Multiple Star Formation to the Bottom of the IMF

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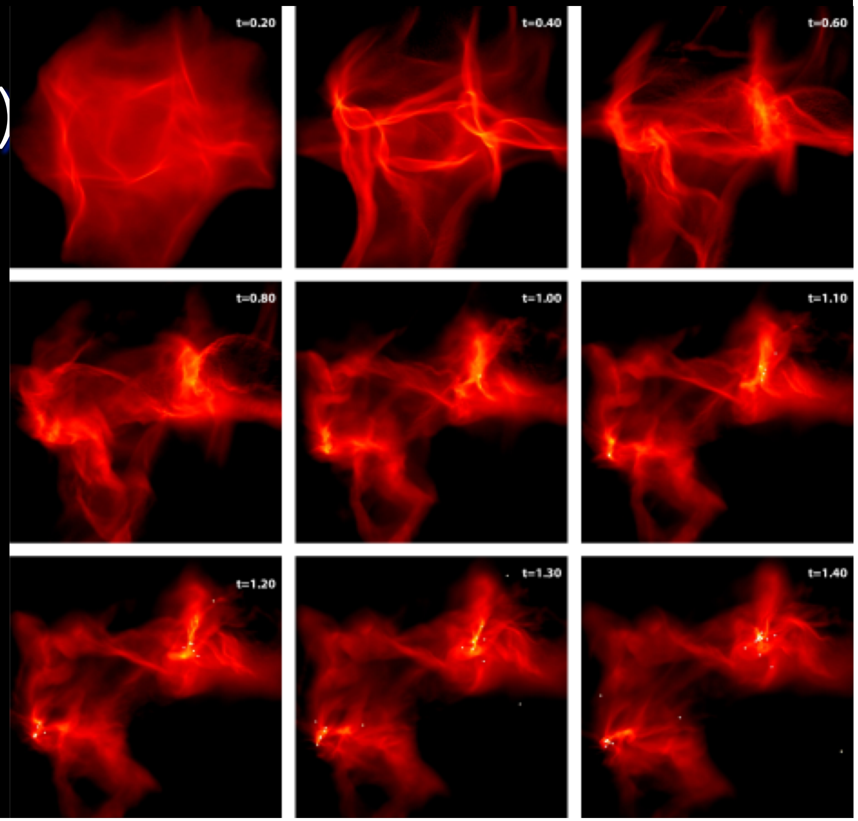
(Credit: A. Cooper, Keck Observatory)

Multiplicity is a Test of Star Formation Processes

- Frequency (Implications for the Initial Mass Function, Ubiquity of Sun-like (Single) Star Formation, Planet Formation)
- Separations (Sizes of Protostellar Cores, Dynamical Evolutionary History)
- Mass Ratios (Accretion History)
- Mass Dependence (Formation Processes for Stars with Mass <<M_{Jeans})



Bate et al. (2009)

Field Population: Frequency

The binary frequency declines with mass; the majority of solar-type stars appear to be in binary stars, while binary brown dwarfs are a distinct minority.

Caveats:

- Coarse mass sampling
- Mass-age degeneracy for L/T dwarfs
- Field is a composite population drawn from widely varying formation environments

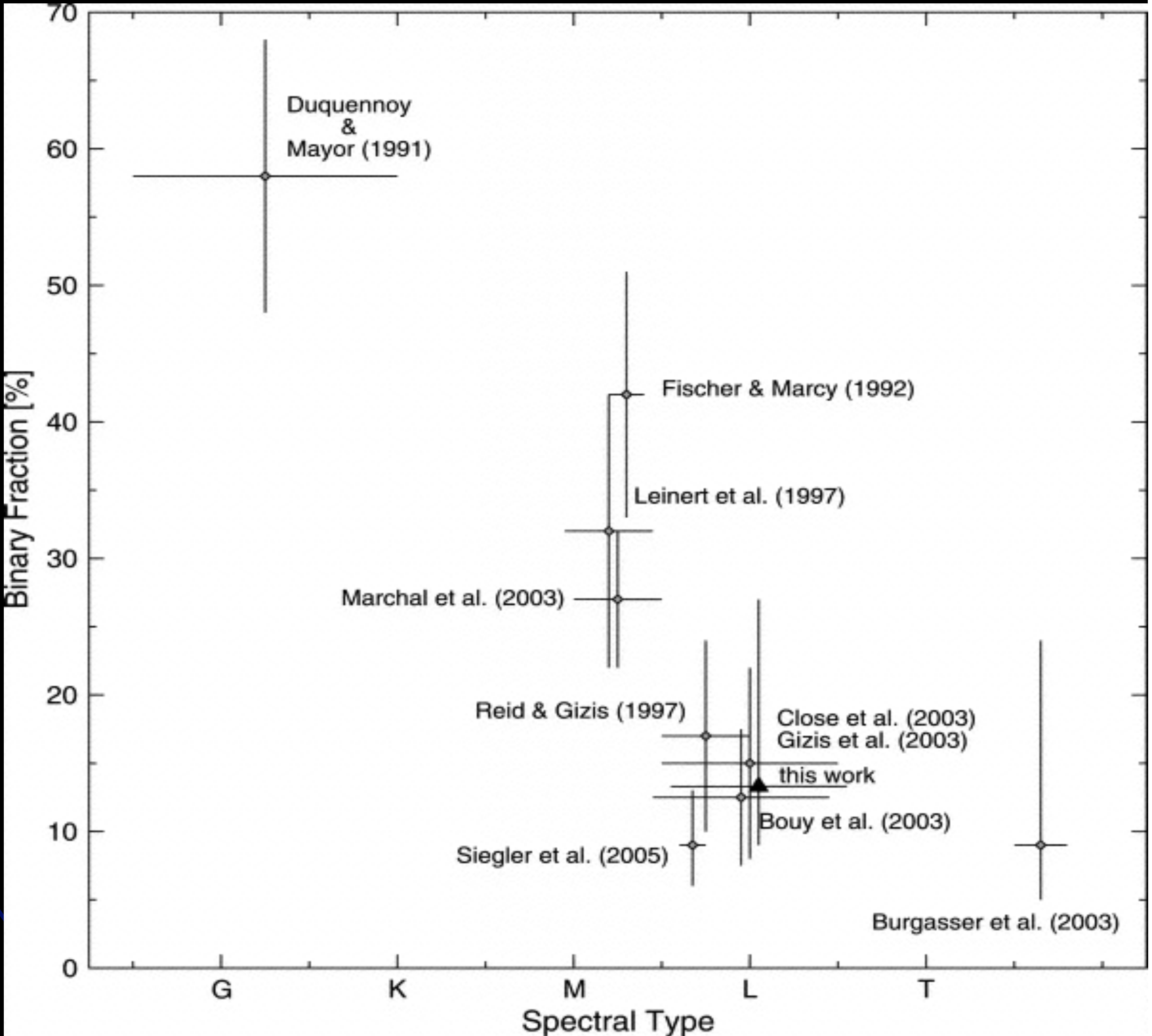


Figure from Bouy et al. (2006)

