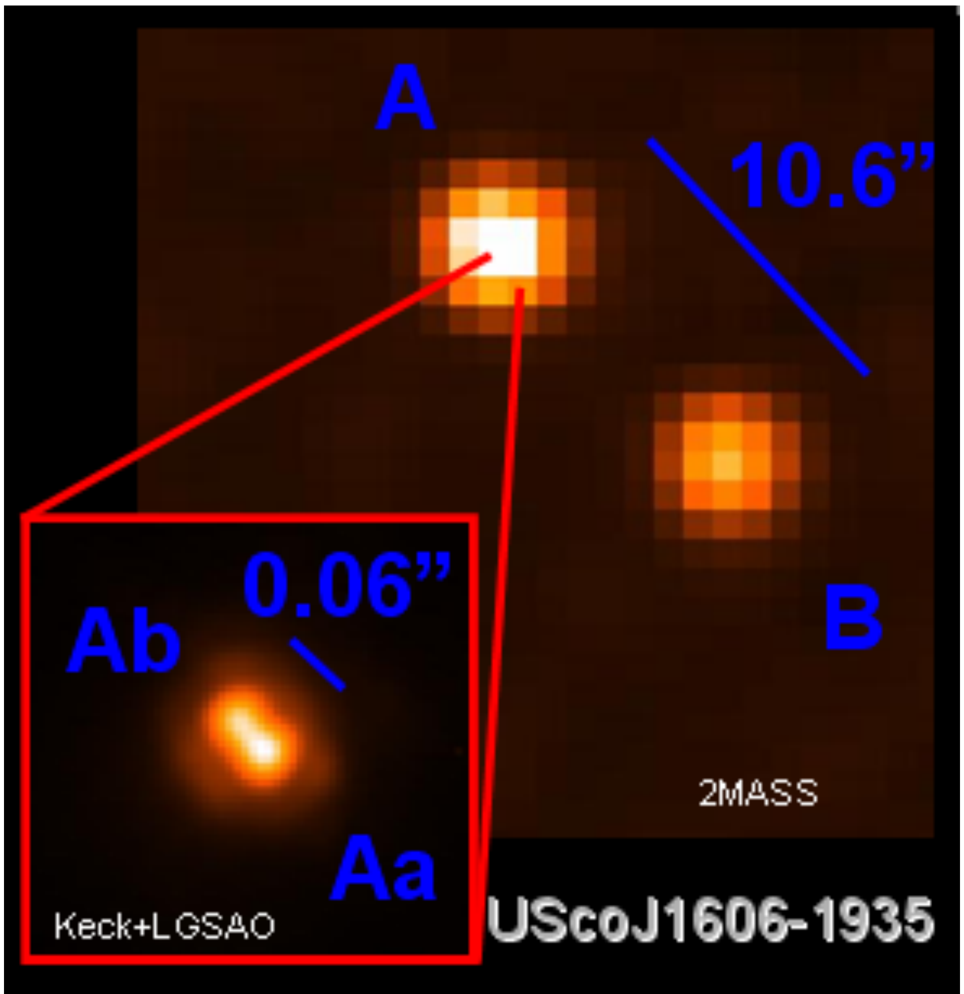
Binarity of Young Stars: Final Conditions for Star Formation, Initial Conditions for Cluster Evolution



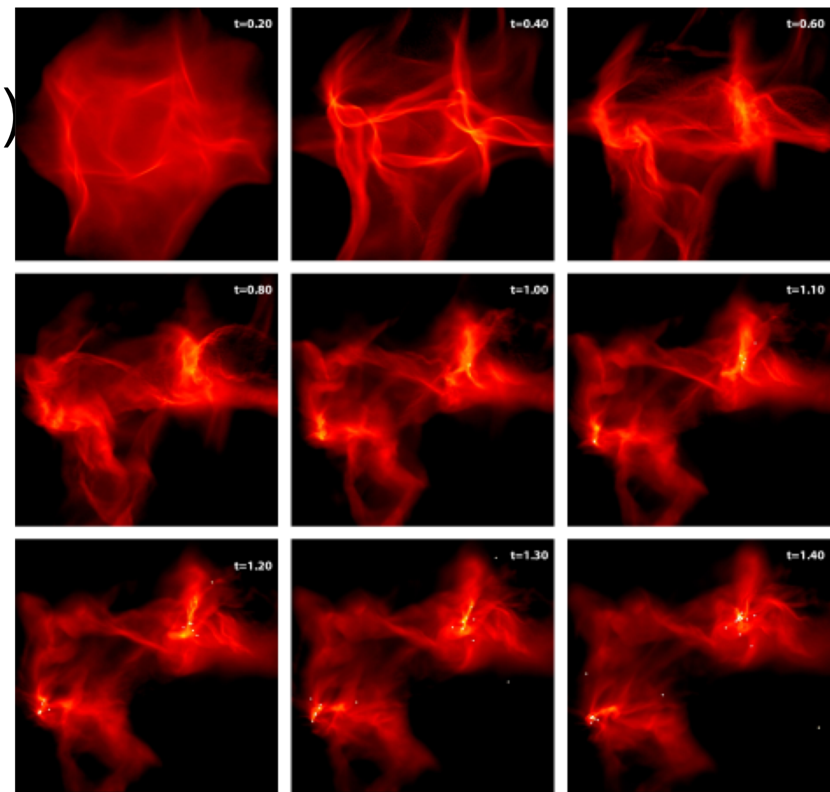
Adam L. Kraus

The University of Texas at Austin

(Including collaborative results with Gaspard Duchene, Michael Ireland, Lynne Hillenbrand)

Multiplicity is a Final Boundary Condition for Star Formation

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



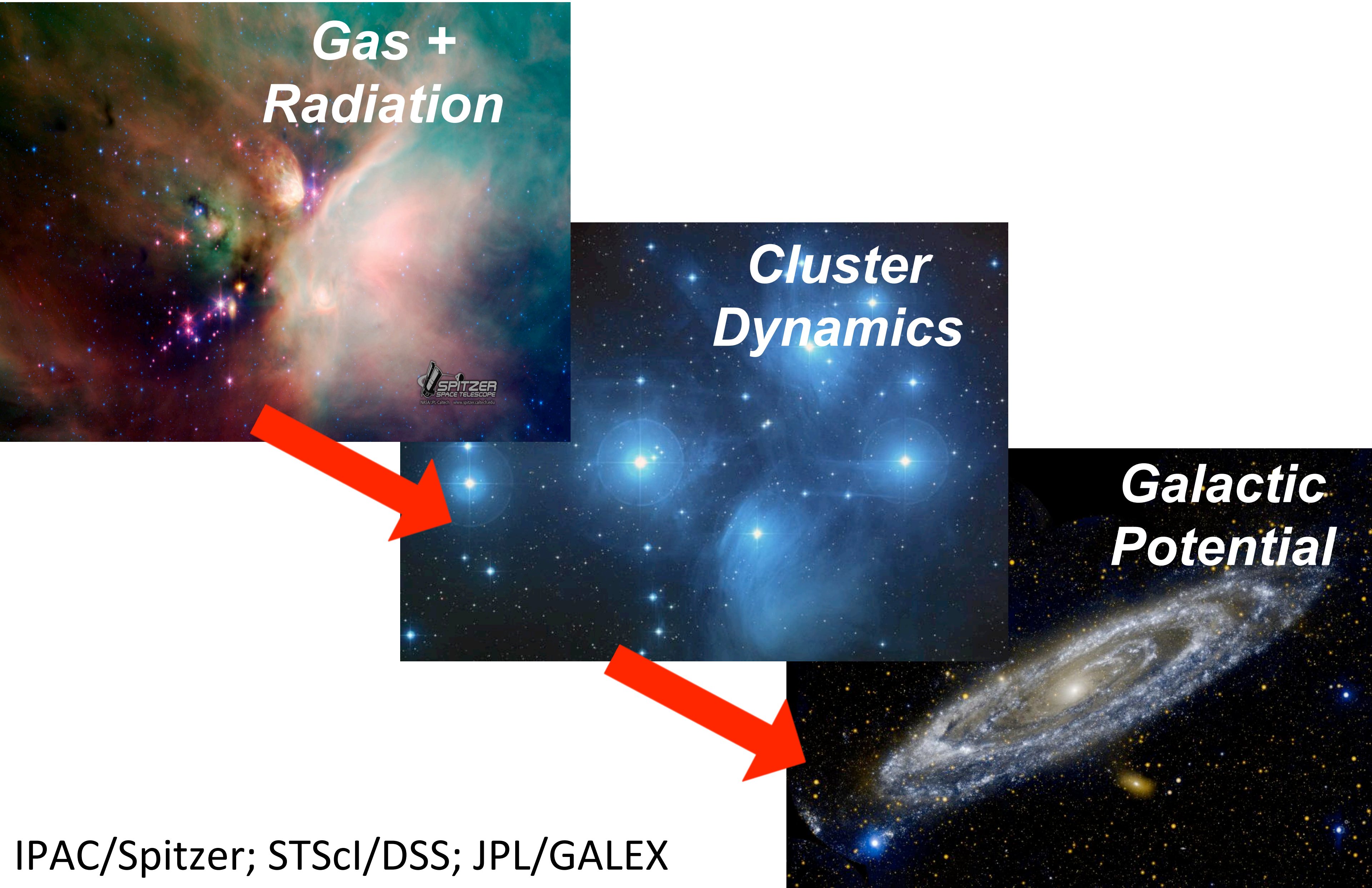
Bate et al. (2009)

Multiplicity is an Initial + Final Boundary Condition for Cluster Evolution

- Frequency (Dynamical Disruption of Binary Systems)
- Separations (Impact Parameters of Dynamical Interactions, Binary Hardening, Kozai-Type Orbital Evolution)
- Mass Ratios (Binary Disruption, Post-Main Sequence Mass Transfer)
- Mass Dependence (Mass Segregation and Tidal Evaporation of Singletons vs Binaries)

