CONSTRAINING THE OUTCOME OF STAR FORMATION
SINGLE STARS AND BINARY SYSTEMS

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ISIMA @ KIAA - 26 July 2011

OUTLINE

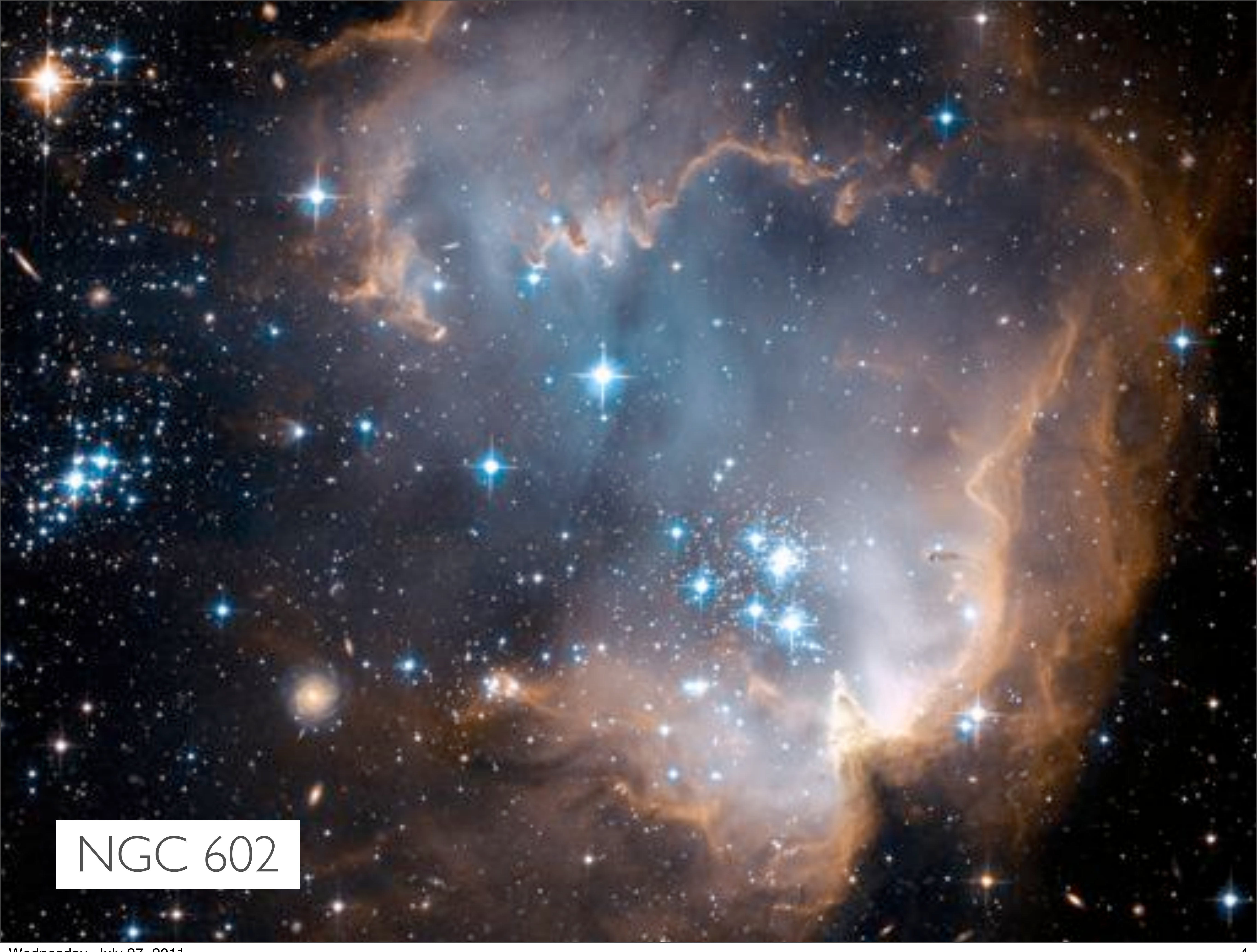
(1) Star formation and binarity

(2) Does a universal IMF imply universal star formation?

(3) The primordial binary population

(4) The origin of very wide binary systems

(1)
STAR FORMATION AND BINARITY


NGC 602

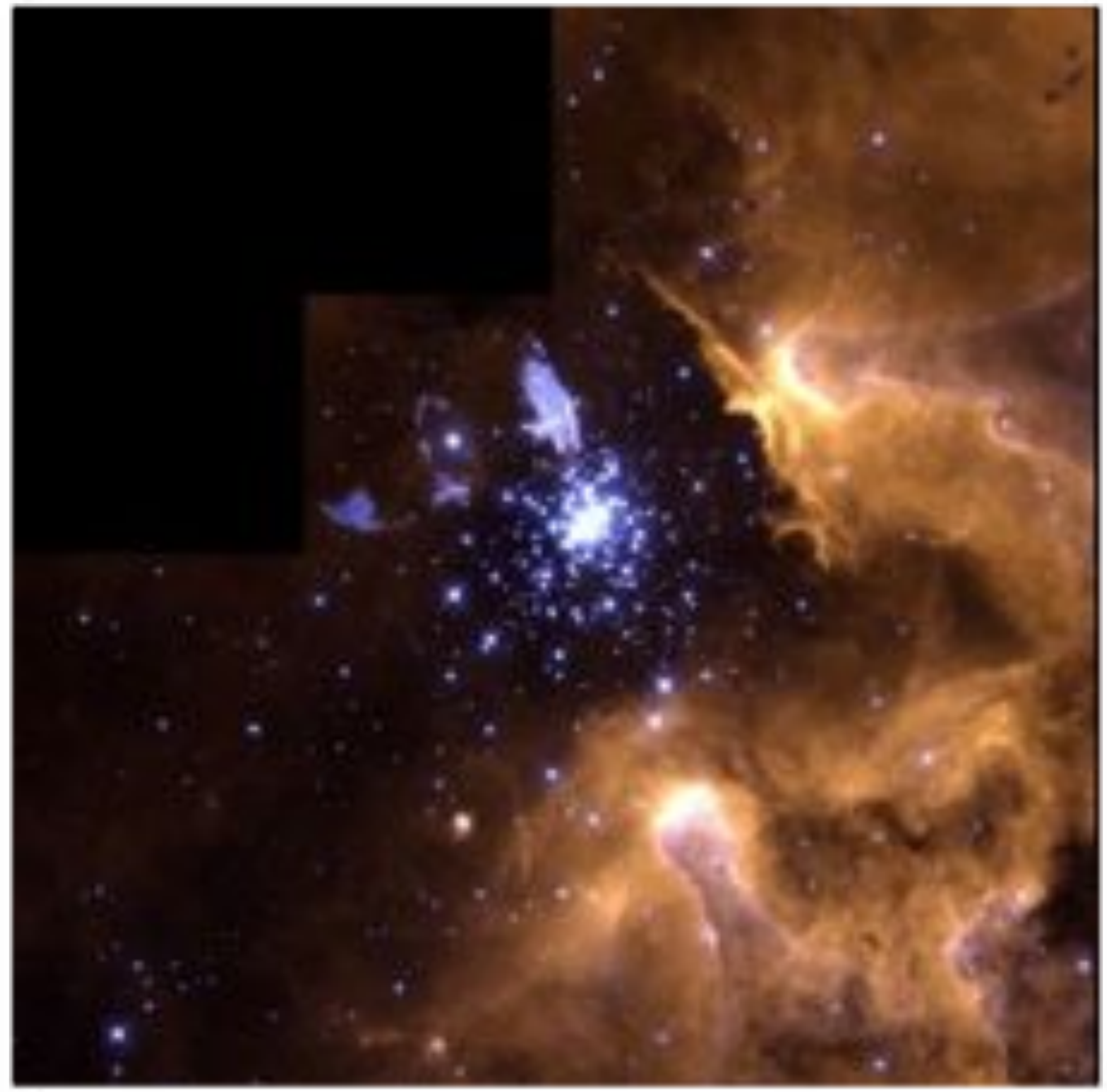
STAR FORMATION

Most young stars are a member of a star cluster

Carpenter 2000, Clarke et al. 2000, Lada & Lada 2003, ...

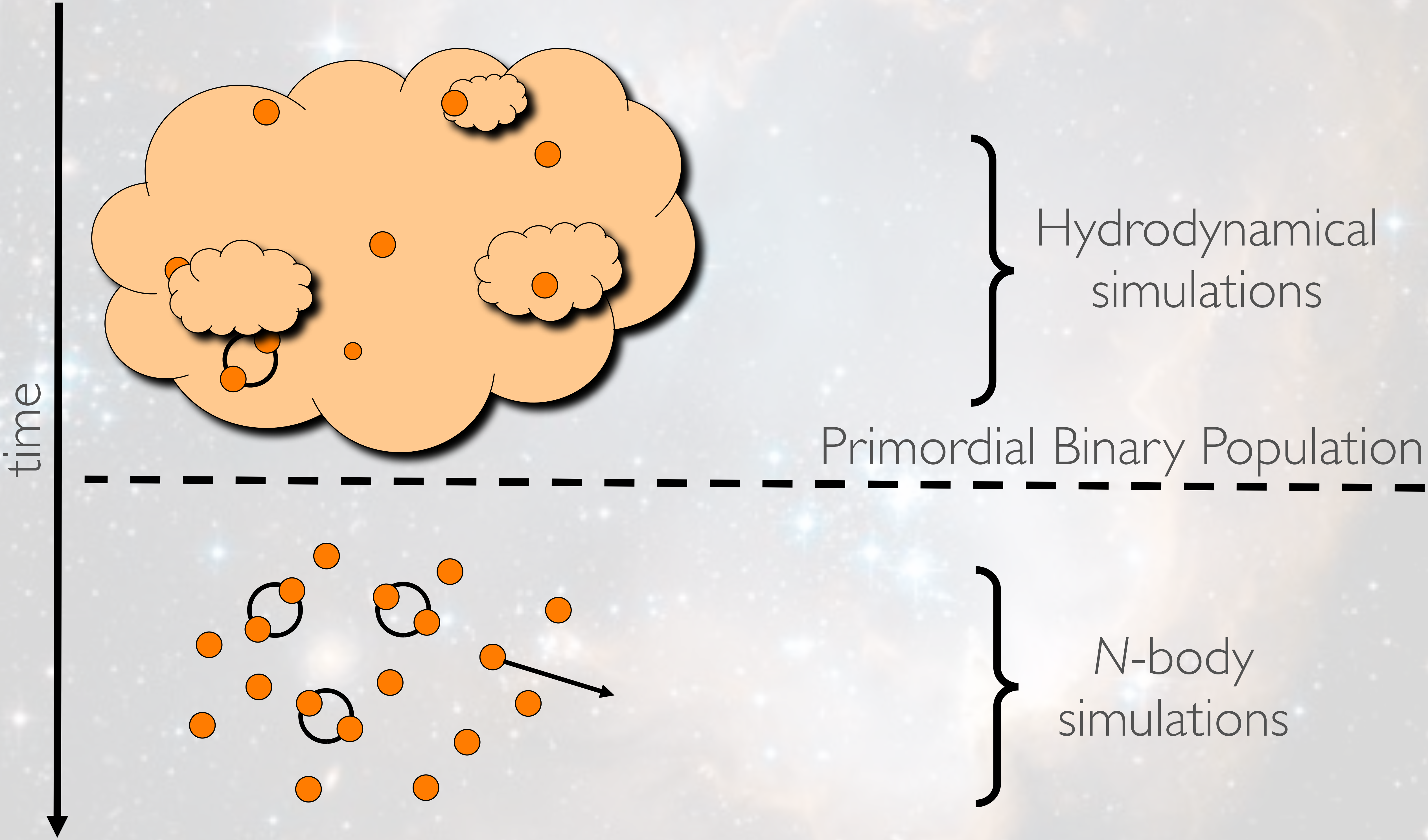
Most young stars are a member of a binary or multiple system

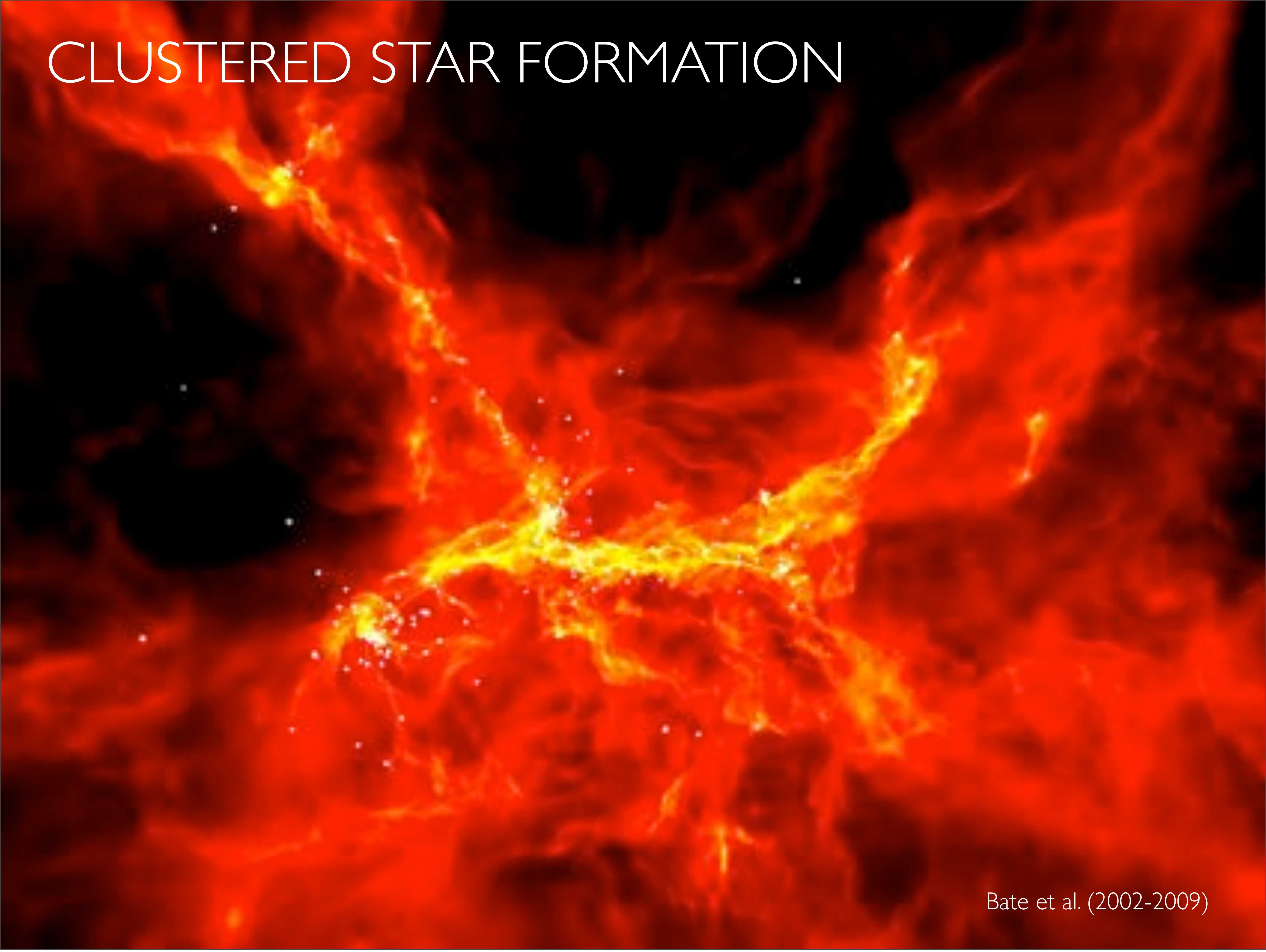
Duquennoy & Mayor 1992, Fisher & Marcy 1992, Mason et al. 1995, Shatsky & Tokovinin 2002, Kouwenhoven et al. 2007, Kobulnicky & Fryer 2007, ...



NGC 3063

THE PRIMORDIAL BINARY POPULATION

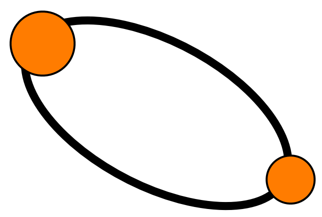



CLUSTERED STAR FORMATION
Bate et al. (2002-2009)

WHY PRIMORDIAL BINARIES?

Many hints about the star formation process

- Binary fraction
- Initial mass function (IMF)
- Mass ratio
- Period / semi-major axis
- Eccentricity
- Higher-order multiple systems



Modeling star formation and star cluster evolution

- End point for hydrodynamical simulations
- Initial conditions for N-body simulations

WHY PRIMORDIAL BINARIES?

Evolution and fate of star clusters

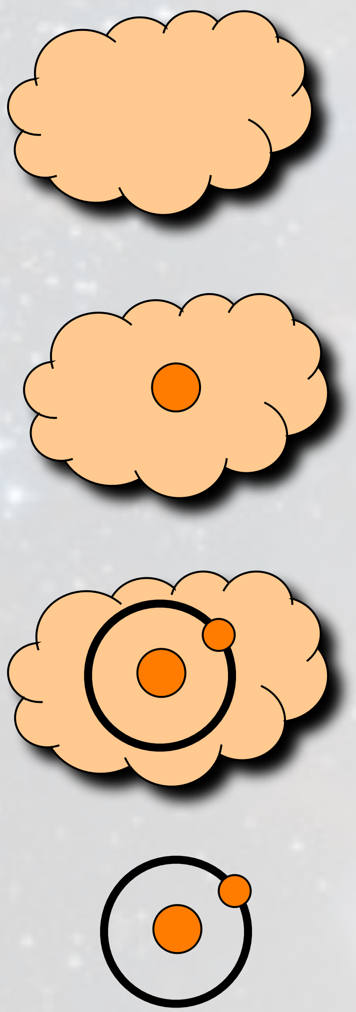
- Binaries dominate cluster evolution
- Disruption / survival of star clusters
- Origin of binaries in the field, OB runaway stars

“Exotic objects”

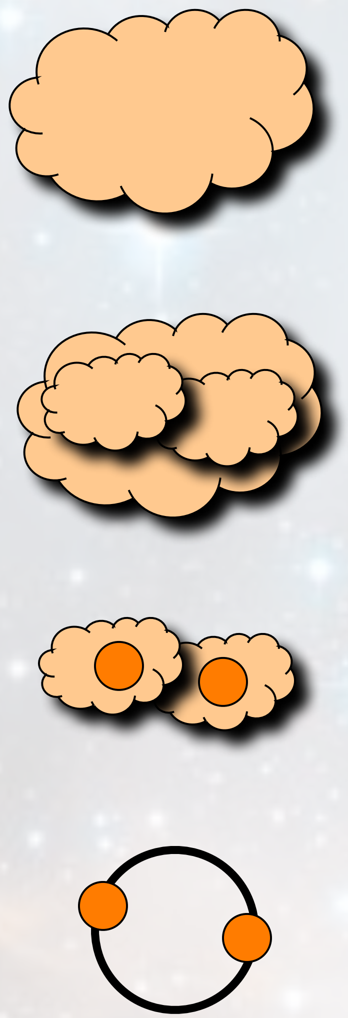
- X-ray binaries, short/long gamma ray bursts, supernovae type Ia, millisecond pulsars, blue stragglers, …

Exoplanets - formation, stability, habitability

BINARY STAR FORMATION MODES

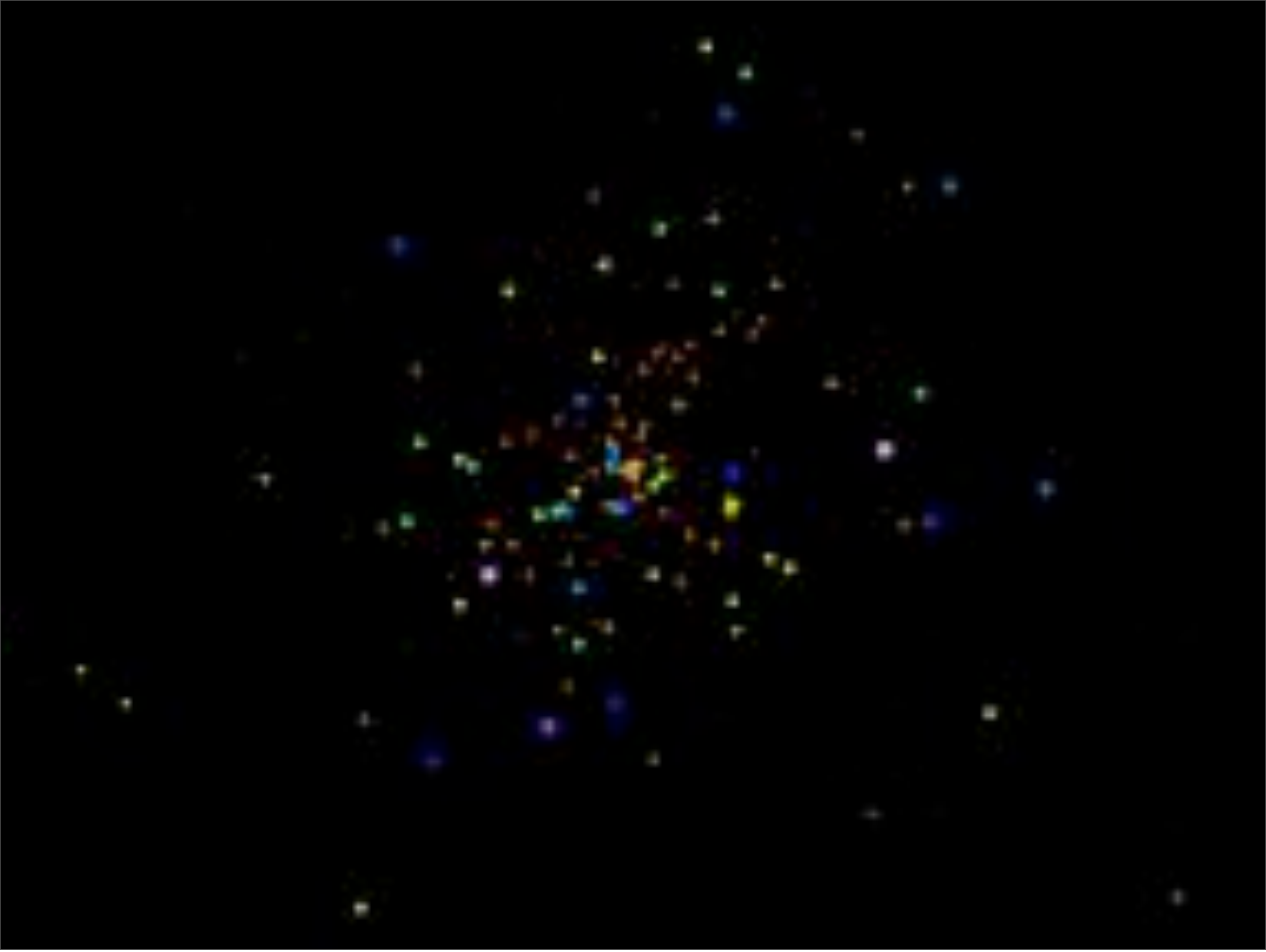


Disk fragmentation



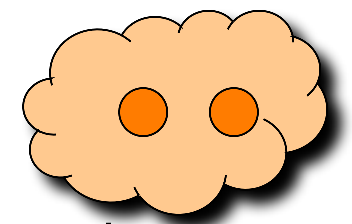
Core fission

Dynamical capture



ORIGIN AND EVOLUTION OF BINARY STARS

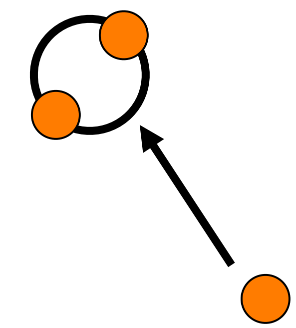
Star formation



- Primordial binaries are the fossil record of star formation

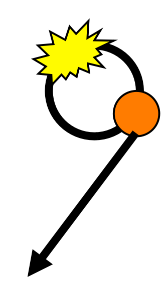
Dynamical evolution

- Exchange, ionization, modification, formation
- Most important in dense clusters



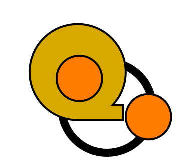
Stellar evolution

- Supernovae, stellar winds
- Most important during early stages



Binary evolution

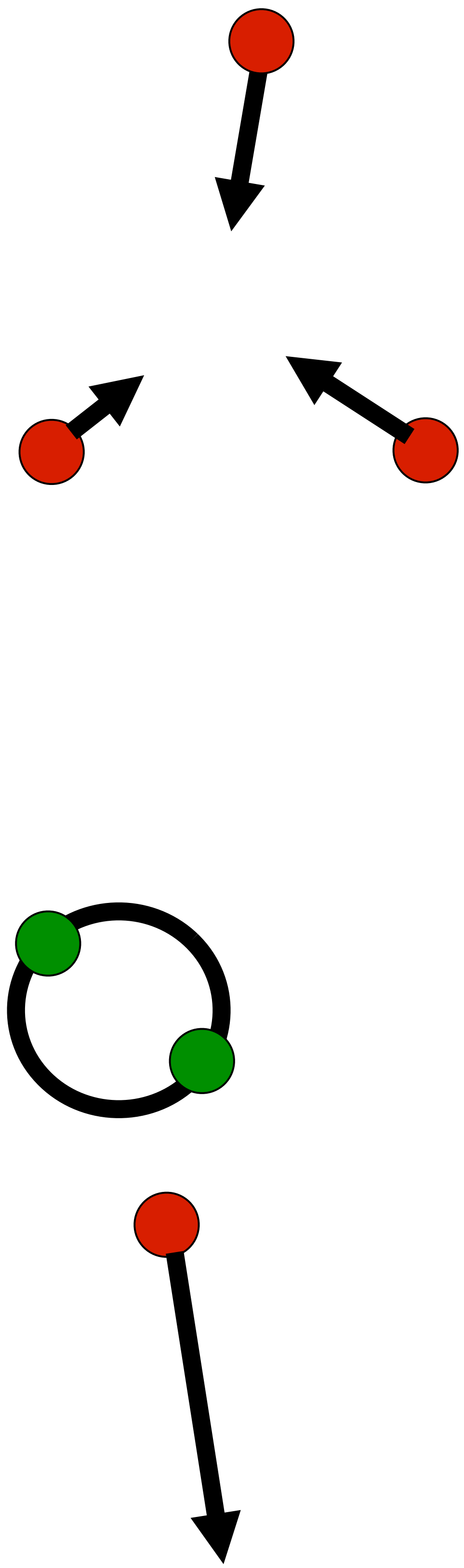
- Roche Lobe overflow, common envelope evolution
- Only for close binaries



