Super star cluster R136: puzzles outside and inside

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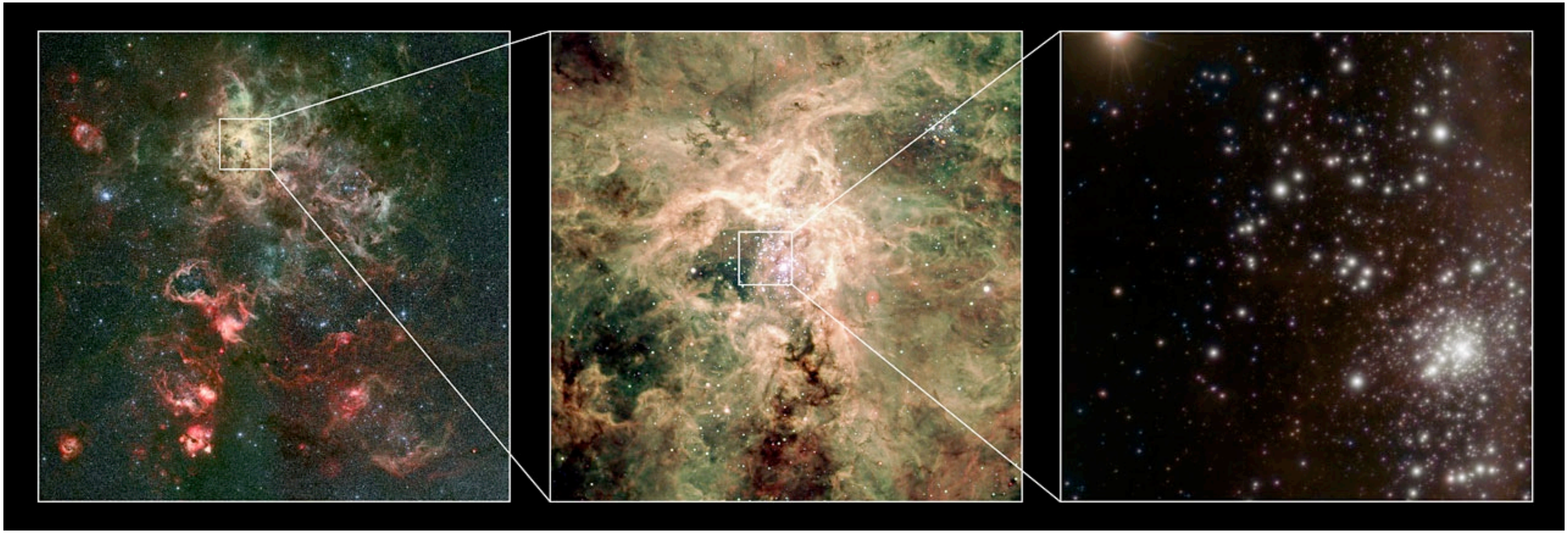
Super-cluster R136: a magnificent gallery of massive stars



30 Doradus (Tarantula Nebula) and R136 cluster in the LMC. Image credit: ESO

Puzzle outside:

- Speeding massive stars (e.g. 30 Dor 016)
- "Slow runaway"s / isolated massive star formation? (e.g. VFTS 682)

Puzzle inside:

- "Monster star"s: most massive star discovered so far! (M $\approx 300M_\odot$)
- R136 in virial equilibrium. No gas expulsion?

Runaway massive stars from R136

Puzzle outside: "slow runaway" star VFTS 682

Image Credit: ESO/VISTA Magellanic Cloud survey

VFTS 682 estimates

Present day mass: $150 M_\odot$

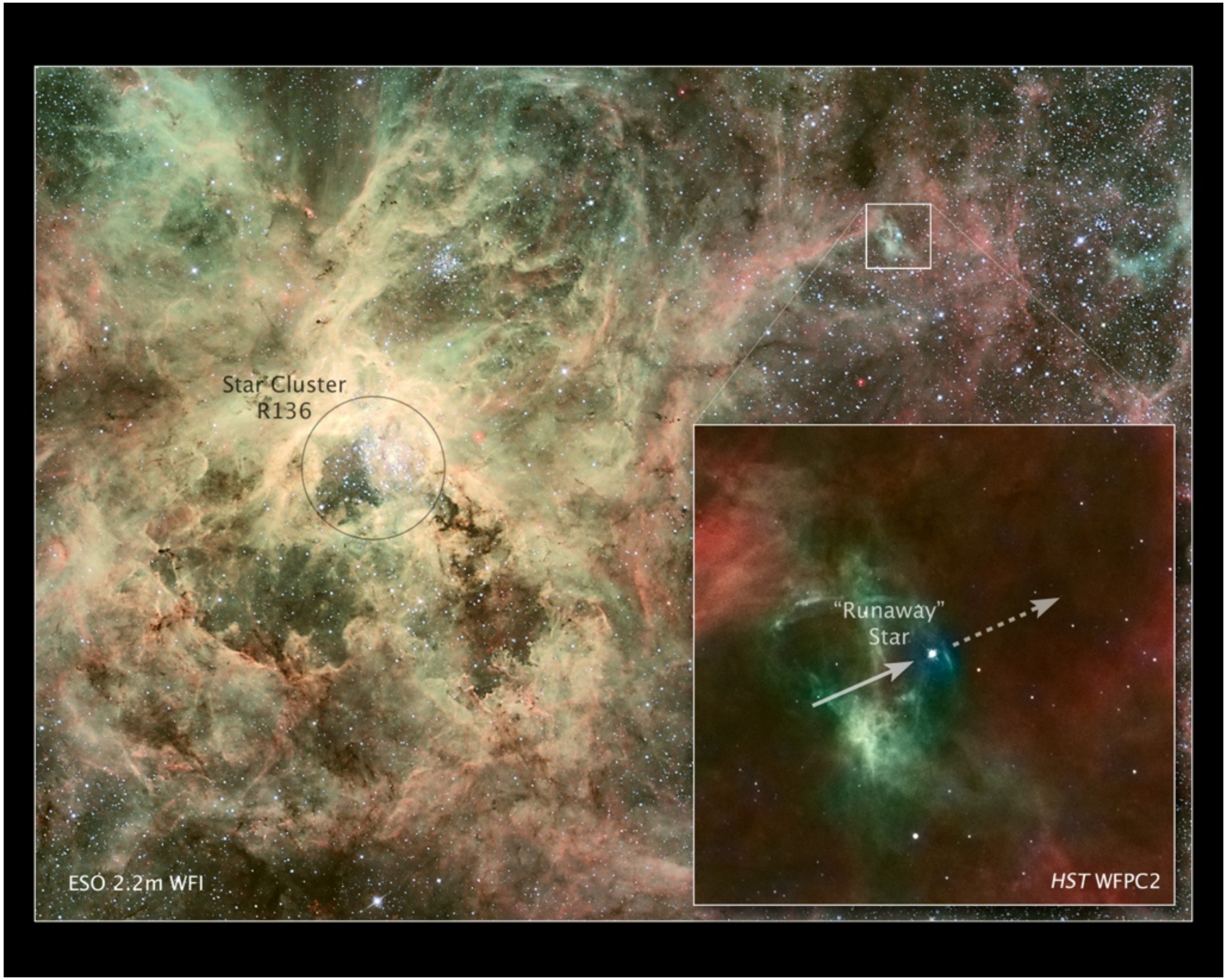
Projected distance: $30\ \mathrm{pc}$

3D velocity: $40\ \mathrm{km\ S}^{-1}$

(Bestenlehner et al. 2011)

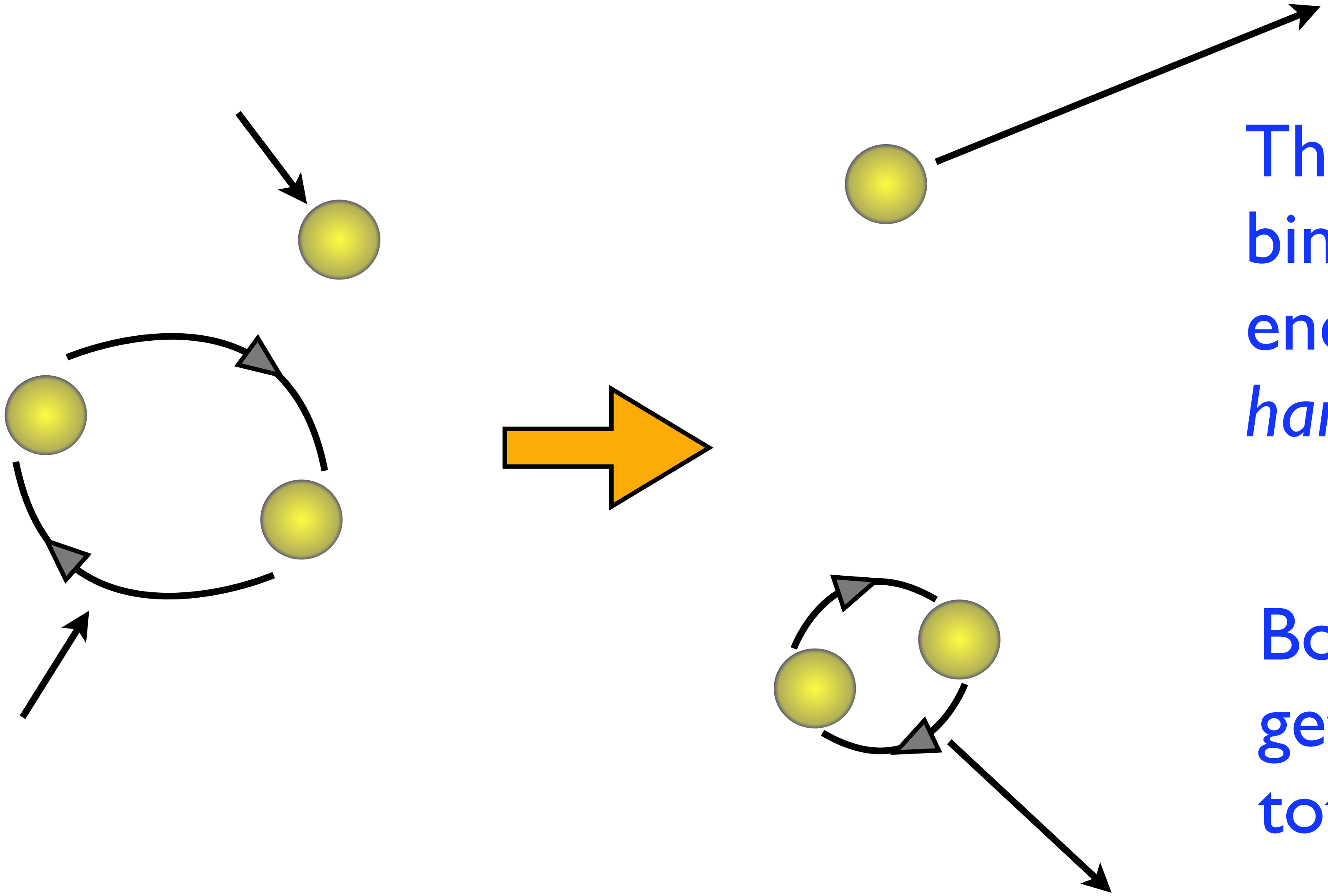
No bow-shock detected

Another runaway: 30 Dor 016



Estimates: PD mass $90 M_{\odot}$; projected distance 120 pc; velocity (3D) 150 km S^{-1} (Evans et al. 2010, ApJ, 715, L74)

"Super-elastic" encounter



The most likely result of a binary---single-star close encounter: *hard binary hardens* (Heggie's law)

Both intruder star & binary get recoiled with larger total K.E.

