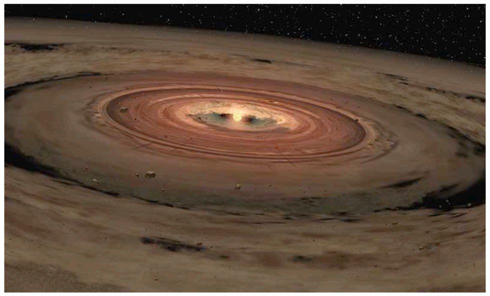
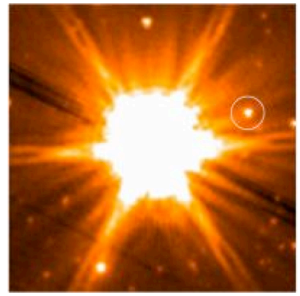
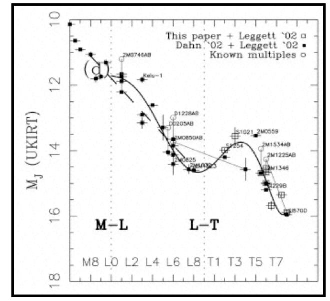
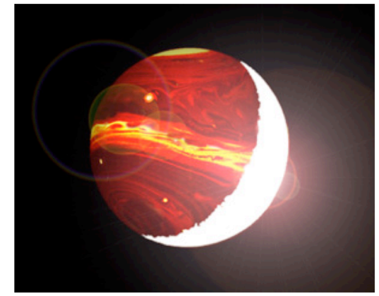
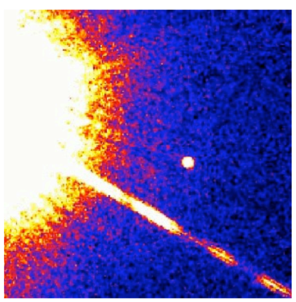
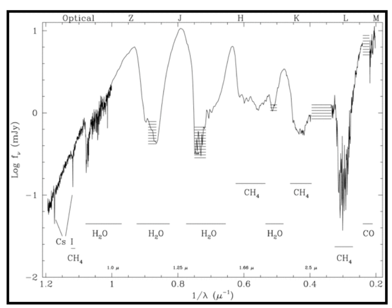
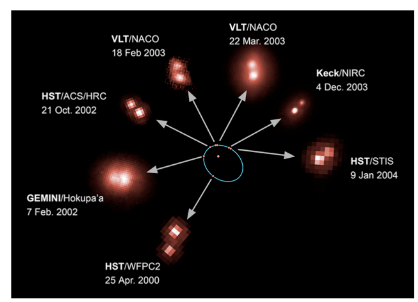
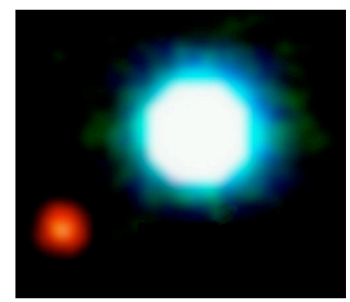






Lecture 12:
Brown Dwarf Multiplicity

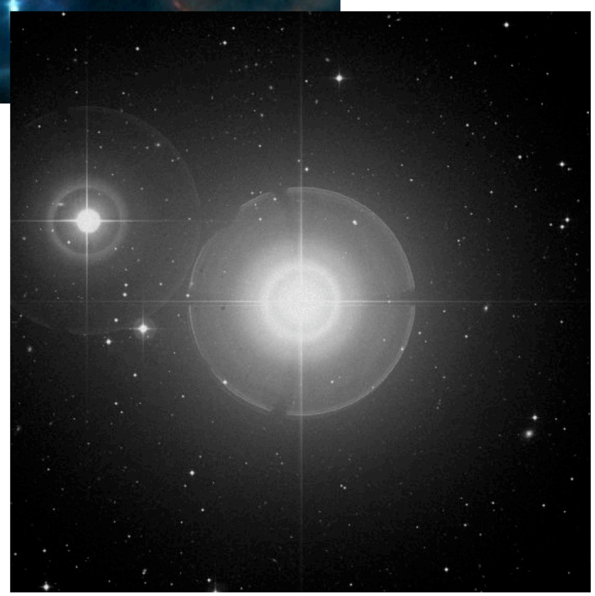







Definitions

Trapezium
(visual multiple)



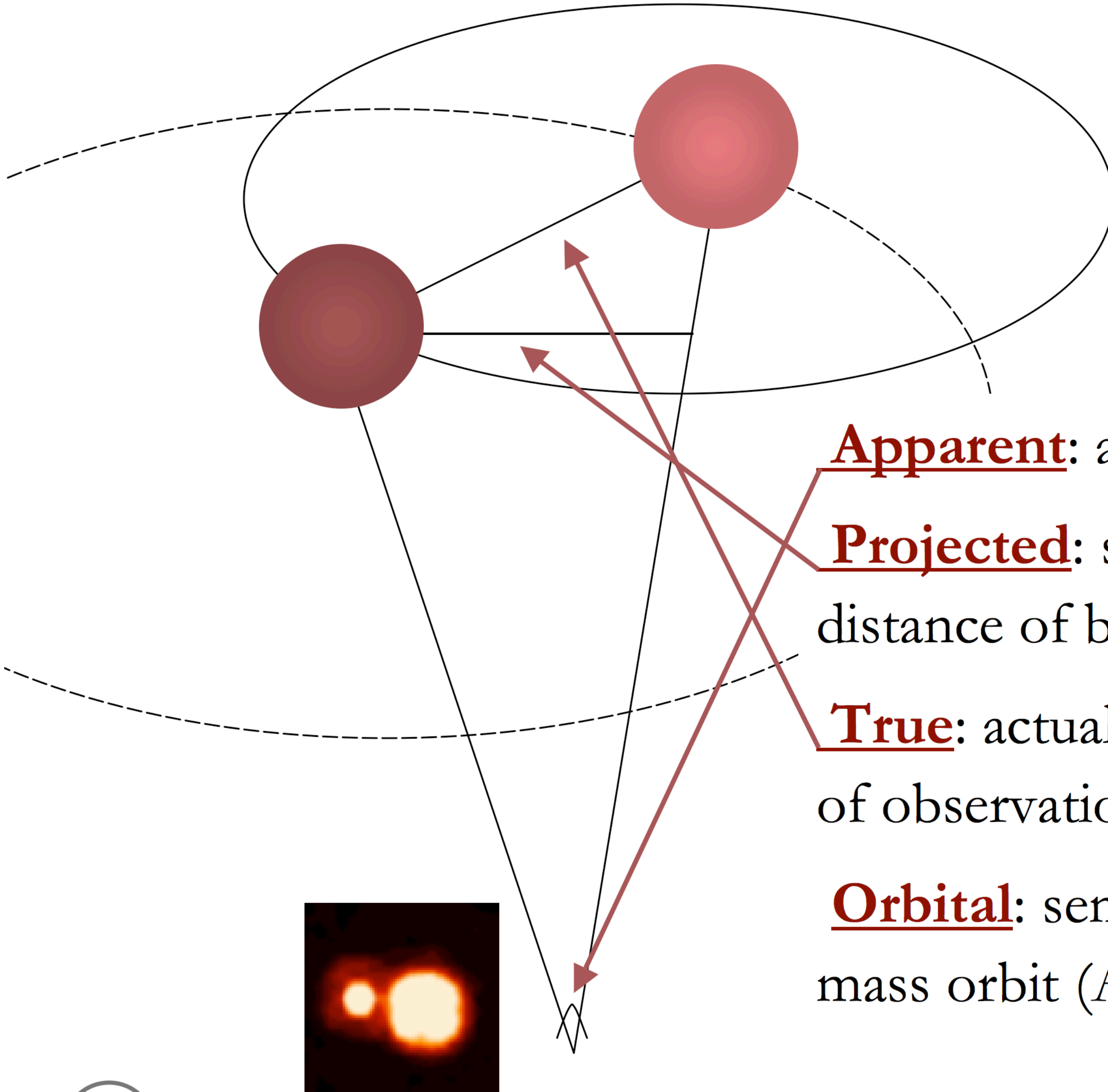
Mizar & Alcor (optical binary)

Multiple/Double Stars: a group of stars close to each other

Visual binary: gravitationally bound system

Optical binary: not bound

Separations



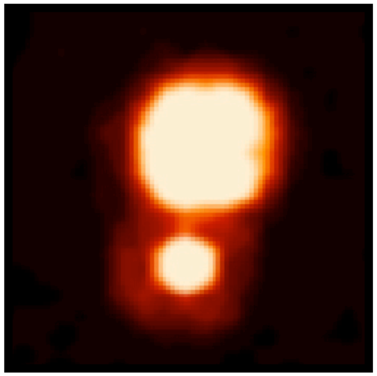
Apparent: angular separation on sky (''

Projected: separation in plane of sky at distance of binary (AU)

True: actual physical separation at time of observations (AU)

Orbital: semimajor axis of center-of-mass orbit (AU)

Flux and Mass Ratios



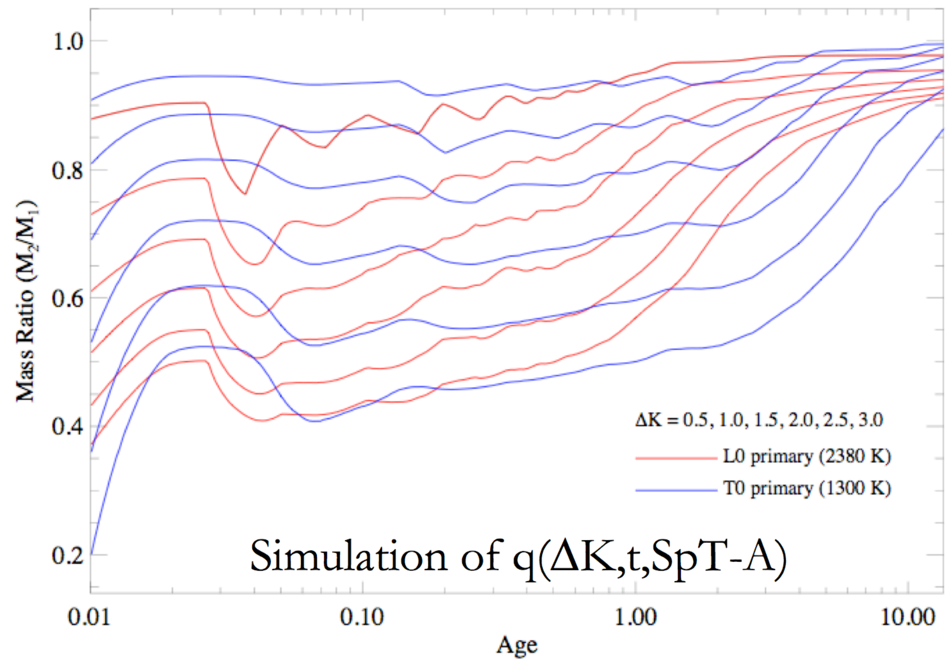
2MASS 1225-2739AB, Δmag = 1.6

Flux ratio: relative brightness

Mass ratio (q): relative mass ($M_2/M_1 \leq 1$)

Caveat emptor!

Changing absorption features, H-burning boundary and age/mass degeneracy makes a 1-1 mapping between flux and mass ratios uncertain.



Learn Your Fractions

Multiplicity fraction = fraction of systems that are multiple

$$\varepsilon_M = (N_{bin} + N_{trip} + N_{quad} + \ldots)/N_{sys}$$

$$\varepsilon_M \approx \varepsilon_B = N_{bin}/N_{sys}$$

Single star fraction = probability that a given star is single

$$f_s = N_{sing}/N_{total} = 1 - (2N_{bin} + 3N_{trip} + 4N_{quad} + \ldots)/N_{total}$$

$$N_{total} = N_{sing} + 2N_{bin} + 3N_{trip} + 4N_{quad} + \ldots$$

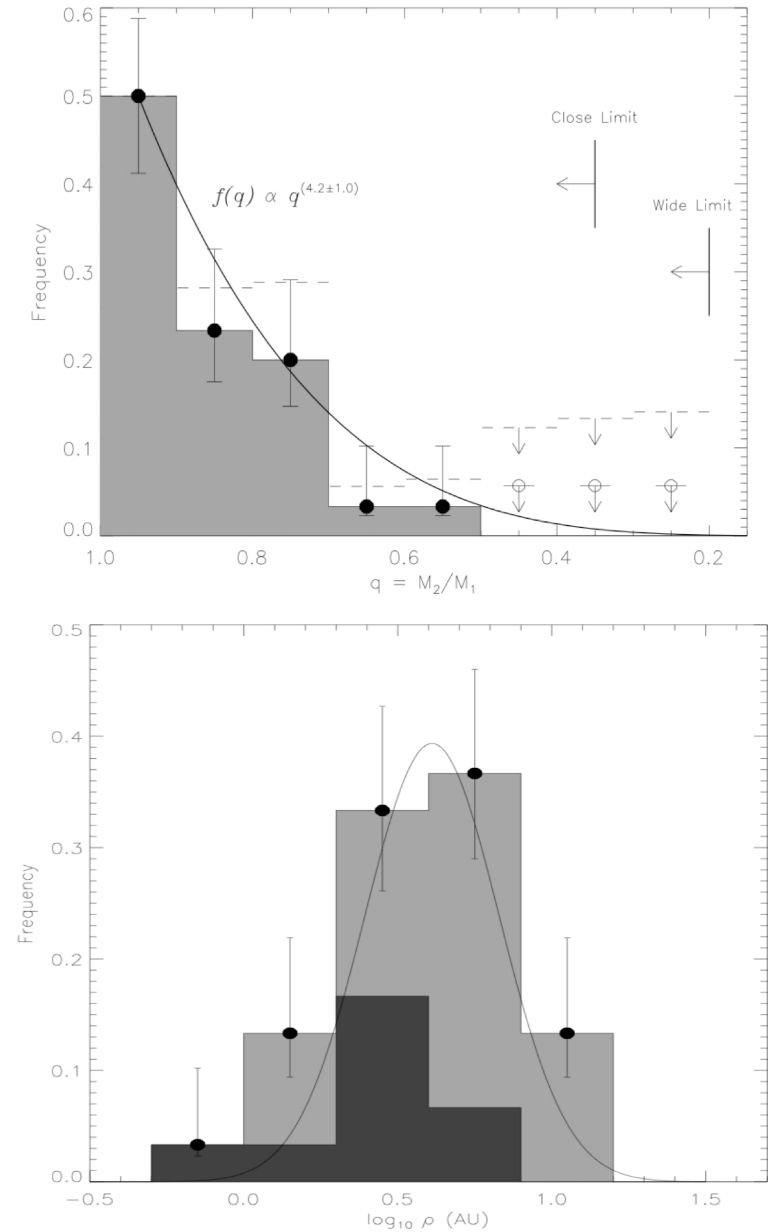
Distributions

Mass ratio distribution = f(q)

