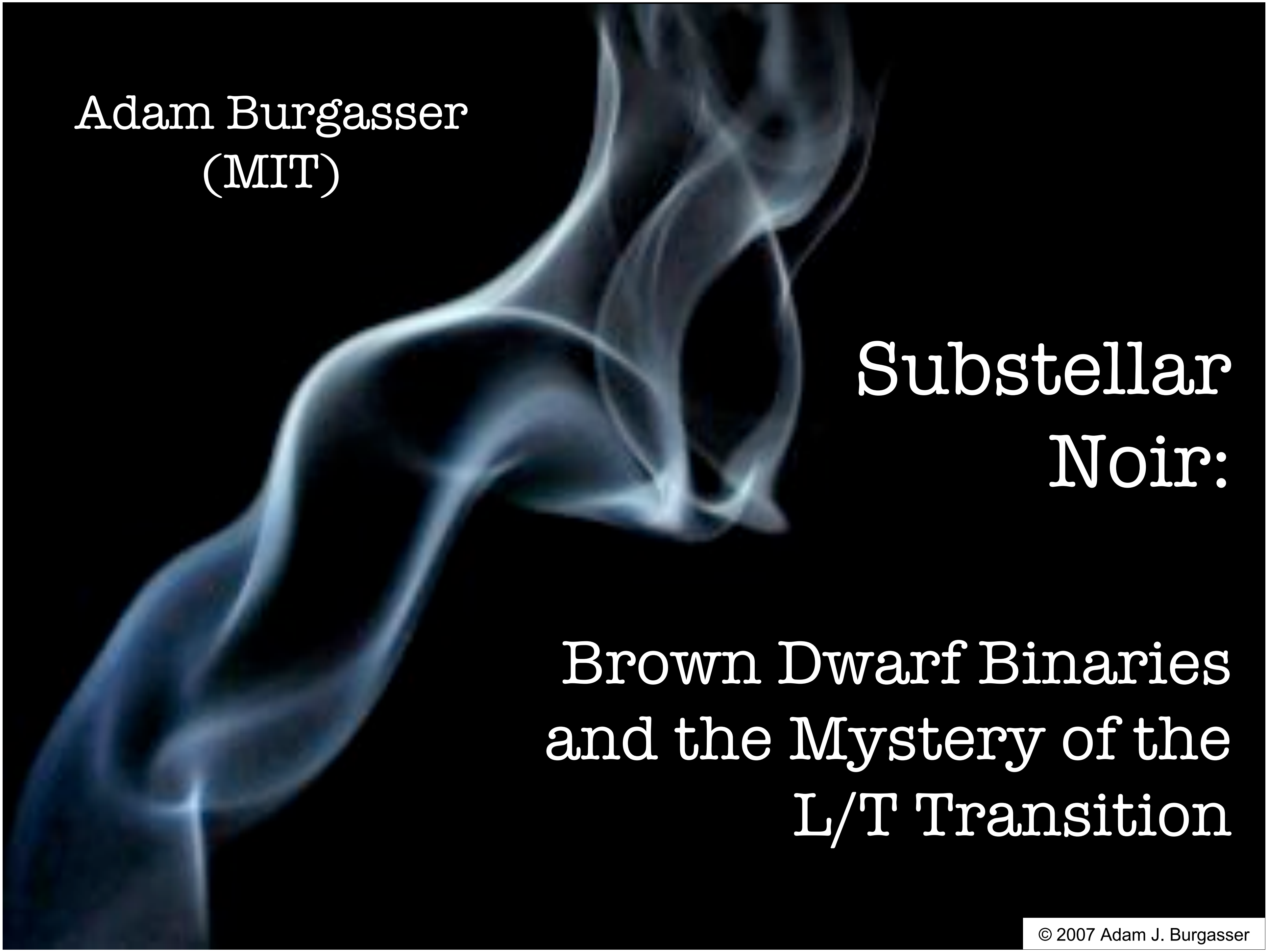
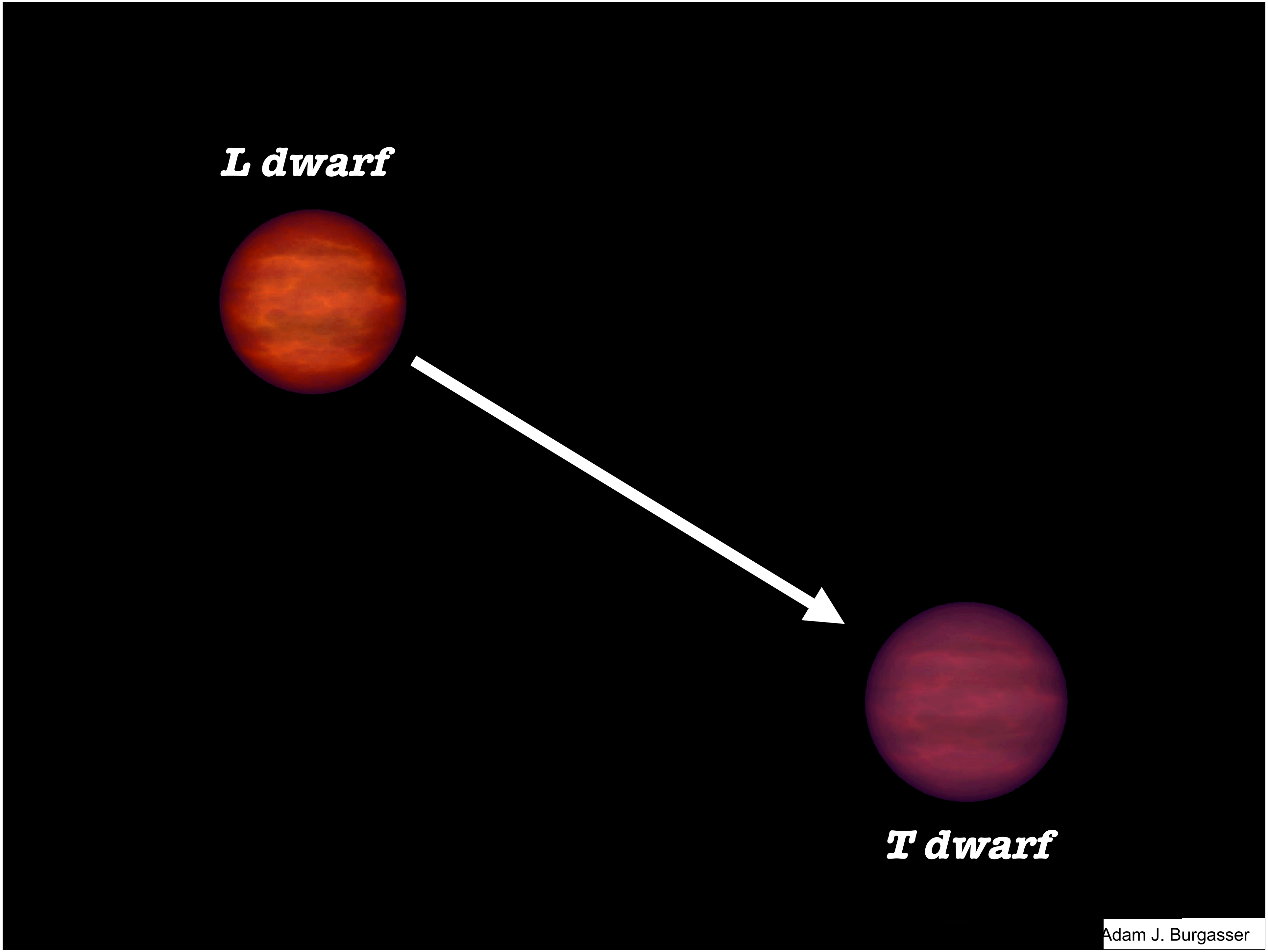
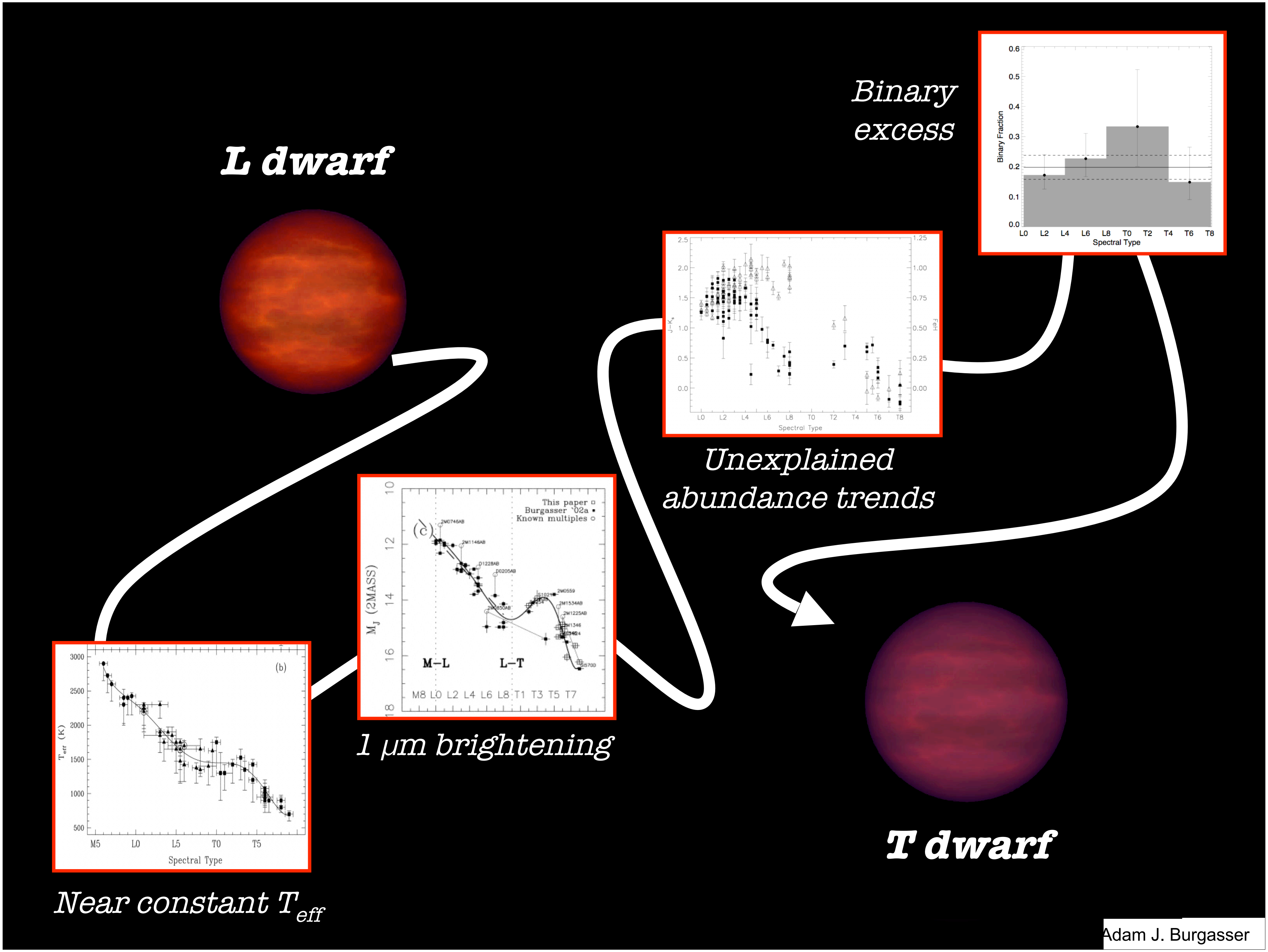


Adam Burgasser
(MIT)

Substellar Noir:

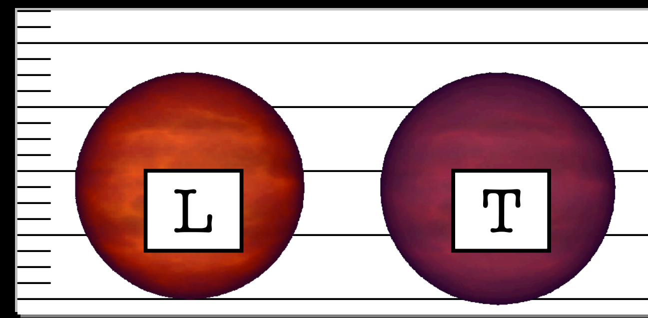
Brown Dwarf Binaries and the Mystery of the L/T Transition


L dwarf
T dwarf
Adam J. Burgasser


L dwarf
Binary excess
Binary Fraction
Spectral Type
Unexplained abundance trends
Spectral Type
1 μm brightening
M_J (2MASS)
This paper
Burgasser '02a
Known multiples
M−L
L−T
M8 L0 L2 L4 L6 L8 T1 T3 T5 T7
Near constant T_eff
(b)
T_eff (K)
M5 L0 L5 T0 T5
Spectral Type
T dwarf
Adam J. Burgasser

The Lineup

L dwarfs & T dwarfs

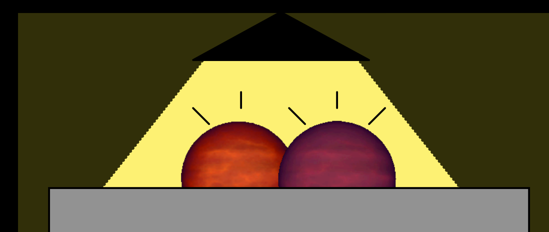


A Mystery... and a Solution?

Strange happenings across the L/T transition

A New Lead

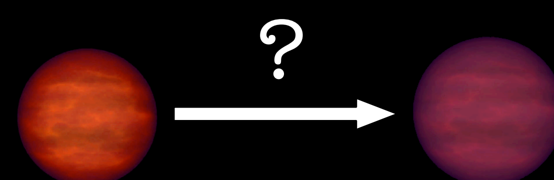
Resolved L/T binaries tell a new tale...



