The population of binary stars in star-forming regions and in the Galactic field:

why are they different ?

Binary and Multiple Stars
in the Era of Big Sky Surveys
Kopal 2024

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Charles University in Prague

Helmholtz-Institute for Radiation und Nuclear Physics (HISKP)
University of Bonn

c/o Argelander-Institut für Astronomie
University of Bonn

Clusters

Galaxies

Imagine we want to predict the
stellar and binary-star population
in
a dwarf irregular galaxy
vs
a massive E galaxy.

Simulations of star formation : impossible on galaxy scale

Instead, seed the galaxy with the units of star formation,
embedded clusters (some of which evolve into star clusters)

and use known dynamics and astrophysical laws that act
on *initial distribution functions (DFs, f)*
(IMF, initial binary DFs).

But what are these *initial distribution functions* ?

But what are these *initial distribution functions* ?

1) The initial distribution of stellar masses
= the *initial mass function* of stars (the *IMF*) = $\xi(m)$

2) The initial distribution of binary-star orbital periods
= the initial semi-major axis / binding energy distribution = $f_P(P : m_{prim})$

3) The initial distribution of binary-star mass ratios
= the *initial mass-ratio distribution* = $f_q(q : m_{prim})$

$q = m_{sec}/m_{prim} \leq 1$

4) The initial distribution of binary-star orbital eccentricities
= the *initial eccentricity distribution* = $f_e(e : m_{prim})$

Constraint : m_{sec} and m_{prim} must obey the IMF (see Oh, Kroupa & Pflamm-Altenburg 2015
Oh & Kroupa 2016)

No existing (successful) theoretical prediction on any of the above.

Need star counts to constrain the above.

But need to understand the *evolution* of the above,
to transform the observed distribution functions to the initial ones.

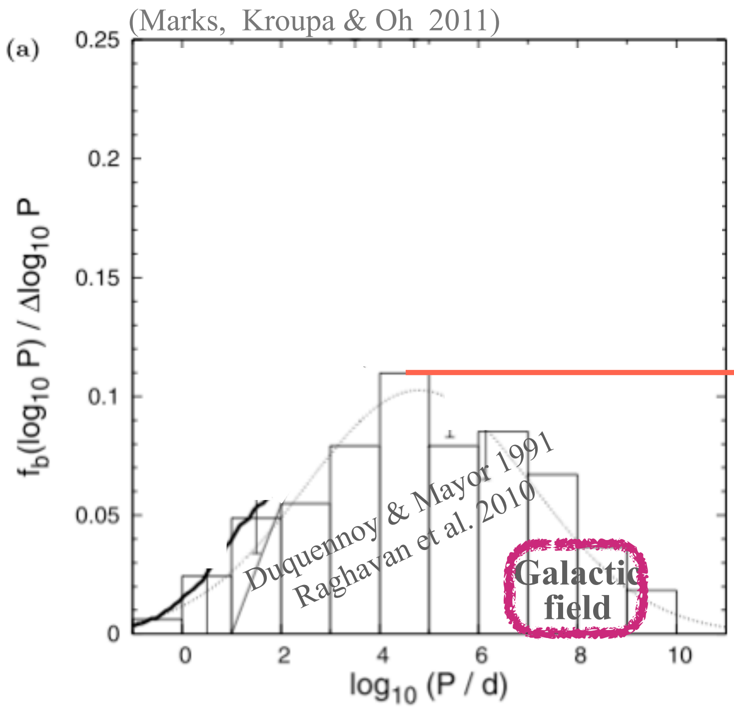
The IMF

another talk

GALCROSS ESO conference
***in Brno* (close-by) next week**
organised by
Tereza Jerabkova +.

The binaries

Binary systems (< few Msun)

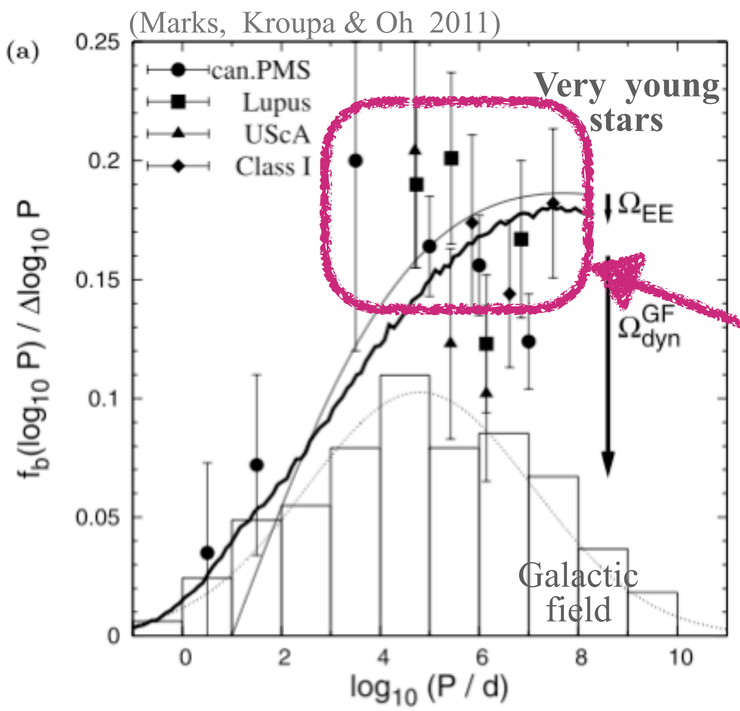


Angular momentum in collapsing pre-stellar core

must form a multiple system

≈11% of all GKM stars in the Solar neighbourhood have a stellar companion orbiting at $10^{4.5}$ days

Binary systems



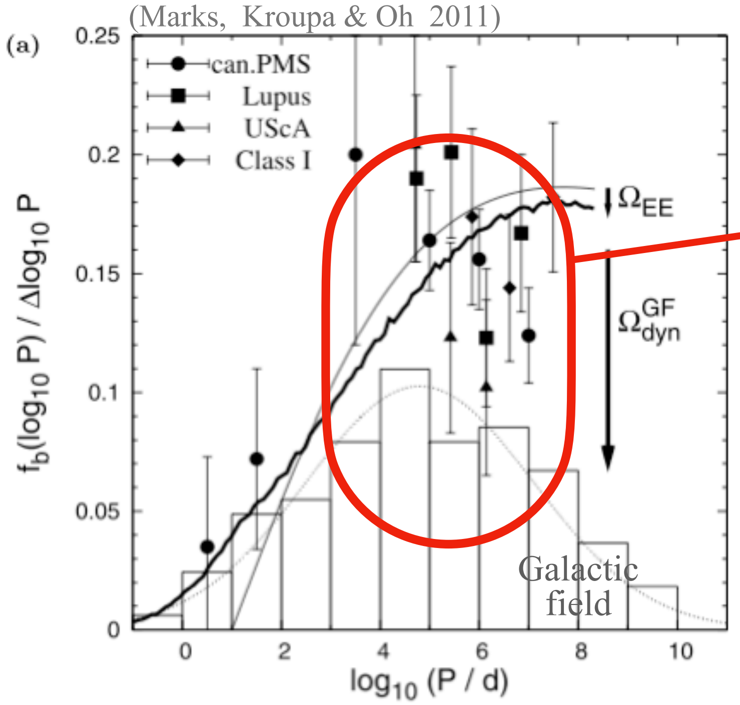
Angular momentum in collapsing pre-stellar core

must form a multiple system

observed very high (>80%) binary fraction in low-density 1 Myr old star-forming regions

must form binaries, because non-hier. triples, quadruples decay within 10^4 - 10^5 yr (Goodwin & Kroupa 2005)

Binary systems



Note this discrepancy :

very young populations have
2 times higher
binary fraction

Problem :

Why the difference ?

Hypothesis :

Stars form as binaries in embedded clusters.
The binaries are dynamically processed to yield the field population.

Aim :

find the initial binary-star distribution functions

and

embedded cluster solutions

$f_P(P : m_{prim})$
$f_q(q : m_{prim})$
$f_e(e : m_{prim})$

Question :

does the above work **?**

The initial distribution functions

(Kroupa 1995a,b)

$\xi(m)$	initial distribution function of stellar masses	✓
$f_P(P : m_{prim})$	initial distribution function of periods or binding energies	?
$f_q(q : m_{prim})$	initial distribution function of mass ratios	?
$f_e(e : m_{prim})$	initial distribution function of eccentricities	?

Procedure :

Iteratively find the combination between

$\Omega_{\rm dyn}^{M_{\rm ecl}, r_{0.5}}$ (= the stellar-dynamical operator = *Aarseth's Nbody5* code)

and the *distribution functions*

that explains
(i) the pre-main sequence data
and
(ii) the Galactic field data (solar neighbourhood)

Galactic field OR OB association ← Initial, star-formation

$$\left.\begin{array}{l} f_{\rm q,\,final}(q) \\ f_{\rm P,\,final}(P) \\ f_{\rm e,\,final}(e) \end{array}\right\} = \Omega_{\rm dyn}^{M_{\rm ecl}, r_{0.5}} \left\{\begin{array}{l} f_{\rm q}(q) \\ f_{\rm P}(P) \\ f_{\rm e}(e) \end{array}\right.$$

What is $\Omega_{\rm dyn}^{M_{\rm ecl}, r_{0.5}}$?