BINARY FORMATION

- Under certain conditions, two stars may form a binary system dynamically
- Requires fine-tuned 3-body encounters (Goodman & Hut 1993)

$$\frac{dN_{\rm binaries}}{dt} = 0.75\,\frac{G^5 M^5 n^3}{\sigma^9}$$



BINARY DESTRUCTION

$$E_{fieldstar} = \frac{1}{2} M_{fieldstar} v^2_{fieldstar}$$

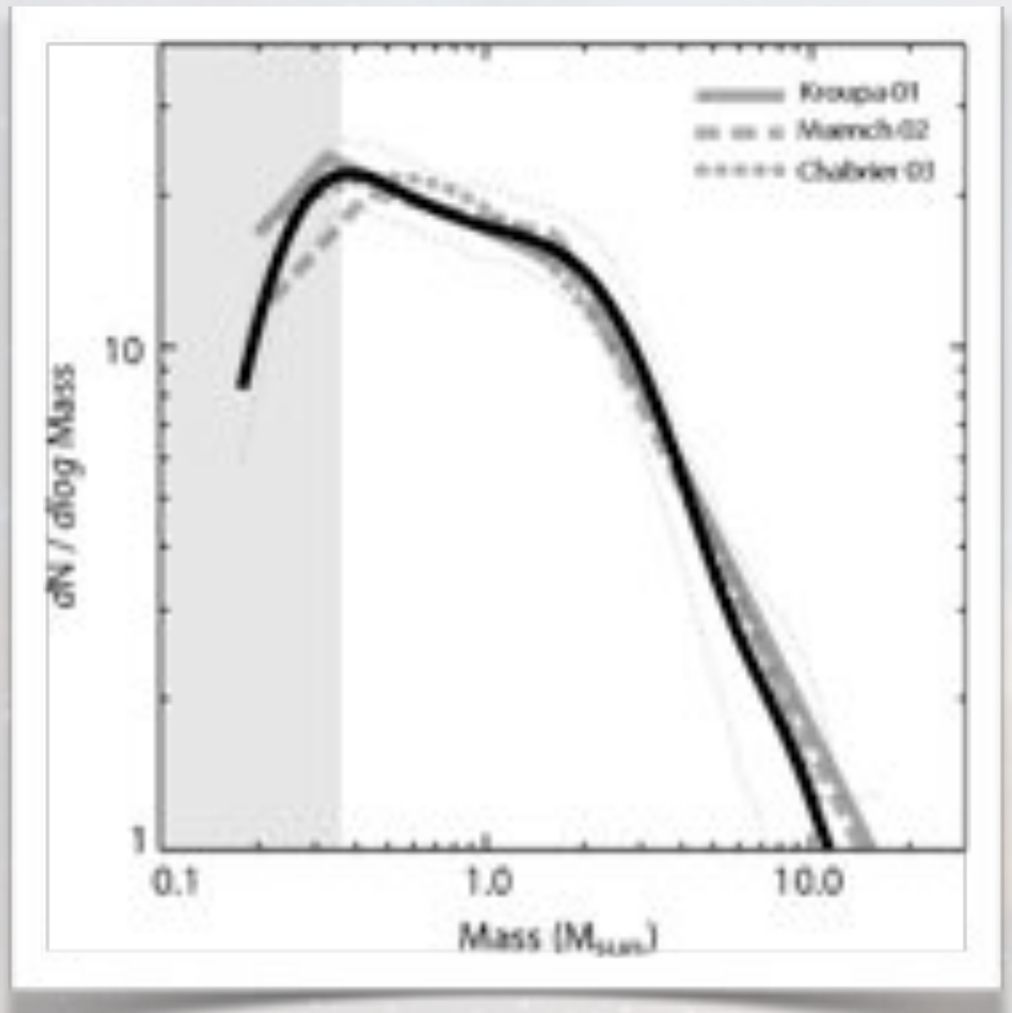
$E_{binary} > E_{fieldstar}$ hard binary

$E_{binary} < E_{fieldstar}$ soft binary

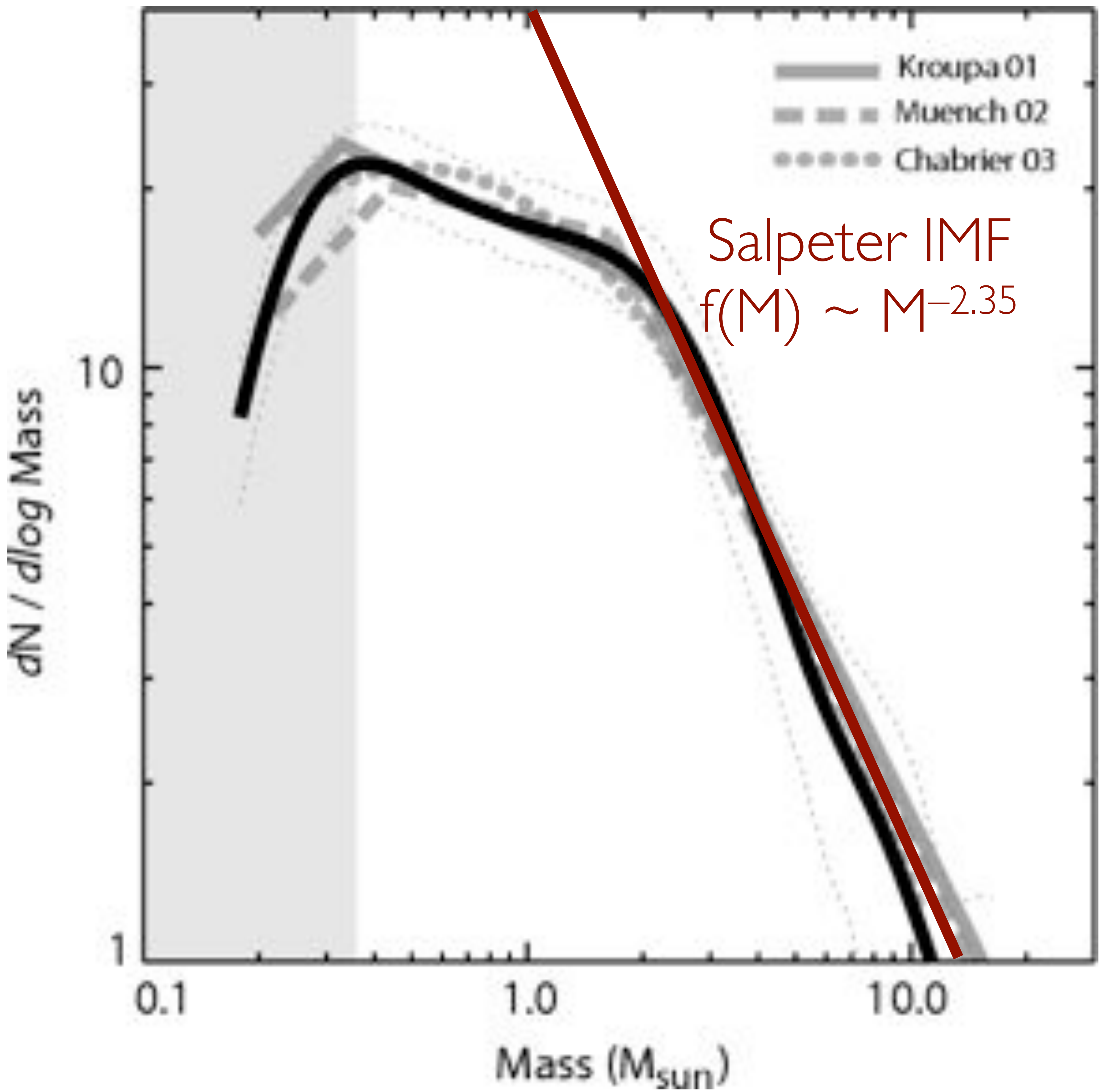
Heggie's law:

"Hard binaries get harder.
Soft binaries get softer
(and eventually destroyed)"

(2)
THE INITIAL MASS FUNCTION (IMF)



THE INITIAL MASS FUNCTION



Alves, Lombardi & Lada (2007)

MASS SEGREGATION

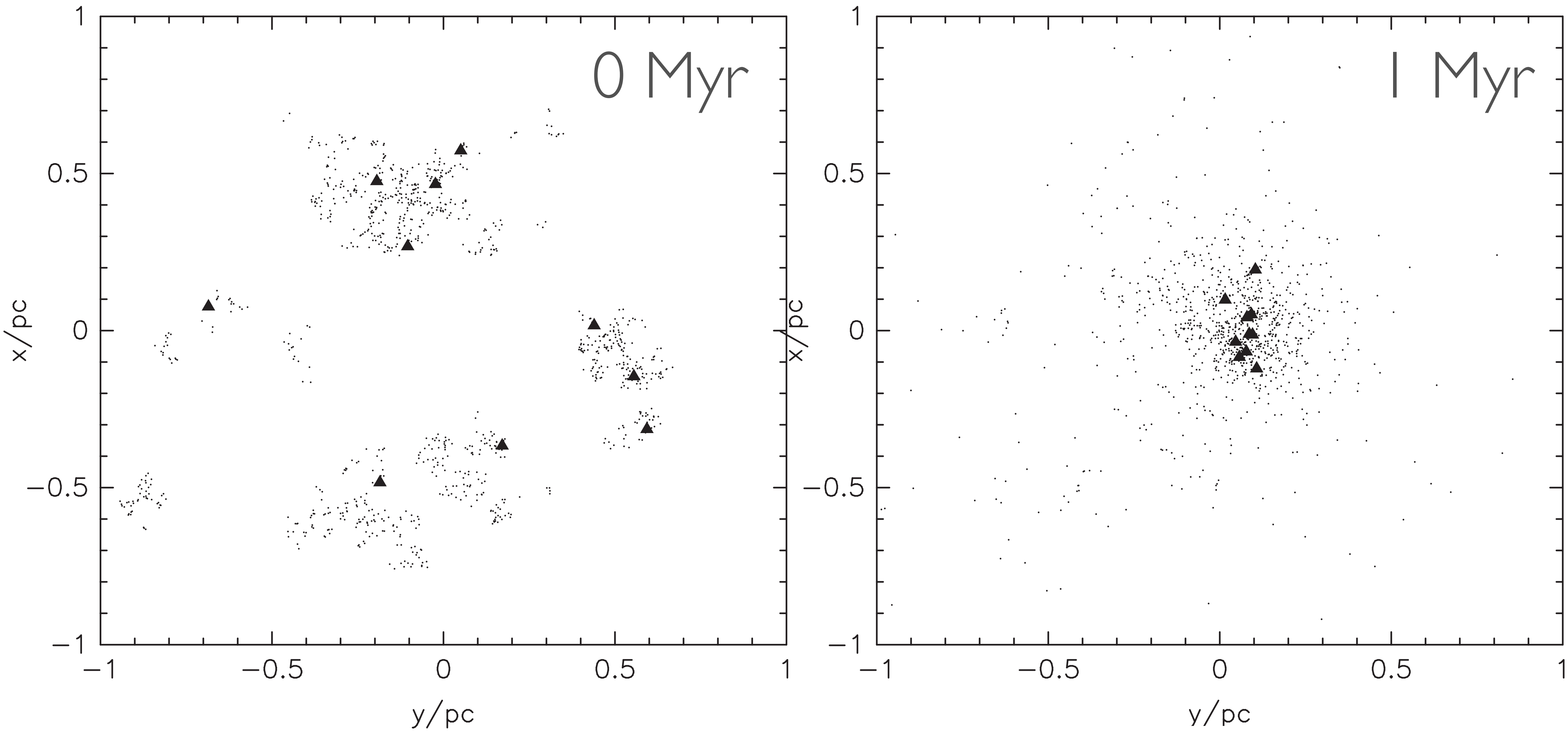
- Dynamical mass segregation timescales can be relatively slow in Plummer-like clusters (e.g. Orion - Bonnell & Davies 1998):

$$t_{ms}(m) \approx \frac{m}{\langle m \rangle} t_{relax} \qquad t_{relax} \approx \frac{0.138}{\ln N} \sqrt{\frac{R^3 N}{G \langle m \rangle}}$$

- Violent relaxation in star clusters with substructure results in rapid mass segregation (e.g. Orion - Allison et al 2009)

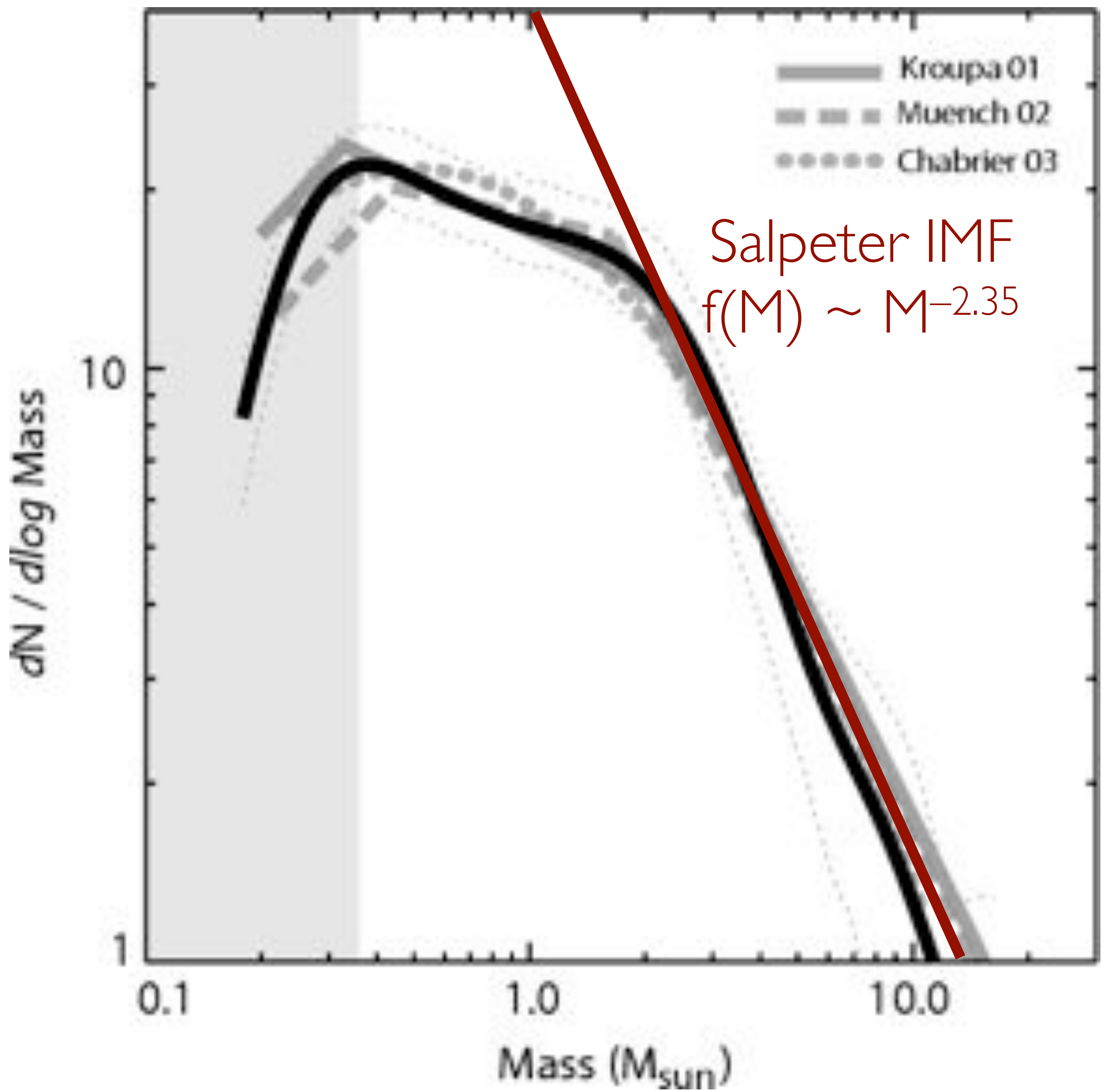
- Primordial mass segregation does not seem necessary. But can we really exclude it?

VIOLENT RELAXATION



Allison et al. (2009)

THE INITIAL MASS FUNCTION



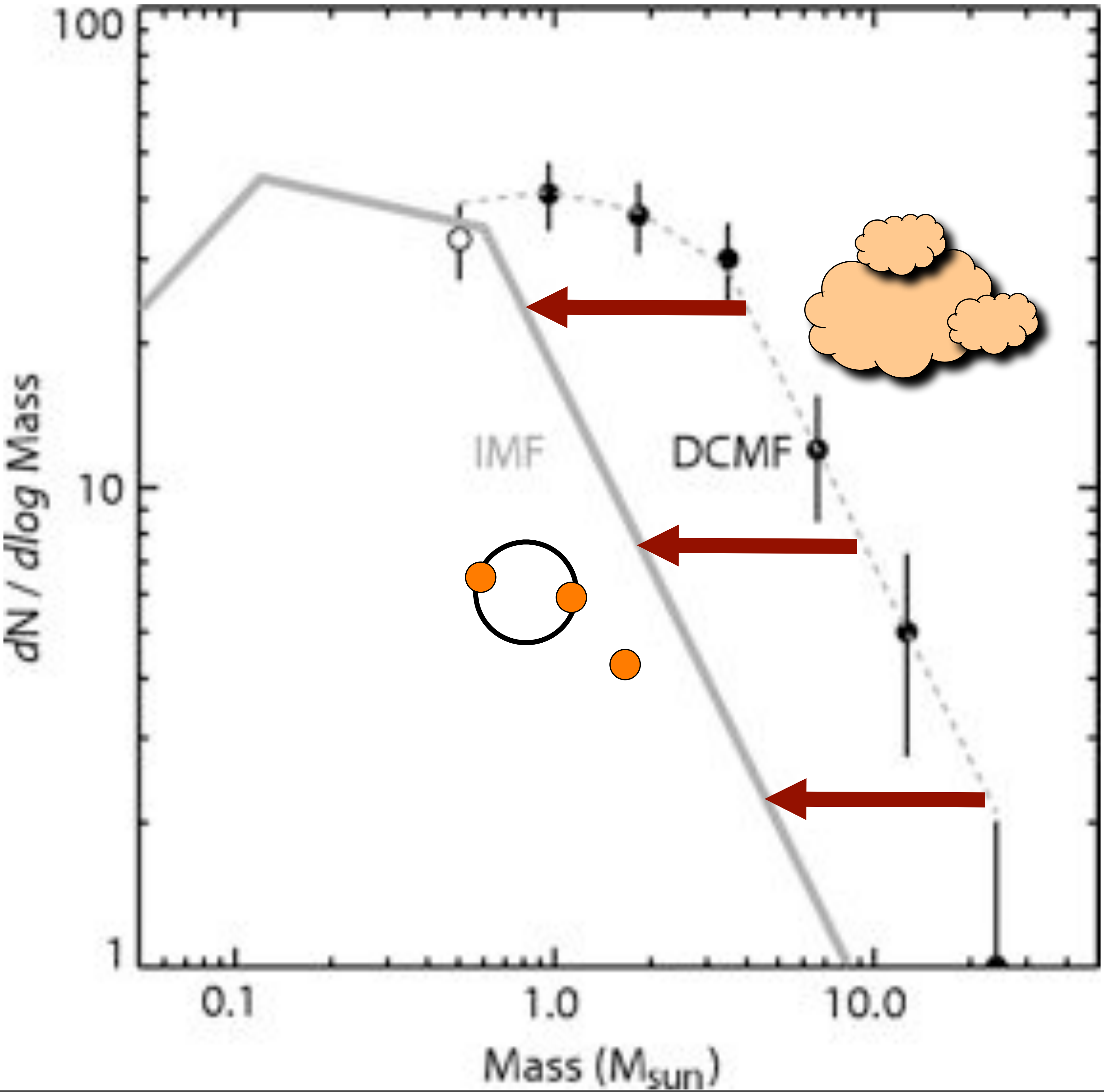
The IMF appears to be universal.

It is the same in many different environments

➙ is star formation universal?

Alves, Lombardi & Lada (2007)

THE CORE MASS FUNCTION



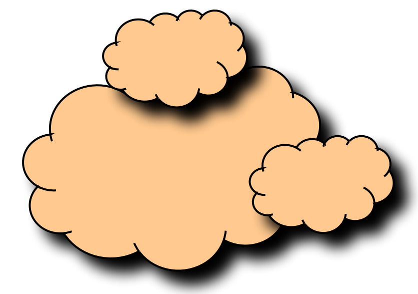
Does the core mass function (CMF) translate directly into the stellar initial mass function (IMF) ?

Alves, Lombardi & Lada (2007)

see also the talk by Patrick Hennebelle

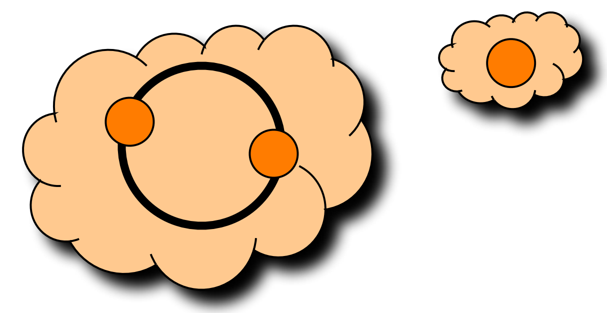
FROM GAS CLUMPS TO STARS

Core mass function (CMF)



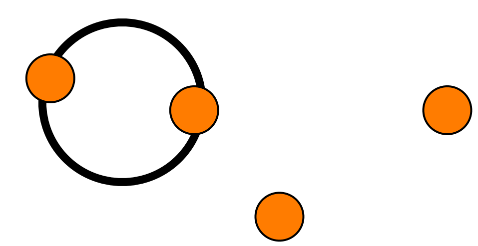
Core-to-system formation efficiency

System mass function (SMF)



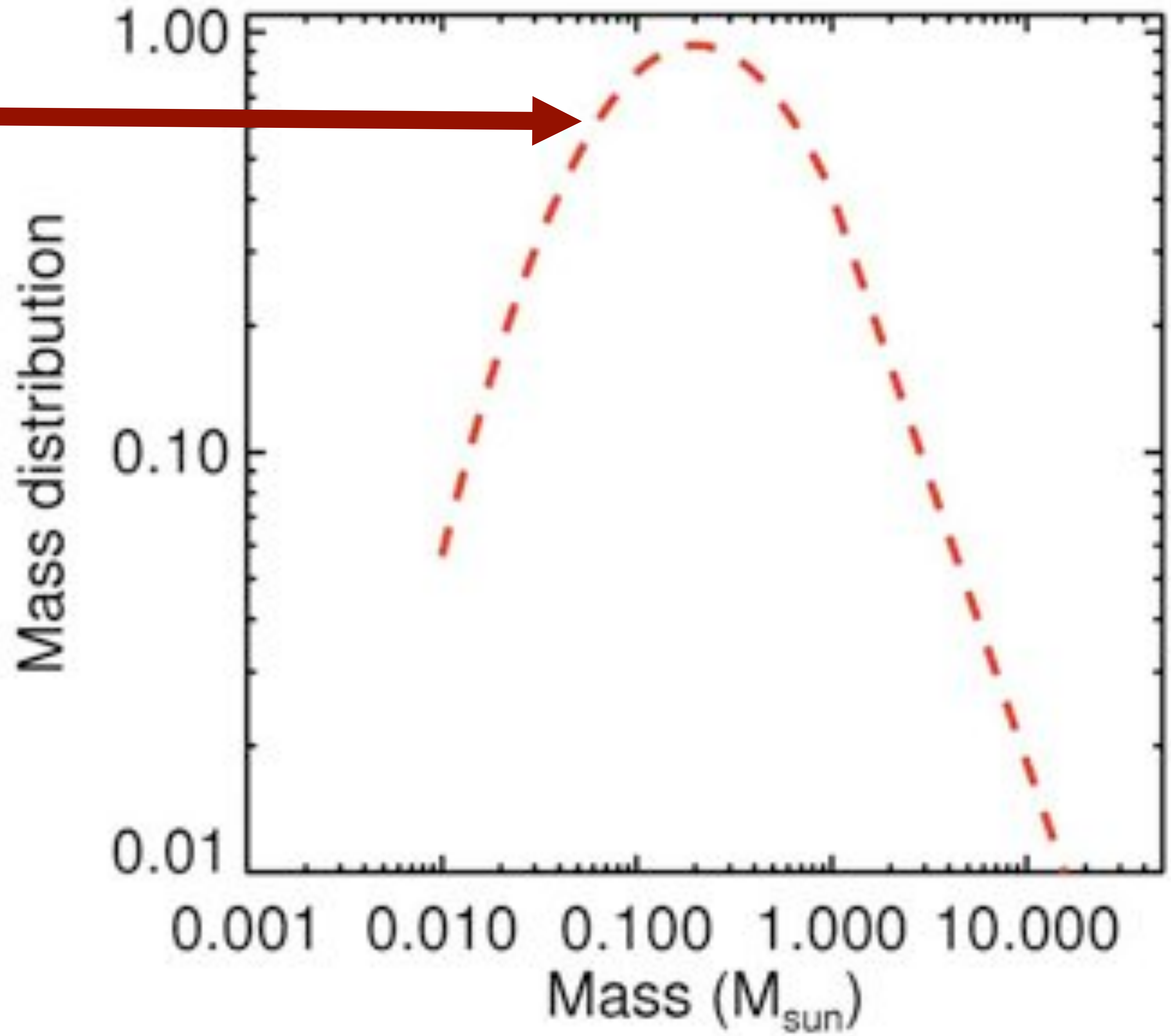
Binary fraction, mass ratios

Initial mass function (IMF)



