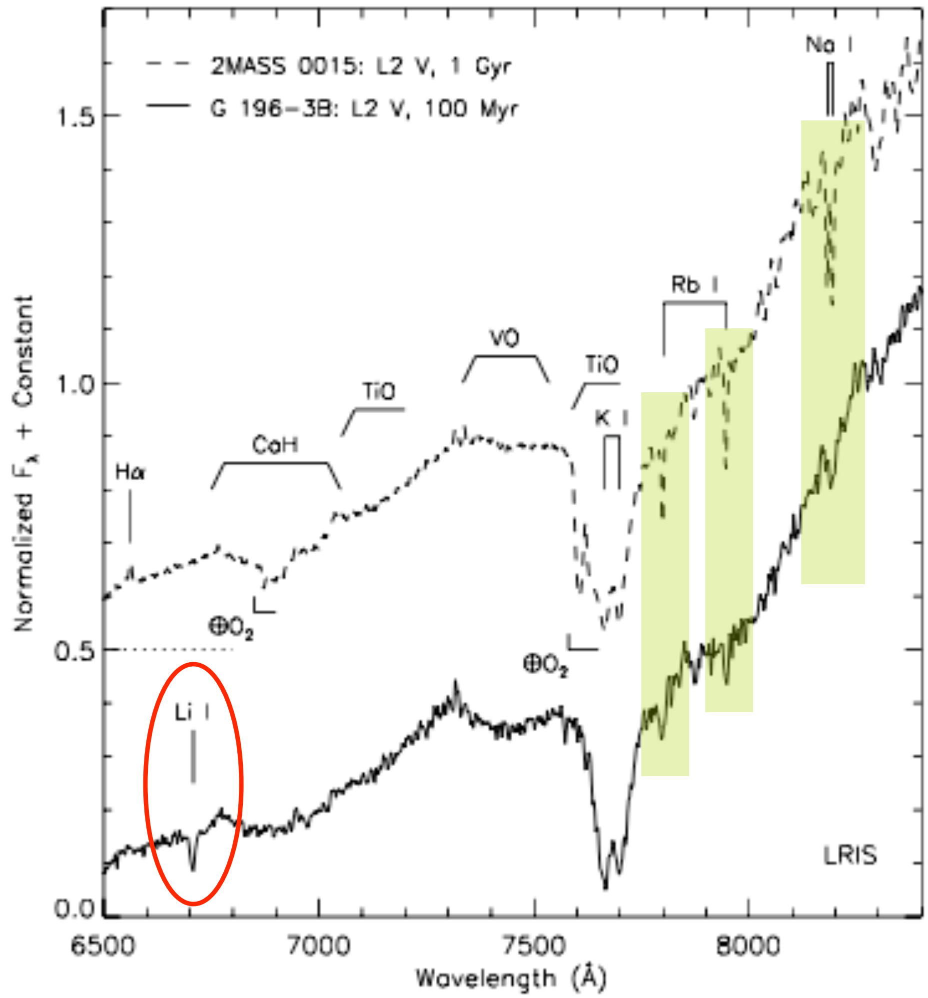
Kirkpatrick et al. (in prep.)


2M 0141-4633
$\sigma_{J-K} < 0.3$
G 196-3B
L0
L1
L2
L3
L4
L5
L6
L7
L8
Spectral Type
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2MASS J-K_s

red dwarfs are young dwarfs

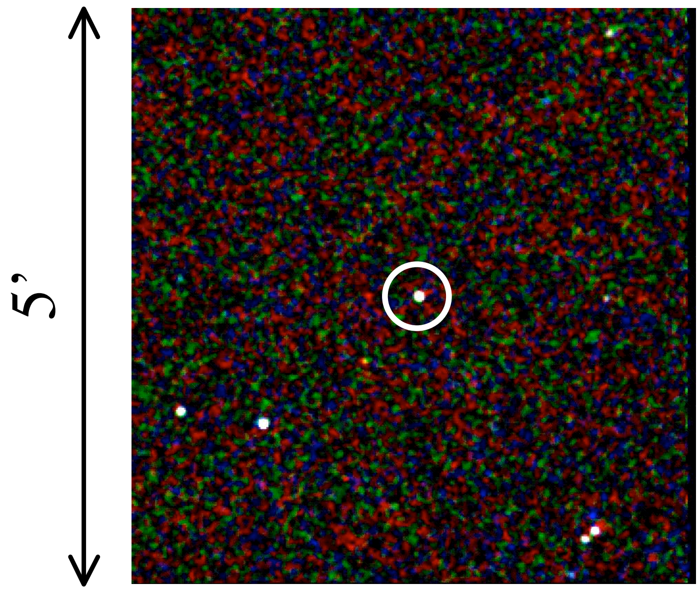


G 196-3B
companion to
~30-300 Myr
G 196-3A



Rebolo et al. (1998); Kirkpatrick et al. (in prep.)
See also Martin et al. (1999); Gorlova et al. (2003); Luhman et al. (2003); Allers et al. (2007)

