Collisions and the formation of (very) massive stars

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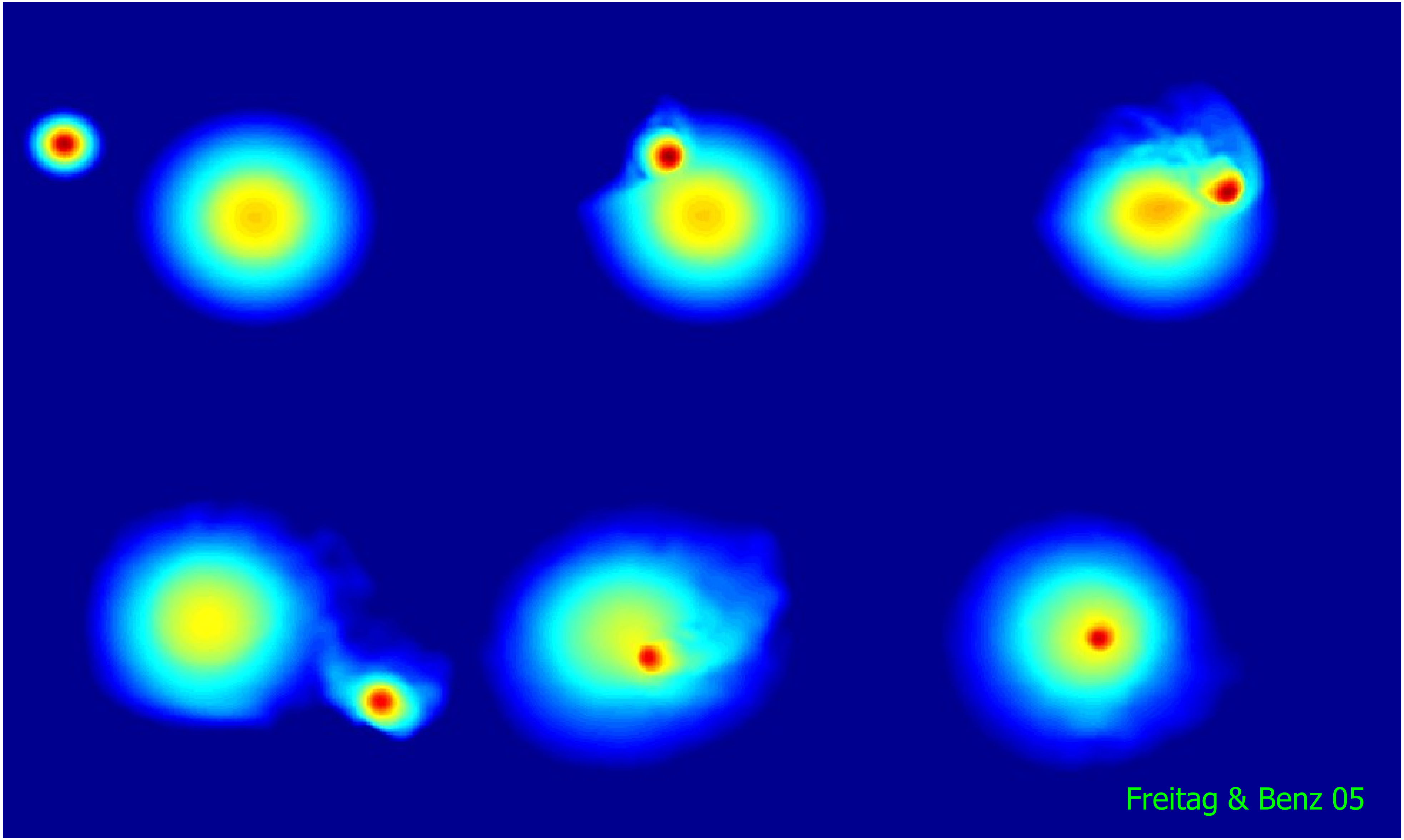
Approximate outline

- In this talk:
  - Some properties of stellar collisions
  - Timescales
  - Stellar dynamical scenarios leading to stellar mergers
    - Role of core collapse
    - Role of binaries
    - Role of gas
- Left out for discussion:
  - Do we need collisions to form massive stars?
  - Observational tests

Outcome of stellar collisions: single MS stars

- MS-MS collisions best studied (e.g. Benz & Hills 87,92; Lai et al. 93; Sills et al. 01; Freitag & Benz 05; Dale & Davies 06)
  - Capture/Merger most likely at Vrel < 100 km/s; mass loss a few %
  - Disruptive collisions require very high velocities (few times escape velocity) and small impact parameter
  - Little hydrodynamical mixing for unequal-mass mergers.
    - Mass elements sort themselves according to “buoyancy” (e.g. Lombardi et al. 96,02,03; Gaburov et al. 07)
    - Lower-mass star sinks to the centre of higher-mass star: rejuvenation
  - Merger product bloated (during a thermal timescale)
    - Subsequent collision more likely (particularly in binary interactions) (e.g. Lombardi et al. 03)
  - Very high rotation rate of merger product
    - Require mechanism to shed angular momentum for star to return to MS (e.g. Sills et al. 05)

Collisions between MS stars



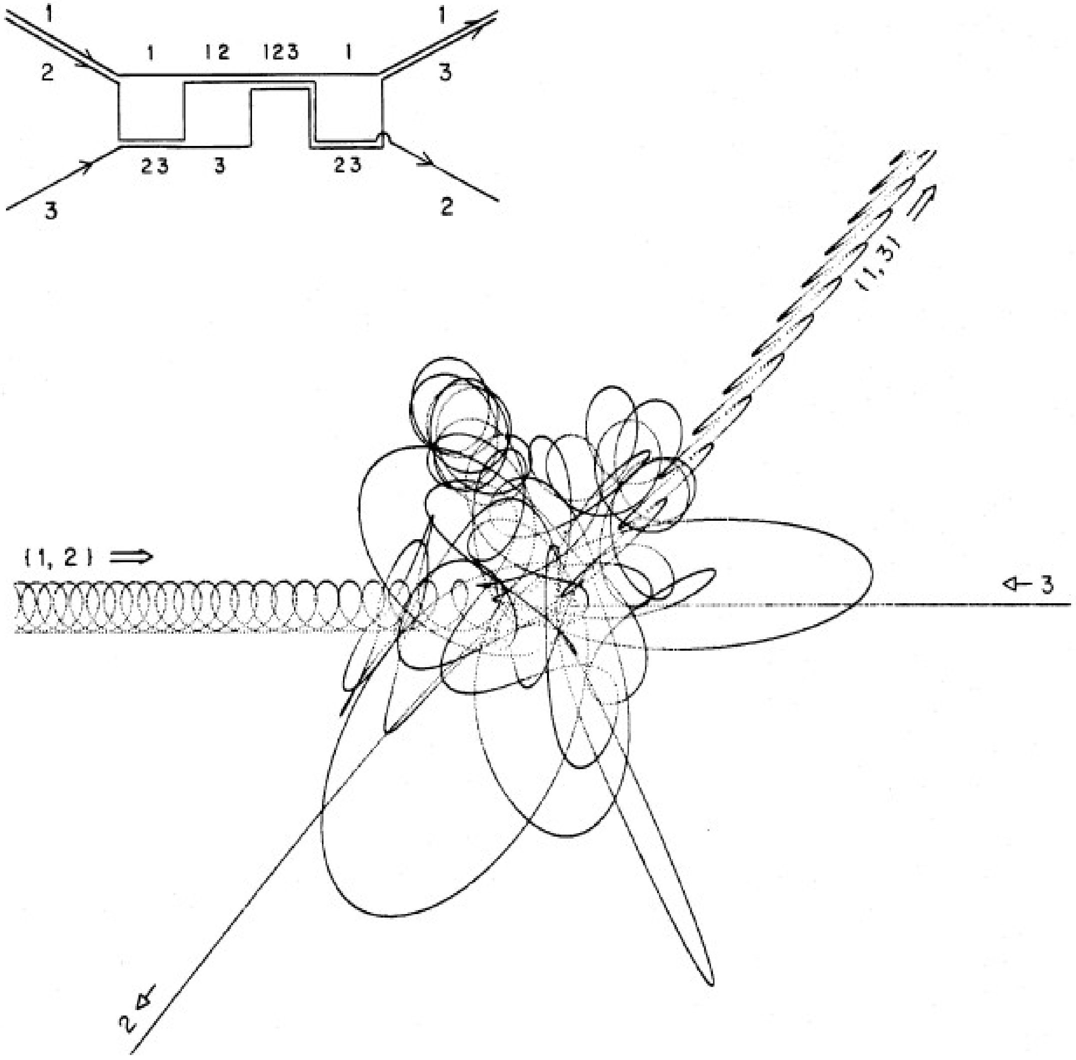
Collisions: binary stars

- Little studied
- Binary interactions can foster collisions (Portegies Zwart & McMillan 02; Fregeau et al. 04; Portegies Zwart et al. 04; Bonnell & Bate 05; Davies et al. 06; Gürkan et al. 06; Gaburov et al. 07)
  - High probability of close encounter during complex “resonant encounter”
  - Eccentric binaries led to merger by small perturbations
- Multiple collisions likely due to post-merger bloated phase (Goodman & Hernquist 91; Lombardi et al. 03; Fregeau et al. 04)

Collisions: binary stars

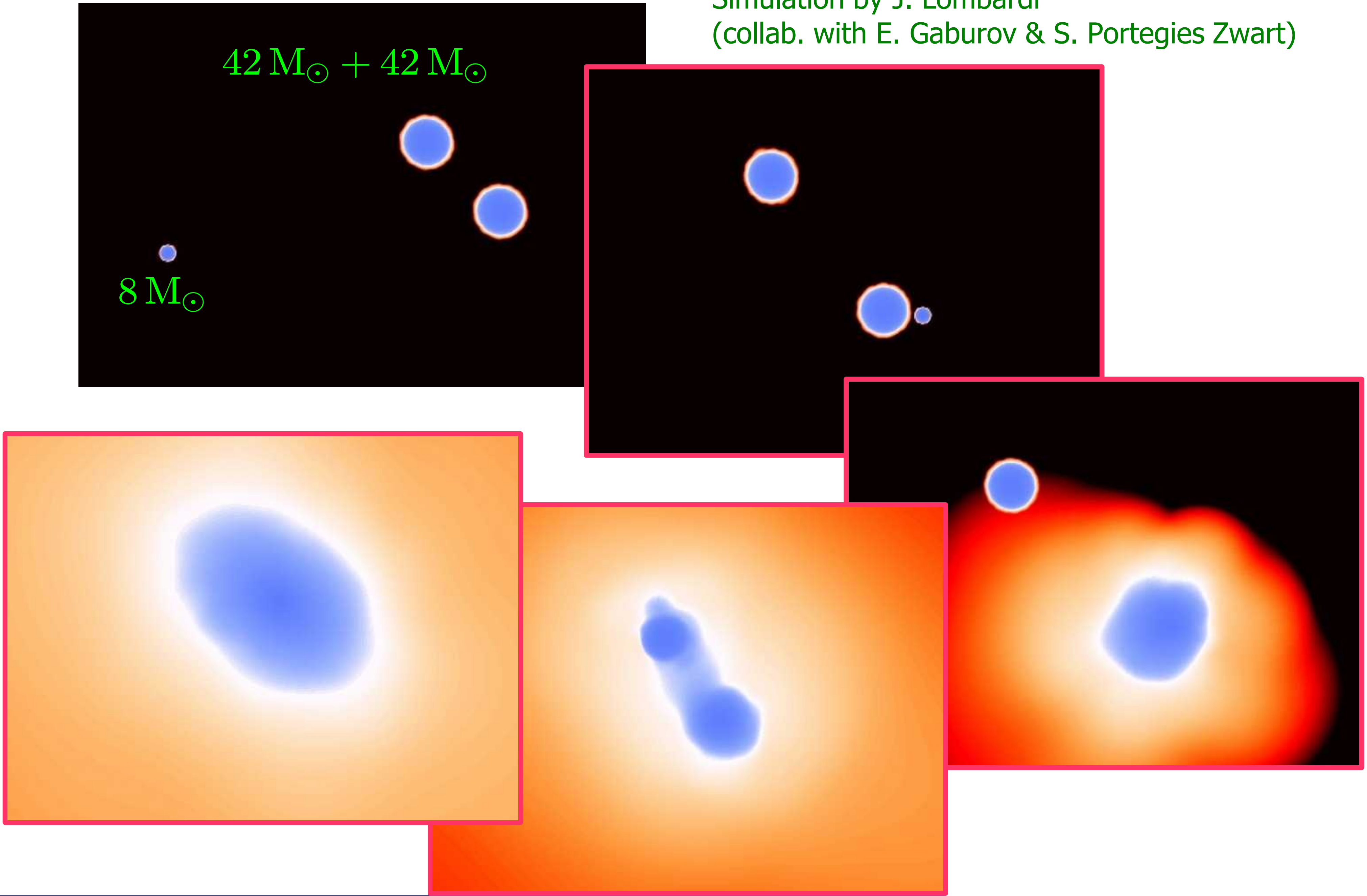
Example of a resonant
binary-single interaction