A Full Investigation

Reconstructing the evidence

Dénouement



Burgasser et al. 2006, ApJS, 166, 585:

"Hubble Space Telescope NICMOS Observations of T Dwarfs: Brown Dwarf Multiplicity and New Probes of the L/T Transition"

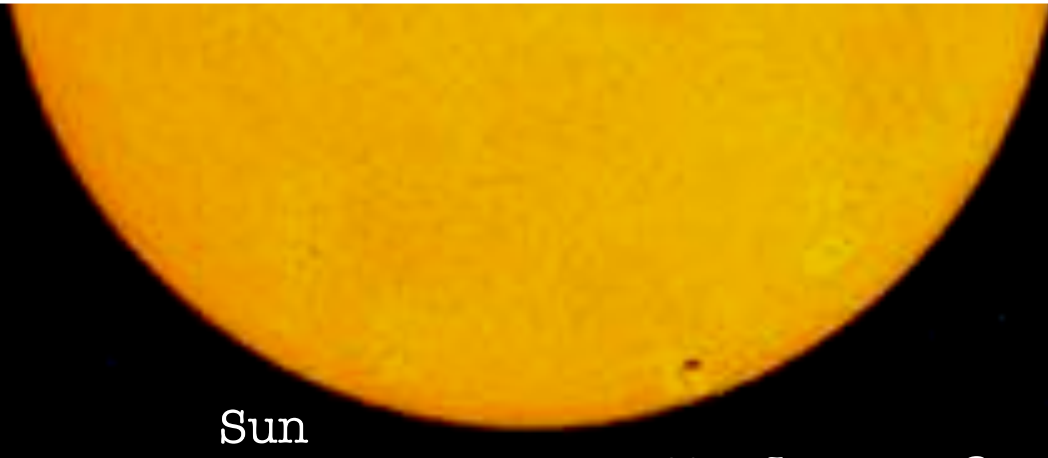
Liu et al. 2006, ApJ, 647, 1393:

"SDSS J1534+1615AB: A Novel T Dwarf Binary Found with Keck Laser Guide Star Adaptive Optics and the Potential Role of Binarity in the L/T Transition"

Burgasser 2007, ApJ, in press (astro-ph/0611505):

"Binaries and the L Dwarf/T Dwarf Transition"


The Lineup
© 2007 Adam J. Burgasser



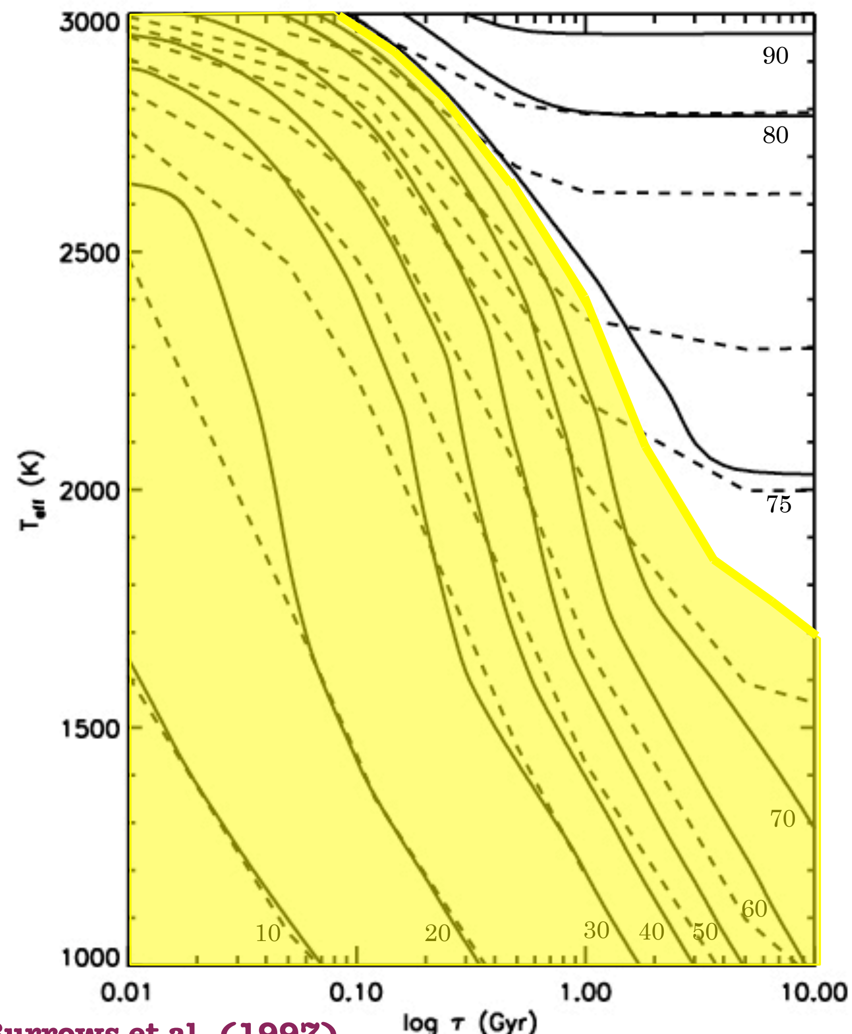
L dwarfs and T dwarfs are two classes of brown dwarf

Objects with masses and surface temperatures intermediate between stars and planets.

Distinguished by the absence of sustained core hydrogen burning

Hundreds *of brown dwarfs known*

Brown Dwarfs "Evolve"



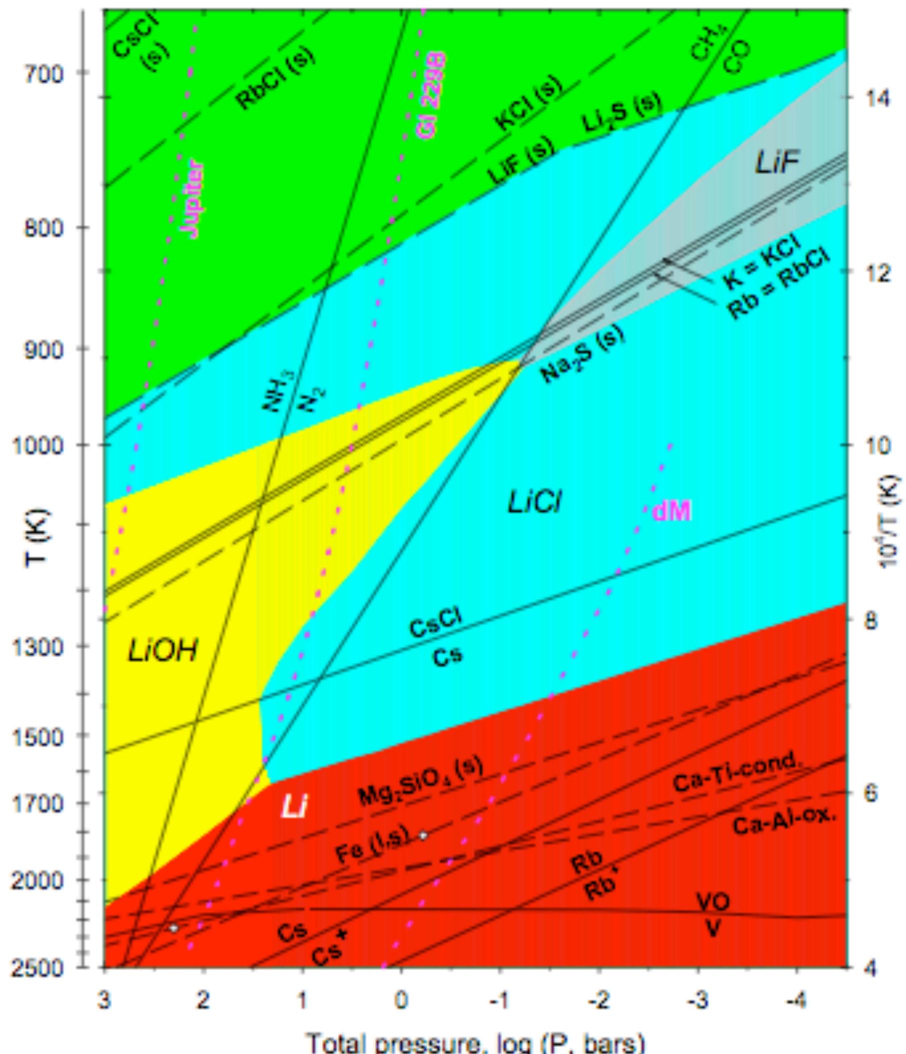
Burrows et al. (1997)
Baraffe et al. (2003)

Without an internal fusion source, brown dwarfs cool to lower effective temperatures and lower luminosities as they age.

"… cool off inexorably like dying embers plucked from a fire."

A. Burrows

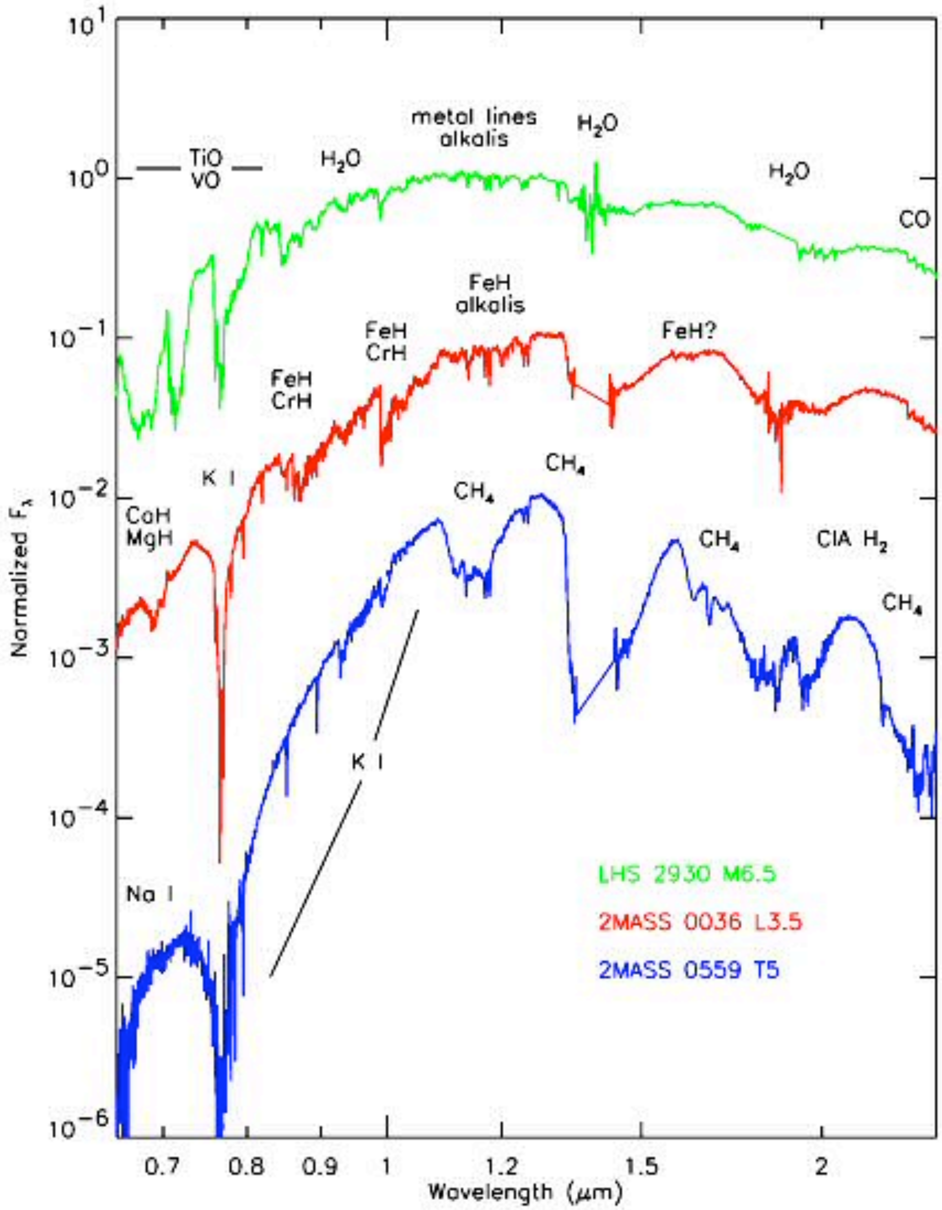
Low Temperatures ⇒ Chemistry



Lodders (1999)

Atomic species combine to form gaseous molecules
(e.g., TiO, VO, FeH, CO, H_2O, CH_4)

Gaseous molecules condense to form grains of dust, ice and "rain"
(e.g., Fe[l], VO[s], $CaTiO_3$[s])



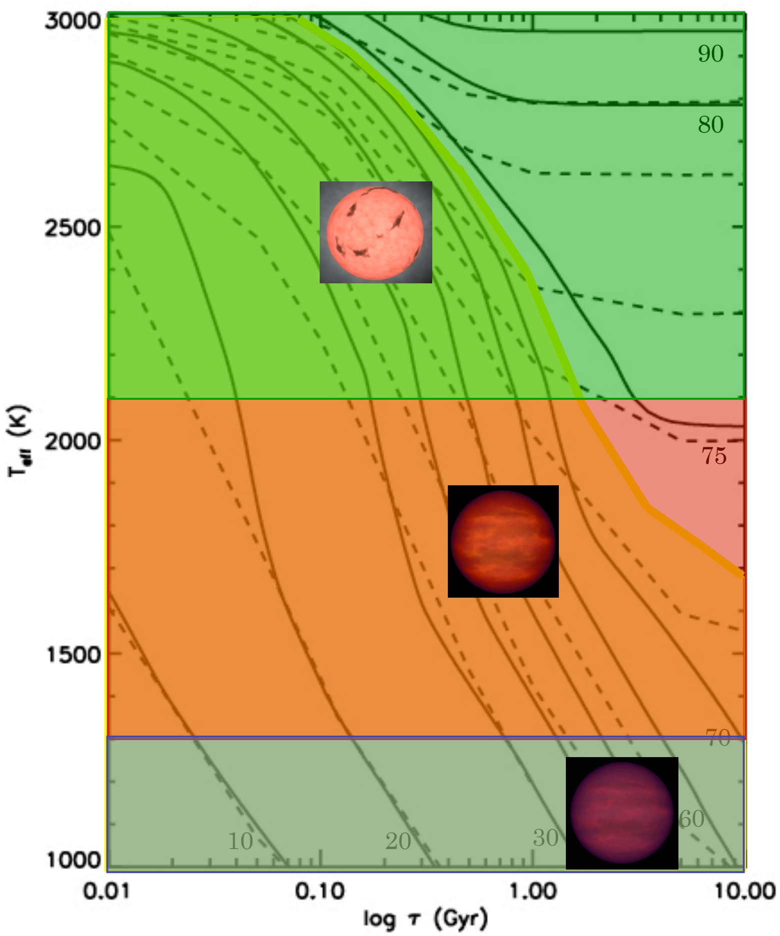
Molecular absorptions give rise to strong spectral features & spectral classes

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.*

M, L, and T dwarfs



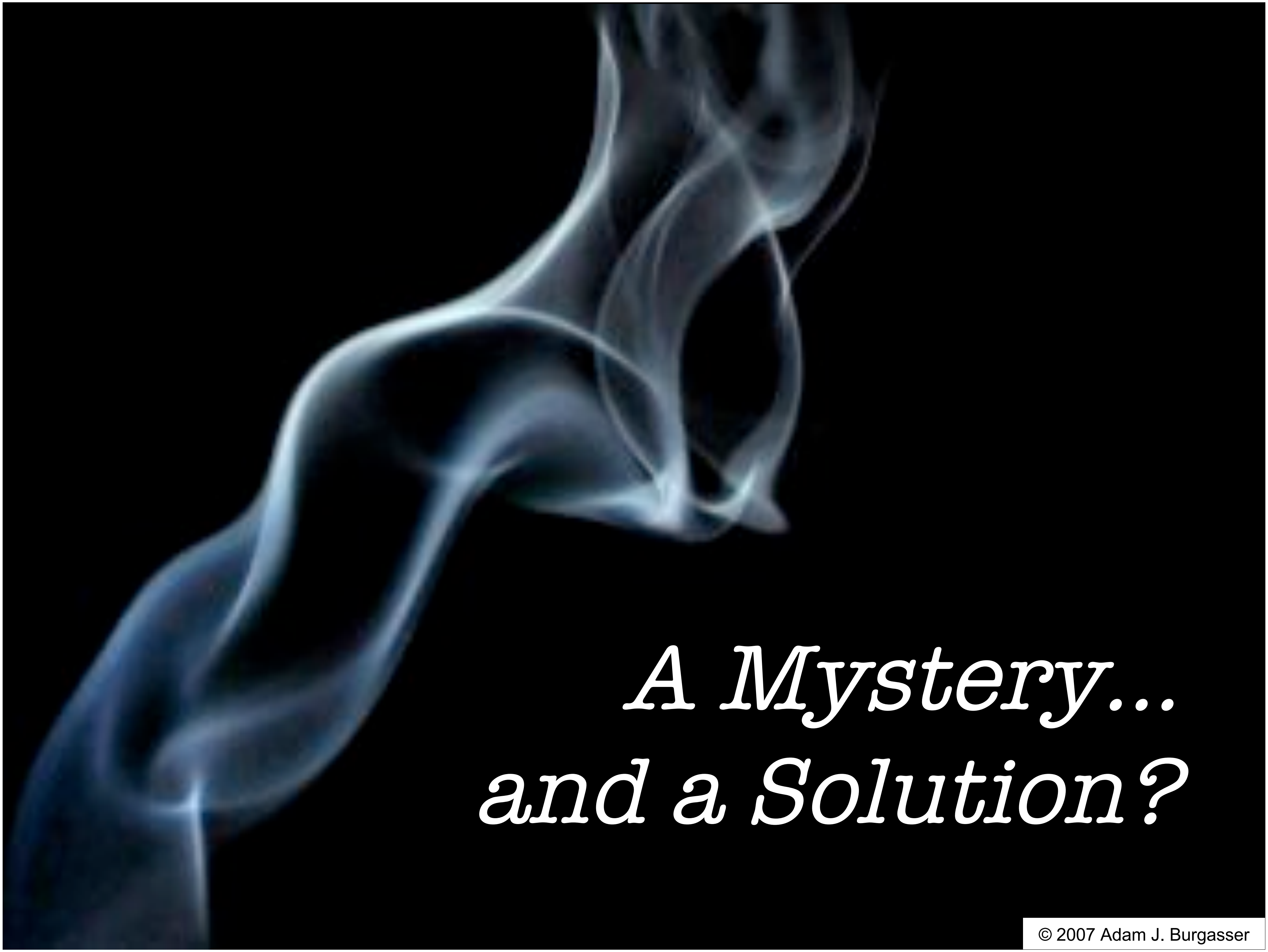
Three spectral classes encompass all known brown dwarfs:

M dwarfs *(T_{eff} = 3800-2100 K):*
Young BDs and low-mass stars.