red dwarfs are young dwarfs

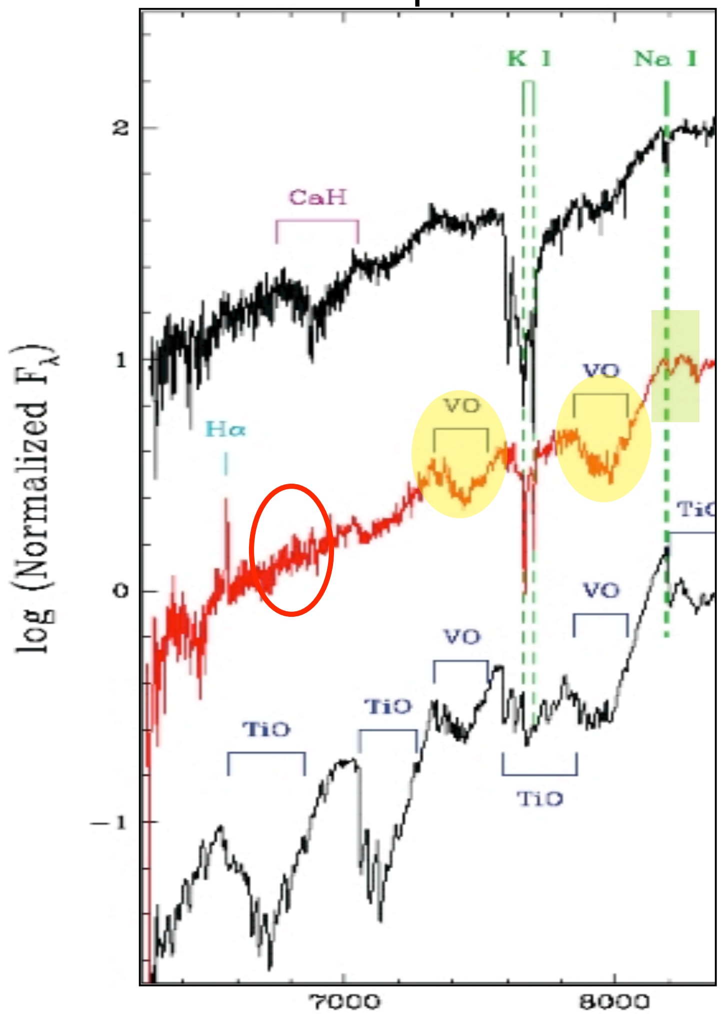


2MASS 0141-4633

possible member of Tucana/Horologium moving association

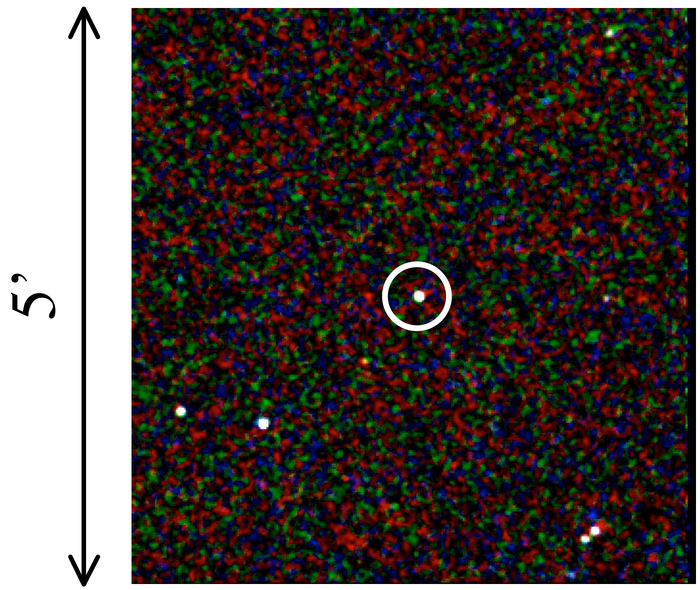
~30 Myr, 6-25 $M_{Jupiter}$

red optical



Kirkpatrick et al. (2006)