(= the stellar-dynamical operator = *Aarseth's Nbody5* code)

It quantifies the stellar-dynamical processing of an initial binary-star population defined by an *embedded star cluster* with stellar mass $M_{\rm ecl}$ and half-mass radius $r_{0.5}$.

Megeath et al. (2016, AJ)

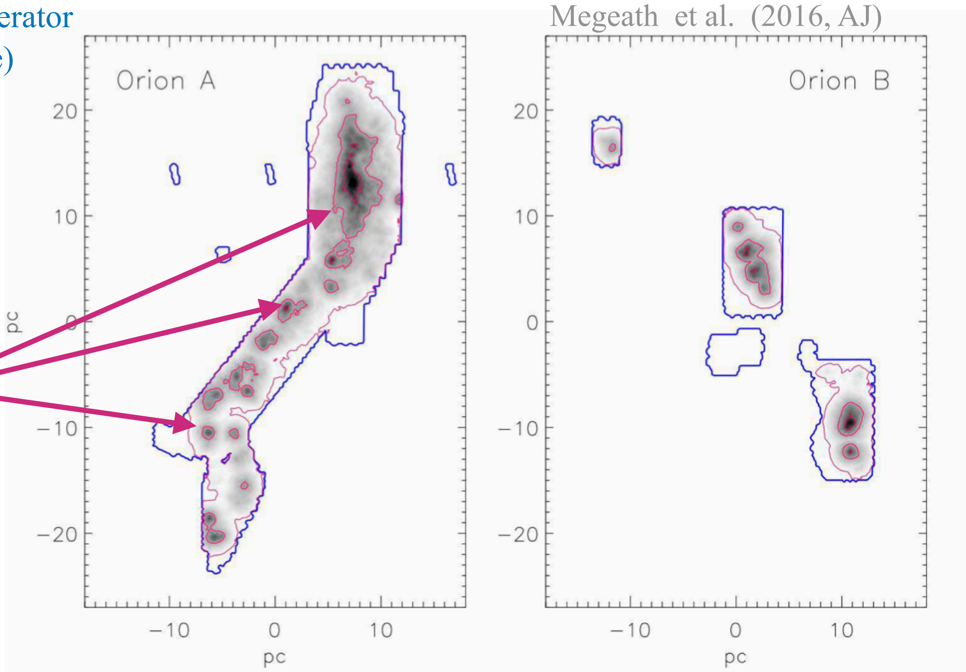


Fig. 8.— Maps of the nearest neighbor surface density in the Orion A and B molecular clouds. We have used the 10th nearest neighbor and have corrected the densities for incompleteness. The blue contour gives the outline of the IRAC field. The inverted gray scale images renders the densities with a logarithmic scaling. The red contours are for 1, 10 and 100 YSOs pc^{-2}. The adopted distance is 414 pc.

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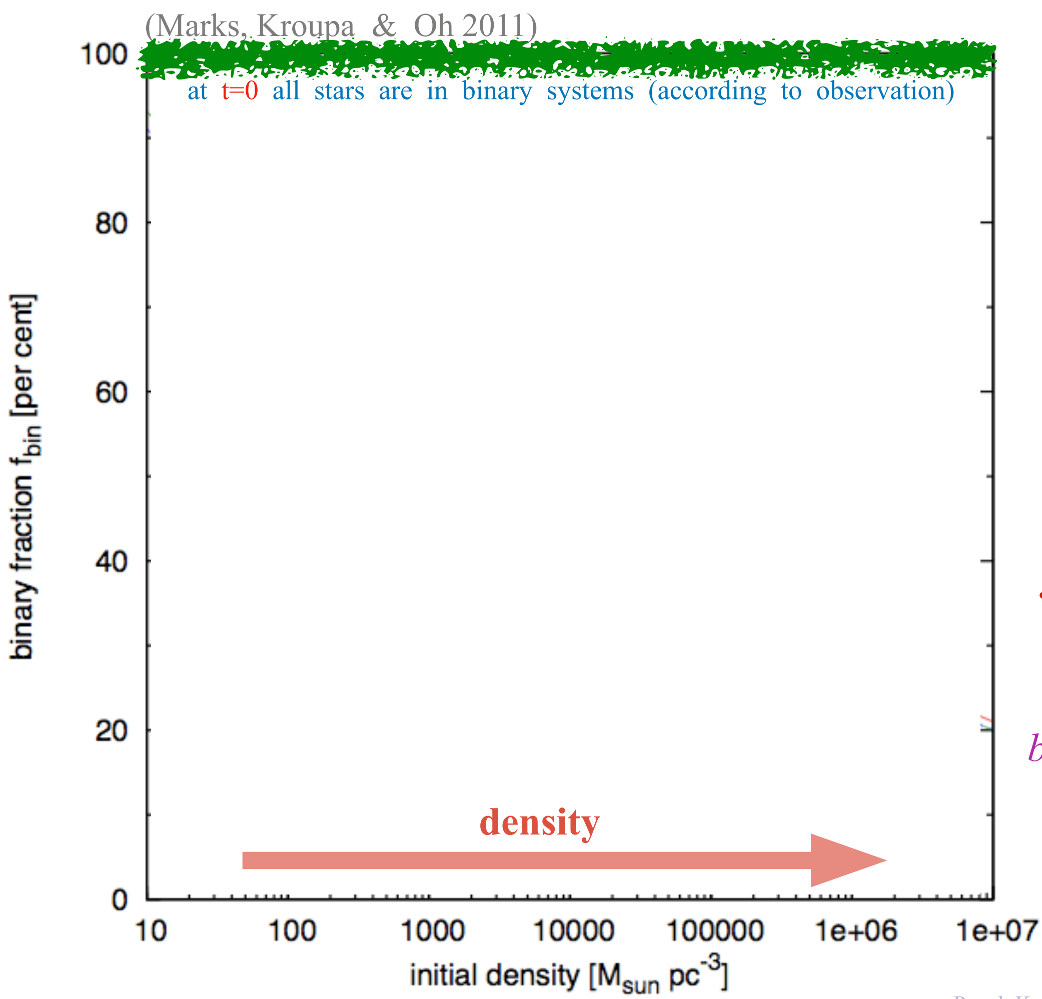
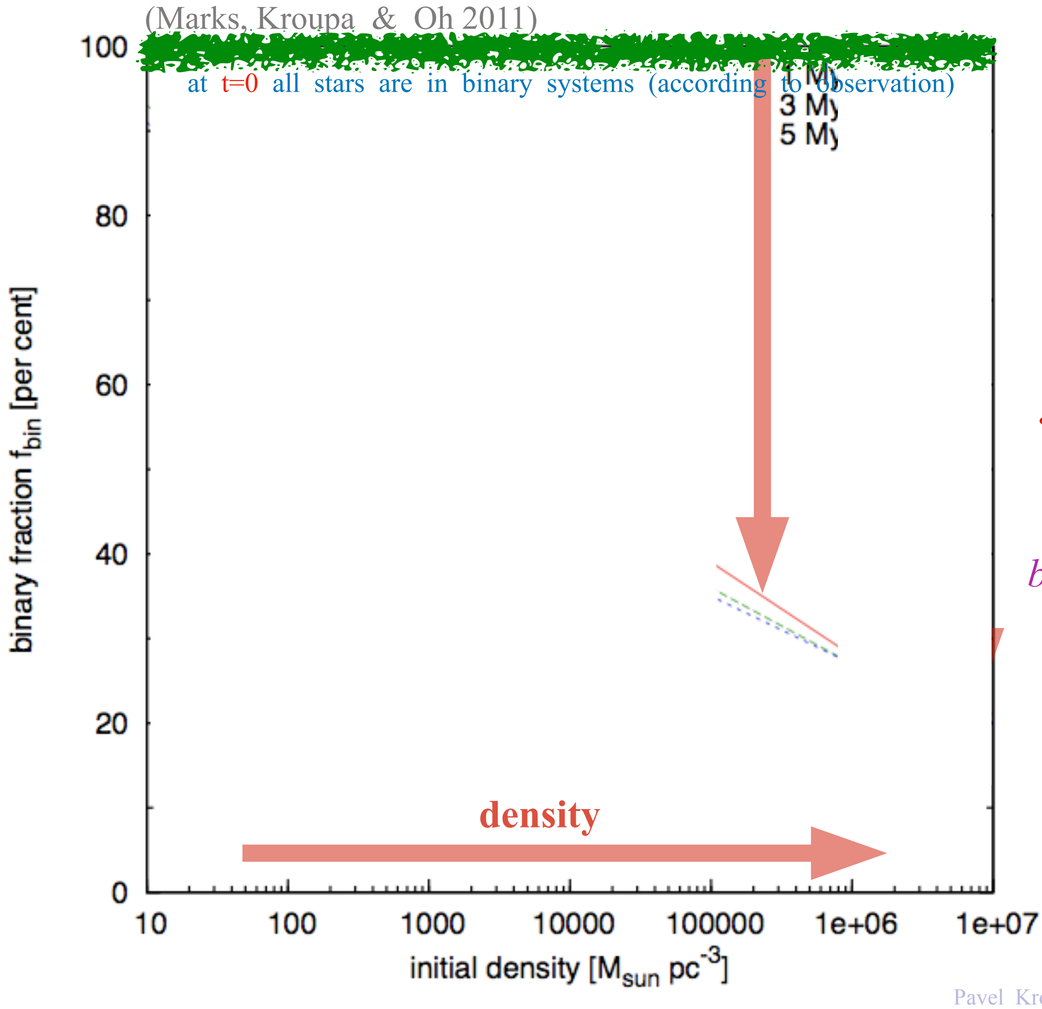


