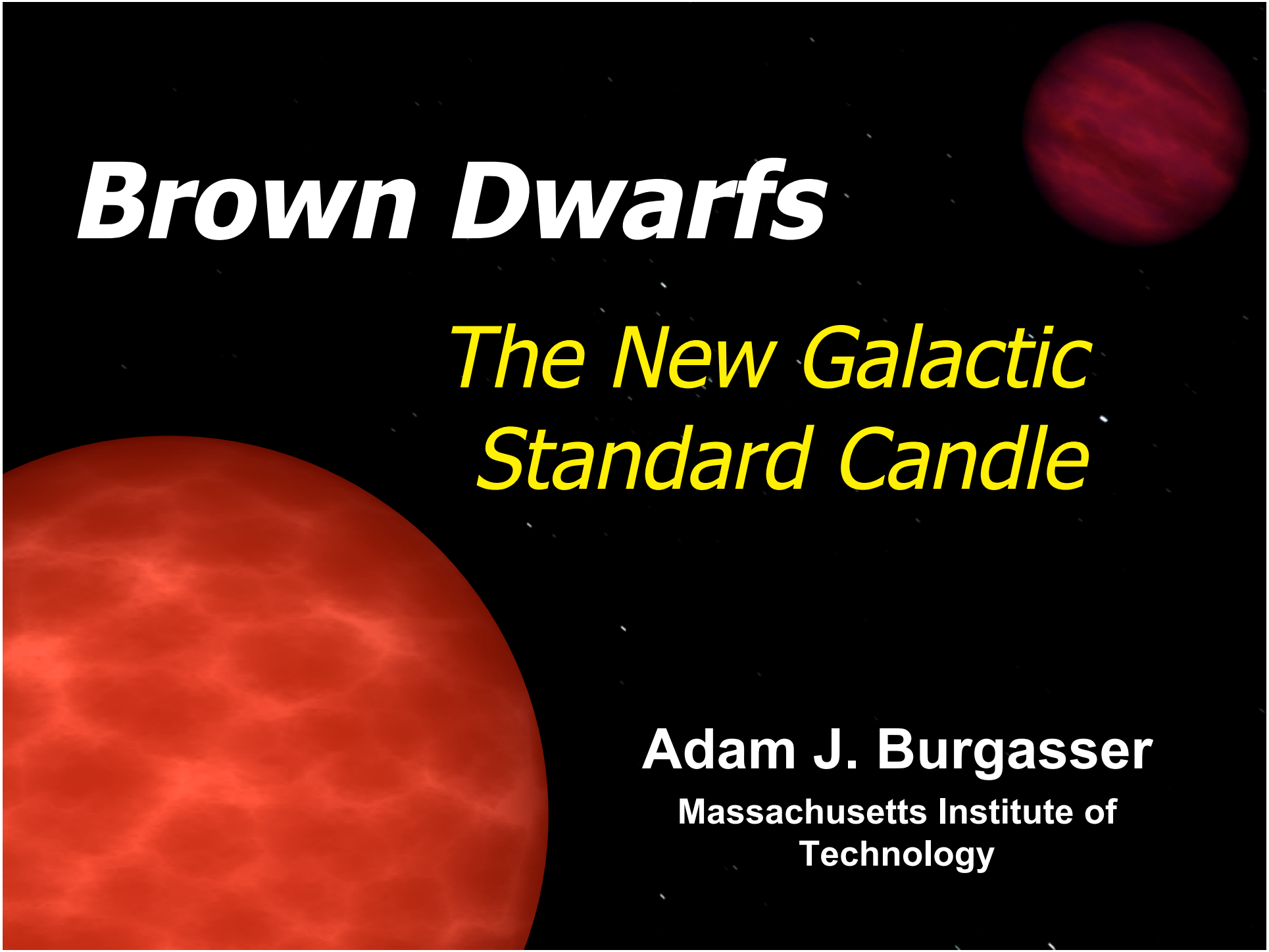
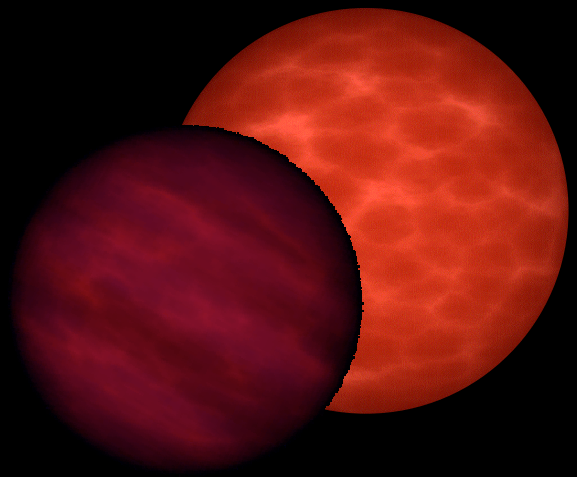

Brown Dwarfs
The New Galactic Standard Candle
Adam J. Burgasser
Massachusetts Institute of Technology



the take-home message

Brown dwarfs are **potentially ideal Galactic standard candles** as they are

- prevalent throughout the Galaxy,
- uniquely characterizable,
- increasingly well-characterized, and
- useable as both rulers and clocks.

overview

what is a brown dwarf?

definition, discovery, spectral types

the preponderance of brown dwarfs

local space density, where brown dwarfs live

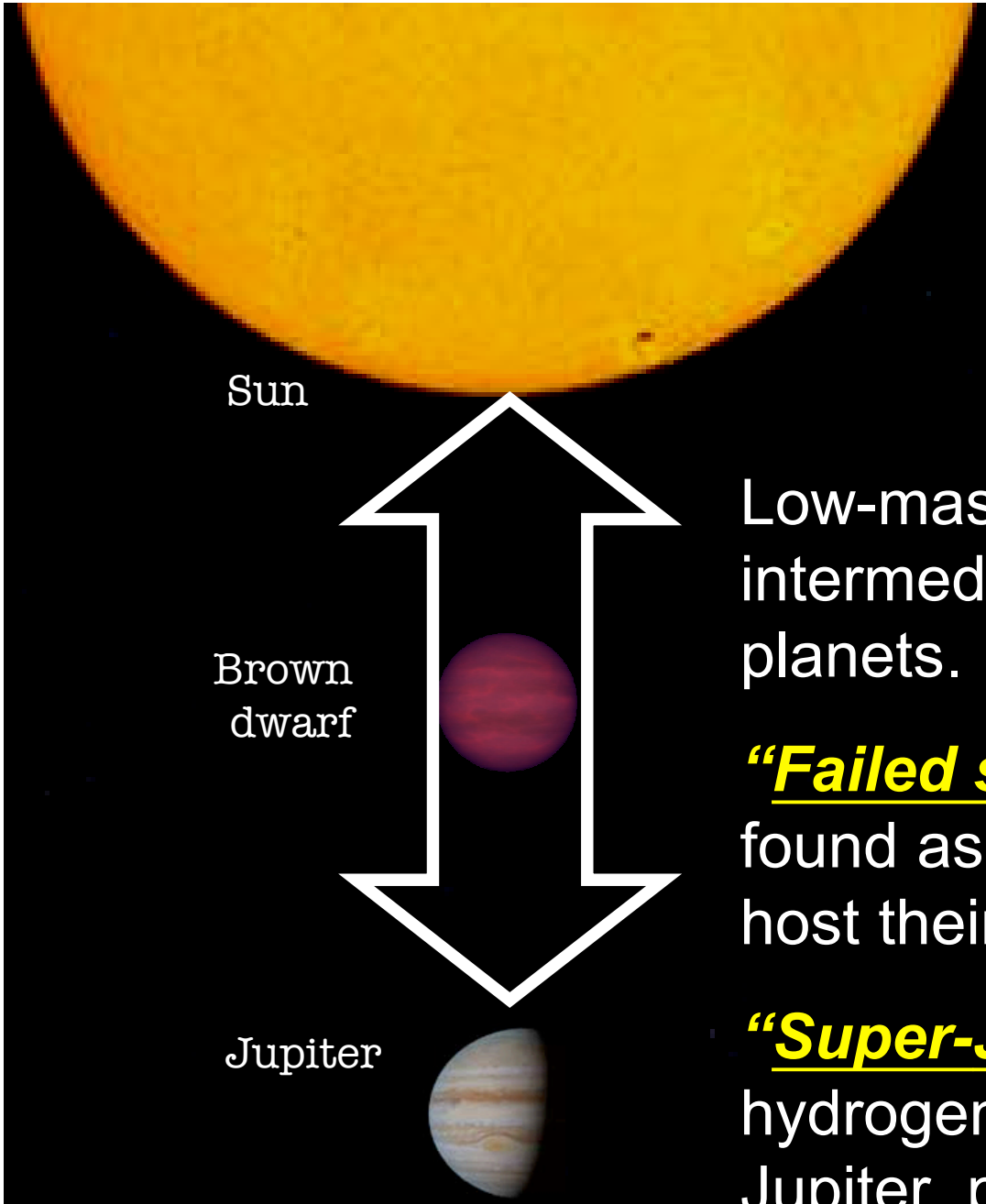
characterizing brown dwarfs

temperature, gravity, composition, clouds

brown dwarfs as rulers and clocks

distance scales & ages

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

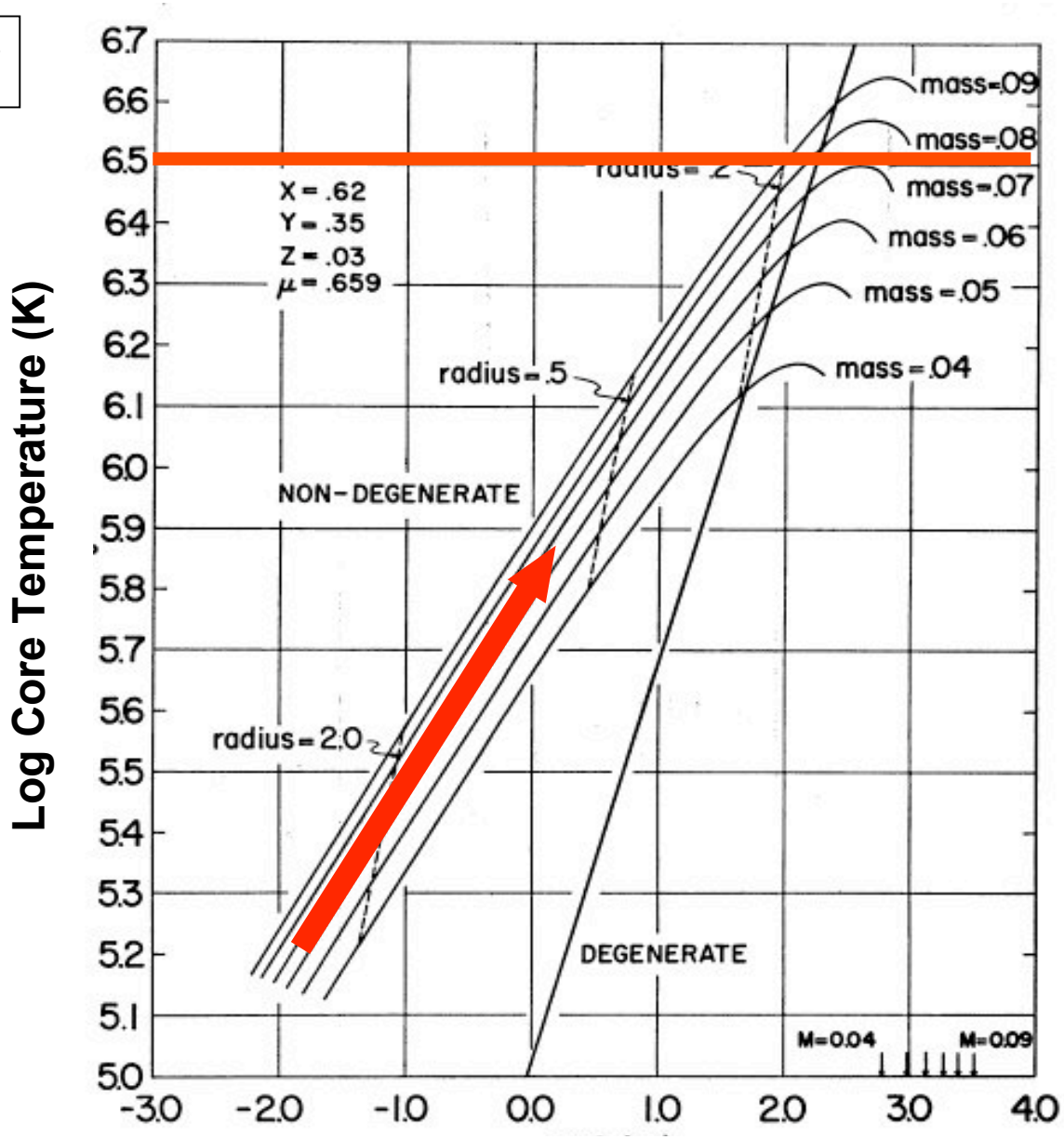


Low-mass objects with properties intermediate between stars and planets.

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

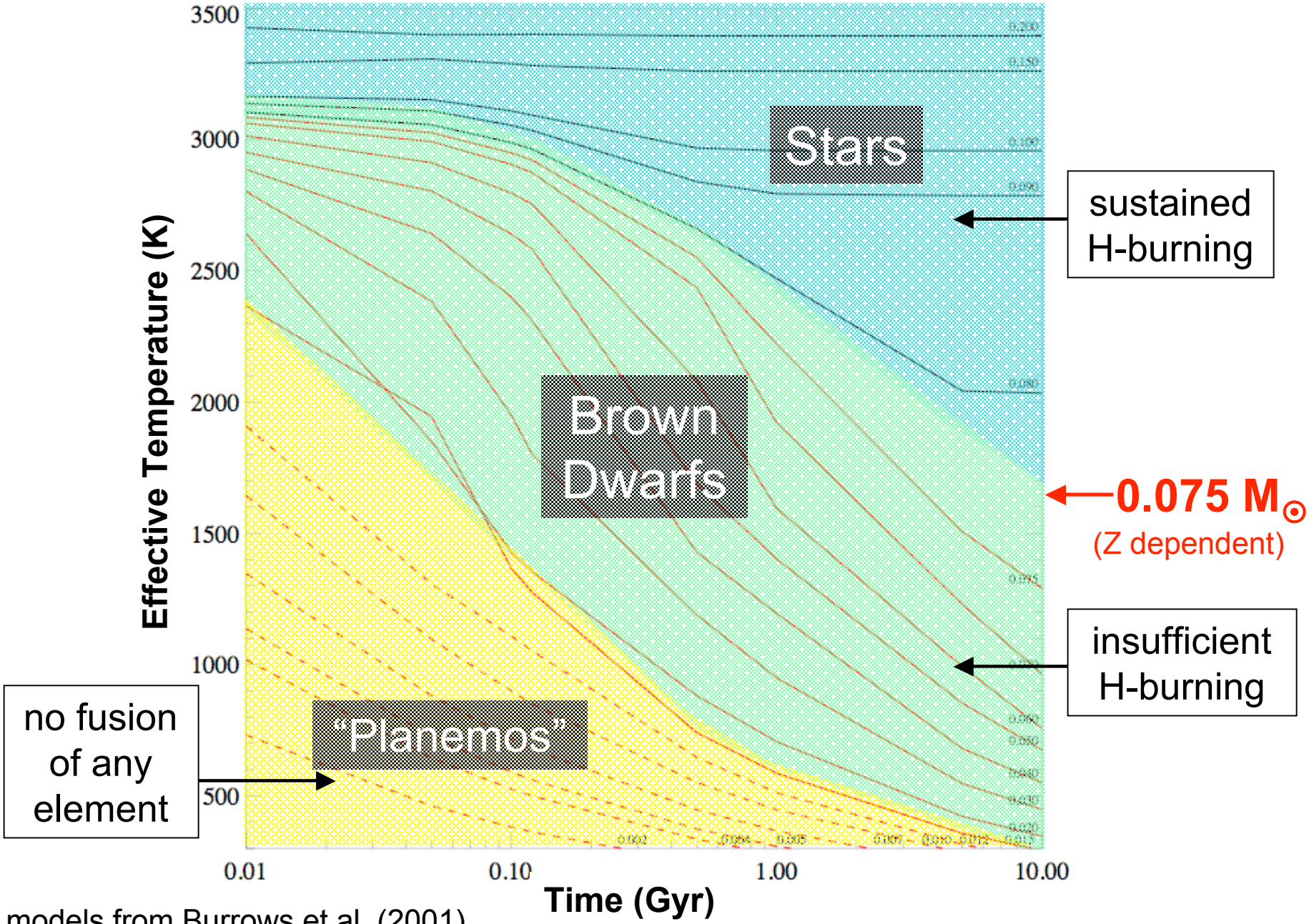
"Super-Jupiters" - do not fuse hydrogen, sizes comparable to Jupiter, planetary atmospheres

ca. 1963

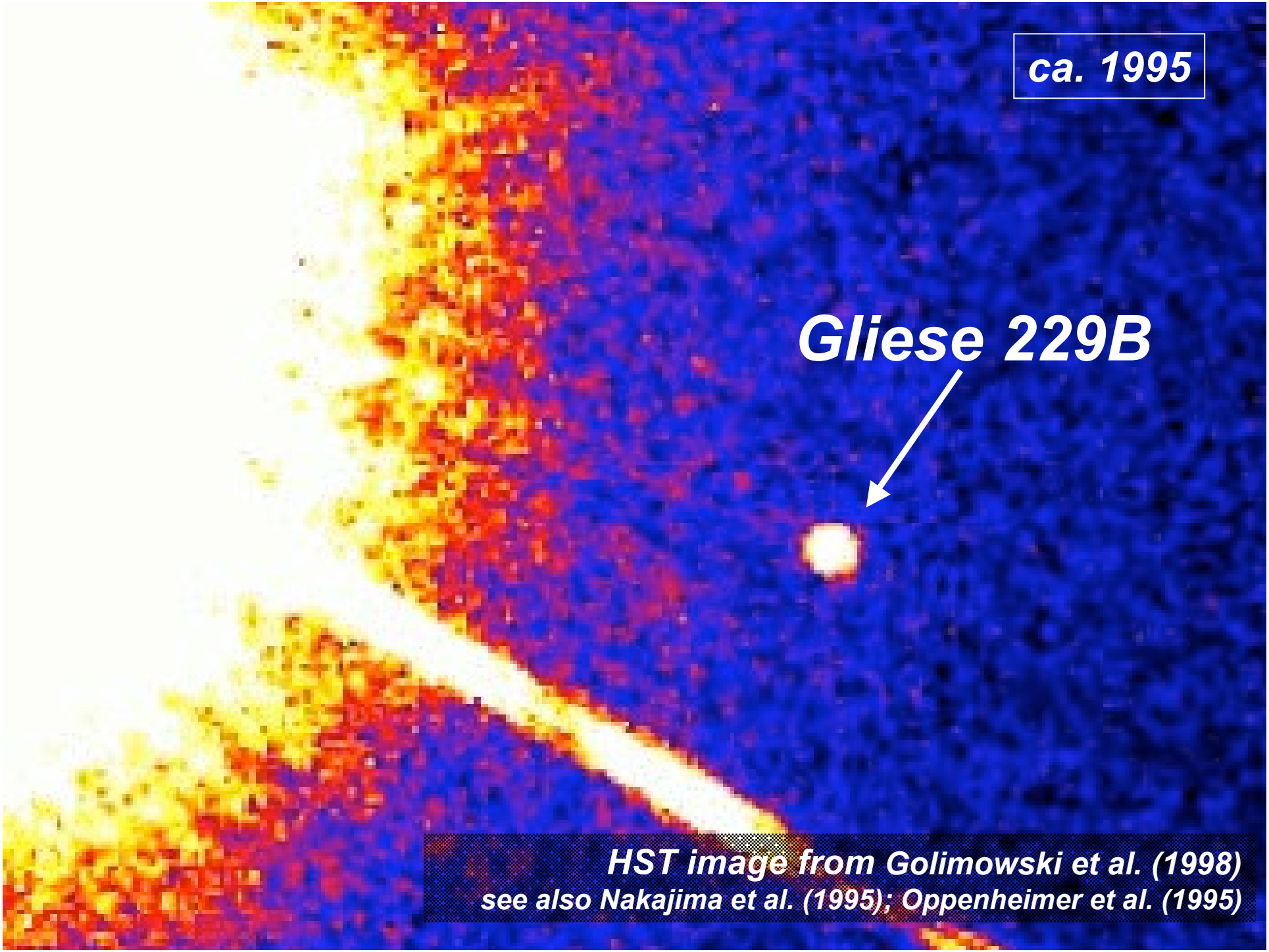


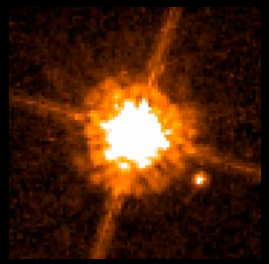
H-burning threshold ≈ 3×10^6 K

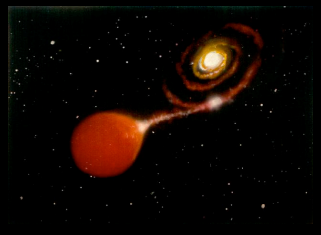
Kumar (1962, 1963)
see also Hayashi & Nakano (1963)

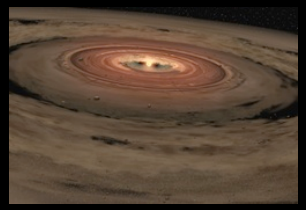


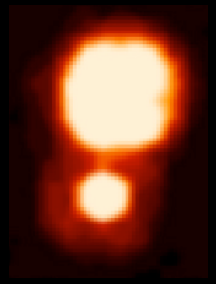
models from Burrows et al. (2001)


ca. 1995
Gliese 229B
HST image from Golimowski et al. (1998)
see also Nakajima et al. (1995); Oppenheimer et al. (1995)