= frequency of binaries as function of M_2/M_1

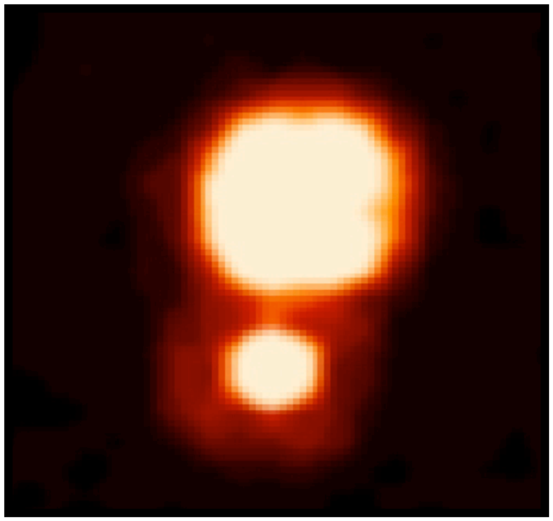
Separation distribution = f(*a*)

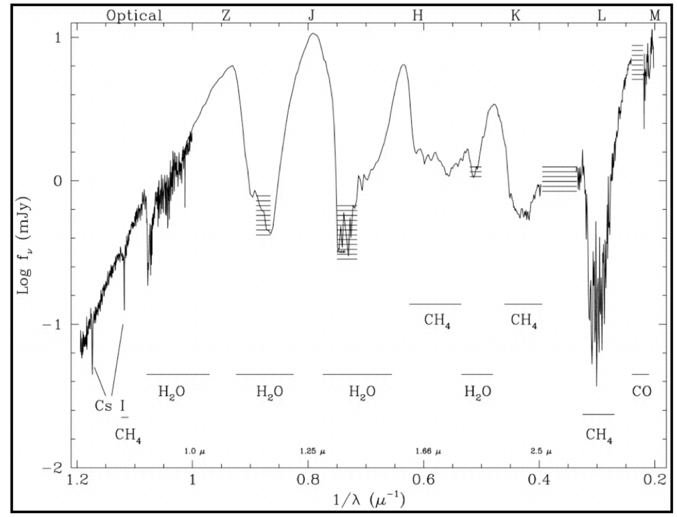
= frequency of binaries as a function of (projected) separation - also shown as a period distribution



Burgasser et al. (2006)

Observational Methods





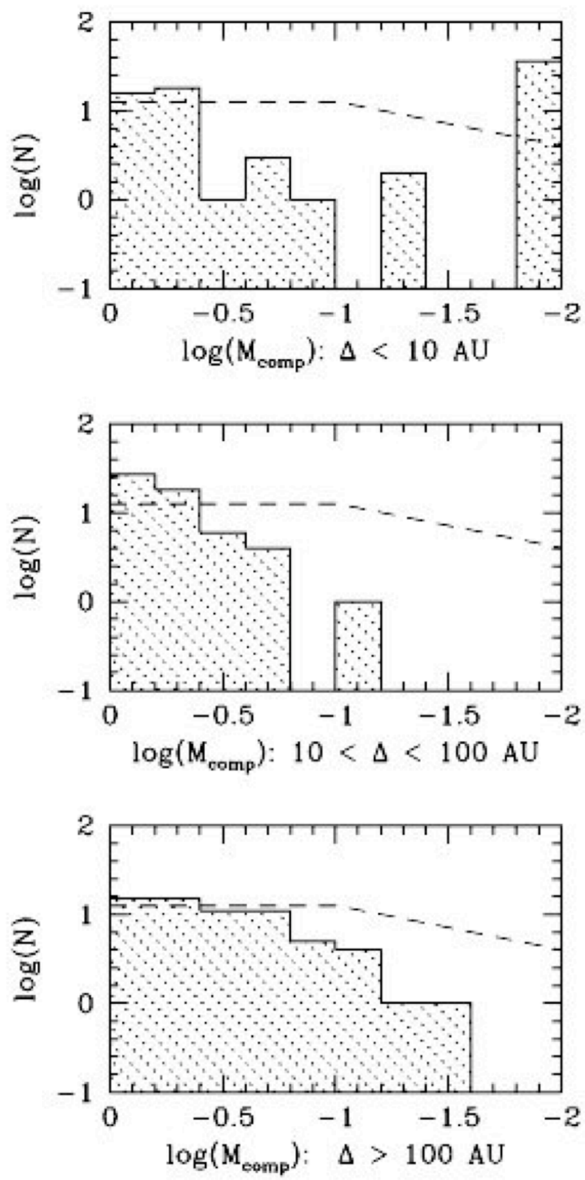
Imaging

***Direct imaging**, eclipses (transits), overluminous (clusters), astrometric wobble, microlensing;

Advanced methods: adaptive optics, coronagraphy, spectral difference imaging, combinations of the above!

Spectroscopy

Radial velocity variability (SB1 & SB2); spectral synthesis modeling (new!)



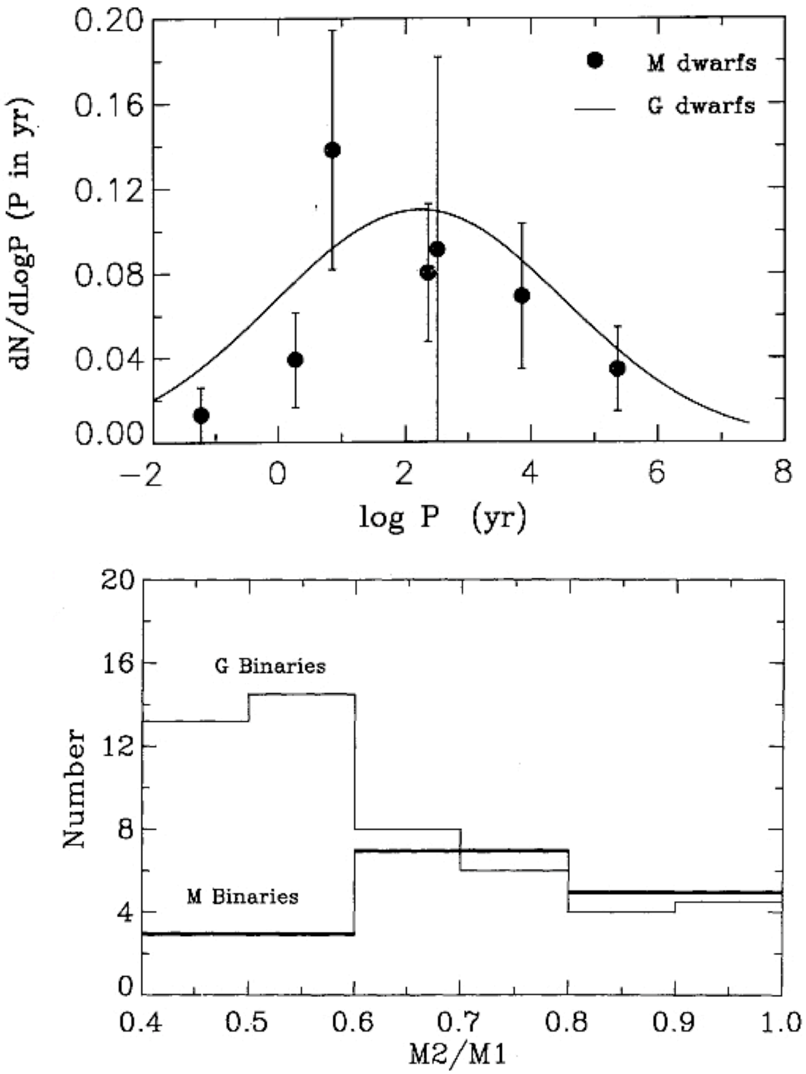
F-K dwarfs, d < 25 pc

Stellar Multiplicity

- Multiplicity fraction decreases with mass
  - A-B stars ~ **80%** (Shatsky and Tokovinin 2002; Kouwenhoven et al. 2005)
  - G dwarfs ~ **65%** (Duquennoy & Mayor 1991)
  - M dwarfs
    - ~ **42%** (Fischer & Marcy 1992)
    - ~ **27%** (Reid & Gizis 1997, Delfosse et al. 2004) **for volume limited samples**
- Separation distribution is broad (0.1 AU - 0.1 pc), peaks ~ 30 AU (G-M dwarfs)
- Mass ratio (q) distribution is flat-ish (separation-dependent), companions apparently drawn from same IMF

Abt & Levy (1967); Abt (1987); Henry & McCarthy (1990); Duquennoy & Mayor (1991); Fischer & Marcy (1992); Mayor et al. (1992); Mazeh et al. (1992,1996,2003); Reid & Gizis (1997); Delfosse et al. (2004)

Stellar Binaries



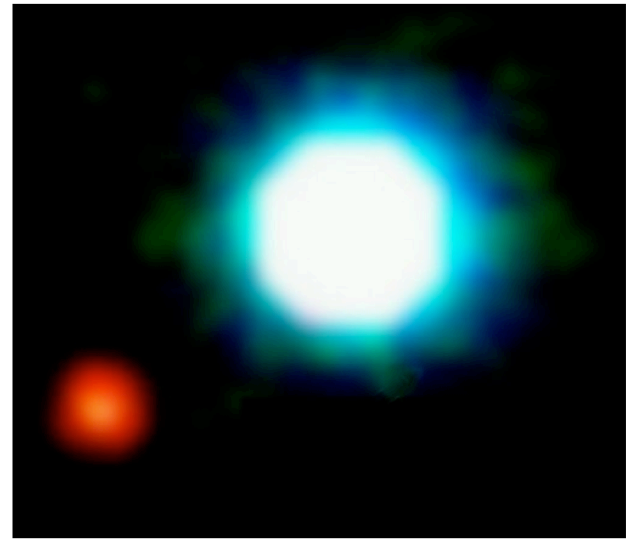
Fischer & Marcy (1992)

G and M dwarfs have:

- Similar period distributions
- Somewhat different mass ratio distributions - but both consistent with random assignment from IMF

Indicative of common formation mechanisms

Known VLM Multiples



2MASS 1207-3932AB
Chauvin et al. (2004)

As of April 2007:

85 multiples with $M_1 \leq 0.1\ M_\odot$

38 have $M_1 \leq 0.072\ M_\odot$

78 identified via direct imaging

7 identified via RV variability

1 identified as an eclipsing system (2MASS 0535-0546; Stassun et al. 2006)

10 are companions to more massive primaries

4 are possible higher order VLM systems

67 are systems in the field

11 are members of young (< 10 Myr) clusters/associations

See http://paperclip.as.arizona.edu/~nsiegler/VLM_binaries/

General Properties of VLM Binaries

(Burgasser et al. 2007 PPV Chapter, and references therein)

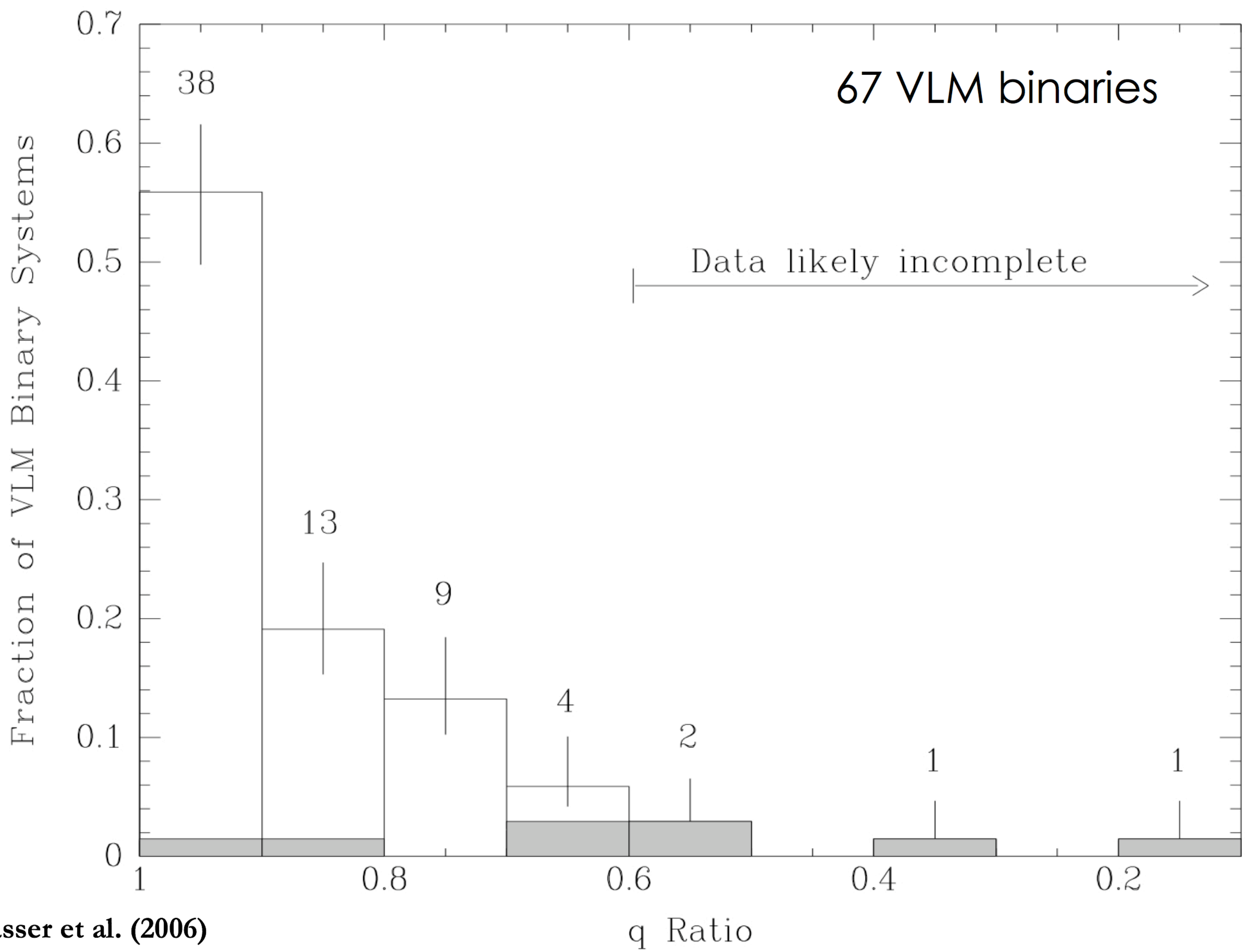
1. Relatively rare (ε_B = 10-20%)
   *different from stellar binaries!

