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2012 FIRB fellow
2015 MERAC prize

The Maxwell's demon of star clusters

a.k.a. the impact of binaries on star clusters

COLLABORATORS: Mario Spera, Nicola Giacobbo, Ugo N. Di Carlo, Alessandro A. Trani, Elisa Bortolas, Alessandro Ballone, Sandro Bressan, Giacomo Beccari, Germano Sacco, Rob Jeffries

The IMPACT of BINARIES on STELLAR EVOLUTION, ESO Garching, July 3 – 7 2017

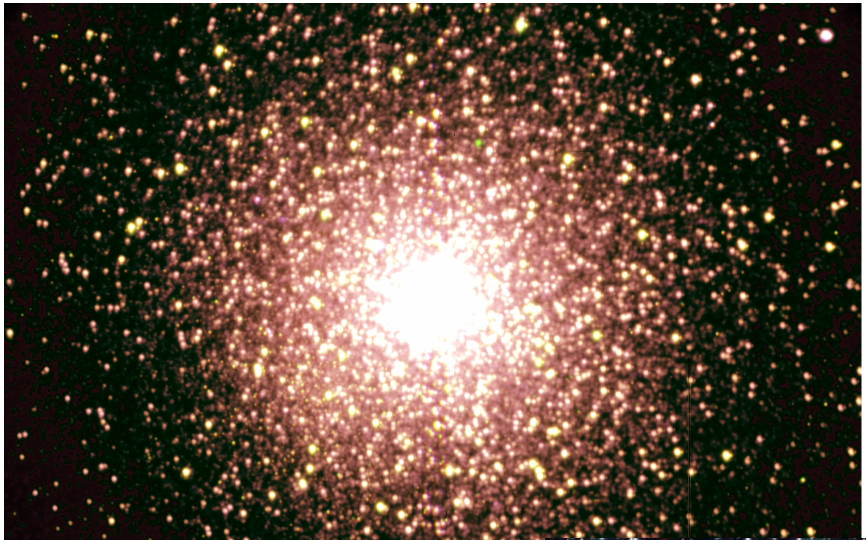
OUTLINE

1. Binaries as source of energy
2. Core collapse
3. Spitzer's instability
4. Stellar EXOTICA
5. Conclusions

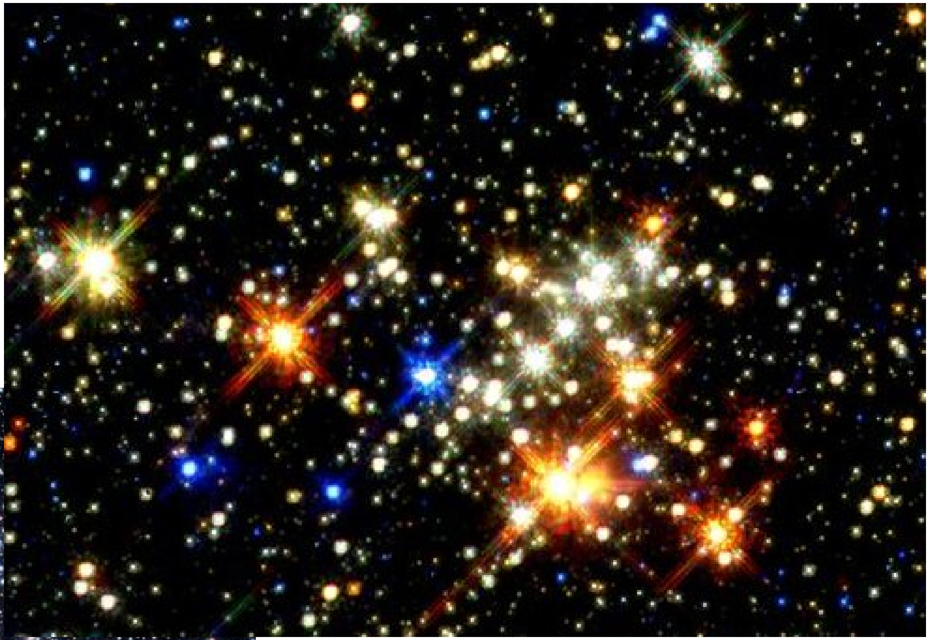
1. Binaries as source of energy

Most star clusters are collisional systems:
Two body encounters drive their evolution

Spitzer & Hart 1971



47Tuc by SALT

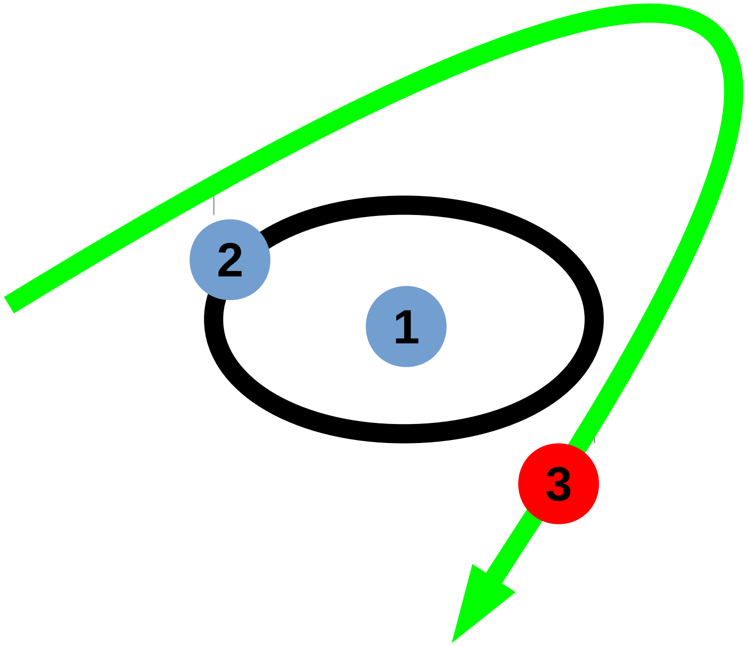


Quintuplet by HST

NGC290 by HST

1. Binaries as source of energy

If two-body encounters are efficient, also 3-body encounters occur



A binary is energy reservoir:

$$\boxed{E_{int} = \frac{1}{2}\,\mu\,v^2 - \frac{G\,m_1\,m_2}{r}}$$

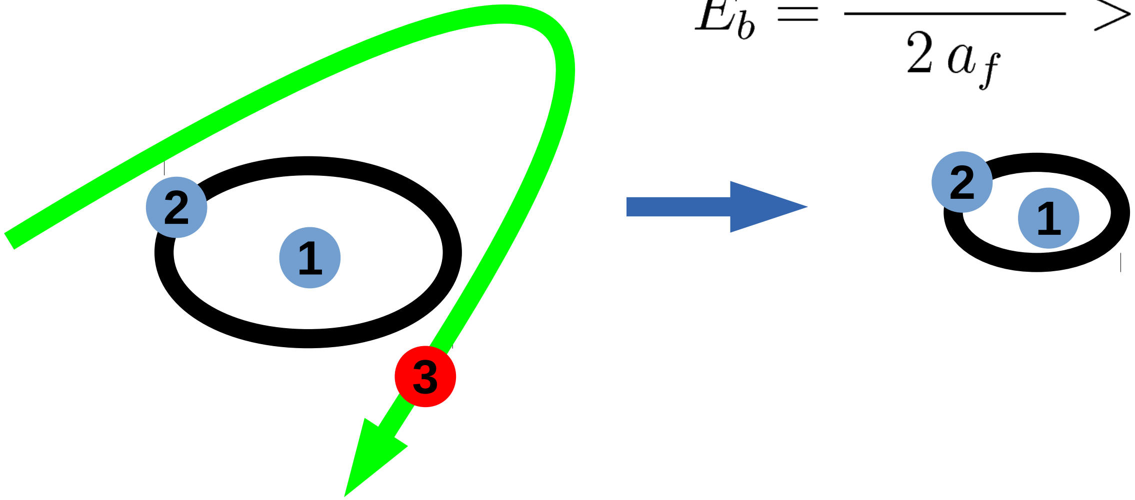
Internal energy can be exchanged with single stars:
Binaries pump kinetic energy in the system changing its dynamical state

1. Binaries as source of energy

If star extracts internal energy from binary, the binary shrinks

Star and binary recoil

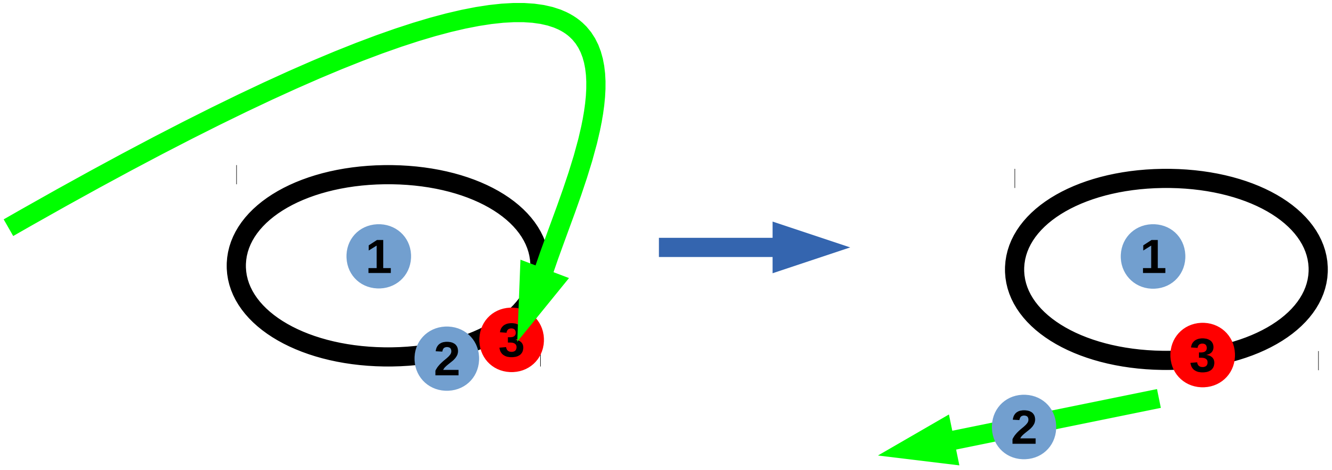
$$E_b = \frac{G\,m_1\,m_2}{2\,a_f} > \frac{G\,m_1\,m_2}{2\,a_i}$$



The star may also replace one of the members of the binary: EXCHANGE

$m_3 > m_2$

$$E_b = \frac{G\,m_1\,m_3}{2\,a} > \frac{G\,m_1\,m_2}{2\,a}$$



1. Binaries as source of energy

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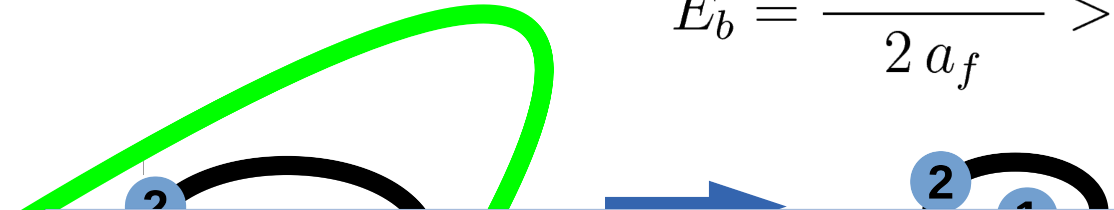
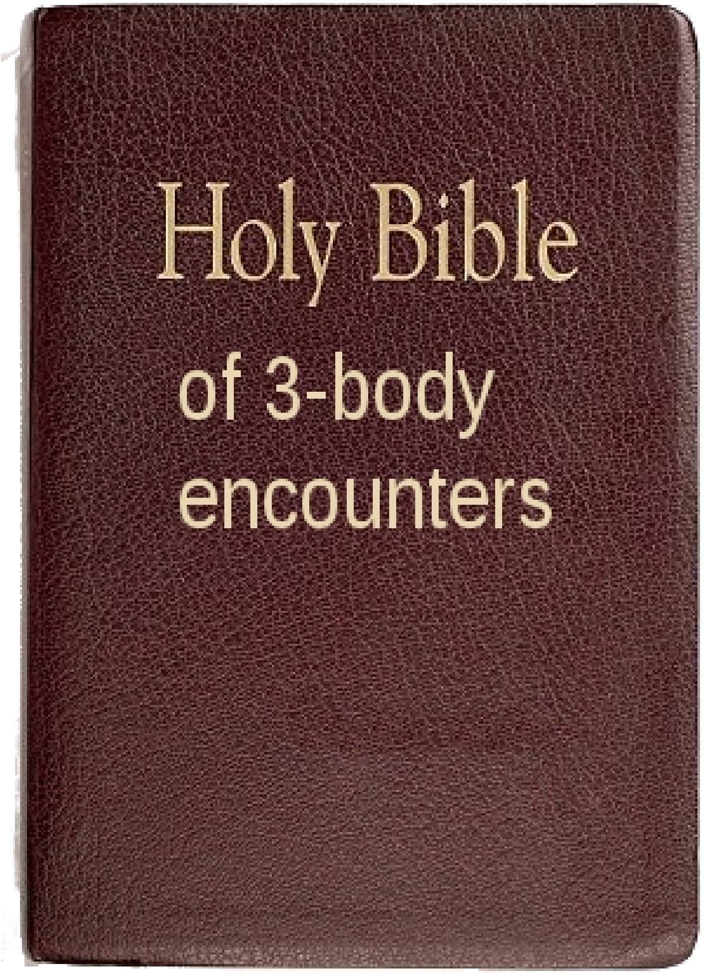
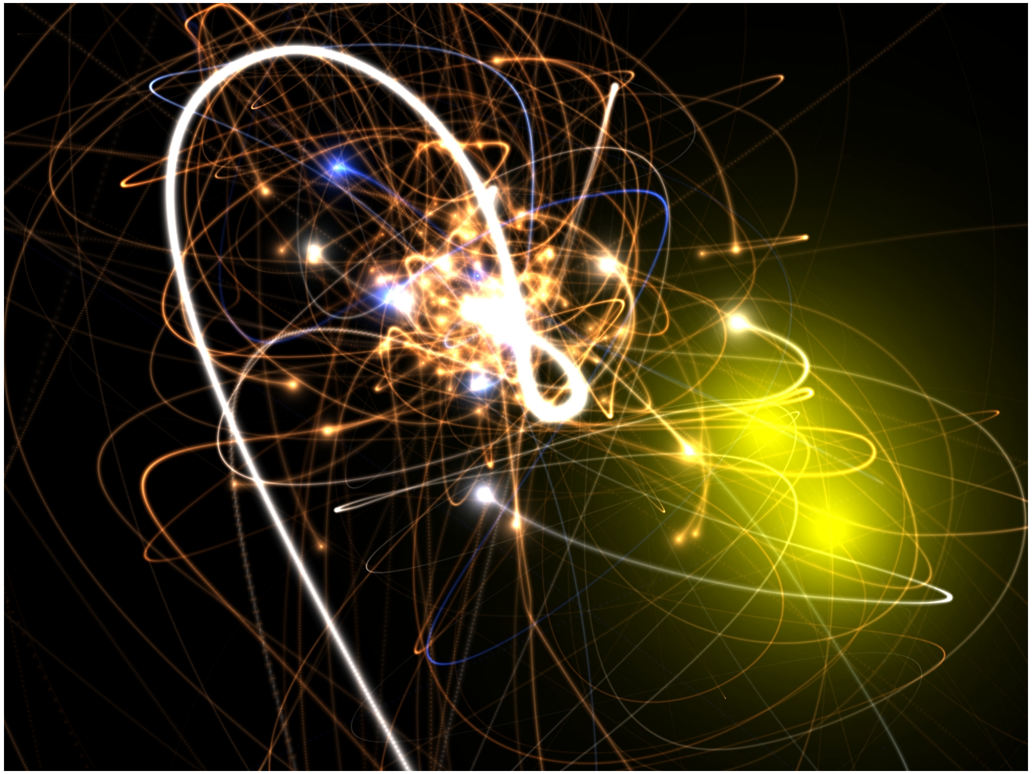


The star

**Douglas Heggie,
Binary evolution in stellar dynamics,
1975, MNRAS, 173, 729**



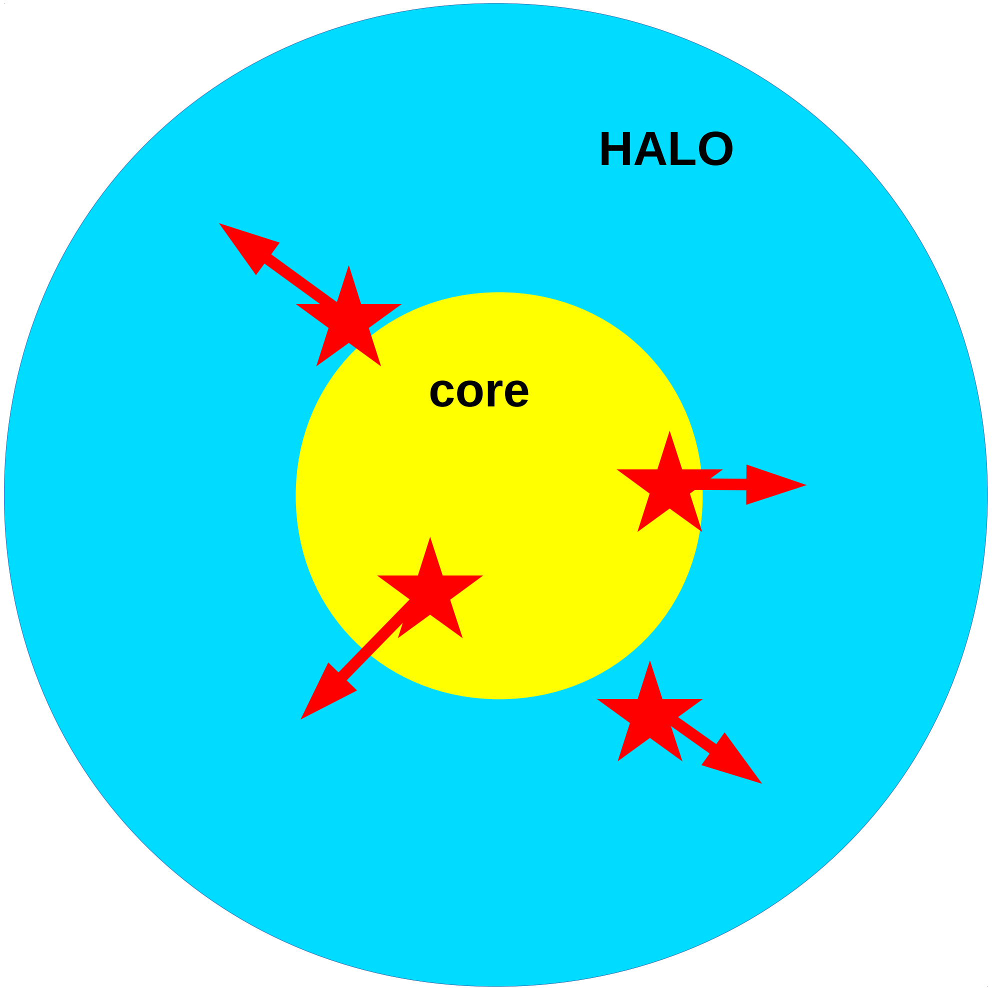
DYNAMICAL PROCESSES DRIVEN BY BINARIES



Credits: A. Geller

2. Core collapse

- two-body encounters are efficient
  → leads to evaporation of the fastest stars from core