>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

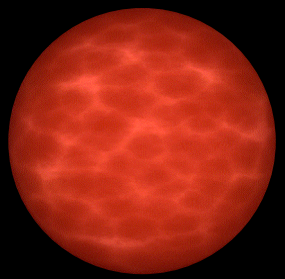
Extrema

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

spectral types

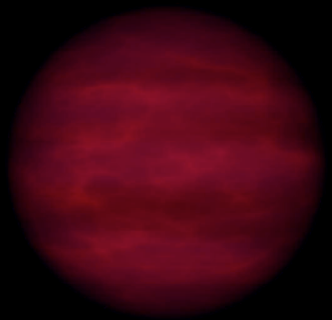
M dwarfs (3500-2100 K)

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



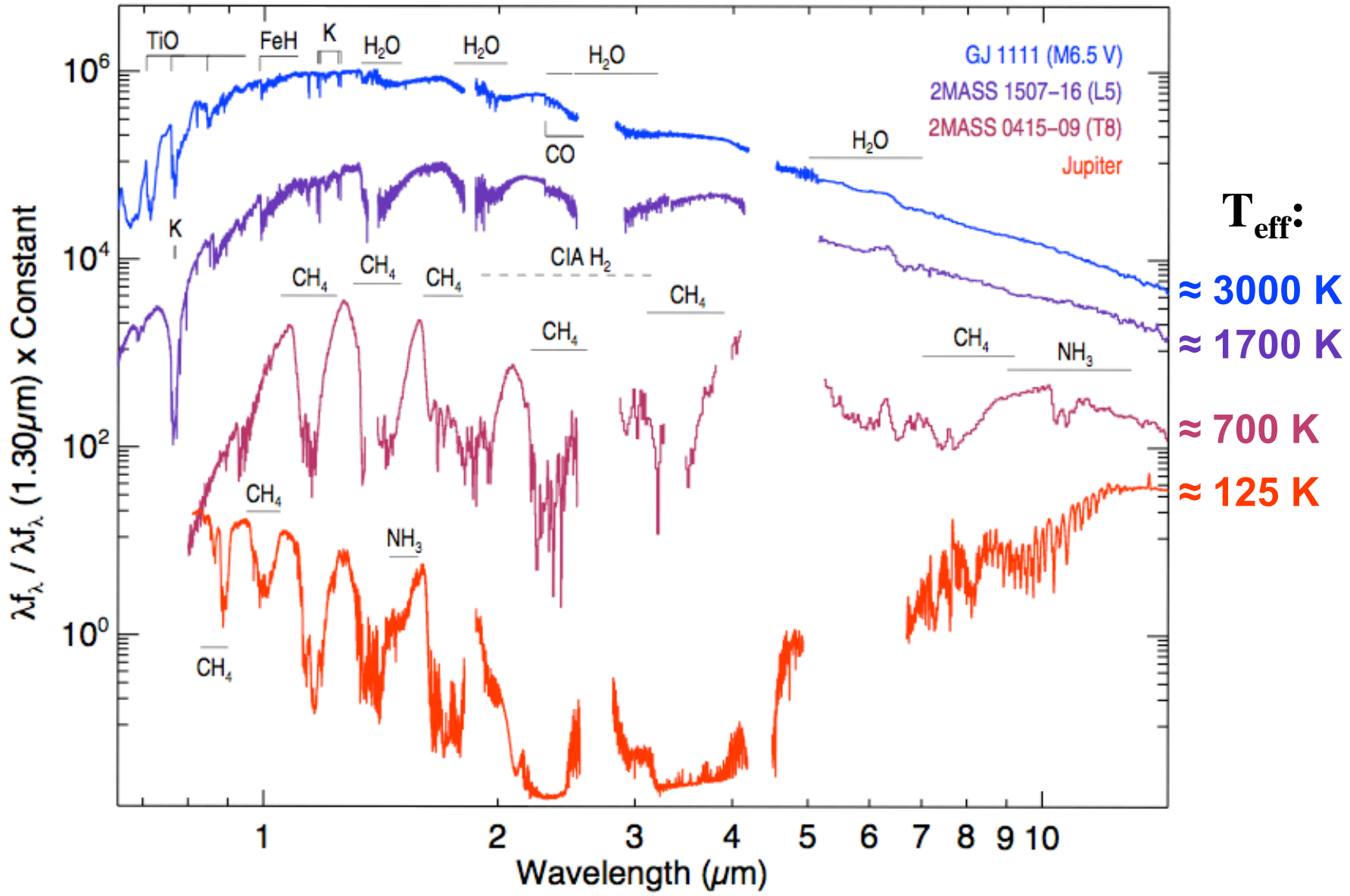
L dwarfs (2100-1300 K)

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



T_{eff}:

≈ 3000 K

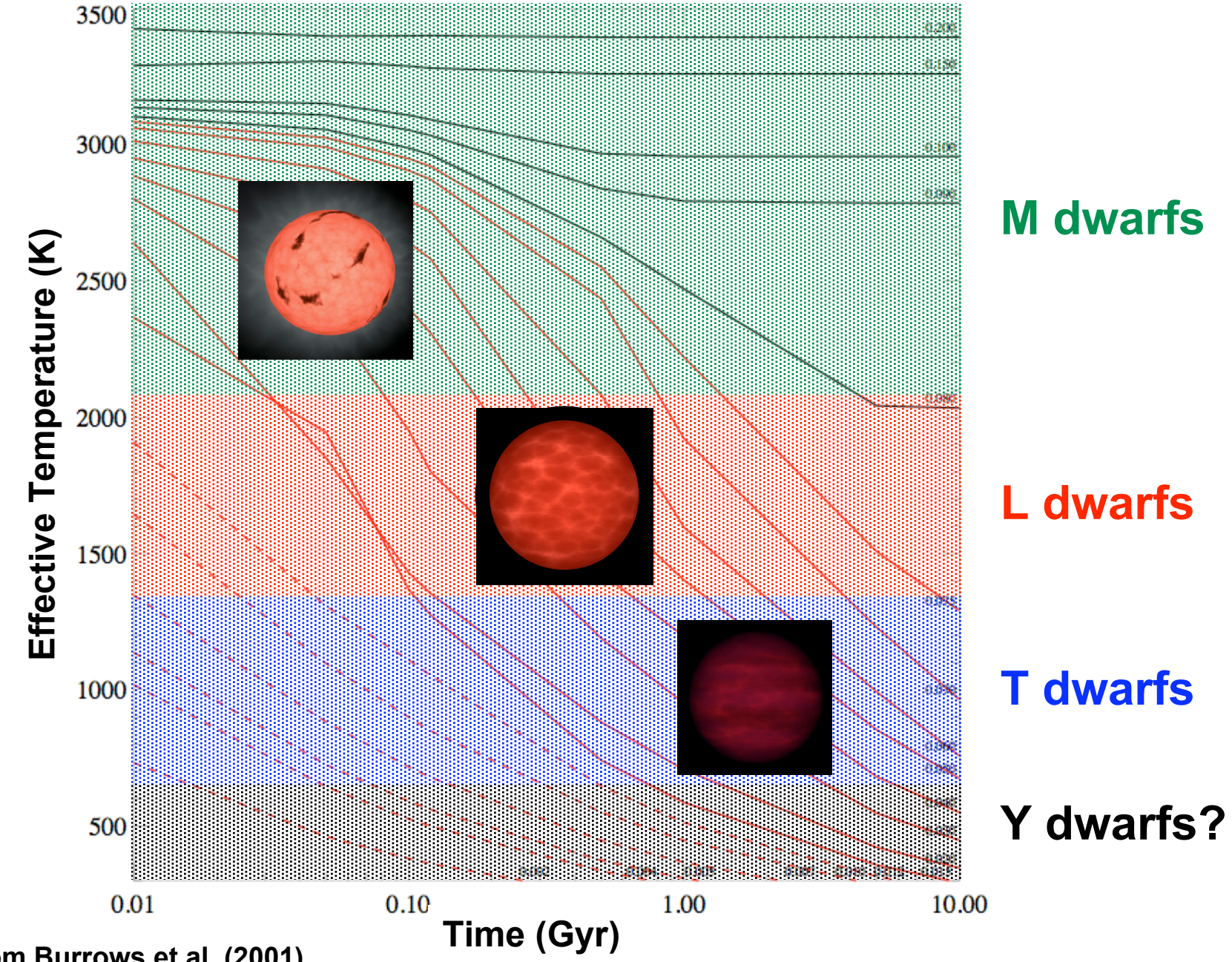
≈ 1700 K

≈ 700 K

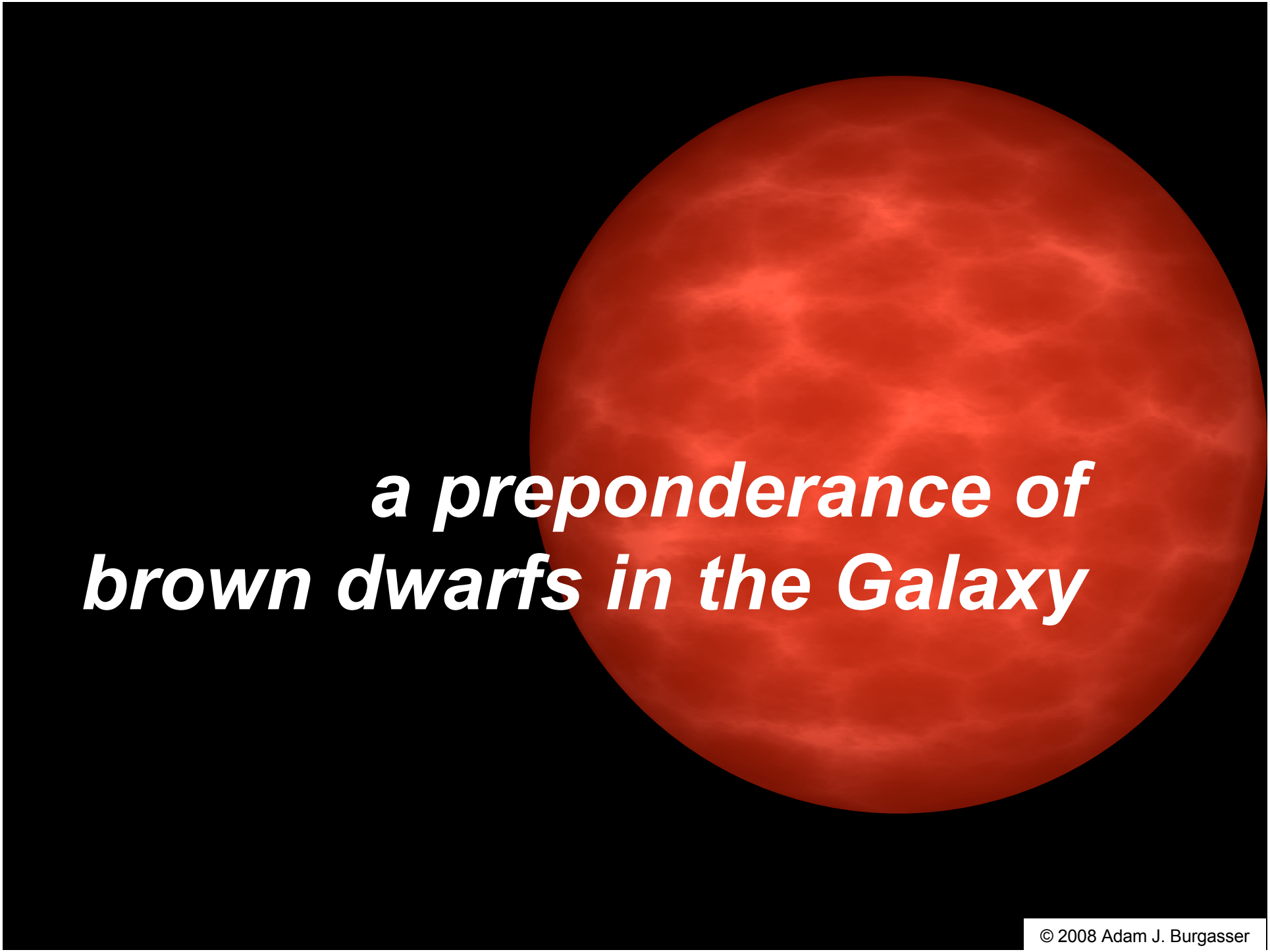
≈ 125 K

Marley & Leggett (2008)

Data from Cushing et al. (2005,2007)



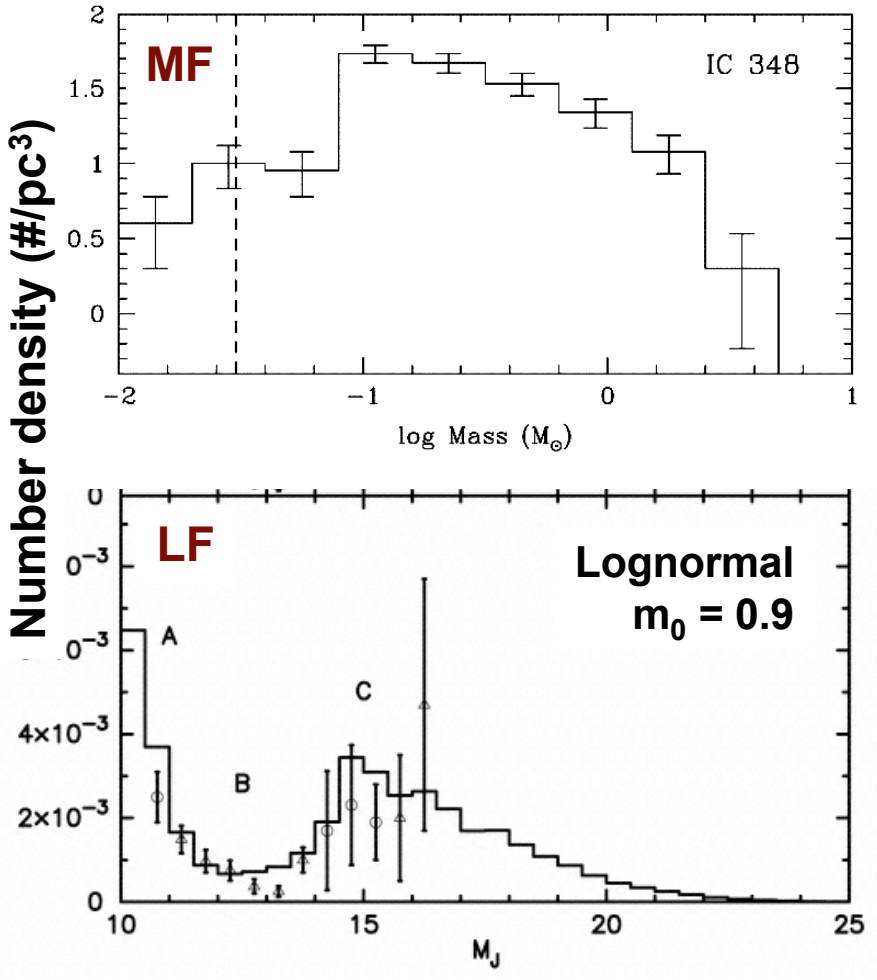
models from Burrows et al. (2001)



$$N_{BD}:N_{*} \approx 1:1$$

roughly…

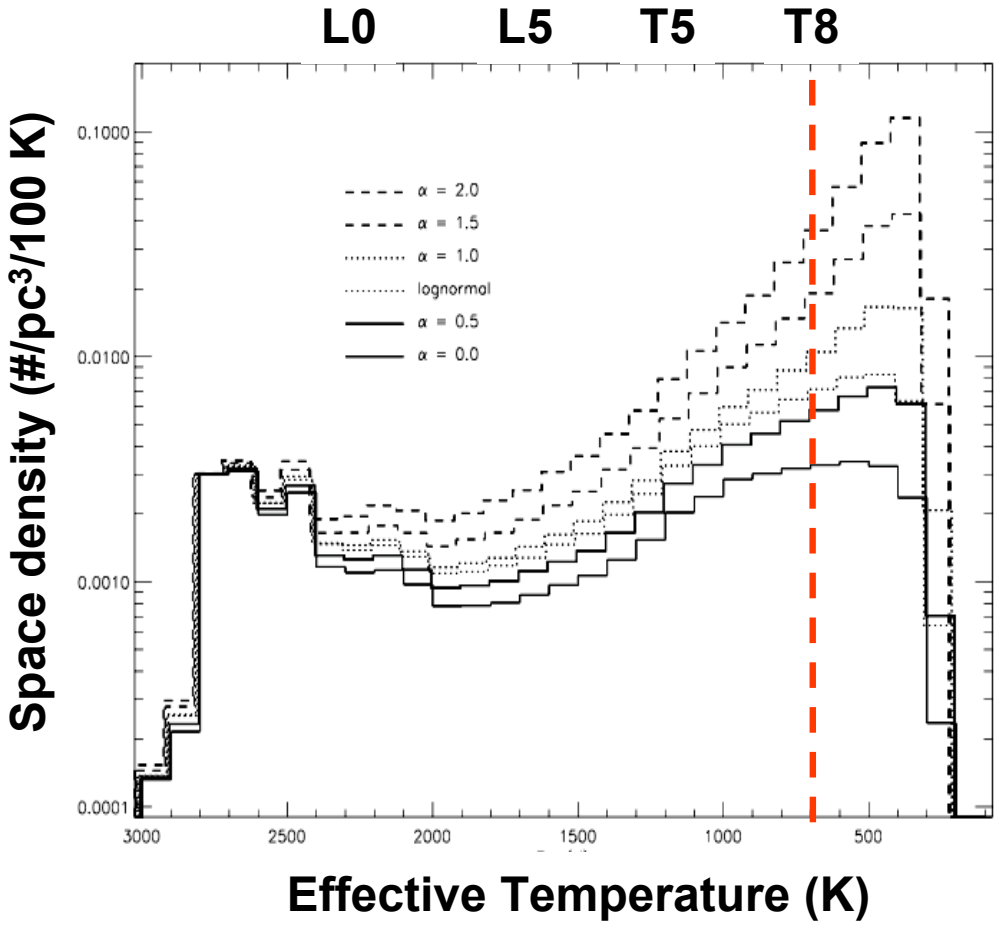
BD/star number fractions



Luhman et al. (2003); Allen et al. (2005)

- Young clusters:
  - dN/dM ∝ $M^{-0.3}$ to $M^{-0.7}$
  - **$N_{BD}/N_* \approx 0.12\text{-}0.26$**
    (e.g. Luhman et al. 2007)
- Field:
  - dN/dM ∝ M^{0} to $M^{-1.3}$
  - **$N_{BD}/N_* \approx 0.1\text{-}2.0$**
    (e.g. Reid et al. 1999)

why is the density of field brown dwarfs so uncertain?

