THE BEGINNING

On the *Nature* and *Origin* of *Brown Dwarves*

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with

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Thesis :

BDs have a *different* formation history.

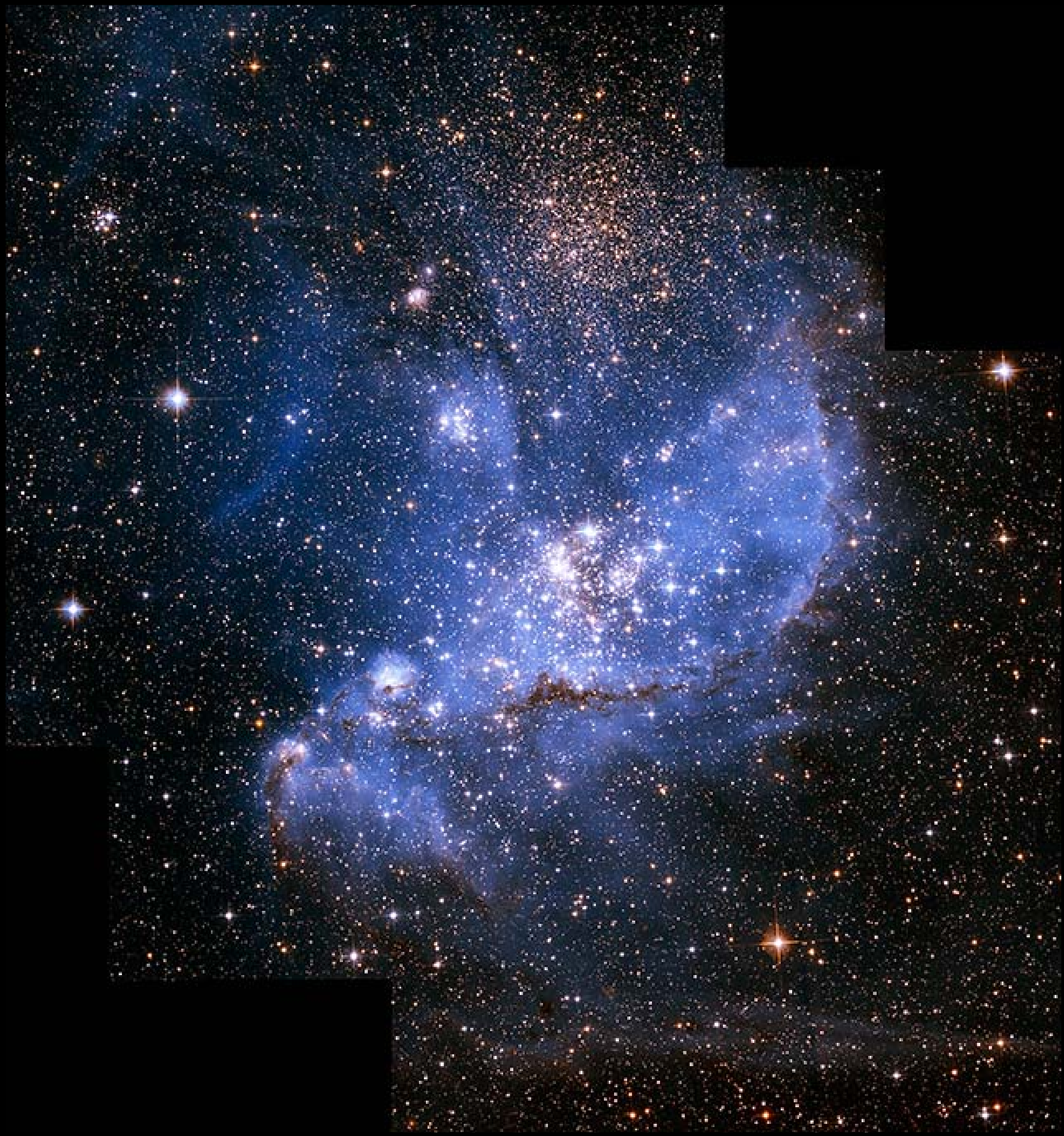
They are an "extra" population,

that is linked to but distinct from the stars.

Outline

- The “standard” star-formation model
- Variable BD populations ?
- BDs as an “extra” population

Star Formation



Pavel Kroupa: *Sternwarte, University of Bonn*

The standard star-formation model

- stars form in clusters
- 100 % binaries
- random pairing from the IMF
- Taurus-Auriga period distribution function; independent of primary mass
- thermal eccentricity distribution

A mathematically concise description of the outcome of star formation.

The *standard model* was derived *w/o BDs* !

With it, a *large variety* of stellar populations can be described in a *compact mathematical form*.

Physically, it corresponds to a *unifying* description of star formation, a ***unification theory***, as it were.

Clusters

Setup for ONC and Pleiades :

(Kroupa, Aarseth & Hurley 2001)

Evolve the cluster with Nbody6 :

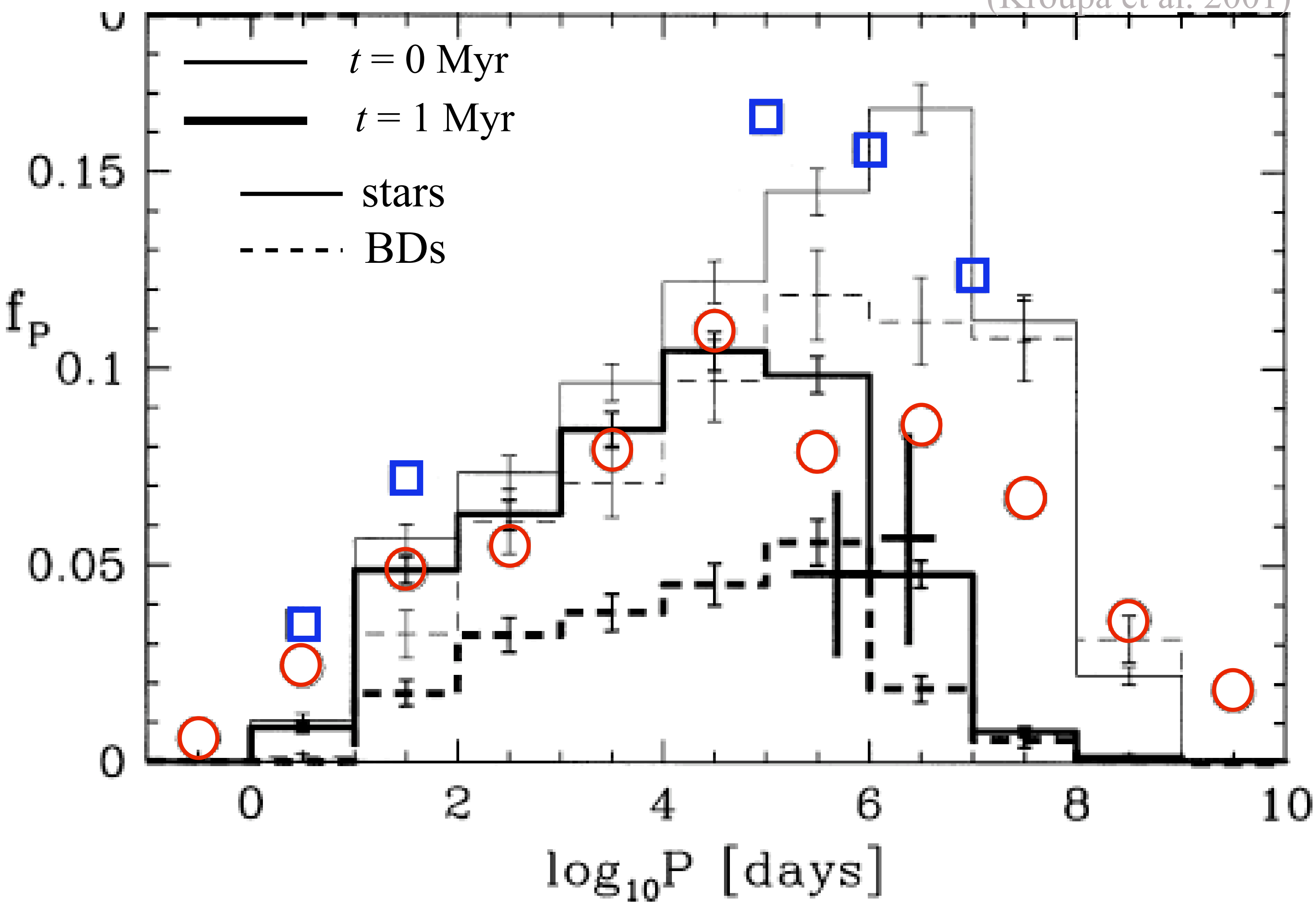
$N = 10^4$ stars and BDs
$R = 0.5\,\mathrm{pc}$
$\epsilon = 33\,\%; \quad \tau_{\mathrm{g}} \approx t_{\mathrm{cross}}$

$t = 1\,\mathrm{Myr}$

$t = 100\,\mathrm{Myr}$

The ONC

(Kroupa et al. 2001)