FROM CMF TO IMF

Chabrier (2003) IMF



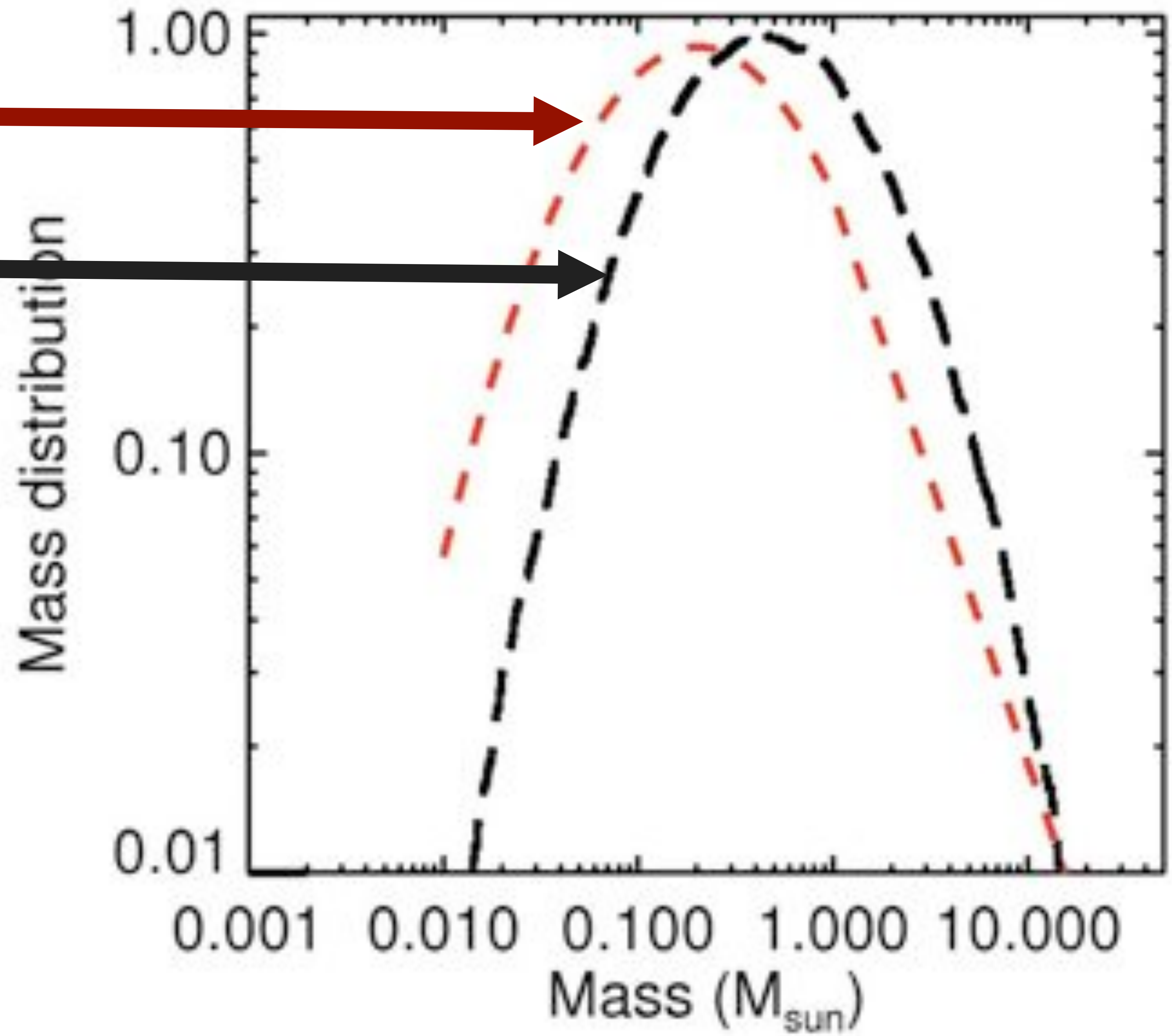
FROM CMF TO IMF

Chabrier (2003) IMF

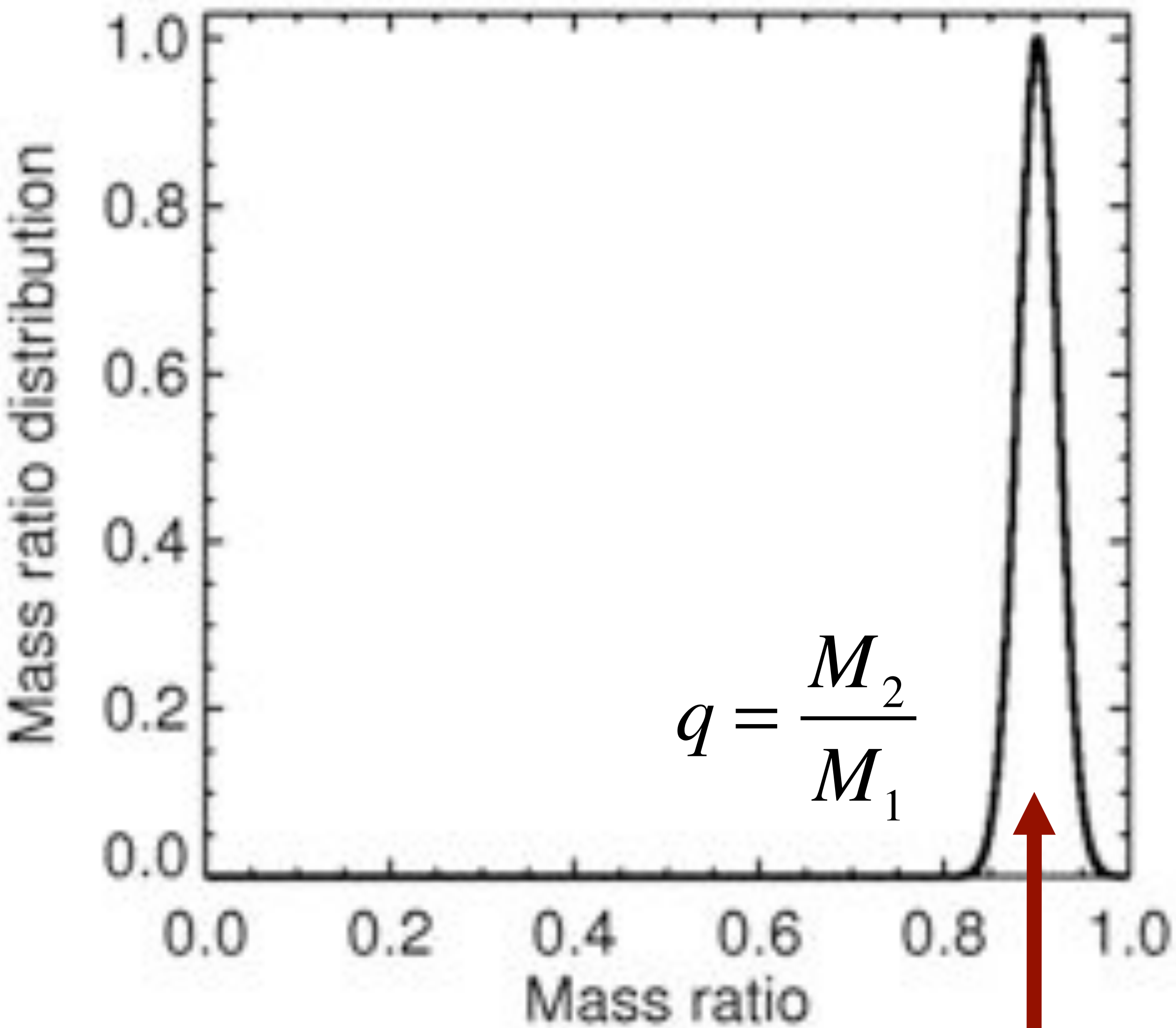
Core mass function

(Alves et al. 2007;

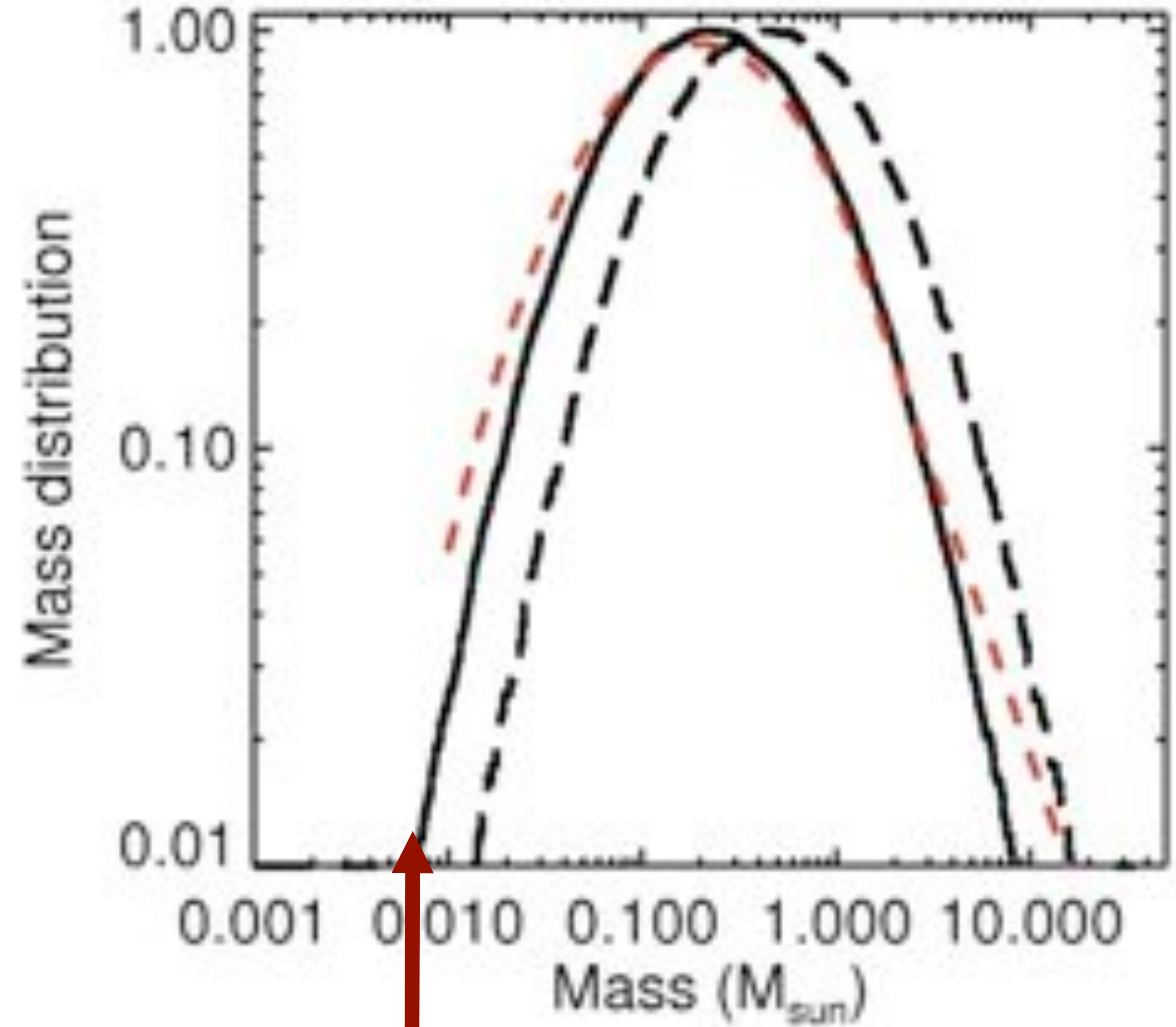
Nutter & Ward-Thomson 2007)



FROM CMF (DASHED BLACK CURVE) TO IMF (SOLID BLACK CURVE)

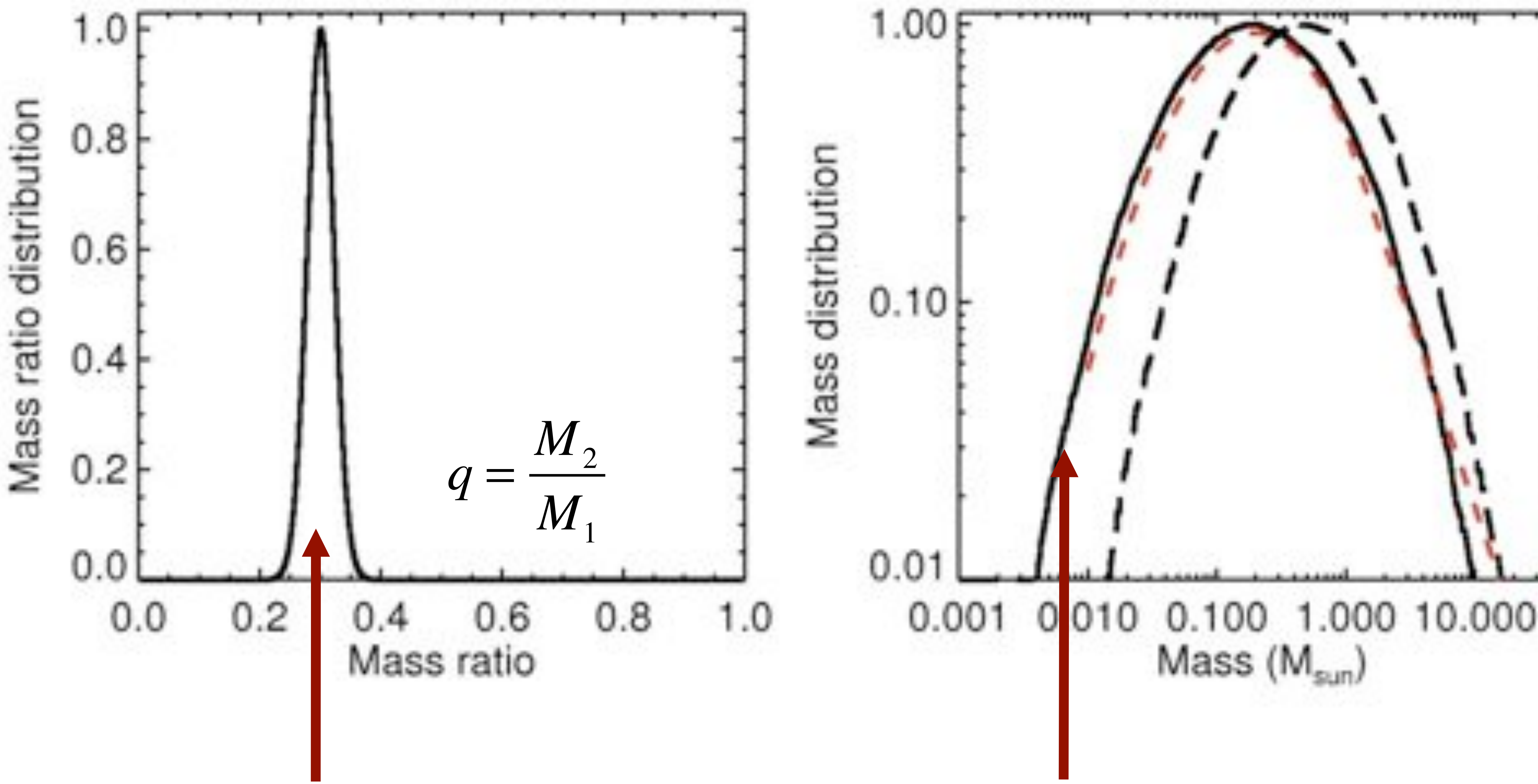


Mass ratio distribution



Resulting IMF

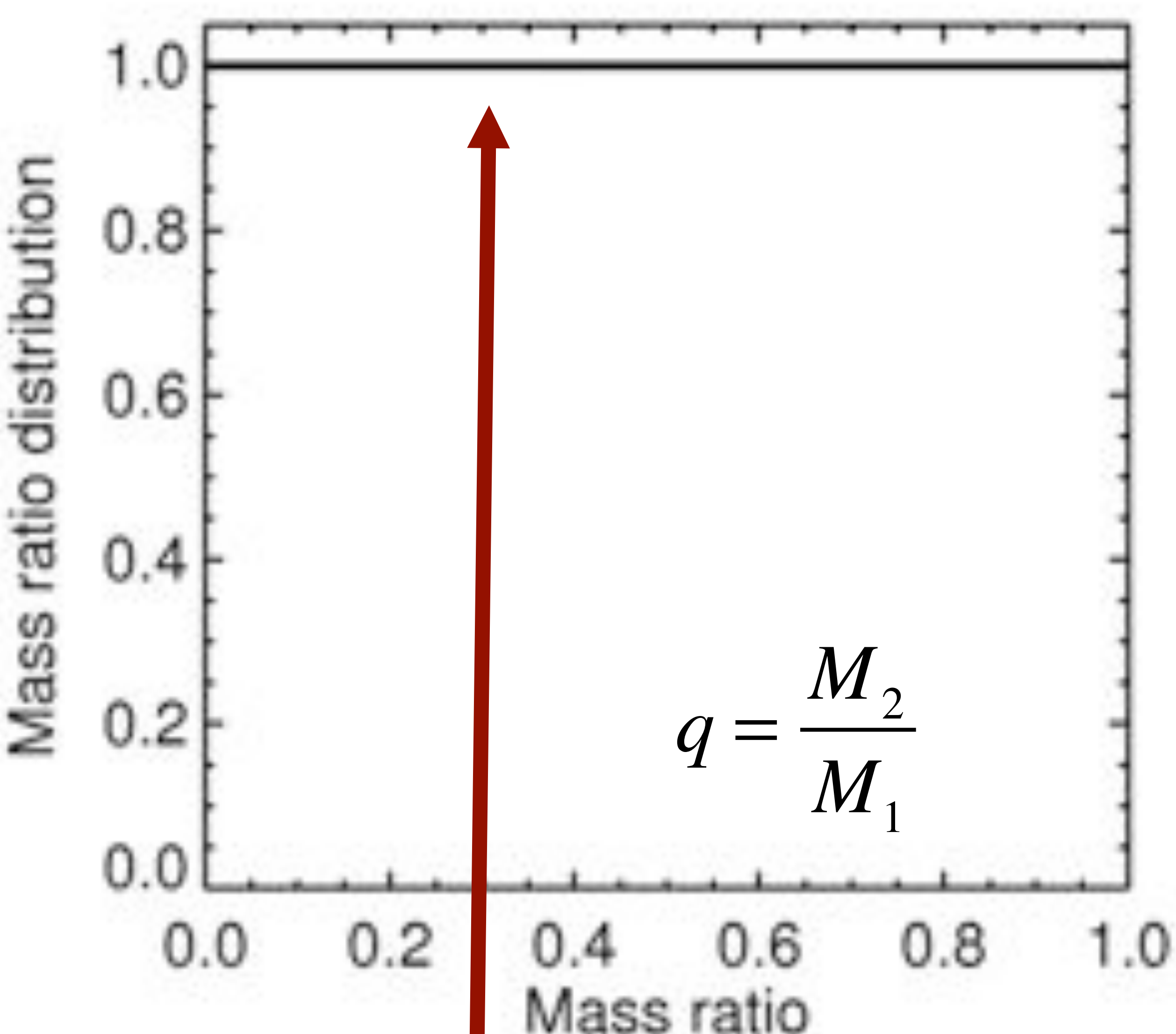
FROM CMF (DASHED BLACK CURVE) TO IMF (SOLID BLACK CURVE)



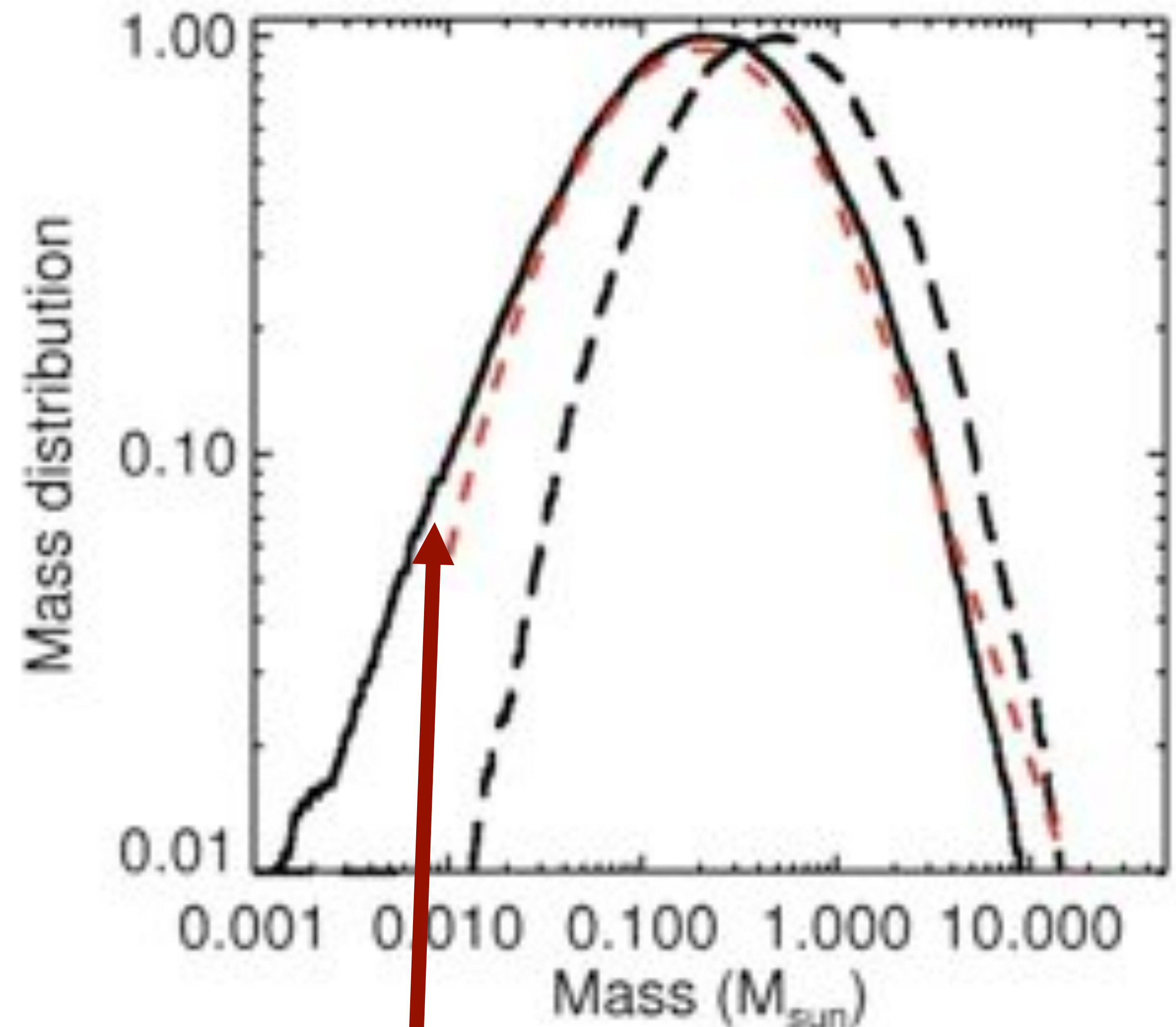
Mass ratio distribution

Resulting IMF

FROM CMF (DASHED BLACK CURVE) TO IMF (SOLID BLACK CURVE)



Mass ratio distribution



Resulting IMF

UNIVERSAL IMF ➝ UNIVERSAL STAR FORMATION?