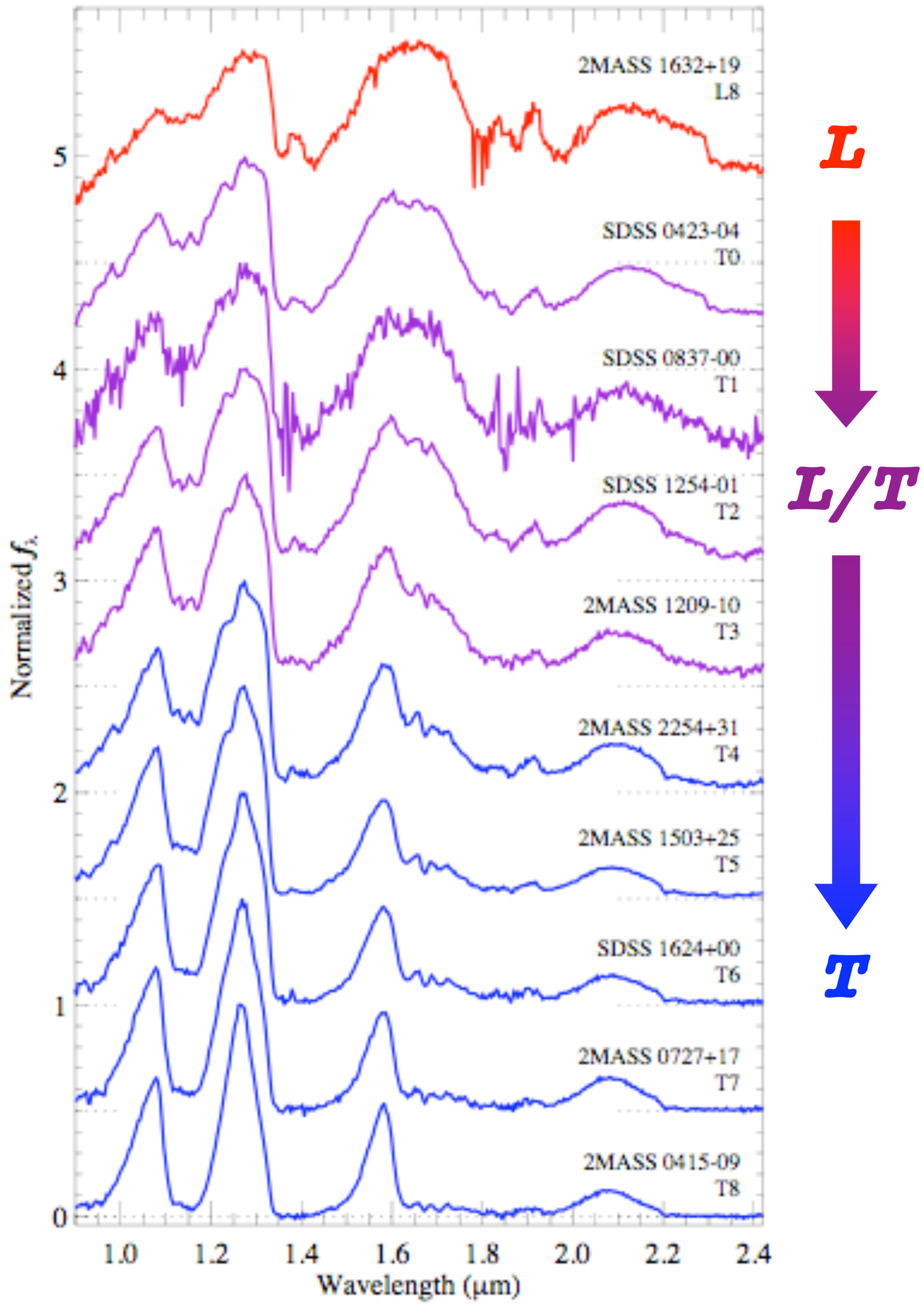
L dwarfs *(T_{eff} = 2100-1300 K):*
BDs and old, very low-mass stars.

T dwarfs *(T_{eff} < 1300 K):*
All BDs; coolest "stars" known.

M→L→T is an evolutionary sequence for a brown dwarf


A Mystery...
and a Solution?

The L/T Transition



Burgasser et al. (2006)

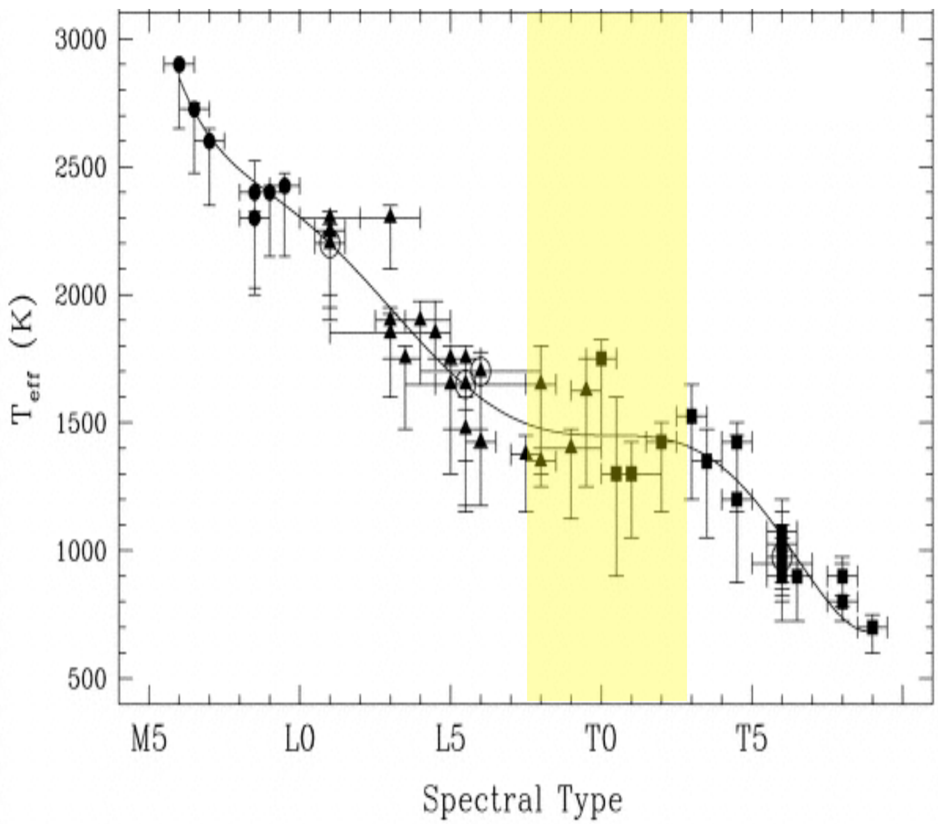
Dramatic changes in spectral energy distributions and colors

$CO \rightarrow CH_4$

Loss of photospheric condensates

And some unusual properties…

The Temperature Scale



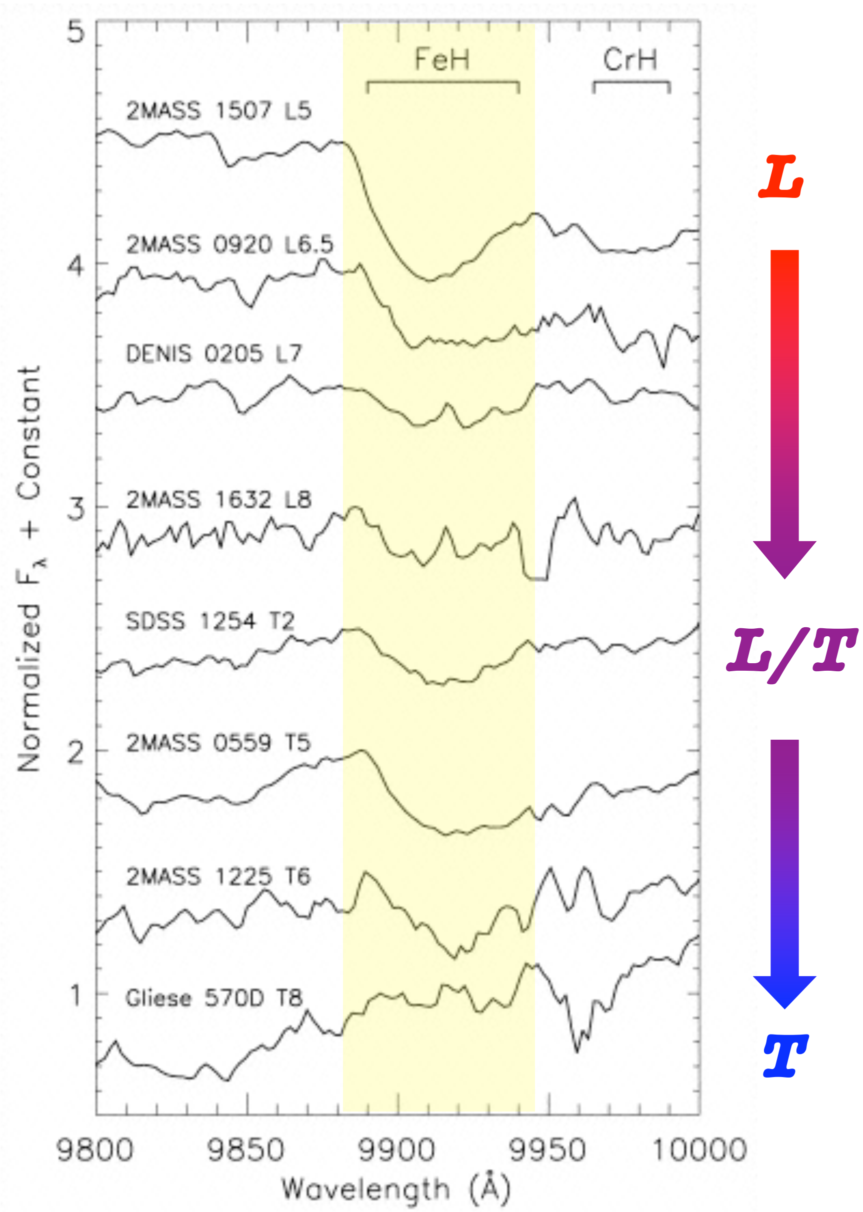
Golimowski et al. (2004)

T_{eff}/Spectral Type relation flattens across the L→T transition

(Kirkpatrick et al. 2000; Golimowski et al. 2004; Vrba et al. 2004)

Do spectral changes occur independent of T_{eff}?

Resurgence of Condensed Species



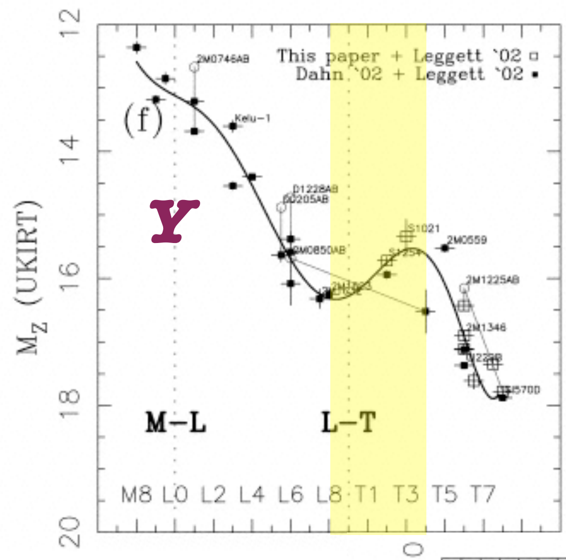
Burgasser et al. (2002)

FeH depleted by Fe(l) condensation in L dwarfs

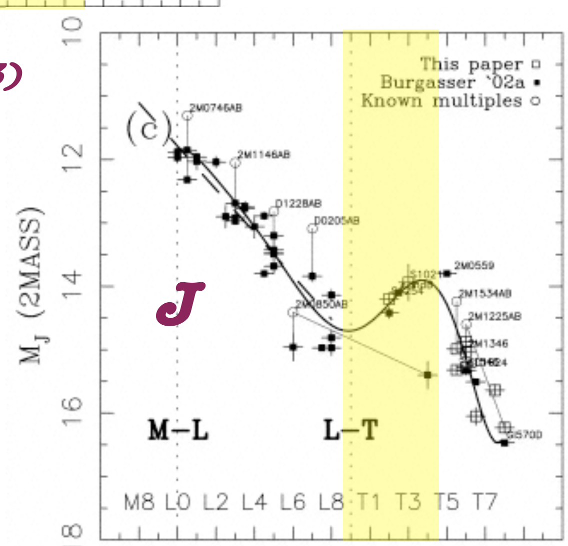
Resurgence across L/T transition
(Burgasser et al. 2002; Cushing et al. 2005; McLean et al. 2005)

Evaporation? Loss of condensates? An opacity effect?