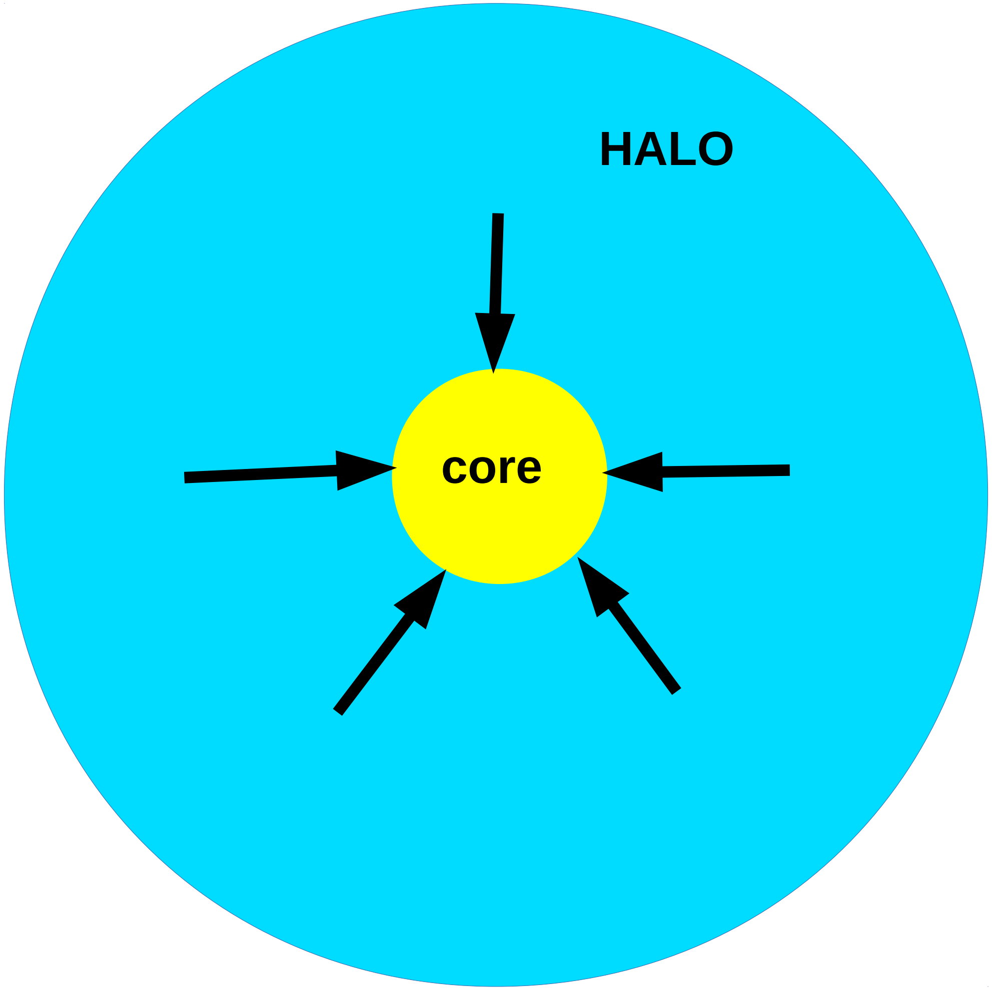


Inspired from Spitzer 1988

2. Core collapse

- leads to decrease of |W| and K
- since fastest stars are lost, the decrease in K is stronger than in |W|

→ core contracts because |W| no longer balanced by K



$|W| \downarrow$

$K \downarrow$

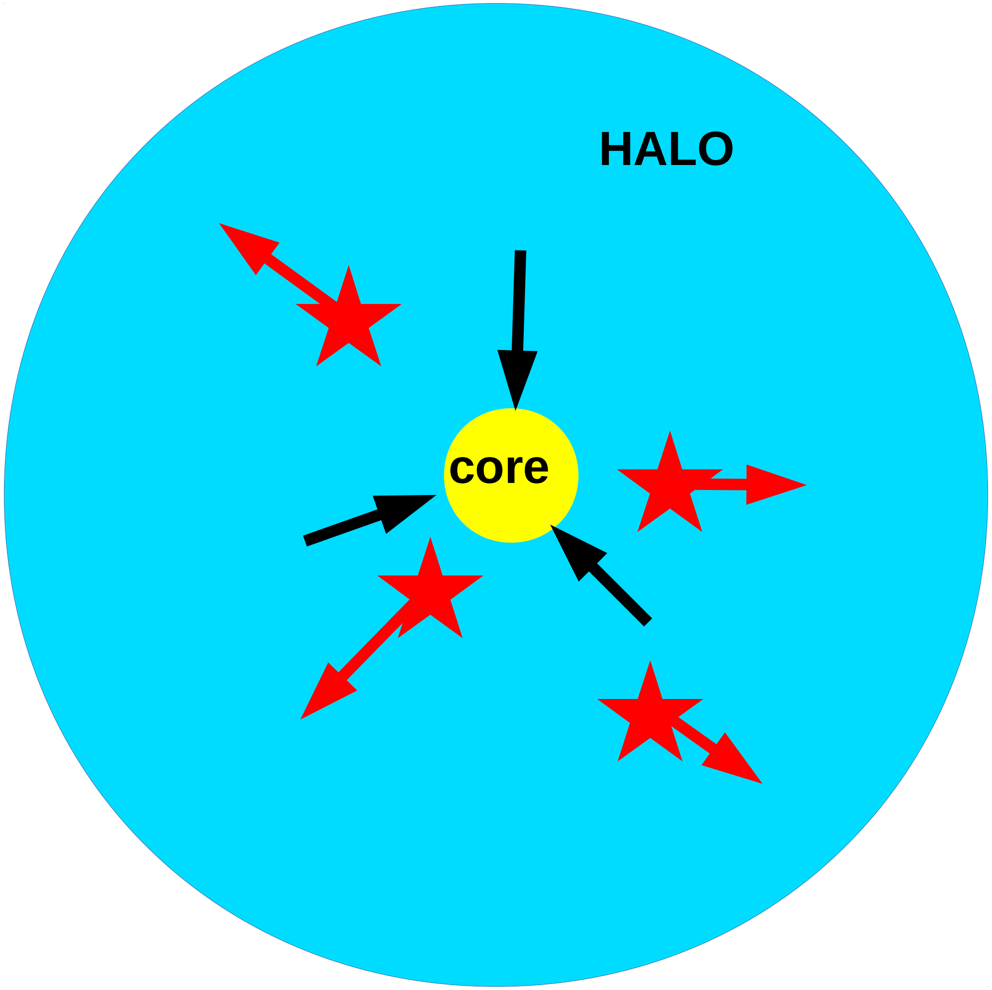
$R_c \downarrow$

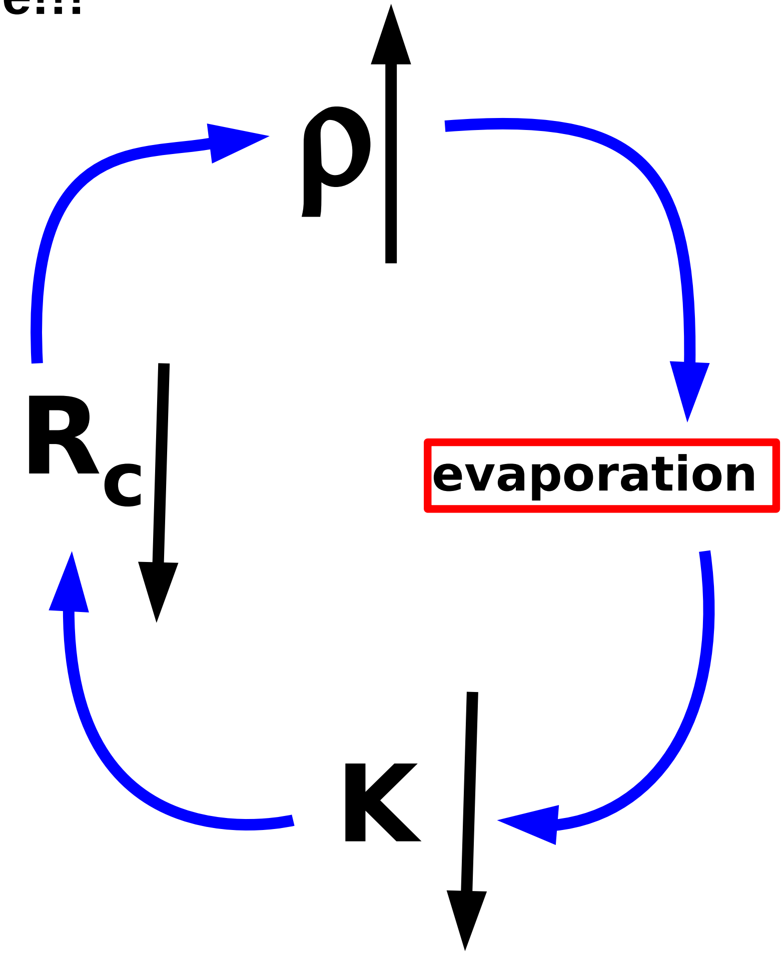
Inspired from Spitzer 1988

2. Core collapse

- density increases and 2body encounter rate increases
→ more fast stars evaporate, K decreases further, radius contracts more

RUNAWAY MECHANISM : core collapse!!!



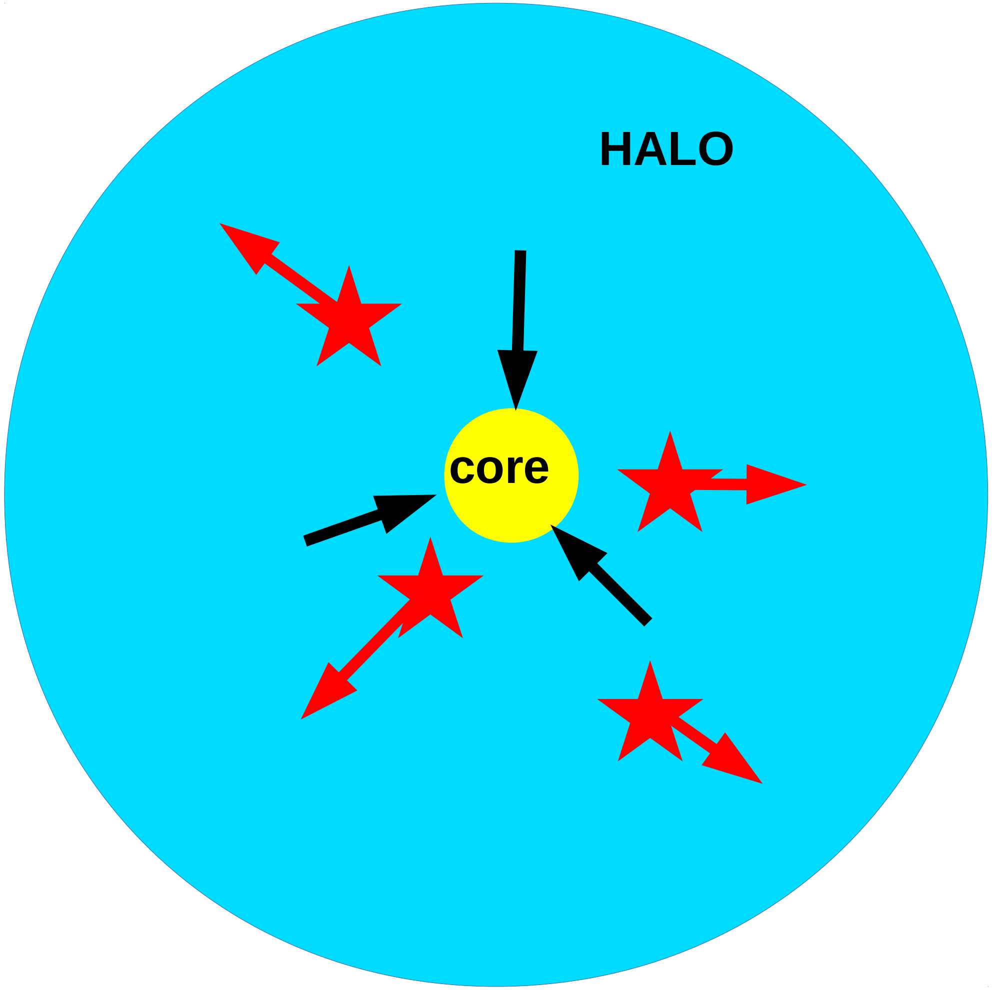


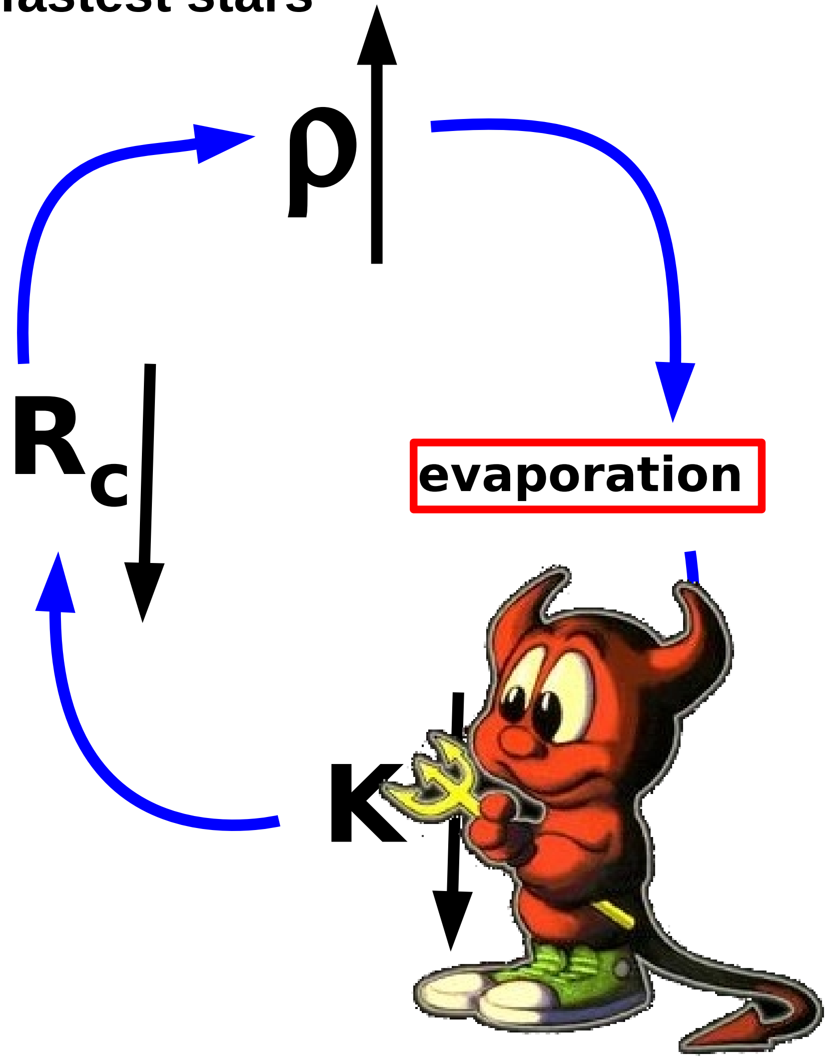
Inspired from Spitzer 1988

2. Core collapse

WE NEED A NEW SOURCE OF ENERGY TO BREAK THIS LOOP

something able to pump NEW kinetic energy in the system without leading to the evaporation of the fastest stars