Field Population: Semimajor Axes

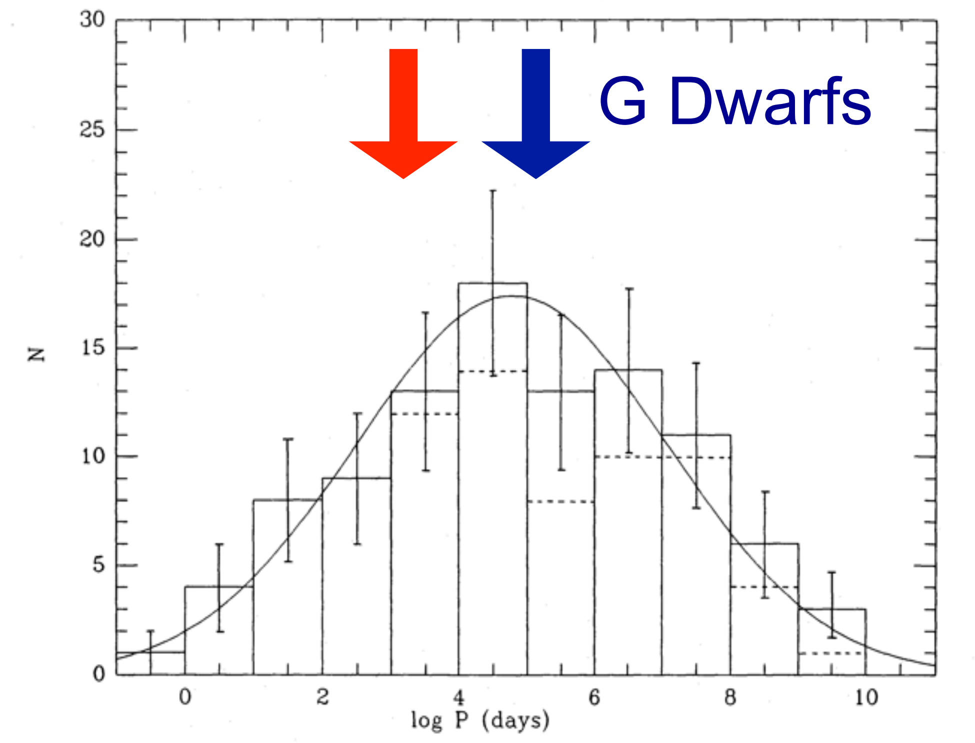
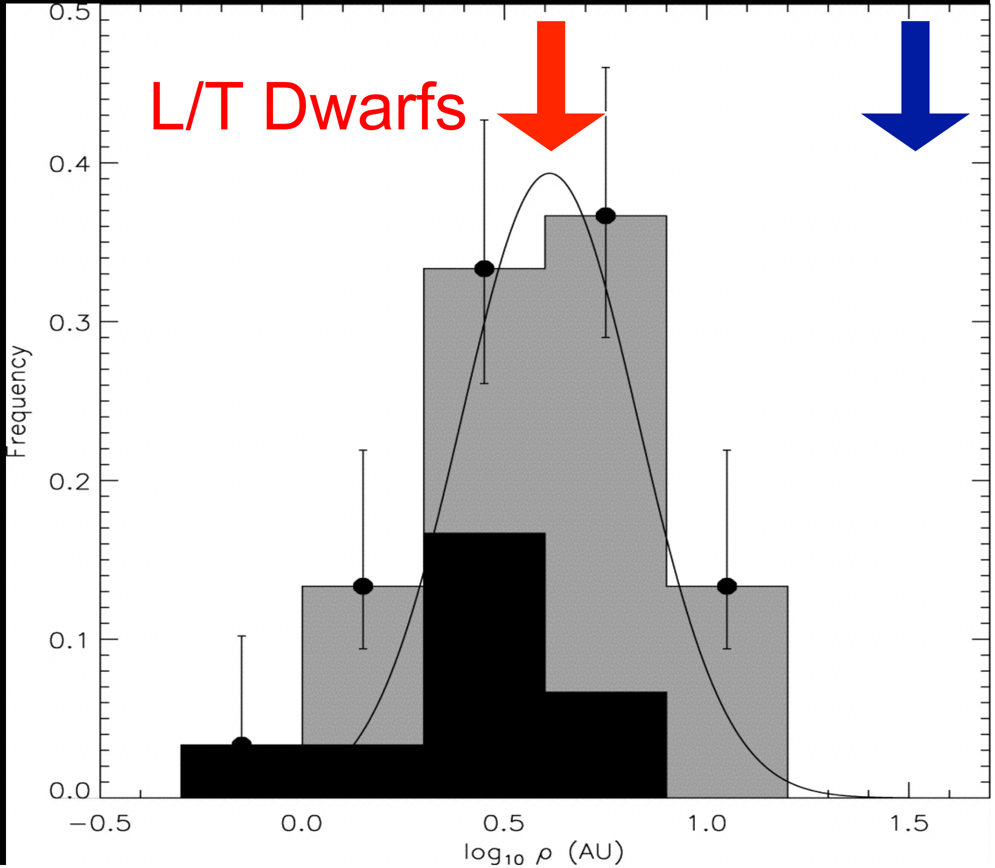


Figure from Duquennoy & Mayor (1991).

In both cases, the binary separation distribution appears to be unimodal and log-normal.

Figure from Burgasser et al. (2006)



However, the mean separation for G dwarfs is 30 AU (blue arrow), while for L/T dwarfs the mean separation is 4 AU (red arrow). There are no L/T dwarf binaries wider than ~10-20 AU.

