Multiplicity in early stellar evolution

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Alan Boss: Carnegie Institute of Washington
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Simon Goodwin: University of Sheffield
Luis Felipe Rodriguez: UNAM
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Andrei Tokovinin:CTIO
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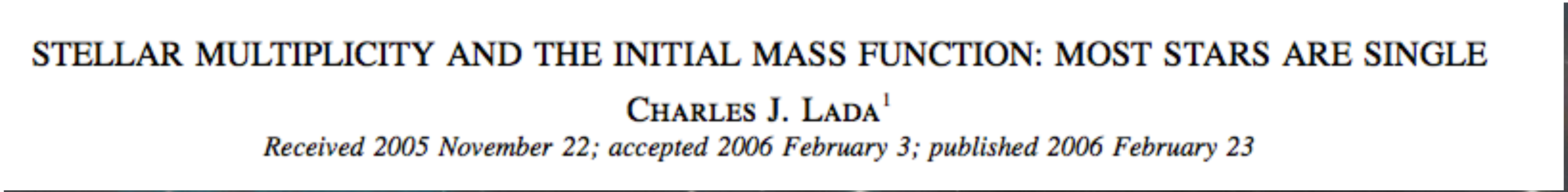
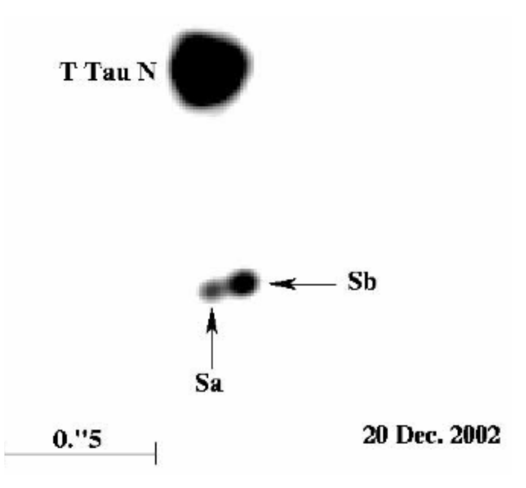


STELLAR MULTIPLICITY AND THE INITIAL MASS FUNCTION: MOST STARS ARE SINGLE

CHARLES J. LADA[1]

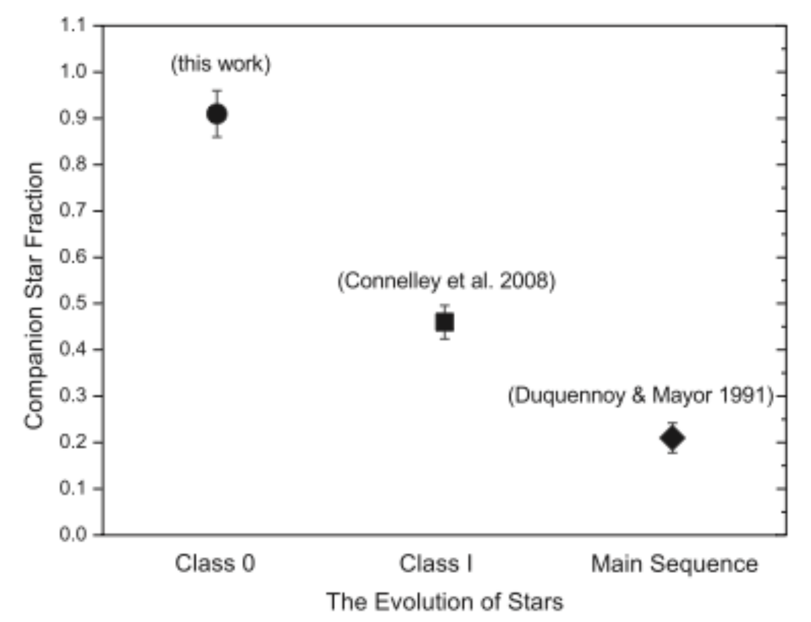
Received 2005 November 22; accepted 2006 February 3; published 2006 February 23

So why do we care?



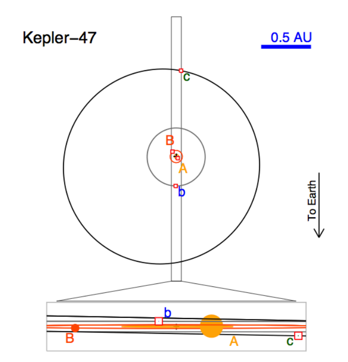
Beck et al 2004
ApJ614,235 Fig 9

Chen et al 2013, ApJ 768,110 Fig. 20

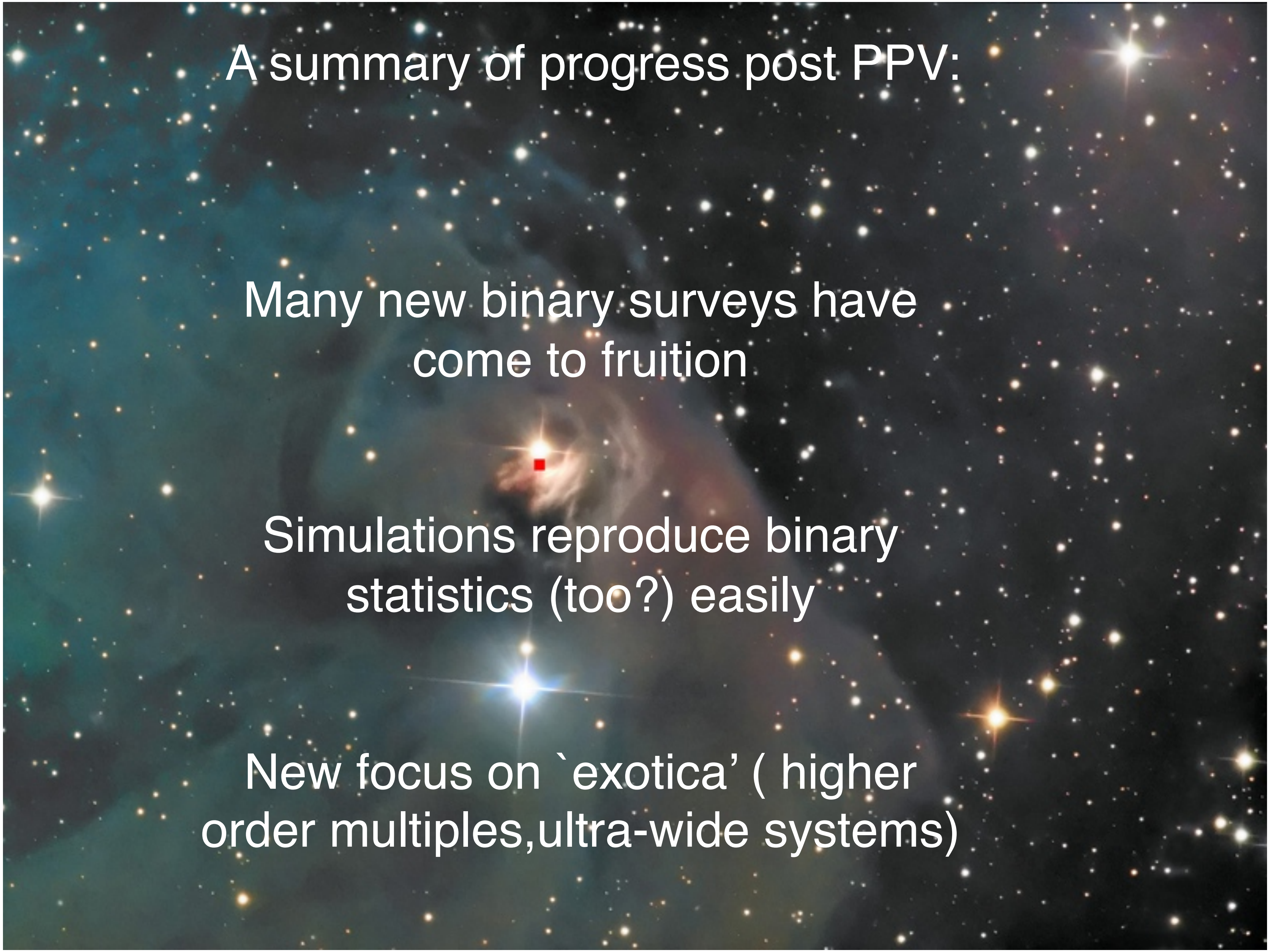


…..Not born single!

New impetus – Kepler circumbinary planets



Orosz et al 2012, Science 337, 6101 Fig. S19



A summary of progress post PPV:

Many new binary surveys have come to fruition

Simulations reproduce binary statistics (too?) easily

New focus on `exotica’ (higher order multiples,ultra-wide systems)

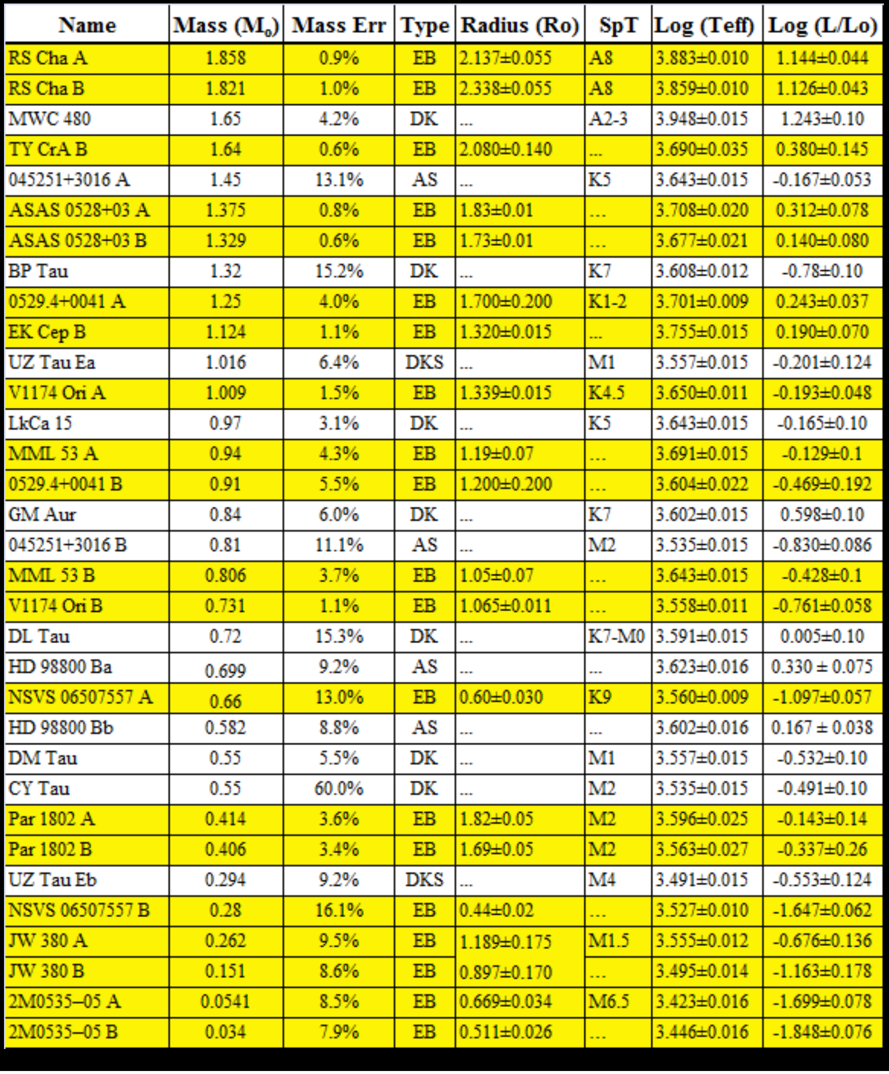
USING BINARIES AS ASTROPHYSICAL LABORATORIES

PMS MASSES AND RADII FROM ECLIPSING BINARIES

Now 23 pms stars in eclipsing binaries

(including 2 brown dwarfs)

