Michela Mapelli

LECTURES on COLLISIONAL DYNAMICS:

4. HOT TOPICS on COLLISIONAL DYNAMICS

Part 1

1) IMBHs: runaway collapse, repeated mergers, ...

2) BHs eject each other?

3) Effects of 3-body on X-ray binaries (formation and escape)

3b) Gravitational waves

4) Effect of metallicity on cluster evolution

5) Formation of blue straggler stars

6) Tools for numerical simulations of collisional systems

7) Three-body and planets

8) Nuclear star cluster dynamics

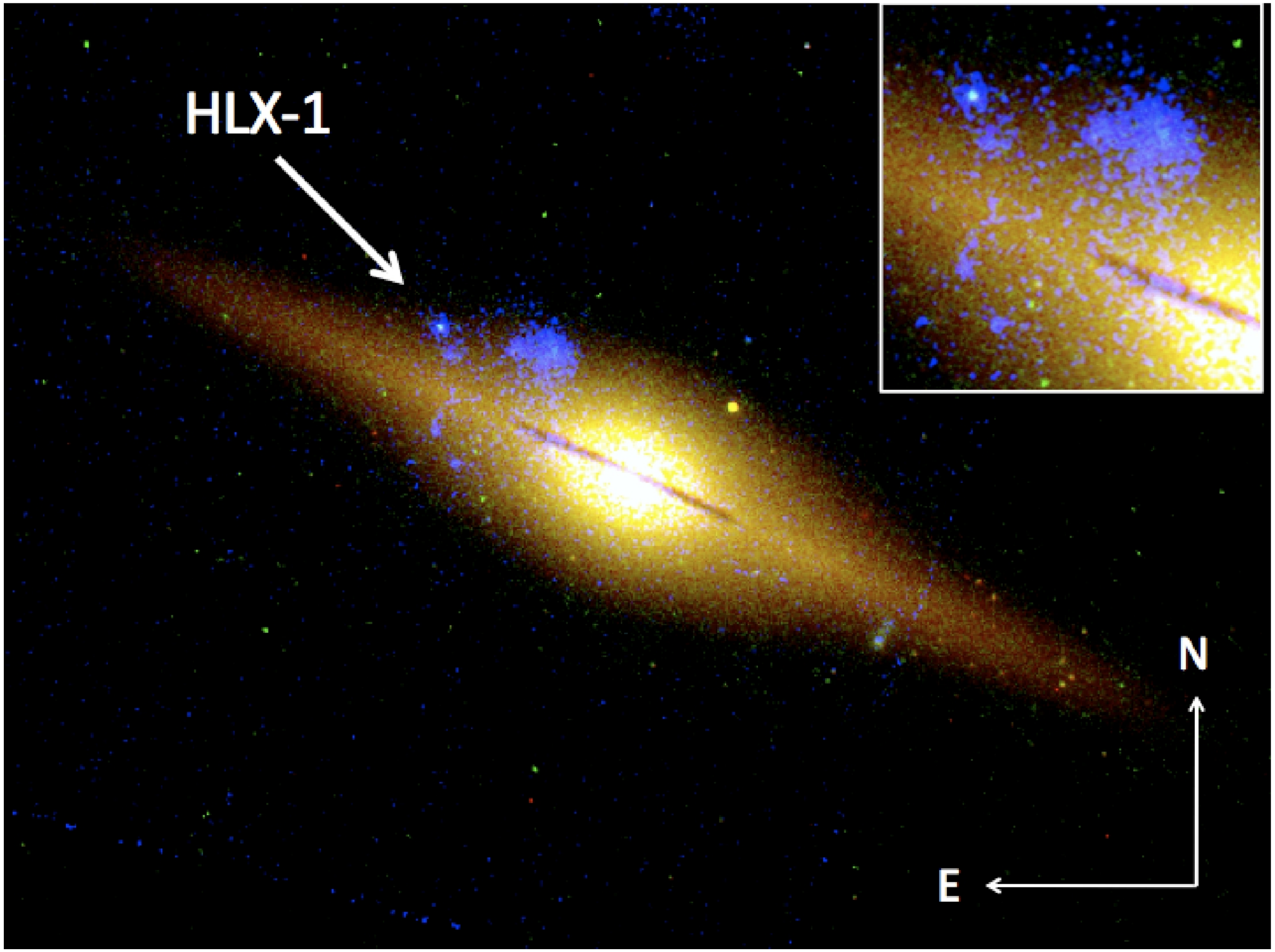
1) Intermediate-mass BHs (IMBHs)

definition: BHs with mass 10^{2-5} M⊙

OBSERVATIONAL EVIDENCES: none, just hints

1* Hyperluminous X-ray source HLX-1 close to ESO 243-49

peak $L_X \sim 10^{42}$ ergs,
X-ray VARIABILITY,
redshift consistent
with ESO 243-49
(not a background object)
→ BH mass~10^4 M⊙



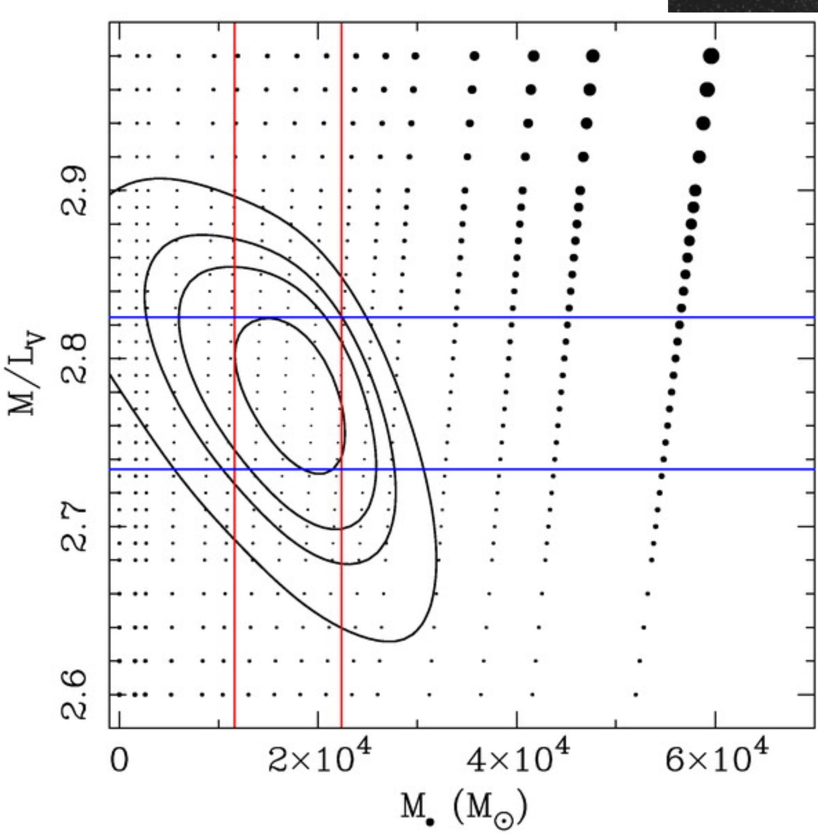
Farrell+ 2009, 2012;
Soria+ 2010, 2012;
MMi+ 2012, 2013

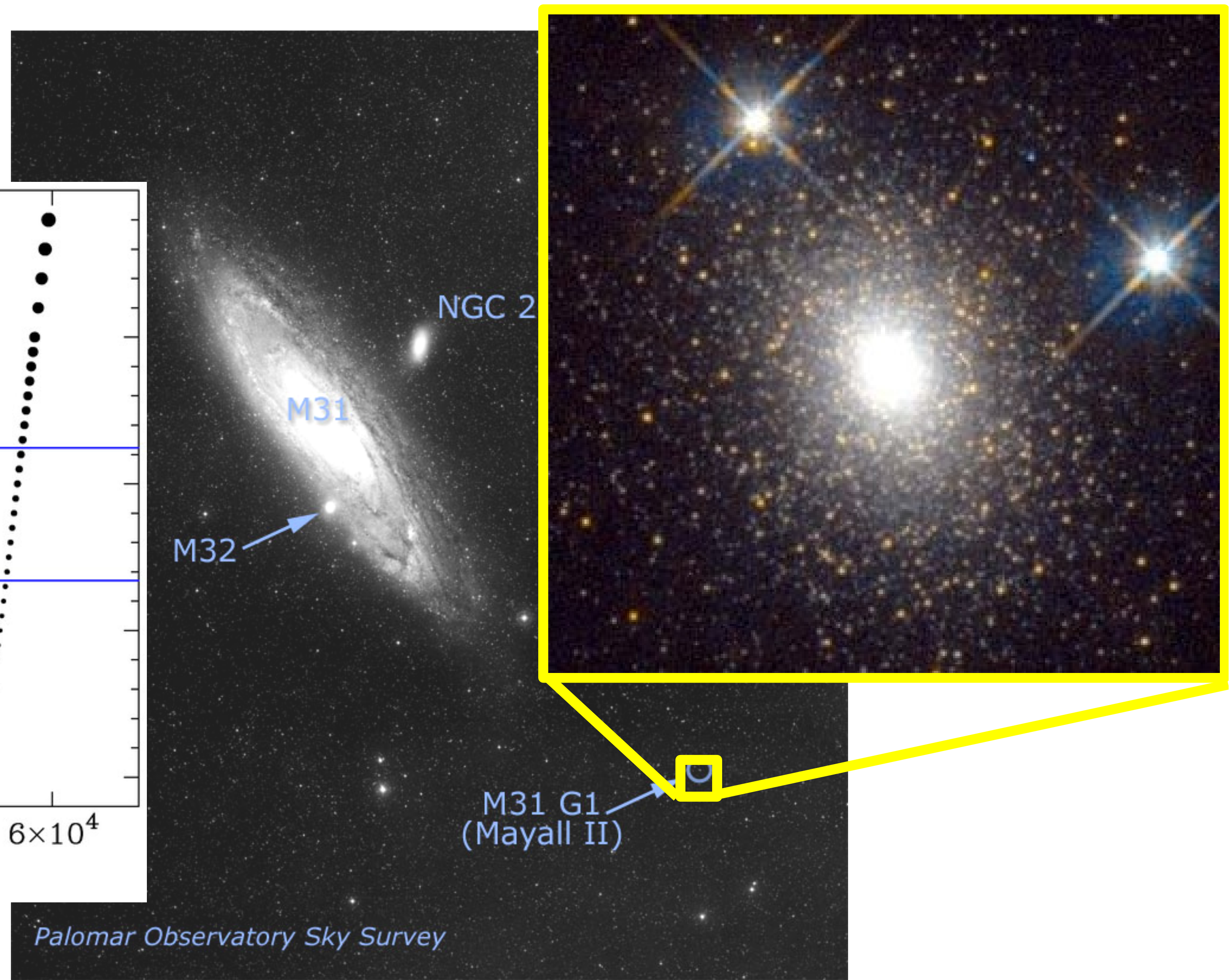
1) Intermediate-mass BHs (IMBHs)

definition: BHs with mass 10^{2-5} M⊙

2* centre of G1 globular cluster (dwarf nucleus?) in Andromeda

Central velocity distribution
+central M/L ratio
suggest BH mass~10^4 M⊙





Gebhardt+ 2005

1) Intermediate-mass BHs (IMBHs)

How do IMBHs form?

1- runaway collapse of stars at centre of star cluster (for systems with core collapse time < evolution of massive stars – e.g. young dense star clusters)

2- repeated mergers of BHs at centre of star cluster (for systems with core collapse time >> evolution of massive stars – e.g. globular clusters)

3- remnants of extremely metal poor stars (independent of environment)

4- low mass end of super-massive BHs (needs gas physics → different PhD course)

1) Intermediate-mass BHs (IMBHs)

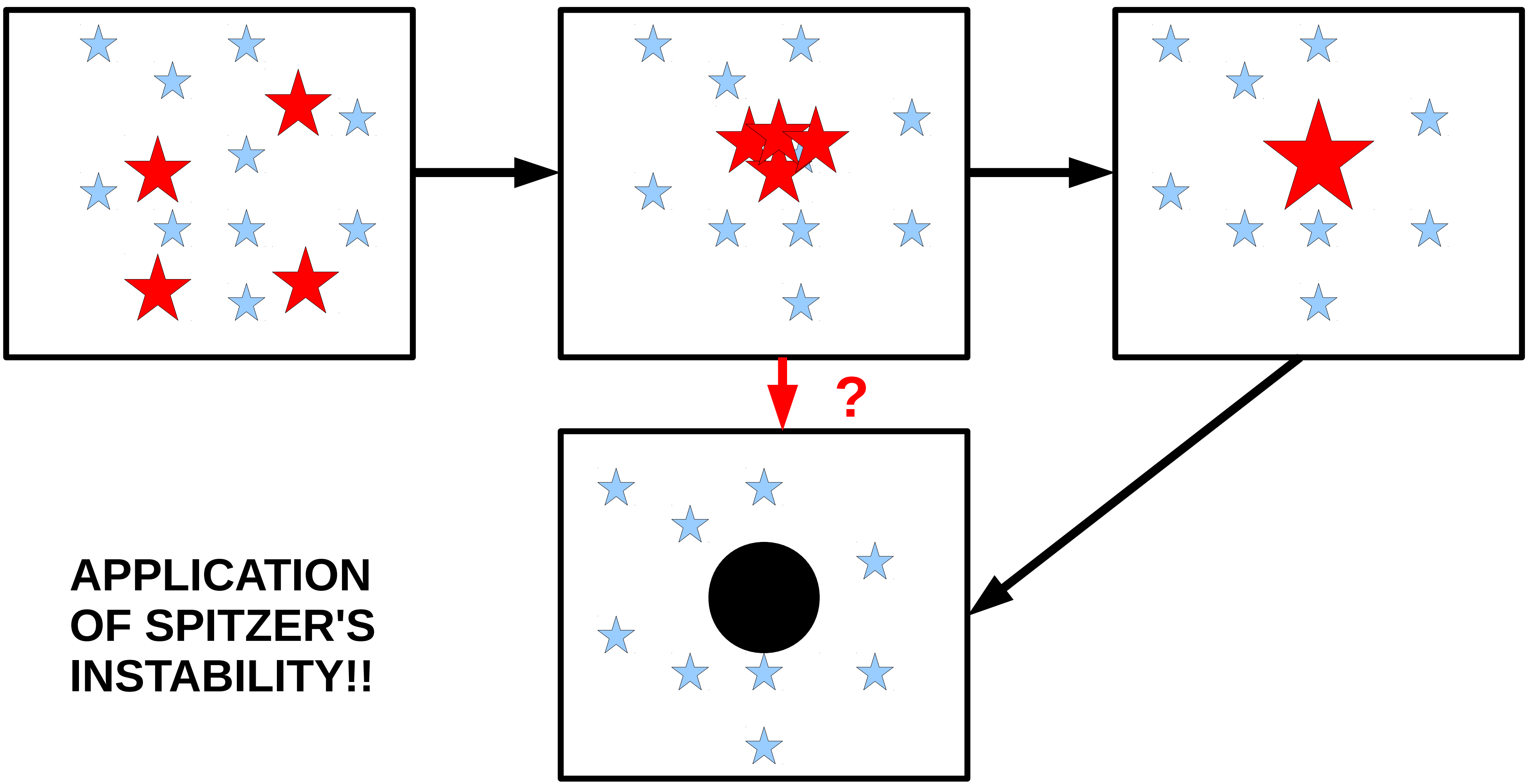
1- runaway collapse of stars at centre of star cluster