Field Population: Mass Ratios

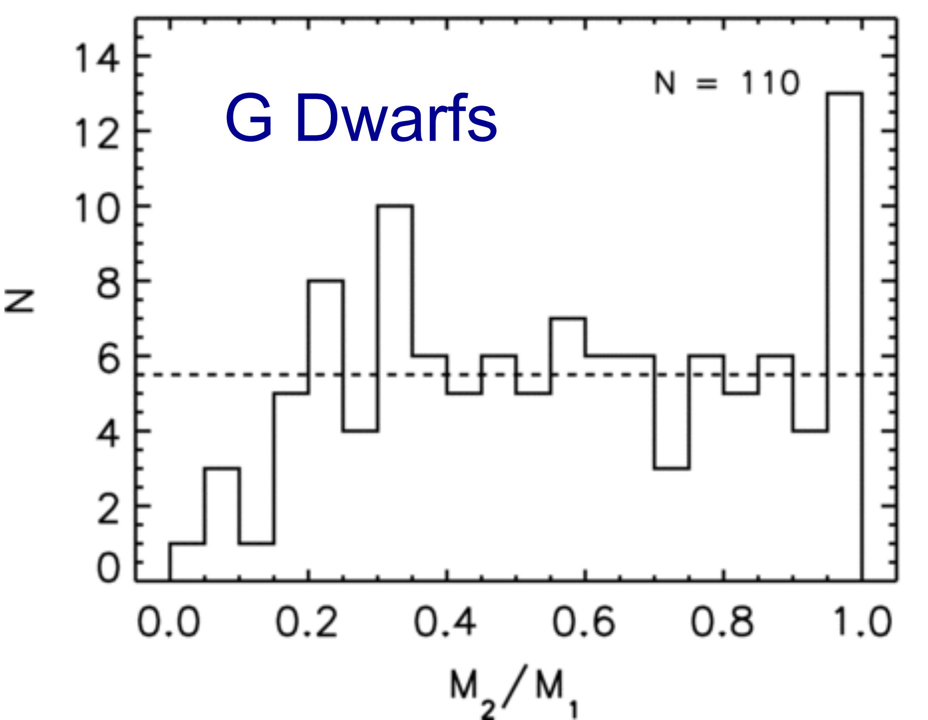
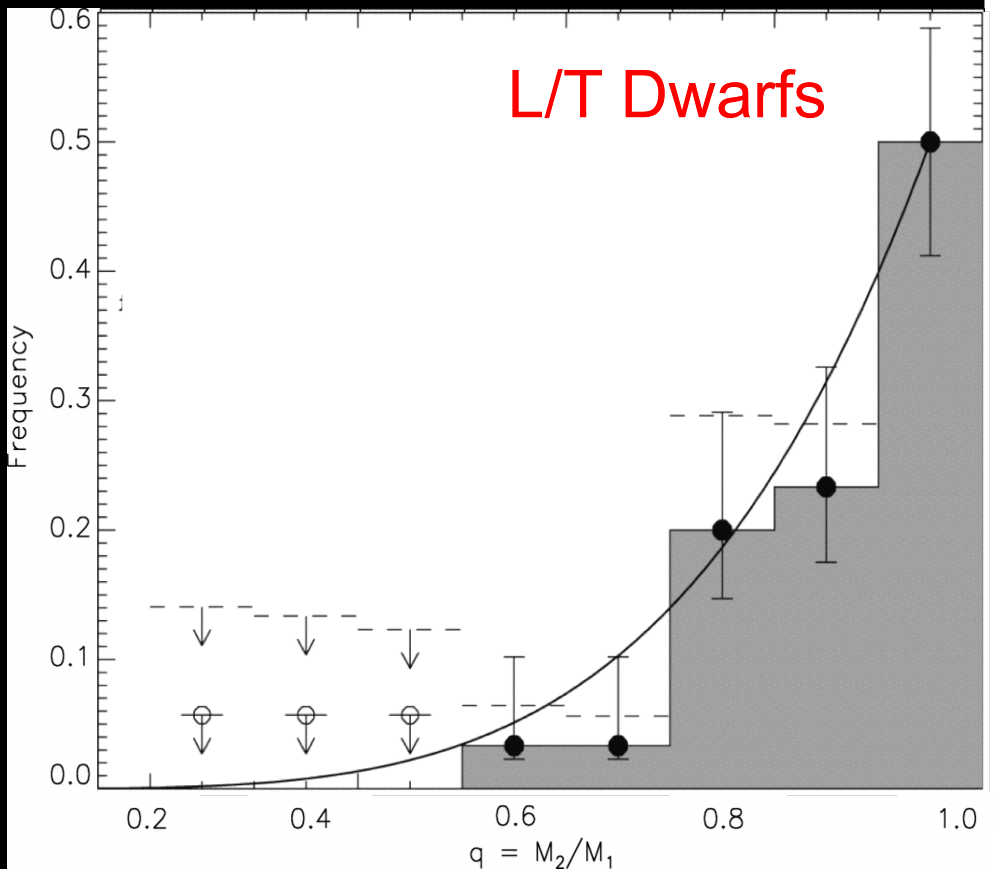


Figure from Raghavan et al. (2010).

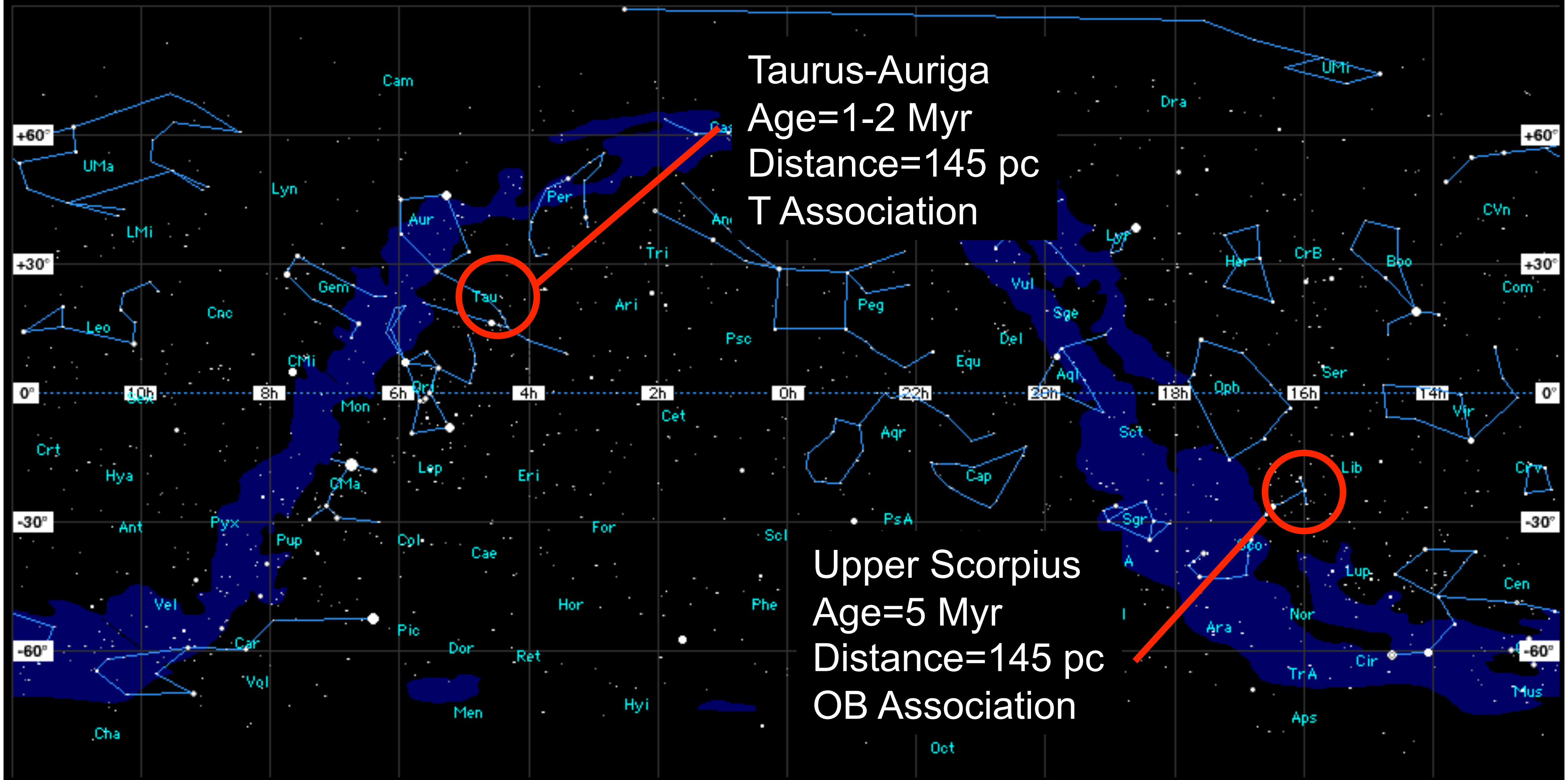
The mass ratio distributions are power laws with very different exponents.