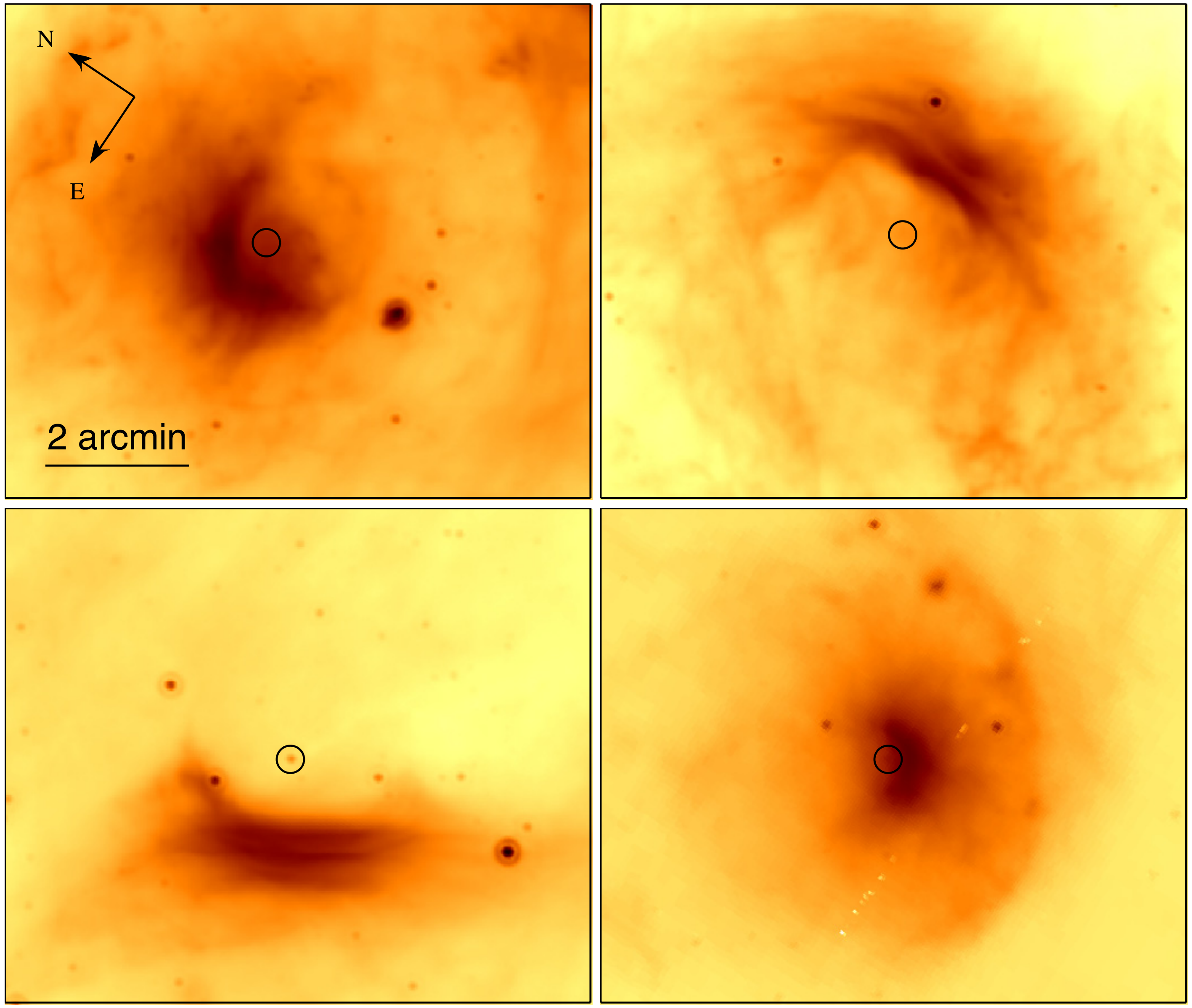
Hard binary $\Rightarrow$ energy source

Launches runaway stars

Image not to scale

Runaway OB stars

- Fast-moving Galactic-field OB stars that apparently are unrelated to any stellar assembly
- Majority of them (with known proper motions) can be traced back to a parent star cluster (e.g. Schilbach & Röser, 2008)
- Also detectable by imaging their 'bow-shocks' (Gvaramadze et al. 2010, 2011)



From Gvaramadze et al., 2011, A&A, 535, A29

Runaway OB stars are widely believed to be former members of star clusters that received high ejection velocities in dynamical encounters

Puzzle outside: "slow runaway" star VFTS 682

Image Credit: ESO/VISTA Magellanic Cloud survey

VFTS 682 estimates

Present day mass: $150 M_{\odot}$

Projected distance: 30 pc

3D velocity: 40 km S^{-1}

(Bestenlehner et al. 2011)

No bow-shock detected

VFTS 682: "Slow runaway" from R136
or
massive star formed alone?

Modeling R136's evolution using direct N-body integration

- Initially Plummer cluster of $M_{cl}(0) \approx 10^5 M_\odot$ (upper mass limit of R136)
- Initial half-mass radius $r_h(0) \approx 0.8$ pc (core radius $r_c \lesssim 0.3$ pc observed upper limit; Mackey & Gilmore 2003)
- Canonical IMF over $0.08 M_\odot < m_s < 150 M_\odot$ and metallicity appropriate for LMC ($Z = 0.5 Z_\odot$)
- Primordial binary distribution truncated at $m_s = 5 M_\odot$
- Synthetic stellar & binary evolution by Hurley et al. (2000, 2002)
- Complete primordial mass segregation
- Star by star N-body integration (4 models) using state-of-the-art "NBODY6" integrator aided by GPU hardware acceleration (Nitadori & Aarseth 2012)

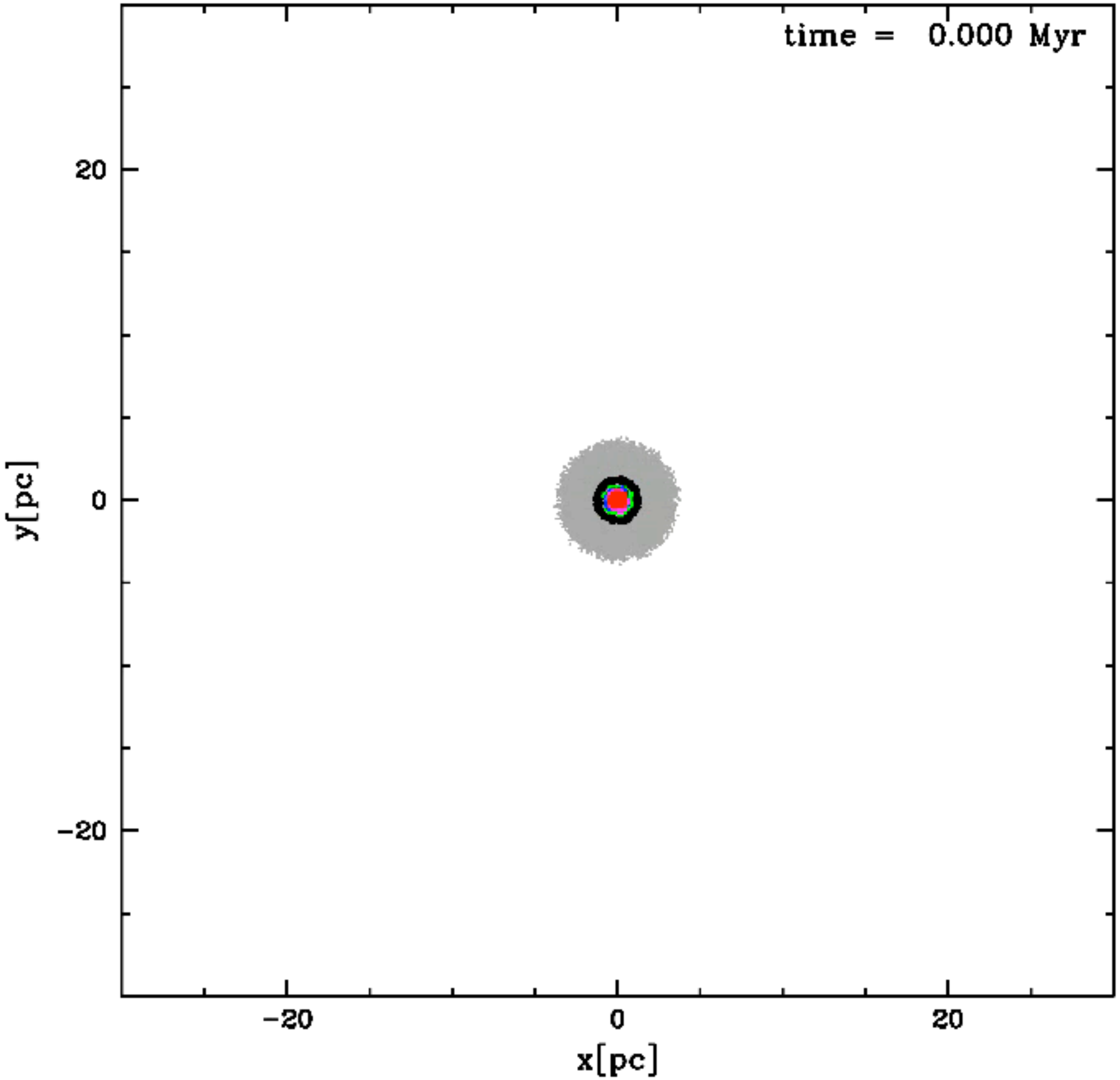
Model R136: primordial binaries constrained by observations

- $m_s > 5M_\odot$ all initially in binaries, rest initially single. Truncation for computational ease; direct integration of $N \approx 1.7 \times 10^5$ system with 100% primordial binaries computationally prohibitive (regularized binary orbits not yet parallelized or accelerated)
- For $m_s > 20M_\odot$ primary, uniform period distribution over $0.5 < \log_{10} P(\mathrm{~day}) < 4$ (Sana & Evans 2011)
- For $m_s < 20M_\odot$, Kroupa (1995) birth period distribution (without pre-main-sequence evolution) over $1.0 < \log_{10} P < 8.43$

Binary energy dist.

- Ordered pairing, thermal eccentricity distribution
- All binaries completely mass-segregated initially
- As such biggest direct N-body simulations so far with *realistic* (and messy) *initial conditions* (tight, massive, segregated primordial binaries)!!