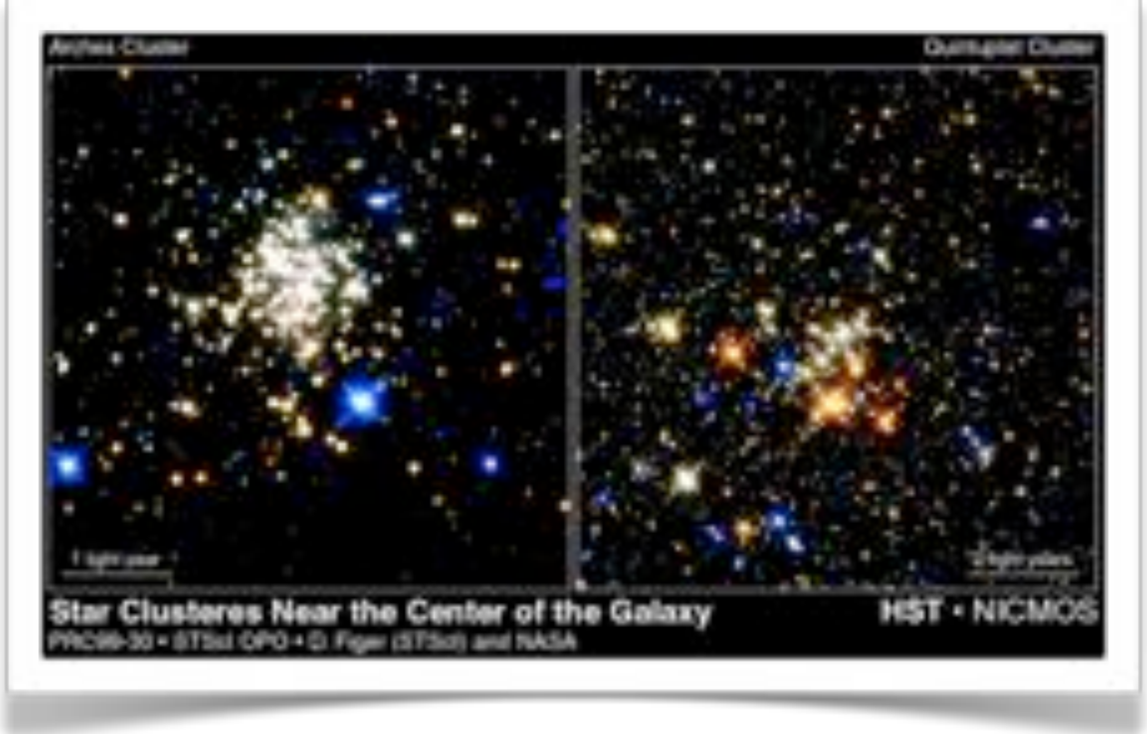
The IMF is sensitive to:

- core mass function
- star formation efficiency

The IMF is insensitive to

- binary fraction
- mass ratio distribution

The IMF does not say much about the details of star formation:



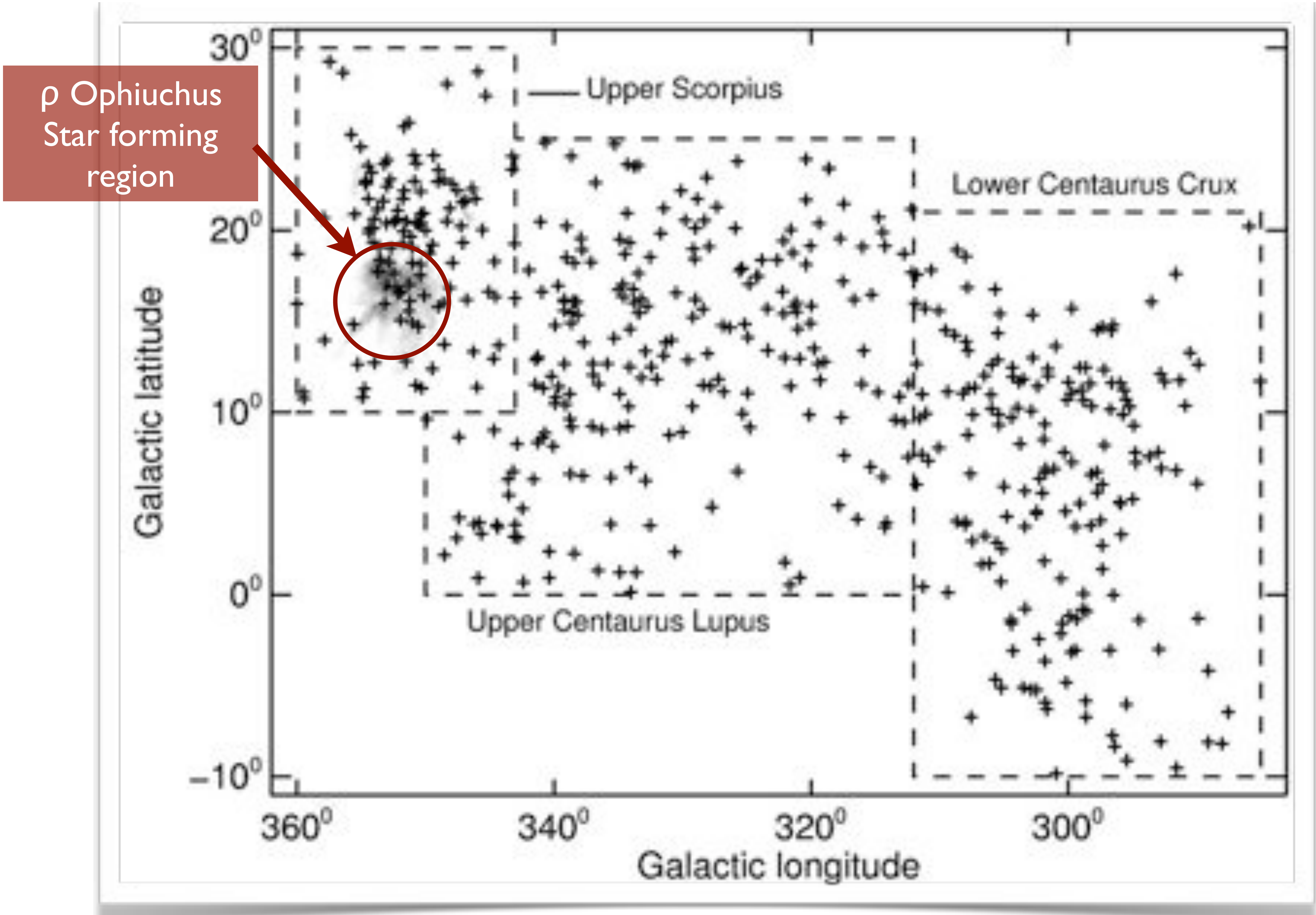
Different IMF ➝ Different star formation process

Identical IMF ➝ ???

Goodwin & Kouwenhoven (2009)

(3)
THE PRIMORDIAL BINARY POPULATION

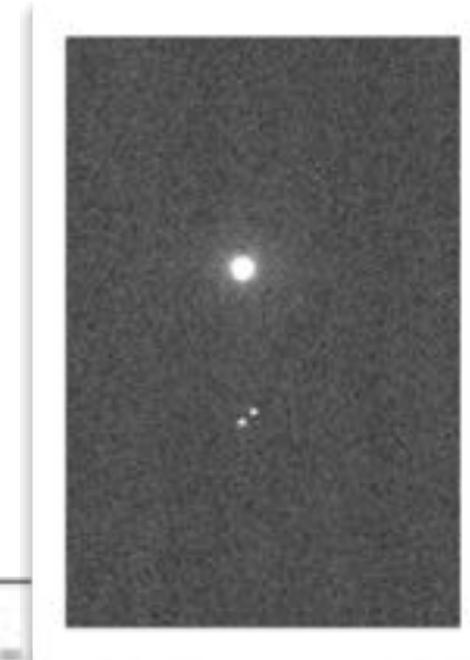
THE SCORPIUS OB ASSOCIATION (SCO OB2)

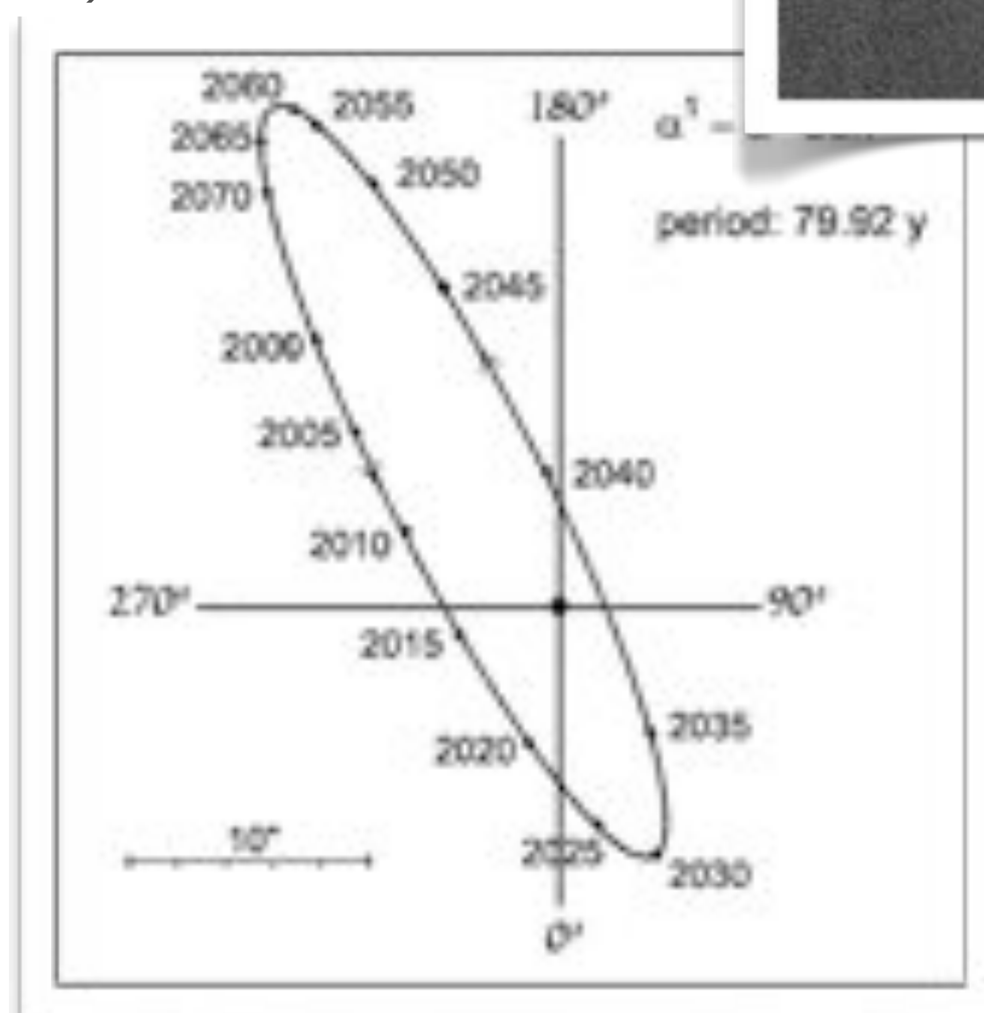


Confirmed Hipparcos members (de Zeeuw et al. 1999)

BINARY DETECTION TECHNIQUES

- Imaging (classical, adaptive optics, interferometry)
- Radial velocity variations (SB1, SBII)
- Astrometry (AB1, ABII)
- Photometry (eclipsing binaries)
- Occultations, microlensing, etc.



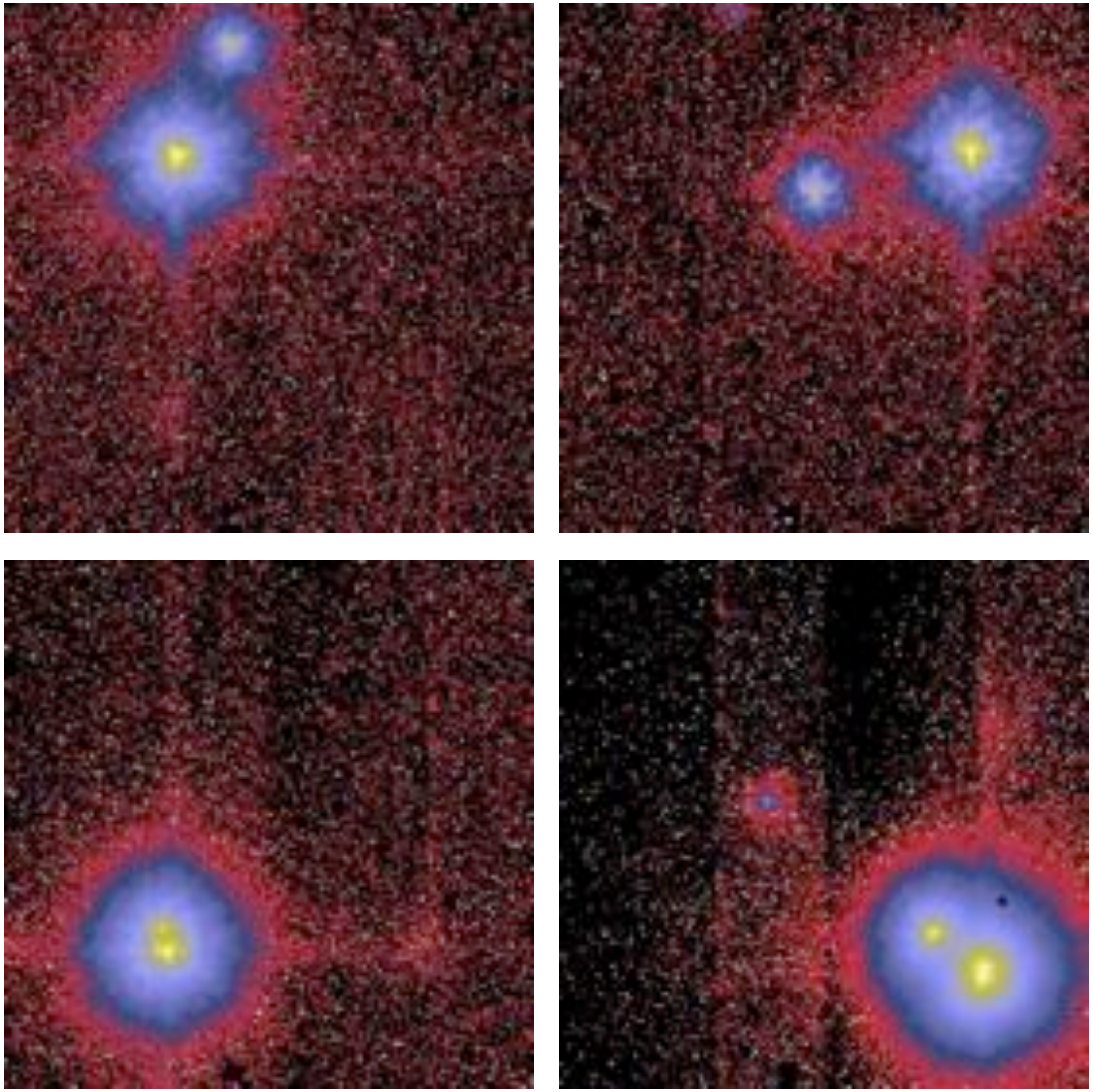


NEAR-IR ADAPTIVE OPTICS OBSERVATIONS

- 200 members
  of spectral type A/B
  in Sco OB2

- ADONIS *JHK*
  (ESO 3.9-m, La Silla)
- NAOS-CONICA *JHK*
  (VLT, Paranal)

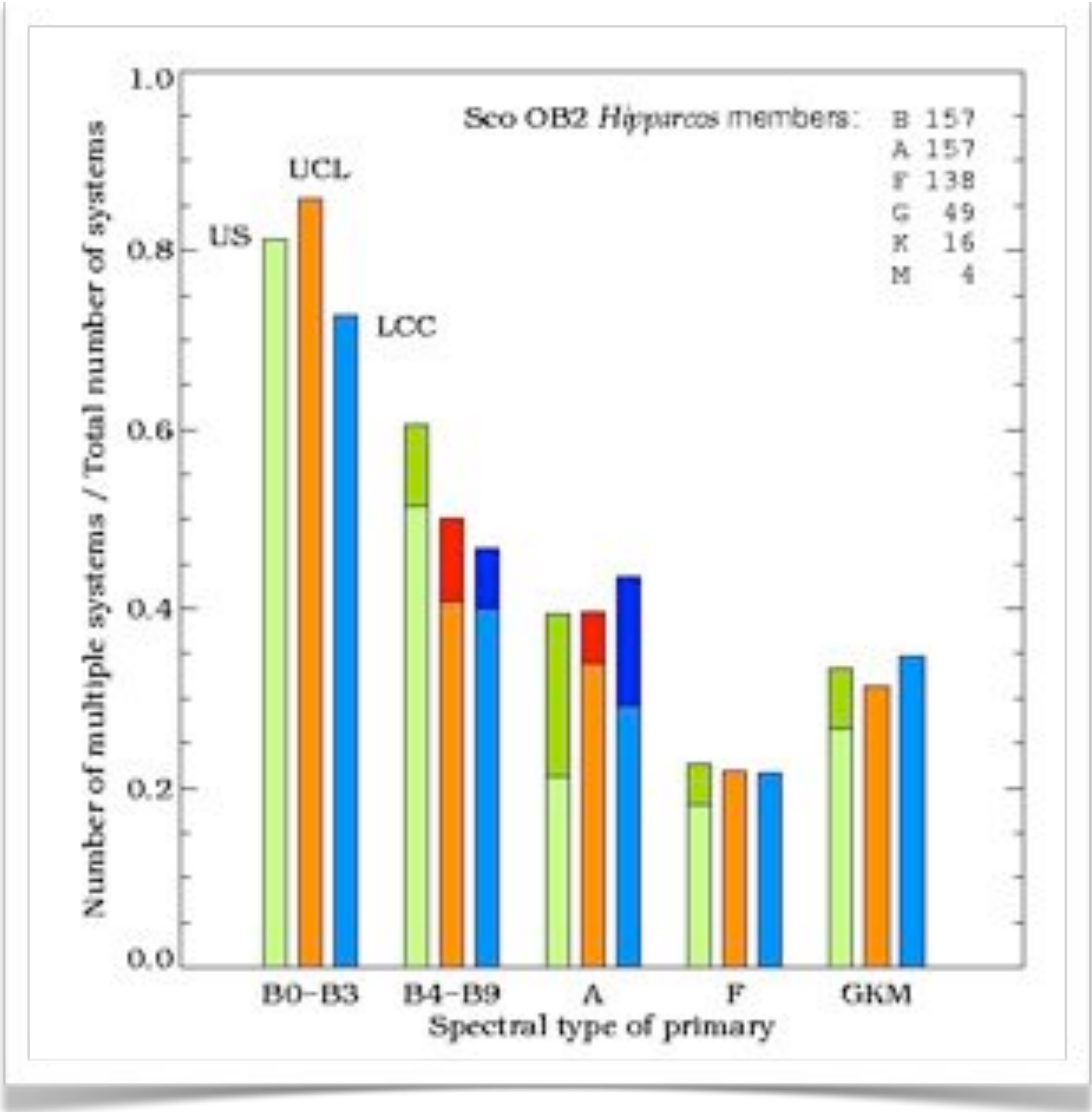
- 44 new companions
  (including brown dwarfs)



HIP53701, HIP58416, HIP76001, HIP80799; K_S -band, 13″x13″

Kouwenhoven et al. (2005, 2007)

BINARY FRACTION VERSUS MASS

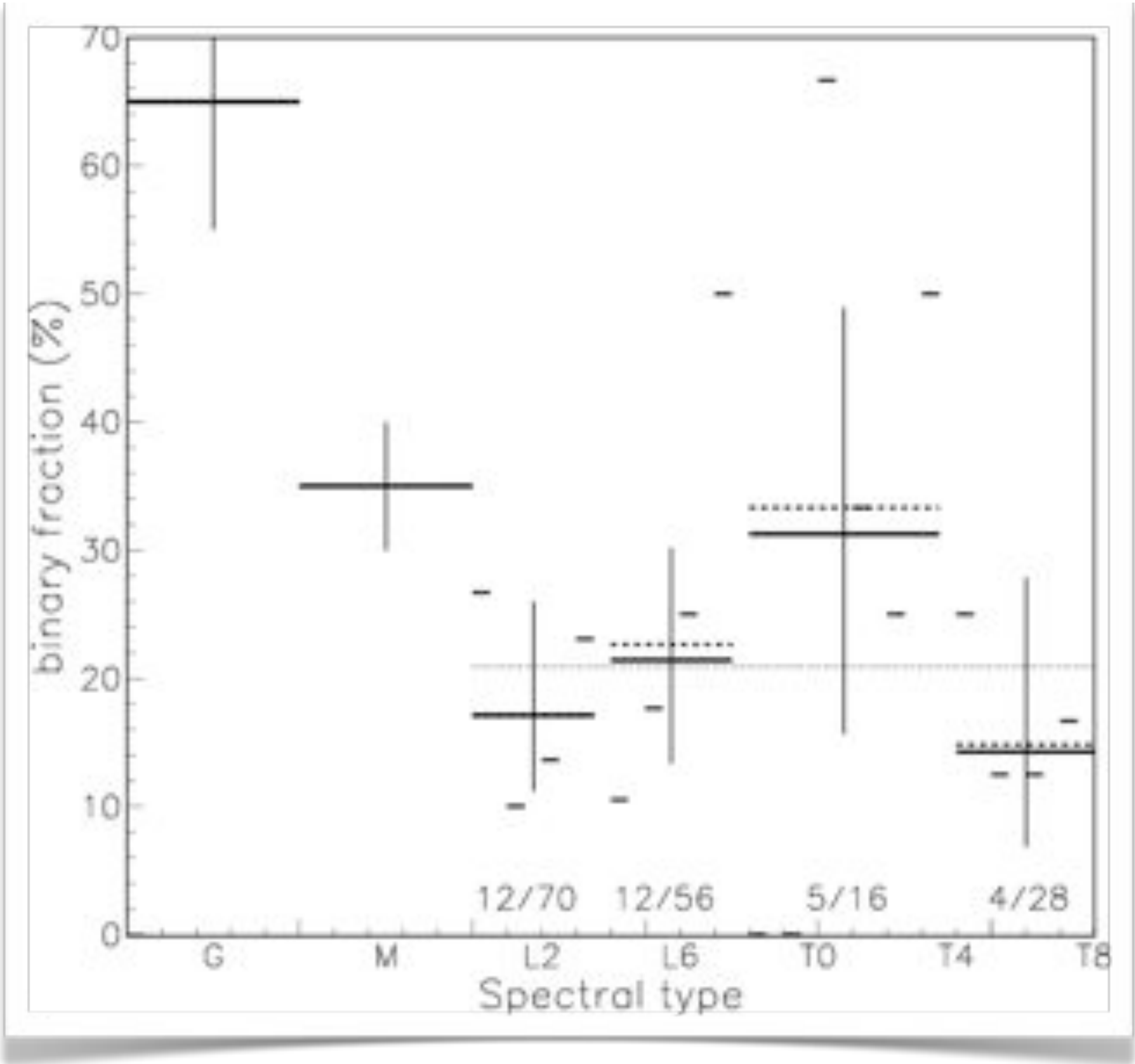


The binary fraction of young stars increases with mass:

~ 100% for O/B/A stars
~ 60% for K/G stars
~ 20% for brown dwarfs

Kouwenhoven et al. (2005, 2007)

BINARY FRACTION VERSUS MASS



The binary fraction of young stars increases with mass:

~ 100% for O/B/A stars
~ 60% for K/G stars
~ 20% for brown dwarfs

Goldman et al. (2008)

DO MOST STARS FORM IN BINARY SYSTEMS?

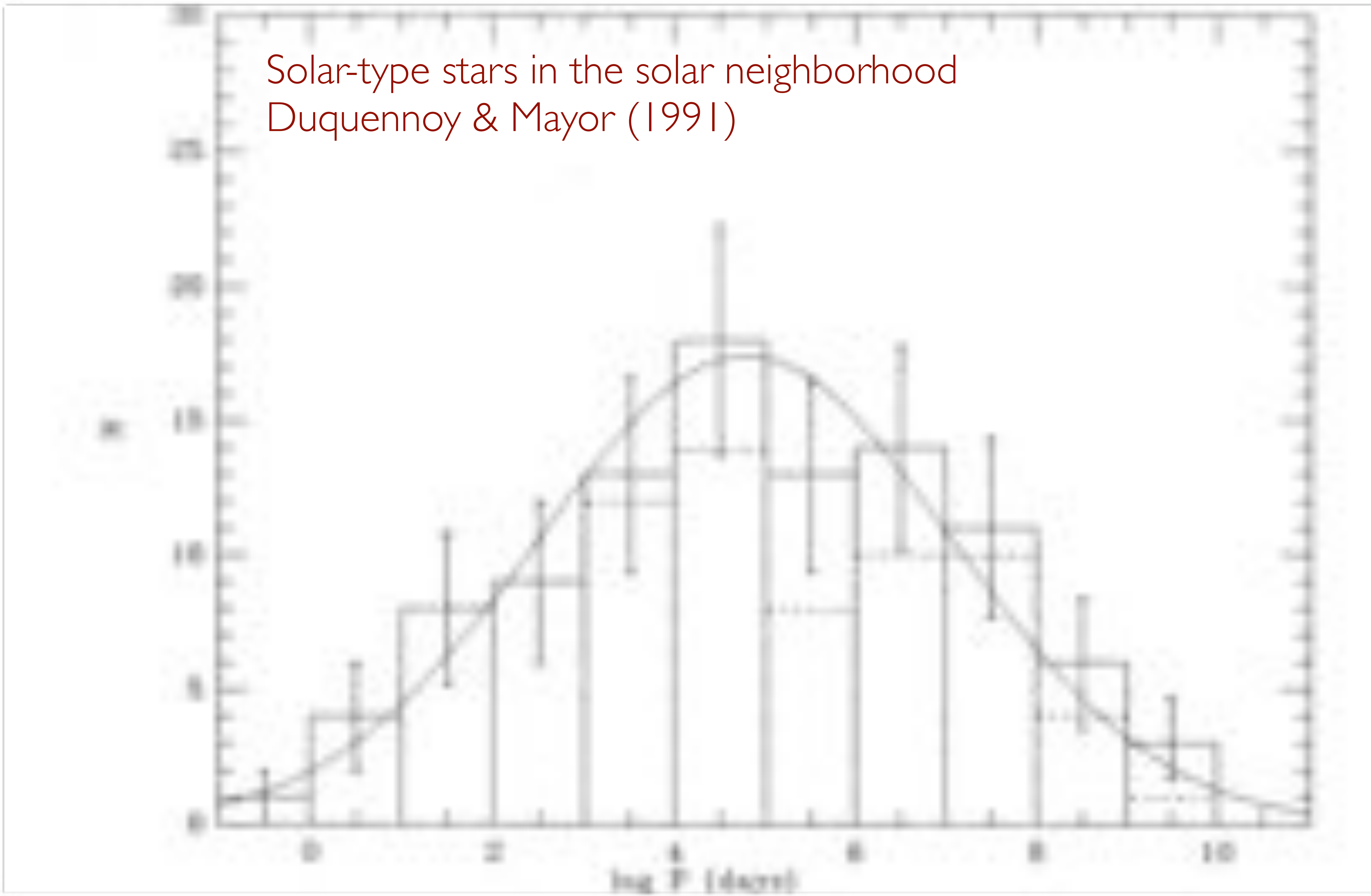
- Lada (2006)

  "... most stellar systems formed in the Galaxy are likely single and not binary ..."