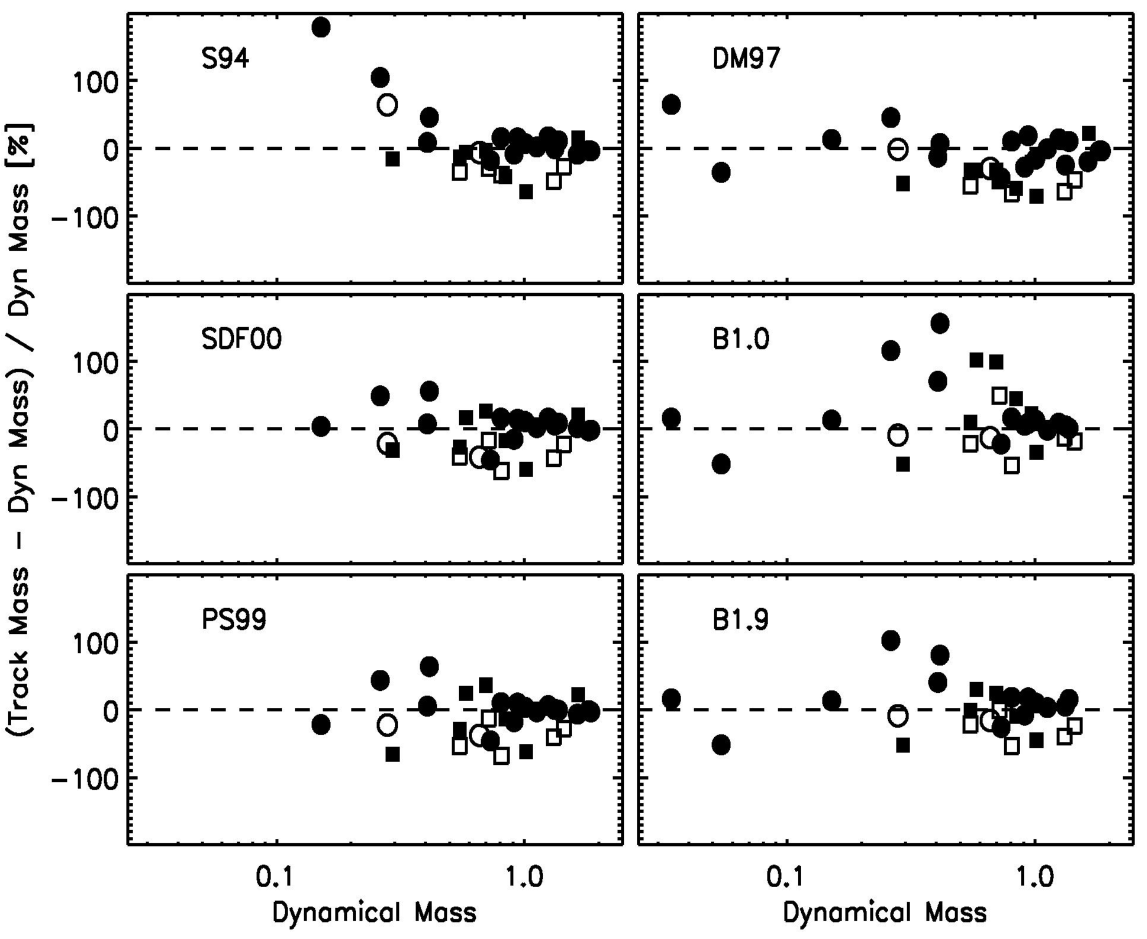
(Stassun et al 2006,2007)



Name	Mass (M_o)	Mass Err	Type	Radius (Ro)	SpT	Log (Teff)	Log (L/Lo)
RS Cha A	1.858	0.9%	EB	2.137±0.055	A8	3.883±0.010	1.144±0.044
RS Cha B	1.821	1.0%	EB	2.338±0.055	A8	3.859±0.010	1.126±0.043
MWC 480	1.65	4.2%	DK	...	A2-3	3.948±0.015	1.243±0.10
TY CrA B	1.64	0.6%	EB	2.080±0.140	...	3.690±0.035	0.380±0.145
045251+3016 A	1.45	13.1%	AS	...	K5	3.643±0.015	-0.167±0.053
ASAS 0528+03 A	1.375	0.8%	EB	1.83±0.01	...	3.708±0.020	0.312±0.078
ASAS 0528+03 B	1.329	0.6%	EB	1.73±0.01	...	3.677±0.021	0.140±0.080
BP Tau	1.32	15.2%	DK	...	K7	3.608±0.012	-0.78±0.10
0529.4+0041 A	1.25	4.0%	EB	1.700±0.200	K1-2	3.701±0.009	0.243±0.037
EK Cep B	1.124	1.1%	EB	1.320±0.015	...	3.755±0.015	0.190±0.070
UZ Tau Ea	1.016	6.4%	DKS	...	M1	3.557±0.015	-0.201±0.124
V1174 Ori A	1.009	1.5%	EB	1.339±0.015	K4.5	3.650±0.011	-0.193±0.048
LkCa 15	0.97	3.1%	DK	...	K5	3.643±0.015	-0.165±0.10
MML 53 A	0.94	4.3%	EB	1.19±0.07	...	3.691±0.015	-0.129±0.1
0529.4+0041 B	0.91	5.5%	EB	1.200±0.200	...	3.604±0.022	-0.469±0.192
GM Aur	0.84	6.0%	DK	...	K7	3.602±0.015	0.598±0.10
045251+3016 B	0.81	11.1%	AS	...	M2	3.535±0.015	-0.830±0.086
MML 53 B	0.806	3.7%	EB	1.05±0.07	...	3.643±0.015	-0.428±0.1
V1174 Ori B	0.731	1.1%	EB	1.065±0.011	...	3.558±0.011	-0.761±0.058
DL Tau	0.72	15.3%	DK	...	K7-M0	3.591±0.015	0.005±0.10
HD 98800 Ba	0.699	9.2%	AS	...	...	3.623±0.016	0.330 ± 0.075
NSVS 06507557 A	0.66	13.0%	EB	0.60±0.030	K9	3.560±0.009	-1.097±0.057
HD 98800 Bb	0.582	8.8%	AS	...	...	3.602±0.016	0.167 ± 0.038
DM Tau	0.55	5.5%	DK	...	M1	3.557±0.015	-0.532±0.10
CY Tau	0.55	60.0%	DK	...	M2	3.535±0.015	-0.491±0.10
Par 1802 A	0.414	3.6%	EB	1.82±0.05	M2	3.596±0.025	-0.143±0.14
Par 1802 B	0.406	3.4%	EB	1.69±0.05	M2	3.563±0.027	-0.337±0.26
UZ Tau Eb	0.294	9.2%	DKS	...	M4	3.491±0.015	-0.553±0.124
NSVS 06507557 B	0.28	16.1%	EB	0.44±0.02	...	3.527±0.010	-1.647±0.062
JW 380 A	0.262	9.5%	EB	1.189±0.175	M1.5	3.555±0.012	-0.676±0.136
JW 380 B	0.151	8.6%	EB	0.897±0.170	...	3.495±0.014	-1.163±0.178
2M0535–05 A	0.0541	8.5%	EB	0.669±0.034	M6.5	3.423±0.016	-1.699±0.078
2M0535–05 B	0.034	7.9%	EB	0.511±0.026	...	3.446±0.016	-1.848±0.076

- Masses and radii from eclipsing binaries extremely accurate and model independent.

COMPARISON OF DYNAMICAL MASSES TO THEORETICAL MODELS IN HR DIAGRAM



Stassun et al. (2010)
Updated from: Hillenbrand & White (2004);
Mathieu et al. (2007)

Good agreement above 1 Msun;
Poor agreement below 1Msun

New generation of pms models

including B fields are promising:

Tognelli et al 2011,

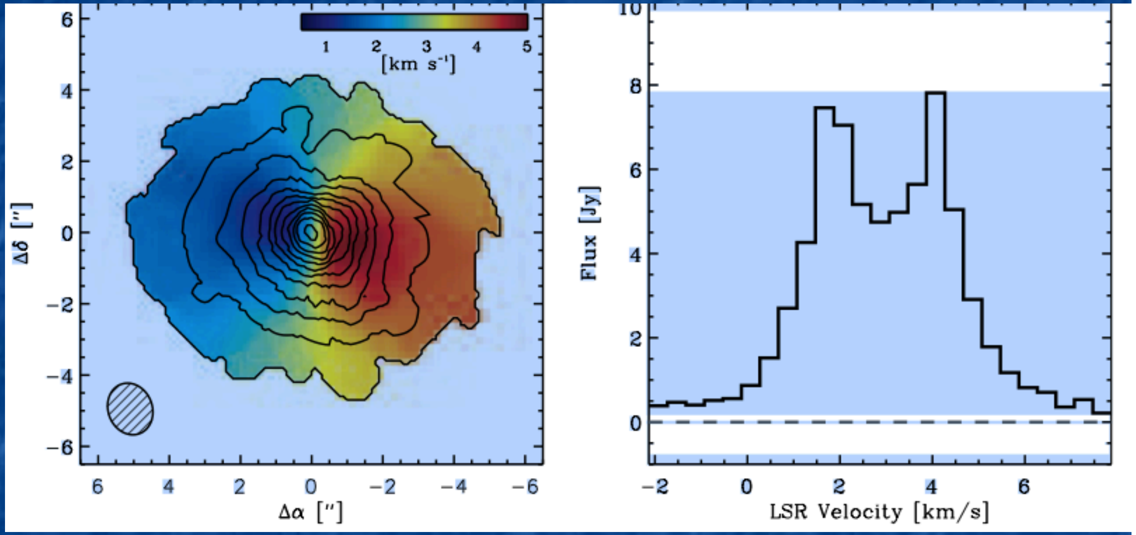
Feiden & Chaboyer 2012

Fit to eclipsing binary data improved by 2-3 (Stassun et al in prep.)

Using binaries as astrophysical laboratories II

Binaries can be used to calibrate other mass determination methods: spatially/ spectrally resolved study of 13 CO emission in circumbinary disc of V4046 Sgr

Rosenfeld et al ApJ 759,119 2012, Figure 2



Binaries as astrophysical laboratories III

Use coevality to study differential disc dispersion

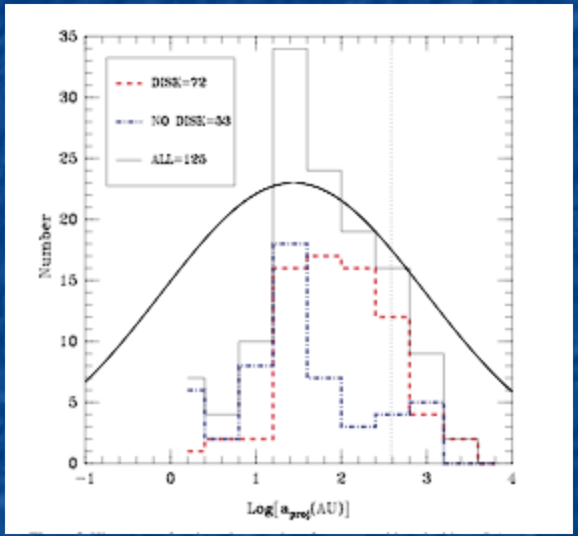
Main results :

a) circumstellar disc lifetimes reduced for a < 10-100 A.U. ➚

b) At a <100 A.U., secondary disc exhausted first. At a > 100 A.U. either disc exhausted first ➘

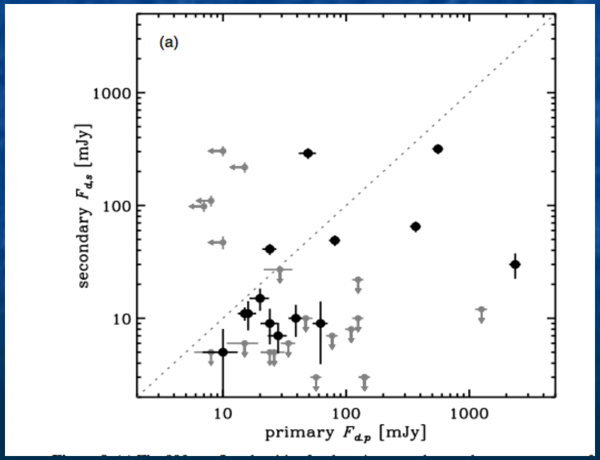
Use wide pairs to test mass dependence of disc dispersal   cf Kneller & Clarke   2013