The "J-band Bump"



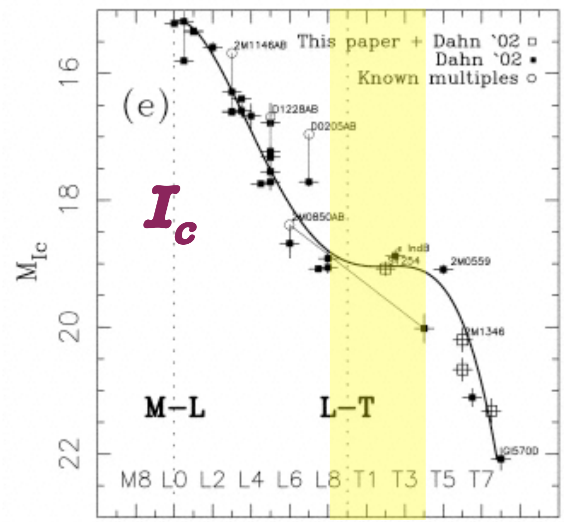
Tinney et al. (2003)



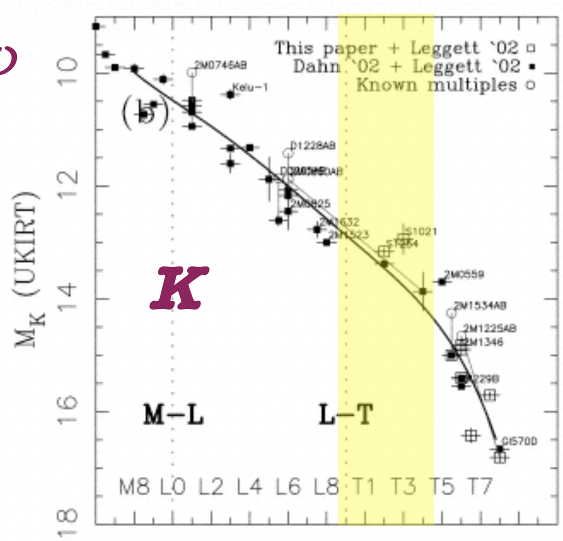
Parallax measurements revealed ***a brightening of ≈1 mag around 1 μm*** *across L/T transition*

(Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004.)

The "J-band Bump"



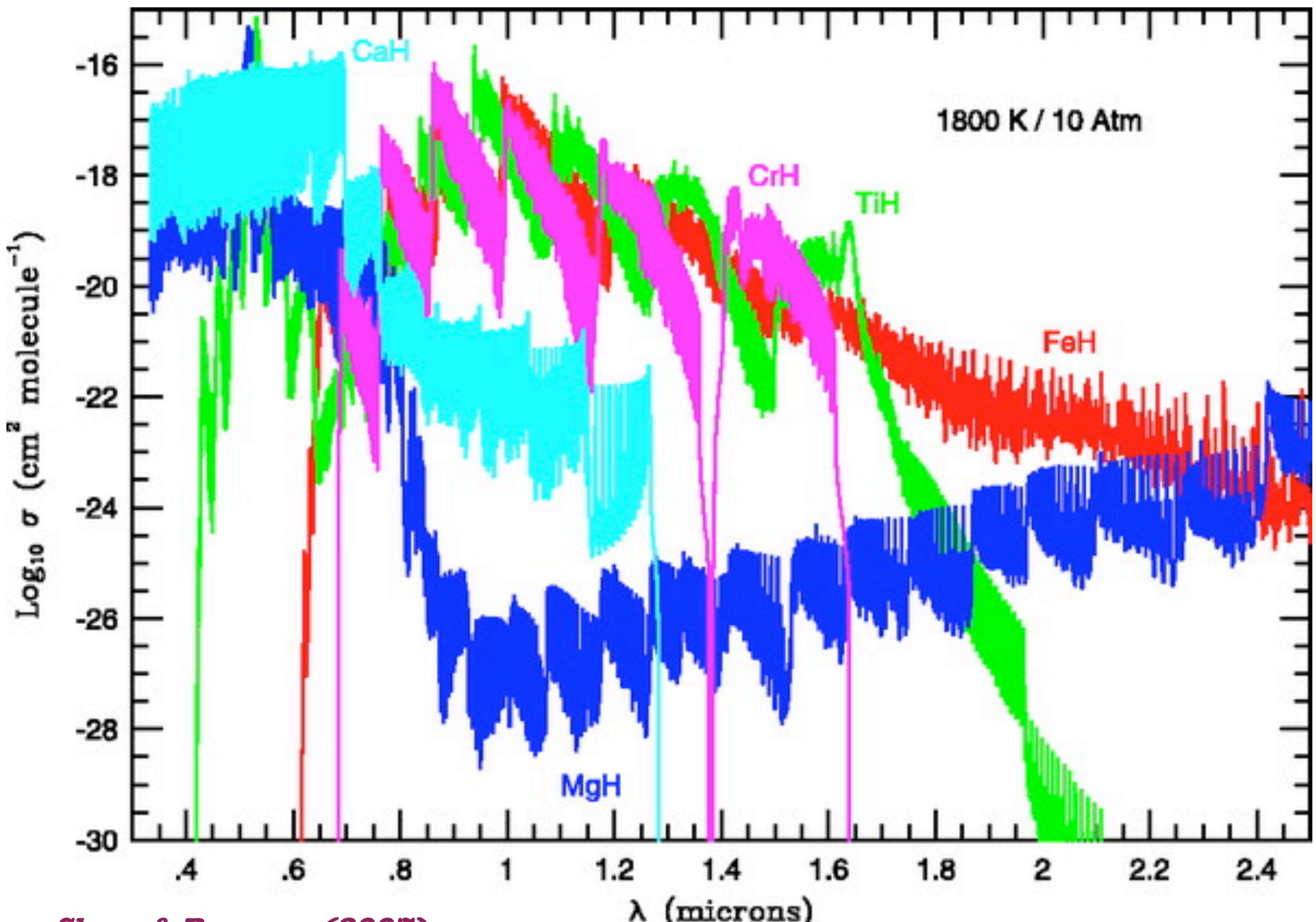
Tinney et al. (2003)



Parallax measurements revealed ***a brightening of ≈1 mag around 1 μm*** *across L/T transition*
(Dahn et al. 2002; Tinney et al. 2003; Vrba et al. 2004.)

Brightening is not observed at I_C (0.85 μm) or K (2.2 μm)

Combined with T_{eff} scale, ***strong indication of opacity effect at play***

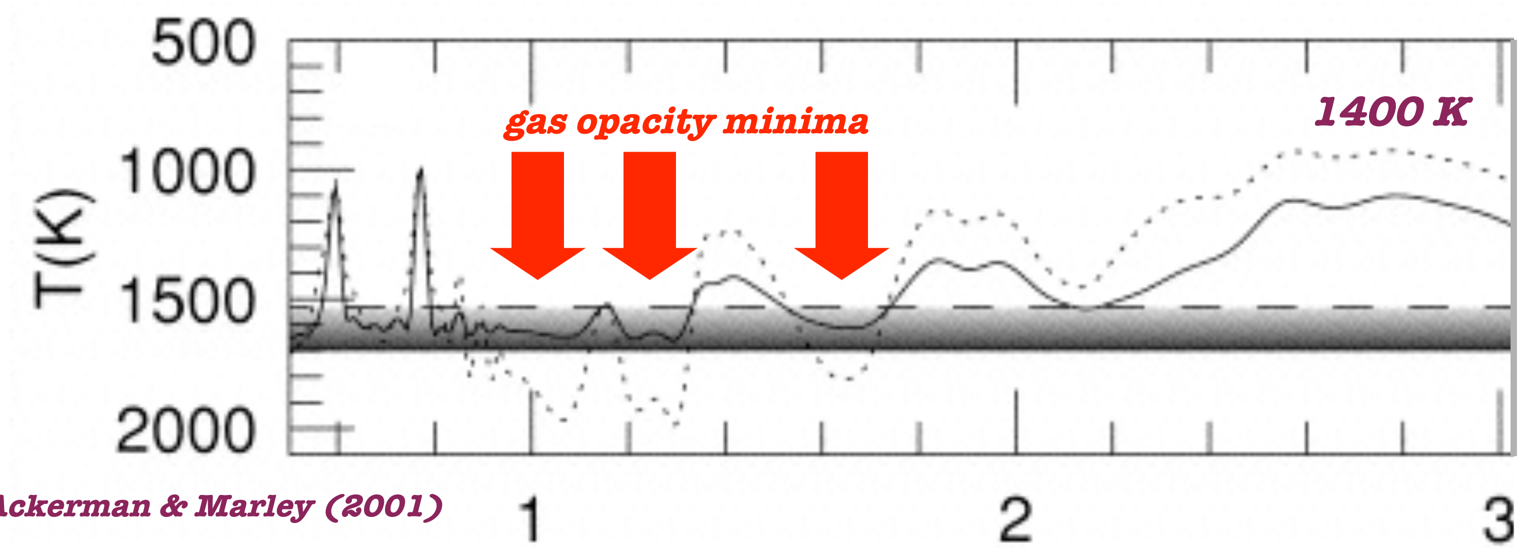


Sharp & Burrows (2007)

Gas opacities in brown dwarf atmospheres generally have complex wavelength dependencies.

Cloud opacity *is roughly constant over optical/NIR region due to large grains (a ≈ 30-100 μm)*

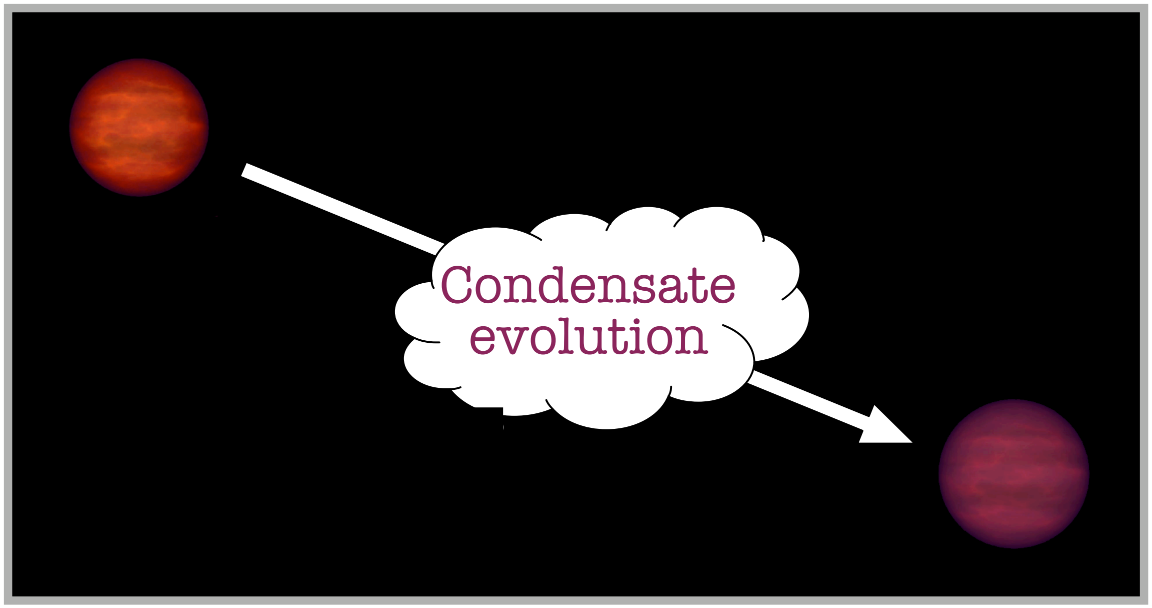
(Ackerman & Marley 2001; Allard et al. 2005; Burrows et al. 2006)



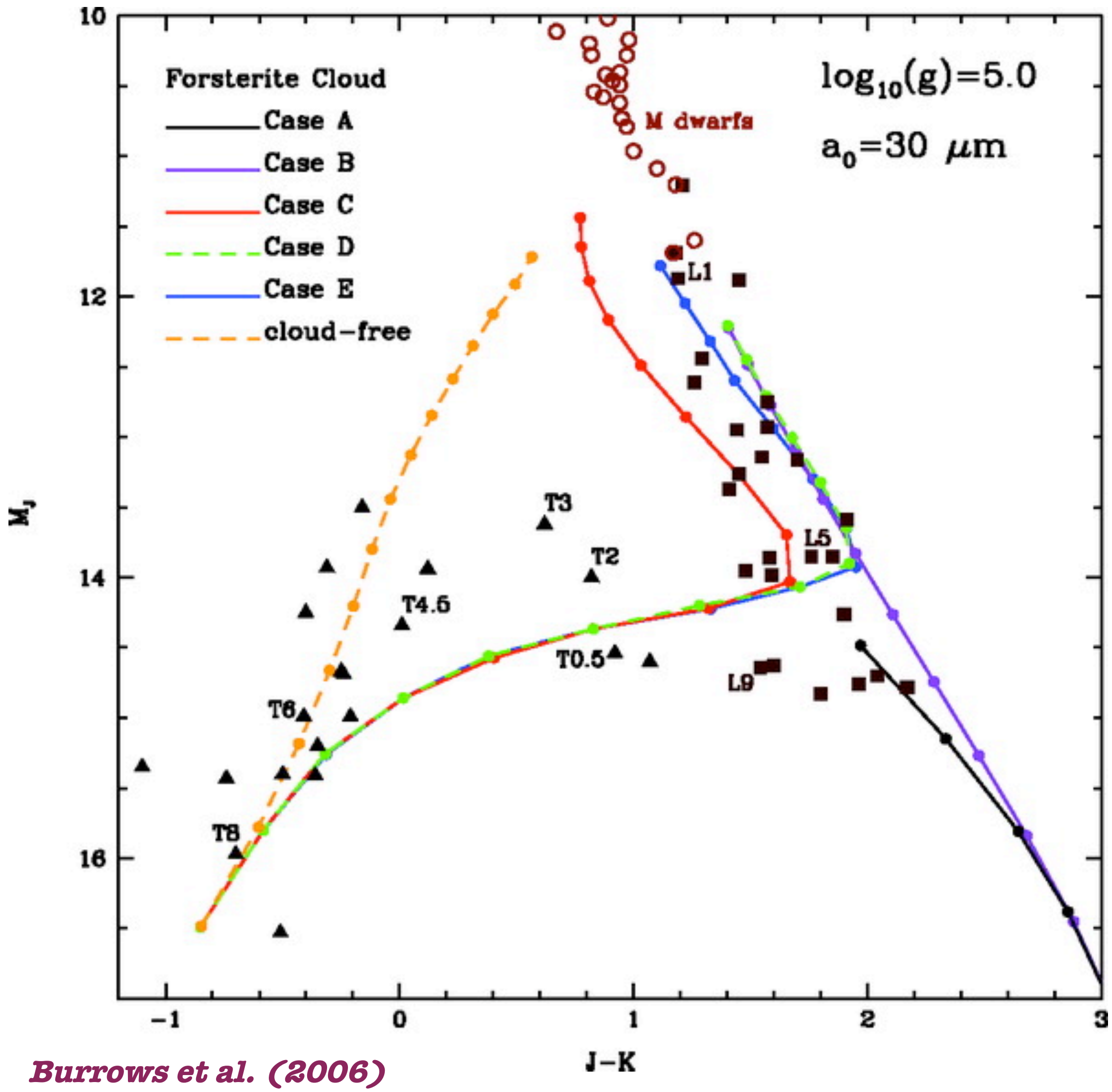
Ackerman & Marley (2001)

Condensate opacity effects are most important at ***1.05 μm*** *(Y-band),* ***1.25 μm*** *(J-band) and* ***1.65 μm*** *(H-band)*

A Picture Emerges...



[but not quite this simple...]