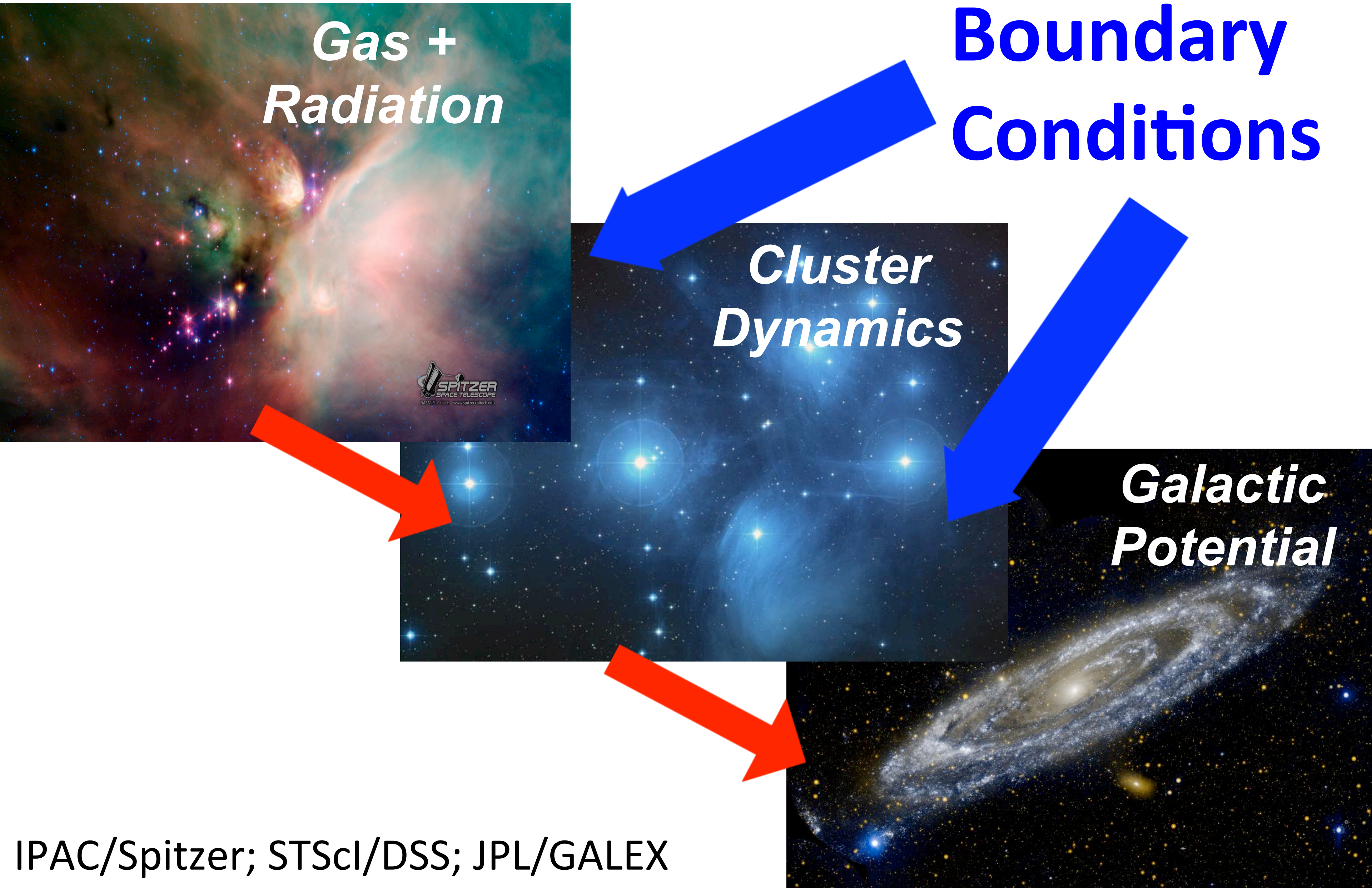
STScI/DSS

Chronology of Binary Evolution



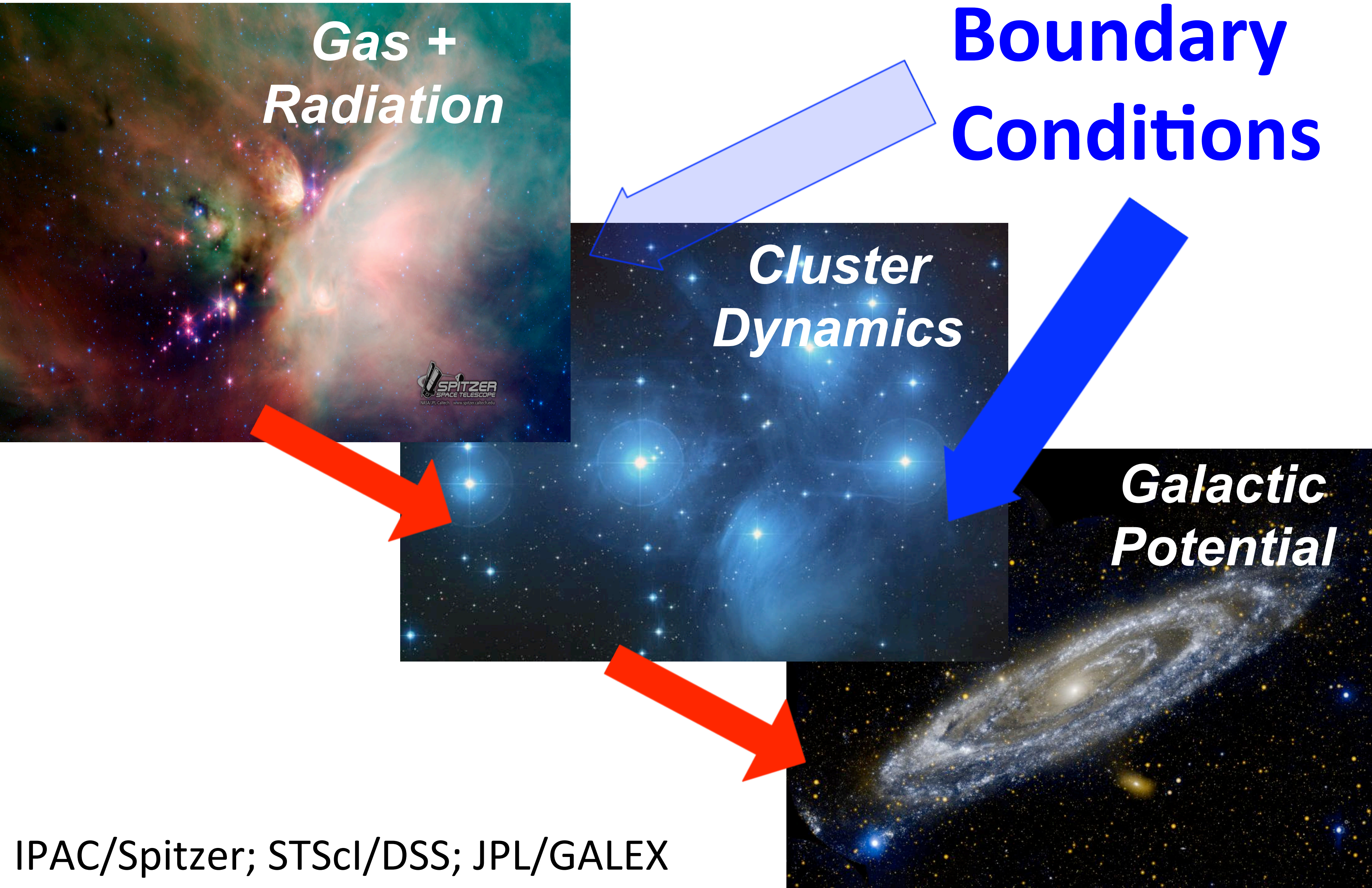
IPAC/Spitzer; STScI/DSS; JPL/GALEX

Chronology of Binary Evolution



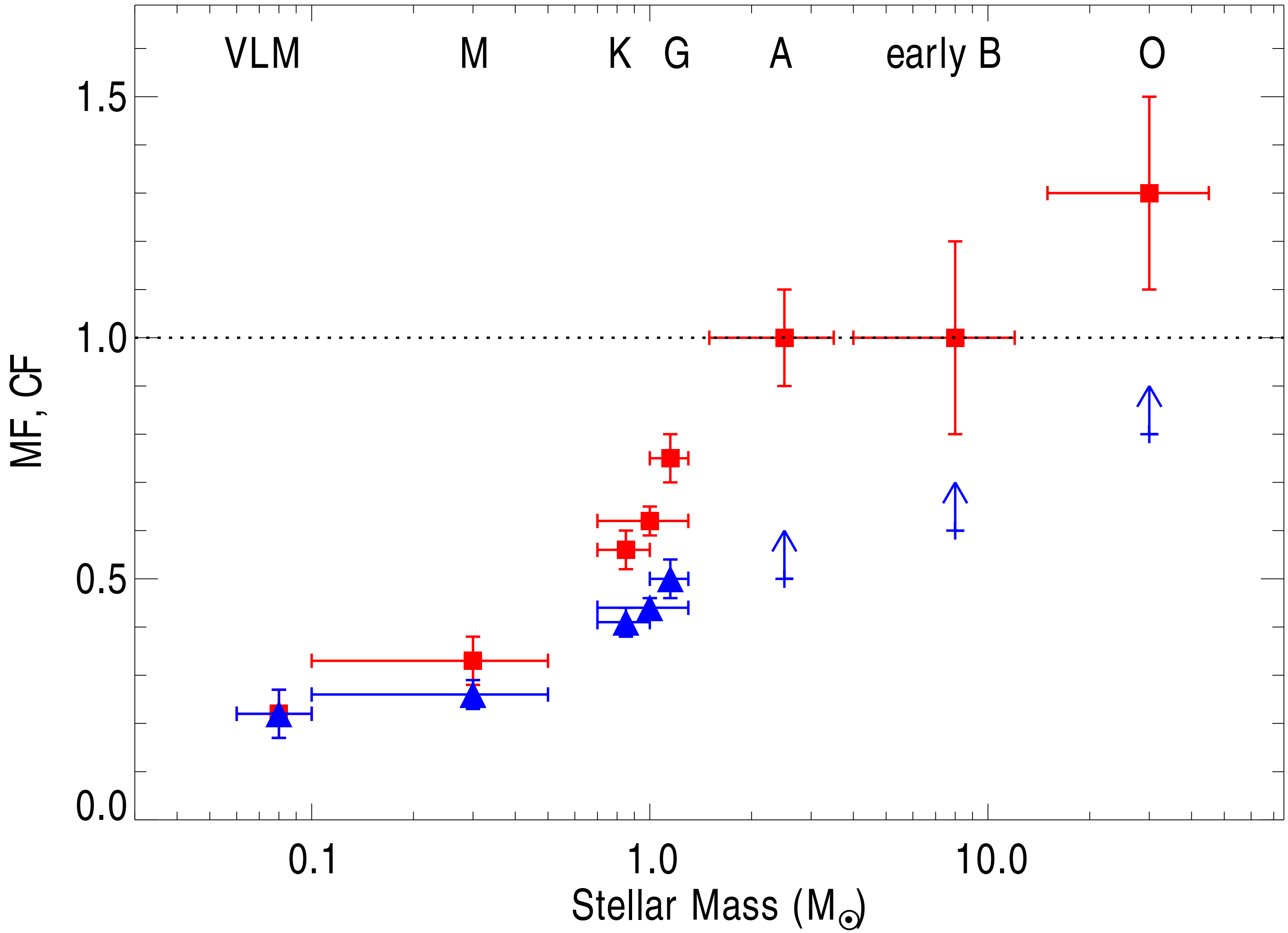
IPAC/Spitzer; STScI/DSS; JPL/GALEX

Chronology of Binary Evolution



IPAC/Spitzer; STScI/DSS; JPL/GALEX

Field Population: Frequencies



From Duchene & Kraus (2013)

Red: Companion Fraction. Blue: Multiple Fraction.

Field Population: Semimajor Axes

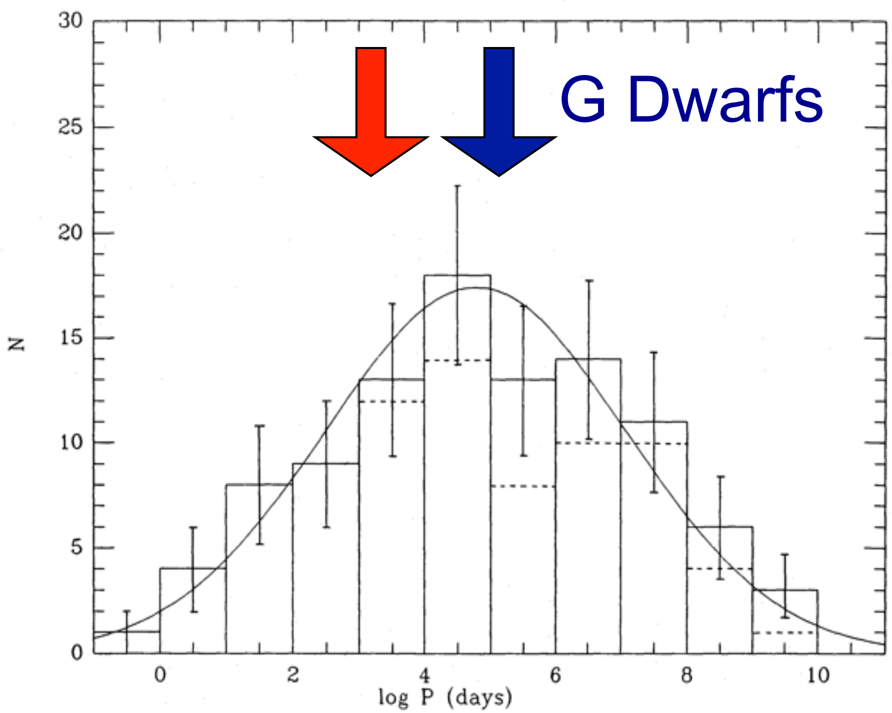
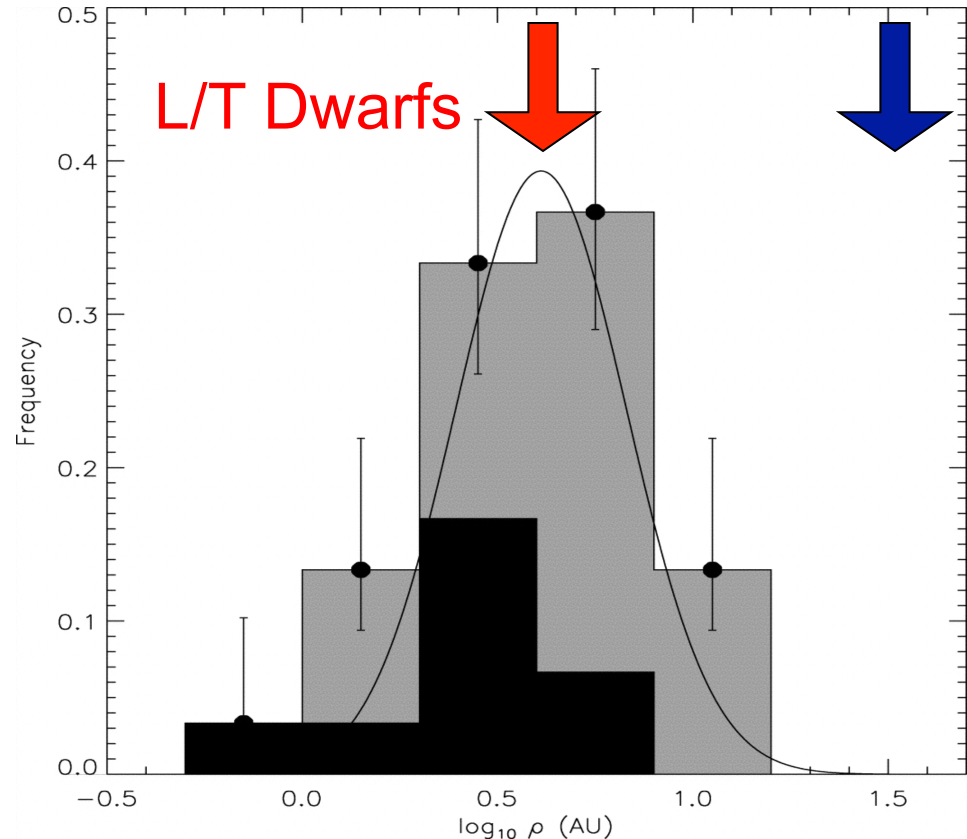


Figure from Duquennoy & Mayor (1991).

Strongly mass dependent: The mean separation for G dwarfs is 30 AU (blue arrow), while for L/T dwarfs the mean separation is 4 AU (red arrow).

The binary separation distribution appears to be unimodal and log-normal.

Figure from Burgasser et al. (2006)



Field Population: Mass Ratios

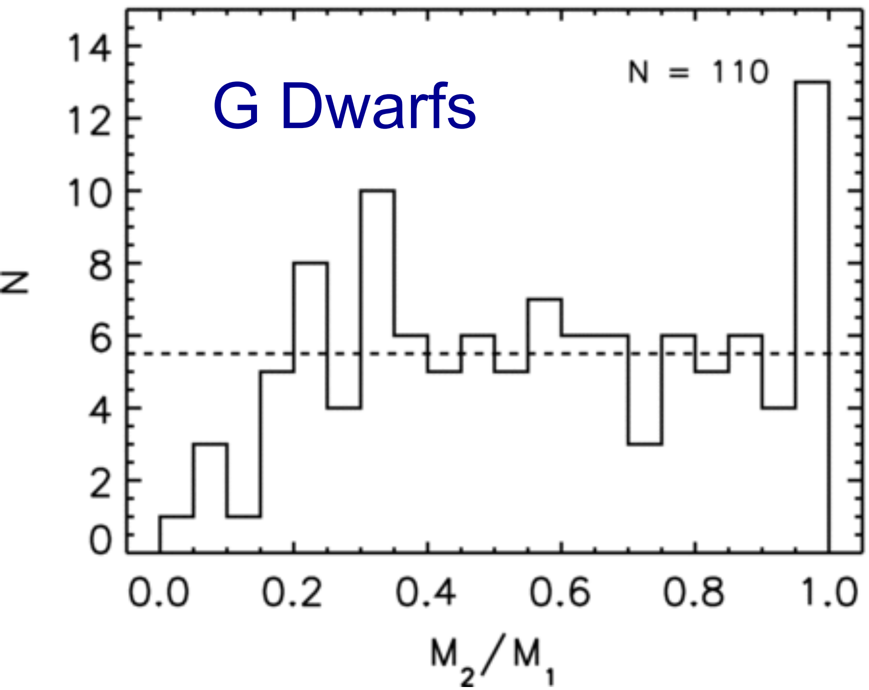
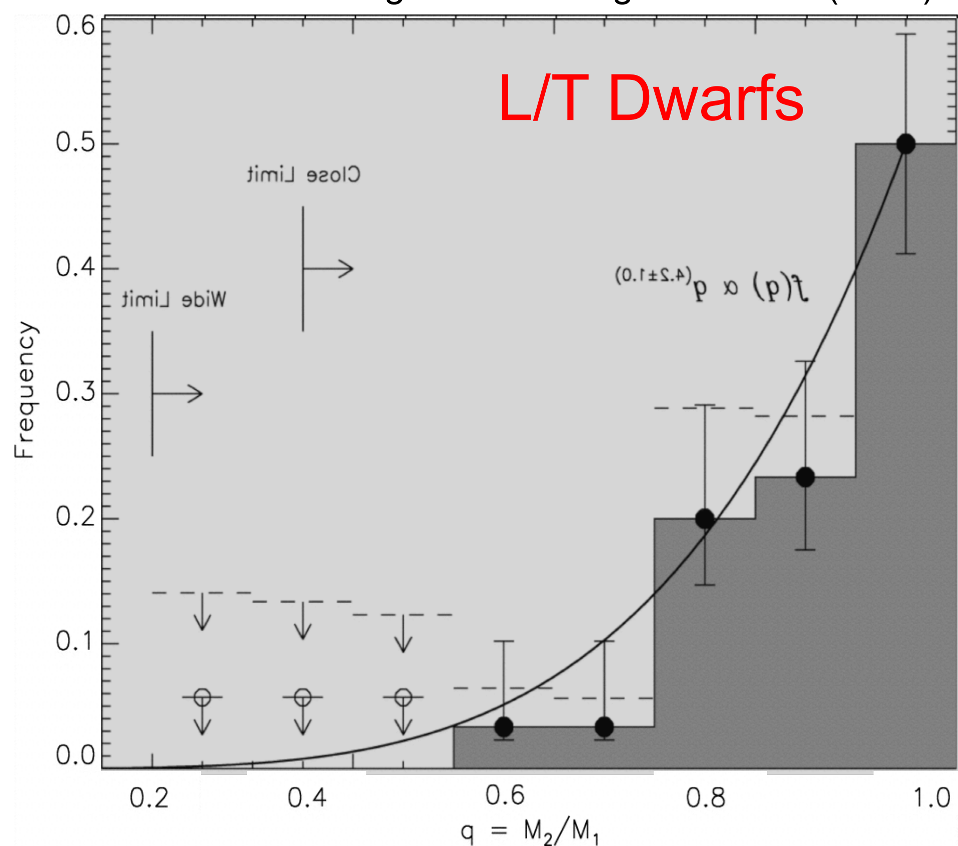


Figure from Raghavan et al. (2010).

