The Brown Dwarf-Exoplanet Connection

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collaborators: Cullen Blake, John Bochanski, Brendan Bowler, Adam Burrows, Michael Cushing, Jackie Faherty, Christiane Helling, Dagny Looper, Mark Marley, Neil Reid, Didier Saumon

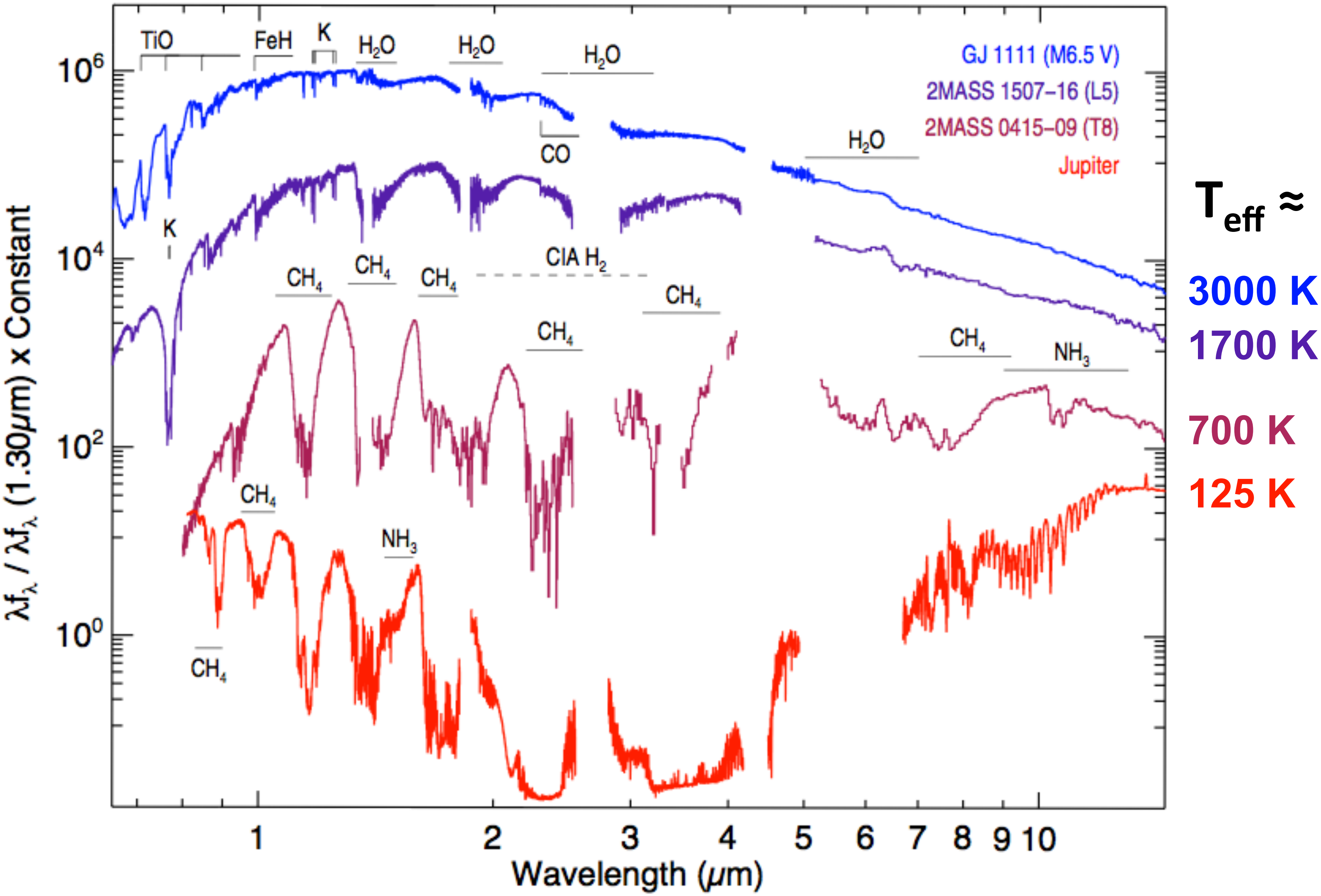
Synergies in Brown Dwarf & Exoplanet Astrophysics

<u>what you get:</u>

- “zeroth case” model of a warm atmosphere
- detailed and high precision observational constraints
- broad diversity of physical states – gravity, T_{eff}, M/H, age, mass, etc

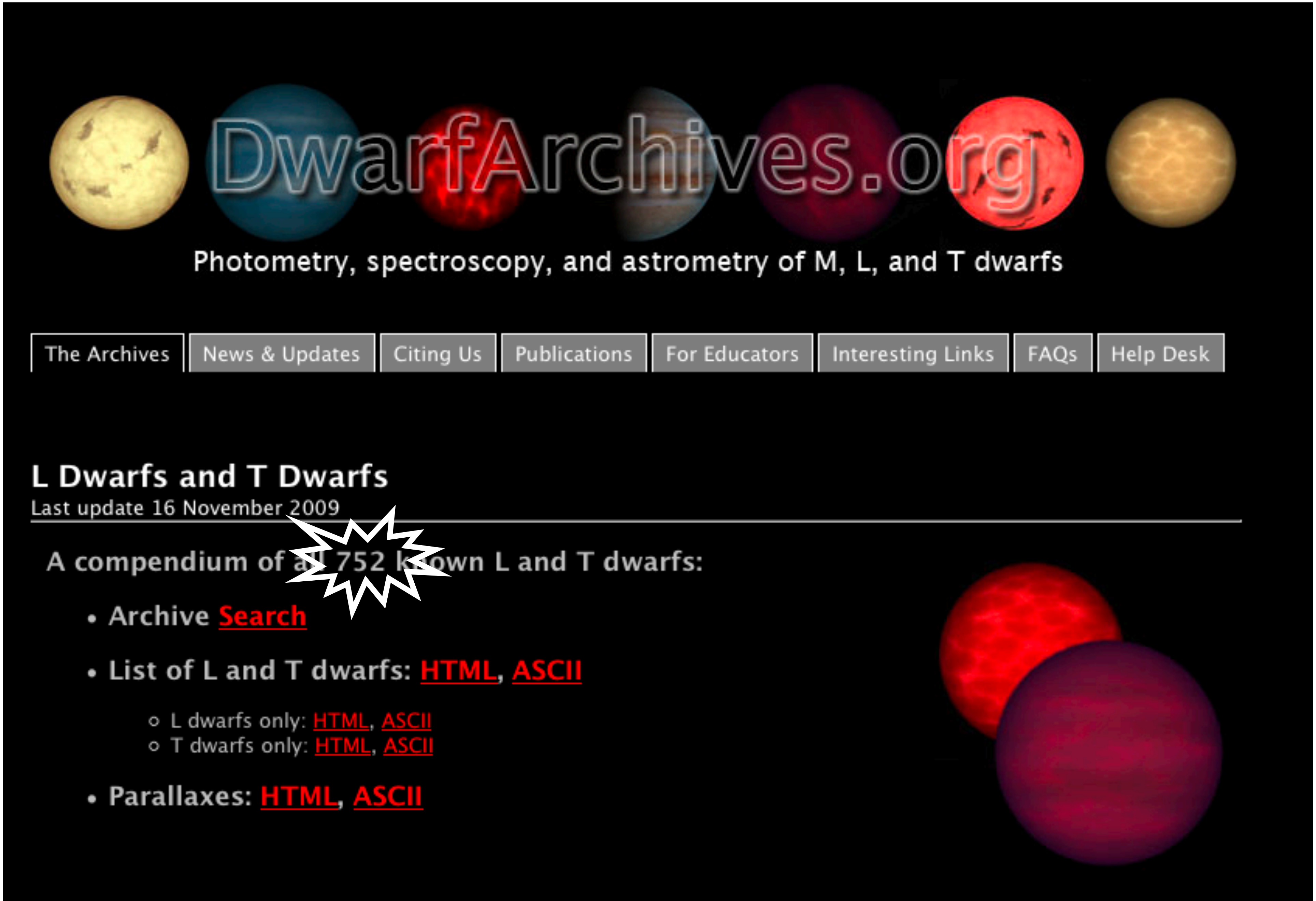
<u>what we get:</u>

- structural information on equivalent bodies
- surface details



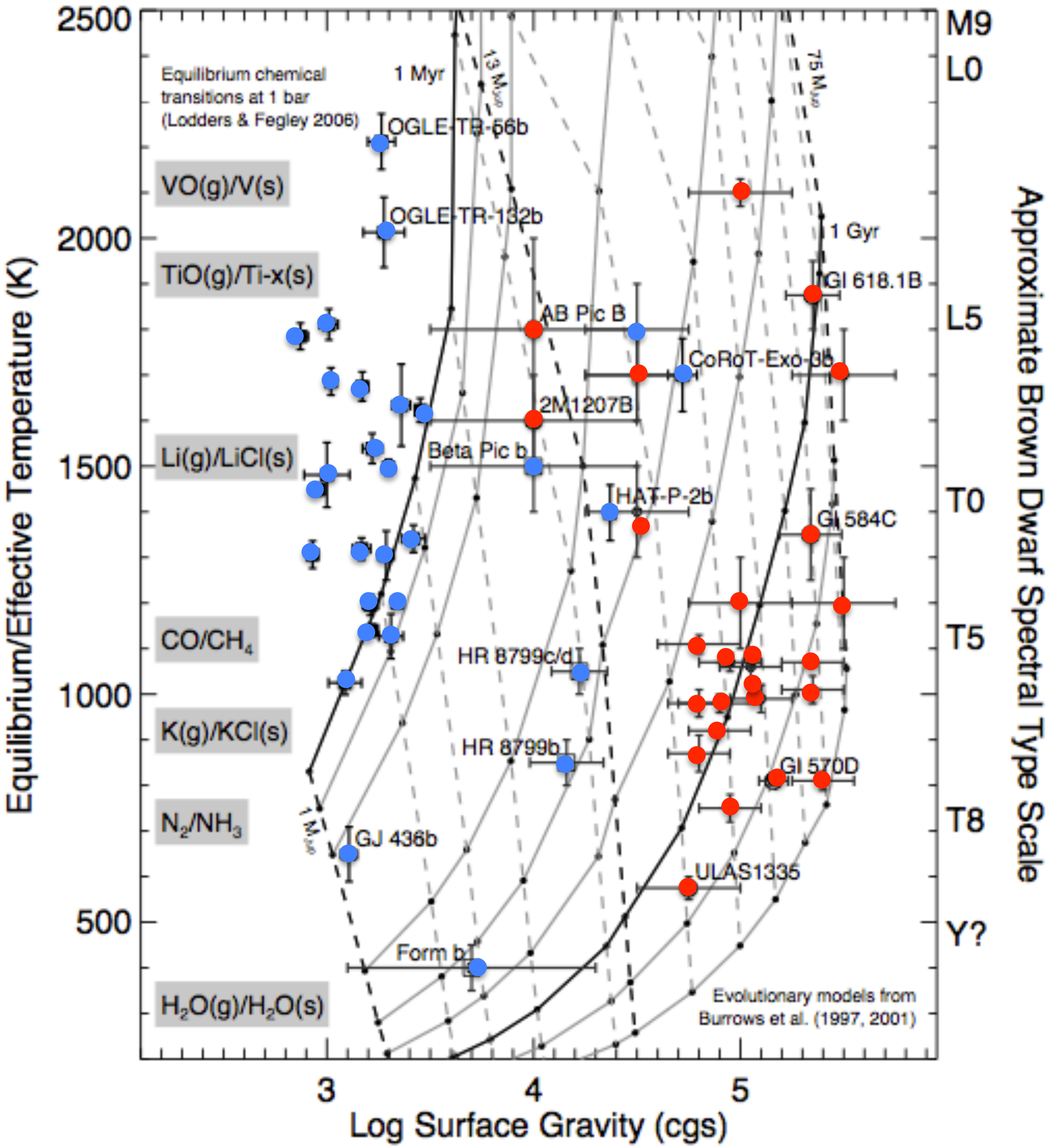
Marley & Leggett (2008)

data from Cushing et al. (2005,2007)



dwarfarchives.org *maintained by Chris Gelino, Davy Kirkpatrick & Adam Burgasser*


None of this.



There is a distinct overlap in the physical properties of young brown dwarfs and massive exoplanets.

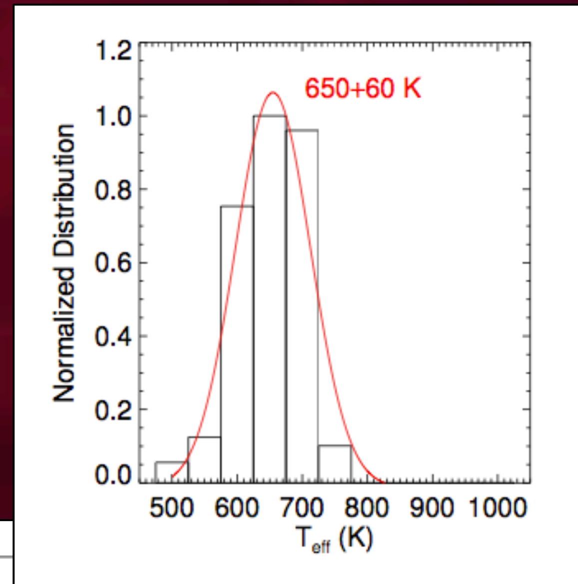
Burgasser (2009)

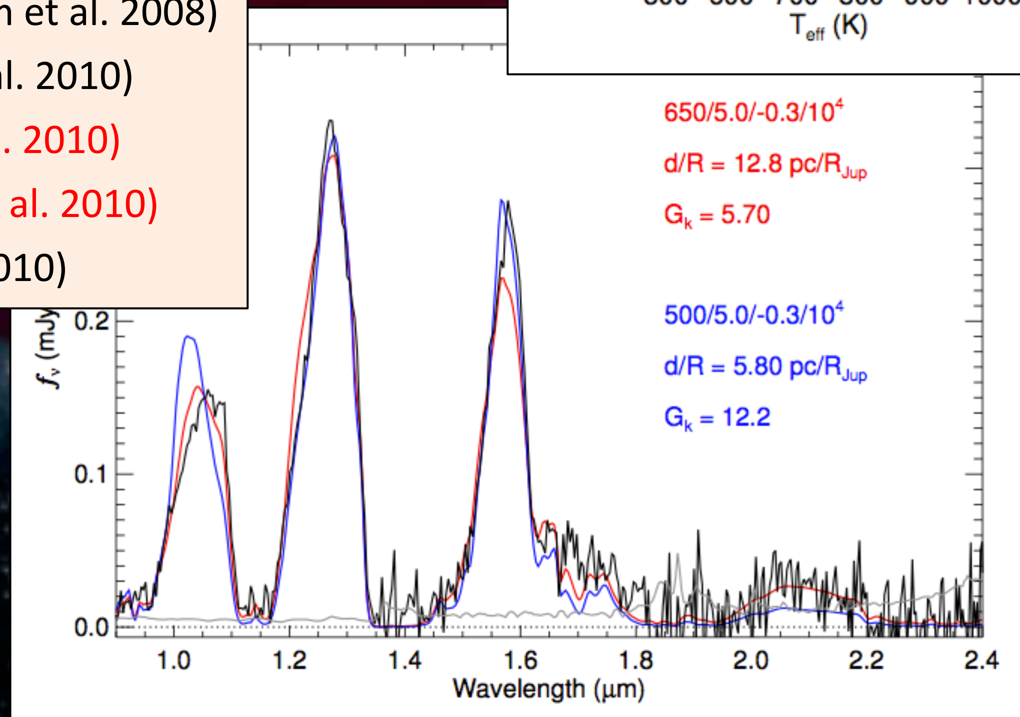
EGPs: Torres et al. (2008); Marois et al. (2008); Kalas et al. (2008); Lagrange et al. (2008)

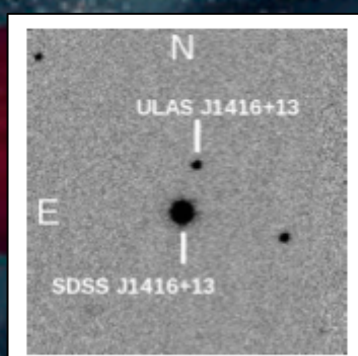
BDs: Kirkpatrick et al. (2001); Wilson et al. (2001); Chauvin et al. (2005); Burgasser et al. (2006); Saumon et al. (2006); Mohanty et al. (2007); Burningham et al. (2008); Cushing et al. (2008)