Burrows et al. (2006)

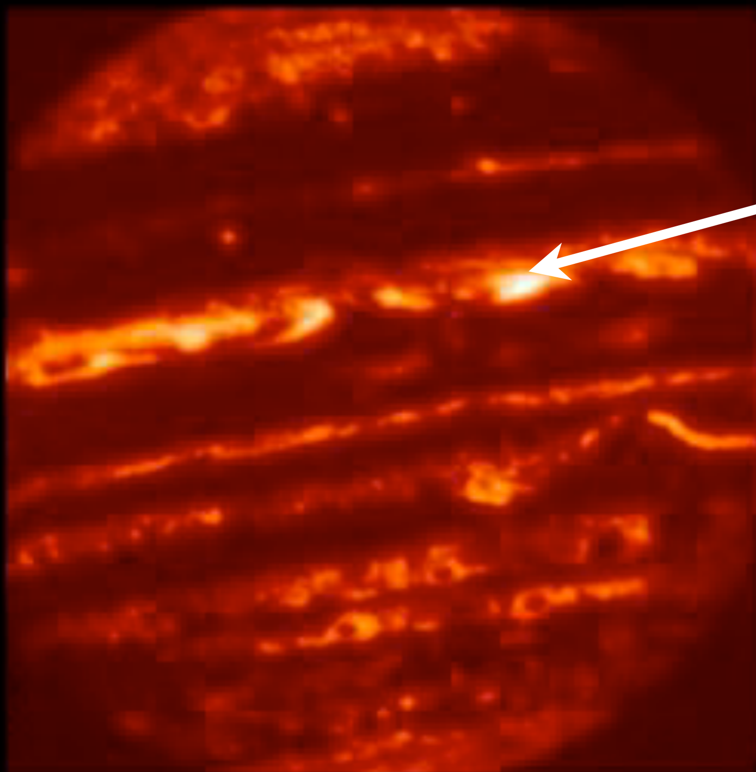
Condensate cloud models assuming chemical and thermodynamic equilibrium cannot reproduce observed features of L/T transition in detail.

A non-equilibrium process?

Ideas...

Cloud fragmentation *(Burgasser et al. 2002): photospheric clouds break up to reveal hotter interior*

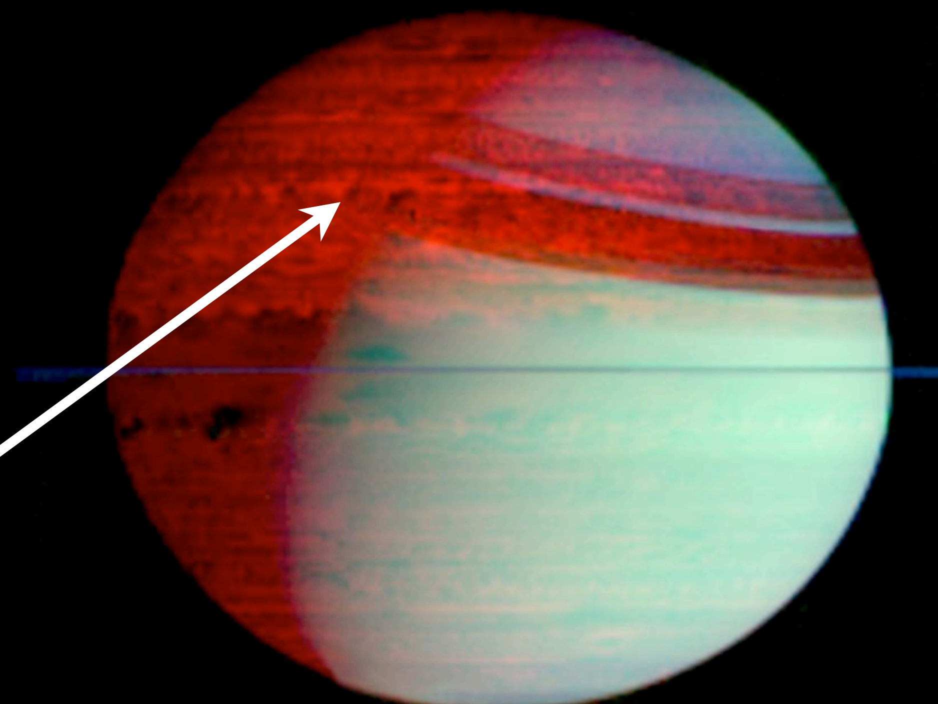
"Hilo rain" *(Knapp et al. 2004): Sudden change in sedimentation efficiency of condensate clouds.*



IRTF NSFCam 4.85μm
c.f., Westphal, Matthews, & Terrile (1974)

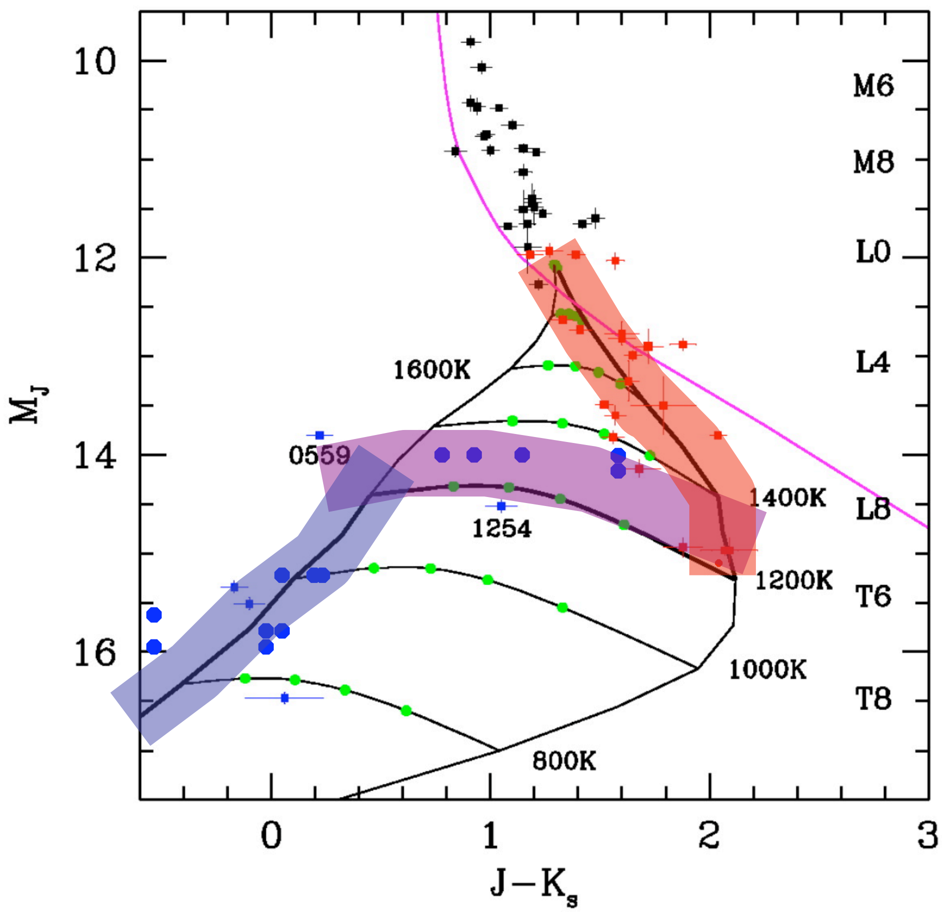
Jupiter's 5μm "Hot spots" - holes in NH_3 clouds

Saturn has hot spots too!



Cassini IR/Visible imaging

A Sudden Downpour?



Burgasser et al. (2002)

Absolute magnitude results can be largely reproduced by a ***sudden breakup of clouds at T_{eff} ≈ 1200-1400 K****.*

Is there physical motivation for this?

- ***CO enhancement*** *in T dwarfs up to 16,000x above LTE* (Noll et al. 1997; Oppenheimer et al. 1998; Golimowski et al. 2004)
- ***NH_3 depletion*** *in T dwarf MIR spectra* (Saumon et al. 2006; Leggett et al. 2007)
- *Both indicative of* ***vertical mixing*** *with eddy diffusion* (Saumon et al. 2006)

Ideas... might work...

Cloud fragmentation *(Burgasser et al. 2002): photospheric clouds break up to reveal hotter interior*

"Hilo rain" *(Knapp et al. 2004): Sudden change in sedimentation efficiency of condensate clouds.*

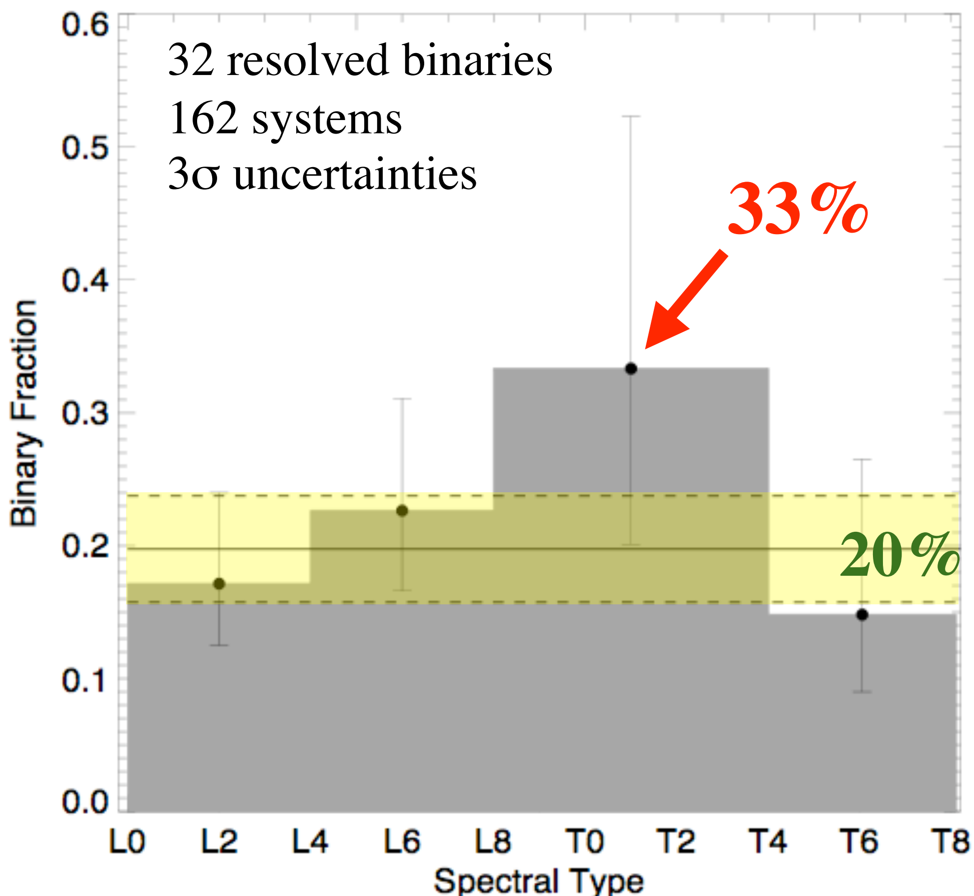
Not everyone is convinced...

Tsuji et al. 2002*: observations skewed by selection biases - gravity/age effects*

Burrows et al. 2006*: "cryptobinarity" - unresolved binaries skewing results*


A New Lead
© 2007 Adam J. Burgasser

One Last Mystery…

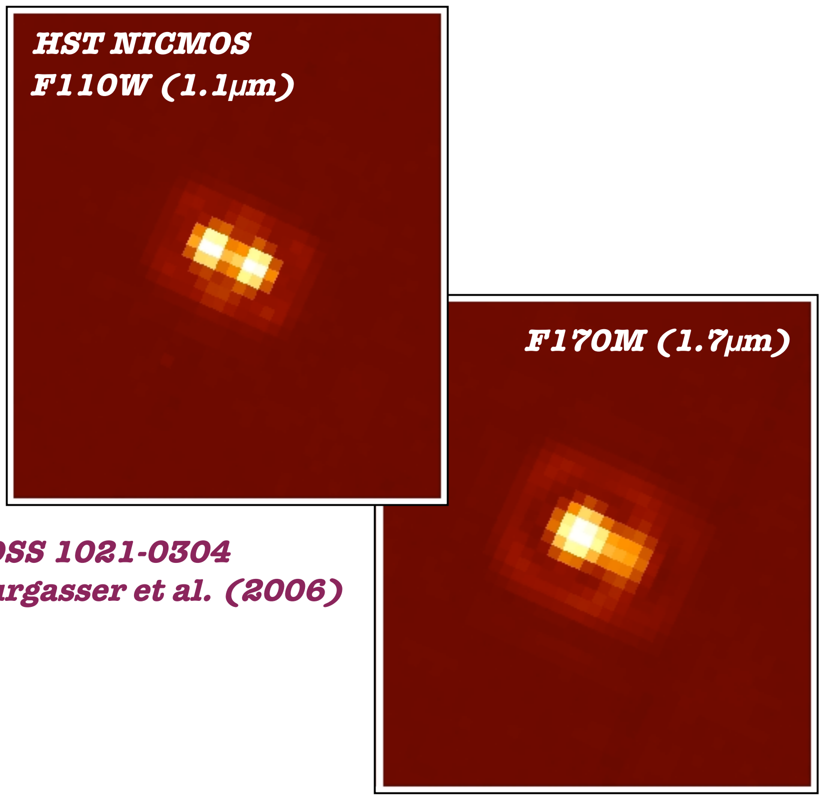


Burgasser et al. (2006)

*The resolved binary fraction of L/T transition objects is **>50% higher** than other spectral types.*

- *Is this a selection effect?*
- *Are L/T transition objects intrinsically more frequently binary? Why?*
- *Is this a clue to the other observed phenomena? Are nonequilibrium processes unnecessary?*

Binaries: Ideal Probes of the L/T Transition



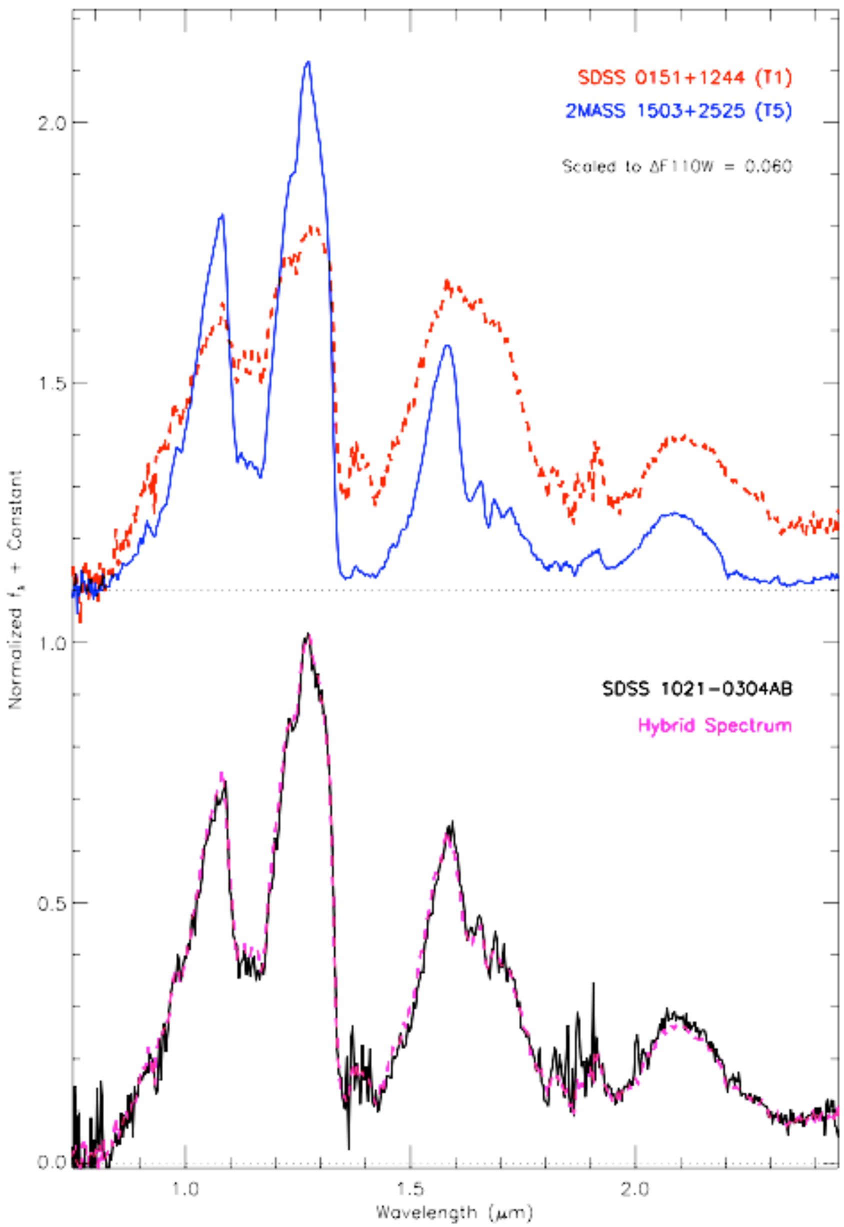
SDSS 1021-0304
Burgasser et al. (2006)