2. Mostly "tight" systems (89% have a < 20 AU)
   *different from stellar binaries!

3. Mostly equal-mass systems (76% have q ≥ 0.8)
   *different from stellar binaries!

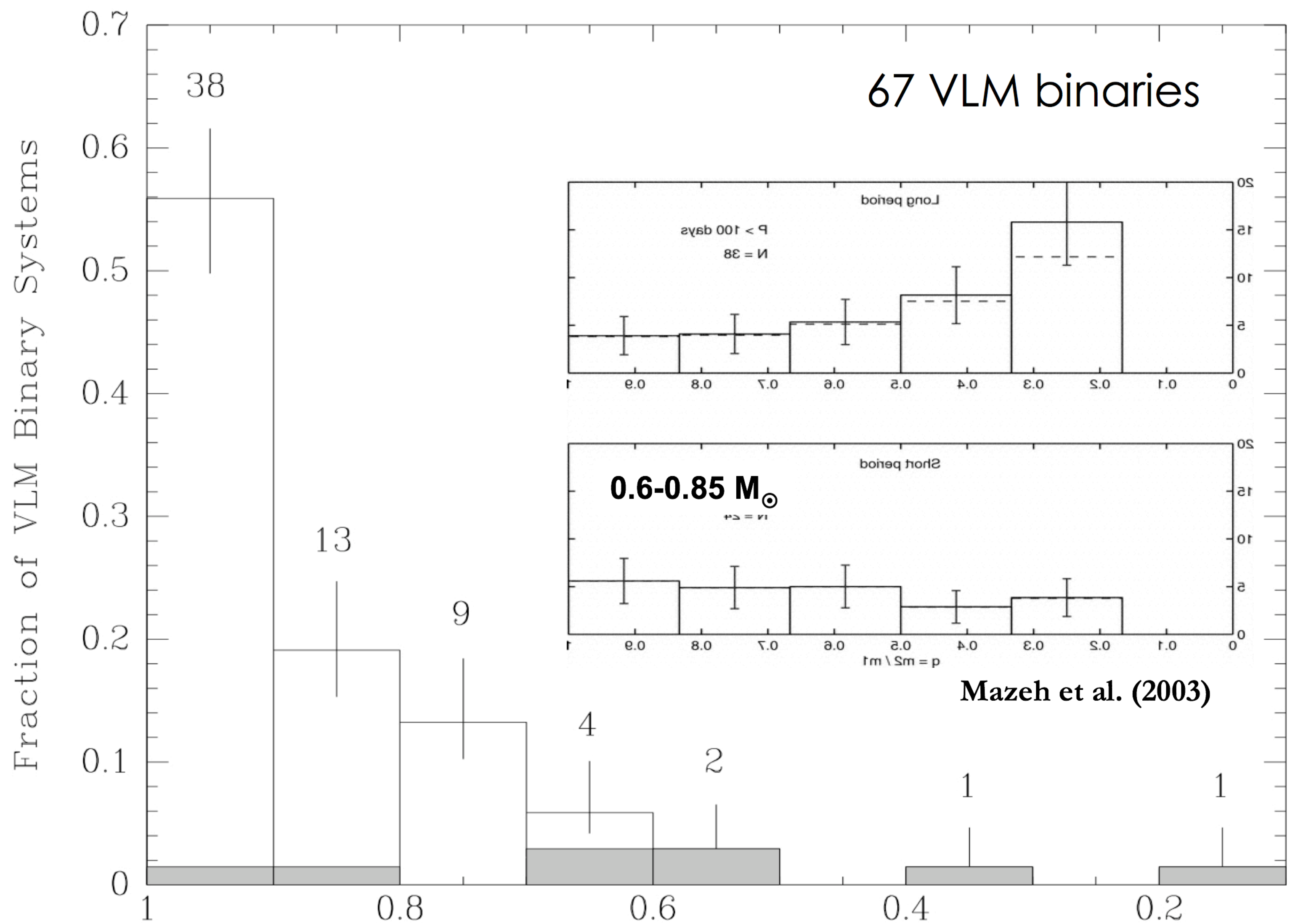
Do differences indicate brown dwarfs form differently than stars?

Mass Ratio Distribution



Burgasser et al. (2006)

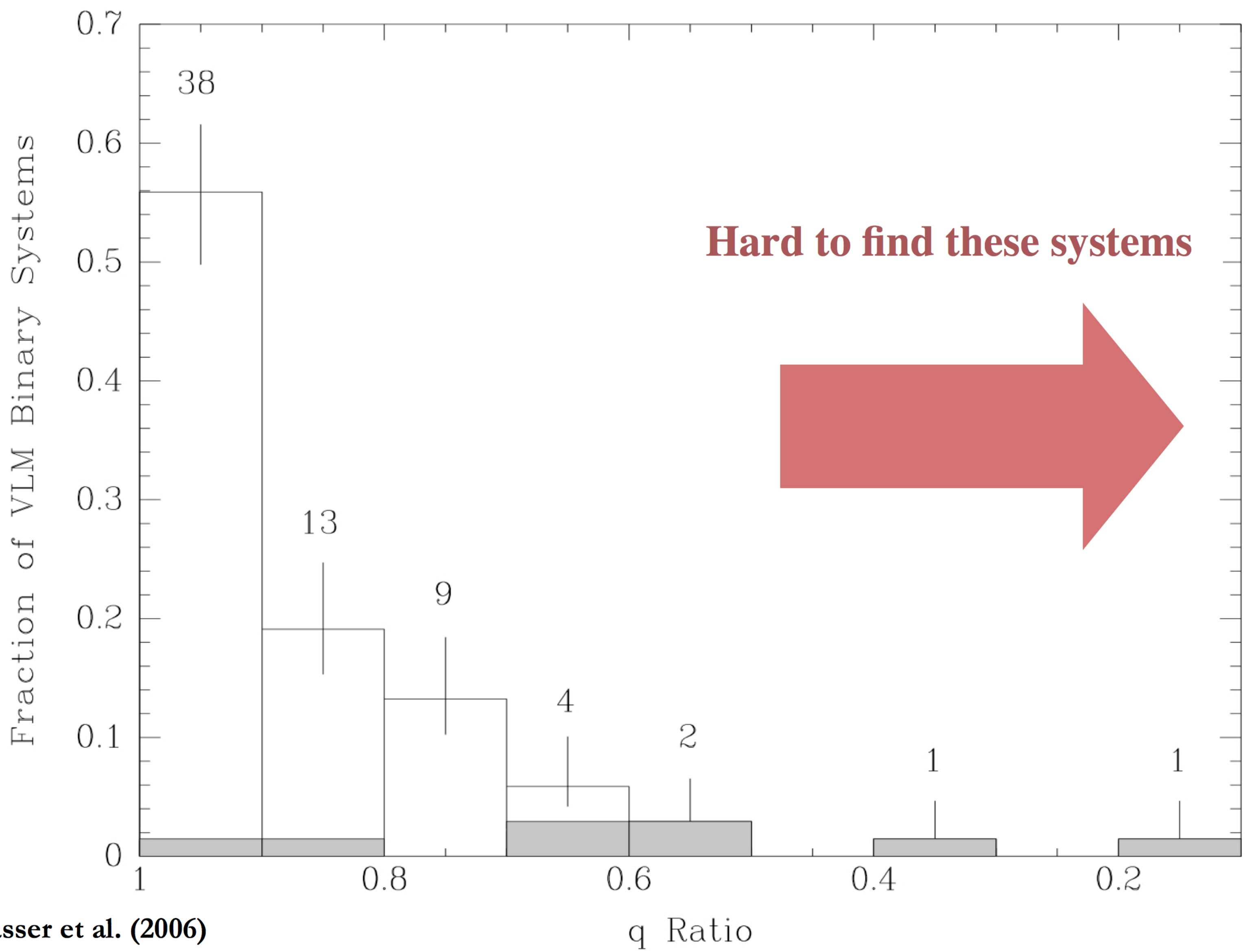
Mass Ratio Distribution



Burgasser et al. (2006)

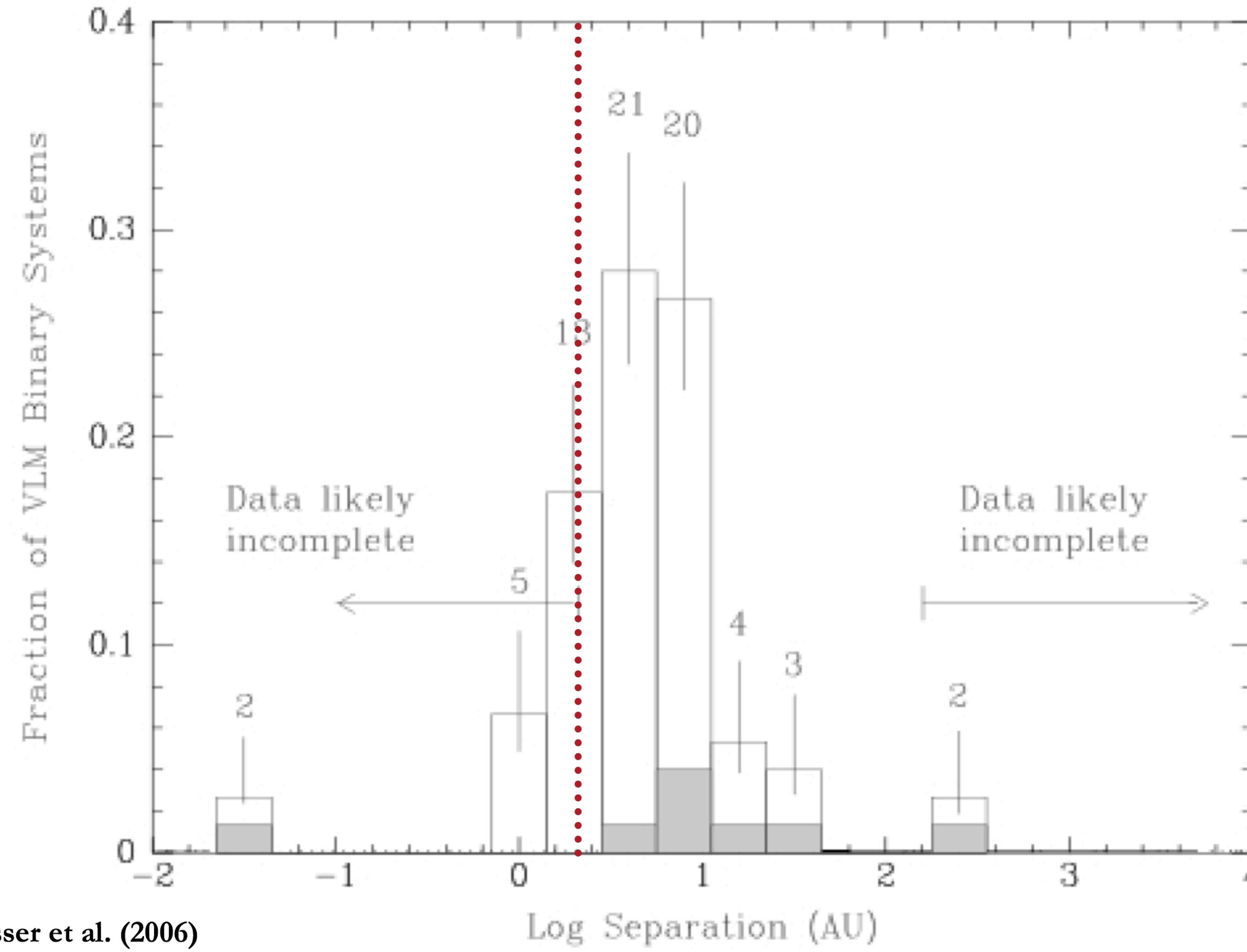
q Ratio

Mass Ratio Distribution



Burgasser et al. (2006)

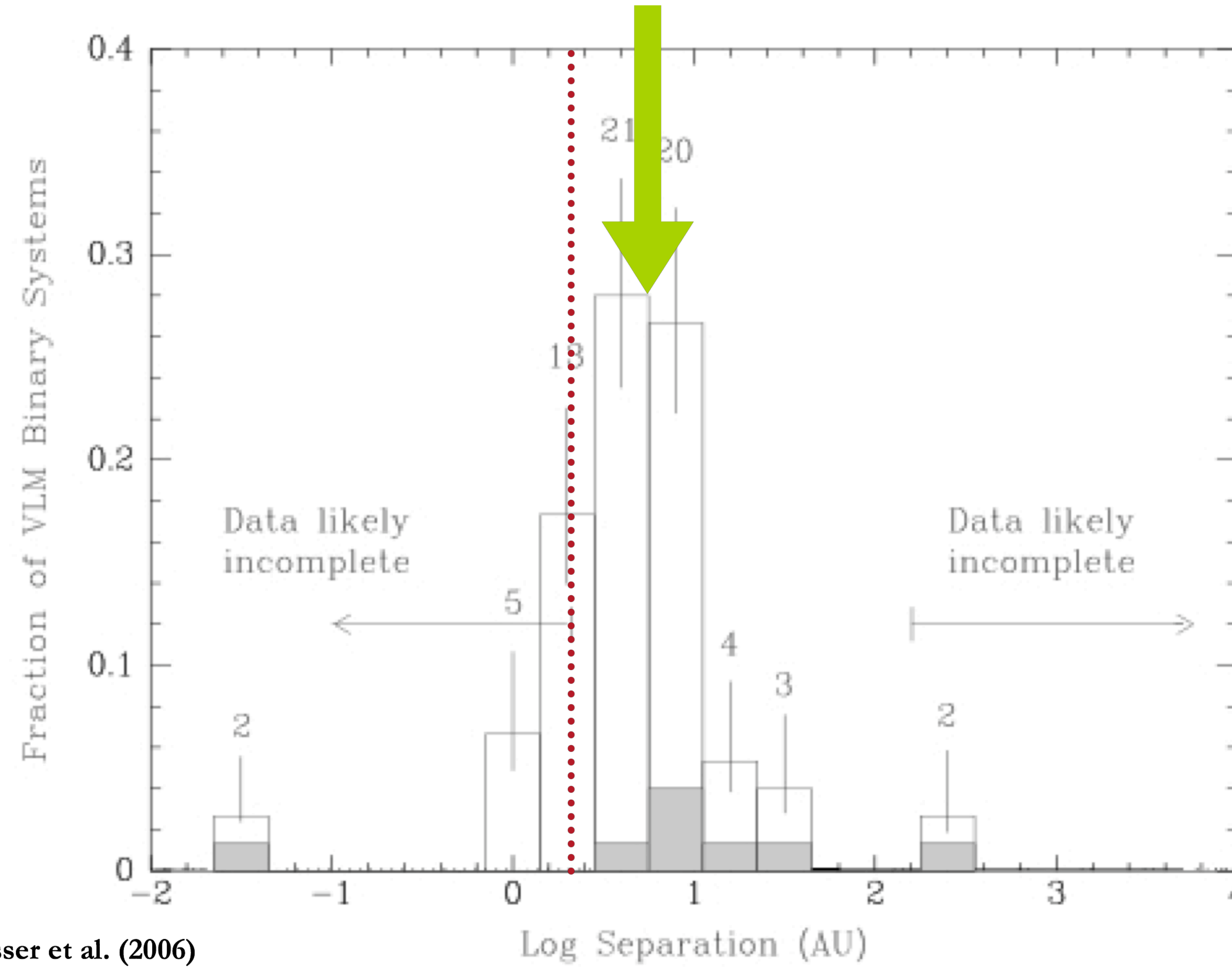
Separation Distribution



Burgasser et al. (2006)