Aarseth-Nbody6-code:
models of clusters with birth binary fraction

$$f_{\rm bin} = 100\%$$

with the *canonical birth binary population* (see below)



Nbody6 models of clusters with birth binary fraction

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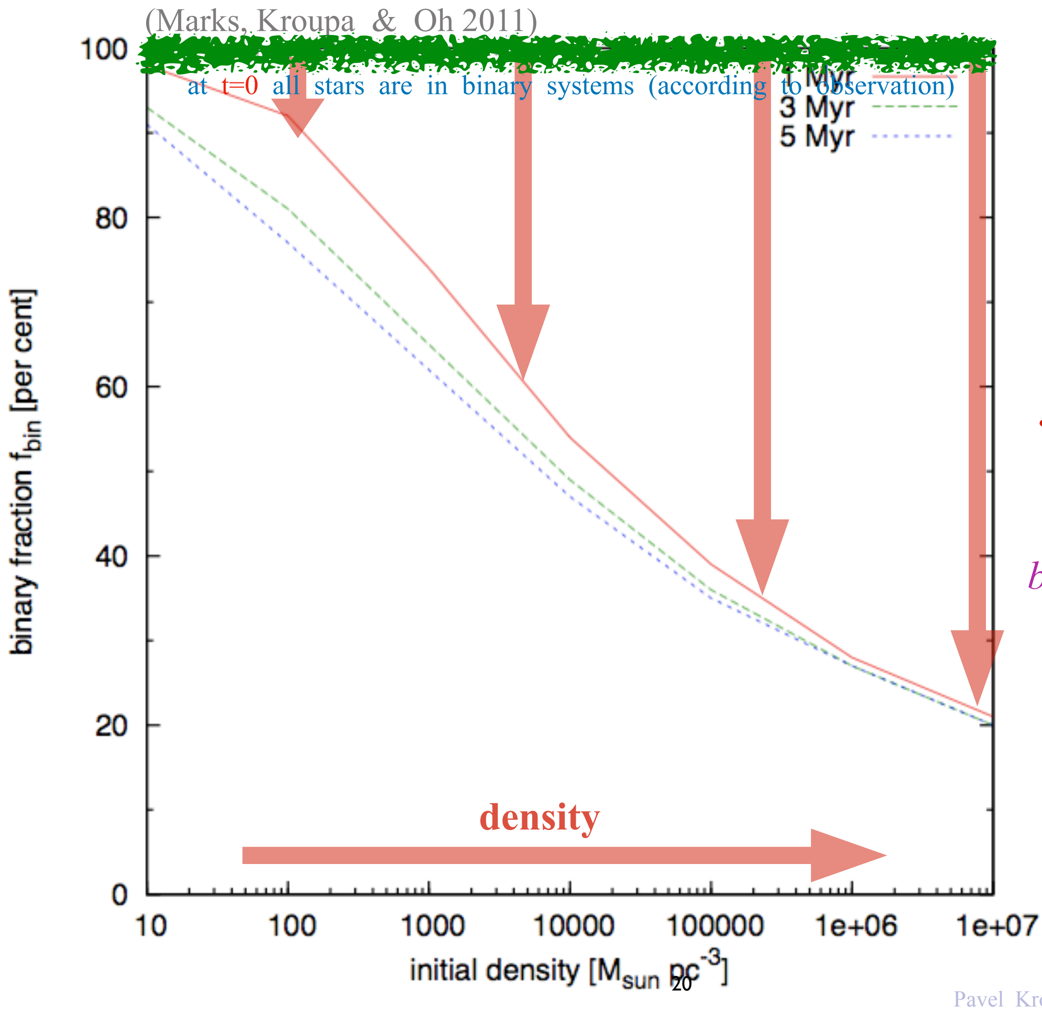

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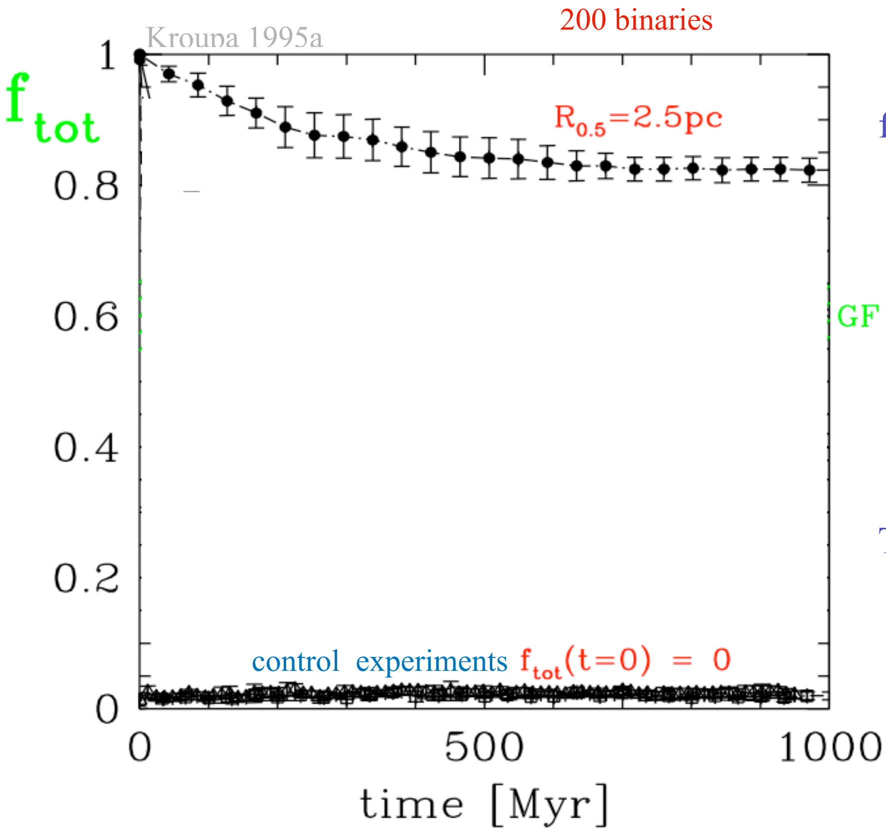
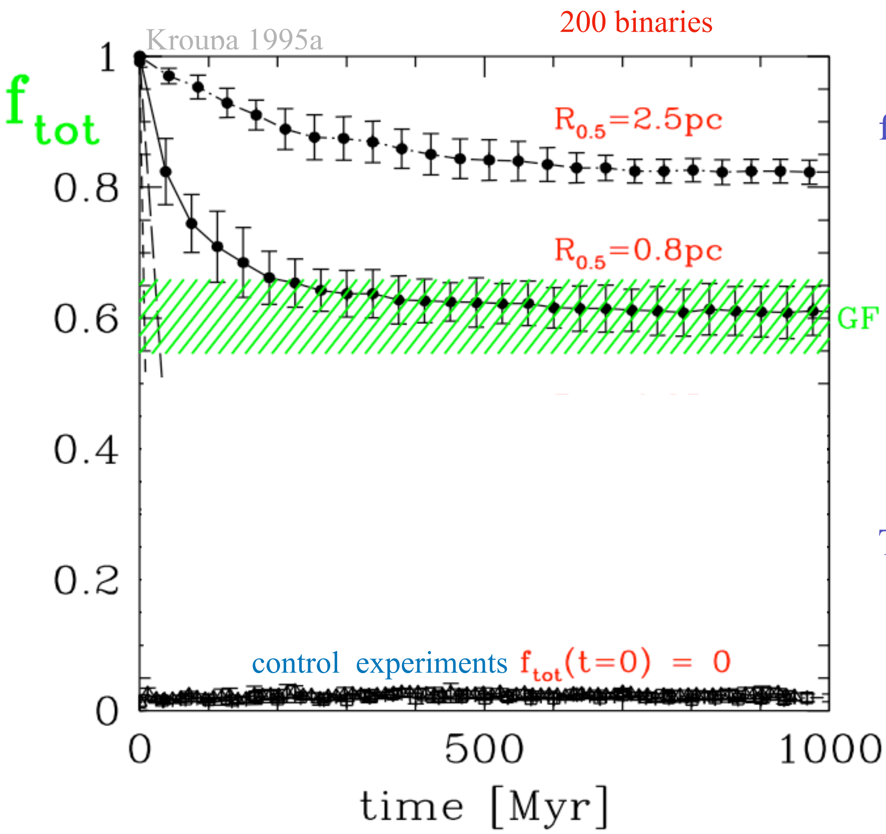


Stars (and brown dwarfs) form in embedded clusters

Observed **:**
Lada & Lada (2003); Porras et al. 2(2003); Megeath et al. (2016); Dinnbier et al. (2022)

*Simulated***:**
e.g. Bates et al. (20003); Bates (2009); González-Samaniego & Vazquez-Semadeni (2020)

The initial binary population is dynamically processed in these.