IDEA: mass segregation brings very massive stars to the centre

If timescale for mass segregation < timescale for stellar evolution

\+ if encounter rate sufficiently high

Massive stars collide, merge and form a super-massive star, which collapses to a BH



APPLICATION OF SPITZER'S INSTABILITY!!

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

IDEA: very hard binaries sink to the centre and likely collide with other stars/binaries unless they are ejected.

The product of the first collisions is SO MASSIVE that it triggers other collisions (=is the main collision target) Starting a RUNAWAY PROCESS

→ Maximum mass that can be grown in a dense star cluster If all collisions involve the same star

$$\frac{dM_{raway}}{dt} = R_{coll}\,\delta m_{coll}$$

Where R_{coll} = collision rate, δm_{coll} = mass transferred per collision on average

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

IDEA: very hard binaries sink to the centre and likely collide with other stars/binaries unless they are ejected

ESTIMATE of *R_{coll}*

Maximum recoil velocity for a binary not to be ejected

$$v_{rec} = v_{esc} = 2\,\sigma$$

Definition of v_{rec}

$$v_{rec} = \frac{m_3}{m_T}\,v_{fin} = \frac{m_3}{m_T}\sqrt{\frac{m_3\,(m_1+m_2)}{m_e\,(m_a+m_b)}\,{v_\infty}^2 + \frac{2\,m_T}{m_e\,(m_a+m_b)}\,\Delta E_b}$$

$$= \frac{m}{3\,m}\sqrt{\frac{m\,(2\,m)}{m\,(2\,m)}\,\sigma^2 + \frac{2\,(3\,m)}{m\,(2\,m)}\,\Delta E_b} = \frac{1}{3}\sqrt{\sigma^2 + \frac{3}{m}\,\frac{m}{2\,m}\,E_b}$$

Nearly equal mass cluster

$$\Delta E_b = \frac{m}{2\,m}\,E_b$$

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

$$v_{rec} = v_{esc} = 2\,\sigma \qquad (1)$$

$$v_{rec} = \frac{1}{3}\sqrt{\sigma^2 + \frac{3}{2\,m}\,E_b} \qquad (2)$$

Combining (1) and (2) $36\,\sigma^2 = \sigma^2 + \frac{3}{2\,m}\,E_b$

$$E_b = \frac{70\,m}{3}\,\sigma^2 = 70\,k_B\,T \sim 10^2\,k_B\,T$$

↑

$$\frac{1}{2} m\,\sigma^2 = \frac{3}{2}\,k_B\,T$$

E_b is the binding energy exchanged by a hard binary during its life (i.e. before it is ejected).

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

We calculate now the number of binaries necessary to reverse core collapse (estimated as 10% of the total potential energy of the cluster, Goodman 1987):

$$N_{bin}\,10^2\,k_B\,T \sim 0.1\,|W| = 0.1\,(2\,\frac{3}{2}\,N\,k_B\,T)$$

$$\longrightarrow N_{bin} \sim 10^{-3}\,N$$

Hard binary formation rate:

$$R_{bin} \sim 10^{-3}\,\frac{N}{t_{rlx}}$$

Assuming that ~ each hard binary undergoes <=1 collision, we estimate the collision rate

$$R_{coll} \sim 10^{-3}\,f_{coll}\,\frac{N}{t_{rlx}}$$

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

IDEA: very hard binaries sink to the centre and likely collide with other stars/binaries unless they are ejected

ESTIMATE of δm$_{coll}$

From dynamical friction timescale

$$t_{df} \sim \frac{\langle m \rangle}{m_{df}} t_{rlx}$$

where <*m*>= average star mass, *M*=total cluster mass, *N*= number of stars

We estimate the minimum mass of star that can sink to the centre in a time *t*

$$\delta m_{coll} \geq m_{df} \sim \langle m \rangle \frac{t_{rlx}}{t_{\rm df}}$$

the mass that can be acquired after a collision (!!!)

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

$$\frac{dM_{raway}}{dt} \sim 10^{-3}\, f_{coll}\, \frac{N}{t}\, \langle m \rangle$$

M_{raway}~$10^{2\text{-}3}$ $M_\odot$ for a dense young cluster with $N>10^5$

1^{st} CONDITIO SINE QUA NON:

core collapse time << massive star evolution time

→ $t_{coll}<3\text{-}25$ Myr

2^{nd} CONDITIO SINE QUA NON:

STAR CLUSTER SUFFICIENTLY MASSIVE AND CONCENTRATED

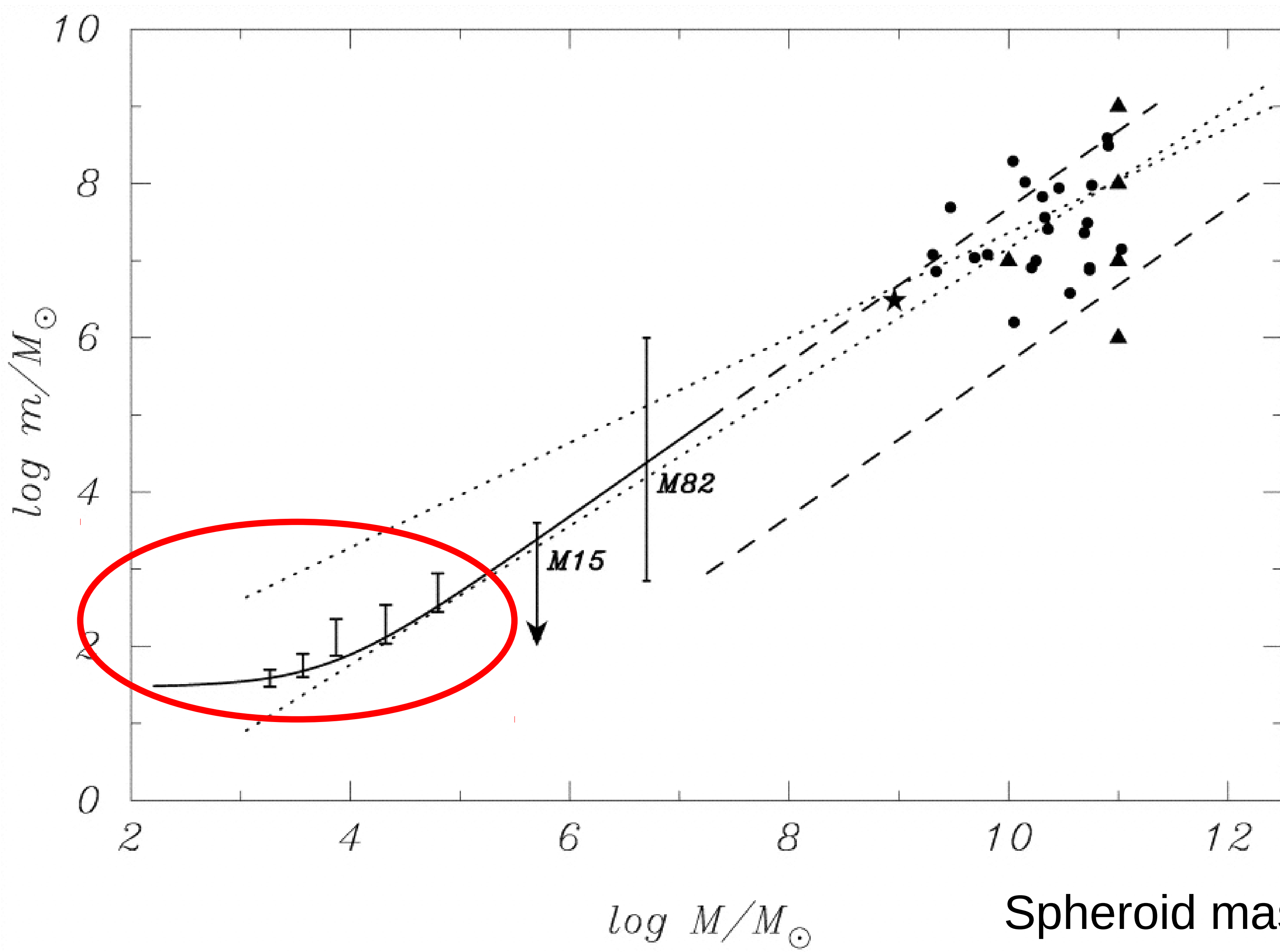
1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

Confirmed by simulations

BH mass



Spheroid mass

1) Intermediate-mass BHs (IMBHs)

1- runaway collapse of stars at centre of star cluster

Formalism by Portegies Zwart & McMillan 2002

MAIN ISSUE: MASS LOSSES!!!

(1) during merger

Recent simulations show mass losses

up to 25% of total mass

(Gaburov, Lombardi & Portegies Zwart 2010, MNRAS, 402, 105)

(2) by stellar winds

After merger the super-massive star will

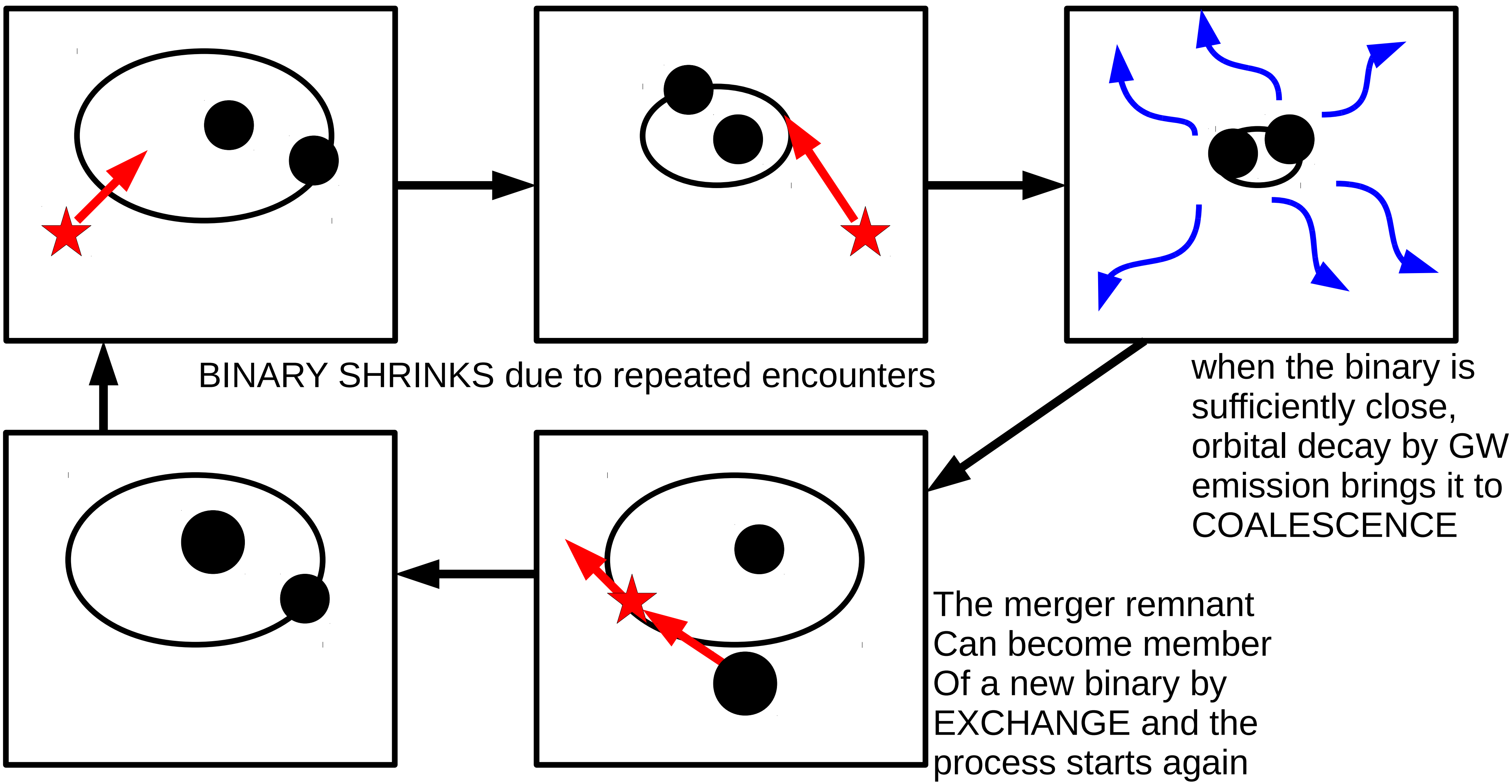
be very unstable (radiation pressure dominated)