Figure from Burgasser et al. (2006)



G dwarf distribution is linear-flat (slope = 0), while L/T dwarf distribution has a clear maximum at q~1 (slope = -4).

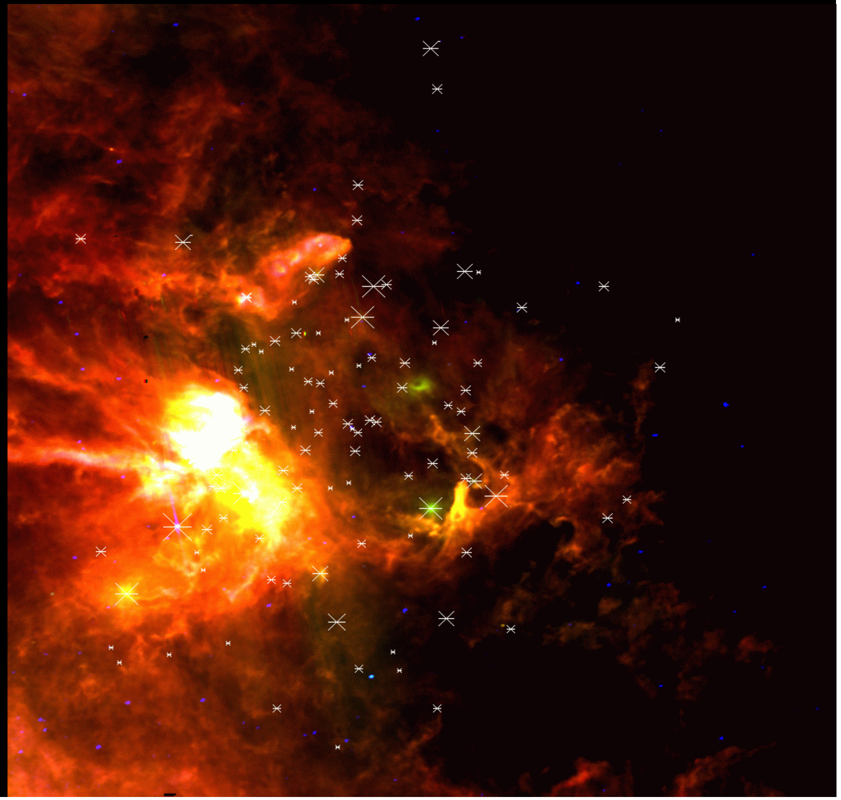
Multiplicity in Star-Forming Regions



These regions are the closest we'll ever get to dynamically primordial tests of fragmentation physics. ***When a protostellar core collapses, do you get one star or two, and what are their properties?***

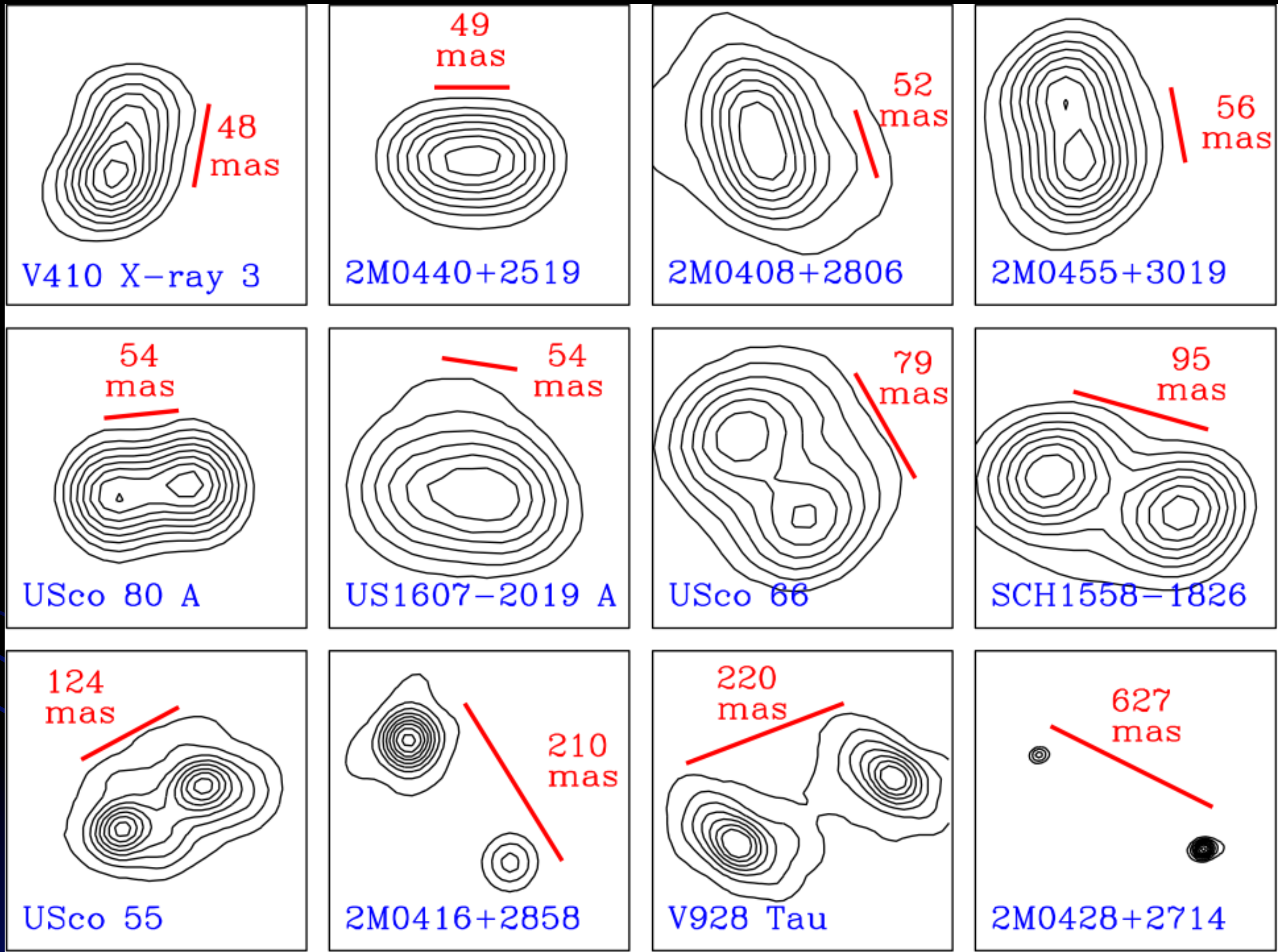
Multiple Star Formation at the Bottom of the IMF

- High-resolution imaging survey with Keck and Laser Guide Star Adaptive Optics
- Observed 80 low-mass (<0.12 M_{sun}) members of Taurus and Upper Sco
- Goals:
  - How does the outcome of multiple star formation depend on the system mass?
  - Does the binary frequency decline through the substellar regime?