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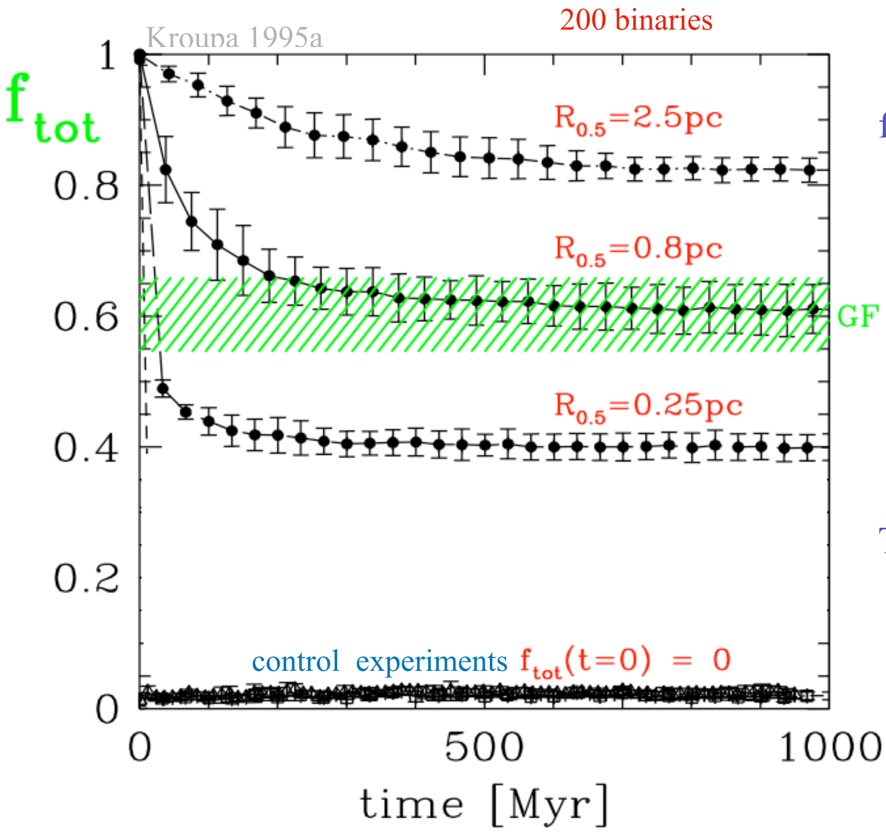

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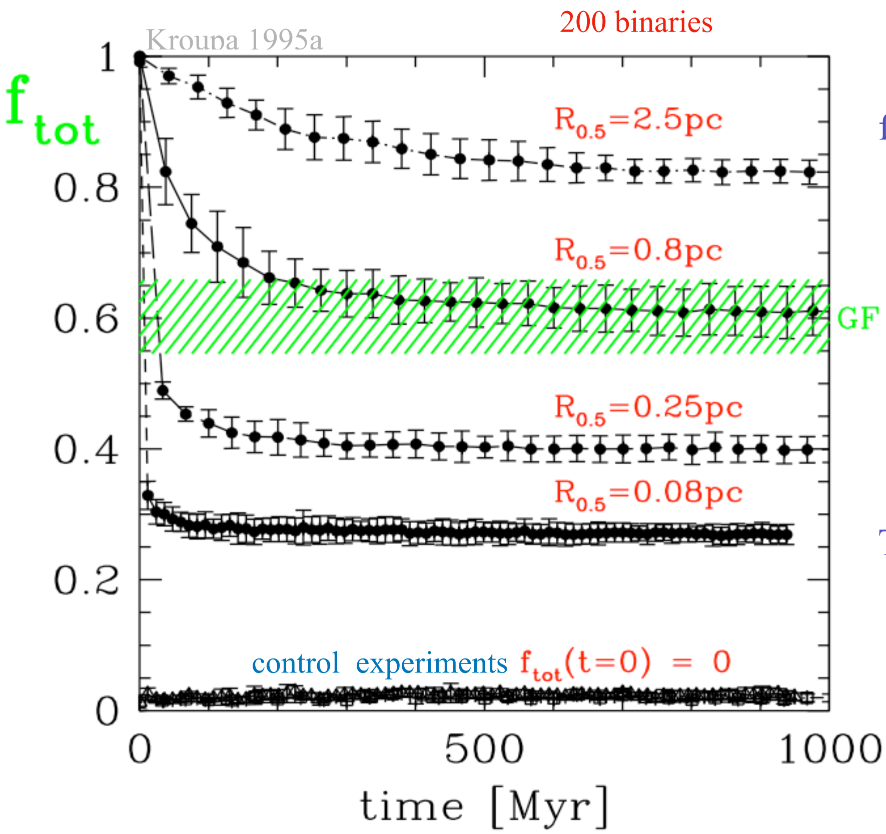

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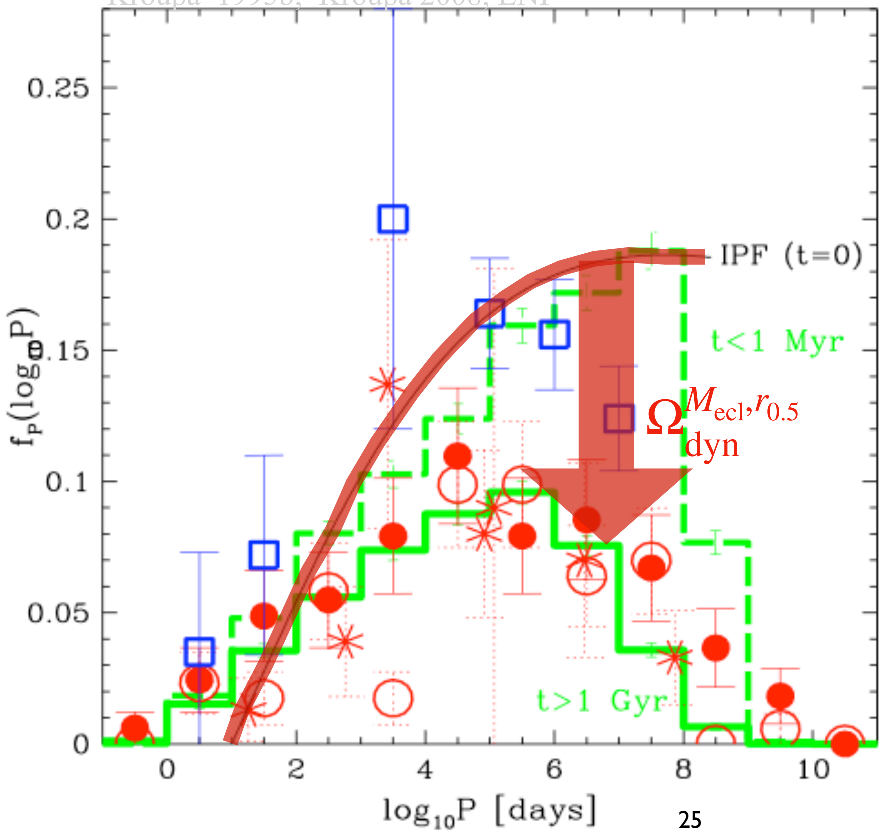
The birth period / energy -distribution function for low-density (isolated) star formation



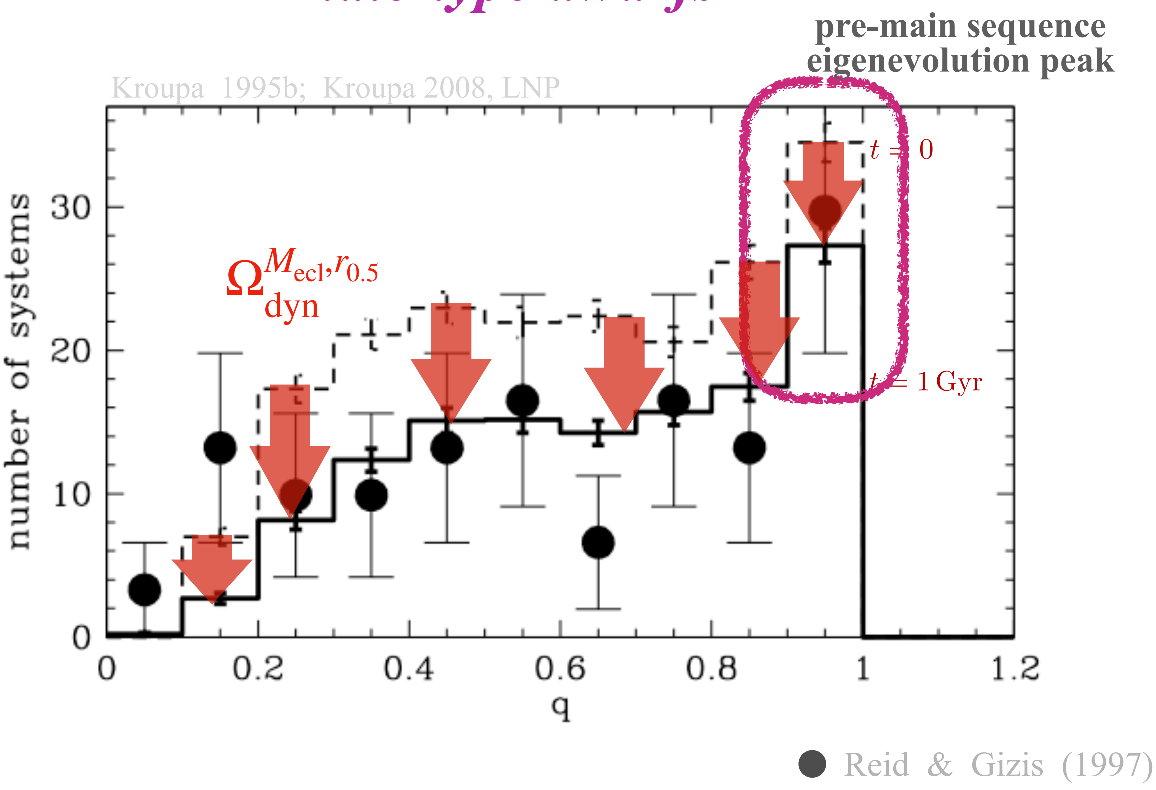
canonical birth binary population:

$$f_{P,\rm birth} = 2.5\,\frac{lP-1}{45+(lP-1)^2}$$

with $lP_{\max} = 8.43$

with subsequent pre-main sequence adjustments (*eigenevolution*) for $P < 10^3\,$d systems