Coldest Brown Dwarfs

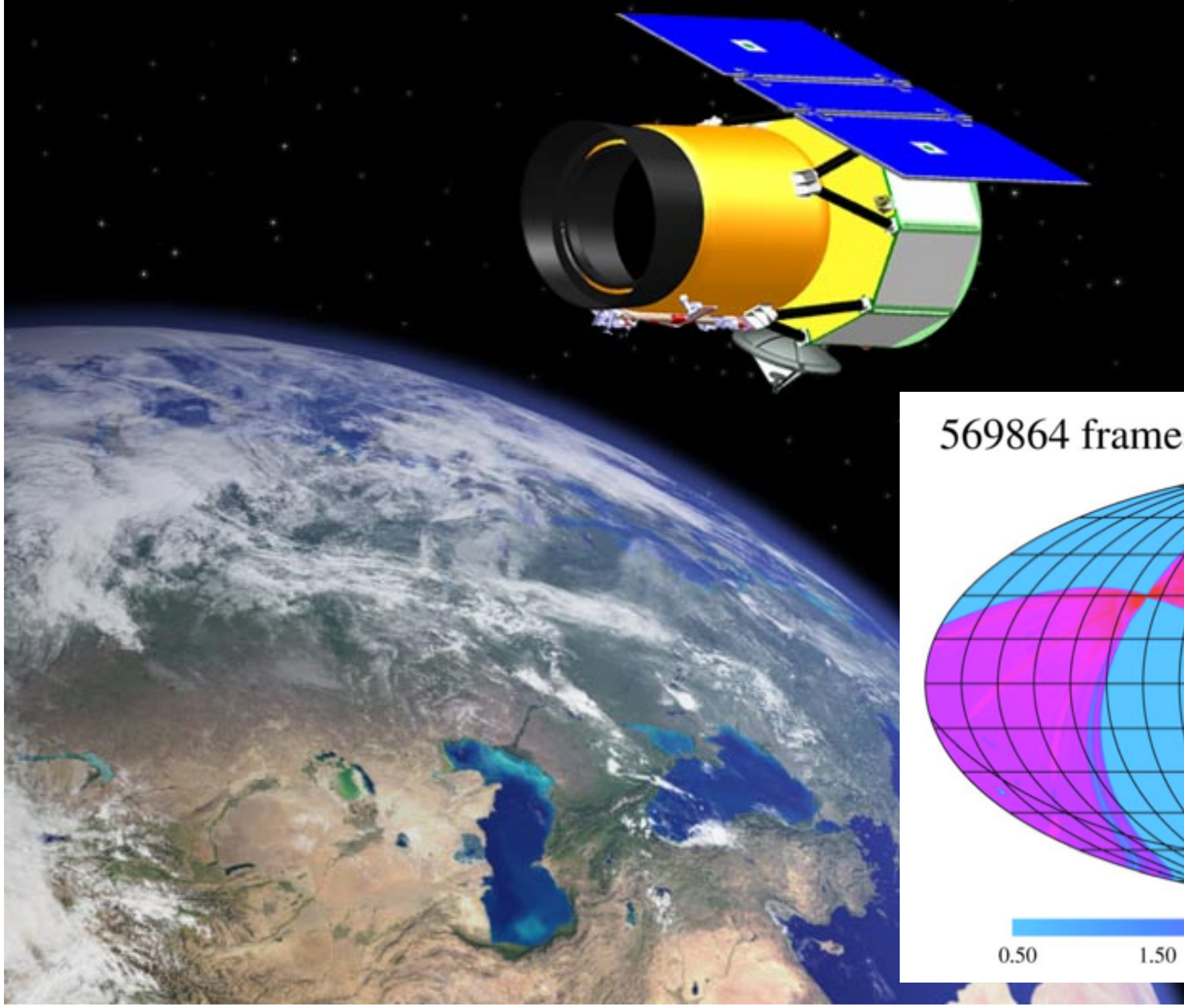
CFBD 0059:	620±15 K (Delorme et al. 2008)
	550-600 K (Leggett et al. 2010)
2M0939AB:	600±35 K (Burgasser et al. 2009)
	500 + 700 K (Leggett et al. 2010)
UL 0034:	550-600 K (Leggett et al. 2010)
Wolf 940B:	570±25 K (Burningham et al. 2009)
UL 1335:	550-600 K (Burningham et al. 2008)
	500-550 K (Leggett et al. 2010)
SD 1416B:	500 K (Burningham et al. 2010)
	650±60 K (Burgasser et al. 2010)
Ross 458C:	500 K (Goldman et al. 2010)

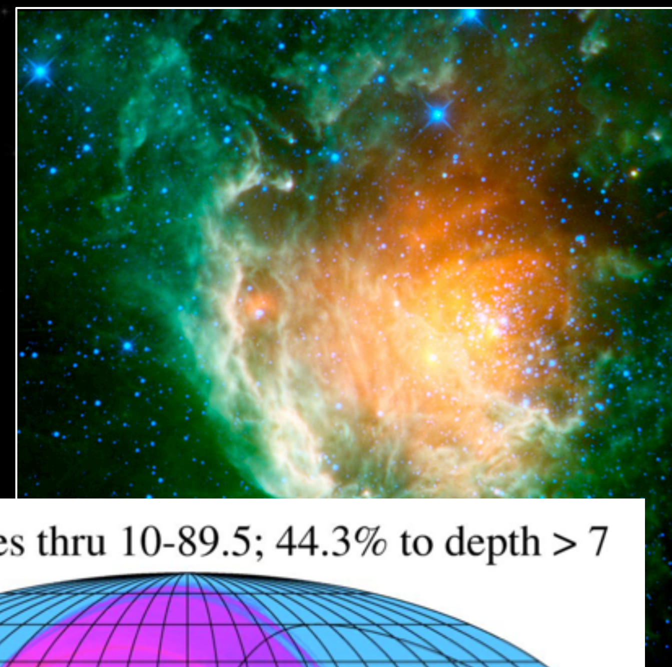


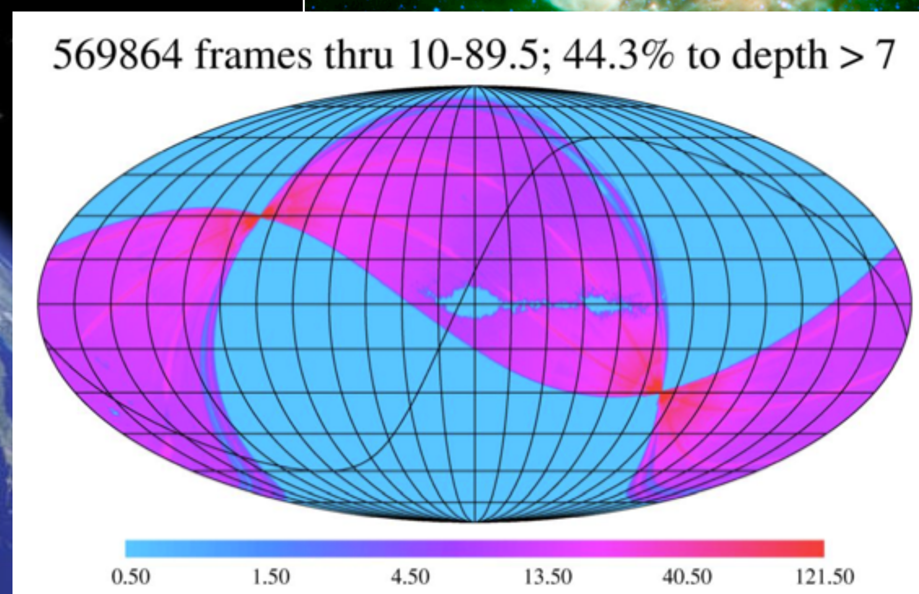


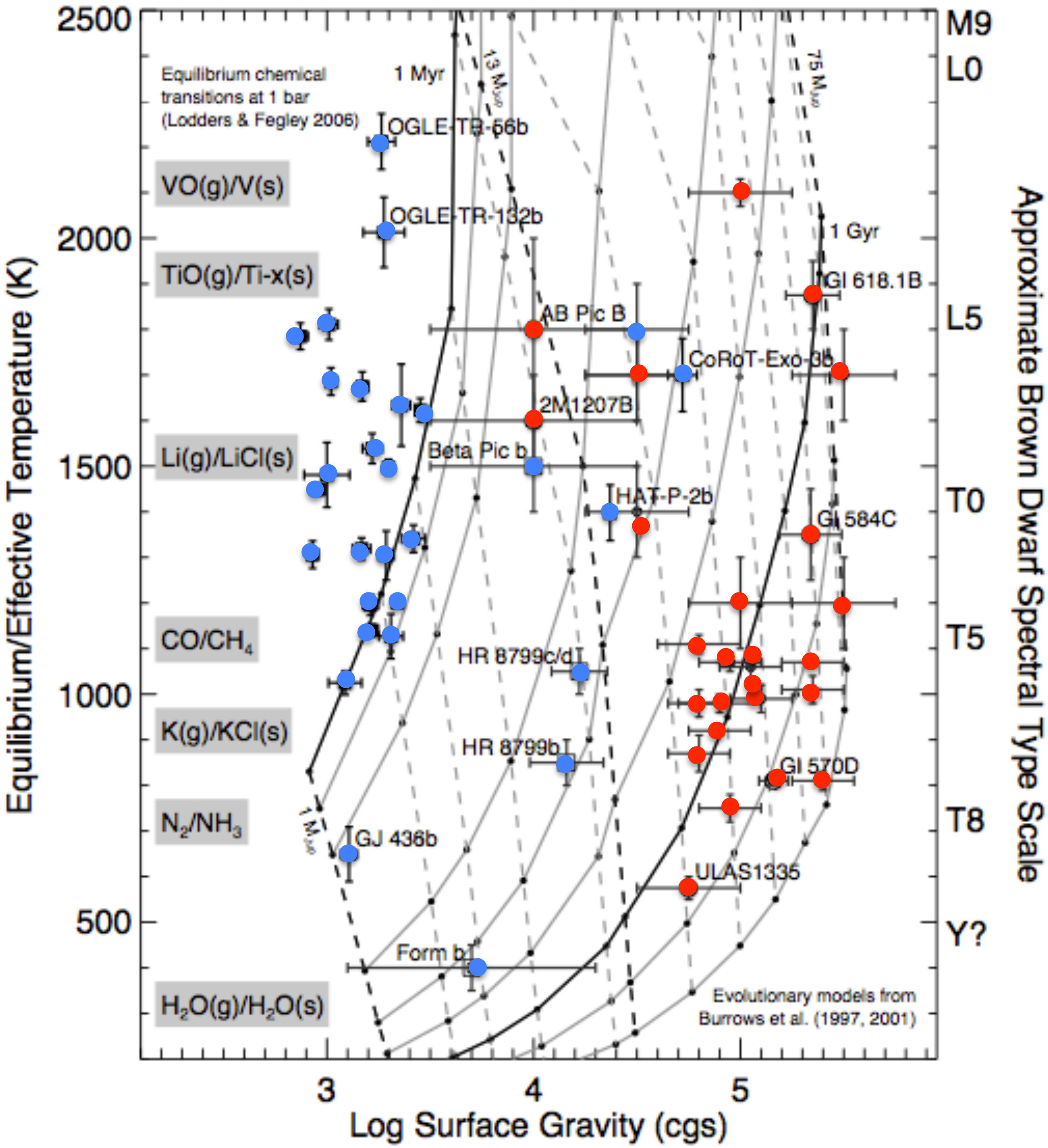


Wide field Infrared Space Explorer (WISE)









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Atmospheres

Spectral Models are Rapidly Improving

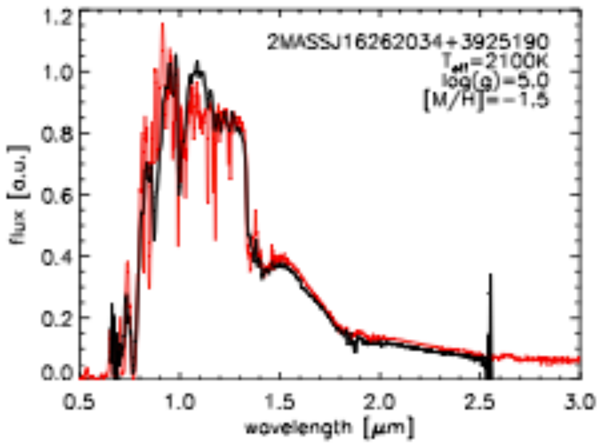


Fig. 7. 2MASS J16262034+3925190 (sDL4) (Burgasser 2004 observation (black) and best fitting model (red)

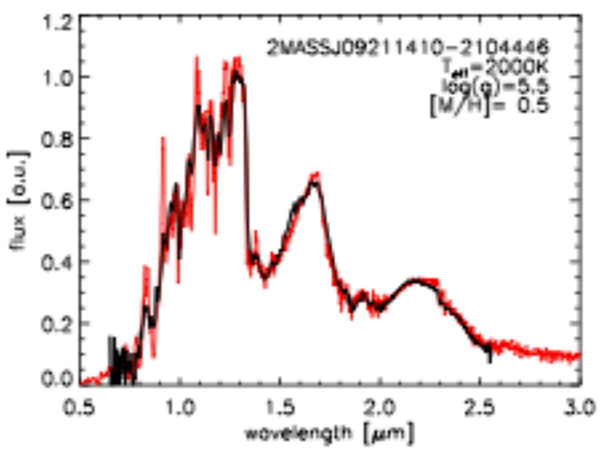
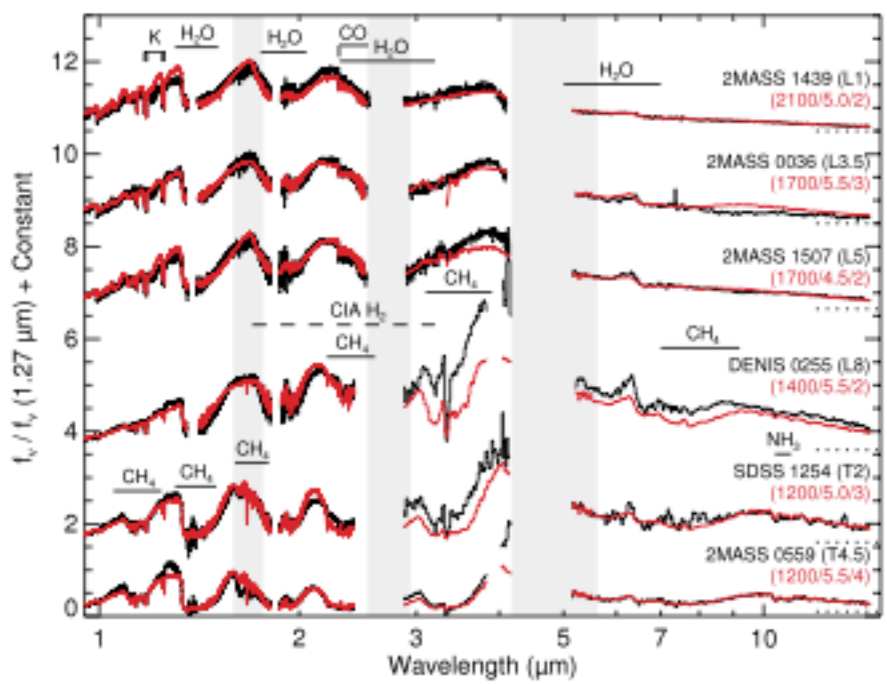


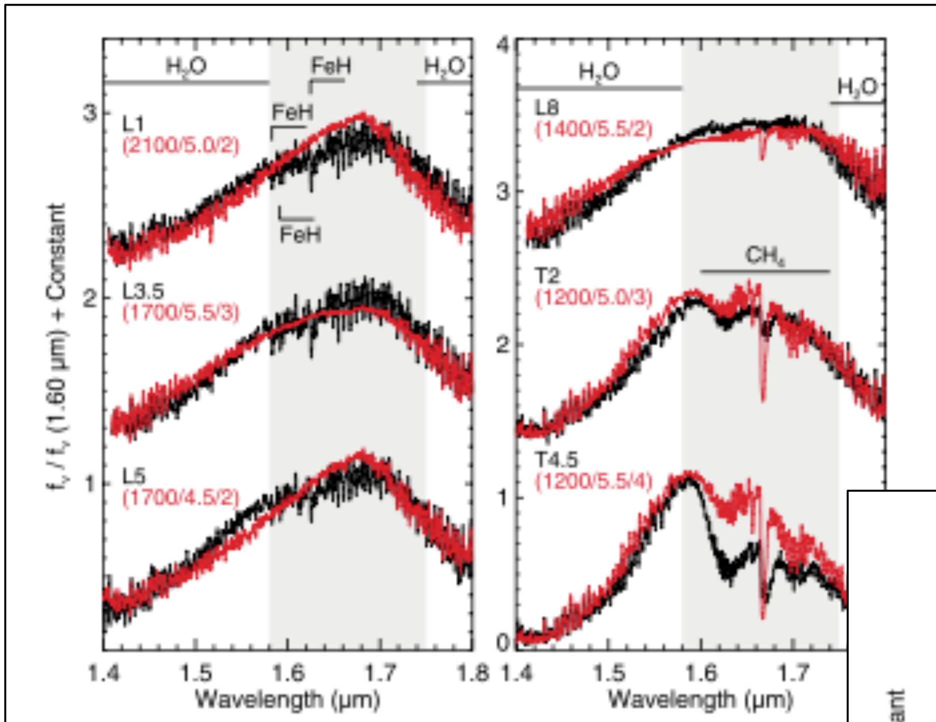
Fig. 9. 2MASS J09211410-2104446 (L2) (Burgasser et al. 2007): observation (black) and best fitting model (red)