red dwarfs are young dwarfs

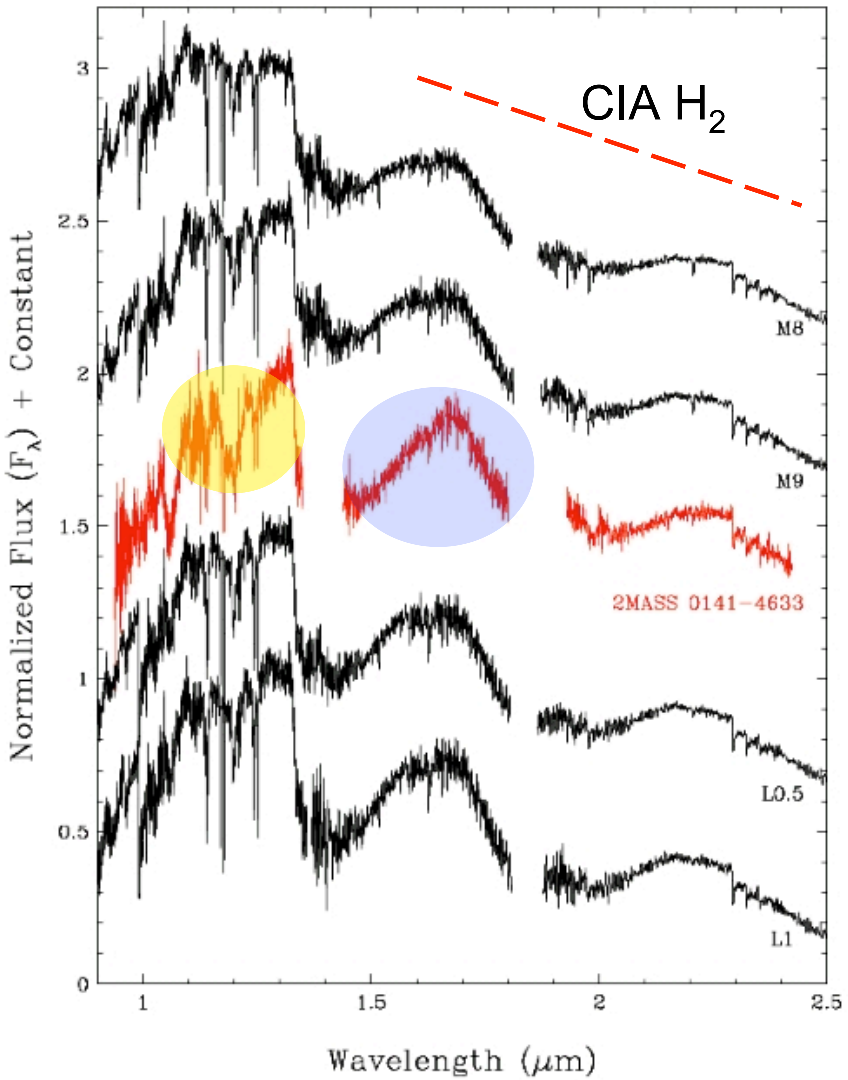


2MASS 0141-4633

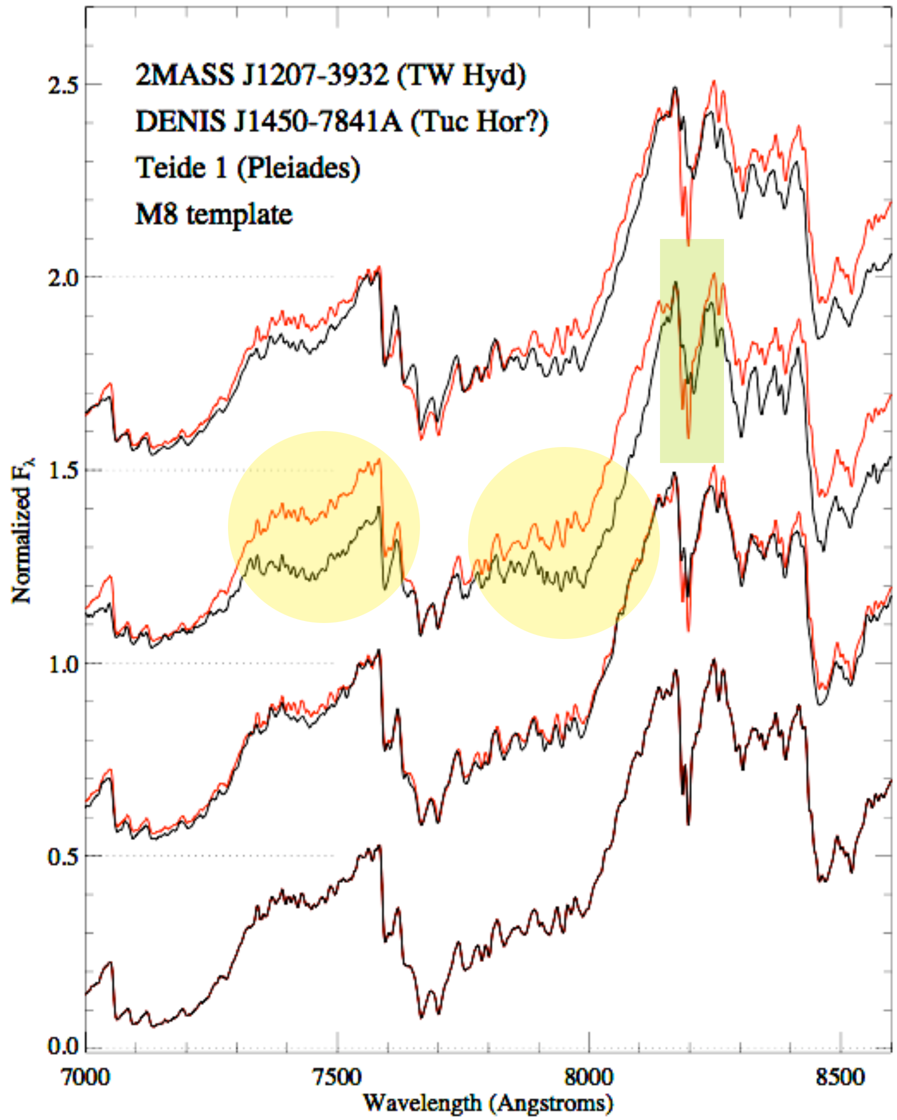
possible member of Tucana/Horologium moving association

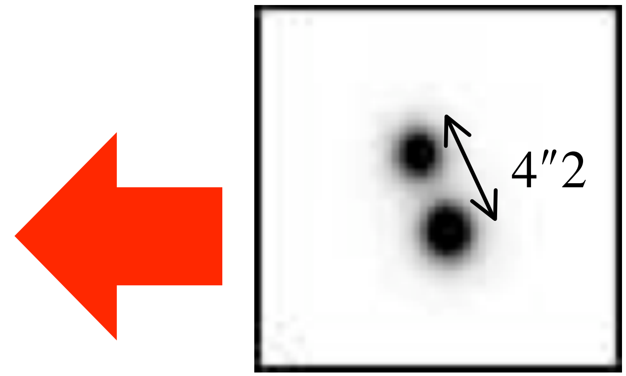
~30 Myr, 6-25 $M_{Jupiter}$

near-infrared



Kirkpatrick et al. (2006)





DENIS 1450-78AB

Young M8/M9 binary

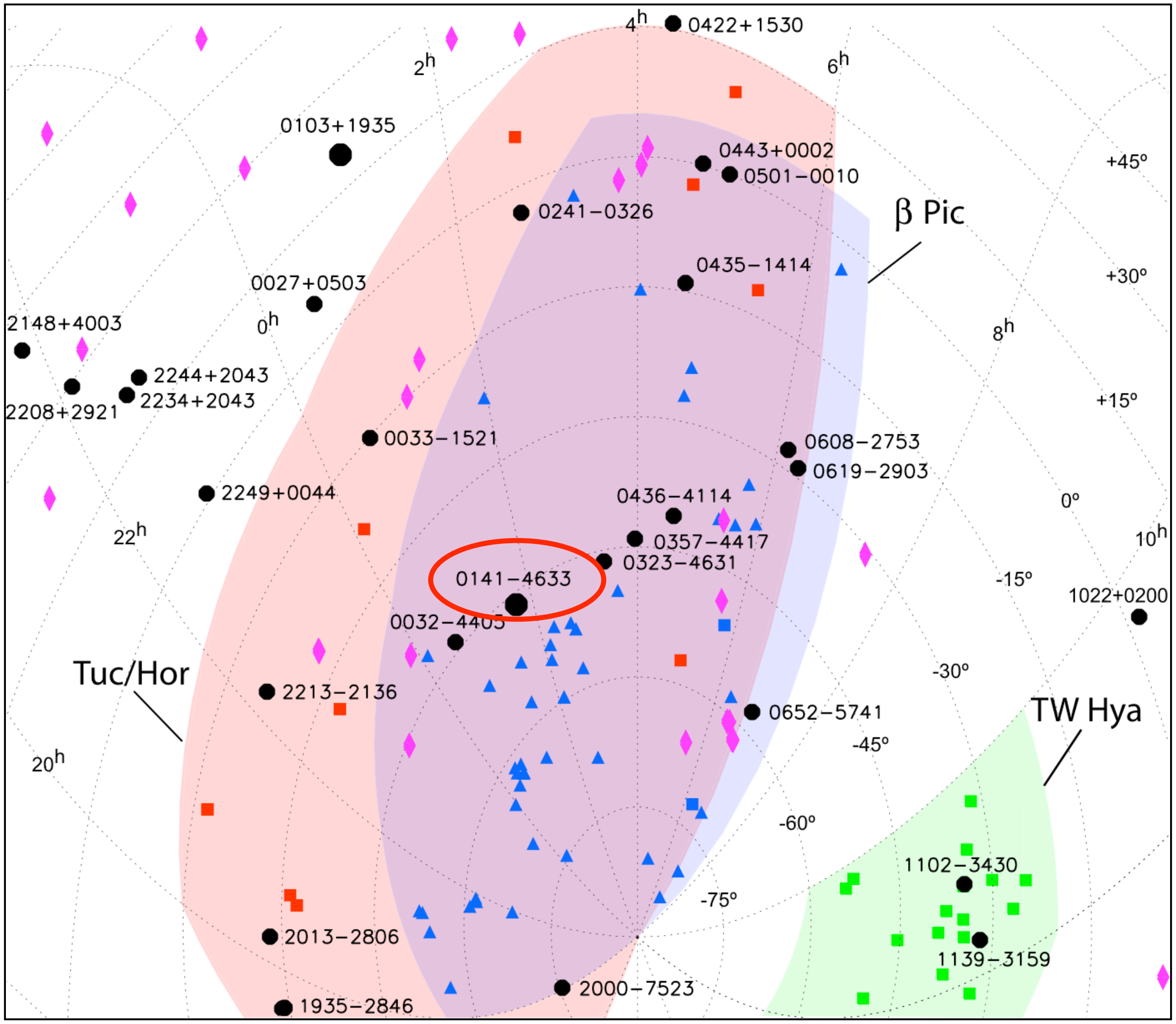
Tucana/Hor? Cha II?