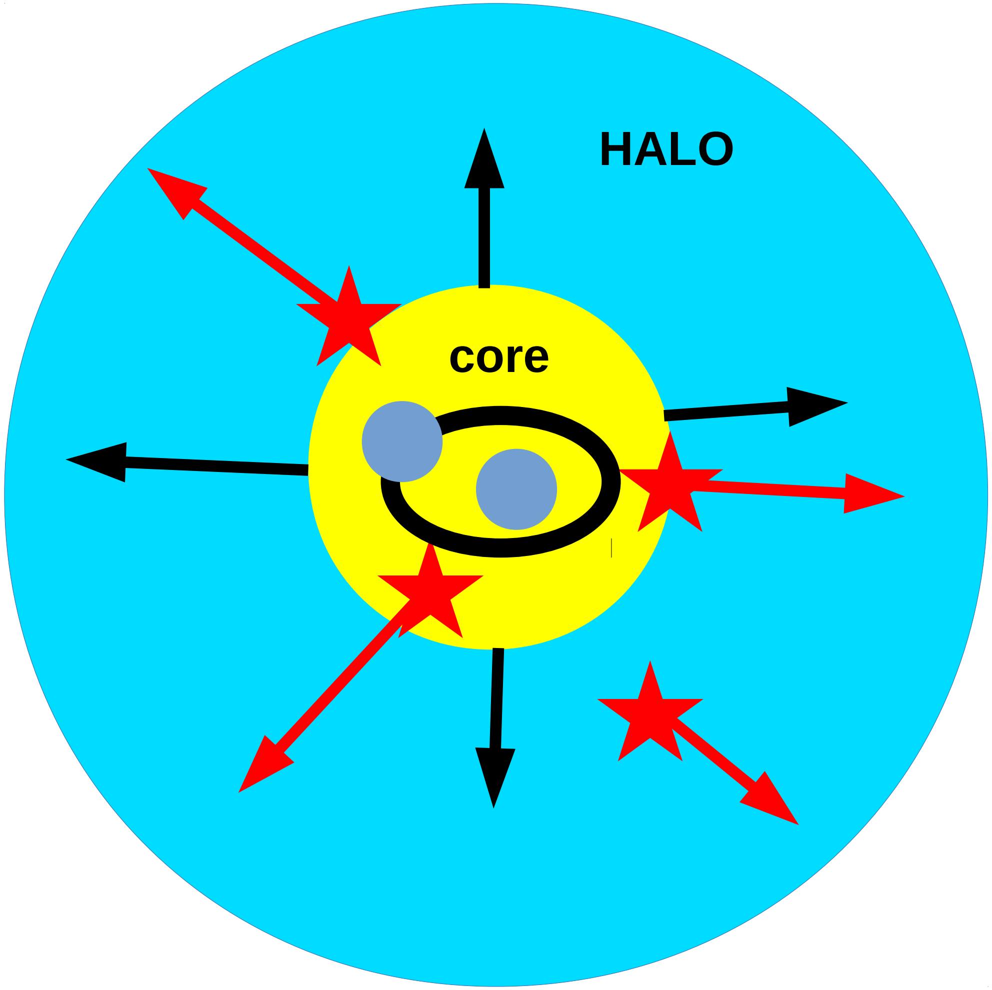
Inspired from Spitzer 1988

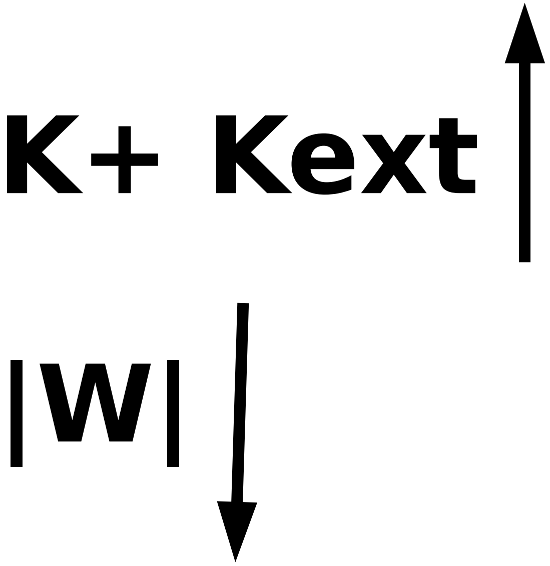
2. Core collapse

SOURCE OF ENERGY TO BREAK THIS LOOP = 3-body encounters

energy extracted from binaries decreases |W| and increases K

→ core collapse is reversed





Inspired from Spitzer 1988

3. Equipartition and Spitzer's Instability

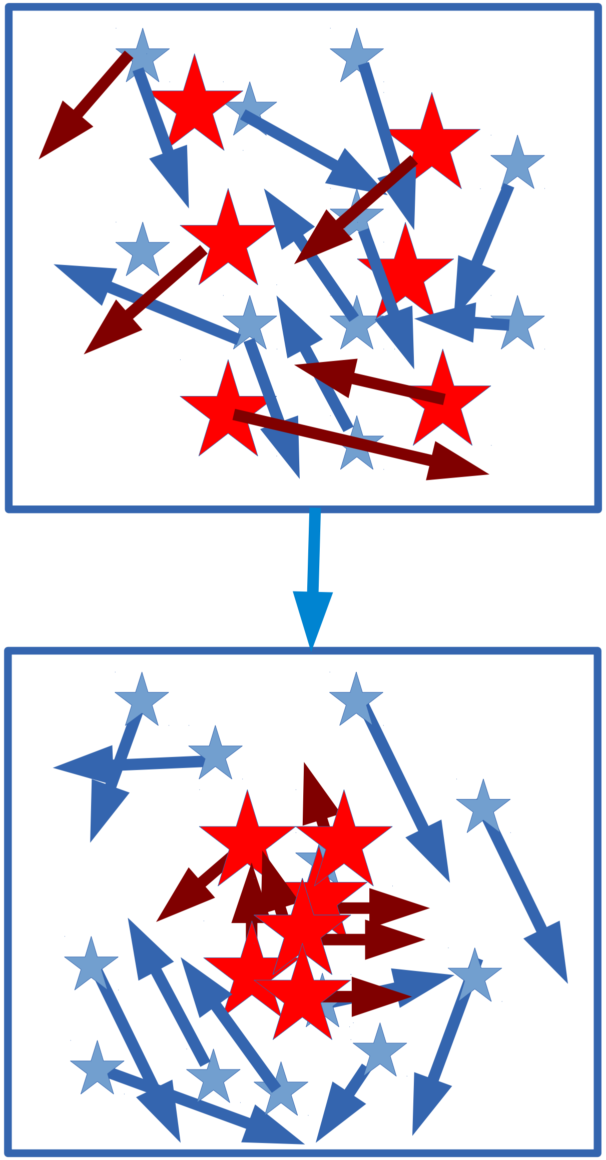
In GAS systems at thermal equilibrium, energy is shared EQUALLY by all particles (Boltzmann 1876)

→ for analogy with gas,
in a two-body relaxed star system

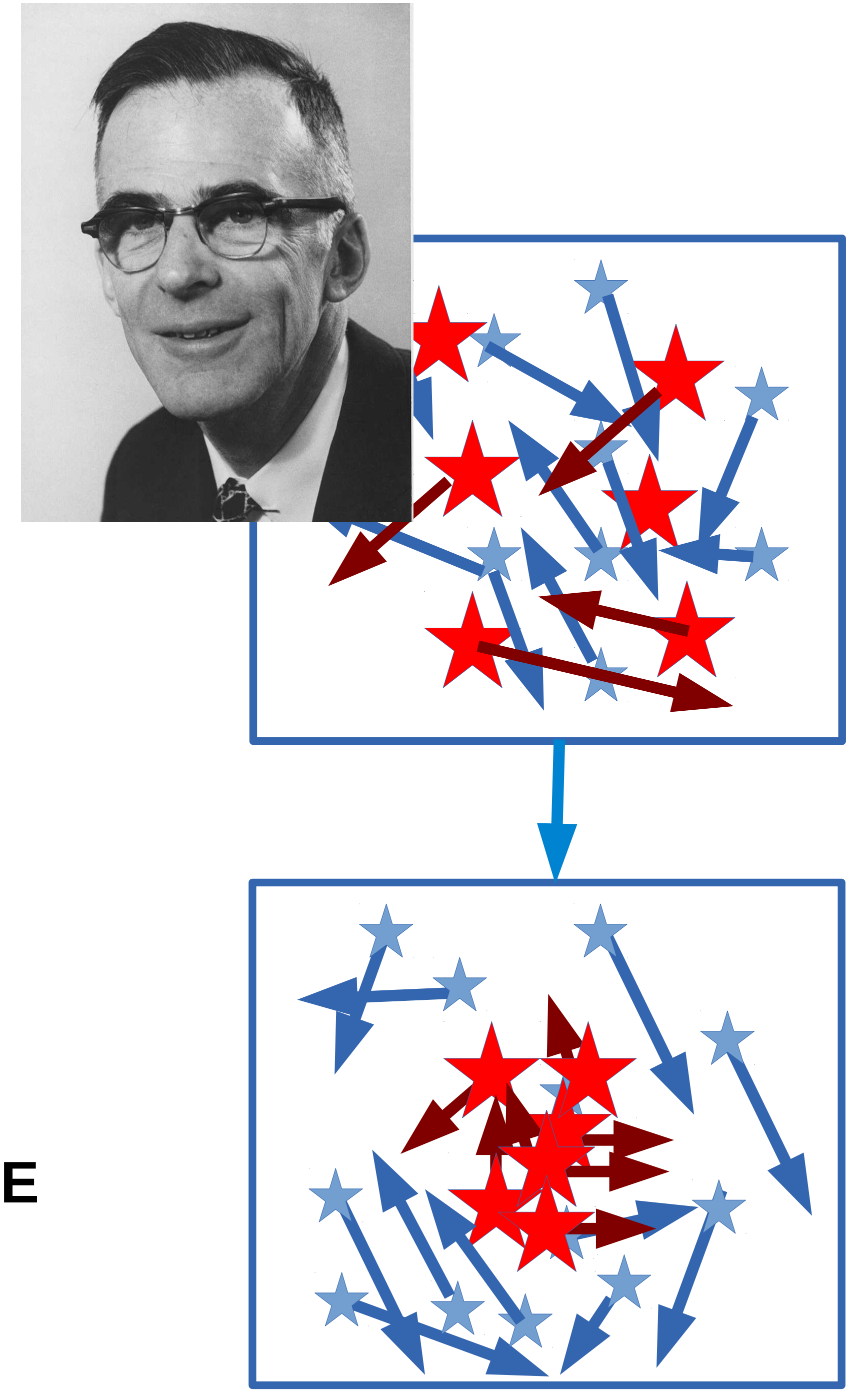
$$m_i\, v_i^2 \;\sim\; m_j\, v_j^2$$

$$\rightarrow\; v(m)\; \mu\;\; m^{-0.5}$$

More massive stars transfer kinetic energy to light stars and slow down



3. Equipartition and Spitzer's Instability



But theorists predict cases when equipartition CANNOT be reached

Spitzer (1969): In an idealized system of 2 masses m_1 and m_2 ($m_2 >> m_1$, $M_i = \Sigma\, m_i$), equipartition cannot be reached if

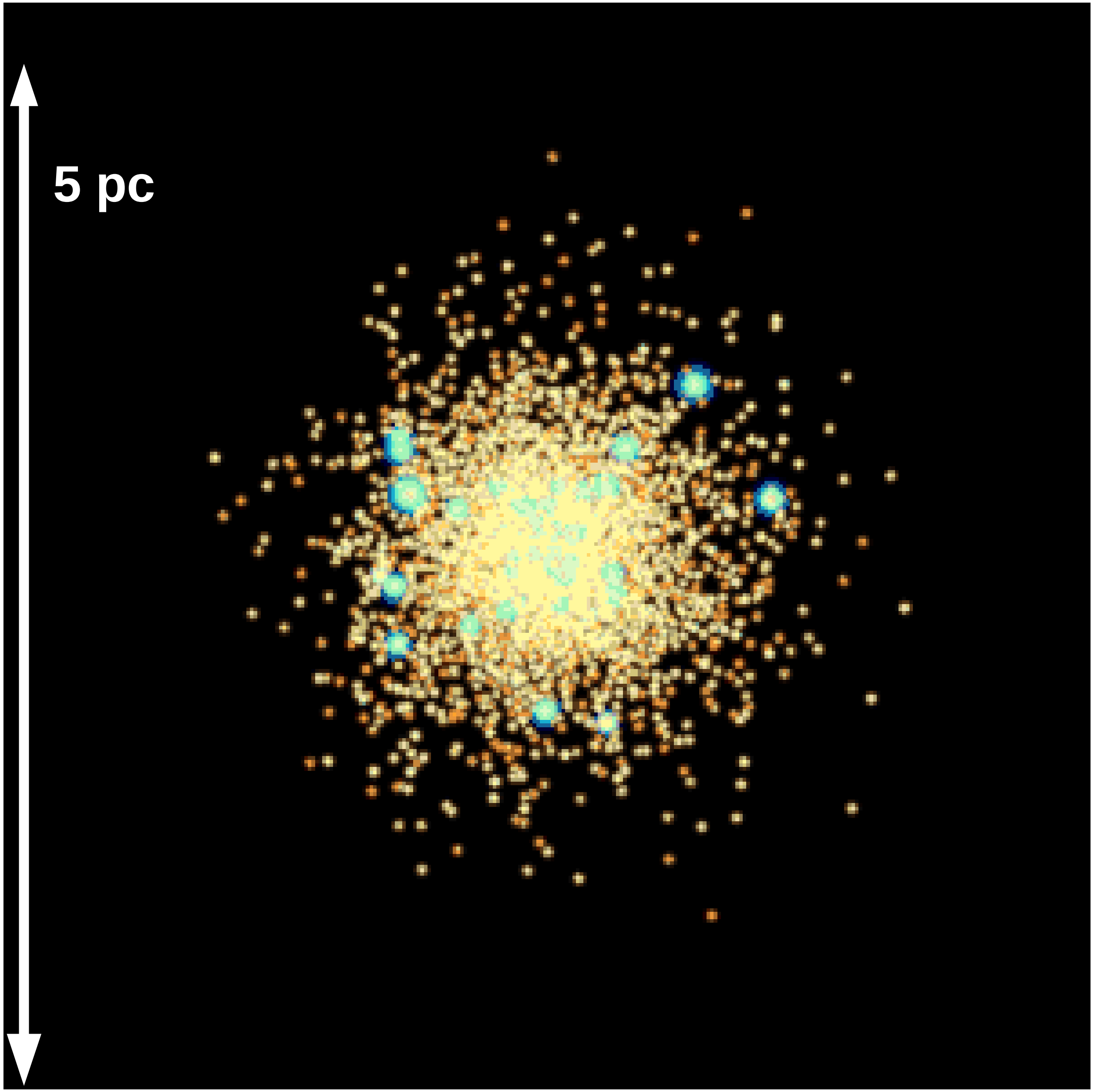
$$\boxed{M_2 > 0.16\, M_1\, (m_2/m_1)^{3/2}}$$

MASSIVE STARS DYNAMICALLY DECOUPLE FROM LIGHT STARS: the velocity dispersion of massive stars grows (Spitzer's instability)

MASSIVE STARS SINK TO THE CENTRE WHERE FORM BINARIES EJECTING EACH OTHER by 3-body

(Bonnell & Davies 1998; Allison+ 2009; Portegies Zwart+ 2010)

How common is Spitzer's instability?



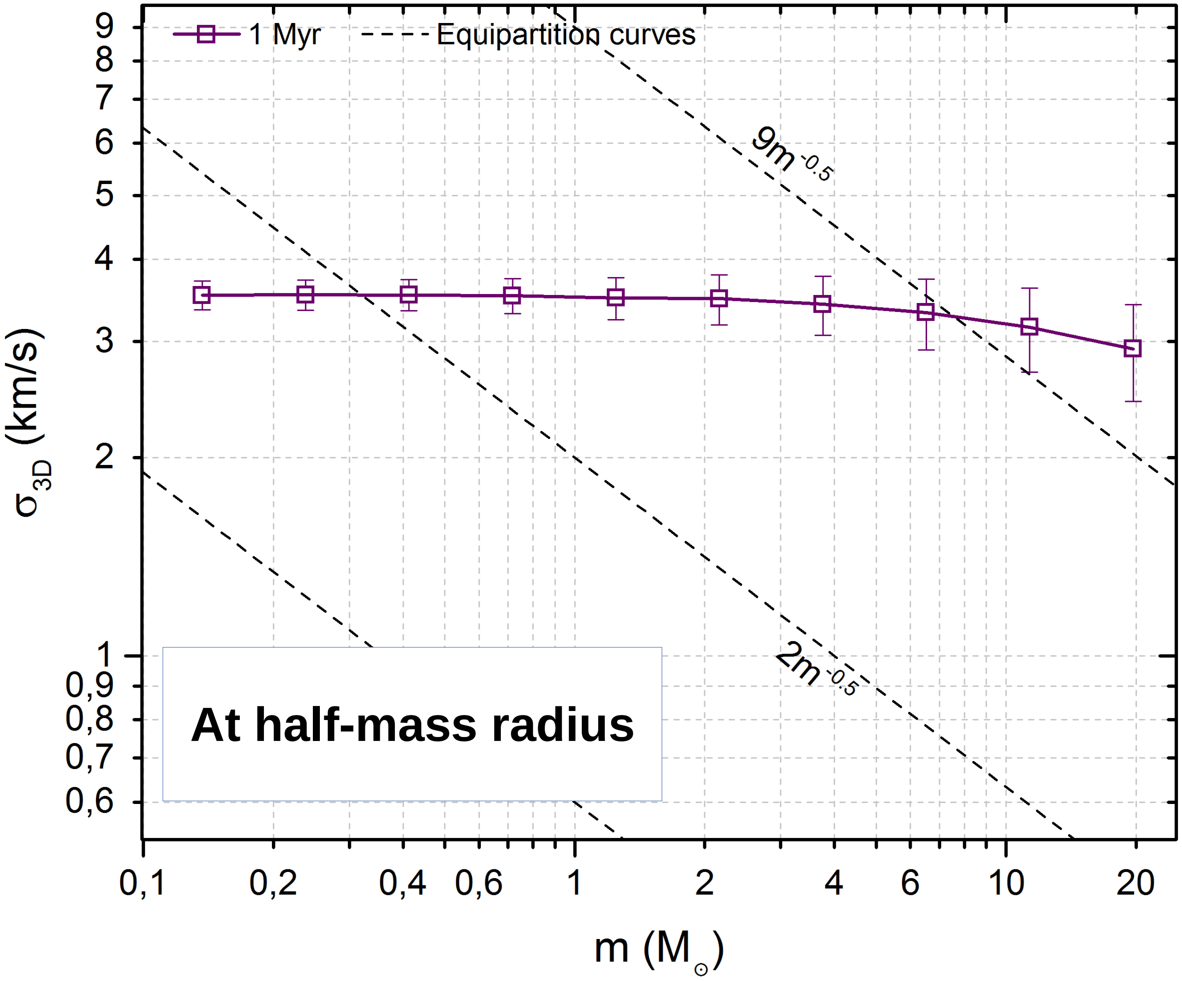
N-body and Monte Carlo simulations needed!

Trenti & van der Marel 2013;
Bianchini et al. 2016;
Parker et al. 2016;
Spera, MM & Jeffries 2016

3. Equipartition and Spitzer's Instability

Star clusters try to reach equipartition but never attain it in steady state:

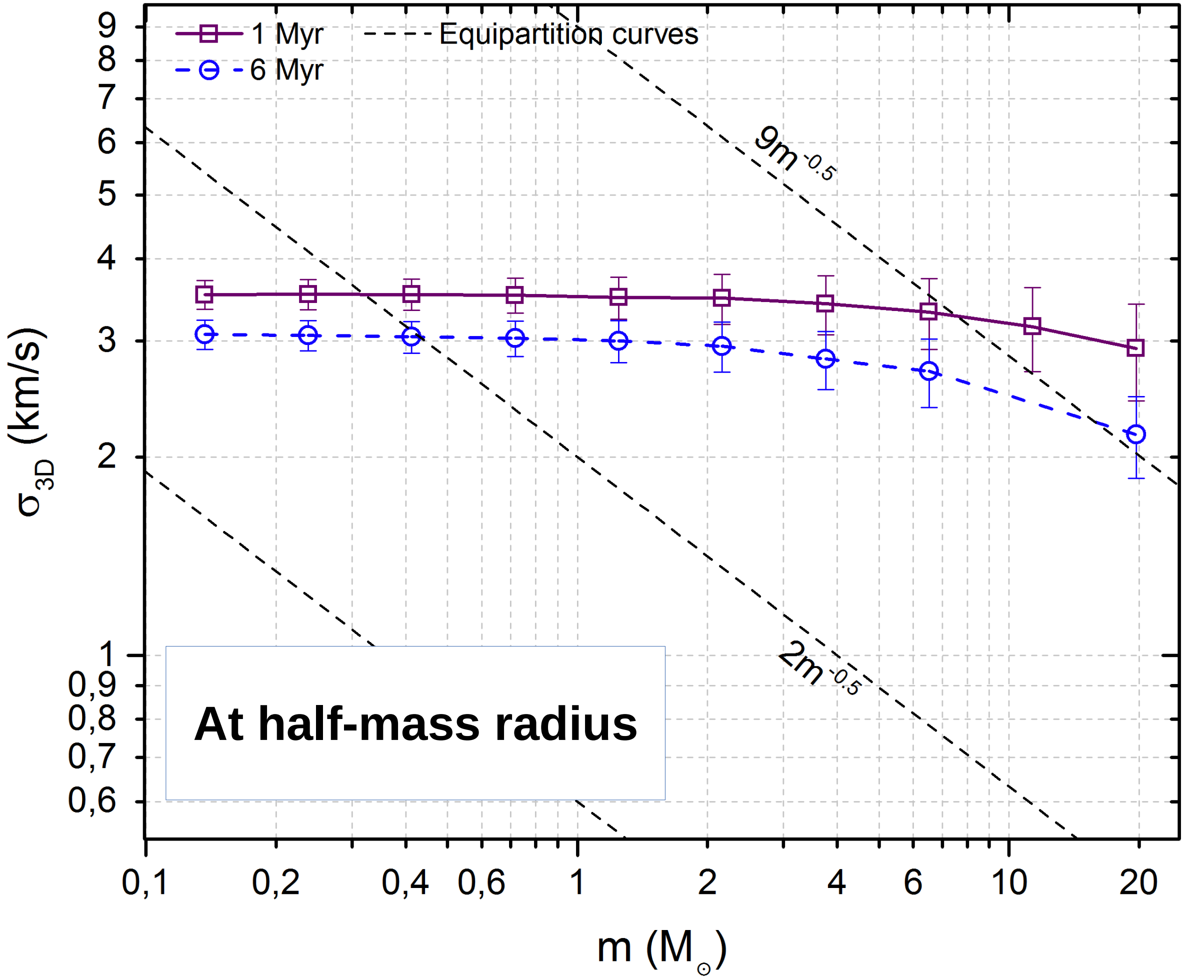
- initially flat sigma profile



At half-mass radius

Figure from Spera, MM & Jeffries 2016
See also Trenti & van der Marel 2013;
Bianchini et al. 2016; Parker et al. 2016