Soeren et al. (2010)

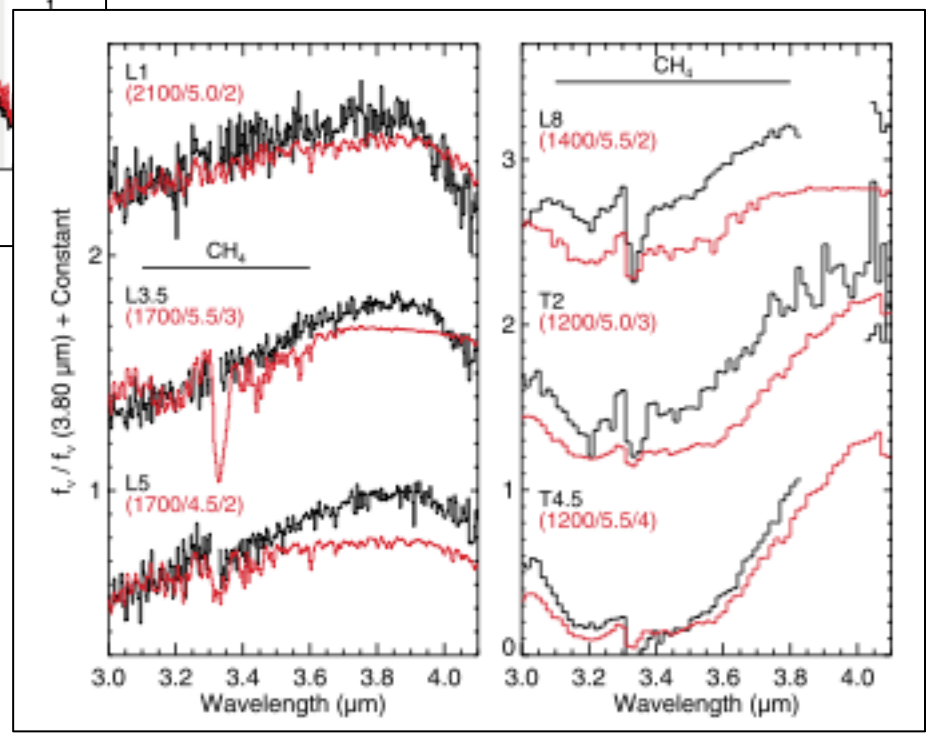


Cushing et al. (2008)

also Saumon et al. (2006,2007); Bowler et al. (2009; Stephens et al. (2009); Testi (2009)



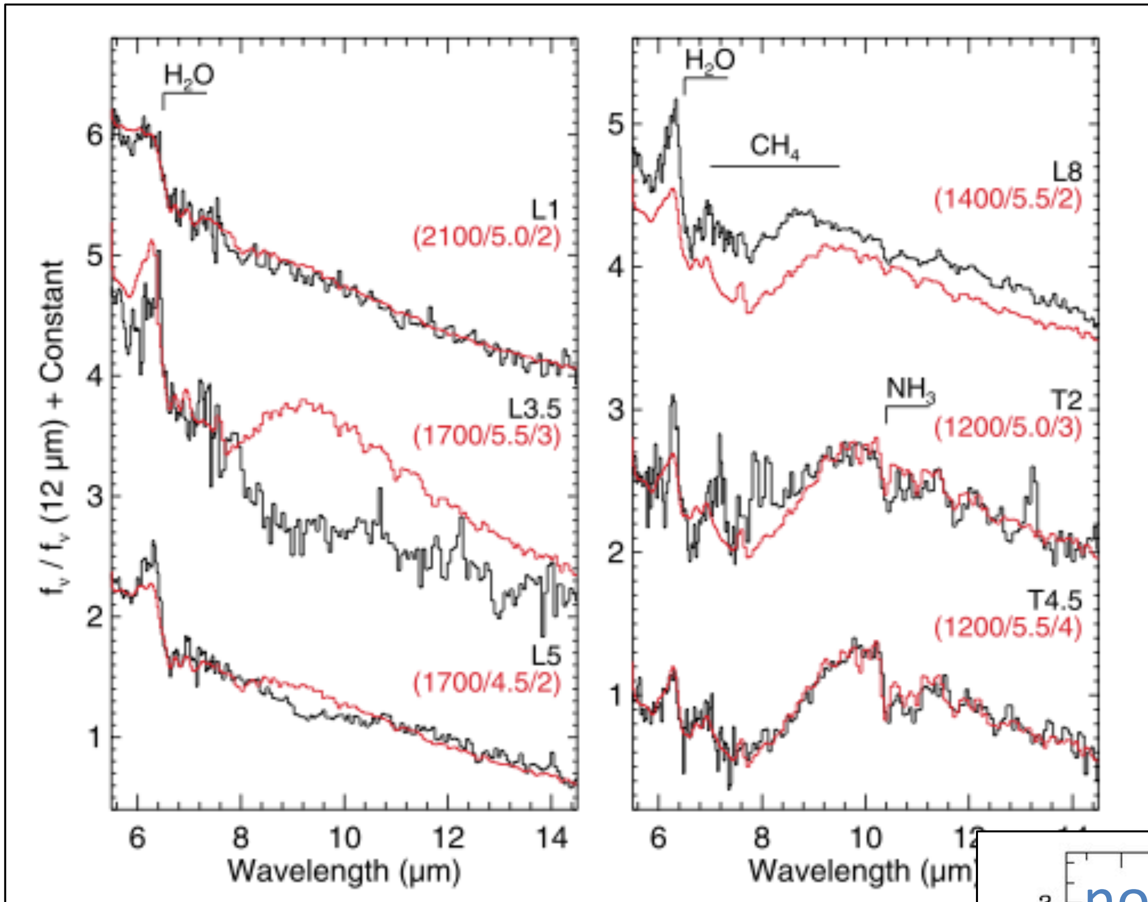
H-band



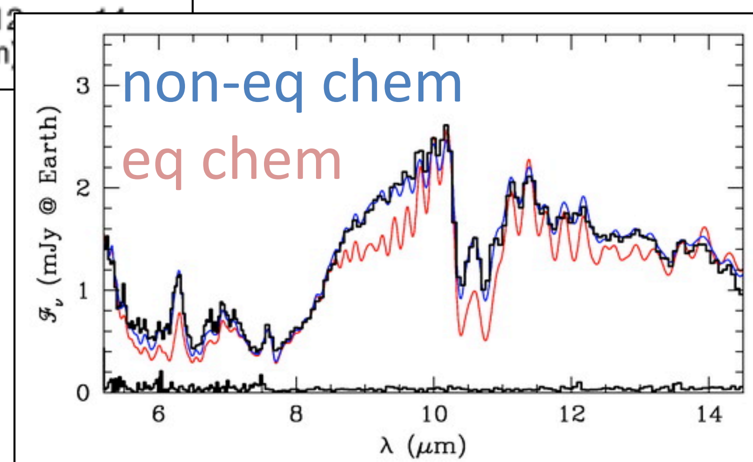
L-band

Cushing et al. (2008)

see also Stephens et al. (2009)



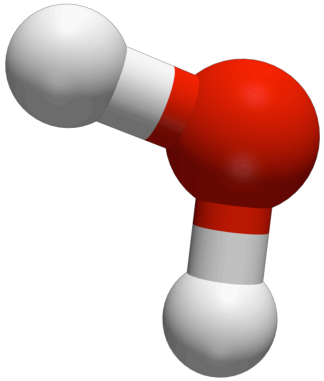
Saumon et al. (2007)



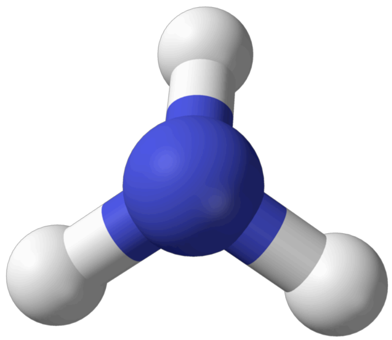
Spitzer/IRS MIR

Cushing et al. (2008)

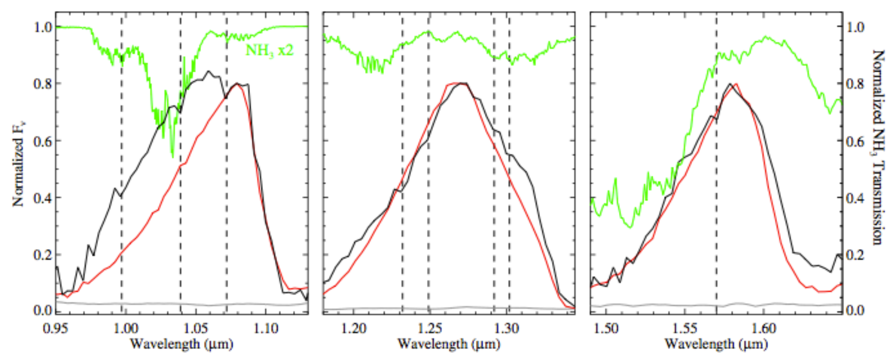
see also Stephens et al. (2009)



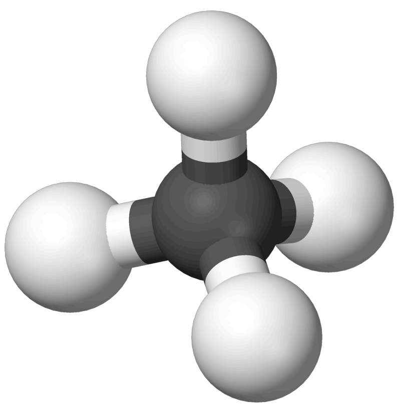
✔ H_2O: Barber et al. 2006; Shirin et al. 2008
HDO: Voronin et al. 2010



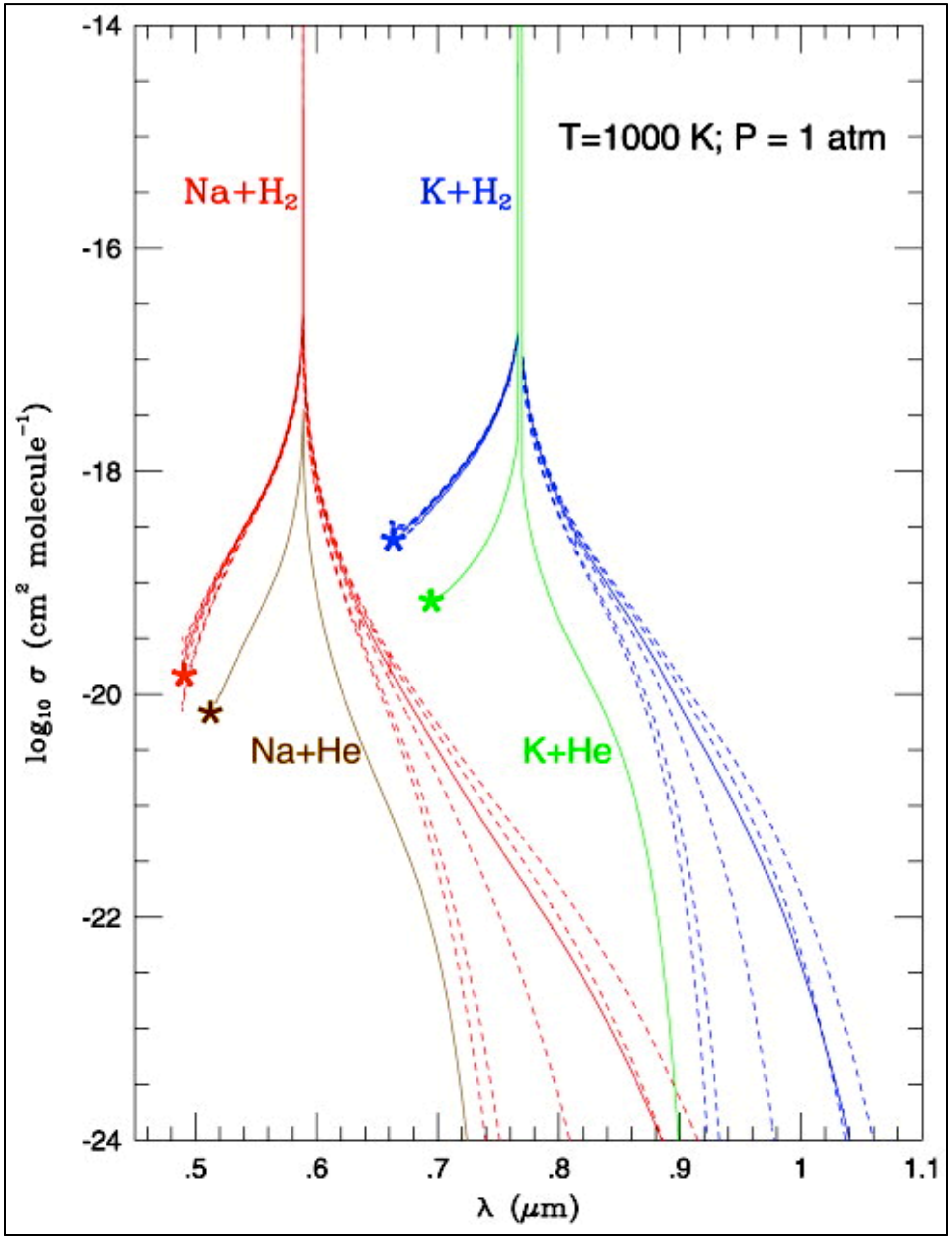
✗ NH_3: Barber et al. in prep.



Burgasser et al. (2010): Near-infrared NH_3?



? CH_4: Homeier et al. 2003
"Spherical Top Database System"

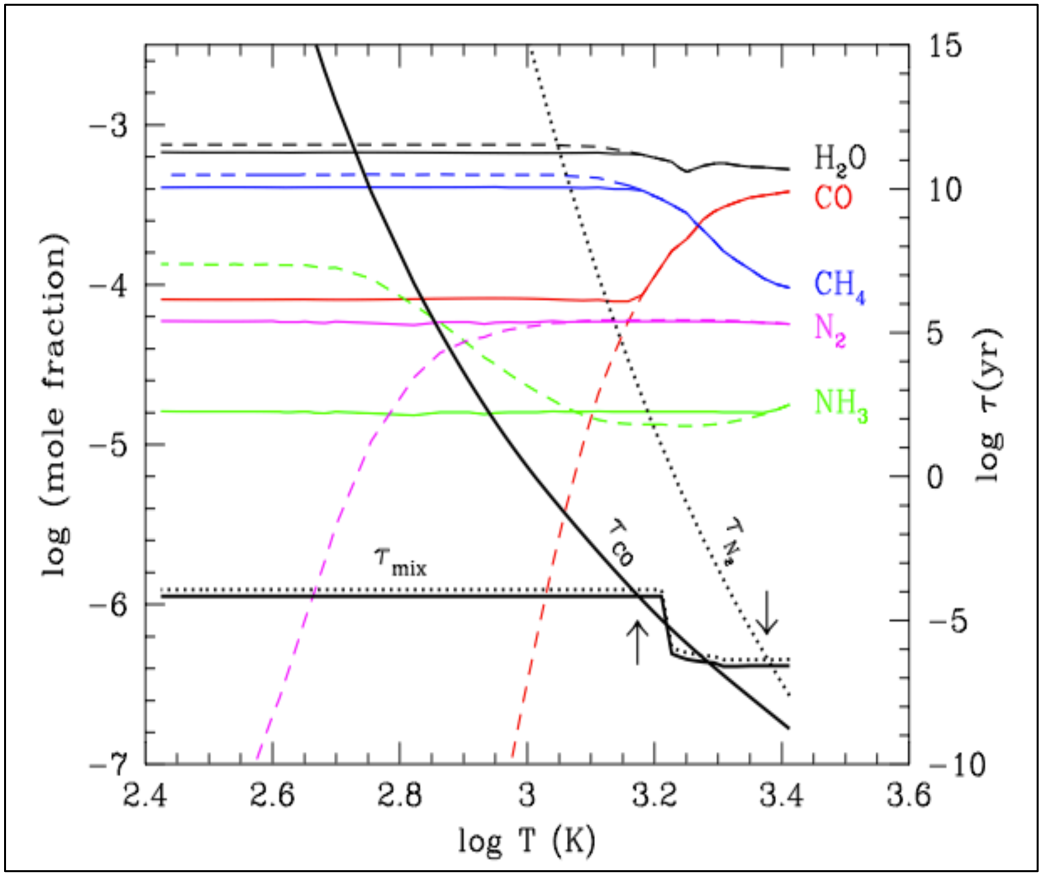


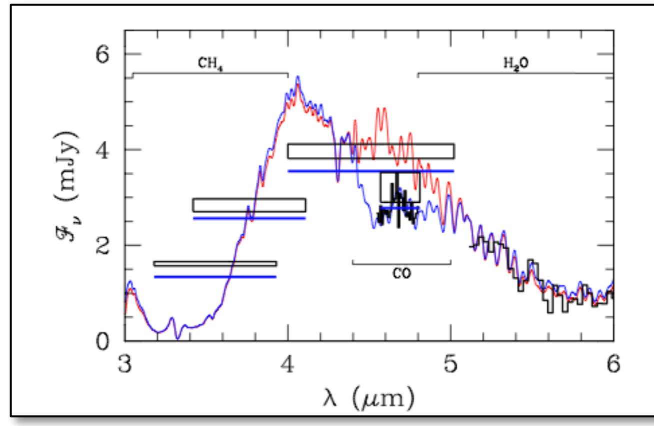
Don’t forget line opacities

Burrows & Volobuyev (2003)

also Allard et al. (2004, 2006 2007); Santra et al. (2005); Zhu et al. (2006); Johnas et al. (2007); Alioua et al. (2008)

Vertical mixing -> Non-equilibrium Chemistry

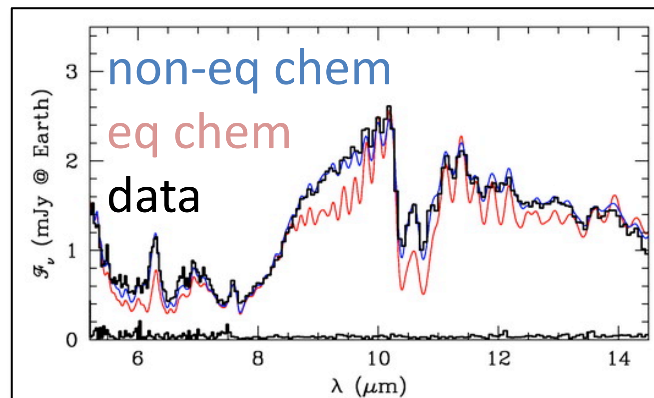




enhances CO abs.

