Multiplicity in the early phases of stellar evolution

Gaspard Duchêne

UC Berkeley - IPAG (Grenoble)

Stellar multiplicity

- Stellar multiplicity is
  - an ubiquitous feature of stellar populations
  - a product of the star formation process(es)
  - not a *fossil record*, however, because of (violent) stellar dynamics ⟶ see R. Parker's talk
- ***Need to probe the early phases of stellar evolution: PMS and protostars***

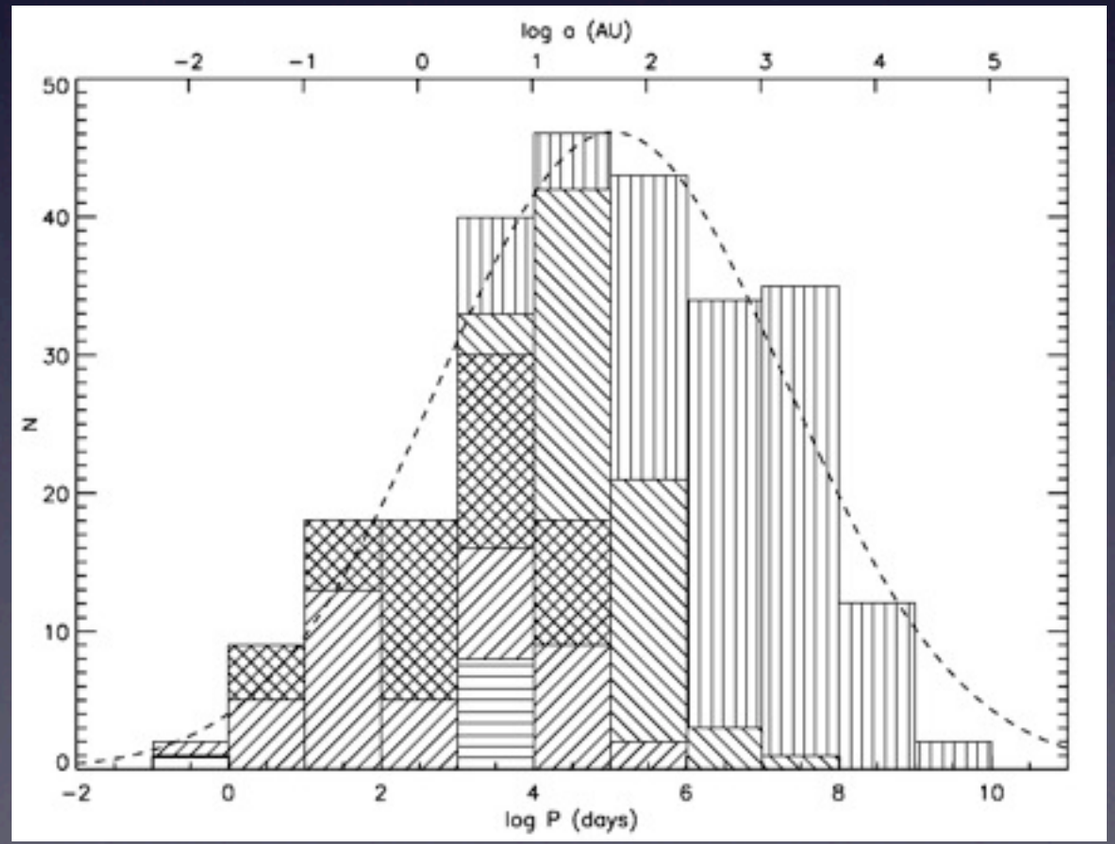
Outline

- Multiplicity to probe of core fragmentation
- Pre-Main Sequence multiplicity
- Protostellar multiplicity...
  - ... among Class I sources
  - ... among Class 0 sources
- Summary

Stellar multiplicity

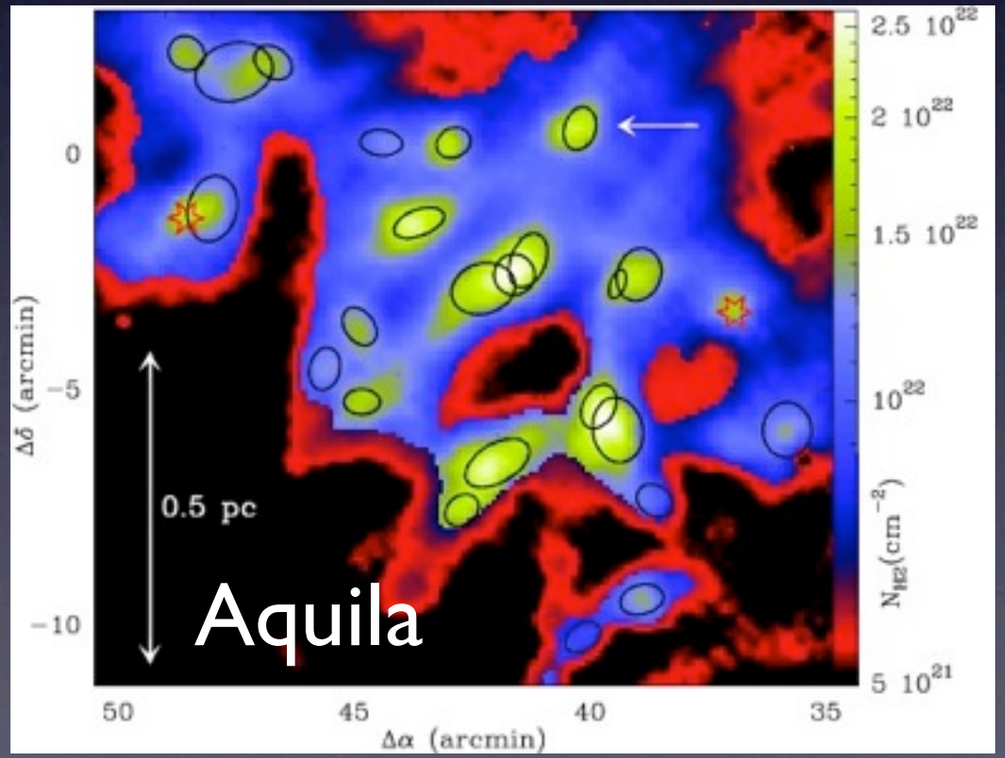
- Very broad range of separations on the MS
  - presumably not a single physical process

Raghavan et al. (2010)

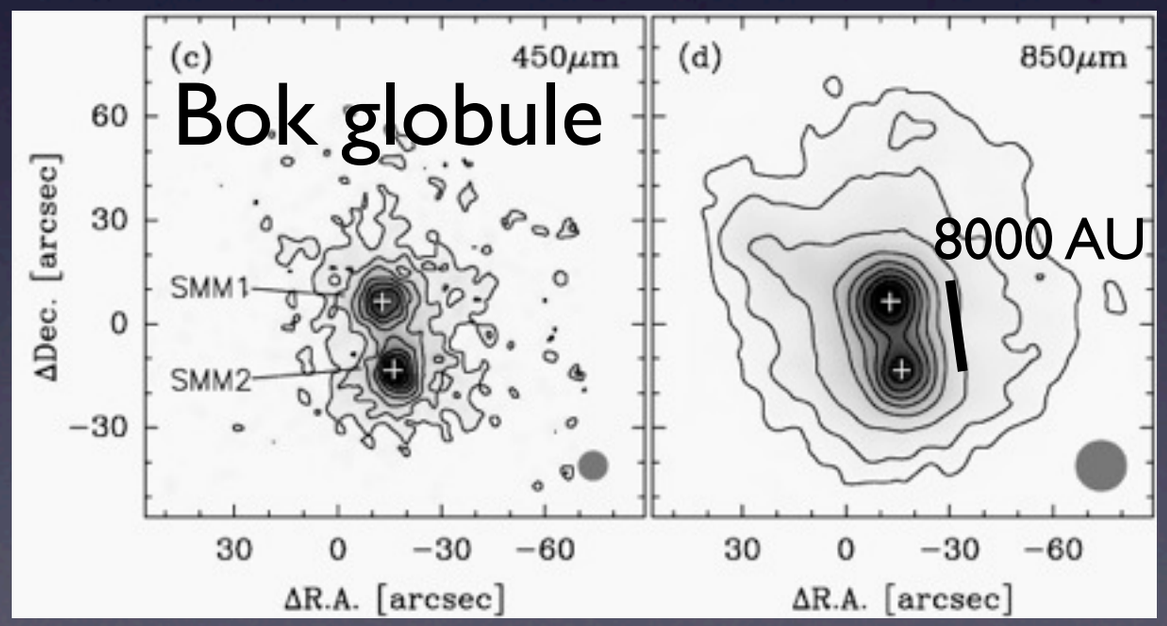


Stellar multiplicity

- Very broad range of separations on the MS
  - presumably not a single physical process
- "Typical" core size ~ 5000 AU



Könyves et al. (2010)