R136 model computation



$0.08M_\odot \le m_s \le 1.0M_\odot$

$1.0M_\odot < m_s \le 5.0M_\odot$

$5.0M_\odot < m_s \le 17.5M_\odot$

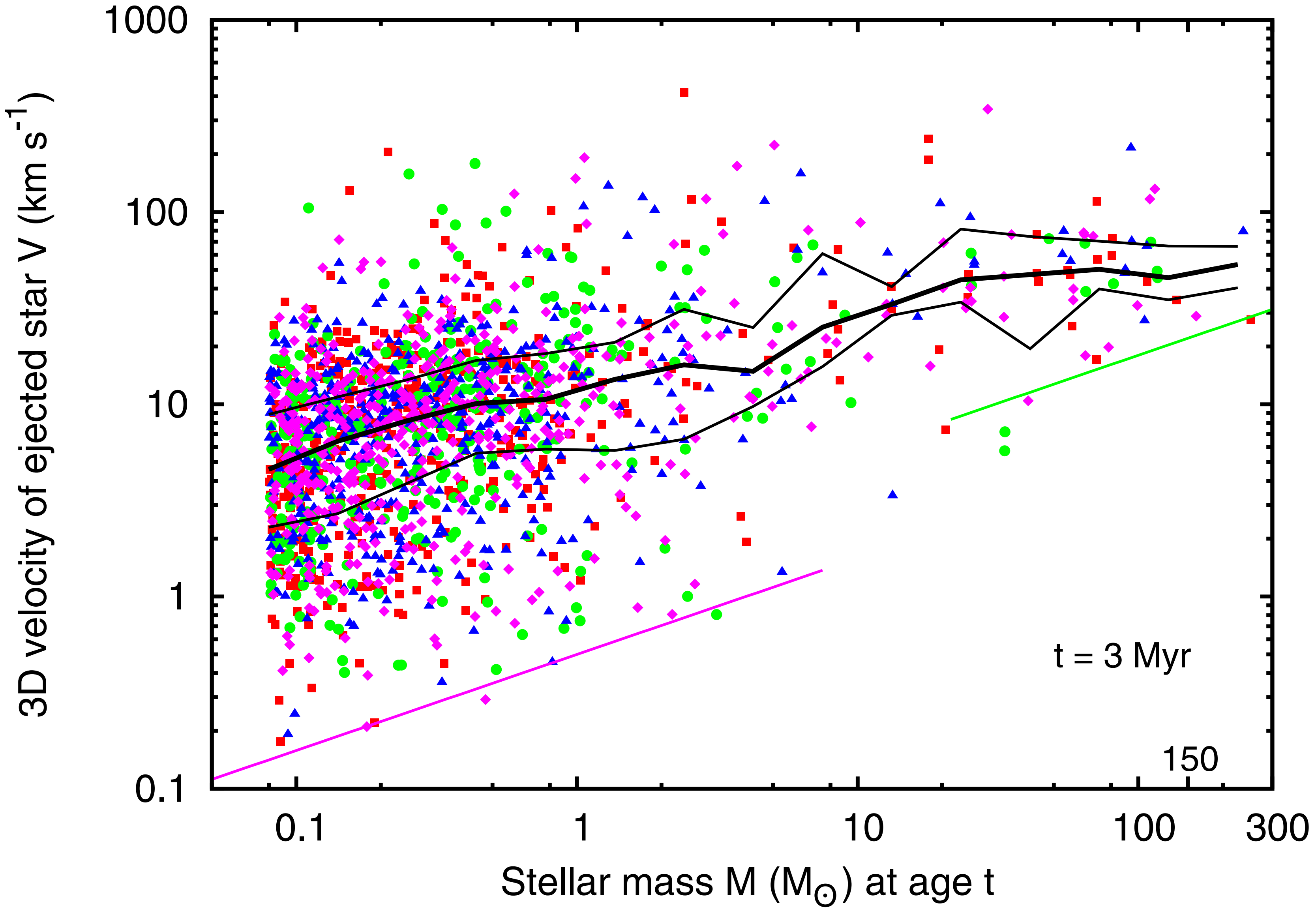
$17.5M_\odot < m_s \le 50.0M_\odot$

$50.0M_\odot < m_s \le 100.0M_\odot$

$100.0M_\odot < m_s$

Movie credit: Seungkyung Oh

Mass dep.



Ejected stars of all masses vs. their 3D velocity (from all 4 simulations):

(a) lower boundary of scatter in V increases moderately with M; $V \propto M^{1/2}$

(b) upper boundary is nearly independent of M

(c) mean $V \rightarrow\approx 50\ \mathrm{km\ S}^{-1}$ quartiles $40 - 60\ \mathrm{km\ S}^{-1}$ for largest M; "slow runaway"!

Note: largest recorded $V \approx 300\ \mathrm{km\ S}^{-1}$

VFTS 682-like slow runaways from computations

Model Number	Time t (Myr)	Mass M ($M_\odot$)	Distance R (pc)	Velocity V (km s^{-1})
1	2.8	256.4	31.9	27.5
	3.2	135.9	26.6	34.8
2	2.6	126.4	27.7	45.7
	2.6	125.9	29.9	49.4
3	2.6	106.9	45.7	27.3
4	1.9	169.1	29.3	29.0
	1.9	116.9	35.2	32.8
VFTS 682	$<$3.0	$\approx$150.0	$\approx$30.0	$\approx$40.0

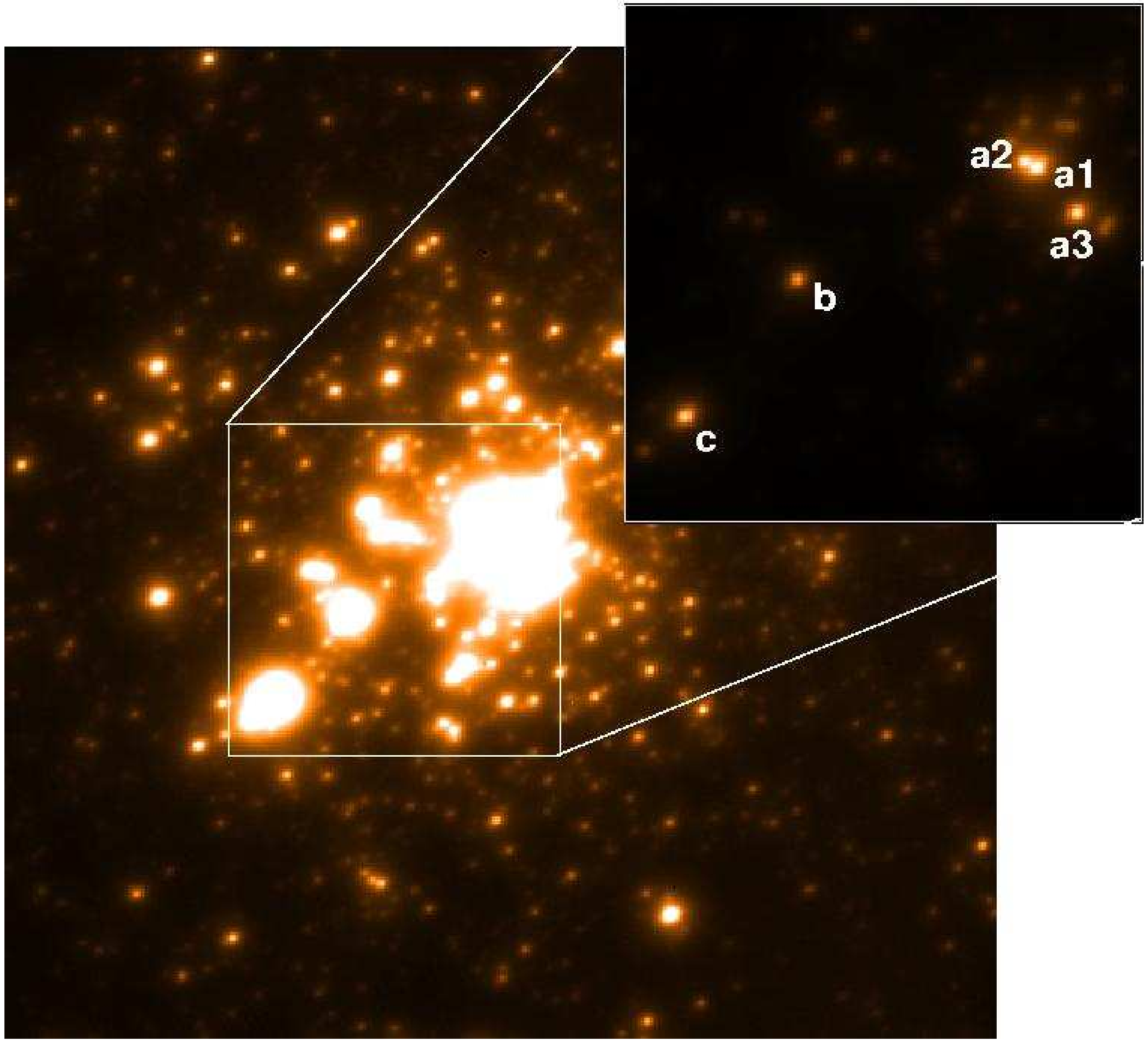
Runaway single stars from computed models matching well with VFTS 682

VFTS 682-like "slow runaway" VMS is common from R136-like cluster $\Rightarrow$ *isolated formation scenario unnecessary* !

Banerjee, S., Kroupa, P. & Oh, S. 2012, ApJ, 746, 15

“Super-canonical” stars in R136

Observation of "super-canonical" stars in R136



VLT IR (Ks) image of central 3 X 3 pc of R136 (inset 1 X 1 pc) showing the "super-canonical" single stars 'a1', 'a2', 'a3' ('c' possibly a binary)

"R136 hosts several stars whose individual masses greatly exceed the accepted $\approx 150 M_{\odot}$ stellar mass limit" - Crowther et al., 2010, MNRAS, 408, 731.

Super-canonical stars $\Rightarrow$

stars with initial masses exceeding the widely accepted $\approx 150 M_{\odot}$ upper limit of stellar IMF.

How do super-canonical stars appear in R136 ?

Primordial formation via star formation process violating canonical $150 M_\odot$ upper limit

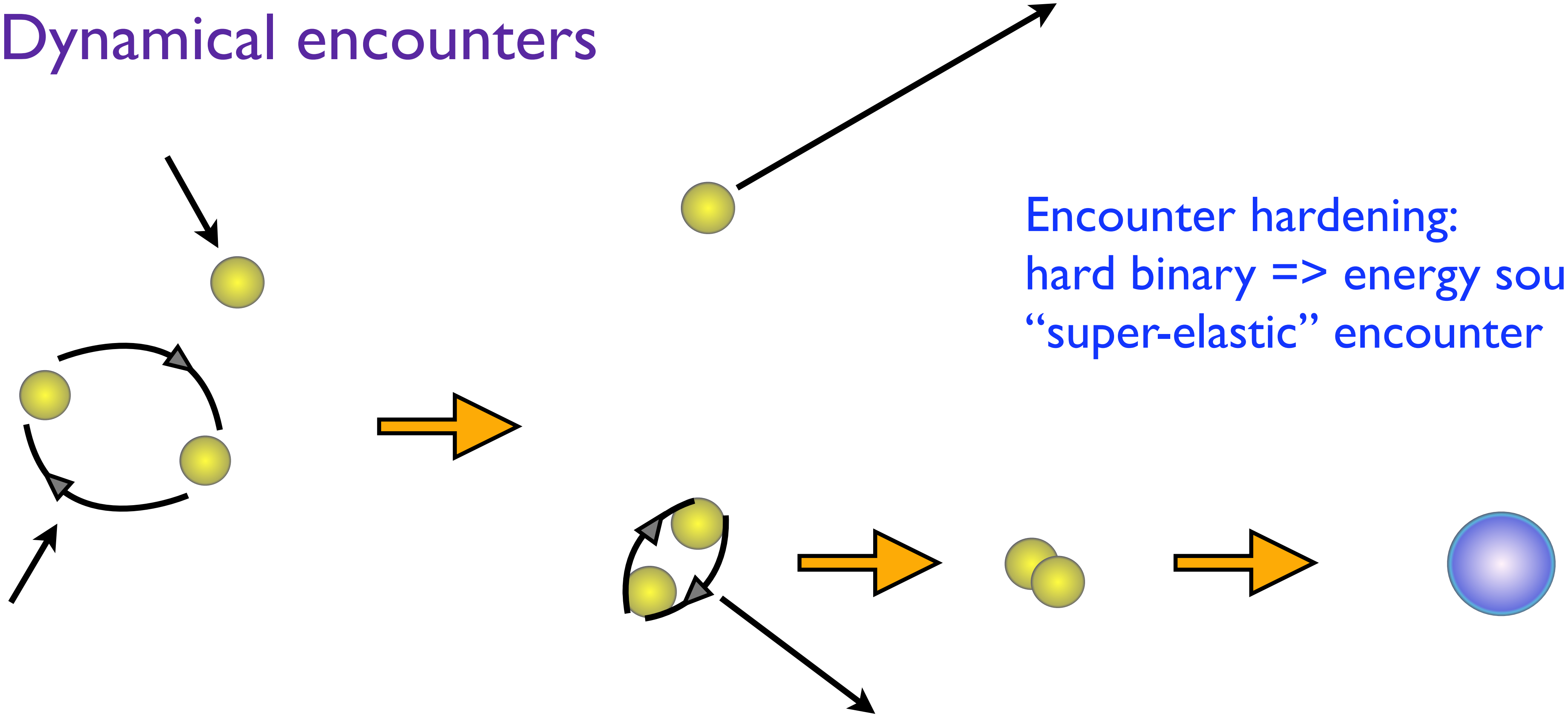
or

Late formation via dynamical means, e.g., dynamically induced merger of massive O-star binaries