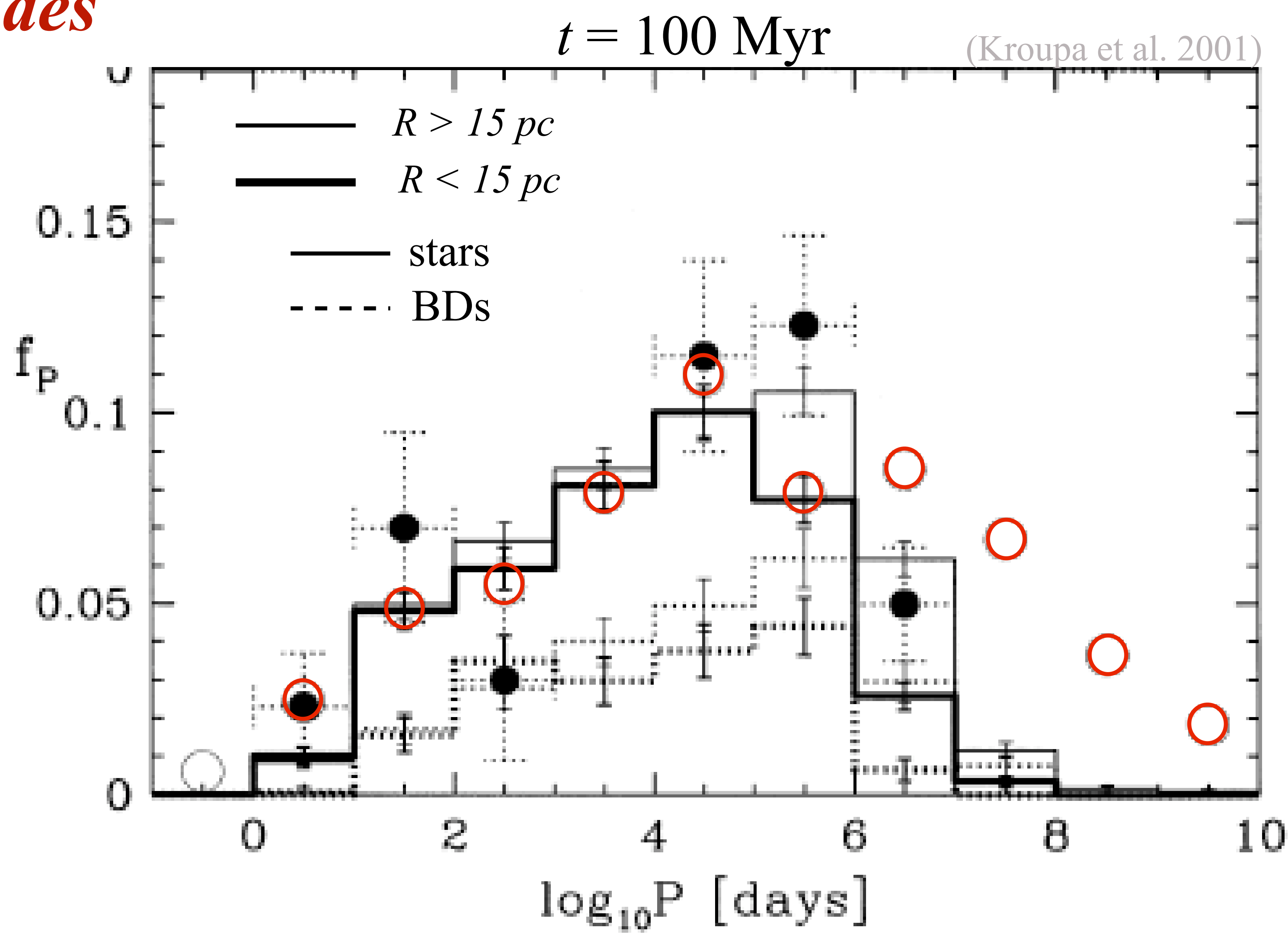


+ Petr (1999)

□ Mathieu (1994)
Richichi et al. (1994)
Koehler & Leinert (1998)

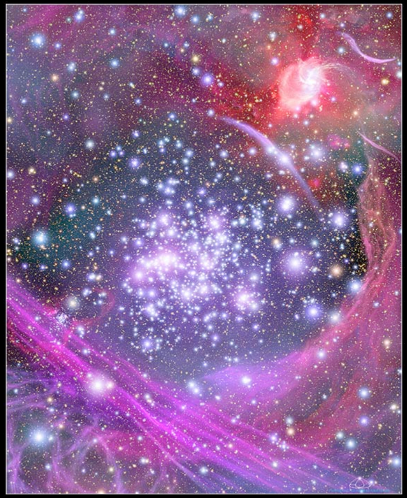
○ Duquennoy & Mayor (1991)

The Pleiades



● Mermilliod et al. (1992)
Bouvier et al. (1997)

Galaxies

$n \times$  $=$ 

Inverse dynamical population synthesis :

Galactic-field population $= \int$ clusters (Kroupa 1995)

Constrain typical cluster parameters $R, \; N$ by matching model :

- period distribution function f_P
- mass-ratio distribution function f_q

to observational data for Galactic field

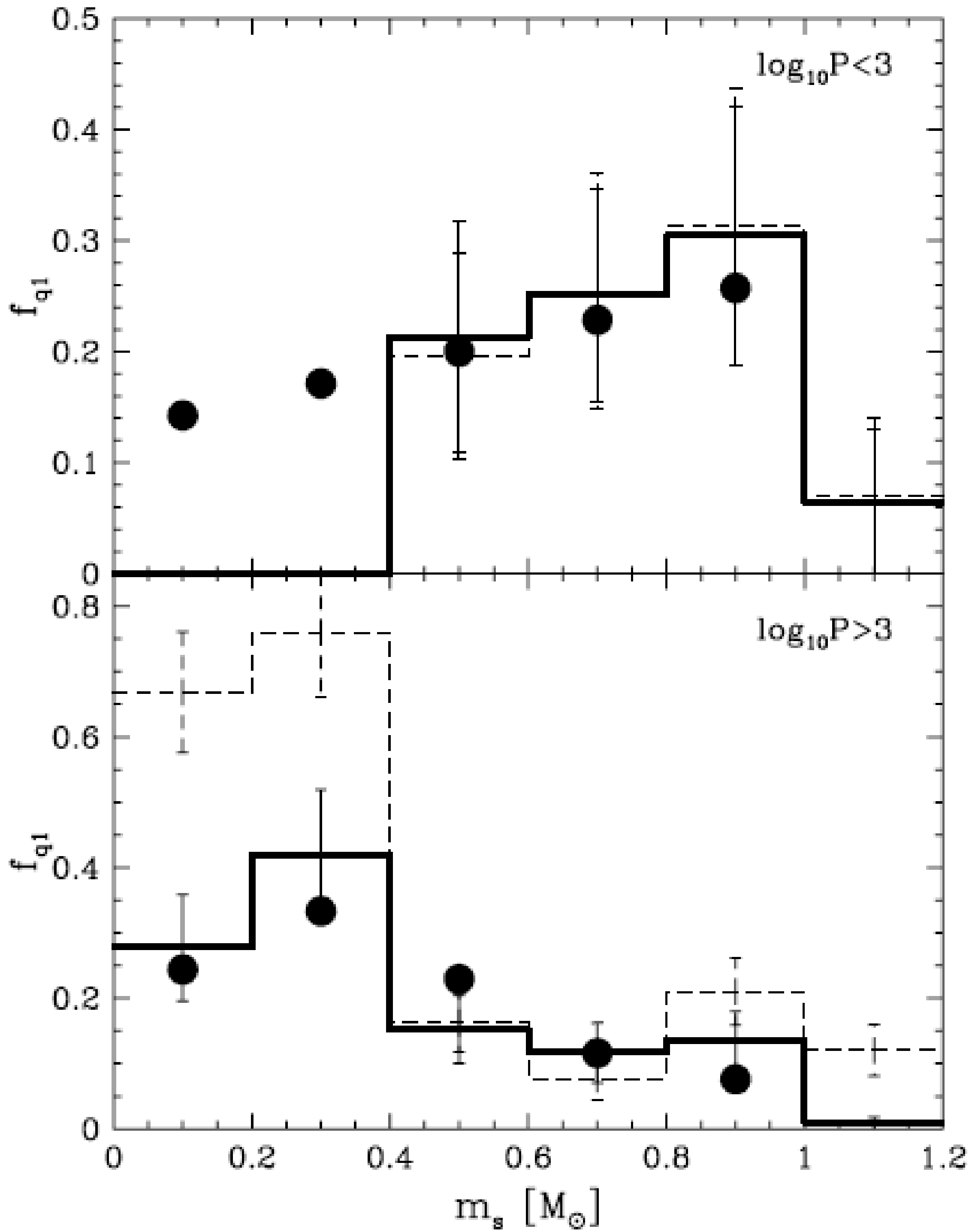
$\Rightarrow$ $R \approx 0.8\,\mathrm{pc}, \;\; N \approx 200$ binaries

the ***dominant mode cluster***

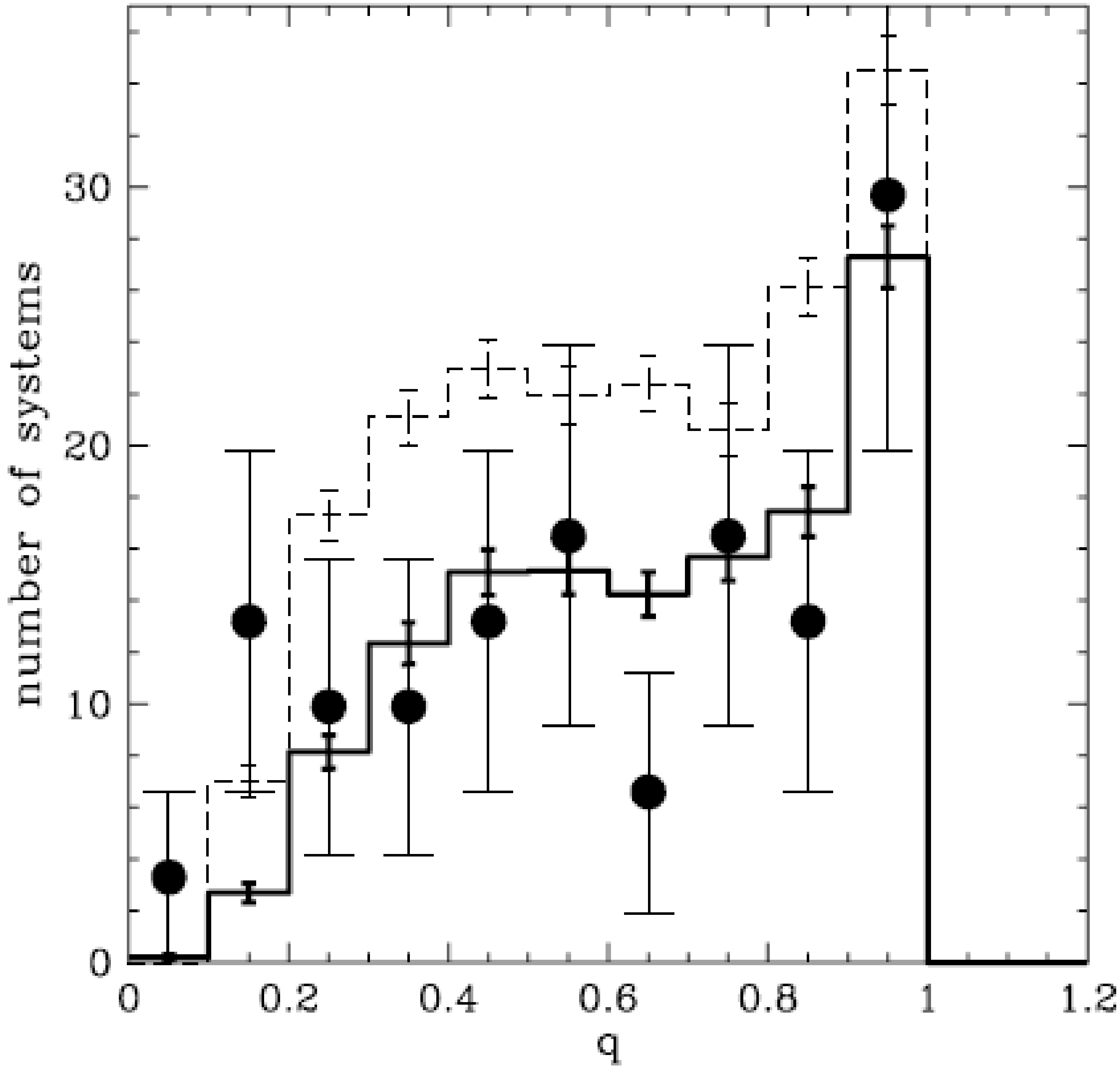
in excellent agreement with local cluster surveys
(Lada & Lada 2003)