Discovered with LDSS-3

Burgasser et al. (in prep.)

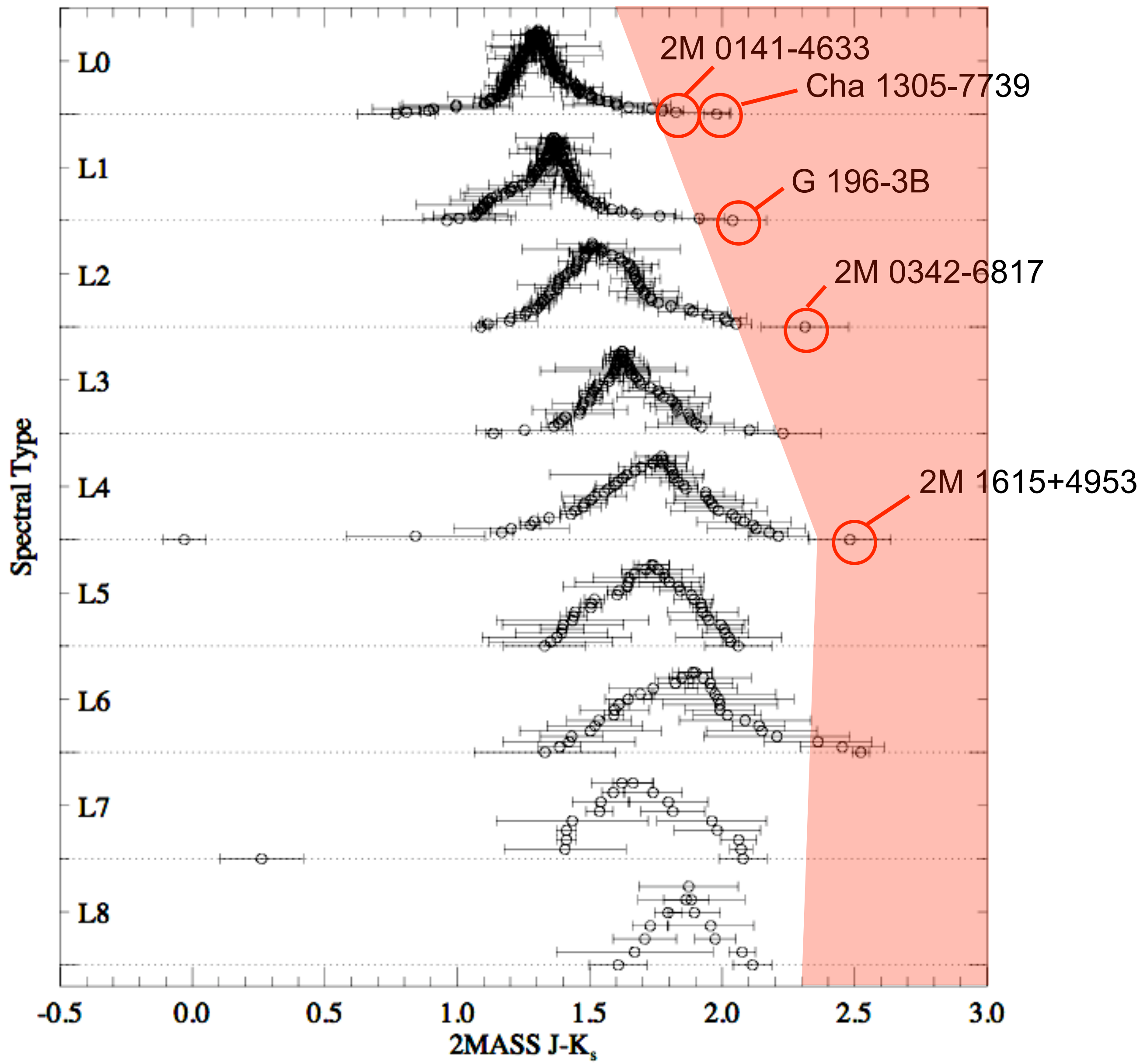
see also Luhman (2004)