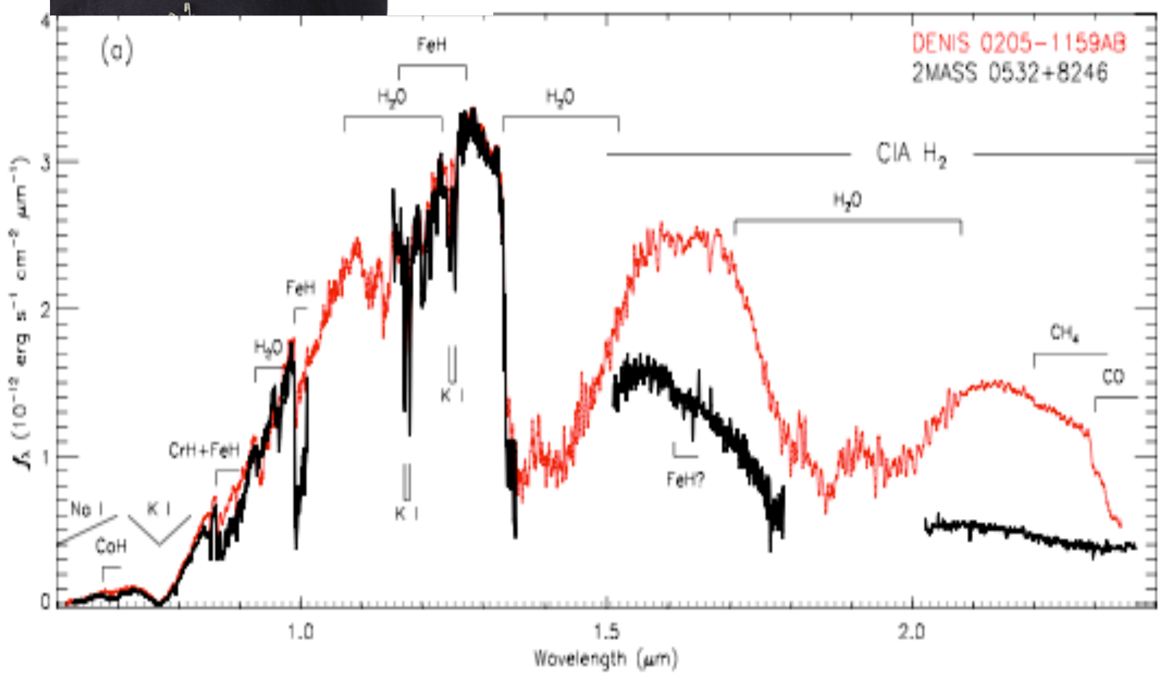
Saumon et al. (2007); Geballe et al. (2009)

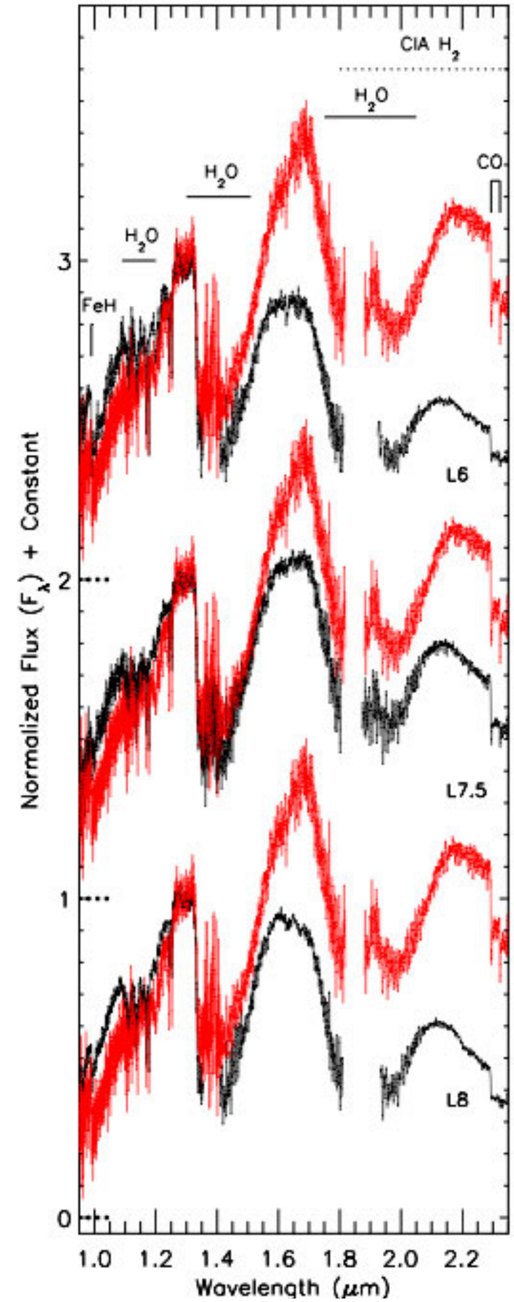
also Griffith & Yelle (1999); Saumon et al. (2006); Hubeny & Burrows (2007)



suppresses NH_3 abs.

Variety is the spice of life

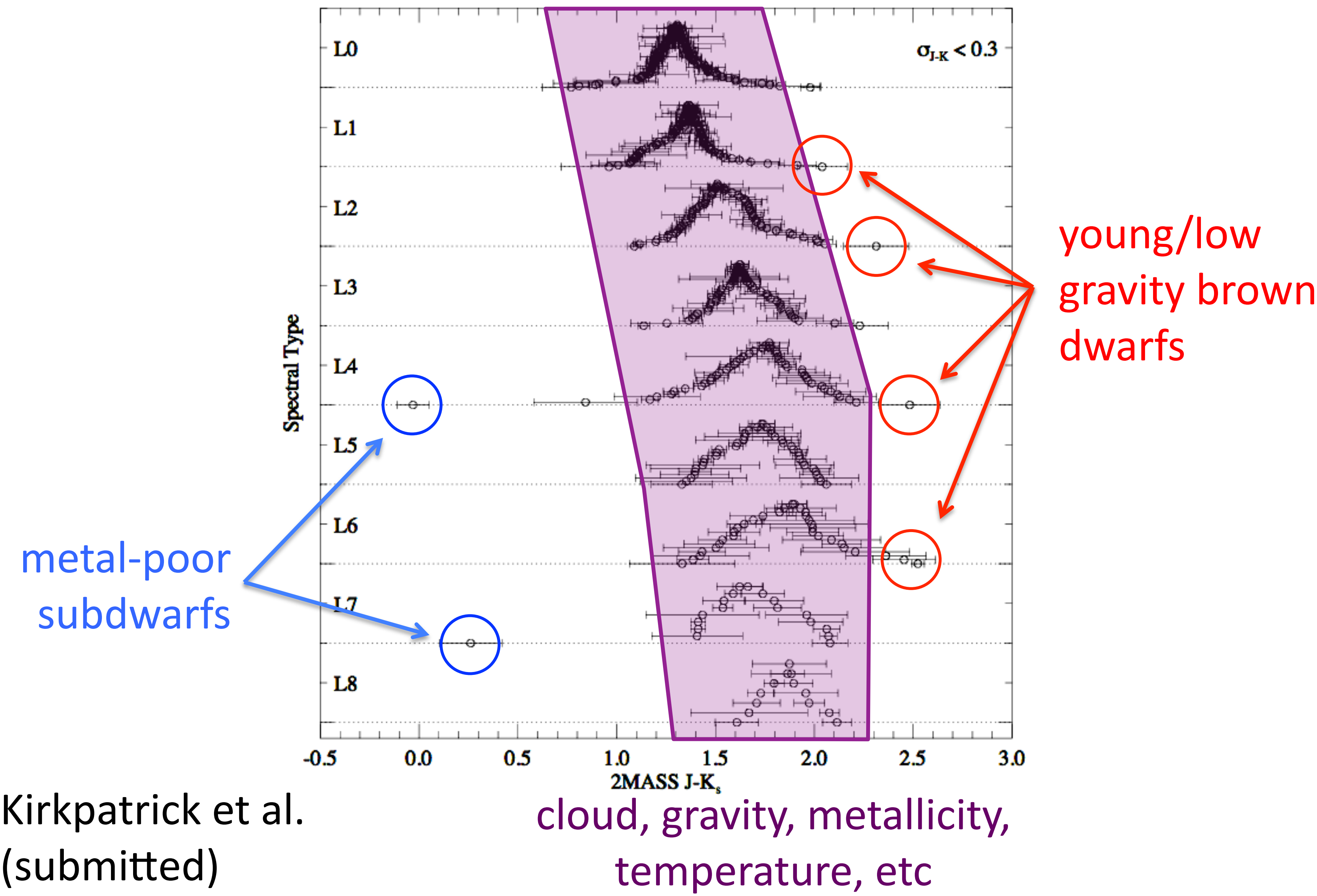




Burgasser et al. (2003); Looper et al. (2008)

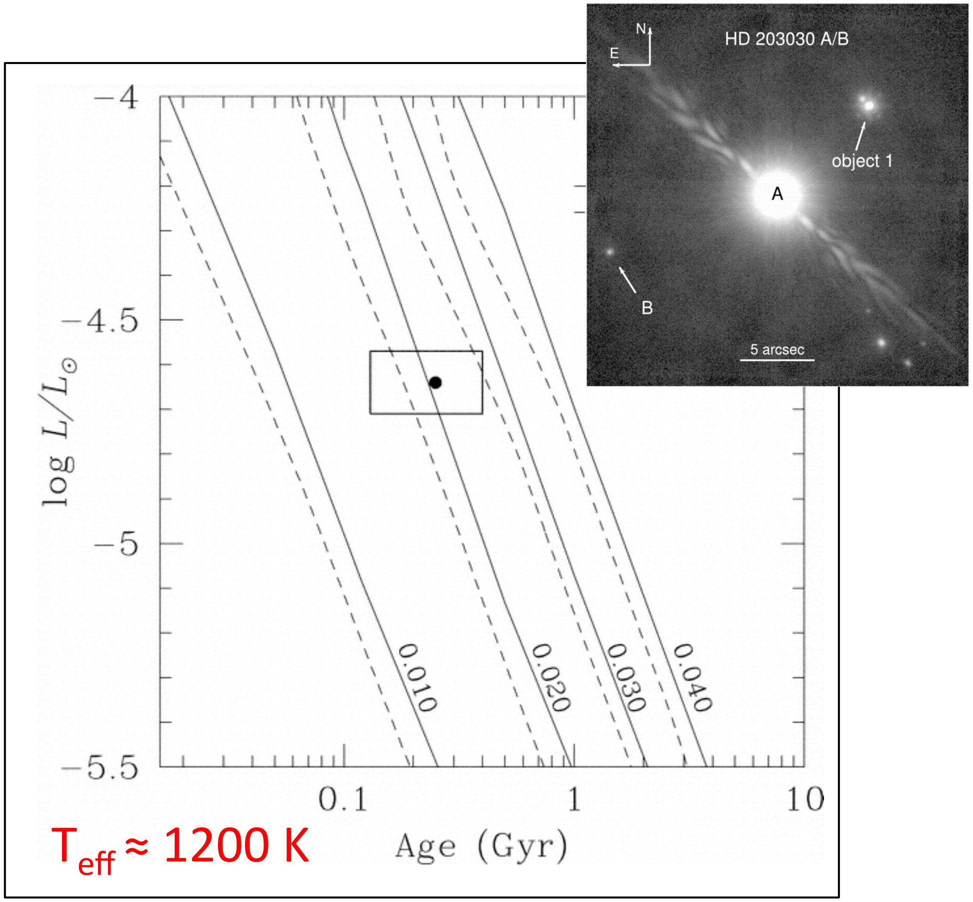
also Kirkpatrick et al. (2000, 2008); Cruz et al. (2003, 2007); Allers et al. (2006); Folkes et al. (2007); Radigan et al. (2008)

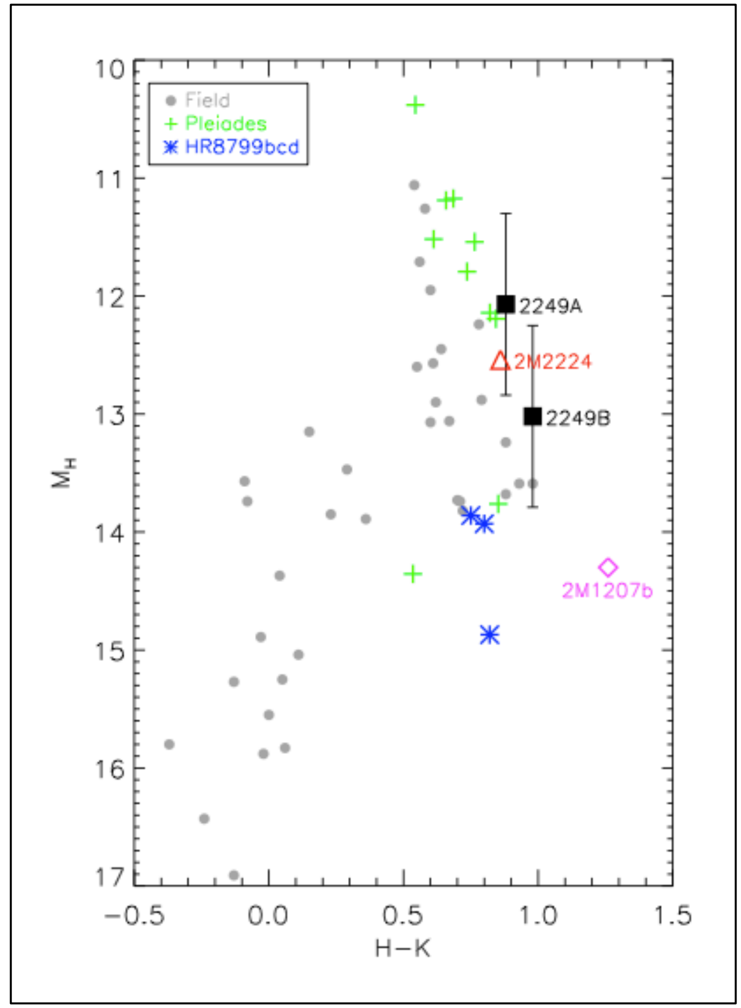
the “shrimp plot”



Kirkpatrick et al. (submitted)