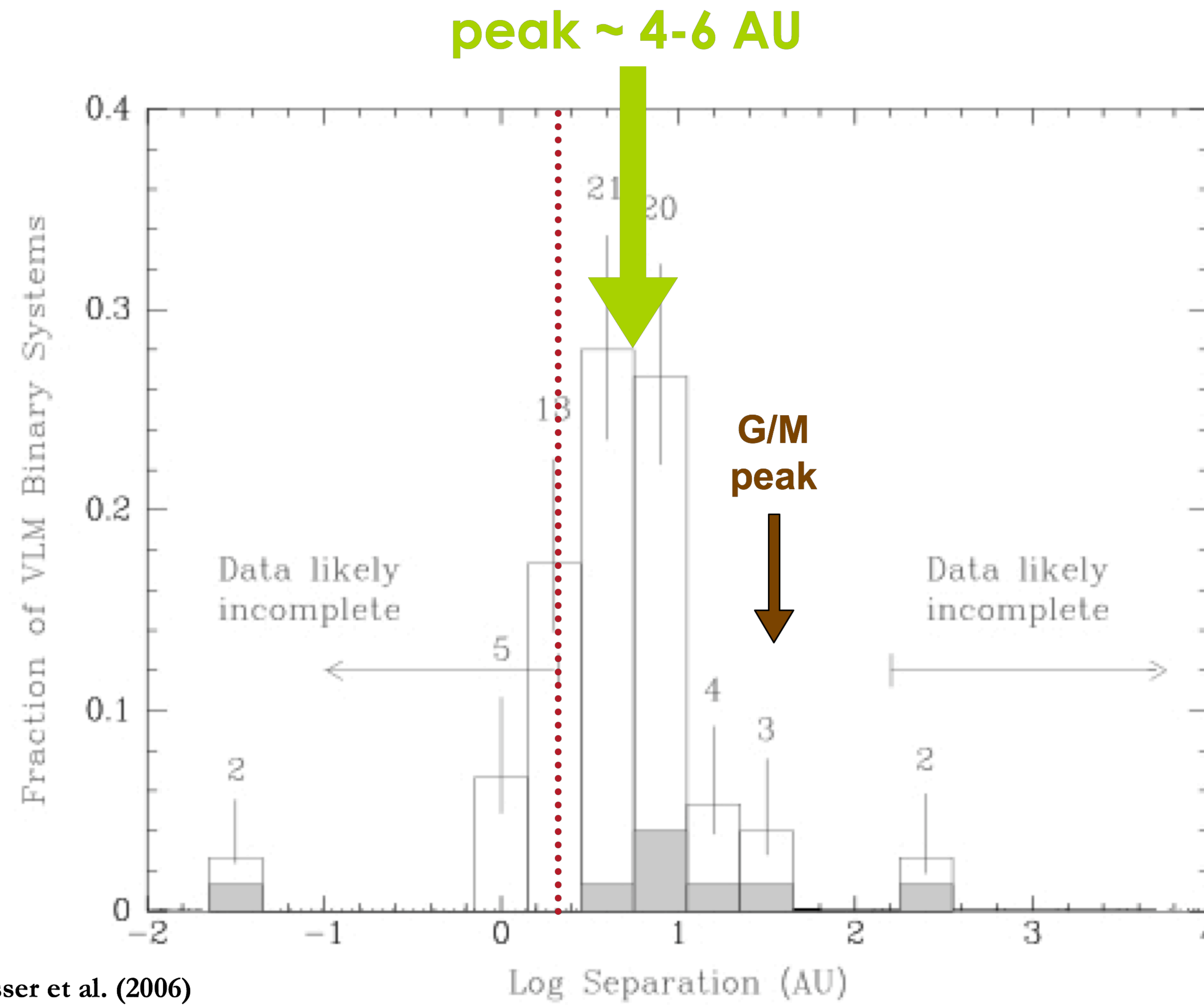
Separation Distribution

peak ~ 4-6 AU



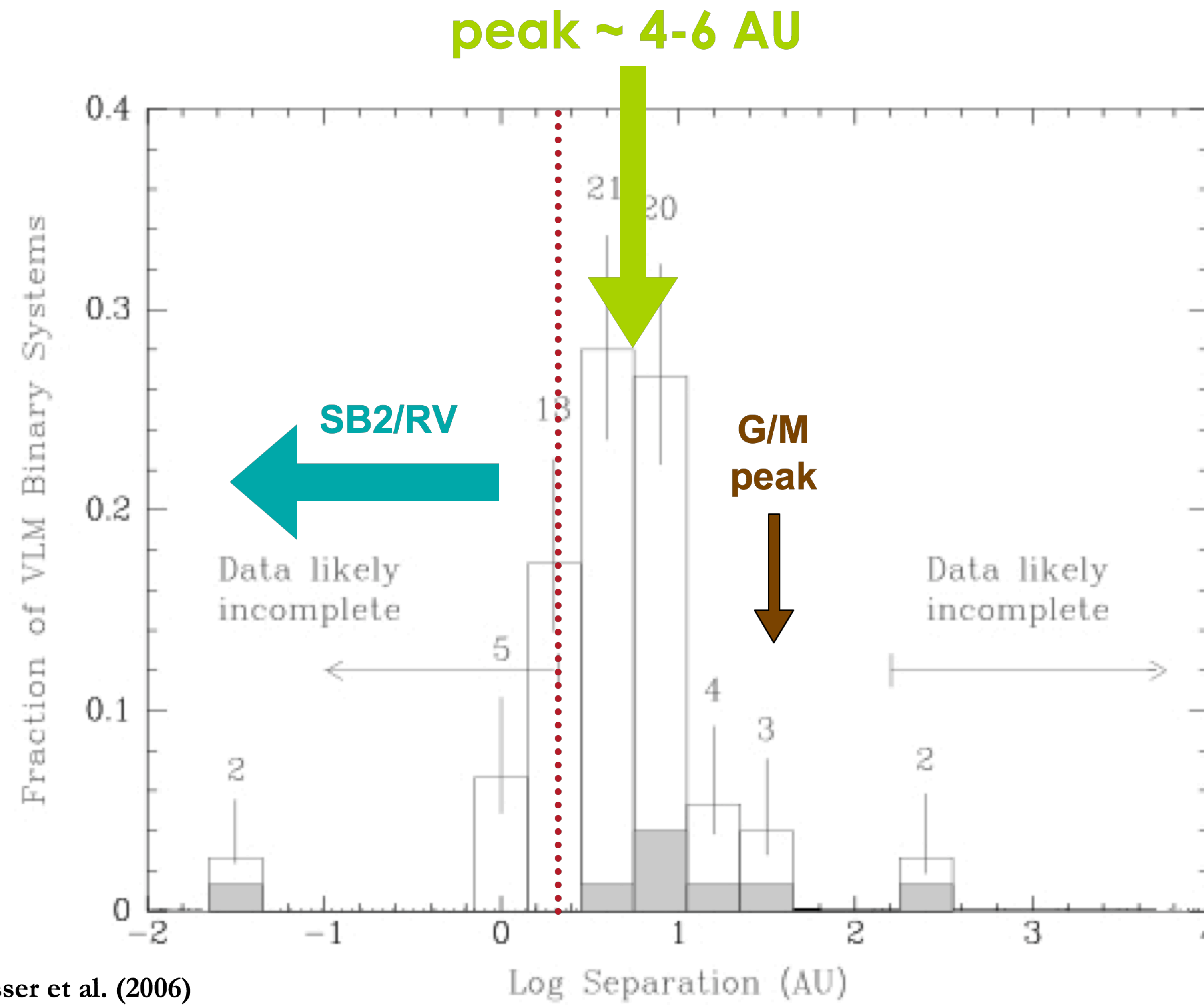
Burgasser et al. (2006)

Separation Distribution



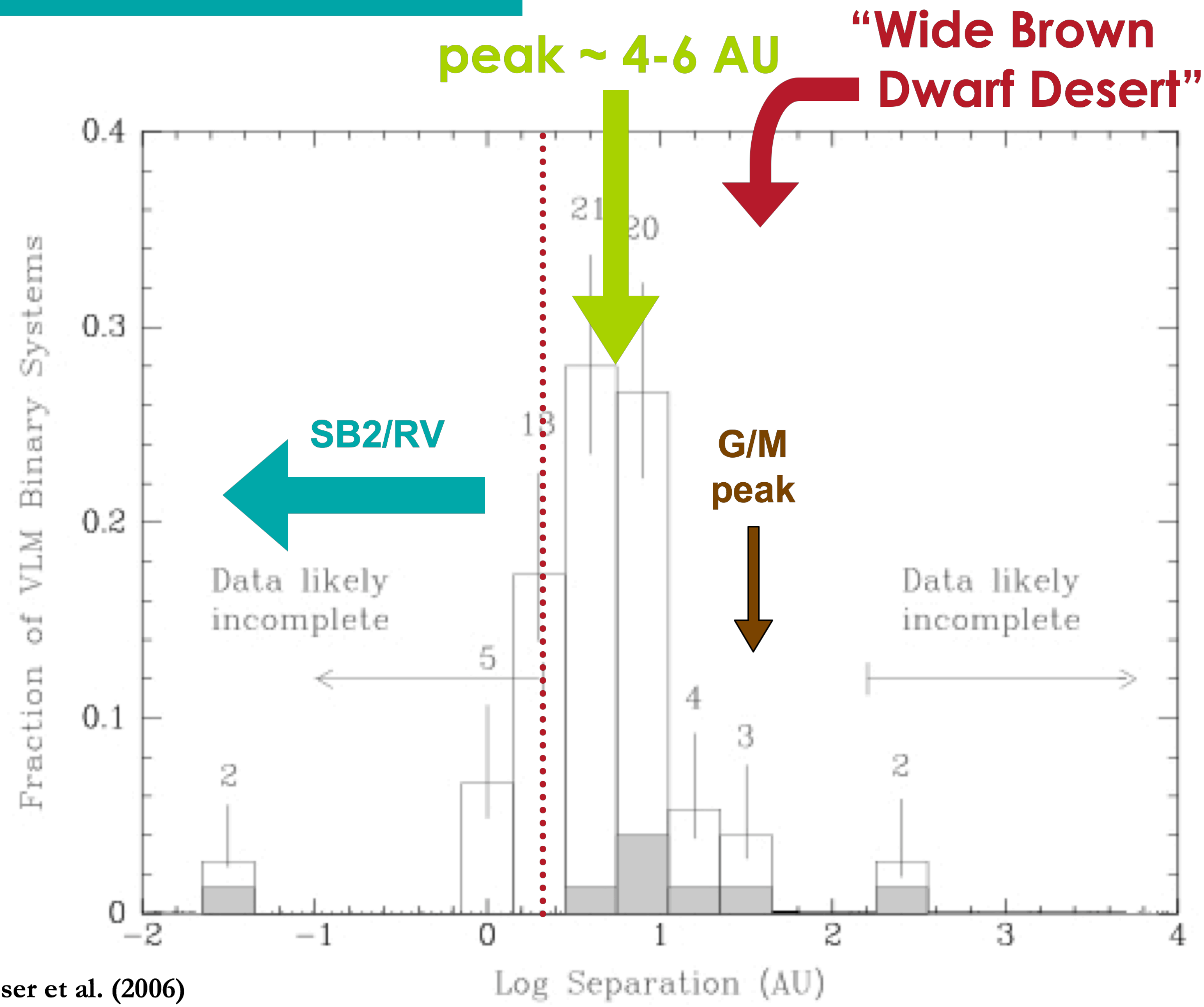
Burgasser et al. (2006)

Separation Distribution

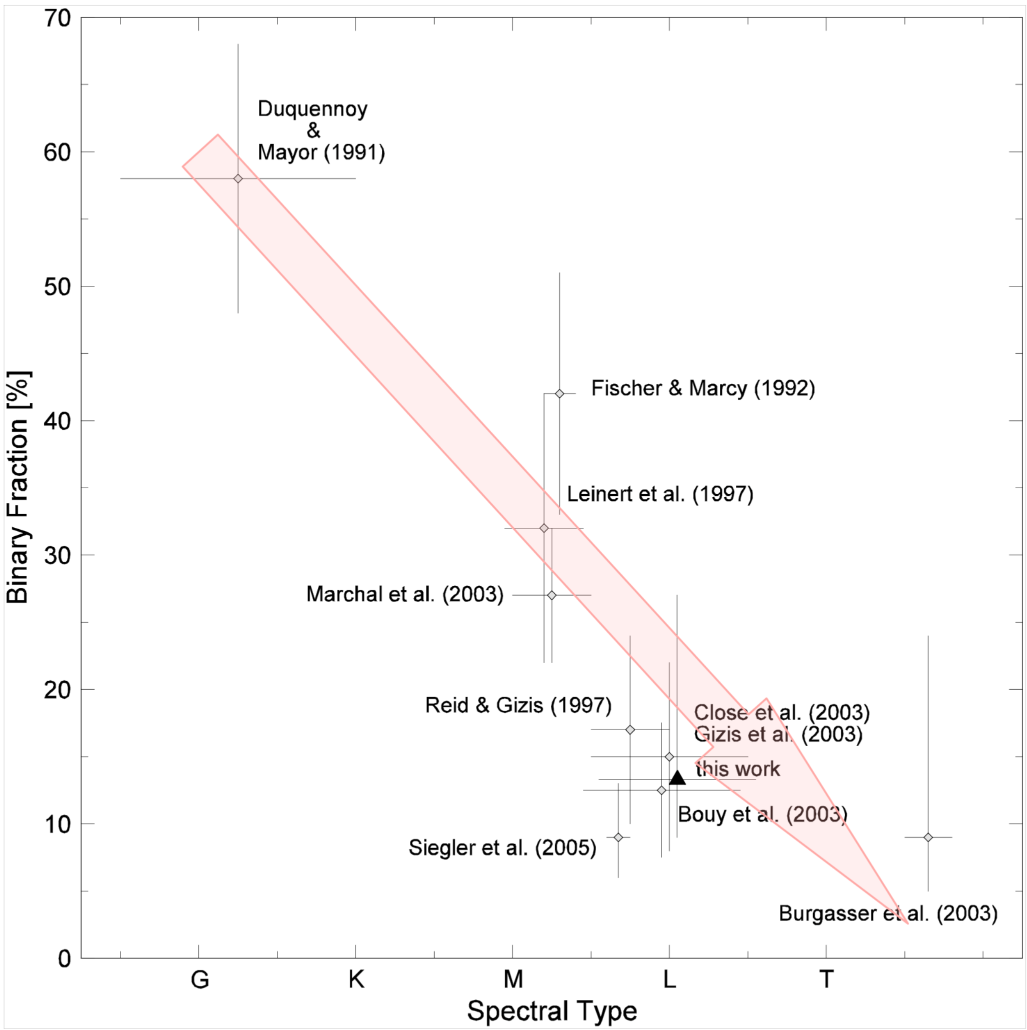


Burgasser et al. (2006)