Many new studies of differential evolution of discs iin binaries e.g. Patience et al 2008,Kraus & Hillenbrand 2009, Cieza et al 2009, Kraus et al 2012, Daemgen et al 2012,2013



Cieza et al 2009, ApJ 696,94 Fig 2

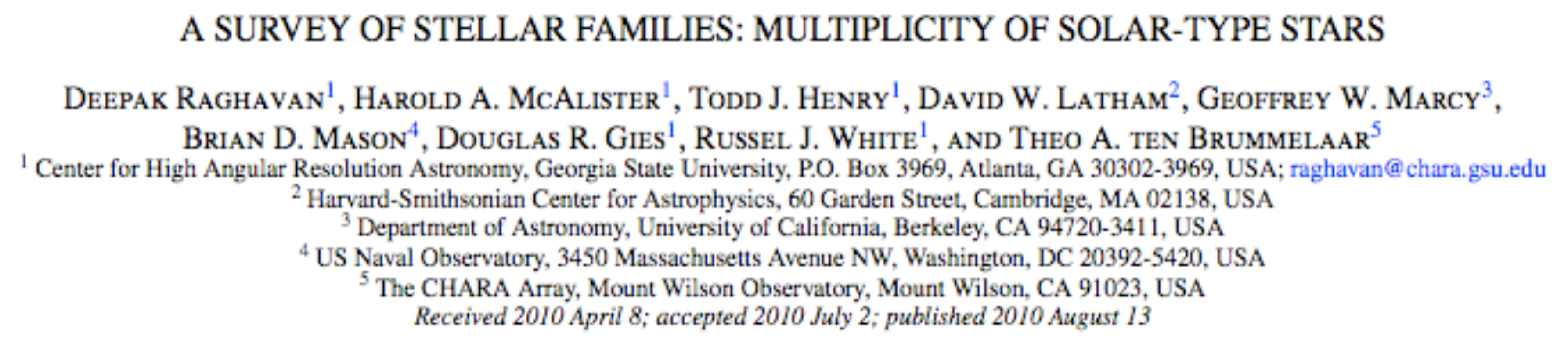
Secondary disc mass



Harris et al 2012 ApJ 751,115 Fig. 9

Primary disc mass

New surveys



A SURVEY OF STELLAR FAMILIES: MULTIPLICITY OF SOLAR-TYPE STARS

Deepak Raghavan[1], Harold A. McAlister[1], Todd J. Henry[1], David W. Latham[2], Geoffrey W. Marcy[3],
Brian D. Mason[4], Douglas R. Gies[1], Russel J. White[1], and Theo A. ten Brummelaar[5]
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Received 2010 April 8; accepted 2010 July 2; published 2010 August 13

Raw results very comparable to Duquennoy & Mayor 1991 but apply smaller incompleteness corrections:

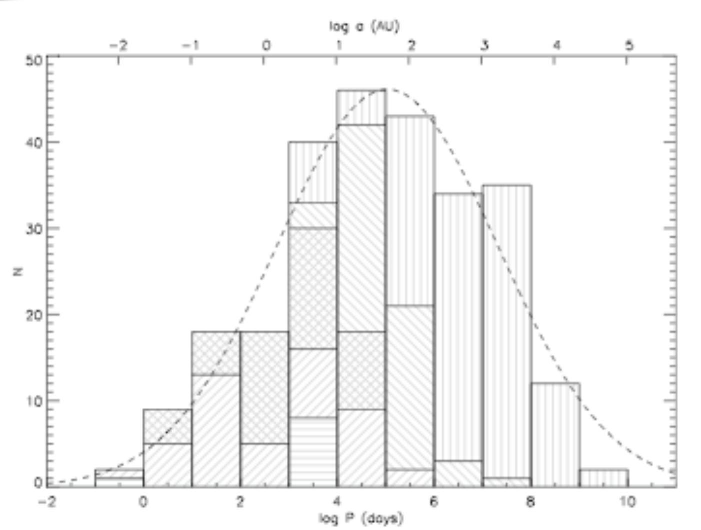
Sun is “typical”! ➘

Roughly double cf DM91 ➚

➘

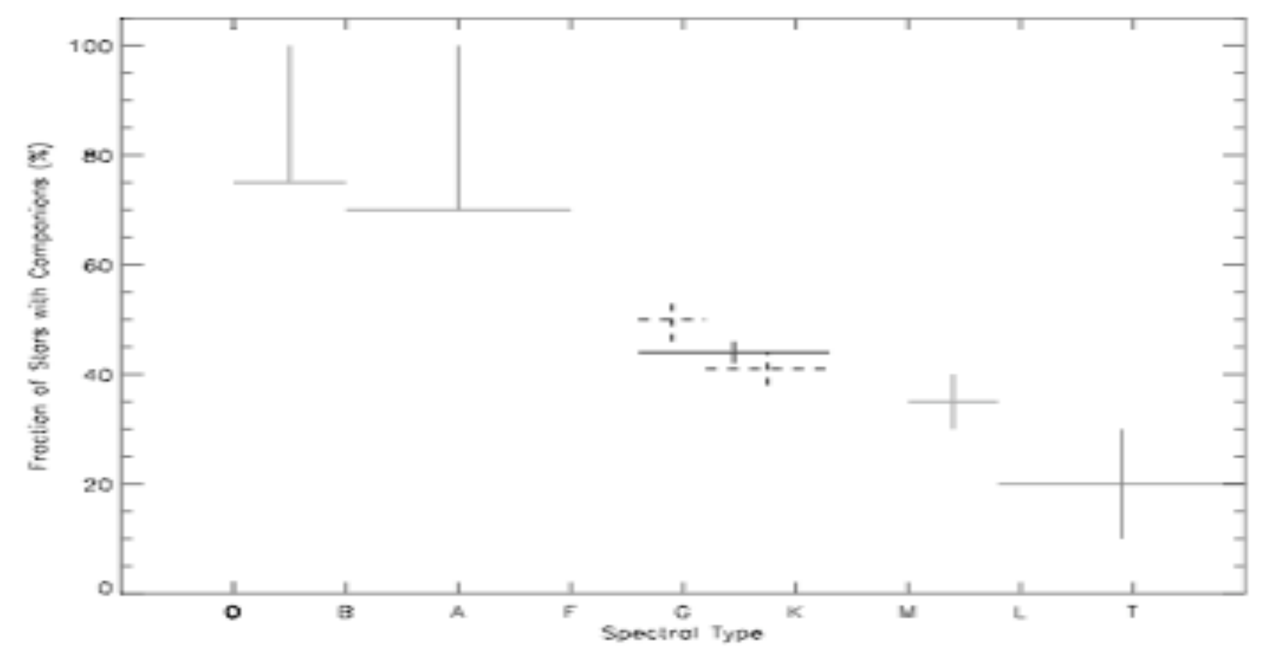
Singles	56%
Binaries	33%
Triple	8%
Higher	3%

Raghavan et al 2010 ApJSupp 190,1 Figure 13



Extension to other primary masses

(from Raghavan et al 2010 ApJ Suppl 190,1 Figure 12)



← increasing primary mass

Monotonic rise of binary fraction towards primary masses of earlier spectral type

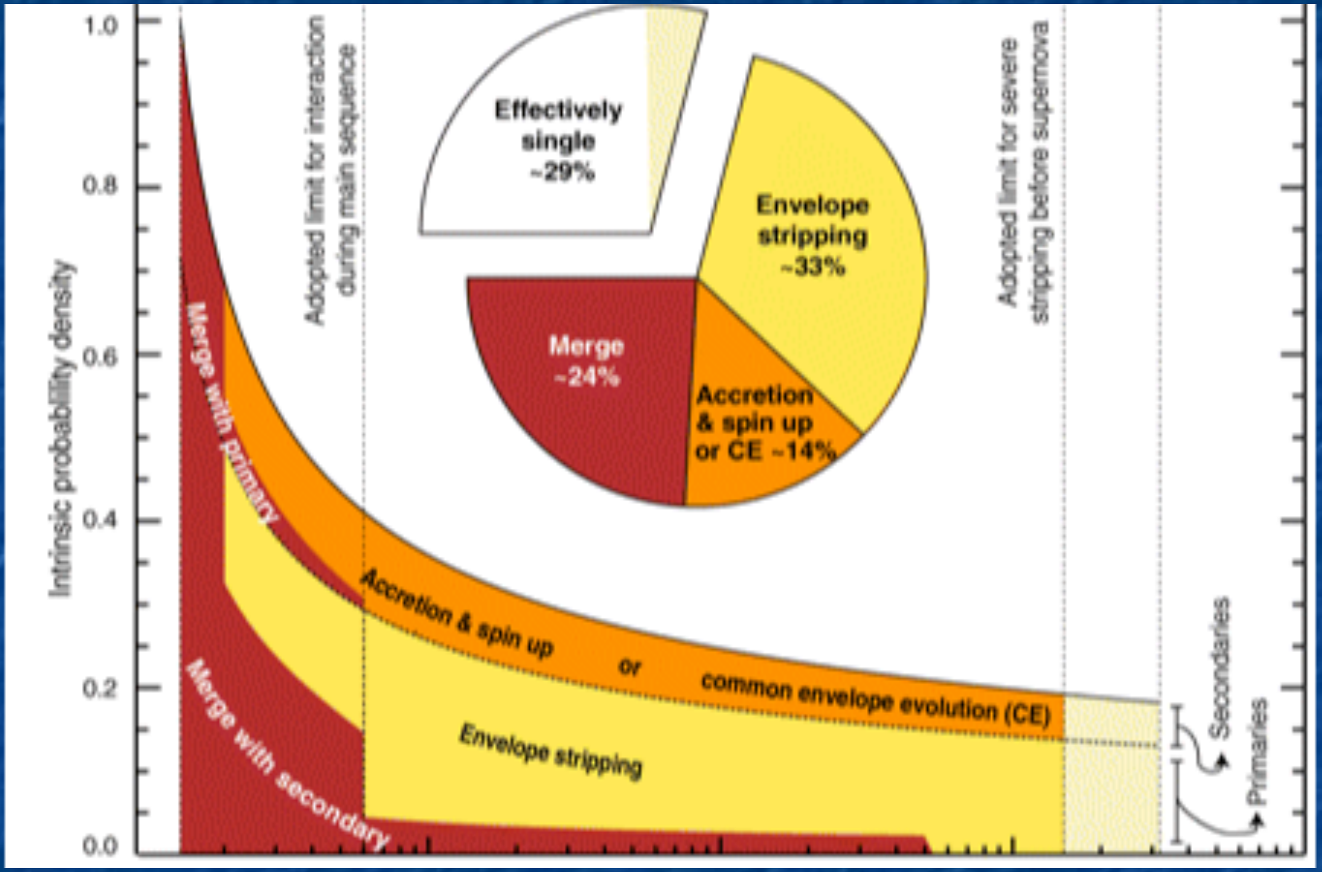
New surveys post PPV

O stars: Mason et al 2009, Chini et al 2012, Sana et al 2012

M dwarf/VLM/Bds: Burgasser et al 2007, Bergfors et al 2010,Kraus & Hillenbrand 2012

Focus on O stars

`>70% of massive stars will exchange mass with a companion, leading to binary merger in ¼ of cases. These numbers greatly exceed previous estimates…' (Sana et al 2012)