Interrelations: gravity & temperature

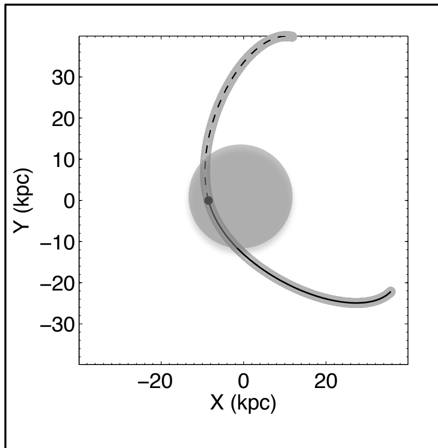




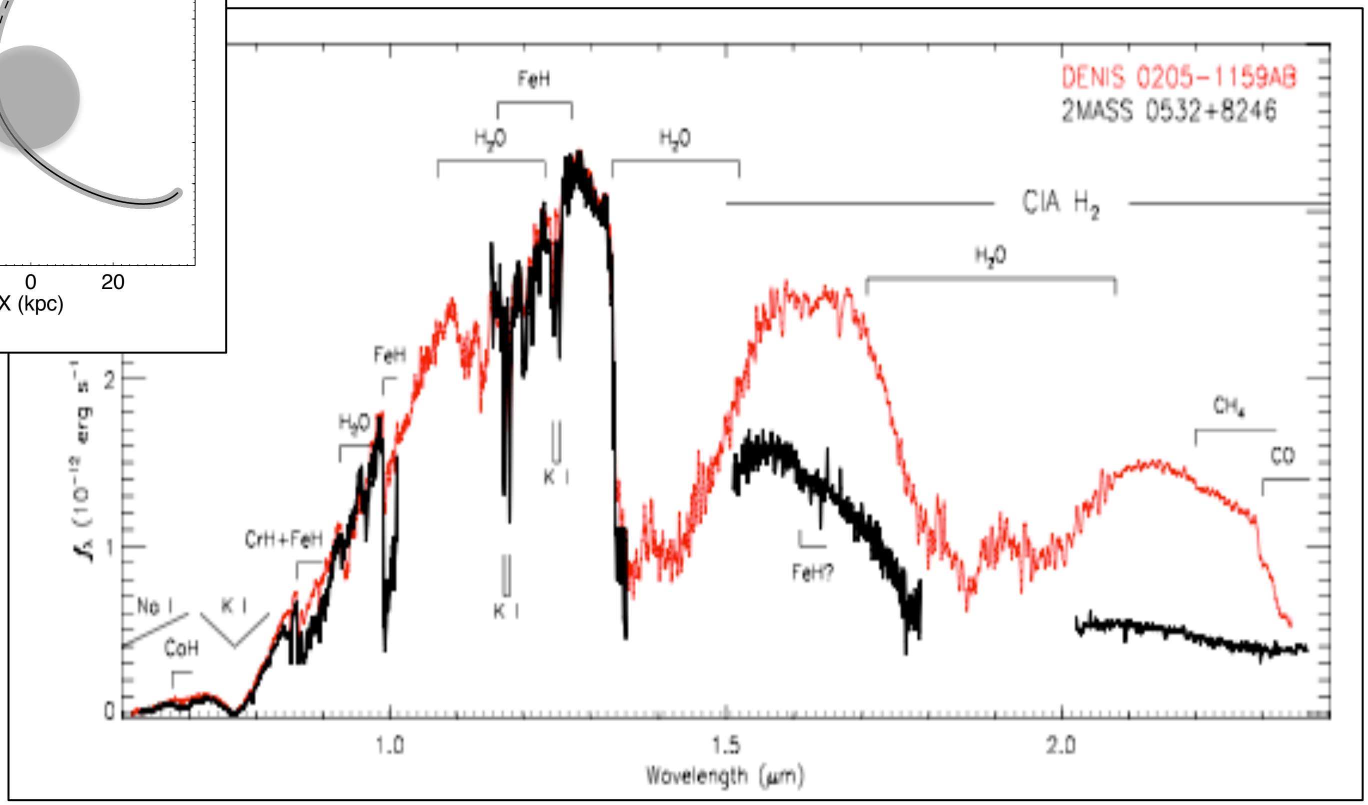
Metchev et al. (2006); Allers et al. (2010)

also Knapp et al. (2004); Burgasser et al. (2006); Dupuy et al. (2009); Konopacky et al. (2010)

Interrelations: abundances & clouds



suppressed cloud formation?

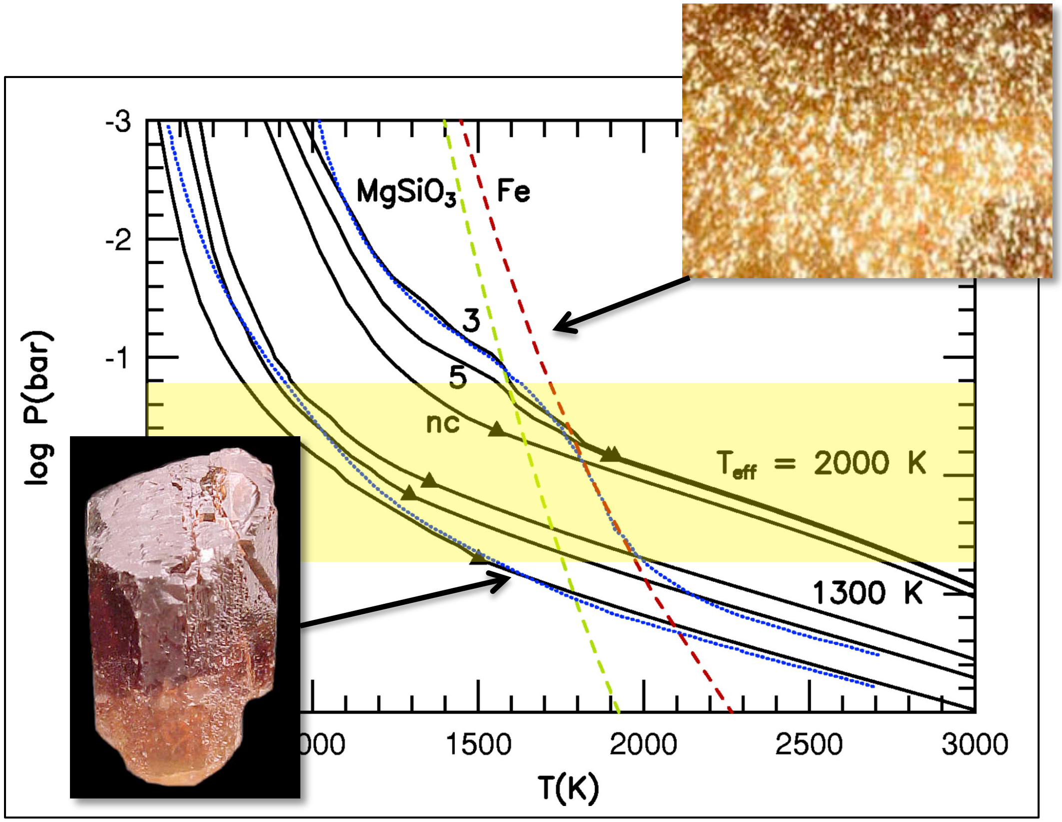


Burgasser et al. (2003); Sanderson et al. (in prep.)

see also Lepine et al. (2003); Burgasser et al. (2004,2008); Cushing et al. (2006,2009); Dahn et al. (2008); Bowler et al. (2009)

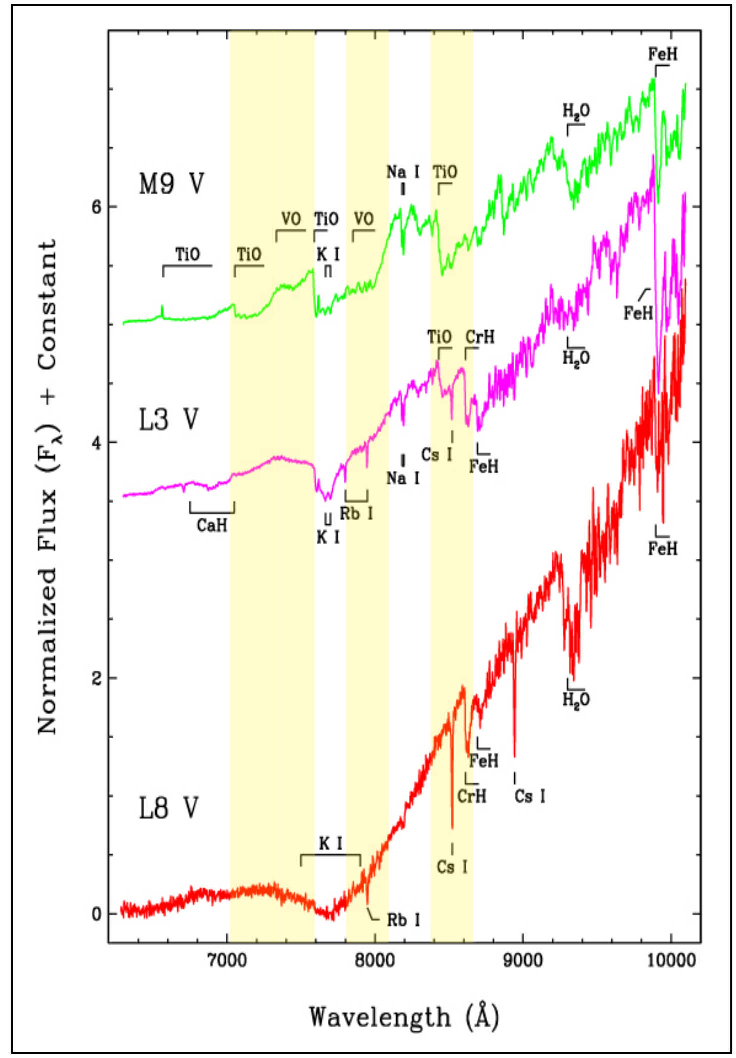

Clouds

Condensation in BD Atmospheres



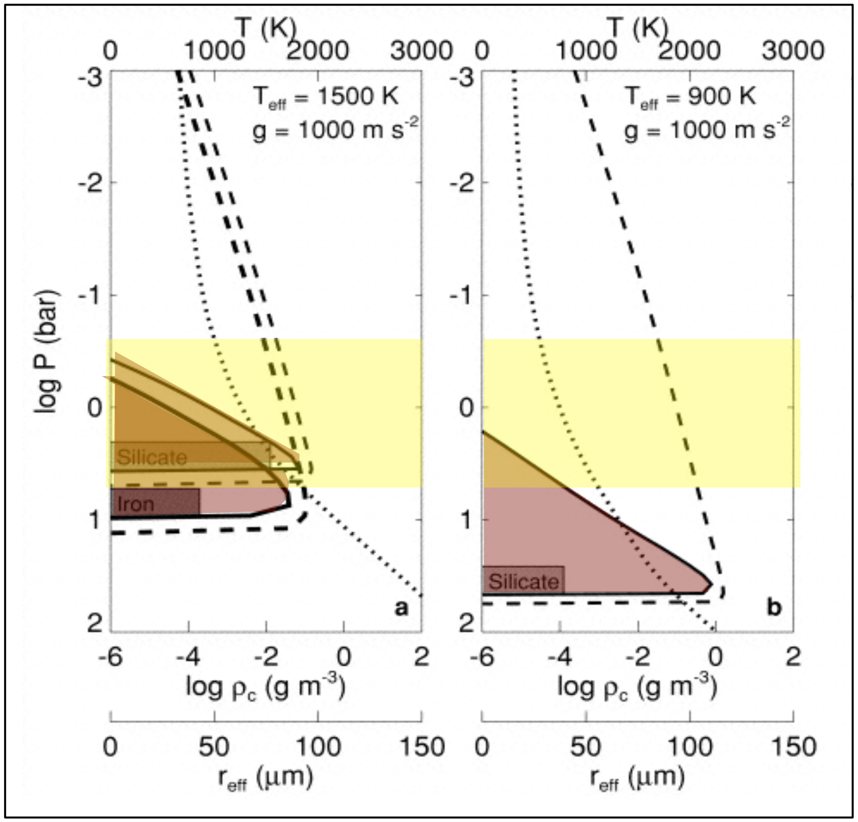
Marley et al. (2002)

also Burrows & Sharp (1999); Allard et al. (2001); Lodders (2002)

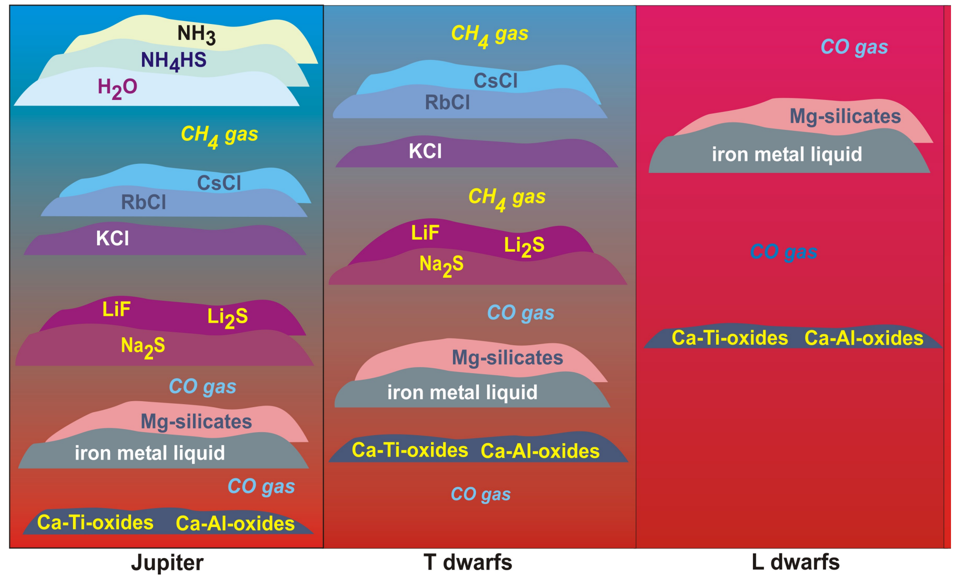


Kirkpatrick et al. (1999)

Clouds in BD Atmospheres



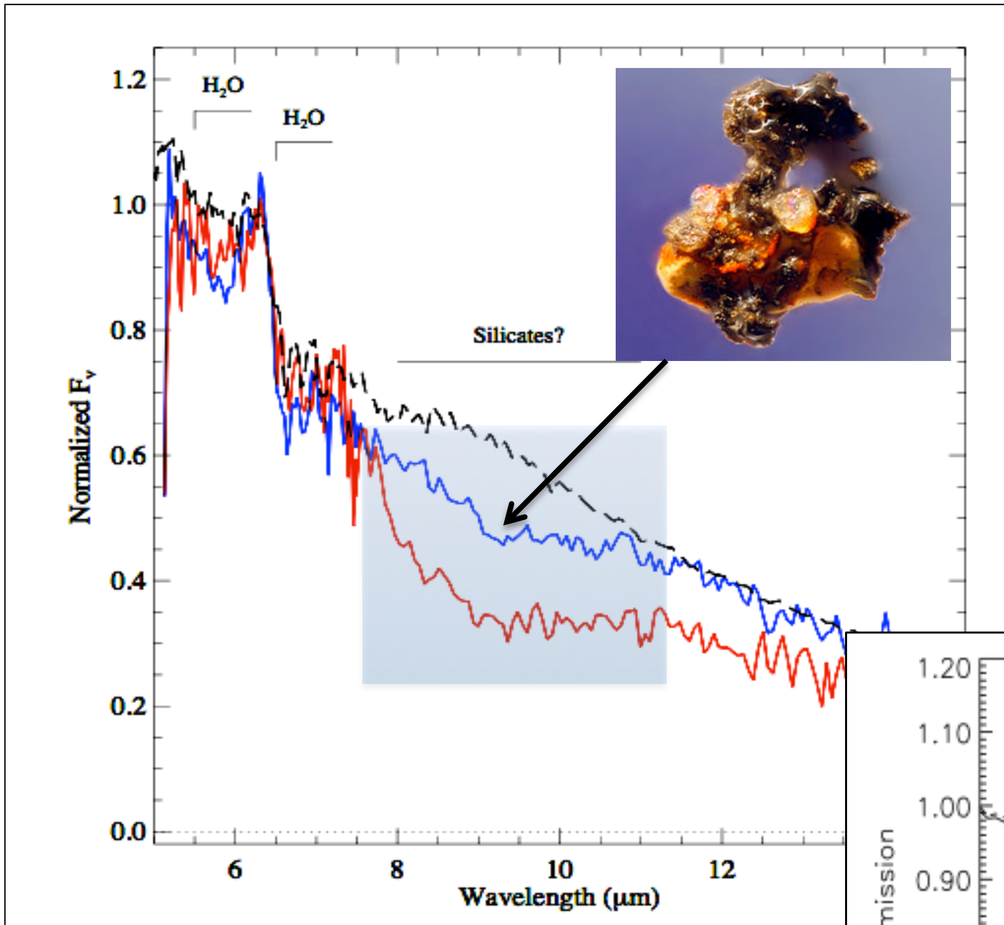
Ackerman & Marley (2001)
also Cooper et al. (2003); Tsuji (2004,2005); Helling et al. (2001,2006,2008)