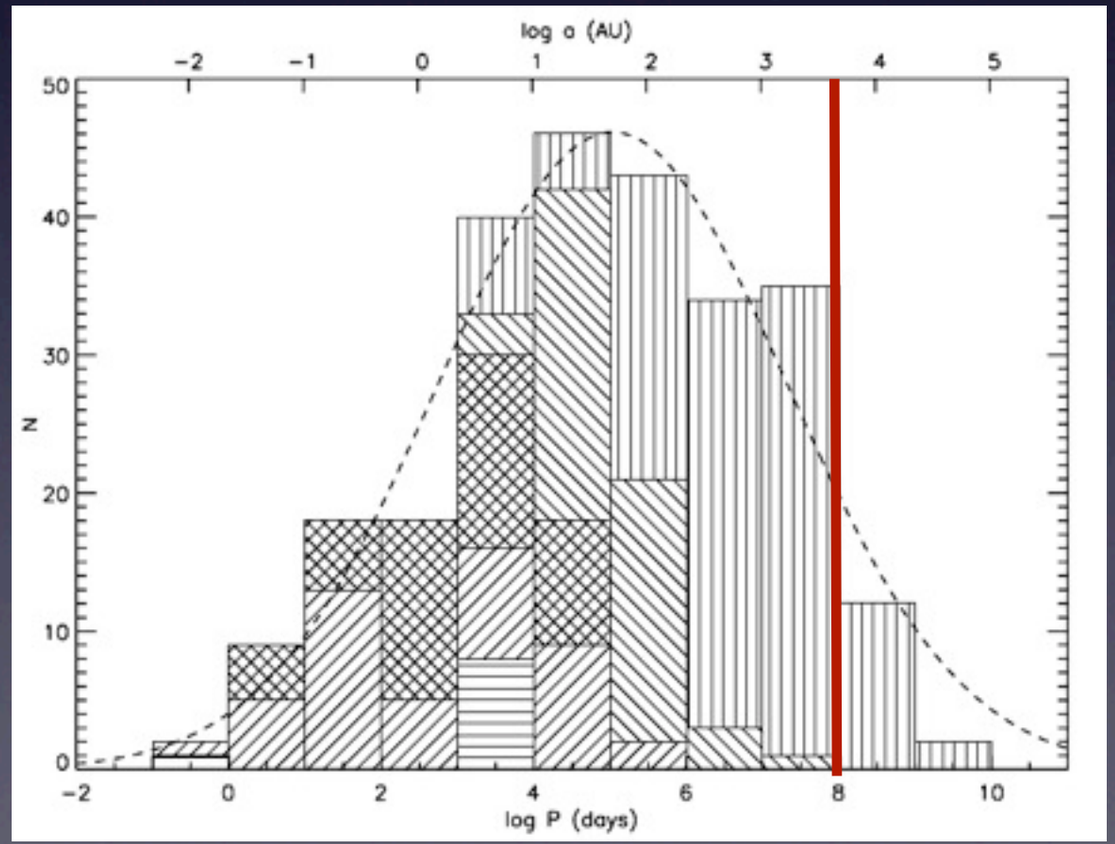


Launhardt et al. (2010)

Stellar multiplicity

- Most wide systems probably form from two separate, nearby, prestellar cores or much later during cluster dissolution

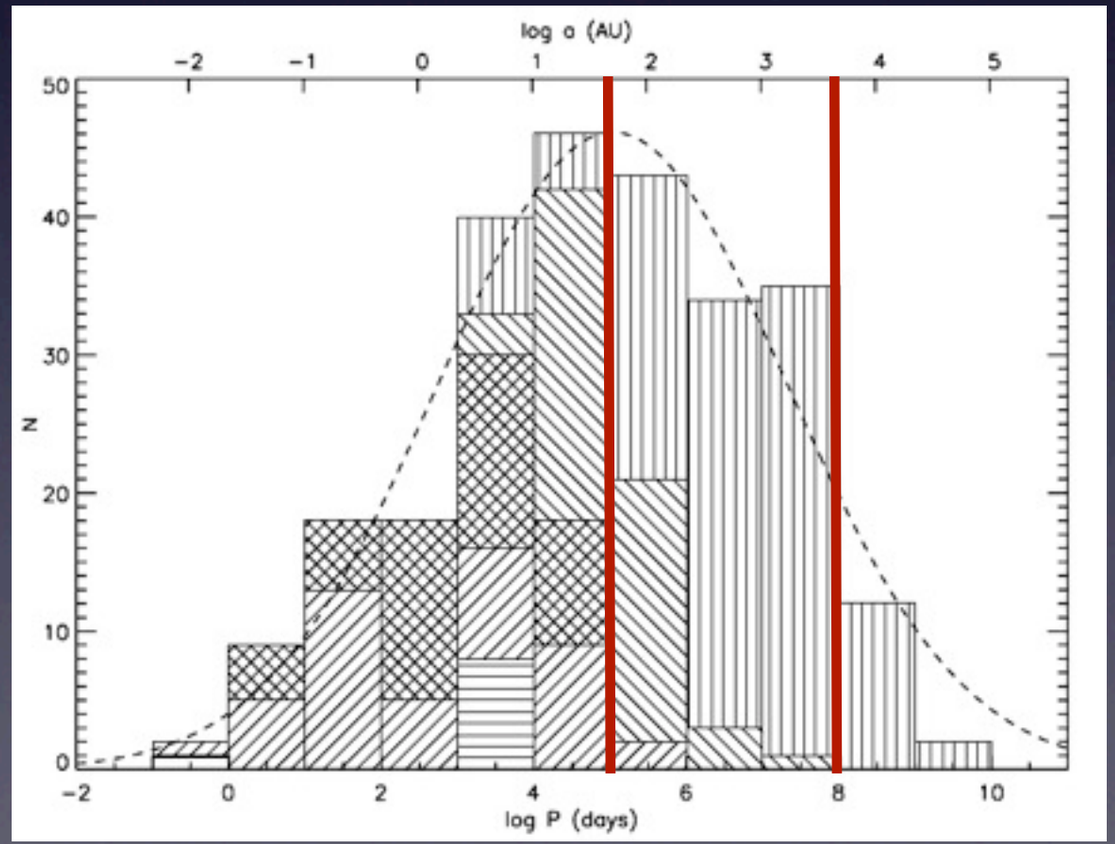
Raghavan et al. (2010)



Stellar multiplicity

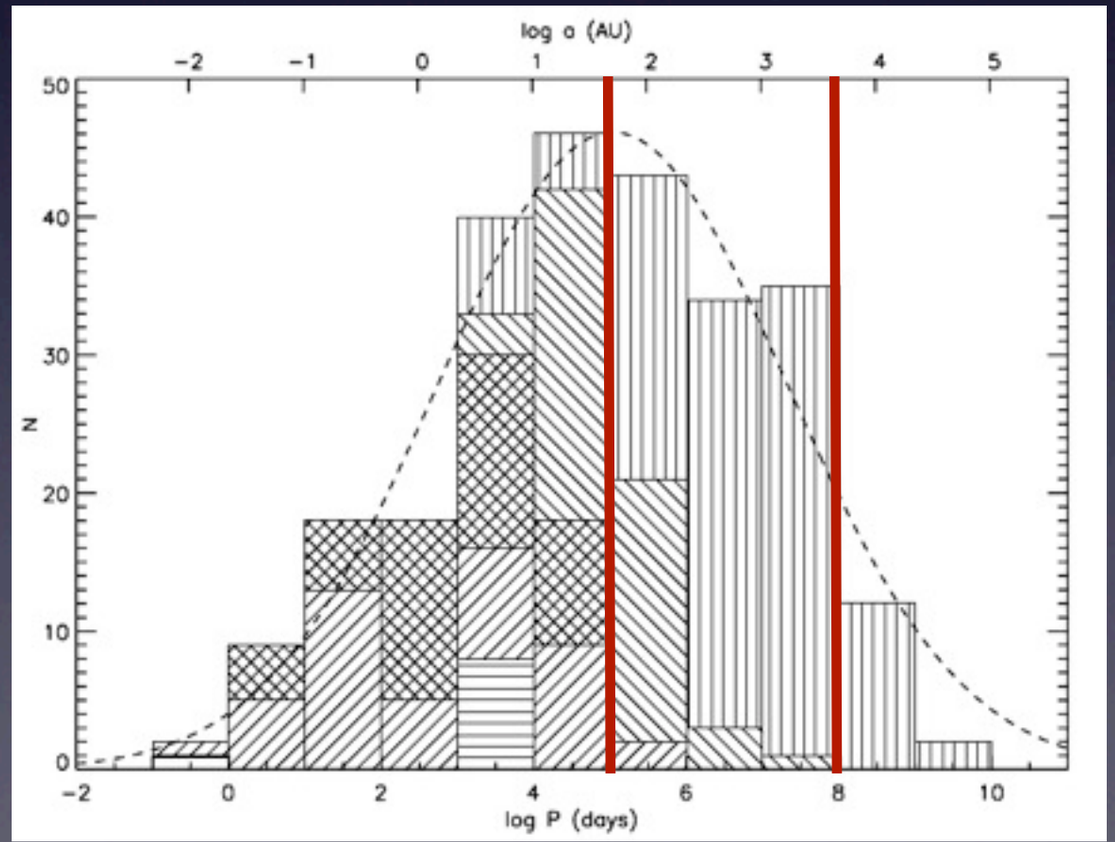
- "Spectroscopic" binaries form through subsequent (disk) fragmentation *and* dynamical interactions

Raghavan et al. (2010)