See also
Chini et al 2012

High binary fraction among OB runaways

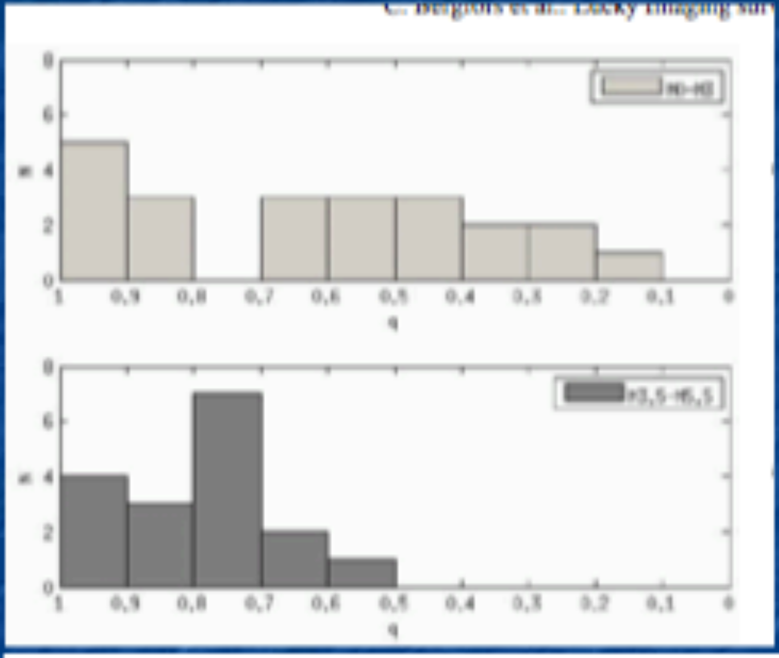
Focus on M stars

Bergfors et al 2010: Lucky imaging of 108 M dwarfs within 52 pc (3-180 AU @median distance)

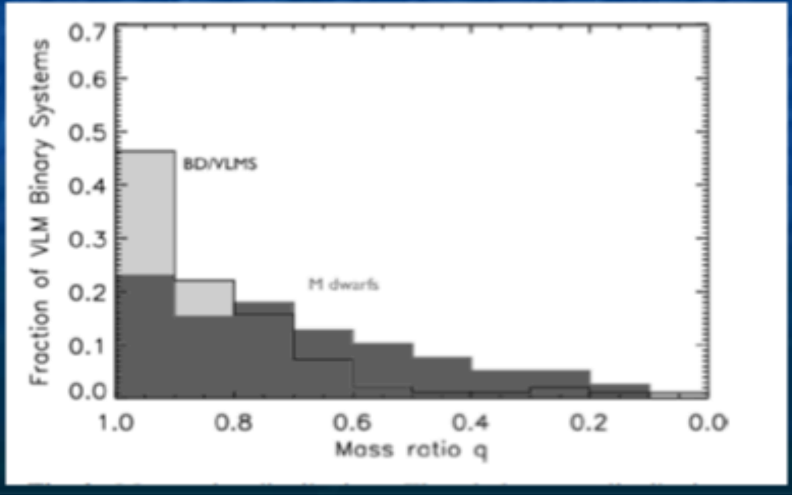
CONTINUOUS VARIATION OF PROPERTIES ACROSS M DWARF SPECTRAL RANGE:

Early M

Late M



M v. BD



Smooth trend towards more equal mass pairs as primary mass decreases – WHY?

VLM/BD stats: see

Kraus et al 2011,

Kraus & Hillenbrand 2012 in associations, Burgasser et al 2007 in the field

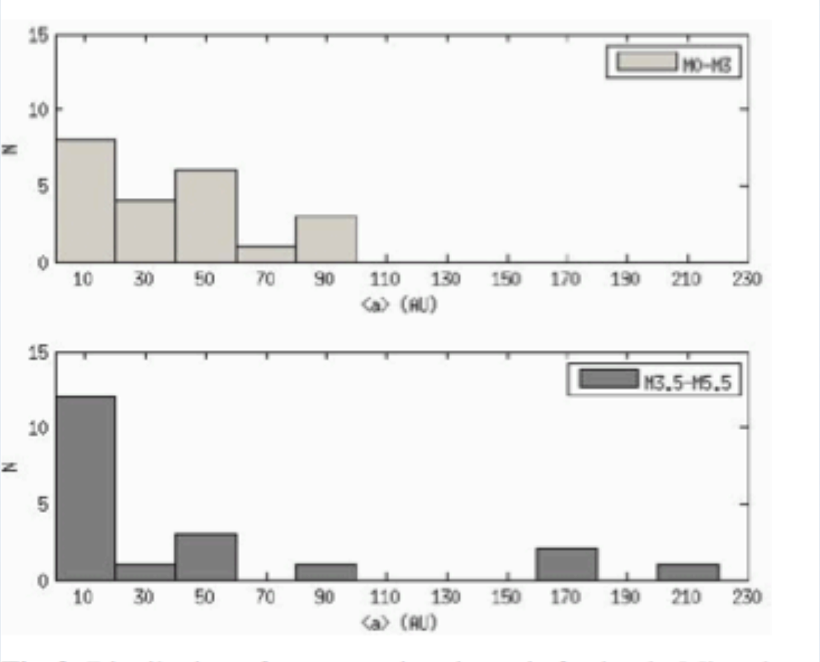
Focus on M stars

Bergfors et al 2010: Lucky imaging of 108 M dwarfs within 52 pc (3-180 AU @median distance)

CONTINUOUS VARIATION OF PROPERTIES ACROSS M DWARF SPECTRAL RANGE:

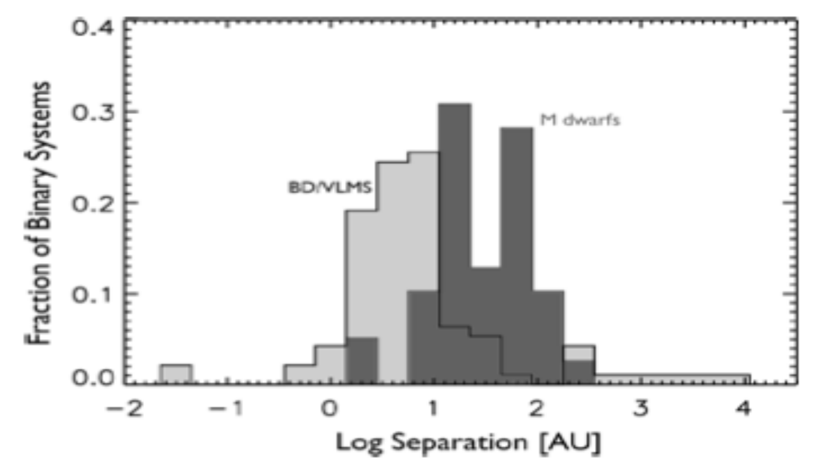
Early M

Late M



Smooth trend towards closer separations as primary mass decreases – WHY?