The G-dwarf mass-ratio distribution

- Mazeh et al. (1992)
- Duquennoy & Mayor (1991)



The overall mass-ratio distribution



● Reid & Gizis (1997)

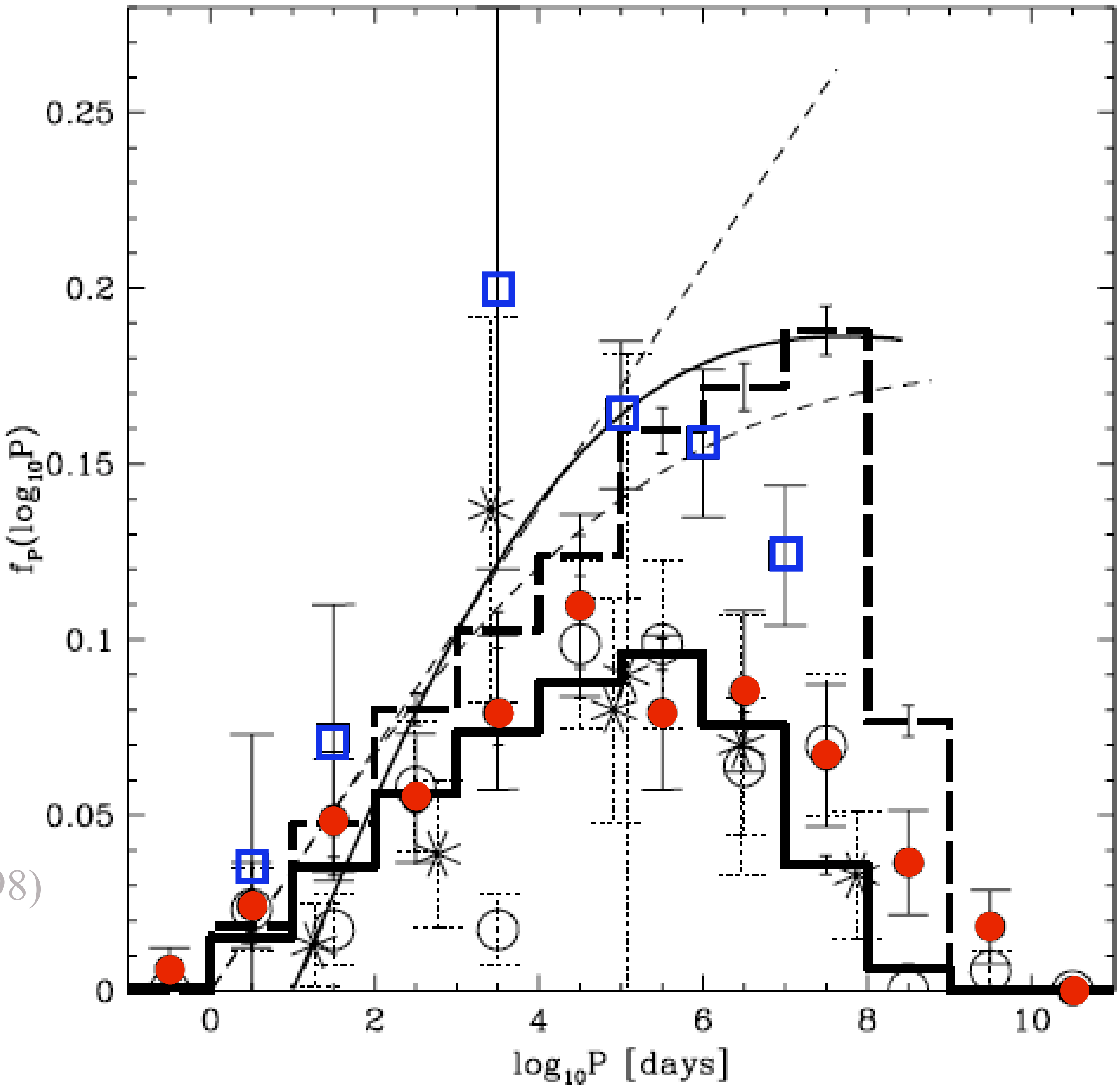
The period distribution

● Duquennoy & Mayor (1991)

○ Mayor et al. (1992)

✳ Fischer & Marcy (1992)

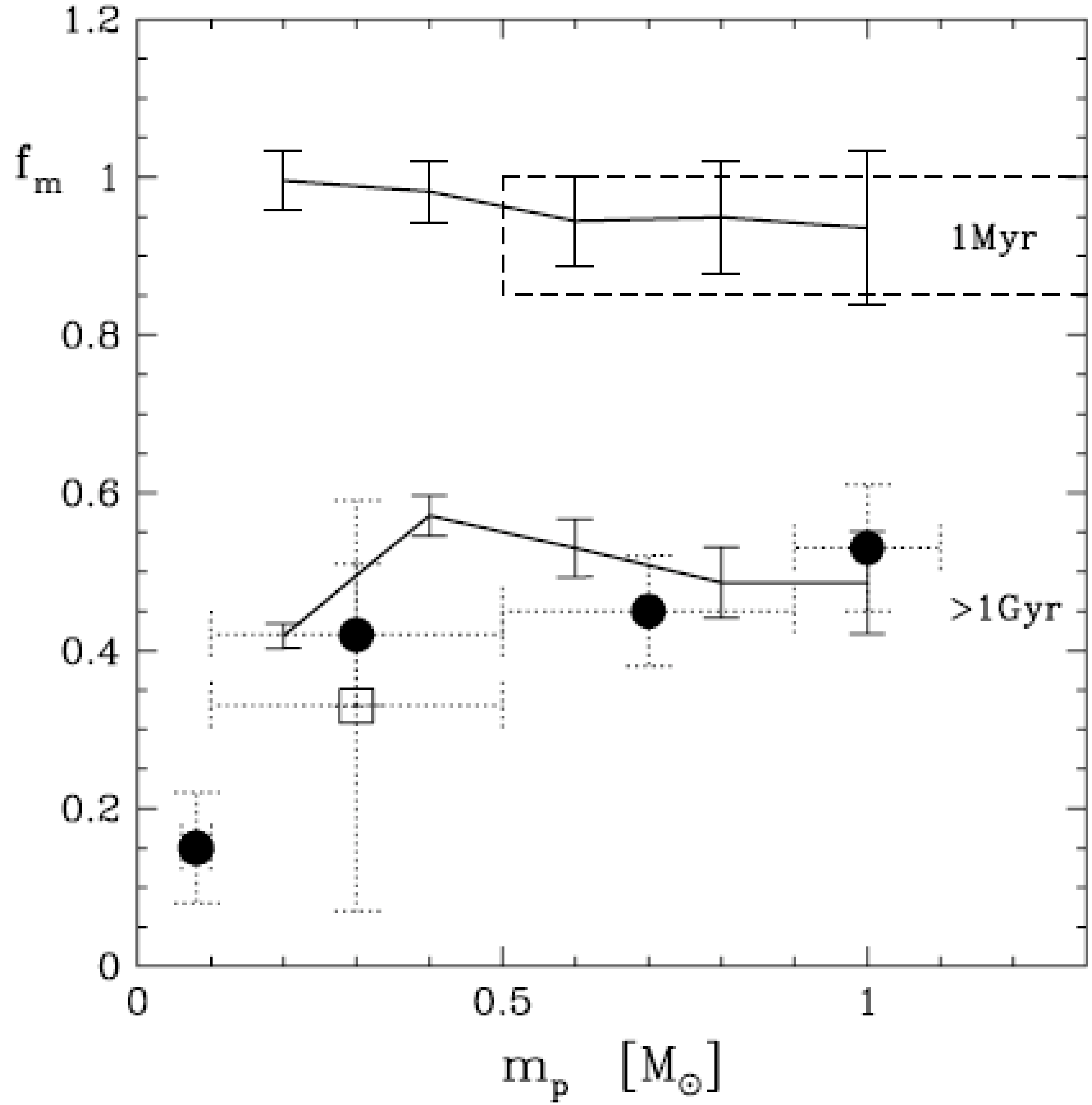
□ Mathieu (1994)
Richichi et al. (1994)
Koehler & Leinert (1998)



The primary-mass-dependent binary fraction

● Duquennoy & Mayor (1991)
Mayor et al. (1992)
Fischer & Marcy (1992)

□ Kroupa et al. (1993)



The

standard model (w/o BDs)

describes the

product of star formation

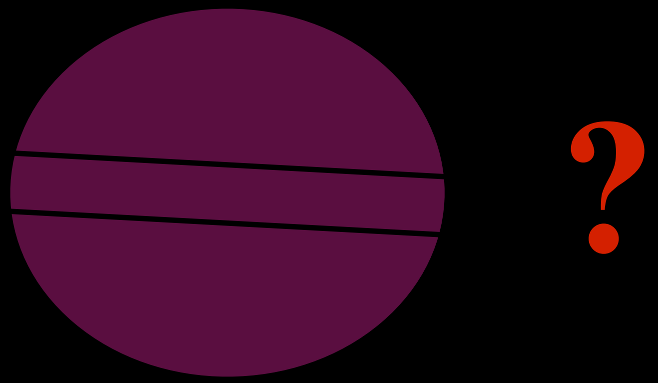
exceedingly well.

Can ***BDs*** be incorporated in a *mathematically consistent* way **?**

Brown Dwarves

vs

Stars



Hypothesis : BDs form like stars.

BDs appear indistinguishable to very young stars : similar K-band excesses, spatial distribution (e.g. White & Basri 2003; Jayawardhana / Mohatny here) .

Implication : Standard star-formation model should be applicable :

- 100 % binaries
- random pairing from the IMF
- Taurus-Auriga period distribution function; independent of primary mass

Contradiction to Hypothesis ?

Briceno, Luhman et al. (2002) survey of known stellar groupings in the *Taurus-Auriga* SF region .

↓

Significant deficit of BDs when compared to *ONC* .