1) Intermediate-mass BHs (IMBHs)

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



1) Intermediate-mass BHs (IMBHs)

2- repeated mergers

Formalism by Miller & Hamilton (2002)

MAIN PROBLEM: seed BH must avoid ejection before merger

$$v_{rec} = \frac{m_3}{m_T}\sqrt{\frac{m_3\,(m_1+m_2)}{m_e\,(m_a+m_b)}\,v_\infty^2 + \frac{2\,m_T}{m_e\,(m_a+m_b)}\,\Delta E_b} \sim \frac{m_3}{m_T}\sqrt{\frac{2\,m_T}{m_3\,(m_1+m_2)}\,\Delta E_b}$$

$$\boxed{m_1 + m_2 \gg m_3}$$

$$\sim \frac{m_3}{m_T}\sqrt{\frac{2\,m_T}{m_3\,(m_1+m_2)}\,\frac{\xi\,m_3}{(m_1+m_2)}\,E_b} \sim \frac{m_3}{m_1+m_2}\sqrt{\frac{2\,\xi}{m_T}\,E_b}$$

We find the minimum binding energy for EJECTION ($E_{b,min}$) by imposing $v_{rec}=v_{esc}$.

$$\Rightarrow E_{b,\,min} \sim \frac{(m_1+m_2)^3}{2\,\xi\,m_3^2}\,v_{esc}^2$$

where we assumed $m_1+m_2 \sim m_T$

$$E_{b,\,min} \sim 2\times10^{50}\ \mathrm{erg}\left(\frac{m_1}{50\,M_\odot}\right)^3\left(\frac{m_3}{10\,M_\odot}\right)^{-2}\left(\frac{\xi}{0.2}\right)^{-1}\left(\frac{v_{esc}}{50\,\mathrm{km\ s^{-1}}}\right)^2$$

1) Intermediate-mass BHs (IMBHs)

2- repeated mergers

Formalism by Miller & Hamilton (2002)

MAIN PROBLEM: seed BH must avoid ejection before merger

Orbital separation in merger regime (see lecture 3):

$$a_{GW} \sim 3 \times 10^{11}\ \mathrm{cm} \left(\frac{t_{GW}}{10^6\ \mathrm{Myr}}\right)^{1/4} \left(\frac{m_1}{50\ M_\odot}\right)^{1/2} \left(\frac{m_2}{10\ M_\odot}\right)^{1/4}$$

Binding energy in merger regime:

$$E_{b,\,merg} = \frac{G\,m_1\,m_2}{2\,a_{GW}} \sim 2 \times 10^{50}\ \mathrm{erg} \left(\frac{t_{GW}}{10^6\ \mathrm{Myr}}\right)^{-1/4} \left(\frac{m_1}{50\ M_\odot}\right)^{1/2} \left(\frac{m_2}{10\ M_\odot}\right)^{3/4}$$

COMPARING $E_{b,min}$ with $E_{b,merg}$:

$$x = \frac{E_{b,\,min}}{E_{b\,merg}} \sim \left(\frac{m_1}{50\ M_\odot}\right)^{5/2} \left(\frac{m_2}{10\ M_\odot}\right)^{-11/4} \left(\frac{t_{GW}}{10^6\ \mathrm{Myr}}\right)^{1/4}$$

If x>1 BINARY MERGES BEFORE EJECTION

If x<1 BINARY IS EJECTED BEFORE MERGER

1) Intermediate-mass BHs (IMBHs)

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

Number of 3-body encounters for a BH to merge with its companion (from lecture 3):

$$N_{merg} = \frac{1}{\xi}\,\frac{m_T}{\langle m\rangle}\,\ln\left(\frac{a_0}{a_{GW}}\right)$$

Time required for 1 merger:

$$dt = -\frac{\sigma}{2\,\pi\,G\,\xi\,\rho}\,\frac{da}{a^2} \longrightarrow \int_0^{t_{GW}} dt = -\frac{\sigma}{2\,\pi\,G\,\xi\,\rho}\int_{a_0}^{a_{GW}}\frac{da}{a^2}$$

$$t_{GW} = \frac{\sigma}{2\,\pi\,G\,\xi\,\rho}\left(\frac{1}{a_{GW}} - \frac{1}{a_0}\right)$$

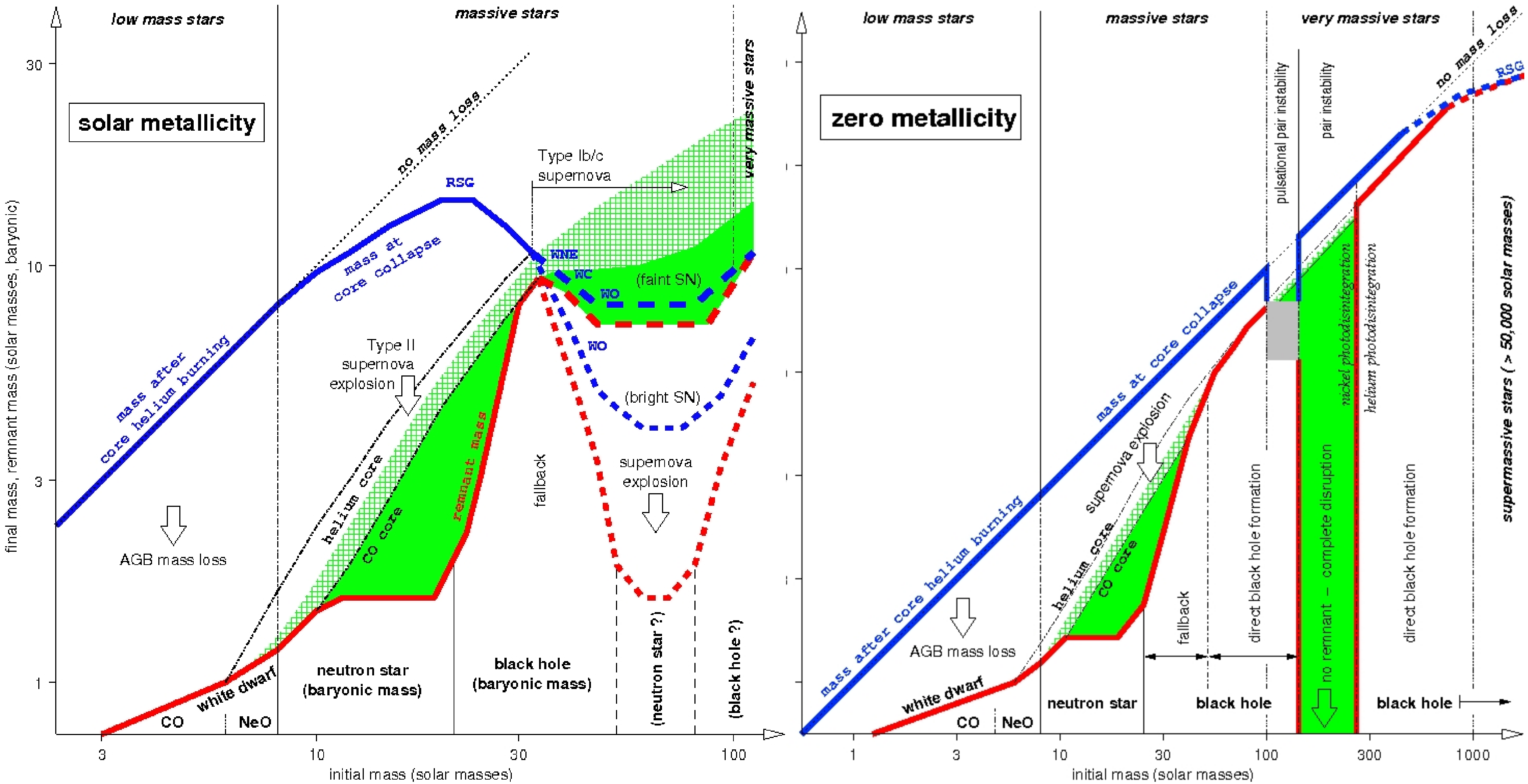
$$t_{GW} \sim 3\times10^8\ \mathrm{yr}\left(\frac{\sigma}{10\ \mathrm{km\ s^{-1}}}\right)\left(\frac{\xi}{0.2}\right)^{-1}\left(\frac{\rho}{10^6\,M_\odot\ \mathrm{pc^{-3}}}\right)^{-1}\left(\frac{a_{GW}}{1\ \mathrm{AU}}\right)^{-1}$$

INEFFICIENT!!!!!

1) Intermediate-mass BHs (IMBHs)

3- remnants of extremely metal-poor stars

Formalism by Heger et al. (2003)



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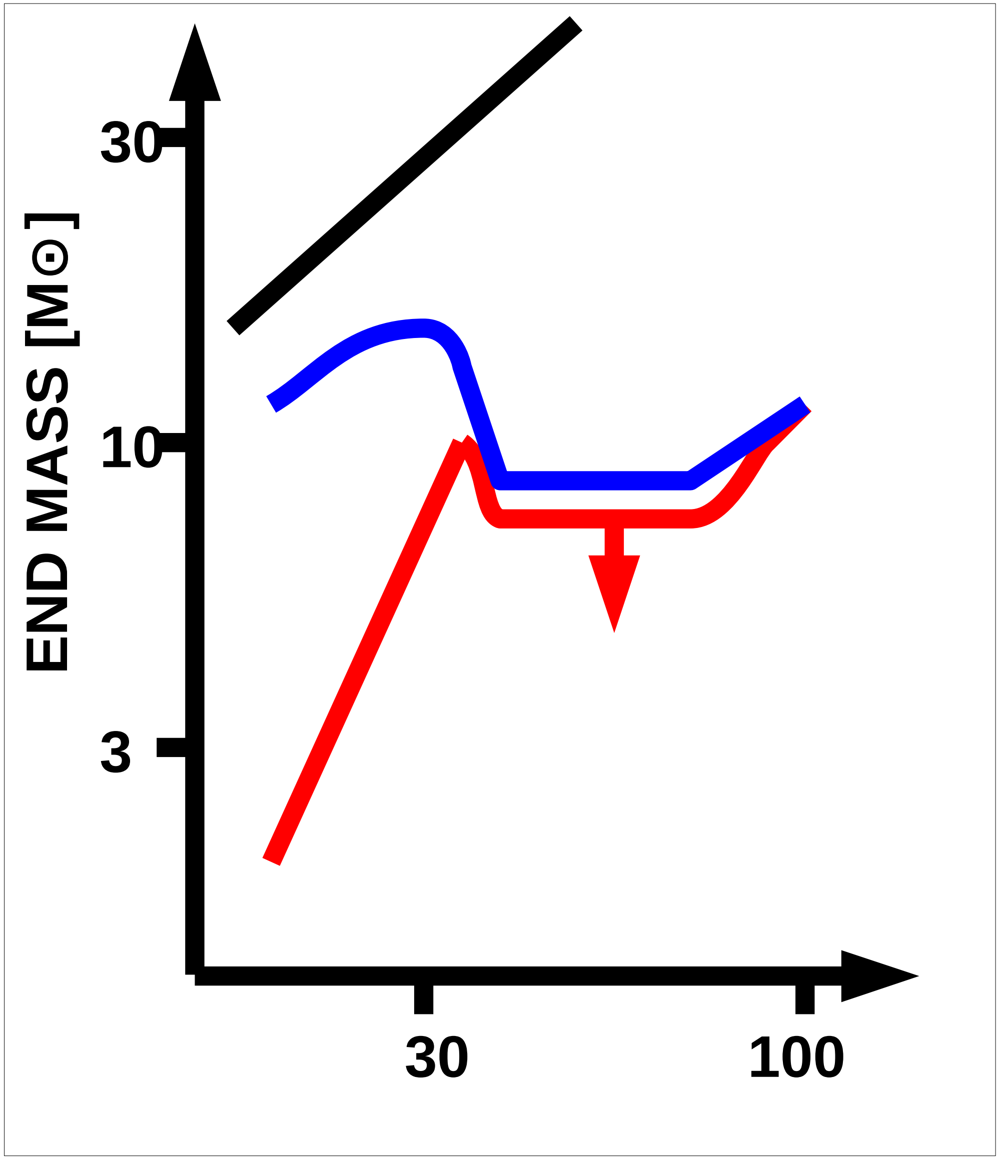