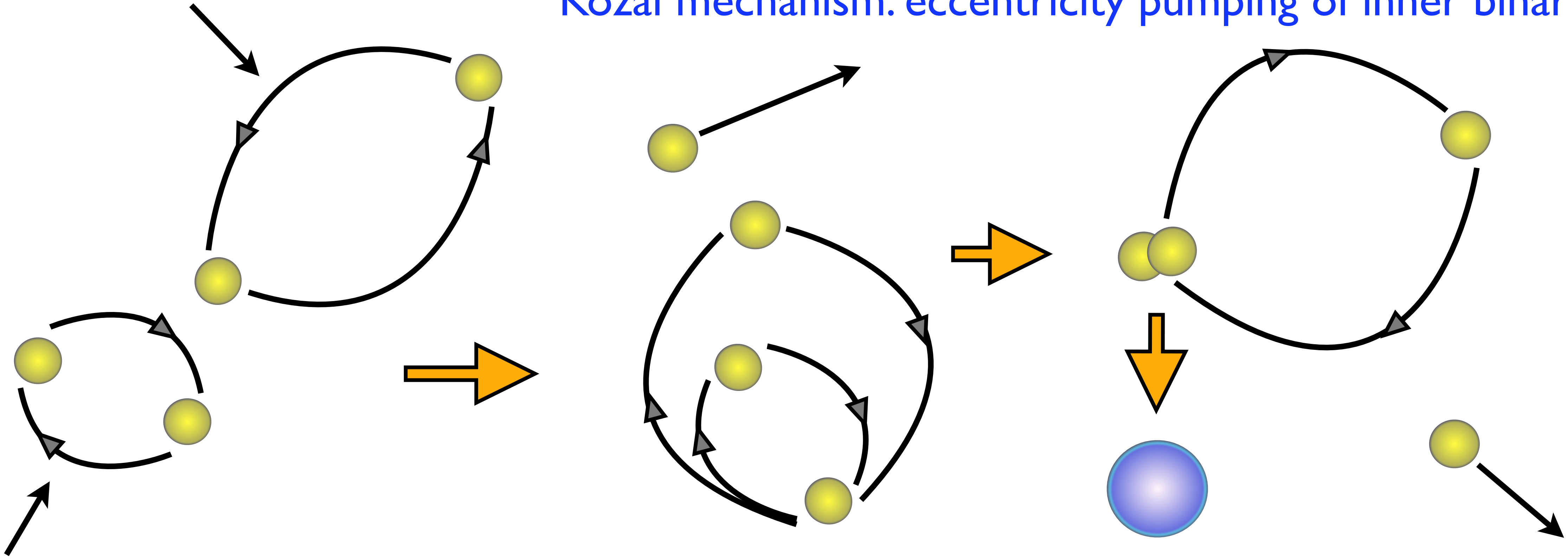
Dense R136 cluster is a factory of binary-single & binary-binary interactions inducing binary stellar mergers!

Dynamical encounters

SC stars



Encounter hardening:
hard binary => energy source
“super-elastic” encounter



Kozai mechanism: eccentricity pumping of inner binary in triple

Model R136: stellar evolution & hydrodynamics

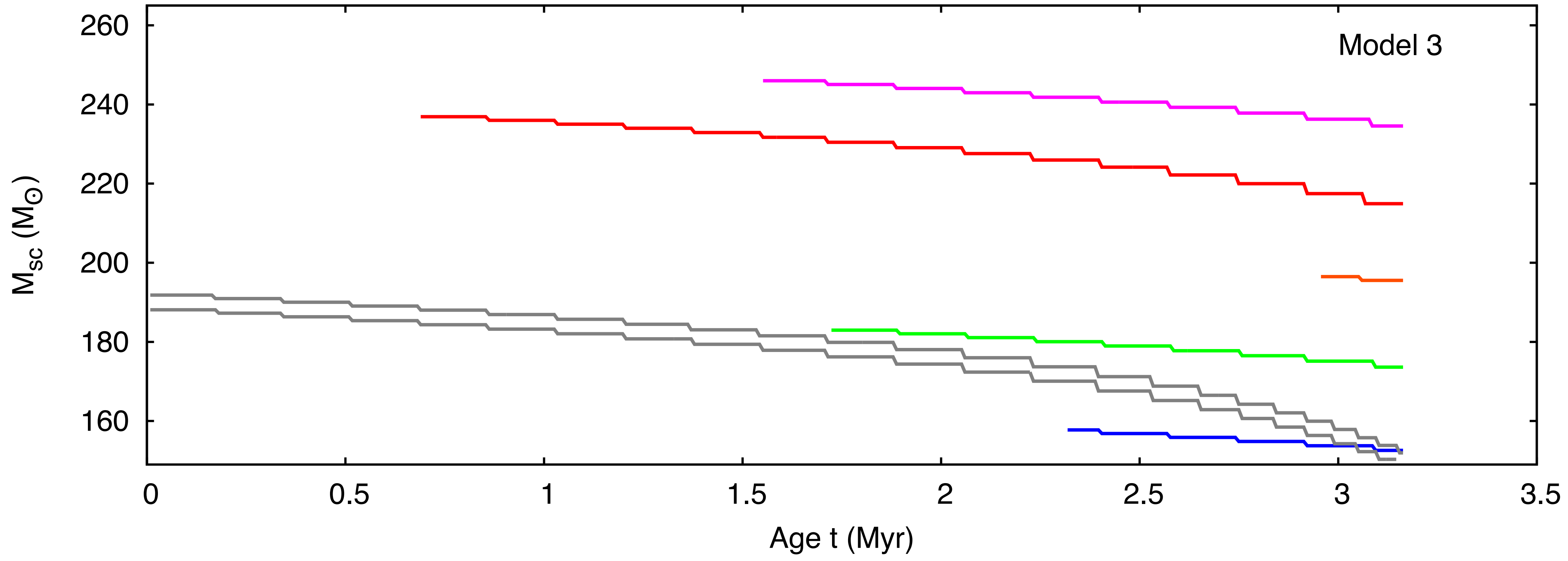
- Analytical stellar and binary evolution schemes by Hurley et al. (2000, 2002) - the SSE and BSE schemes

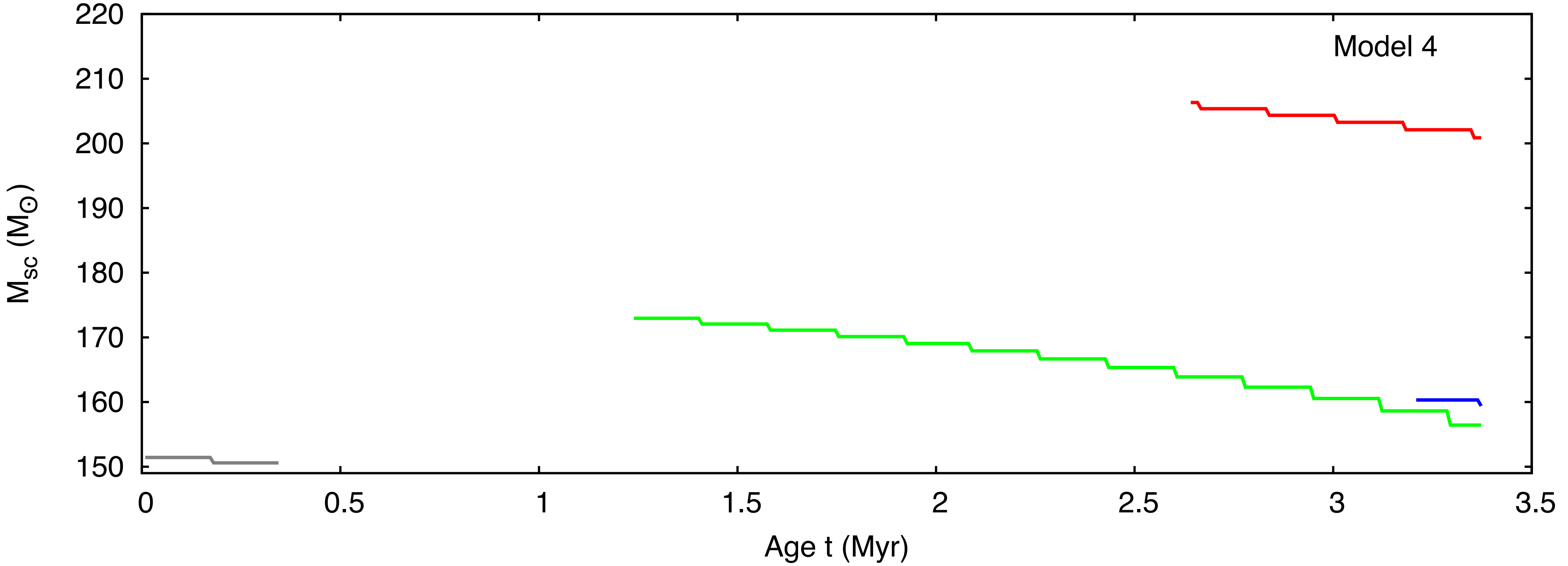
- Wind: only Nieuwenhuijzen & de Jager empirical scheme for massive MS stars, transition to WR-phase not included --- wind mass loss grossly underestimated

- Idealized treatment of MS-MS collisions: (a) no mass loss (b) complete mixing (Hurley et al. 2005). Gives most massive, youngest and chemically most homogeneous merger product