Stellar multiplicity

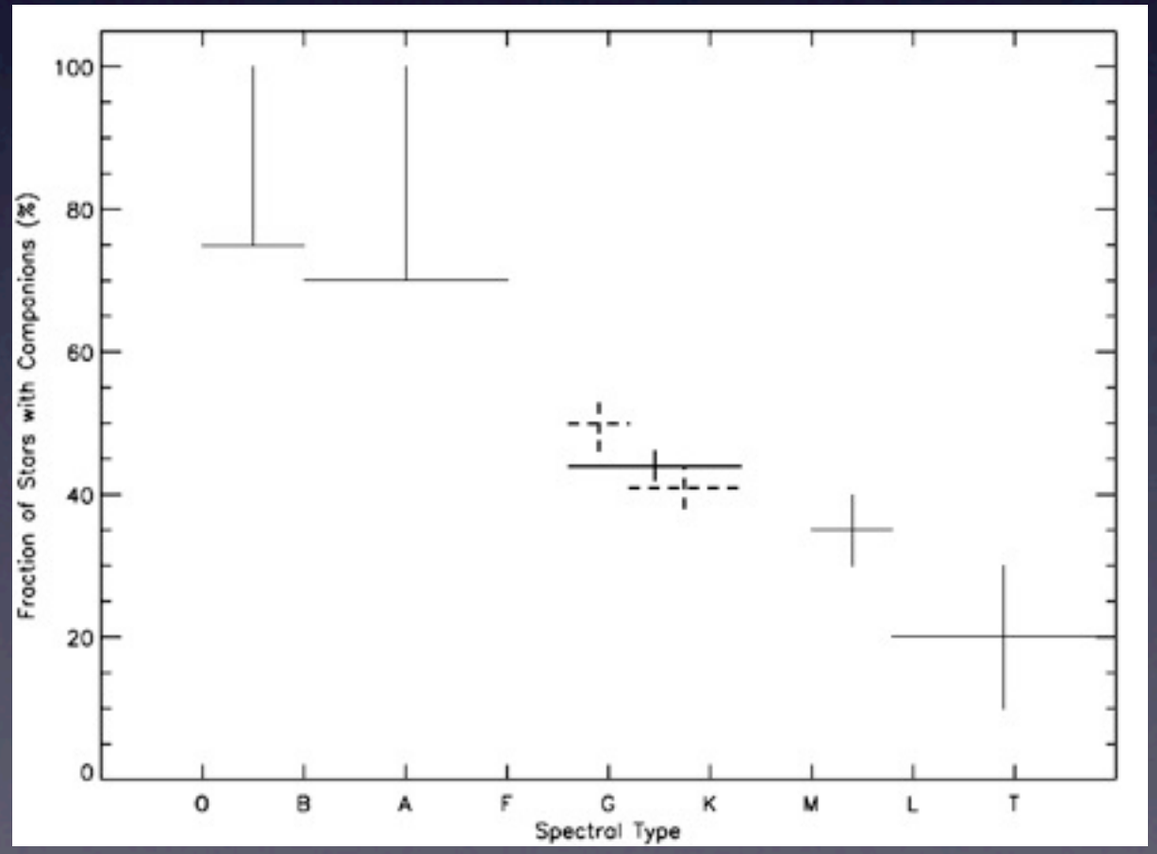
- *Separation range ~ 50-5000 AU is the domain of core fragmentation*
  - But may not be a pristine population! *Raghavan et al. (2010)*



VLMS/BD multiplicity

- Not nearly as frequent as solar-type stars
  - Binary fraction ~ 20-35%

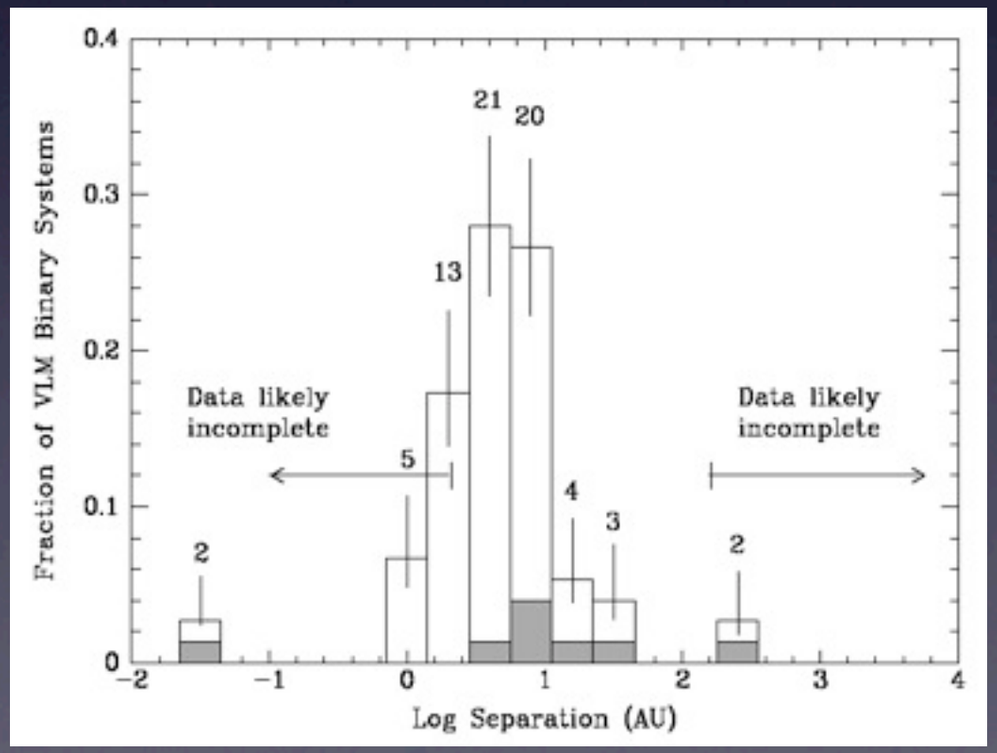
Raghavan et al. (2010)

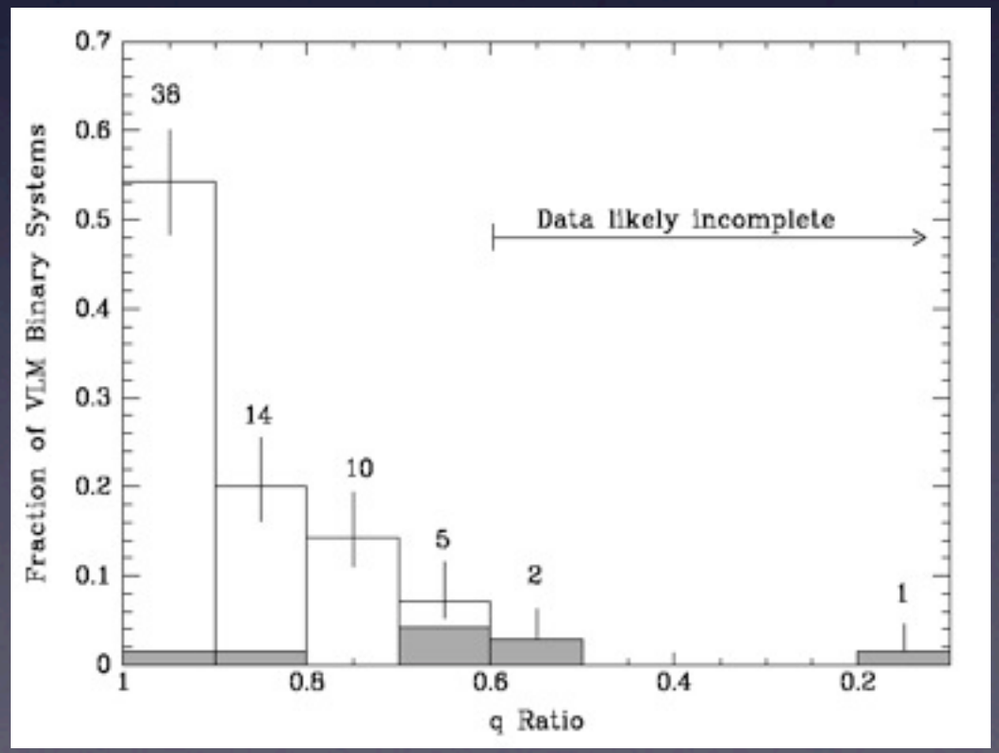


VLMS/BD multiplicity

- Not nearly as frequent as solar-type stars
- *Mostly* limited to very tight and equal-mass systems

Burgasser et al. (2007)





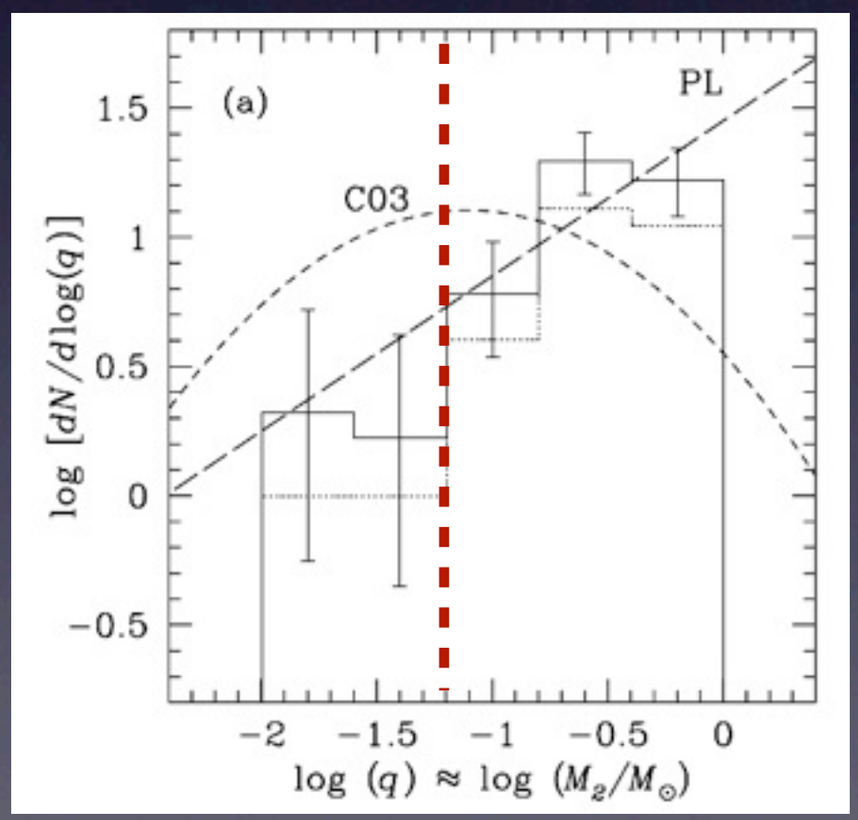
VLMS/BD multiplicity

- Not nearly as frequent as solar-type stars
- *Mostly* limited to very tight and equal-mass systems
- see Joergens', Dupuy's, Brandner's talks
- Are these properties related to the formation of these systems or driven by dynamical interactions? Test in the earlier phases...

VLMS/BD as companions

- VLMS/BD are quite rare at all separations around solar-type stars ("BD desert")

Metchev & Hillenbrand (2009)



VLMS/BD as companions

- VLMS/BD are quite rare at all separations around solar-type stars ("BD desert")
- For "wide" system, this is probably telling us about post-fragmentation accretion
  - or are they disrupted during dynamical interactions?