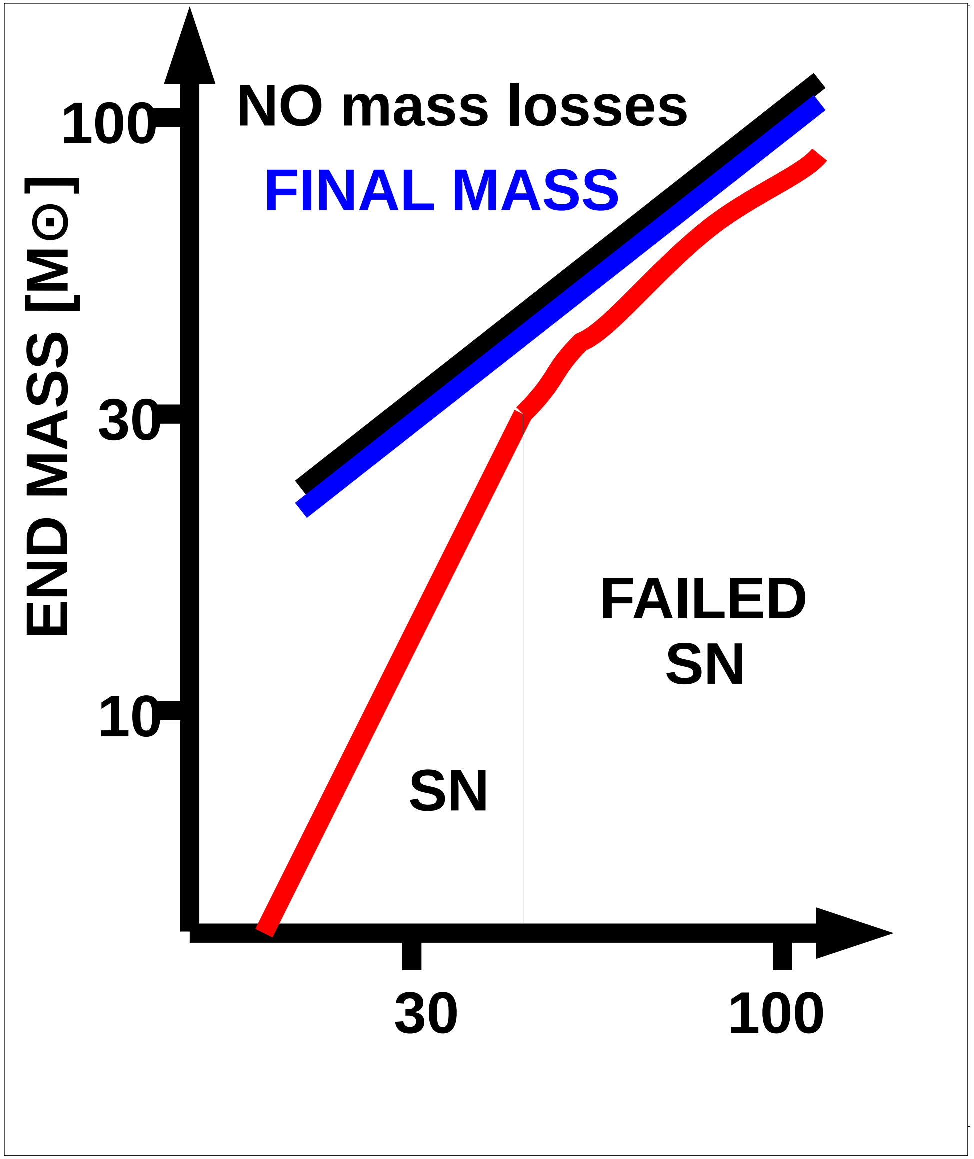

1) Intermediate-mass BHs (IMBHs)

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TWO INGREDIENTS:

1) STELLAR WINDS depend on METALLICITY

$$\dot{M}(Z) \propto \left(\frac{Z}{Z_\odot}\right)^\alpha$$

$$\alpha = 0.5 - 0.9$$

at low Z, stars lose less mass by stellar winds!

Vink+ (2001)

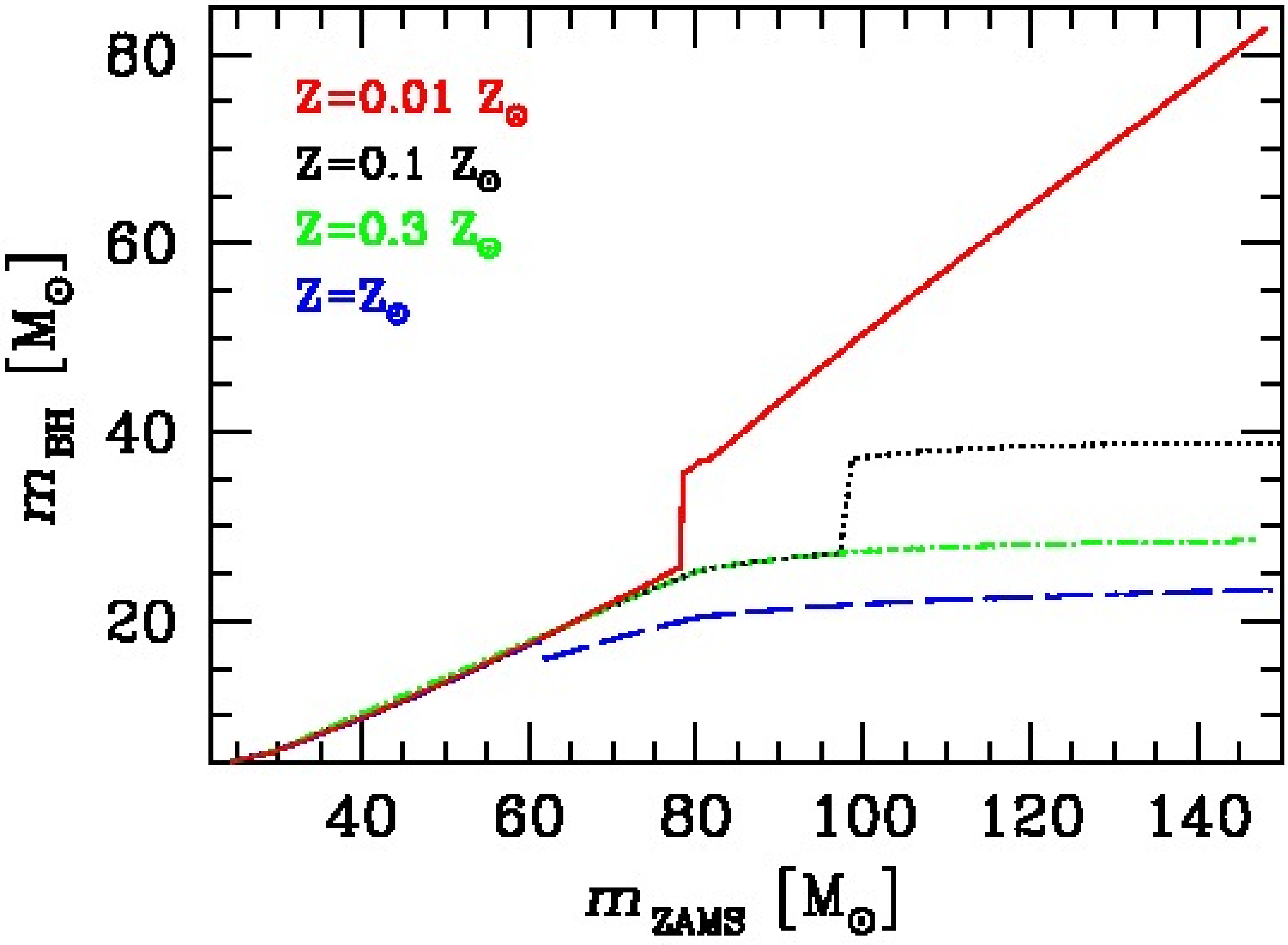
2) IF FINAL MASS SUFFICIENTLY HIGH (> 40 Msun), SN EXPLOSION CANNOT SUCCEED: almost NO EJECTA and direct collapse to BHs (FAILED SUPERNOVAE, Fryer 1999)

1) Intermediate-mass BHs (IMBHs)

3- remnants of extremely metal-poor stars

Formalism by Heger et al. (2002)

NOT ONLY AT ZERO METALLICITY



MM+09; Zampieri & Roberts 2009; Belczynski+2010; Fryer+2012; MM+2013

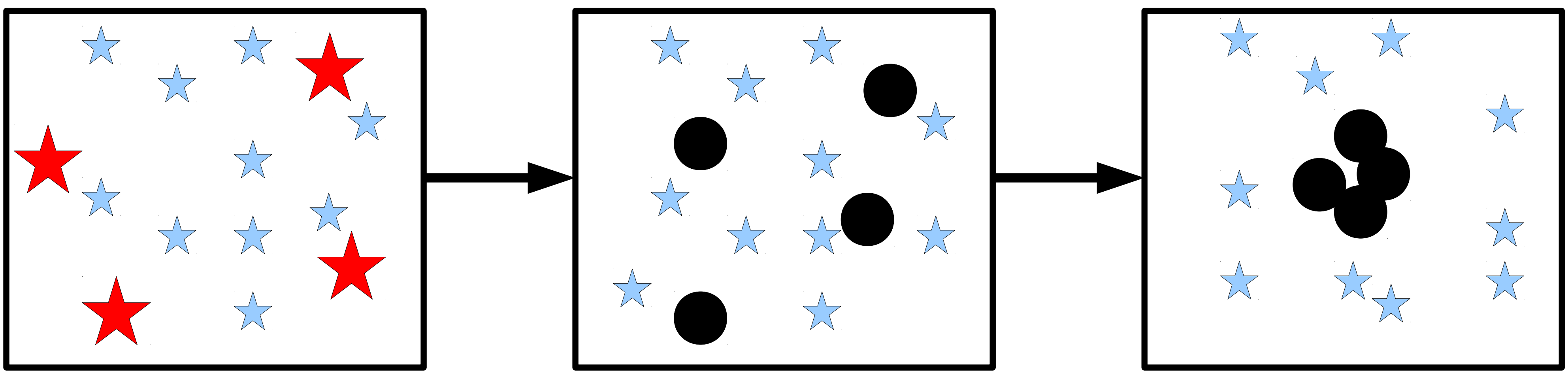
2) BHs eject each other?

Note: valid for globular clusters! Why? BHs form before progenitors segregate to the centre (no runaway collapse)

N_{bh}~10^2 expected to form in GCs

Segregate to the centre in

$$t_{df} \sim 3 \times 10^7 \text{ yr} \left(\frac{\sigma}{10\,\text{km s}^{-1}}\right) \left(\frac{r_c}{1\,\text{pc}}\right)^2 \left(\frac{m_{BH}}{10\,M_\odot}\right)^{-1}$$



2) BHs eject each other?

What happens when BHs are in the core?

1) Total mass of BHs sufficiently large to have SPITZER'S INSTABILITY →

* formation of a **dynamically decoupled core of BHs**!!!
* **core collapse** for BHs on faster timescale than expected for stars
* **efficient formation of BH-BH** binaries
* **fast ejection of all lighter stars** from the BH dominated core
* ejections of (nearly) all single BHs in halo or out of cluster
* **ejections of binary BHs** with x>1

$$x = \frac{E_{b,\,min}}{E_{b\,merg}} \sim \left(\frac{m_1}{50\,M_\odot}\right)^{5/2} \left(\frac{m_2}{10\,M_\odot}\right)^{-11/4} \left(\frac{t_{GW}}{10^6\ \mathrm{Myr}}\right)^{1/4}$$

How many BHs left in the cluster?? 0, 1, 2, boh...

How massive? It depends whether mechanism by Miller & Hamilton (2002) is efficient or not – i.e. it depends on the mass of available seeds

From Kulkarni, Hut & McMillan 1993, Nature 364, 421
Sigurdsson & Hernquist 1993, Nature 364, 423

2) BHs eject each other?

What happens when BHs are in the core?

2) Total mass of BHs relatively small with respect to stars →

* efficient formation of BH-BH binaries on standard core-collapse time
* ejection of lighter stars from the core (BH-BH binaries harden)
* ejections of (nearly) all single BHs in halo or out of cluster
* ejections of binary BHs with $x>1$

$$x = \frac{E_{b,\,min}}{E_{b\,merg}} \sim \left(\frac{m_1}{50\,M_\odot}\right)^{5/2} \left(\frac{m_2}{10\,M_\odot}\right)^{-11/4} \left(\frac{t_{GW}}{10^6\ \mathrm{Myr}}\right)^{1/4}$$

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2) BHs eject each other?

What do data tell us?