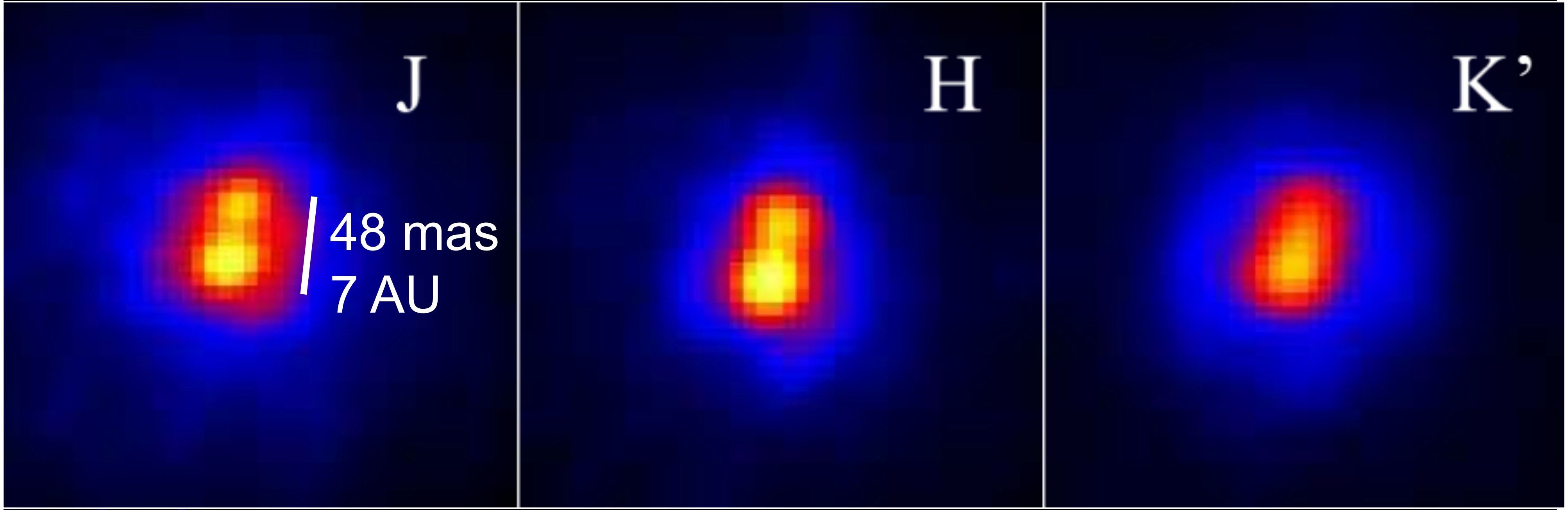


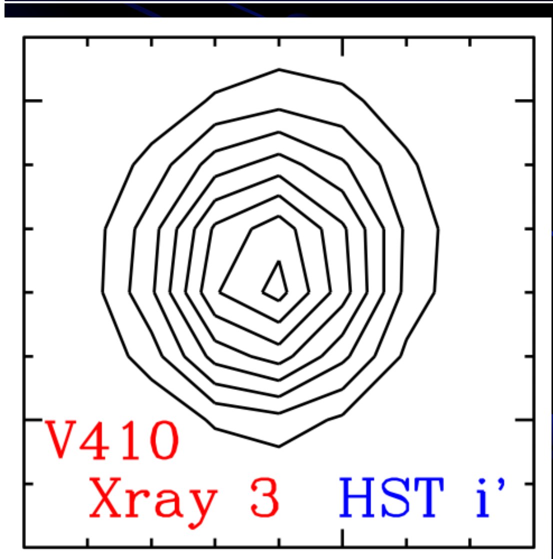
Upper Scorpius OB Association (T. Preibisch)

Binary Systems



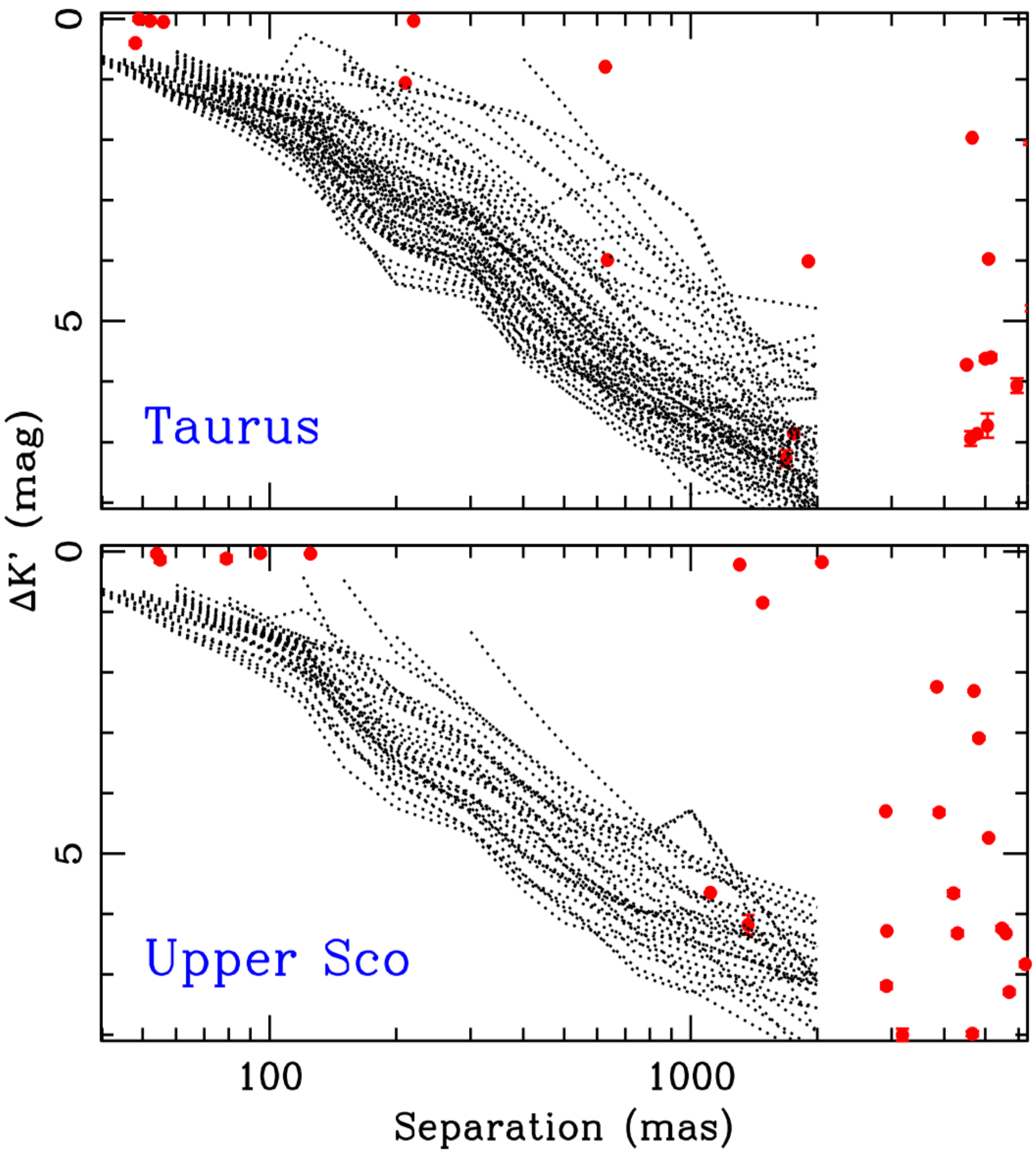
HST vs Keck: V410 X-ray 3





V410 X-ray3 (0.08+0.06 Msun) was very marginally resolved in HST discovery images, but is clearly elongated in K and clearly resolved in H and J at Keck.