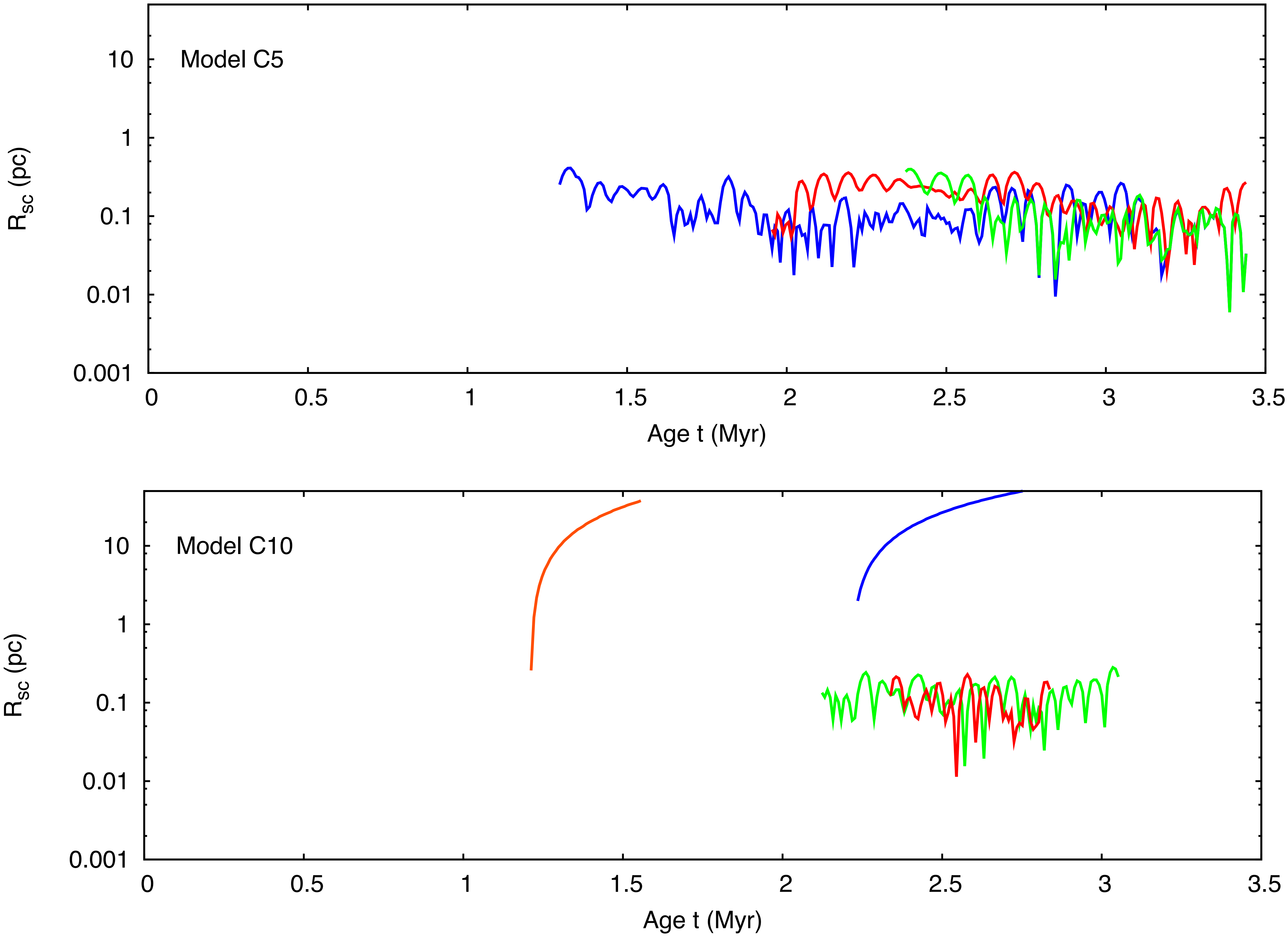
- Despite limitations, best available treatments in a direct N-body model (possible effects discussed later)

Appearance of SC stars in computed models



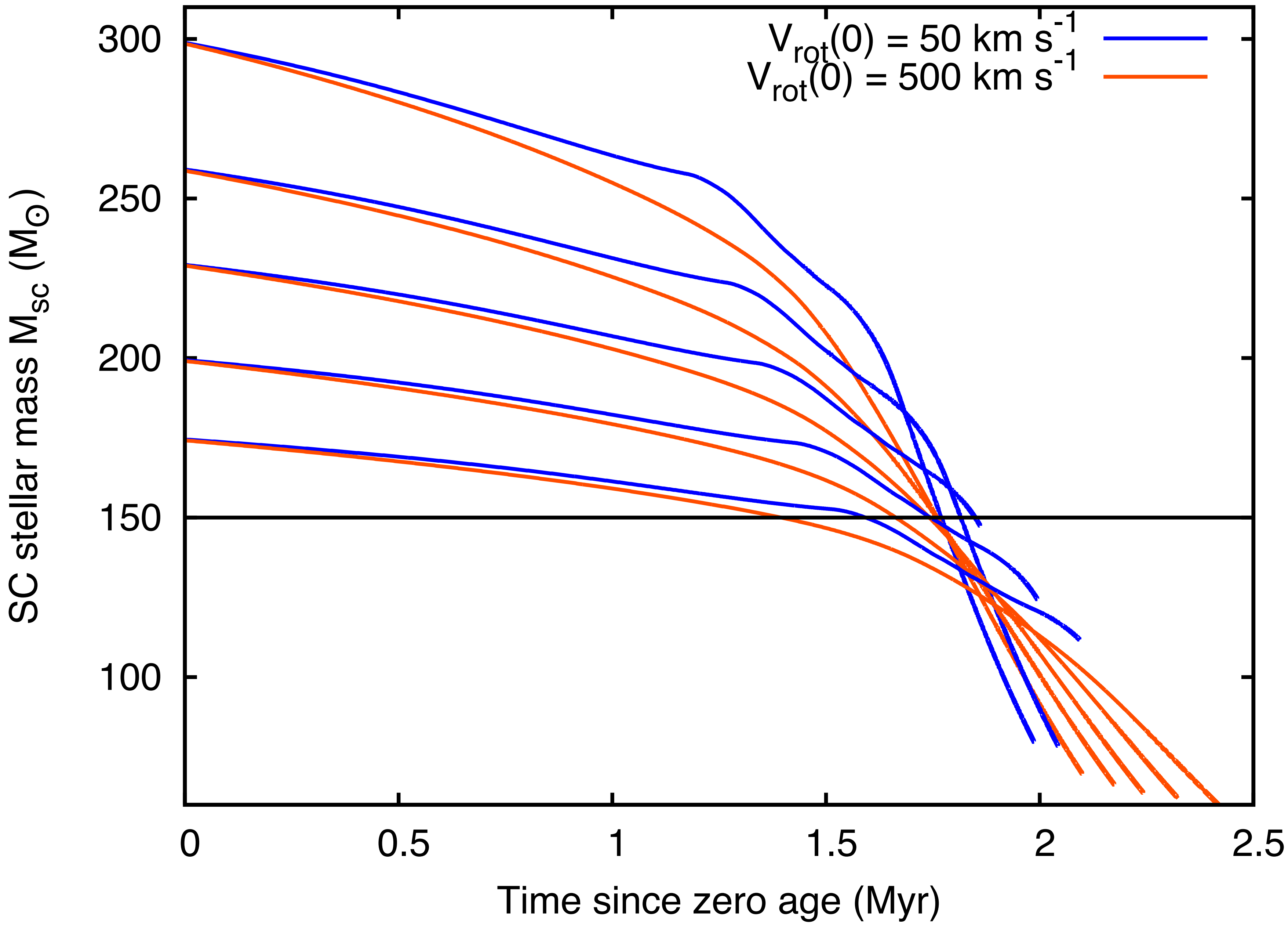


(Spurious SC members: instant mergers of highly eccentric primordial binaries)



SC stars either remain close to cluster center or are born runaways

A more realistic stellar evolution: implications



Mass Evolution of SC stars (computed by Köhler & Langer, 2012) for $Z \approx 0.5 Z_\odot$

1D hydrodynamic code by Heger et al. (2000), Petrovic et al. (2005), Yoon et al. (2006)

MS wind of Vink et al. (2001)

WR-phase for surface He-abundance $Y_s \geq 0.7$ (Hamann et al. 1995 wind)

Fast-rotating stars

Lifetime in super-canonical phase $(M > 150 M_\odot) \tau_{sc} \approx 1.5\ \mathrm{Myr}$

Model ID	T_0 (Myr)	M_0 ($M_\odot$)	$M_{\max}$ ($M_\odot$)	$T_{\max}$ (Myr)	$\mathcal{N}_{\max,\mathrm{in}}$	$\mathcal{N}_{\mathrm{tot}}$
1	2.6	193.9	193.9	2.6	1	2
2	2.0 (3.0)^a	155.2 (181.4)^a	181.4	3.0	1	2
3	0.7	236.8	246.0	1.5	4	5
4	1.2	172.5	206.2	2.6	1	2
C2	1.4	220.6	220.6	1.4	1	2
C5	1.3	224.0	224.0	1.3	3	3
C10^b	1.2 (2.1)^a	152.4 (162.5)^a	225.9	2.2	2	4

Multiple single SC stars form dynamically within 3 Myr - likely age of bulk of R136; Andersen et al. (2009)

SC stars appear from $T_0 \approx 1$ Myr and tend to form equally likely over $1-3$ Myr

Typical most massive SC star in a model $M_{\max} \gtrsim 200 M_\odot$ appearing within $T_{\max} < 3$ Myr

Multiple SC stars co-exist close to cluster center over SC lifetime $\tau_{\mathrm{sc}} \approx 1.5$ Myr within $T < 3$ Myr

SC stars may form with runaway velocities and escape immediately

Therefore:

It is quite plausible that a collection of dynamically-formed super-canonical stars would be observable at the center of a very young, massive starburst cluster like the R136.

Banerjee, S., Kroupa, P. & Oh, S., 2012, MNRAS, 426, 1416

Velocity dispersion of R136

Kinematics of R136: recent results

Hénault-Brunet et al. 2012, A&A, 546, A73 (HB et al.):

- Multiple epoch "VLT-FLAMES" spectroscopy of stars in the central zone of R136 $(1\ \mathrm{pc} < R < 5\ \mathrm{pc})$.
- Non-variable or *single* stars used to measure line-of-sight/radial velocity (V_r) - effectively "binary-corrected".
- $4\ \mathrm{km\ s^{-1}} \lesssim V_r \lesssim 5\ \mathrm{km\ s^{-1}}$ within $1\ \mathrm{pc} < R < 5\ \mathrm{pc}$.
- Consistent with *R136 in virial equilibrium* at such young age $(< 3\ \mathrm{Myr})$.

So, did gas-expulsion happen in R136?

Gas-expulsion from embedded clusters: model

Exponential mass loss from gas+star system mimicking gas expulsion:

$$\begin{aligned} M_g(t) =& M_g(0) & t \leq \tau_d, \\ M_g(t) =& M_g(0) \exp\left(-\frac{(t-\tau_d)}{\tau_g}\right) & t > \tau_d. \end{aligned}$$

Representative values:

$$\tau_g = \frac{r_h(0)}{v_g}$$

$v_g \approx 10 \text{ km s}^{-1};$ sound speed in HII gas

$\tau_d \approx 0.6 \text{ Myr};$ from lifetimes of Ultra-Compact HII regions

Gas + stars follow Plummer profile: in agreement with observed ISM filaments' cross-section profiles (Malinen et al. 2012).

Gas-expulsion from embedded clusters: model

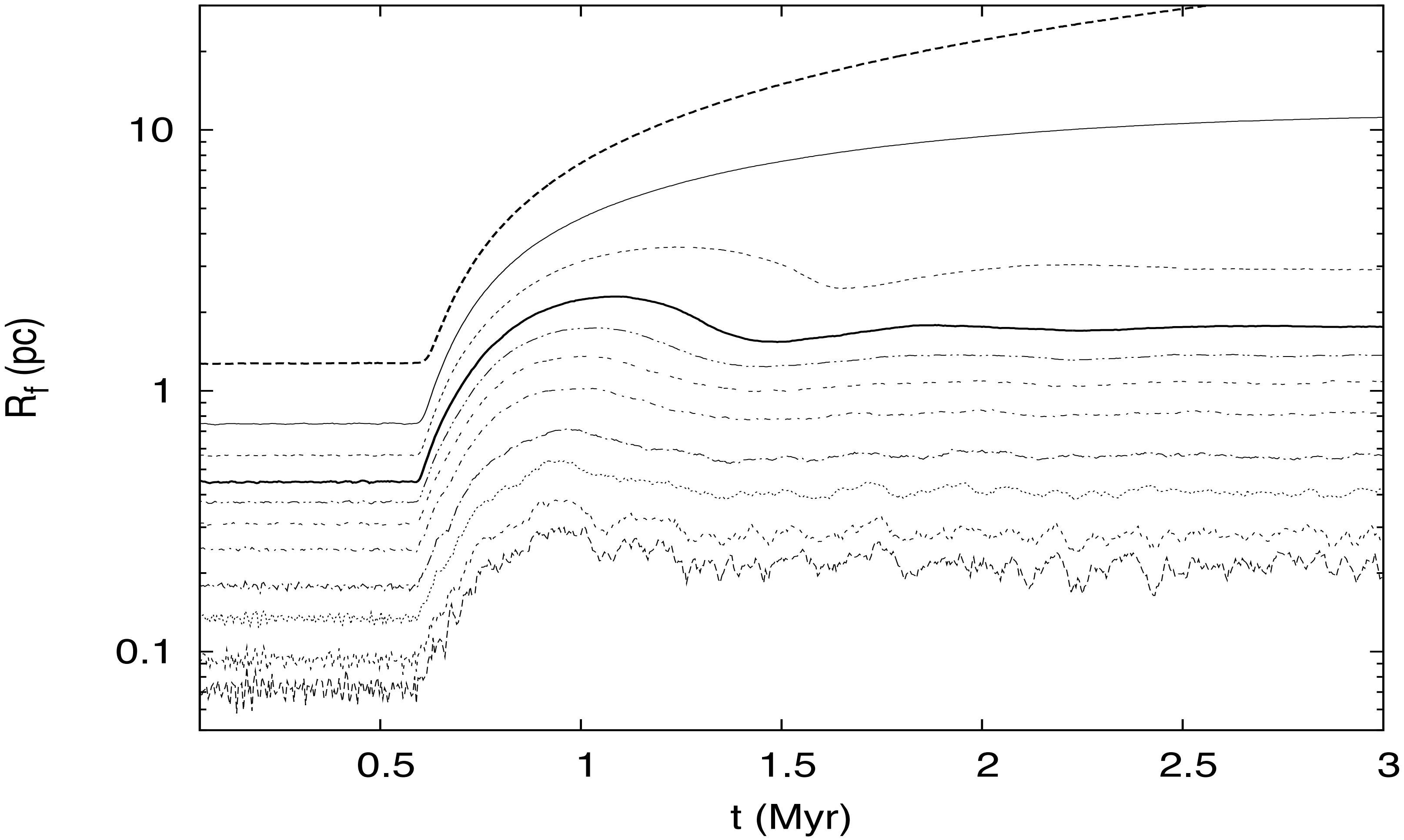
Mass-radius relation of initial embedded systems (Marks & Kroupa, 2012):