* The only 4 strong **BH candidates in MW GCs are:**

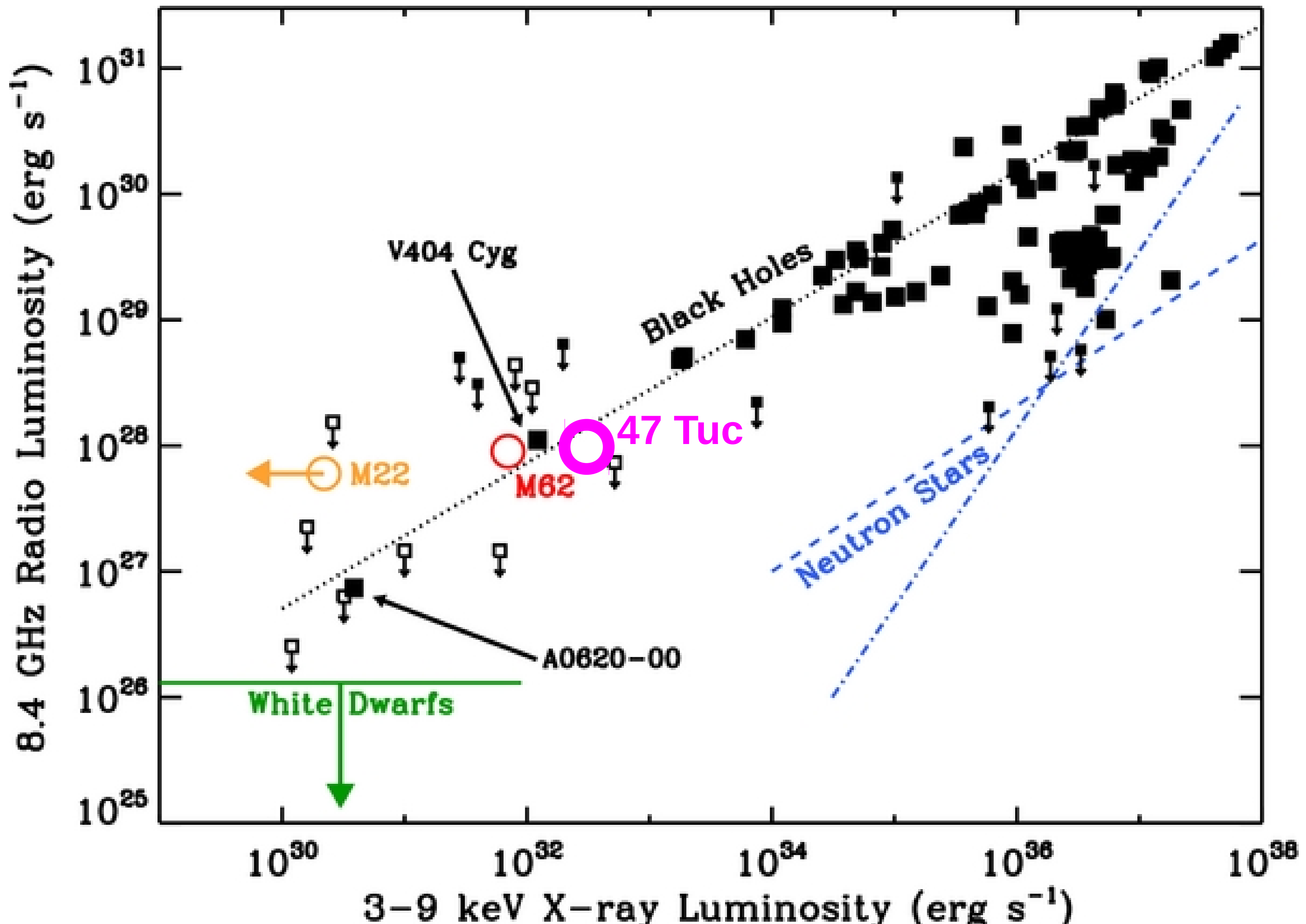
  - 2 RADIO SOURCES in M22 (Strader et al. 2012, Nature, 490, 71).
  No X-ray detection ($<10^{30}$ erg/s) → log $L_R/L_X > -2.6$ (too high for NSs)

  - 1 radio+X source in M62, Chomiuk et al. 2013
  - 1 radio+X source in 47 Tuc, Strader et al., in prep.?, see
  http://www.astro.uni-bonn.de/~sambaran/DS2014/Modest14_Talks/Strader.pdf

* 5 sources in **GCs of elliptical galaxies** are strong BH candidates for X-ray variability:

  - NGC 4472 (Maccarone et al. 2007, Nature, 445, 183)
  - NGC 4472 (2^{nd} source, Maccarone et al. 2011, MNRAS, 410, 1655)
  - NGC 3379 (Brassington et al. 2010, ApJ, 725, 1805)
  - NGC 1399 (Irwin et al. 2010, ApJ, 712, L1)
  - NGC 1399 (2^{nd} source, Shih et al. 2010, ApJ, 721, 323)

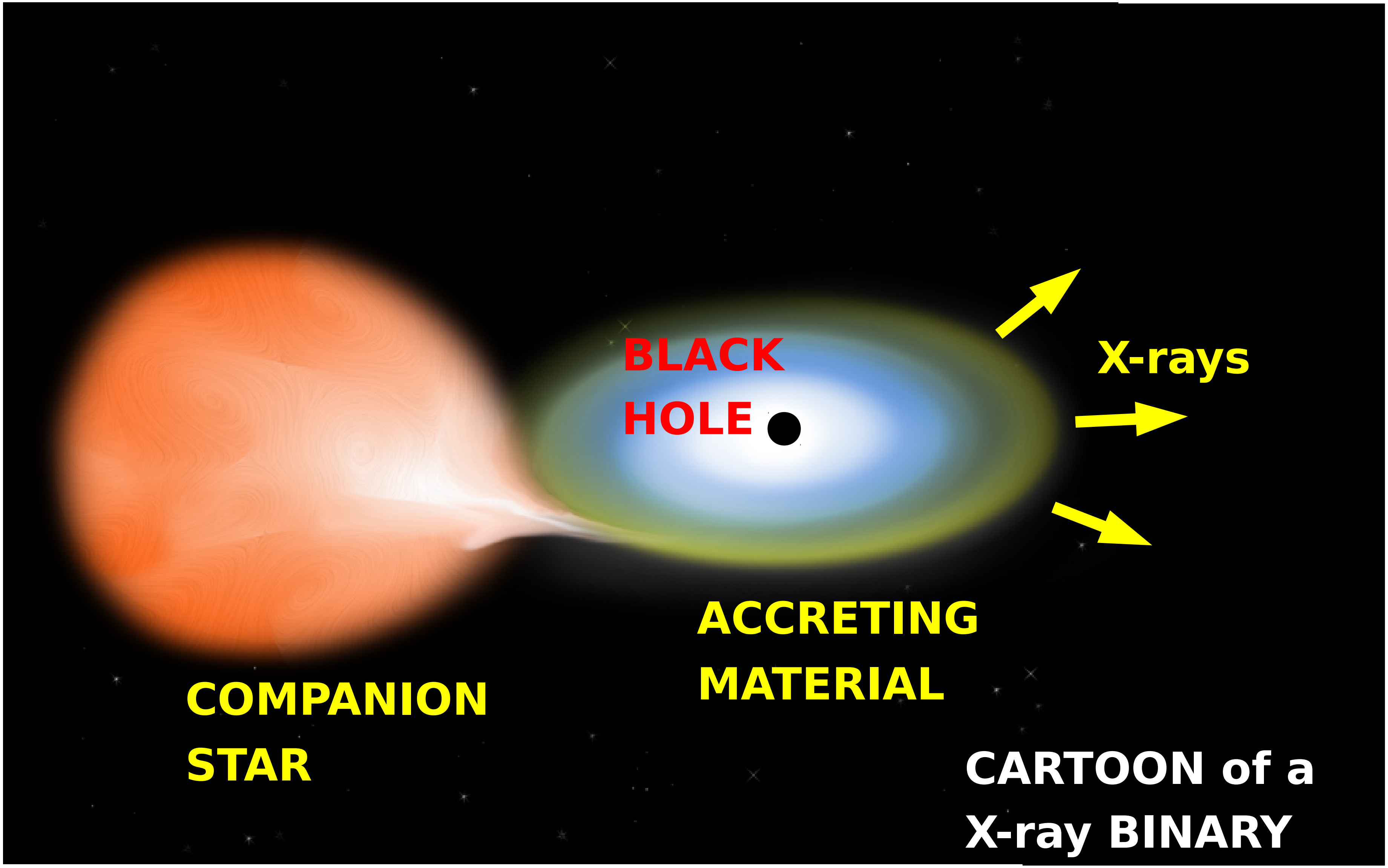
2) BHs eject each other?



Corbel et al. 2013
Chomiuk et al. 2013

3) Effects of 3-body on X-ray binaries (formation and escape)

Compact object accreting matter from companion star via Roche lobe overflow or stellar winds



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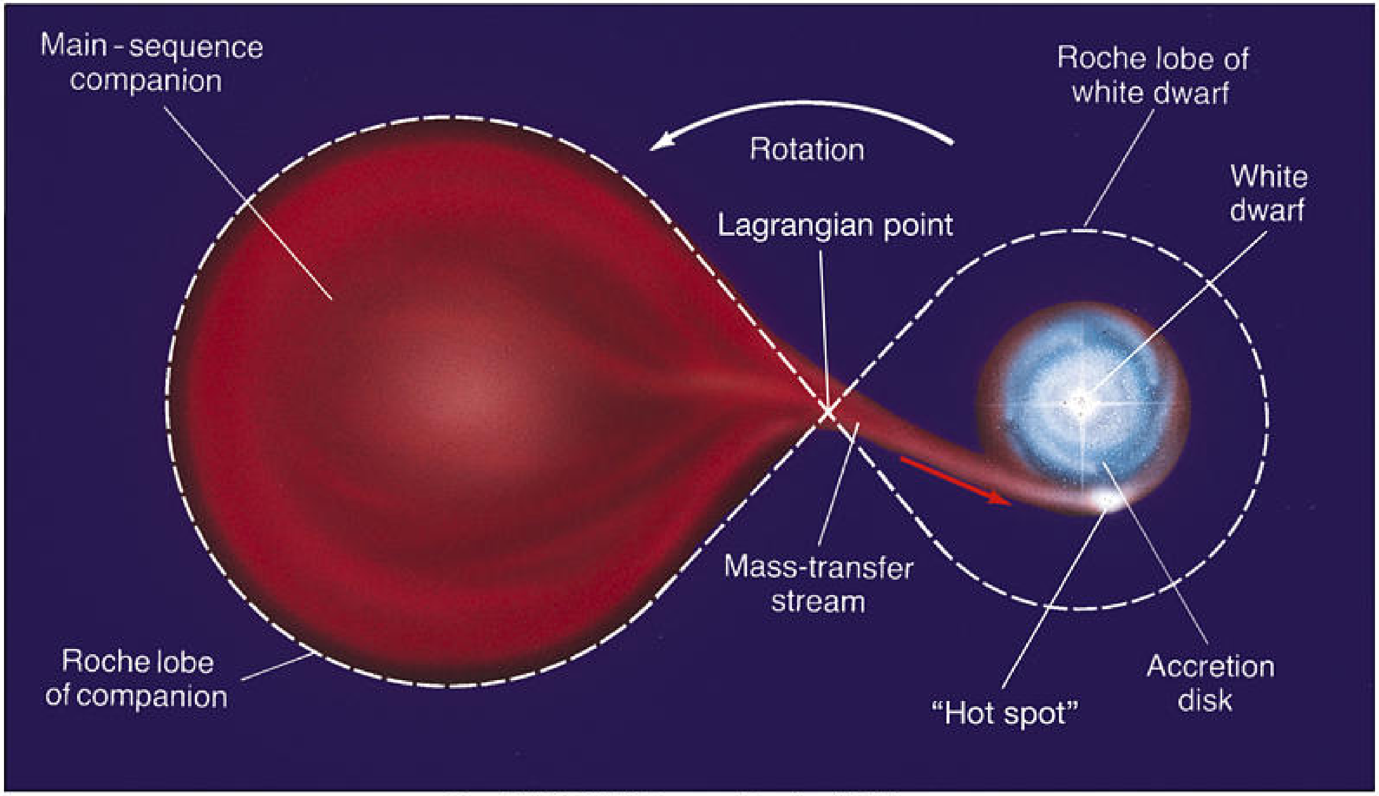
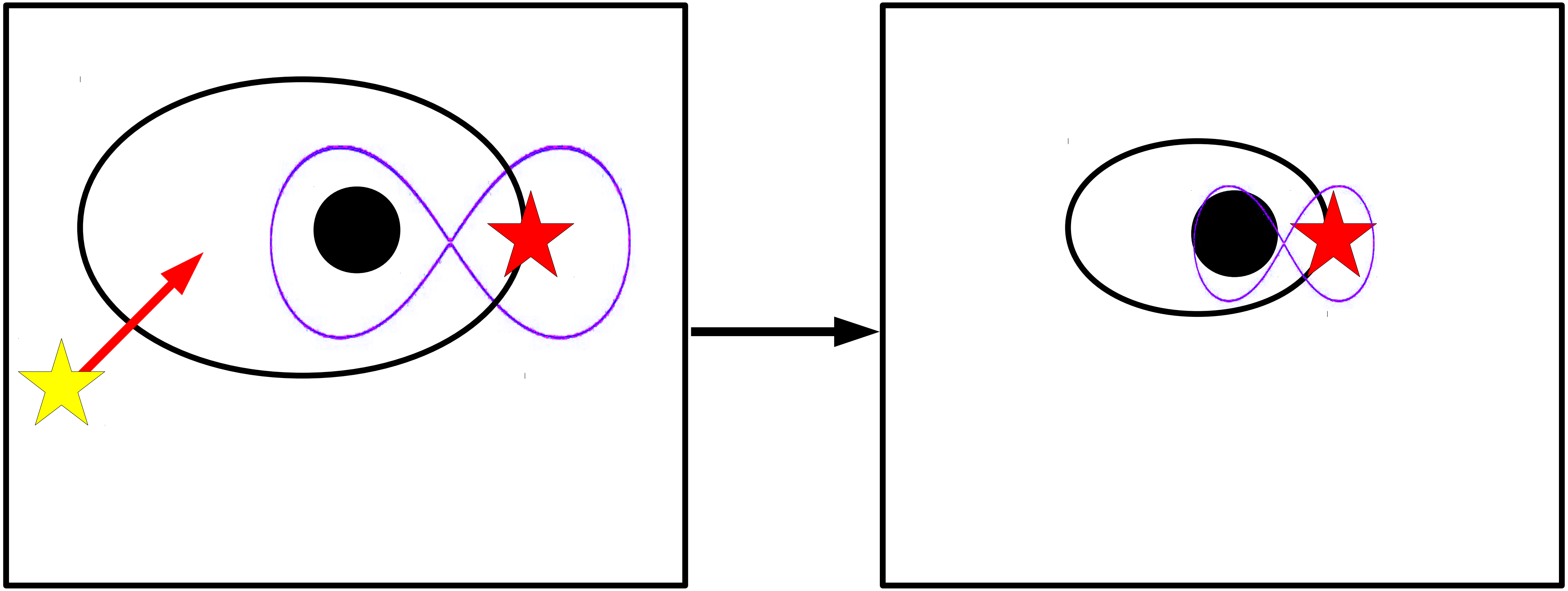