- Goodwin & Kroupa (2005)

  "... cores must typically produce only 2 or 3 stars."

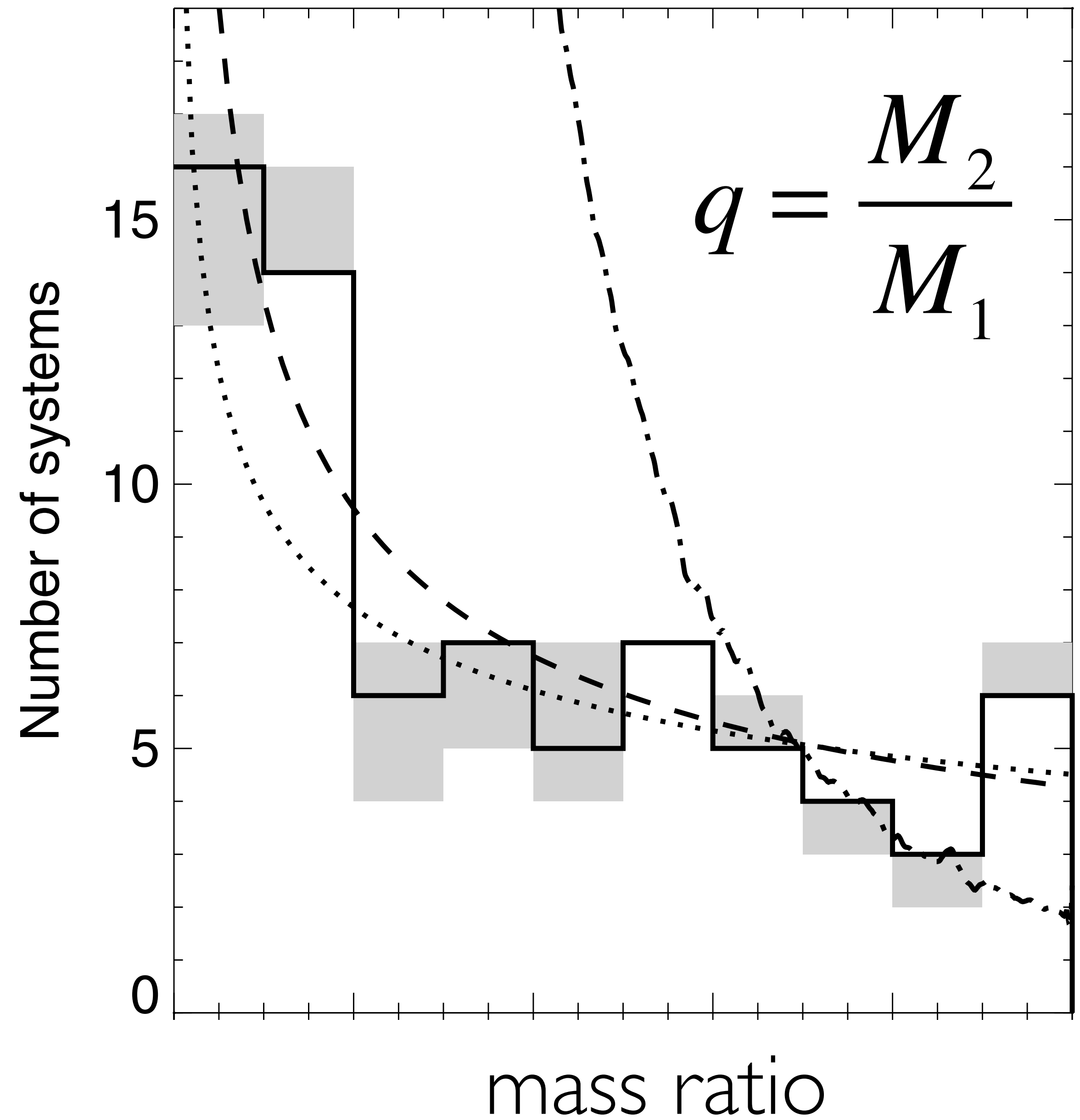
ORBITAL PERIOD DISTRIBUTION



THE MASS RATIO DISTRIBUTION

- Random pairing of components
  - Primary and companion mass are "uncorrelated"
  - Observations strongly exclude random pairing

- Mass ratio distribution
  - Primary and companion mass are strongly correlated
  - Observations suggest $\frac{dN}{dq} \propto q^{-\gamma}$



Kouwenhoven et al. (2005)

THE MASS RATIO DISTRIBUTION

Reggiani & Meyer 2011

$$\frac{dN}{dq} \propto q^{-\gamma} \qquad \gamma \approx 0.5 \pm 0.3$$

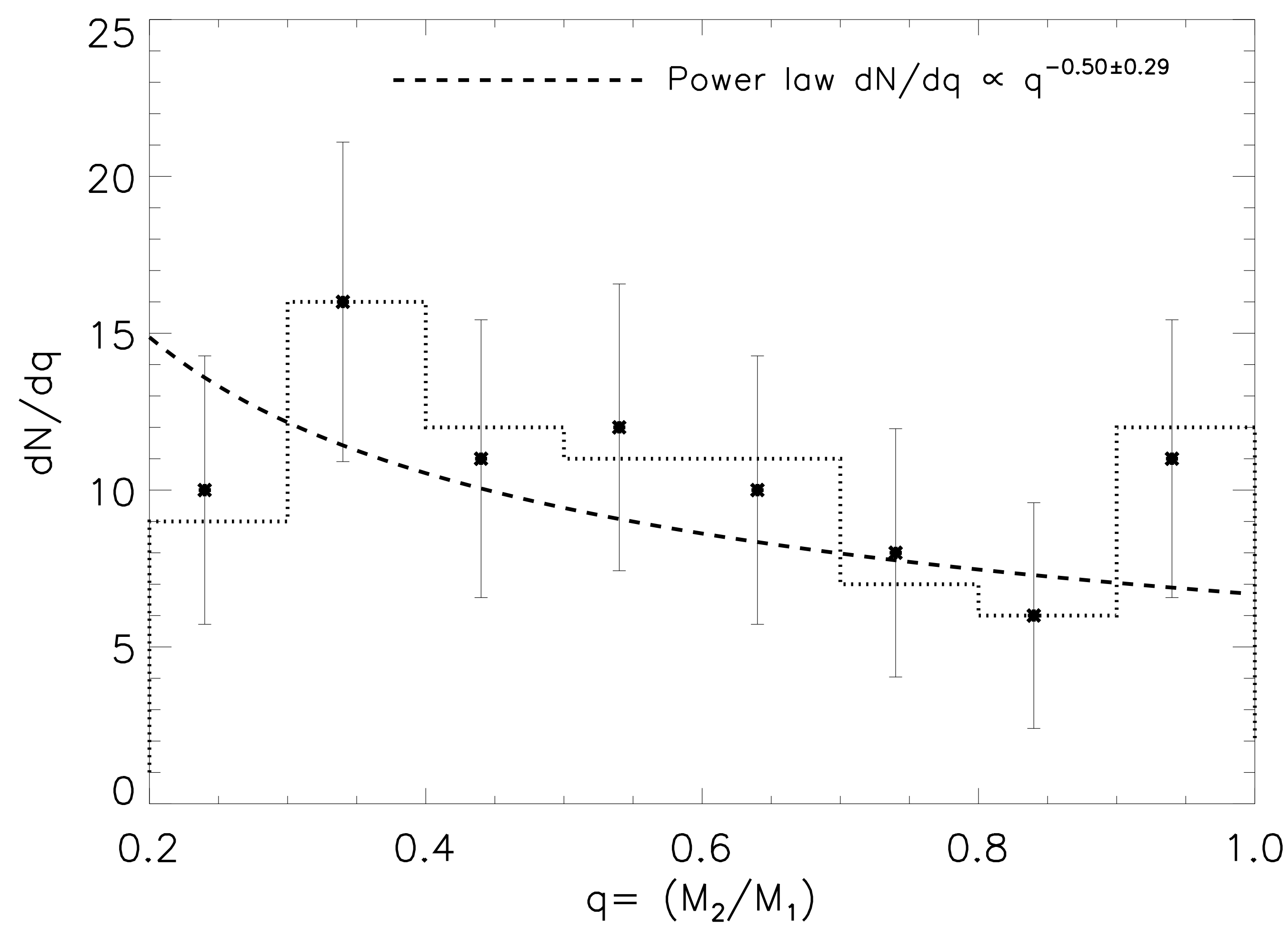
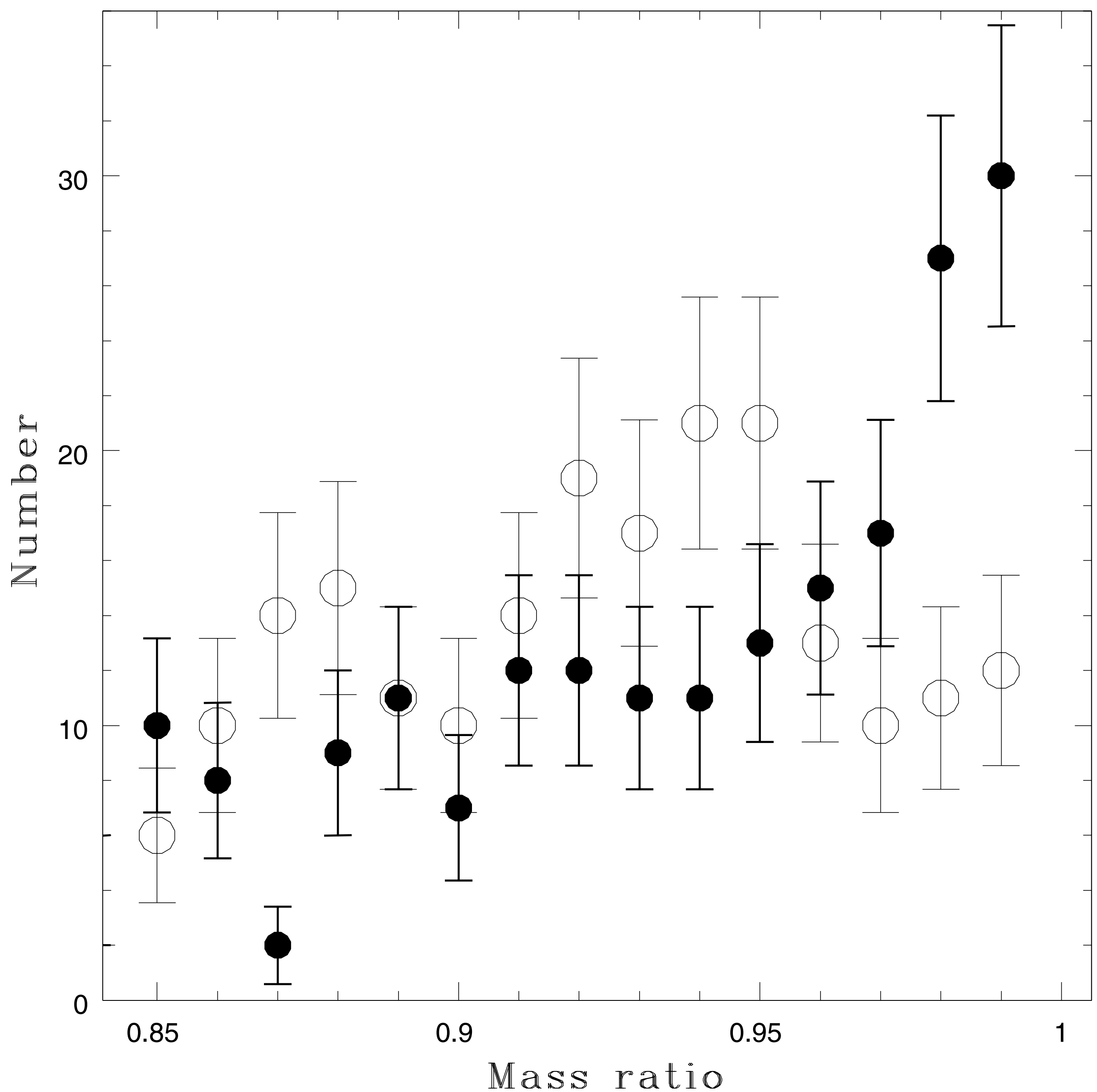


TABLE 2
KS TEST PROBABILITIES

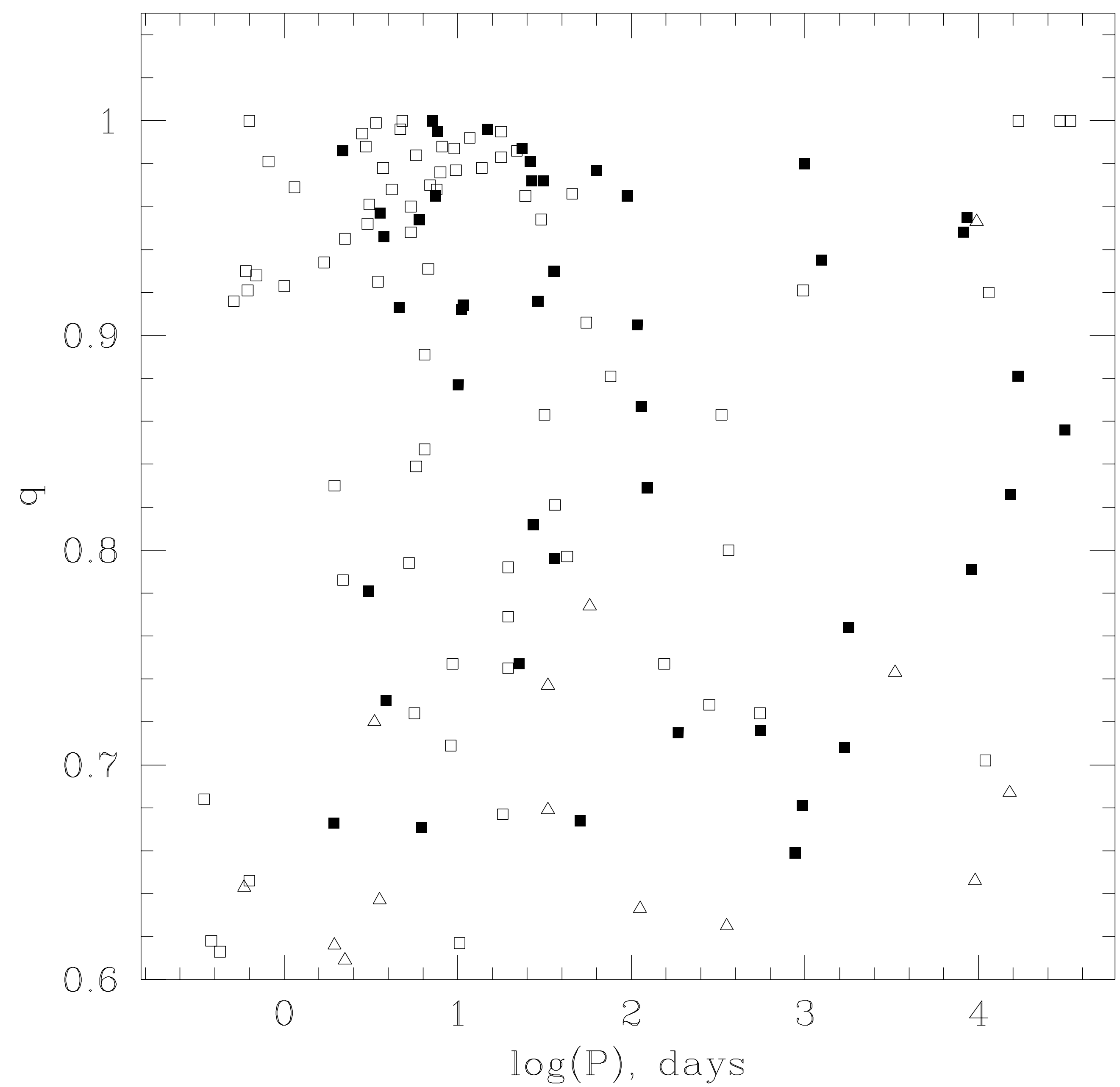
Sample - Type	Ref [a]	No. Systems	Bo2010 (%)	Flat CMF (%)	$dN/dM_2 \propto M_2^{-0.4}$ (%)
Field - M	1	27	1	58	24
Field - F/G	2	30	10^{-3}	2	58
ScoOB2 - A/late-B	3	60	10^{-13}	0.4	30
Pleiades - F/G	4	24	10^{-4}	34	17
α Persei - F/G	5	18	0.1	27	89
Chamaeleon I - K/G	6	13	17	30	76
Taurus- K/G	7	40	10^{-11}	45	2

[a] References: (1) Fischer & Marcy (1992) , (2) Metchev & Hillenbrand (2009), (3) Kouwenhoven et al. (2005), (4) Bouvier et al. (1997), (5) Patience et al. (2002), (6) Lafrenière et al. (2008), (7) Kraus et al. (2011).

CLOSE BINARIES ARE OFTEN TWINS

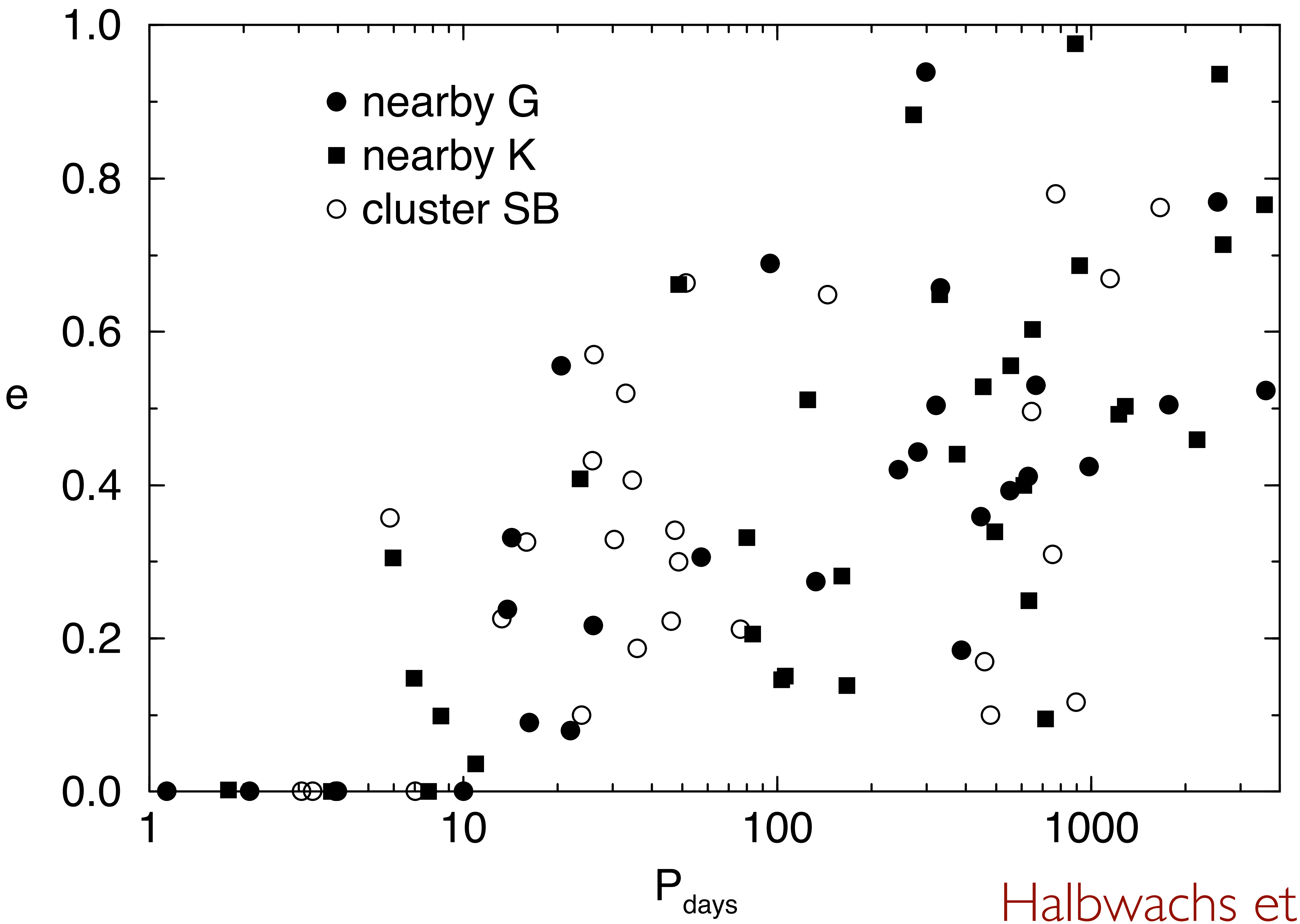


Early-type stars (Lucy 2003)



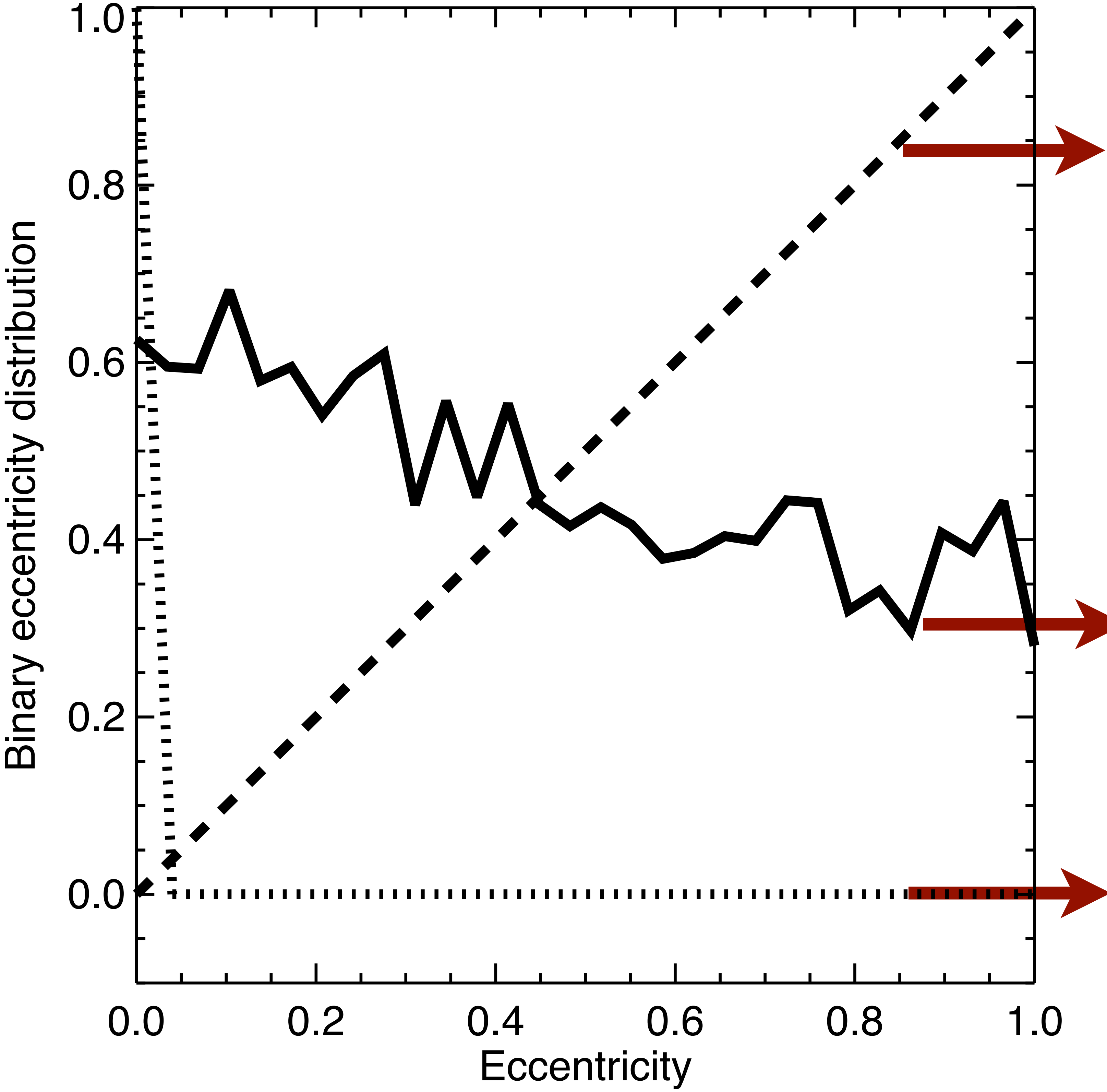
Solar-type stars (Tokovinin 2000)