$$\frac{r_h(0)}{\mathrm{pc}} = 0.10^{+0.07}_{-0.04} \times \left(\frac{M_{\mathrm{ecl}}(0)}{M_\odot}\right)^{0.13\pm0.04}$$

Factor of 10 compact than present day young massive clusters but in good agreement with observed cross-sections of ISM filaments (e.g. Andre et al. 2011).

Star formation efficiency (SFE) $\epsilon \approx \frac{1}{3}$ (e.g. Lada & Lada 2003)

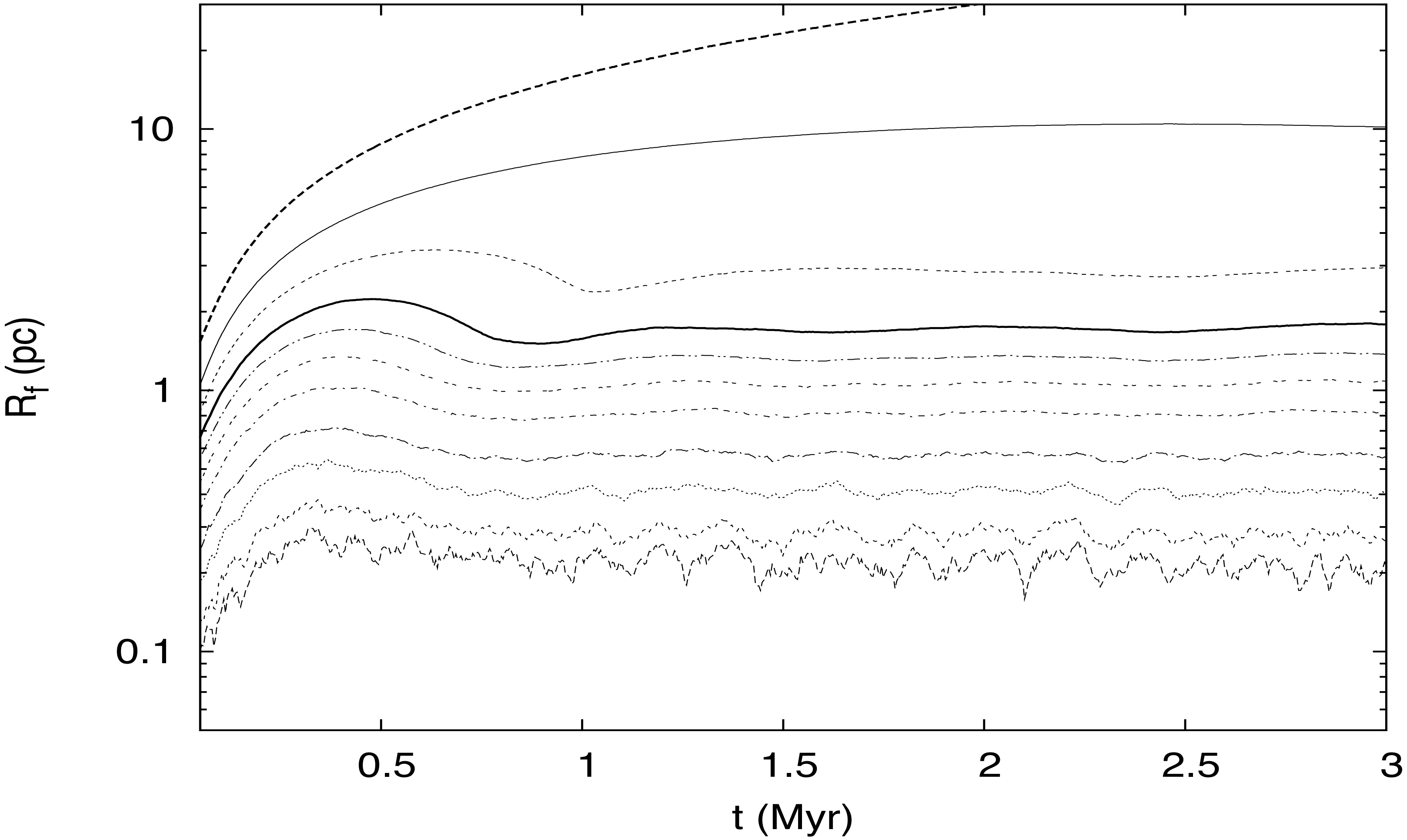
Mass segregated single stars only in preliminary study, no tidal field.



$\tau_d = 0.6$ Myr

$\tau_{\rm vir} \approx 1.0$ Myr

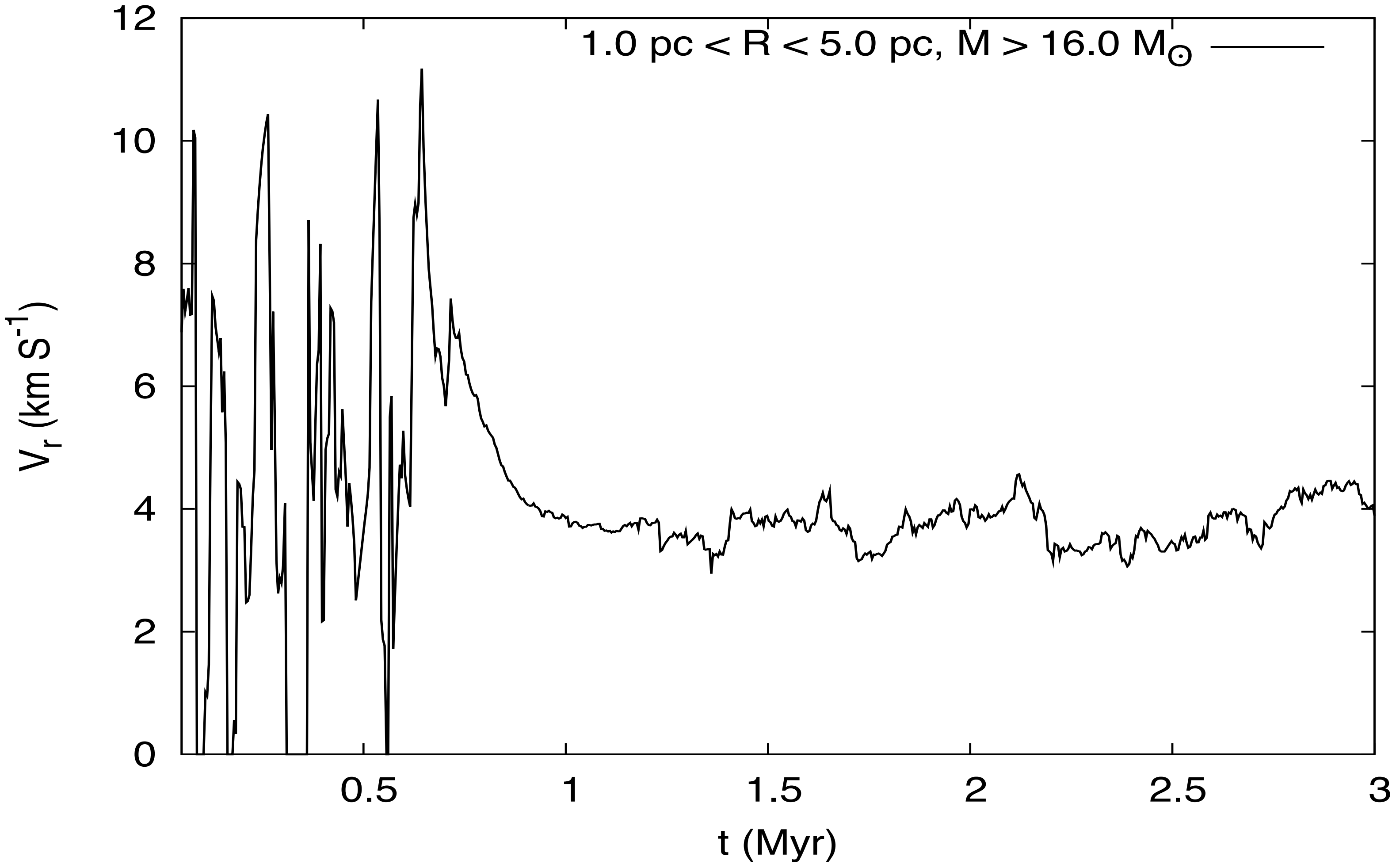
Lagrangian radii: computed R136 model exhibit rapid re-virialization following gas-expulsion driven expansion (violent relaxation)