Luca Zampieri's course

$$r_{RL} = \frac{0.49\, a\, (M_1/M_2)^{2/3}}{0.6\, (M_1/M_2)^{2/3} + \ln\left[1 + (M_1/M_2)^{1/3}\right]}$$

3) Effects of 3-body on X-ray binaries

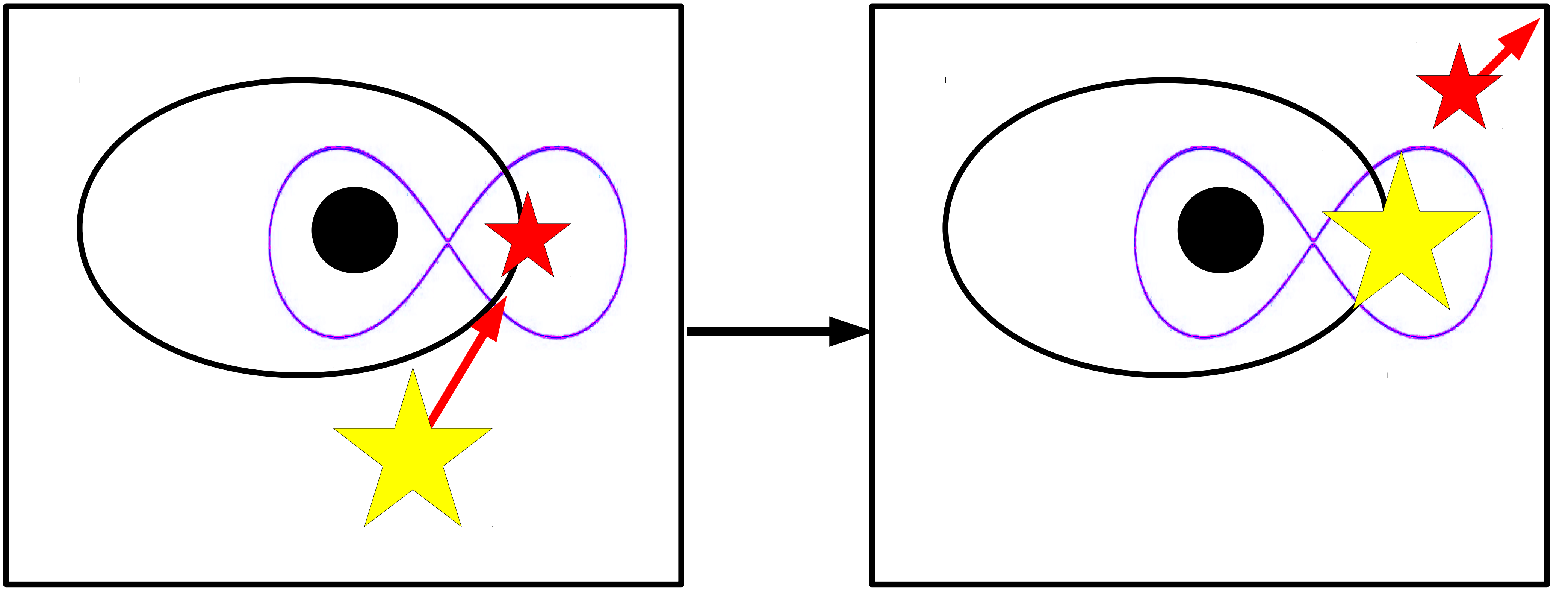
Which is the effect of 3-body encounters on X-ray binaries?



After 3-body encounters, the semi-major axis shrinks and the radius of the companion equals the Roche lobe

3) Effects of 3-body on X-ray binaries

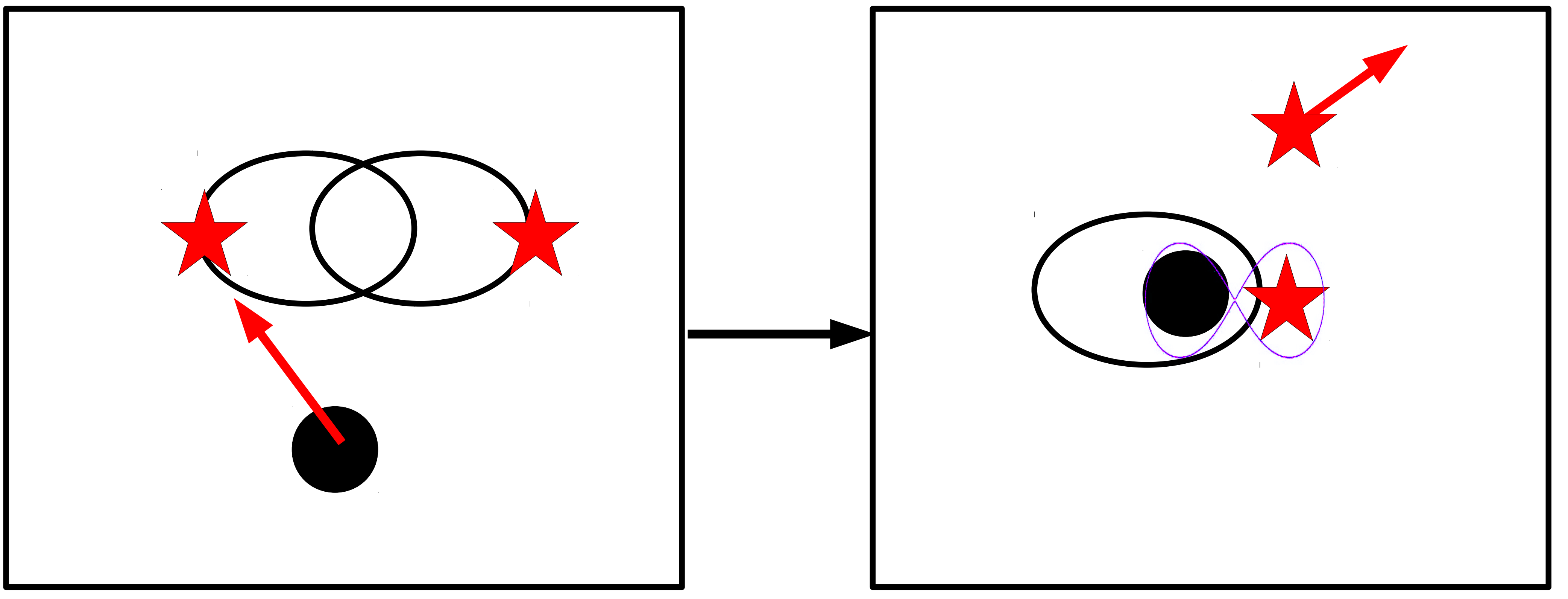
Which is the effect of 3-body encounters on X-ray binaries?



Exchanges are very important: (1) bring stars with larger radius in the binary

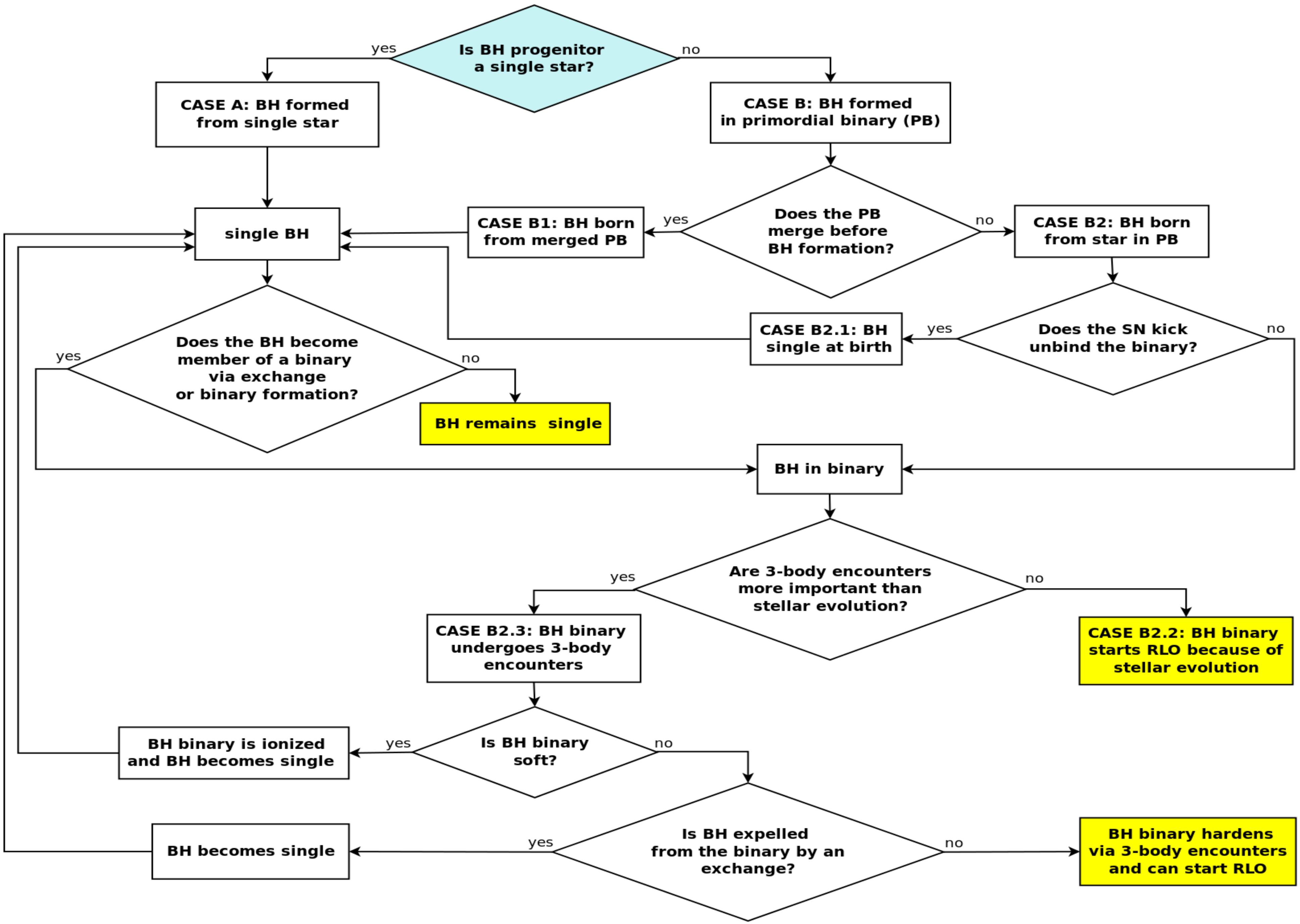
3) Effects of 3-body on X-ray binaries

Which is the effect of 3-body encounters on X-ray binaries?



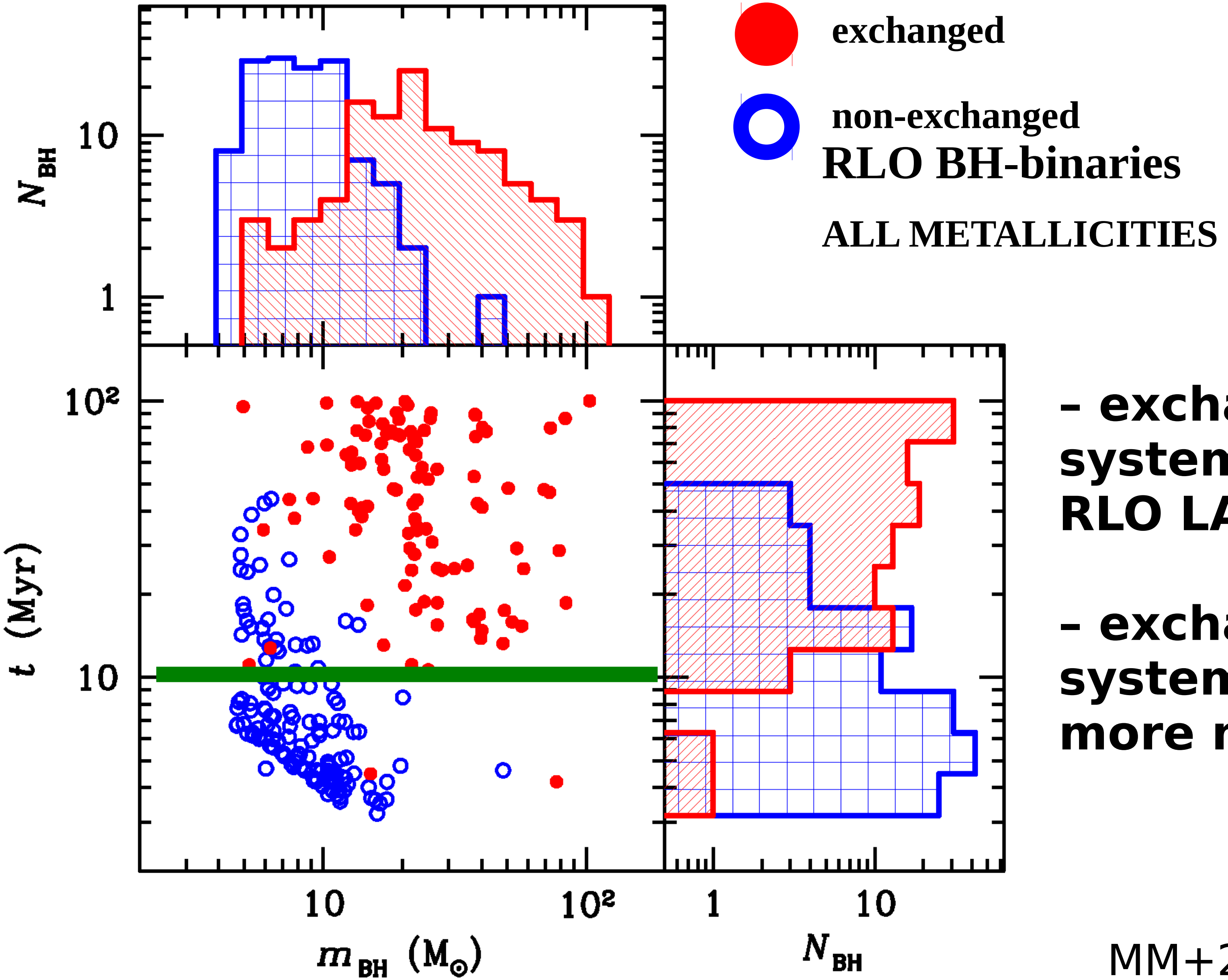
Exchanges are very important: (2) bring single BHs in binaries