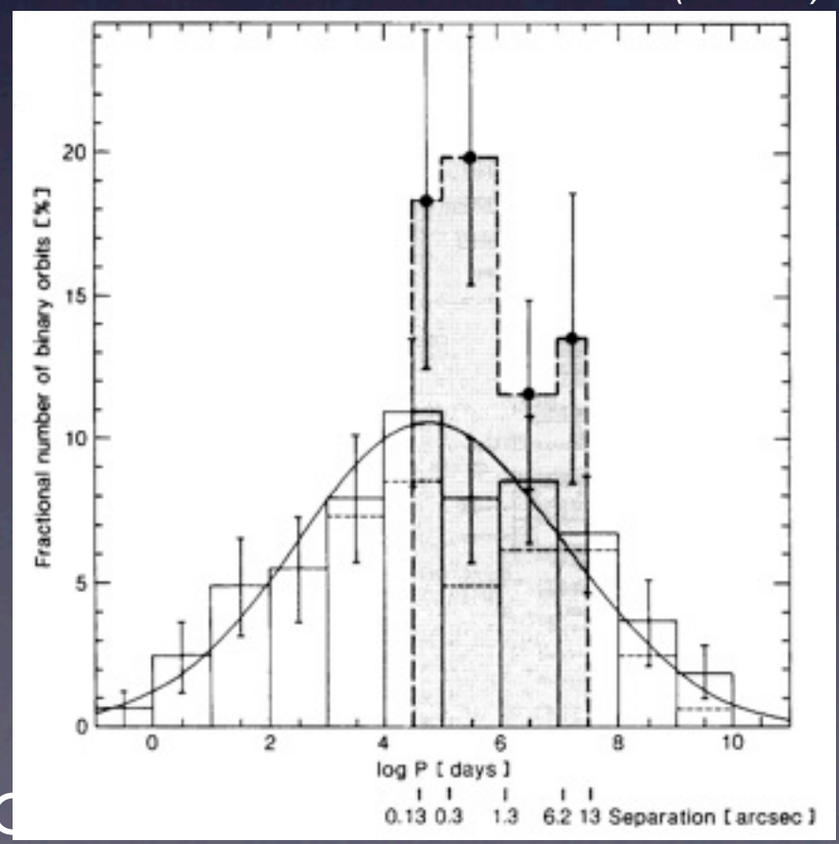
PMS multiplicity

- Establishing statistical multiplicity properties in PMS phases faces several critical issues
  - D > 100 pc (subarcsecond resolution needed)
  - masses are (sometimes) difficult to estimate
  - incompleteness when envelopes are present
- ***The issues are getting worse as one goes further back in time!***

T Tauri stars multiplicity

- Best-studied regions: Tau-Aur, Cha, Ori, Oph, Up Sco
  - Multiplicity is generally high
  - $CSF_{\text{Tau-Aur}}$ ~ 100%
  - fraction of single stars ~ 25-30%

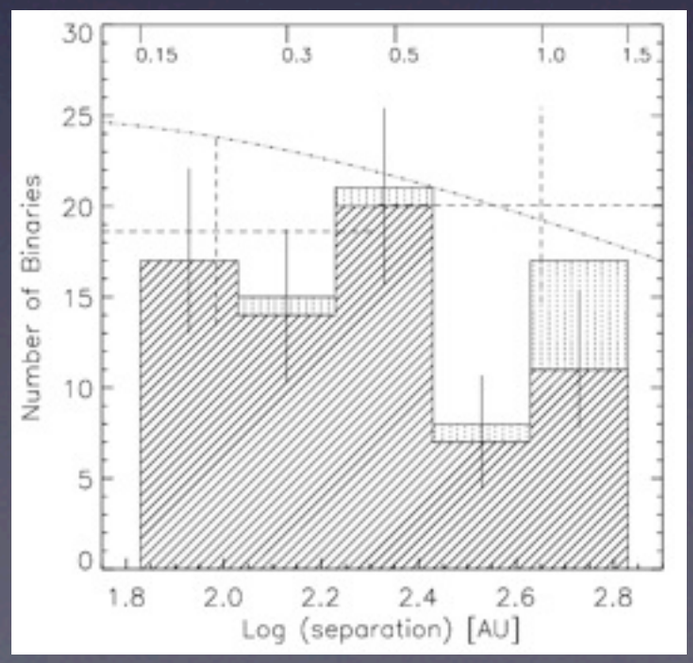
Leinert et al. (1993)



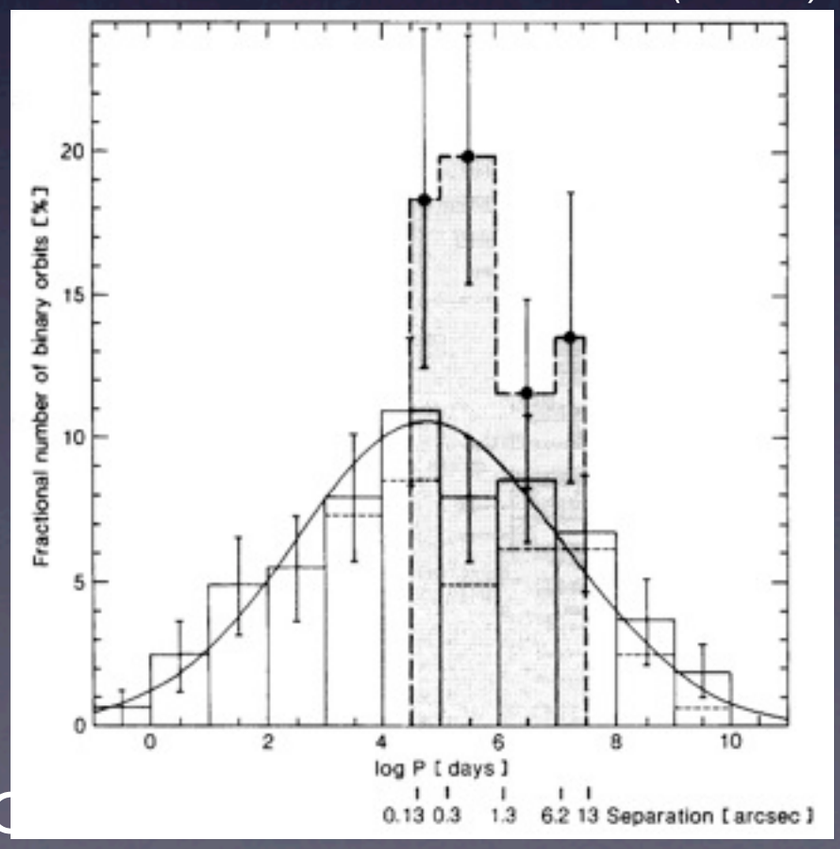
T Tauri stars multiplicity

- Possibly environment-dependent: clusters vs. loose associations
  - No system wider than 1000 AU in the ONC (Scally et al. 1999)
  - Much lower CSF in clusters

Reipurth et al. (2007)



Leinert et al. (1993)