ECCENTRICITY AND PERIOD



Halbwachs et al. (2003)

ECCENTRICITY DISTRIBUTION

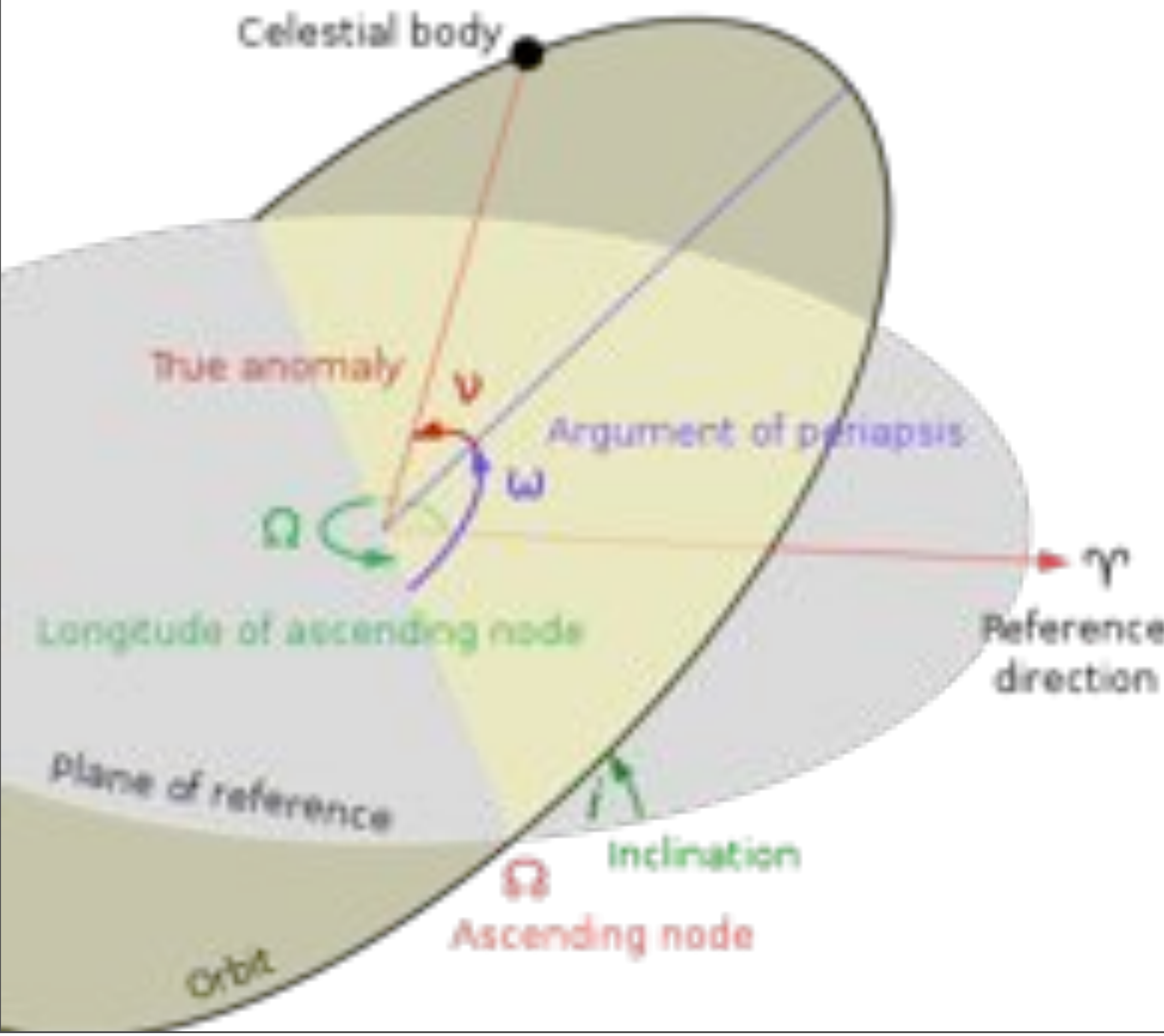


Thermal eccentricity distribution f(e)=2e (Heggie 1975) from dynamical interactions

"Primordial" eccentricity distribution ???

Tidal circularization

ORBITAL ORIENTATION



The orientation of a binary is defined by three angles:

$$i,\ \Omega,\ \omega$$

- often assumed and observed to be randomized
- irrelevant to star cluster dynamics

ORBITAL ORIENTATION

- ... but they are relevant in systems containing additional stars or planets
- Stellar encounters can change the orientation elements relatively easily
- Spin-orbit interactions
- Internal instabilities
- Kozai mechanism: $\sqrt{1-e^2}\cos i = \text{constant}$

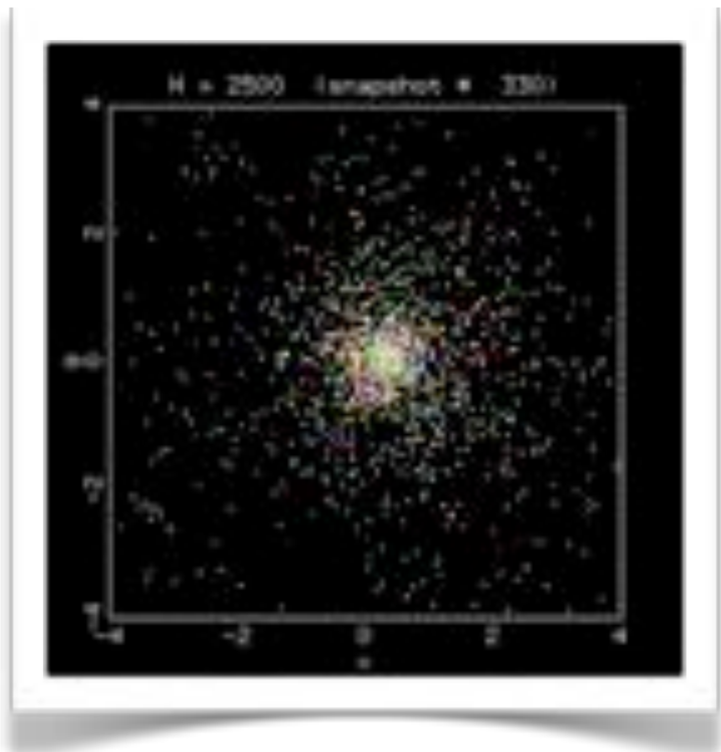
e.g., Parker & Goodwin (2009), Xu & Kouwenhoven (in prep.)

FINDING THE PRIMORDIAL BINARY POPULATION

Primordial binary population

Dynamical interactions
Stellar evolution
Observational biases

Observed binary population



comparison

Initial simulated star cluster

N-body simulations
including stellar evolution
Synthetic observations

Observations of simulated star cluster

BINARITY IN SCORPIUS OB2

Near-infrared adaptive optics surveys with ADONIS/NACO

- All 200 A/B members of Sco OB2 surveyed
- 77 companions confirmed (44 new)

The current binary population in Sco OB2 (for A/B stars)

- Binary fraction ~100%
- $f(q) = q^{-0.4\pm0.1}$; random pairing excluded

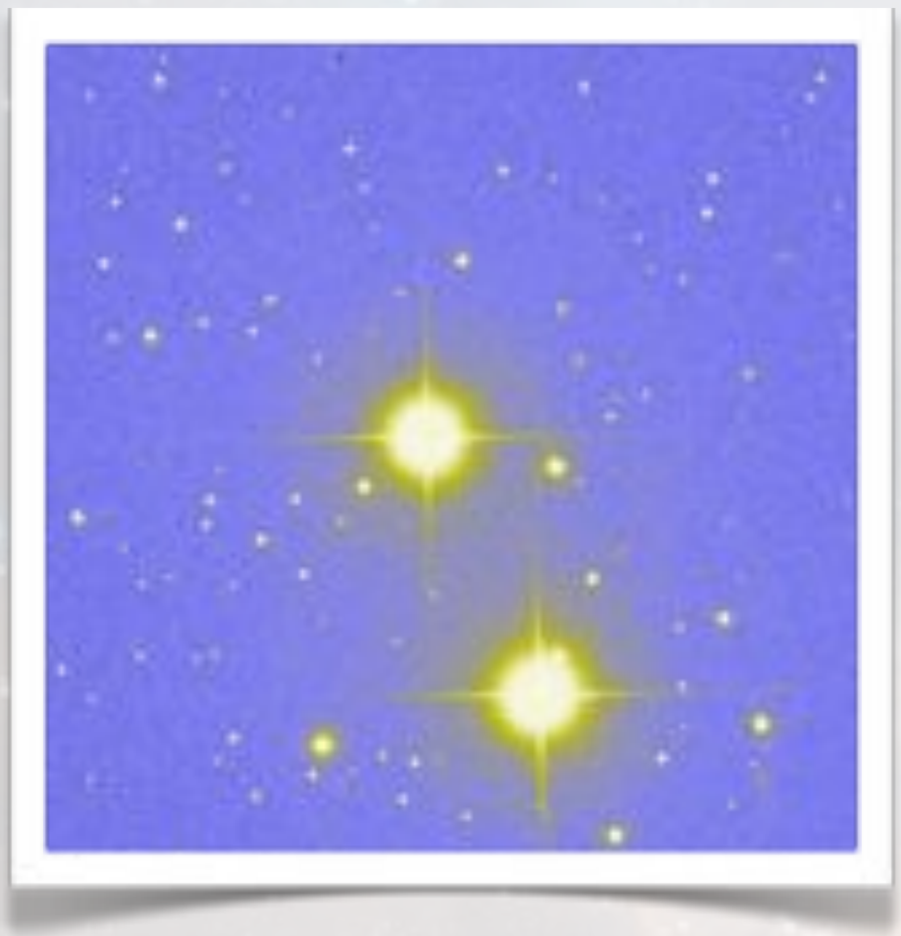
$$q = \frac{\text{companion star mass}}{\text{primary star mass}}$$

The primordial binary population of Sco OB2

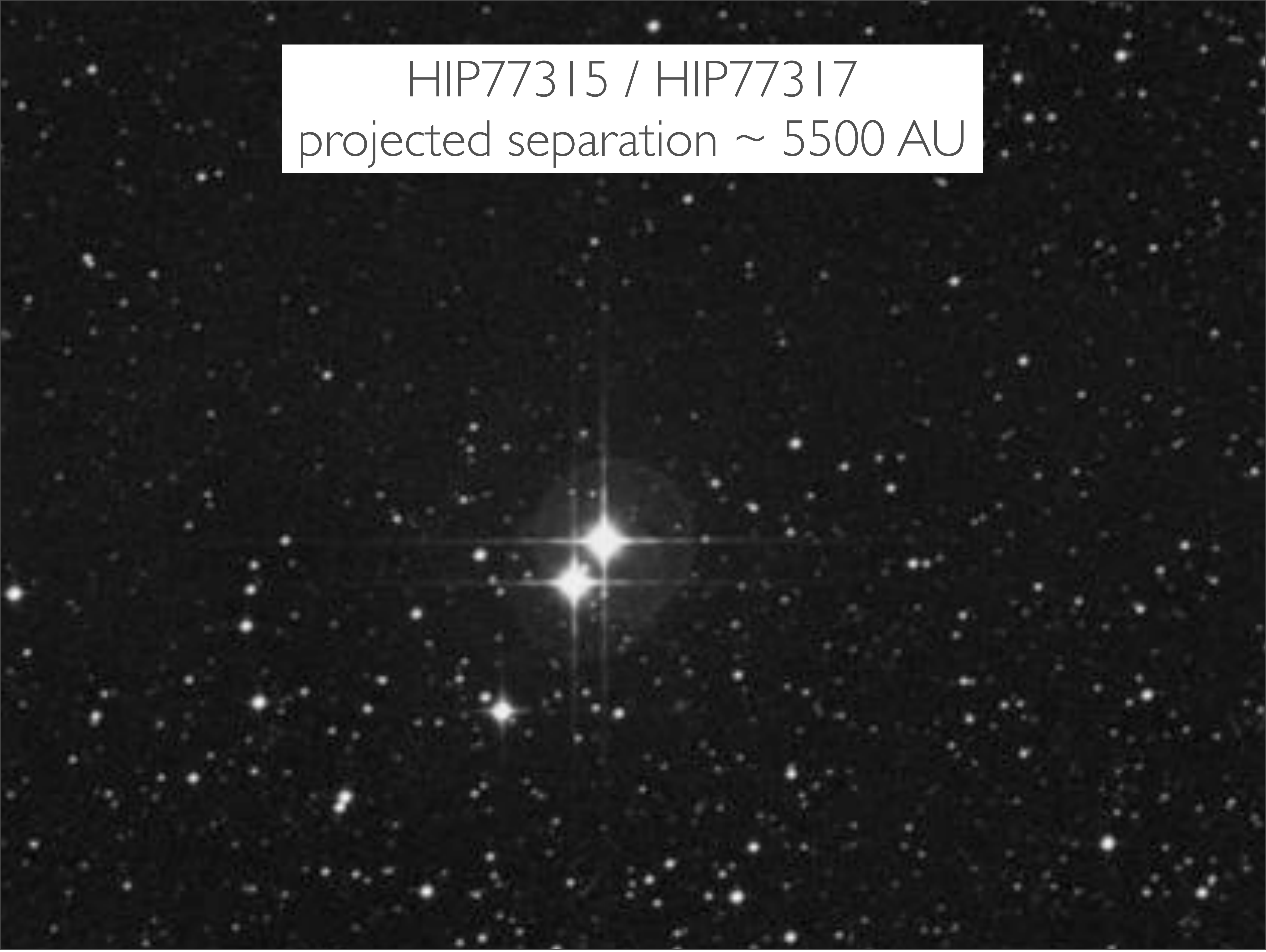
- Binary population mildly affected by stellar/dynamical evolution ➔ fossil record of the star forming process

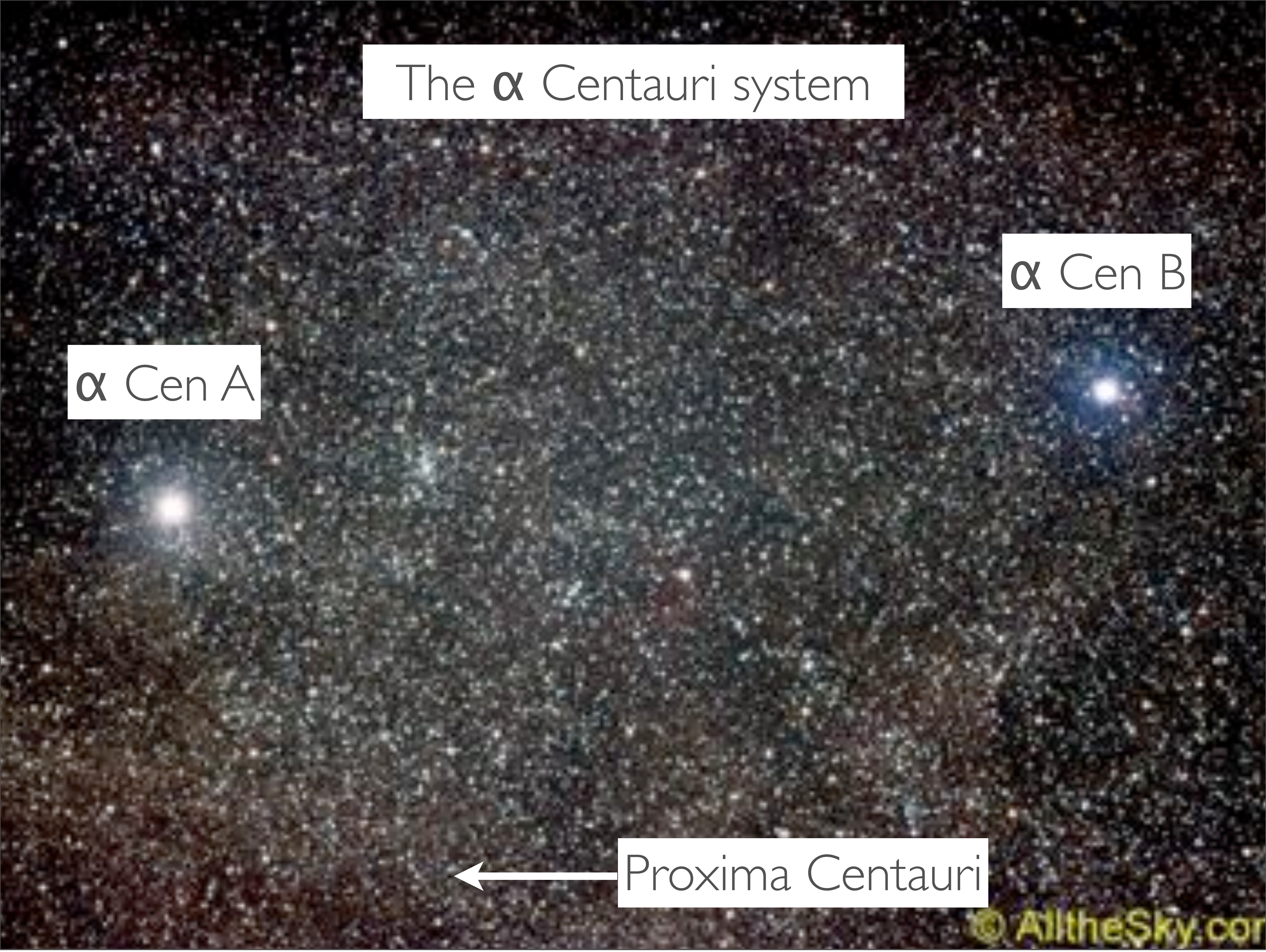
Kouwenhoven et al. (2005, 2007)

(4)
THE ORIGIN OF VERY WIDE BINARY SYSTEMS



HIP77315 / HIP77317
projected separation ~ 5500 AU




The α Centauri system
α Cen B
α Cen A
Proxima Centauri
© AlltheSky.com

WIDE BINARY SYSTEMS

- Constraints on massive dark objects (MACHOs, molecular clouds, dark matter substructure, ...) in the halo

- Constraints on the environment in which they were formed (e.g. dynamical history or star formation process)

DYNAMICAL DETECTION

Common proper motion and radial velocity

The binary orbital velocity is much smaller than the velocity dispersion of surrounding population

Parallax

Stars should have approximately the same distance

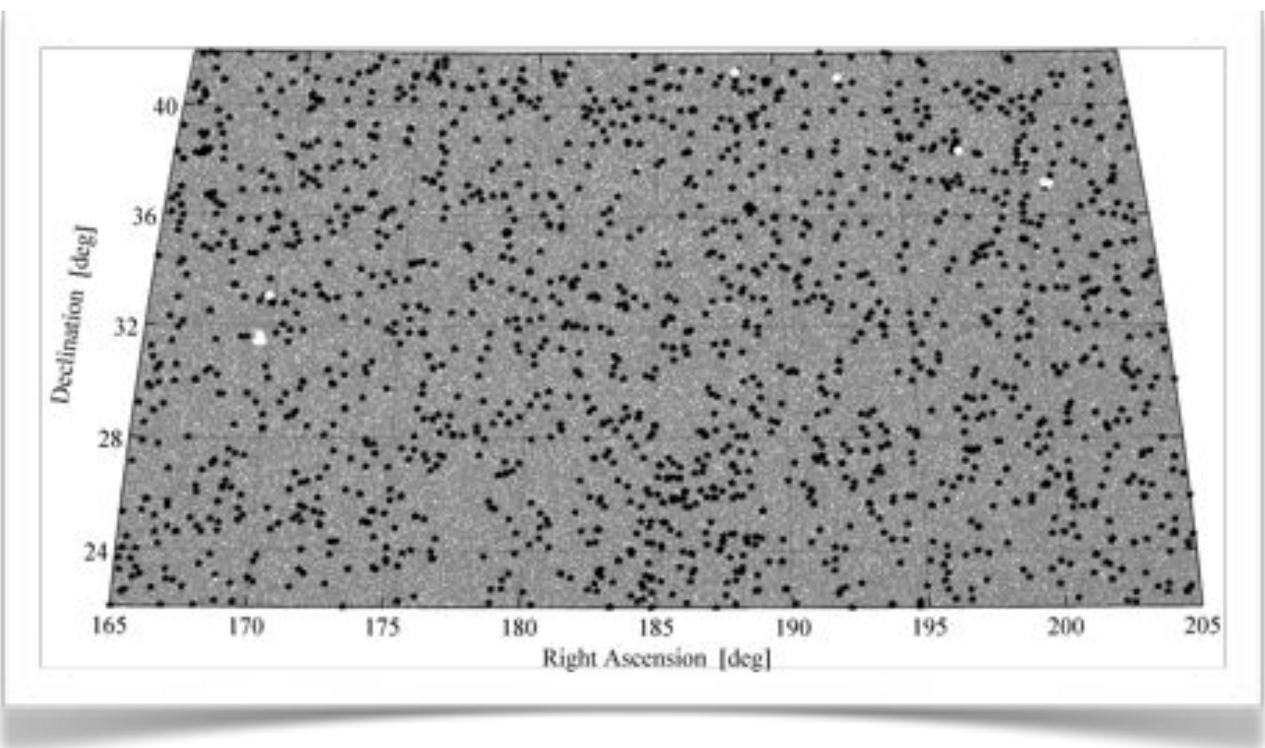
Age and metallicity

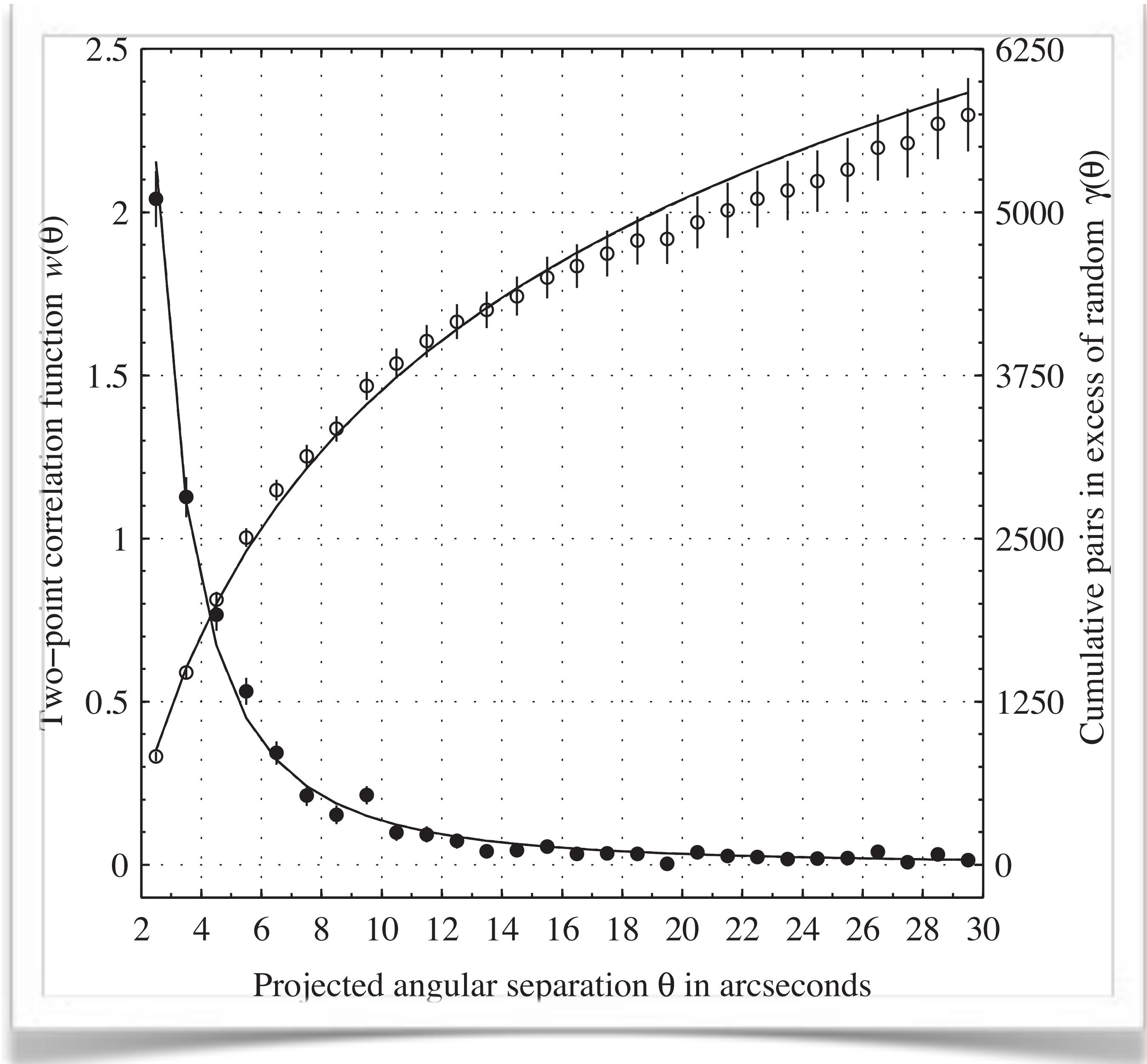
The age and metallicity should be identical, unless the binary is dynamically formed