Hut & Bahcall 83



Collisions: binary stars

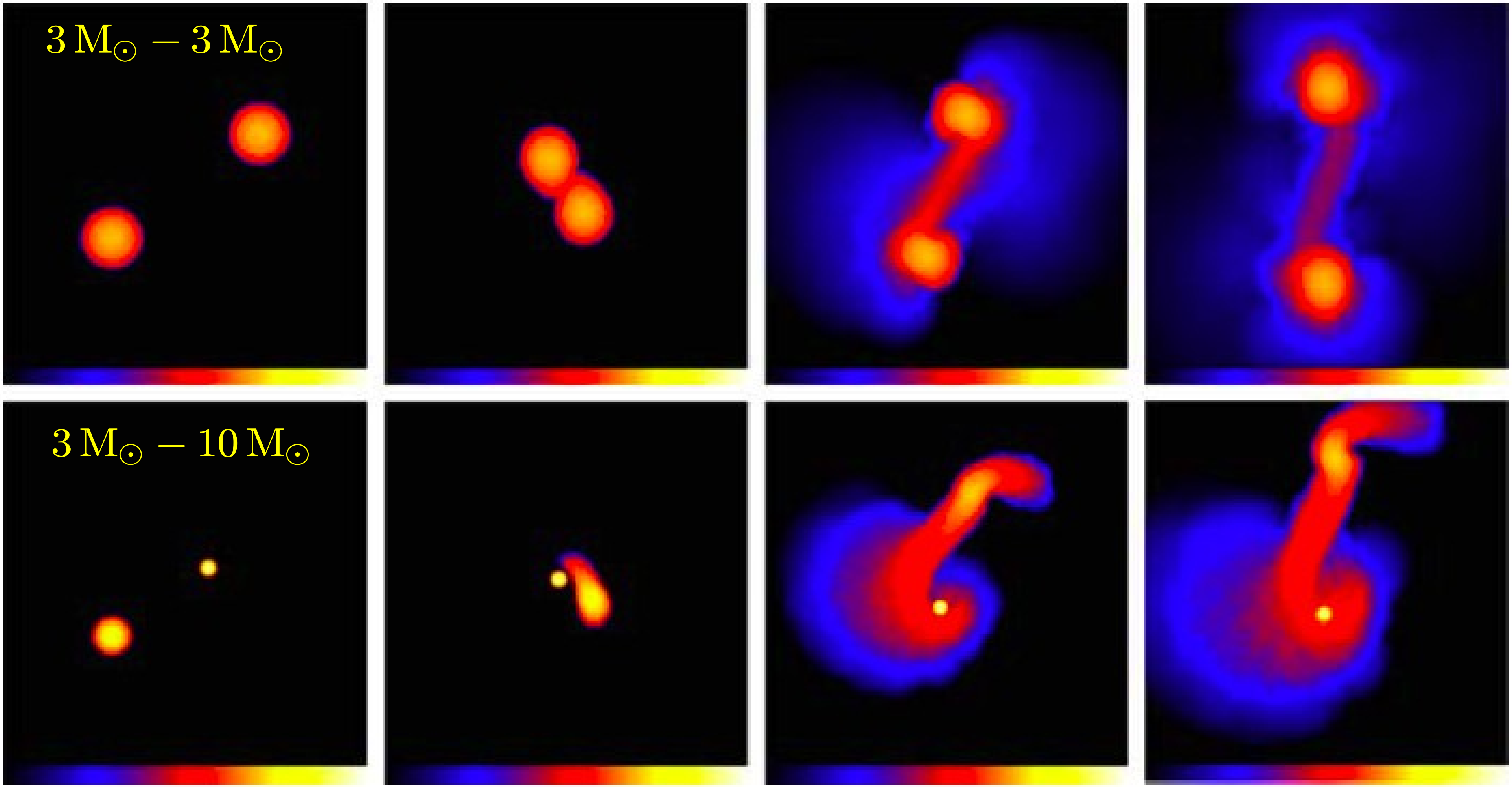
Simulation by J. Lombardi
(collab. with E. Gaburov & S. Portegies Zwart)



Collisions: pre-MS stars

- Little studied (Laycock & Sills 05; Davies et al 06)
- Low-M stars form and contract slower: larger and less dense than massive stars
  - Can be tidally disrupted by massive stars and form a disk around them
- Massive disks around young stars increase capture/merger probability
  - Also a possible explanation for high binarity fraction in massive stars (Moeckel & Bally 06, 07)

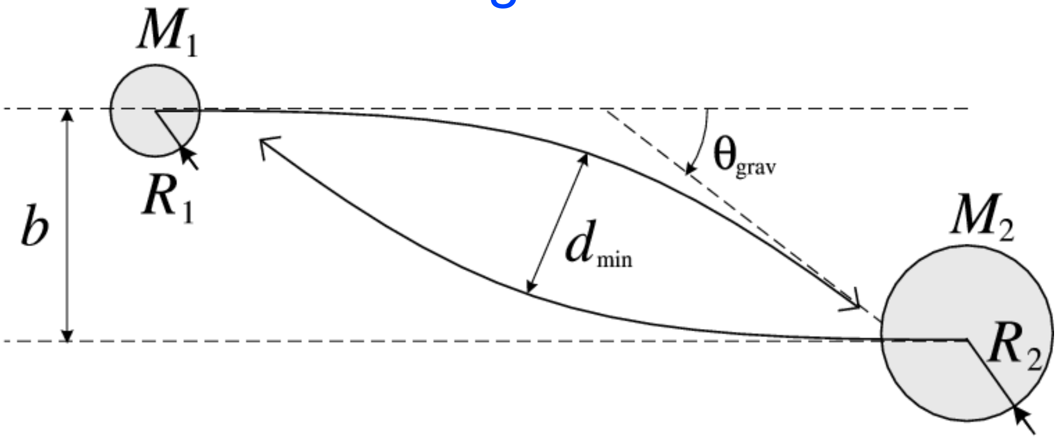
Collisions: pre-MS stars



Davies et al. 06

Collision time

- Direct collisions between single stars



$$t_{\rm coll}^{-1} = S_{\rm coll} V_{\rm rel} n_* \quad S_{\rm coll} = \pi (R_1 + R_2)^2 \left(1 + \frac{2G(M_1 + M_2)}{(R_1 + R_2) V_{\rm rel}^2} \right)$$

$$t_{\rm coll} \simeq 8 \times 10^9\,{\rm yr}\, \frac{10^6\,{\rm pc}^{-3}}{n_*} \frac{\sigma_v}{10\,{\rm km\,s}^{-1}} \frac{{\rm R}_\odot}{R_*} \frac{{\rm M}_\odot}{M_*}$$

- Binary interaction

$$t_{\rm inter} \simeq 7 \times 10^7\,{\rm yr}\, \frac{10^6\,{\rm pc}^{-3}}{n_*} \frac{\sigma_v}{10\,{\rm km\,s}^{-1}} \frac{\rm AU}{a_{\rm bin}} \frac{{\rm M}_\odot}{M_*}$$

How to make a cluster collisional (1)?

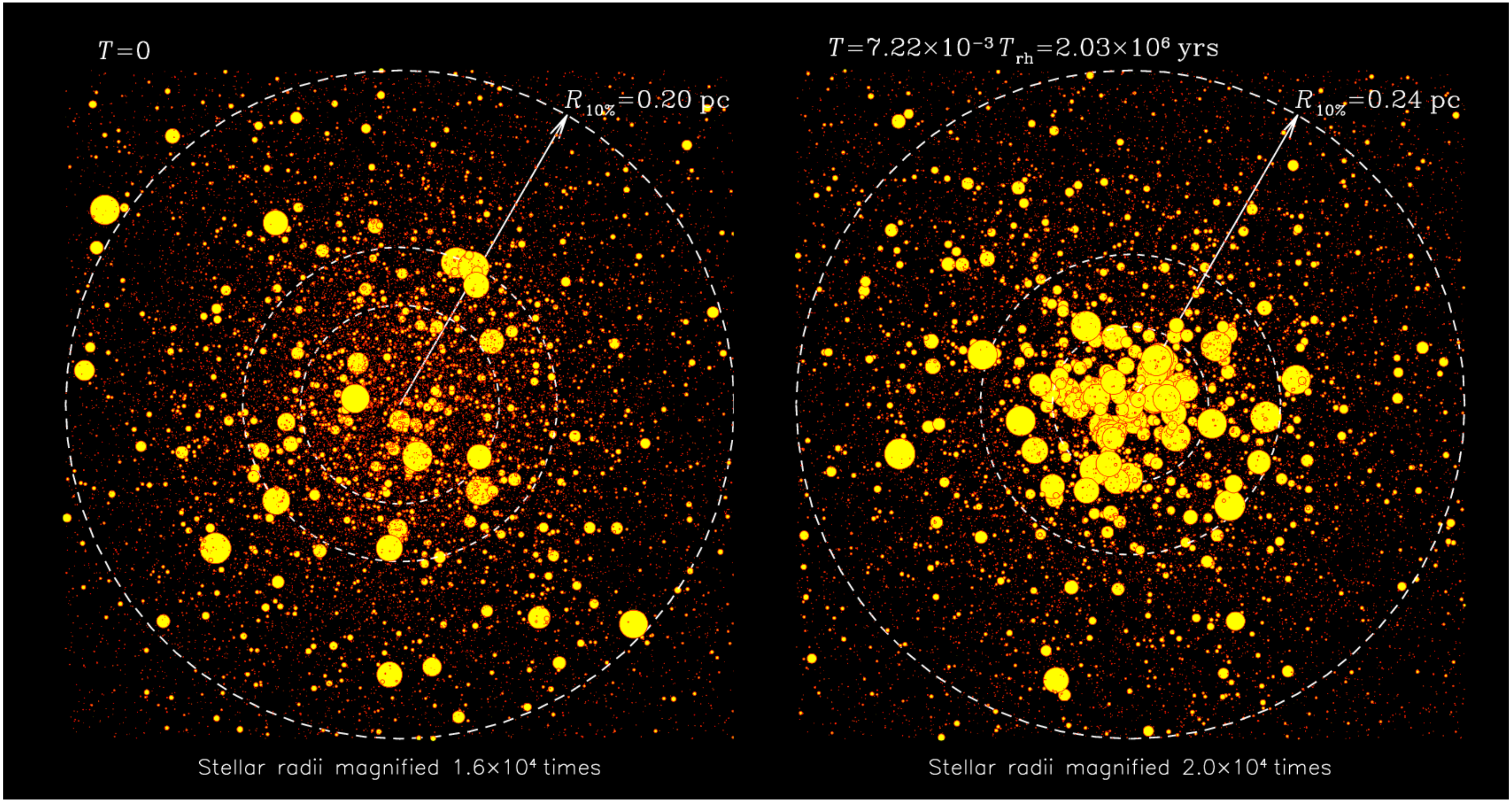
- Core collapse due to 2-body relaxation (Lee 87; Quinlan & Shapiro 90, Portegies Zwart & McMillan 02; Portegies Zwart et al 04; Gürkan et al. 04; Freitag et al. 06a,b; Belkus et al. 07; ...)
  - Start with cluster with a mass spectrum and “sufficiently short” trelax
  - Massive stars concentrate in the centre through energy exchange with lighter stars
  - System of massive stars becomes self-gravitating before energy equipartition is reached => Spitzer instability
  - Central density increases until collisions occurs
    - Unless process is stopped by binaries !?
  - “Runaway” growth of one (or two?) very massive stars (VMS)
    - Not a continuous high-M spectrum
    - What is the mass freached by the VMS? What does it become?