10-50 Myr brown dwarfs < 100 pc from the Sun

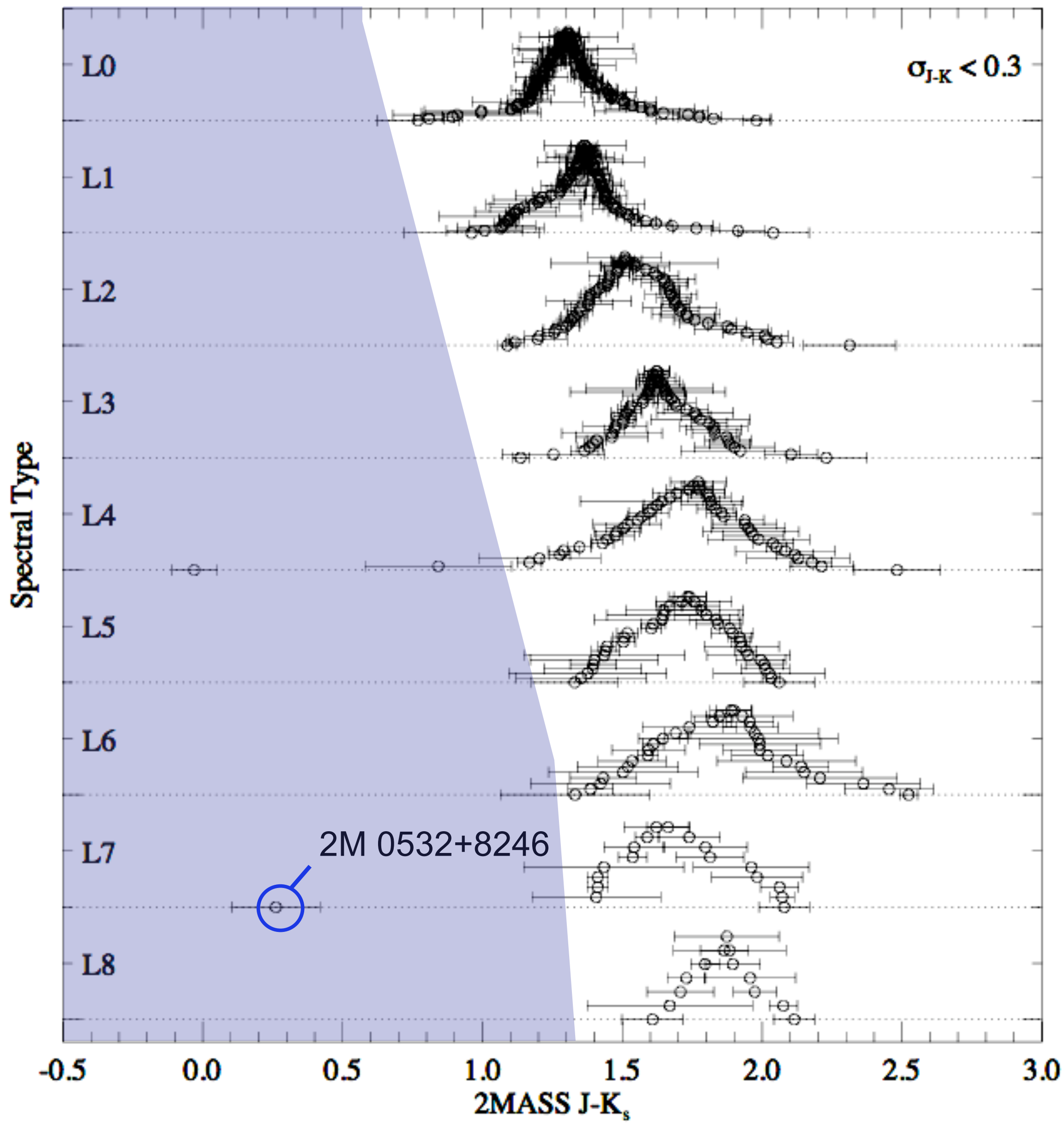


Cruz et al. (2007)

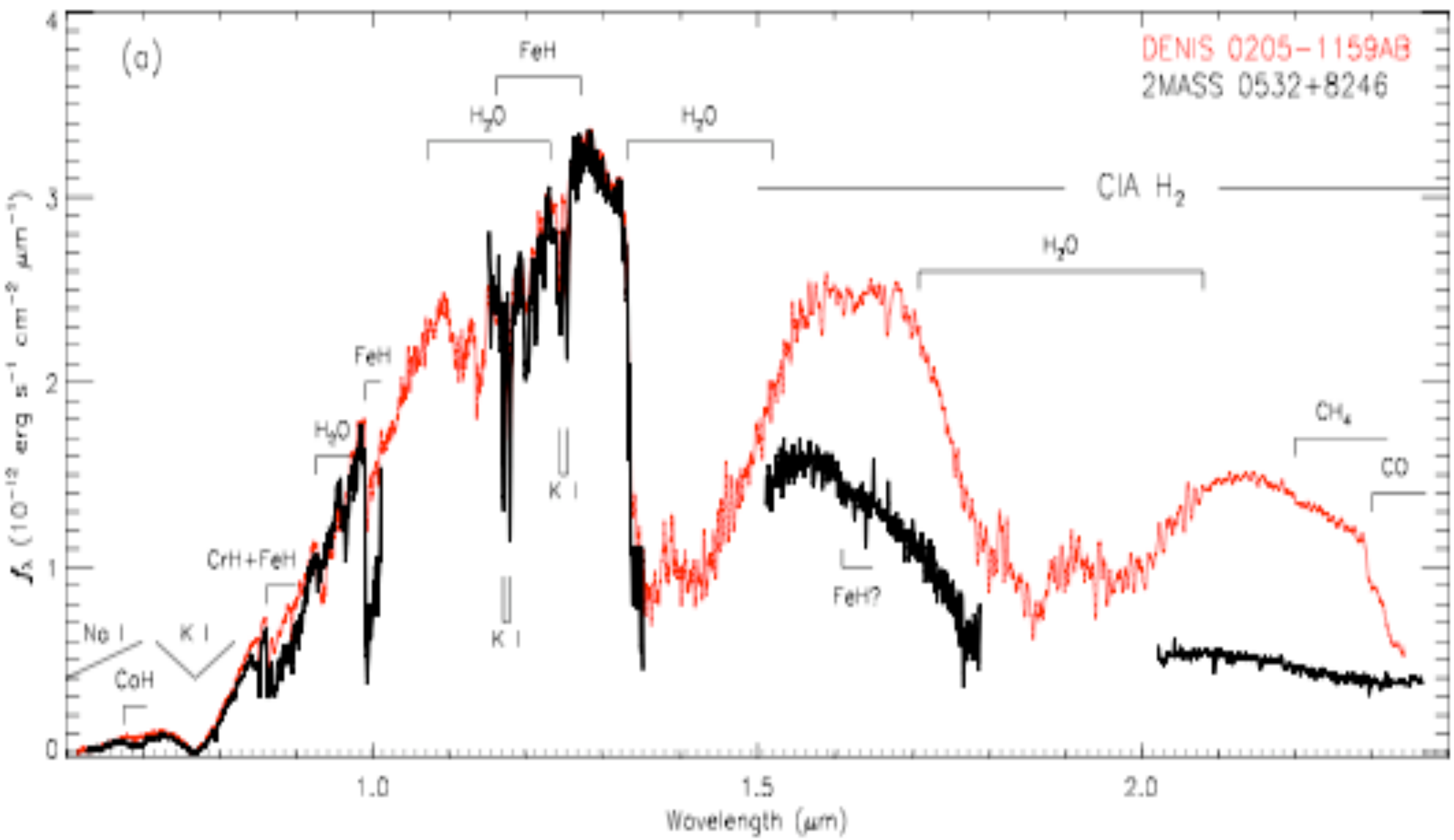
see also Zuckerman & Song (2004); Lopez-Santiago et al. (2006); Torres et al. (2006)