The final mass-ratio distribution for late-type dwarfs



Summary: the "standard / canonical model"

(Kroupa 1995a, 1995b; Belloni et al. 2017)

For stars in the mass range $0.1 < m/M_{\odot} < \text{few}$

the **canonical birth binary population** (BBP) can be described by

$$f_{P,\mathrm{birth}} = 2.5 \, \frac{lP - 1}{45 + (lP - 1)^2}$$

$f_{\mathrm{q}}(q) =$ **random pairing !**

$f_{\mathrm{e}}(e) =$ **thermal !**

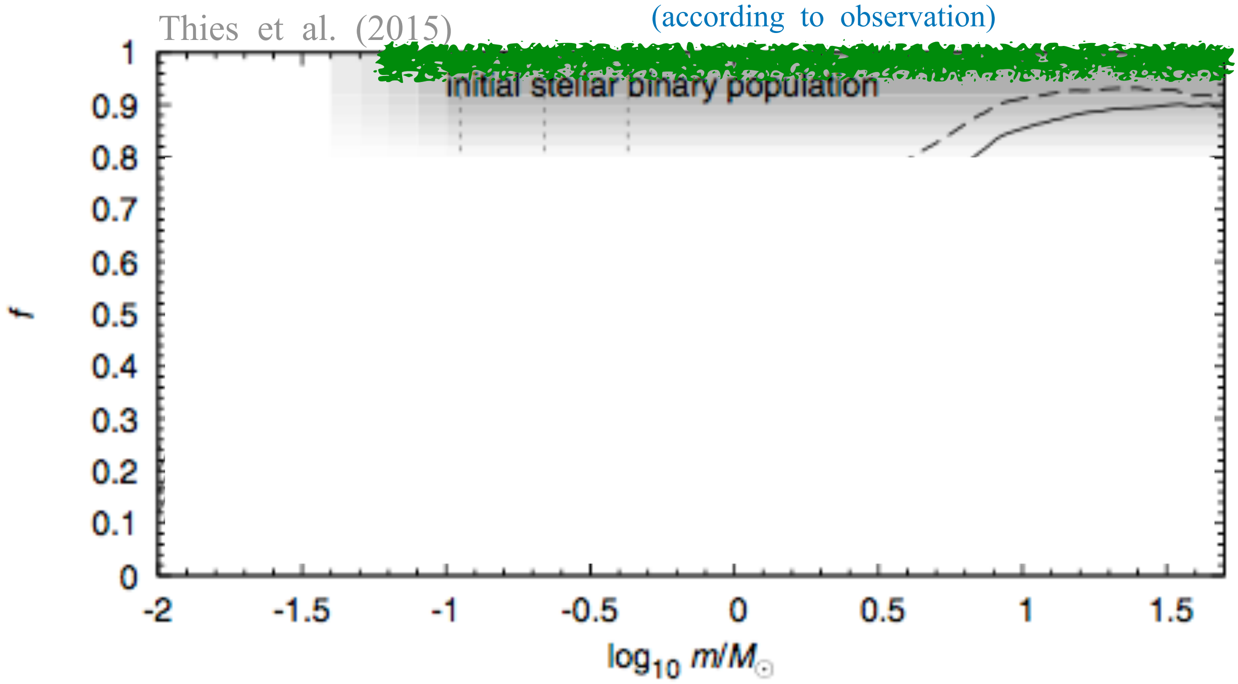
with $lP_{\mathrm{max}} = 8.43$

with adjustments (*pre-main-sequence eigenevolution*) for $P < 10^3$ d systems

This *unifies the populations* :
The very young population is dynamically processed in their birth embedded clusters before these disperse.

The binary fraction as a function of mass of primary

at t=0 all stars are in binary systems
(according to observation)



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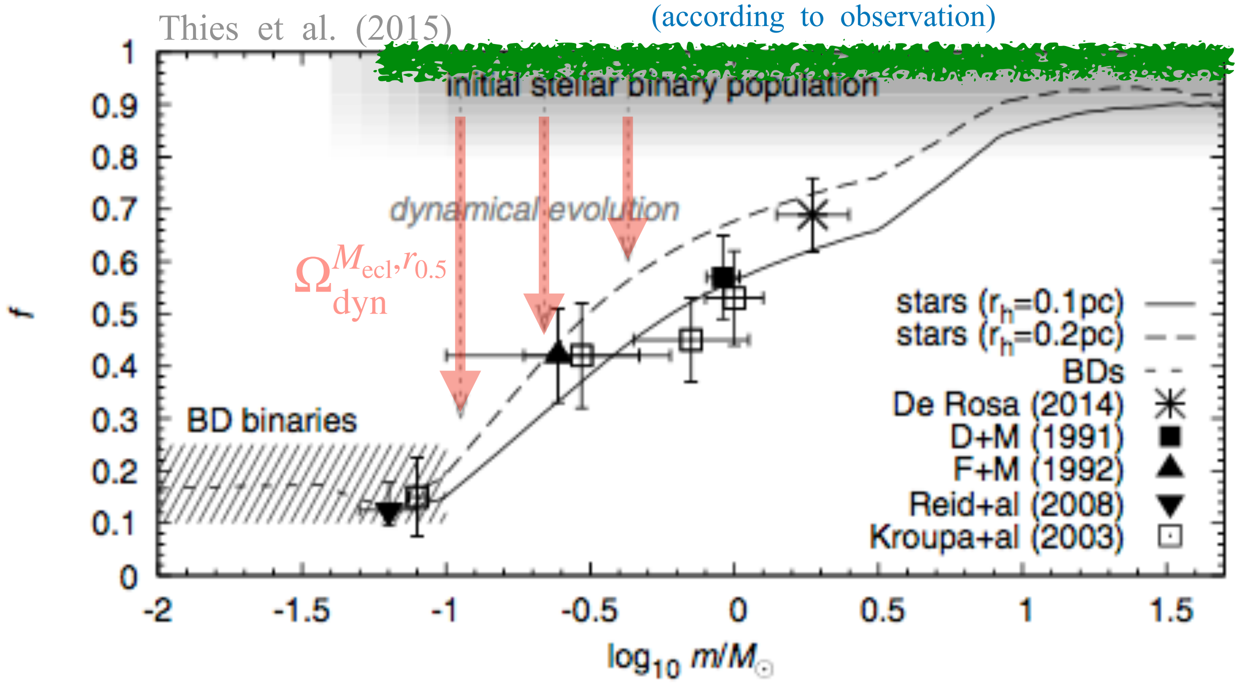