3. Equipartition and Spitzer's Instability



Star clusters try to reach equipartition but never attain it in steady state:

- initially flat sigma profile

- high mass stars tend to equipartition

Figure from Spera, MM & Jeffries 2016
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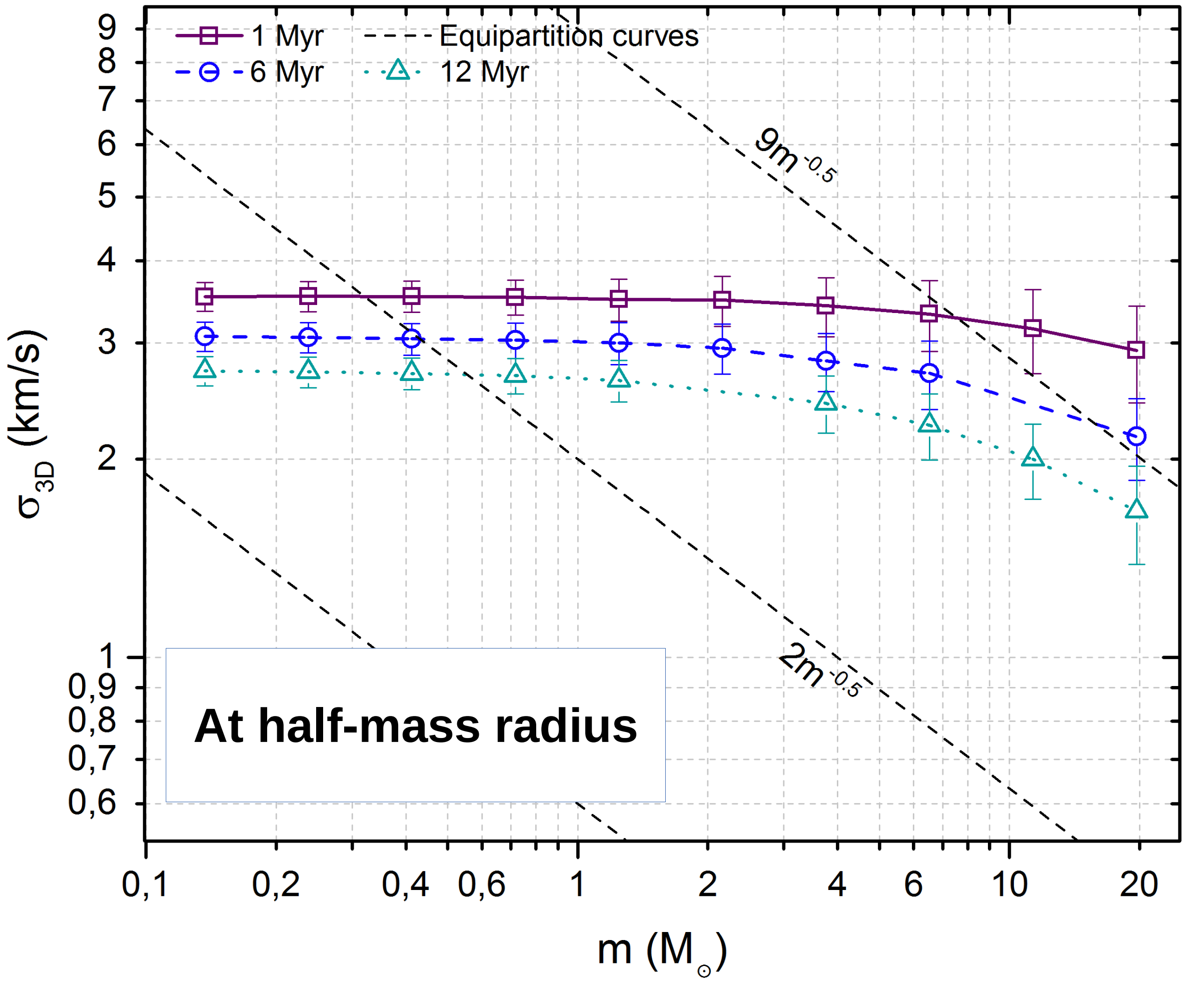

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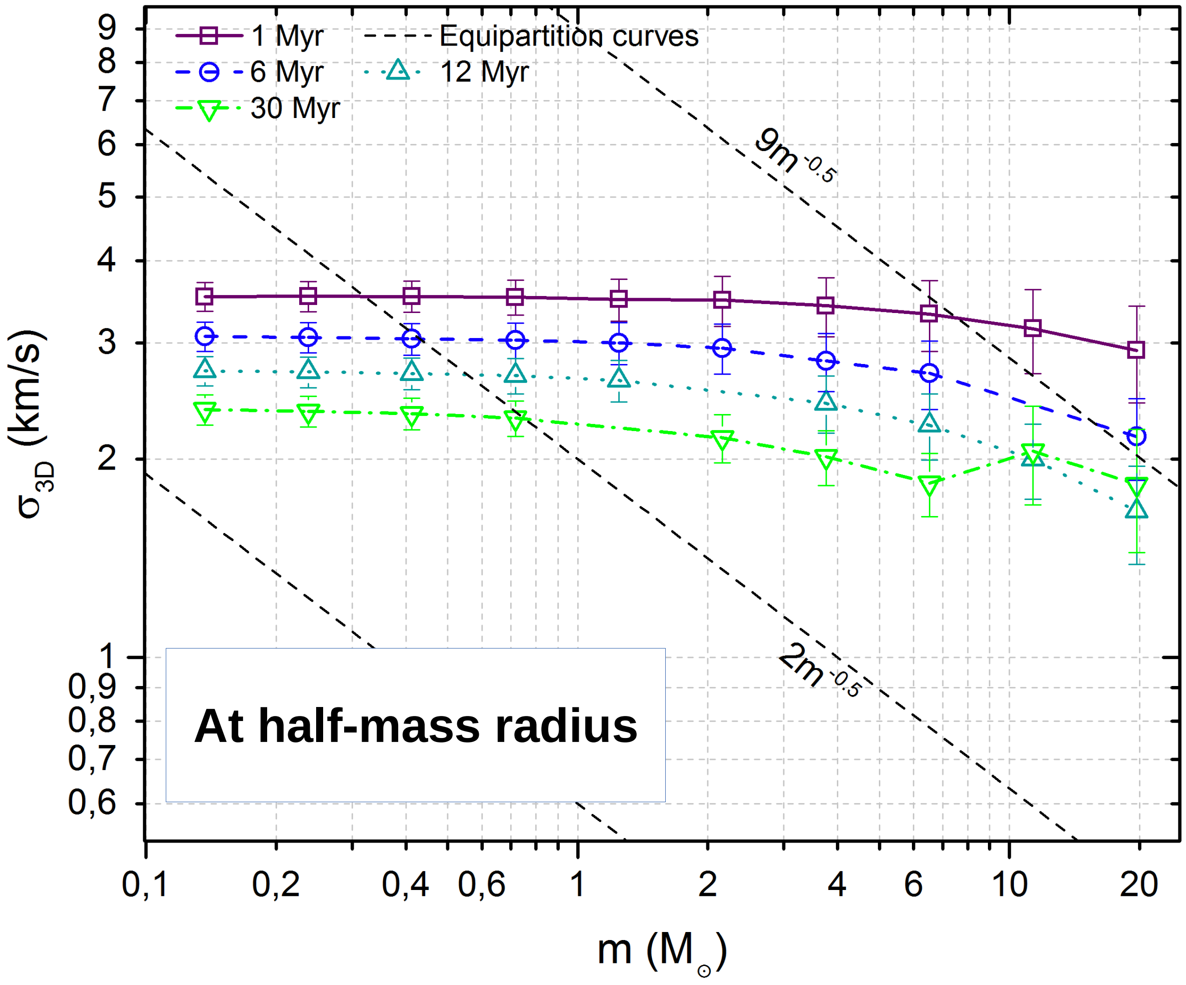

Star clusters try to reach equipartition but never attain it in steady state:

- **initially flat sigma profile**

- **high mass stars tend to equipartition**

- **high mass stars sink to the centre where form binaries**

- **high mass stars become hotter**

Figure from Spera, MM & Jeffries 2016
See also Trenti & van der Marel 2013; Bianchini et al. 2016; Parker et al. 2016

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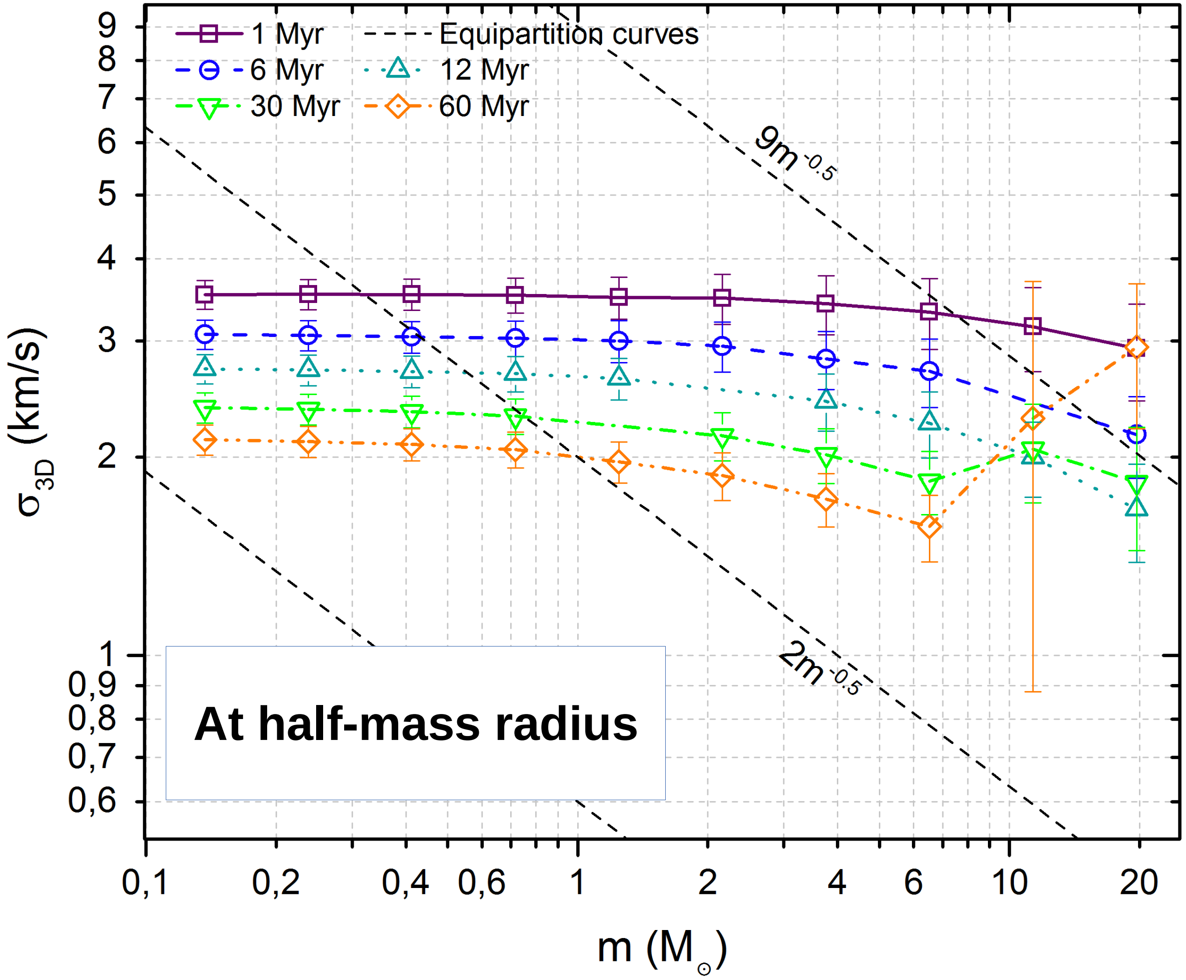

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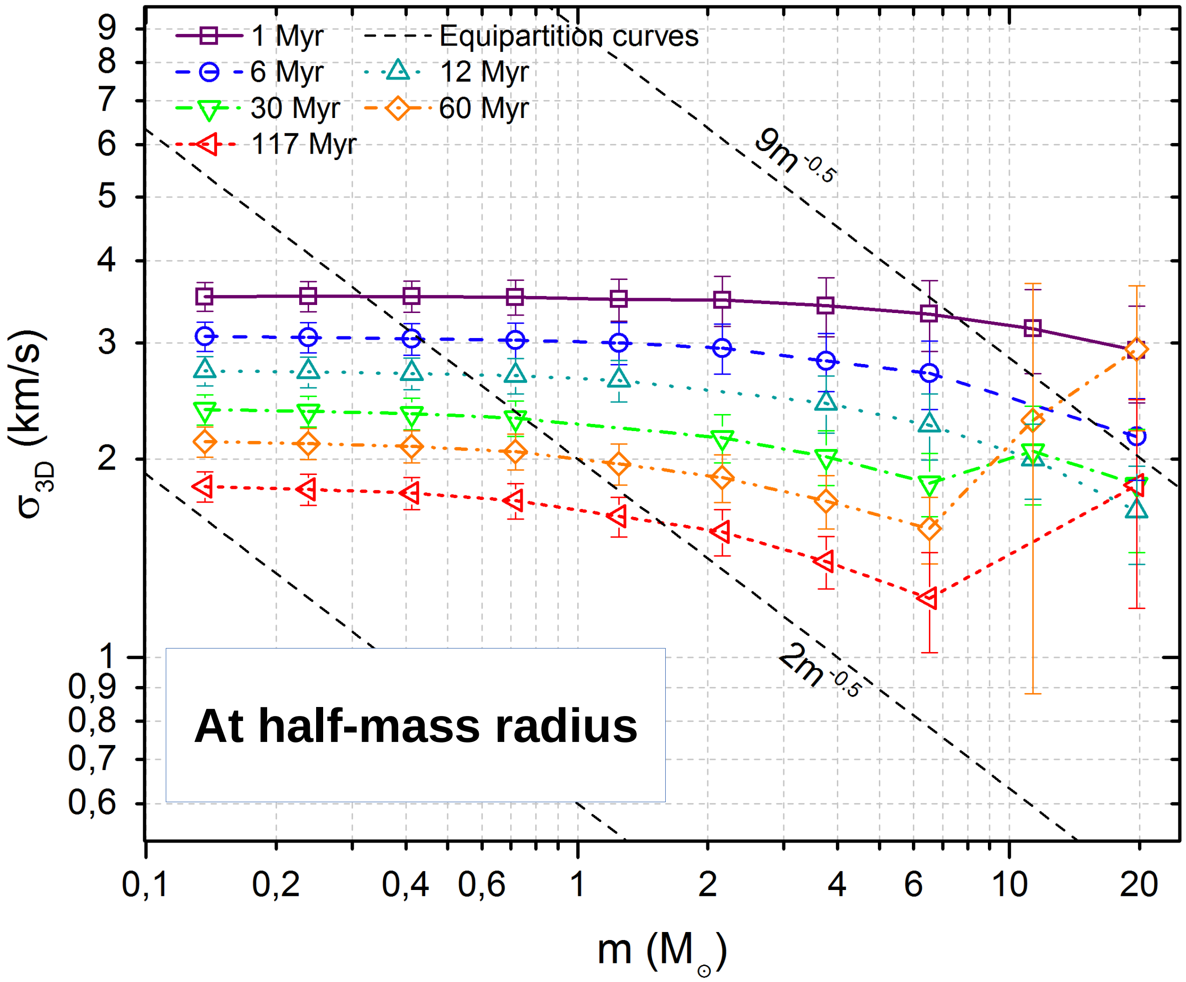

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Star clusters try to reach equipartition but never attain it in steady state:

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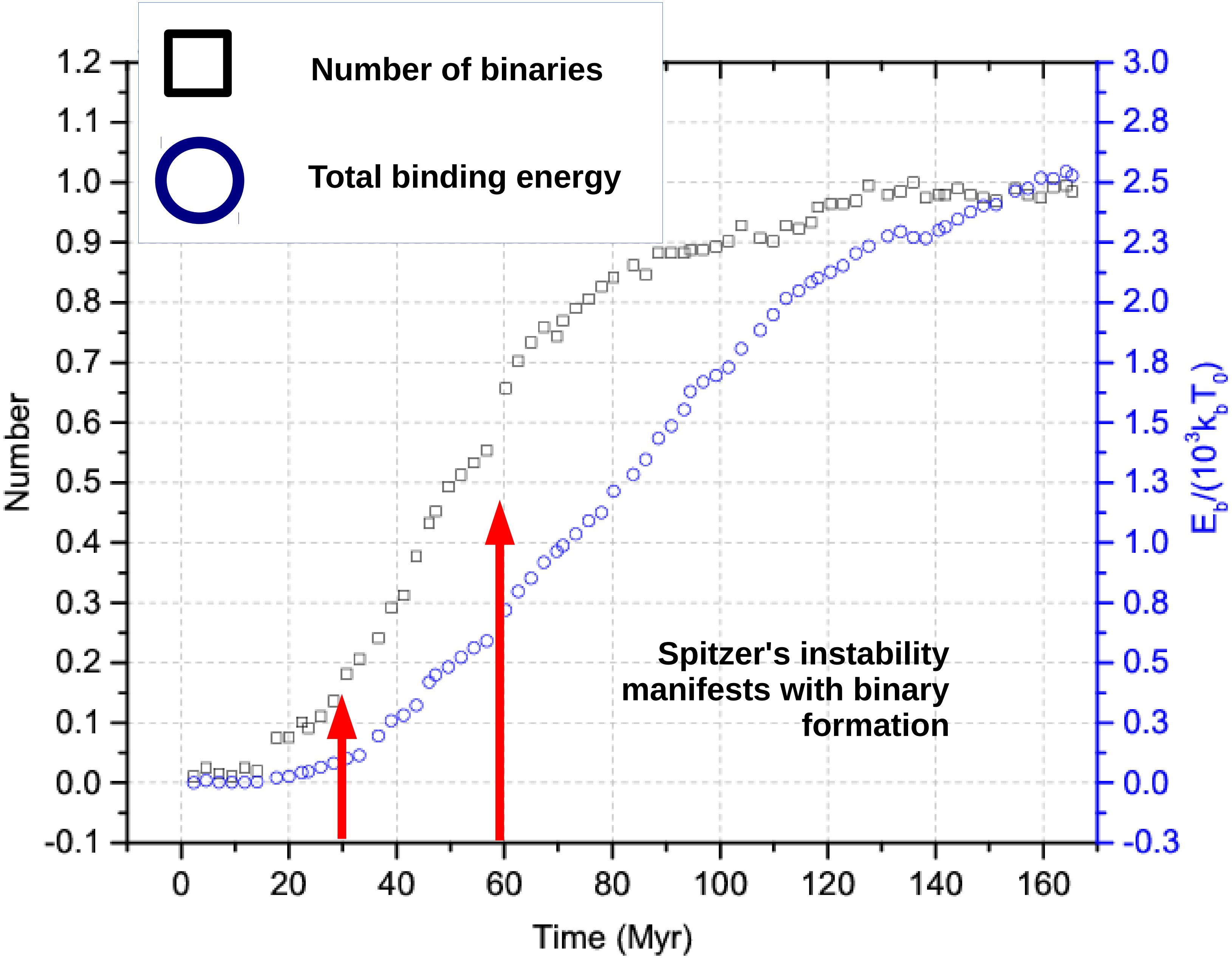
BEHAVIOUR EXPECTED FROM SPITZER INSTABILITY