2M 0141-4633
Cha 1305-7739
G 196-3B
2M 0342-6817
2M 1615+4953
L0
L1
L2
L3
L4
L5
L6
L7
L8
Spectral Type
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2MASS J-K$_s$


σJ-K < 0.3
L0
L1
L2
L3
L4
L5
L6
L7
L8
2M 0532+8246
Spectral Type
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2MASS J-Ks

very blue dwarfs are metal-poor dwarfs



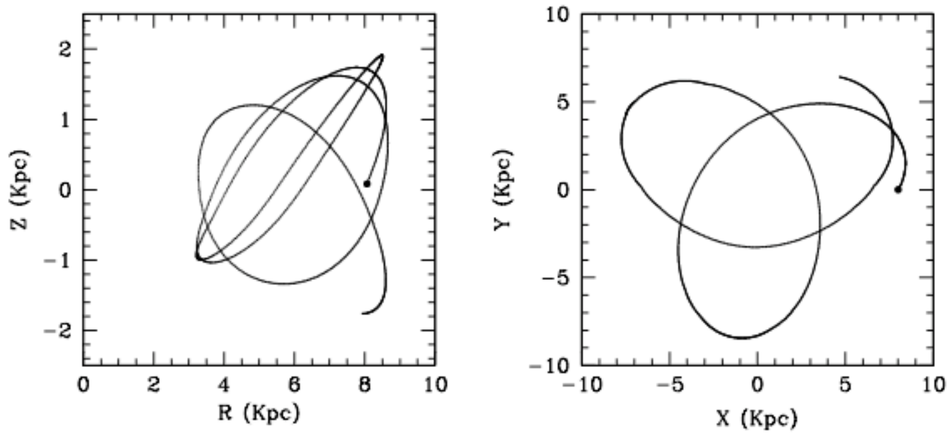
Burgasser et al. (2003)

2MASS 0532+8246

J-K = 0.17±0.07 (>1.5 mag too blue)

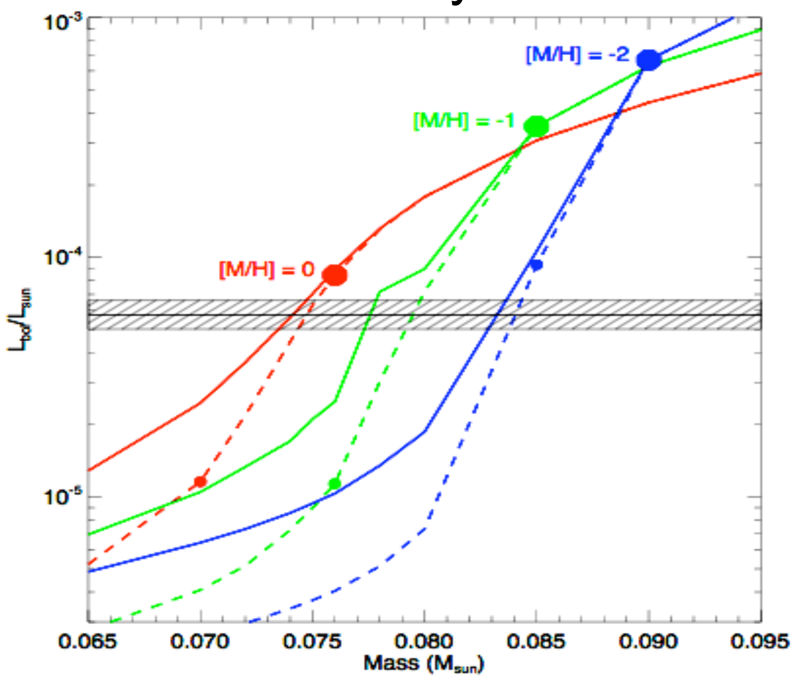
halo kinematics (V = -350 km/s)