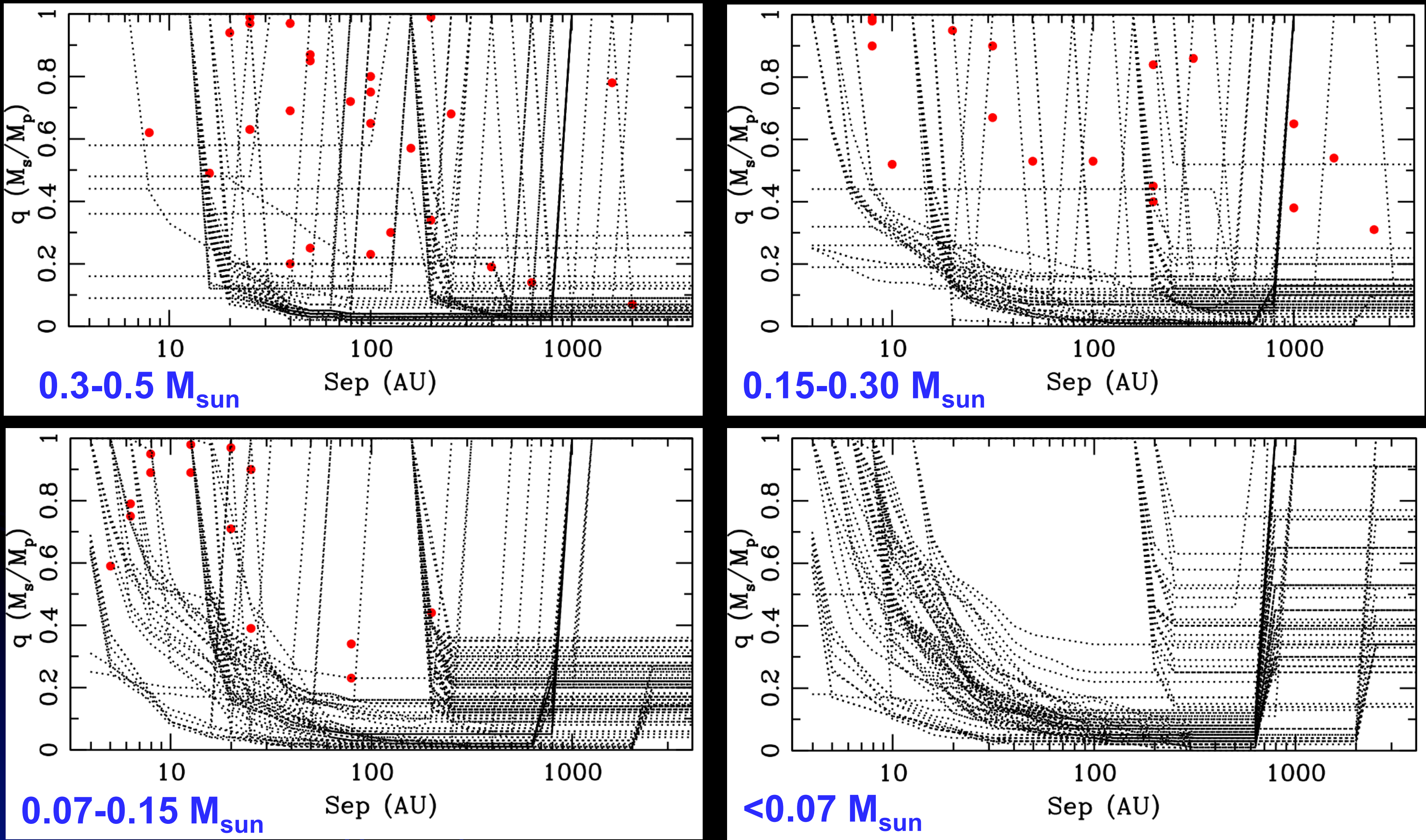
Candidate Companions



- Quite a few binary companions at small separations, a few at wider separations
- No binary companions to targets with M<70 M_{Jup}
- Many faint/distant sources which are most likely background stars
- A few close/faint sources (None are comoving - I didn't find any 2M1207b analogs.)

Red: Candidate Companions
Dashed Lines: Detection Limits

Expanded Sample: 513 VLMS/BDs



Everything I could find in Taurus, USco, Cha-I. (Kohler, Biller, Konopacky, Ahmic, Lafreniere, numerous others, and several of my own previous surveys.)

Bayesian Analysis

Histograms are not ideal. Since data is rarely uniform, you end up either using dubious completeness corrections or degrading the most sensitive limits.

The answer is Bayes' theorem:

$$P(model \mid data) \propto P(data \mid model) P(model)$$

Bayesian Analysis

Model the binary population in terms of four parameters:

- The total binary frequency F
- A power-law mass ratio distribution with exponent γ
- A log-normal separation distribution with mean log(μ) and standard deviation $\sigma_{\log(s)}$

$$N(q,s) \propto F \times q^{\gamma} \times \exp\left(\frac{(\log(s)-\log(\mu))^2}{2\sigma^2_{\log(s)}}\right)$$