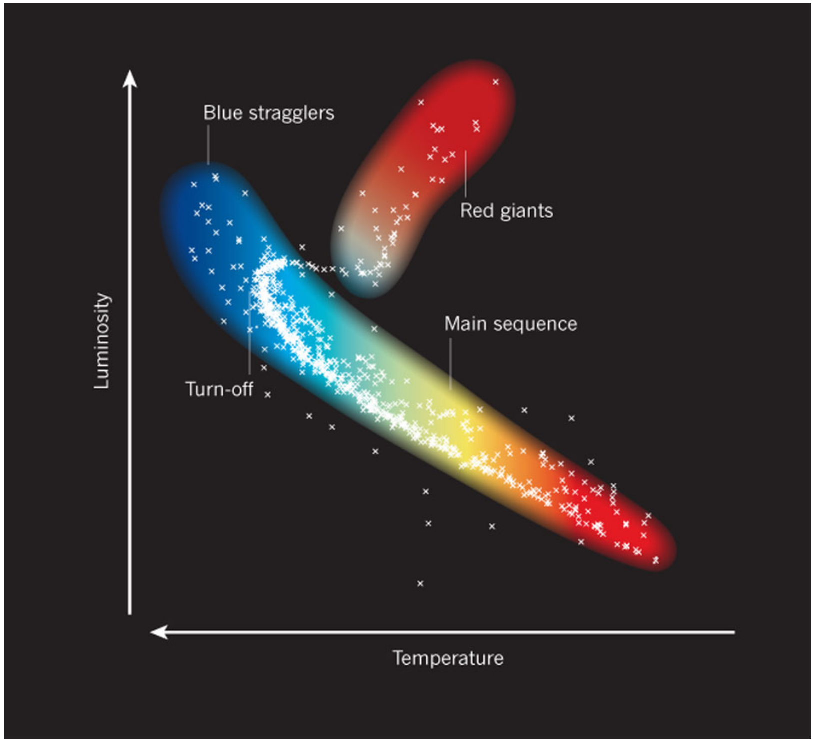
3. Equipartition and Spitzer's Instability



Spitzer's instability manifests with binary formation

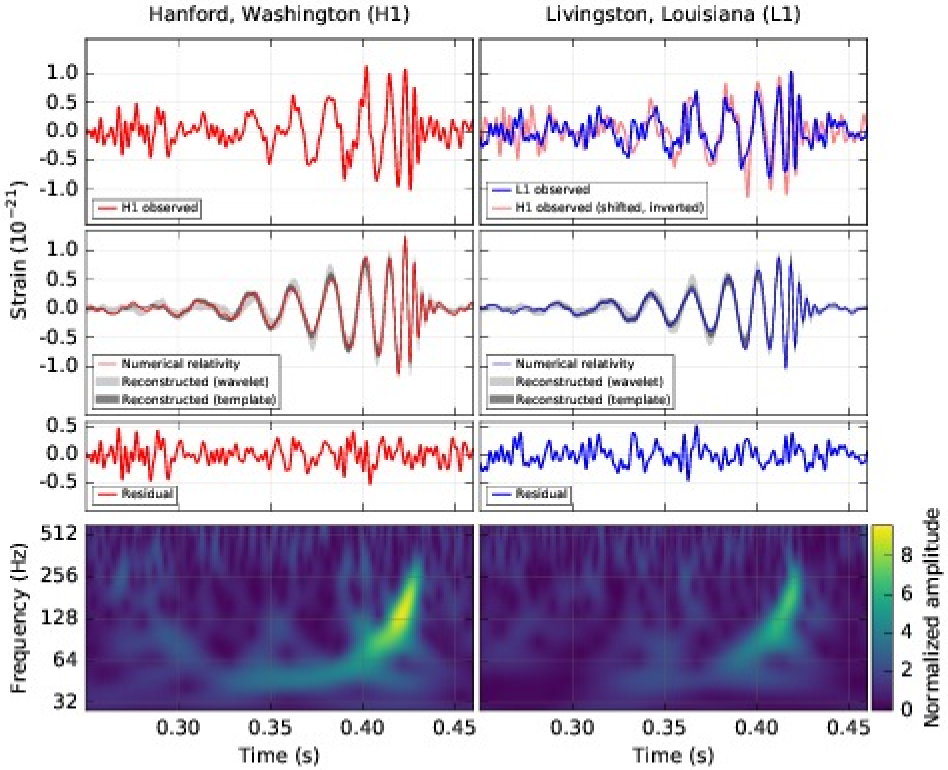
Figure from Spera, MM & Jeffries 2016
see also Trenti & van der Marel 2013; Bianchini et al. 2016; Parker et al. 2016

4. Stellar EXOTICA



- * blue straggler stars

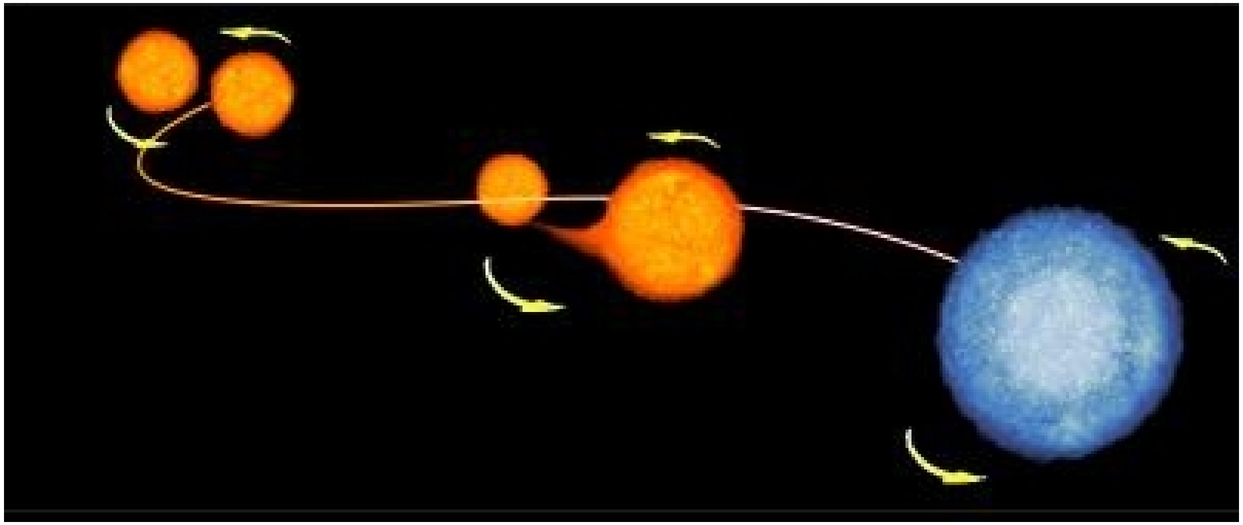
- * massive
  black hole
  binaries
  >20 Msun



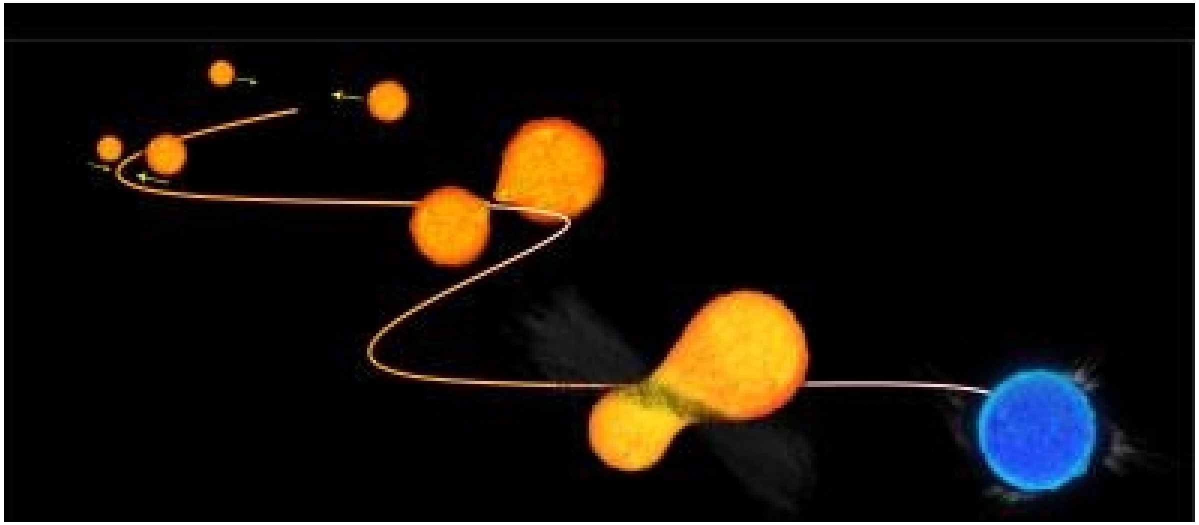
- * intermediate-mass
  black holes (IMBHs)
  100 – 10'000 Msun

© The LIGO and Virgo Collaborations, Physical Review Letters 116, 061102 (2016)

4.1 Blue straggler stars



MASS TRANSFER in BINARIES



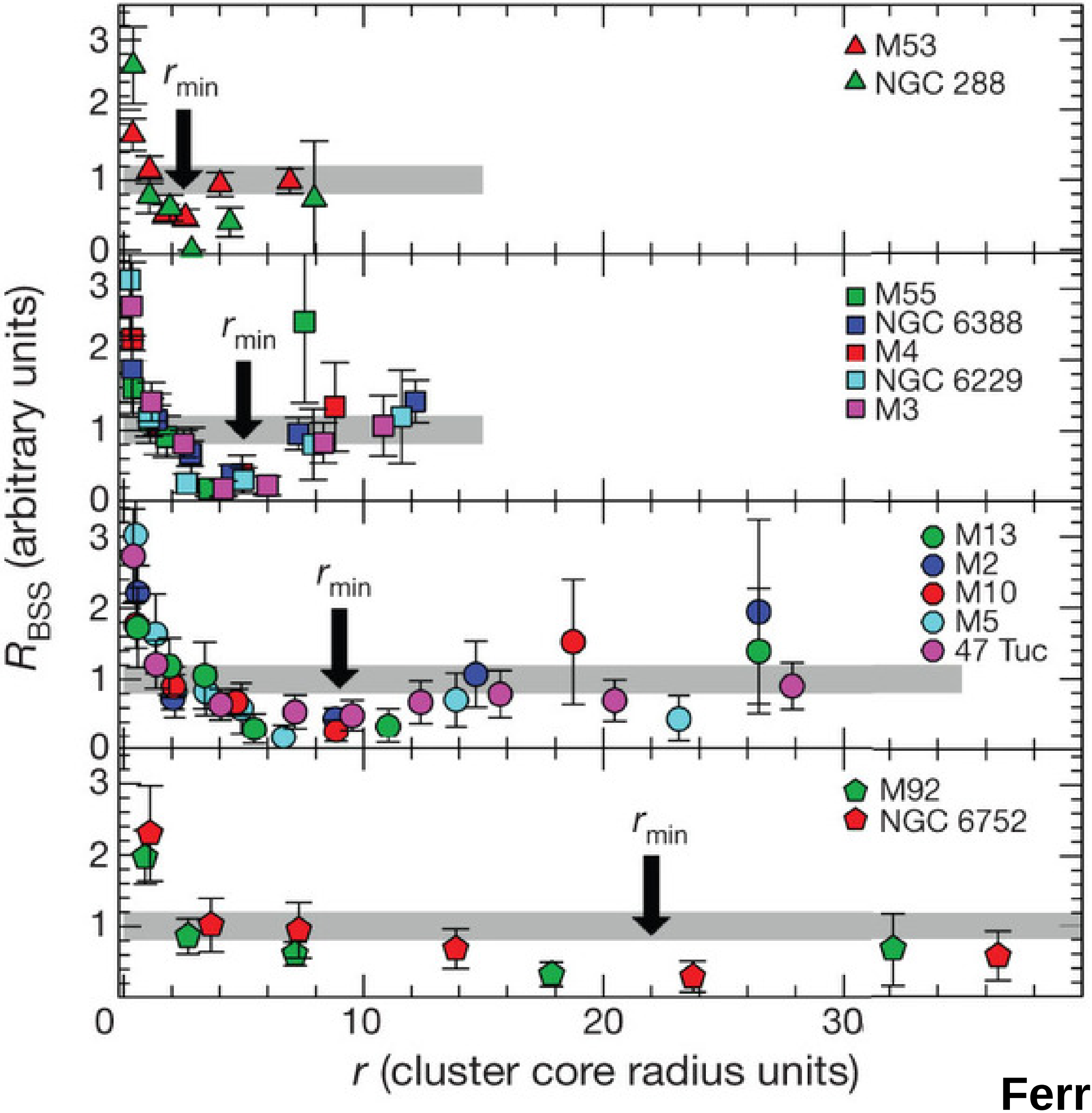
THREE-BODY ENCOUNTERS CAN TRIGGER COLLISIONS

See Francesco's talk yesterday

McCrea 1964, MNRAS, 128, 147; Ferraro et al. 1993, AJ, 106, 2324; Sigurdsson et al. 1994, ApJ, 431, L115; Procter Sills et al. 1995, ApJ, 455, L163; Hurley et al. 2001, MNRAS, 323, 630; Davies et al. 2004, MNRAS, 349, 129; Piotto et al. 2004, ApJ, 604, L109; MM et al. 2004, ApJ, 605, L29; MM et al. 2006, MNRAS, 373, 361; Ferraro et al. 2006, ApJ, 638, 433; Leigh et al. 2007, ApJ, 661, 210;
Ferraro et al. 2009, Nature, 462, 1028; Knigge et al. 2009, Nature, 457, 288 and many others