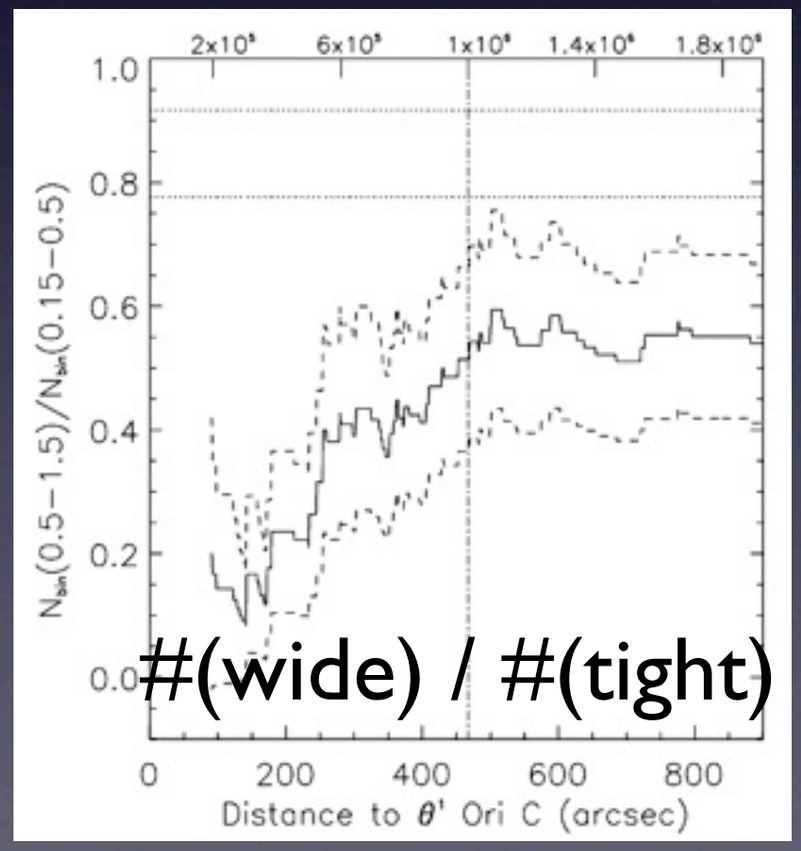


The formation of

T Tauri stars multiplicity

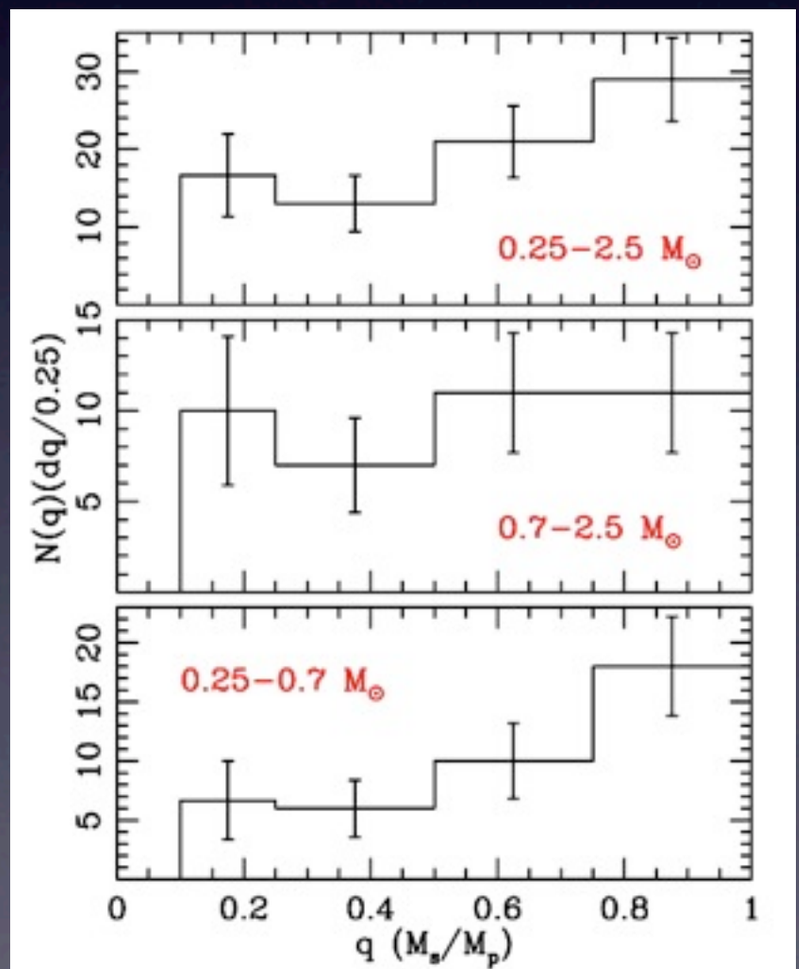
- Possibly environment-dependent: clusters vs. loose associations
  - No system wider than 1000 AU in the ONC (Scally et al. 1999)
  - Much lower CSF in clusters
  - Evidence for binary disruption?
  - Or is it an intrinsic difference?

Reipurth et al. (2007)



T Tauri stars multiplicity

- The mass ratio distribution is roughly flat for solar-type, *not* following the IMF
  - similar to the MS distributions

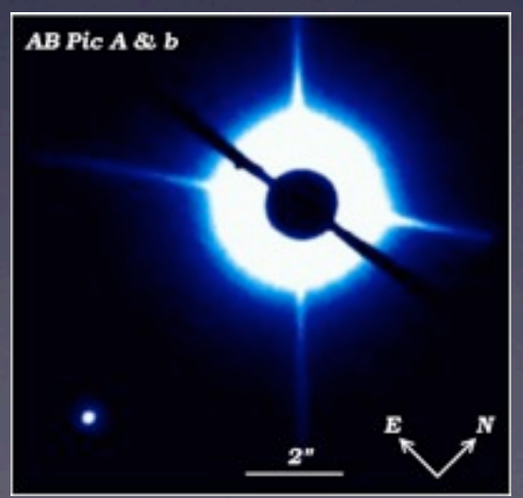


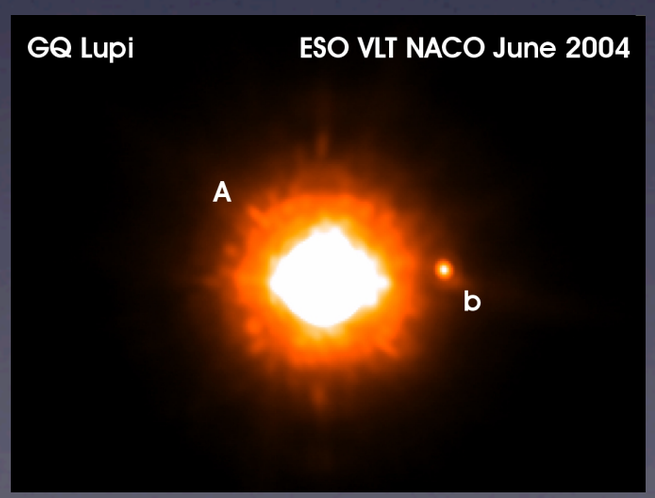
Kraus et al. (2011)

T Tauri stars multiplicity

- The mass ratio distribution is roughly flat for solar-type, *not* following the IMF
  - similar to the MS distributions
  - BD companions are less rare than among Main Sequence stars but not frequent either

Chauvin et al. (2005)

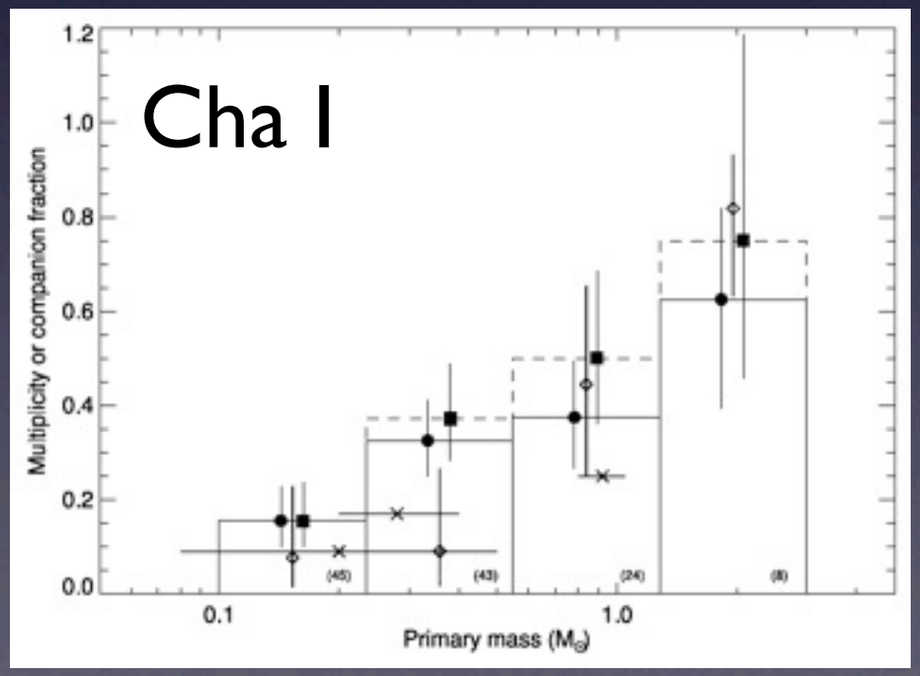




Neuhauser et al. (2005)

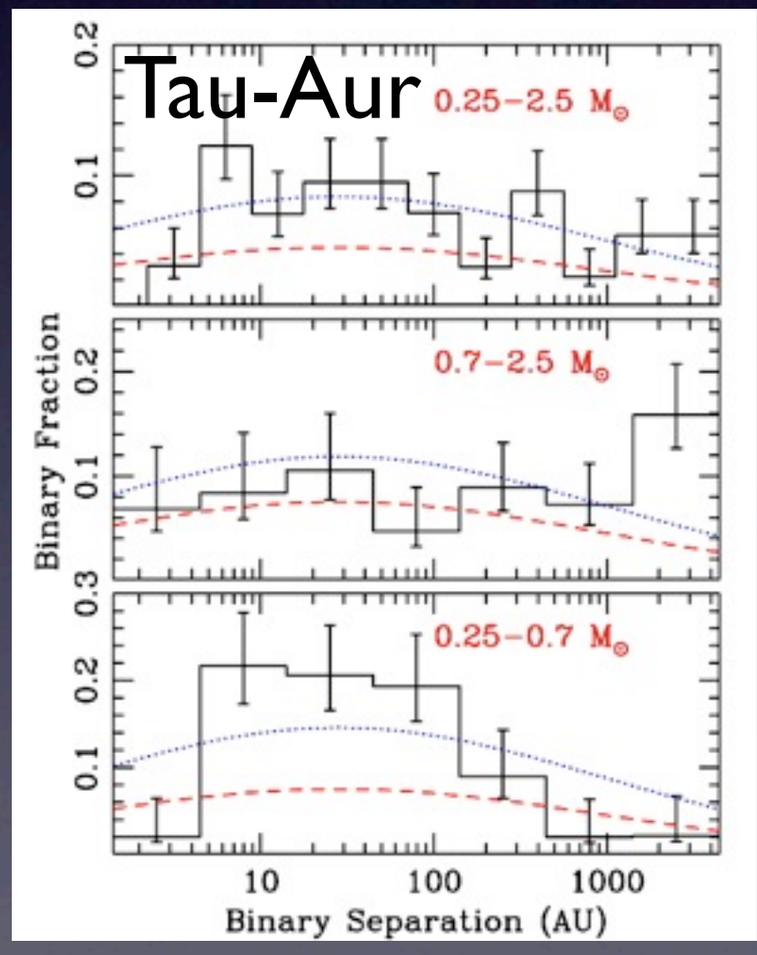
T Tauri stars multiplicity

- Clear trends as a function of stellar mass



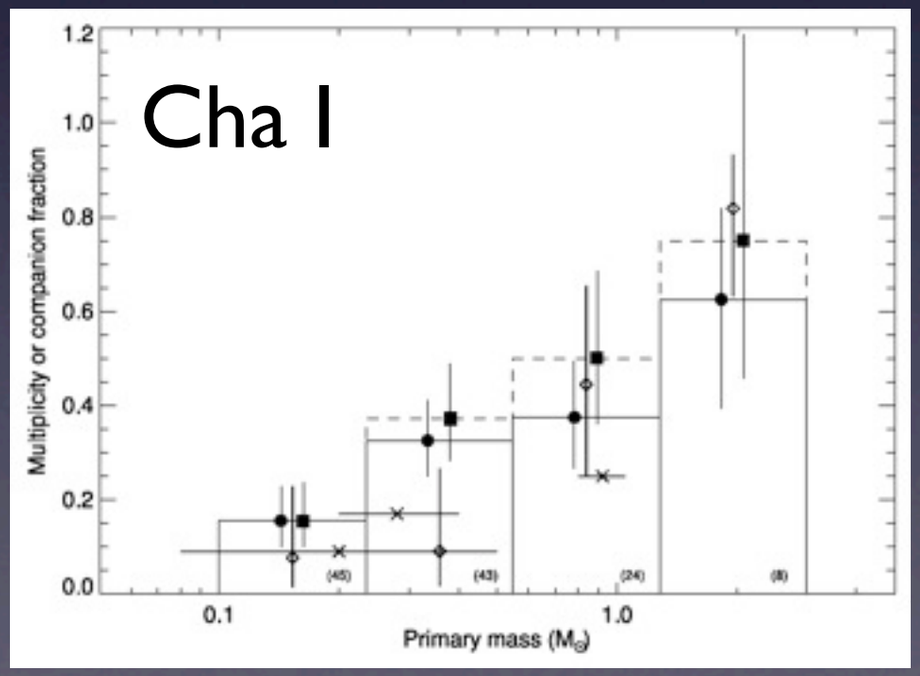
Lafrenière et al. (2008)

Kraus et al. (2011)



T Tauri stars multiplicity

- Clear trends as a function of stellar mass
  - similar to the MS trends
  - dynamics not important? too late?