Bayesian Analysis

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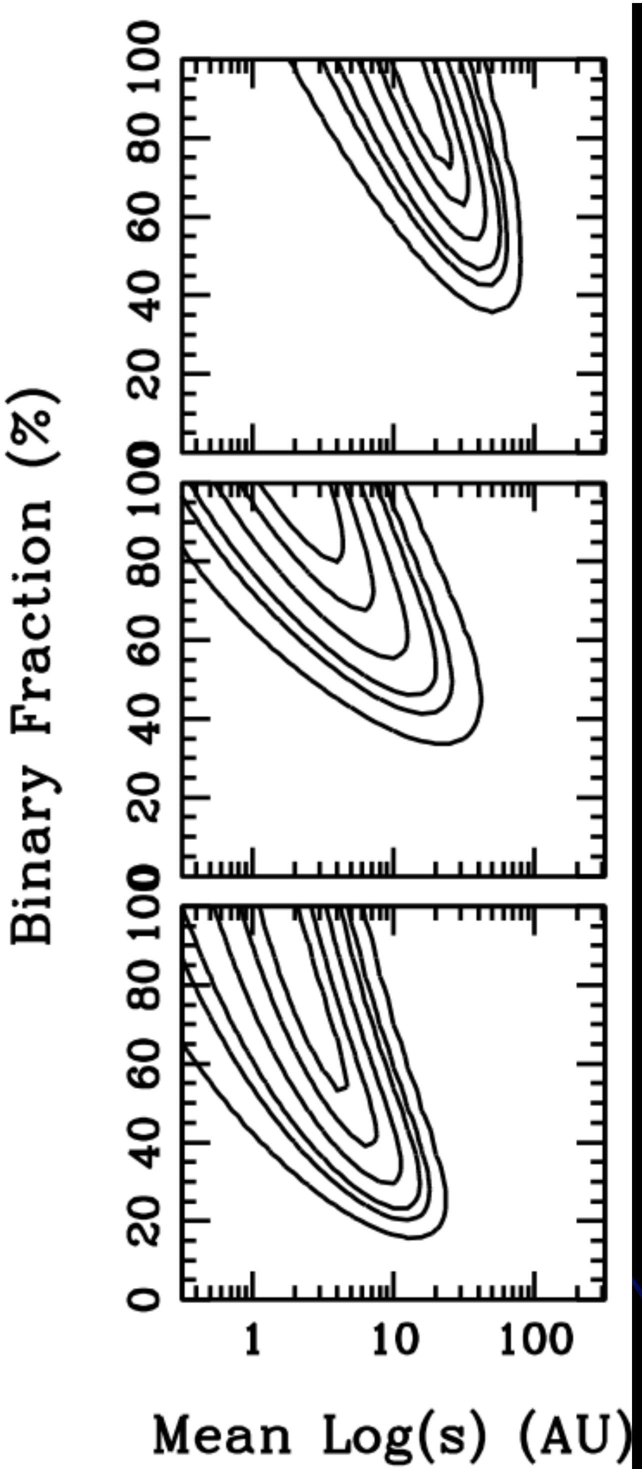
The result isn't a PDF for the population, but rather a PDF for the parameters that *describe* the population.

For more math: Allen (2007), Kraus (2009), Kraus et al. (2011).