Condition: Core collapse before massive stars evolve (3 Myr)

Core collapse through mass segregation

Initial conditions

Core collapse

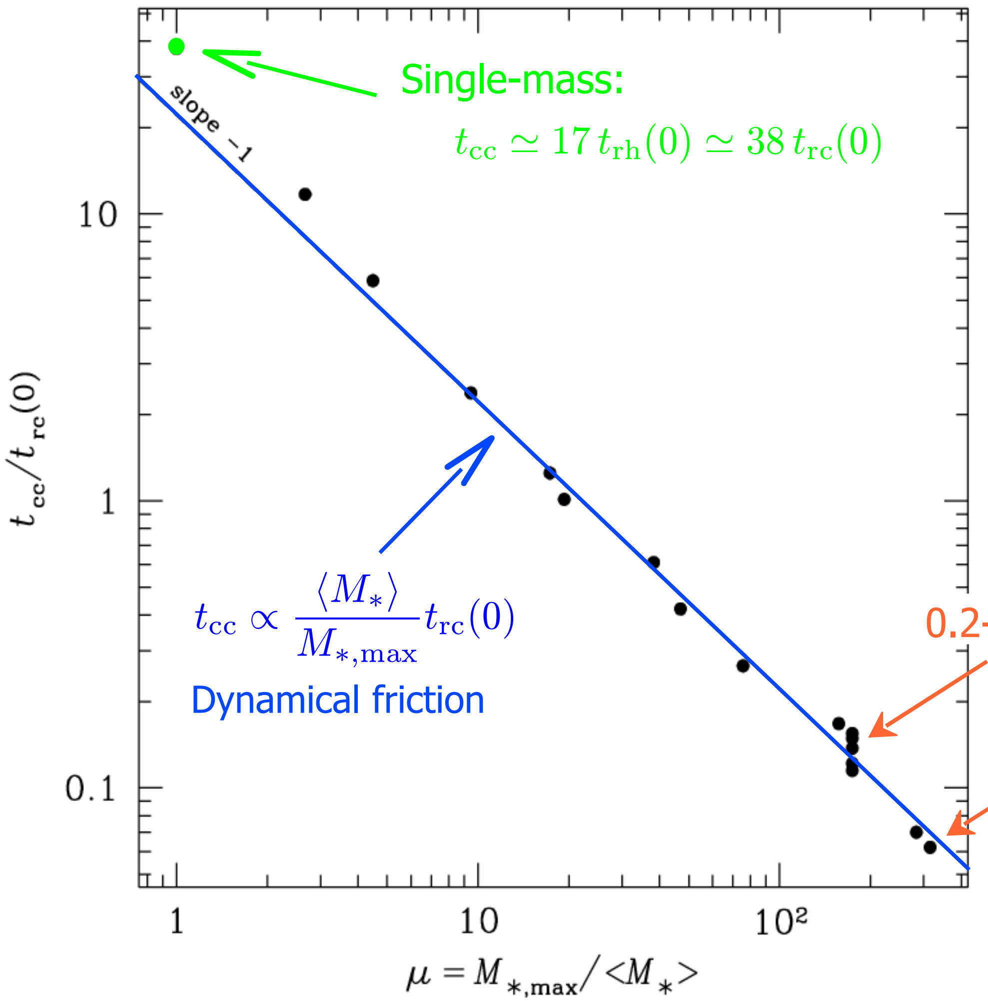


Gürkan, Freitag & Rasio 2004; Freitag, Rasio & Baumgardt 2005

How fast is core collapse?

MC runs with various mass functions, $N \geq 300{,}000$

Gürkan et al. 2004
Freitag unpublished



$$t_{cc} \lesssim 0.15 t_{rc}(0)$$

$$t_{rlx} \simeq 1.8\,\mathrm{Myr}\,\frac{10^6\,\mathrm{pc}^{-3}}{n_*}\left(\frac{\sigma_v}{10\,\mathrm{km\,s}^{-1}}\right)^3\left(\frac{\mathrm{M}_\odot}{\langle M_*\rangle}\right)^2$$

An example (for Hans): R136

Table 3. Stellar properties of R136 — Brandl 05

Quantity	*Value*	*Reference*
age	$\approx 2 \pm 1$ Myr	[a]
central density ρ_c	$5.5 \times 10^4 M_\odot \, pc^{-3}$	Hunter et al. (1995)
total mass m_{tot}	$6.3 \times 10^4 M_\odot^b$	Hunter et al. (1995)
core radius r_c	0.12 pc (0.″5)	Brandl et al. (1996)
half-mass radius r_{hm}	1.2 pc (5″)	Brandl et al. (1996)
tidal radius r_t	5 pc (21″)	Meylan (1993)
IMF slope ξ	2.2[c]	(Andersen et al. 2005)

- Central collision time for a 120 Msun star: ~ 80 Myr :-(
- Core collapse time (assuming Kroupa IMF): ~ 3-4 Myr ;-)
- Caveats:
  - What was the “initial” central density?
  - Initial mass segregation?
  - Cluster not rich enough for clean, fast core collapse ?

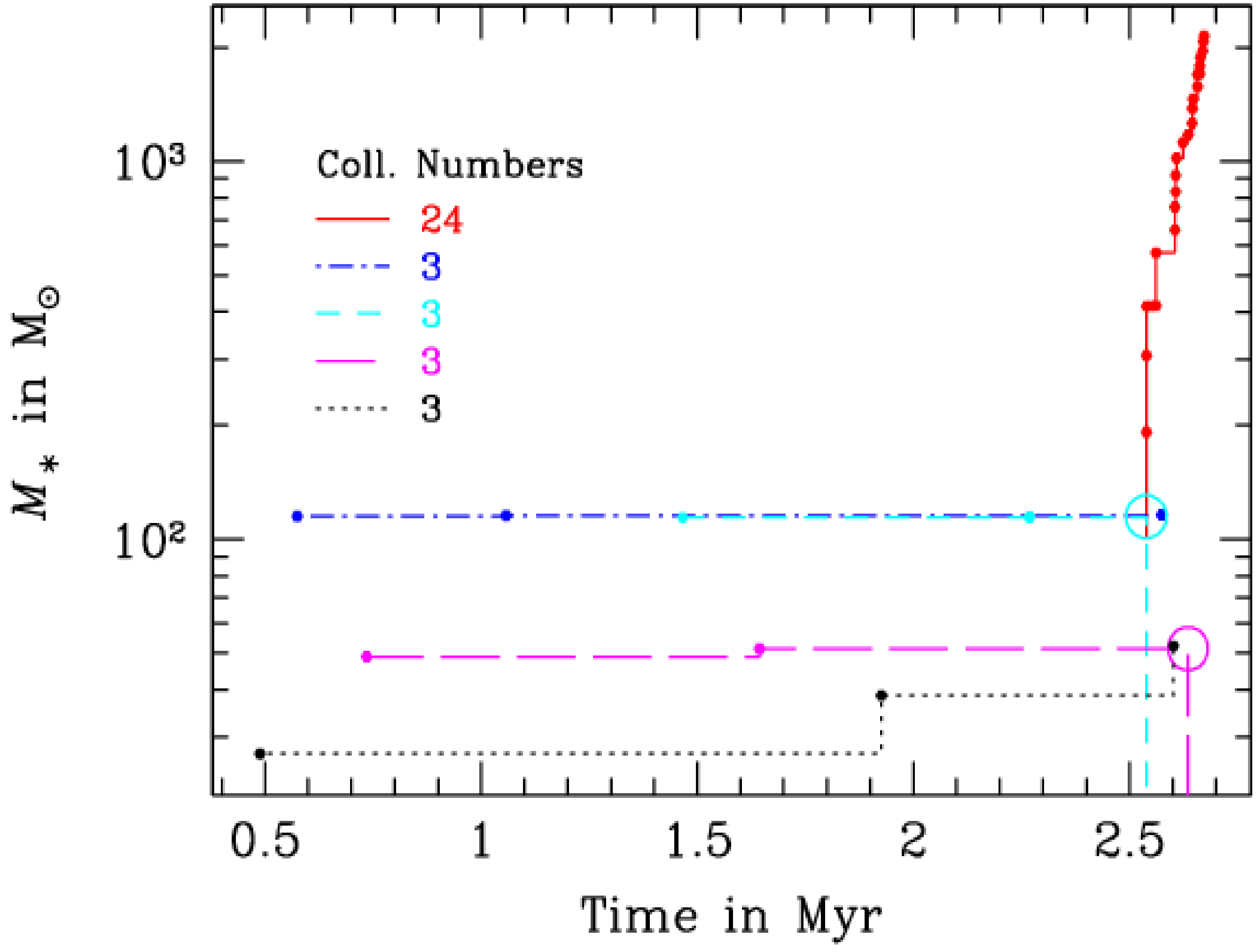
Runaway growth in short t_{cc} clusters

MC simulations with N =3x10^5-9x10^6

Freitag et al. 2006b

❢ no binaries

☺ "realistic" coll.



How to make a cluster collisional (2)?

- Core collapse due to 2-body relaxation
- Accretion of gas in embedded phase (Bonnell, Bate & Zinnecker 98; Bonnell & Bate 02)
  - Accretion of gas by stars leads to contraction of (sub)clusters

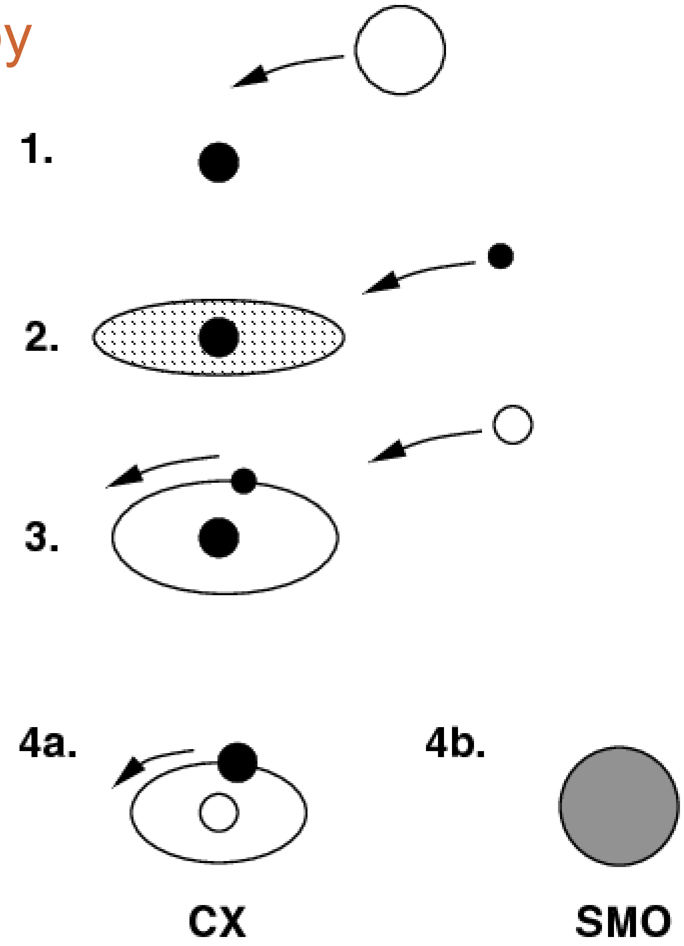
$$n_\star \propto M_{\mathrm{cl},\star}^{3-9}$$

← if $t_{accr} >> t_{dyn}$ and gas as zero momentum

    - Until collisions occur or system evaporates through 2/3/4-body encounters (if low N) (Clarke & Bonnell, in prep.)
  - Involves stars still on pre-MS and/or with discs (e.g. Bally & Zinnecker 05; Davies et al. 06; Moeckel & Bally 06, 07; Pfalzner at al. 06; Pfalzner & Olczak 07)
  - Cluster expands/disperses when gas expelled by ionisation due to massive stars or first SNe (e.g. Kroupa et al. 91; Geyer & Burkert 01; Goodwin & Bastian 06; Baumgardt & Kroupa 07)

(Possible) effects of pre-MS structure

- "Shred and add" (Davies et al. 06)
  - Low-M stars (< 5 Msun) tidally disrupted by massive ones
  - Forms a massive disk
  - Disk allows capture of another star (large cross section)
  - Can reduce necessary density to grow 50 Msun star in 1 Myr by factor ~ 10
- Non-monotonous M-R relation might allow non-runaway growth



