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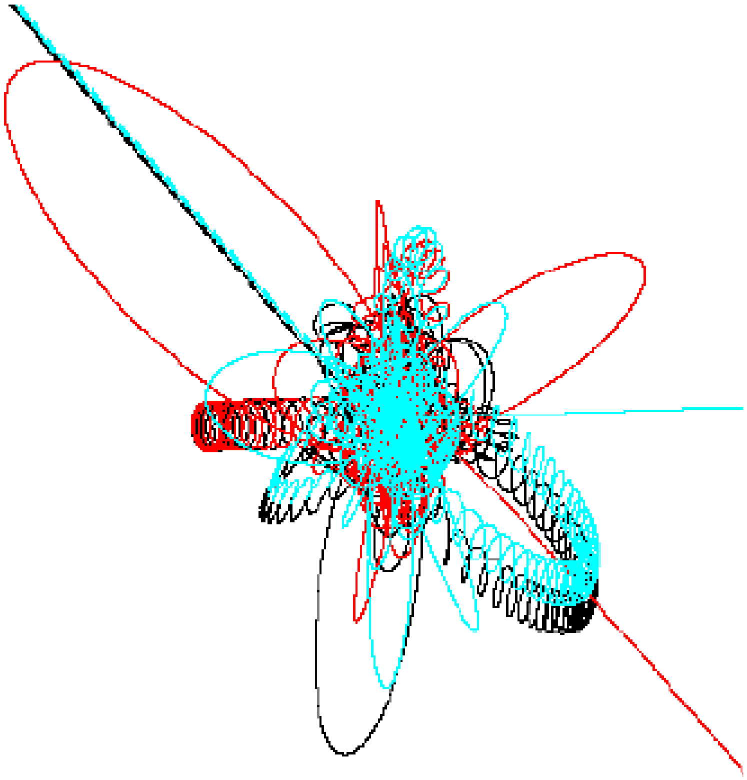
DYNAMICS and ULTRALUMINOUS X-ray sources:



Milano, January 30 2014

3 main effects of dynamics on ULXs:

1. **3-body encounters trigger ULXs in star clusters (SCs)**

2. **3-body encounters and evaporation trigger ejection of ULXs from SCs**

3. **3-body encounters and/or mass segregation trigger formation of intermediate-mass black holes (IMBHs)**

OUTLINE:

1. introduction about dynamics of SCs and 3-body encounters

2. 3-body encounters enhance ULX formation

3. 3-body encounters trigger ULX ejection

4. mechanisms for formation of IMBHs

COLLISIONAL/COLLISIONLESS?

- Collisional systems are systems where interactions between particles are EFFICIENT with respect to the lifetime of the system
- Collisionless systems are systems where interactions are negligible

When is a system collisional/collisionless?

RELAXATION TIMESCALE

Gravity is a LONG-RANGE force → cumulative influence on each star/body of distant stars/bodies is important: often more important than influence of close stars/bodies

Two-body encounters are important even if 2 bodies are distant

→ **two-body relaxation timescale**: timescale needed for a star to lose completely memory of its initial velocity ($\Delta v/v \sim 1$) by the effect of two body encounters

COLLISIONAL/COLLISIONLESS?

two-body relaxation timescale: timescale needed for a star to lose completely memory of its initial velocity ($\Delta v/v \sim 1$) by the effect of two body encounters

$$t_{\rm rlx} = n_{\rm cross}\, t_{\rm cross} = \frac{N}{8\,\ln N}\,\frac{R}{v}$$

with more accurate calculations, based on diffusion coefficients (Spitzer & Hart 1971):

$$t_{\rm rlx} = 0.34\,\frac{\sigma^3}{G^2\,m\,\rho\,\ln\Lambda}$$

MOST USEFUL EXPRESSION:

$$t_{\rm rlx} = 10\,{\rm Myr}\,\left(\frac{M_{\rm TOT}}{3500\,{\rm M}_\odot}\right)^{1/2}\,\left(\frac{r_{\rm hm}}{1\,{\rm pc}}\right)^{3/2}$$

Which is the typical t_{rlx} of stellar systems?