↓

$$M_{\rm J,TA} > M_{\rm J,ONC}$$

Set-up standard model :

(Kroupa, Bouvier et al. 2003)

$N = 25$ binaries

$R = 0.3 - 0.8$ pc

$\epsilon = 33$ %; $\tau_g = 1$ Myr

Different IMFs for $m < 0.08\, M_\odot$:

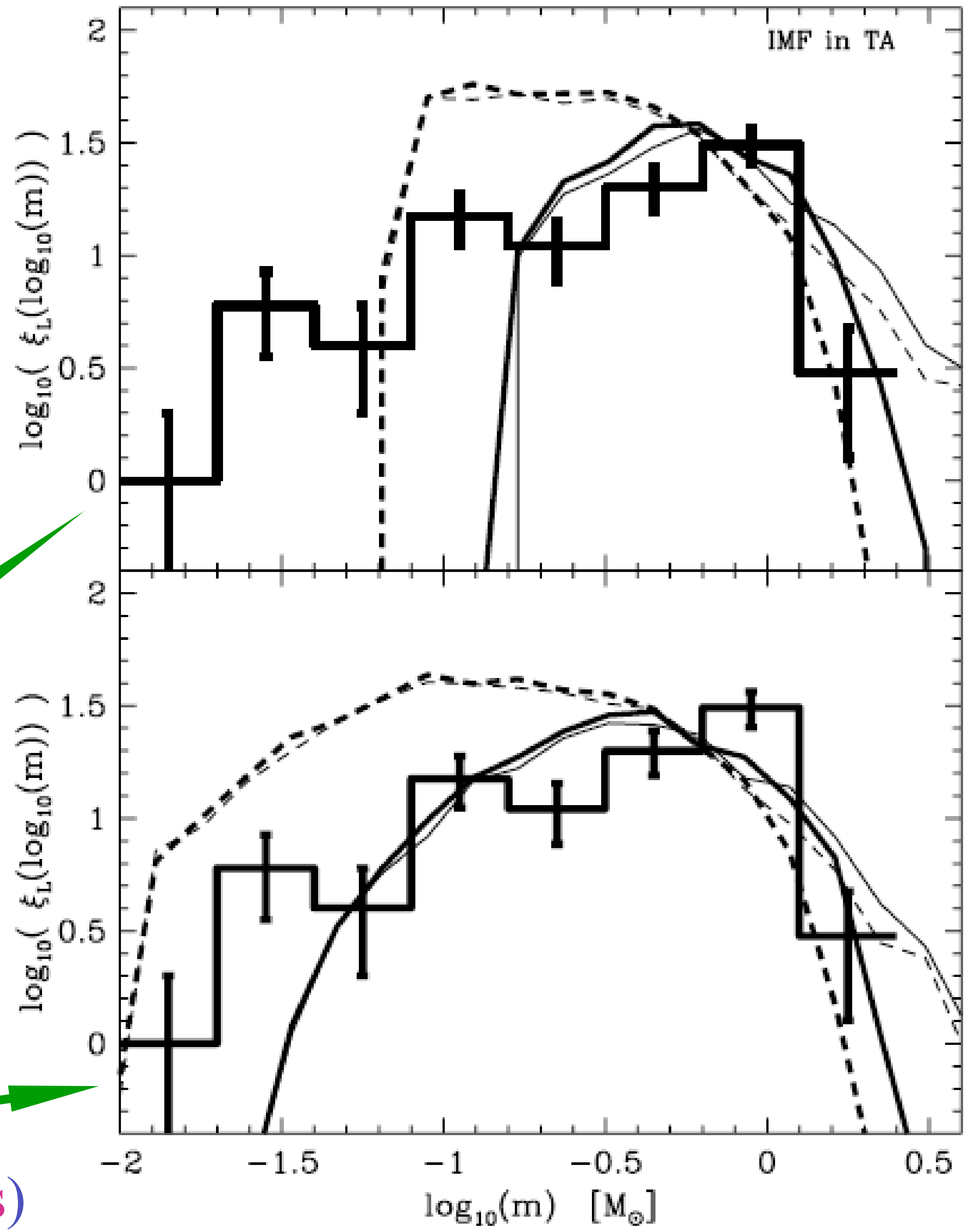
$\alpha_0 = -\infty$

⋮

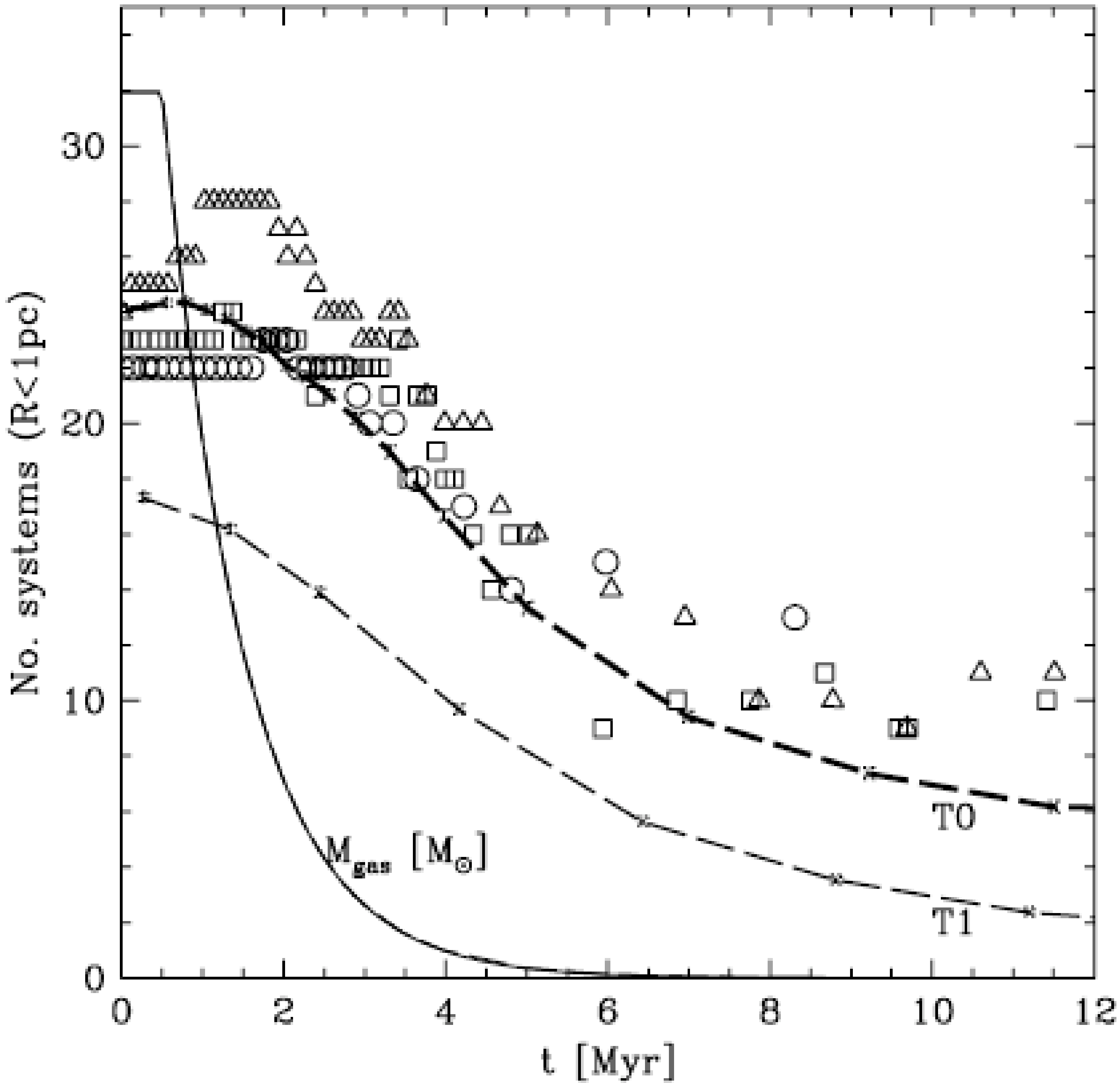
$\alpha_0 = -4.2$

$\alpha_0 = +0.3$ (standard)

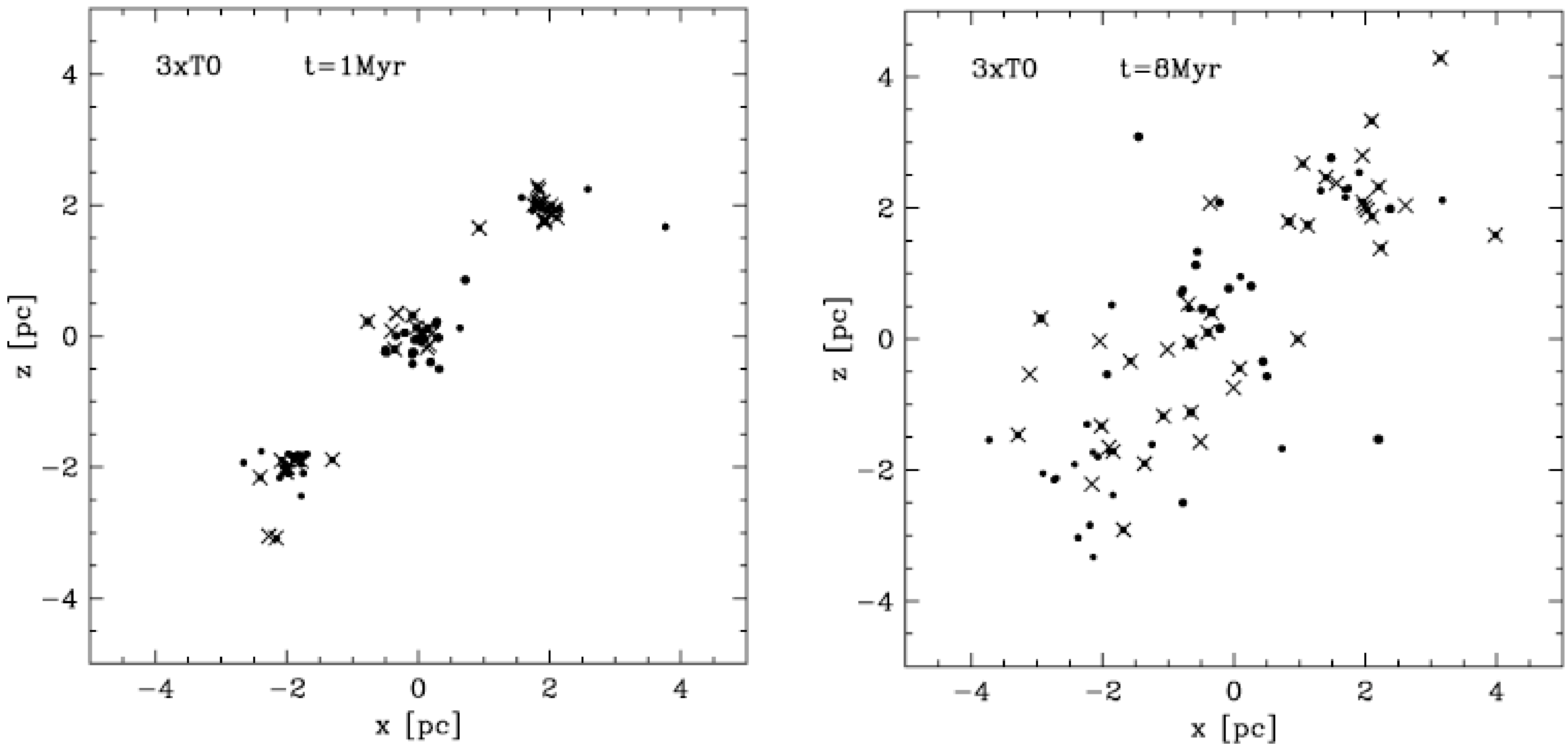
(37% of population are BDs)