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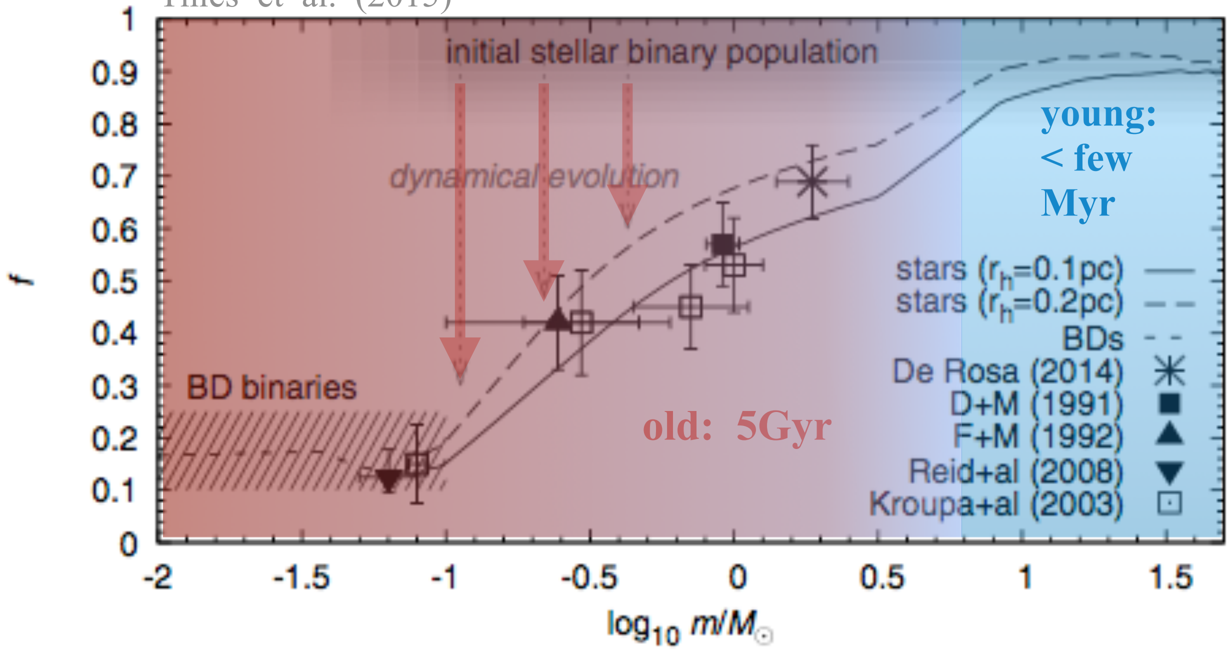
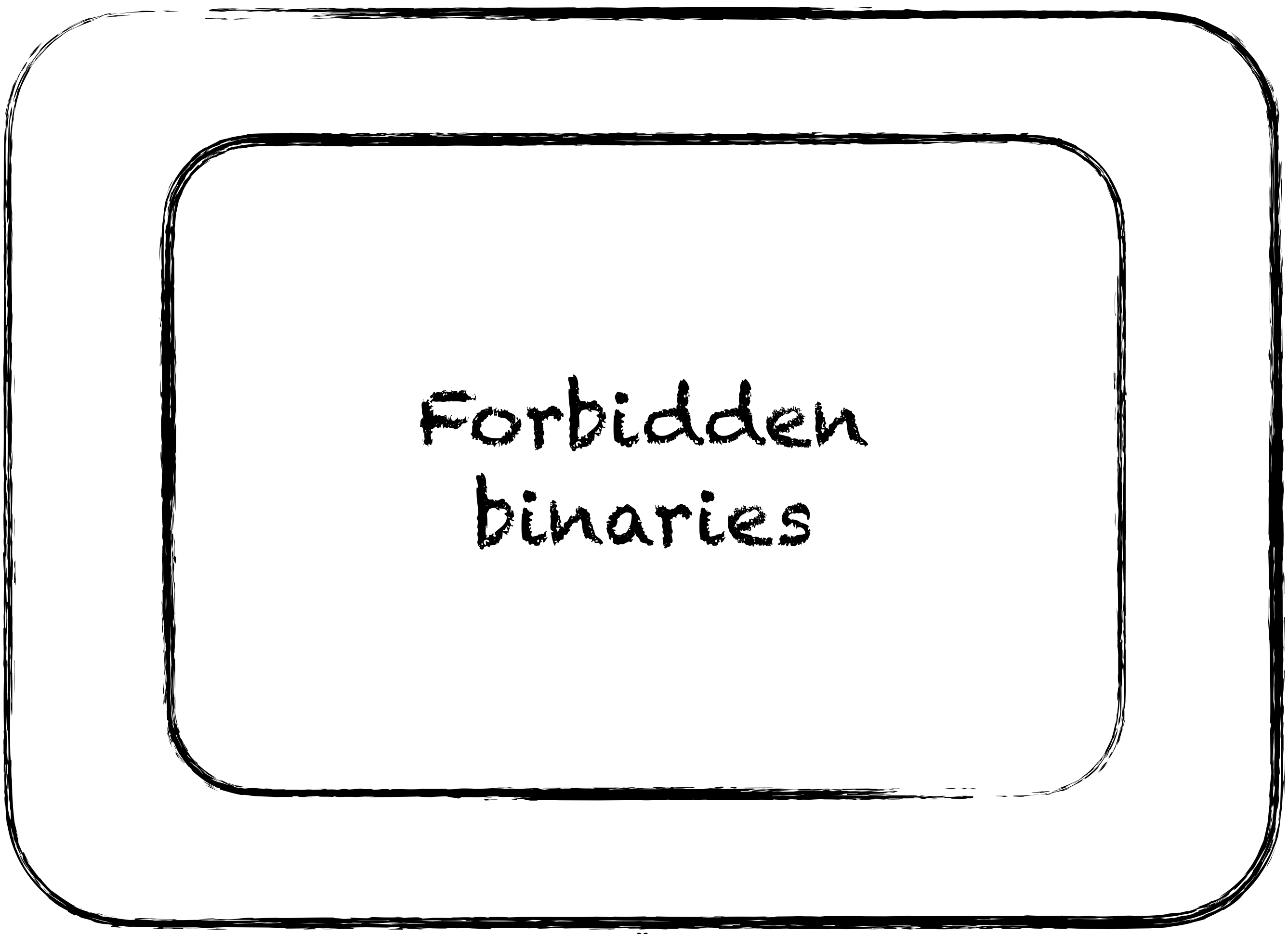
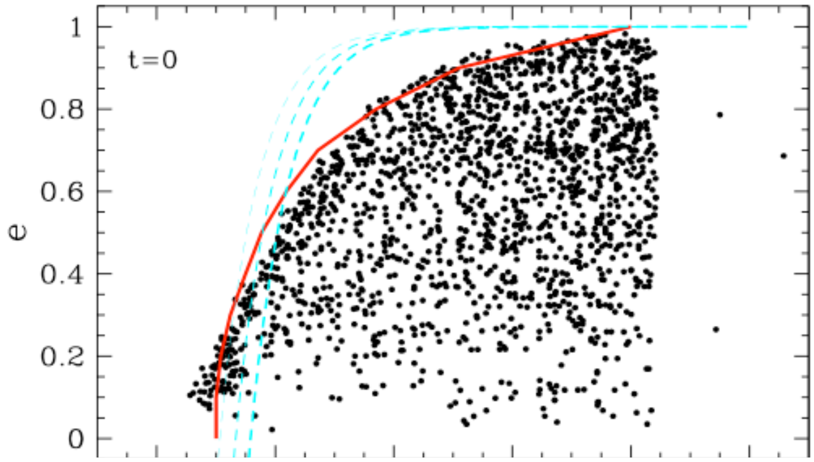
Thies et al. (2015)

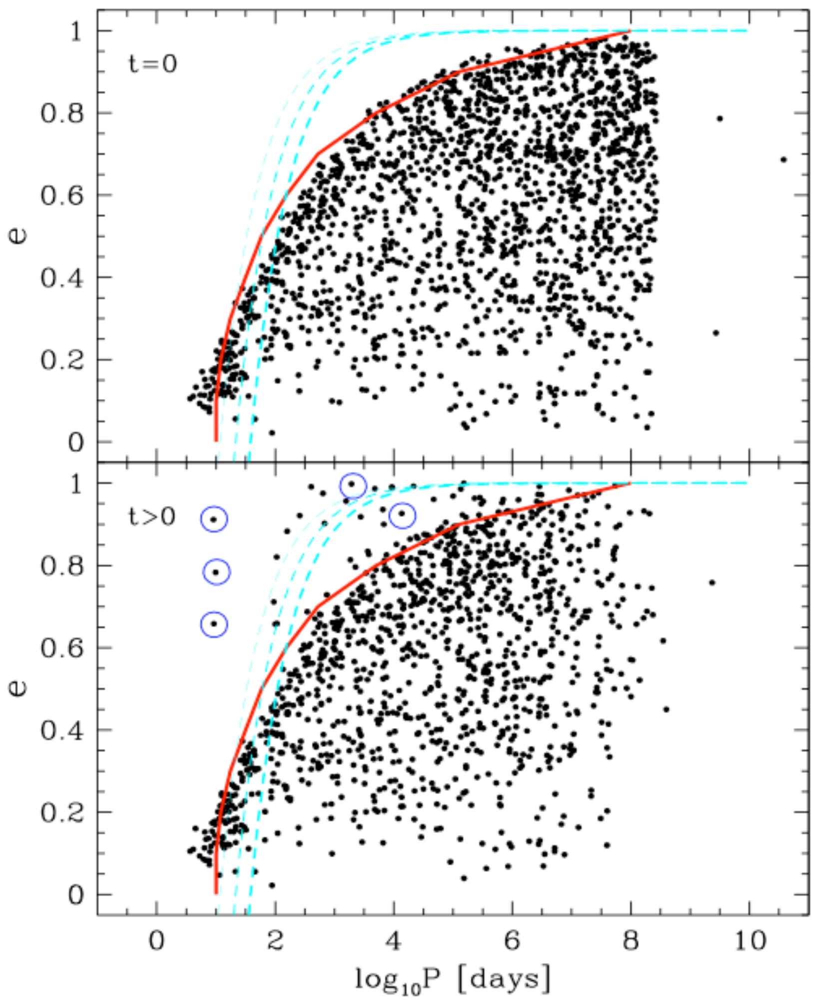






forbidden binaries

In a cluster,
binaries get knocked about
in the ecc--period diagram.
They may end up in the
forbidden region.



forbidden binaries

In a cluster,
binaries get knocked about
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They may end up in the
forbidden region.