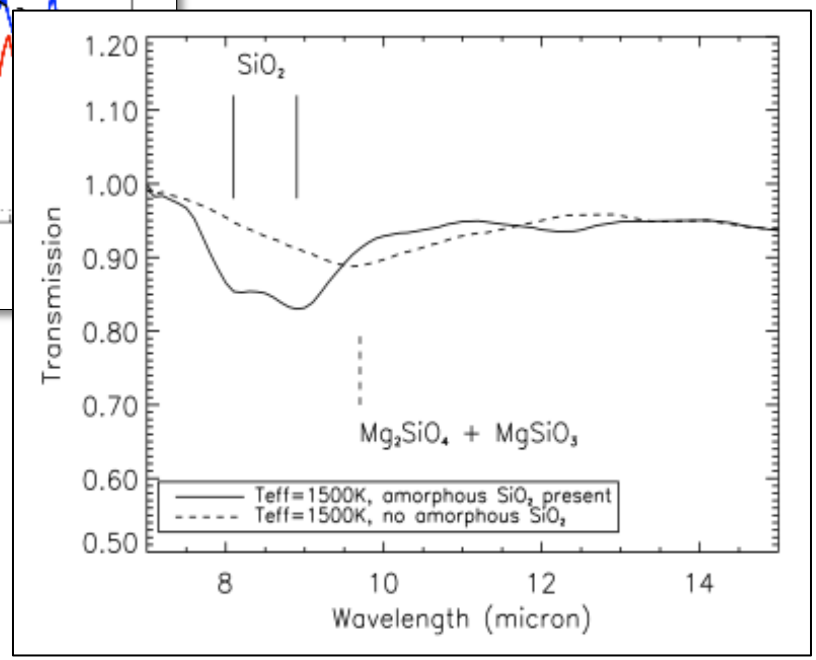
Lodders & Fegley (2006)

Condensate cloud formation is predicted in the balance of "rainout" and vertical mixing

Direct detection of silicate cloud grains



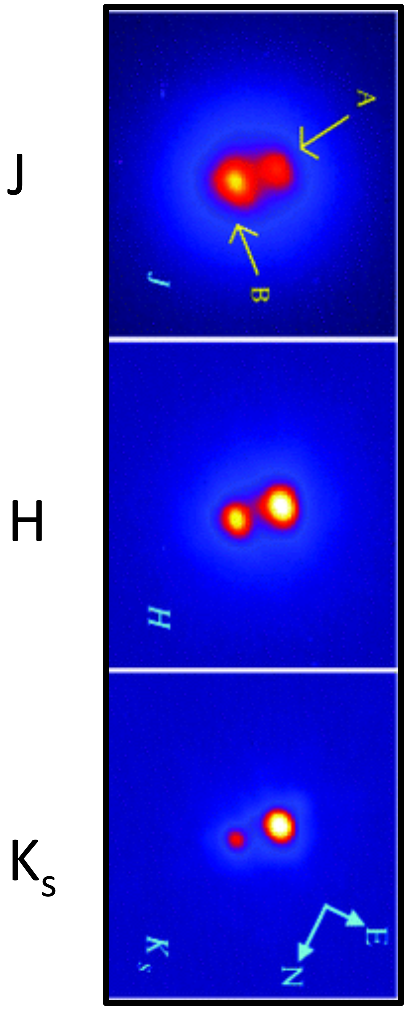
Burgasser et al. (2008);
data from Cushing et al. (2006)



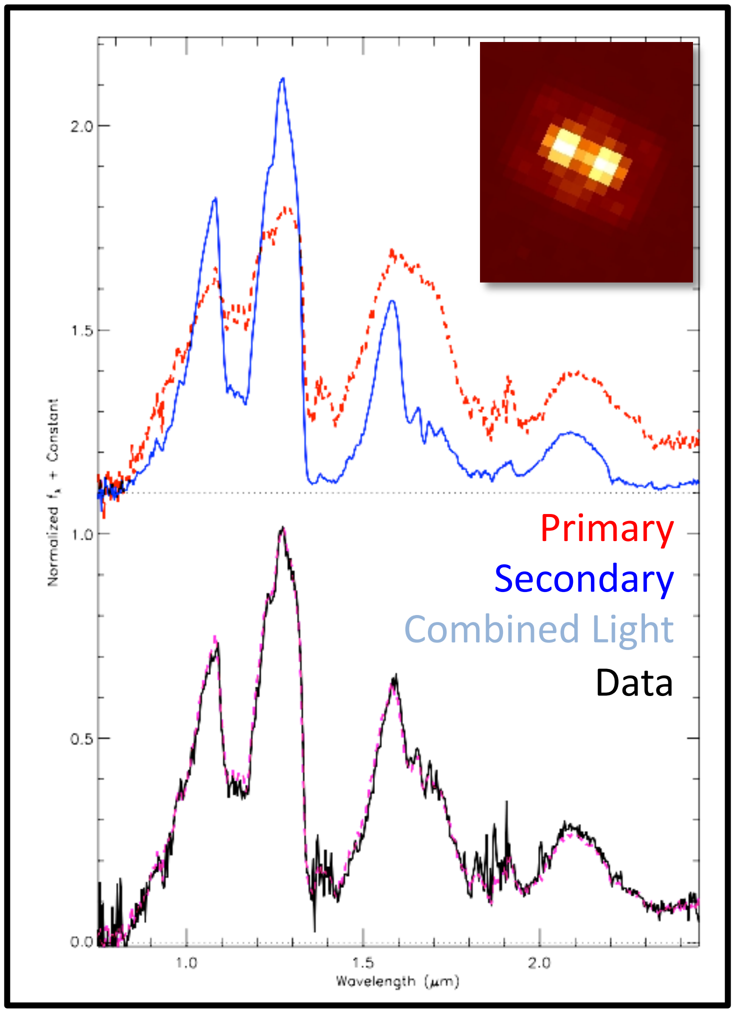
Helling et al. (2006)

The J-band bump

2M 1404-3159



SD 0423-0414

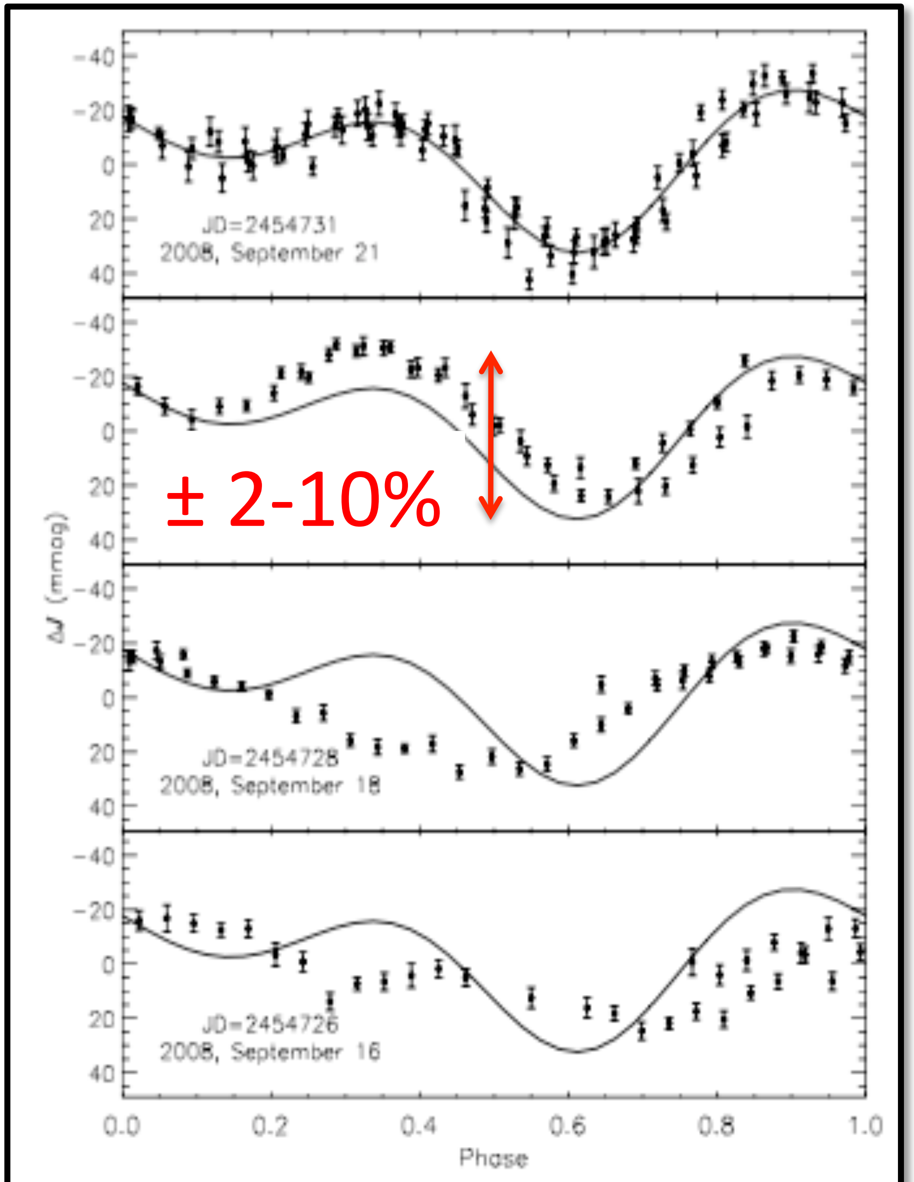


Rapid loss of condensate clouds at L/T transition – dynamic effects?

Looper et al. (2008); Burgasser et al. (2006)

See also Gizis et al. (2003); Cruz et al. (2004); Liu et al. (2006); Burgasser et al. (2007,2008,2010)

Variability: cloud structure?



brown dwarfs exhibit a range of variability roughly synched to rotation period, but also long-term changes (and no variability)

Artigau et al. (2009)

See also Bailer-Jones & Mundt (1999, 2001); Bailer-Jones (2002, 2004, 2008); Clarke et al. (2002); Bailer-Jones et al. (2003); Gelino et al. (2002); Enoch et al. (2003); Koen (2003 ,2004, 2005, 2006, 2008); Caballero et al. (2004); Littlefair et al. (2006, 2008); Morales-Calderon et al. (2006); Rockenfeller et al. (2006); Goldman et al. (2008); Blake et al. (2008)

What are the scales of surface features?

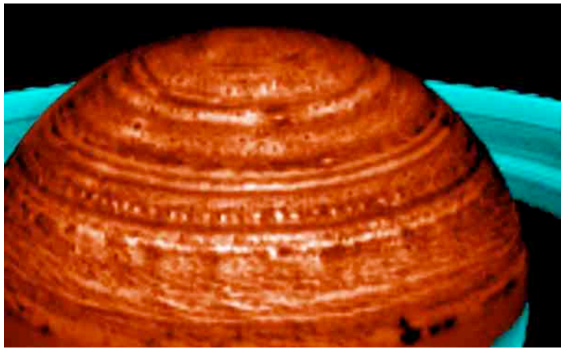
(ala Showman et al. 2007)

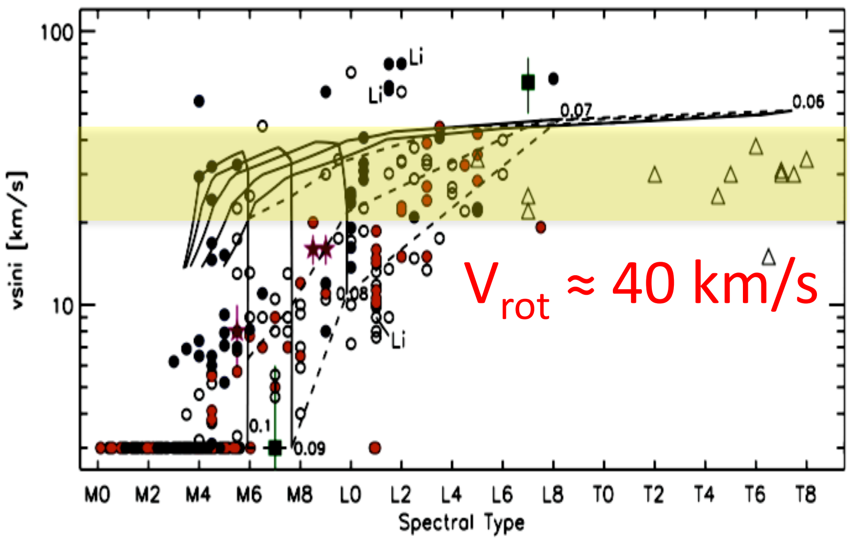
Rhine's Length $= (U/\beta)^{0.5}$

$\approx R(U/V_{rot})^{0.5} \approx 0.2\ R$

Rossby deformation radius = NH/f

$\approx R(gH_{scl})^{0.5}/V_{rot} \approx 0.03\ R$





Reiners & Basri (2008)

cf. Jupiter & Saturn:

$R_L \approx 0.03\ R$

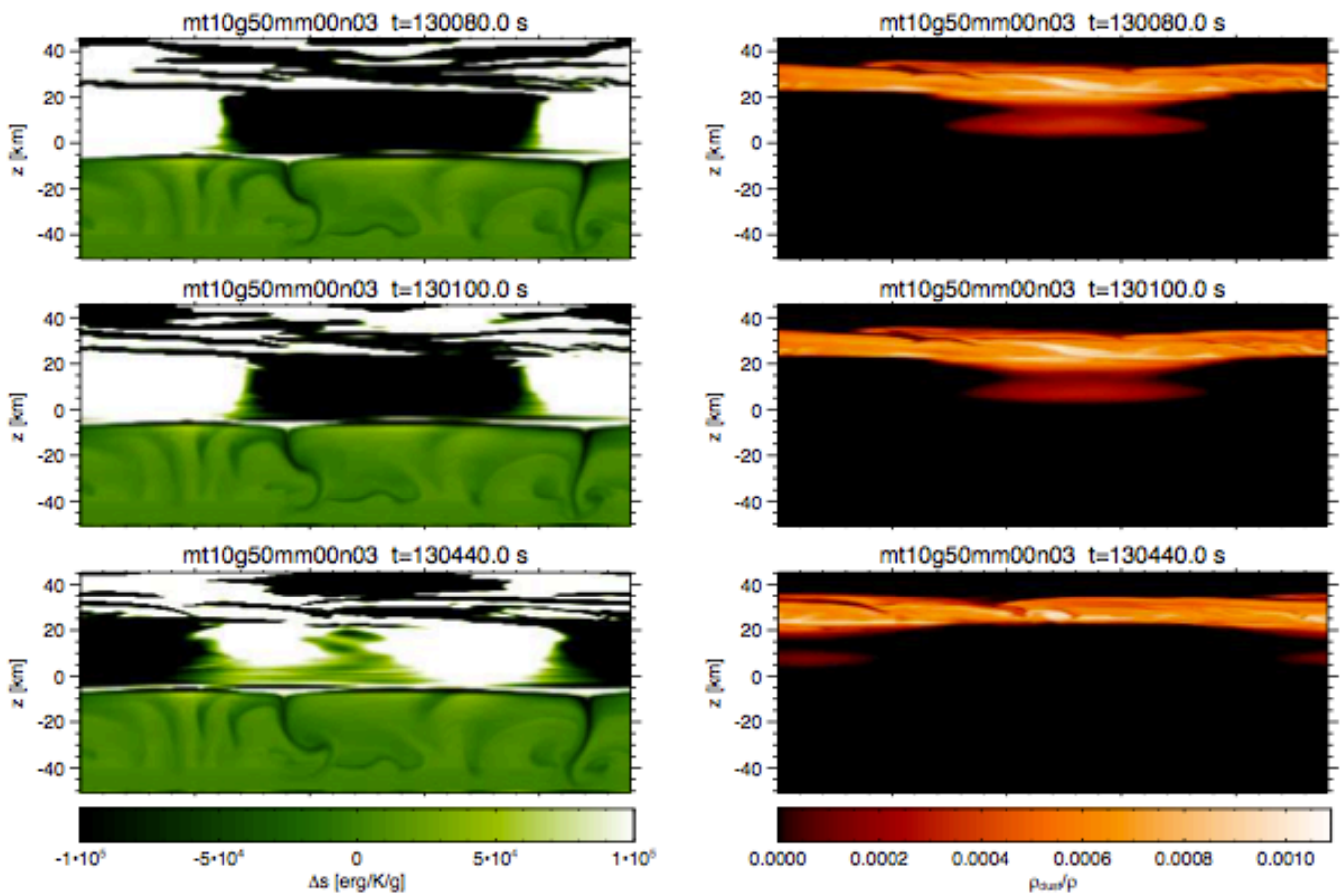
$R_d \approx 0.1\ R$

thick bands, small vorticies?