Separation Distribution



Burgasser et al. (2006)



Bouy et al. (2005)

The Binary Fraction

From imaging studies, apparent $\varepsilon_B \approx 20\%$

Selection effects:

(1) Magnitude-limited samples (⇓)

(2) Resolution limits (⇑)

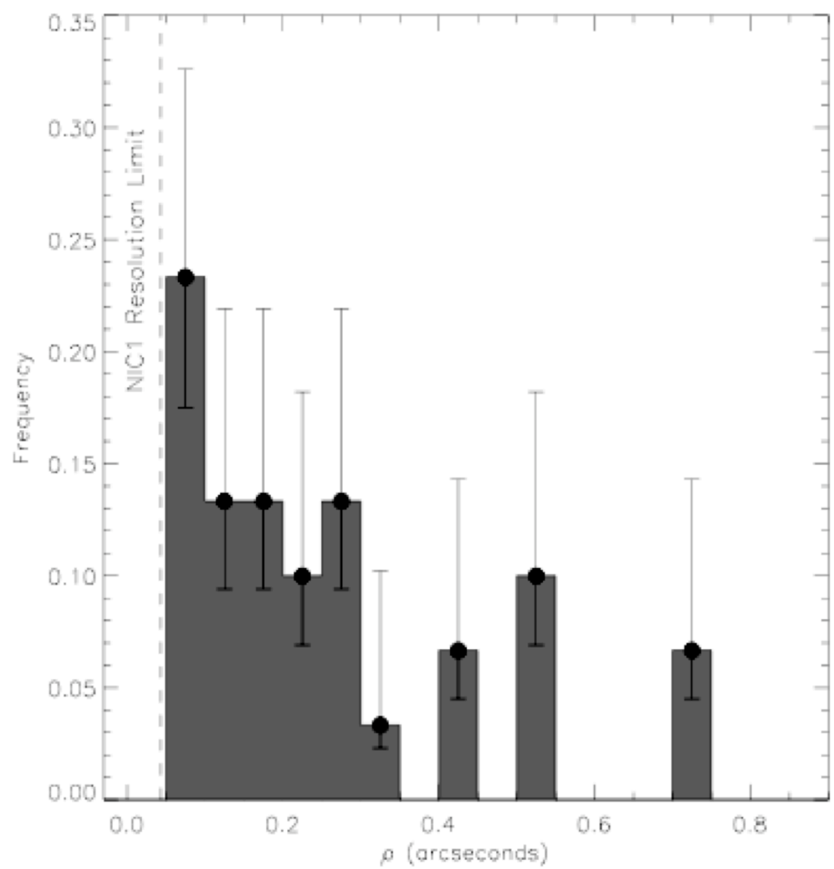
(3) Sensitivity limits (⇑)

Correcting for (1)

$\Rightarrow$ **$\varepsilon_B \approx$ 10-15%**

Reid et al. (1997); Bouy et al. (2005); White et al. (2006)

Missing the close ones?

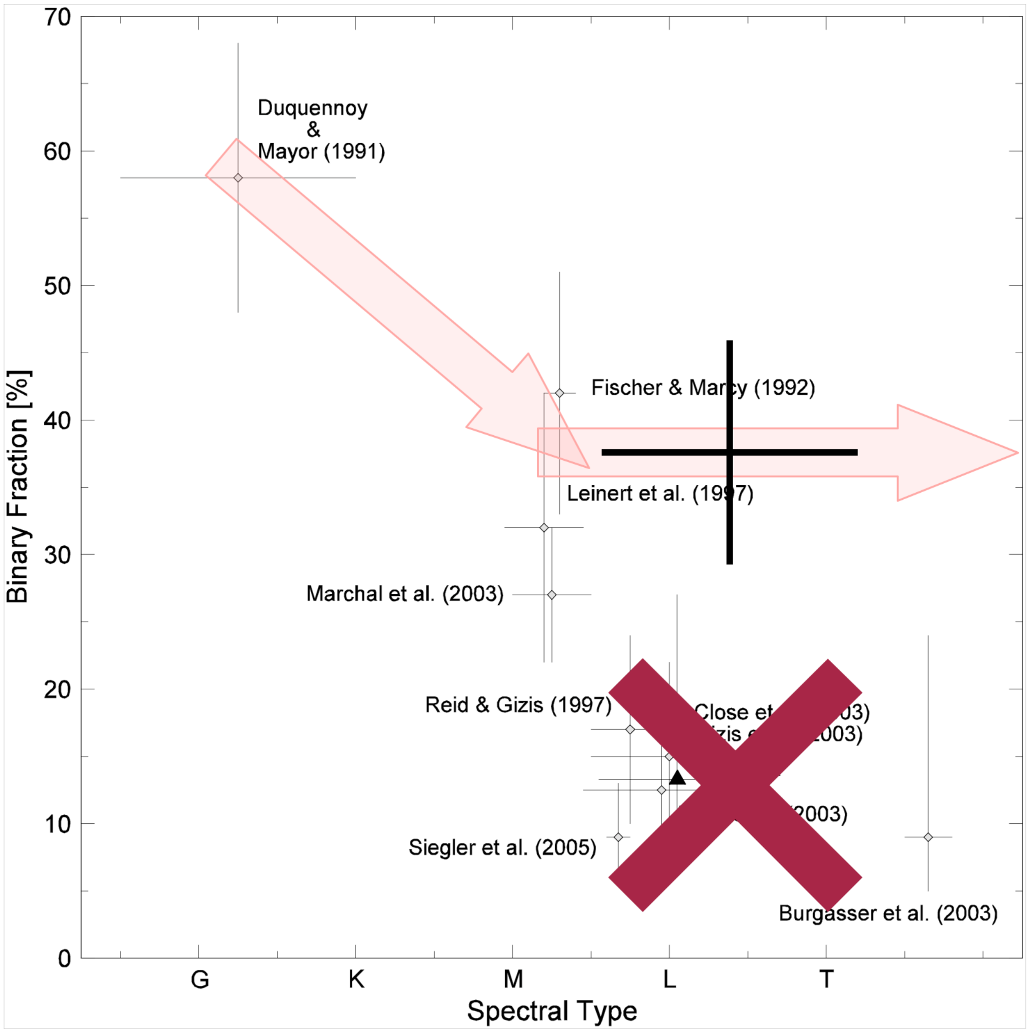


Pinfield et al. (2003) & Chapelle et al. (2005): unresolved overluminous sources in young clusters suggest **ε_B = 30-60%**

Maxted & Jeffries (2005): analysis of early spectroscopic binary results indicates ε_b = 17-30% for $a < 2.6$ AU ⇒ **ε_B = 32-45%** for all VLM binaries

Burgasser (2007): overluminous (unresolved) L/T transition objects suggests **ε_B = 24-53%** for brown dwarfs.

The Binary Fraction



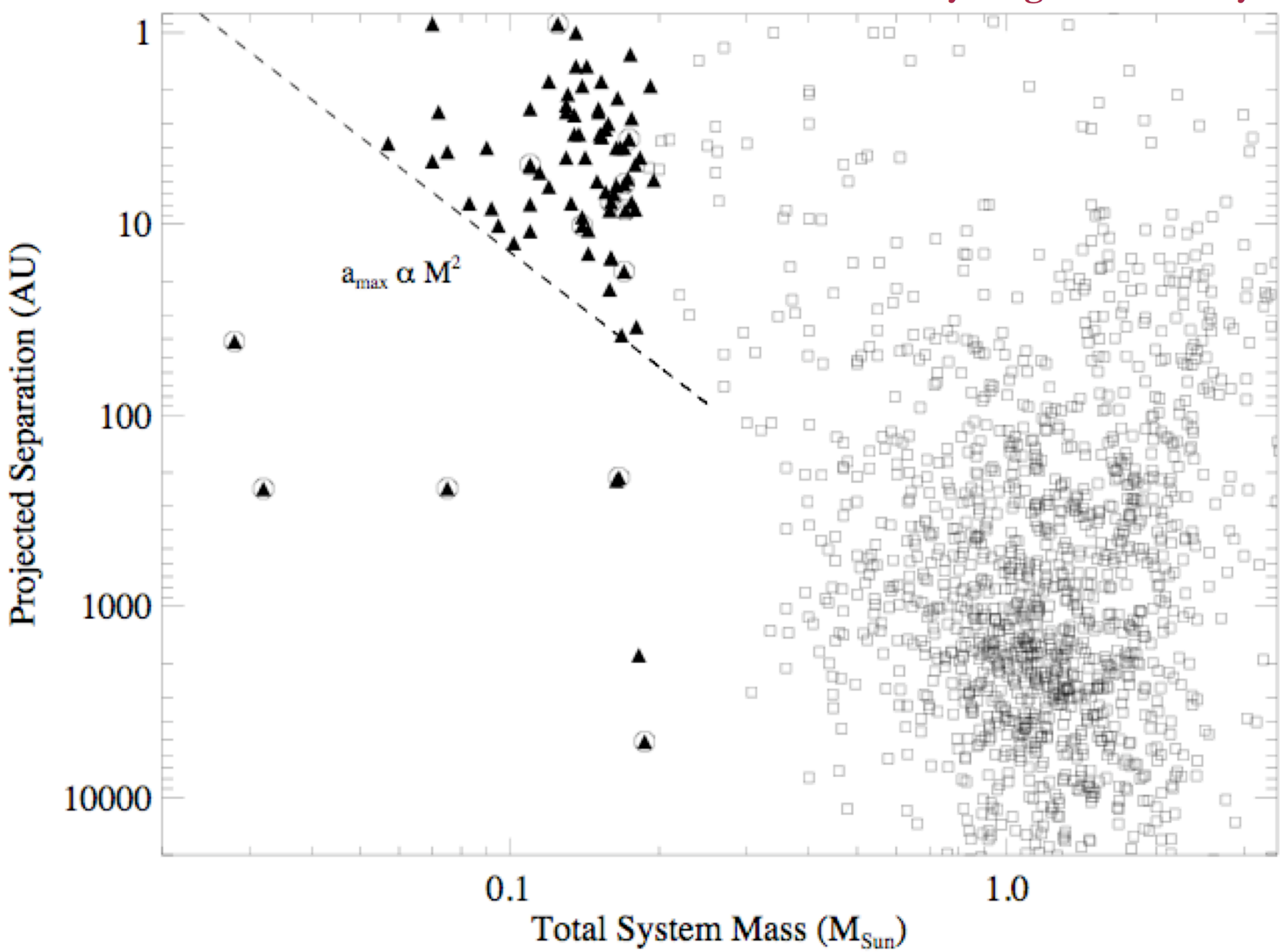
Bouy et al. (2005)

The VLM/BD multiple fraction may be much higher than currently stated if there are a large number of spectroscopic binary systems

Are most VLM stars and BDs in multiple systems?