3) Effects of 3-body on X-ray binaries



3) Effects of 3-body on X-ray binaries

X-ray binaries from stellar evolution switch on in the first stages



- exchanged systems start RLO LATER

- exchanged systems contain more massive BHs

MM+2013; Mapelli & Zampieri 2014

3) Effects of 3-body on X-ray binaries

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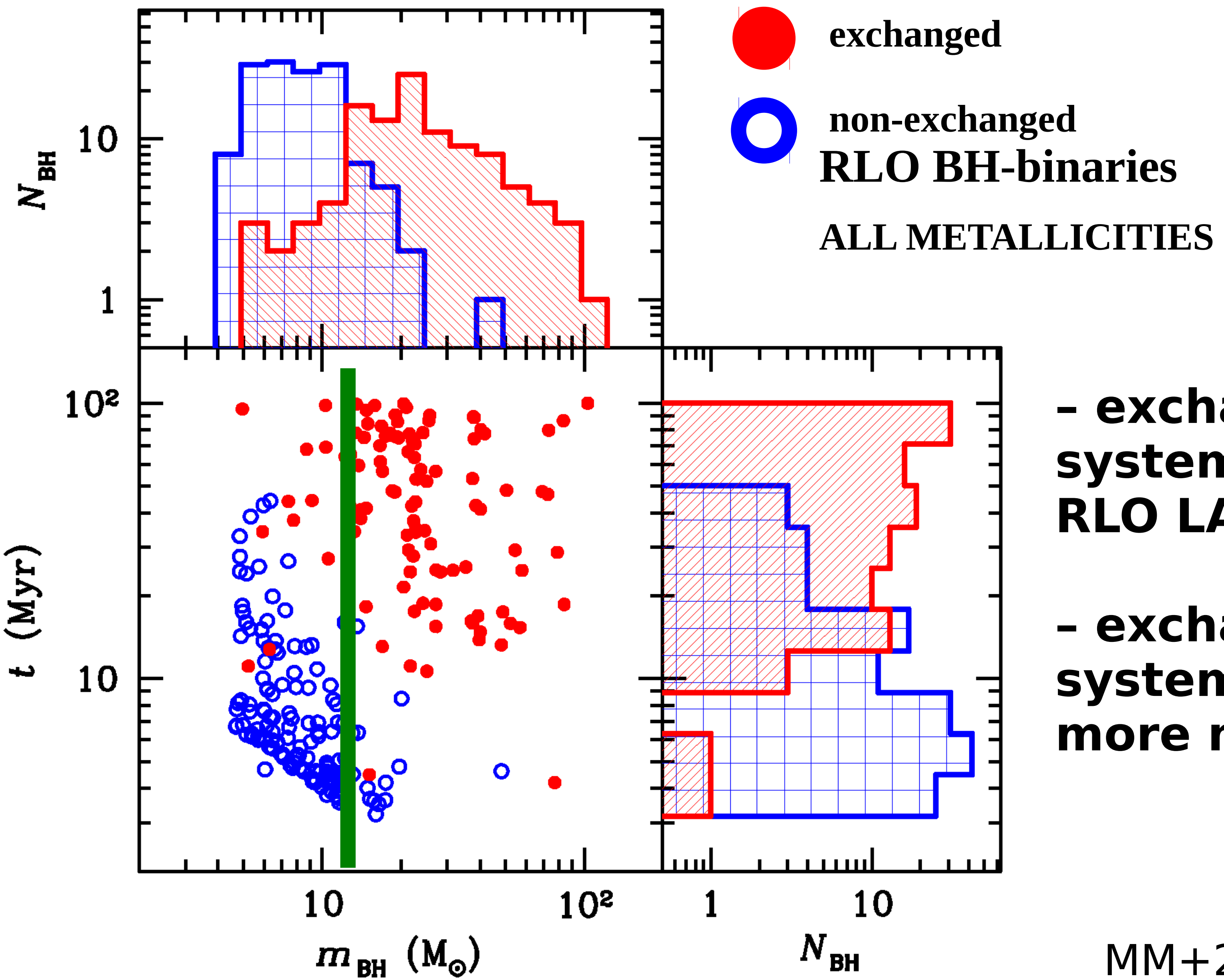

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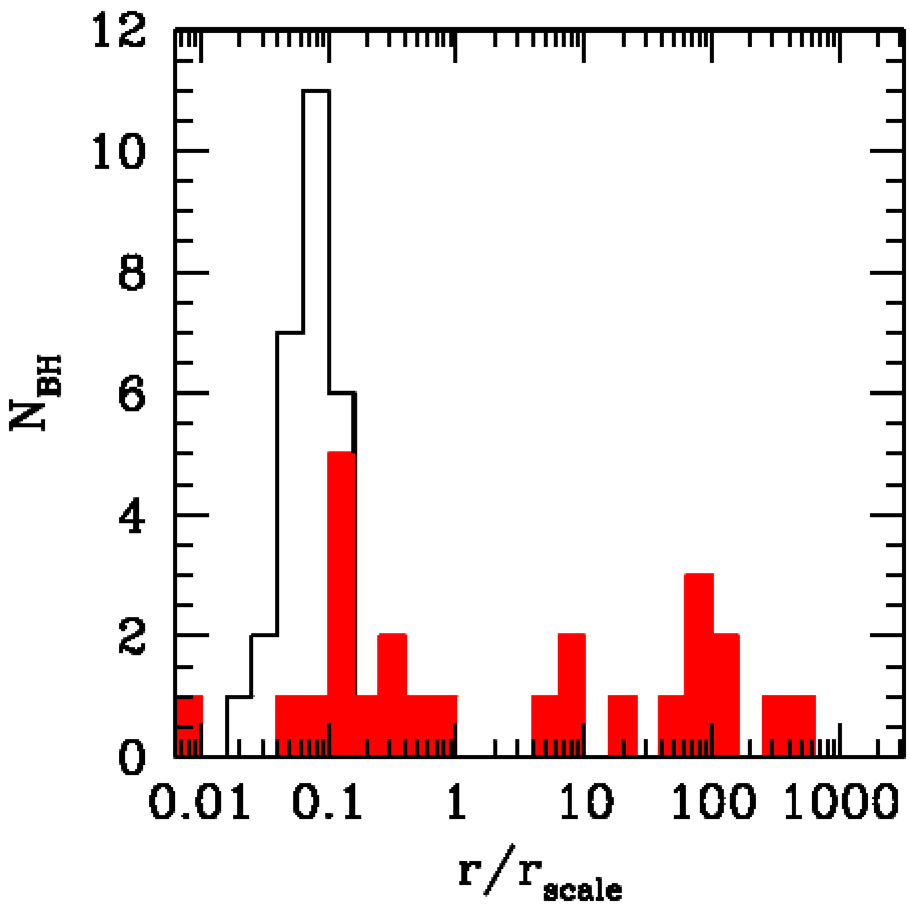
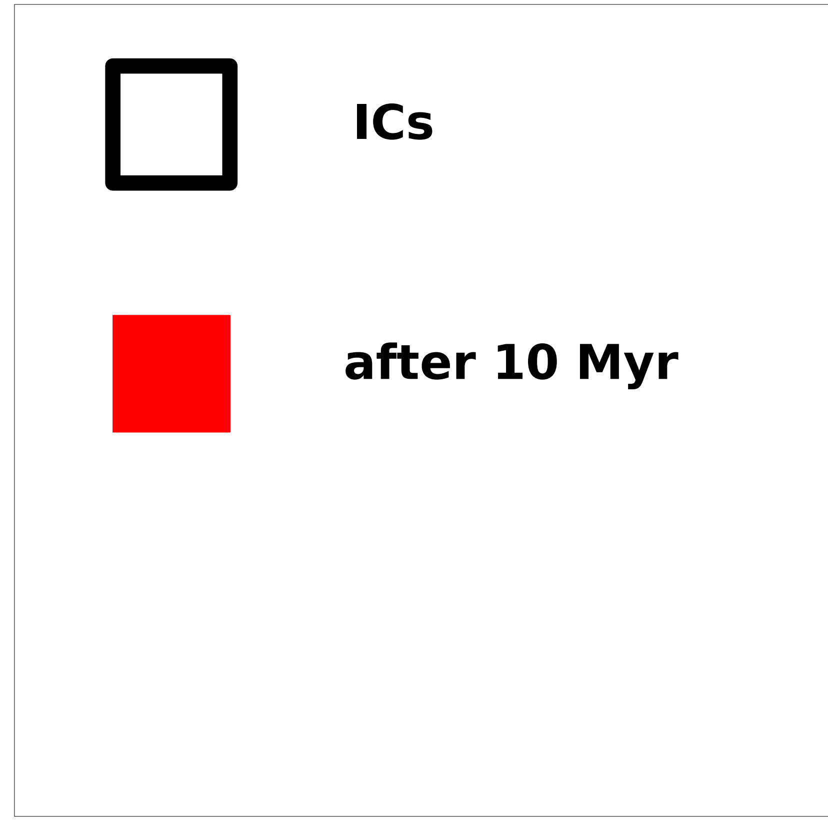
MM+2013; Mapelli & Zampieri 2014

3) Effects of 3-body on X-ray binaries

Simulations of young star clusters + MSBH binary with Starlab:





~30-40 %
BHs are ejected
with MS companion before RG phase!!

MM et al. 2011

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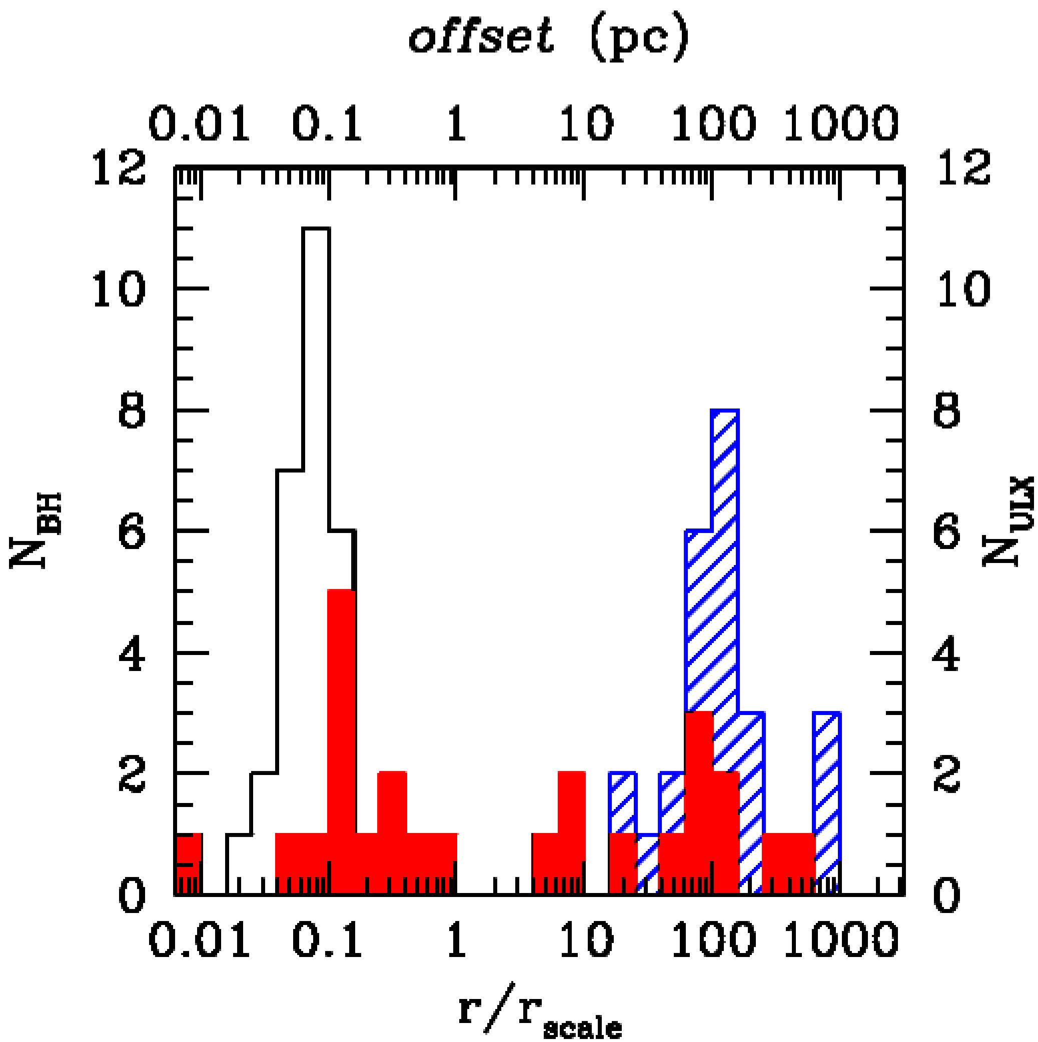