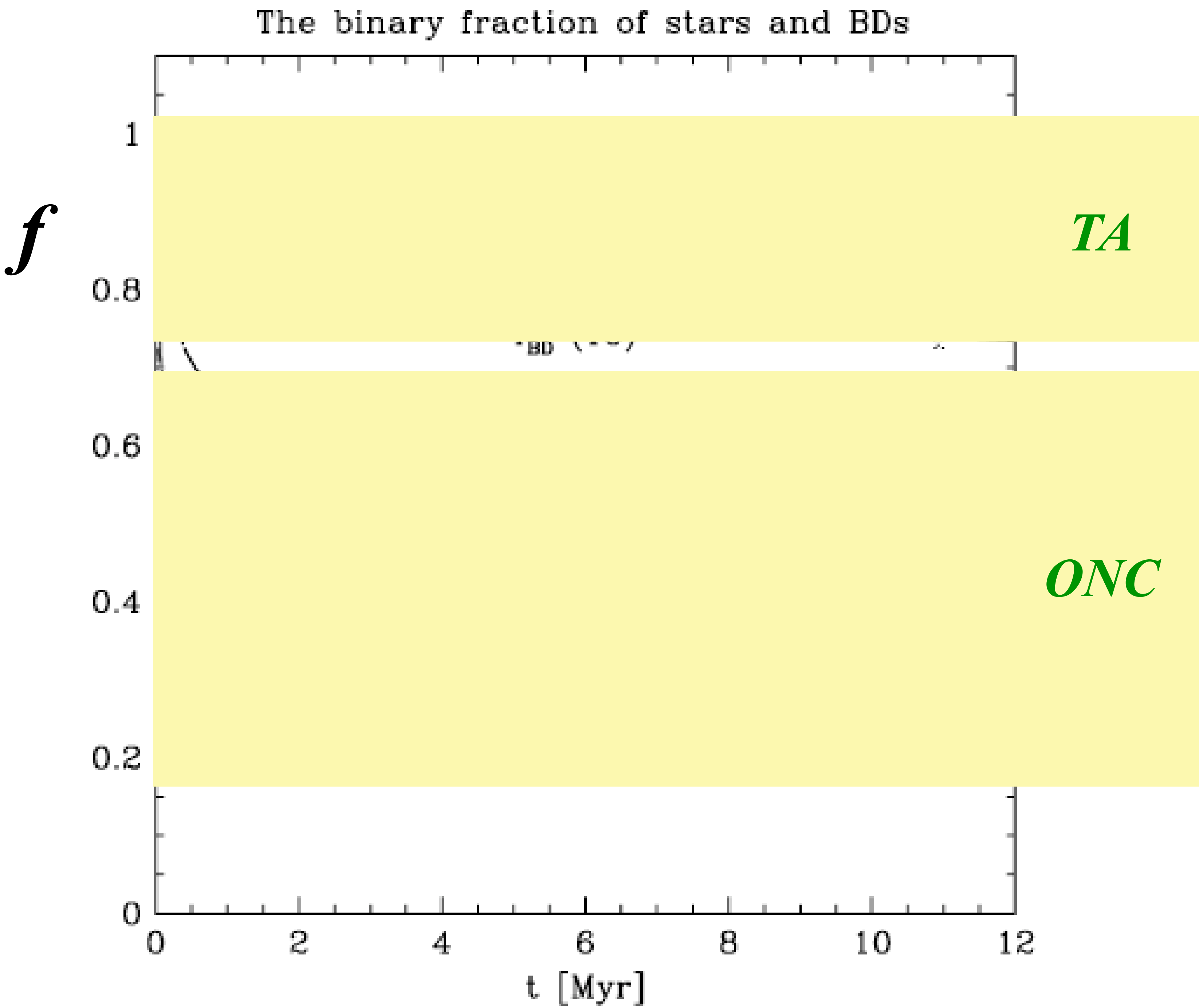
(Kroupa, Bouvier et al. 2003)



(Kroupa, Bouvier et al. 2003)



(Kroupa, Bouvier et al. 2003)



BDs per star

$$\mathcal{R}_{\rm obs} \equiv \frac{N_{\rm sys}(0.02 - 0.08\,M_\odot)}{N_{\rm sys}(0.15 - 1.0\,M_\odot)}$$

$$\mathcal{R}_{\rm obs,TA} = \frac{10}{59} = 0.17 \pm 0.06$$

(Briceno, Luhman et al. 2002)

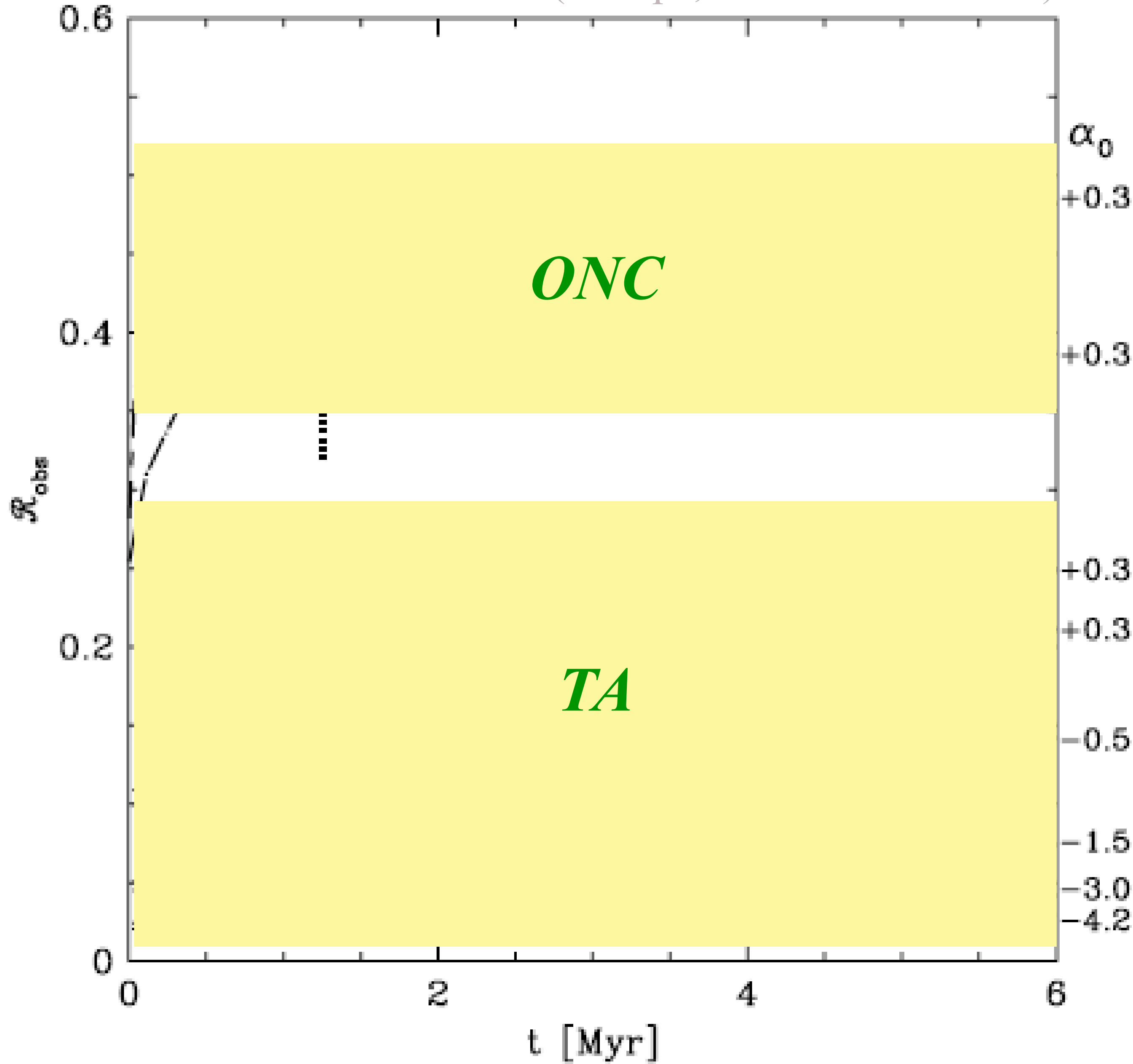
$$\mathcal{R}_{\rm obs,ONC} = \frac{47}{125} = 0.38 \pm 0.06$$

Note :

$\mathcal{R}_{\rm model} = 0.81$

without binaries
and
for standard IMF
$\alpha_0 = +0.3$

(Kroupa, Bouvier et al. 2003)



Thus, standard model *with BDs* appears to work excellently **!**

Let's test it more ...

Concentrate on

- BD-BD semi-major-axis distribution,
- star-BD semi-major-axis distribution,
- star-star binary fraction.