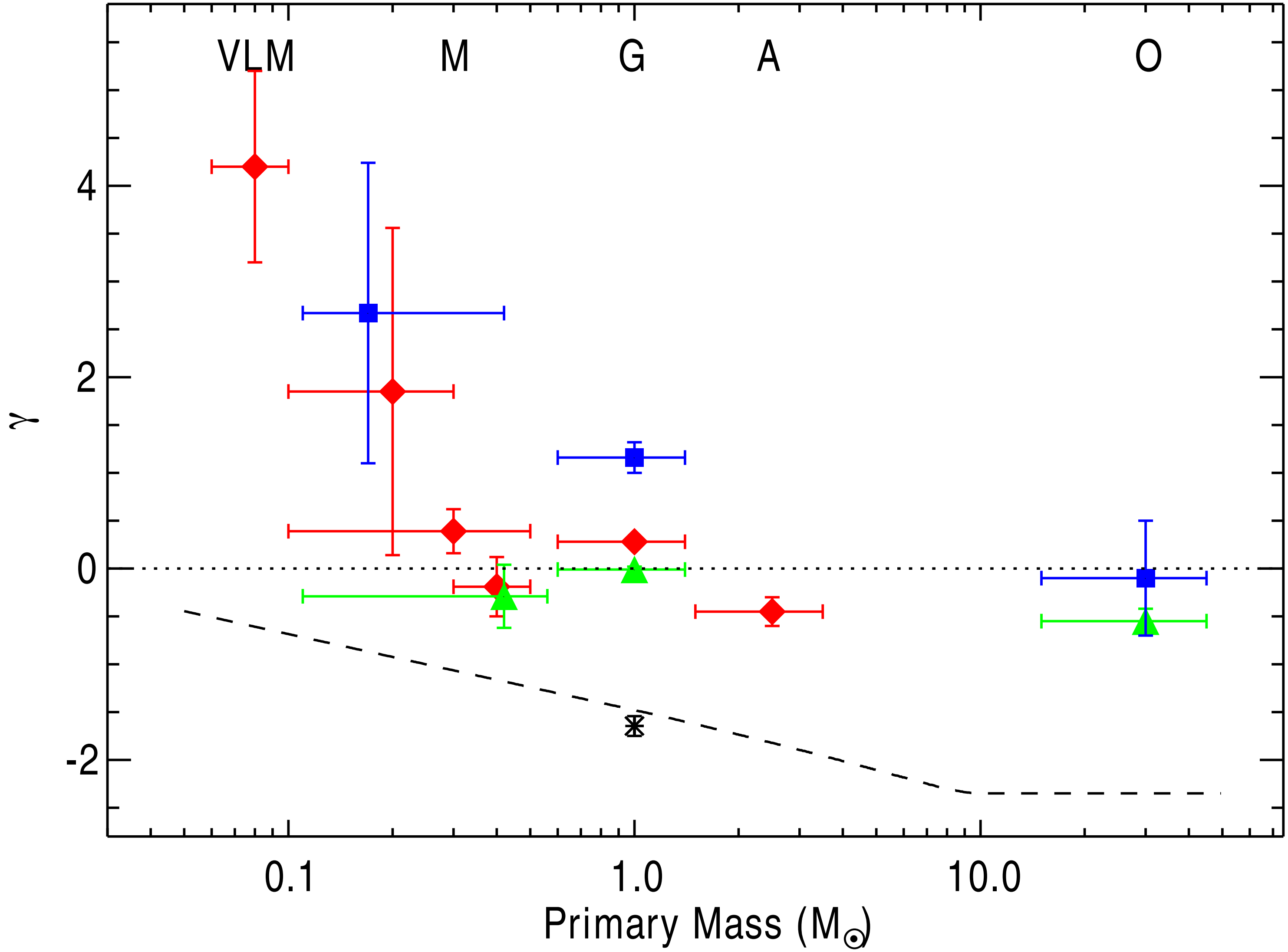
The mass ratio distributions are power laws with mass-dependent exponents.

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).

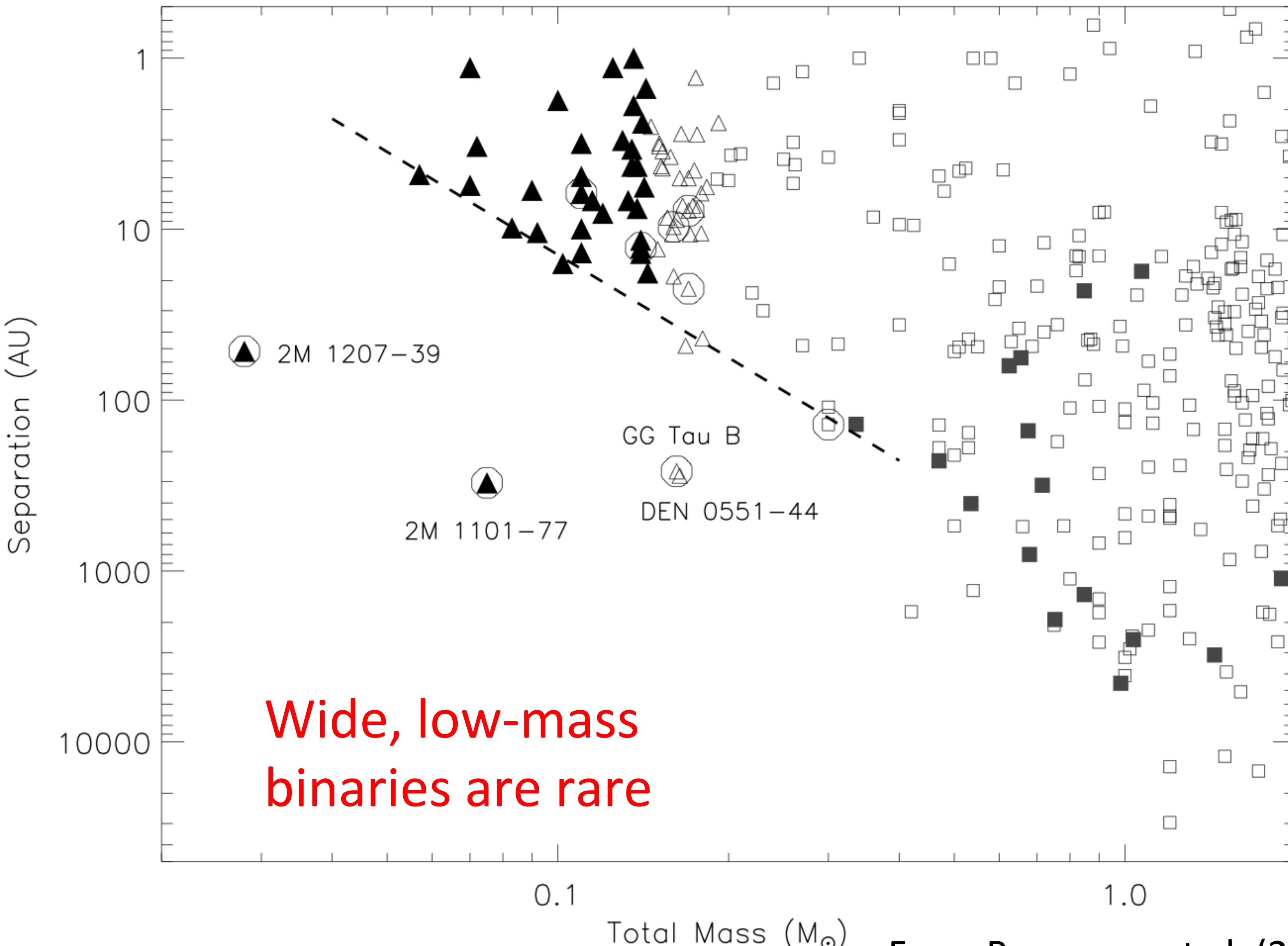
Field Population: Mass Ratios



From Duchene & Kraus (2013)

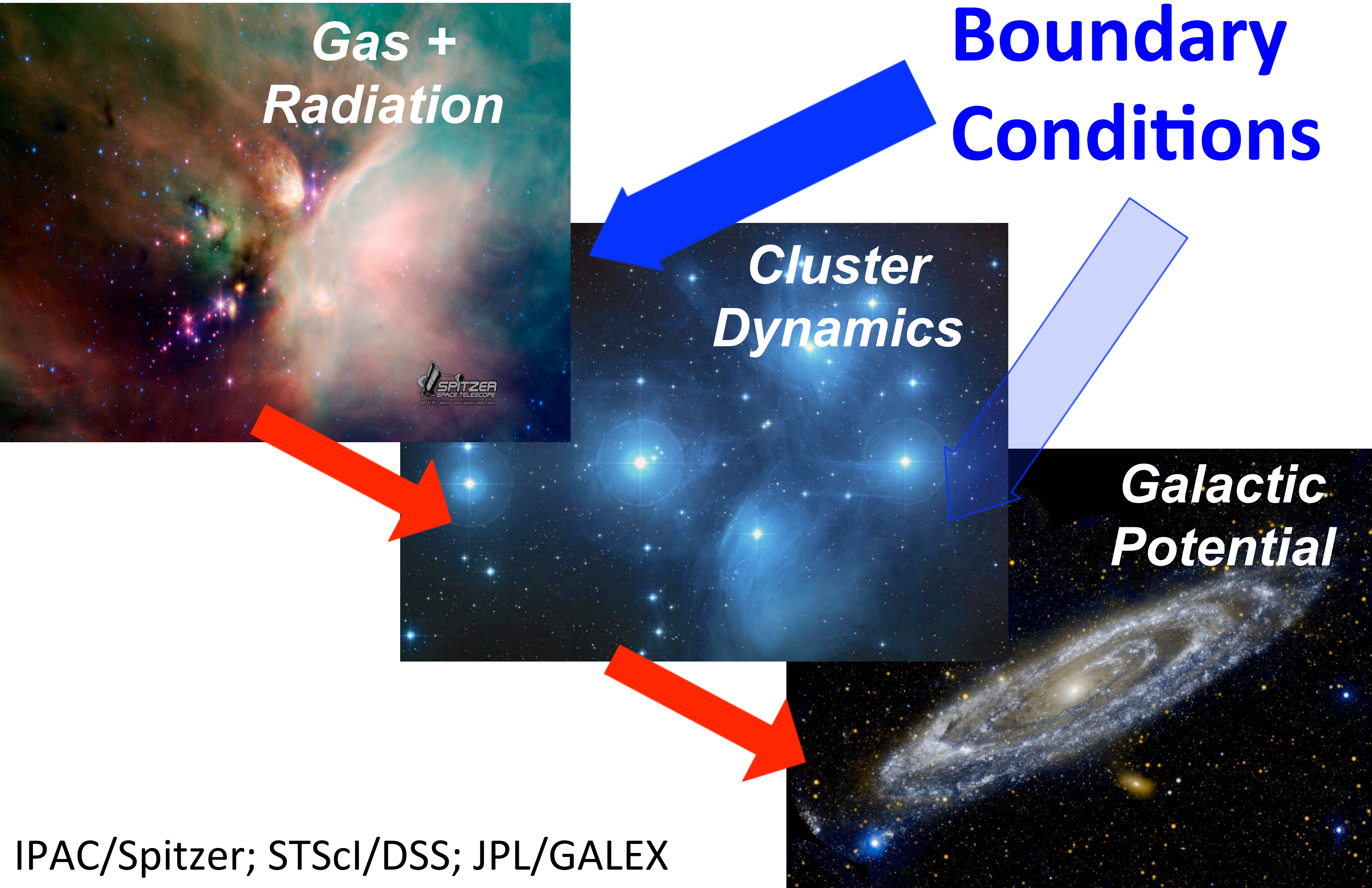
Red: All periods. Blue/Green: Close/wide subsamples.