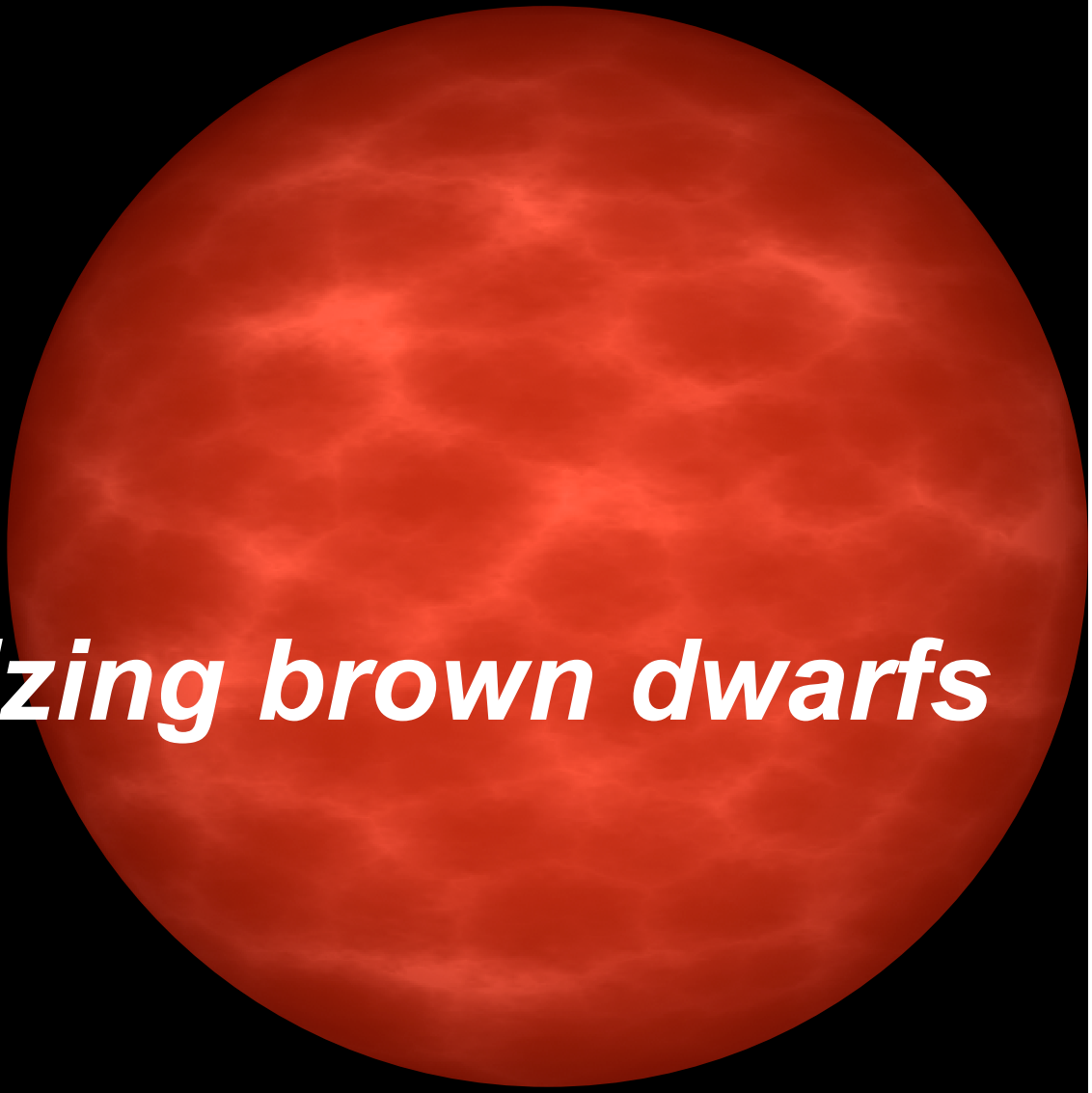


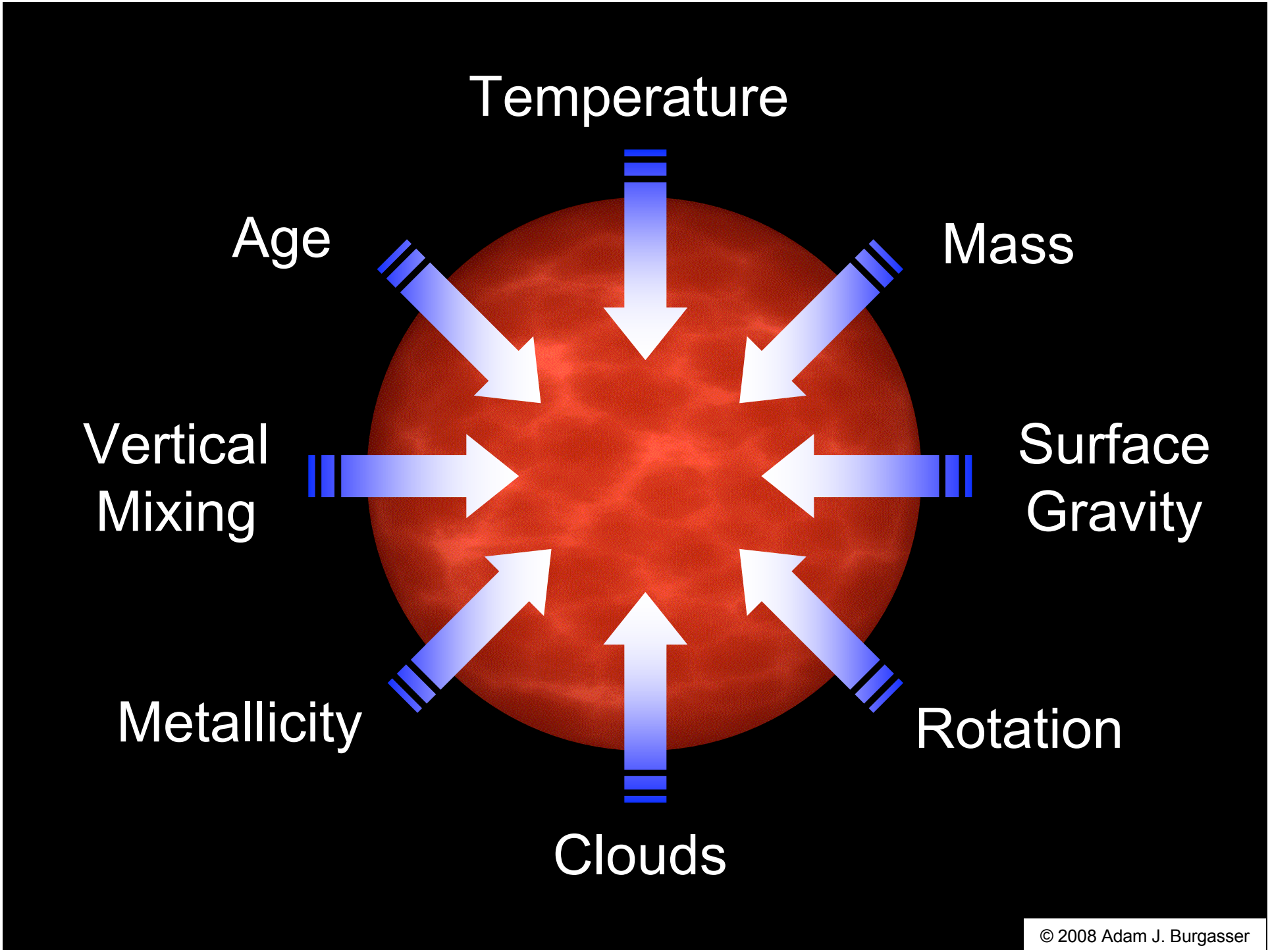
Mass/age degeneracy of brown dwarfs ⇒ converting LF→MF is a ***statistical exercise***.

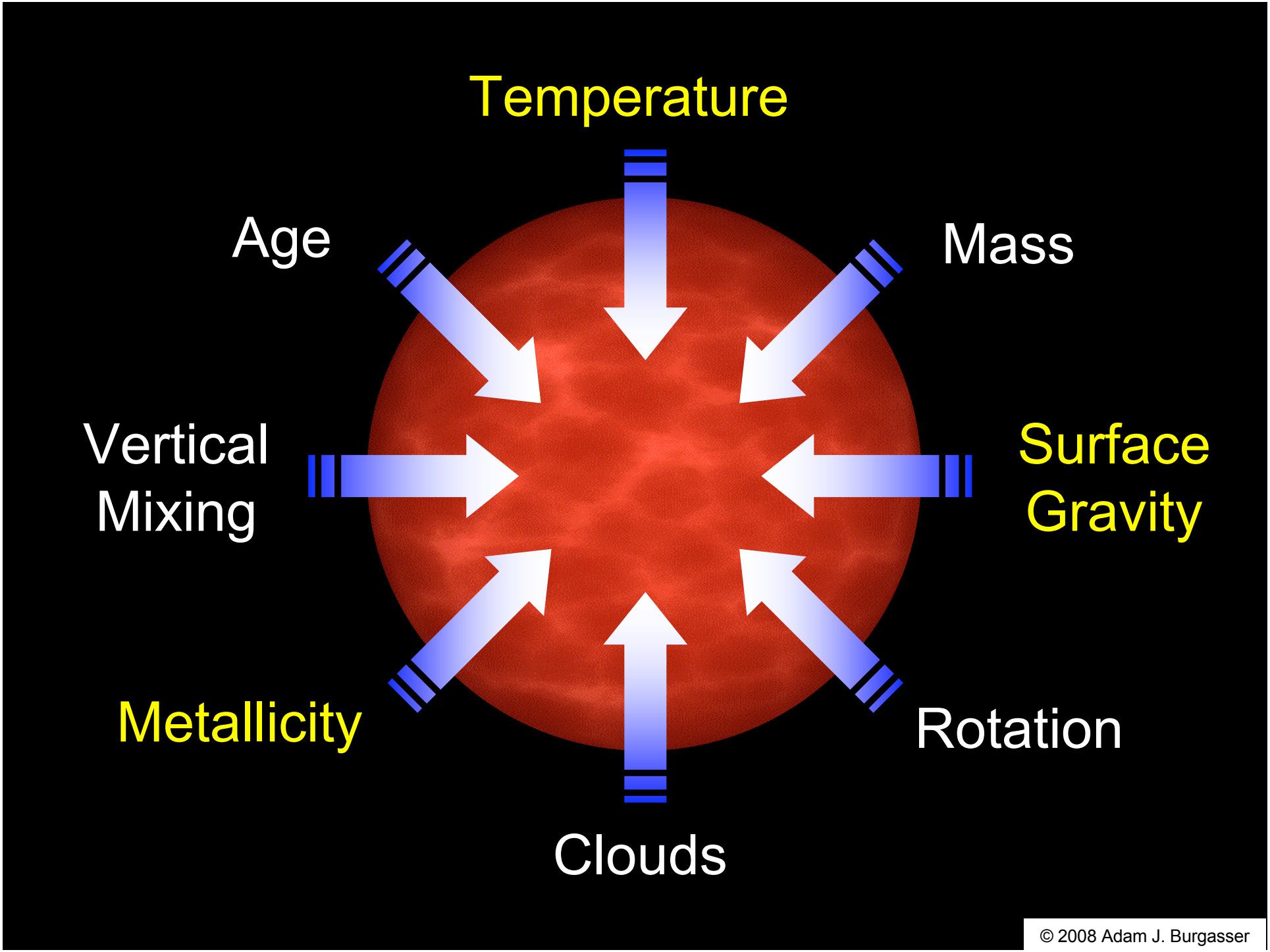
Most field brown dwarfs are now extremely cold (T_{eff}<700 K, SpT>T8)

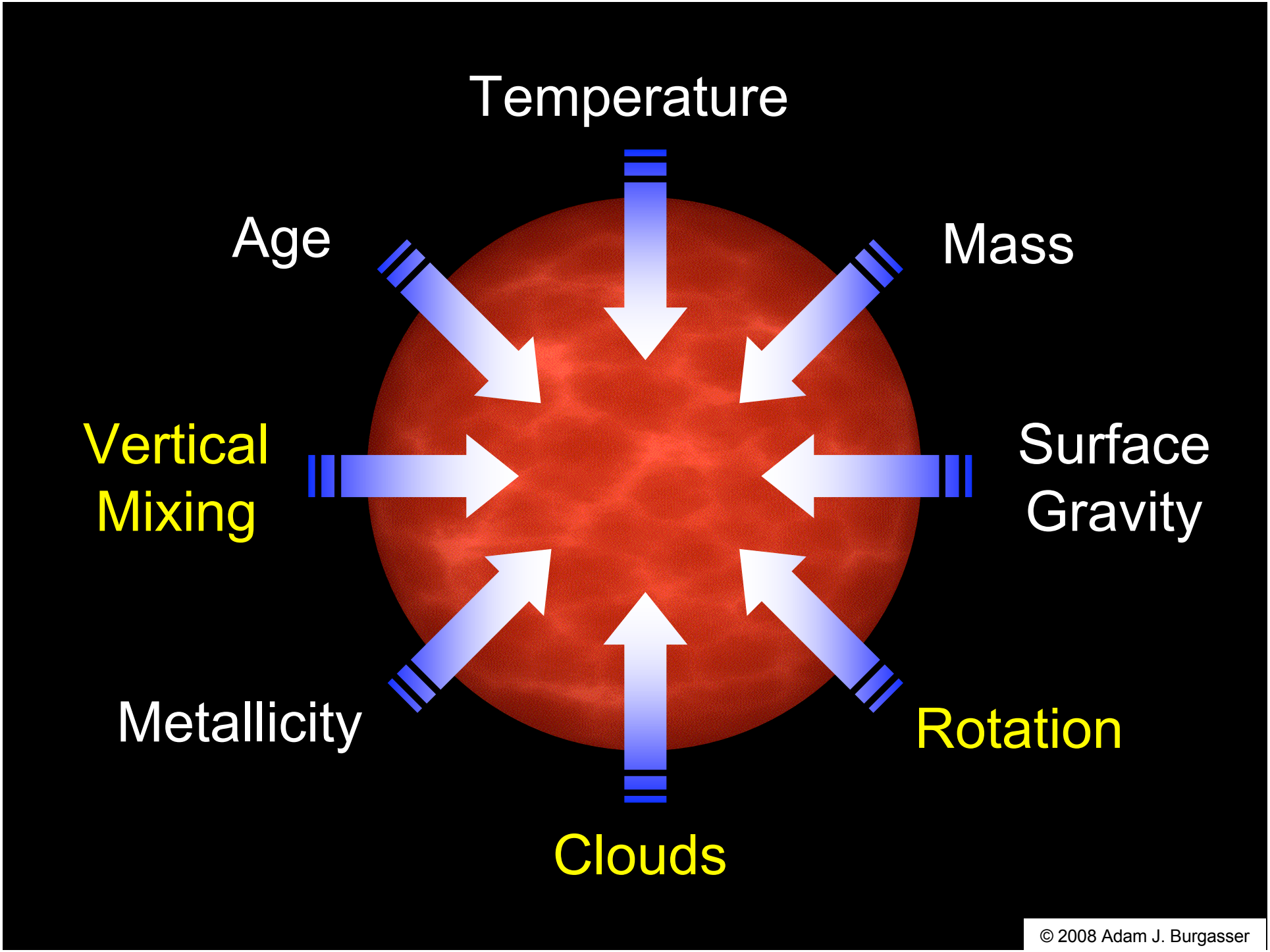
Burgasser (2004)
see also Allen et al. (2005)