M v. BD

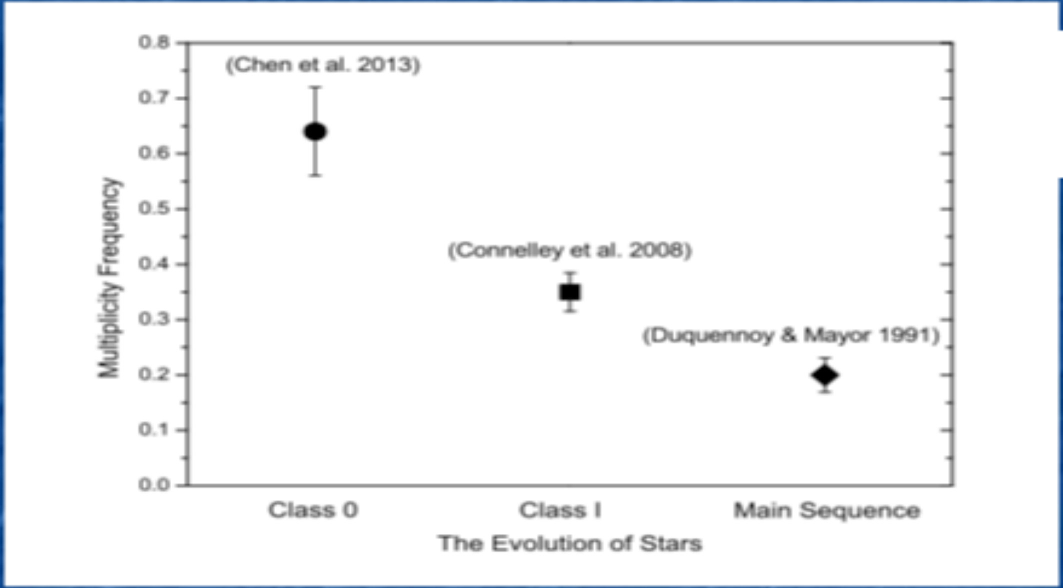


The multiplicity of Class 0 Protostars

$$MF = \frac{B+T+Q}{S+B+T+Q}$$

$$CSF = \frac{B+2T+3Q}{S+B+T+Q}$$

For 50 Au < a <5000Au



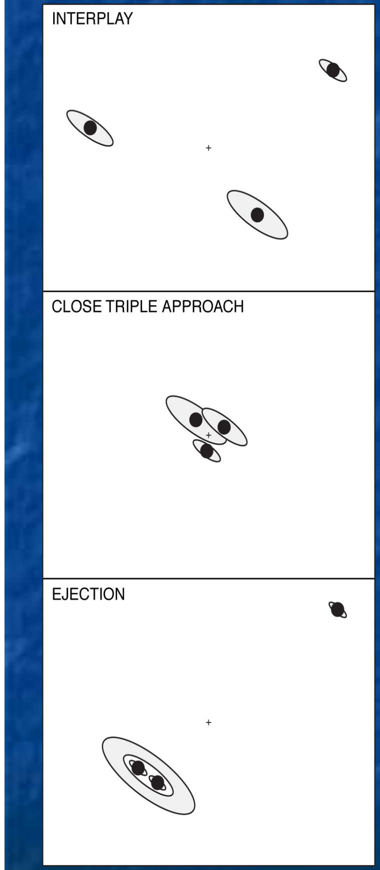
From Chen at al 2013 ApJ 768,110 Fig 20

In Class 0, MF is 3 x main sequence, CSF is 4 x main sequence

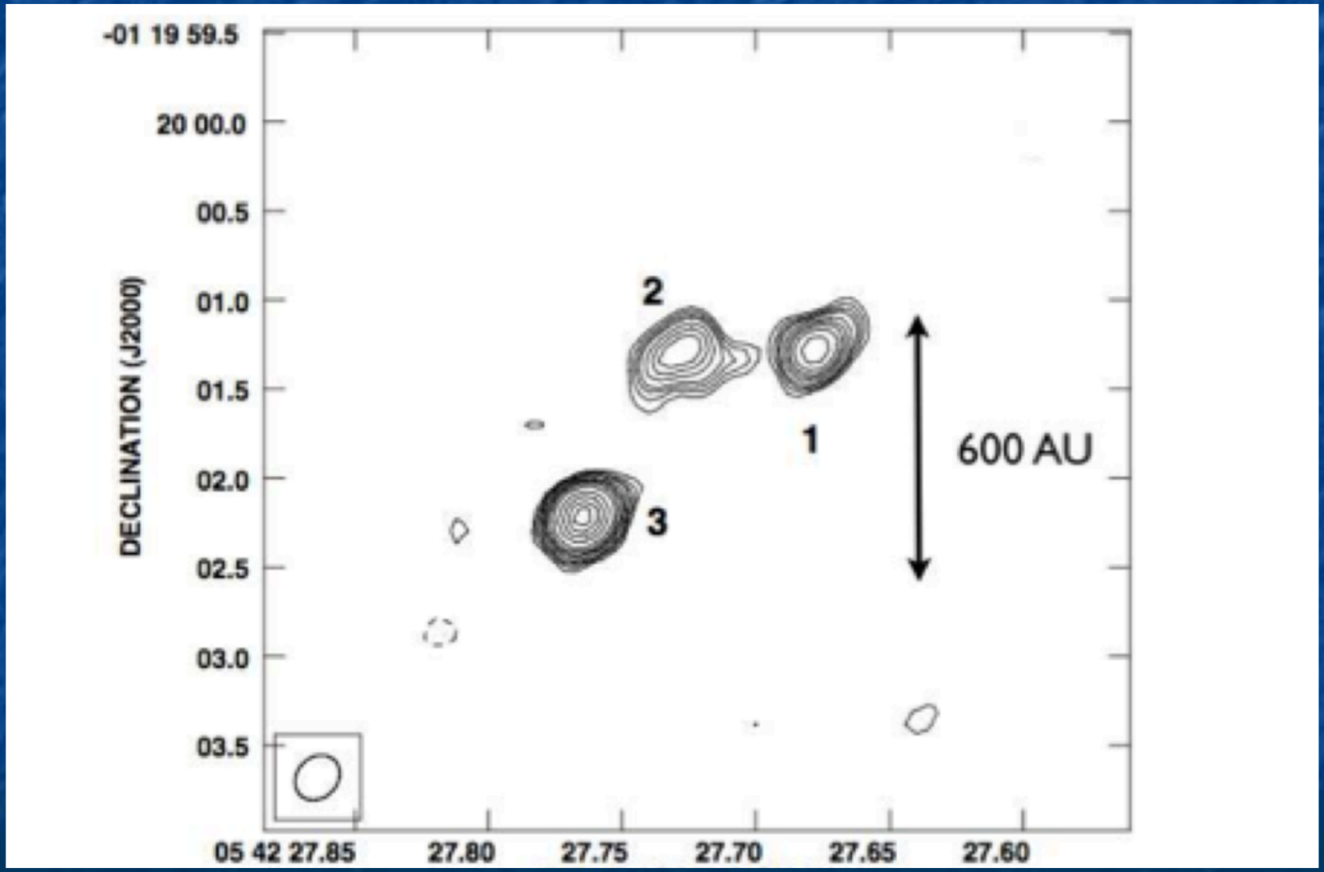
Caveat: reality of companions - see Maury et al 2010

Higher order multiples common at Class 0 Stage

Includes non-hierarchical pairs , but at a <1000 AU many decay on << Class 0 lifetime



Reipurth 2000
AJ 120,3177



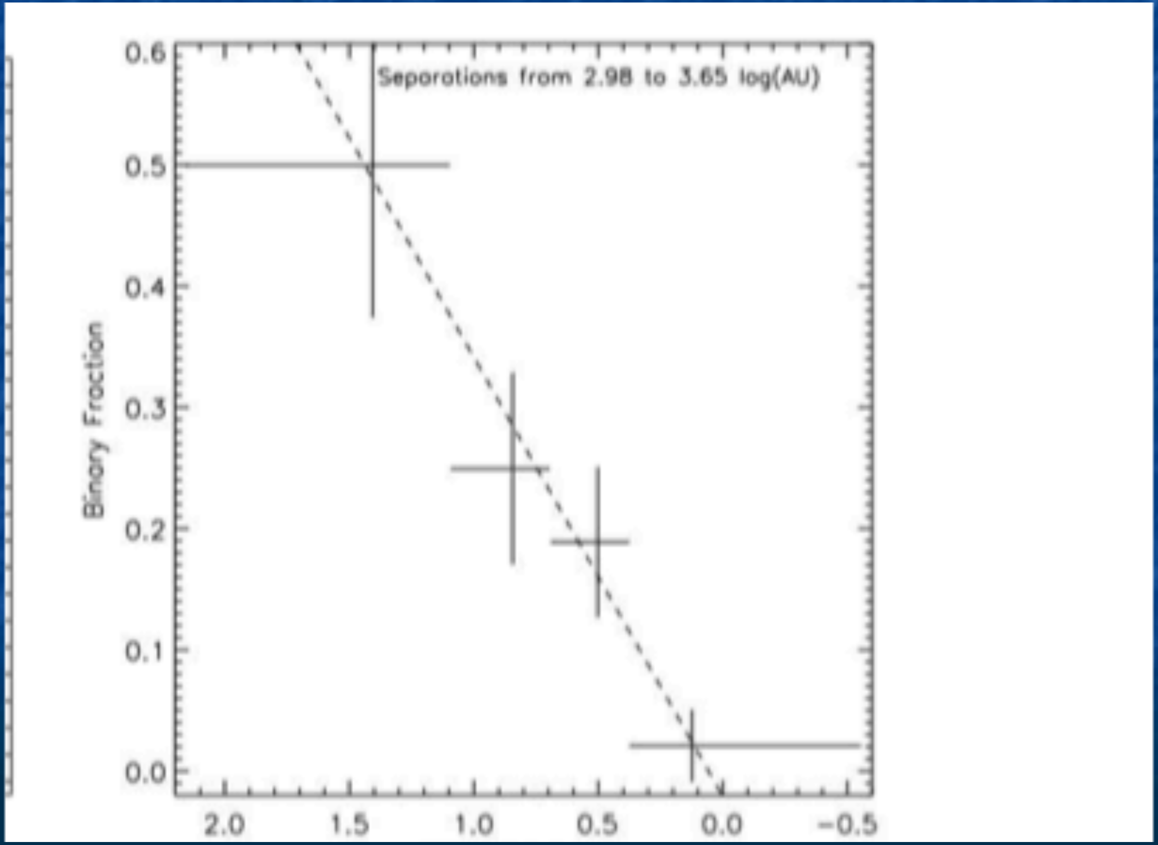
Rodriguez & Reipurth unpublished

MULTIPLICITY IN CLASS I STAGE:

Connelley et al 2008a,b;
Duchene et al 2004,2007

Evidence of decline in binary fraction at ~ 1000 AU with age

Connelley et al 2008b AJ 135,2256 Fig 7



Spectral index

Orbital reconfiguration?

If eject unstable member should

travel to ~ 25000 AU

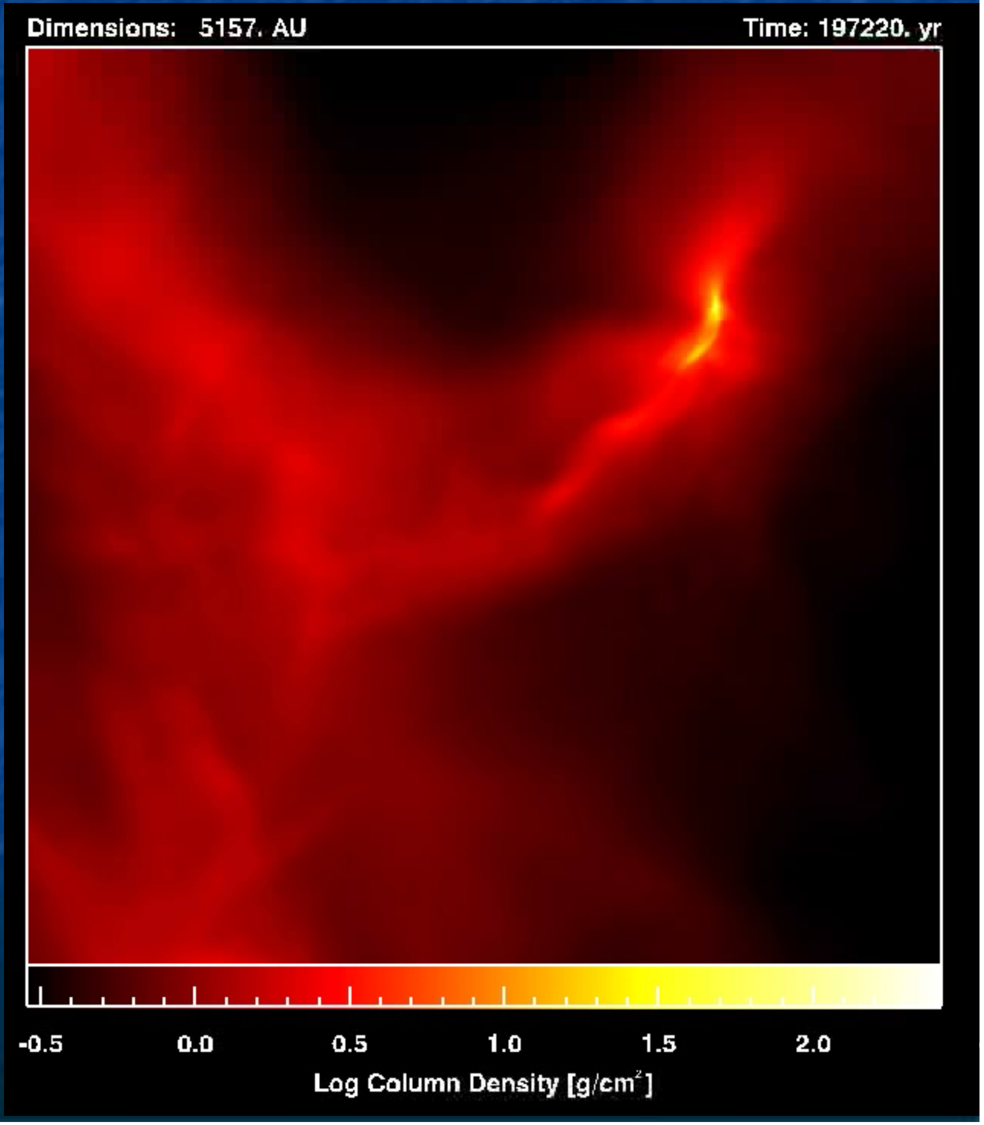
during Class I stage

All (9/9) pairs at < 200 AU have such a wide outlier ✔

Reproducing binary stats. apparently easy..

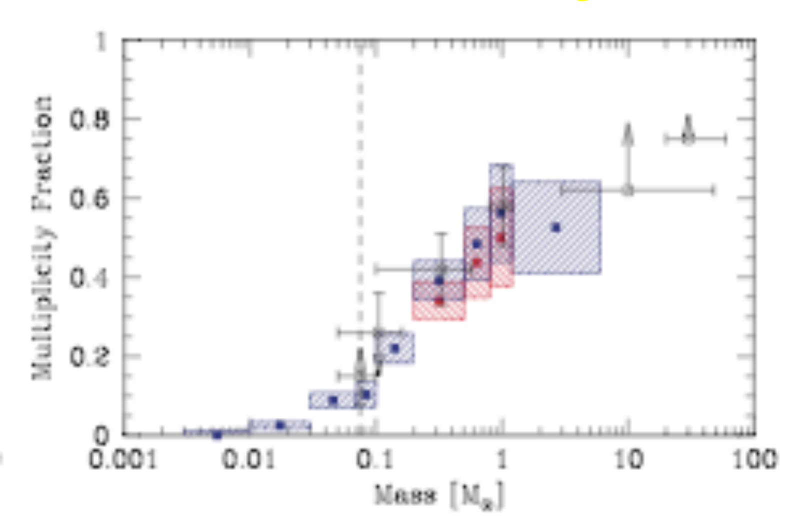
Even in simplest calculations…

- `turbulent' cloud
- Barotropic eqn. state
- no magnetic fields, no feedback



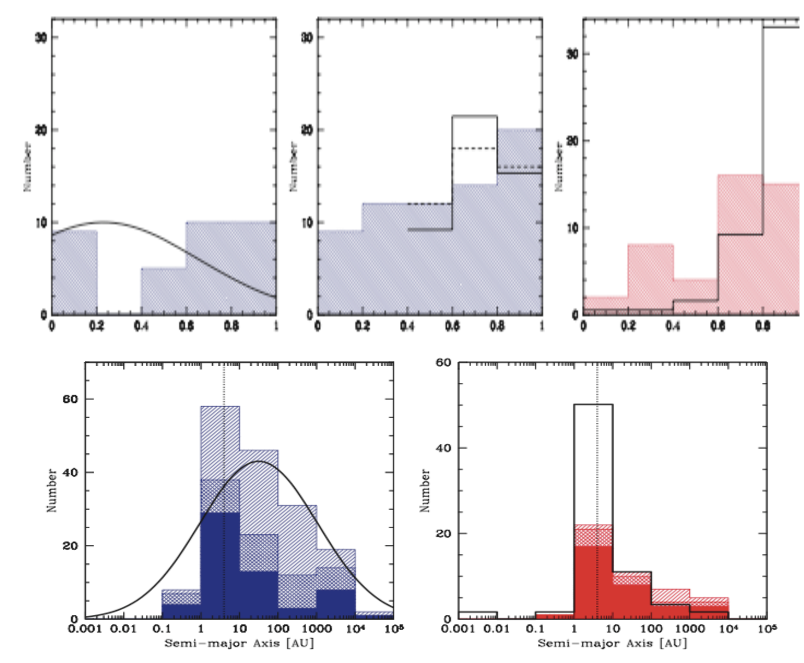
Bate 2009: 1250 stars and brown dwarfs produced

Bate 2009 MNRAS 392,590 Figs 15,19,17



- Binary fraction as function of primary mass ✔

solar VLM



- q distributions as function of primary mass ?