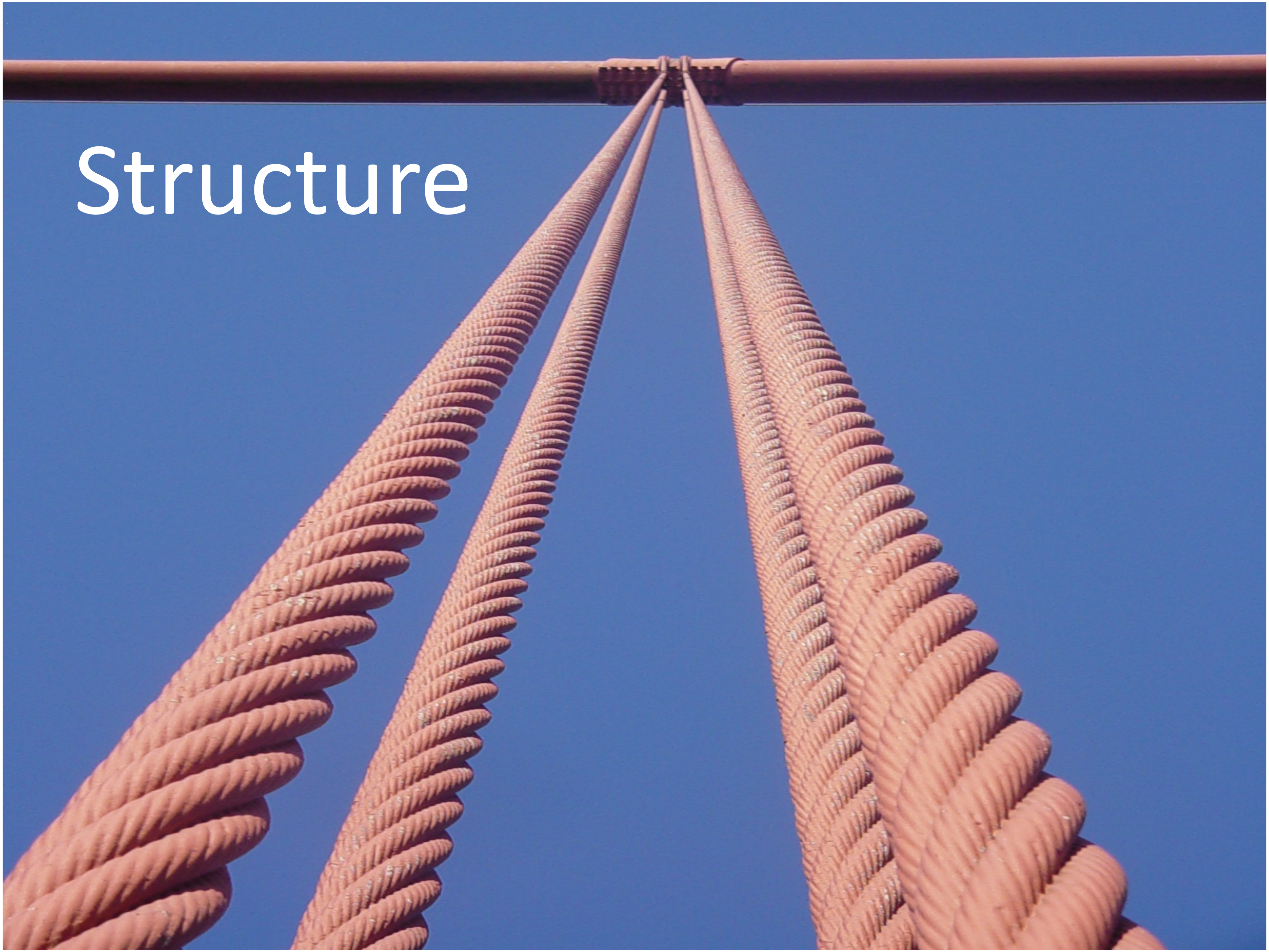
NEED HELP WITH THIS PROBLEM!

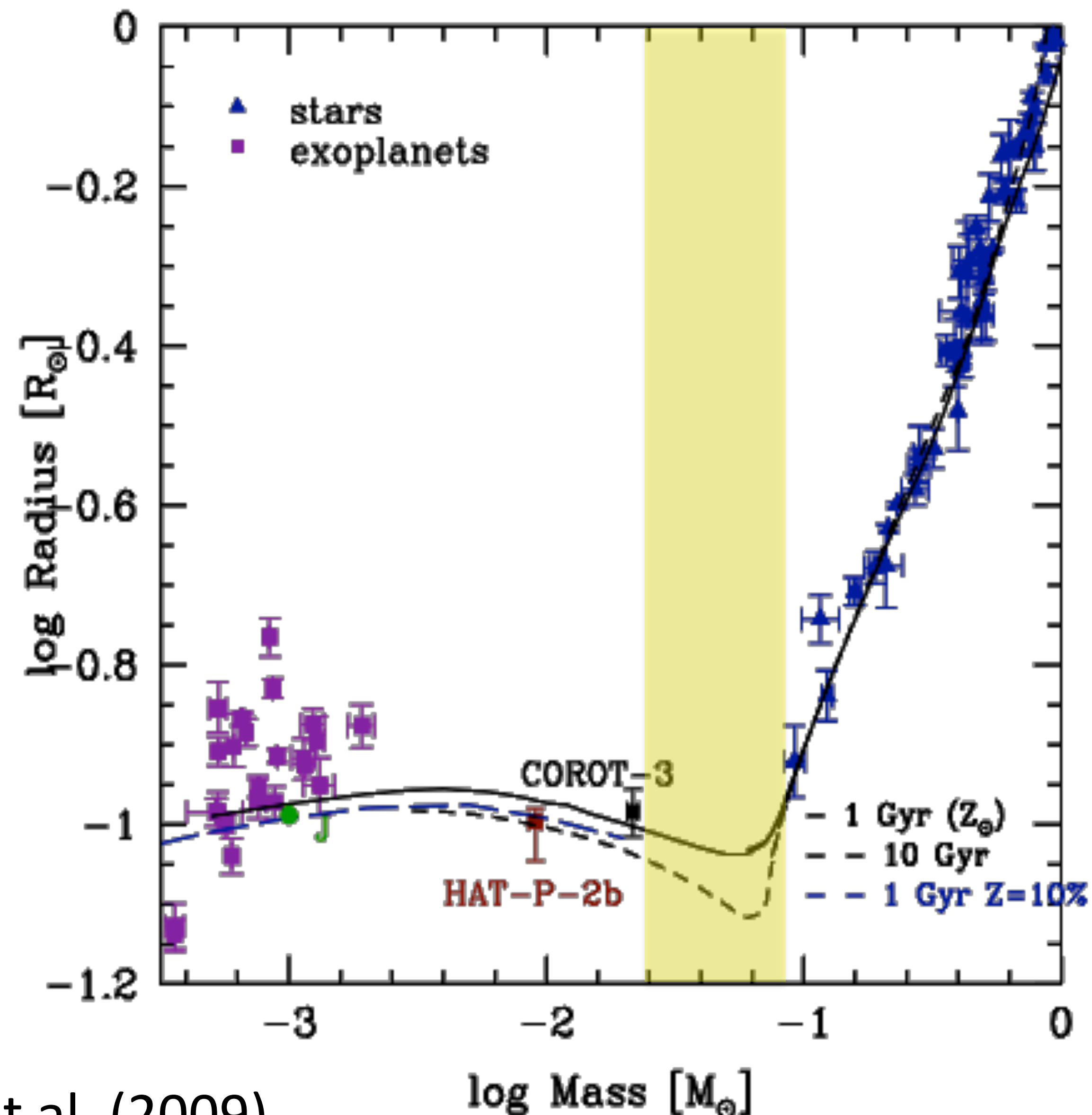
2D radiative-hydrodynamics

entropy fluctuations: dust concentration:



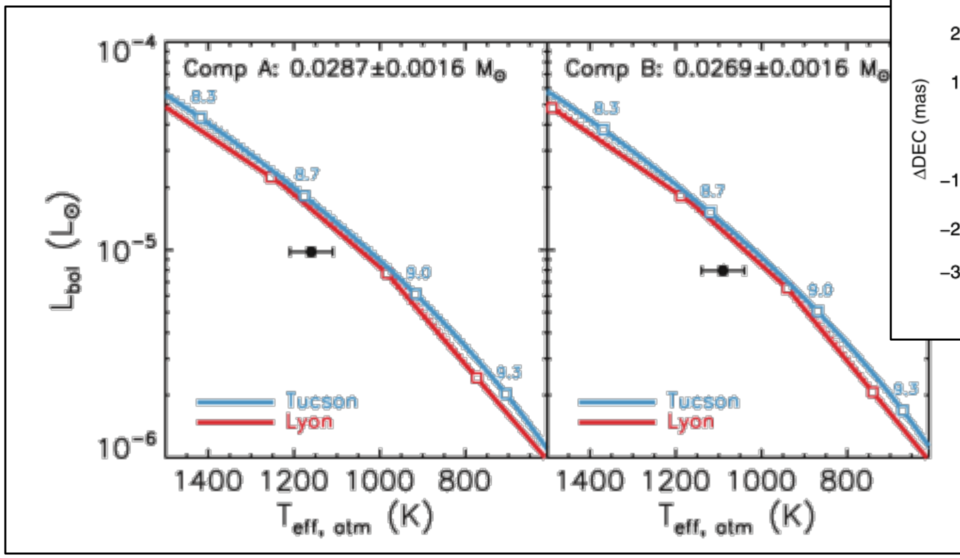
Freytag et al. (2010)

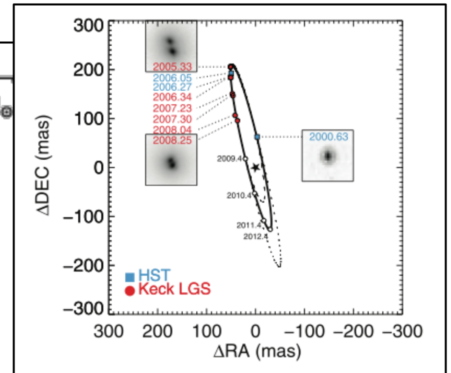

Structure

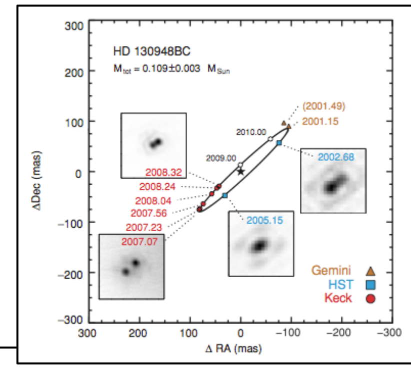


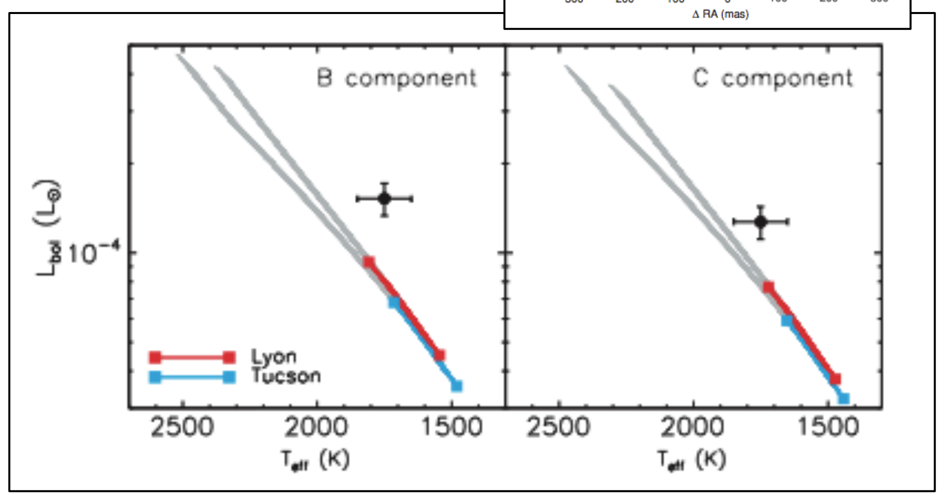
Chabrier et al. (2009)

Hints of Radius Problems?





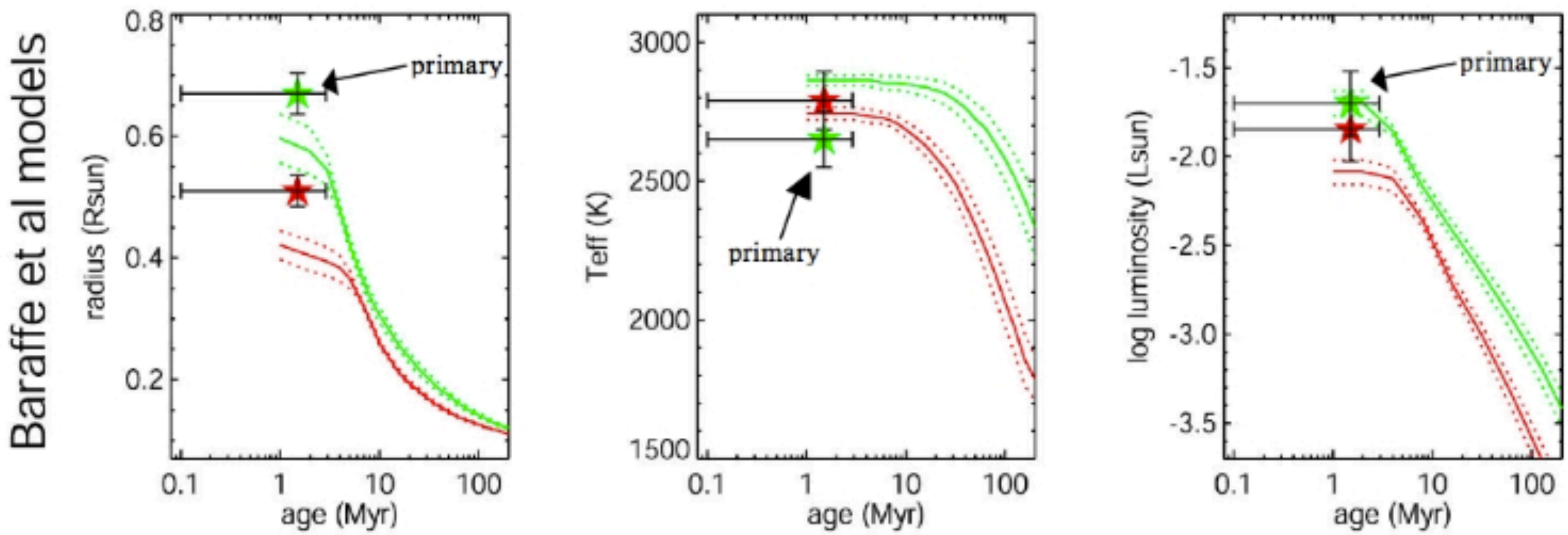




Liu et al. (2008); Dupuy et al. (2009)

see also Zapatero Osorio et al. (2004); Konopacky et al. (2009)

2M0535: A Cautionary Tale



≈1 Myr eclipsing brown dwarf system has a "temperature reversal" ≈ enlarged radius

(Stassun et al. 2006; Reiners et al. 2007; Gomez-Chew et al. 2009; Mohanty et al. 2009)

Suppression of convection and cool spots from B fields?

(e.g., Chabrier et al. 2007; Reiners et al. 2007; MacDonald & Mullen 2009)

Non-coeval?

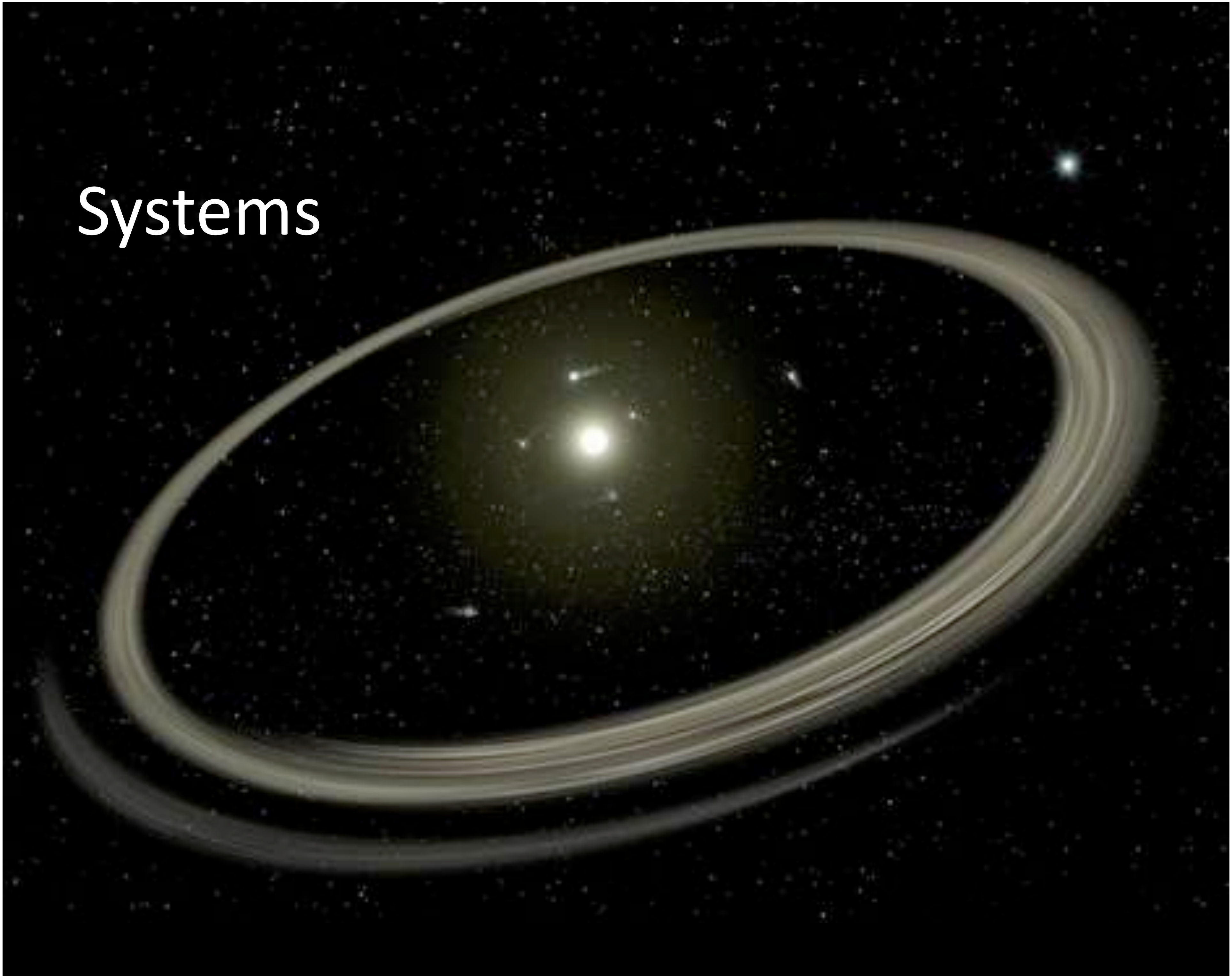
(e.g., Stassun et al. 2007)

Tidal effects?