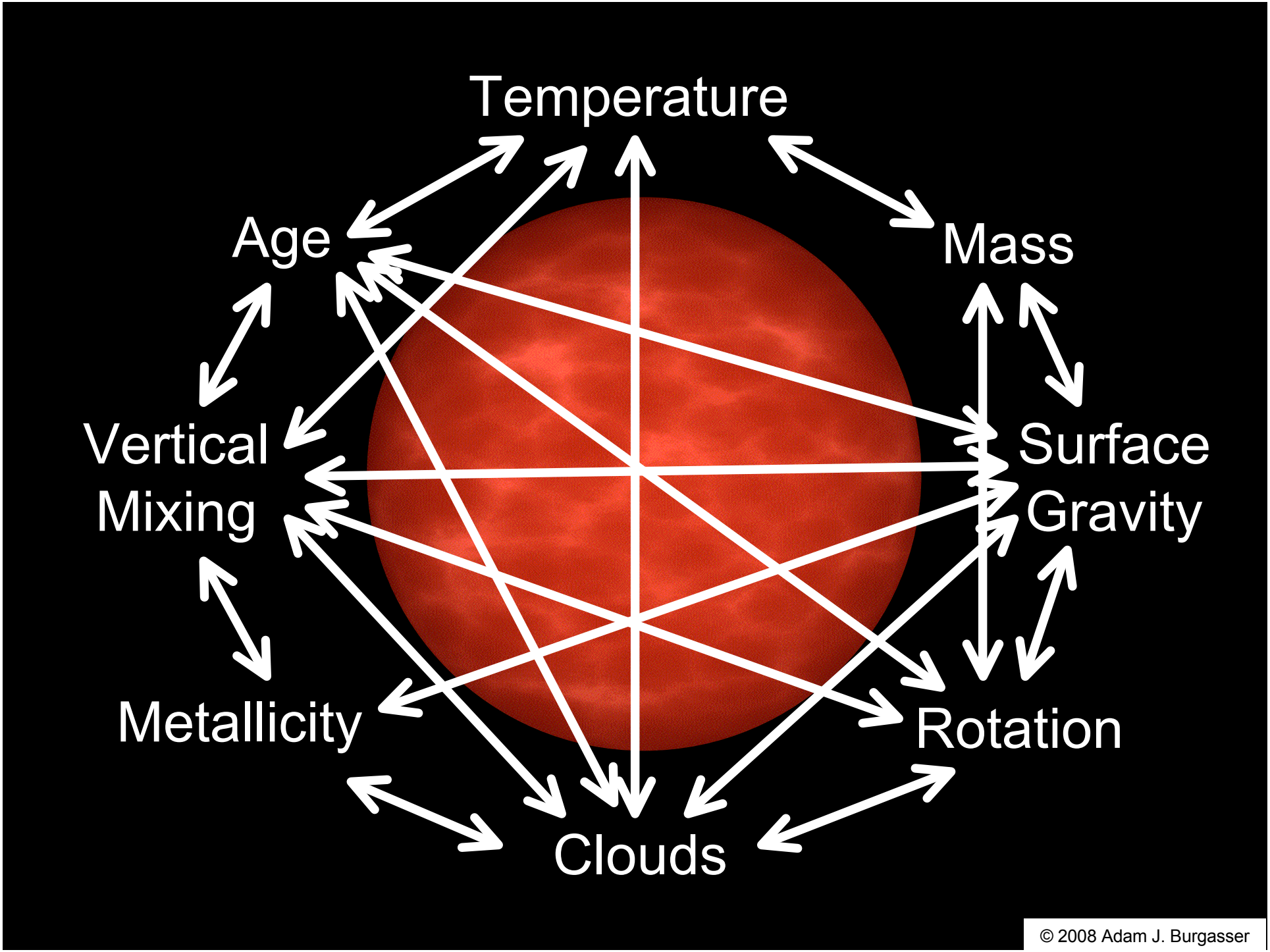
characterizing brown dwarfs

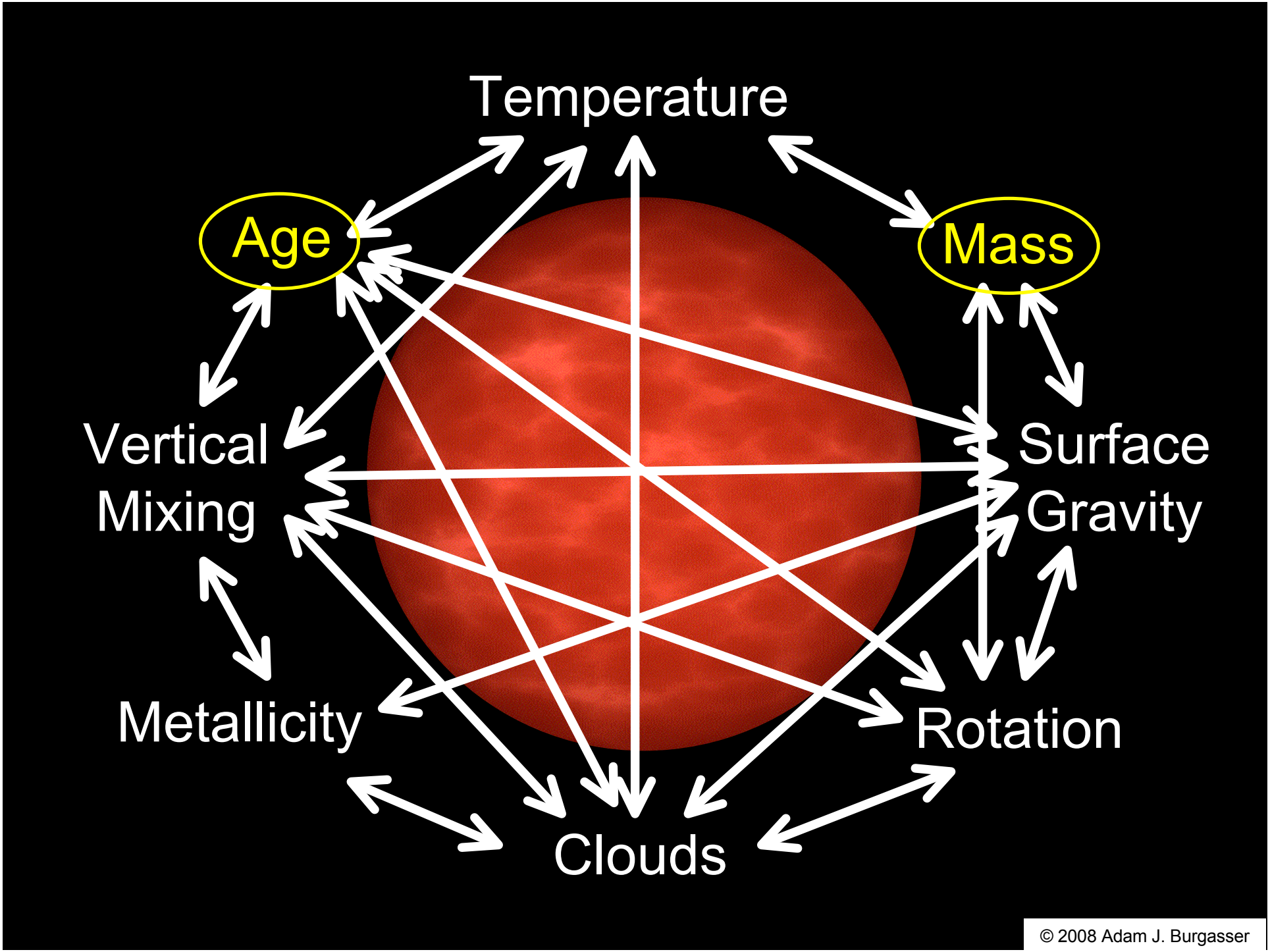




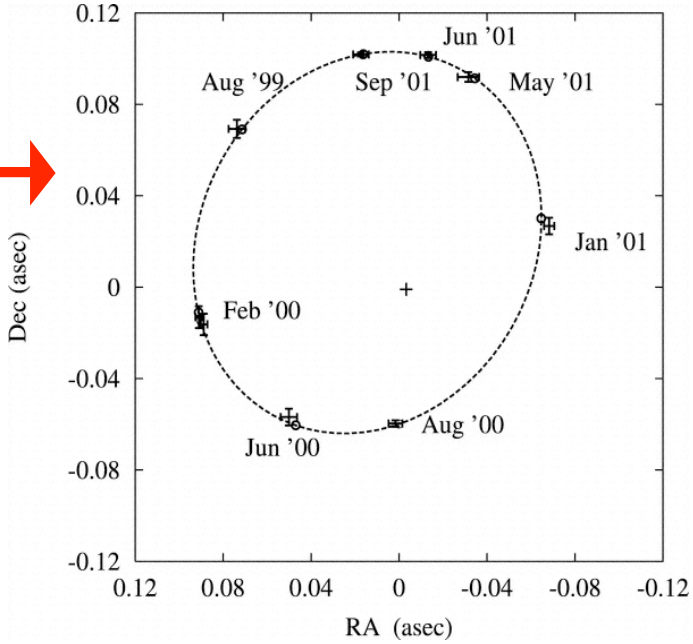




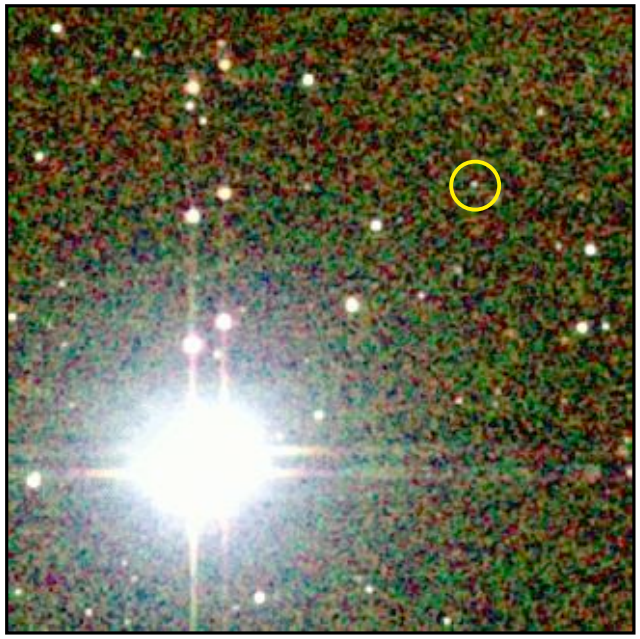




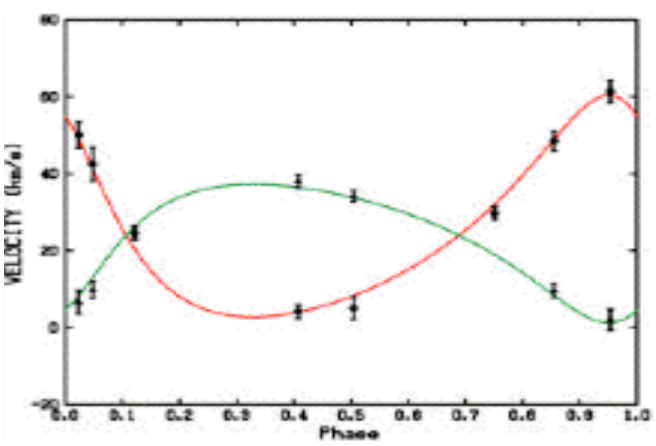
some are easy…



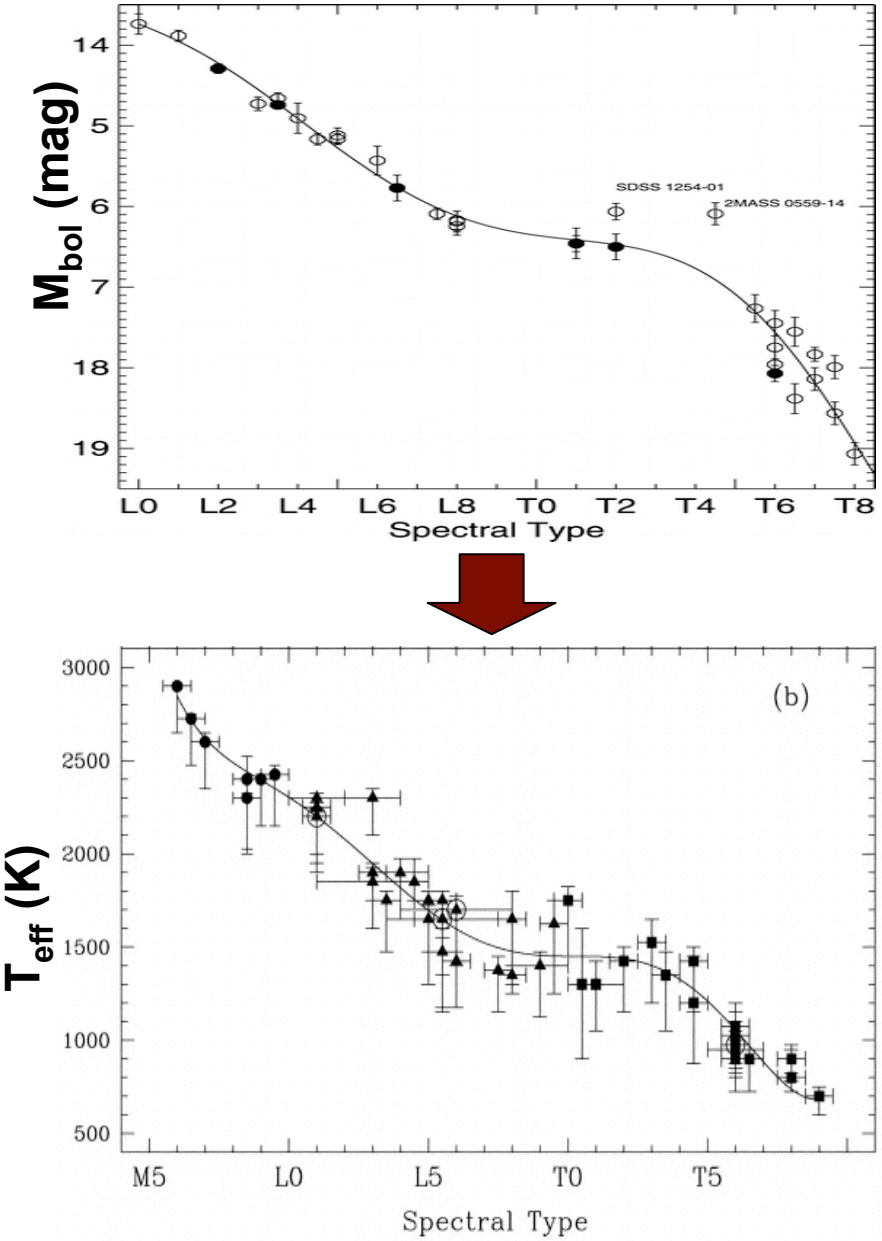
GJ 569Bab (e.g., Lane et al. 2001)
Astrometric binary and companion to nearby young star (mass, age and distance)



Gliese 570D (e.g., Burgasser et al. 2000)
Brown dwarf companion to nearby star (age and distance)



2MASS 0535-0546AB (e.g., Stassun et al. 2006)
Eclipsing spectroscopic binary in Orion (mass, age, distance and radius)



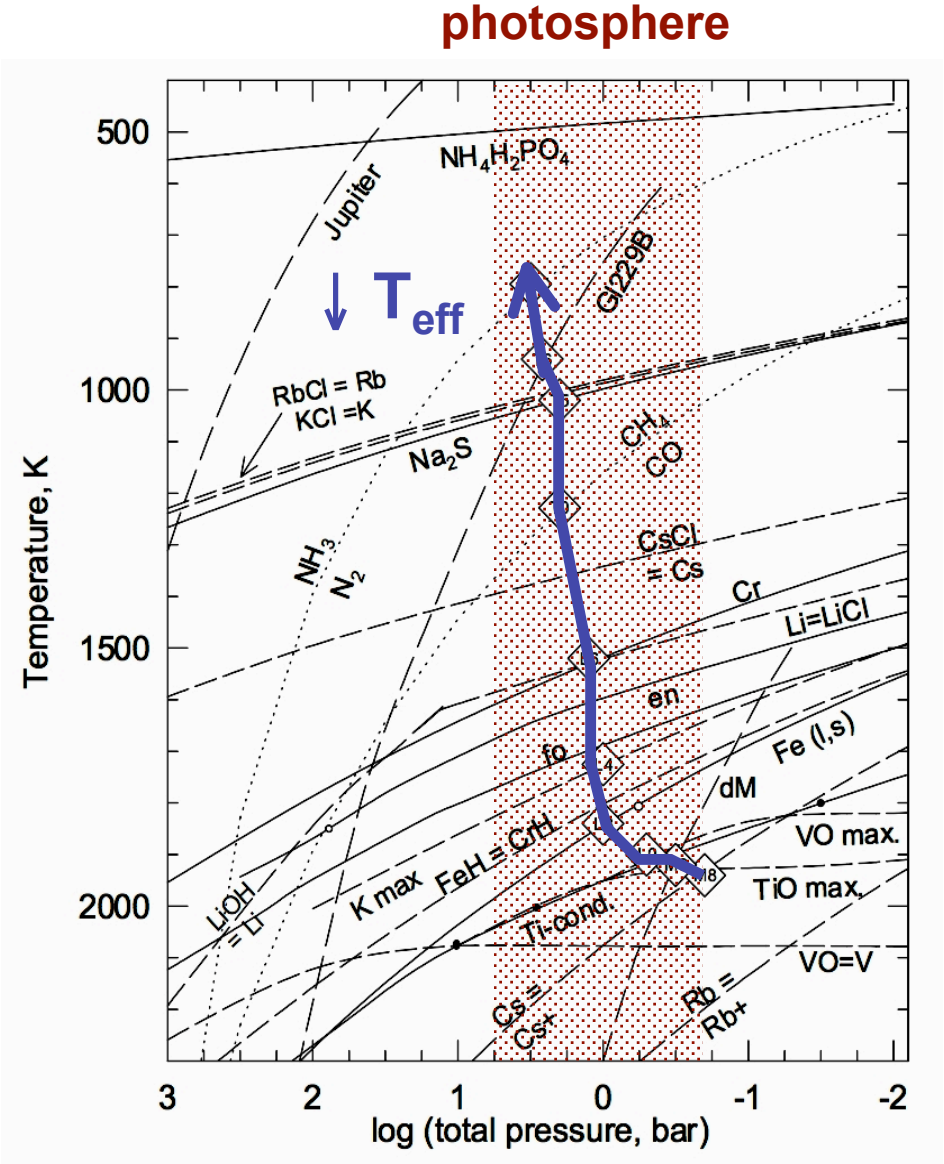
Burgasser (2007); Golimowski et al. (2004)

temperature

(1) $L_{bol} \propto T_{eff}^4$

Takes advantange of near-constant radius of BDs ($R \approx R_{Jupiter}$), directly measurable through parallax & bolometric flux measurements

(e.g., Dahn et al. 2002; Golimowski et al. 2004; Vrba et al. 2004; Burgasser et al. 2008)



temperature

(2) chemistry

- spectral model fits
- chemical conversions

e.g.:

$TiO \rightarrow TiO_2(s) \approx 2100\text{-}2300$ K

$VO \rightarrow VO(s) \approx 1900\text{-}2100$ K

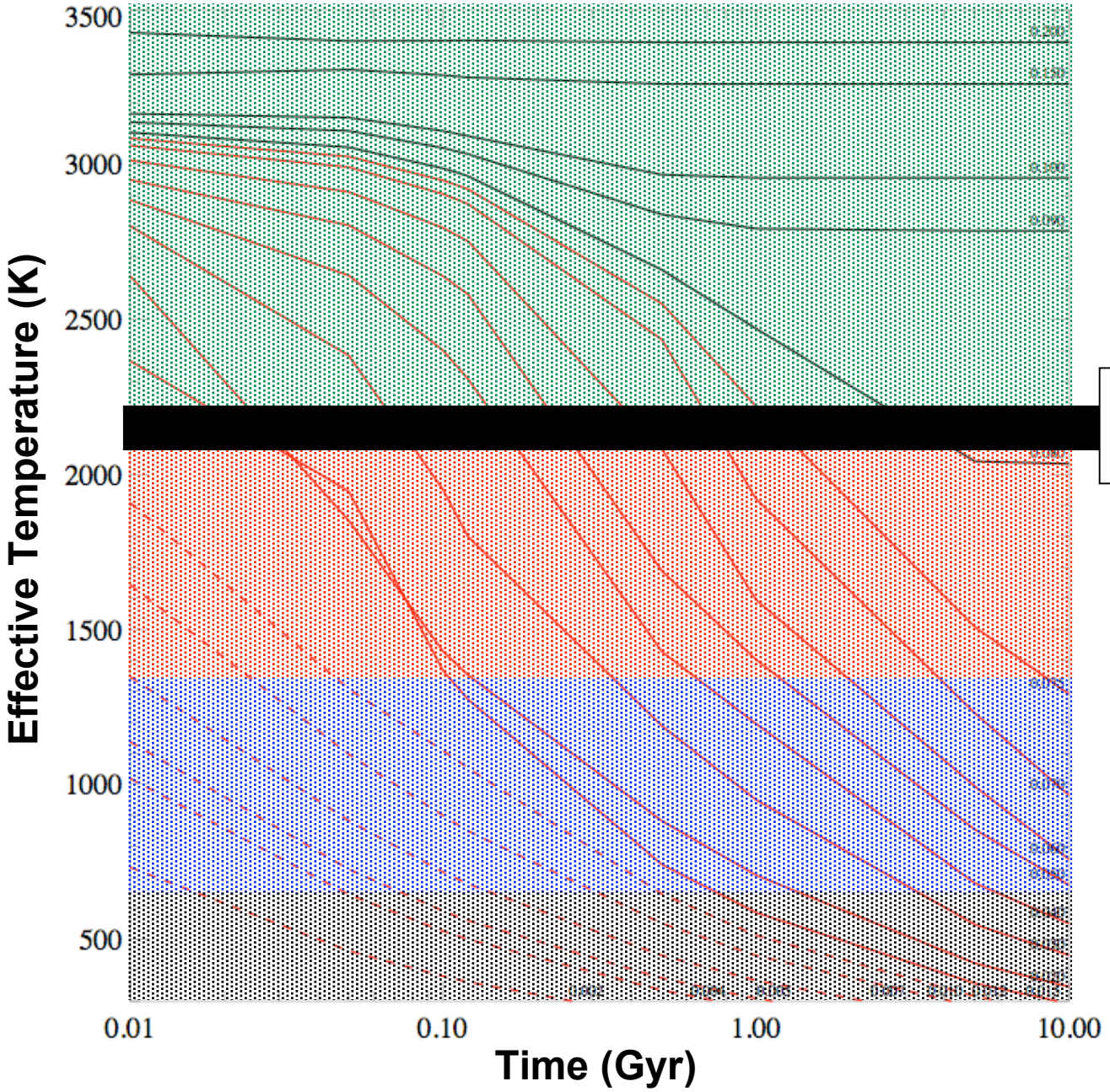
$CO \rightarrow CH_4 \approx 1200$ K

$Rb/K \rightarrow RbCl/KCl \approx 1000$ K

$H_2O \rightarrow H_2O(l) \approx 400$ K

Lodders (2006)

See also Burrows & Sharp 1999; Lodders 1999; Mohanty et al. 2006; Saumon et al. 2007)



M dwarfs
(3000-2100 K)

Brown dwarf or star?

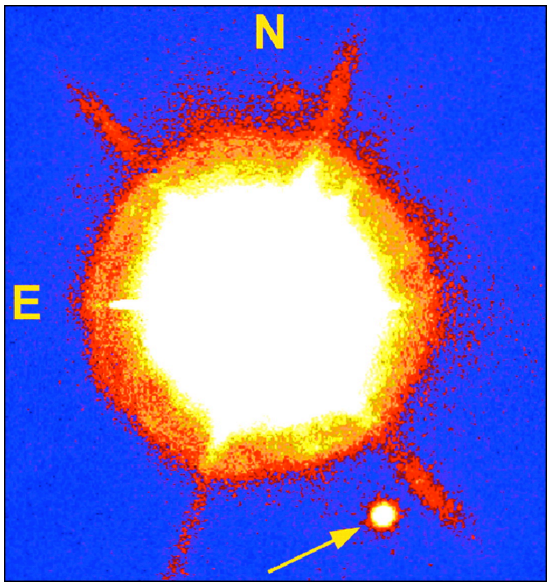
L dwarfs
(2100-1300 K)

T dwarfs
(1300-600?K)

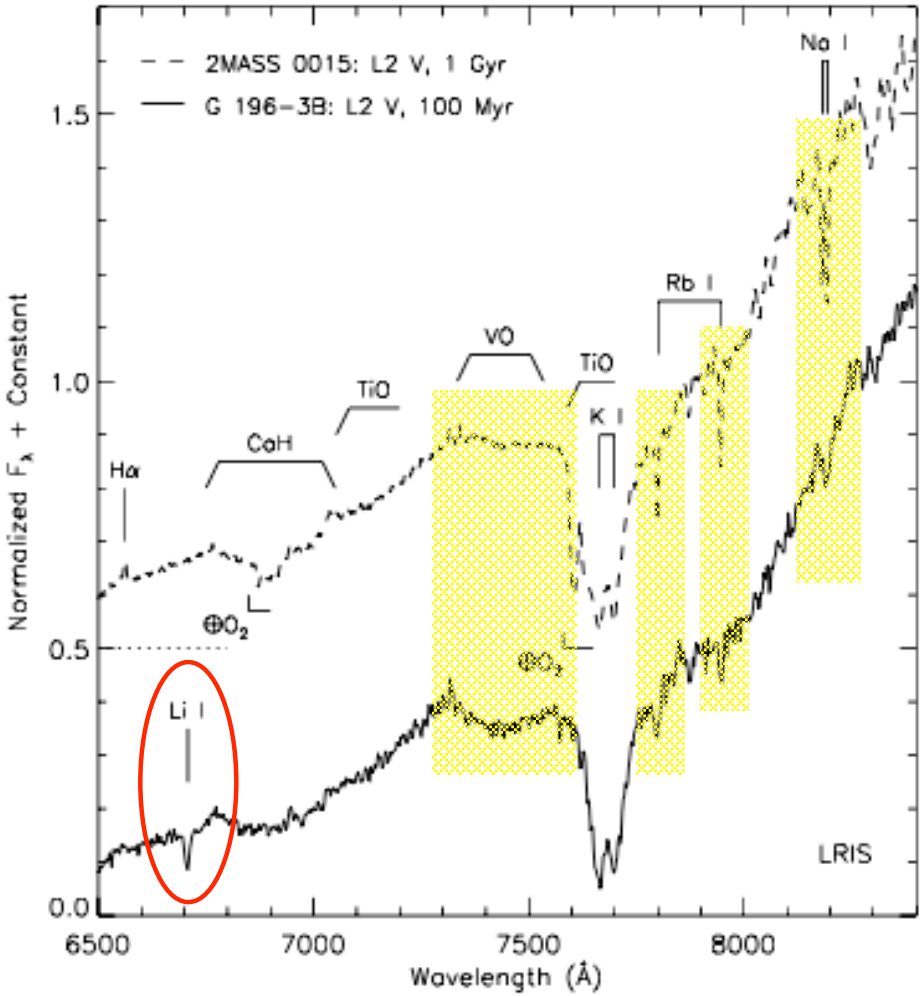
Y dwarfs?
(< 600? K)

models from Burrows et al. (2001)

surface gravity effects

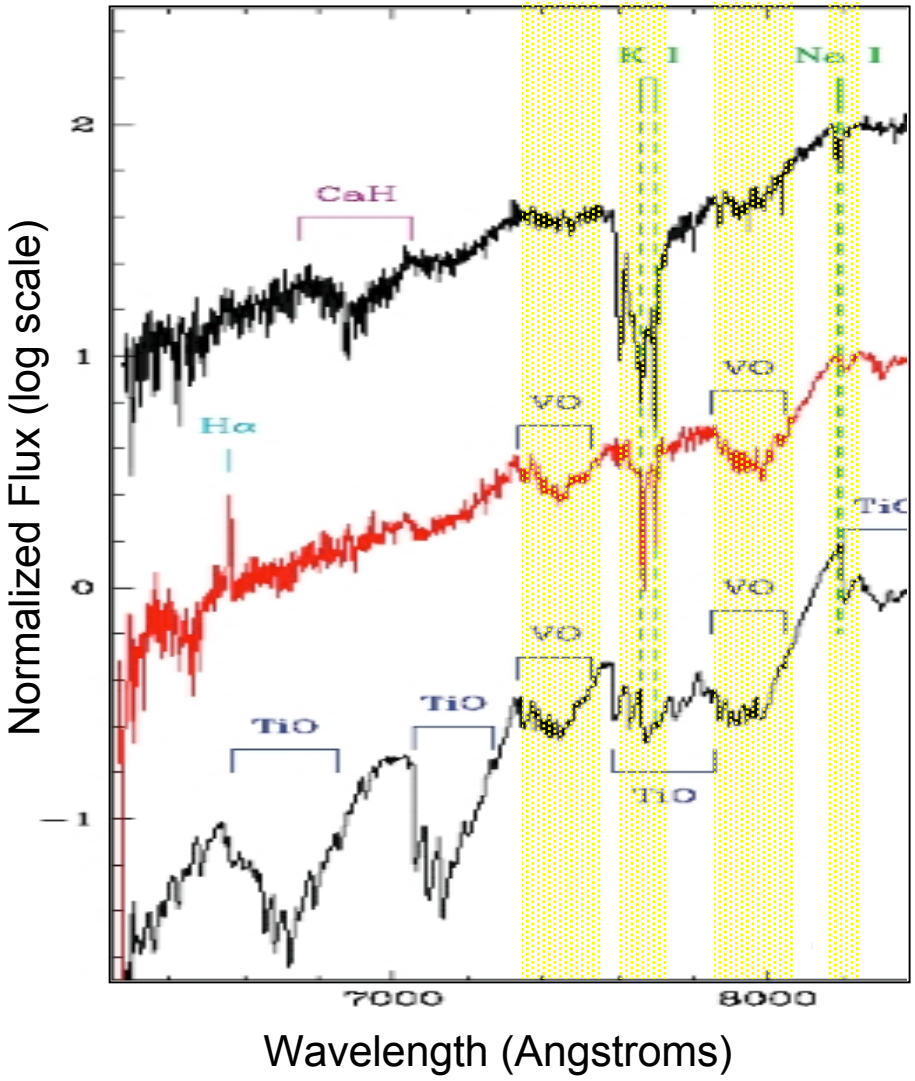


G 196-3B
companion to
~30-300 Myr
G 196-3A



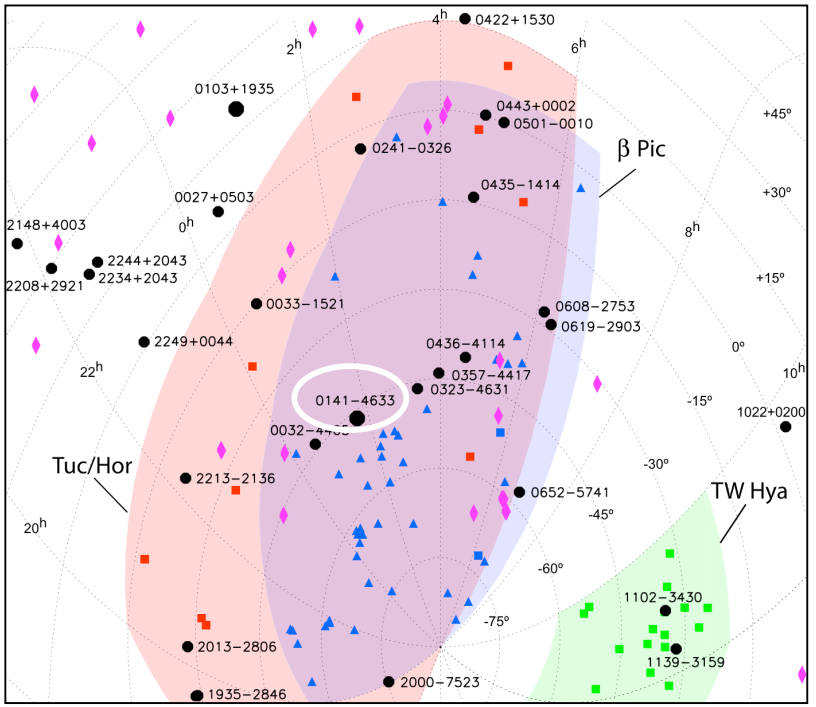
Rebolo et al. (1998); Kirkpatrick et al. (in prep.)
See also Martin et al. (1999); Gorlova et al. (2003); Luhman et al. (2003); Allers et al. (2007)

spectral gravity features



Kirkpatrick et al. (2006)
see also Cruz et al. (2007)