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

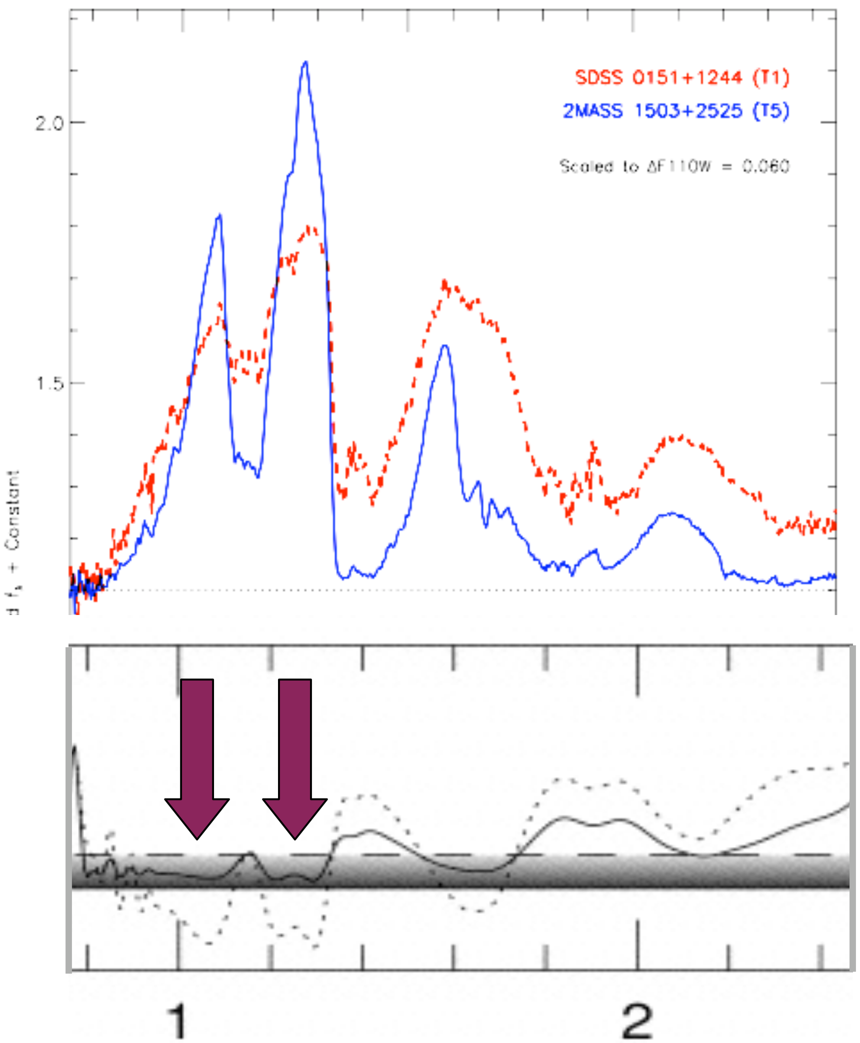
(Burgasser et al. 2006)

Resolved with ***HST NICMOS***

Spectral synthesis*: find best match to composite spectrum between two templates scaled to observed 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

(Burgasser et al. 2006)

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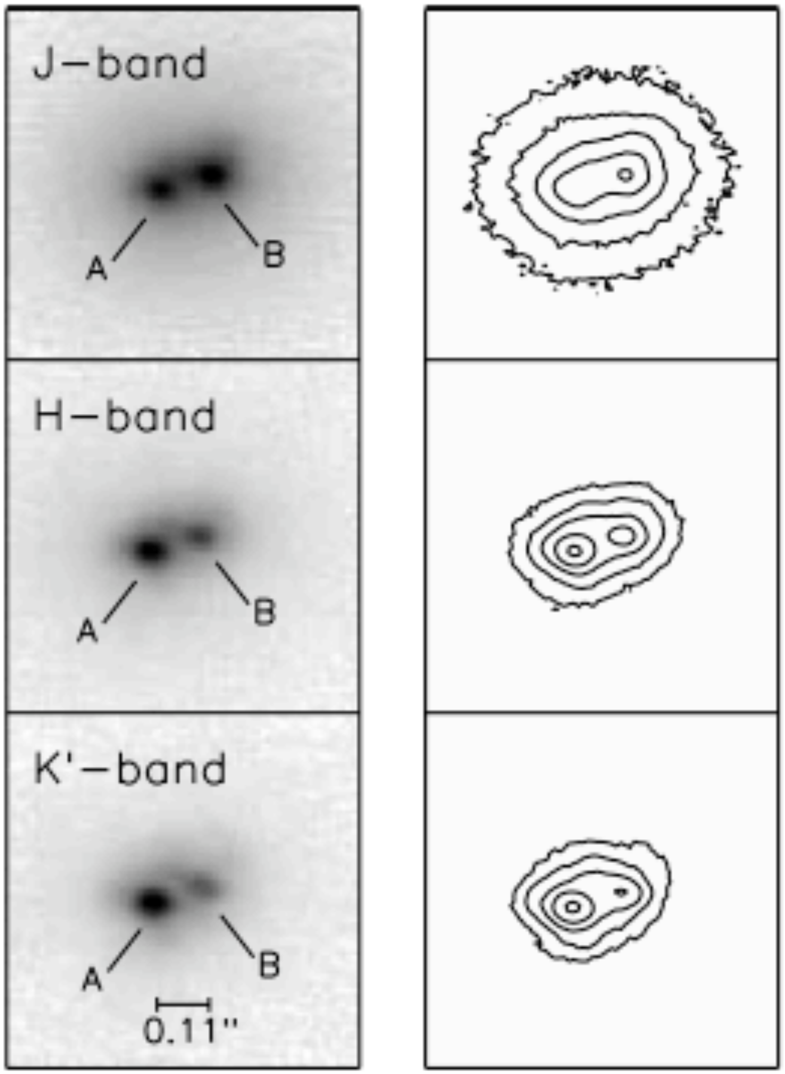
Burgasser et al. (2006)



Liu et al. (2006)

SDSS 1534+1615

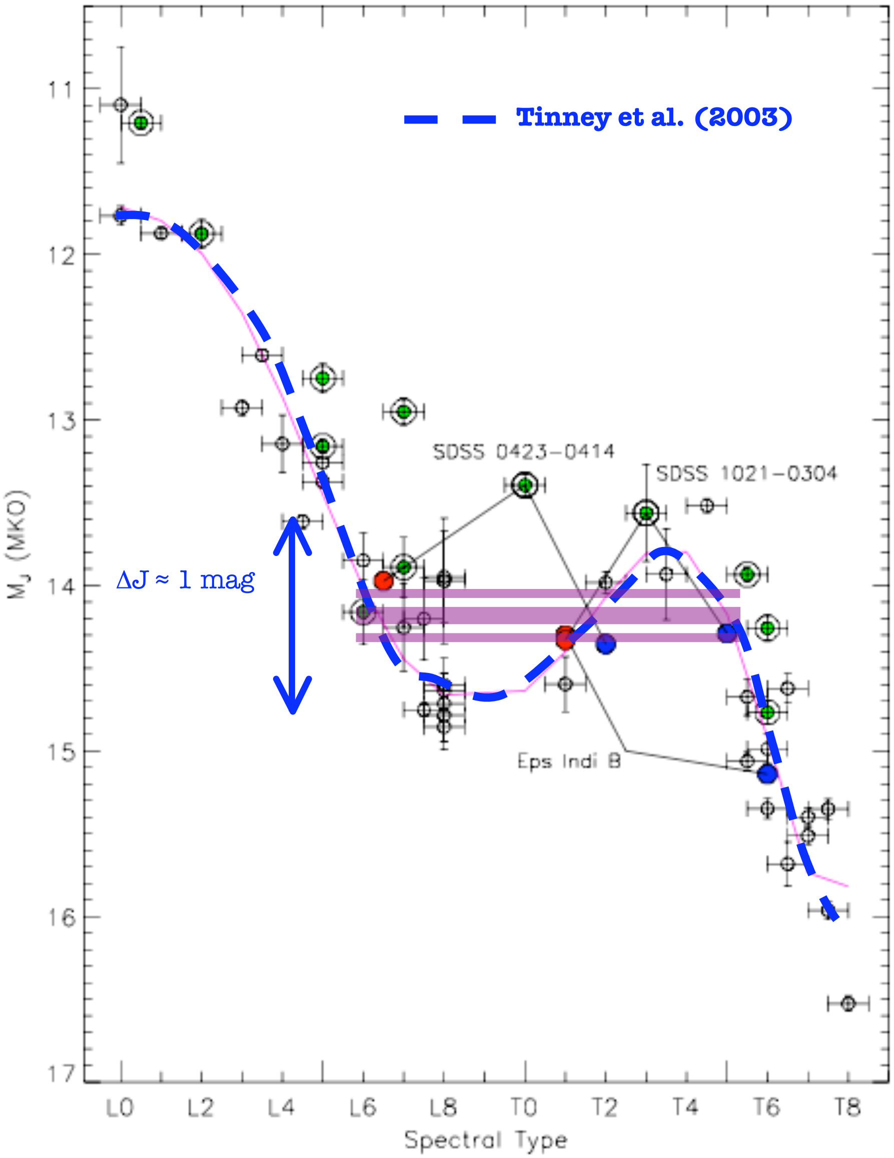
(Liu et al. 2006)

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**



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

How Big of a Bump?

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?


A Full
Investigation

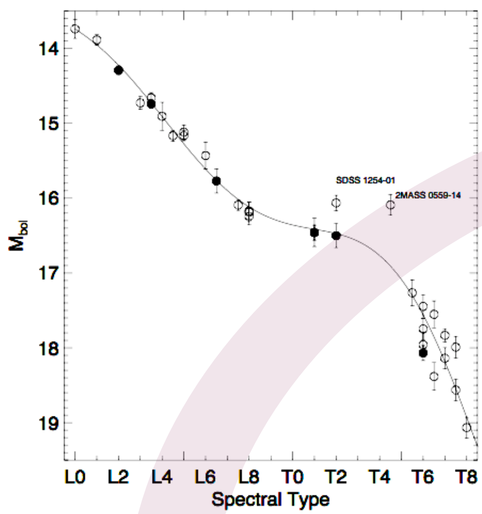
The Questions...

Do L/T transition objects have a fundamentally higher multiplicity fraction that other brown dwarfs?

If so, what does this higher fraction have to do with the L/T transition itself?

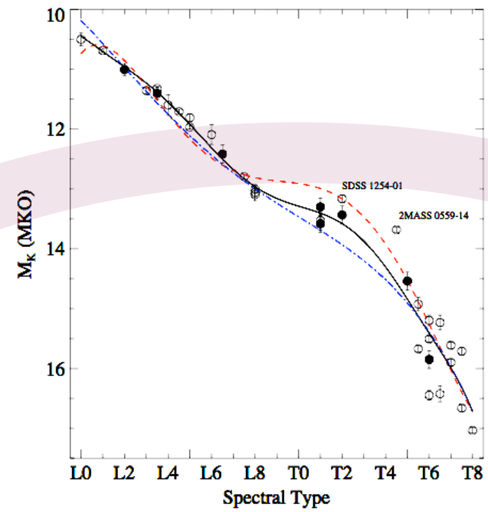
The Approach...

An end-to-end simulation of the multiplicity fraction of L and T dwarfs in the neighborhood of the Sun
(Burgasser 2007)



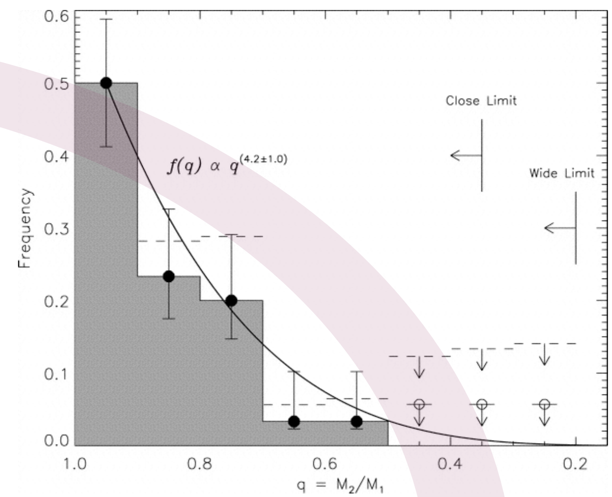
L_{bol}/SpT Conversion

(e.g. Golimowski et al. 2004; Vrba et al. 2004)



SpT/M_K Conversion

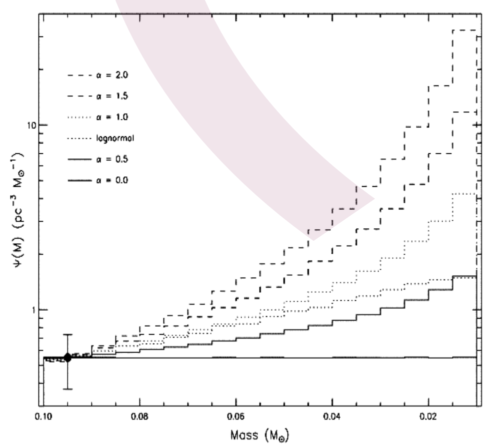
(e.g. Golimowski et al. 2004; Liu et al. 2006)



Binary Properties: ε_b and $f(q)$

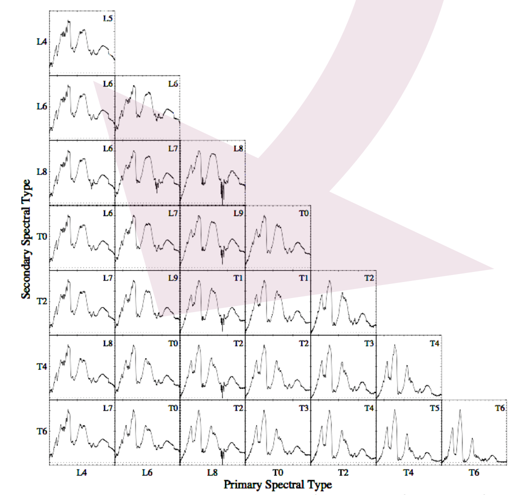
(e.g. Bouy et al. 2003; Burgasser et al. 2003,2006; Close et al. 2003; Gizis et al. 2003; Reid et al. 2006; VLM Binary Archive)