ONC & TA :

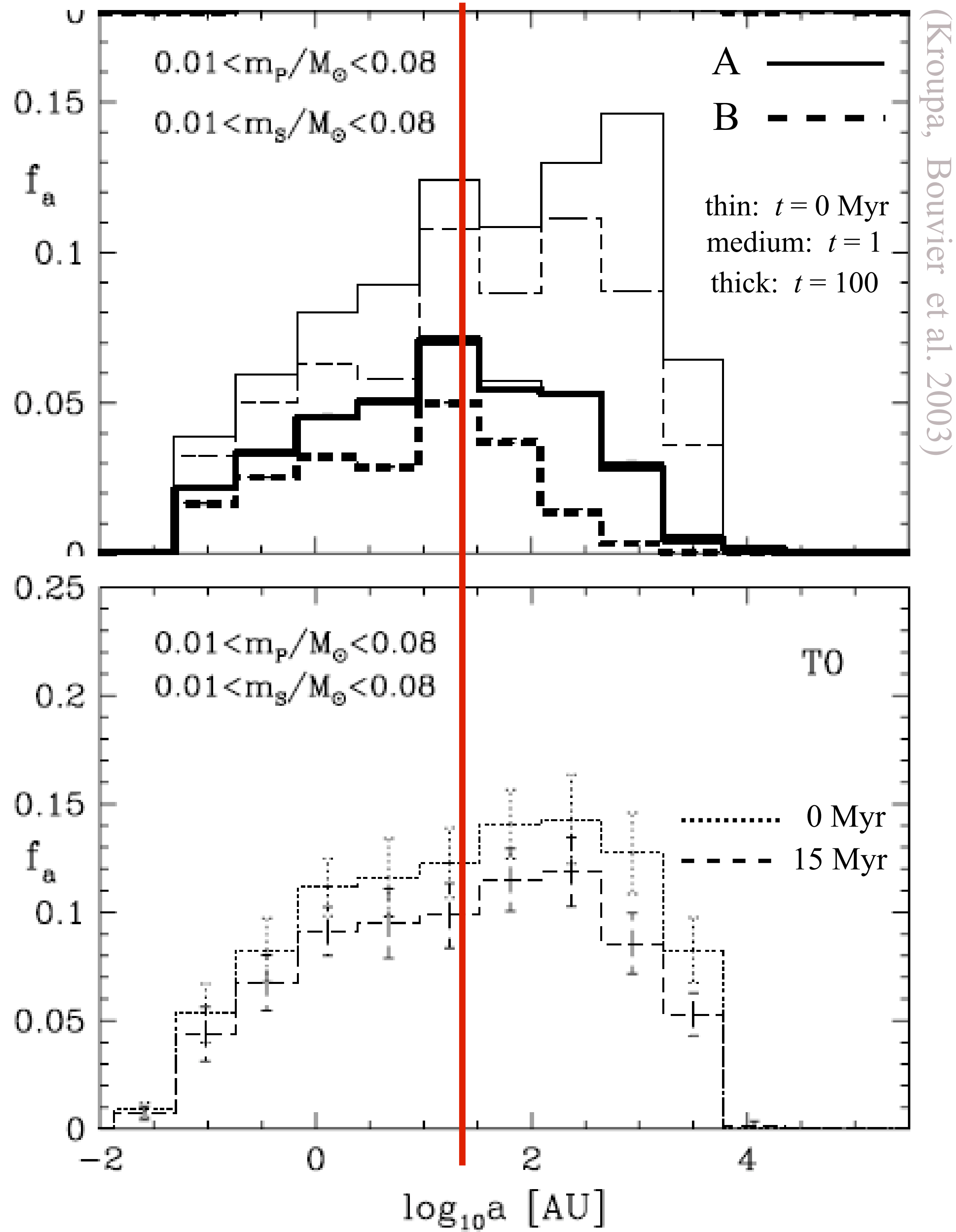
BD-BD semi-major-axis distribution

Thus

13 % in *ONC* and *Pleiades*,
40 % in *TA*,
of BDs ought to have
BD companions with
$a \gtrsim 20$ AU .

None are observed in *Pleiades*
(Martin et al. 2003)
nor in the *field*
(Close et al. 2003; Bouy et al. 2003) .

Model excluded !



Taurus-Auriga : star-BD semi-major-axis distribution

Thus

23 % of all stars in *TA* should have BD companions with $a \in (10^2 - 10^4 \text{ AU})$

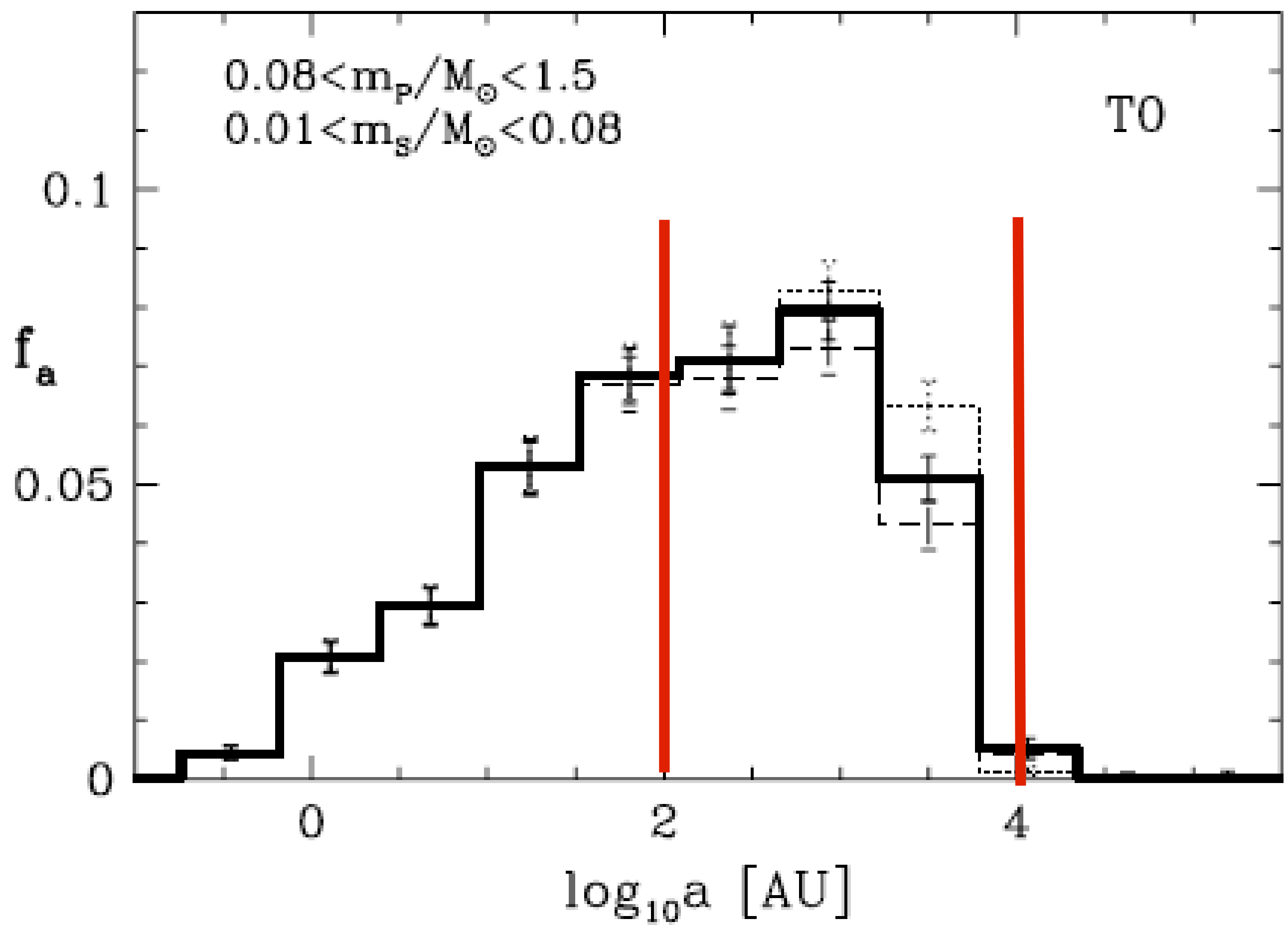
i.e. 17 of the 76 stars in survey by Briceno, Luhman et al. (2003) .

Only one (GG Tau Bb) is known.

Model excluded with confidence

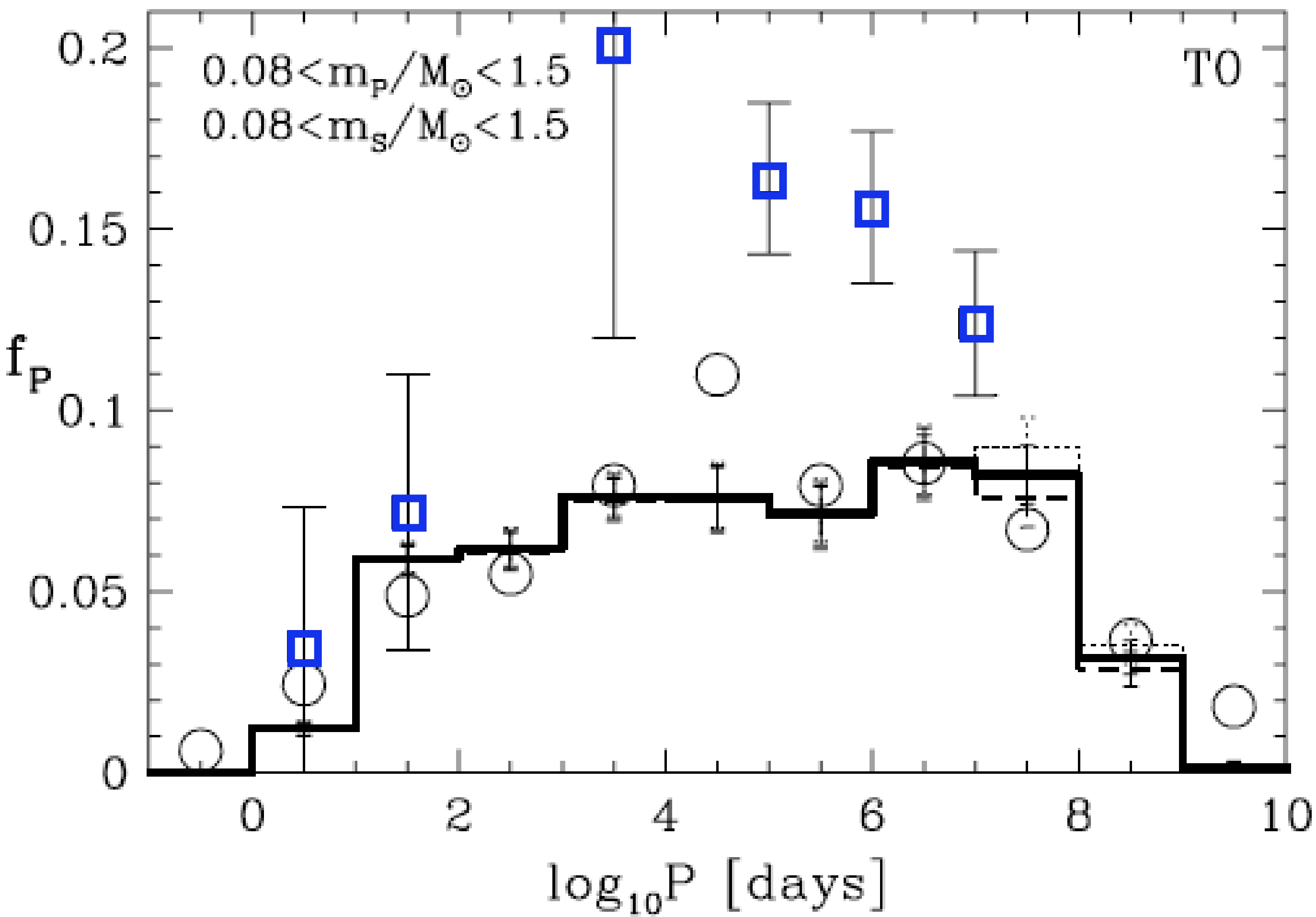
$$P = 10^{-6.15}$$

(Kroupa, Bouvier et al. 2003)



Taurus-Auriga : star-star binaries

(Kroupa, Bouvier et al. 2003)



Pre-main-sequence *model* does not reproduce pre-main-sequence *data*.