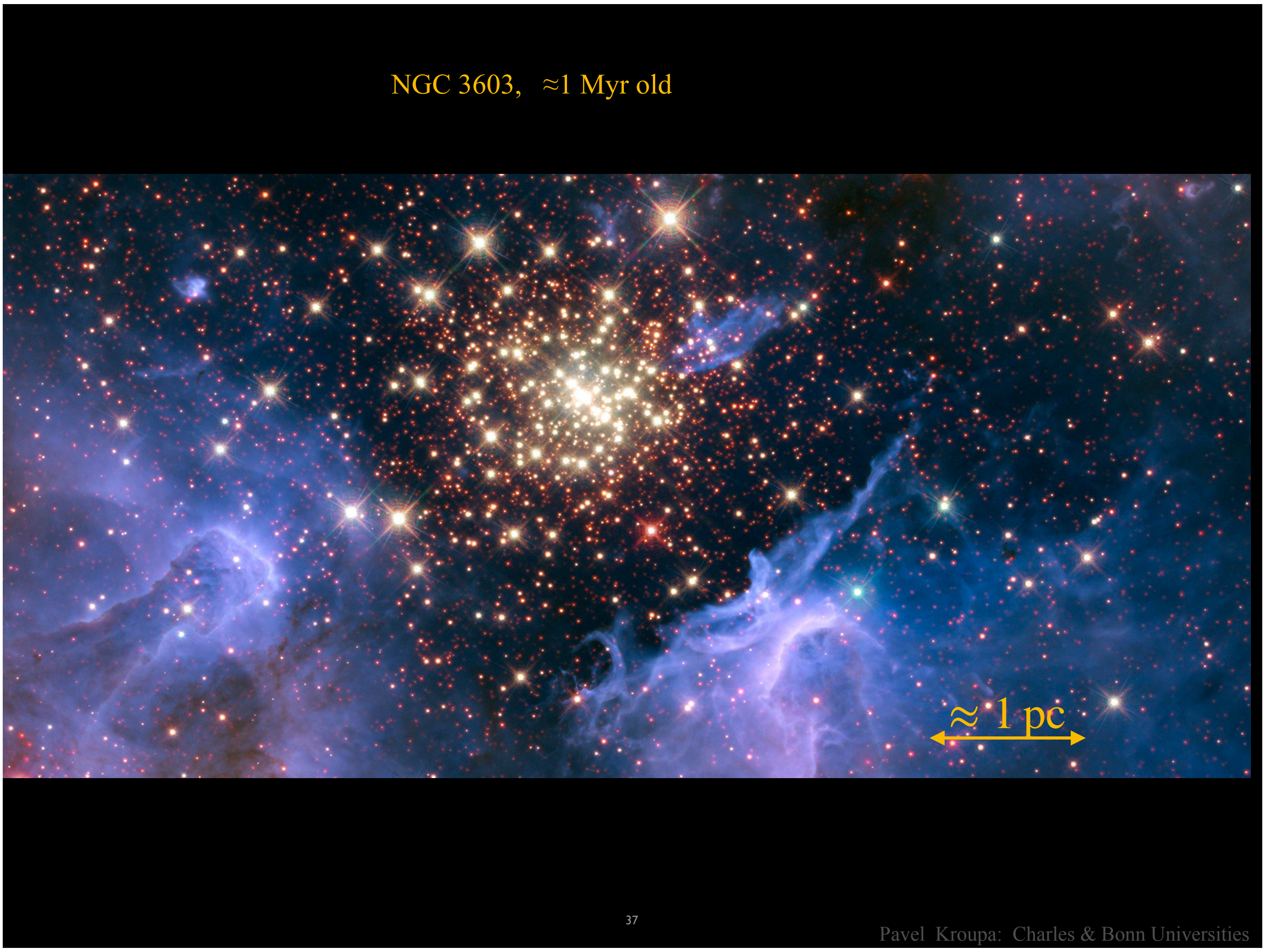
Forbidden binaries are important
for testing
tidal circularisation theory
and to
probe the interior of stars

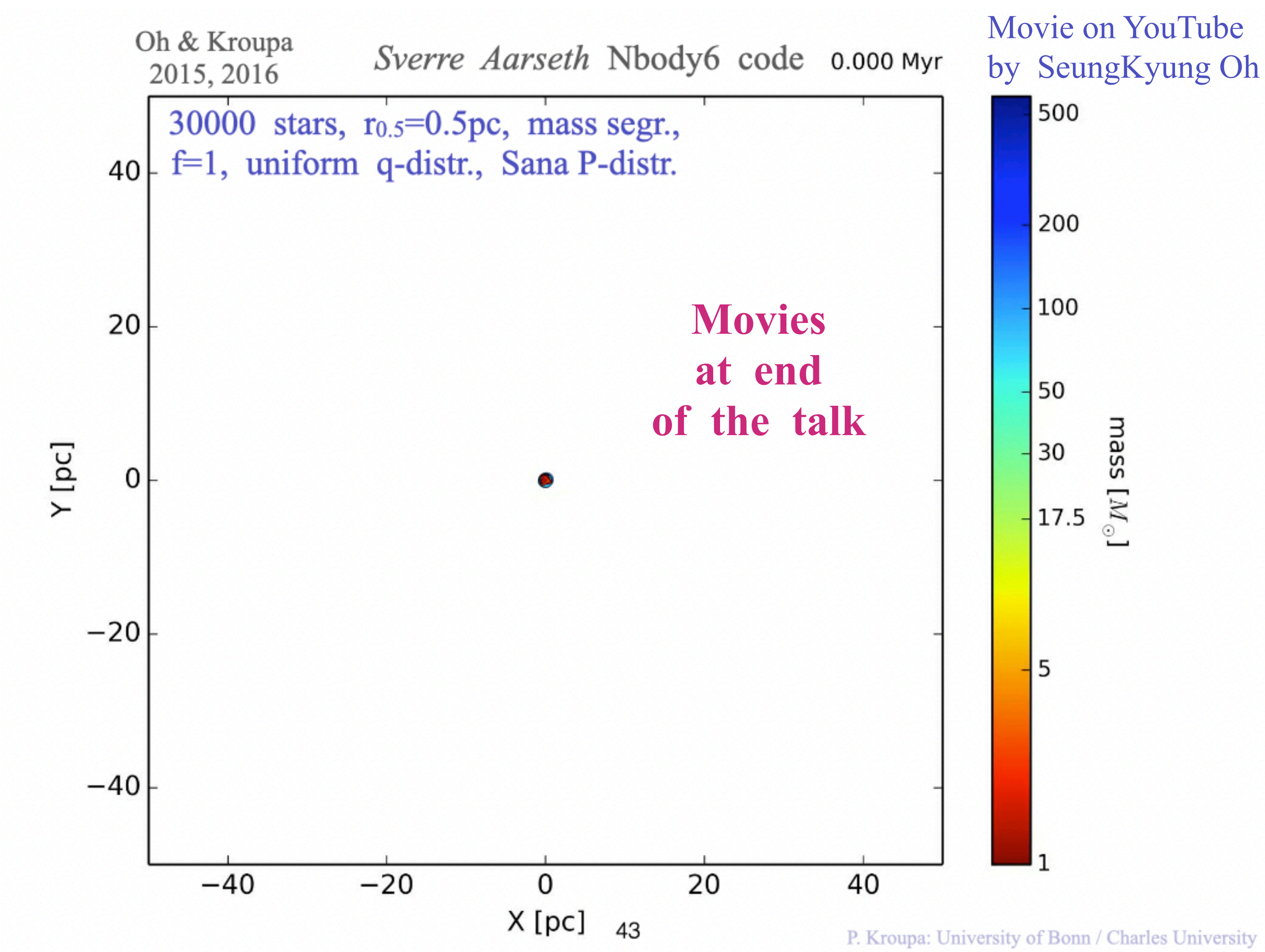
(also talk by ***Sophie Rosu***
on Monday;
observed cases:
Beck, Mathis et al. 2018)