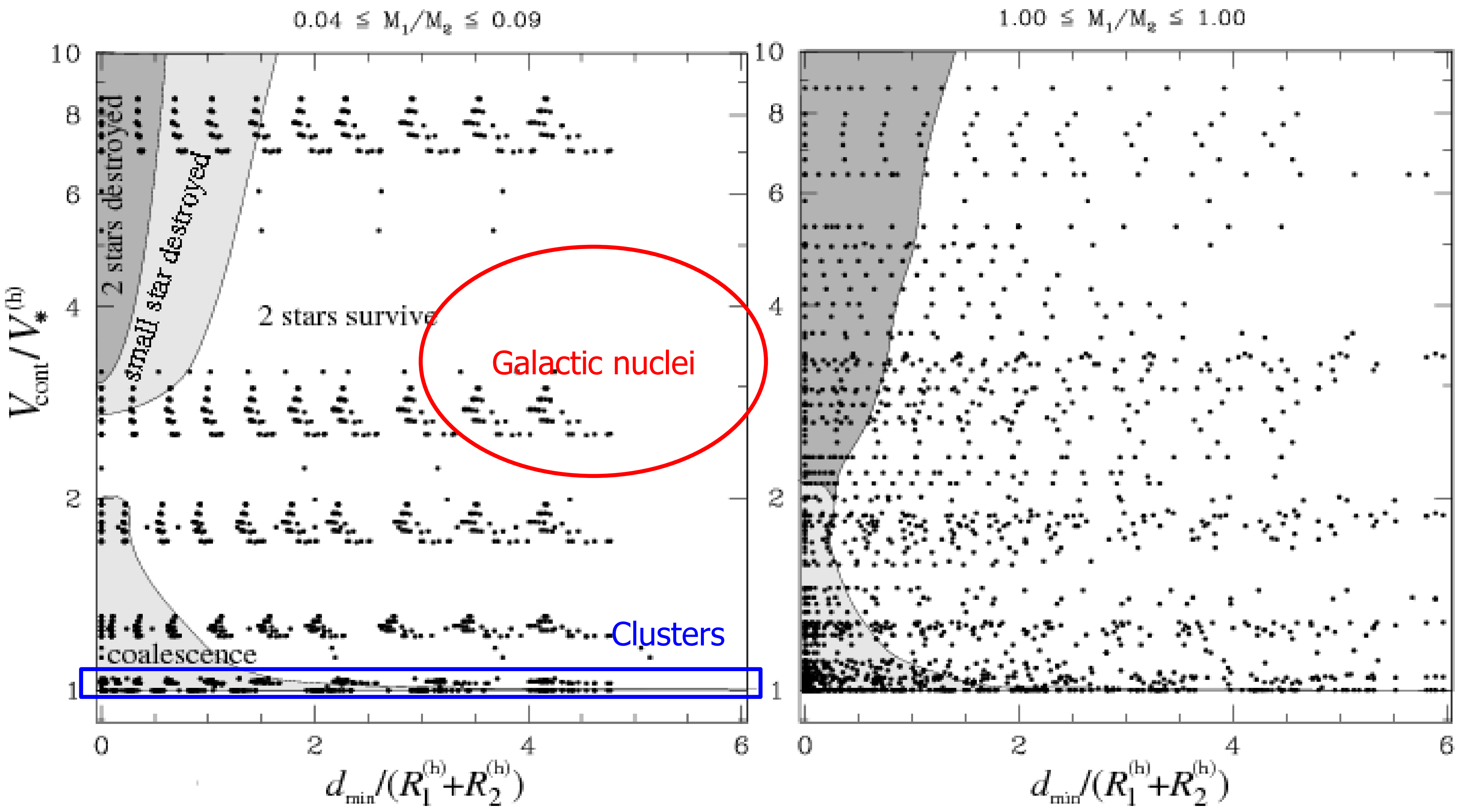
Summary and questions

- Importance of collisions in young clusters: still an open question
  - Complex physics: stellar dynamics, gas accretion and expulsion, cluster substructure, role of pre-MS, disks, binaries
  - Requires very high star density but (maybe) not unrealistically so
    - Density increase driven by mass-segregation and/or gas accretion
    - Cluster naturally re-expands after gas expulsion (or if an IMBH is formed!!)
  - What is the outcome of runaway collisions?
  - How to have non-runaway collisions?
- Do we need mergers to explain massive stars, binarity?
- How to test whether collisions are happening or have happened? (see suggestions by Bally & Zinnecker 05)

Thank you!

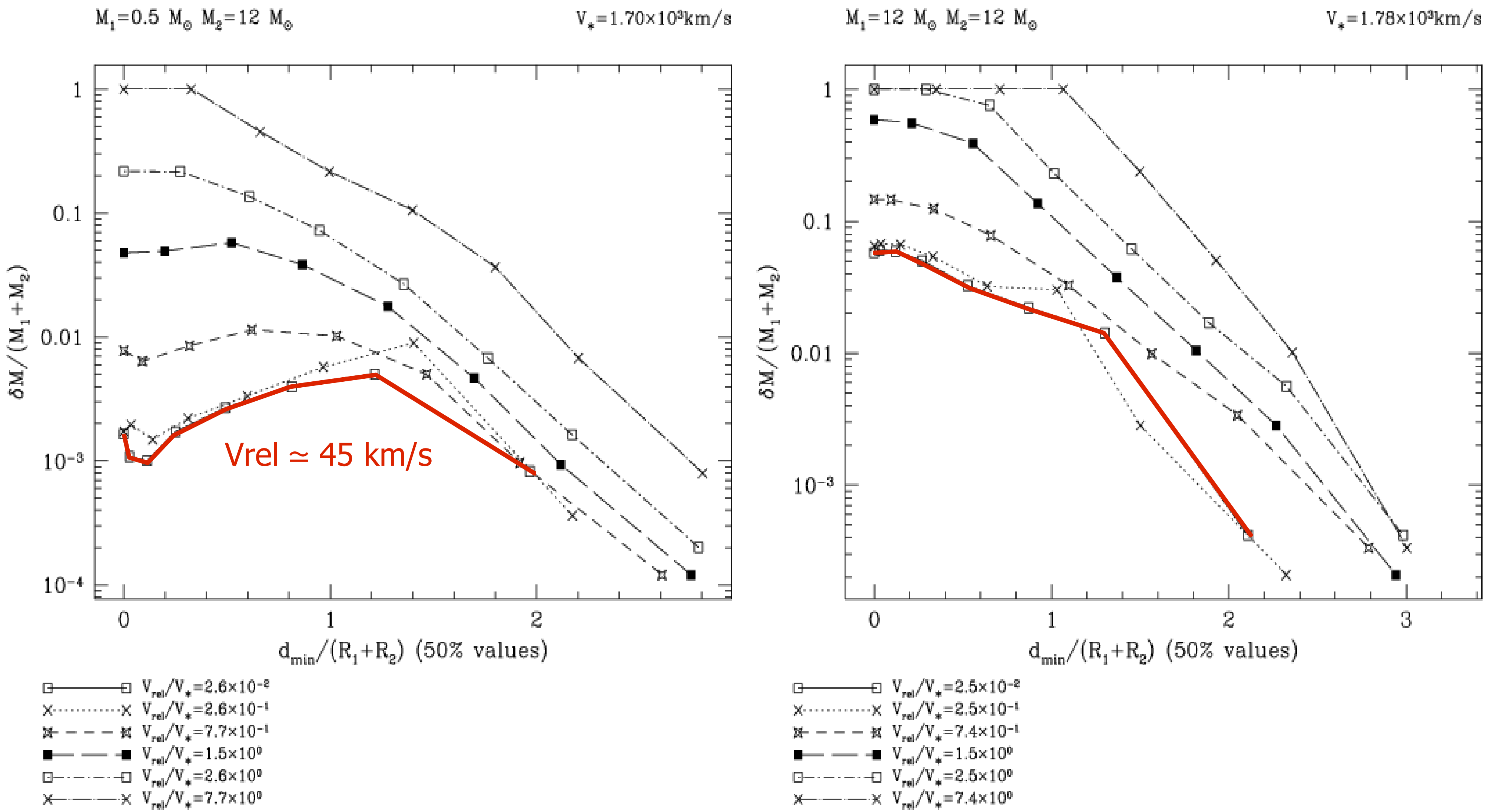
Outcome off MS-MS collisions

Freitag & Benz 01,05



Mass loss in MS-MS collisions

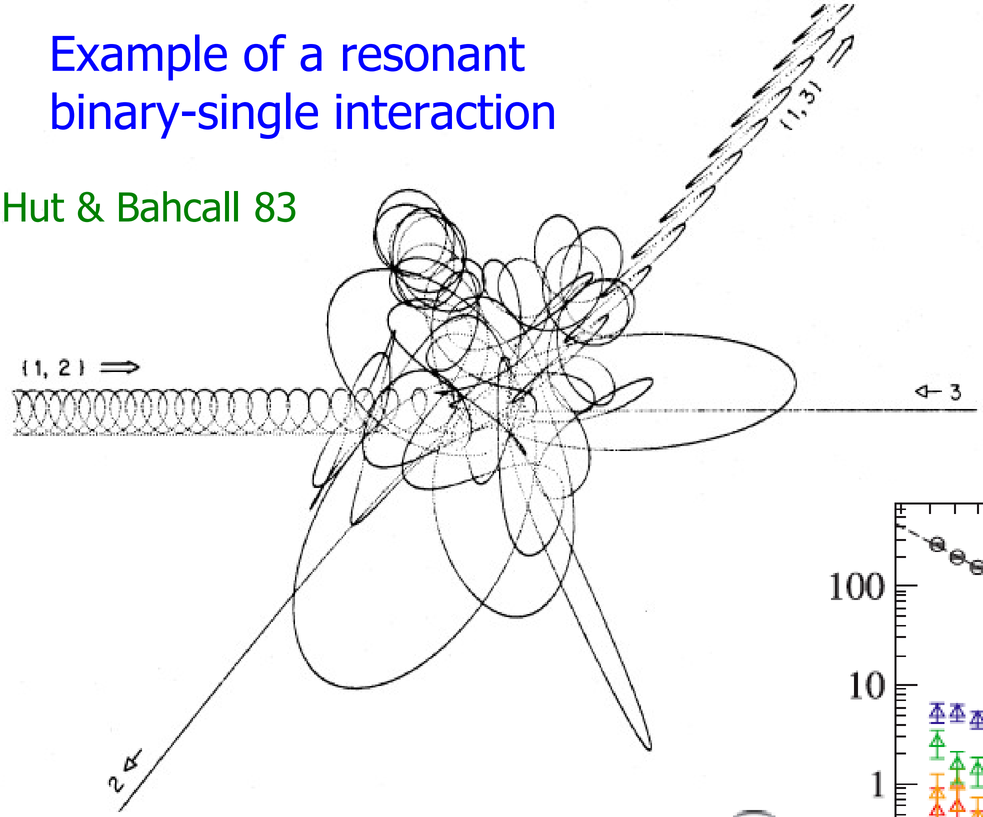
Freitag & Benz 05



Collisions: binary stars

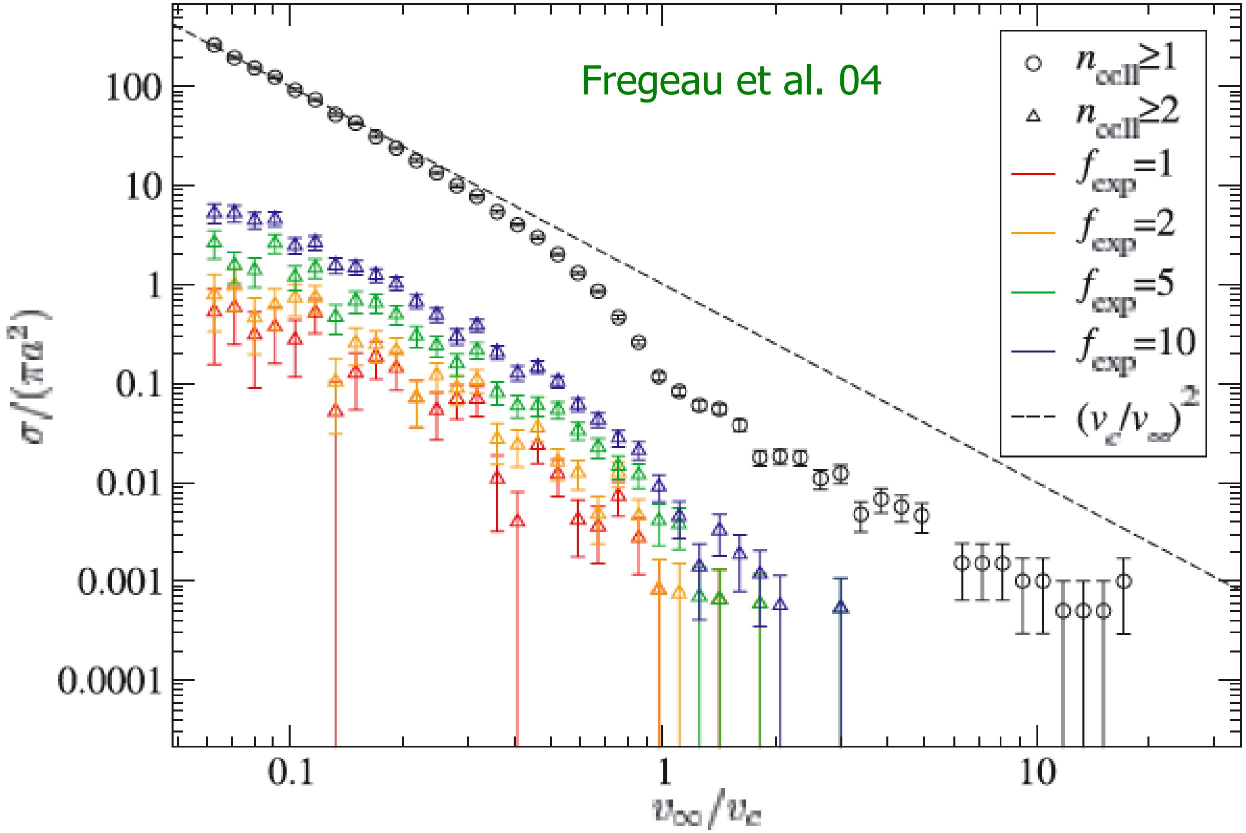
Example of a resonant binary-single interaction