Model excluded. Same argument for *Pleiades* & *ONC*.

Implications

The model with BDs ***fails*** to account for the

- BD-BD semi-major-axis distribution,
- star-BD semi-major-axis distribution,
- star-star binary fraction.

Thus, the standard model *with BDs* fails **!**

There is no consistent description that includes BDs.

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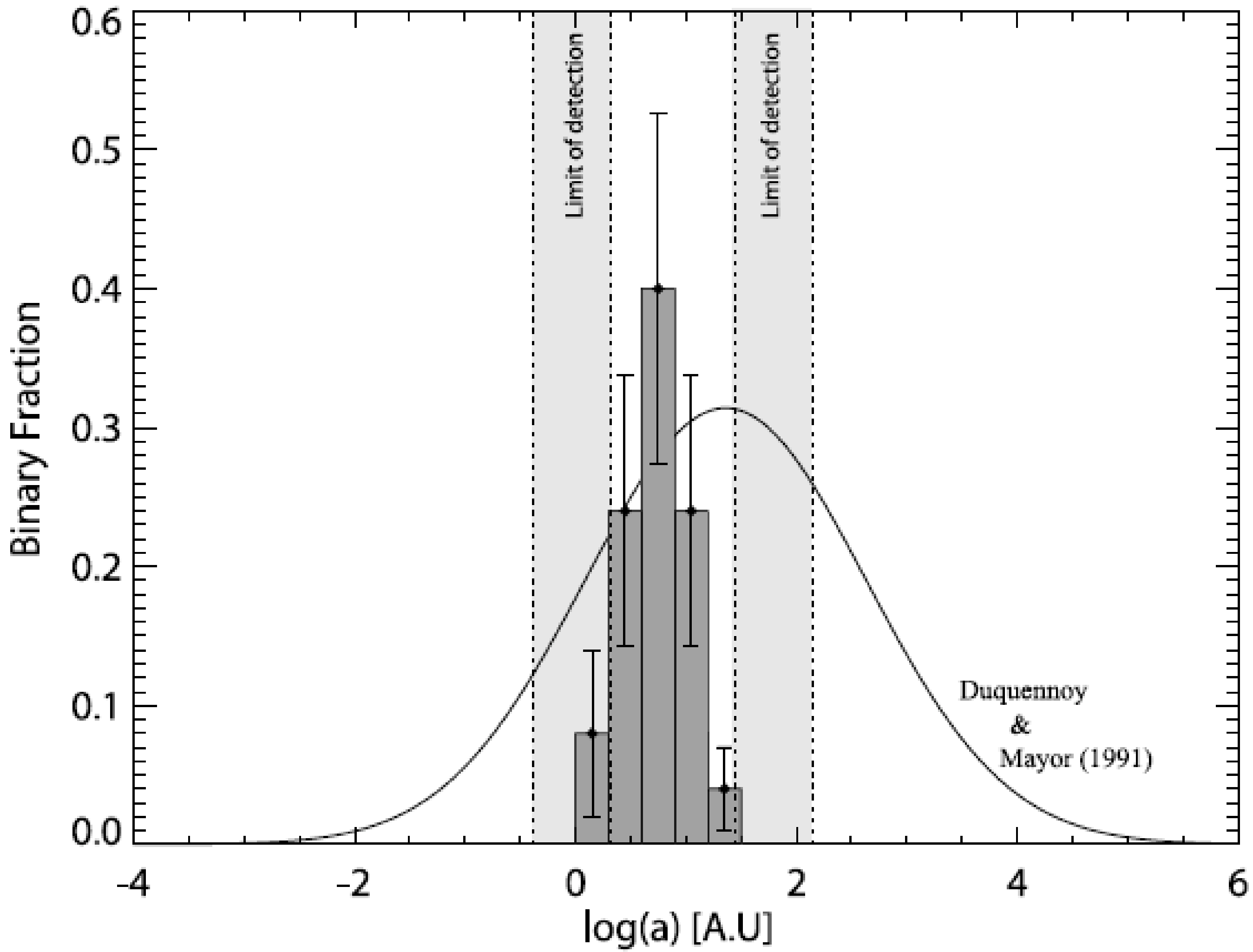
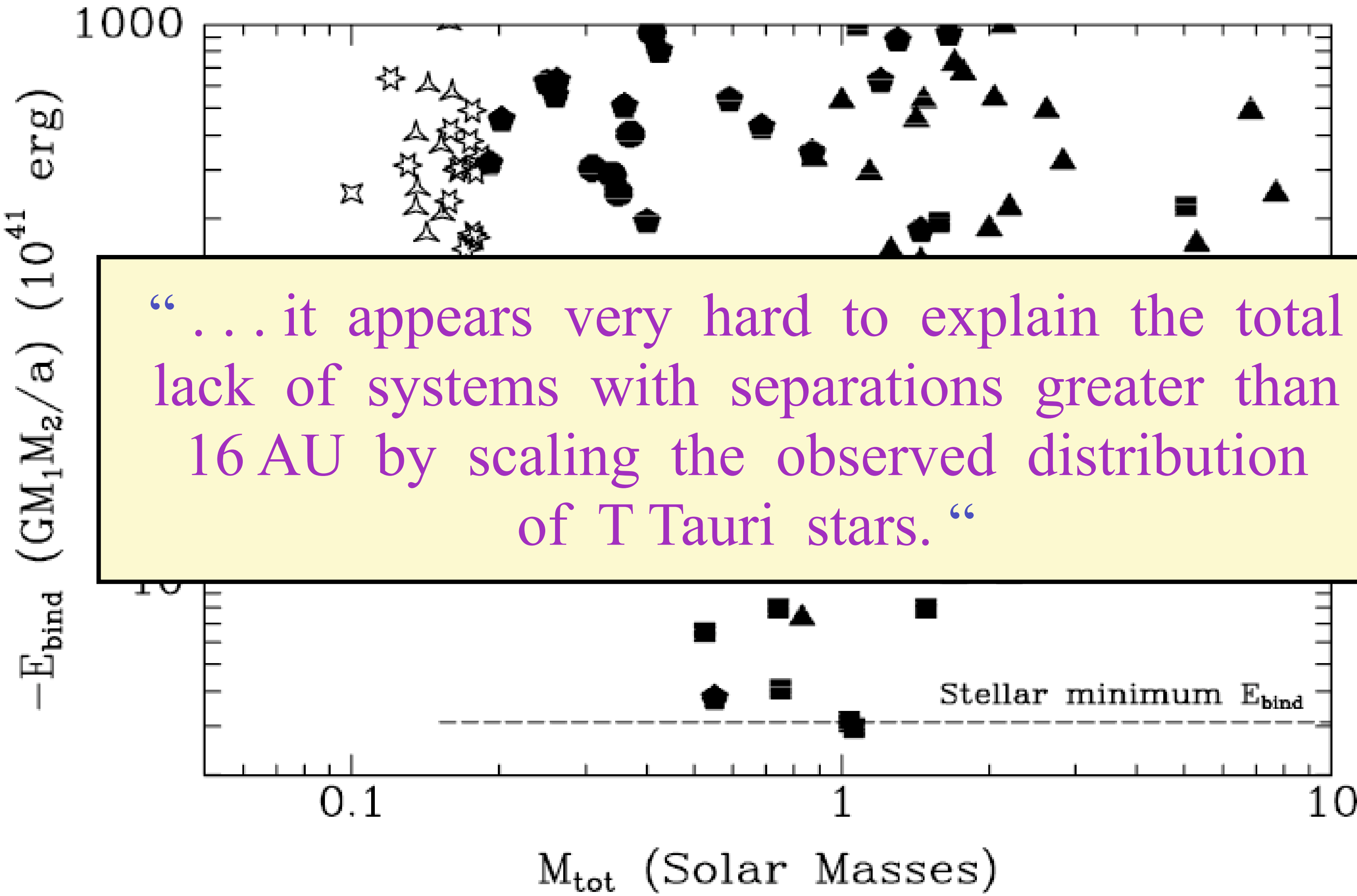
Bouy et al. (2003) : HST observations of 134 very-low-mass field binaries.

"... there are major differences in the formation and evolution processes of these ultracool objects in comparison with stars."



There is no consistent description that includes BDs.

Close et al. (2003) : Adaptive-optics observations on Gemini North Telescope of 39 very-low-mass field binaries.