A Monte Carlo Simulation



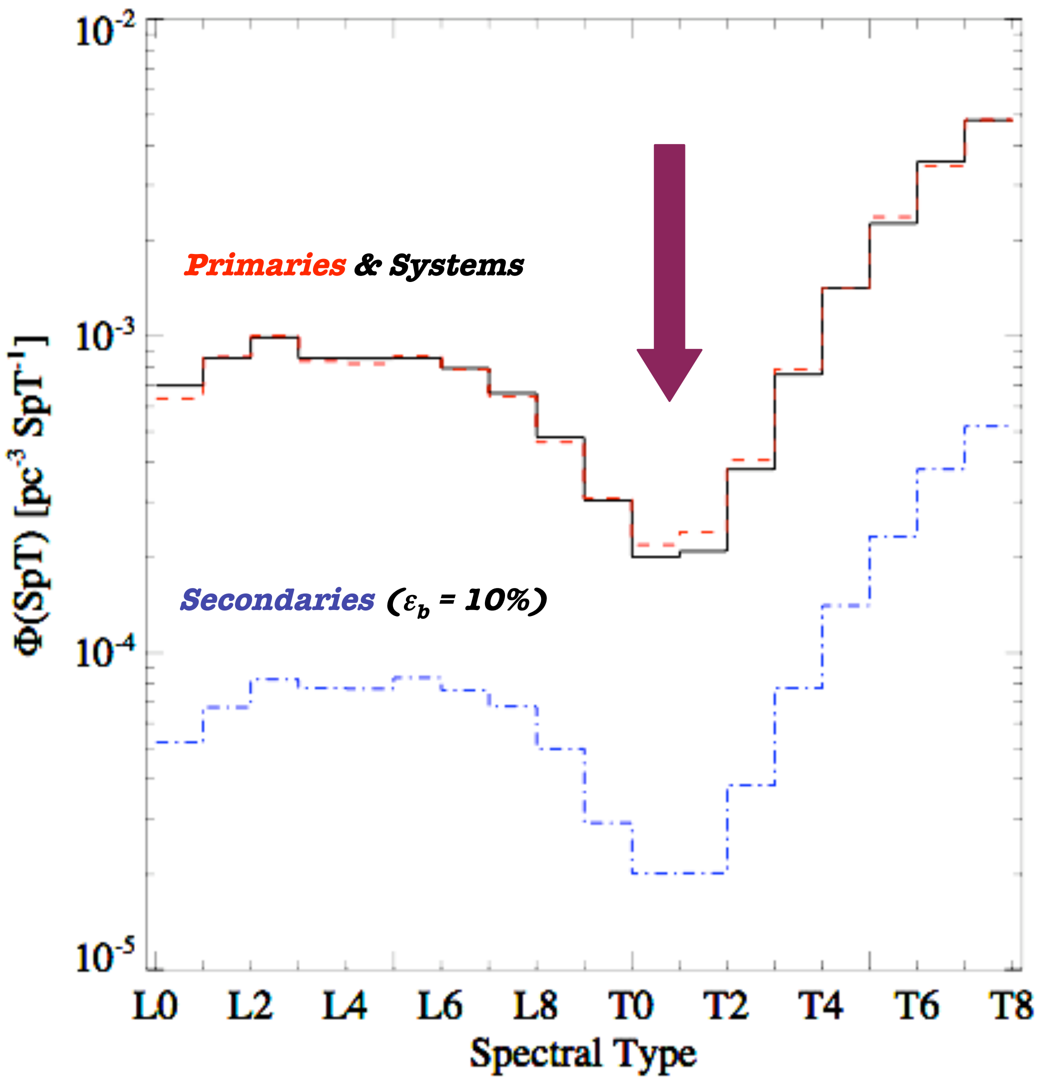
Mass Function Simulation

(e.g. Burgasser 2004; Allen et al. 2005)



Construct & Classify Binaries

(e.g. Burgasser et al. 2005,2006)

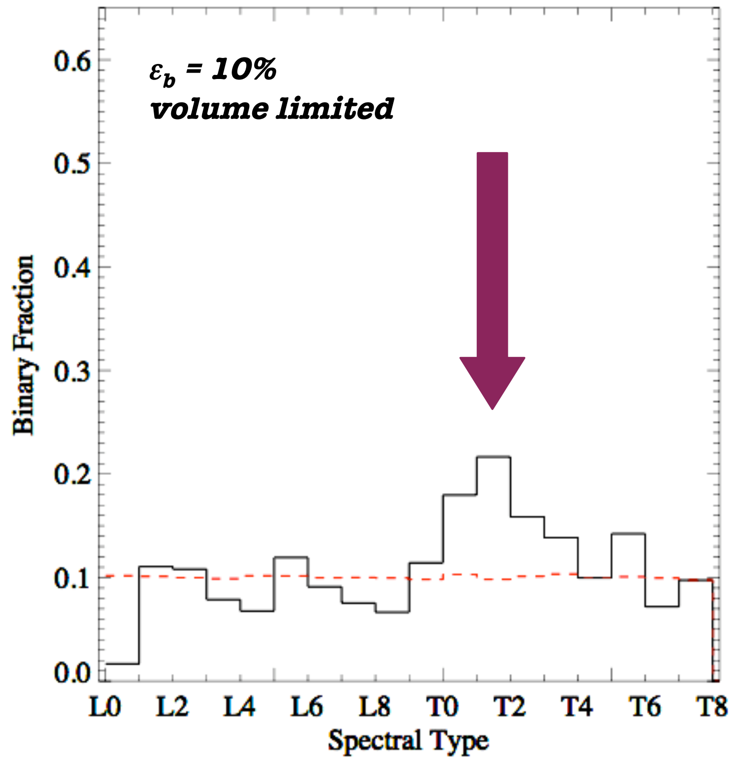


Results: The LF

The flattening in M_{bol} results in a prominent dip in the space density of individual L/T transition objects.

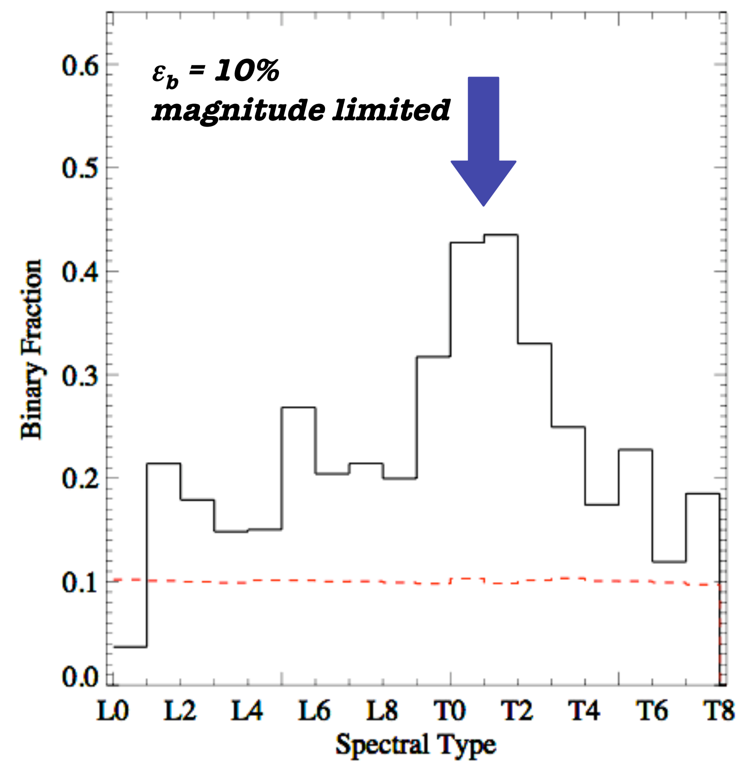
i.e., ***single L/T transition objects are rare.***

Results: The BF

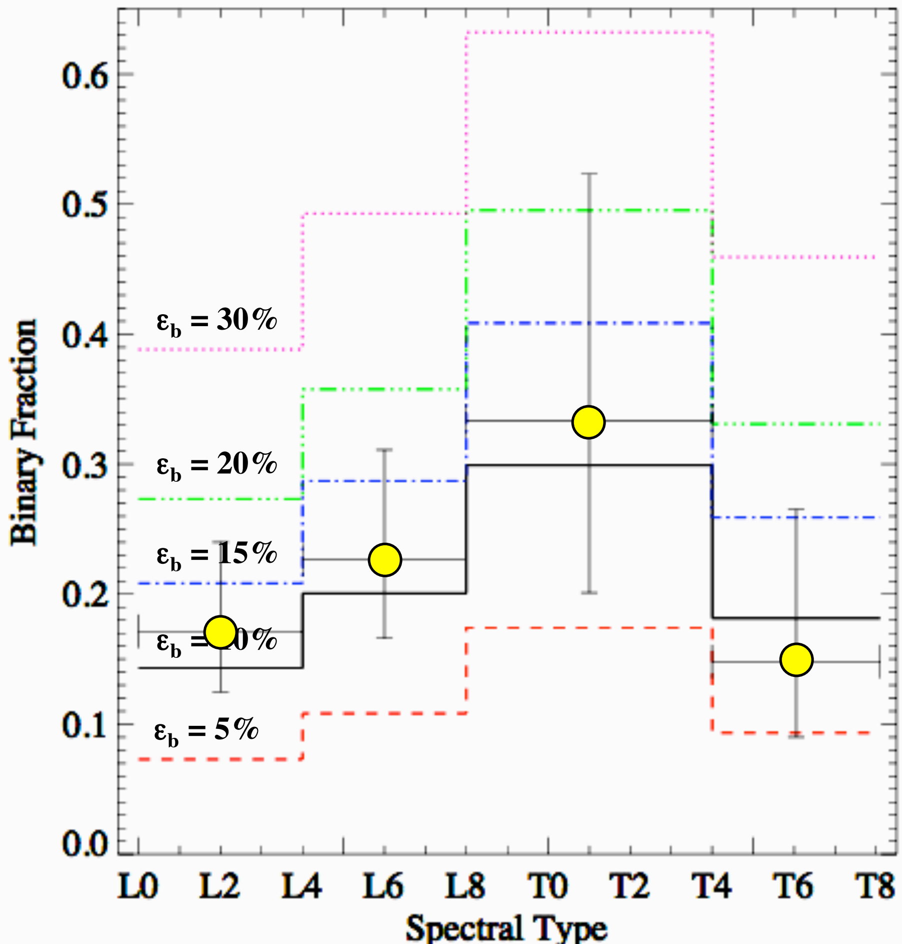


The binary fraction in a volume-limited sample ***increases ≈2×*** *for early-type Ts*

Effect is more pronounced in magnitude-limited sample:
ε_b = 10% ⇒ ε_b(obs) = 20-40%



Comparison to Observations



Burgasser (2007)

Excellent agreement *between data and binned magnitude-limited simulations*

Best fit binary fraction:

$$\varepsilon_b^{res} = 11^{+4}_{-2}\%$$

This is the ***resolved*** *fraction. If 66% of L/T transition objects are binary then:*

$$\varepsilon_b^{int} = 38^{+17}_{-14}\%$$

(Bouy et al. 2003; Close et al. 2003; Burgasser et al. 2003,2006; Jeffries & Maxted 2005; Basri & Rieners 2006 ; Reid et al. 2006)

Success!

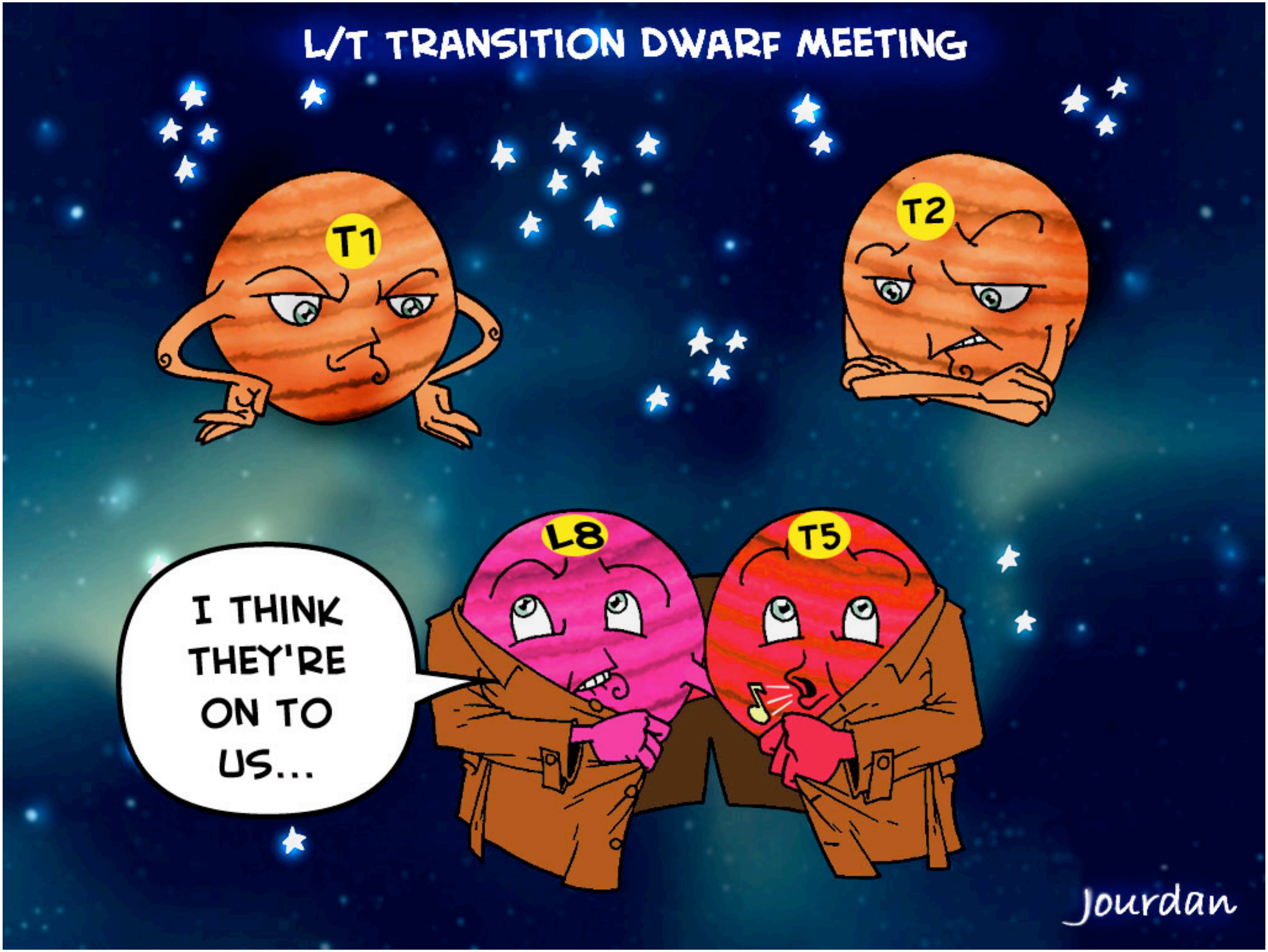
But what does it mean? What actually drives the high binary fraction for L/T transition objects?