Bayesian Results Frequency vs Mean Separation

0.3-0.5 M_{sun}

0.15-0.3 M_{sun}

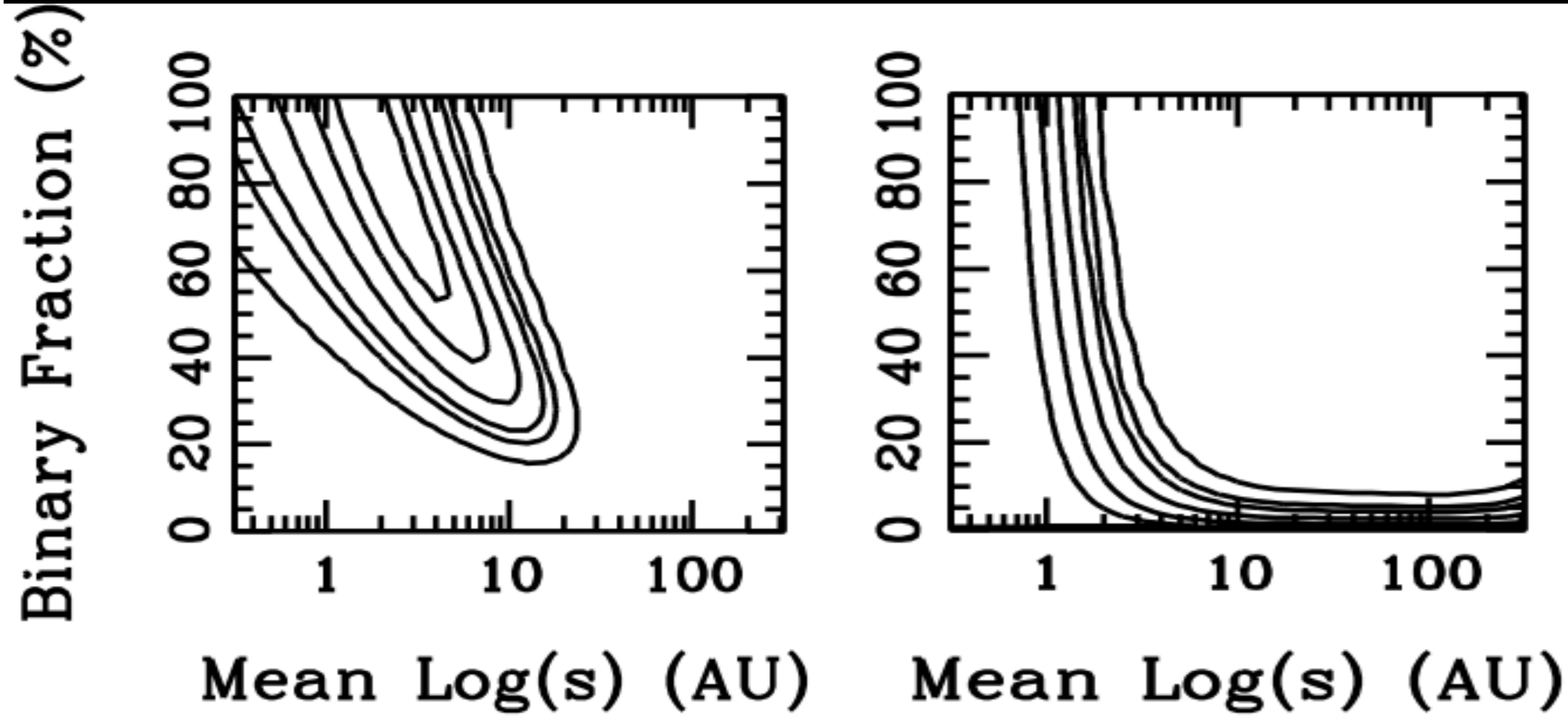
0.07-0.15 M_{sun}

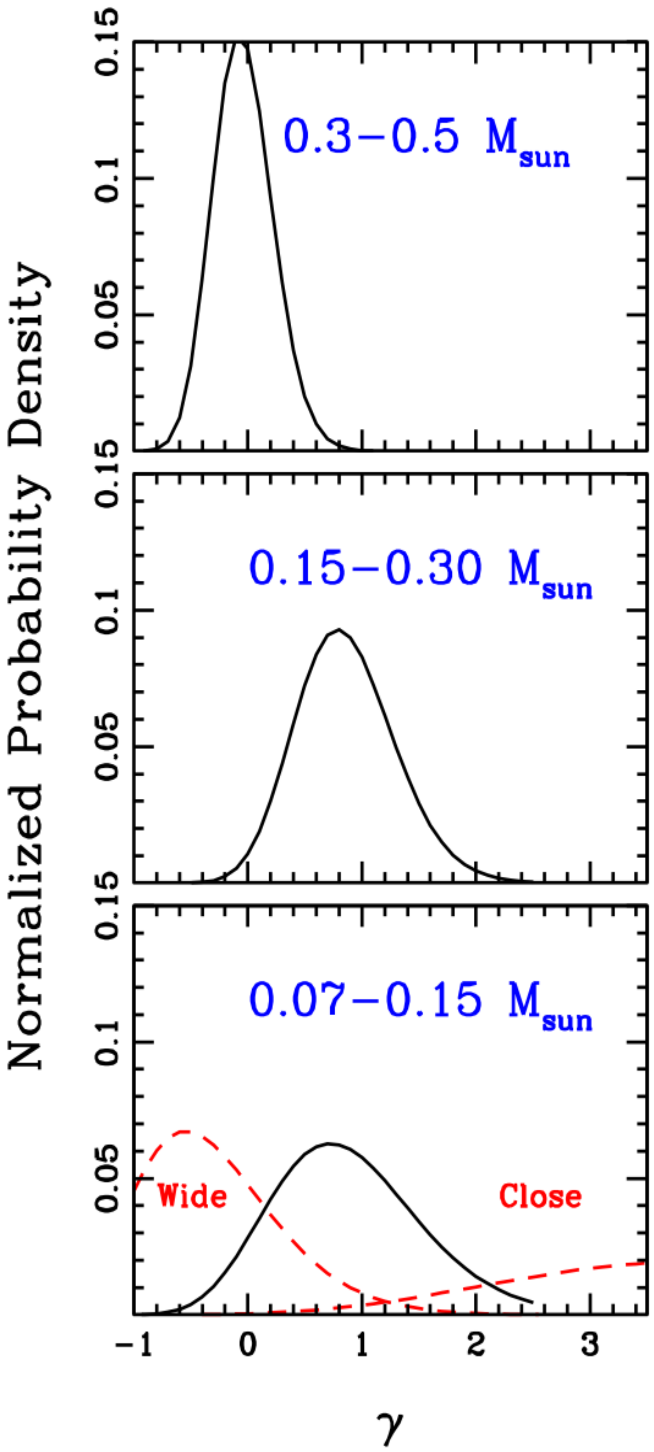
For lower-mass subsamples, the locus of possible values moves in and downward, showing a mass dependent trend toward lower mean separations and/or lower frequencies.

Note: More imaging data isn't the answer to the frequency/separation degeneracy; we need RV surveys to break it and measure unambiguous properties for the binary population.

Bayesian Results
Frequency vs Mean Separation

0.07-0.15 M_{sun} <0.07 M_{sun}





0.3-0.5 M_{sun}

0.15-0.3 M_{sun}

0.07-0.15 M_{sun}

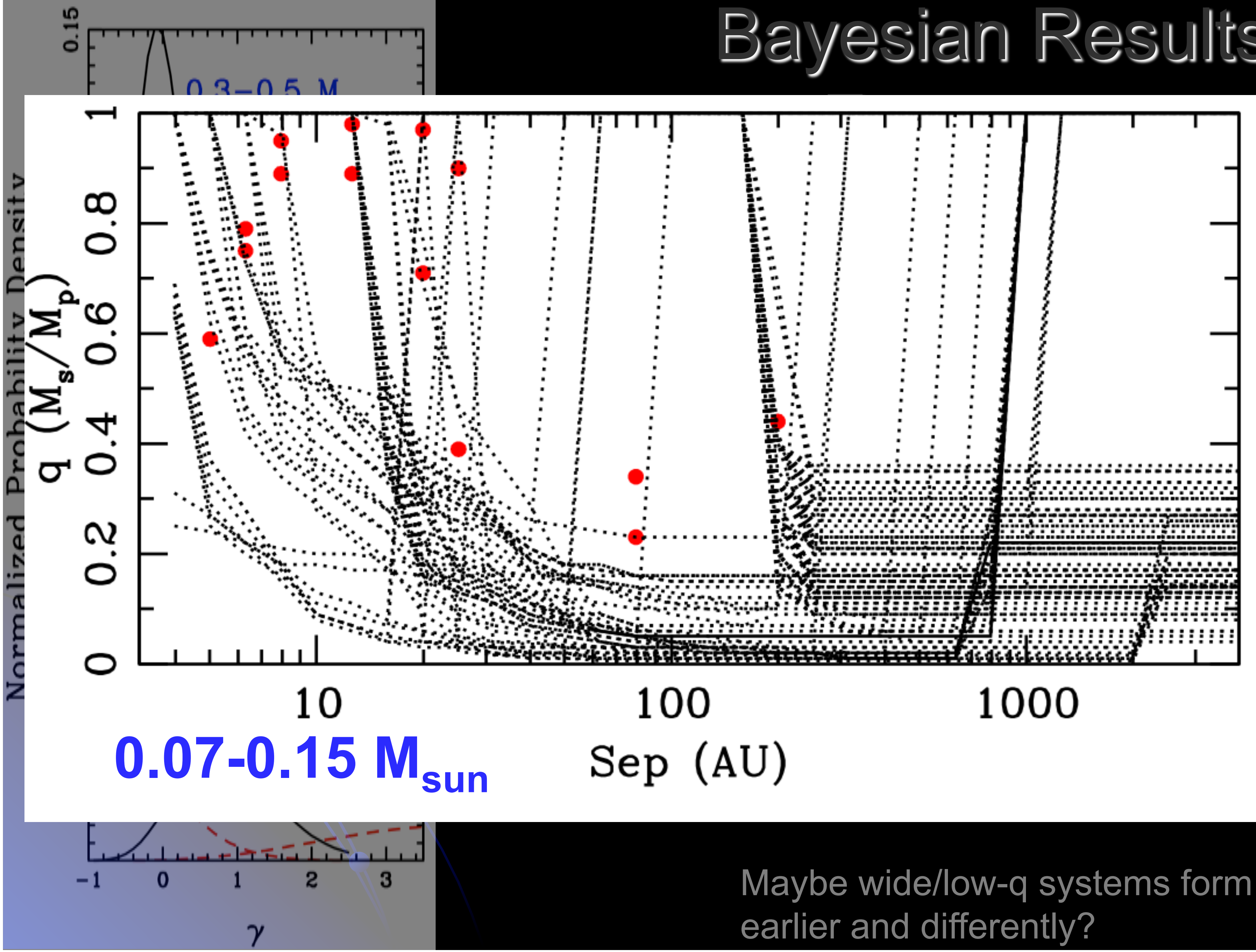
Bayesian Results Frequency vs Gamma

I expected a trend for steeper mass ratio distributions (more peaked at unity) at lower masses, but it's a little more complicated.

In the 0.07-0.15 Msun subsample, 10/11 binaries with separations <25 AU have mass ratios near unity, while 4/5 binaries with separations >25 AU have mass ratios <0.5. (You hardly see any >25 AU binaries in this mass range in the field.)

Maybe wide/low-q systems form earlier and differently?

Bayesian Results



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Maybe wide/low-q systems form earlier and differently?

Implications for Star Formation

- Field mass dependence of features is primordial, not dynamical. Lower mass => lower frequencies, smaller separations. ***VLM cores are smaller when they undergo fragmentation?***
- All companion masses are equally probable down to M_{prim}~0.3 M_{sun}, but then equal masses become increasingly probable. ***Fragmentation occurs later, while less mass is still in the envelope?***
- Properties are continuous with mass. ***Stars/BDs form in a similar manner; no special formation process?***

Next: Run simulated binary populations through the same statistical machinery. Will the confidence intervals overlap with observations?

Coming soon…