$\tau_d = 0$ Myr

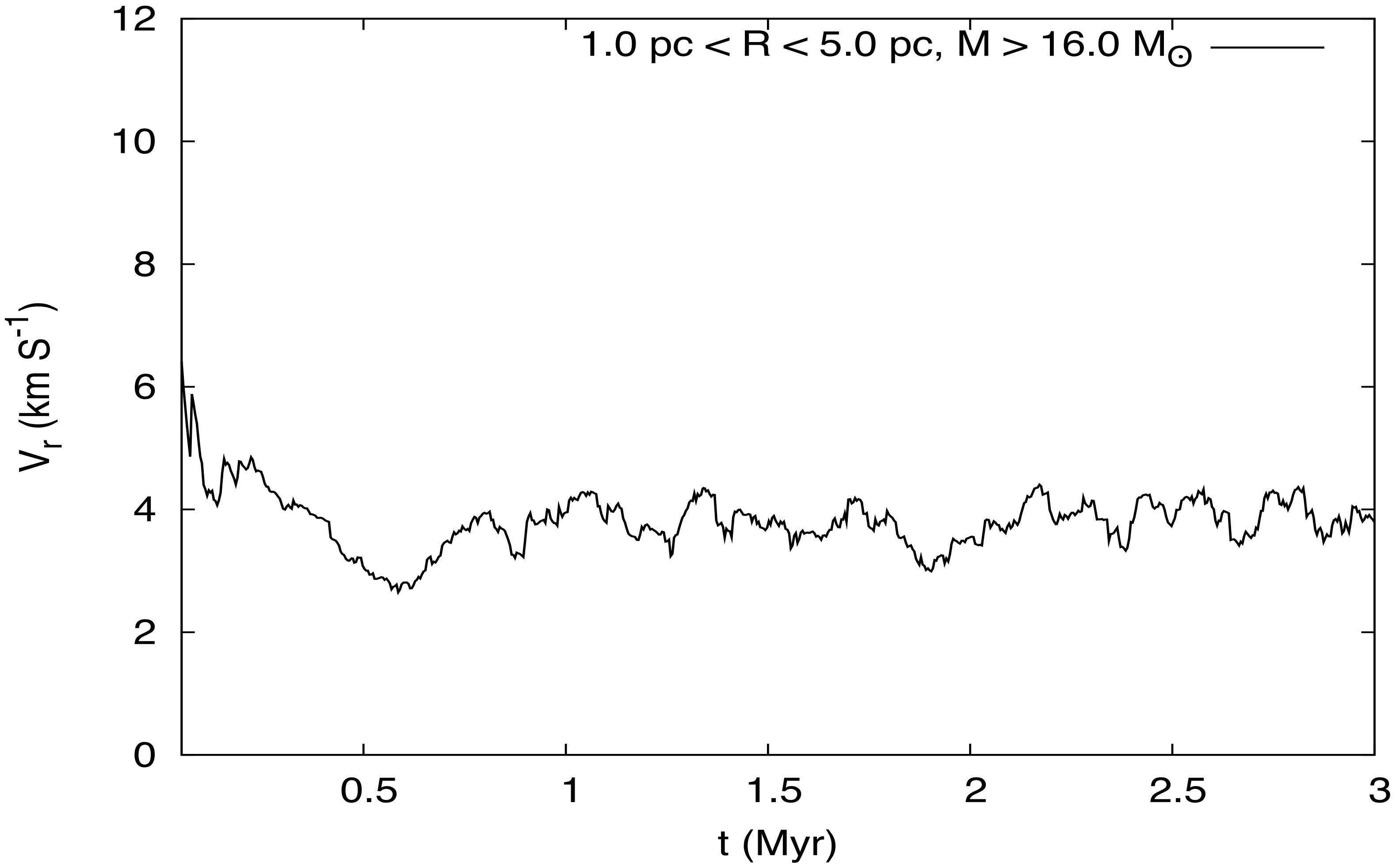
$\tau_{\rm vir} \approx 1.0$ Myr

R136 re-virialized at present epoch



$\tau_d = 0.6$ Myr

RV dispersion evolution for O-type single stars within $1 \text{ pc} < R < 5 \text{ pc}$ implies close agreement with HB et al measurements.



$\tau_d = 0$ Myr

Computed models. ONC-A/B from Kroupa et al. (2001)

Cluster	$M_{\rm ecl}(0)/M_\odot$	$M_g(0)/M_\odot$	$r_h(0)/\text{pc}$	$Z/Z_\odot$	τ_g/Myr	$\tau_{\rm cr}(0)/\text{Myr}$	τ_d/Myr	`BSE`	$\tau_{\rm vir}/\text{Myr}$
R136	1.0×10^5	2.0×10^5	0.45	0.5	0.045	0.021	0.0, 0.6	Yes	0.9
NYC	1.3×10^4	2.6×10^4	0.34	1.0	0.034	0.038	0.0, 0.6	Yes	2.2
ONC-A	3.7×10^3	7.4×10^3	0.45	1.0	0.045	0.23	0.6	Yes	> 10
ONC-B	4.2×10^3	8.4×10^3	0.21	1.0	0.021	0.066	0.6	Yes	≈ 3

Lower mass clusters take longer to re-virialize. $\tau_{\rm vir}$ too long for NGC 3603 Young Cluster (NYC) to be presently in virial equilibrium (c.f. Rochau et al. 2010).

NYC

An observed dynamical equilibrium state of a very young stellar cluster does not necessarily dictate that the cluster has not undergone a gas-expulsion phase.

R136 is very plausibly a re-virialized young cluster.

Banerjee, S. & Kroupa, P., 2012, ApJ (accepted)

Conclusions:

VFTS 682-like "slow runaway" VMS is common from R136-like cluster: isolated formation scenario unnecessary.

It is quite plausible that a collection of dynamically-formed super-canonical stars would be observable at the center of a very young, massive starburst cluster like the R136.

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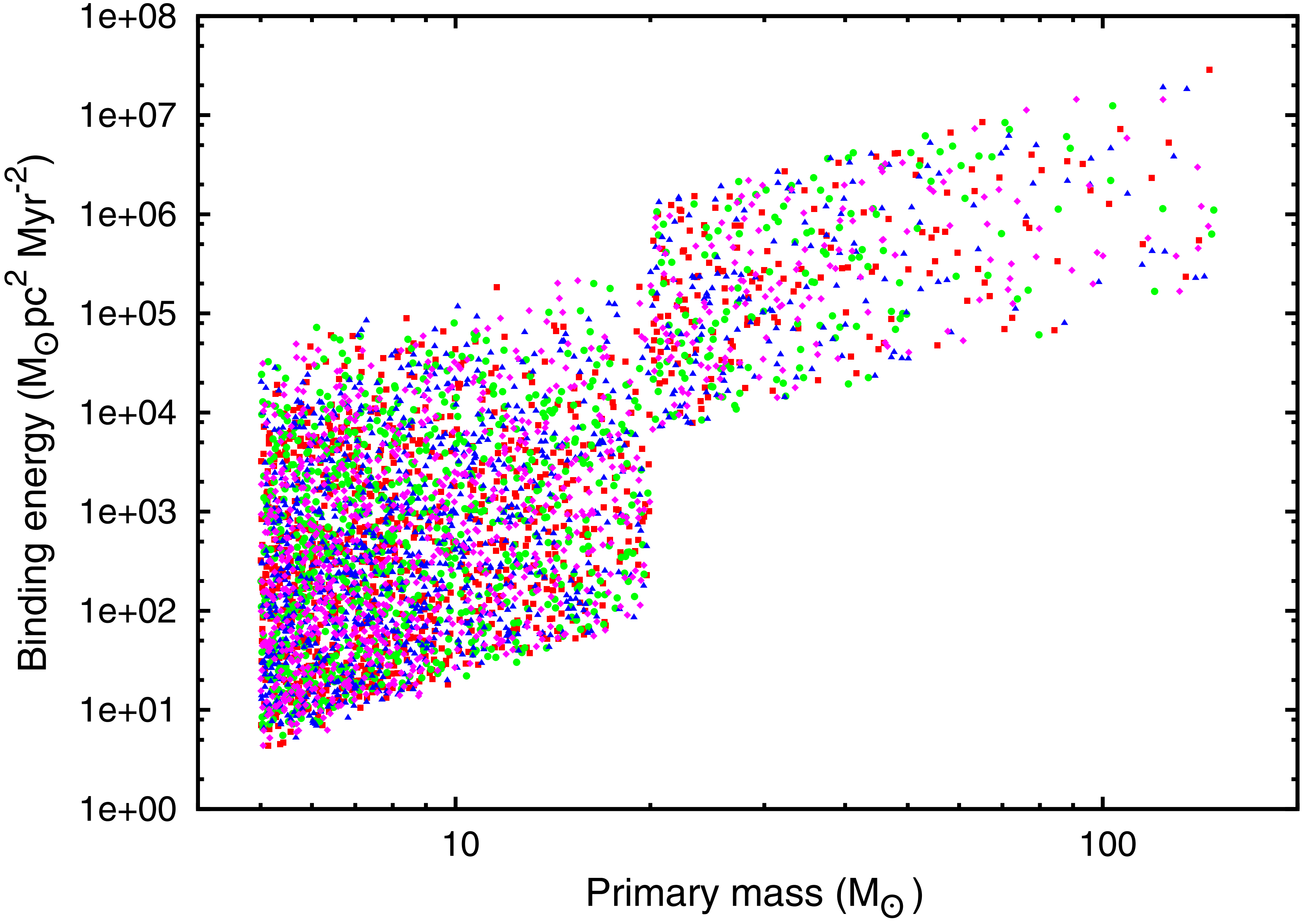

Binding energies of the initial binaries vs. primary mass showing two distinct binary distributions across $20 M_\odot$