Hut & Bahcall 83



Collision cross section for binary-single
a = 1 AU, $R_{1,2,3}$=1 R_{sun}, $M_{1,2,3}$=1 M_{sun}

Fregeau et al. 04

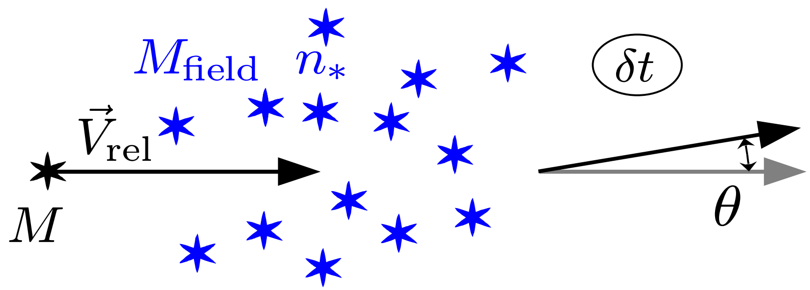


Relaxation time

- 2-body relaxation

  E, J drift and diffusion due to graininess of potential

  - Core collapse
  - Mass segregation



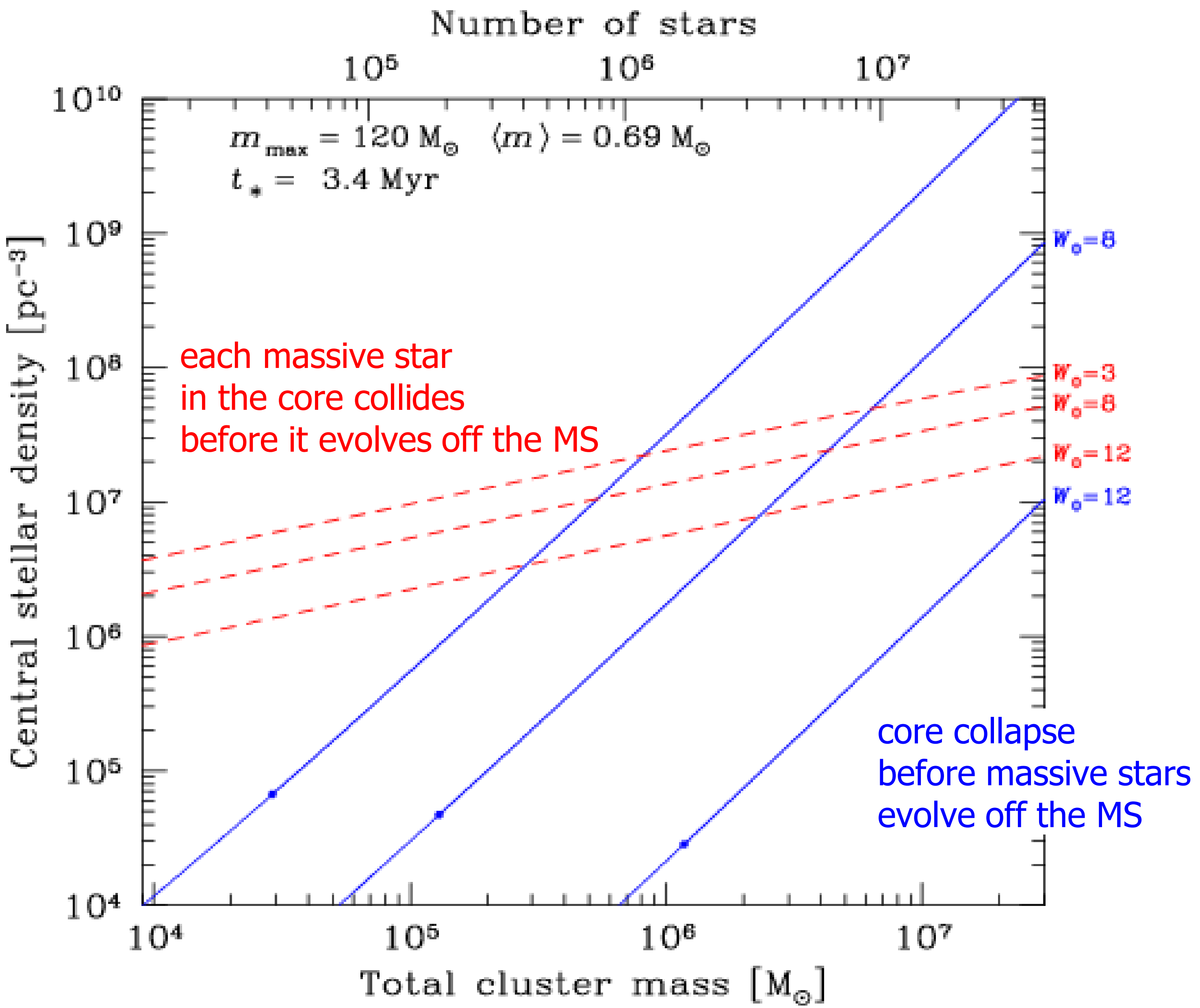
$$\langle \theta \rangle = 0$$
$$\langle \theta^2 \rangle = \left(\frac{\pi}{2}\right)^2 \frac{\delta t}{t_{\rm rlx}}$$

$$t_{\rm rlx}^{-1} = k \ln \gamma N_* \cdot \frac{G^2 M M_{\rm field} n_*}{V_{\rm rel}^3} \approx \frac{\ln \gamma N_*}{N_*} t_{\rm orb}^{-1}$$

$$t_{\rm rlx} \simeq 2 \times 10^6\,{\rm yr}\,\frac{10^6\,{\rm pc}^{-3}}{n_*}\left(\frac{\sigma_v}{10\,{\rm km\,s}^{-1}}\right)^3 \left(\frac{{\rm M}_\odot}{M_*}\right)^2$$

How dense does the cluster need to be?

(for collisions between single stars)



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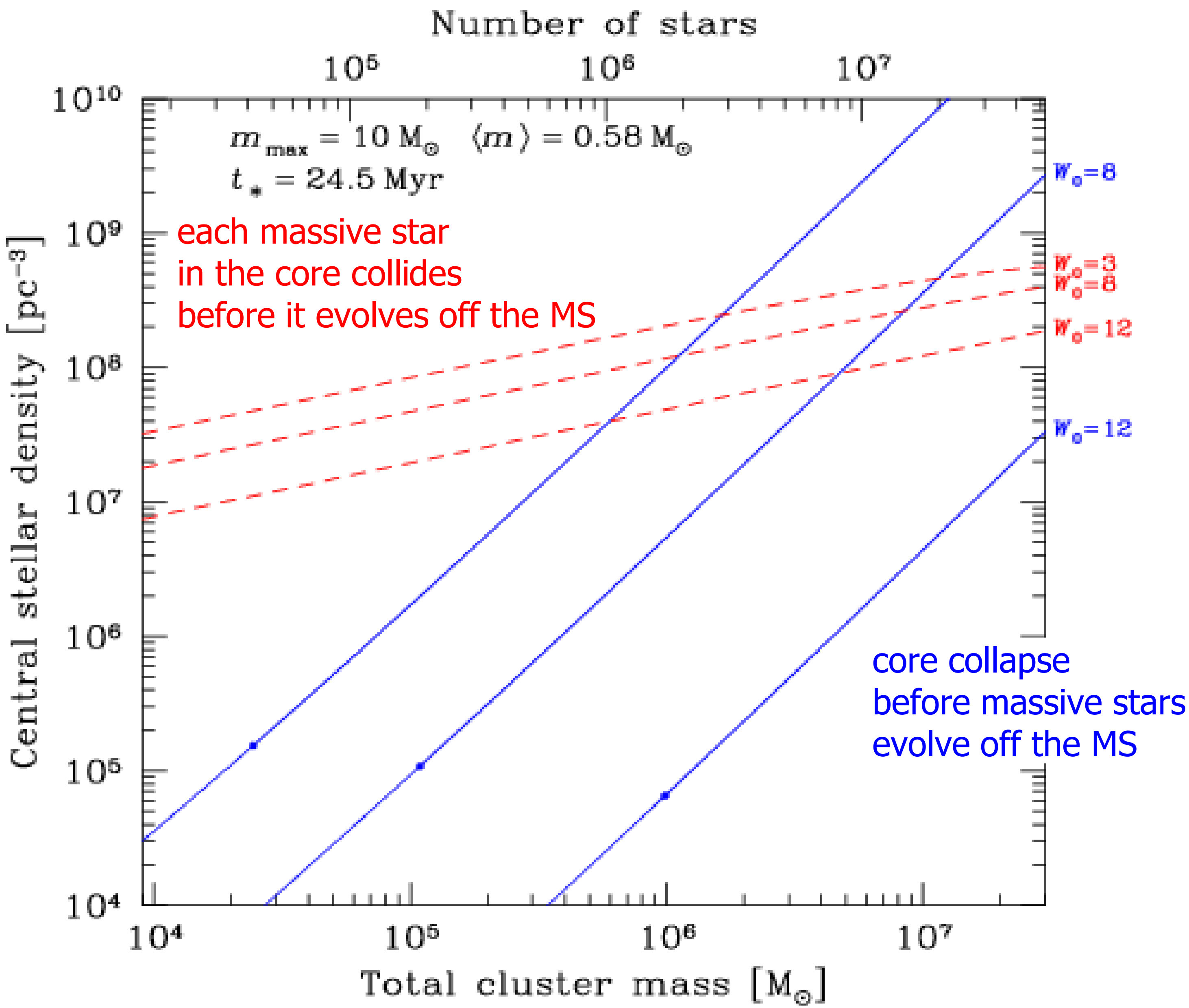