* **globular clusters, dense young star clusters, nuclear star clusters** (far from SMBH influence radius)
  R~1-10 pc, N~10^3-10^6 stars, v~1-10 km/s

$$t_{rlx} \sim 10^{7-10}\ \mathrm{yr}$$

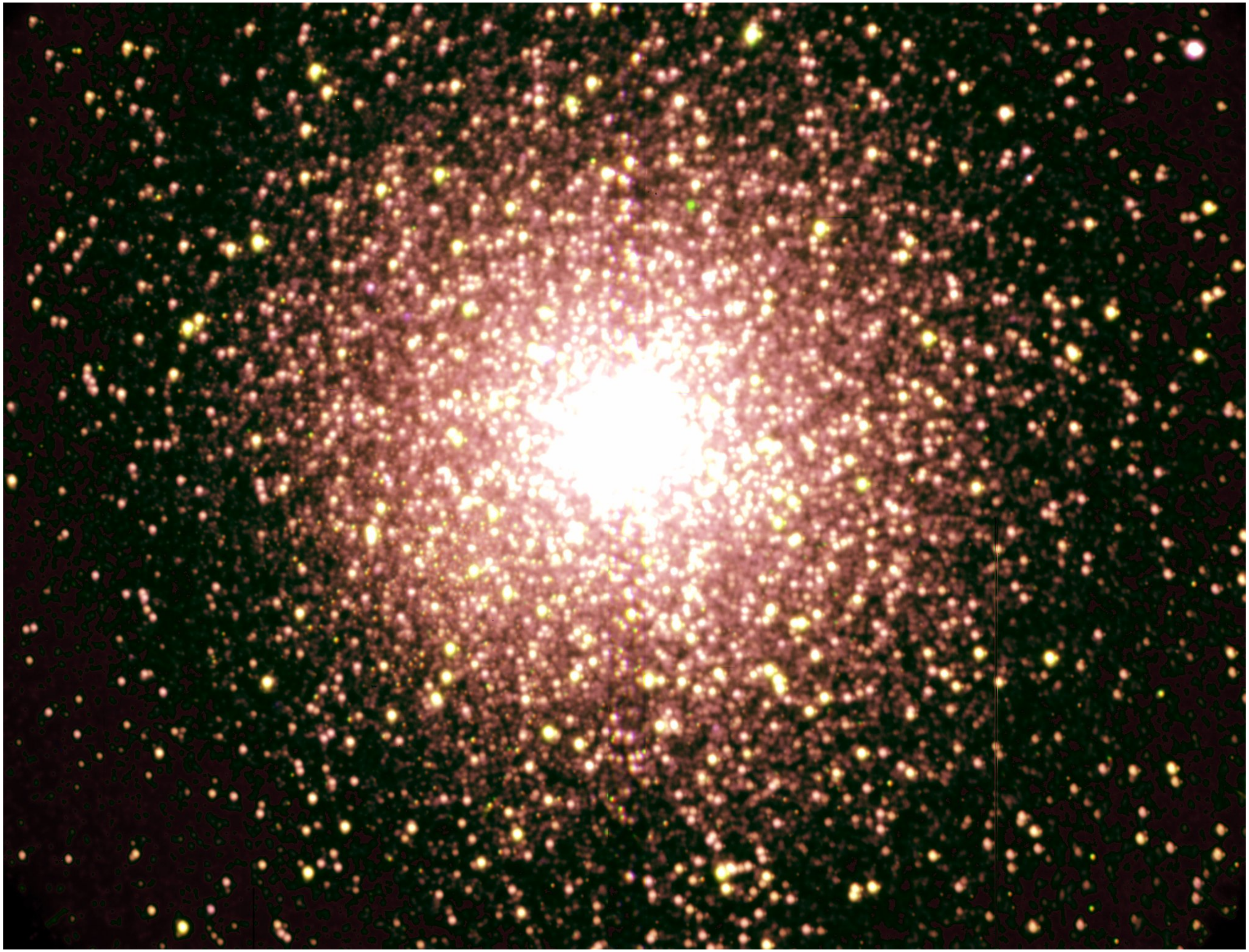
→ **COLLISIONAL**

* **galaxy field/discs**
  R~10 kpc, N~10^10 stars, v~100-500 km/s

$$t_{rlx} >> \text{Hubble time}$$