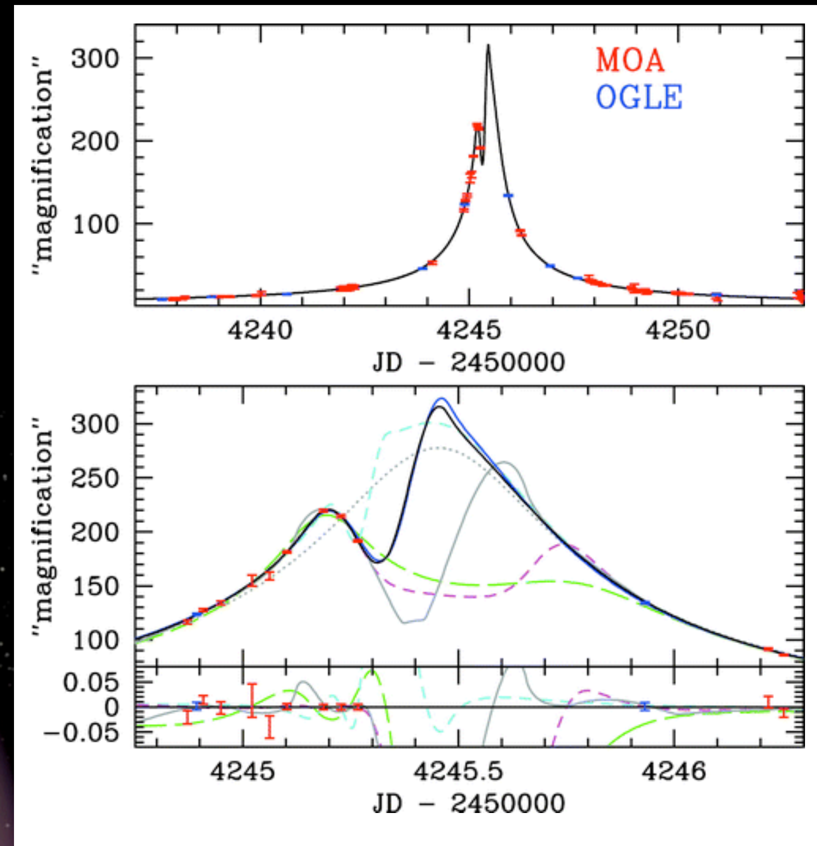
(e.g., Heller et al. 2010)

Corot/Kelper/MEarth dans l'infrarouge?

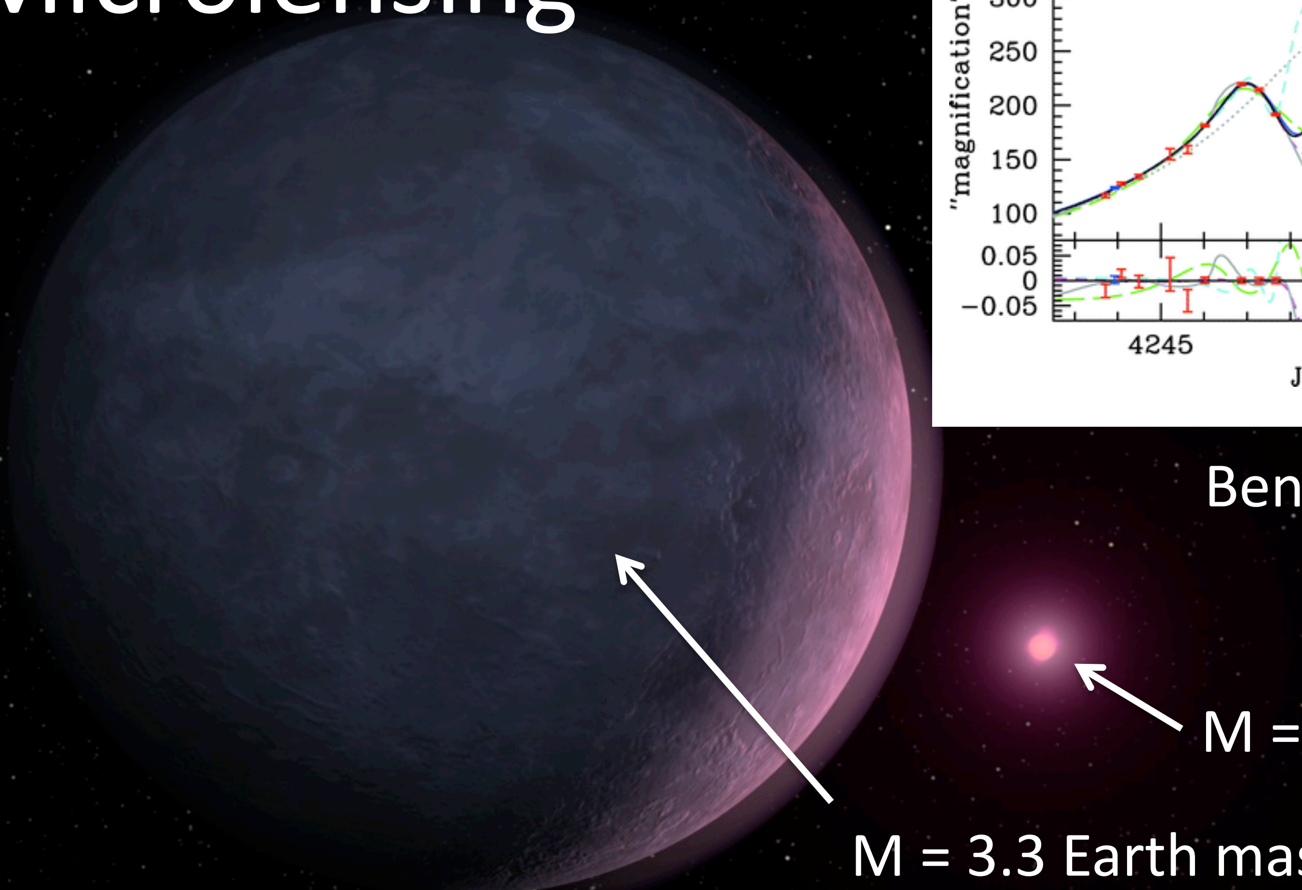
Systems



Brown dwarf – planet systems: Microlensing



Bennett et al. (2009)



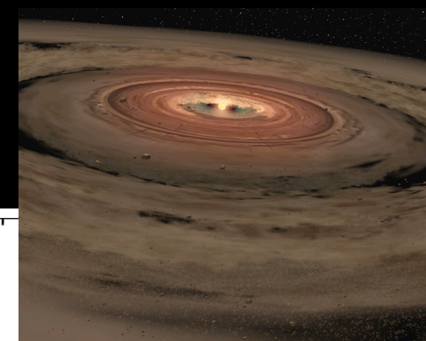
Brown Dwarfs with Planetary Systems

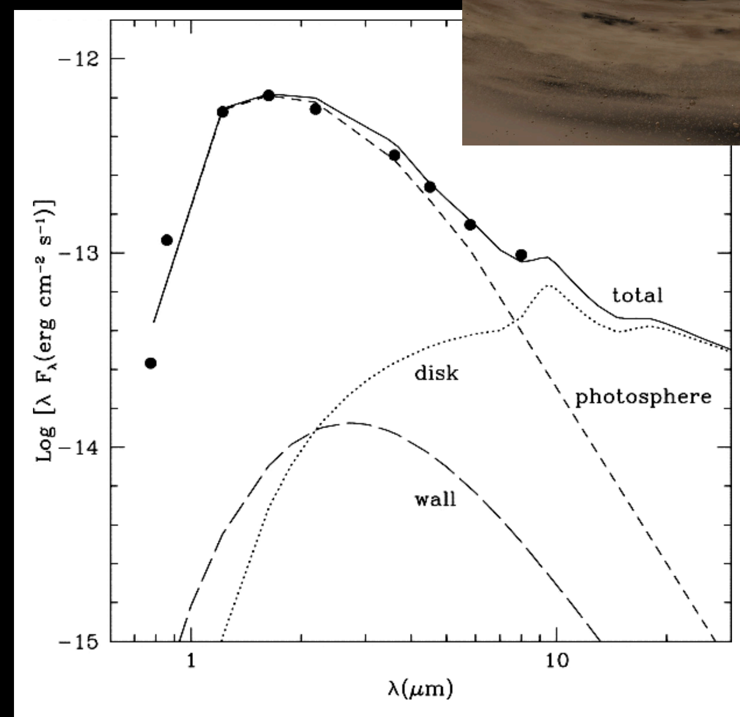
2MASS 1207AB
≈ 8 Myr old

2MASS 1207A
≈25-30 $M_{Jupiter}$

2MASS 1207B
≈3-10 $M_{Jupiter}$

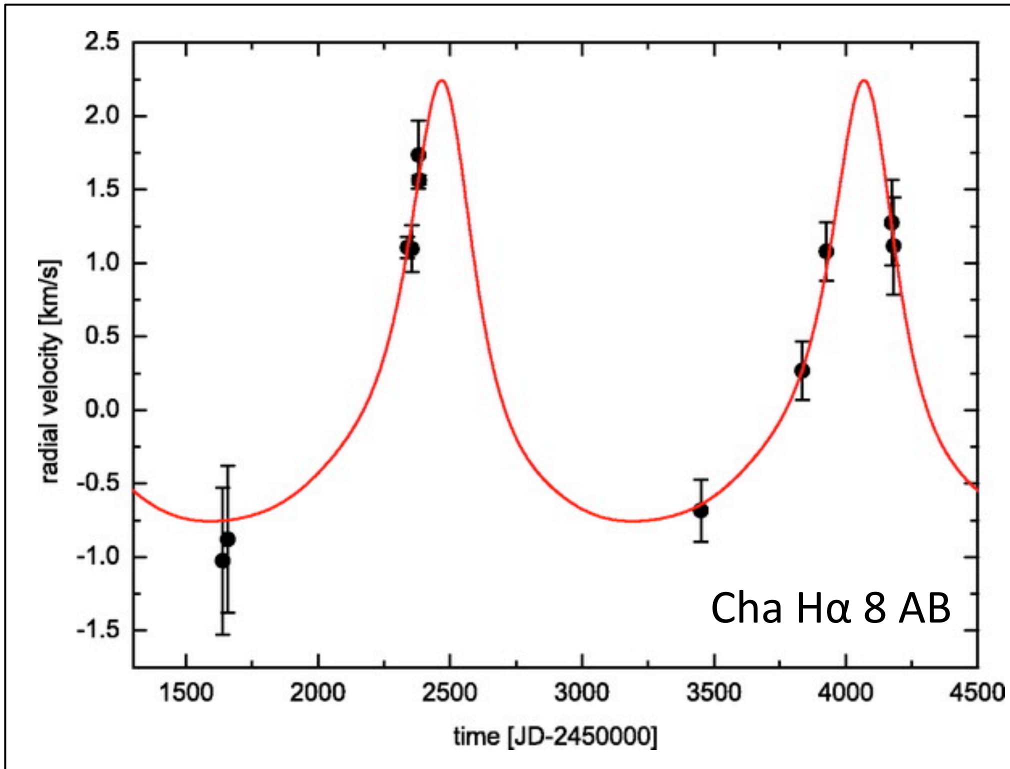
Cha 1109-77
2 Myr, 5-15 $M_{Jupiter}$





Chauvin et al. (2004,2005); Luhman et al. (2005)

NIR RVs of Cool Dwarfs



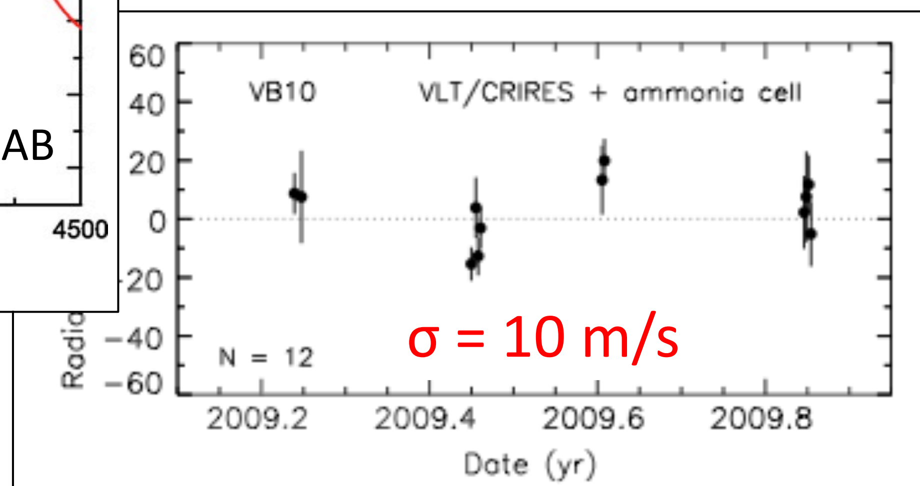
Joergens & Müller (2008)

0.07-0.1 $M_{\odot}$ primary

16-20 $M_{Jupiter}$ secondary

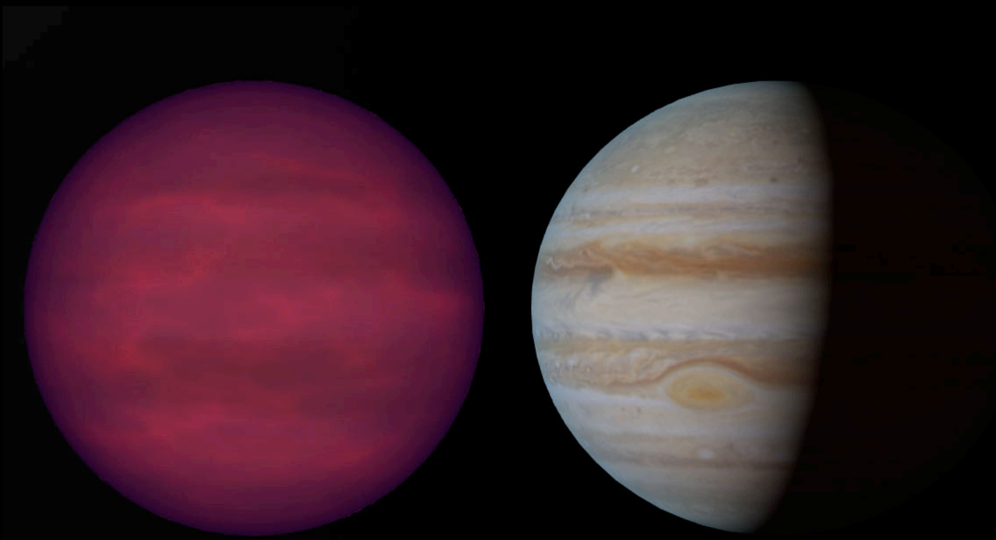
see also Zapatero Osorio (2006,2007); Blake et al. (2007,2008); Konopacky et al. (2010)

Brown dwarfs are increasingly becoming the (successful) hunting grounds for planetary companions



Bean et al. (2010)

VB 10 (M8), CRIRES + Iodine cell



Areas of productive overlap

Opacities – a problem for both BD & EGP atmospheres

Coldest brown dwarfs ≈ widely-separated planets

Brown dwarf weather – proving ground for EGP surface distribution models; understand BD variability

Developing stellar detection techniques for substellar primaries (NIR RV, NIR/MIR monitoring)

Structure – let's close the R-M relation gap!

For further reference:

- Reid & Metchev (2008) “The Brown Dwarf-Exoplanet Connection” in Exoplanets: Detection, Formation, Properties, Habitability
- Burgasser (2009) “The Brown Dwarf Exoplanet Connection” in "Molecules in the Atmospheres of Extrasolar Planets"
- New Technologies for Probing the Diversity of Brown Dwarfs and Exoplanets (Shanghai, July 2009)