1. ***Single L/T transition objects intrinsically rare*** *due in part to a flattening in the M_{bol}/SpT relation*

2. *Combined spectrum of* ***late L + mid T binary mimics a single L/T transition object*** *due in part to brightening of secondary at 1 μm*

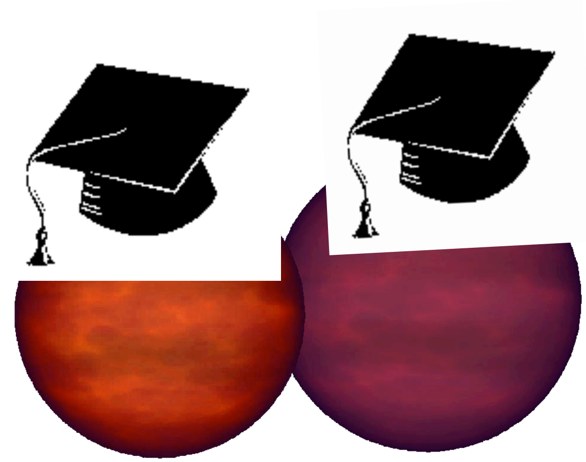
In fact, both require a more rapid evolution across the L/T transition than predicted
≈100 Myr for a 0.03 $M_{\odot}$ object!


Dénouement


L/T TRANSITION DWARF MEETING
T1
T2
L8
T5
I THINK THEY'RE ON TO US...
Jourdan

What have we learned?

Binaries have provided a much clearer picture of the L/T transition:

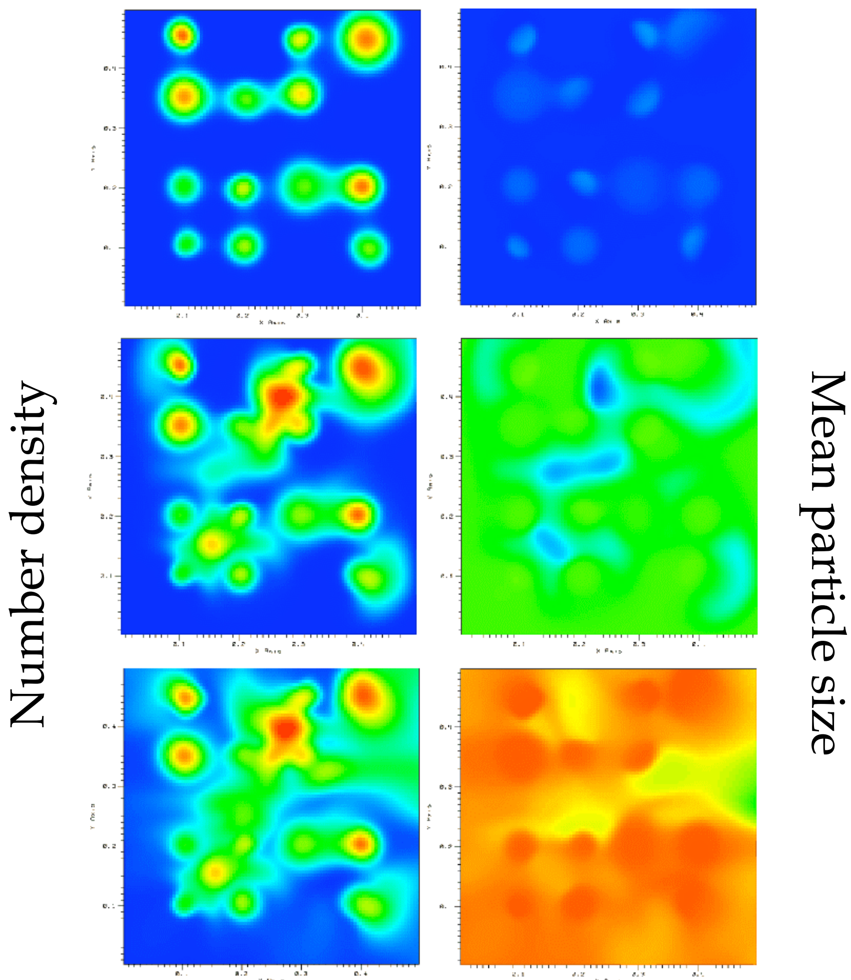


Studies of resolved binaries prove that ***brown dwarfs <u>do</u> brighten around 1 μm as they transition from cloudy L dwarfs to cloud-free T dwarfs*** *- directly linked to a "sudden" loss in condensate opacity*

The high frequency of L/T transition binaries is further evidence that the ***luminosity relation is flat across this transition*** *⇒ a rapid evolution*

Both features confirm that clouds must be removed quickly from the atmospheres of brown dwarfs ⇒ ***<u>a dynamic process</u>***

Work in Progress...



Helling et al. (2001)

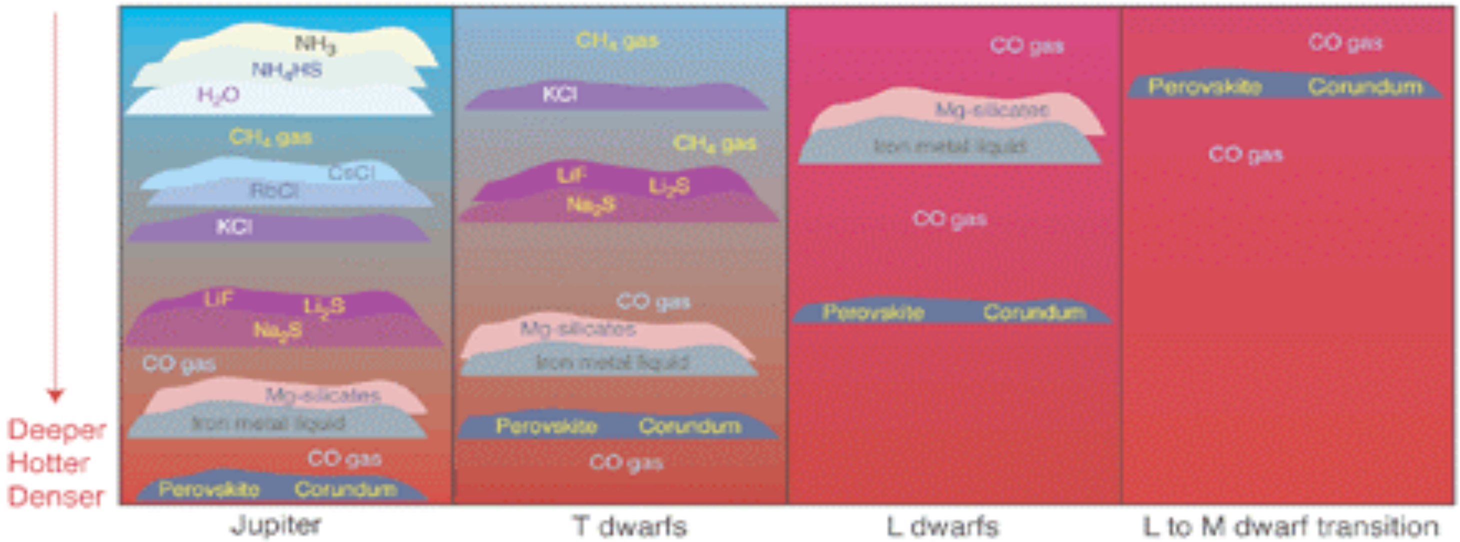
2D and 3D atmosphere models *are now exploring dust formation across the atmosphere*

Turbulence and rapid accumulation of condensate material results in ***patchy structure***

Structure models indicate ***multiple convective layers form when CO → CH_4***

(cf Helling et al. 2001, 2002; Burrows et al. 2006)

Expect to see this behavior again...



As we identify even cooler brown dwarfs, new sequences of condensate clouds will emerge:

1000 K: Na_2S *(pesticide)*
800 K: KCl *(fertilizer & lethal injection)*
400 K: PH_3 *(pesticide)*

*****300 K: H_2O*** *(swimming pools)*
200 K: NH_4HS *(Jupiter's coloring)*
150 K: NH_3 *(fertilizer & rocket fuel)*

(e.g. Lodders 1999, 2004; Lodders & Fegley 2006)

Clouds are also key for Exoplanets

Planet Classifications:
(Sudarsky et al. 2000)

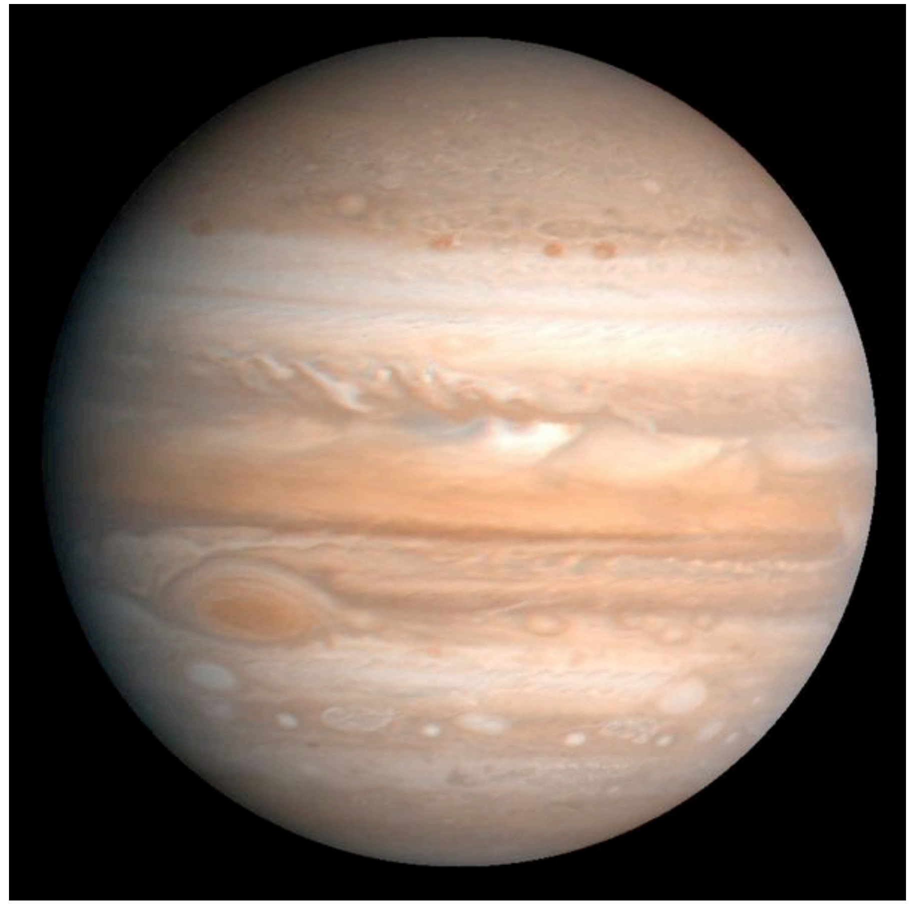
Class I: Ammonia Clouds
($T < 150$ K, $\alpha \approx 0.4$)

Class II: Water Clouds
($150 < T < 350$ K, $\alpha \approx 0.8$)

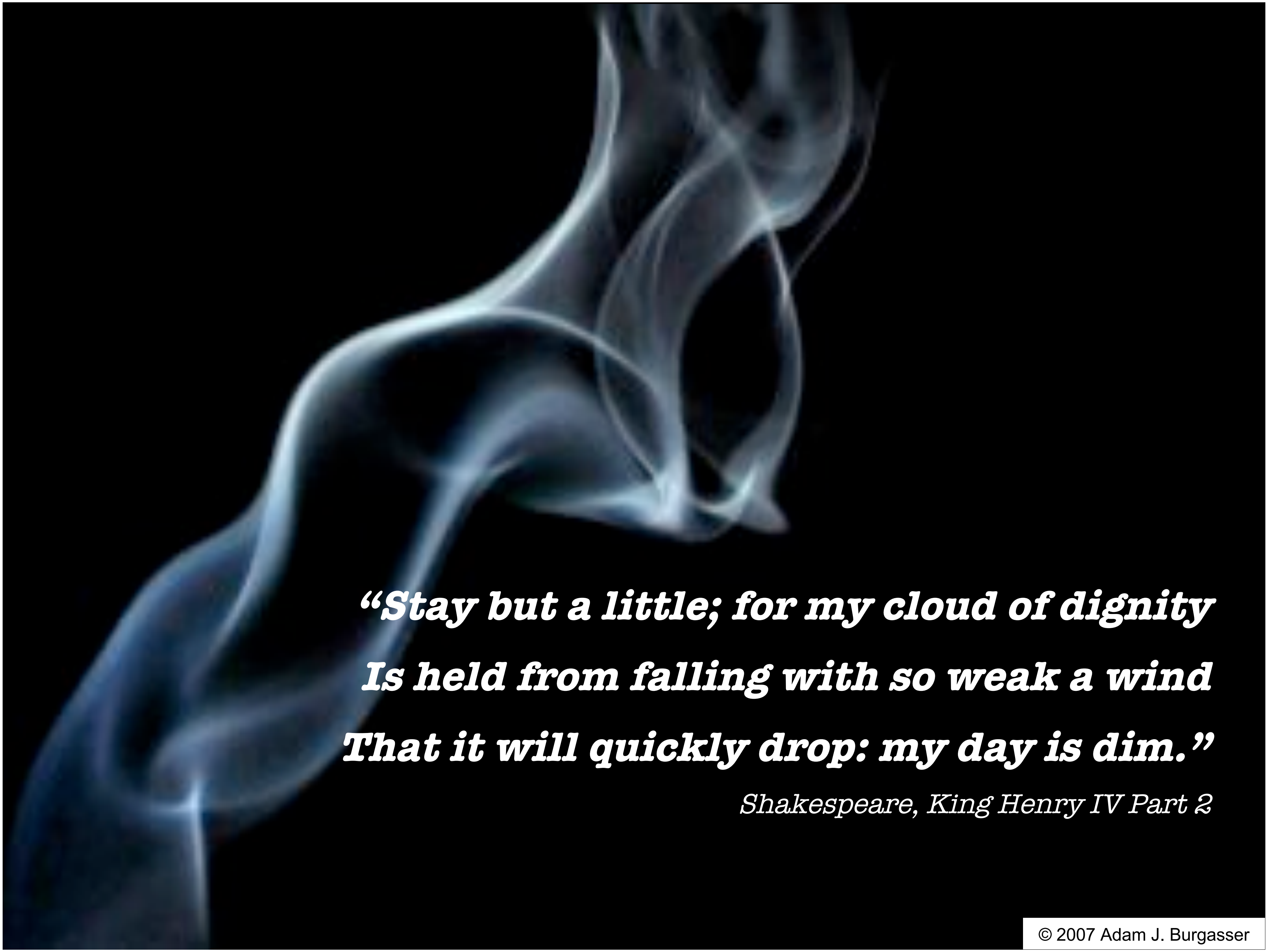
Class III: Clear
($350 < T < 900$, $\alpha \approx 0.1$)

Class IV: Alkali metal absorption
($900 < T < 1500$, $\alpha \approx 0.03$)

Class V: Silicate
($T > 1500$ K, $\alpha \approx 0.6$)



Jupiter, a Class I planet?


"Stay but a little; for my cloud of dignity
Is held from falling with so weak a wind
That it will quickly drop: my day is dim."
Shakespeare, King Henry IV Part 2
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