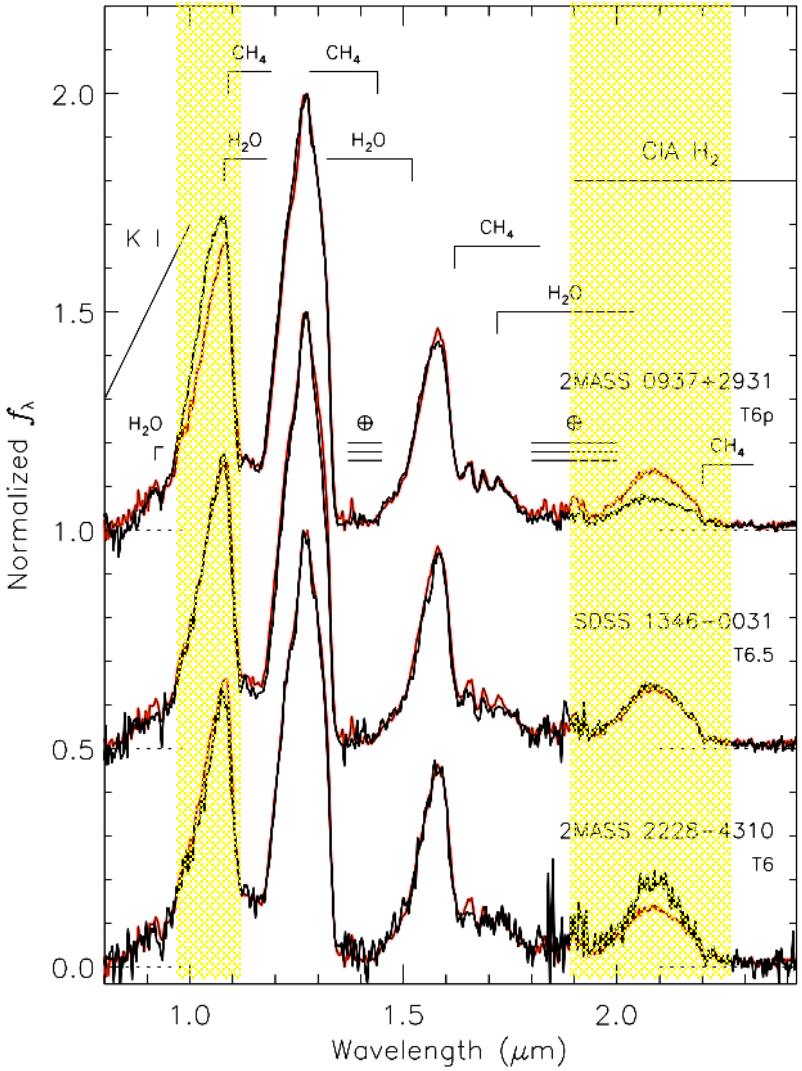
spatial map



2MASS 0141-4633

possible member of
Tucana/Horologium
moving association
~30 Myr, 6-25 $M_{Jupiter}$

surface gravity effects

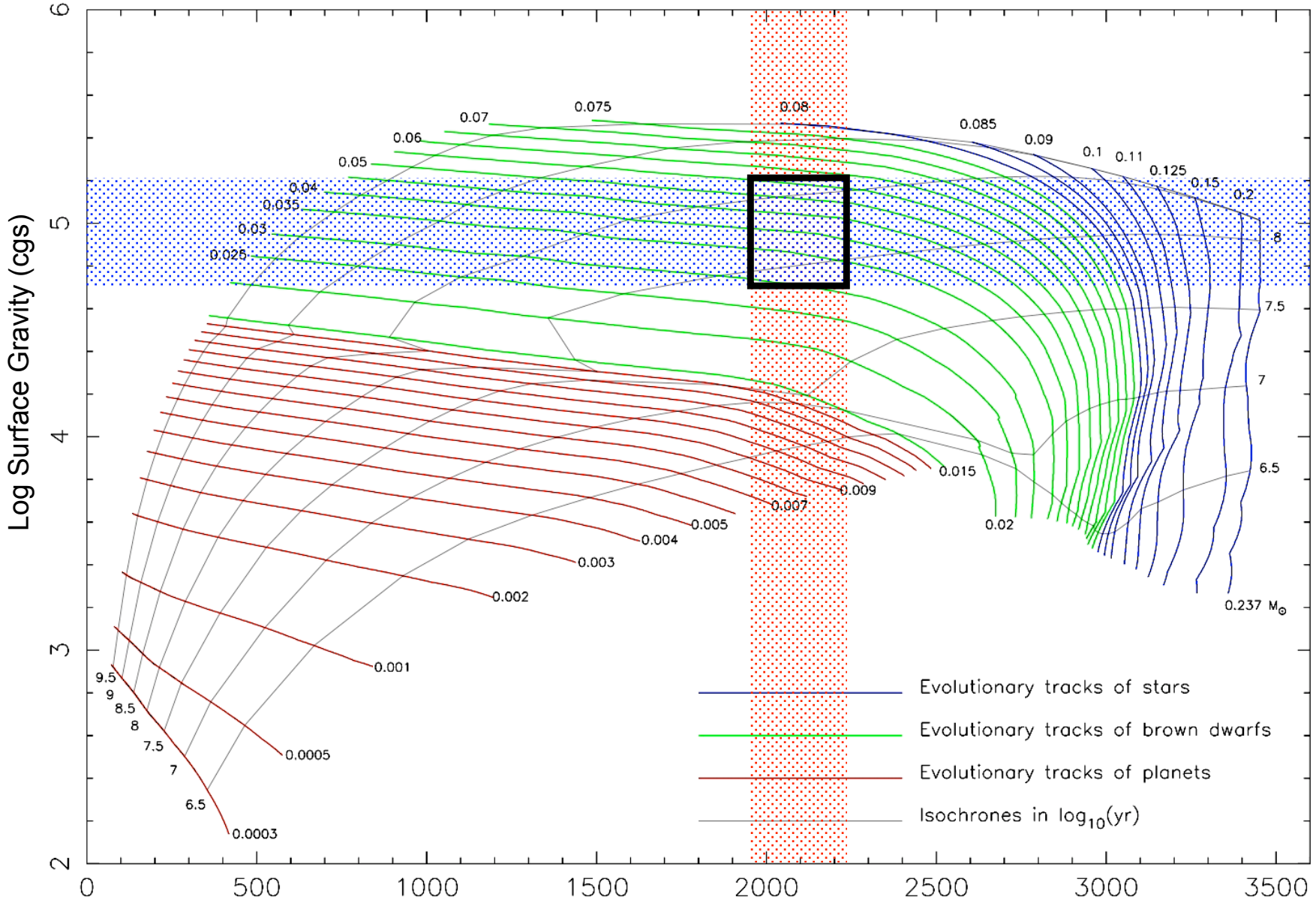


Burgasser, Burrows & Kirkpatrick (2006)

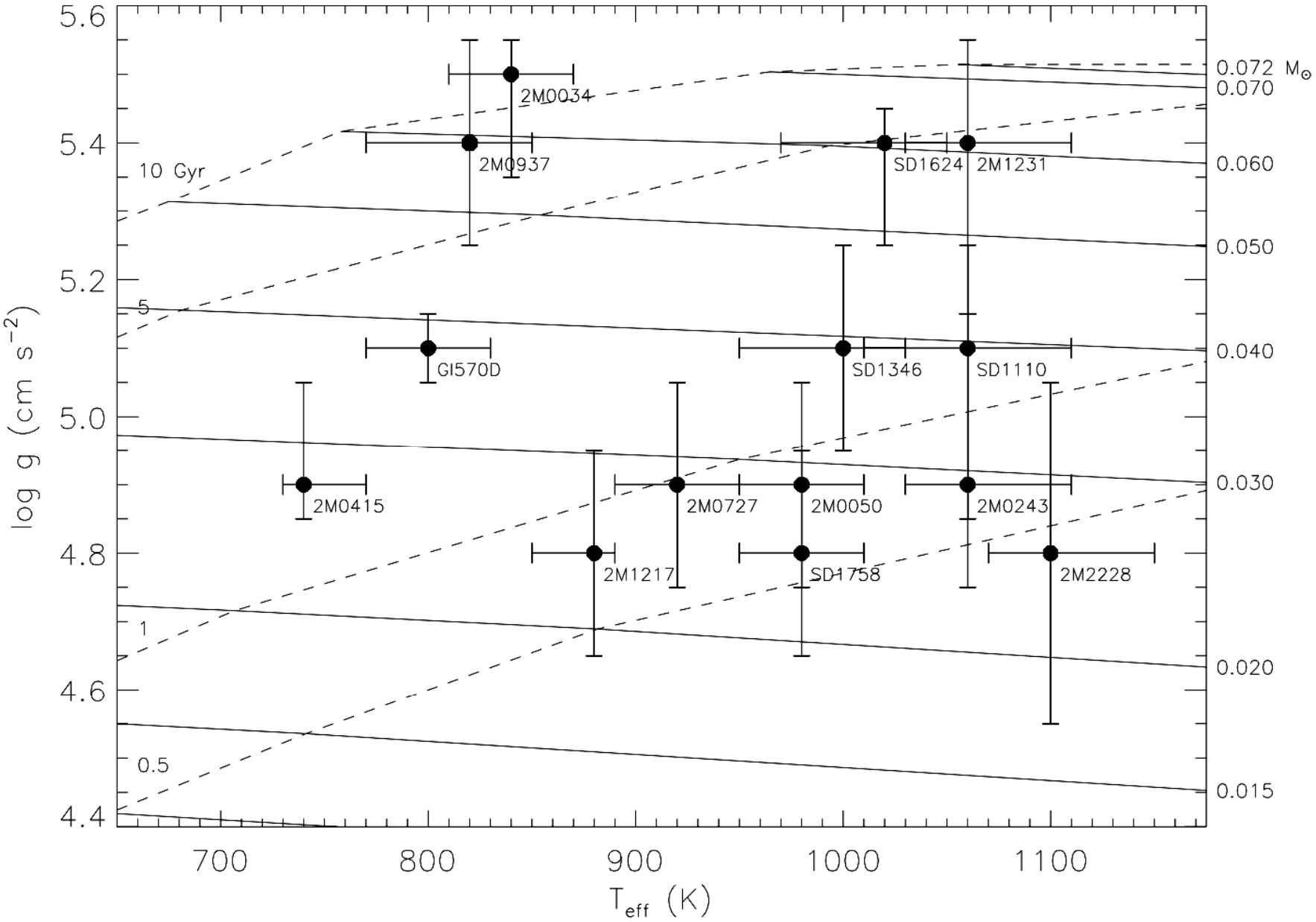
Species such as H_2 (collision induced absorption) and K I/Na I wings are specifically pressure sensitive.

$$P_{phot} \approx g/\kappa_r \propto M/R^2$$

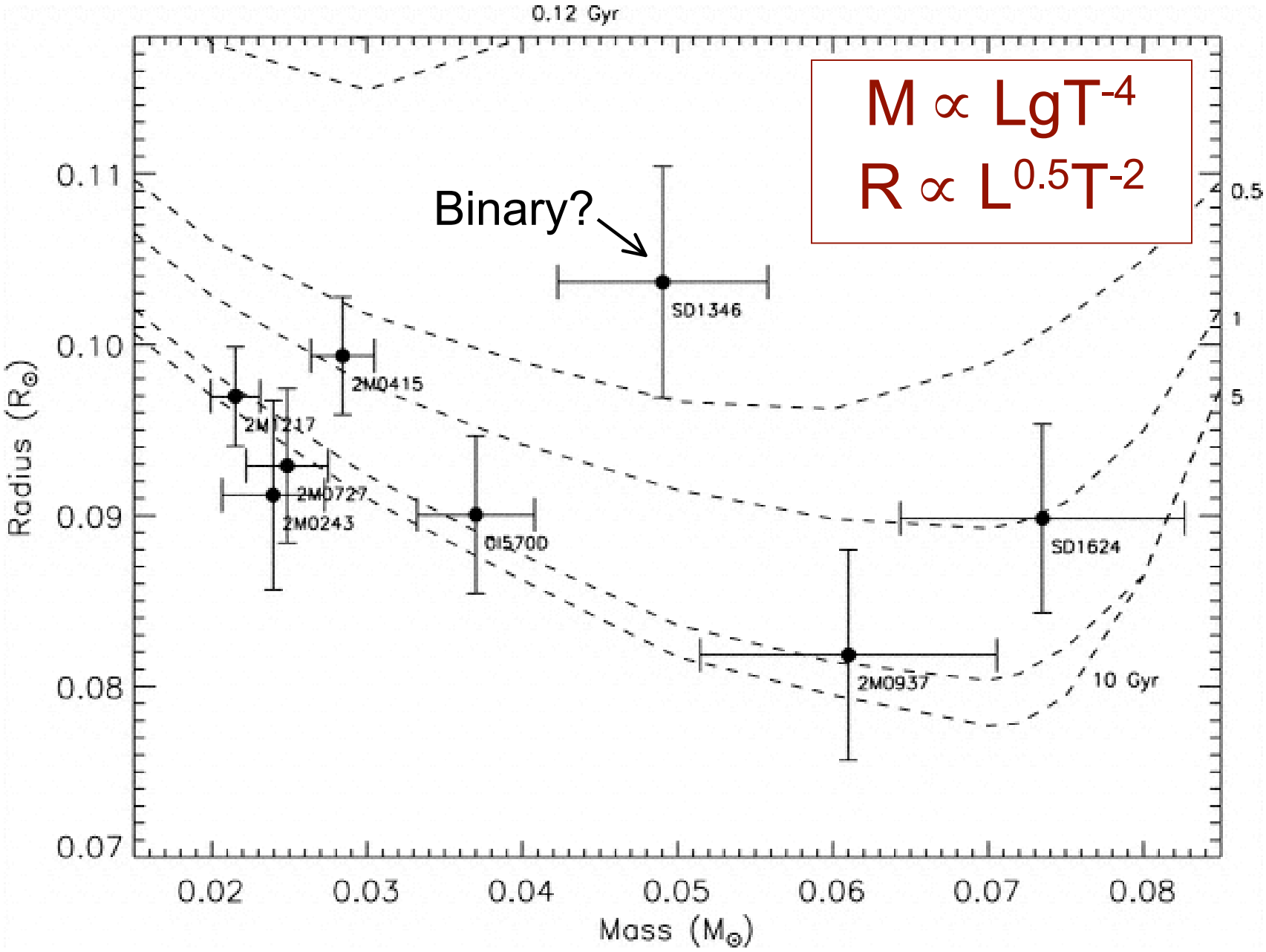
see also Knapp et al. (2004); Burgasser (2007); Liebert & Burgasser (2007); Leggett et al. (2008)



Burrows et al. (1997)

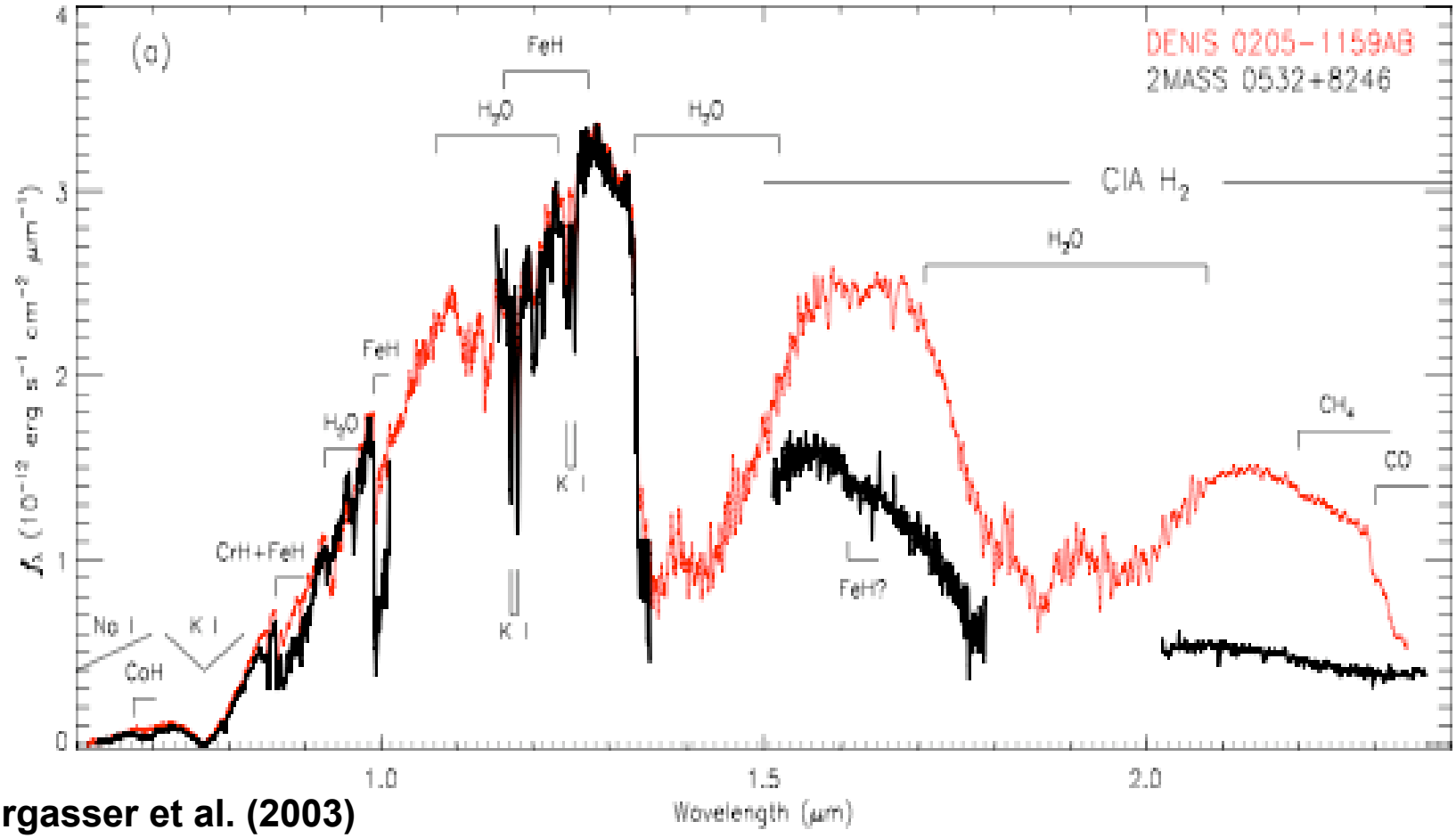


Burgasser, Burrows & Kirkpatrick (2006)



Burgasser, Burrows & Kirkpatrick (2006)

metallicity is a confounding factor



Burgasser et al. (2003)

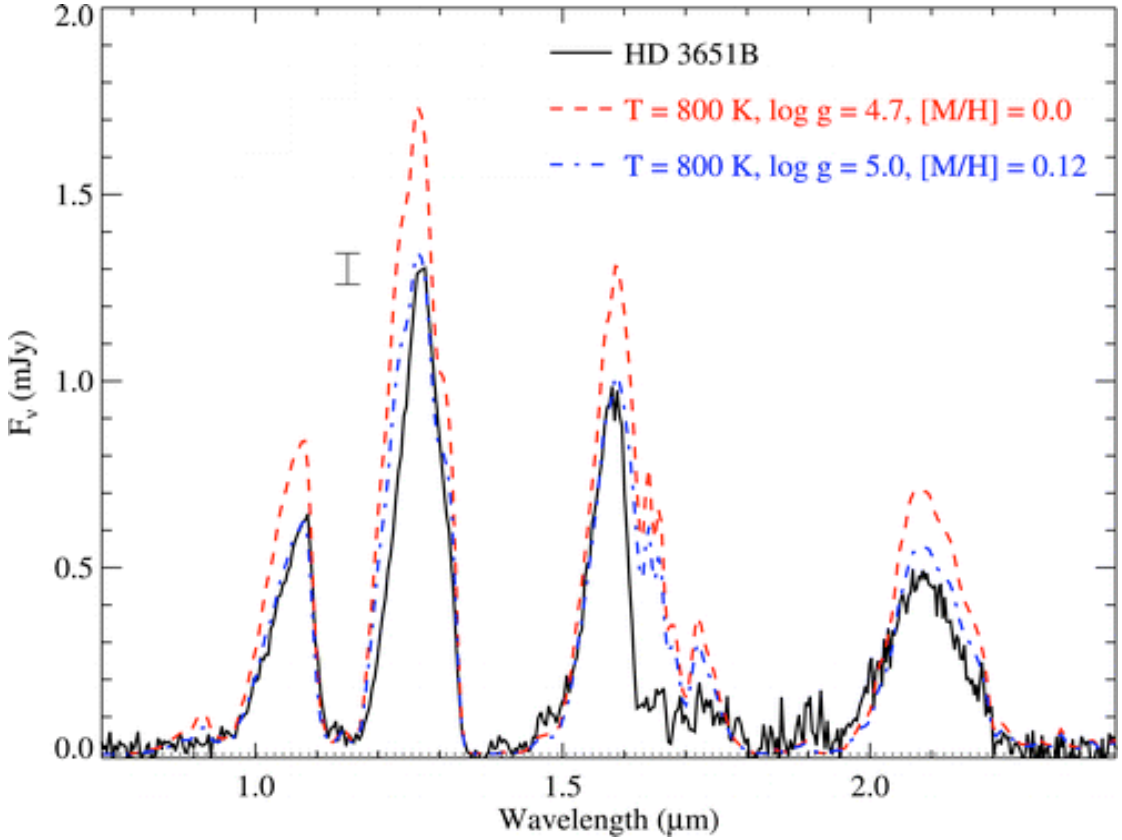
L subdwarf 2MASS 0532+8246

J-K = 0.17±0.07 (>1.5 mag too blue)
halo kinematics (V = -350 km/s)