- a distribution as function of primary mass ✔

And yet…clearly omit important physics…

Simulations that add more physics:

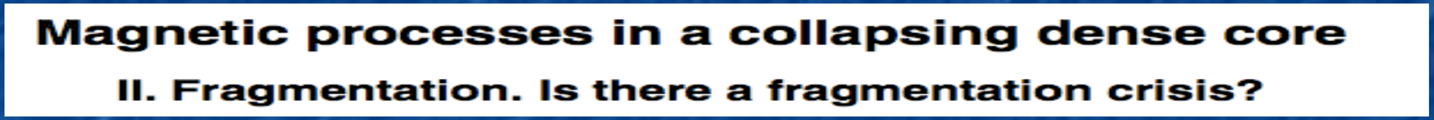
↓

Thermal feedback	Bate 2009, Ofner et al 2009 Bate 2012
B fields	Price & Bate 2007 Hennebelle & Teyssier 2008, Hennebelle & Fromang 2008, Machida et al 2008 Price & Bate 2009 Burzle et al 2011 Joos et al 2012 Seifried et al 2012 Boss & Keiser 2013
Both	Boss 2009 Commercon et al 2010,2011 Hennebelle et al 2011

ⓘ SHOULDN’T IGNORE B-FIELDS

(dynamically significant even though mass to flux ratio is `supercritical’: Crutcher (2012))

- Do magnetic fields present problems for binary star formation?



Magnetic processes in a collapsing dense core

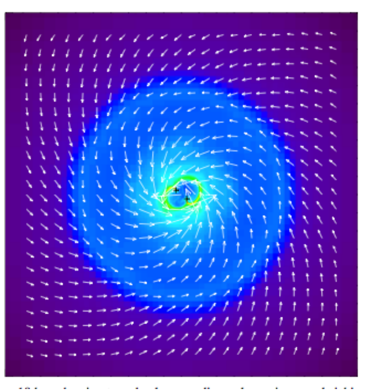
II. Fragmentation. Is there a fragmentation crisis?

Hennebelle & Teyssier 2008

Magnetic braking by toroidal fields suppressess disc formation, hence binary fragmentation

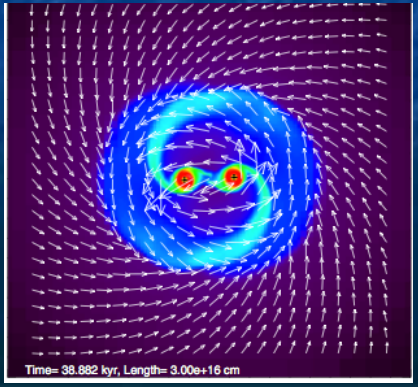
- Also if put in binary seeds`by hand’ B-fields change subsequent accretion pattern dramatically…

With B



Zhao & Li 2013
ApJ 763,7 Figs
1 and 8

No B



Effect of B fields:

Greater orbital shrinkage

Accretion onto primary => q = M_2/M_1 decreases

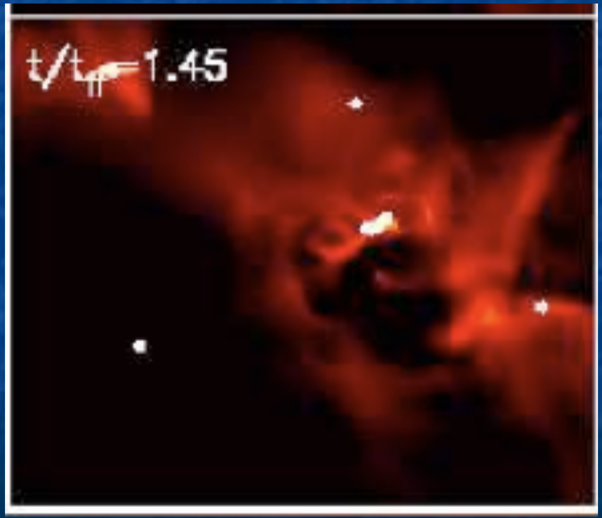
Probably an artefact of initial conditions..

Particularly…

No turbulence (cf Seifried et al 2010); B field aligned with rotation axis (cf Ciardi & Hennebelle 2009,Joos et al 2012), small amplitude initial density perturbations

- Probably explains why binaries do form in magnetised whole cloud simulations

Price & Bate 2008

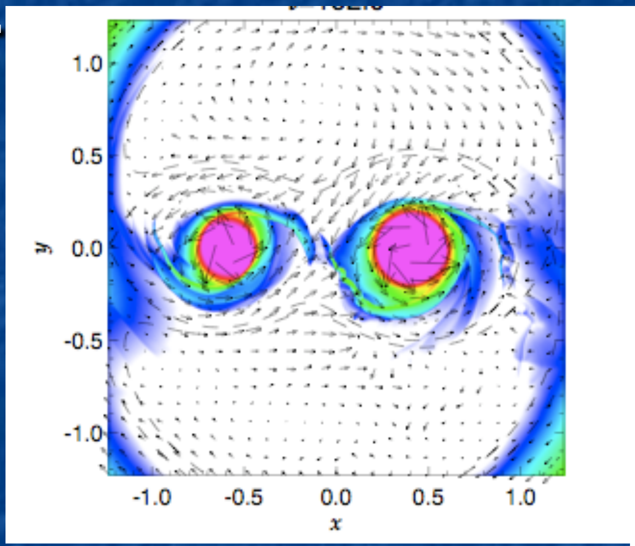


NO STATISTICS YET……

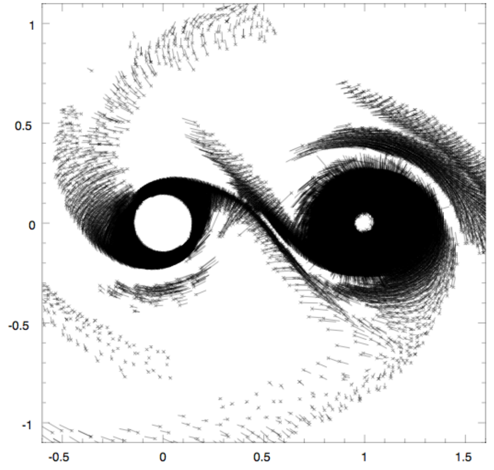
Do models properly treat the effects of accretion onto proto-binaries?

REMINDER: BINARY PROPERTIES LARGELY SET BY SUBSEQUENT ACCRETION , NOT INITIAL FRAGMENTATION…

- A topic ripe for convergence testing/code comparisons
- Temperature and 2D/3D important; numerical code less so



AMR: Hanawa et al 2010, ApJ 708,485 Fig. 11



SPH:Clarke unpublished

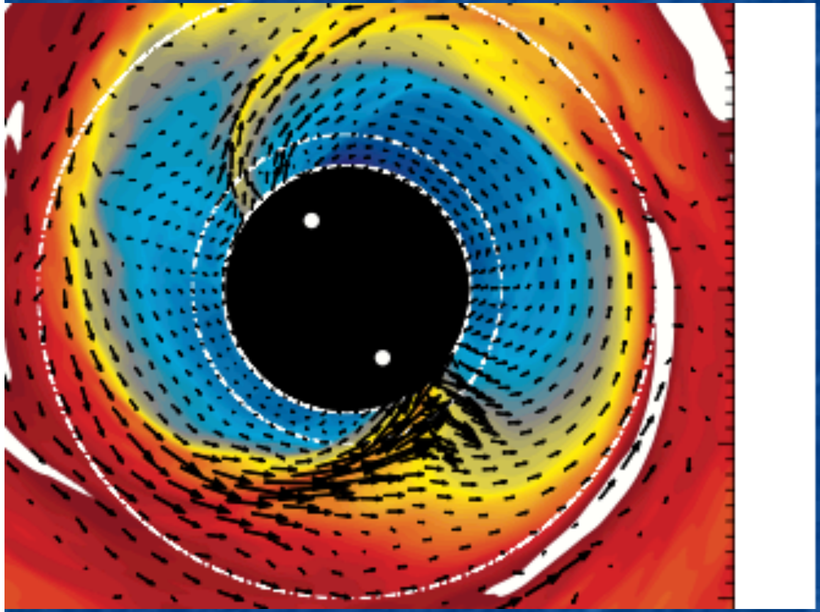
NO PROPERLY CONVERGED STEADY STATE SOLUTIONS

Further complications: circumbinary discs with `live MRI'

↑

Magneto-rotational instability

Shi et al 2012 ApJ749,118 Fig 14



PREDICTS MUCH MORE VIGOROUS ACCRETION ONTO BINARY (FOR GIVEN OUTER DISC SURFACE DENSITY) THAN PREVIOUS α-DISC SIMULATIONS

Binary evolution depends on delicate balance between disc torques and accretion torques

Sensitivitity to disc thermodynamics (cf Type I planet migration)?

ADDS TO UNCERTAINTY…..

The role of multi-body dynamics in binary evolution I:

- Are binary populations significantly `processed' in dense birth environments?
- Can binary statistics be used to constrain the birth environments of the bulk of field stars?

Advent of efficient N-body codes have enabled many such `inverse population synthesis' studies

Goodwin 2010, Marks & Kroupa 2011,

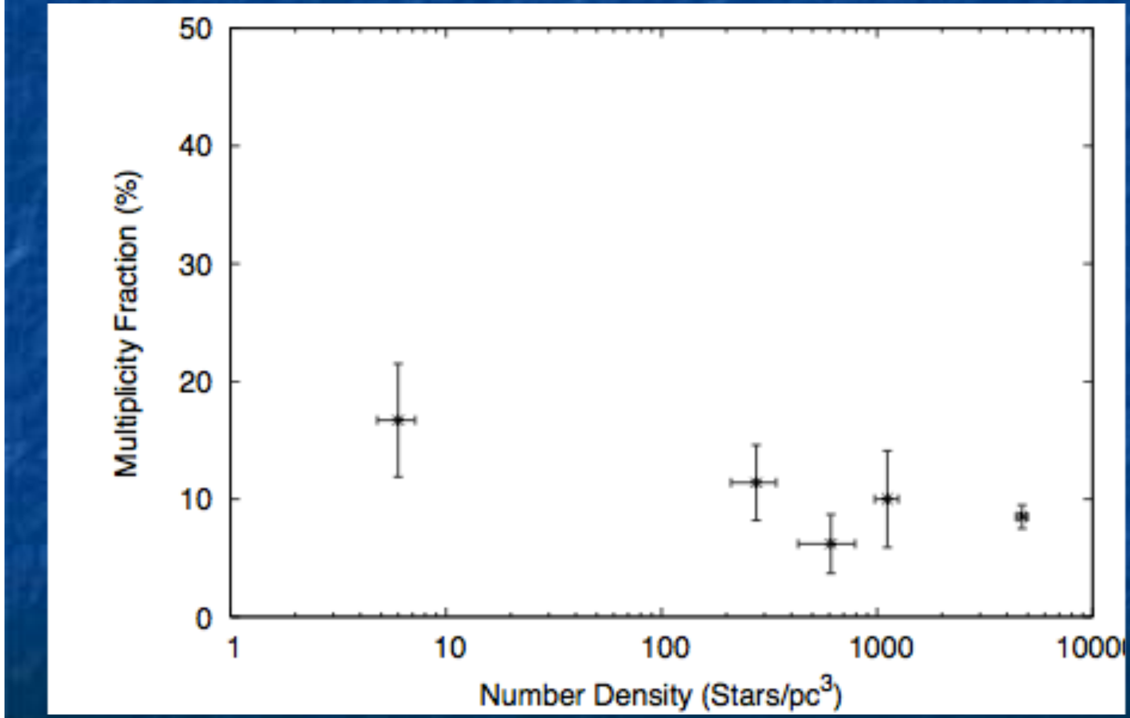
Parker & Goodwin 2012, Parker et al 2012