Field Population: Wide Binaries



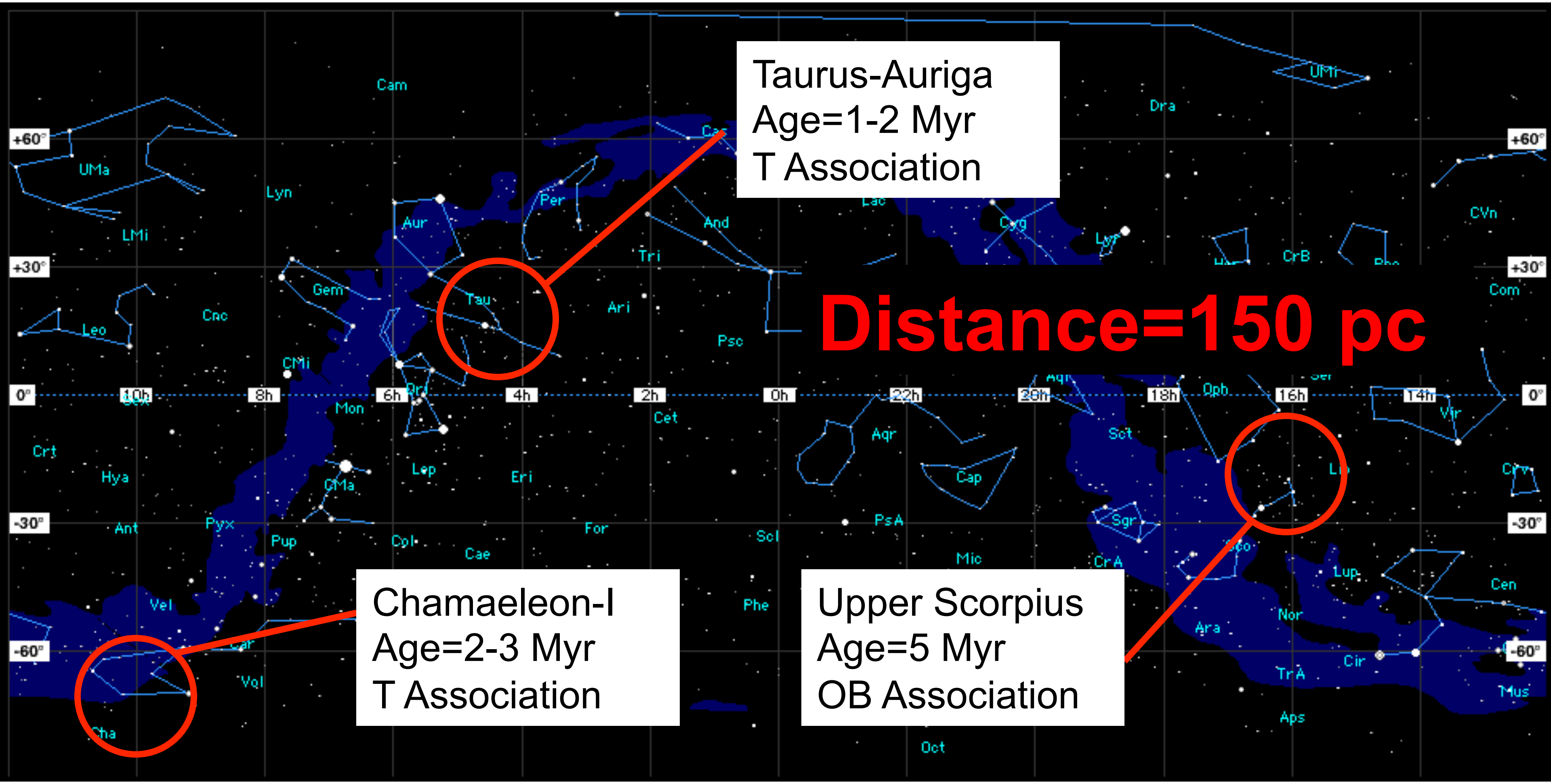
From Burgasser et al. (2007)

Chronology of Binary Evolution



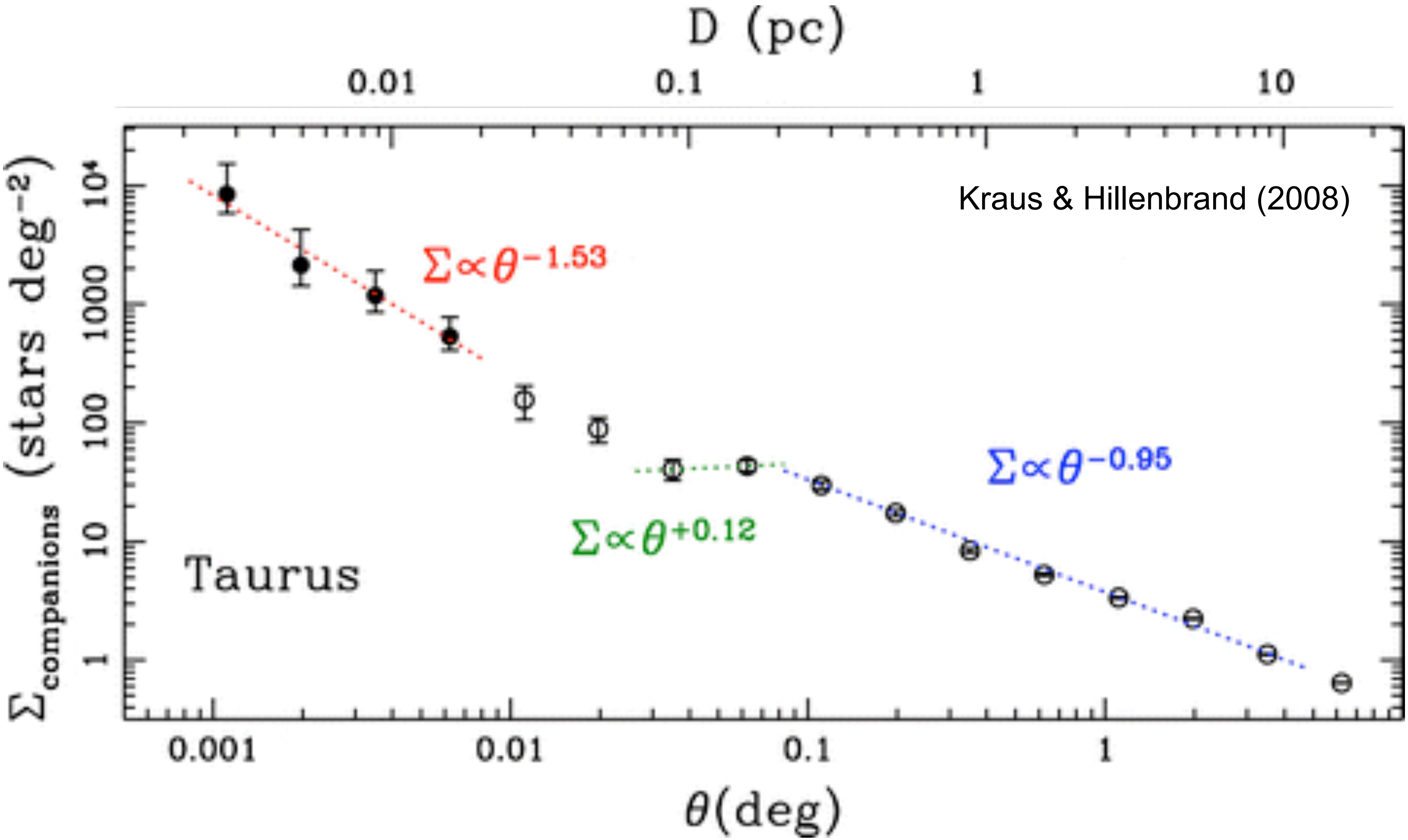
IPAC/Spitzer; STScI/DSS; JPL/GALEX

Nearby, Isolated Star Formation



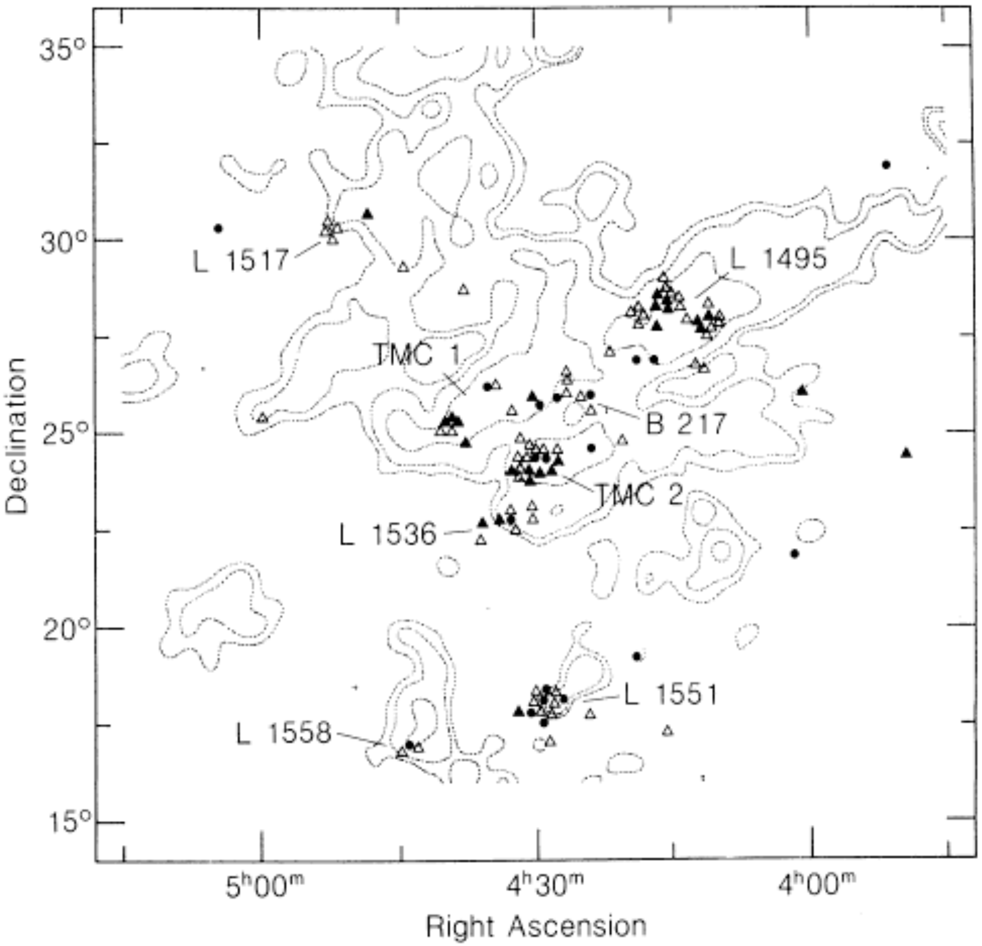
Turning a drawback into a bonus: We don't have any nearby young clusters to observe, but we have plenty of examples of binary formation with minimal dynamics.

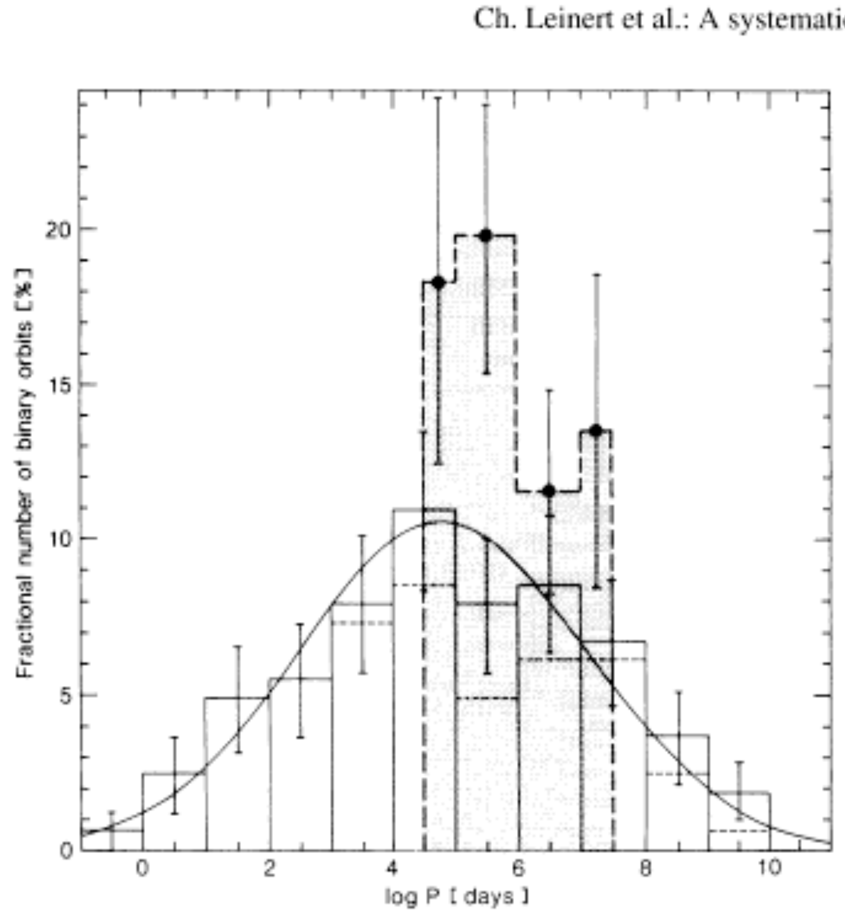
Sparse Regions are Dynamically Primordial



Populations are unmixed on scales of >0.2 pc (>10^5 AU).