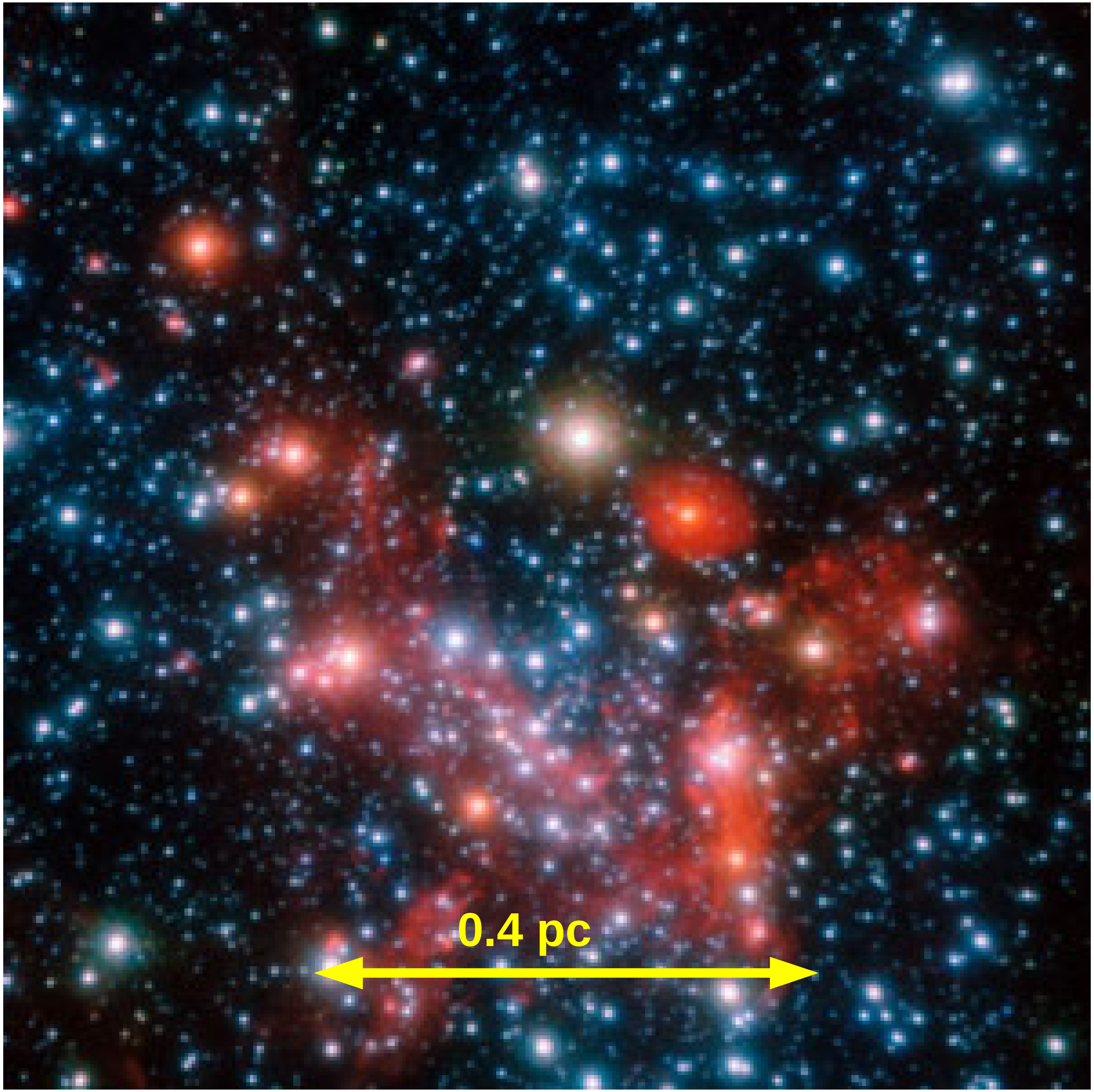
→ **COLLISIONLESS**

EXAMPLES of COLLISIONAL stellar systems



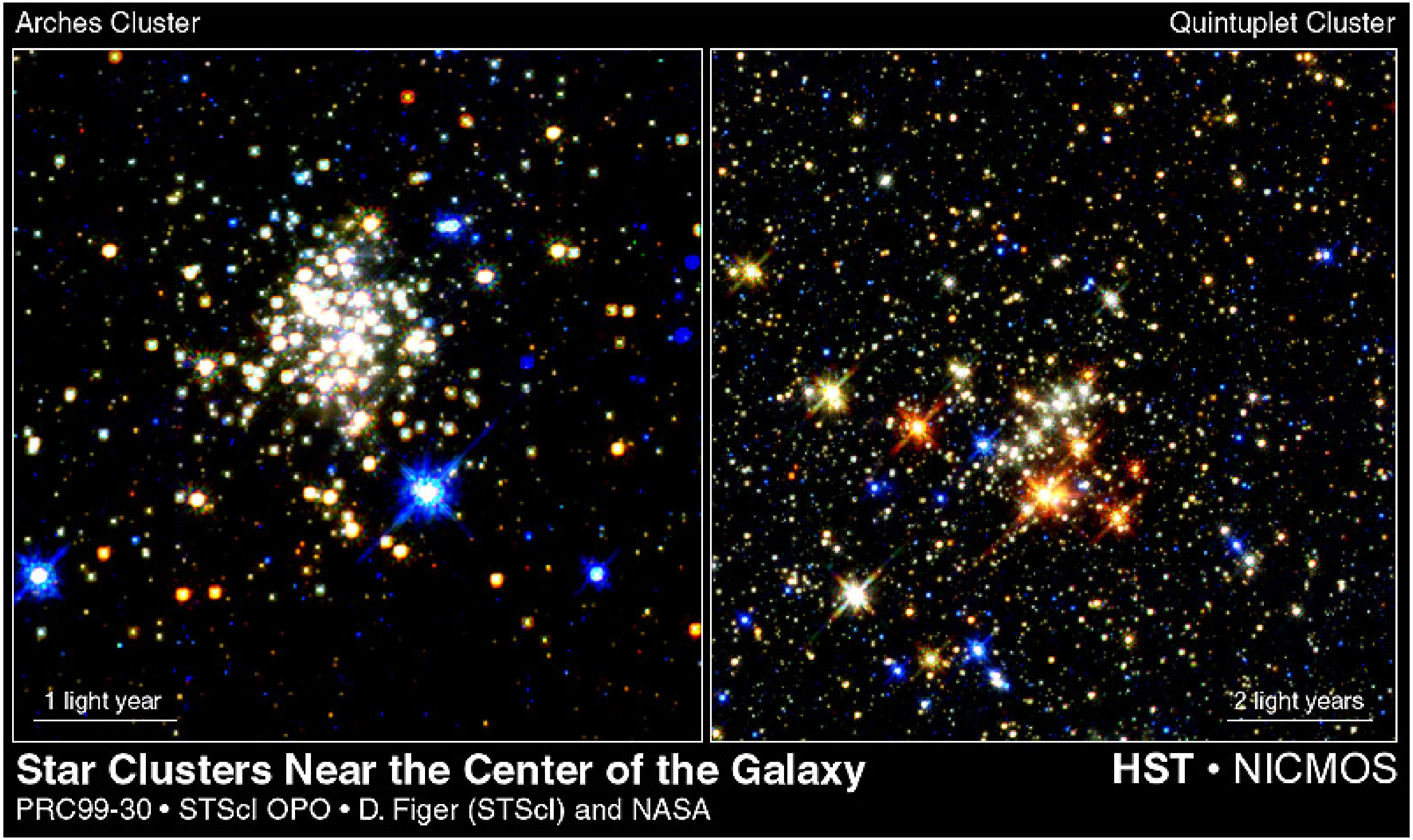
Globular clusters (47Tuc)