HD 3651ABb

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

K0+T8+planet
BD T_{eff} = 790±30 K

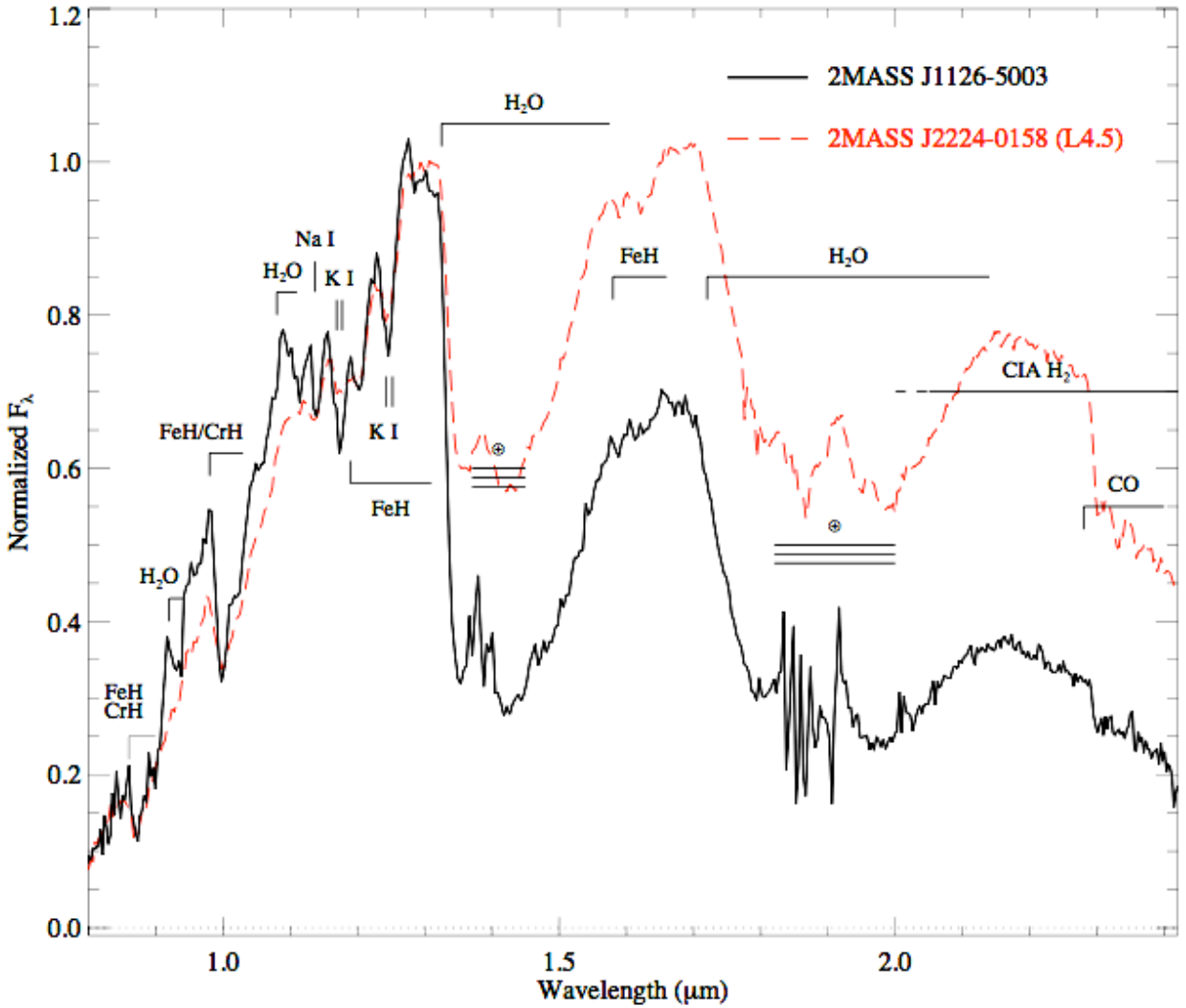


Burgasser (2007)
see also Liu et al. (2007); Leggett et al. (2008)

[M/H] = 0
log g = 4.7±0.2
age = 0.4-1.2 Gyr

[M/H] = 0.12±0.04
log g = 5.0±0.2
age = 0.7-4.7 Gyr

clouds: a fourth parameter!



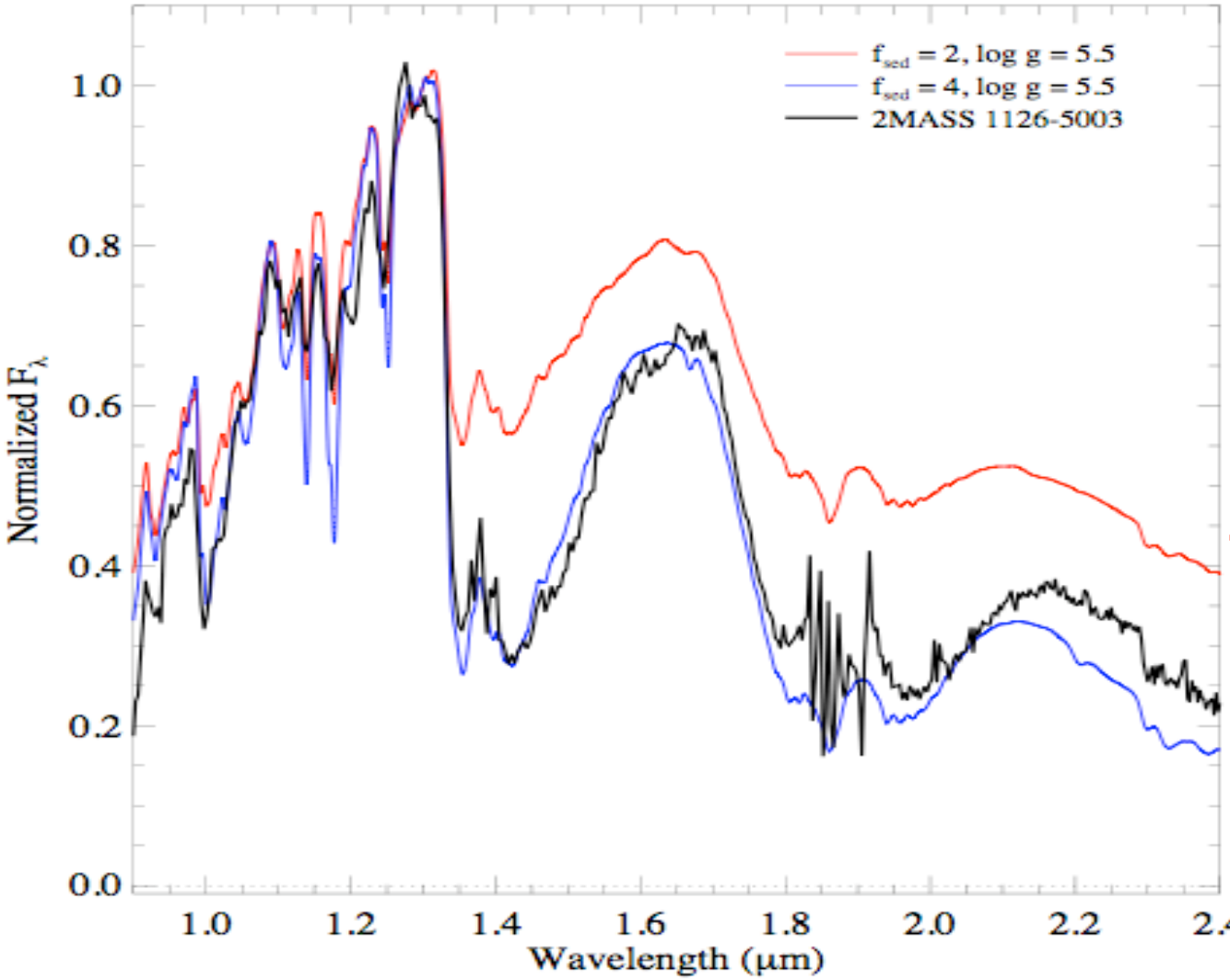
Red L dwarf

Blue L dwarf

Burgasser et al. (2008)

See also Ackerman & Marley (2001); Knapp et al. (2004); Cruz et al. (2007); Cushing et al. (2008)

clouds: a fourth parameter!

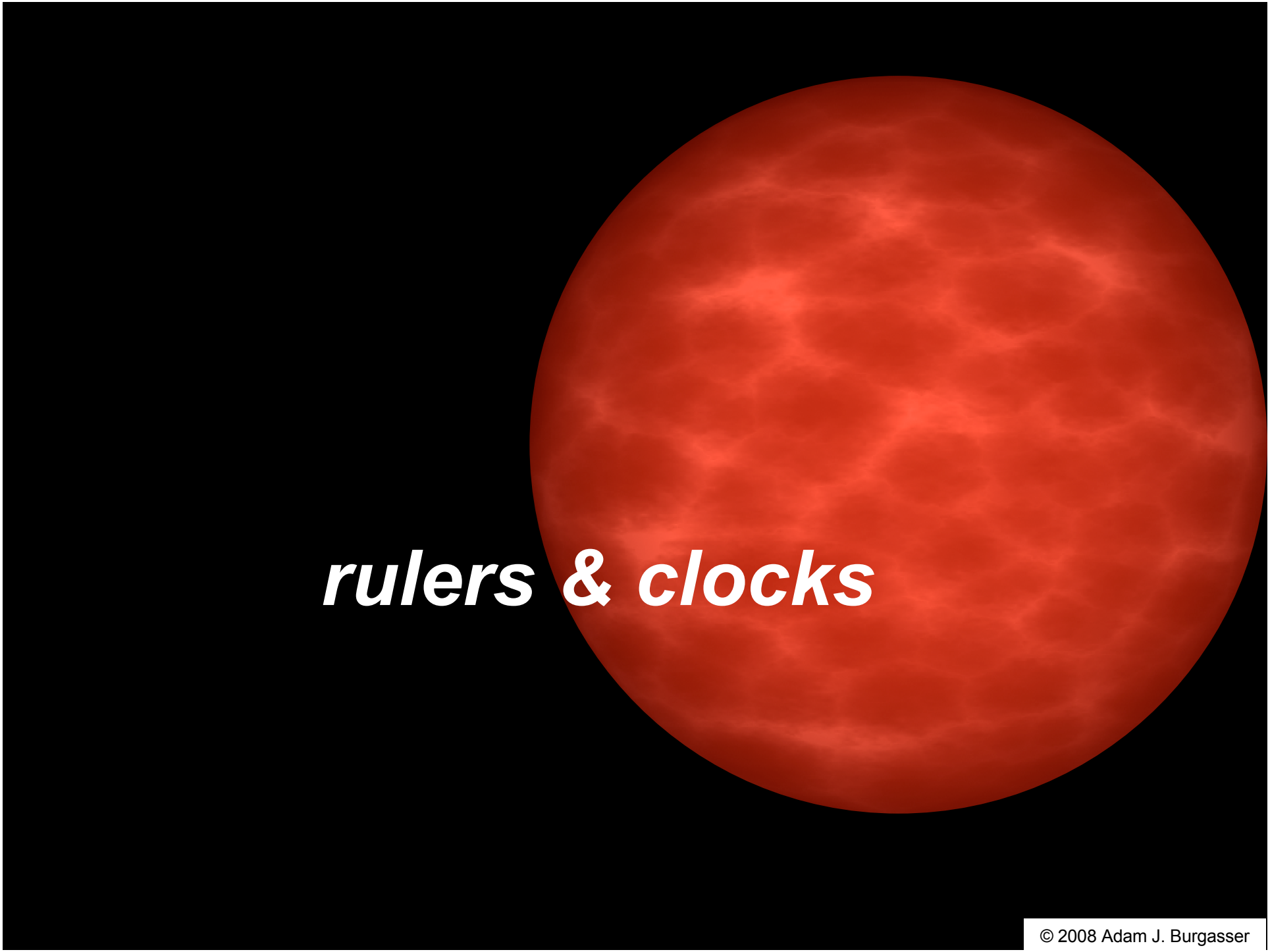


Thick clouds

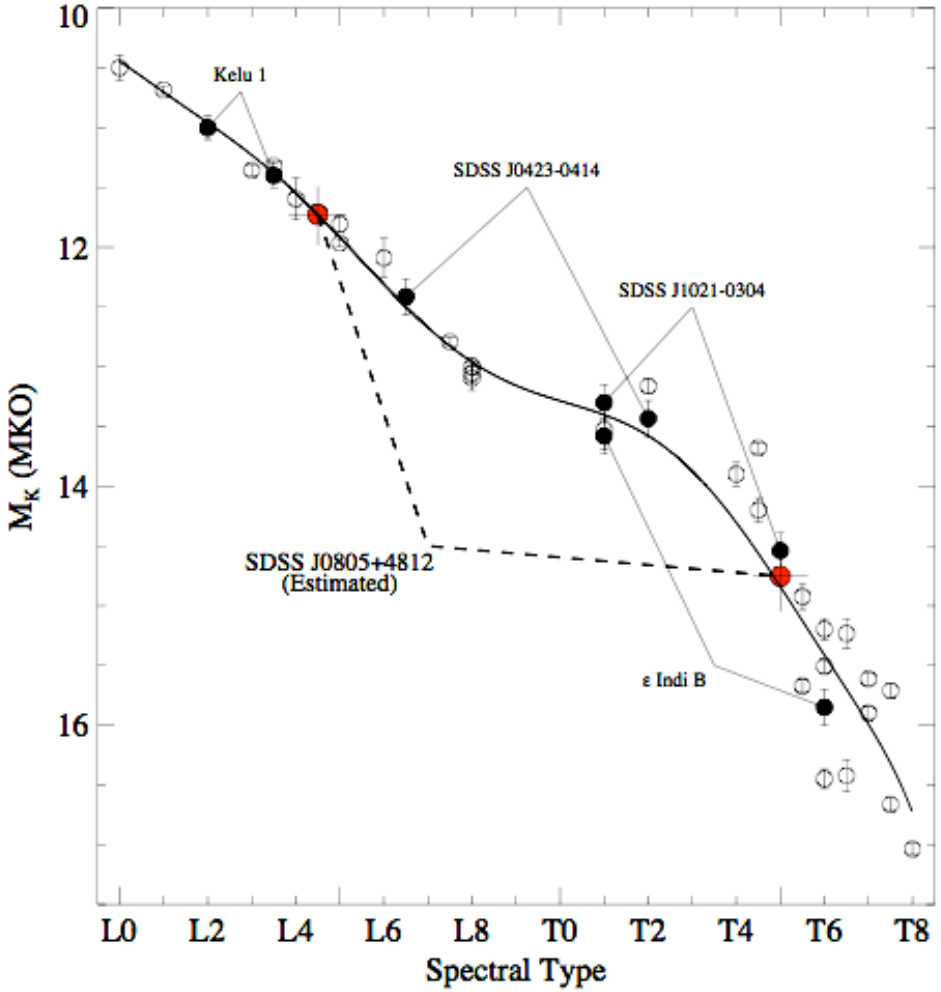
Thin clouds

Burgasser et al. (2008)

See also Ackerman & Marley (2001); Knapp et al. (2004); Cruz et al. (2007); Cushing et al. (2008)



brown dwarfs as rulers



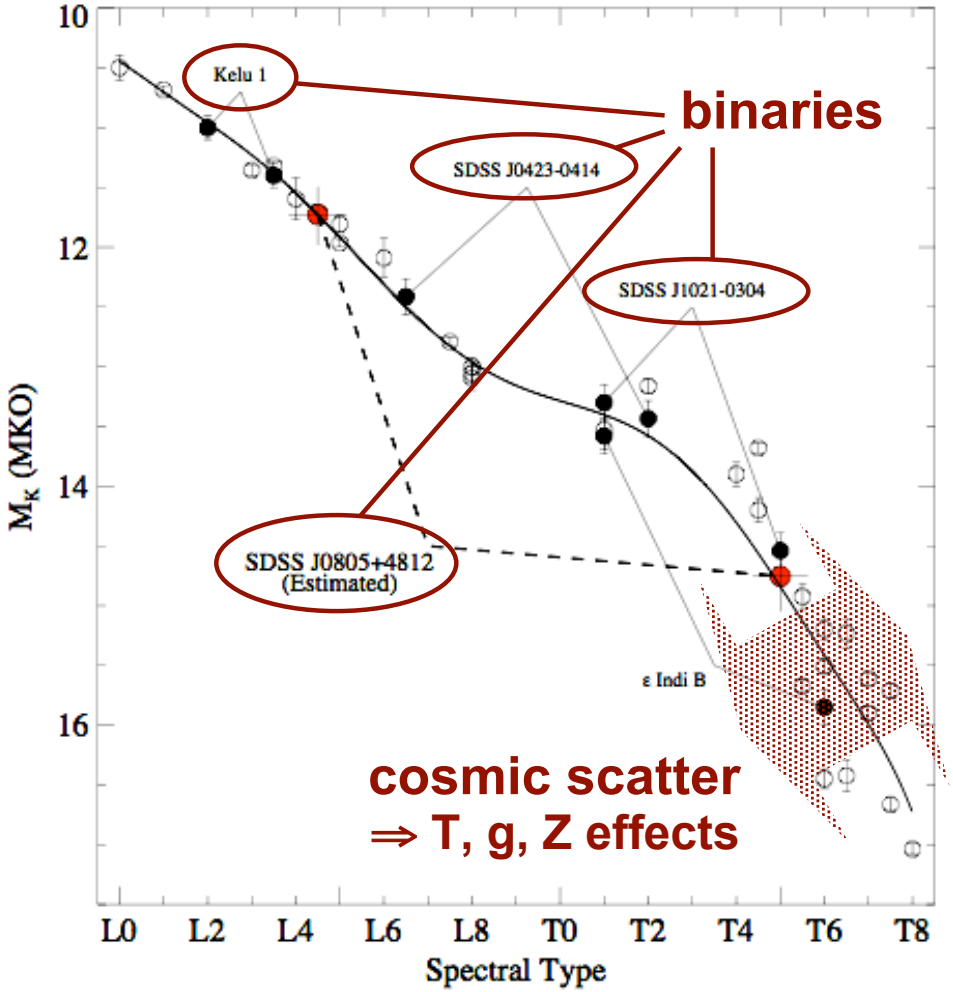
Basic astrometry…

Accurate parallax measurements have been obtained for 80 late-M, L and T-type brown dwarfs to date.

Brown Dwarf Kinematics Project:
Extend π sample to complete 20 pc

Burgasser (2007)
see also Dahn et al. (2002); Tinney et al. (2003); Vrba et al. (2004)

brown dwarfs as rulers



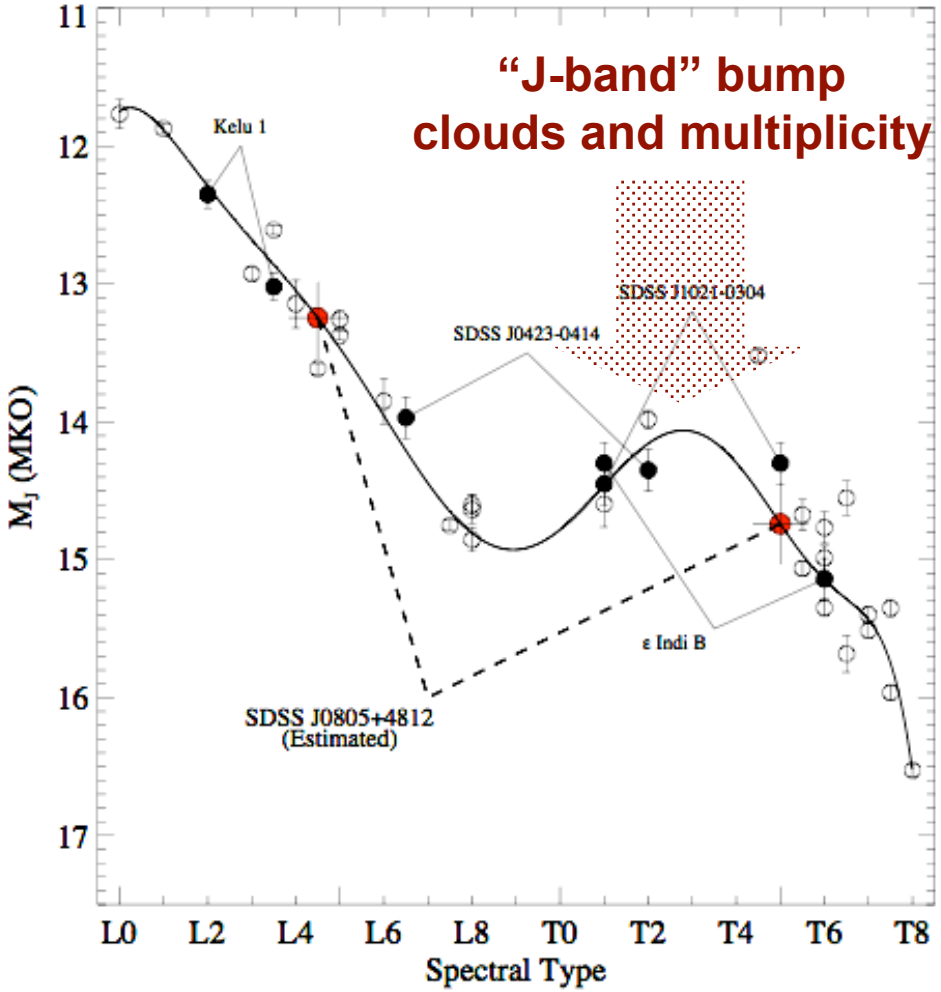
Basic astrometry… and more!