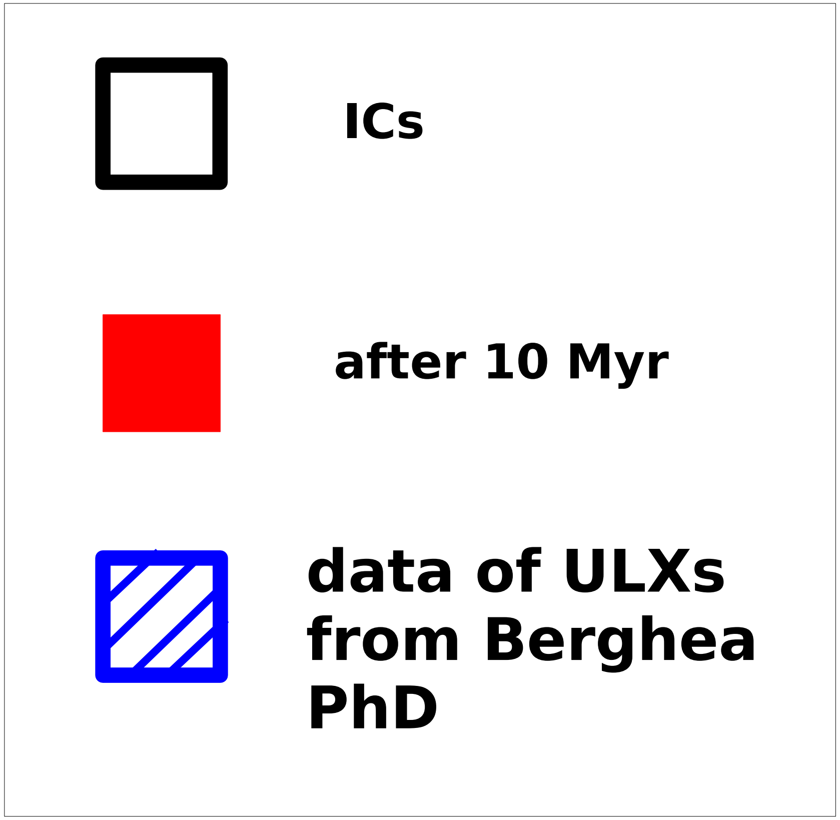

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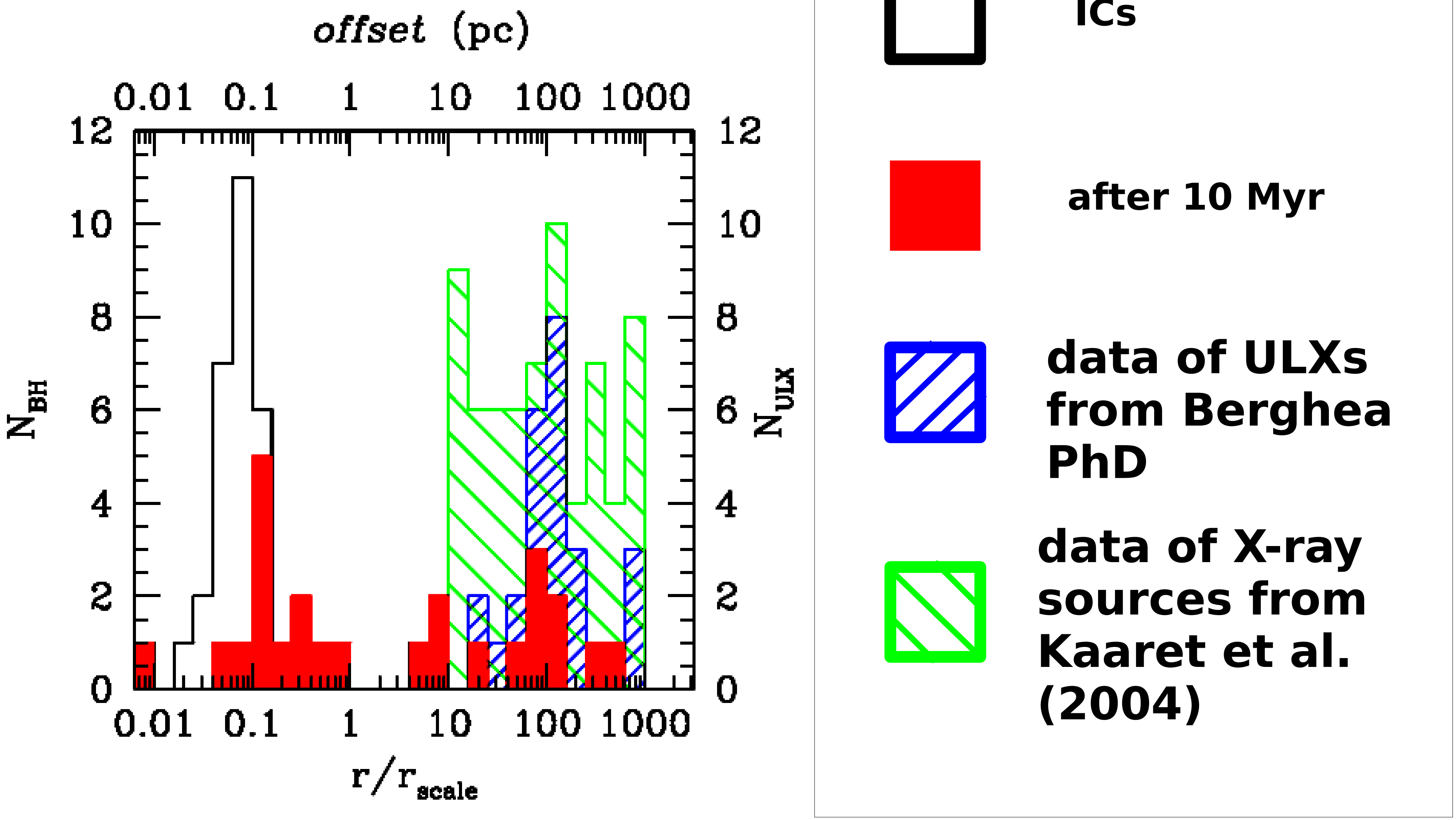
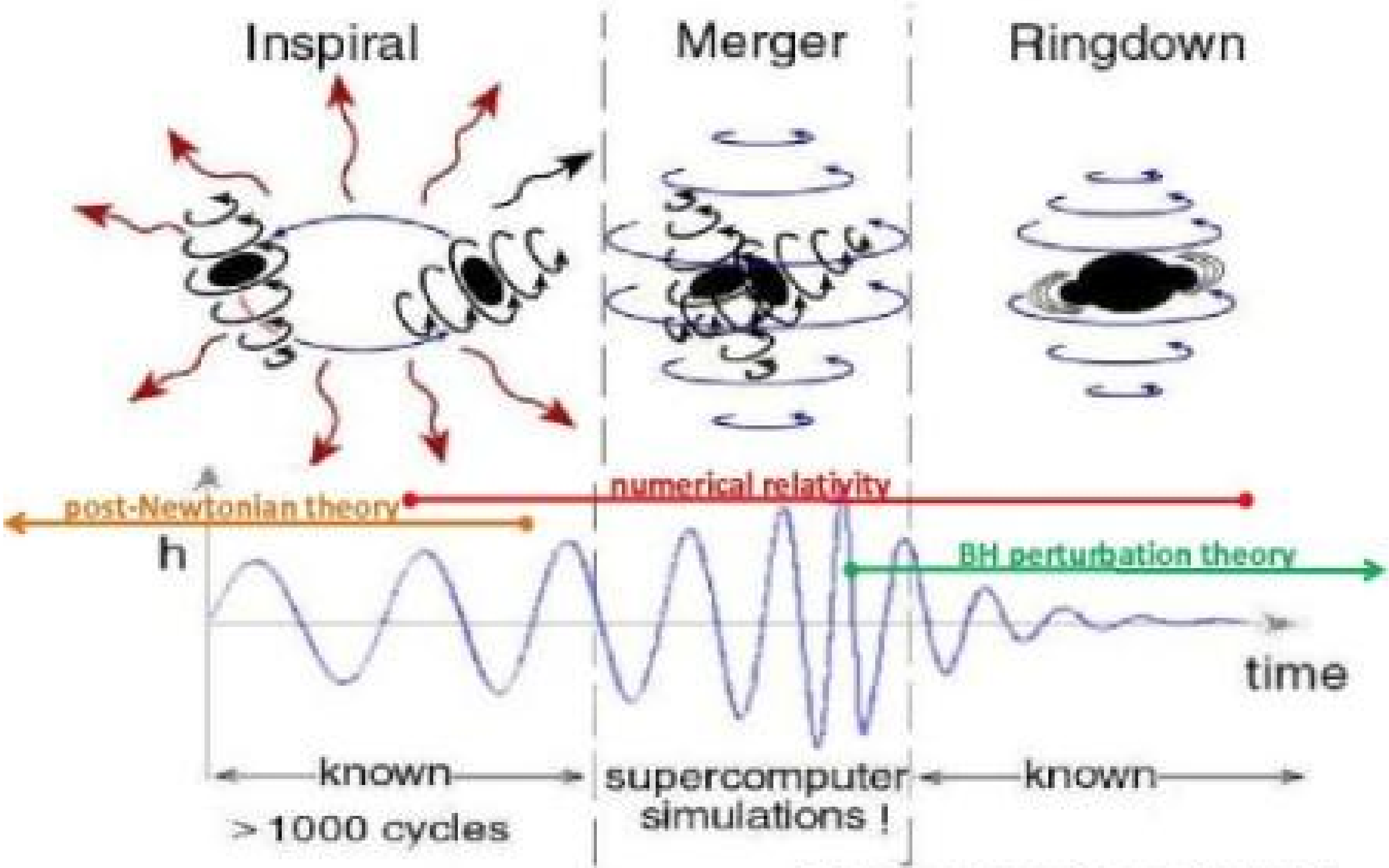


MM et al. 2011

3b) Effects of 3-body on GW sources

GWs:= perturbations of space-time that propagate as WAVES,
Predicted by Einstein's theory
It can be shown that merging compact-object binaries are SOURCEs of GWs

Cartoon of BH coalescence:

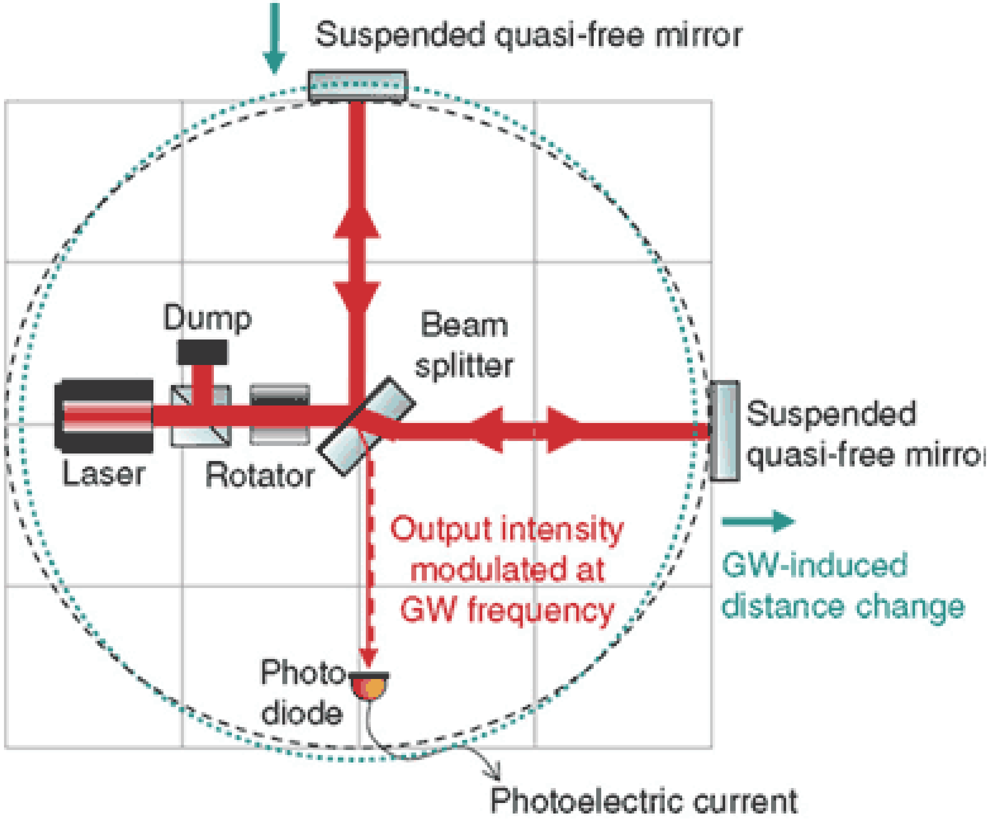


[slide adapted from Thorne, Centrella]

3b) Effects of 3-body on GW sources

* Only INDIRECT evidence by orbital decay of NS-NS binaries
(Hulse & Taylor)

* In 2015-2016 the second-generation ground based detectors
Advanced VIRGO and Advanced LIGO start operating !!!!!!!!!!!



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* BH-BH, BH-NS and NS-NS are sources of GWs

* In star clusters BH-BH and BH-NS are among the most massive
BINARIES: (i) form efficiently by **exchange (~95 % of BH-BH)**
(ii) are hard → **shrink by 3-body encounters**

and are LONG LIVED (because BH and NS do not evolve)

→ **ENHANCEMENT of GW sources by 3-body encounters?**

To be checked with SIMULATIONS for young clusters!!!
(see eg Ziosi et al. 2014)

References:

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* Mapelli et a. 2011, MNRAS, 416, 1756