Background star statistics

STATISTICAL DETECTION

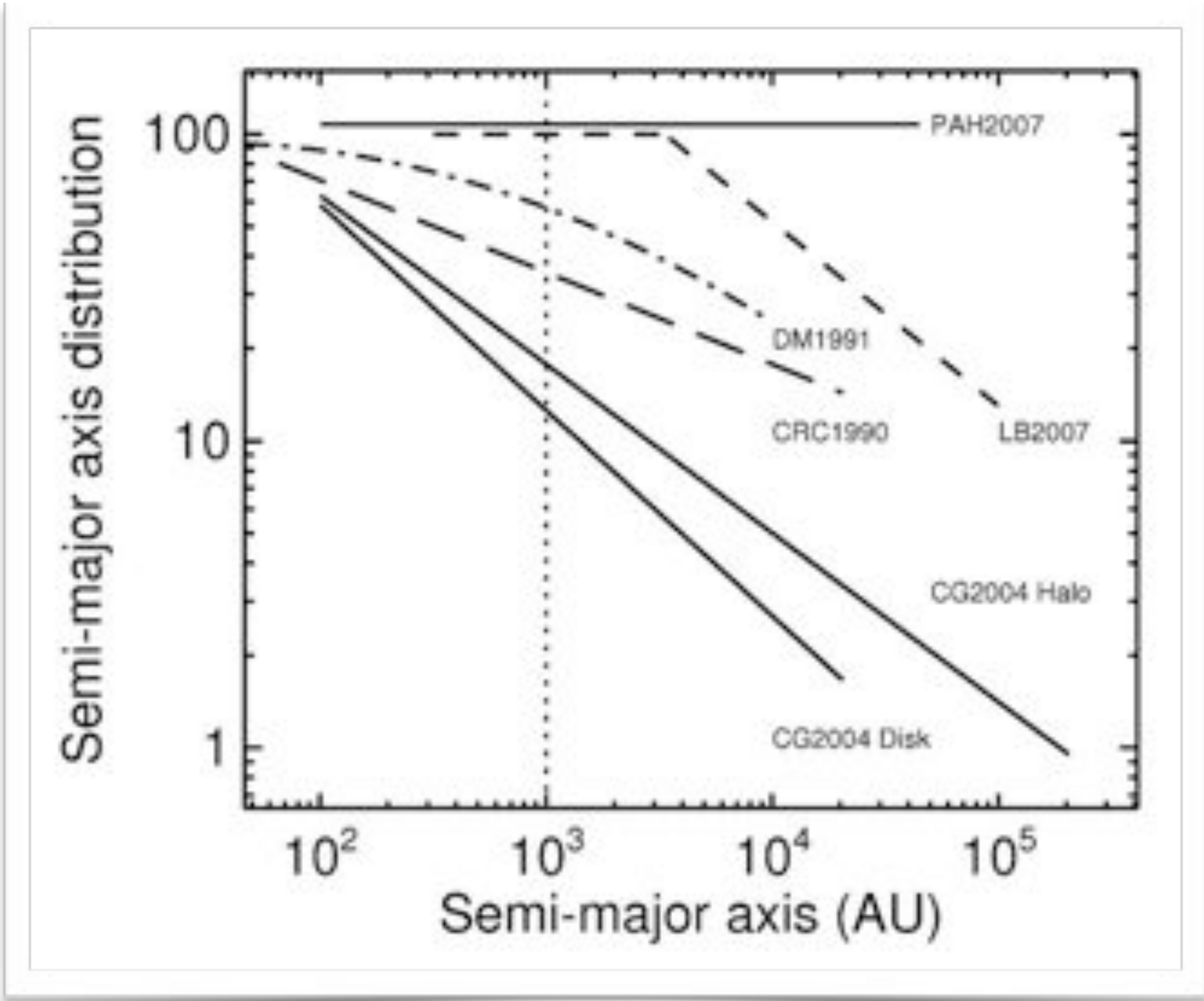
Statistical properties of the wide binary population can be obtained using the two-point correlation function





Longhitano & Binggeli 2010

VERY WIDE BINARIES IN THE FIELD

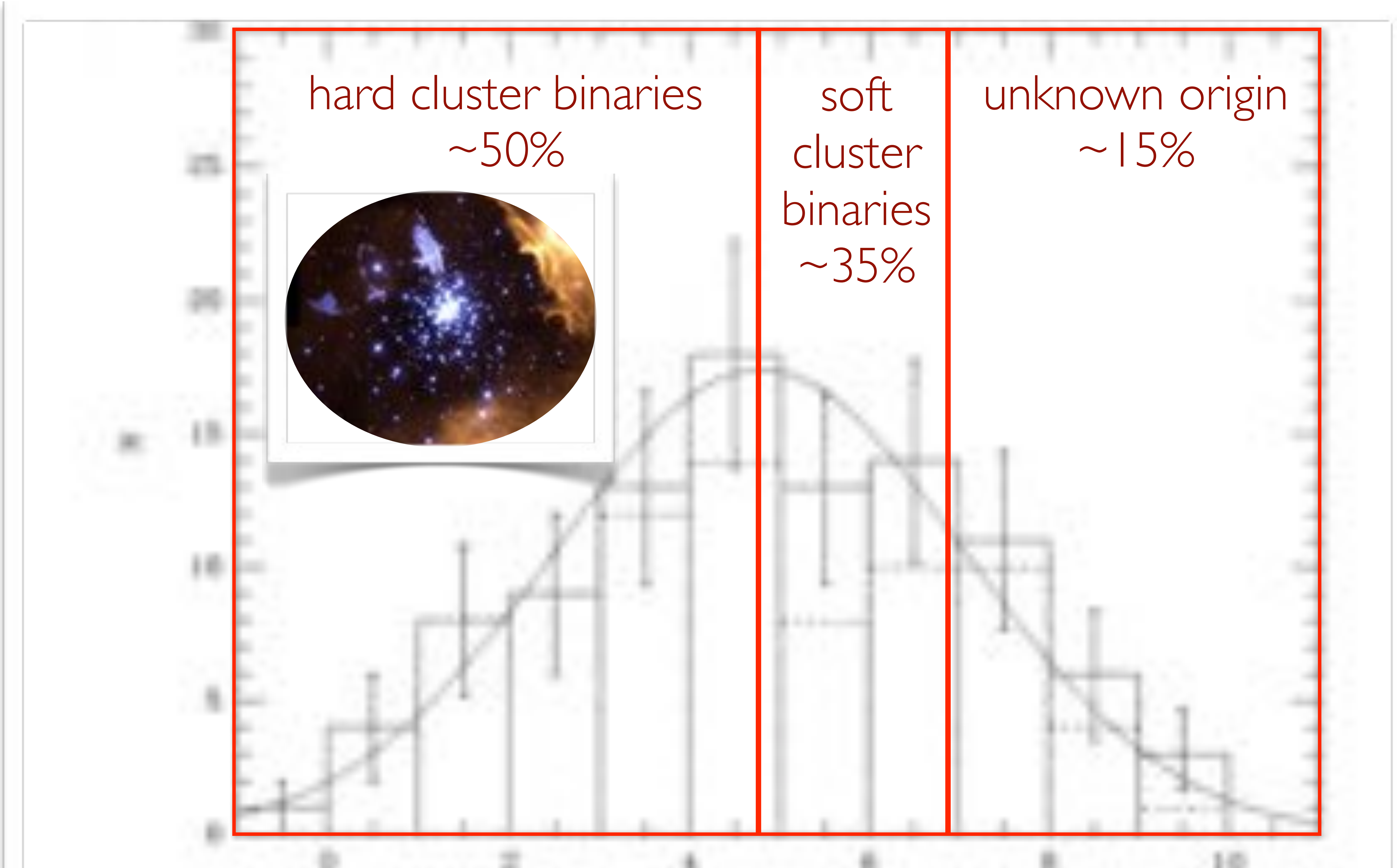


Kouwenhoven et al. 2010

~15% of the known binary systems have a > 1000 AU

Poveda et al.2007
Lépine & Bongiorno 2007
Duquennoy & Mayor 1991
Close et al. 1990
Chanamé & Gould 2004

ORBITAL PERIOD DISTRIBUTION



Duquennoy & Mayor (1991)

THE ORIGIN OF VERY WIDE BINARIES

(1) Clustered star formation ?

(2) Diffuse (isolated) star formation ?

(3) Dynamical capture in the field ?

(4) Formation during star cluster disruption ?

(1) CLUSTERED STAR FORMATION

> 70–90% of stars form in clusters

- cluster radius ~ 0.3 pc (Lada & Lada 2003)
- crossing time < 1 Myr
- 100 – 10,000 member stars

wide binary separation ≈ embedded cluster size

➙ wide binaries cannot form in star clusters

e.g., Parker et al. (2009)

Trapezium cluster - HST WFPC2/NICMOS

(2) DIFFUSE STAR FORMATION

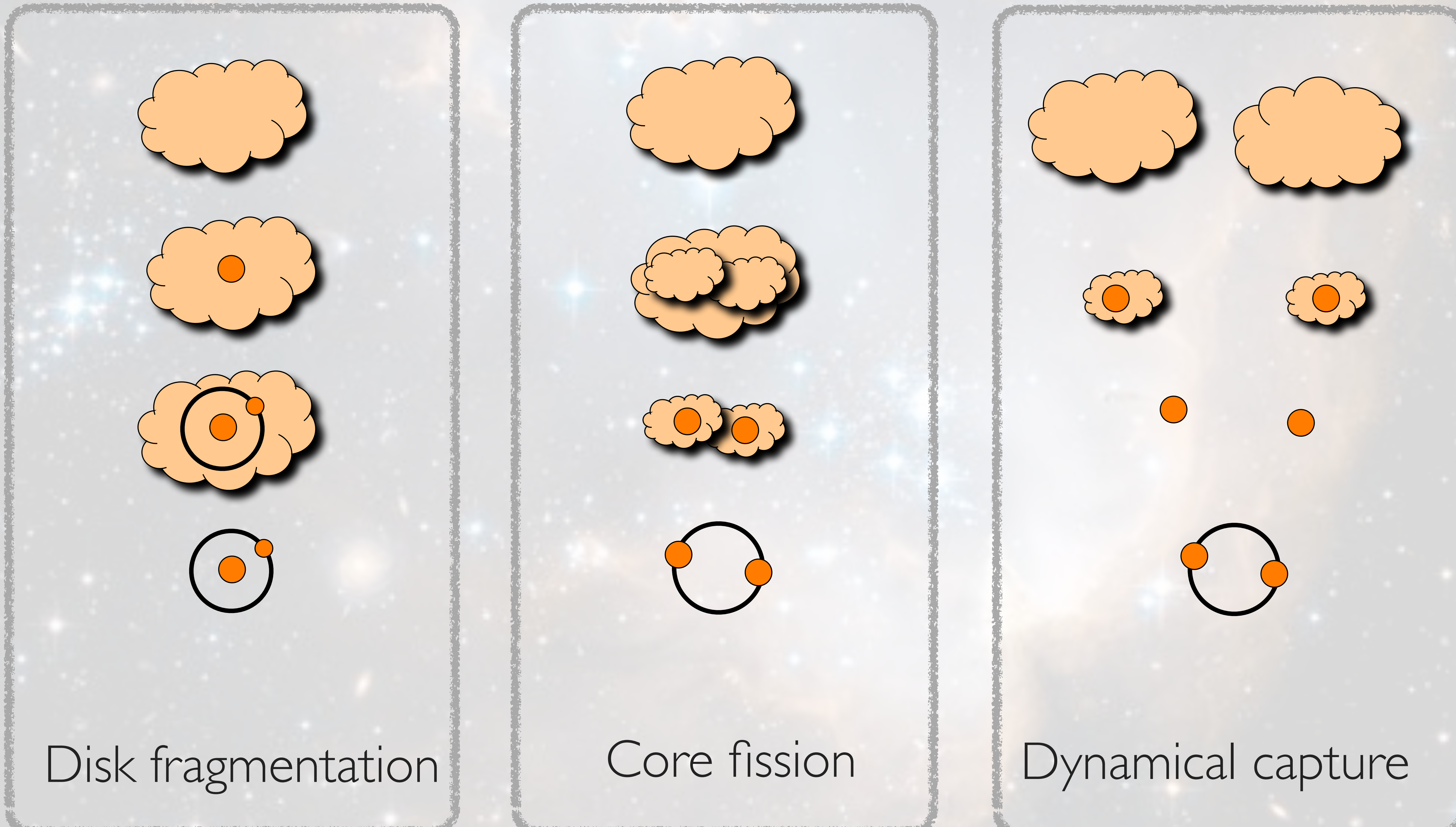
< 10–30% of stars form in diffuse regions

This could explain ~ 10% wide binaries if

- most/all of these stars form as wide binaries and
- diffuse and clustered star formation very different

Wide binaries have separations 1000 AU ≤ a ≤ 1 pc
➙ requires an unrealistically large protostellar disk

BINARY STAR FORMATION MODES



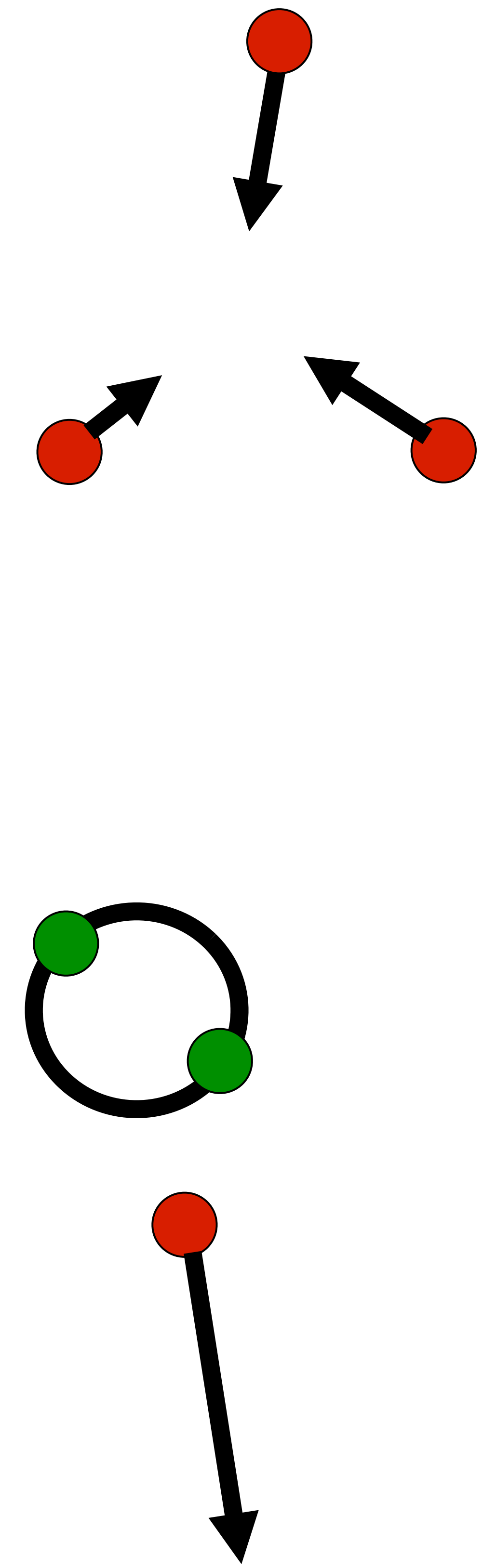
(3) CAPTURE IN THE FIELD

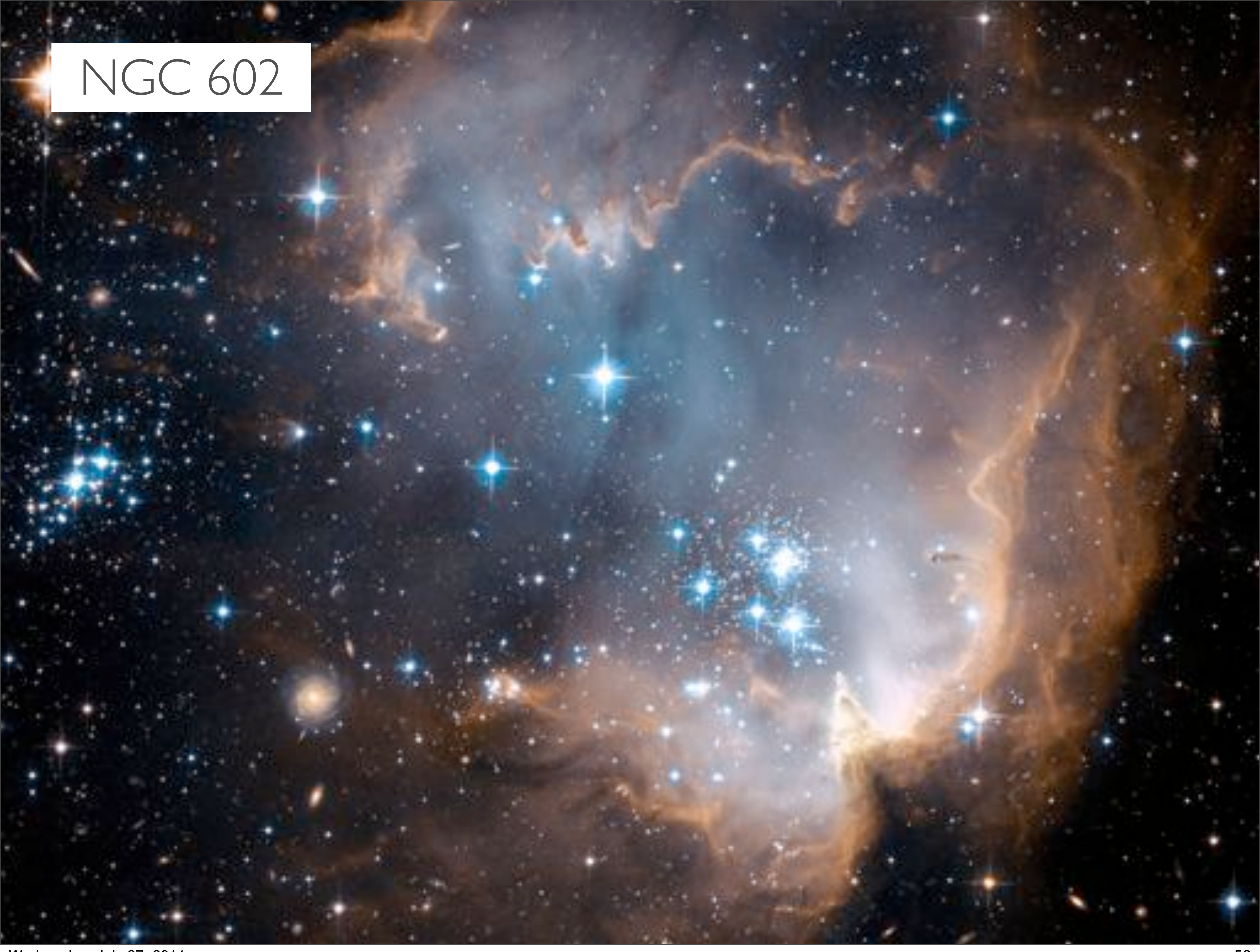
- Under certain conditions, two stars may form a binary system dynamically

- Requires fine-tuned 3-body encounters (Goodman & Hut 1993)

$$\frac{dN_{\rm binaries}}{dt} = 0.75\,\frac{G^5 M^5 n^3}{\sigma^9}$$

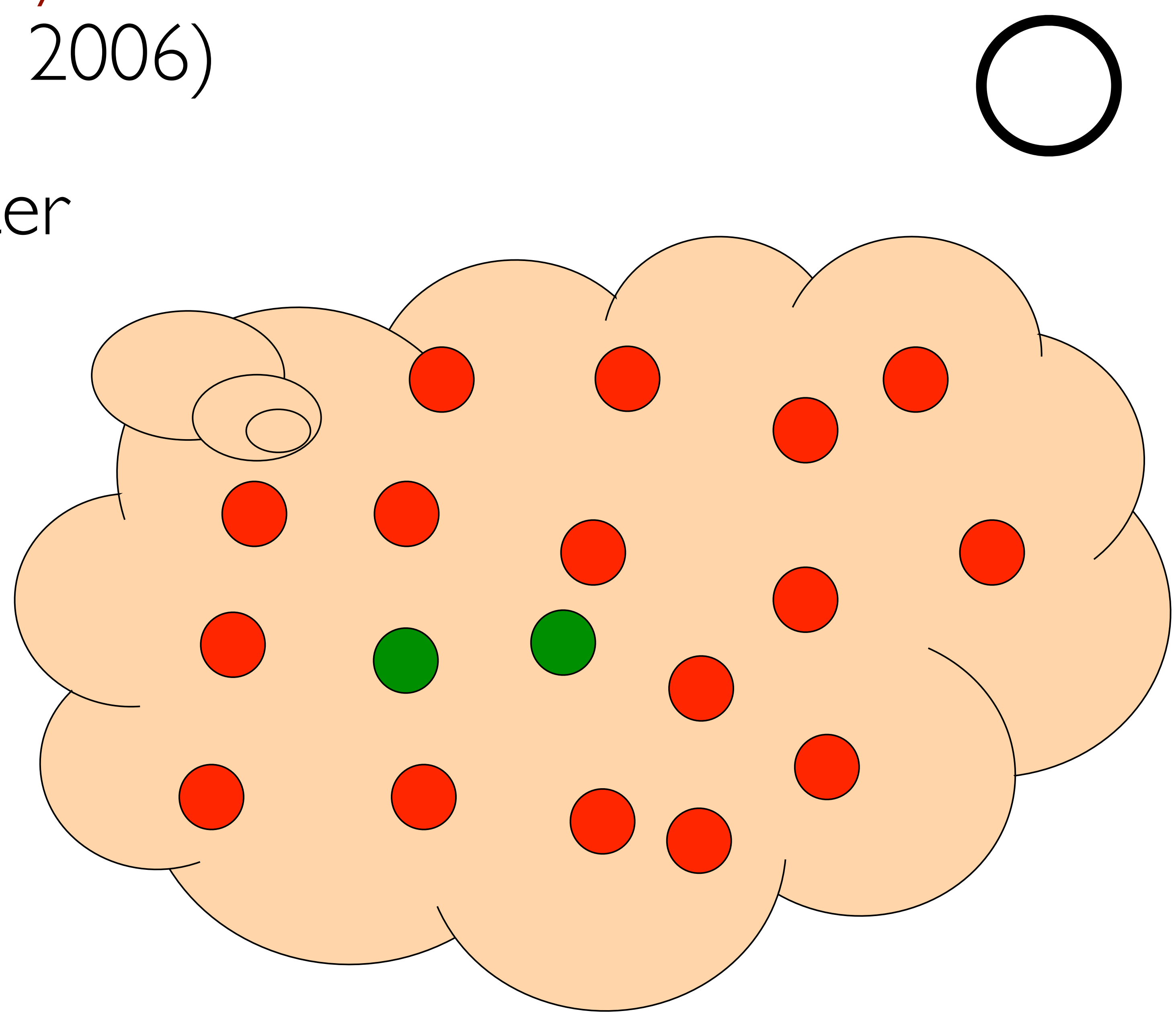
- Extremely unlikely in the Galactic field (a few binaries per galaxy)