Runaway growth in short t_{cc} clusters

MC simulations with *N* =3x10⁵-9x10⁶

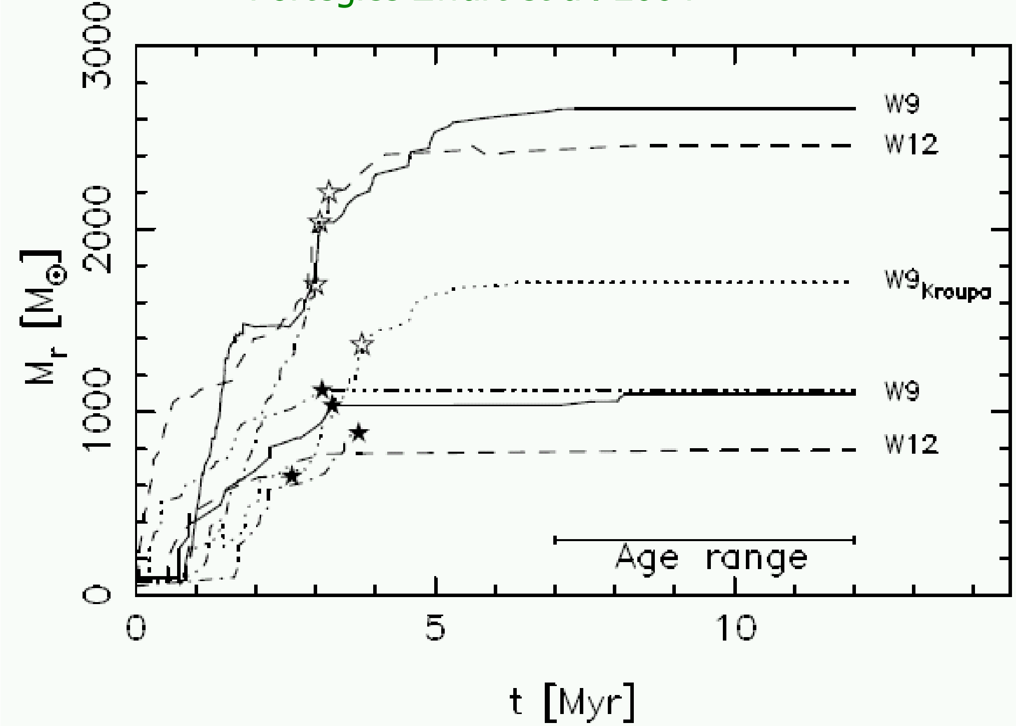
Freitag et al. 2006b

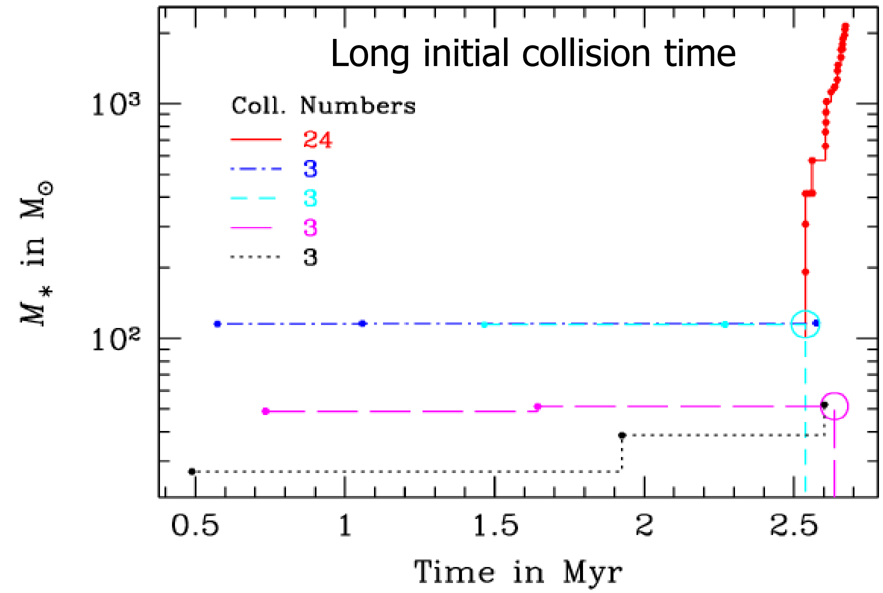
❢ no binaries

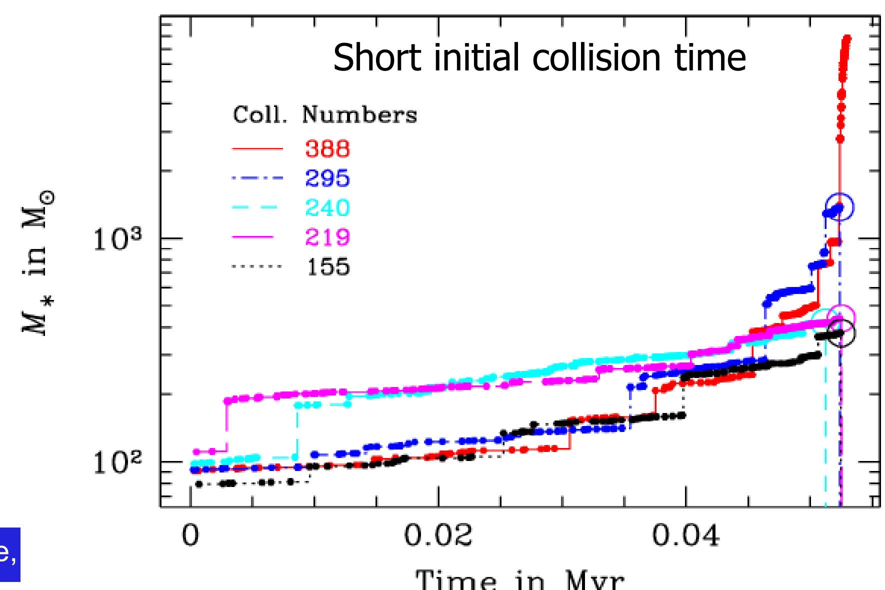
☺ “realistic” coll.

N-body simulations with *N* =1.3-5.9x10⁵

Portegies Zwart et al. 2004



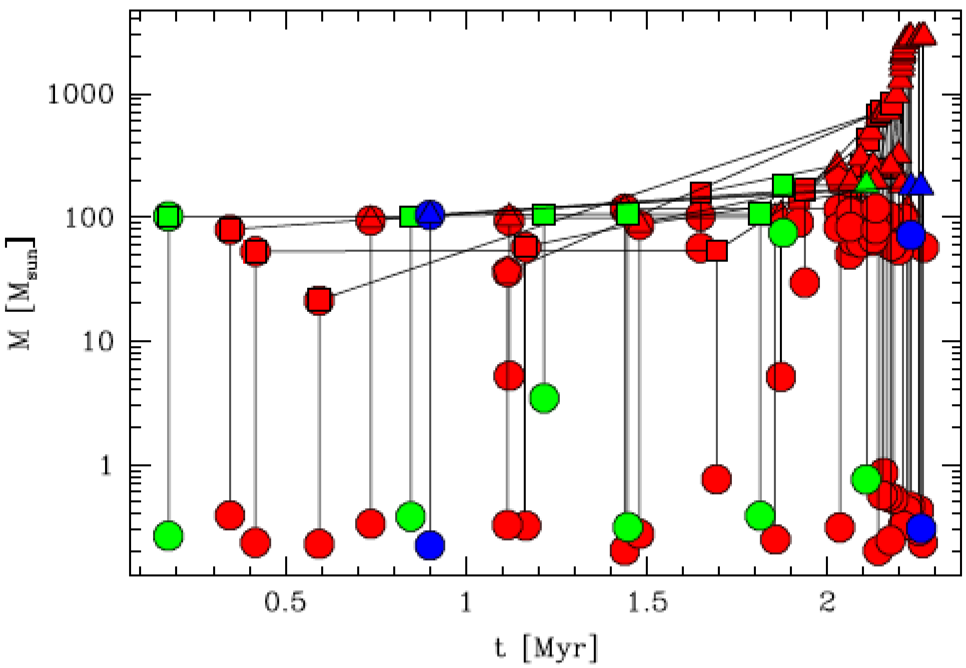




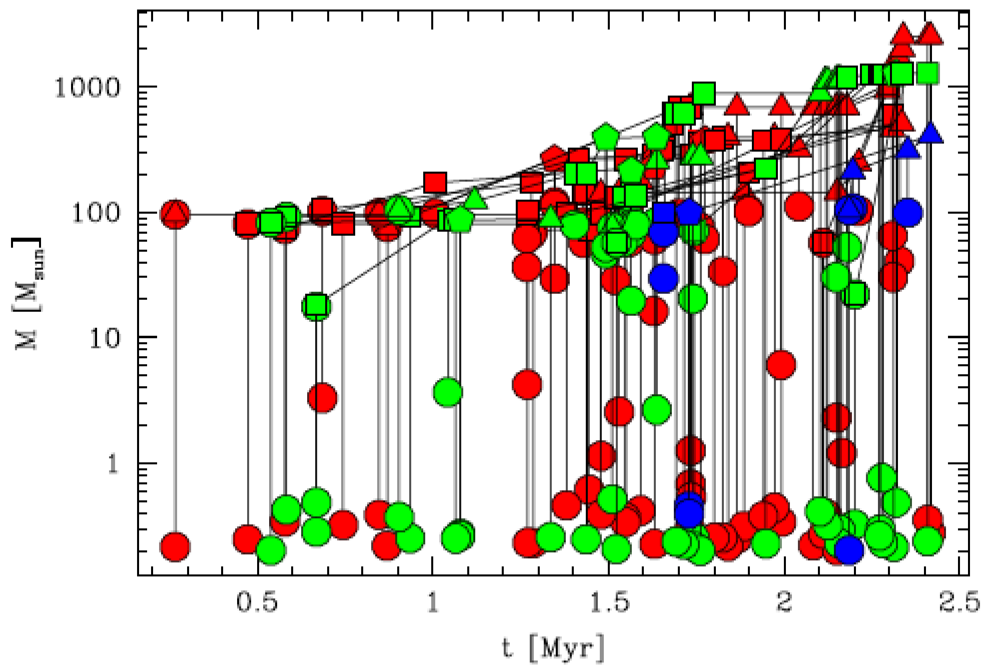
Double runaway?

Gürkan, Fregeau & Rasio 2006

5% of primordial binaries

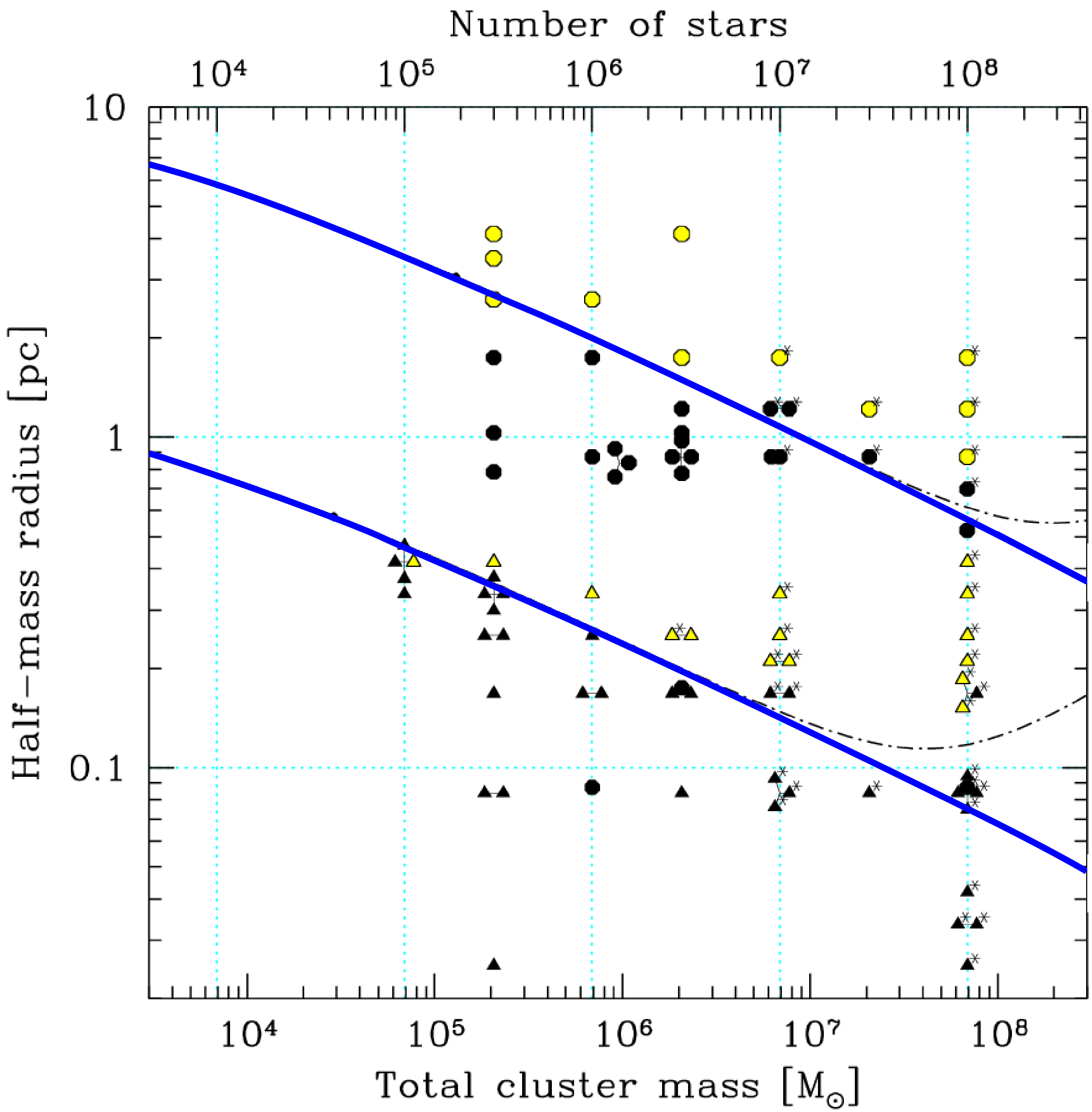


10% of primordial binaries



Possibility of forming a binary "very massive object"!