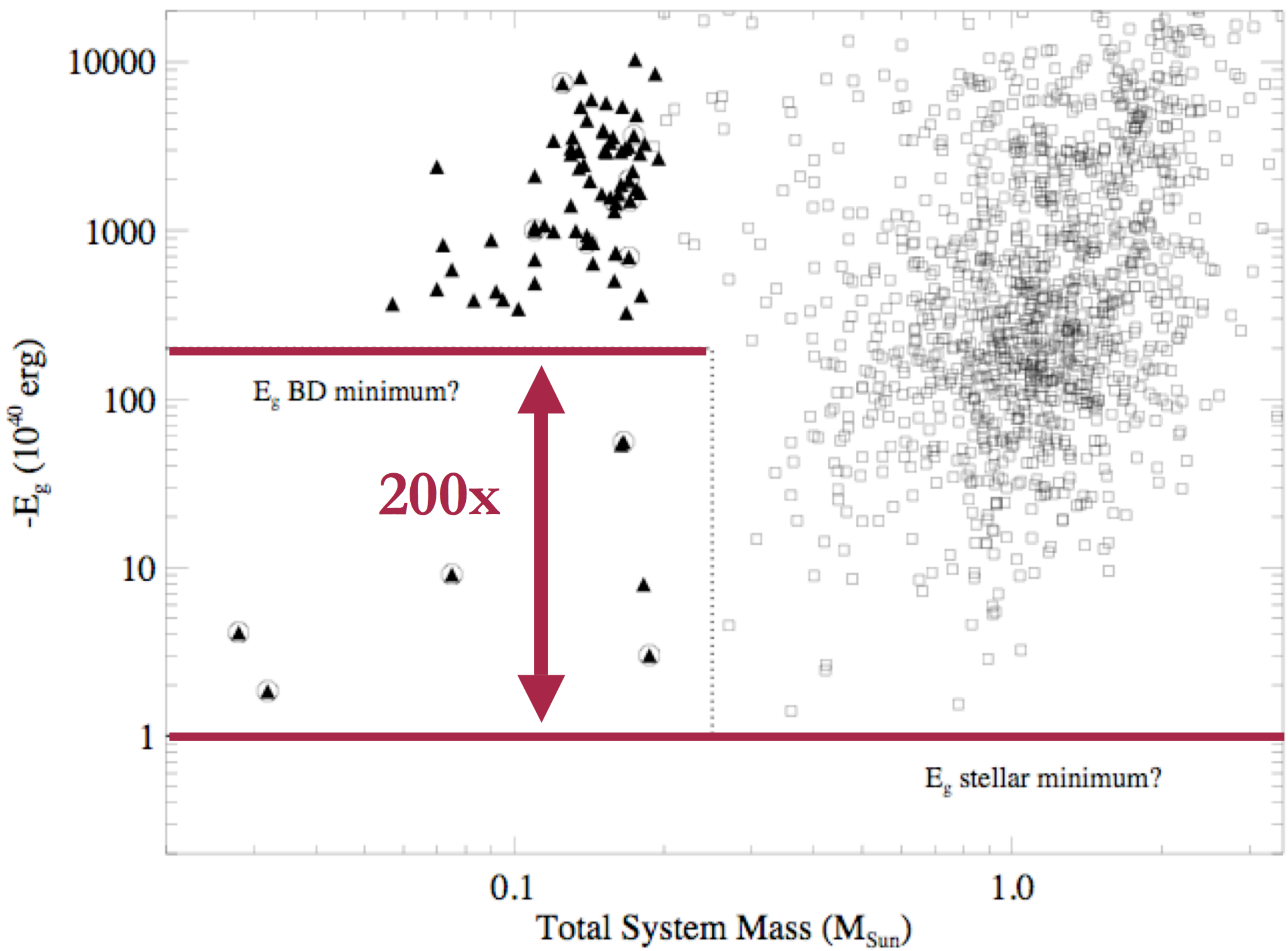
Mass vs. Separation

Circles sources are younger than 10 Myr



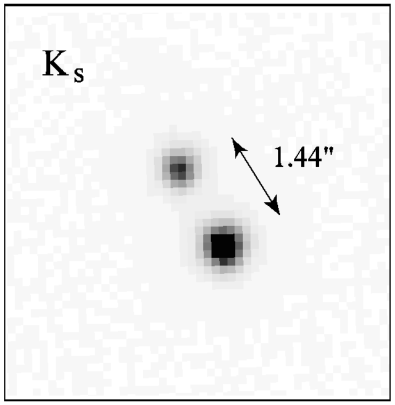
Mass vs. Binding Energy

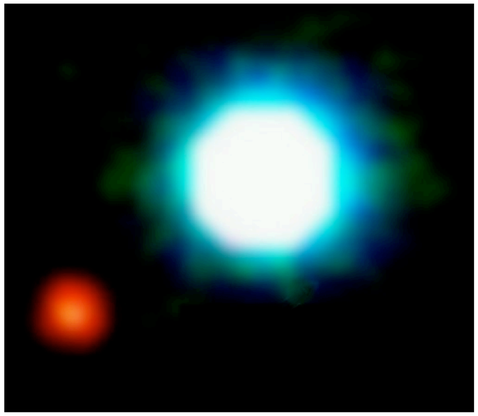
Circles sources are younger than 10 Myr

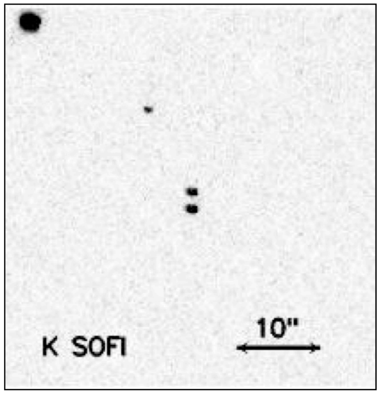


Common Outliers

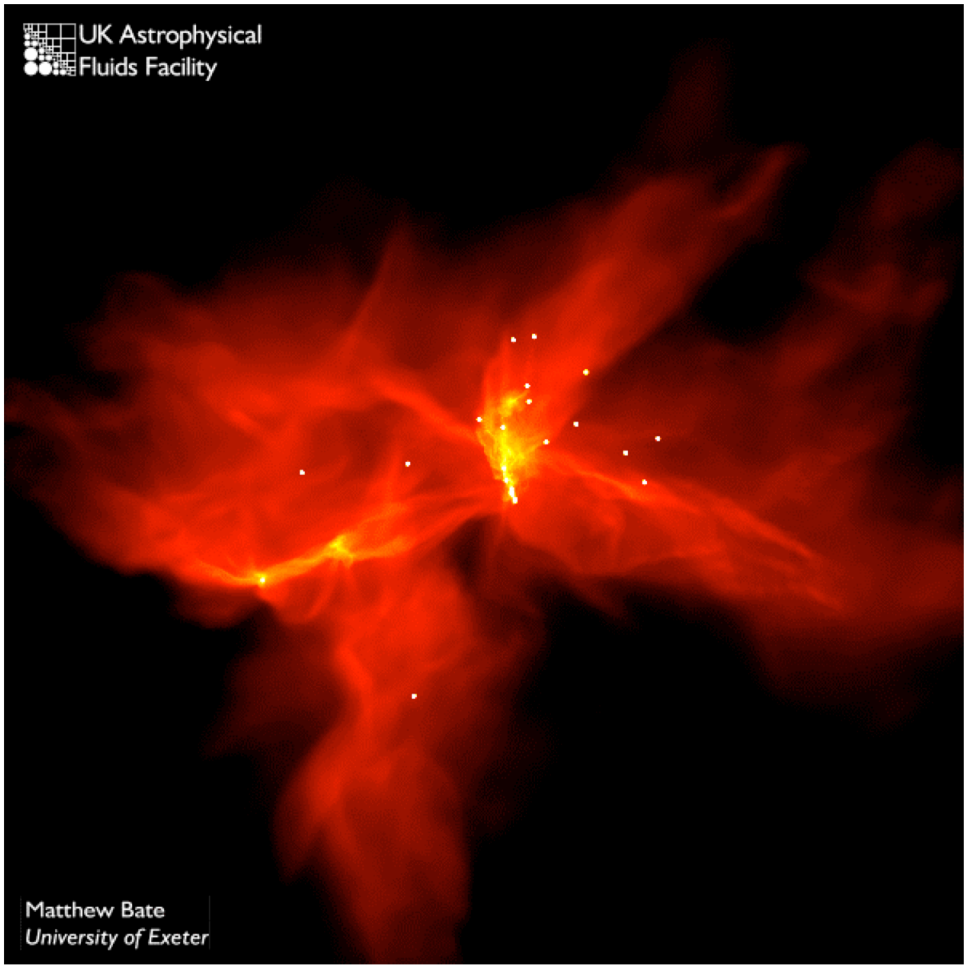
- **2MASS 1207-3932AB** (42 AU): member of ≈8 Myr low density TW Hydrae association, still accreting (Chauvin et al. 2004, 2005)
- **2MASS 1101-7732AB** (242 AU): member of ≈2 Myr Chameleon I low density association (Luhman 2004)
- **Oph 11AB & 16AB** (243 & 212 AU): members of ≈5 Myr low density ρ Ophiuchus cloud complex (Allers 2005; Jayawardhana & Ivanov 2006; Close et al. 2006)
- **2MASS 0126-5022AB** (5100 AU!): probable member of ≈8 Myr low density TW Hydrae association (Artigau et al. 2007)
- ***DENIS 0551-4434AB** (220 AU): old field M9/L0 pair (no Li I absorption) at 100 pc ⇒ very rare? (Billeres et al. 2005)







How do formation models compare?

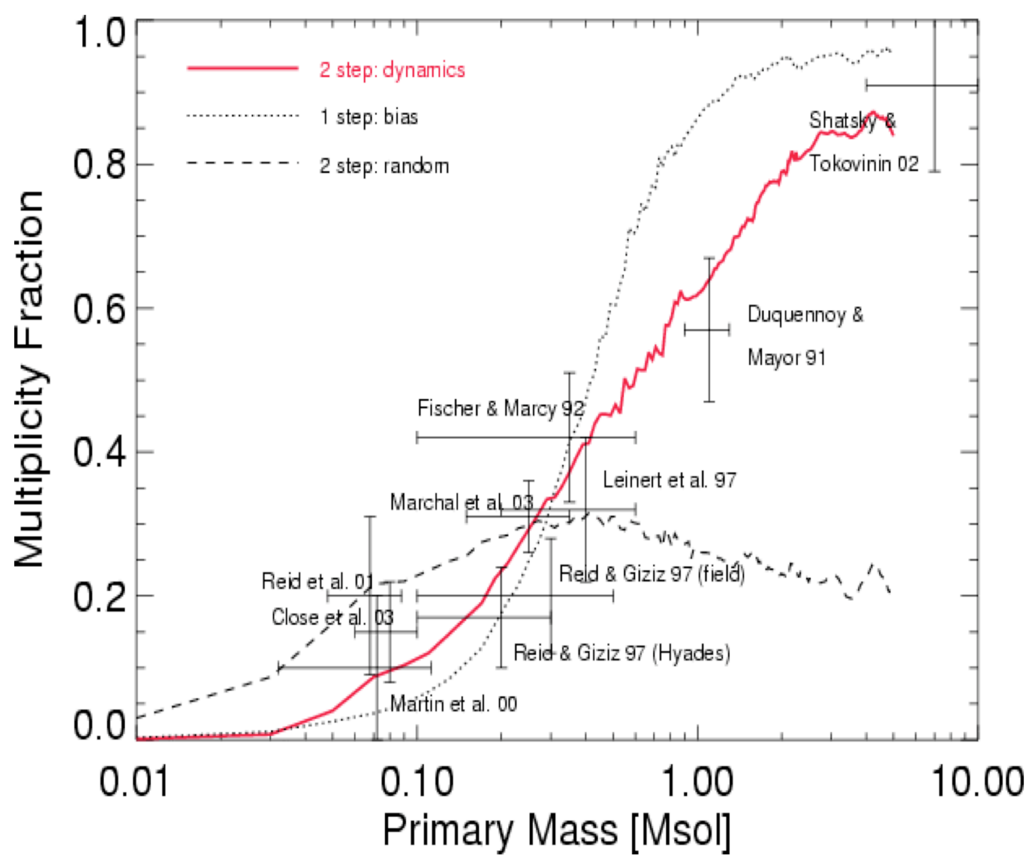


Bate et al. (2002)

SPH simulations (gas → stars) predict low VLM binary fractions (< 5% to 8%) and wider binaries for high density clouds ⇒ **not in line with observations**.

Limitations of sink particle size/Newtonian softening?

How do formation models compare?



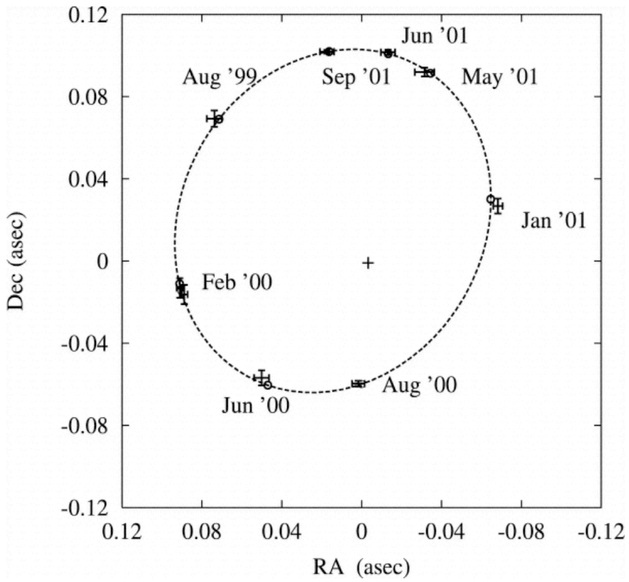
Sterzik & Durison (2003)

N-body simulations (dynamics of small groups): reproduce decrease of binary fraction with mass, median separation ≈ 3 AU, few very close systems⇒ **better match to data (perhaps)**

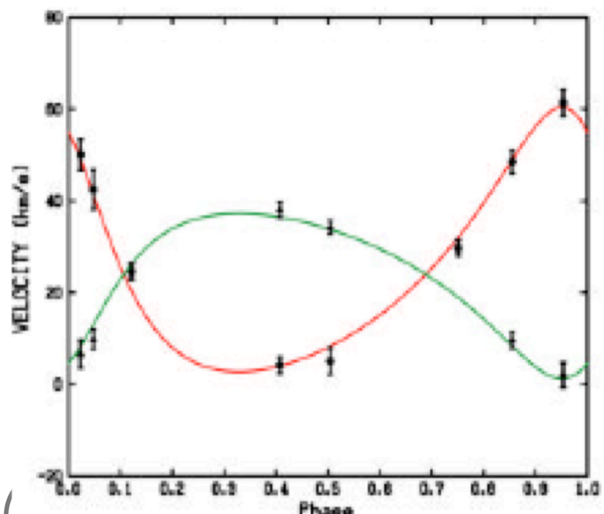
Mass Measurements

Several systems have now been monitored for spectroscopic and/or astrometric orbital motion

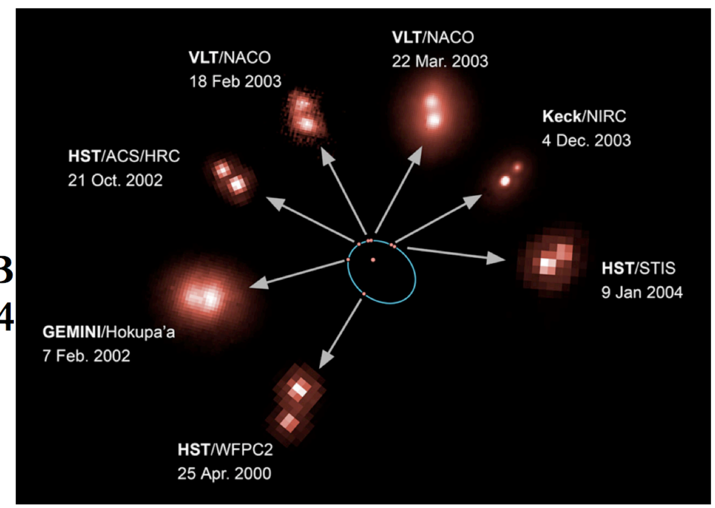
Resulting mass measurements provide first real empirical tests of theoretical evolutionary models