- Also need to test against good observational dataset on binary properties as a function of environment

Apparently very little difference in binary fraction★ between star forming regions of very different density

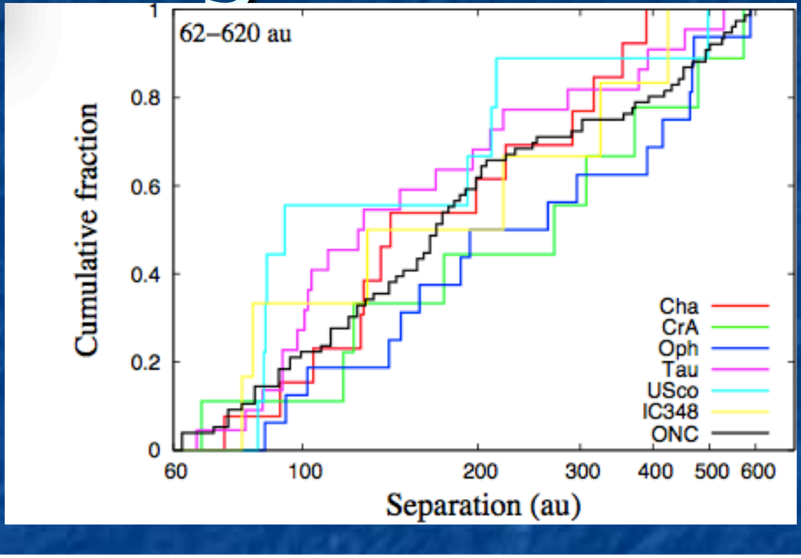
★ In range 62-620 AU

King et al 2012 MNRAS 420,2025, Fig 6



Compare stats in Taurus, Cham I, Ophiuchus, IC 348, Orion Nebula Cluster

Separation distributions indistinguishable in different regions



King et al 2012b MNRAS 427,2636

Fig. 5

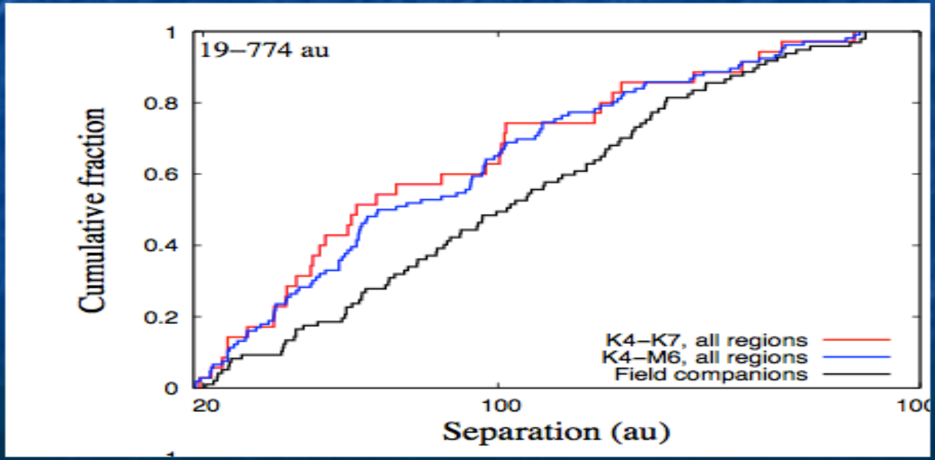


Fig. 6

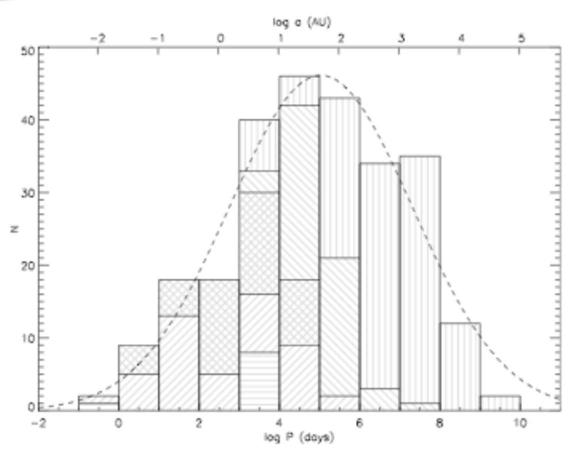
IF ANYTHING, EXCESS WRT FIELD IS AT < 100 AU ……

Black = field; coloured= SFR

The role of multi-body dynamics in binary evolution II

- Can we explain the origin of the ultra-wide tail of the binary distribution?

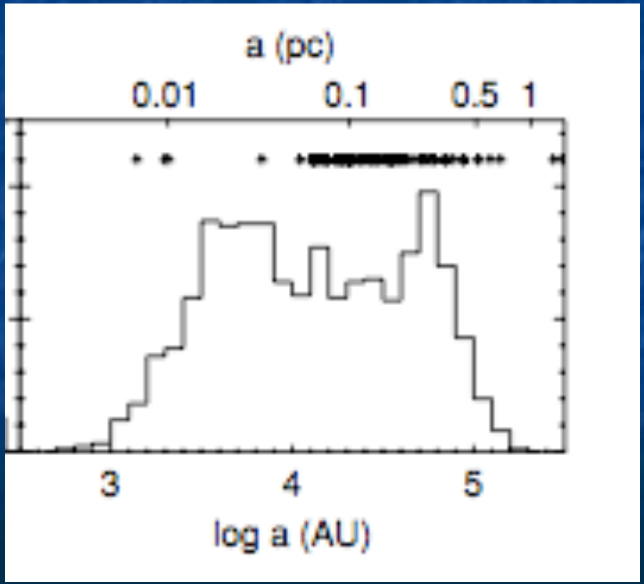
Puzzling! Separations > natal cloud cores



↑ Raghavan et al 2010
ApJ Suppl. 190,1

Figure 13

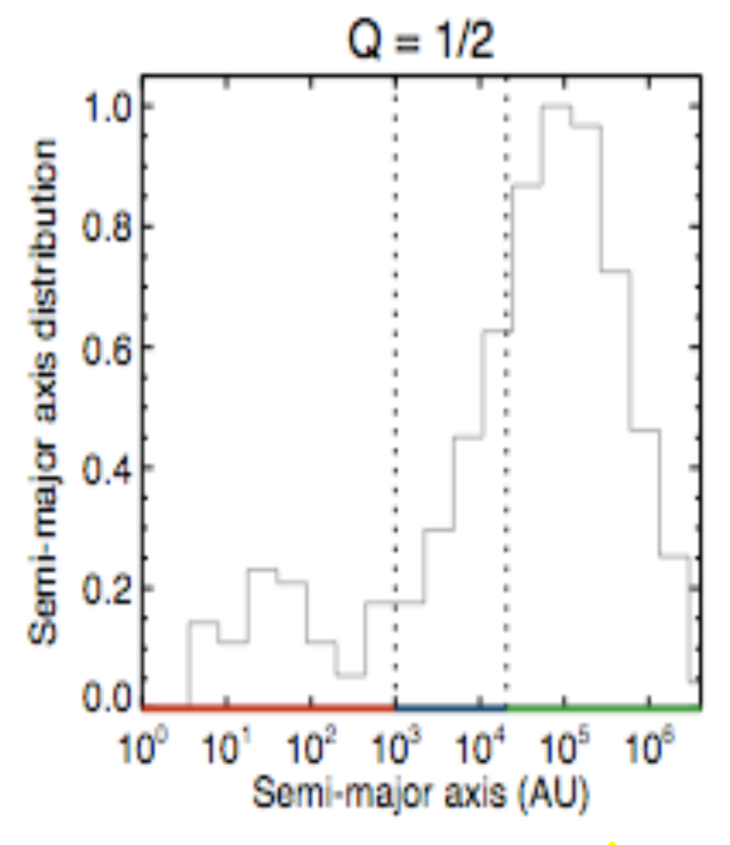
These will be much better characterised in future: see Dhital et al 2010 for cpm pairs in SDSS..



Dhital et al 2010, AJ 139,2566 Fig 13

A new channel for forming ultra-wide binaries in dissolving clusters

Kouwenhoven et al 2010 MNRAS 404,1835 Fig 7



↑ Hard binaries (expected)

↑ Soft binaries: surprising that form or survive in cluster

See Kouwenhoven et al 2010, Moeckel & Bate 2010 Moeckel & Clarke 2011

Predicted properties:

- separation distribution flat in log a
- randomly paired from IMF
- components not necessarily close ★ binaries
- incidence scales as 1/N

★ Cf small multiple decay model: see later

The role of multi-body dynamics in binary evolution III

- Can we explain the statistics of higher order multiples?
- Ongoing analysis of new FG-67pc sample

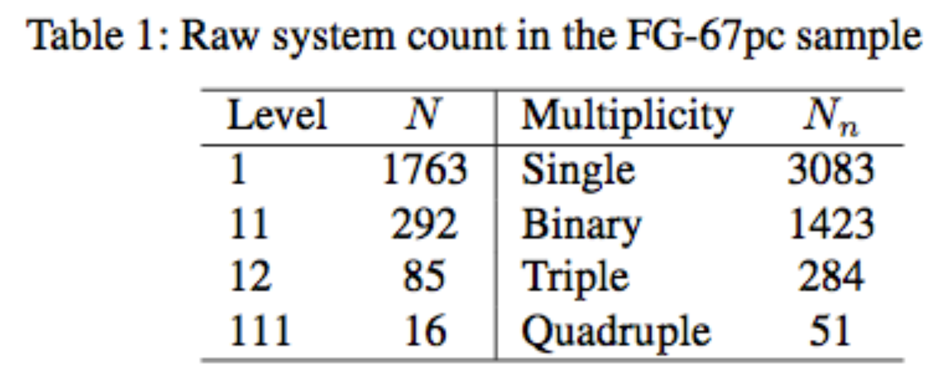


Table 1: Raw system count in the FG-67pc sample

Level	N	Multiplicity	N_n
1	1763	Single	3083
11	292	Binary	1423
12	85	Triple	284
111	16	Quadruple	51

Tokovinin et al in prep.