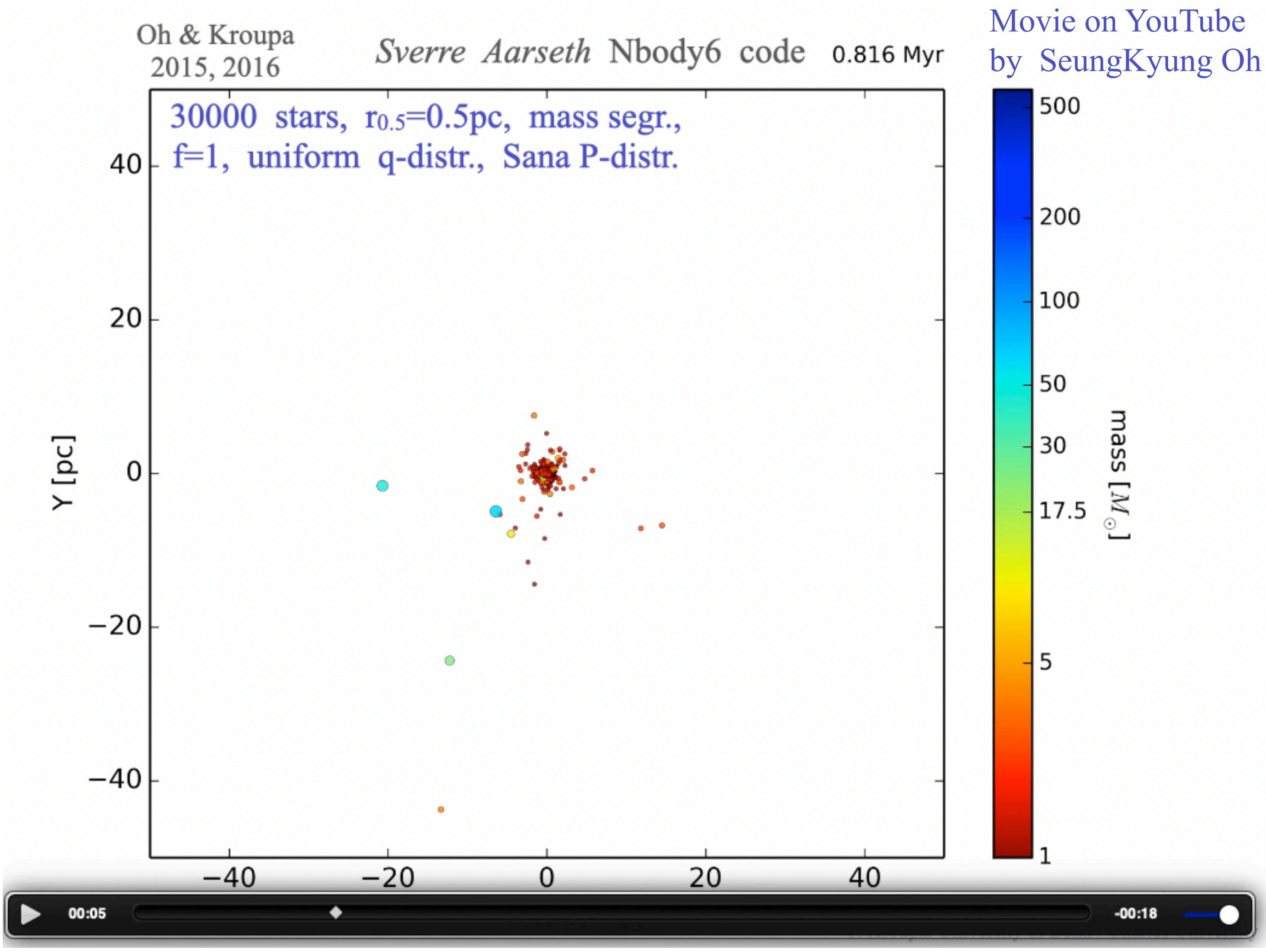
Massive stars

Initial distribution function **:** differ from less massive stars
(work in progress)

EXTREME VIOLENCE
EXTREMELY QUICKLY,
RAPID DYNAMICAL PROCESSING


NGC 3603, ≈1 Myr old
≈ 1 pc
37
Pavel Kroupa: Charles & Bonn Universities


Oh & Kroupa
2015, 2016
Sverre Aarseth Nbody6 code
0.000 Myr
Movie on YouTube
by SeungKyung Oh
30000 stars, r0.5=0.5pc, mass segr.,
f=1, uniform q-distr., Sana P-distr.
Movies
at end
of the talk
Y [pc]
X [pc]
mass [$M_\odot$]
43
P. Kroupa: University of Bonn / Charles University


Oh & Kroupa
2015, 2016
Sverre Aarseth Nbody6 code 0.816 Myr
Movie on YouTube
by SeungKyung Oh
30000 stars, $r_{0.5}$=0.5pc, mass segr.,
f=1, uniform q-distr., Sana P-distr.
Y [pc]
mass [$M_\odot$]
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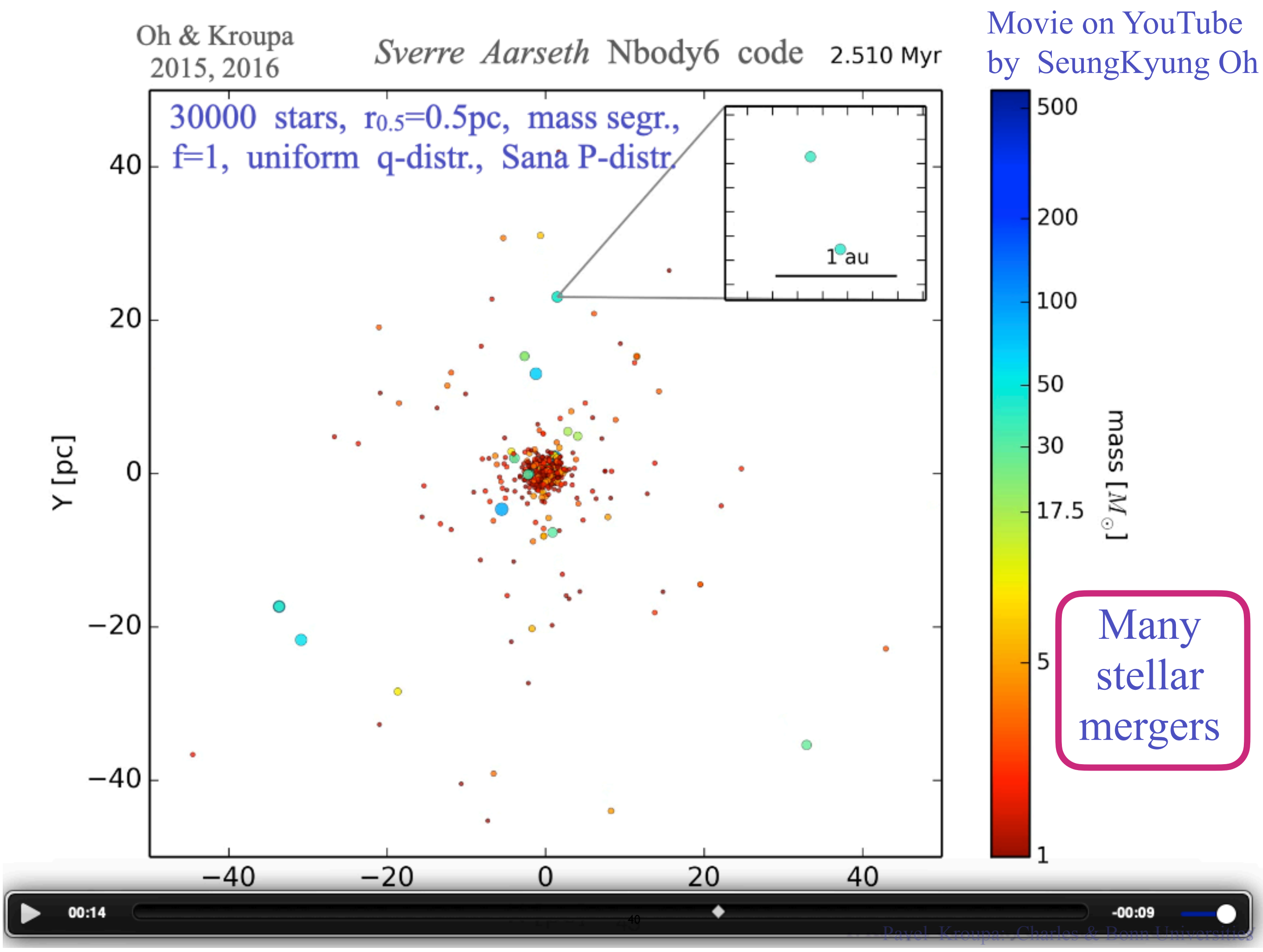
Oh & Kroupa
2015, 2016
Sverre Aarseth Nbody6 code 2.510 Myr
Movie on YouTube
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30000 stars, $r_{0.5}$=0.5pc, mass segr.,
f=1, uniform q-distr., Sana P-distr.
1 au
Y [pc]
mass [$M_\odot$]
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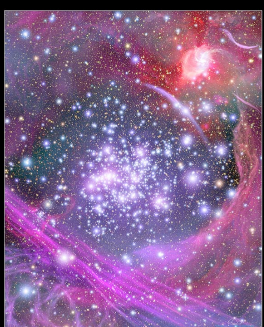
Many stellar mergers
00:14
-00:09
Pavel Kroupa: Charles & Bonn Universities

Galaxies

Galaxies

$n \times$  $=$ 

Dynamical population synthesis :

Galactic-field population (Kroupa 1995; Kroupa et al. 2013)

$$= \int_{\text{galaxy or region}} \text{embeddded clusters}$$

Predictions : Marks & Kroupa 2011
(of field distribution functions: $f_P(P)$, $f_q(q)$, $f_e(e)$)

dwarf star-forming galaxies : $f_{bin} \approx 0.8$

Milky-Way-type galaxies : $f_{bin} \approx 0.5$

Massive E galaxies : $f_{bin} \approx 0.35$

The Conclusions

Distribution functions

(Kroupa 1995a,b
Belloni et al. 2017)

$f_m(m) = \mathrm{IMF}$ initial distribution function of stellar masses ✓

$f_\mathrm{P}(P)$ initial distribution function of periods or binding energies ✓

$f_\mathrm{q}(q)$ initial distribution function of mass ratios ✓

$f_\mathrm{e}(e)$ initial distribution function of eccentricities ✓

We have a consistent description of the stellar binary population
-- in star-forming regions,
-- in the Milky Way field,
-- in galaxies.

All ***stars*** form in binaries with well-defined
IMF, *birth period* and *birth eccentricity distributions*
(Kroupa 1995; Marks & Kroupa 2011; Belloni et al. 2017)
and for primaries < 5 M_{Sun}
companion masses
taken randomly from the canonical IMF.

Distribution functions differ for
massive stars (work in progress: Franta Dinnbier)
and *brown dwarfs* (Marks et al. 2015, 2017)

The many stellar-dynamical encounters in the birth embedded clusters

emergence of many exotic stellar systems
(magnetic A stars, A[e] stars, cataclysmic variables, X-ray binaries, Cepheids with wrong ages)
Research in Prague: Dana Korcakova, Nela Dvorakova

Dvorakova, Korcakova, Dinnbier & Kroupa (2024, in press)

26 - 30 % of all O-type stars are mergers.
13 - 24 % of all B-type stars are mergers.
5 - 8 % of all B-type stars are mergers.

Dinnbier, Andersen & Kroupa (2024, in press)

40 % of all Cepheids are mergers.
10 % of all Cepheid binaries have exchanged companions
3 - 5 % of all Cepheids have a compact companion

cf. to Paulina Karczmarek's talk on Tuesday

Movie 1

Movie 2

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The END