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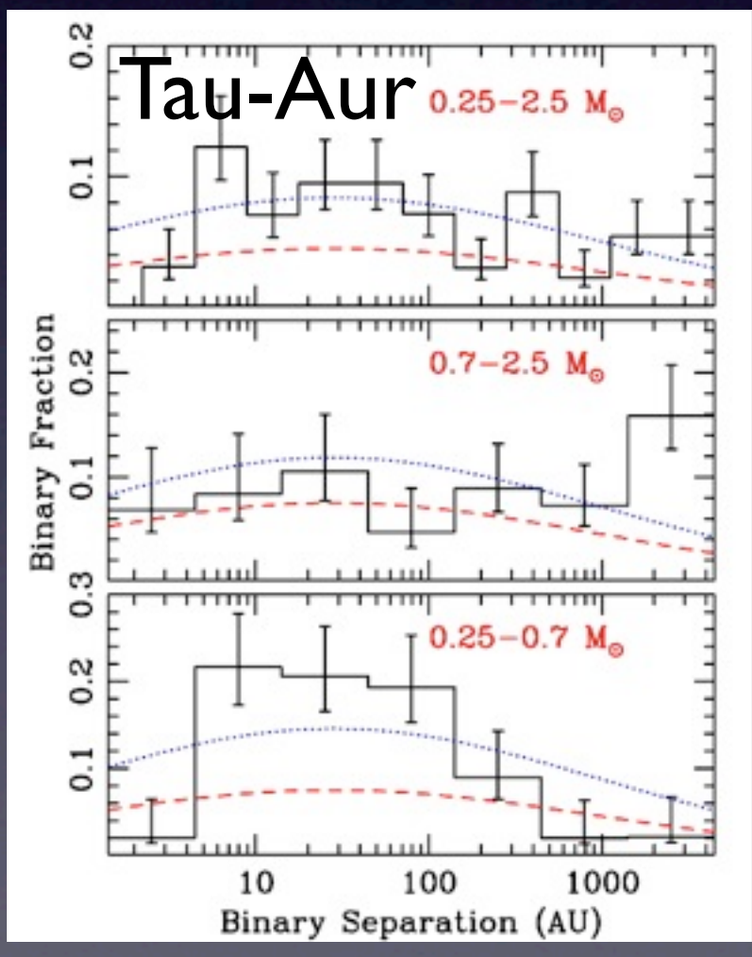
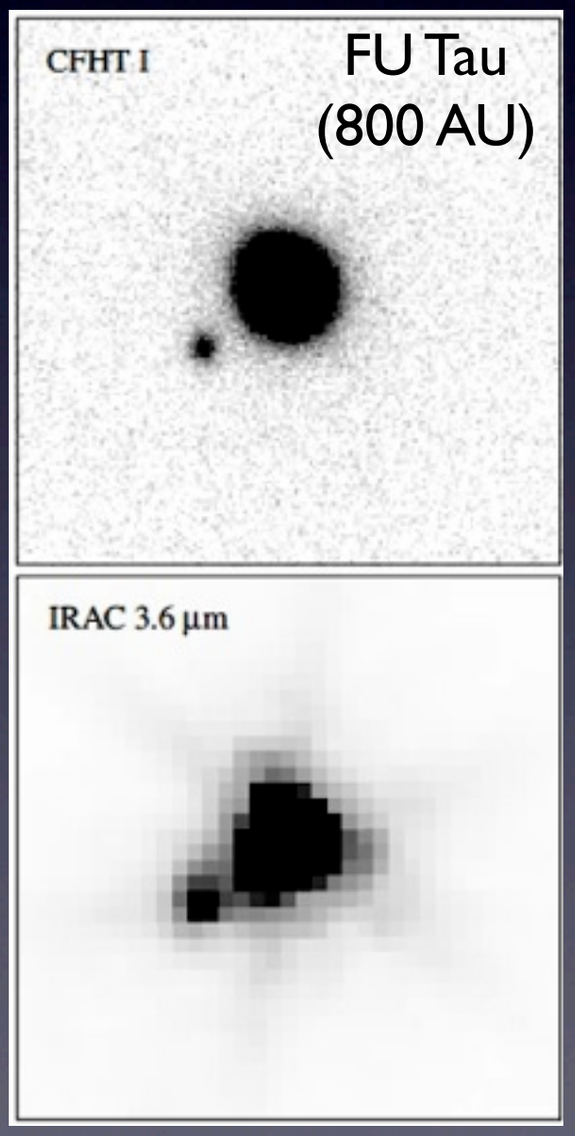


T Tauri stars multiplicity

- Clear trends as a function of stellar mass
  - similar to the MS trends
  - dynamics not important? too late?
  - some wide BD-BD pairs
    - (see A. Kraus' talk)

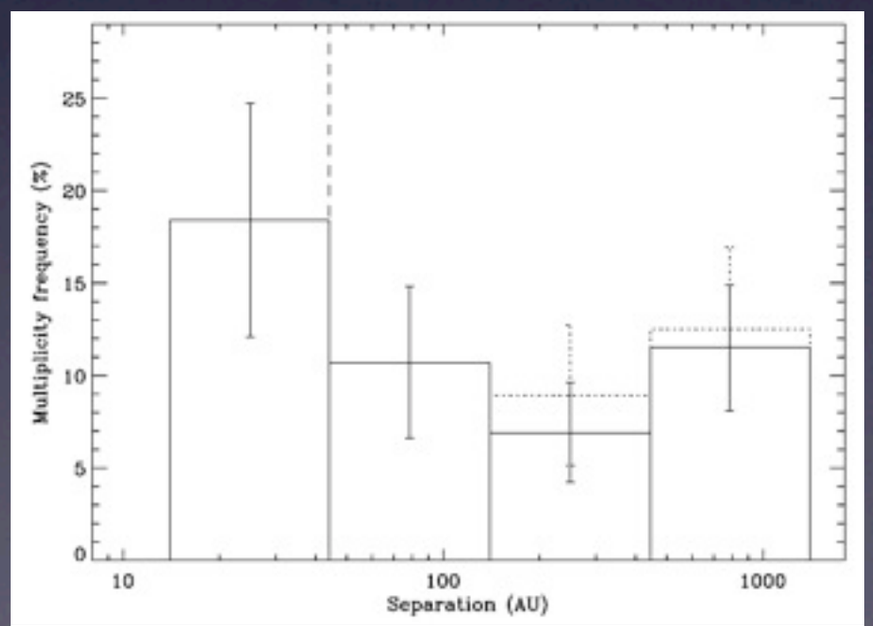


Luhman et al. (2009)

Class I protobinaries

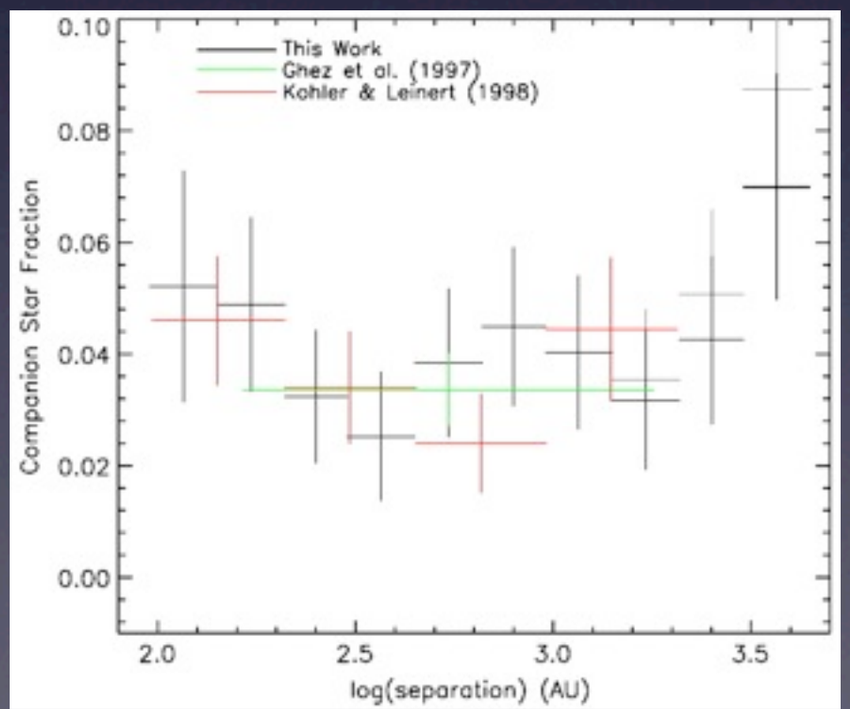
- Fairly large samples now known, allowing statistical multiplicity studies (down to 15 AU)
- High multiplicity, comparable to T Tauri stars in