An accurate distance scale requires detailed characterization of physical effects:

- temperature (brightness)
- surface gravity (radius)
- metallicity (opacity)
- binaries (overluminous)
- clouds (opacity + brightness)

Burgasser (2007)
see also Dahn et al. (2002); Tinney et al. (2003); Vrba et al. (2004)

brown dwarfs as rulers



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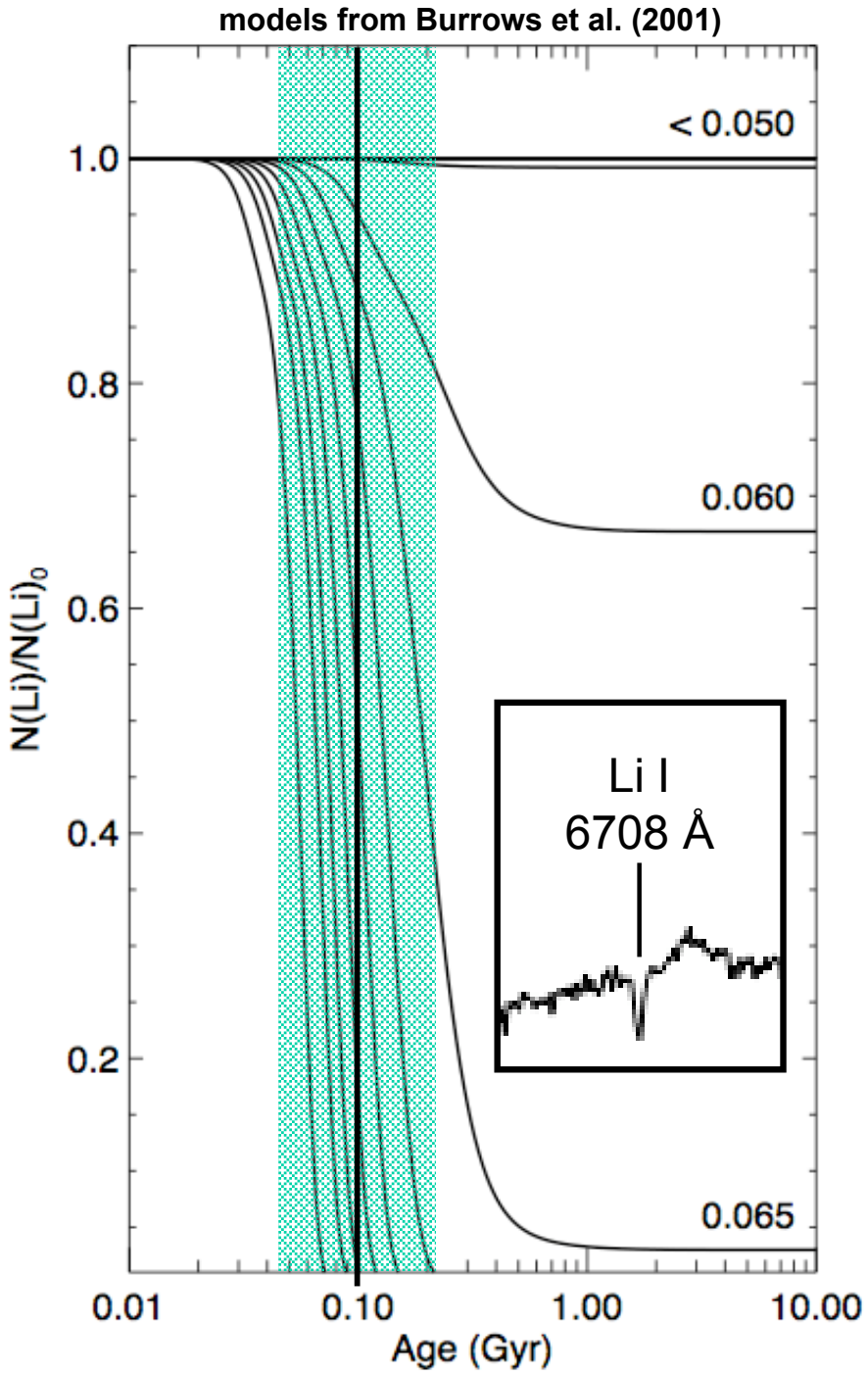
Burgasser (2007)
see also Dahn et al. (2002); Tinney et al. (2003); Vrba et al. (2004)



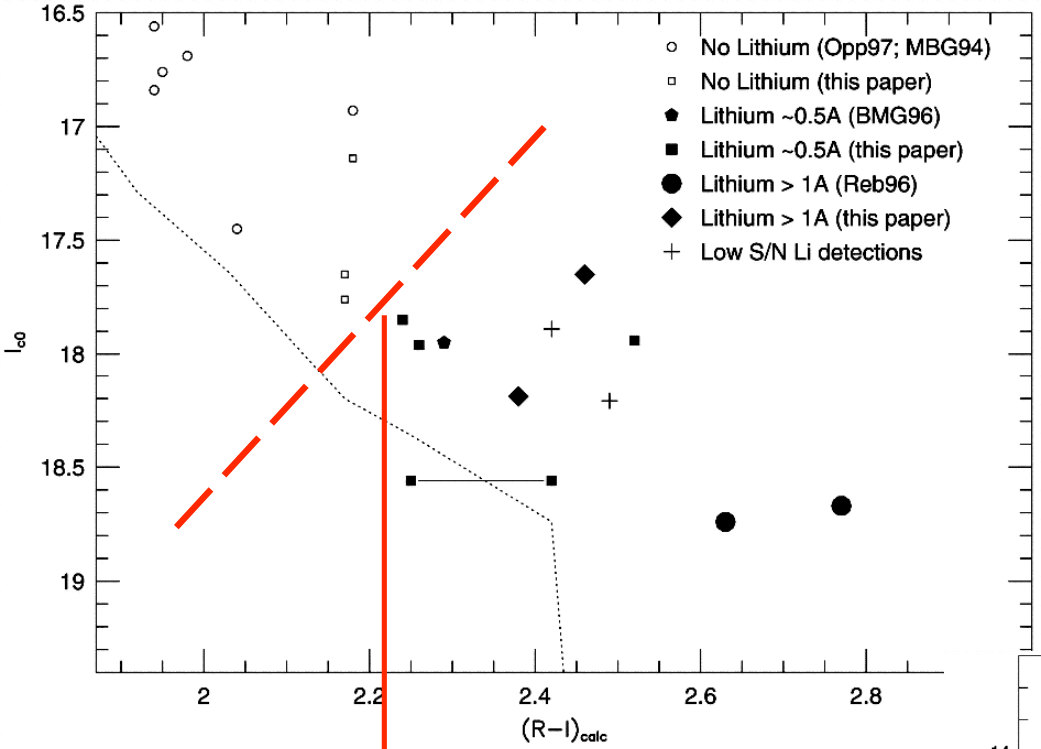
clocks of Li

Li is fused to exhaustion in the cores of objects with $M > 0.065\ M_\odot$, ages > 50 Myr

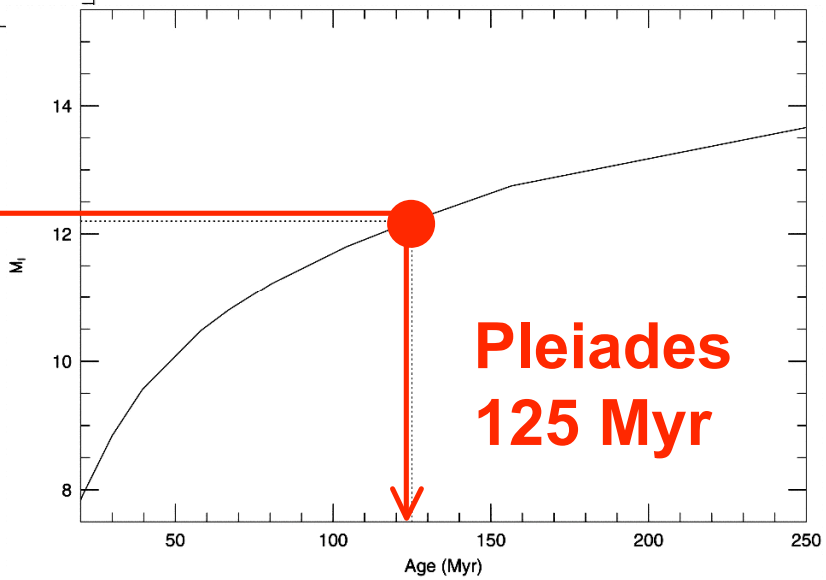
For ages < 200 Myr, Li depletion depends strongly on both age and mass

For clusters with ages ≈ 50-200 Myr the **Li depletion boundary** provides an alternative age-dating method

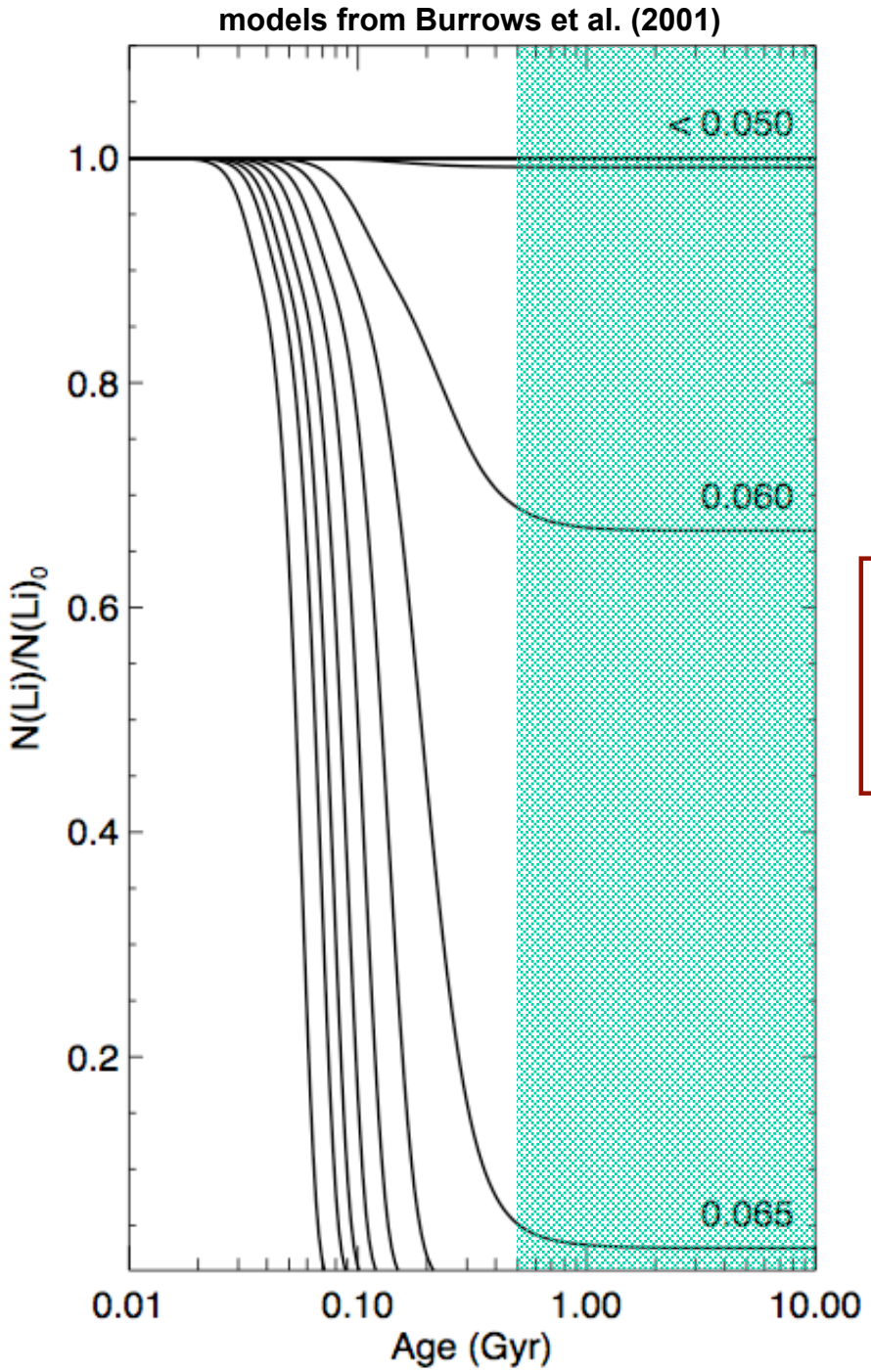
(e.g. Rebolo et al. 1992; Bildsten et al. 1997; Stauffer et al. 1998)



Luminosity where Li I line disappears can be matched to a corresponding mass & age



Stauffer et al. (1998)
see also Barrado y Navascués et al. (1999); Stauffer et al. (1999); Oliveira et al. (2003); Manzi et al. (2008)



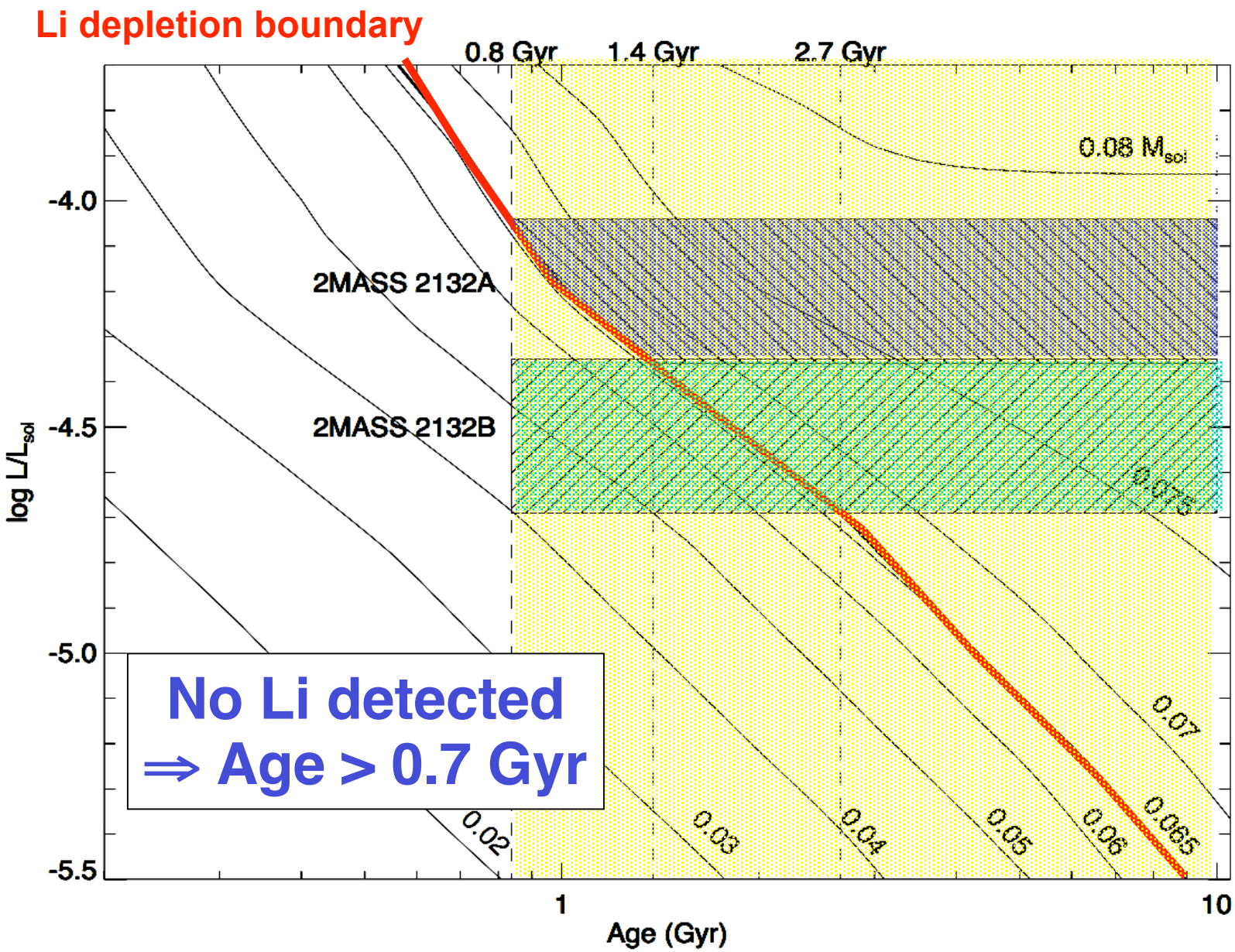
clocks of Li

For ages > 500 Myr, Li is fully depleted in massive BDs and stars ⇒ Li becomes a mass diagnostic

- Li I ⇒ M < 0.065 $M_\odot$ ⇒ BD
- no Li I ⇒ M > 0.065 $M_\odot$ ⇒ ?

Complications:

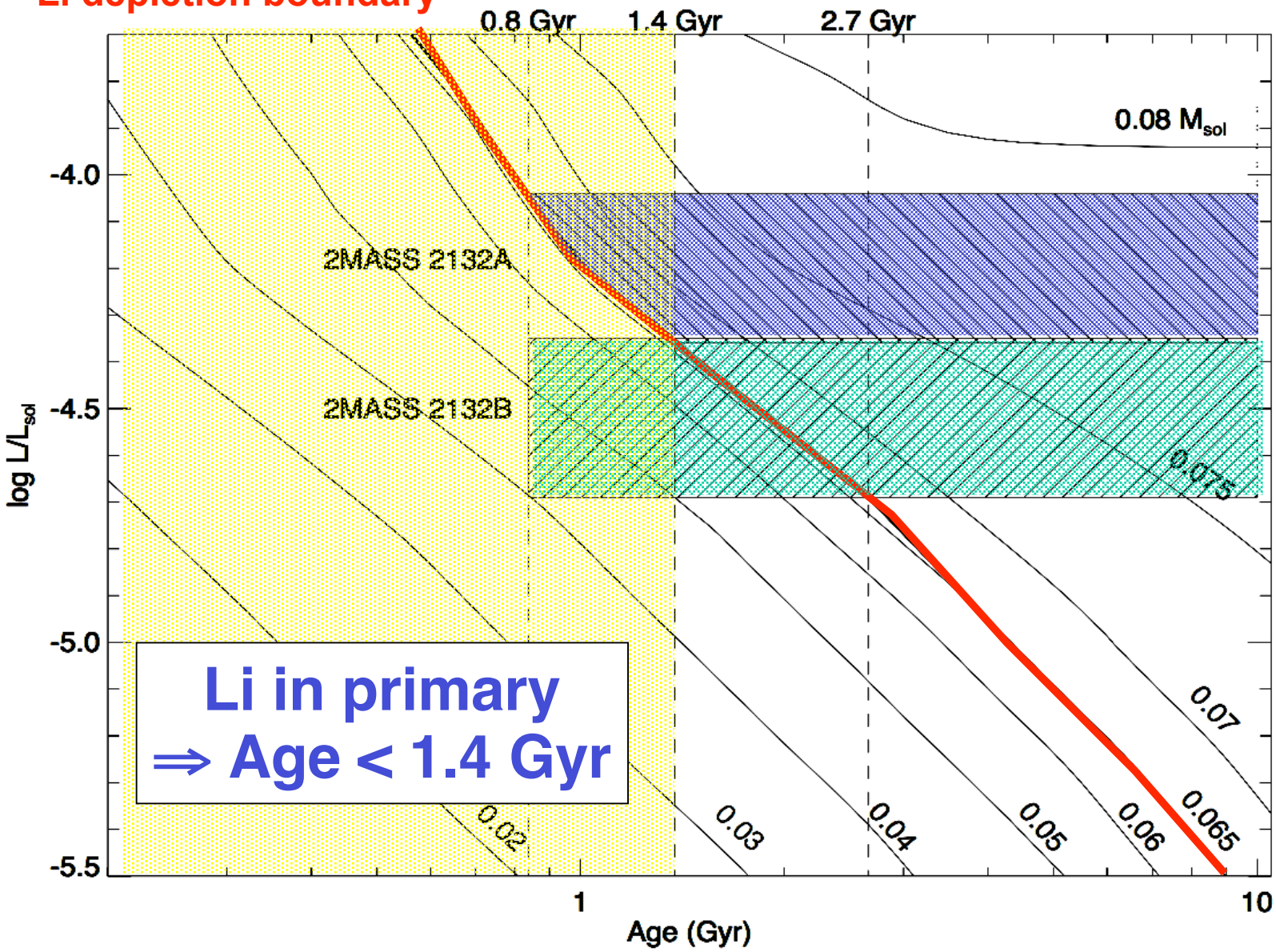
- Faint part of spectrum (low S/N)
- T_{eff} < 1300 K Li → LiCl
- low surface gravity ⇒ weak line
- only an upper/lower limit



Siegler et al. (2007)
See also Liu & Leggett (2005); Burgasser et al. (2006, in prep.)