4.1 Blue straggler stars

Blue straggler radial distribution interpreted as dynamical clock



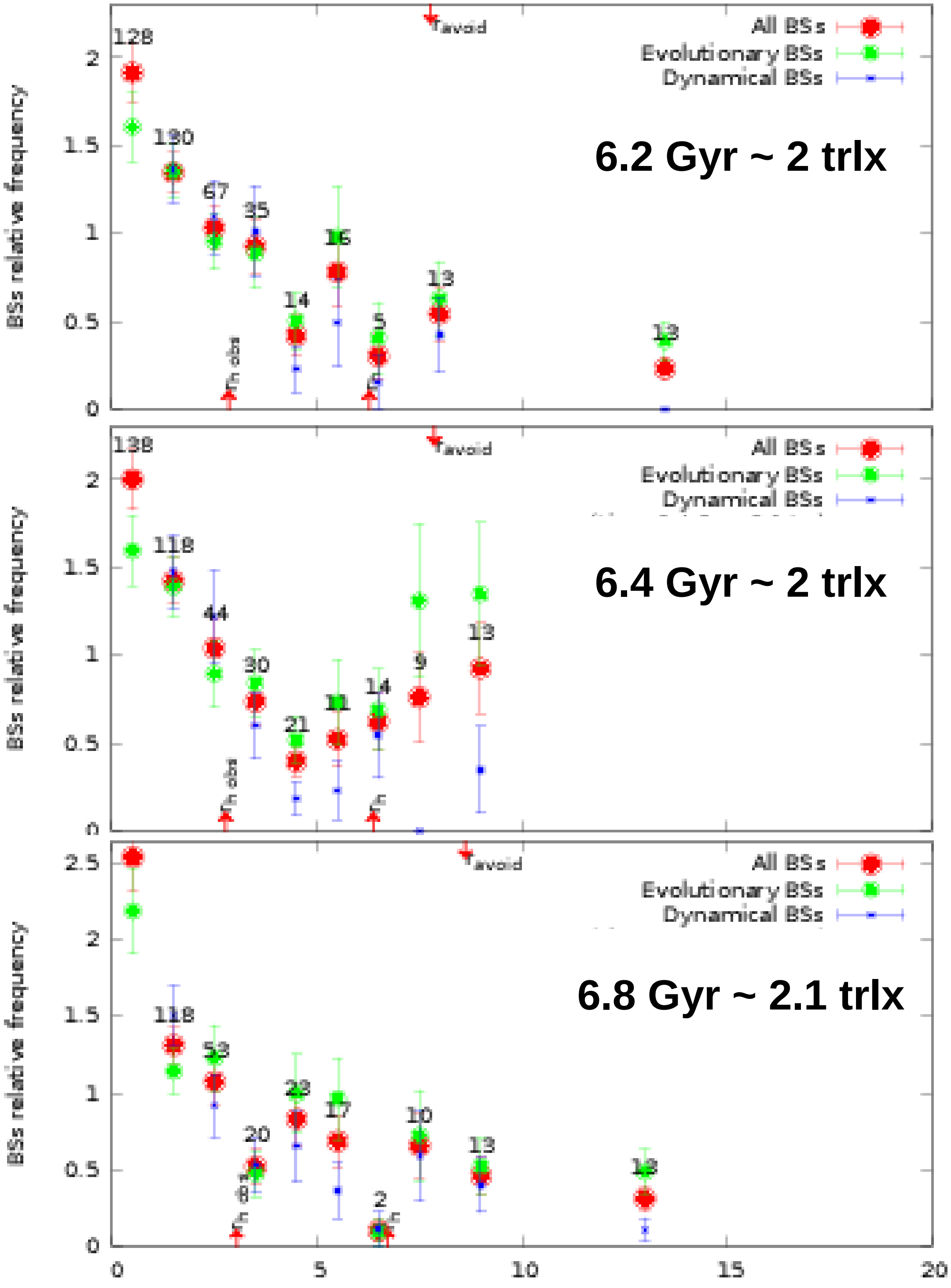
See Francesco's talk

Ferraro et al. 2012, Nature, 492, 393

4.1 Blue straggler stars

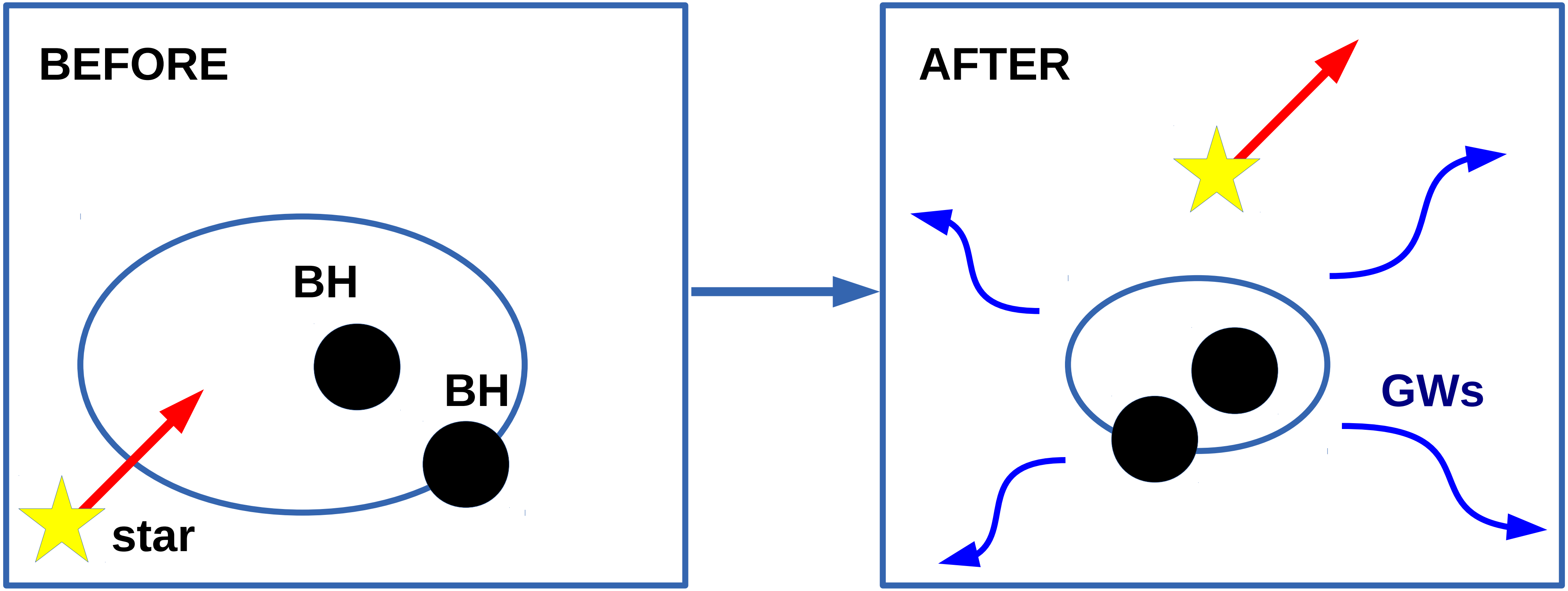
Blue straggler radial distribution interpreted as dynamical clock

but Monte Carlo simulations suggest minimum is TRANSIENT



Hypki & Giersz 2017, arXiv:1604.07054v1

4.2 Massive black hole binaries

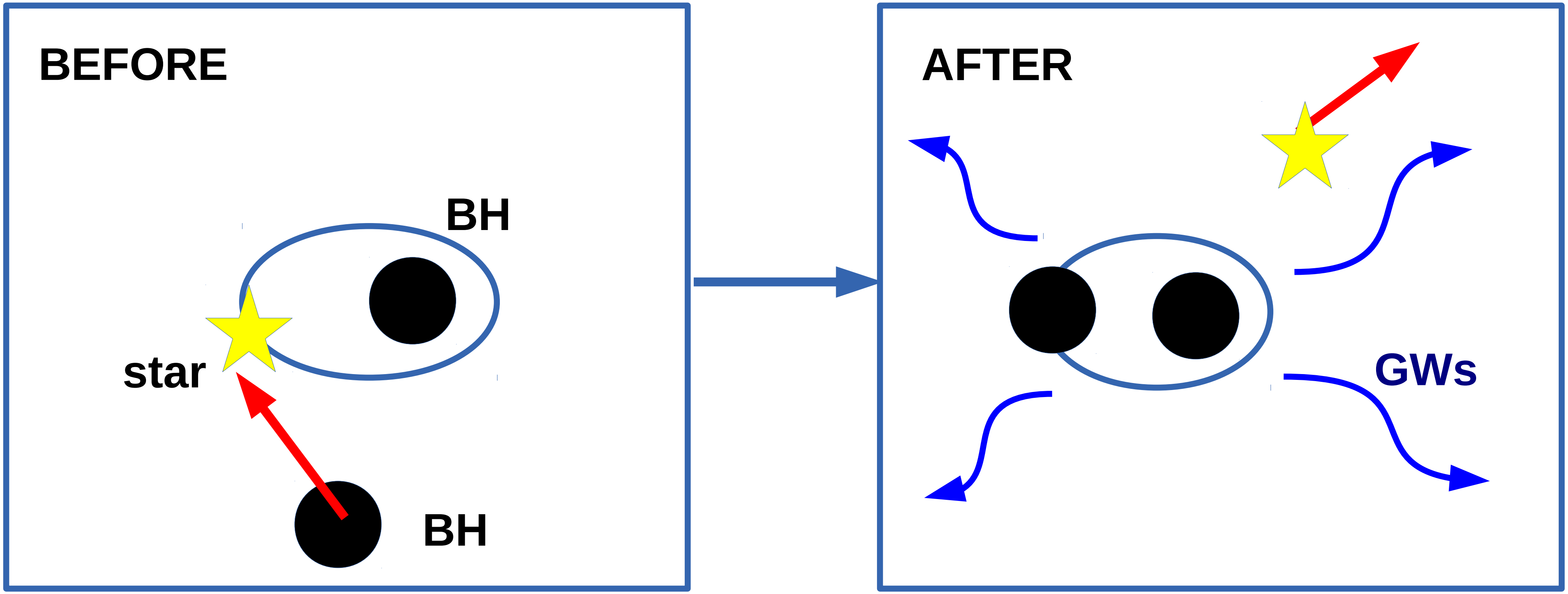


In a flyby, the star acquires kinetic energy from the binary

→ *the binary shrinks*

→ *shorter coalescence time*

4.2 Massive black hole binaries

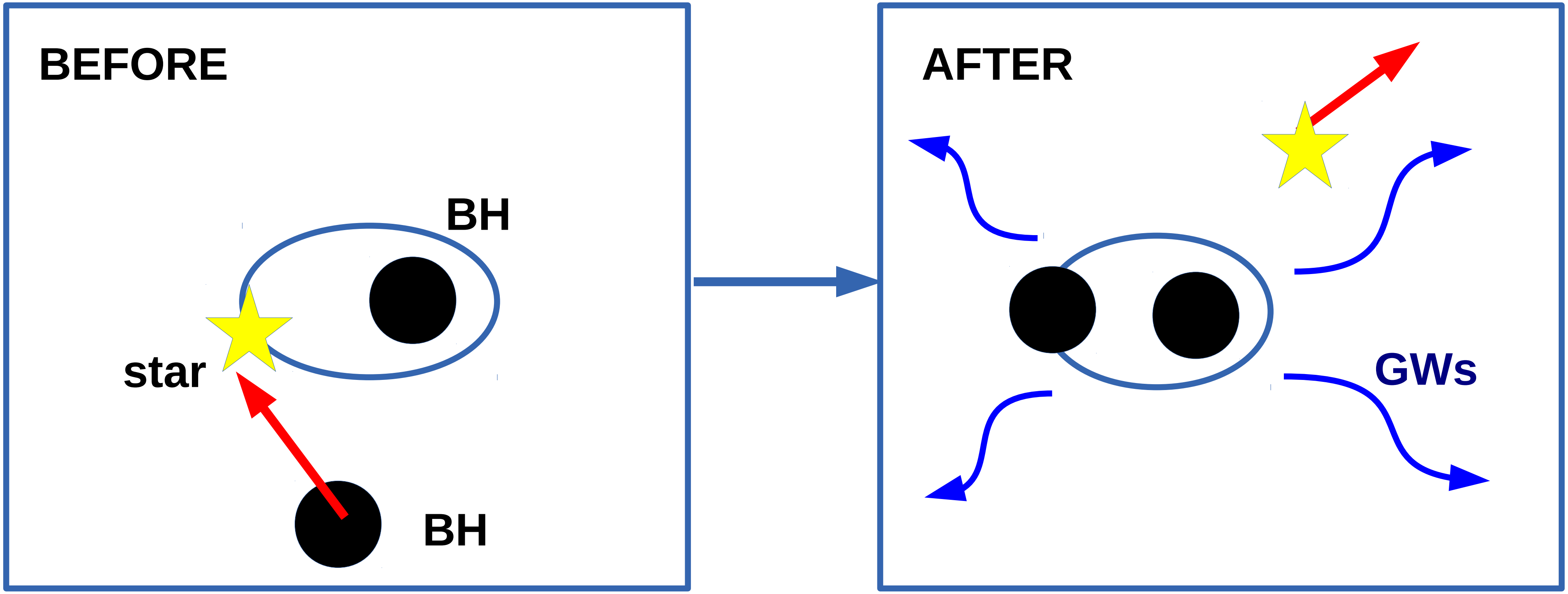


Exchanges bring BHs in binaries

BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!

BH born from single star in the field never acquires a companion
BH born from single star in a cluster likely acquires companion from dynamics

4.2 Massive black hole binaries



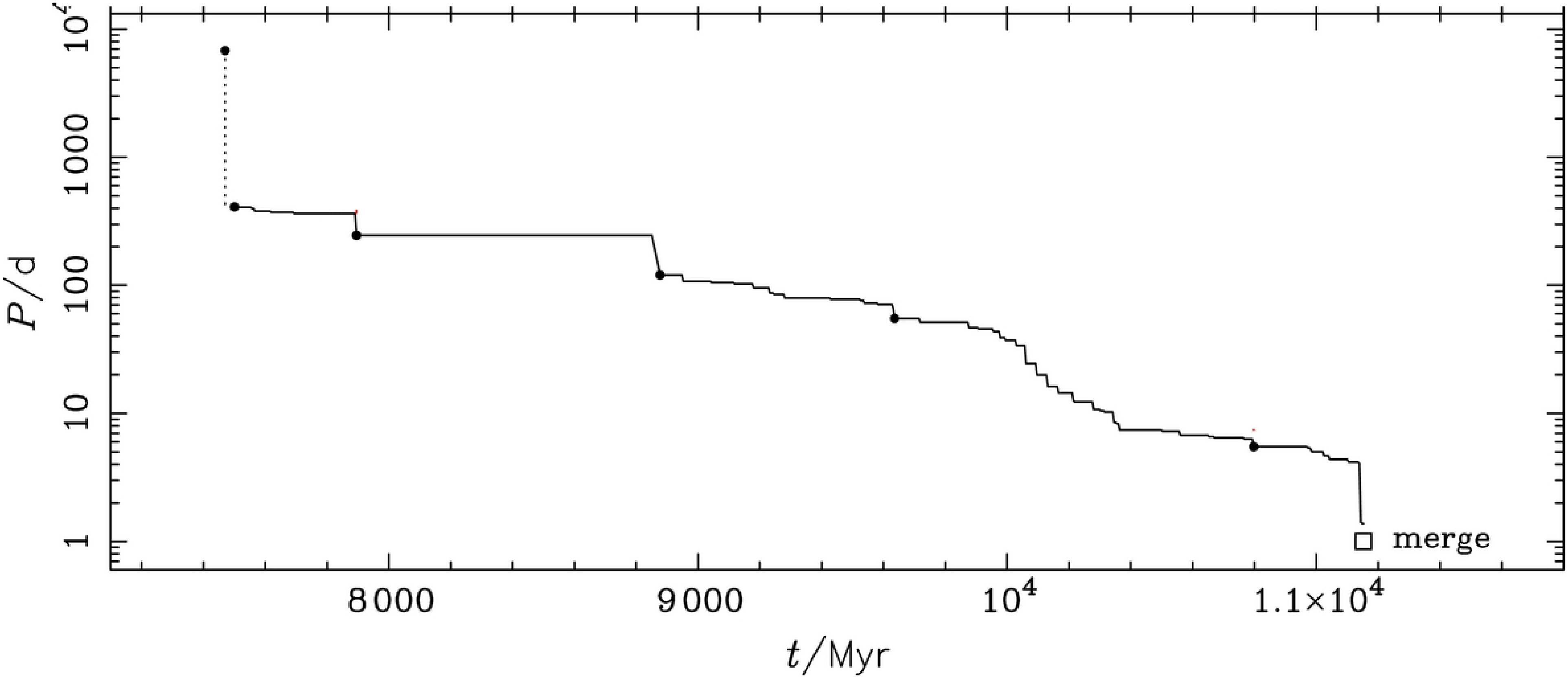
>90% BH-BH binaries in young star clusters form by exchange

(Ziosi, MM+ 2014, MNRAS, 441, 3703)

EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH

- *THE MOST MASSIVE BHs*
- *HIGH ECCENTRICITY*
- *MISALIGNED BH SPINS*

4.2 Massive black hole binaries



Hurley+ 2016, PASA, 33, 36

Hills 1992, AJ, 103, 1955; Sigurdsson & Hernquist 1993, Nature, 364, 423;
Portegies Zwart & McMillan 2000, ApJ, 528, L17; Aarseth 2012, MNRAS, 422, 841;
Breen & Heggie 2013, MNRAS, 432, 2779; MM+ 2013, MNRAS, 429, 2298;
Ziosi+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, PhRvL, 115, 1101;
Rodriguez+ 2016, PhRvD, 93, 4029; MM 2016, MNRAS, 459, 3432;
Banerjee 2017, MNRAS, 467, 524 and many others

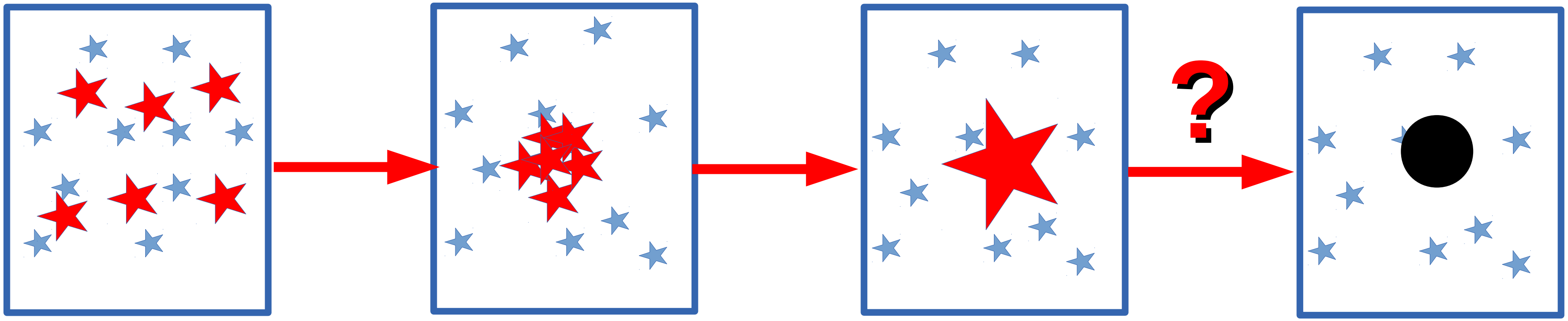
4.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

1. RUNAWAY COLLISIONS

Mass segregation is fast in young star clusters:

$$t_{\rm DF}(25\,M_\odot) \sim 2\,Myr\,\left(\frac{t_{\rm rlx}}{50\,{\rm Myr}}\right) < t_{\rm SN}$$

Massive stars segregate to the centre where form binaries and collide



Massive super-star forms and possibly collapses to IMBH

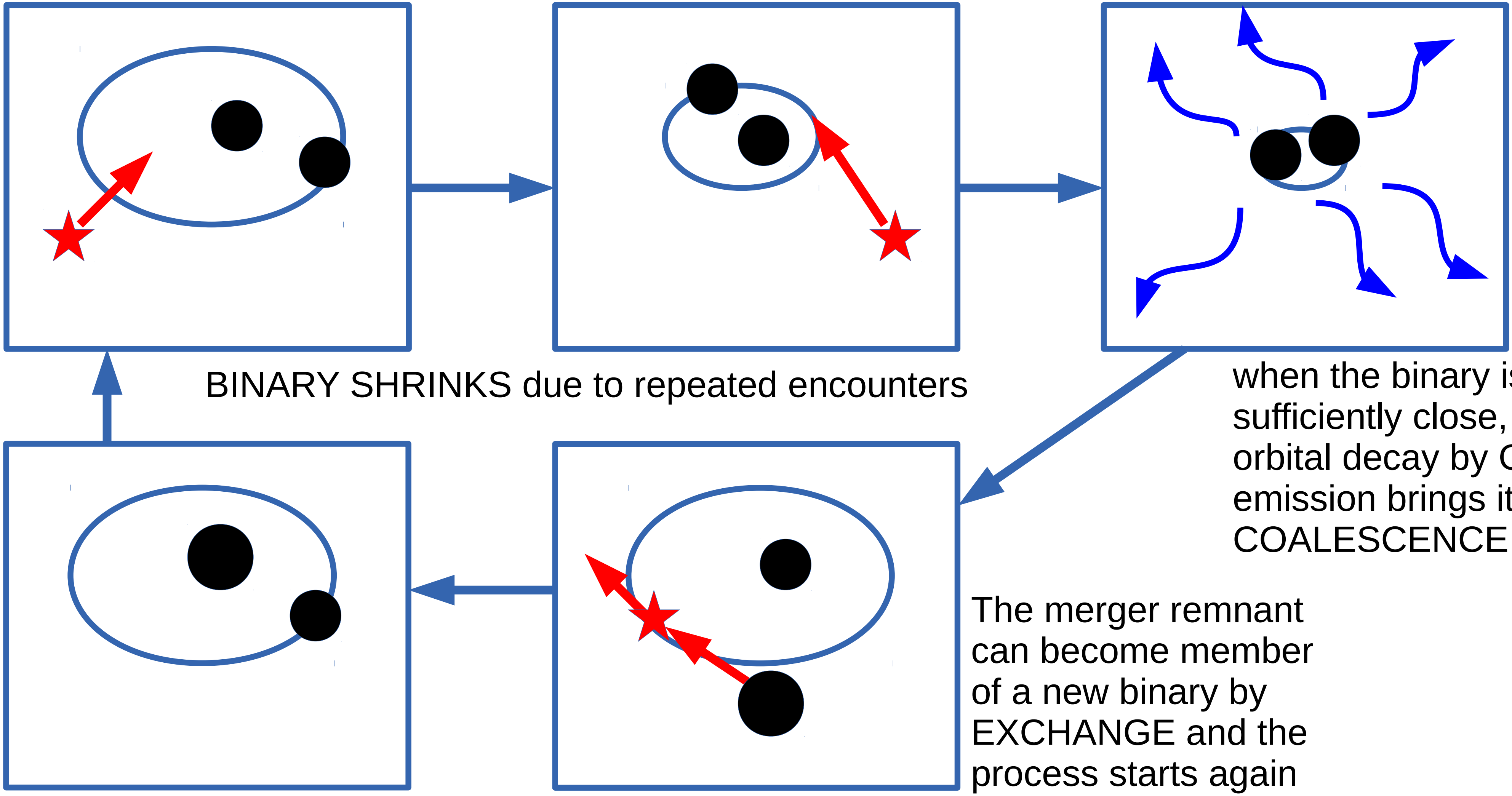
What is the final mass of the collision product?
DEPENDENCE ON METALLICITY and SN!!!