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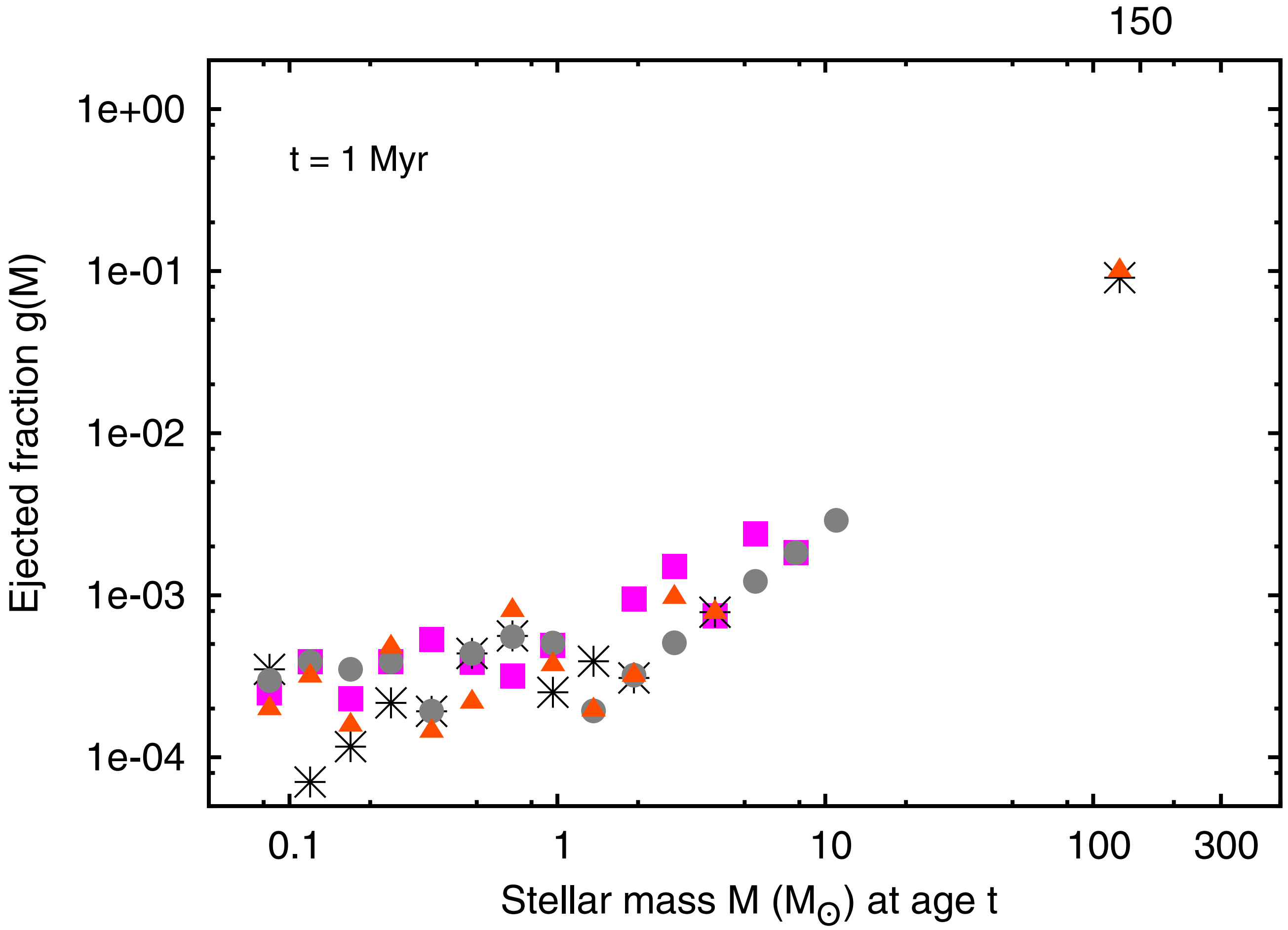
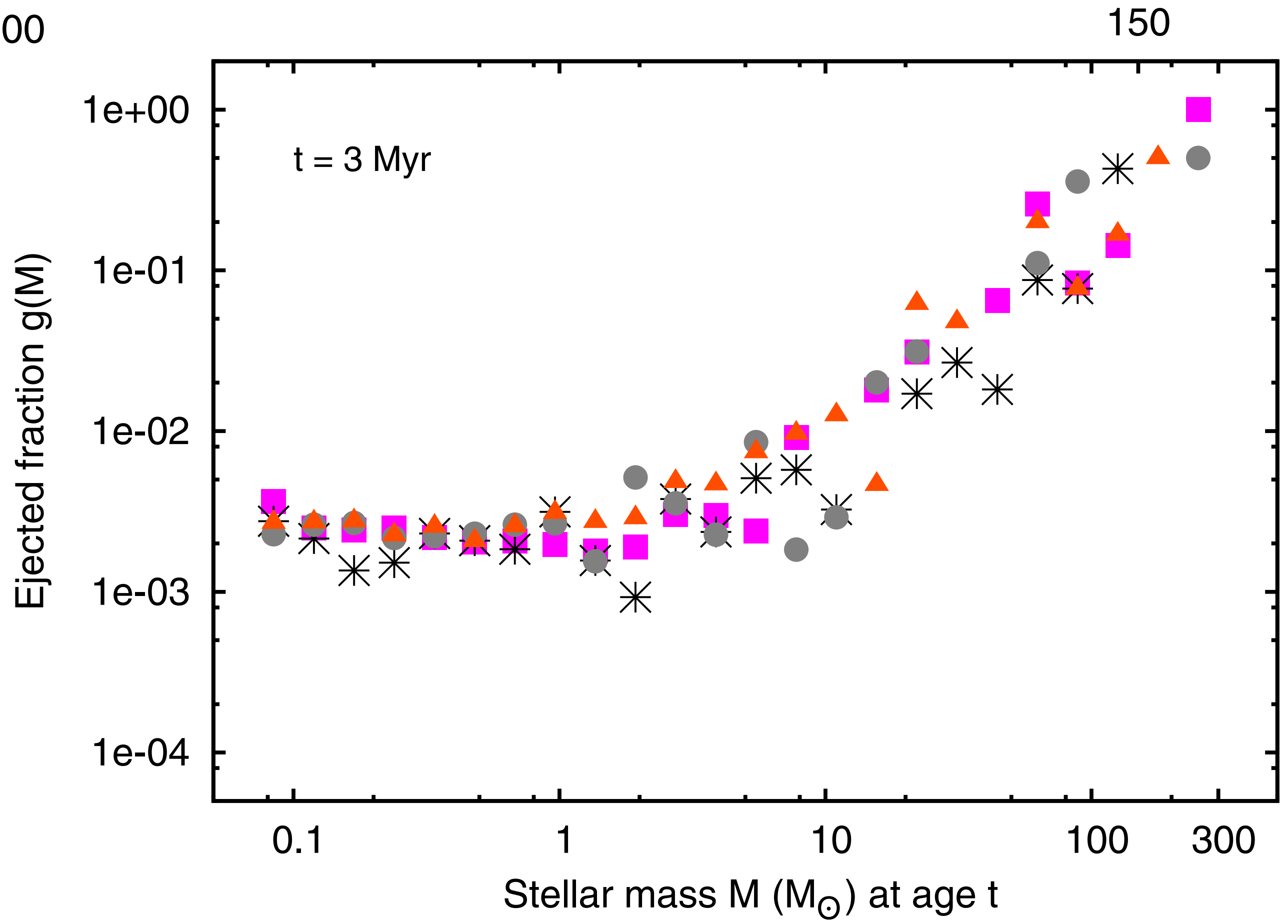
Mass Dependence of Runaway Stars





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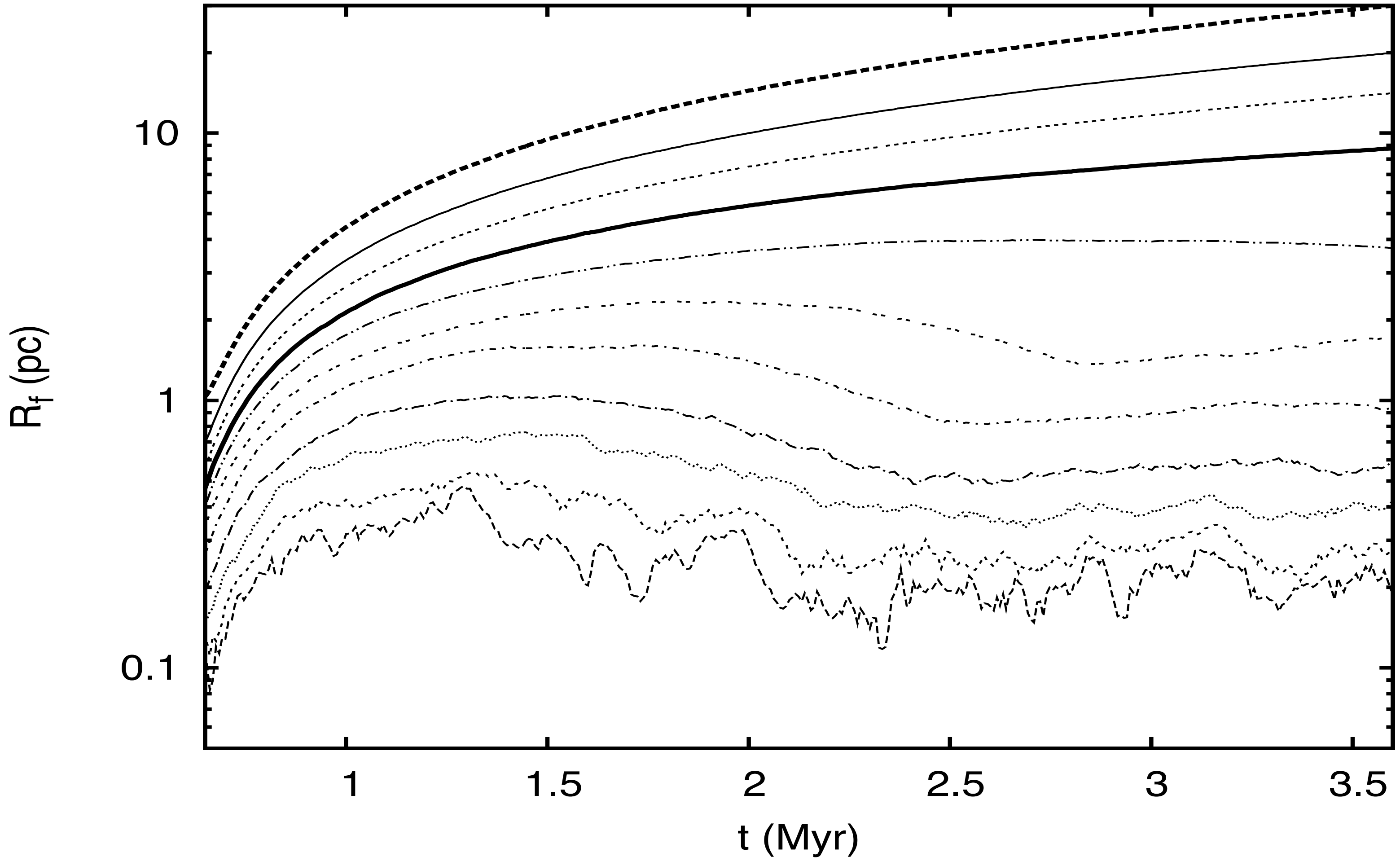
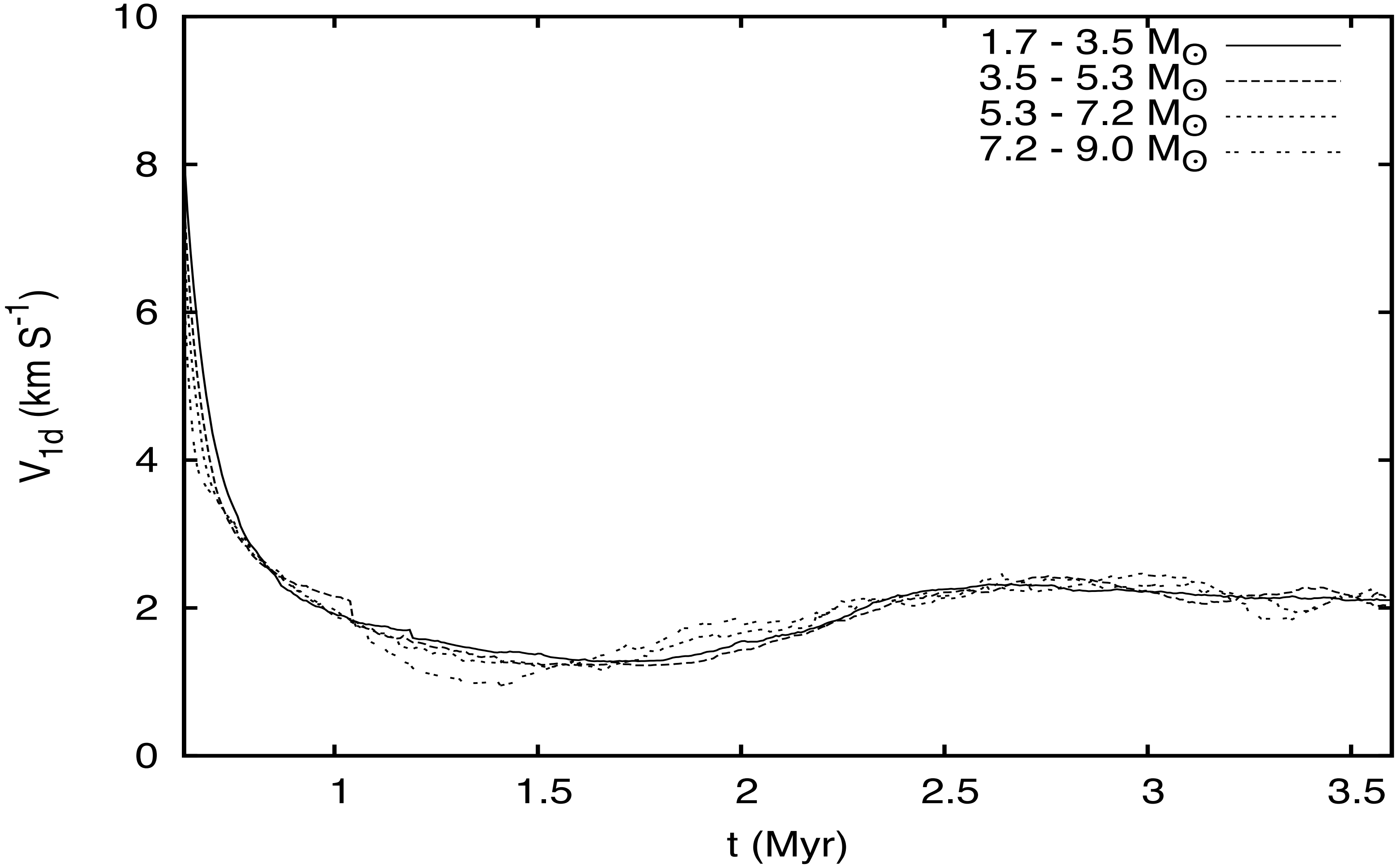
NYC computations





Longer re-virialization time.

Likely super-virial system at present epoch.

Consistent with proper-motion measurements of Rochau et al. 2010.

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