galactic orbit



2MASS 0532+82 is a **halo L-type (sdL) brown dwarf**

mass/metallicity constraints

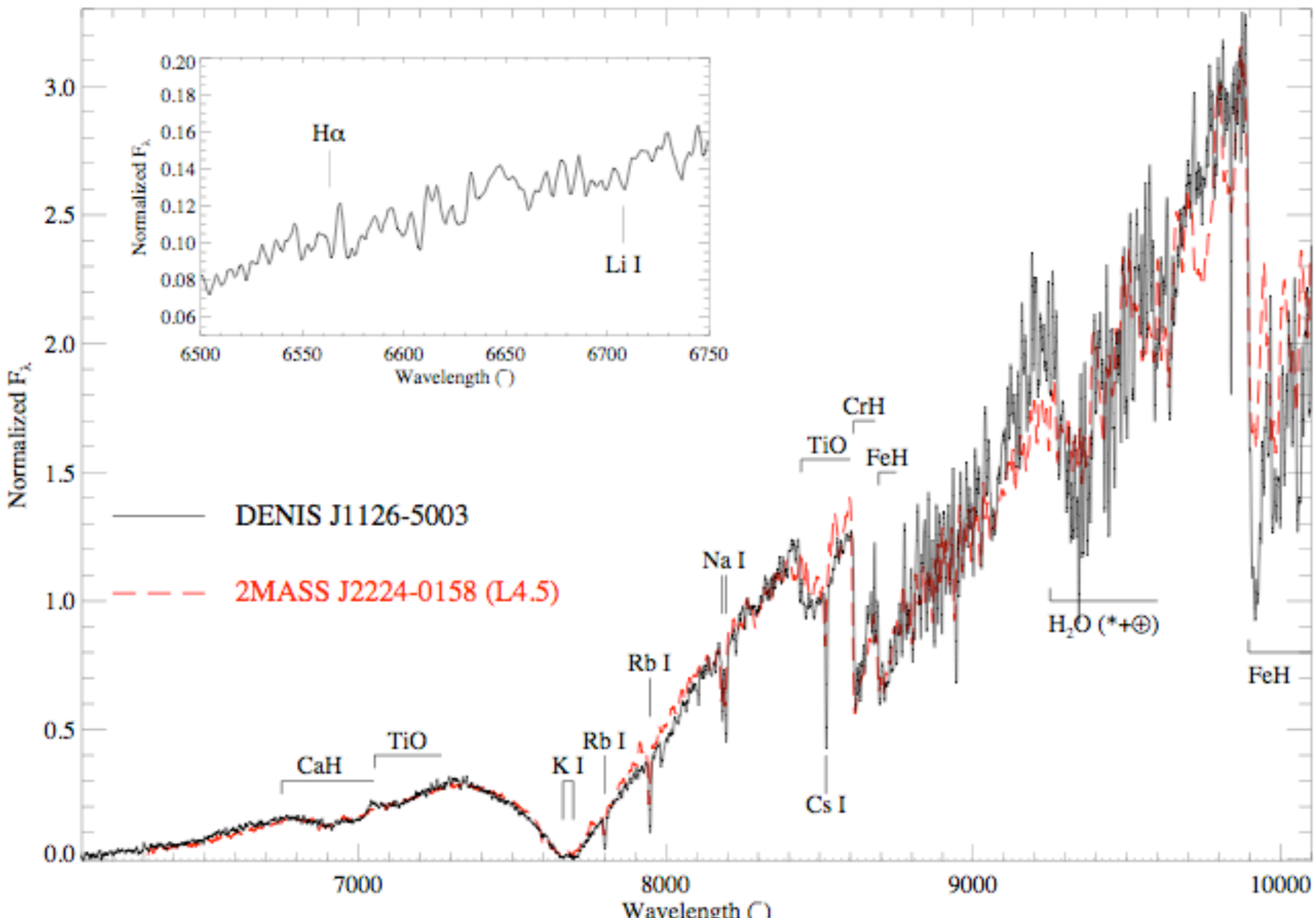


4 sdLs identified to date:

Name	SpT	$J-K_s$
SD 1256-02	sdL3	<0.7
2M 1626+39	sdL4	-0.03
☆ 2M 0616-64	sdL6	<-0.1
2M 0532+82	sdL7	0.26

☆ *Newly identified with LDSS-3*
(Cushing et al. in prep.)

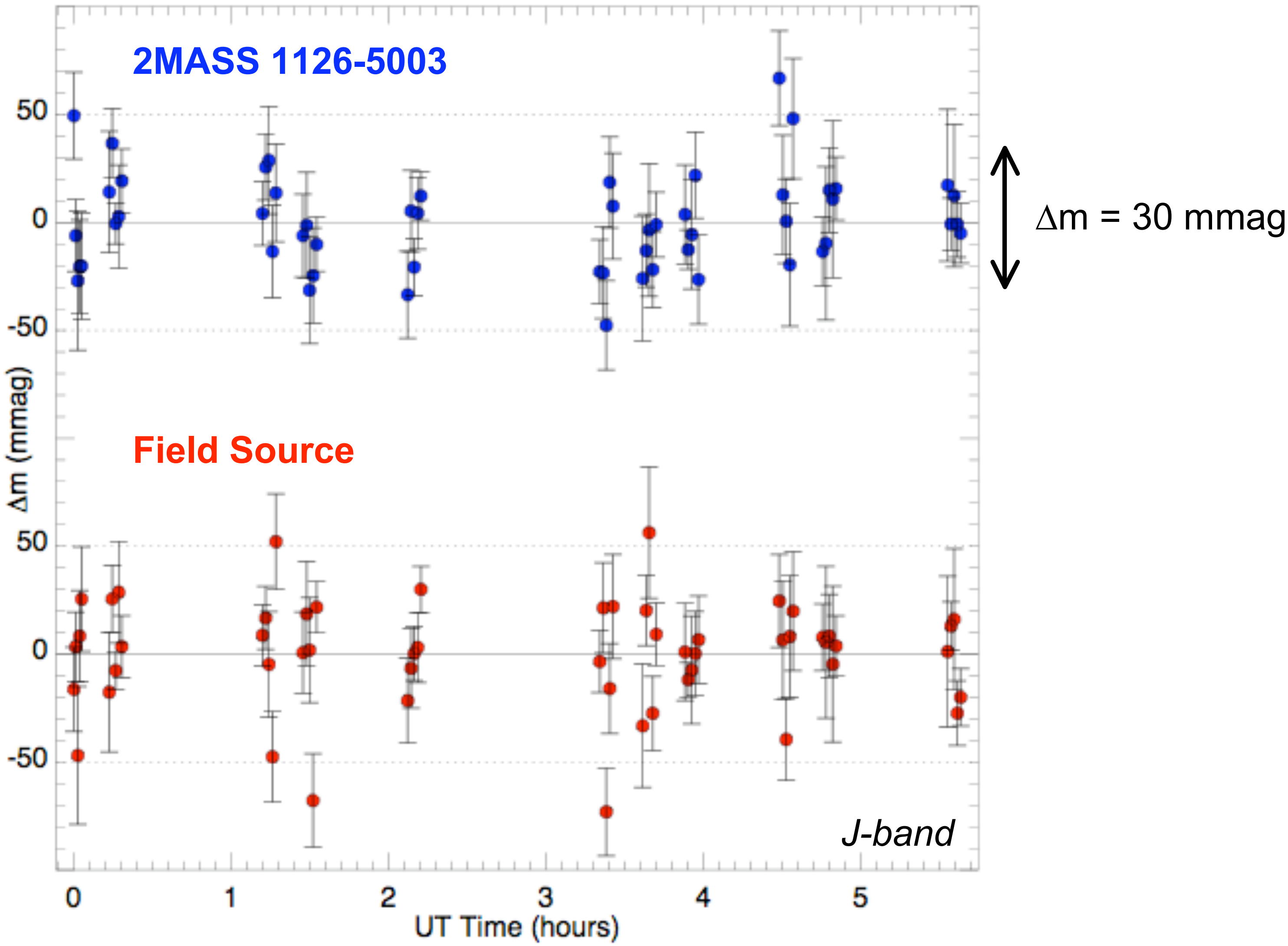
Burgasser et al. (2008)