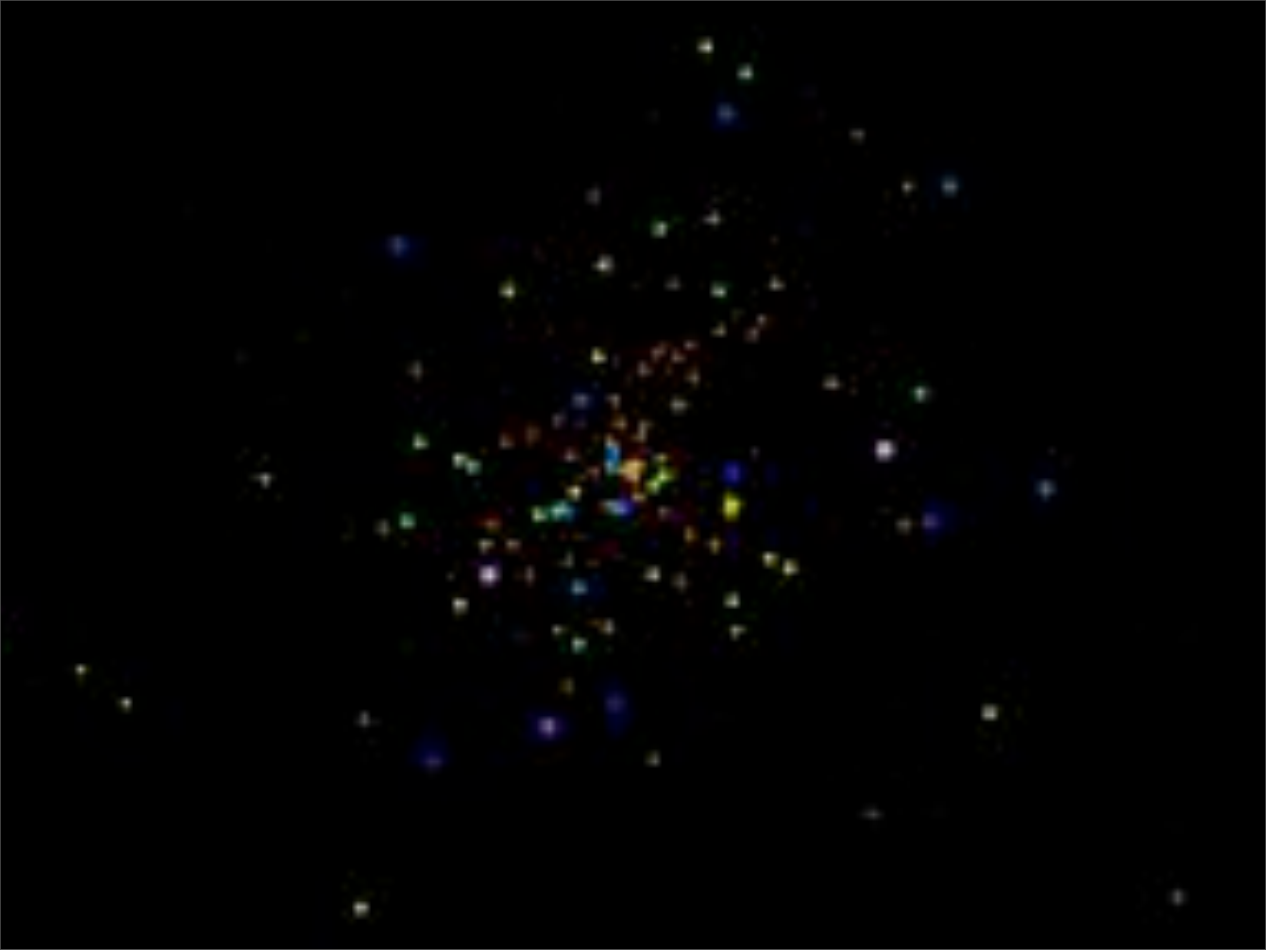

NGC 602

(4) FORMATION DURING STAR CLUSTER DISSOLUTION

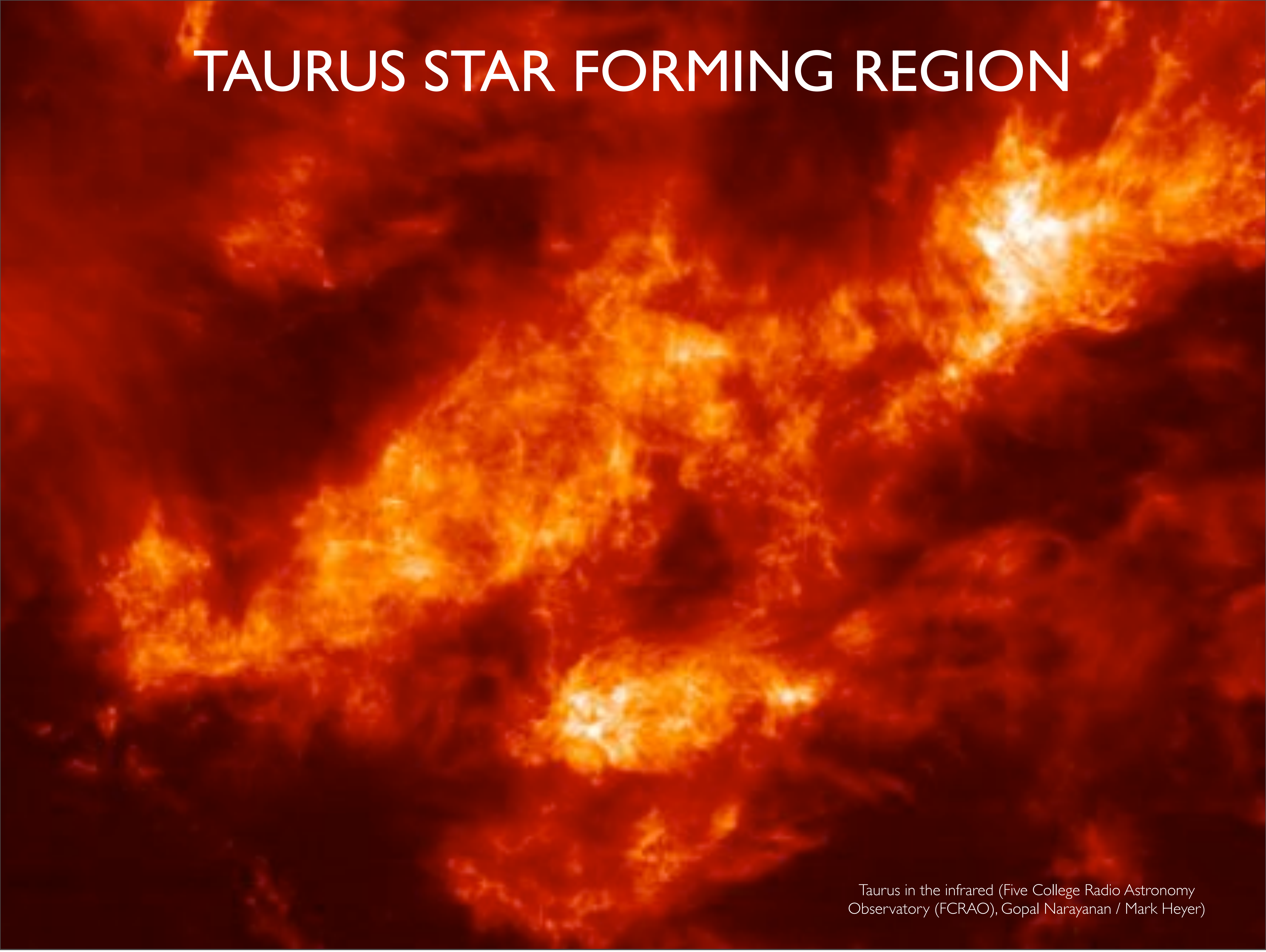
- Star forming efficiency ~33% (Bastian & Goodwin 2006)
- Rapid dissolution after gas expulsion



Binaries "formed and frozen in" (Kouwenhoven et al. 2010), or a transient soft population frozen in (Moeckel & Clarke 2011)??

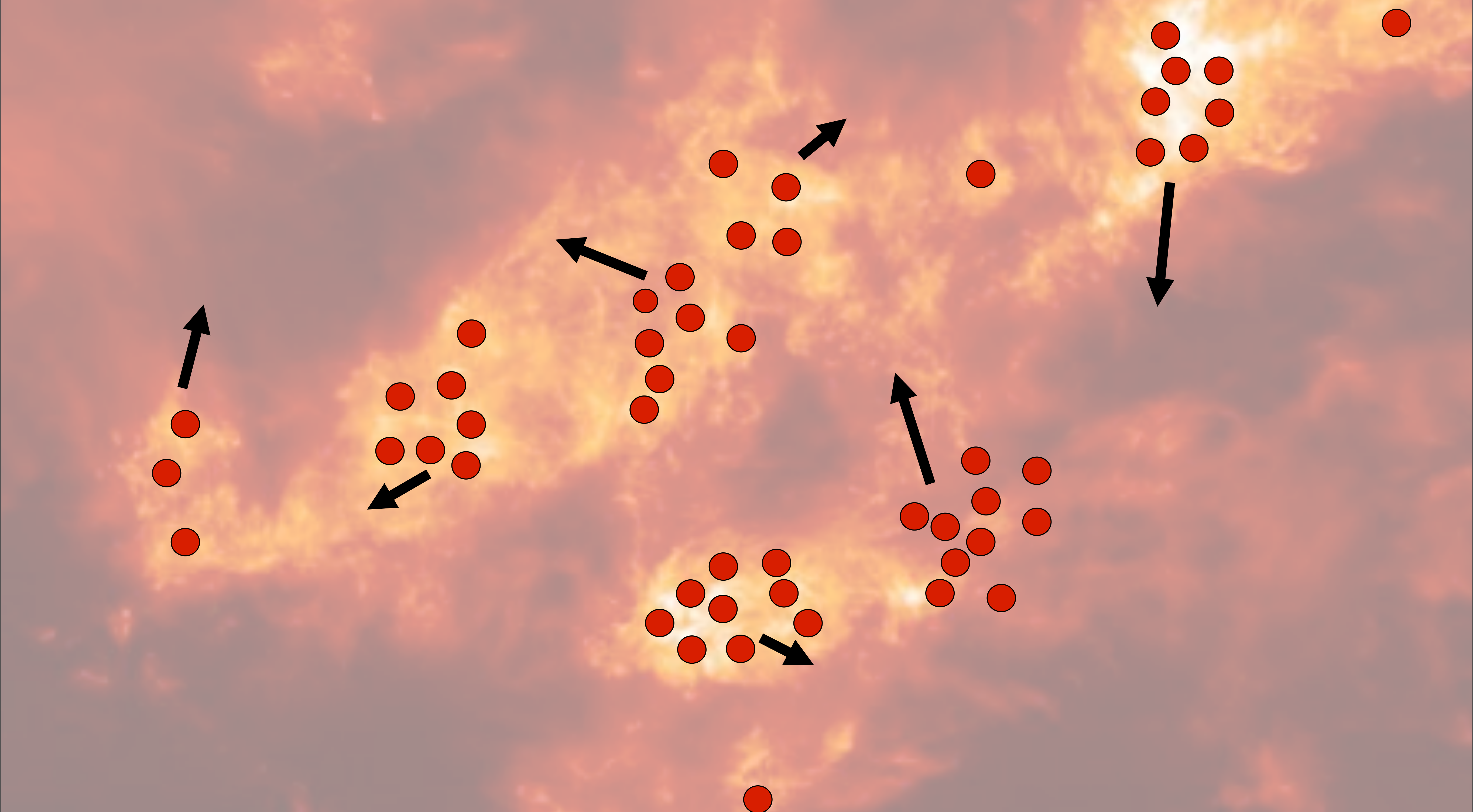


TAURUS STAR FORMING REGION



Taurus in the infrared (Five College Radio Astronomy Observatory (FCRAO), Gopal Narayanan / Mark Heyer)

N-BODY SIMULATIONS OF SUBSTRUCTURED CLUSTERS



Initial conditions with substructure (e.g. Cartwright & Whitworth 2004)

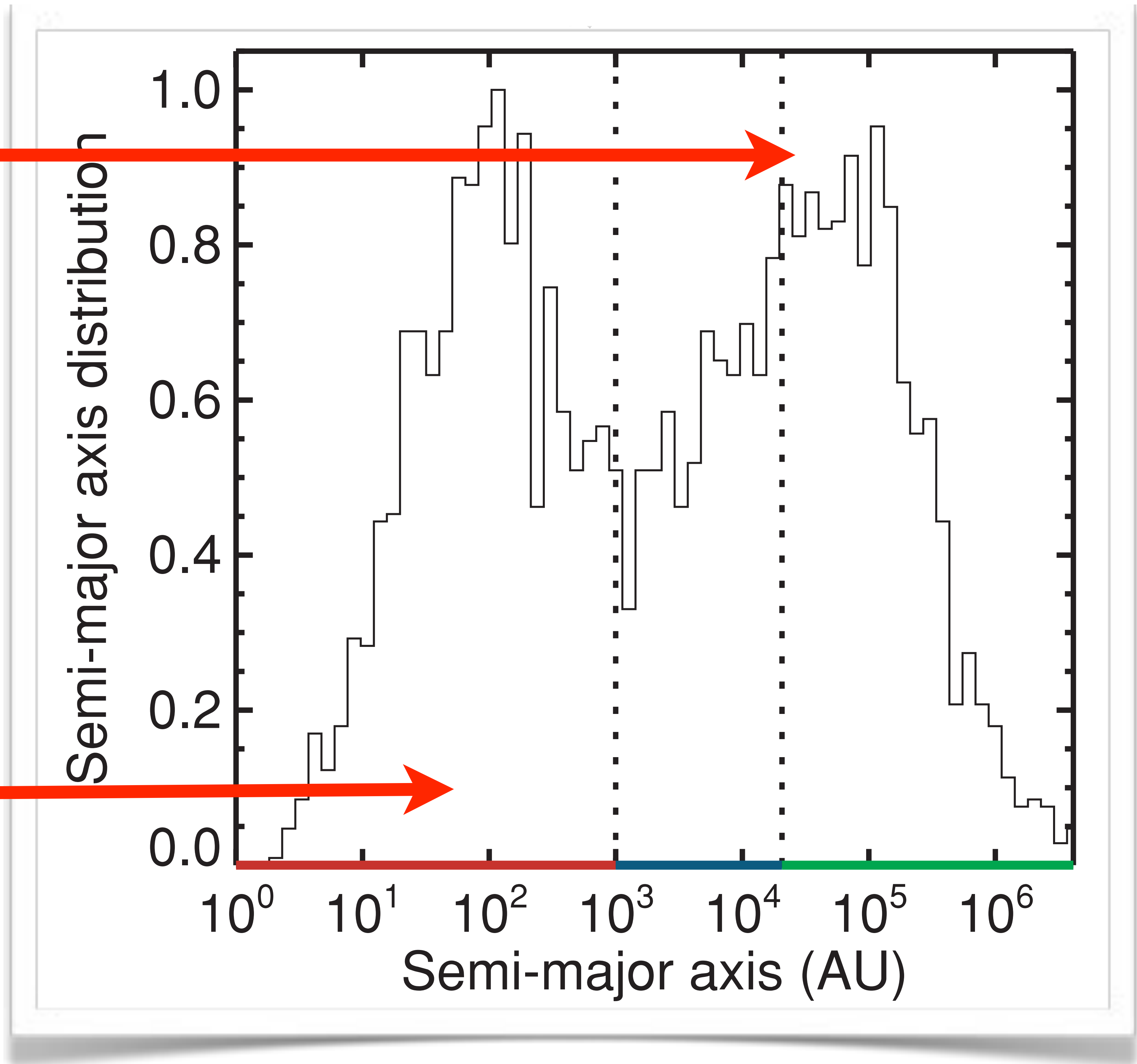
SEMI-MAJOR AXIS DISTRIBUTION

(example)

Wide binary systems formed during cluster dissolution

$$a \approx 0.1 R_{cluster}$$

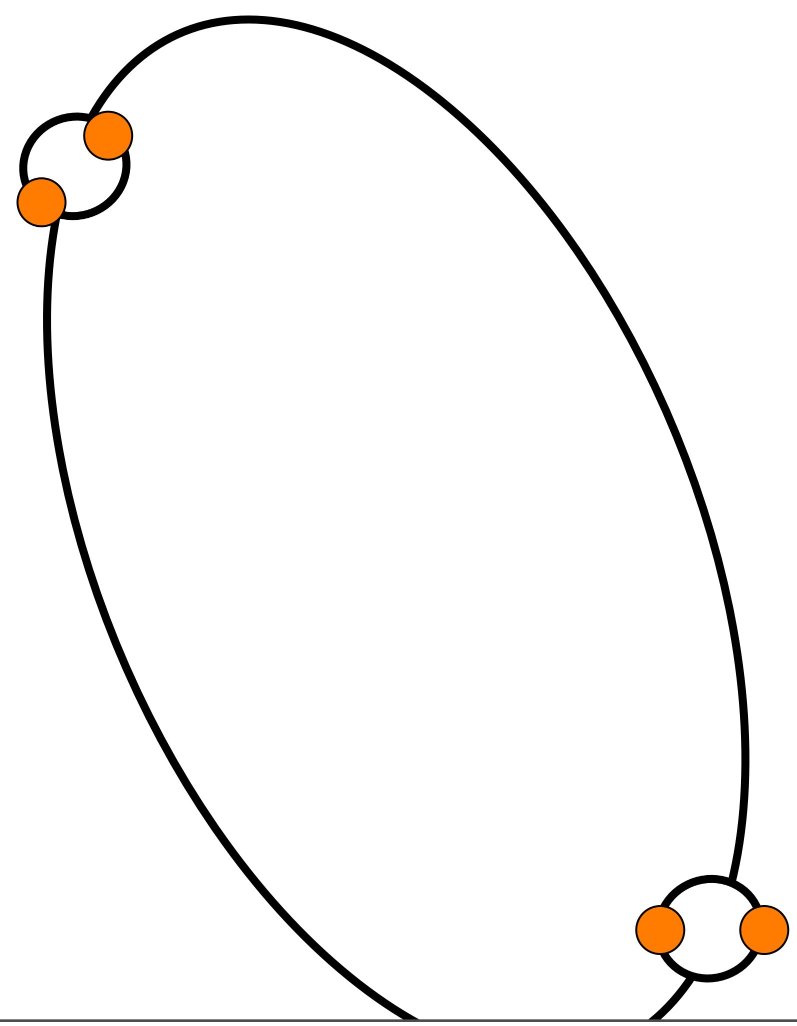
Close binary systems formed via 3-body interactions in the cluster center

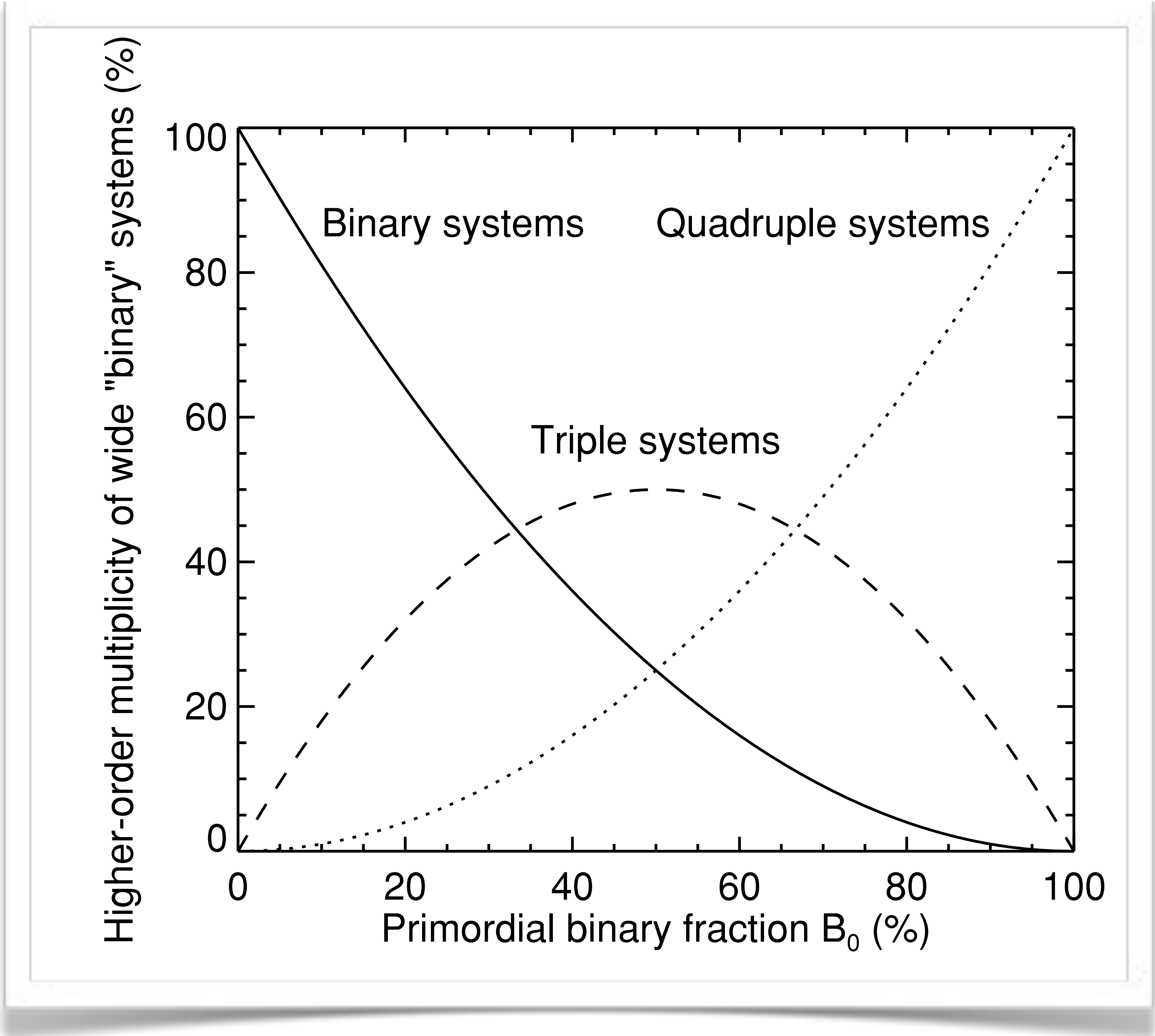


WIDE "BINARIES" ARE MULTIPLE

(*N*=3 or *N*=4)

Most stars form in (close) binaries ➞ most wide "binaries" are triples/quadruples





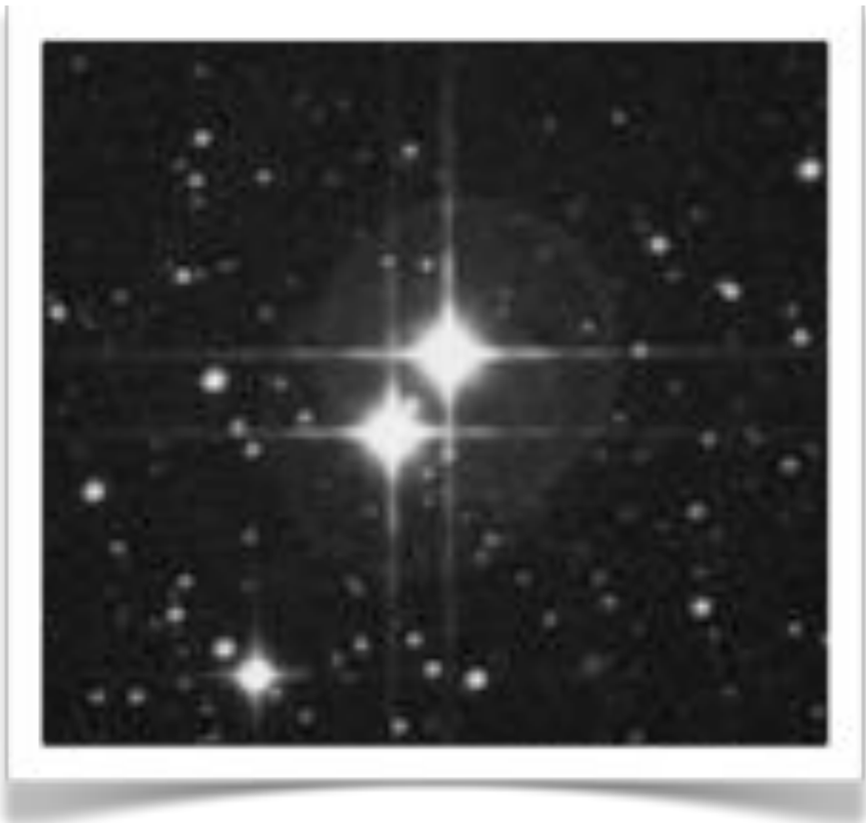
WIDE BINARY ORBITS - PREDICTIONS

Multiplicity of wide "binary" stars

- 1–20 %, depends on cluster mass, cluster size, cluster morphology
- Primordial binary systems ➙ wide multiples (*N*=3, *N*=4)

Orbital size and period

- Semi-major axis ≈ 0.01 – 1.0 $R_{cluster}$



Eccentricity

- Thermal eccentricity distribution: $f(e) = 2e$

Mass ratio distribution

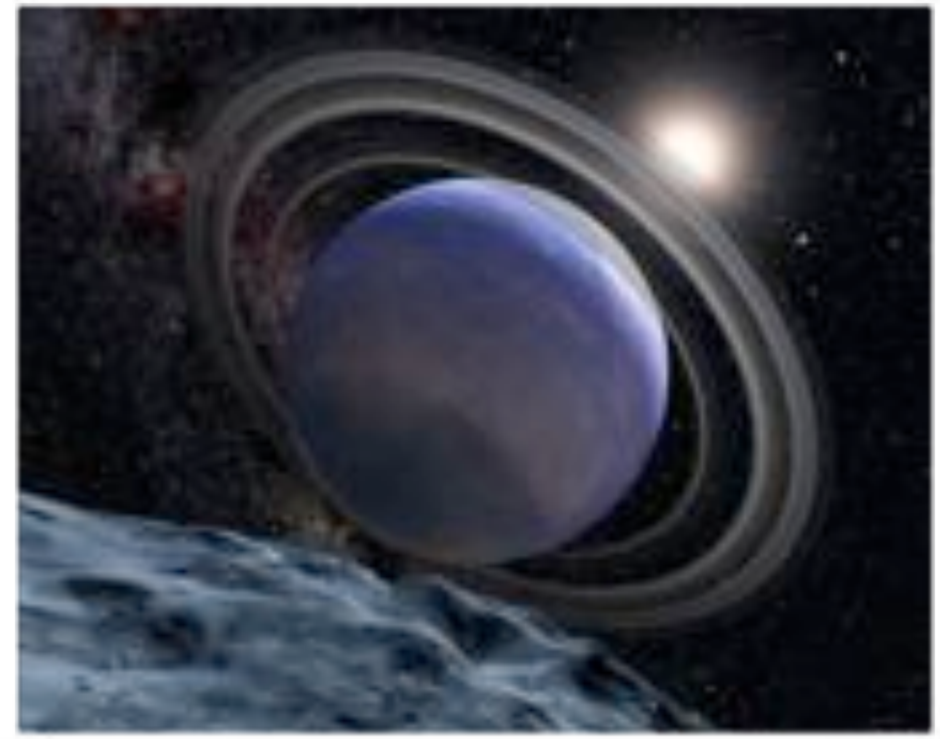
- Gravitationally-focused random pairing

Stellar rotation and orbital orientation uncorrelated

SUMMARY

- Most young stars form are in clusters and part of a binary/ multiple systems
- Binarity a key parameter for understanding star formation
- The IMF doesn't give all information about star formation; need to look at young binary systems
- Binary stars in Scorpius OB2: 100% among A/B stars; random pairing excluded, $f(q) \sim q^{-0.4}$
- Very wide binaries are formed during star cluster dissolution; most are wide triple/quadruple systems

PLANETS....



- How do planetary systems evolve in star clusters? (Wei Hao, Xiaochen Zheng)
- What is the "primordial planet population" and its early evolution? (Li Yun)
- Free-floating planets? (Long Wang)