“ . . . it appears very hard to explain the total lack of systems with separations greater than 16 AU by scaling the observed distribution of T Tauri stars. “

Binding-Energy distributions of M dwarves and BDs

10^7 ***BD binaries***

$\xi(m) \propto m^{-0.3}$

$0.04 - 0.1\, M_\odot$

Close et al. (2003) f_a

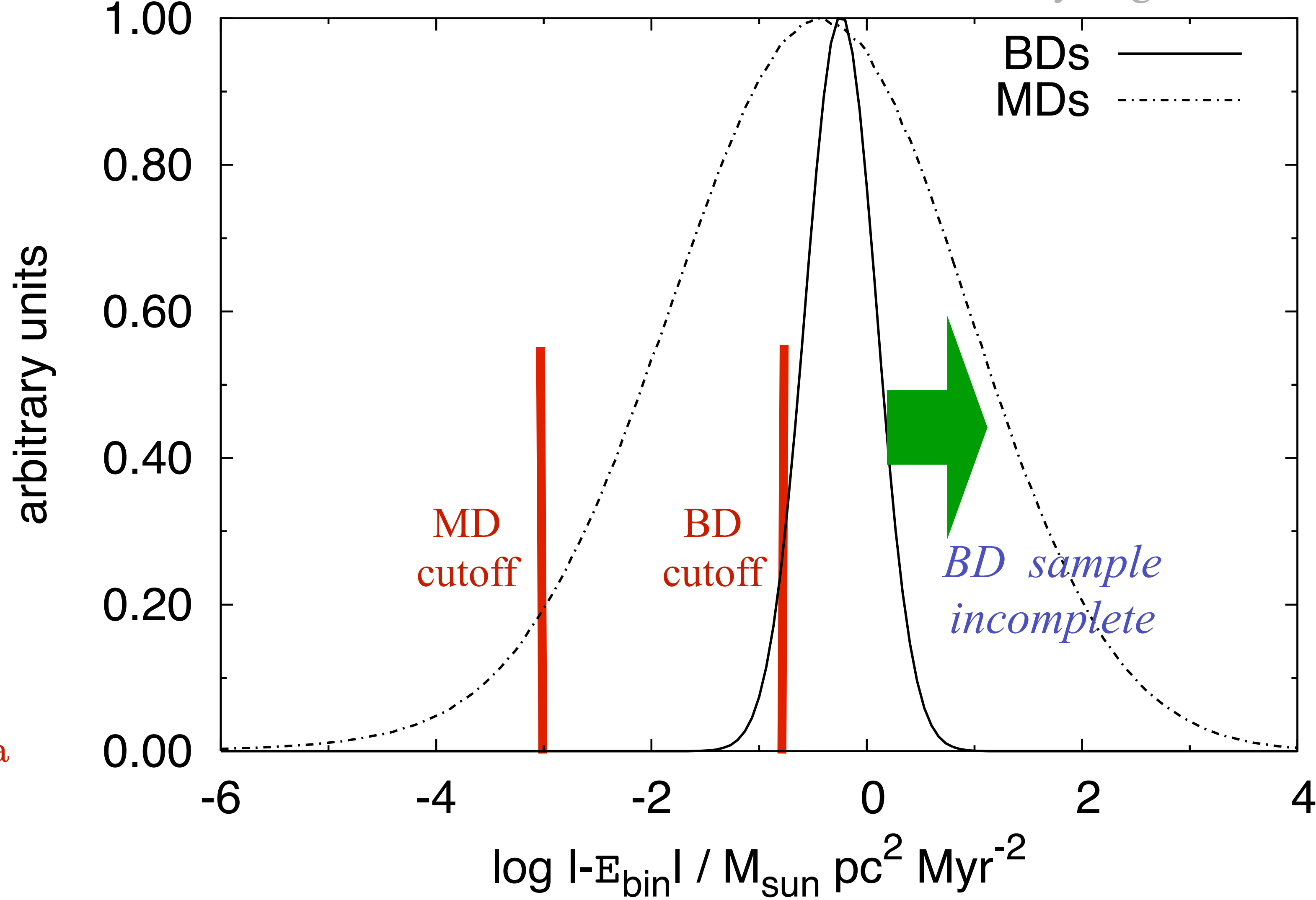
10^7 ***MD binaries***

$\xi(m) \propto m^{-1.3}$

$0.1 - 0.5 M_\odot$

Fischer & Marcy (1992) f_a

Courtesy Ingo Thies

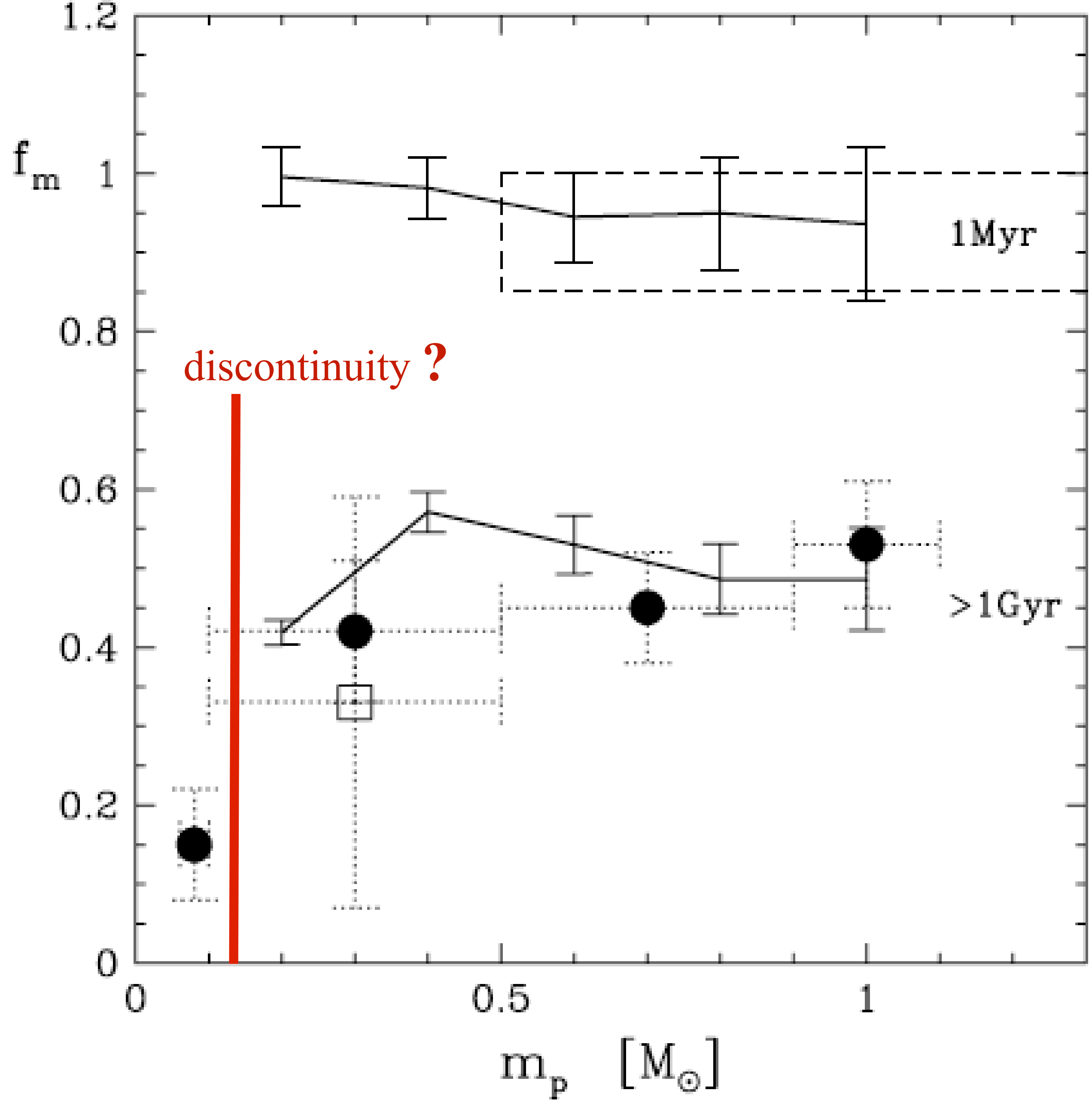


Thus, *our* results and those of
Bouy et al., *Close et al.*, *Martin et al.*
are mutually consistent **!**

The ***BD*** and ***stellar*** energy distributions
are ***fundamentally different :***

∃ a ***discontinuity*** in binary properties near the
hydrogen burning limit.

Remember :



● Duquennoy & Mayor (1991)
Mayor et al. (1992)
Fischer & Marcy (1992)

□ Kroupa et al. (1993)

Thus, in the stellar regime,
stellar populations can be well-described
by the standard model.

BDs can only be incorporated by
changing the pairing rules,
by treating BDs as a
separate population.

Production rate of BDs per star

$$\text{for } i = 1 \ldots N, \quad \mathcal{CREATE}_i$$

The production rate of BDs per star

Let $R \equiv \frac{N(0.02 - 0.08\,M_\odot)}{N(0.15 - 1.0\,M_\odot)} \equiv \frac{N_{\rm BD,tot}}{N_{\rm st,tot}}$

But $R_{\rm obs} = \frac{N_{\rm BD,obs}}{N_{\rm st,obs}} = N_{\rm BD,tot}\,(\mathcal{B}+\mathcal{U})\,\frac{1}{N_{\rm st,sys}}$

$$= N_{\rm BD,tot}\,(\mathcal{B}+\mathcal{U})\,\frac{(1+f)}{N_{\rm st,tot}}$$

Luhman (2004) observes :

$$R_{\rm TA,obs} = 0.25 \qquad = (1+f_{\rm TA})\,R_{\rm TA}\,(\mathcal{B}_{\rm TA}+\mathcal{U}_{\rm TA})$$

➡ $R_{\rm TA} = 0.18 \qquad (\,f_{\rm TA} = 1, \quad \mathcal{B}_{\rm TA}+\mathcal{U}_{\rm TA} = 0.35+0.35\,)$

Slesnick, Hillenbrand & Carpenter (2004) observe :

$$R_{\rm ONC,obs} = 0.28 \qquad = (1+f_{\rm ONC})\,R_{\rm ONC}\,(\mathcal{B}_{\rm ONC}+\mathcal{U}_{\rm ONC})$$

➡ $R_{\rm ONC} = 0.19 \quad (f_{\rm TA} = 0.5, \quad \mathcal{B}_{\rm ONC}+\mathcal{U}_{\rm ONC} = 1+0)$

Therefore, the TA and ONC

BD/star data (Luhman 2004)

can be understood if

≈ 1 embryo is ejected per 5 stars

(Kroupa, Bouvier et al. 2003)

with

$$\sigma_{\rm ej} \approx 1.3\,{\rm km/s}\ .$$

This is consistent with the binding-energy cutoff **!**

Close et al. discuss BD binary properties in terms of the ***embryo-ejection*** scenario.

A disconcerting realisation :

The IMF for MDs : $\alpha_1 = +1.3$

But,
the IMF for field-VLMOs $-1.5 < \alpha_0 < +1$
(Allen et al. 2005)

And,
the IMF for cluster BDs $\alpha_0 = +0.3 \pm 0.7$
(Kroupa 2001; Bouvier et al. 2002)

Whereas,
TA & ONC $(\mathcal{R} = 0.19)$ → $\alpha_0 = -3.3$ **?**

Conclusions

(i) BDs have a different formation history than stars.

(ii) This is evident from the discontinuity in the binary properties near the H-burning limit.

(iii) The notion that most BDs may be ejected embryos seems to be consistent with these findings.

(iv) Universal production mechanism: 1 BD per 5 stars

(v) A disconcerting disagreement for BD IMFs

The END