GJ 569Bab:
Martin et al. 2000; Lane et al. 2001; Zapatero Osorio et al. 2004

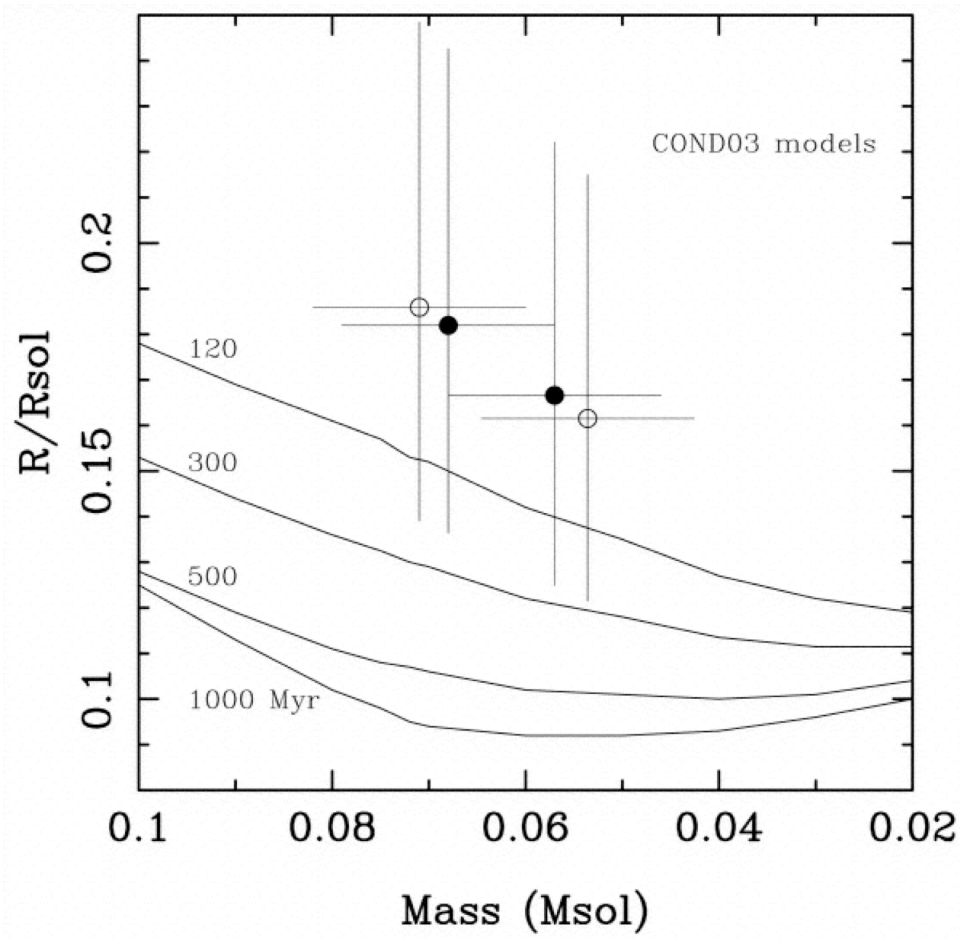


2MASS 0535-0546AB
Stassun et al. 2006



2MASS 0746+2000AB
Bouy et al. 2004

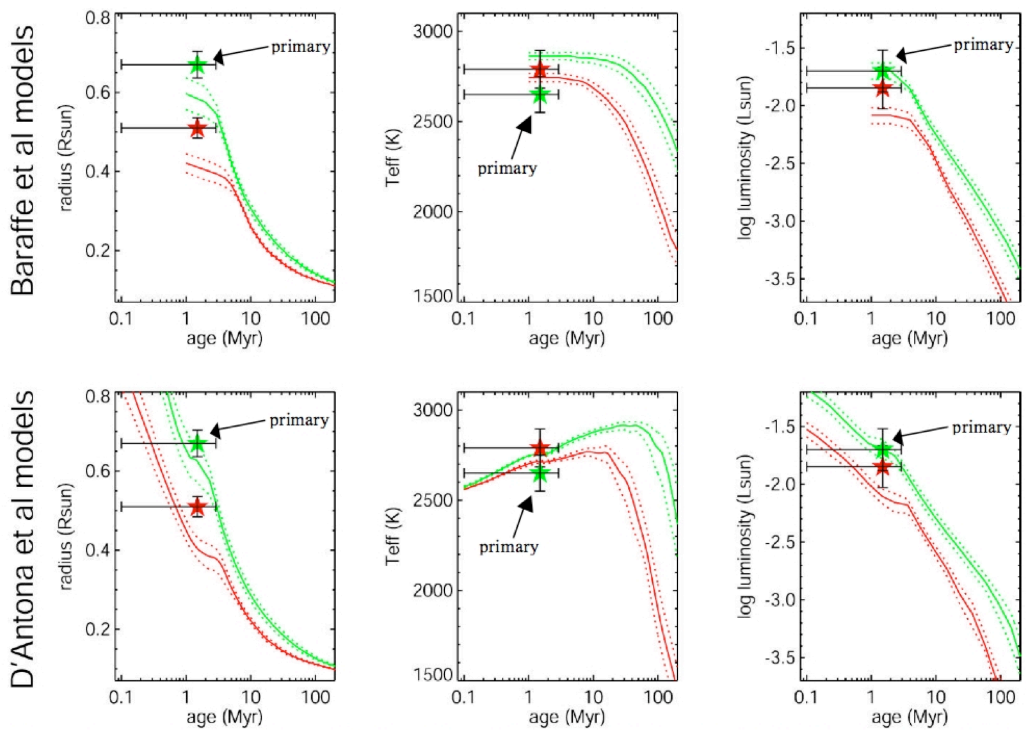
Observations v. Theory



Zapatero Osorio et al. (2004) for GJ 564Bab

Results for young systems GJ 564Bab (Zapatero Osorio et al. 2004) and 2MASS 0535-0546AB (Stassun et al. 2006) suggest **predicted substellar radii that may be too small at young ages.**

2MASS 0535-0546AB: Only Eclipsing Brown Dwarf Binary

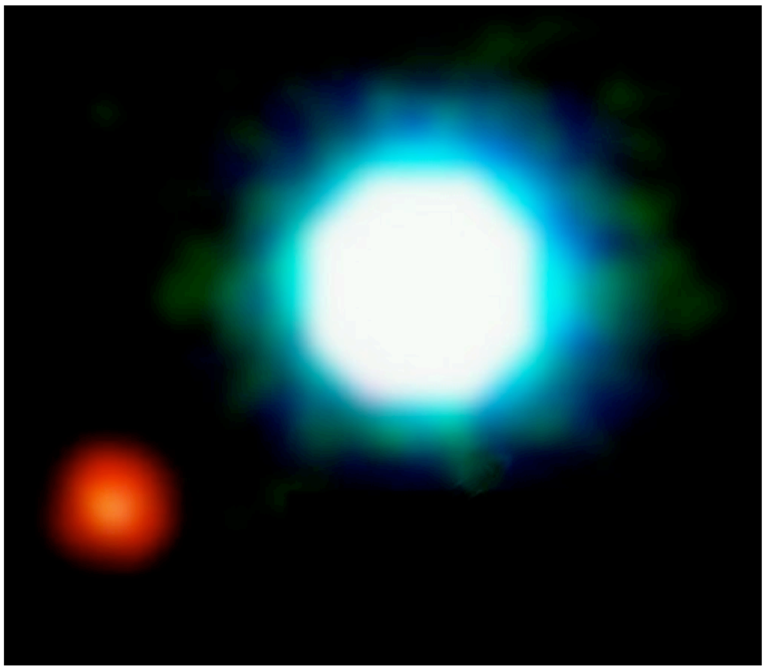


Stassun et al. (2006)

Young (≈ 1 Myr) system, masses 0.05 & 0.03 $M_{\odot}$, P = 9.8 days

Unexplained temperature reversal - indicative of magnetic effects? Accretion?

2MASS 1207-3932AB: Accreting Brown Dwarf + "Planet"?



Chauvin et al. (2004)

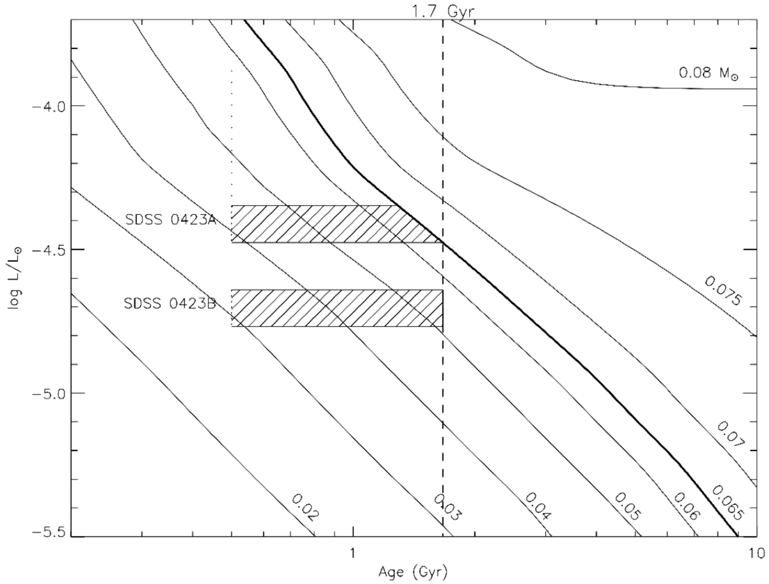
M8 + L:: identified by adaptive optics, member of ≈8 Myr TW Hydrae association (d ~ 50 pc)

Primary exhibits optical & X-ray accretion and IR excess

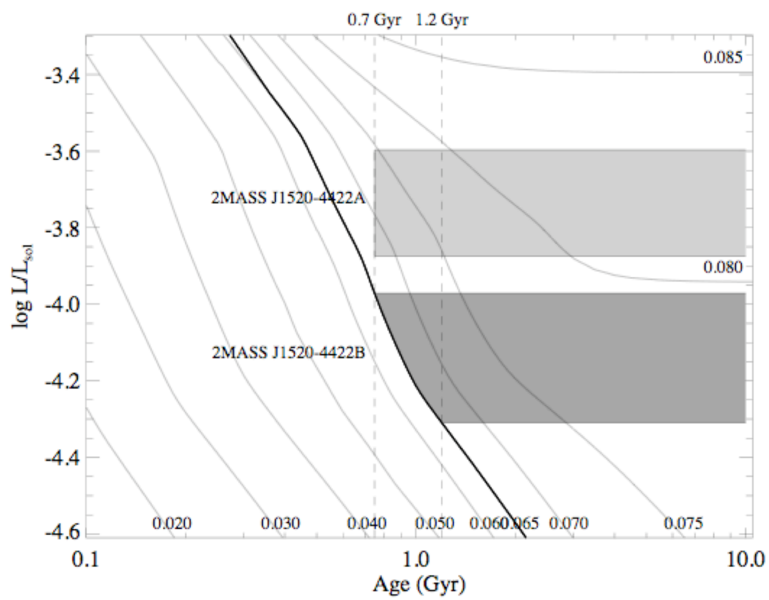
Secondary $M \approx 3\text{-}8\ M_{Jupiter}$ (model-dependent)

Gizis (2002); Jayawardhana et al. (2003); Mohanty et al. (2003,2005,2007); Chauvin et al. (2004, 2005); Sterzik et al. (2004); Gizis et al. (2004; 2005); Mamjek (2005); Scholz et al. (2005, 2006); Song et al. (2006)

Binary Lithium Test



Li detected



no Li detected

Burgasser et al. (2006, in prep)

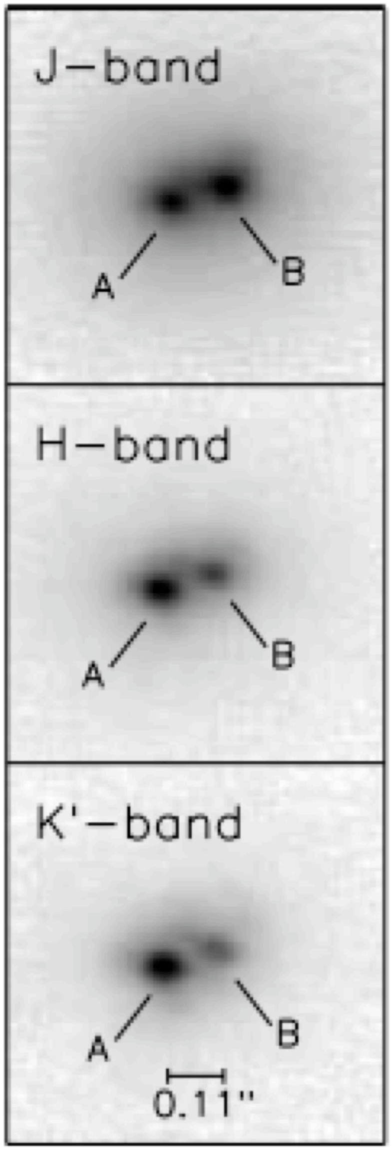
Detection/absence of the 6708 Å Li I line in the spectrum of either component of a late-type M or L dwarf can provide constraints for both components, assuming coevality (Liu & Leggett 2005)

Test has yet to be done on resolved optical spectra!

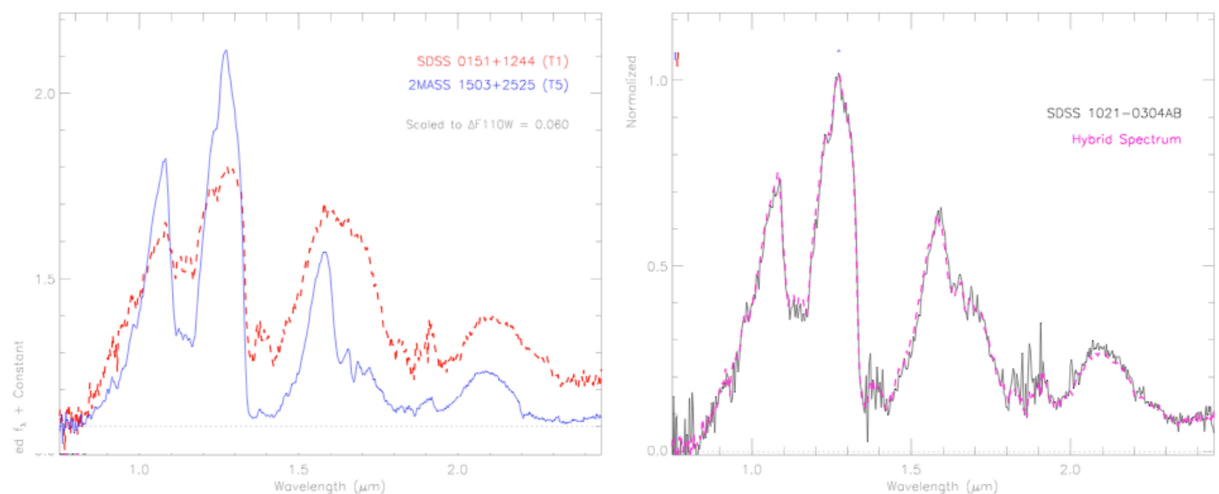
Binaries and the L/T Transition

Transition between L and T spectral types poorly understood, but there are an **abundance of binaries** amongst them (~40% compared to ~20% observed) .