Colgate 1967; Sanders 1970; Portegies Zwart+ 1999, 2002, 2004; Gurkan+ 2004; Freitag+ 2006; Giersz+ 2015; MM 2016

4.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

2. REPEATED MERGERs *(Formalism by Miller & Hamilton 2002)*

In a old cluster stellar BHs can grow in mass because of repeated mergers with the companion triggered by 3-body encounters

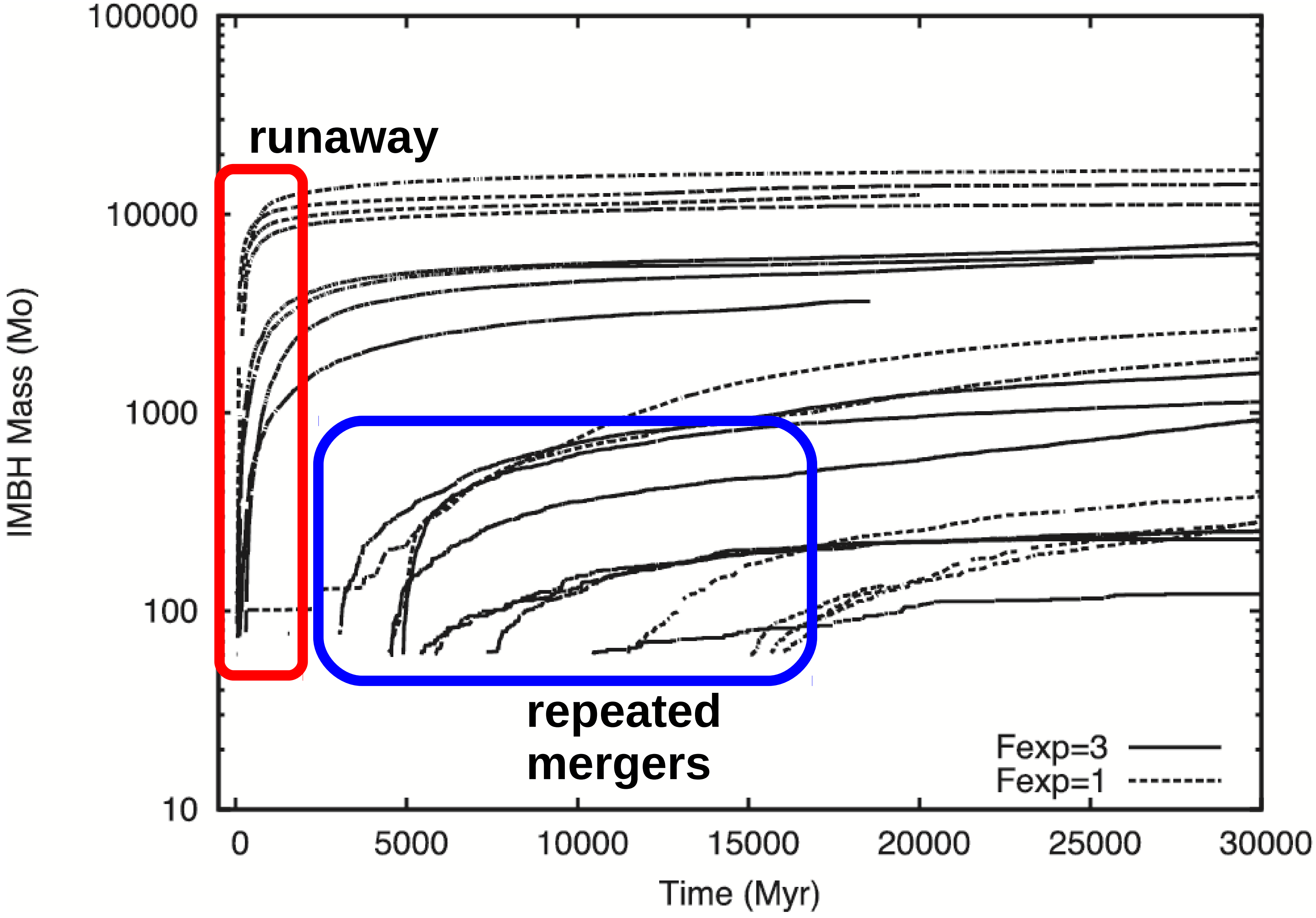


BINARY SHRINKS due to repeated encounters

when the binary is sufficiently close, orbital decay by GW emission brings it to COALESCENCE

The merger remnant can become member of a new binary by EXCHANGE and the process starts again

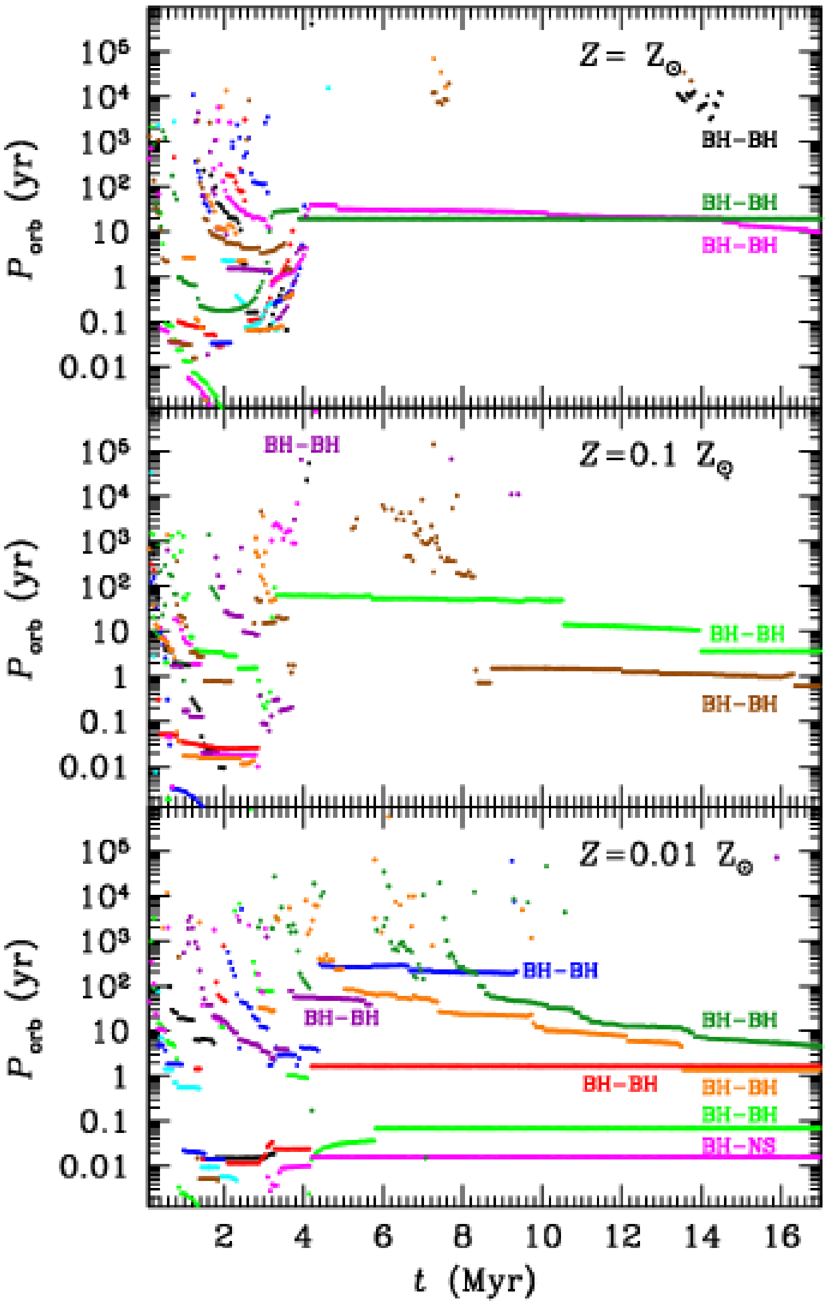
4.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)



Giersz +2015, MNRAS, 454, 3150

4.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

N-body simulations of massive clusters + stellar evolution



Collision products are efficient in acquiring companions dynamically

8 collision products out of 30 form stable binaries with other BHs:

4 BH-BH at Z = 0.01 Zsun
2 BH-BH at Z = 0.1 Zsun
2 BH-BH at Z = 1 Zsun

+ 1 BH-NS at Z = 0.01 Zsun

PERIOD from few hours to few years

Possibly JOINT SOURCES for LISA and for LIGO-Virgo

MM 2016, MNRAS, 459, 3432

5. Conclusions

– Binaries are main energy reservoir of N-body systems, through 3- or multi-body encounters (Heggie 1975)

– Core collapse reversal is most popular effect of binaries, but not the only one (Spitzer 1988 and many others)

– Binaries play major role when Spitzer's instability develops (Trenti & van der Marel 2013; Bianchini+ 2016; Parker+ 2016; Spera, MM & Jeffries 2016)

– Binaries power formation of STELLAR EXOTICA:

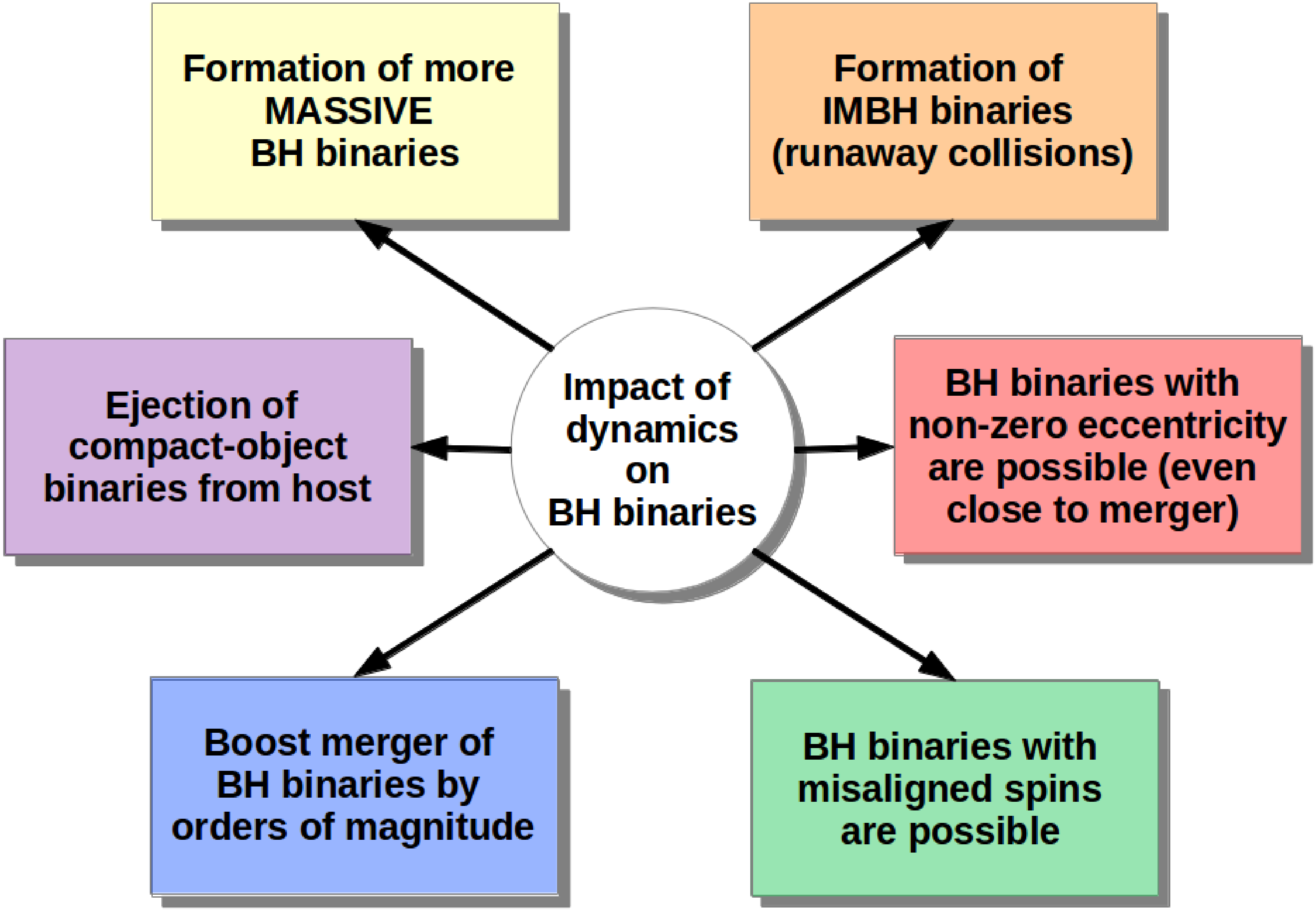
Blue straggler stars (e.g. Ferraro+ 2012; Hipky & Giersz 2017)

Massive black hole binaries
(e.g. Ziosi+ 2014; Rodriguez+ 2016; Hurley+ 2016; Banerjee 2017; Zevin+ 2017)

Intermediate mass black holes
(e.g. Portegies Zwart+ 2004; Giersz+ 2015; MM 2016)

Thank You!

4.2 Massive black hole binaries + 4.3 Intermediate-mass black holes



Impact of dynamics on BH binaries

Formation of more MASSIVE BH binaries

Formation of IMBH binaries (runaway collisions)

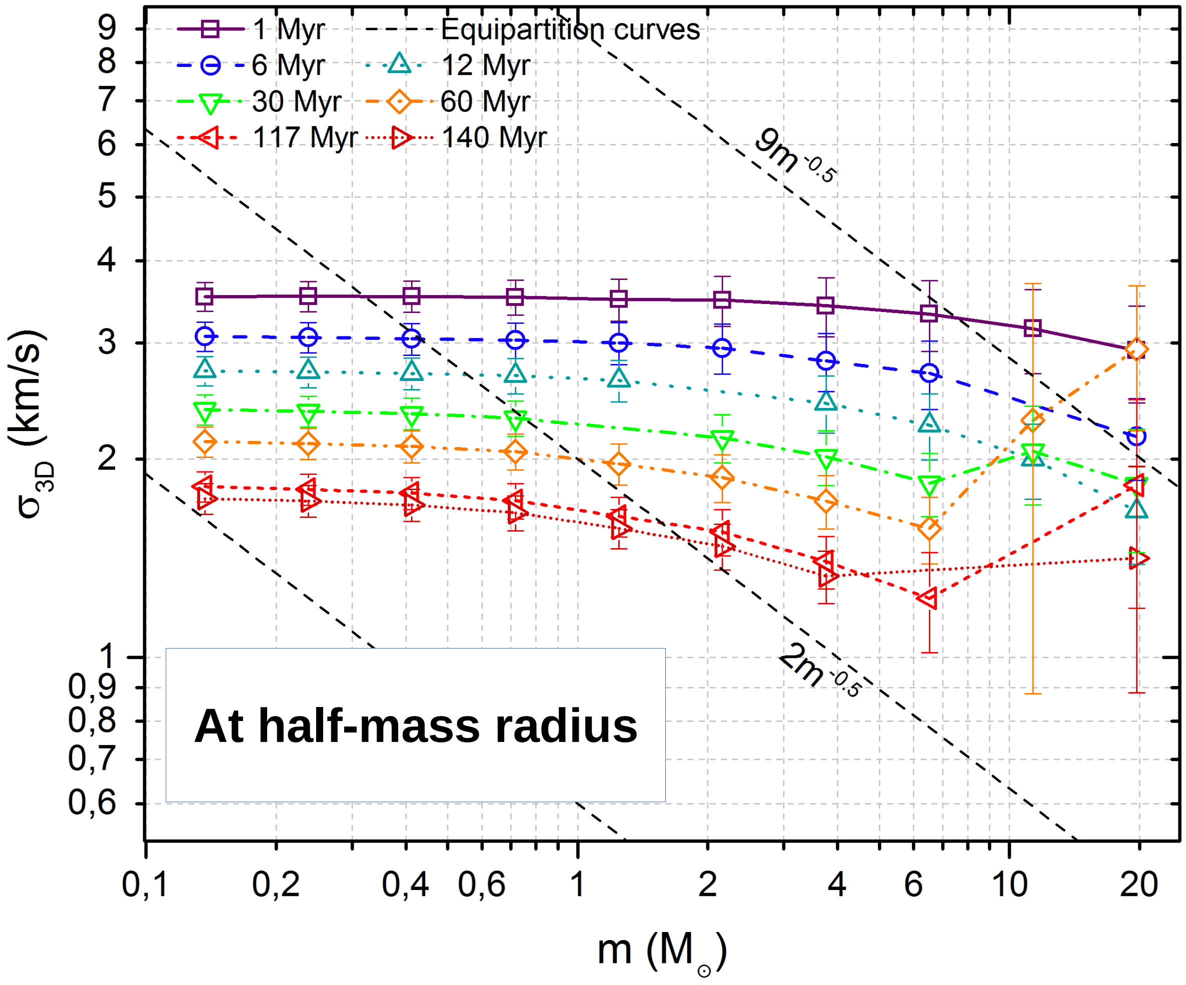
Ejection of compact-object binaries from host

BH binaries with non-zero eccentricity are possible (even close to merger)

Boost merger of BH binaries by orders of magnitude

BH binaries with misaligned spins are possible

3. Equipartition and Spitzer's Instability



Star clusters try to reach equipartition but never attain it in steady state:

- initially flat sigma profile

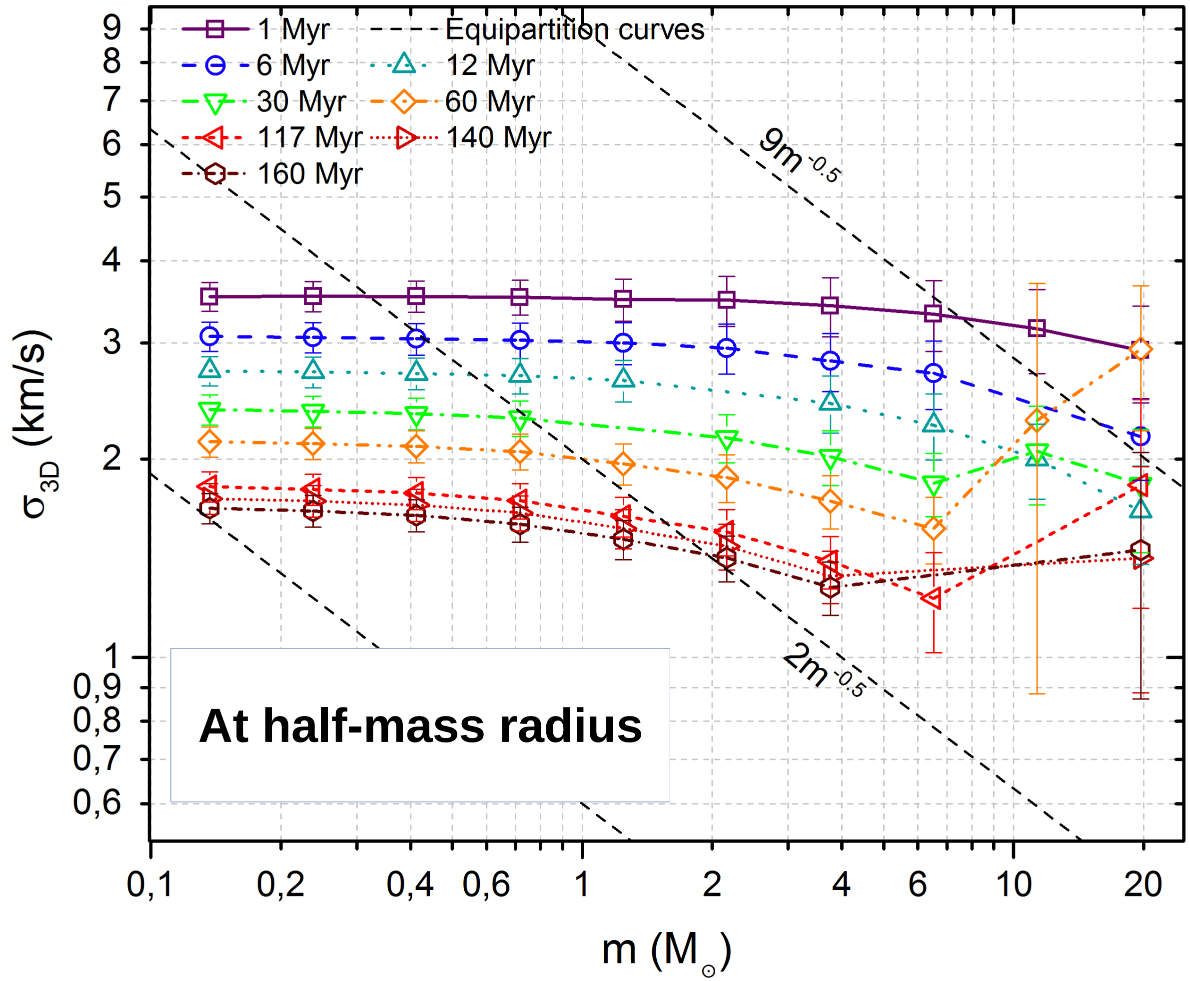
- high mass stars tend to equipartition

- high mass stars sink to the centre where form binaries

- high mass stars become hotter

Figure from Spera, MM & Jeffries 2016
See also Trenti & van der Marel 2013; Bianchini et al. 2016; Parker et al. 2016

3. Equipartition and Spitzer's Instability



Star clusters try to reach equipartition but never attain it in steady state:

- initially flat sigma profile

- high mass stars tend to equipartition

- high mass stars sink to the centre where form binaries

- high mass stars become hotter

BEHAVIOUR EXPECTED FROM SPITZER INSTABILITY

Figure from Spera, MM & Jeffries 2016
See also Trenti & van der Marel 2013; Bianchini et al. 2016; Parker et al. 2016

2. State-of-the-art simulations

How do we study impact of binaries on N-body dynamics?

DIRECT-SUMMATION N-BODY SIMULATIONS
(resolve star-binary interactions)

→ solve Newton's equation directly

$$\ddot{\vec{r}}_i = -G \sum_{j \neq i} m_j \frac{\vec{r}_i - \vec{r}_j}{\left|\vec{r}_i - \vec{r}_j\right|^3}$$

computationally expensive
(scale with N^2)

GPUs saved us (since ~2007)
Portegies Zwart+ 2007, NewA, 12, 641

better if coupled with regularization
Mikkola & Aarseth 1993, CeMDA, 57, 439

2. State-of-the-art simulations

How do we study impact of binaries on N-body dynamics?

DIRECT-SUMMATION N-BODY SIMULATIONS
(resolve star-binary interactions)

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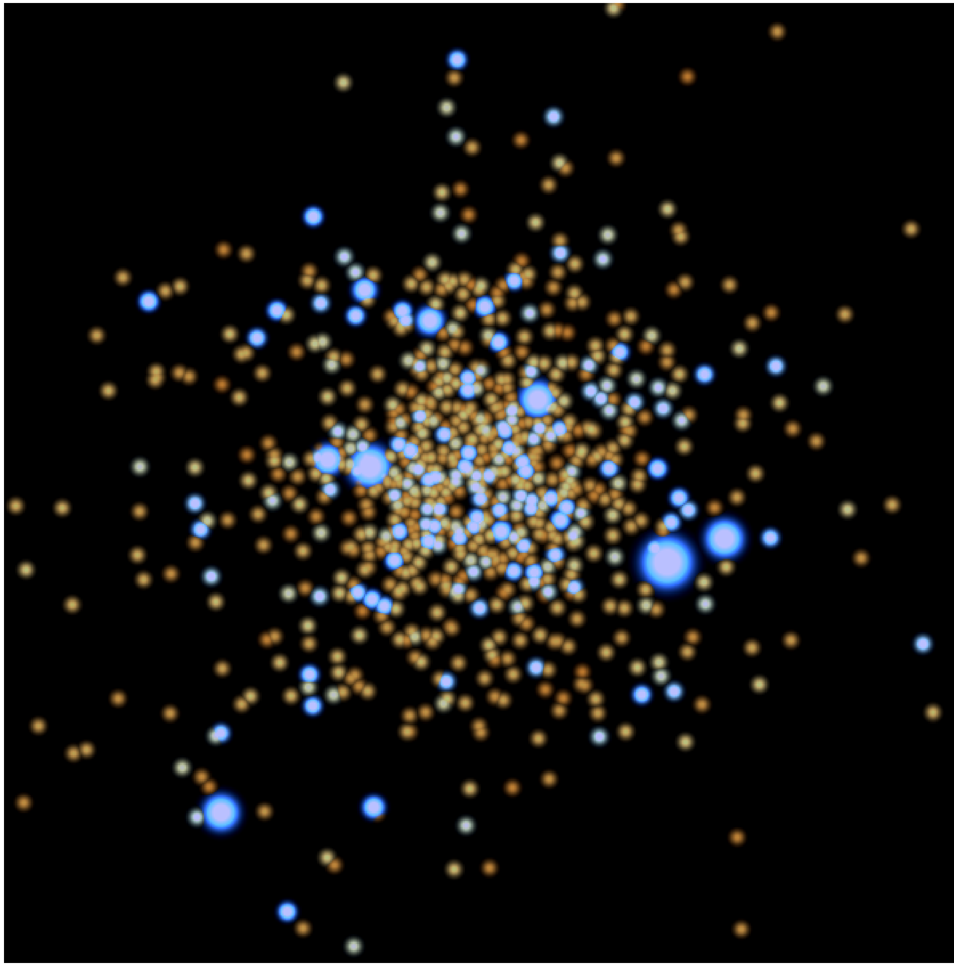
POPULATION SYNTHESIS RECIPES
(evolve single stars and binaries)

- single stellar evolution
- wind mass transfer
- Roche lobe mass transfer
- common envelope
- tidal evolution
- magnetic braking
- orbital evolution
- recipes for supernova explosion
- recipes for remnant formation



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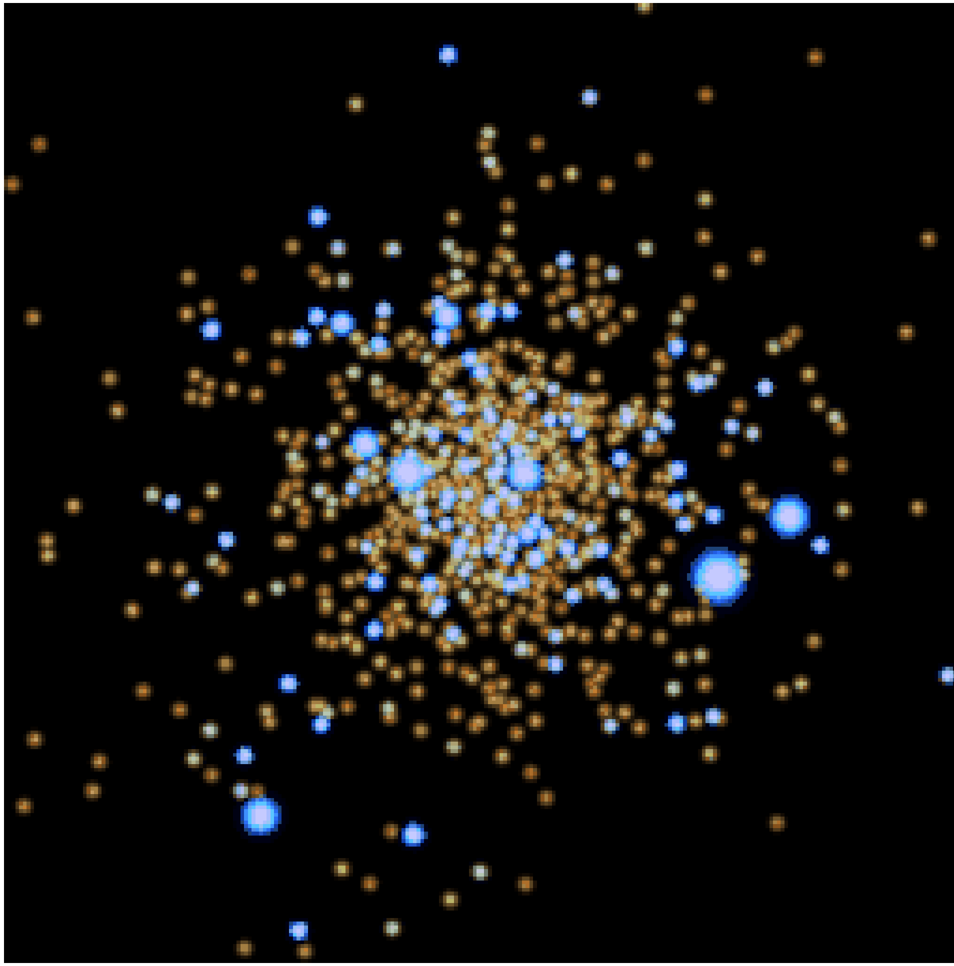

2. State-of-the-art simulations

How do we study impact of binaries on N-body dynamics?

MONTE CARLO CODES for the “smooth” evolution of the cluster (Hénon 1971)

+

DIRECT N-body CODES (only for close encounters with binaries)

+

POPULATION SYNTHESIS RECIPES
(evolve single stars and binaries)

- single stellar evolution
- wind mass transfer
- Roche lobe mass transfer
- common envelope
- tidal evolution
- magnetic braking
- orbital evolution
- recipes for supernova explosion
- recipes for remnant formation

2. State-of-the-art simulations: the open source community

DIRECT-SUMMATION N-BODY CODES:

N-body6: https://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm

HiGPUs: http://astrowww.phys.uniroma1.it/dolcetta/HPCcodes/HiGPUs.html

Starlab: https://www.sns.ias.edu/~starlab/

MONTE CARLO CODES:

MOCCA: https://moccacode.net/

POPULATION SYNTHESIS CODES:

BSE: http://astronomy.swin.edu.au/~jhurley/

SeBa: https://www.sns.ias.edu/~starlab/seba/

SEVN: https://gitlab.com/mario.spera/SEVN

MESA (a stellar evolution code): http://mesa.sourceforge.net/

2. State-of-the-art simulations: the open source community

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St

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MOCCA: https://moccacode.

AMUSE software environment to interface them https://github.com/amusecode/amuse

POPULATION SYNTHESIS CODES:

BSE: http://astronomy.swin.edu.au/~jhurley/

SeBa: https://www.sns.ias.edu/~starlab/seba/

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MESA (a stellar evolution code): http://mesa.sourceforge.net/

5.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

Massive stars (>30 Msun) might lose >50% mass by winds

(Vink+ 2001, 2005, 2016; Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)

Mass loss affects:

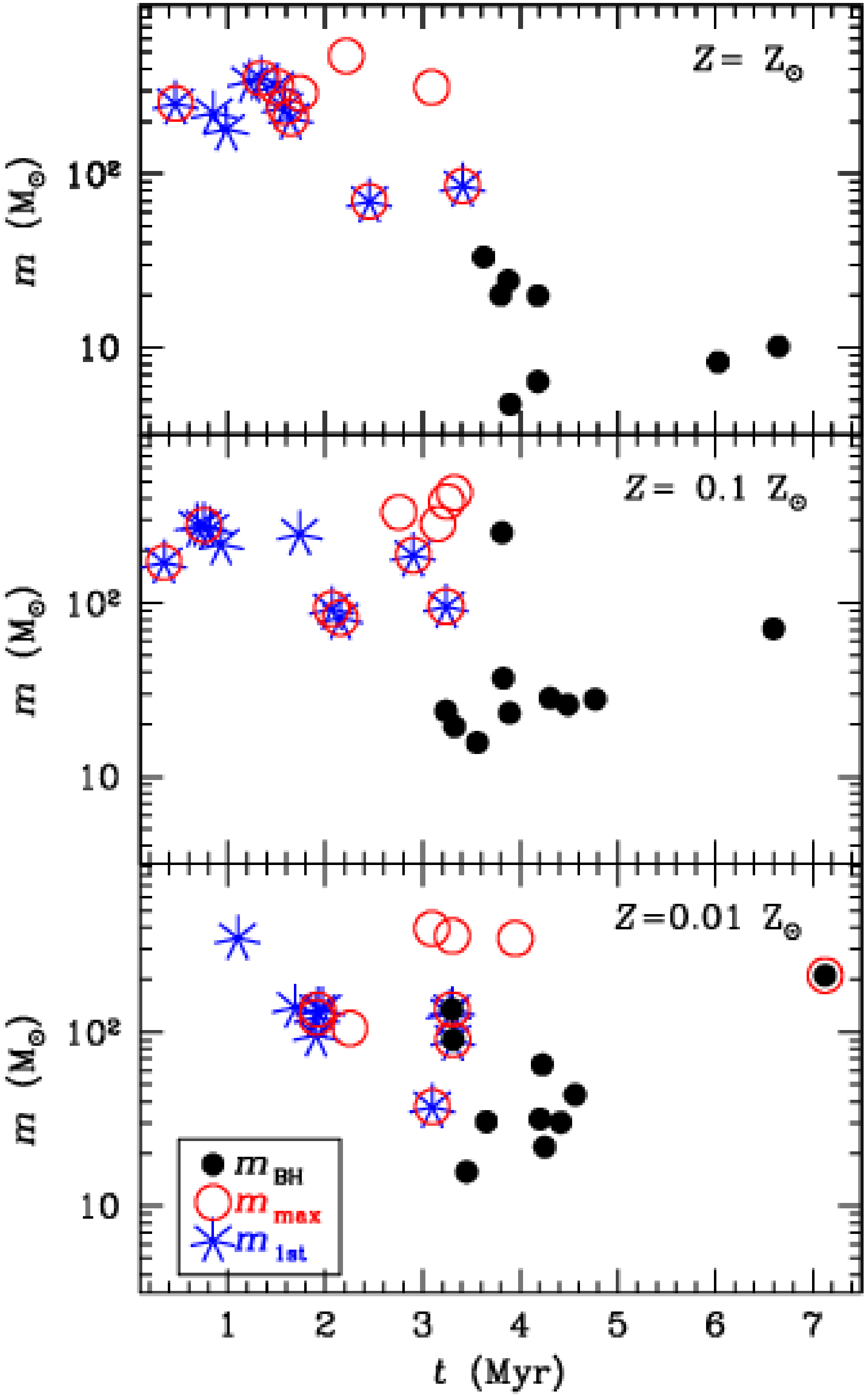
1 - the probability that the merger product undergoes more collisions and grows in mass

→ less collisions if the merger product loses mass: important to include winds in the N-body simulation

2 - the possibility that the remnant is massive

→ BH mass depends on the pre-supernova (SN) mass

5.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)



Mass of runaway collision product accounting for metallicity:

*** maximum mass up to 500 Msun**

*** 1/10 BH in the IMBH regime (>100 Msun) at Z = 0.01 – 0.1 Zsun**

NO IMBHs from runaway collisions at SOLAR METALLICITY!

*** CAVEAT 1: uncertainties in the evolution of very massive stars**

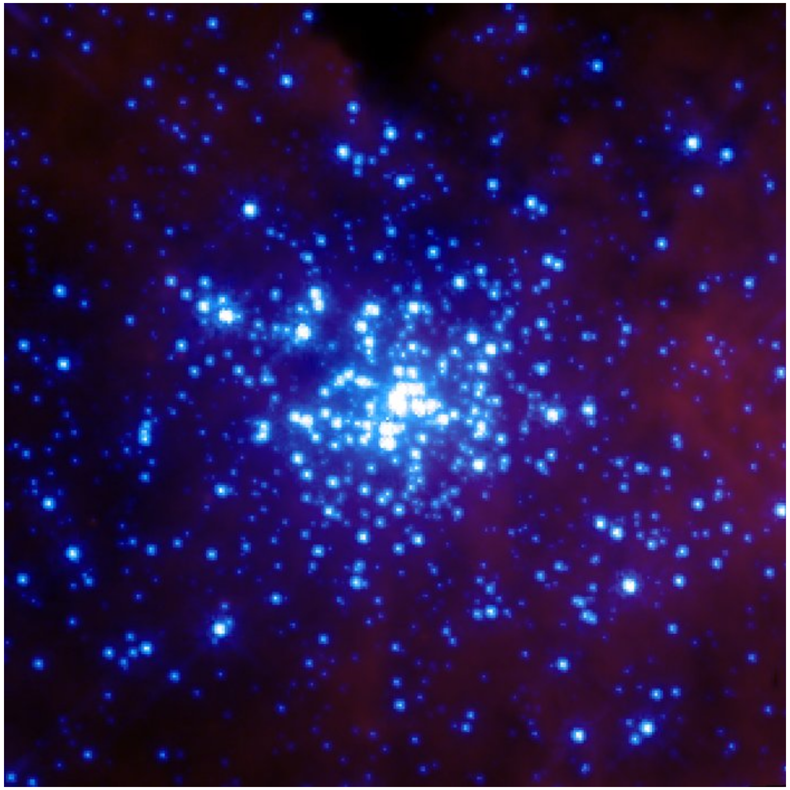
*** CAVEAT 2: uncertainties in mass-loss during/after collisions**

5.3 Intermediate-mass black holes (IMBHs, 100 – 10'000 Msun)

RUNAWAY COLLISION SCENARIO VS OBSERVATIONS:

1. VERY MASSIVE STARS (>100 Msun) ONLY IN DENSE STAR CLUSTER even at solar metallicity
Crowther+ 2010, 2016; Vink+ 2015

☑



2. IMBHs AT LOW METALLICITY

?????

PREDICTION TO BE CHECKED WITH LIGO – VIRGO AND LISA