Tau-Aur and other associations



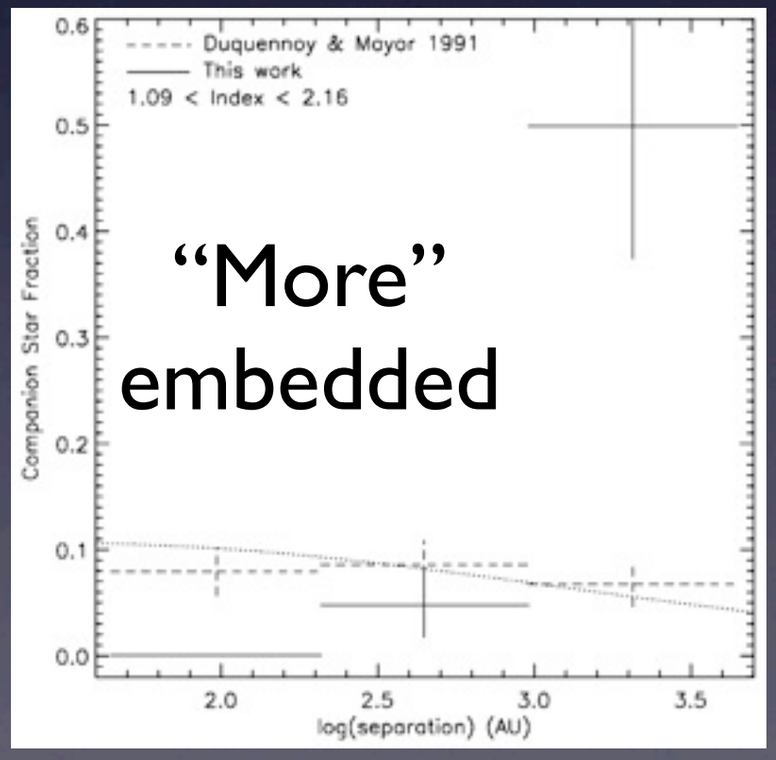
Connelley et al. (2008)

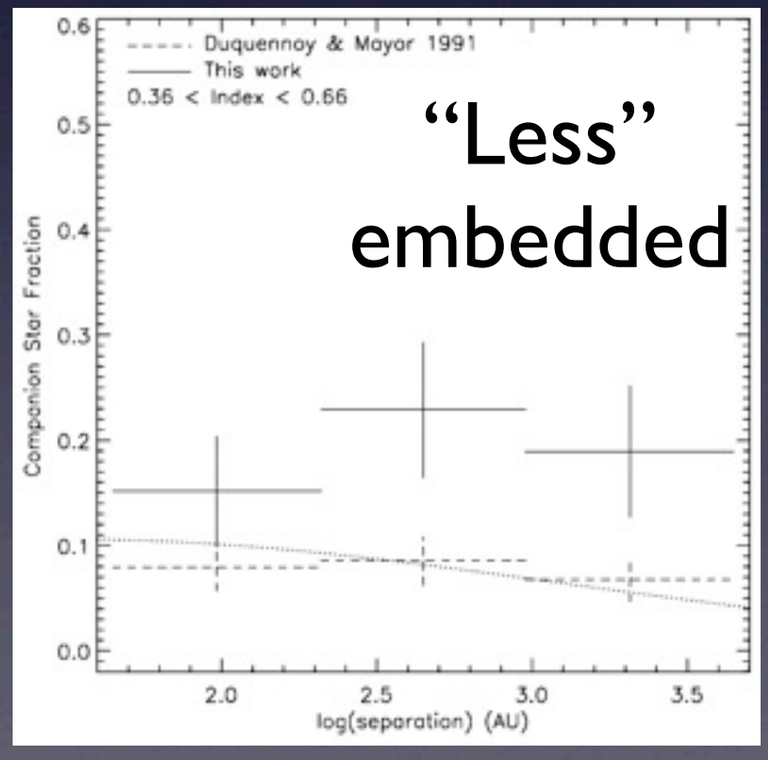
Duchêne et al. (2007)



Class I protobinaries

- Tentative evolutionary trend
  - more embedded systems are much wider
  - “small groups” instead of binaries? or real?





Connelley et al. (2008)

Class I protobinaries

- Tentative evolutionary trend
  - more embedded systems are much wider
  - "small groups" instead of binaries?

- Tentative trend with environment
  - Orion (not ONC!) Class I binaries are predominantly tight, with separation close to/under 100 AU
    - *Duchêne et al. (2007), Connelley et al. (2008)*

Class I protobinaries

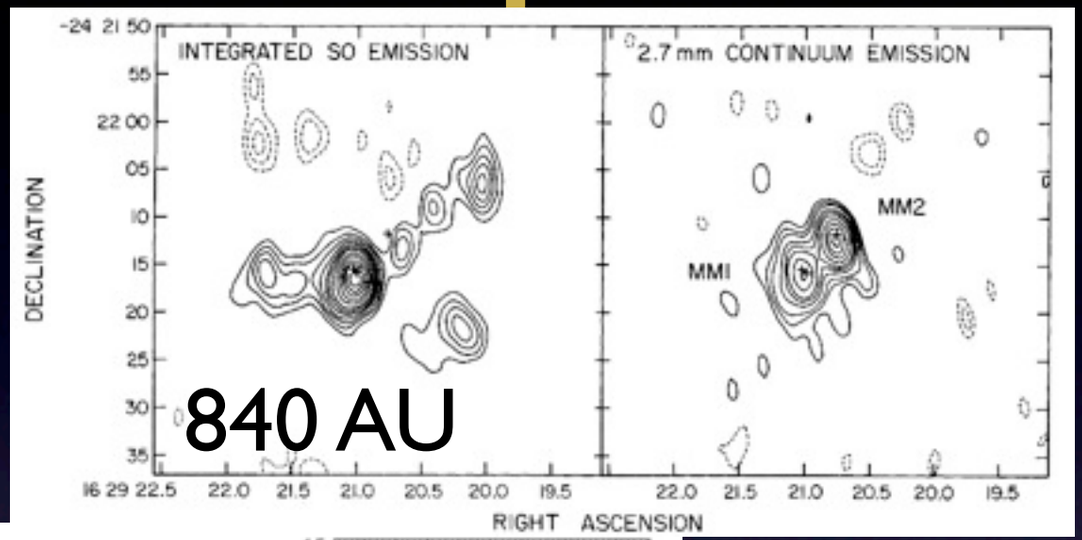
- Tentative evolutionary trend
  - more embedded systems are much wider
  - “small groups” instead of binaries?
- Tentative trend with environment
  - Orion (not ONC!) Class I binaries are predominantly tight, with separation close to/under 100 AU
- Mass ratios cannot be reliably estimated!

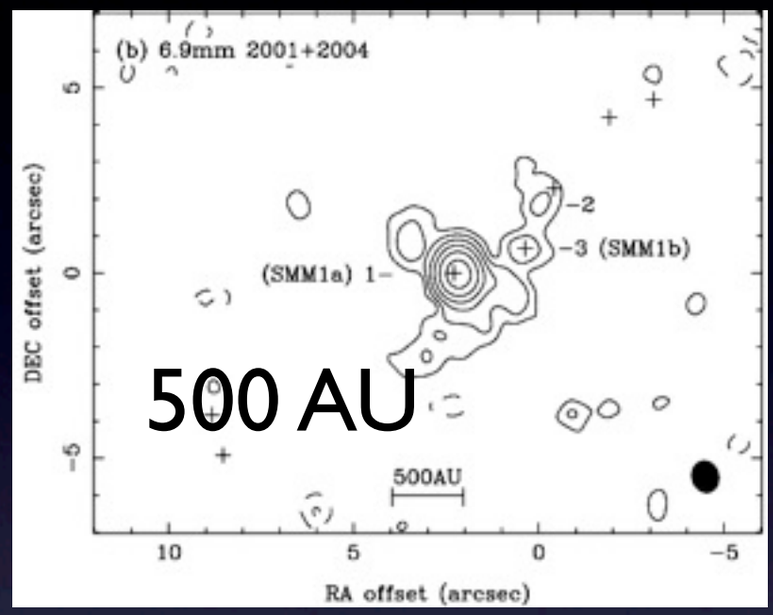
Class 0 protobinaries

- This is the new frontier, as close to the "initial conditions of multiplicity" as can be
- Difficult observationally as massive envelopes get in the way (need interferometry)
- Large distances limit linear resolution
- Envelope/disk mass estimates, how does that translate to final mass ratio?