Binaries reveal brightening at 1.05 & 1.25 μm between early- & mid-T possibly indicative of nonequilibrium loss of condensates (aka weather?)

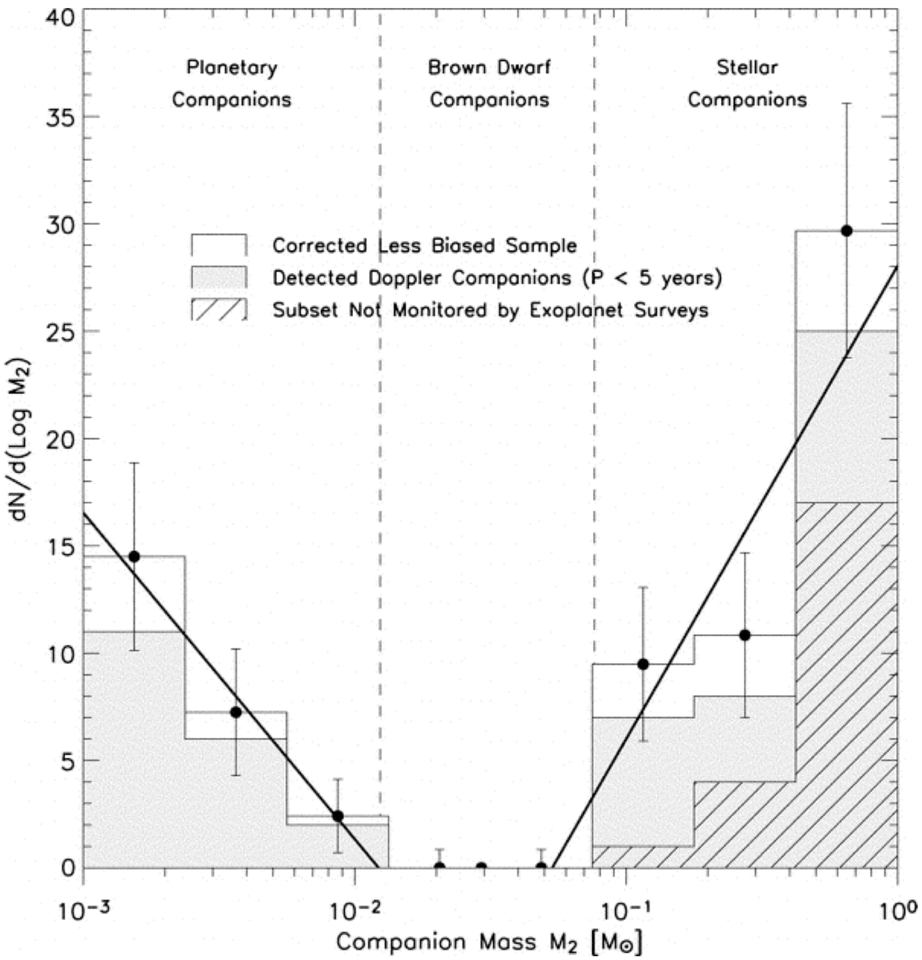


SDSS 1534+1615AB: Liu et al. (2006)



SDSS 1021-0304AB: Burgasser et al. (2006)

Brown dwarfs as companions

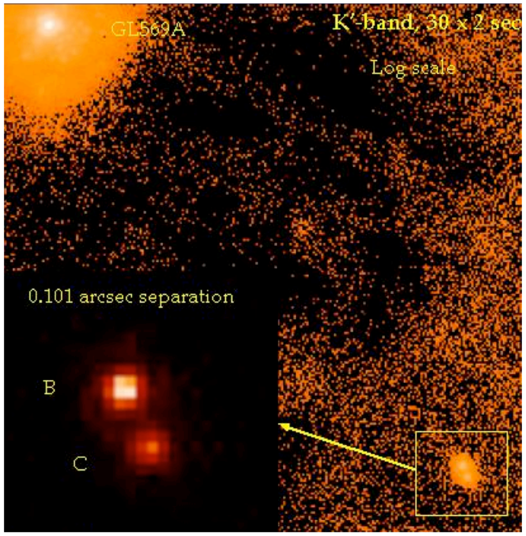


Grether & Lineweaver (2006)

Brown dwarfs are very rare as close companions (< 5 AU) to stars: **"brown dwarf desert"**

At wider separations, brown dwarf companions are more common (2-15% for 30-1600 AU; Metchev 2005)

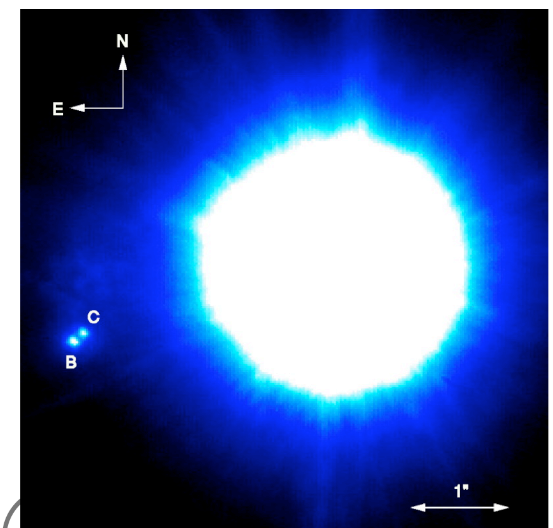
Binaries as Companions



GJ 569Bab:
Martin et al. 2000; Lane et al. 2001; Zapatero Osorio et al. 2004

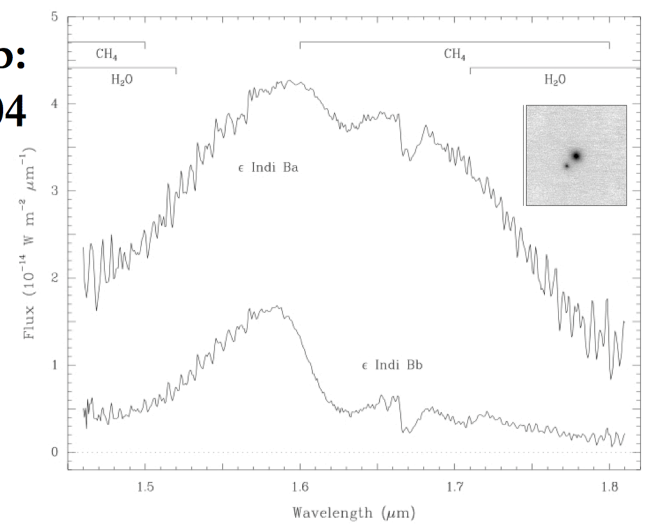
Many wide BD companions to nearby stars are themselves binary ⇒ excellent laboratories for testing models

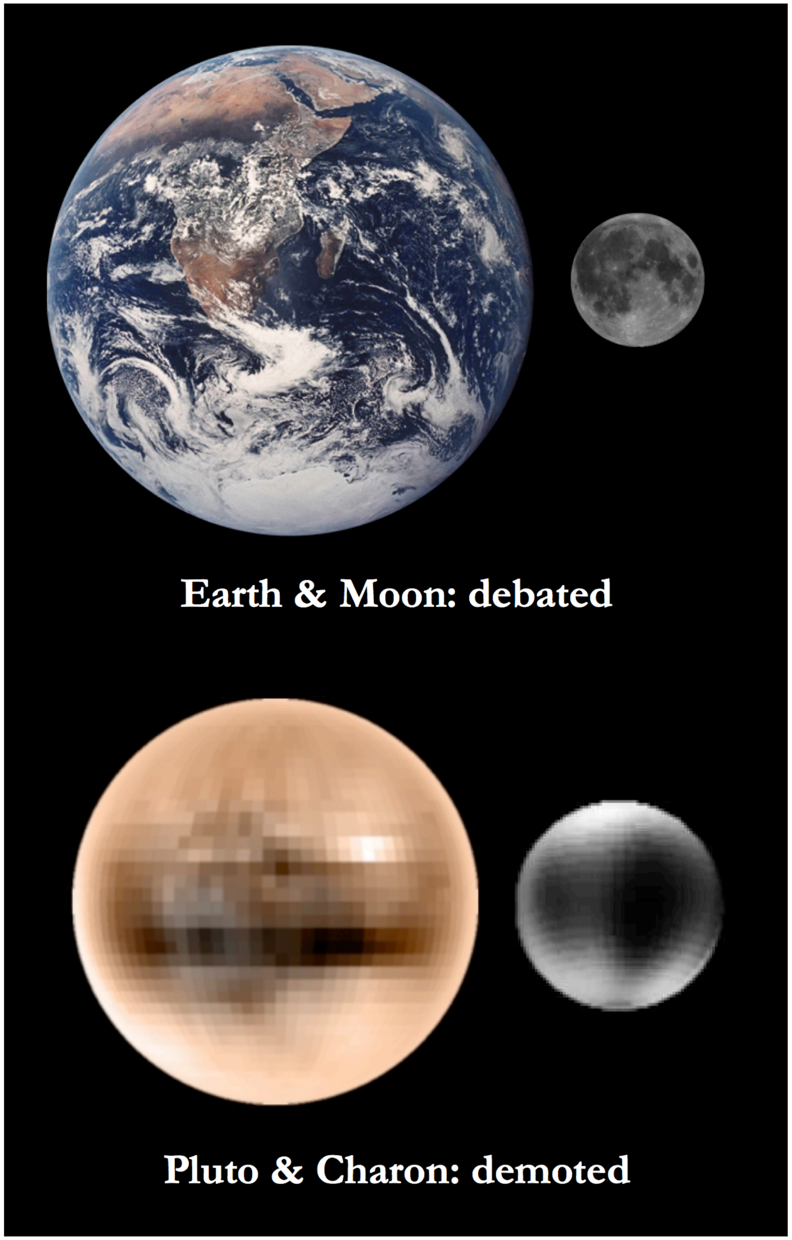
Some indication that companion BDs are more frequently binary (Burgasser et al. 2005): a clue to formation?



HD 130948Bab:
Potter et al. (2002)

Epsilon Indi Bab:
McCaughrean et al. 2004

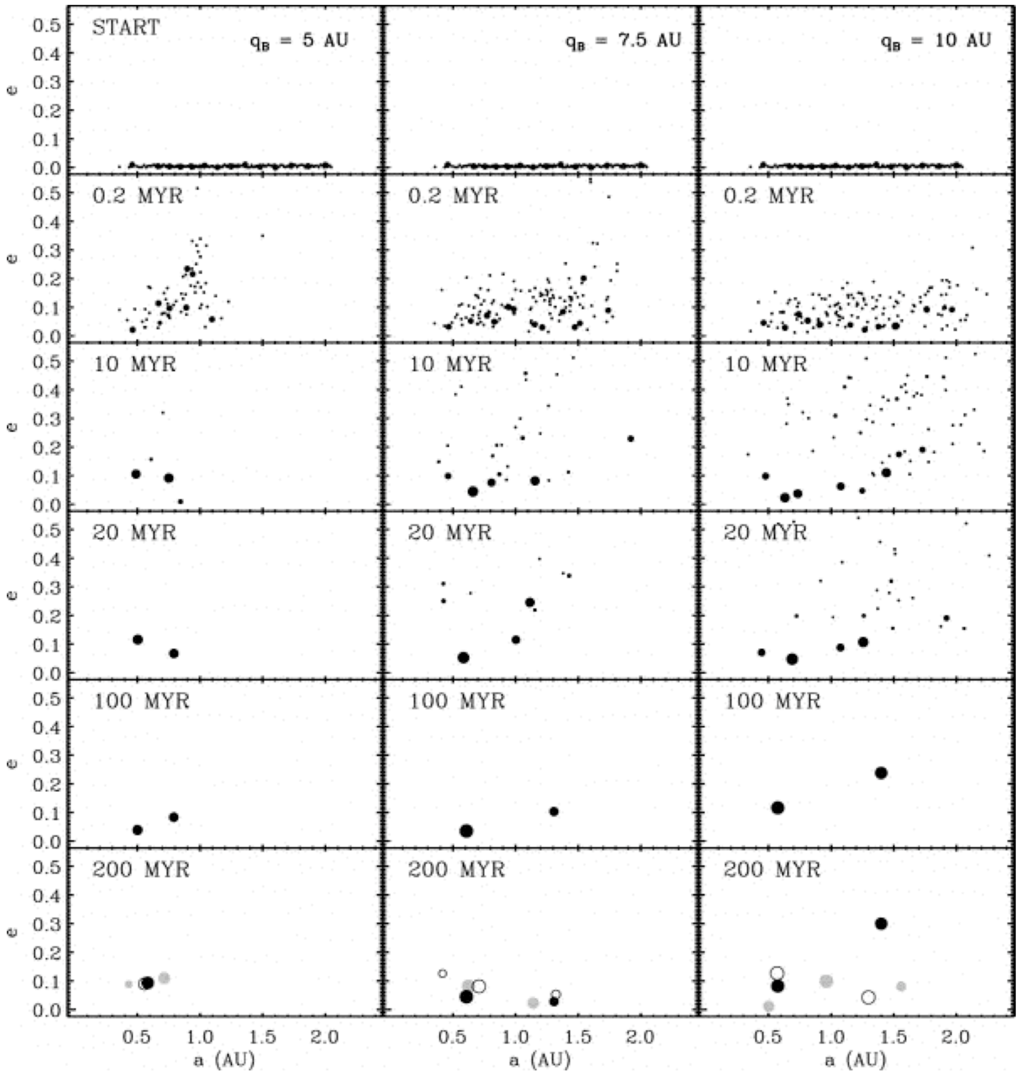




Double planets

As of 2006, there are (officially) **no** double planets known! (Earth-Moon and Pluto-Charon were closest contenders)

Several multiple planet systems are known (including Solar System!)



Quintana et al. (2006)

Planets in binary systems

> 23% of known EGPs reside in multiple systems (Raghavan et al. 2006), including one with a brown dwarf (HD 3651; Luhman et al. 2006; Mugrauer et al. 2006)

Simulations indicate that habitable terrestrial planets can be formed in systems with q_B > 10 AU (Quintana et al. 2006)