The Long Tale of Binarity in Taurus

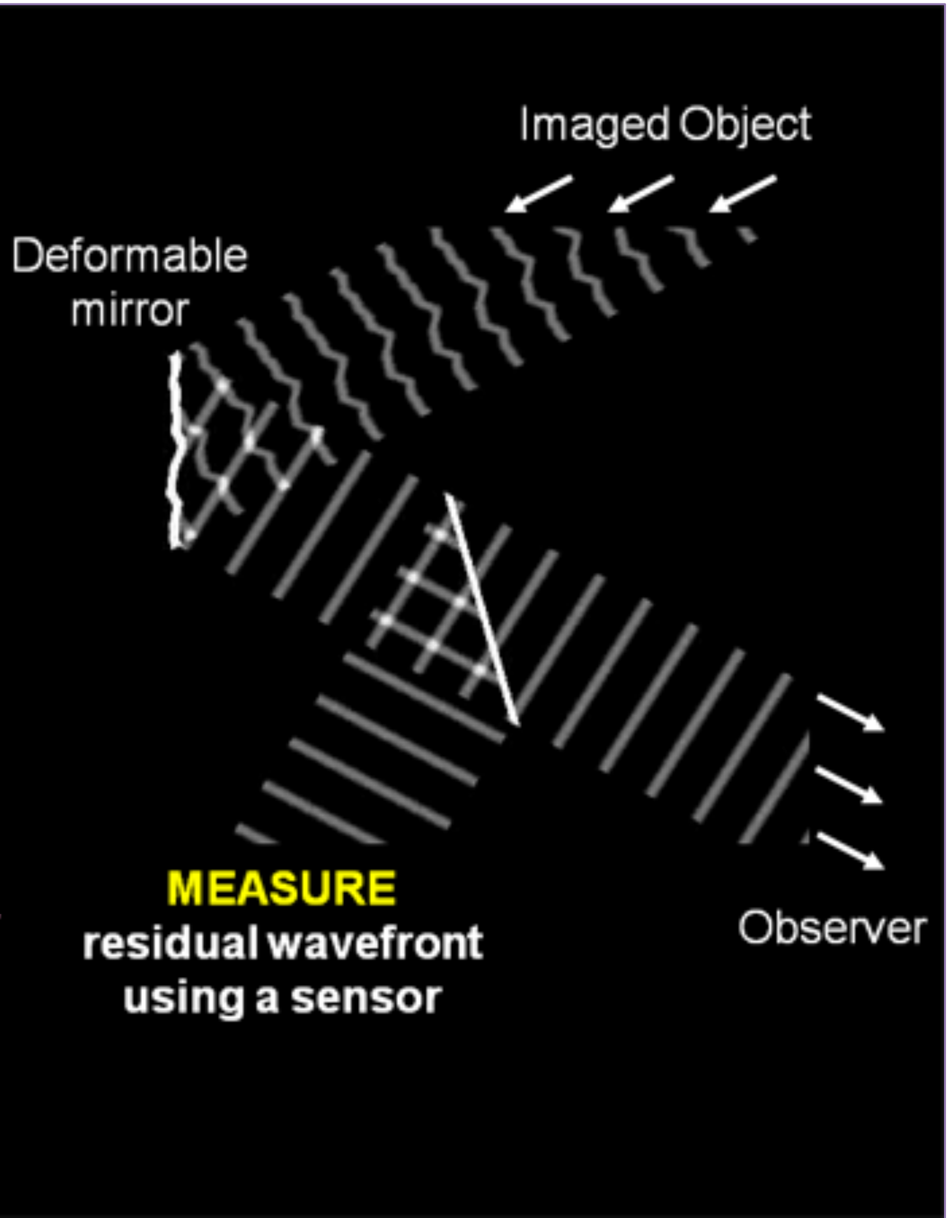


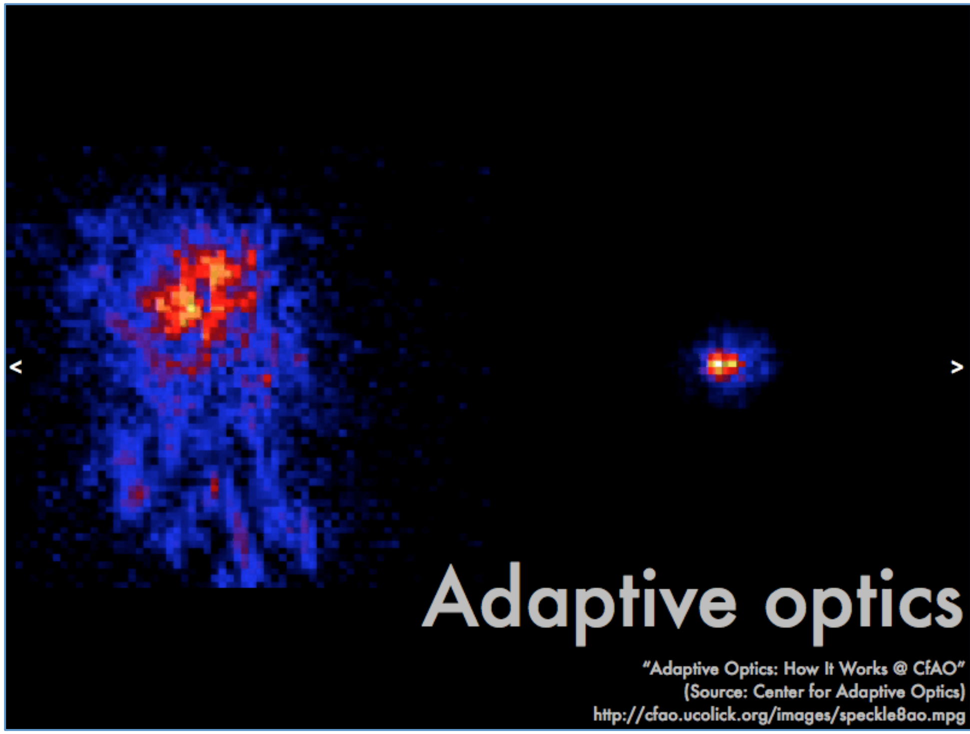


Leinert et al. 1993; Ghez et al. 1993; Richichi et al. 1994; Simon et al. 1995; Kohler et al. 1998; Duchene et al. 1999; White & Ghez 2001; Kraus et al. 2005; Konopacky et al. 2007; Kraus et al. 2011; Kraus & Hillenbrand 2012…

For high-mass stars, must go elsewhere: Kouwenhoven et al. 2005, 2007; Sana et al. 2012, etc.

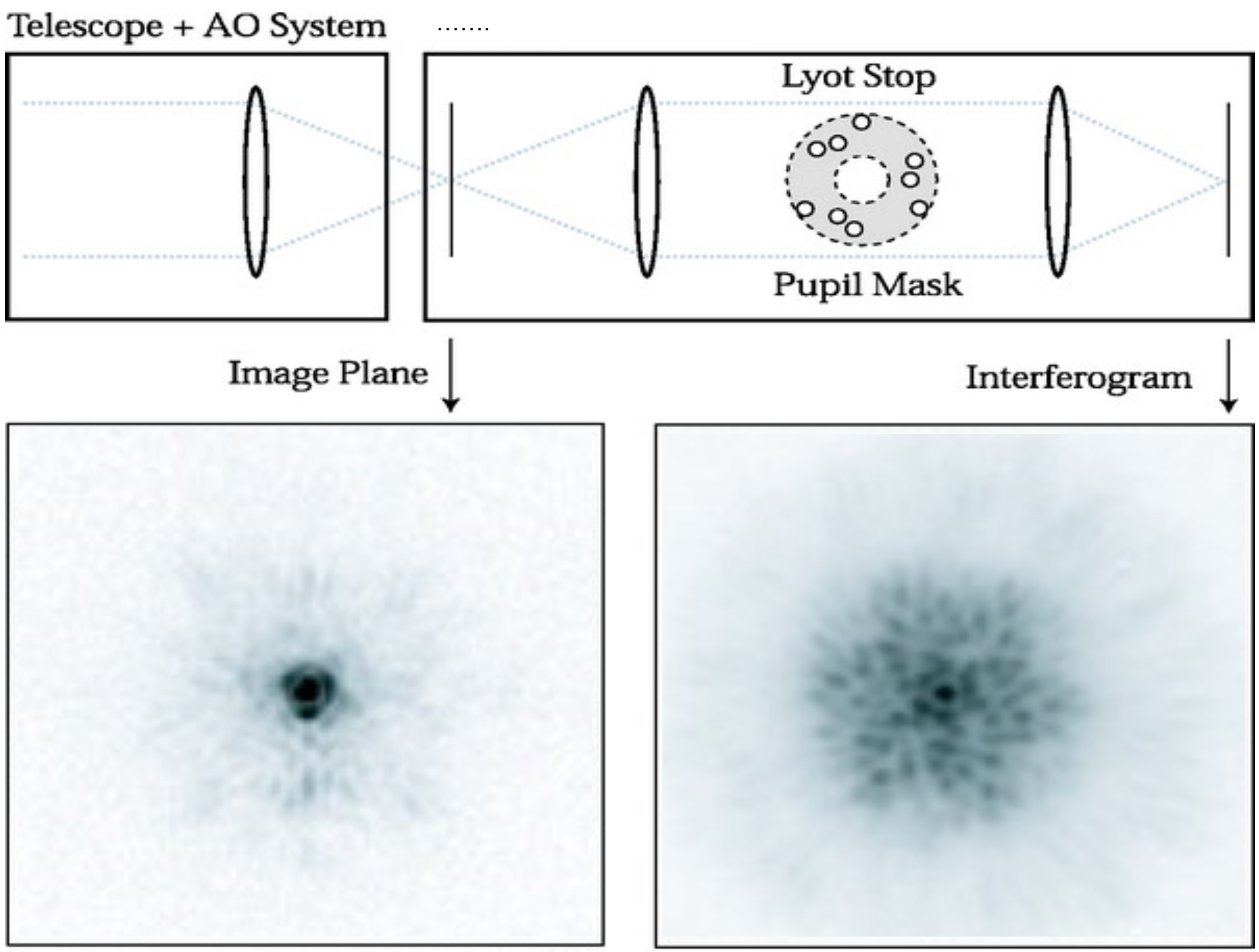
Observing Taurus, 1: Adaptive Optics





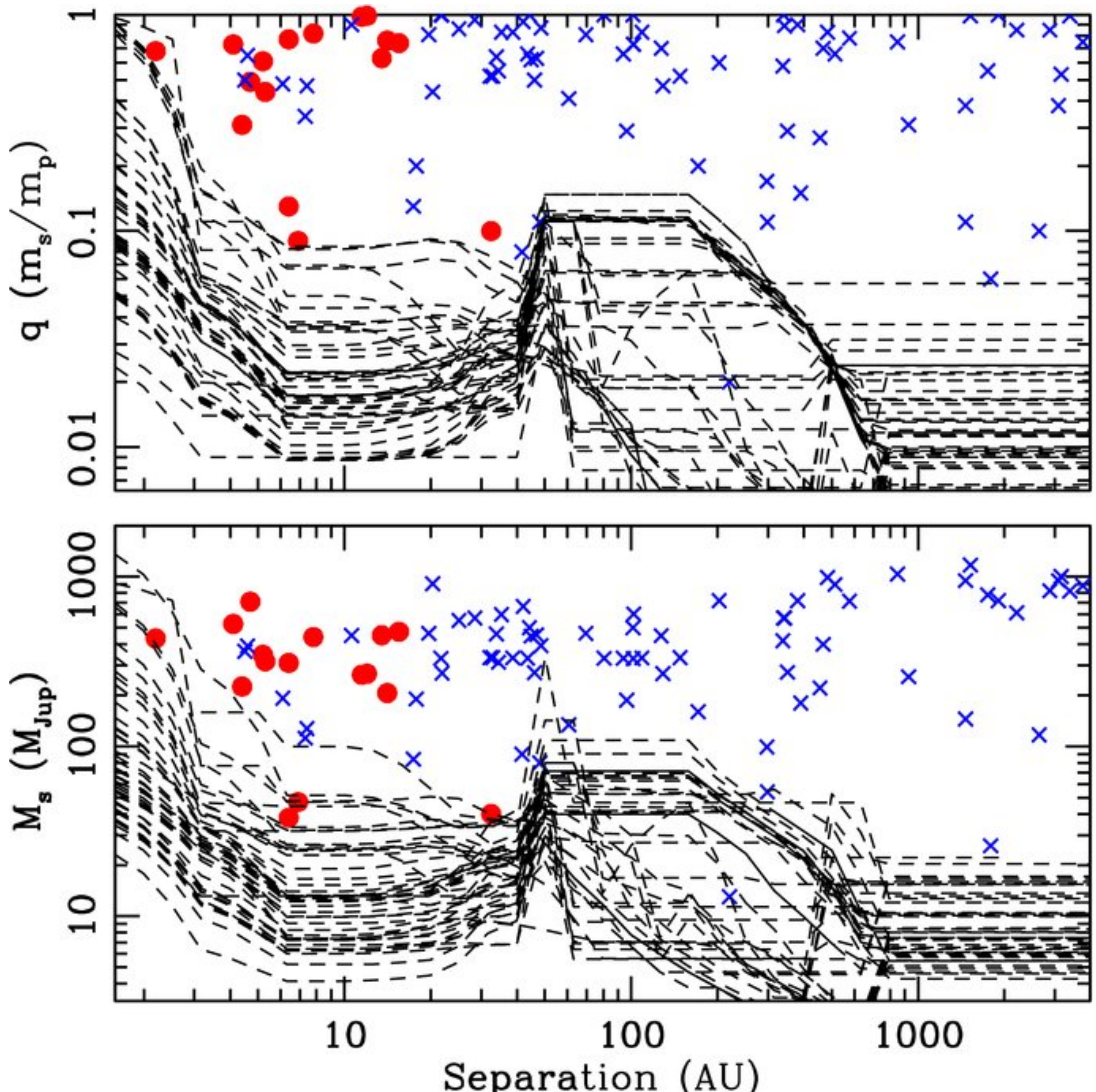
Correct the turbulence introduced by the atmosphere, and hence concentrate the light of the primary star away from the planet.

Observing Taurus, 2: Interferometry



Nonredundant Mask Interferometry (NRM): Place an aperture mask in the pupil plane, turning the single mirror into a sparse array. Fourier analysis techniques (i.e. closure phases) filter almost all remaining noise from turbulence and AO errors. (It's called SAM on the VLT.)

The Binary Population of Taurus-Auriga

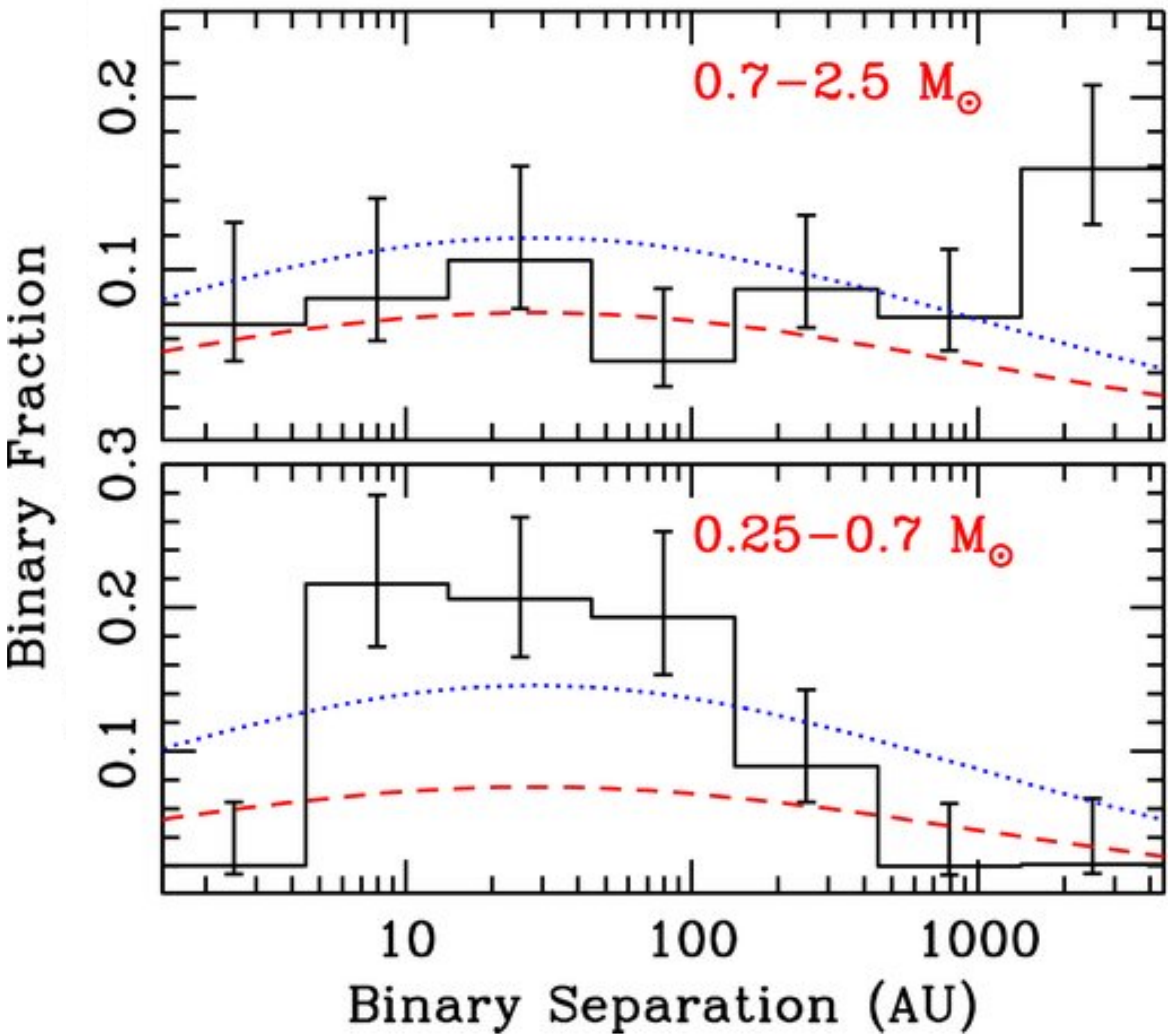


From Kraus et al. (2012)