Conditions for runaway collisions



Freitag et al. 2006b

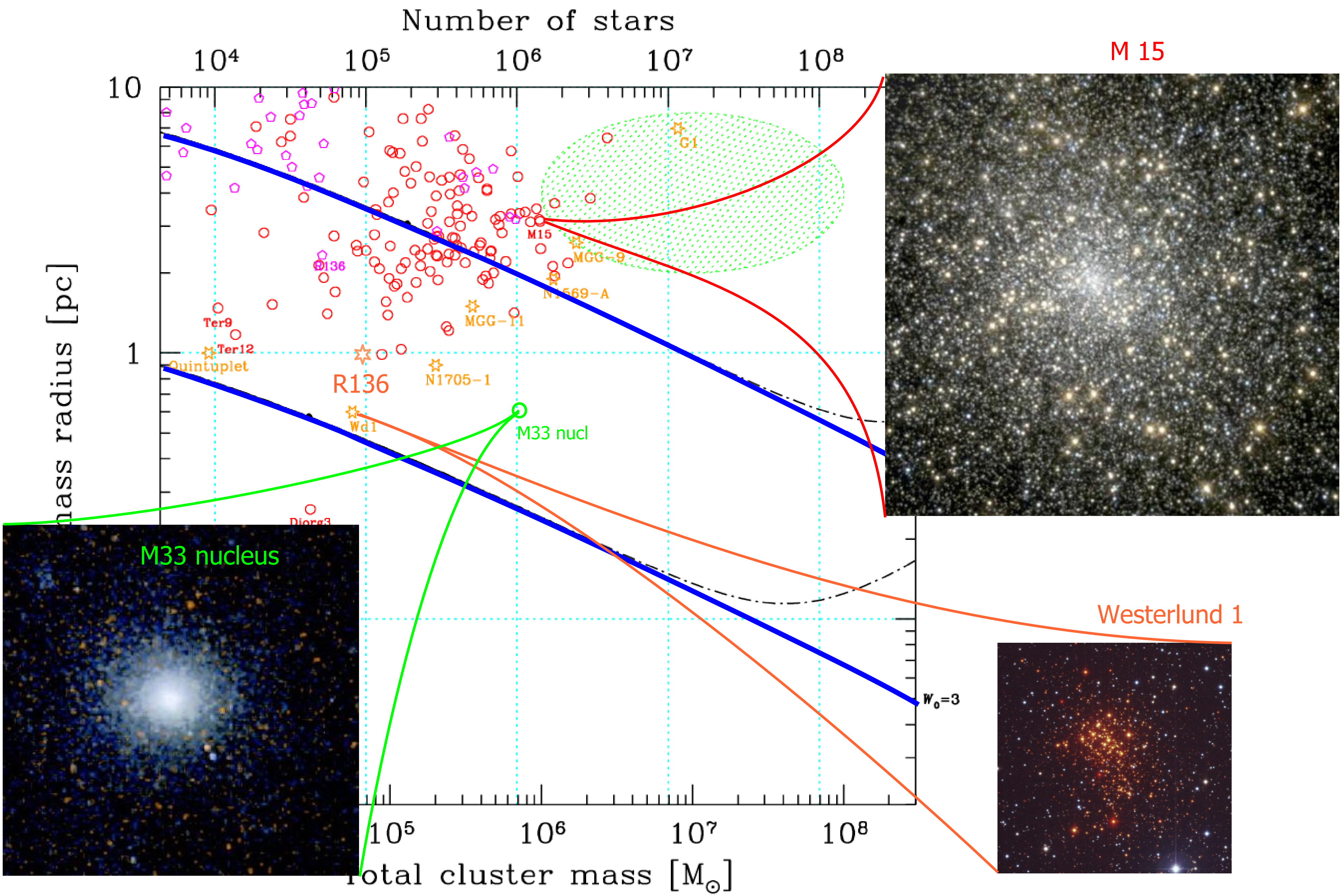
MC simulation results

- W_0=8 no runaway
- W_0=8 runaway
- W_0=3 no runaway
- W_0=3 runaway

$t_{\rm cc,rlx} = 0.12\, t_{\rm rc}(0) = 3\,{\rm Myr}$

Time scale
for evolution
of massive stars

Conditions for runaway conditions

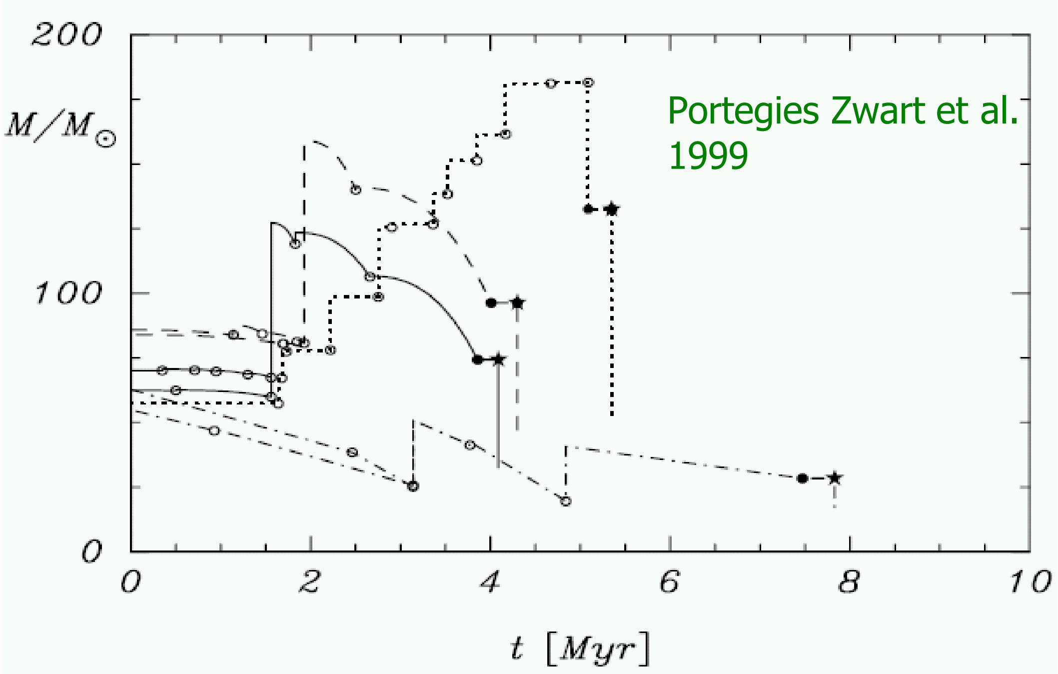


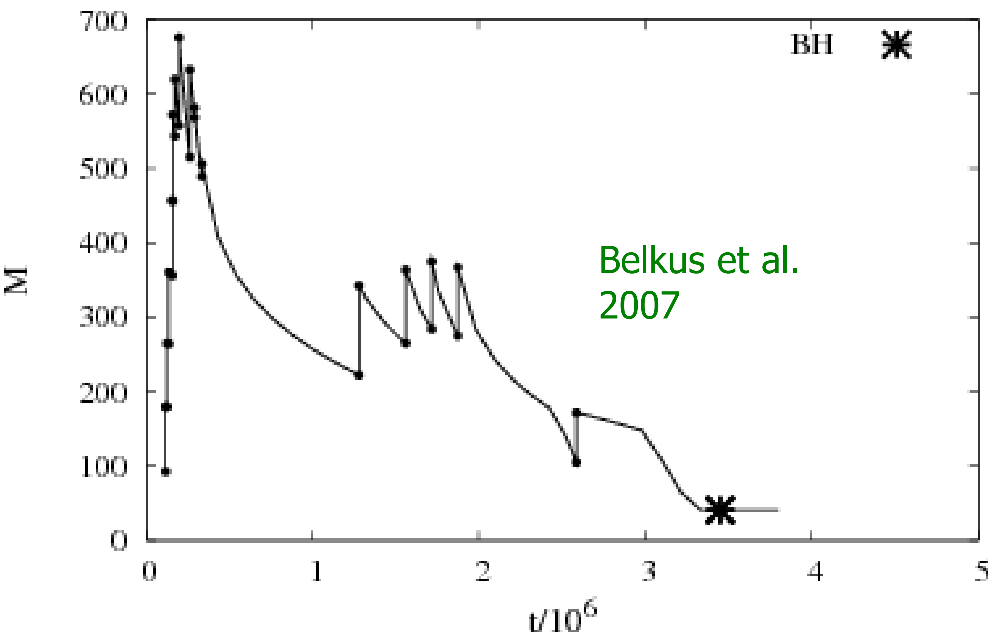
Criticisms of core collapse scenario (in the context of massive star formation)

- Only a (small?) fraction of clusters might have short t_{cc}
  - Needs a broad IMF to begin with
  - N-body simulations indicate more restrictive condition for N<few x 10^5 (Portegies Zwart et al. 04)
- Not a continuous mass spectrum, but 1 or 2 very massive stars
  - No strong observational evidence for VMSs.
    - Pistol star?
    - Intermediate-mass black holes?
  - VMS growth may maybe prevented by several processes
    - "Normal" stellar mass loss (Portegies Zwart et al. 99; Belkus et al. 07)
    - Transparency to impactors if VMS is bloated (Colgate 67)
    - Multicore evolution (Dale & Davies 06)

Forming a very massive star? Role of stellar mass loss

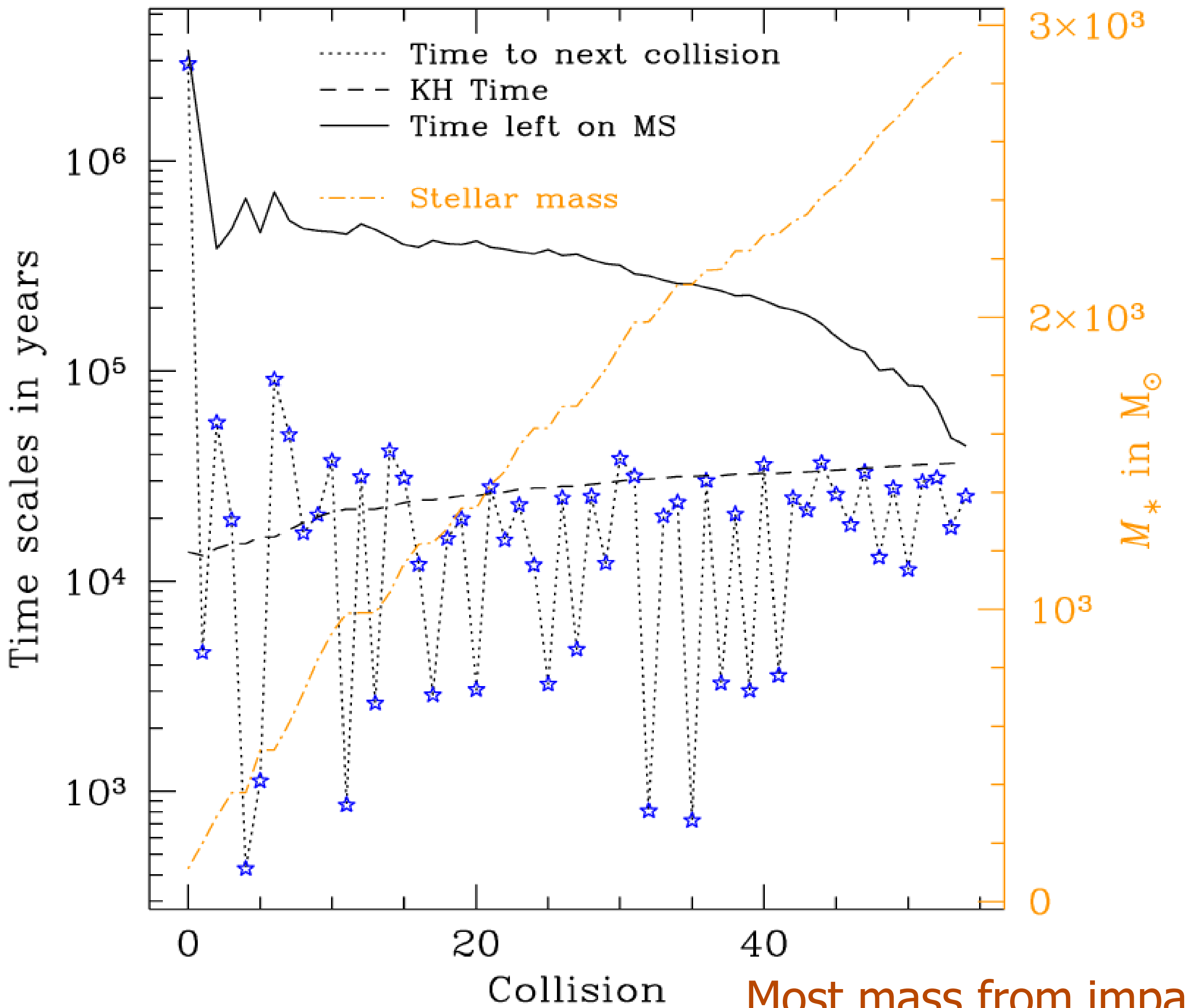
- Competition between collisional gain and mass loss
  - Average growth rate during runaway 10^{-3}-0.1 $M_\odot$/yr
  - Loss rate unknown but may be large as star is big and luminous
  - Losses may win when collision frequency decreases
  - Can collisions suspend stellar evolution?