data from LDSS-3

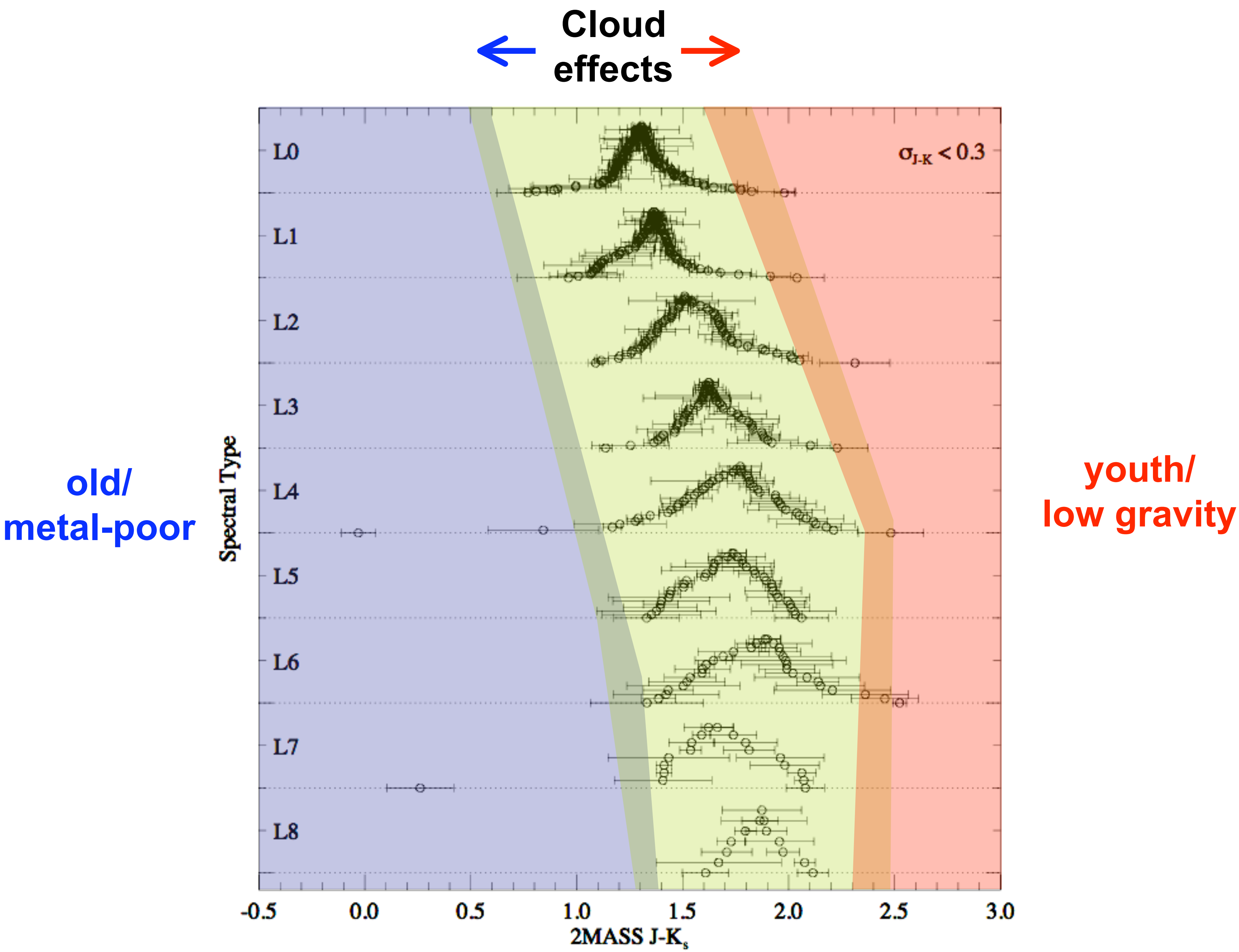
Burgasser et al. (2008)

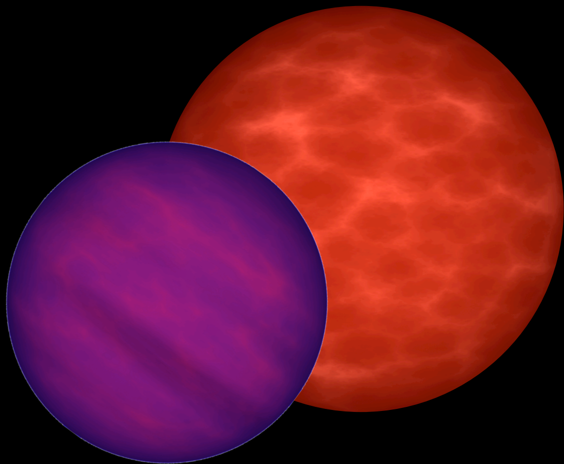
weather from clouds - variability



data from PANIC

See also Bailer-Jones & Lamm (2002)


Cloud
effects
old/
metal-poor
youth/
low gravity
σJ-K < 0.3
L0
L1
L2
L3
L4
L5
L6
L7
L8
Spectral Type
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
2MASS J-Ks



The take-home message

Brown dwarf science is moving beyond its discovery phase, and developing into a broader topic influencing planetary, stellar and Galactic science. Yet more work is needed to fully characterize the atmospheric properties of individual sources, test structural models, improve atmospheric theory, and take measure of the broader population.