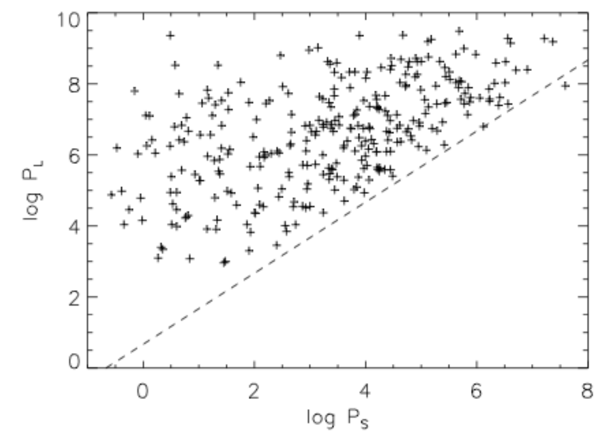
Some preliminary results:

Systems fill phase space within dynamical stability limit

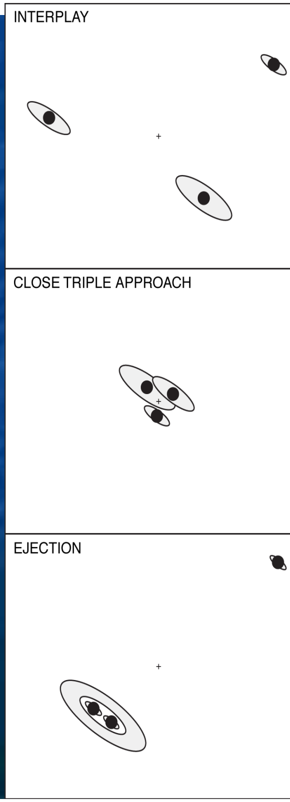
(Mardling & Aarseth 2001)

But not compatible with <u>pure</u> N-body decay of initially non-hierarchical systems

Tokovinin 2008 MNRAS 389,925 Fig. 3



Outer body not low mass or high e; system not close to stability limit

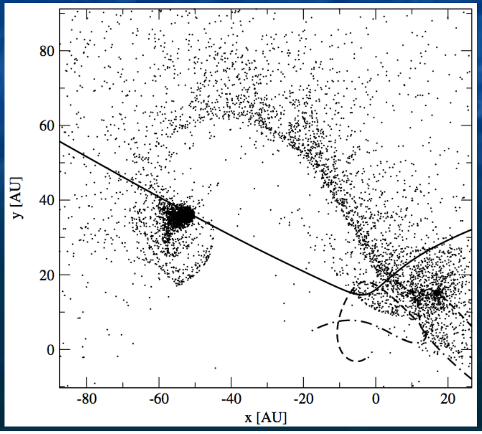


Reipurth 2000 AJ 120,3177

Fig. 1

Need extra ingredient:gas

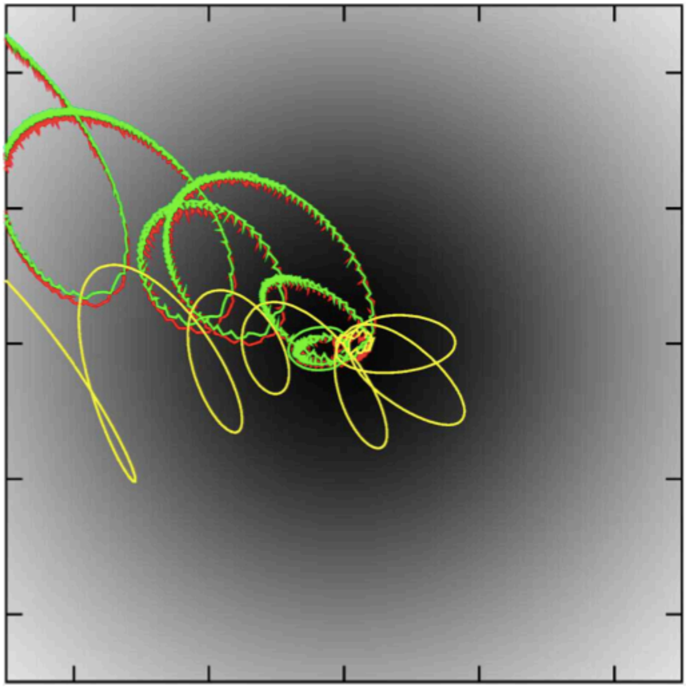
Clarke & Pringle 1991

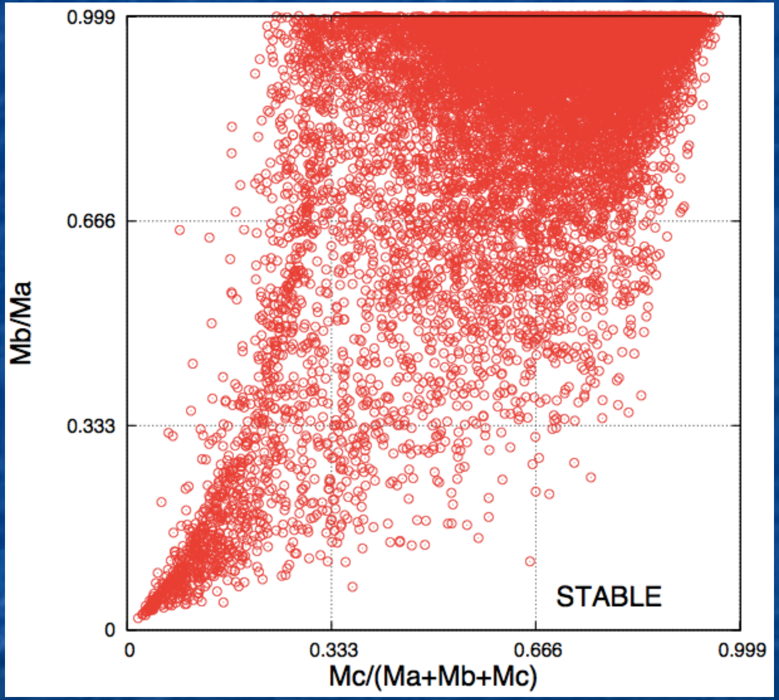


Umbreit et al 2011, ApJ 743,106 Fig. 12

Making triples/quadruples from small unstable groups

Need few-body dynamics AND gas





See Reipurth & Mikkola 2010,2012
for possible obervable conseqeunces
during protostellar phase

Reiprth & Mikkola unpublished

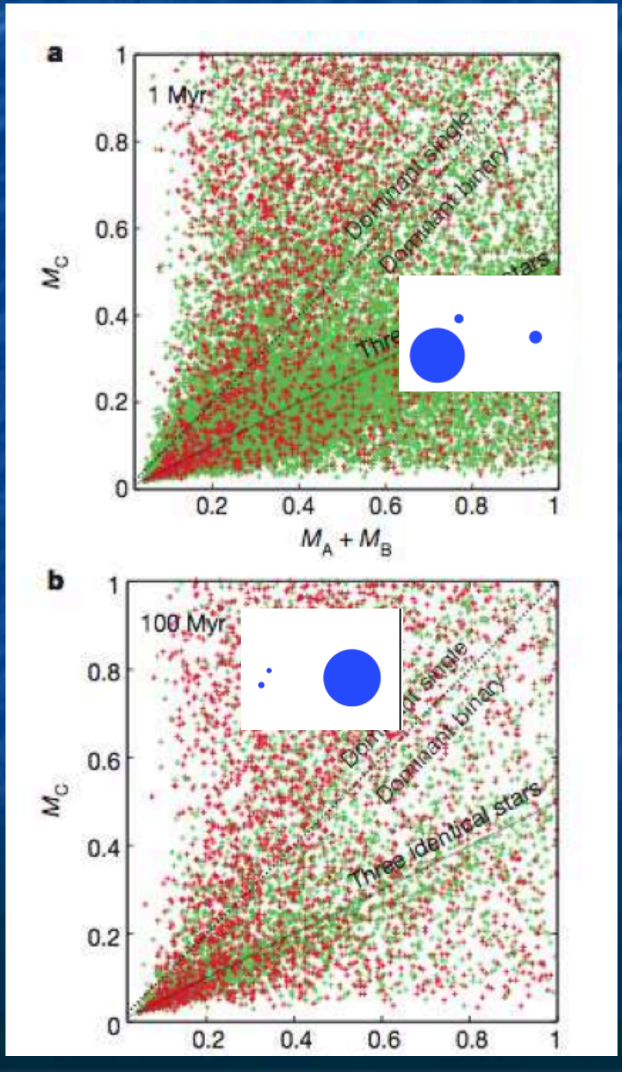
EXPLORE STATISTICAL OUTCOME FOR SYSTEM ARCHITECTURE

- See preference for formation of systems where binary mass exceeds `outlier'
- But preference for survival of systems where `outlier' mass exceeds binary…

Adapted from Reipurth & Mikkola 2012
Nature 492,221 Fig 3

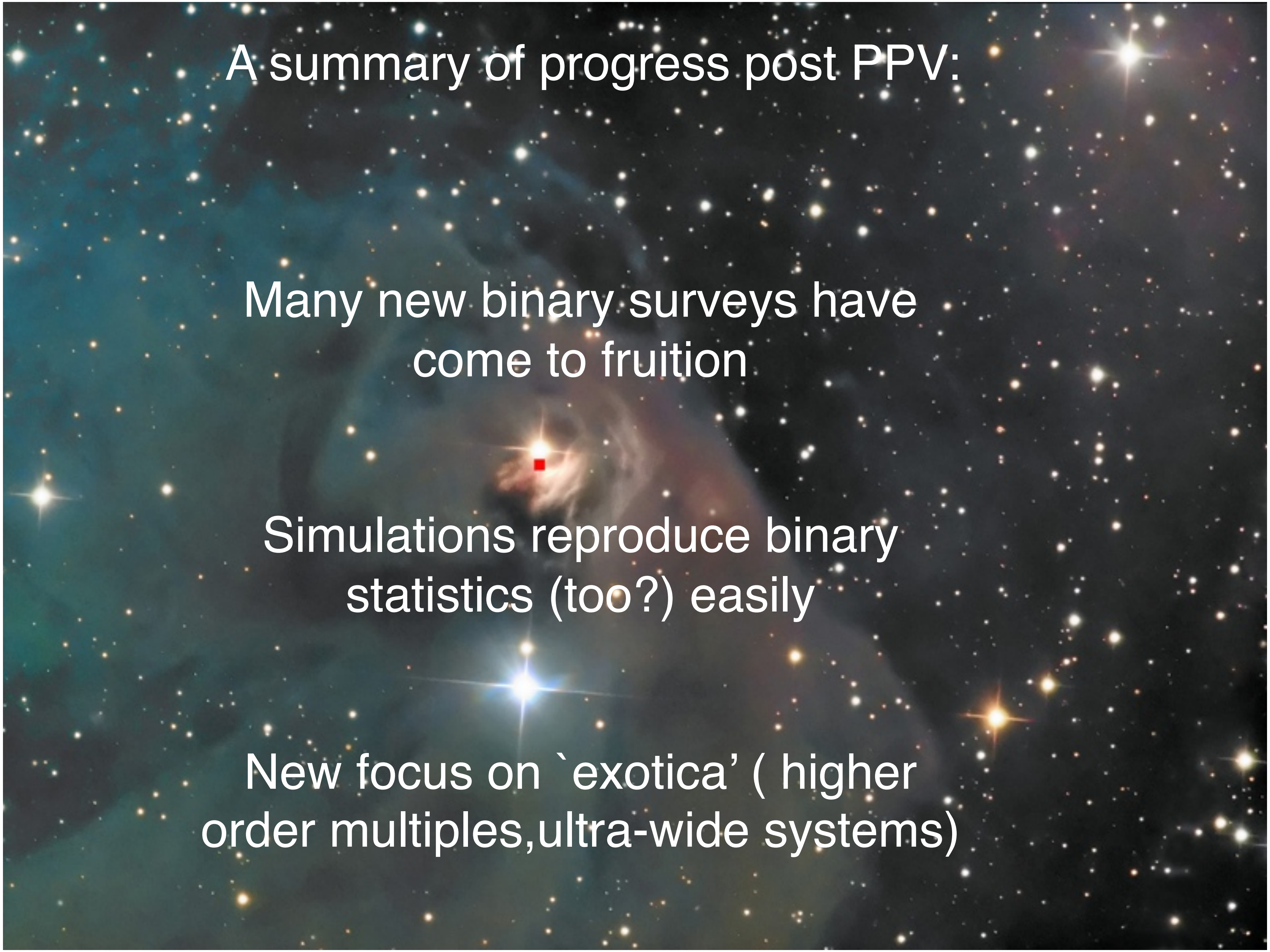
1 Myr

100 Myr



NB: THIS IS ANOTHER WAY TO MAKE ULTRA-WIDE BINARIES

Distinguish via multiplicity statistics…? (cf Law 2011)



A summary of progress post PPV:

Many new binary surveys have come to fruition

Simulations reproduce binary statistics (too?) easily

New focus on `exotica’ (higher order multiples,ultra-wide systems)