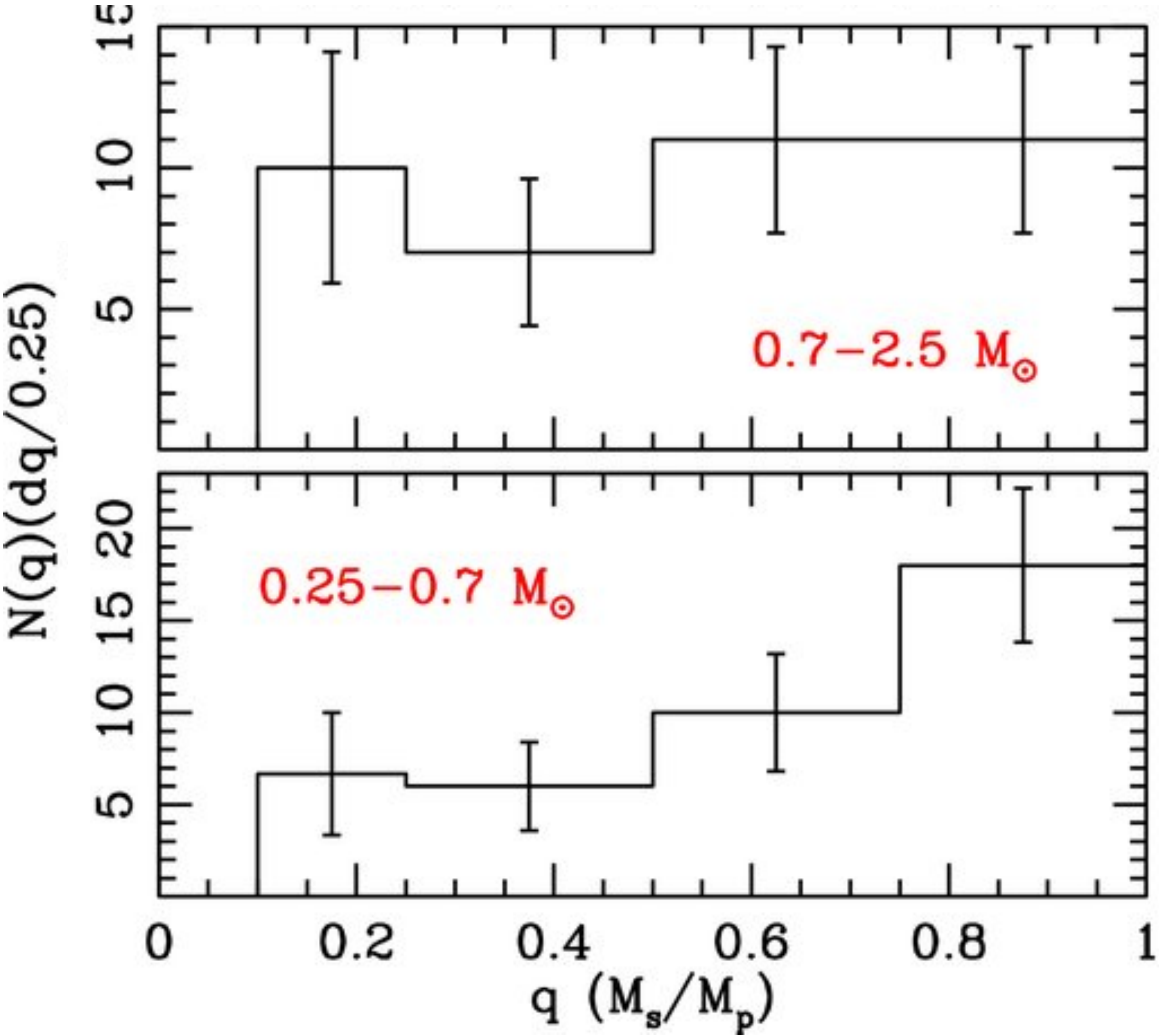
Red: New companions
Blue: Previously known
Dashed: Detection Limits

Sample: ~90% of the known Class II/III Taurus members with M > 0.25 Msun

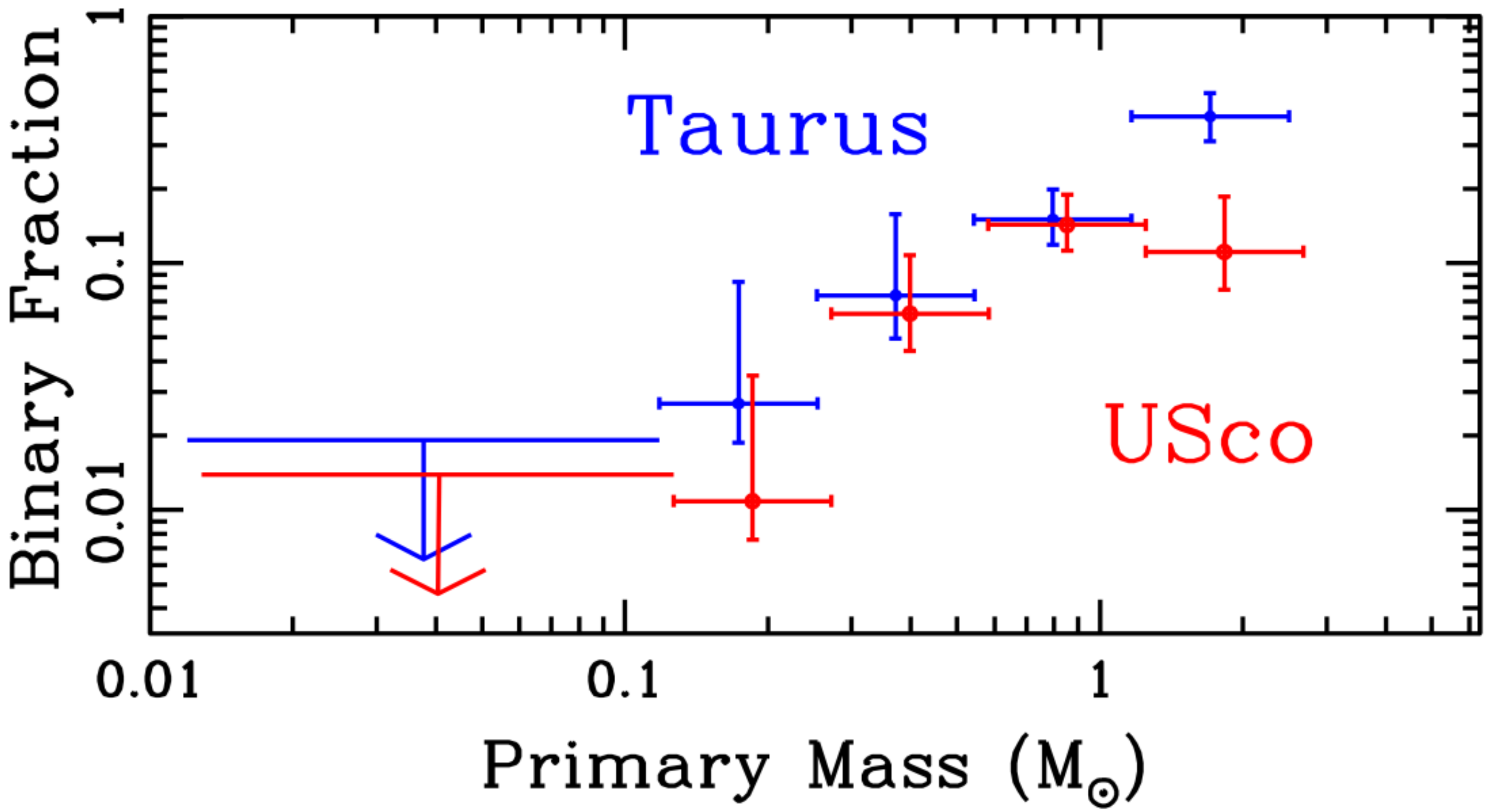
The Binary Population of Taurus-Auriga



The Binary Population of Taurus-Auriga

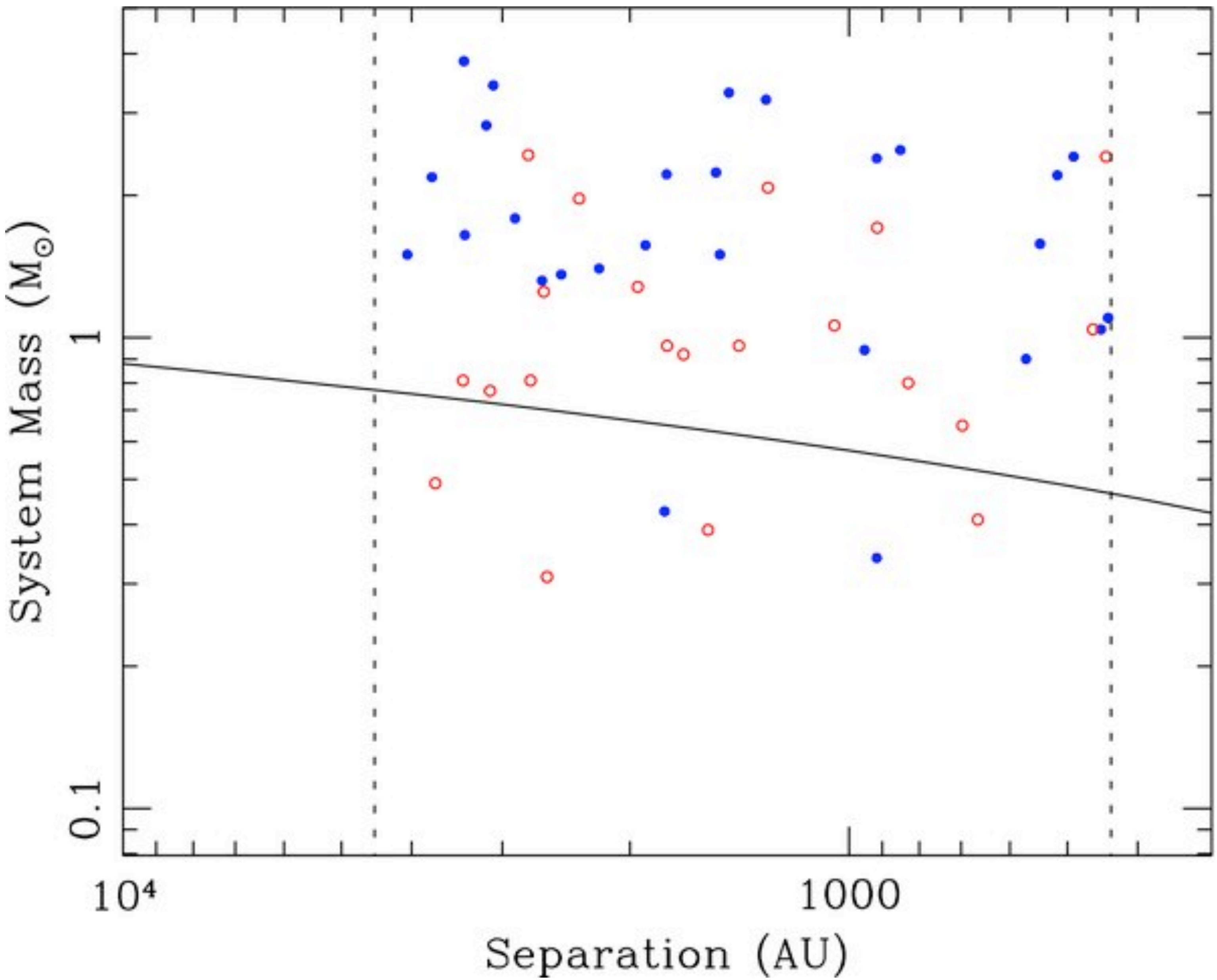


Wide Binary Systems



Few wide (500-5000 AU) low-mass binaries, but plenty (too many) for solar-type stars as compared to the field. Most high-mass field stars must lose their wide companions in dynamical interactions, but low-mass stars never had them. From Kraus & Hillenbrand (2009).