Runaway timescales

Long initial collision time



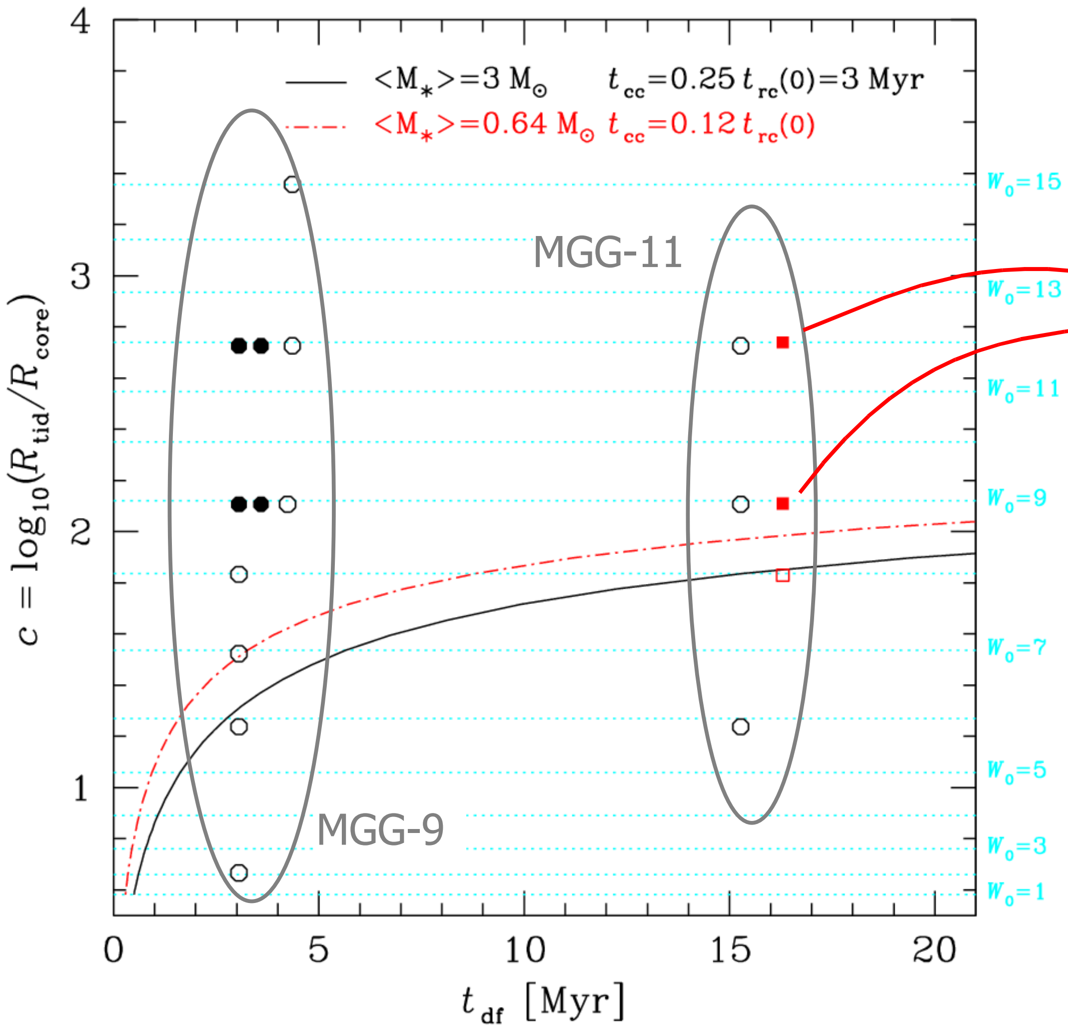
Freitag et al. 2006b

Most mass from impactors with $M_* > 70\ M_\odot$

Runaway star probably out of thermal equilibrium

Conditions for runaway: N-body vs MC

Portegies Zwart et al. 2004: Models for M82 clusters



- MGG-9 too small for MC simulations!
- MGG-11 MC models with large star number show runaway for $W_0 > 8$
- Role of binaries?

Condition for runaway growth

- Simple mathematical model (based on coagulation eqn.)
  (e.g. Lee 93, 00; Malyshkin & Goodman 01)
  - Start with particles of identical mass in a homogeneous "box"
  - Assume "sticky spheres"
  - Assume cross section for merger

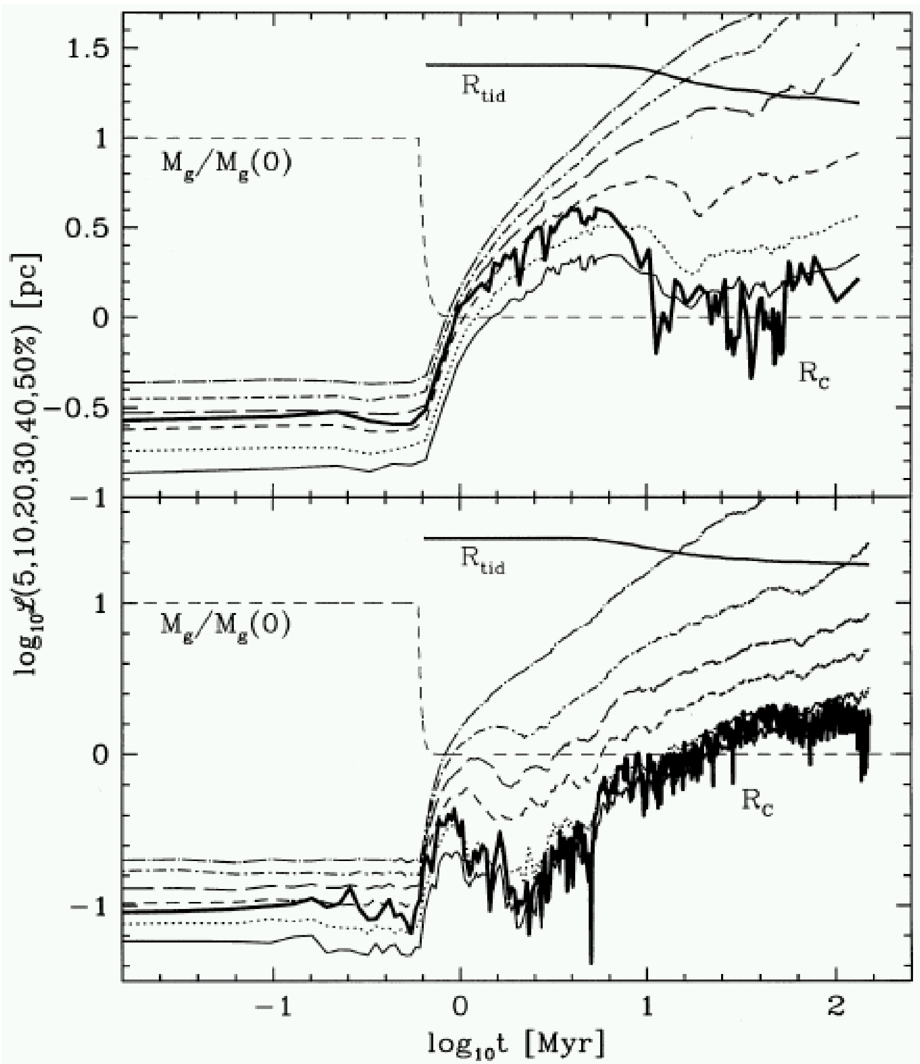
$$S_{\mathrm{coll}}(M, m) \propto M^{\nu} \quad \text{for} \quad M > m$$

Then

$$\frac{M_{\max}}{M_{\mathrm{next}}} \to \infty \quad \text{if} \quad \nu > 1$$

  - With gravitational focusing $\nu \simeq 1 + \beta$ if $R_* \propto M_*^{\beta}$

Runaway stopped by gas expulsion?



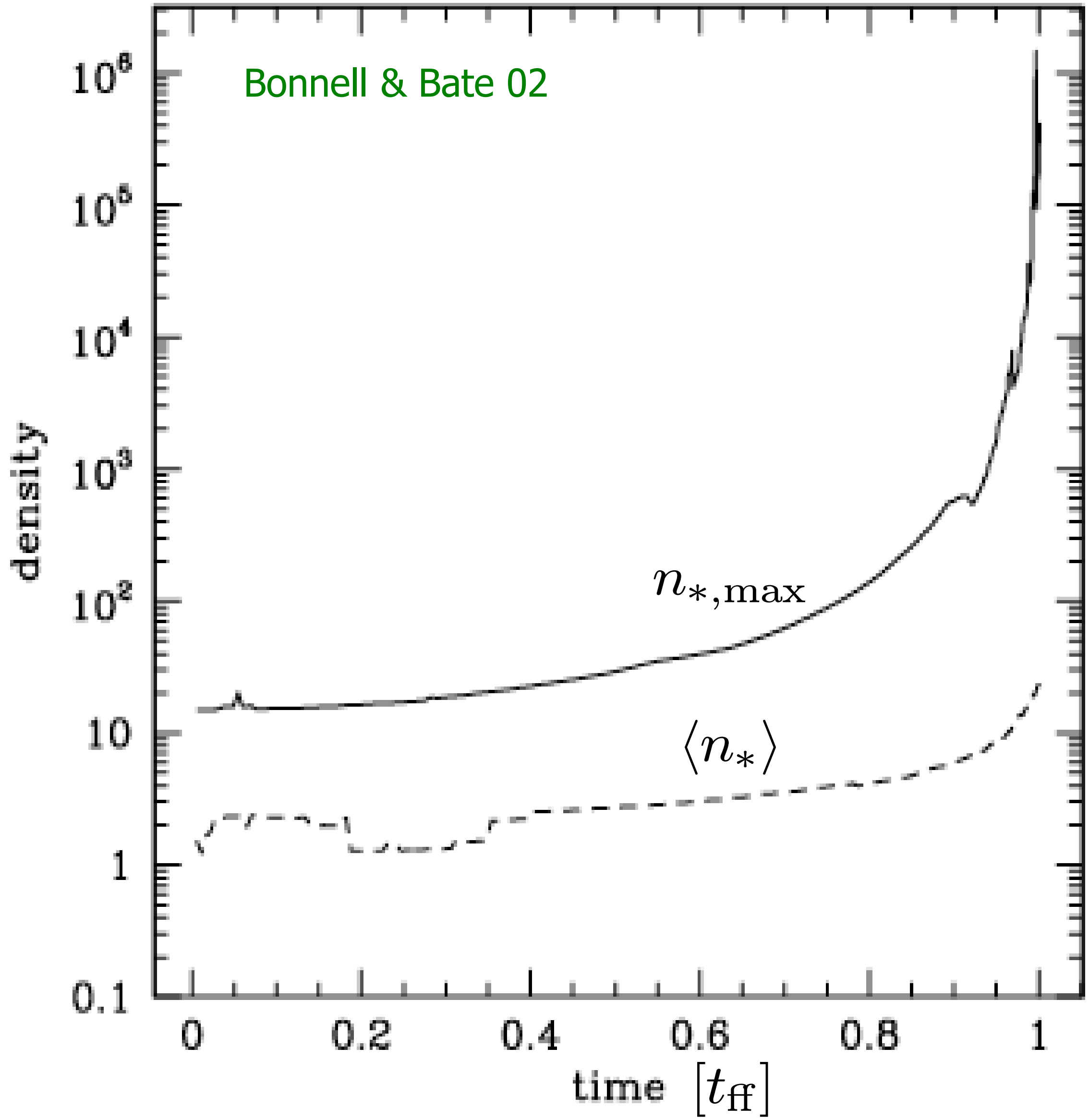
N-body simulation by Kroupa et al. 91

- Young clusters already devoid of gas at ~1-2 Myr
  - Less time for core collapse & runaway
- Most clusters disrupted by mass loss
  - Explains cluster-less ULXs (if runaway forms IMBH) ?
- Surviving clusters X (≈3-10) times more massive when embedded, Y (≈10) smaller
  - Relaxation time $Y^{3/2}X^{-1/2}$ times shorter => easier core collapse

Should consider dynamical evolution of embedded clusters!

Stellar density increase due to gas accretion

SPH simulation with 1000 accreting "stars"



Collisional growth of massive stars in very young cluster