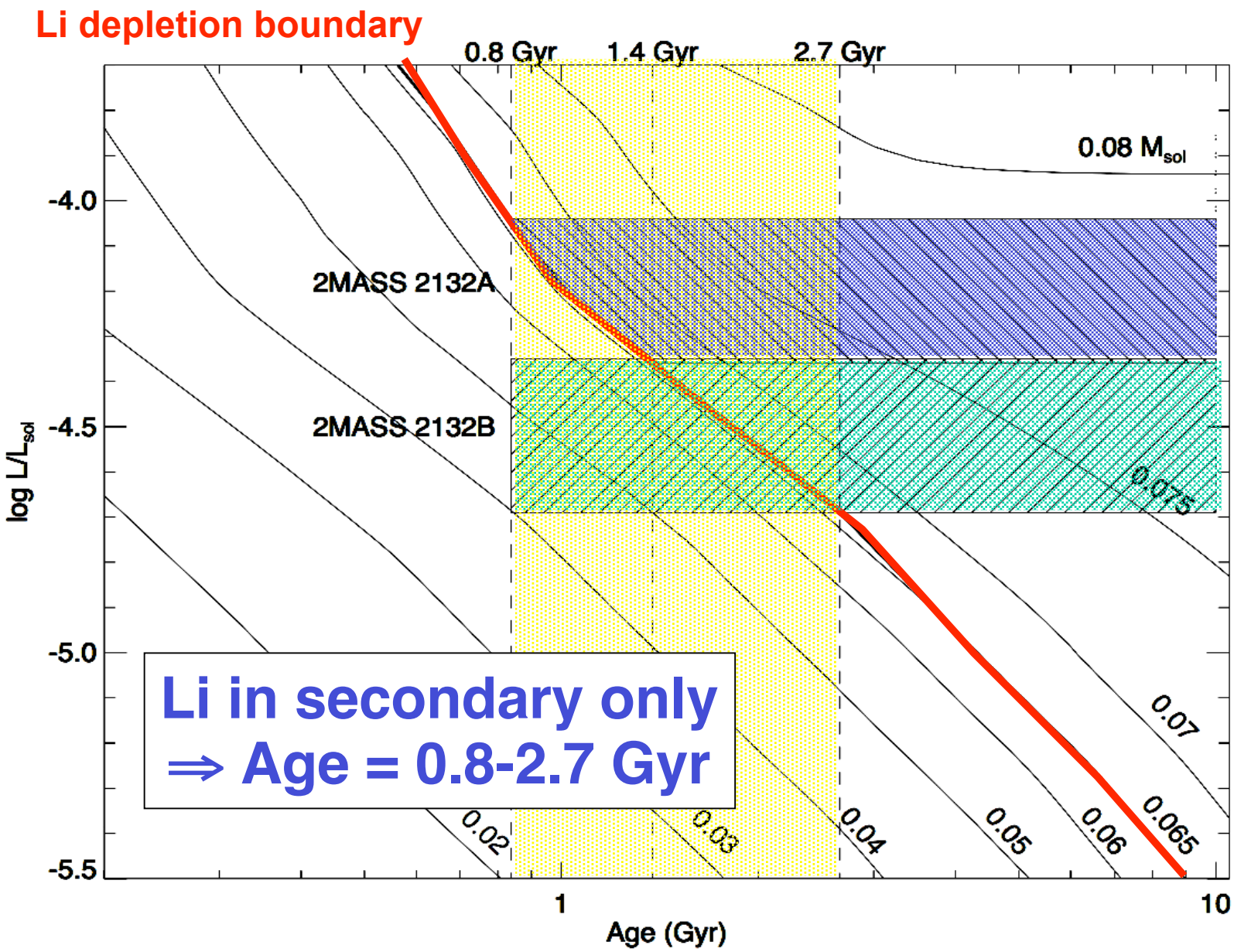
binary Li test

Li depletion boundary



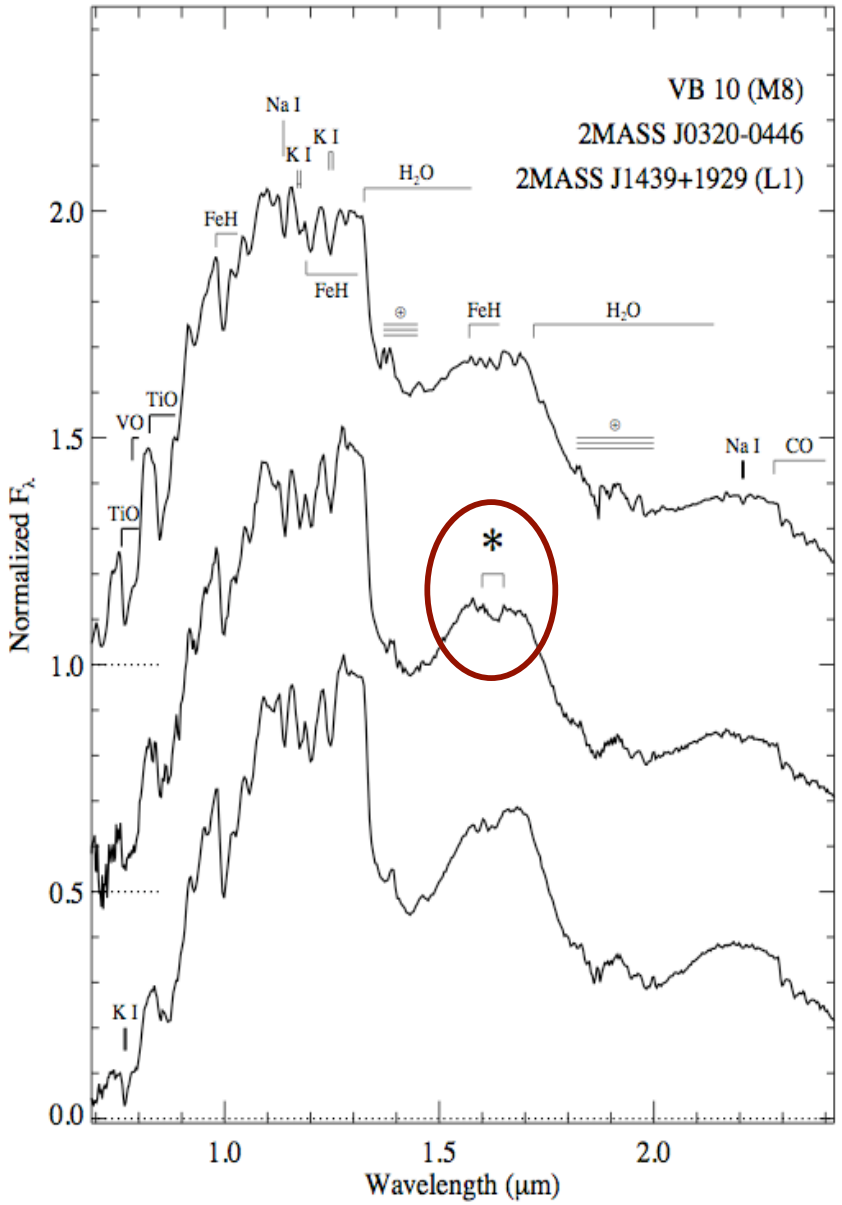
Siegler et al. (2007)
See also Liu & Leggett (2005); Burgasser et al. (2006, in prep.)

binary Li test



Siegler et al. (2007)
See also Liu & Leggett (2005); Burgasser et al. (2006, in prep.)

binary Li test



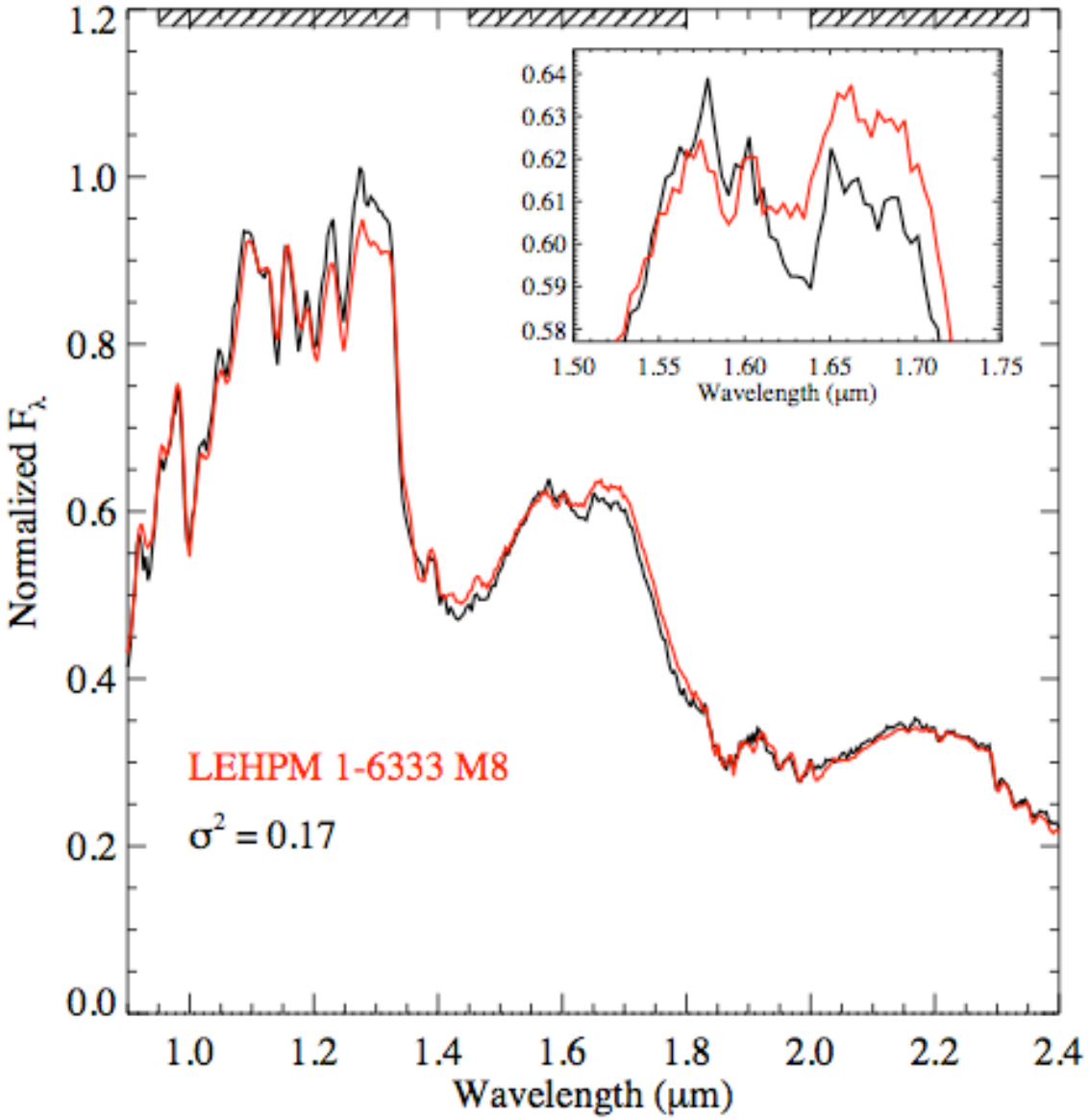
Burgasser et al. (2008)

2MASS J0320-0446: A binary clock

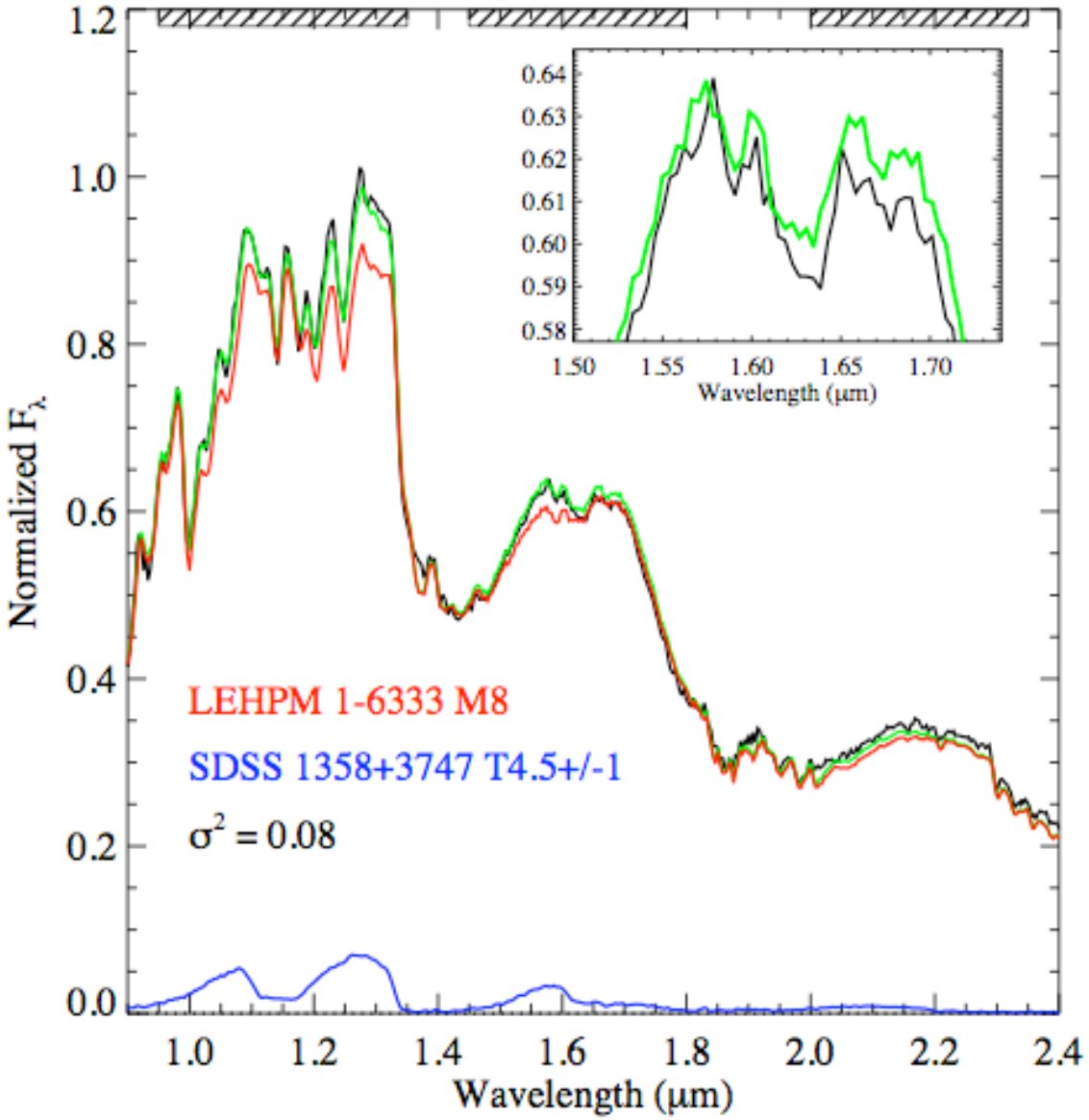
A “peculiar” M8/L1 dwarf @ 25 pc, largely ignored

Unusual feature at 1.6 μm not seen in other late-M/L dwarf spectra

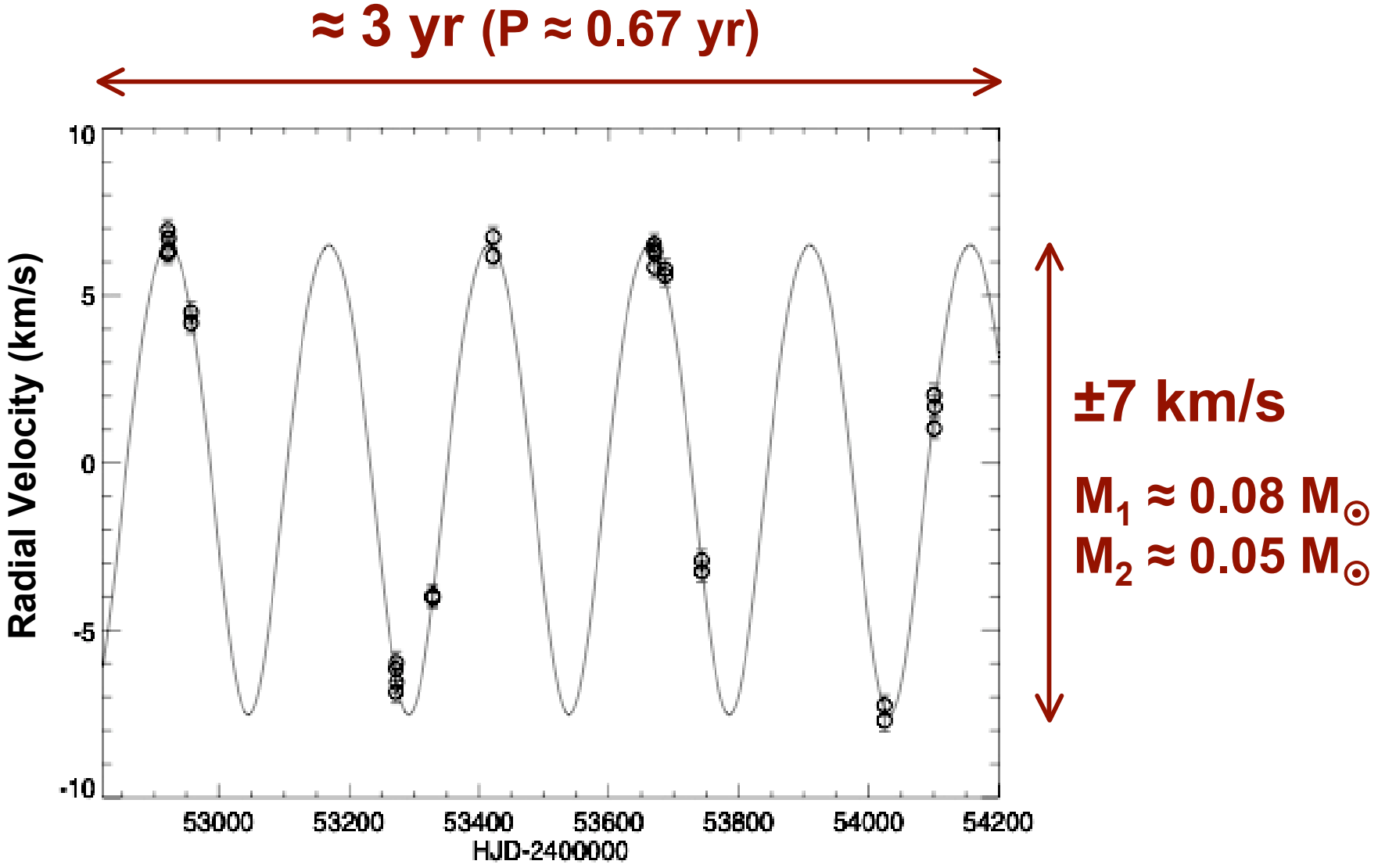
NIR spectrum can be well-reproduced as an M8.5+T5 binary



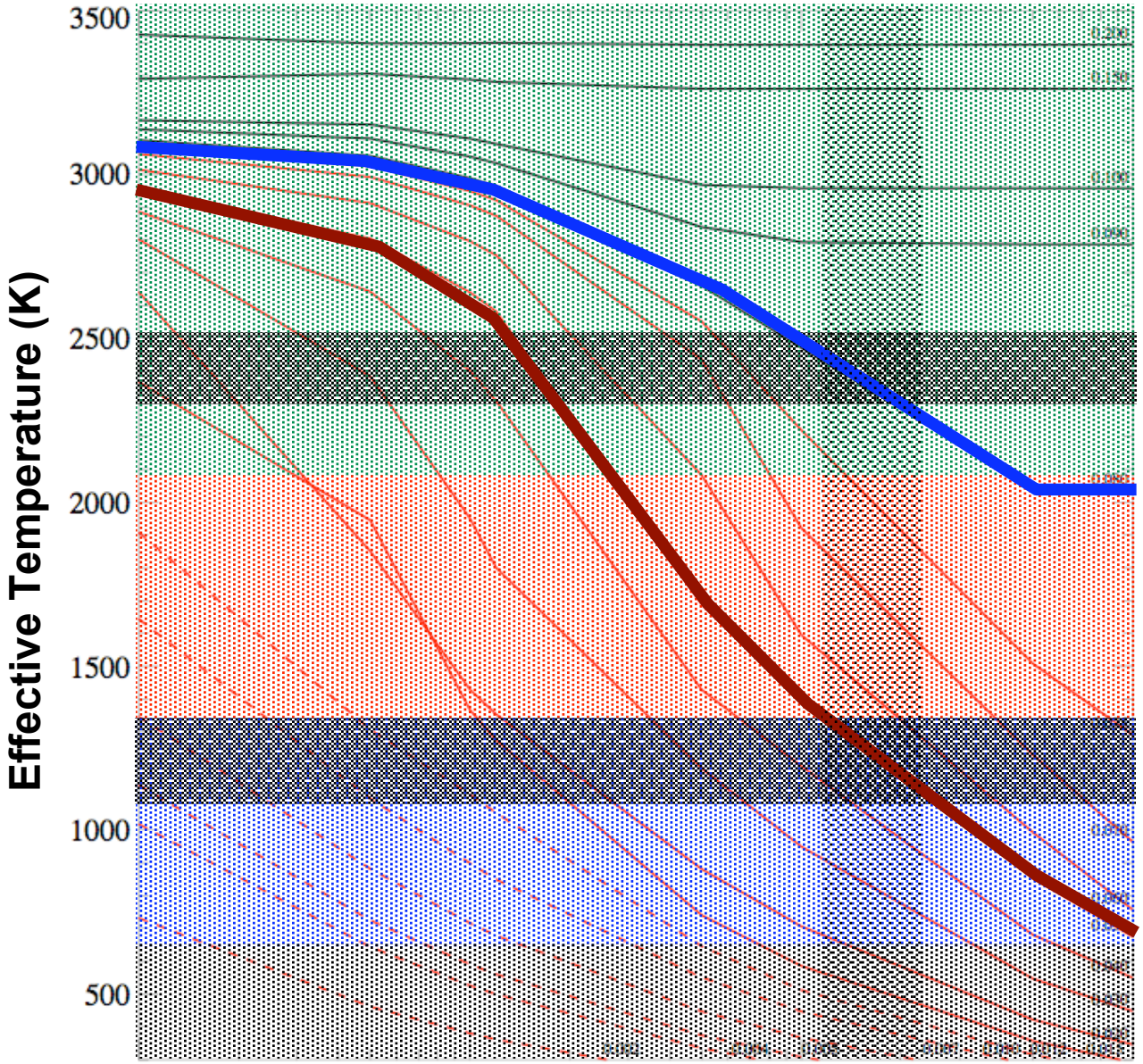
Single spectrum fit



Binary spectrum fit



Blake et al. (2008): 2M 0320-0446 is a spectroscopic binary



M8.5 primary
(≈ 2300-2500 K)

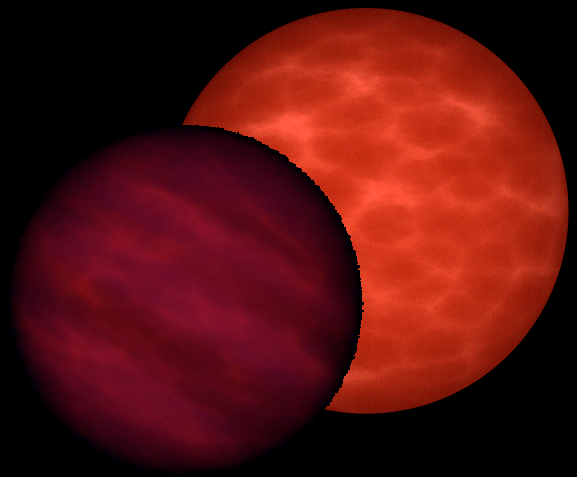
$M_1 \approx 0.08\ M_\odot$

T5±1 secondary
(≈ 1100-1300 K)

$M_2 \approx 0.05\ M_\odot$

Age
≈ 1.5-2.5 Gyr

Burgasser et al. (in prep.)
models from Burrows et al. (2001)



the take-home message

Brown dwarfs are **potentially ideal Galactic standard candles** as they are

- prevalent throughout the Galaxy,
- uniquely characterizable,
- increasingly well-characterized, and
- useable as both rulers and clocks.