Wide Binary Systems



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:

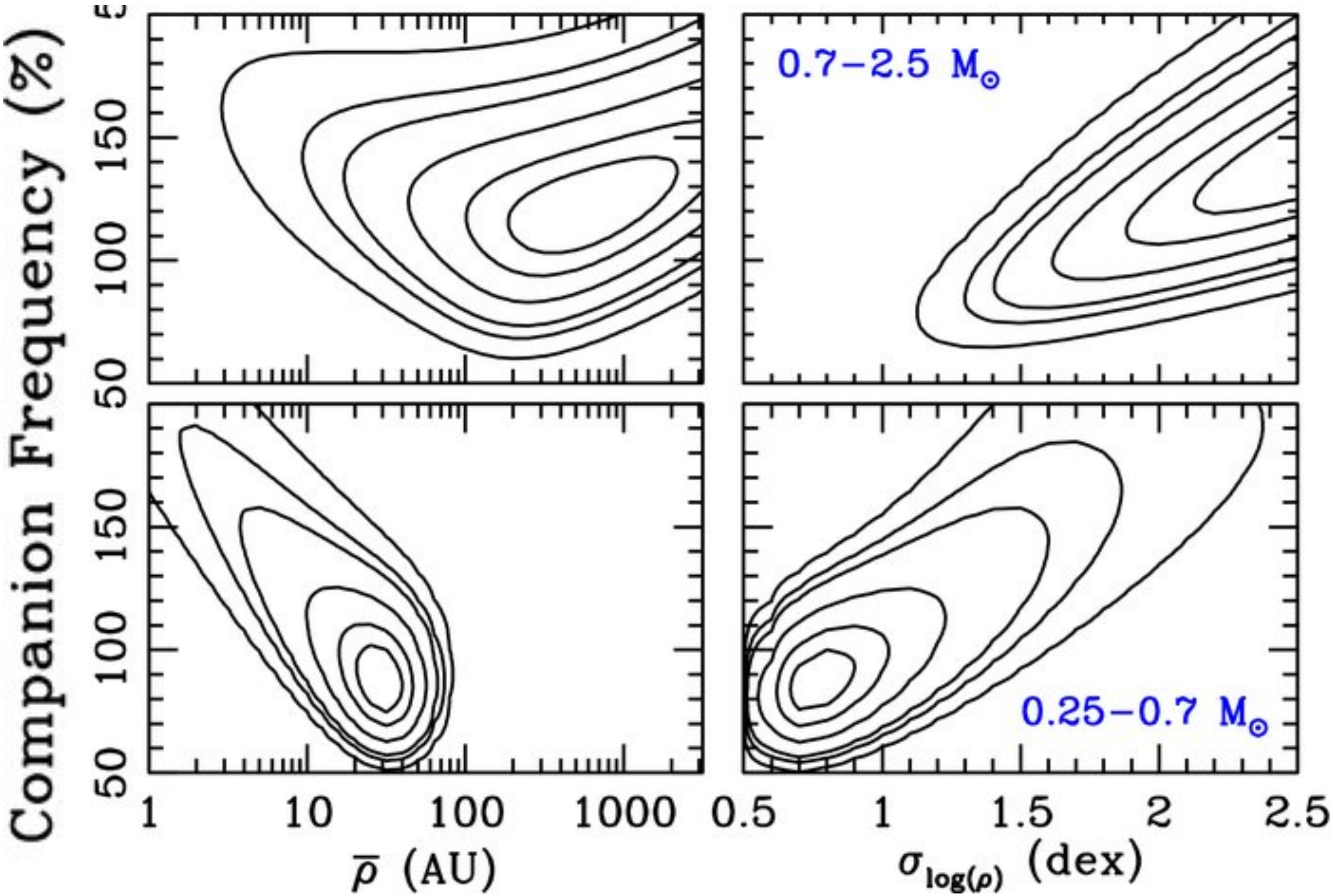
- The total binary frequency F
- A power-law mass ratio distribution with exponent γ
- A log-normal separation distribution with mean log(μ) and standard deviation $\sigma_{\log(s)}$

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

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).

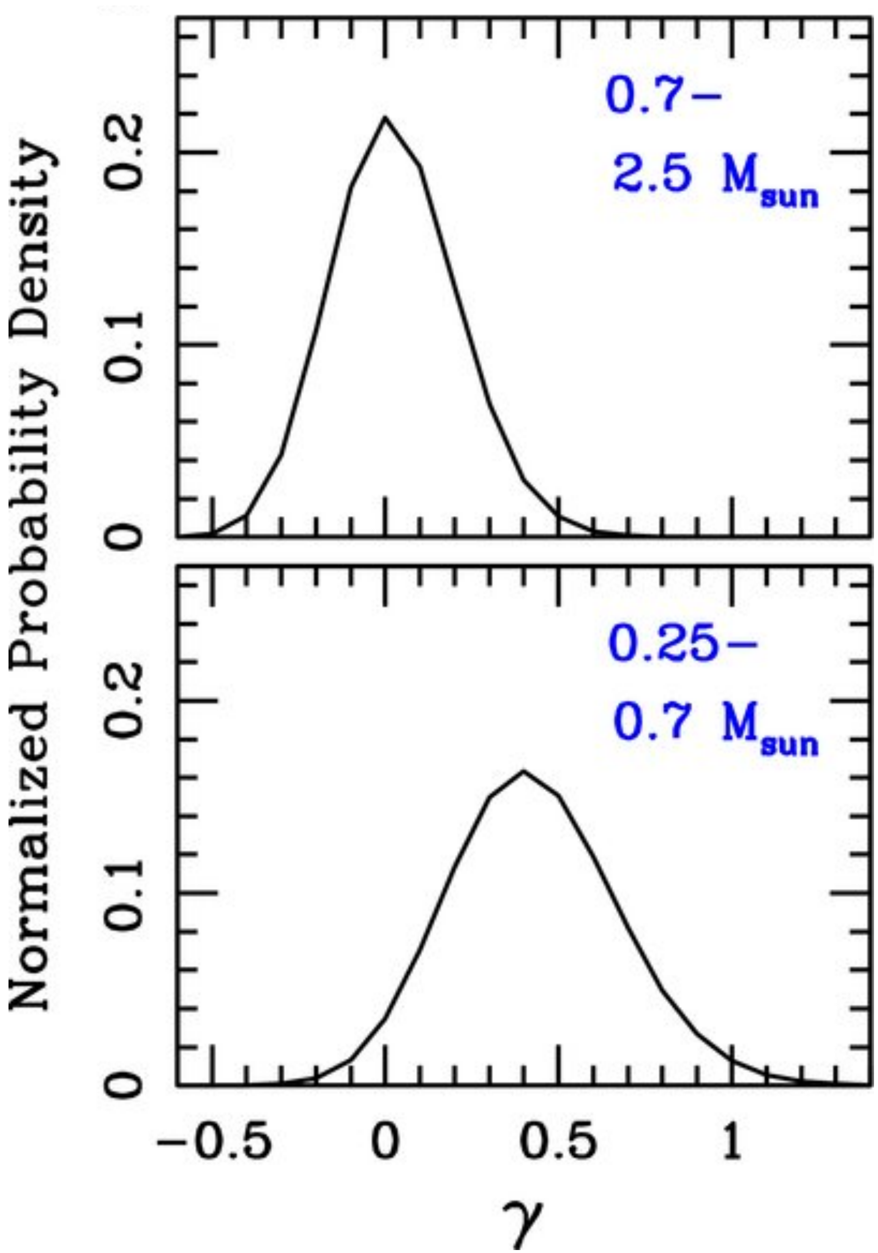
The Binary Population of Taurus-Auriga



Solar-Type: Log-flat, Opik's Law? (wide σ, uncertain ρ)

M Dwarfs: Strongly peaked at a few 10s of AU

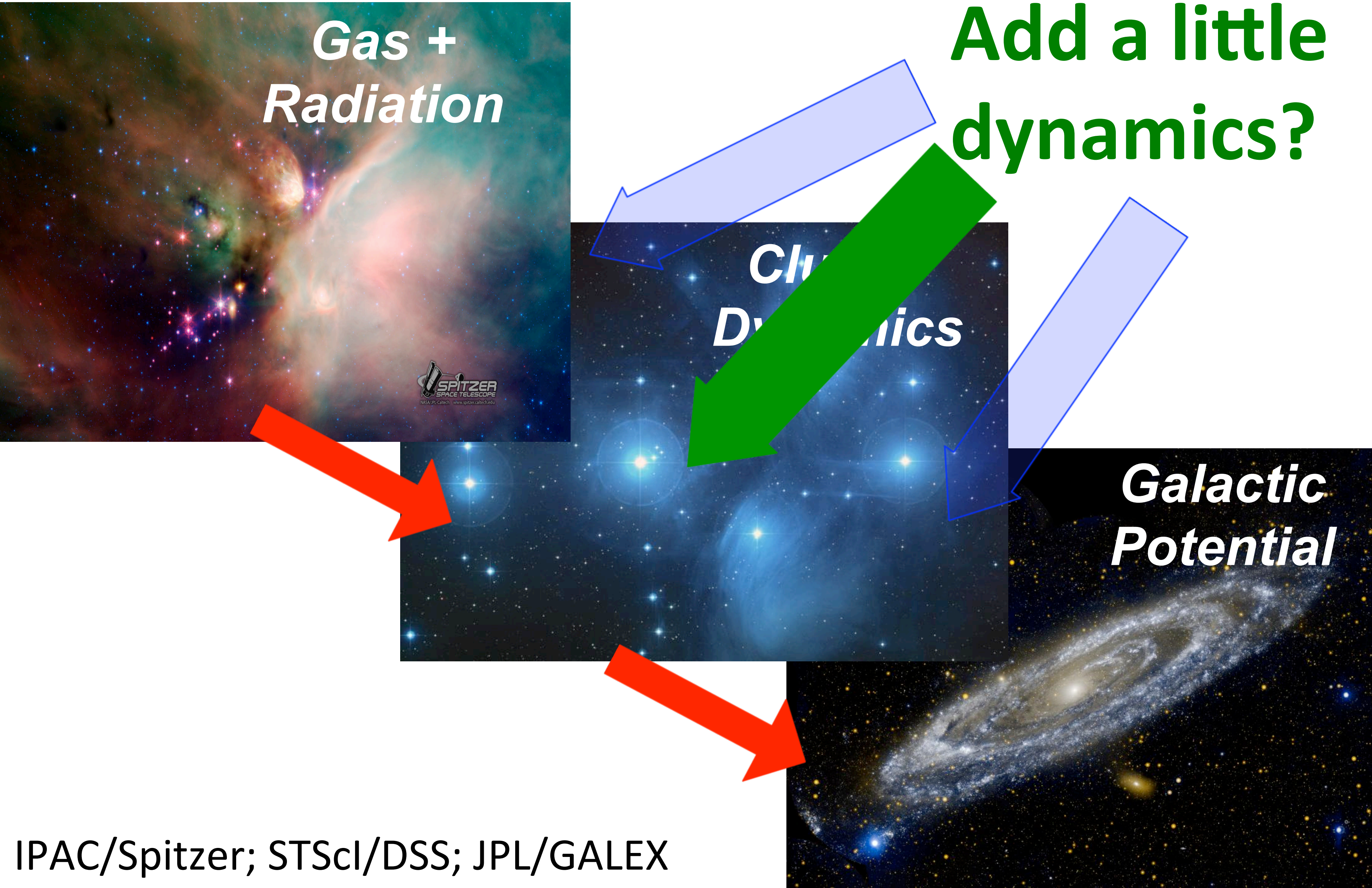
The Binary Population of Taurus-Auriga



Mass ratio distribution is linear-flat for solar-type stars, becoming steeper for lower-mass stars.

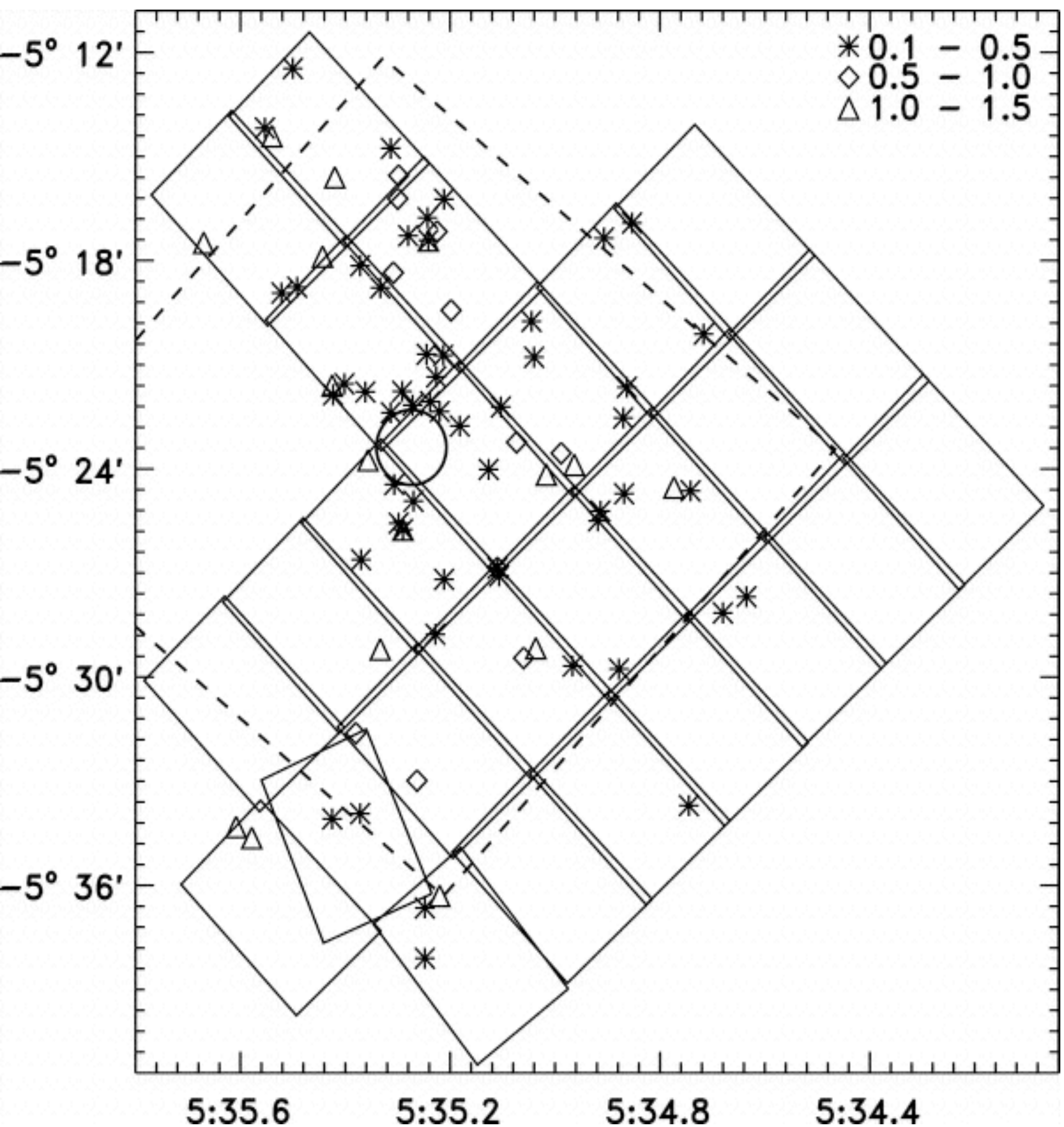
All these trends continue into the VLM regime – see Kraus & Hillenbrand (2012).