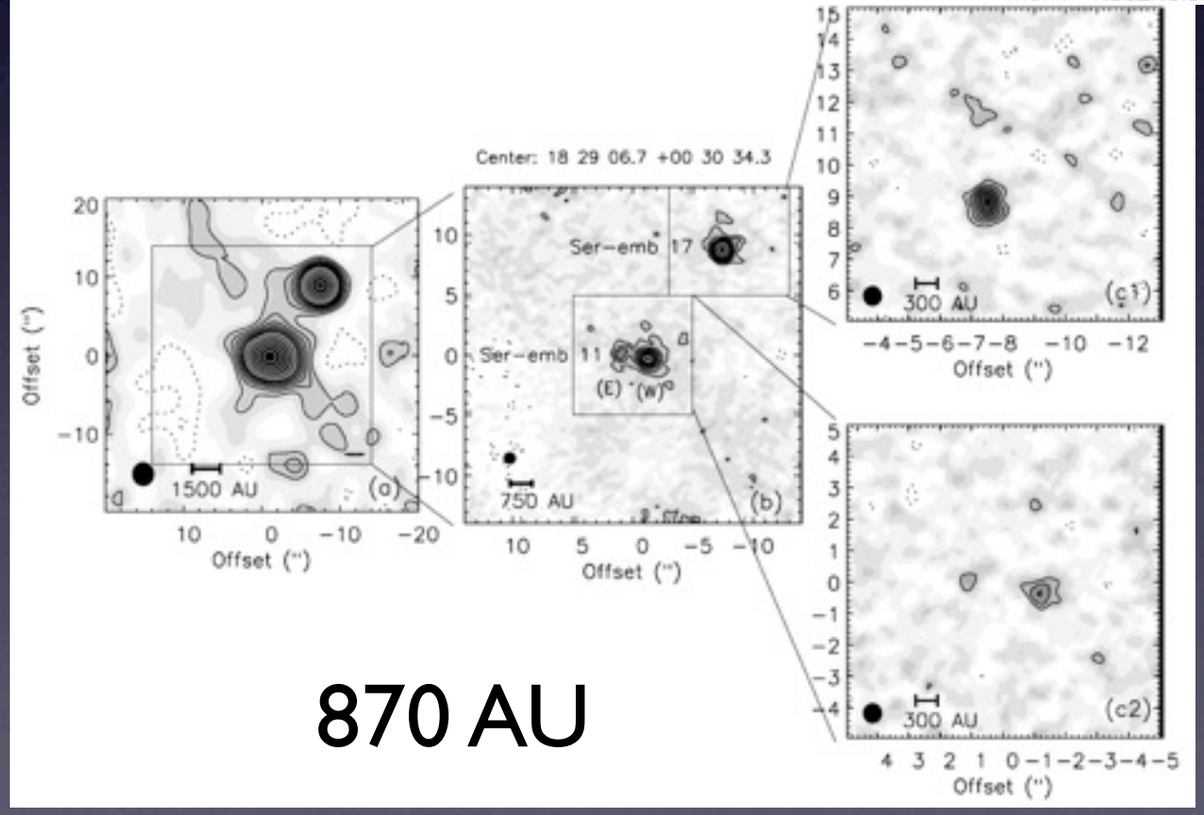
Class 0 protobinaries

Mundy et al. (1992)

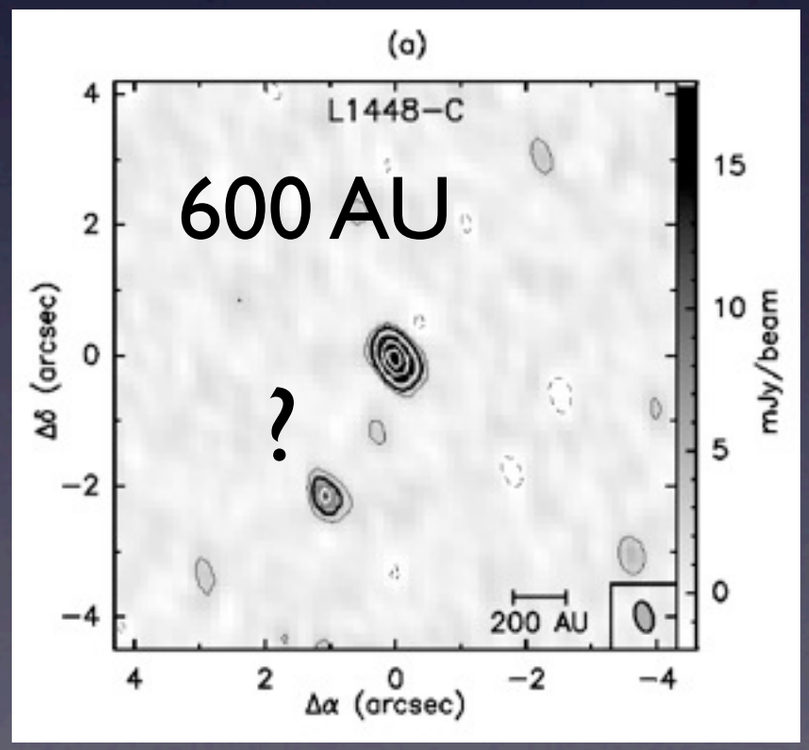




Choi (2010)



Enoch et al. (2011)



Maury et al. (2010)

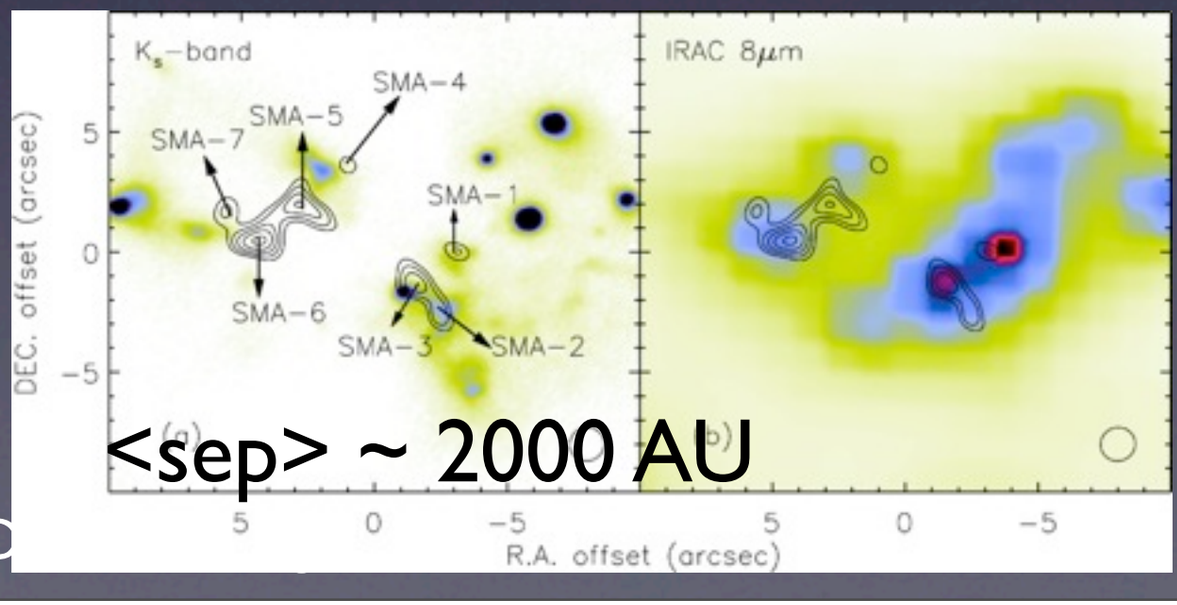
The formation of VLMSs and BDs - Garching - Oct 12 2011

Class 0 protobinaries

- Low frequency at separation 100-2000 AU
  - ~10% instead of 20-30% in TTS and Class I sources
  - further orbital evolution? too early for fragmentation?

- Some systems in the 1000s of AU, but are these physically bound or "small groups"?

Teixiera et al. (2007)

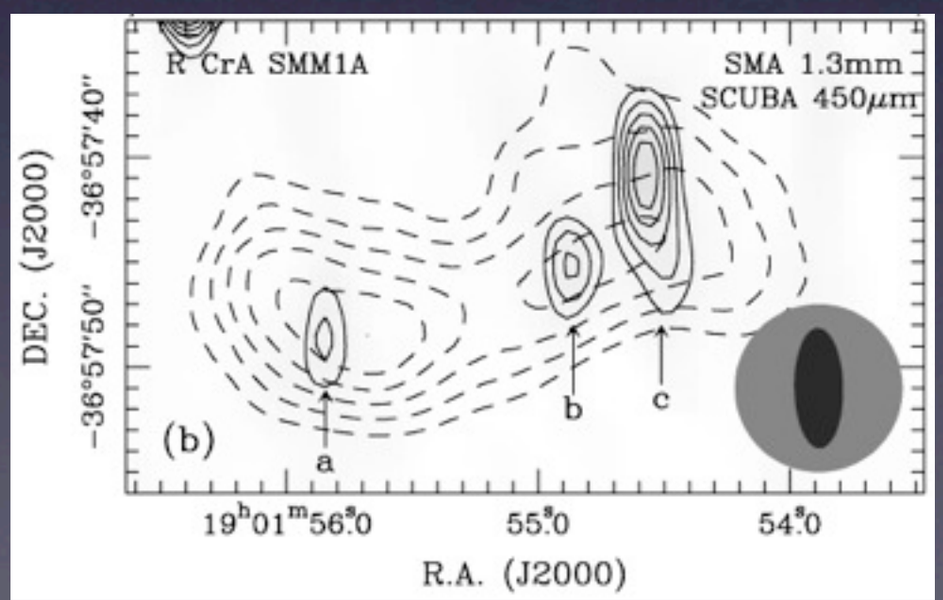


<sep> ~ 2000 AU

The formation of VLMSs and BD

Core fragmentation?

- Going one step further back in time?
- Even more challenging observationally...
  - One example, but will it form a bound system?
    - only 10% of the total mass is in the fragments



Chen et al. (2010)

VeLLOs

- These are possible precursors to VLMS and BDs (although status still under debate)
- Too few candidates to reach any significant conclusion regarding their multiplicity properties
  - at least one wide binary (see T. Huard's talk)
- Will need reinvestigating in the future...

On the degree of multiplicity

- Single stars (N=1) are the minority in the PMS phase (~25-30%), except in clusters (?)
  - Not too many systems can be disrupted later
- High-order systems (N>2) are relatively common among PMS populations
  - ~ 1 in 3 "binary" is a multiple
  - important for subsequent dynamical evolution

Spectroscopic binaries

- Tight systems (<10-100 AU) form through later fragmentation (in a disk?)
  - important role played by outer companions to exchange angular momentum
- They already exist by the T Tauri phase
- Relative lack of knowledge in the early phases, unfortunately (see P. Almeida's talk)

Is multiplicity universal?

- Difficult to test really different environments because of (selection and observational) biases
- Protobinaries are not yet conclusive (lack of proto-clusters studied)
- Deficit of wide (>1000 AU) T Tauri binaries in clusters presumably is intrinsic (space density)
  - Is this related to the lower multiplicity at < 500 AU ?

Summary

- The multiplicity properties of the PMS populations can inform us on the physics of core fragmentation *and* later evolution
- Class I and Class 0 protobinary populations are now being established statistically
- Still only a partial picture, especially in the earliest phases (wait for ALMA!)
- VLMS/BD regime unexplored in Class 0/I