Chronology of Binary Evolution



IPAC/Spitzer; STScI/DSS; JPL/GALEX

Toward Dynamics: The ONC Core



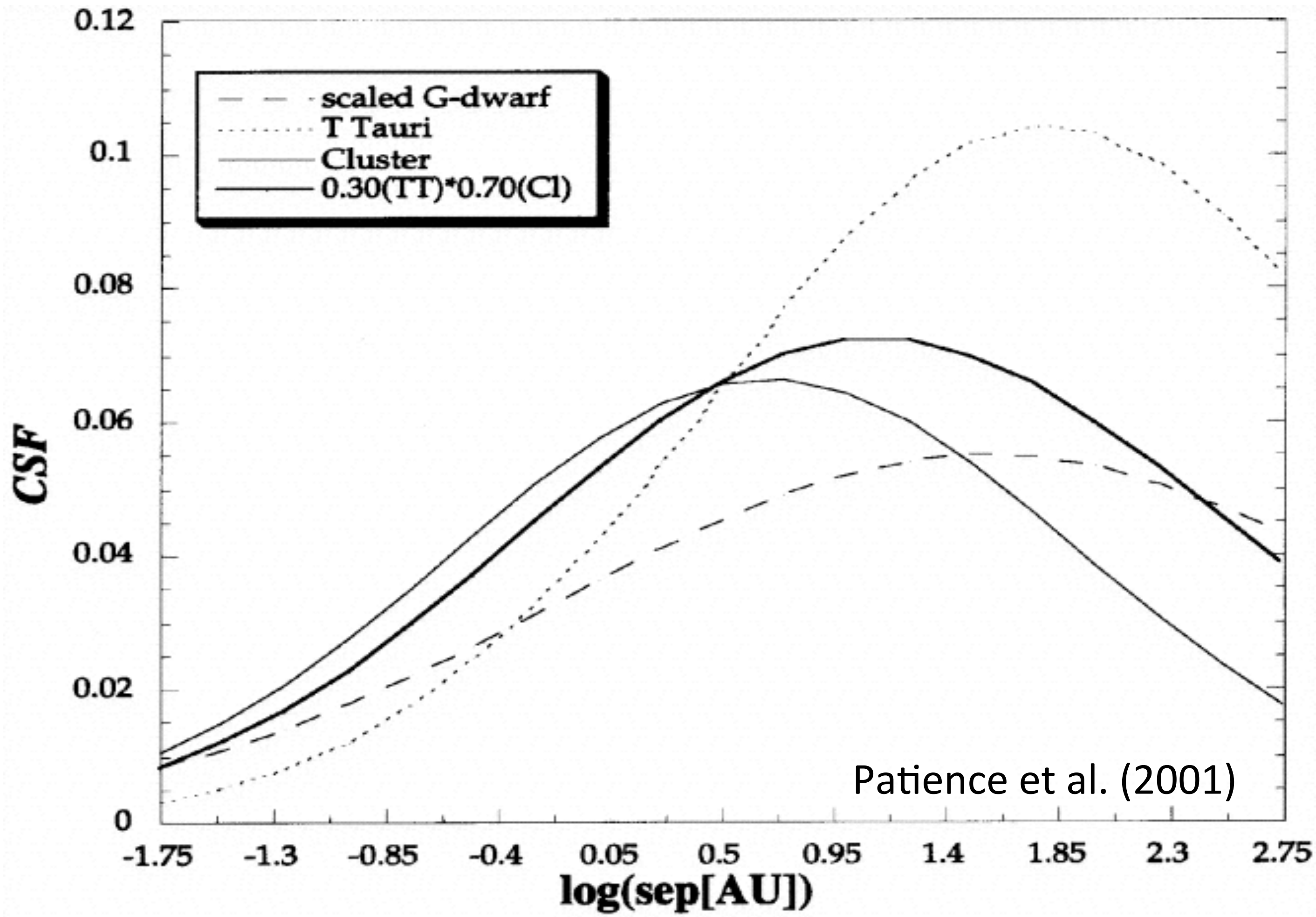
From Reipurth et al. (2007), where symbols show binaries in three separation ranges.

Across all binary separations, frequency suppressed compared to Taurus (dynamics or initial conditions?).

At >200 AU, frequency profoundly suppressed in core, even versus halo (probably dynamics).

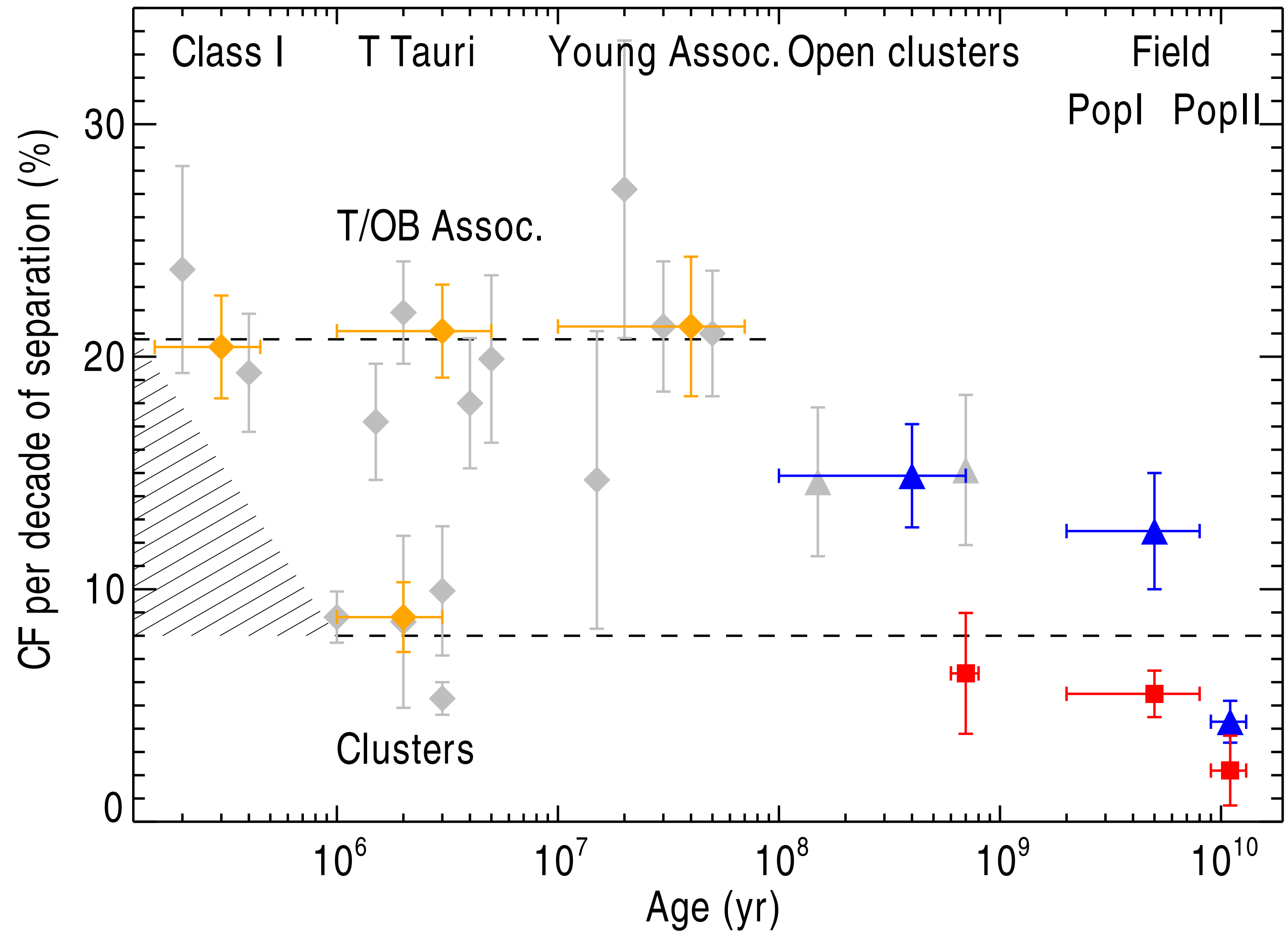
Consistent with Kohler et al. (2006).

Intermediate-Age Clusters



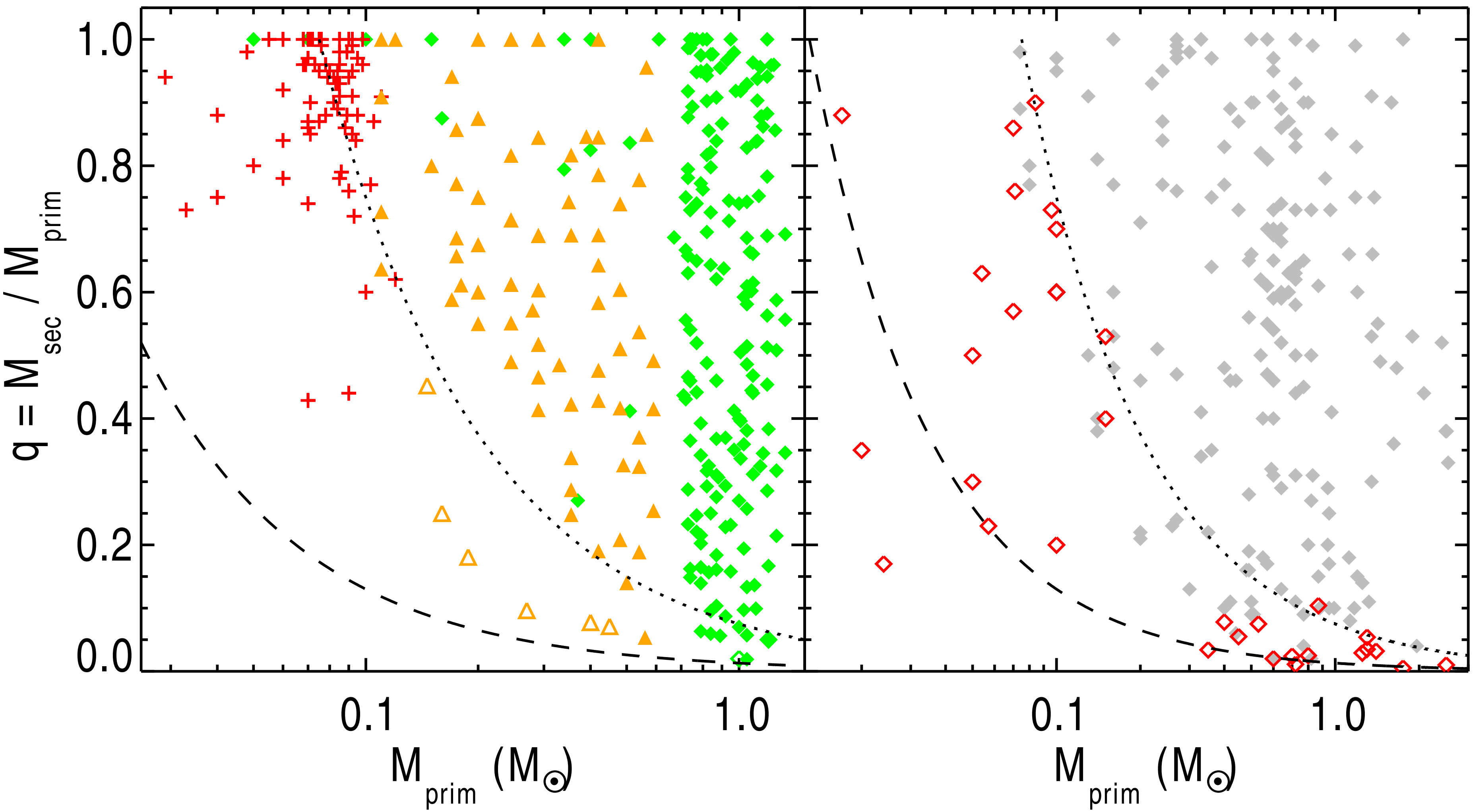
Similar results in intermediate-age clusters. Per Brander & Kohler (1998) and Patience et al. (2002), the field can be modeled as an admixture of sparse associations and clusters.

Trends with Age/Environment



From Duchene & Kraus (2013). Blue: Solar-mass stars. Red: Low-mass stars. Orange: Overall. Gray: Individual surveys. It is unclear if the cluster/association dichotomy results from initial conditions (gas density/temperature) or early dynamical evolution.

Field Population: Mass Ratios



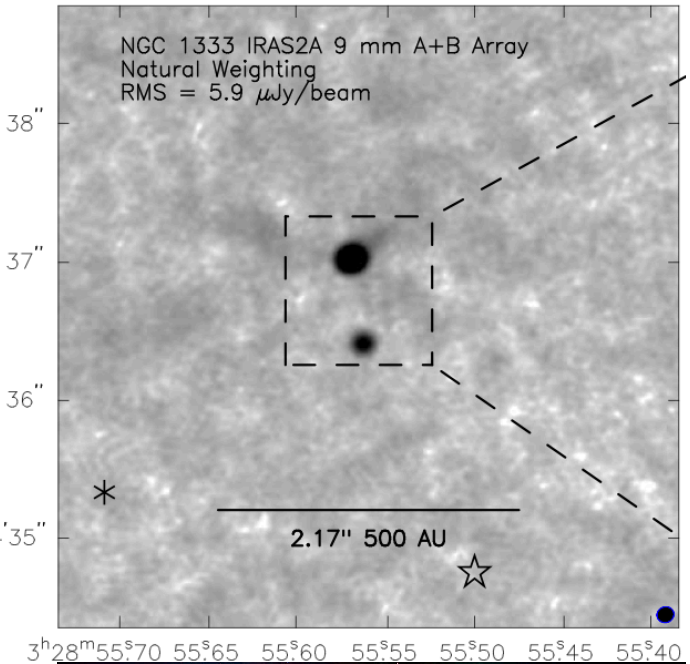
From Duchene & Kraus (2013)

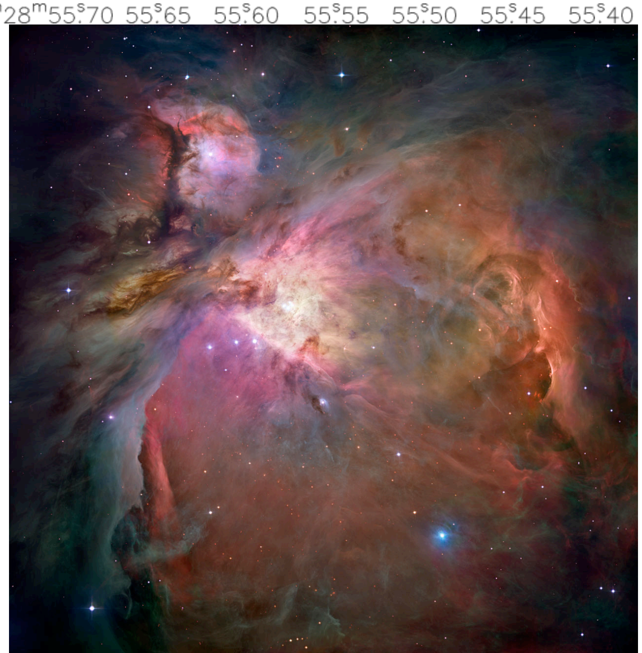
Left: Field. Right: Young populations.

Implications for Formation/Evolution

- Field mass dependence of features is primordial, not dynamical. Lower mass => lower frequencies, smaller separations. ***Indicates core size at fragmentation, not preferential dissolution of low-mass systems.***
- Wide binaries are less common in the field and (young) clusters. **Preferential dissolution of widest systems, with threshold set by cluster density?**
- 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?***

Future Directions





- Surveys at younger ages (with ALMA) for initial conditions and accretion/gas driven evolution (e.g., Tobin et al. 2014)
- Close (5-50 AU) binaries to provide a more dynamically pristine environment tracer in clusters (e.g., Kohler et al. 2006; Reipurth et al. 2007; Robberto et al. 2013)
- Updated surveys of nearby old clusters, using new member lists: Pleiades, Hyades, Praesepe
- What happens inside 5 AU?