EXAMPLES of COLLISIONAL stellar systems



Nuclear star clusters (MW)
NaCo @ VLT
Genzel+2003

EXAMPLES of COLLISIONAL stellar systems



Young dense star clusters (Arches, Quintuplet)

1) VERY IMPORTANT BECAUSE ARE THE BIRTHPLACE OF STARS IN LOCAL UNIVERSE!!

2)MANY ULXs are associated with regions of star formation!

BINARIES as ENERGY RESERVOIR

Binaries have a energy reservoir (their internal energy) that can be exchanged with stars.

INTERNAL ENERGY: total energy of the binary – kinetic energy of the centre-of-mass

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

where m_1 and m_2 are the mass of the primary and secondary member of the binary, μ is the reduced mass (:= $m_1\, m_2/(m_1+m_2)$).
r and v are the relative separation and velocity.

$E_{int}<0$ if the binary is bound

Note that E_{int} can be interpreted as the energy of the 'reduced particle': a fictitious particle of mass μ orbiting in the potential – $G\, m_1\, m_2/r$

BINARIES as ENERGY RESERVOIR

As far as the binary is bound, the orbit of the reduced particle is a Kepler ellipse with semi-major axis *a*. Thus, the energy integral of motion is

$$E_{int} = -\frac{G\, m_1\, m_2}{2\, a} = -E_b$$

where E_b is the **BINDING ENERGY** of the binary.

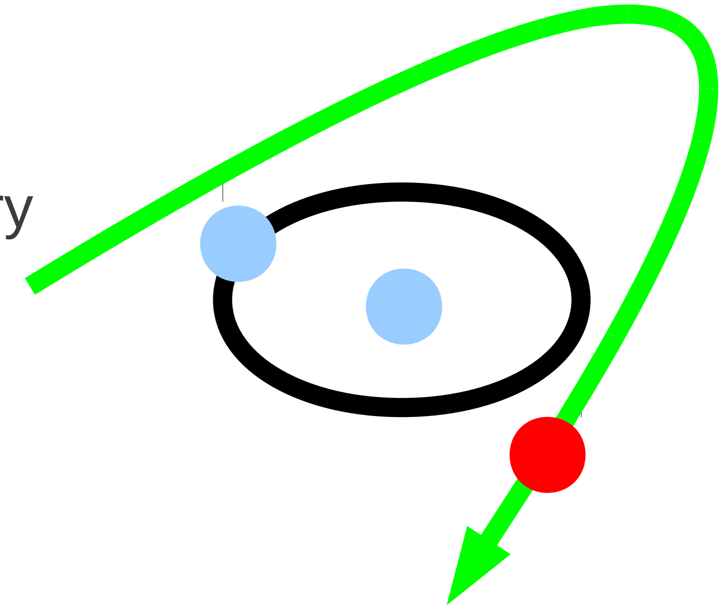
THE ENERGY RESERVOIR of BINARIES can be EXCHANGED with stars:

during a **3-BODY INTERACTION**,
i.e. an interaction between a binary and a single star,

the single star can either

EXTRACT INTERNAL ENERGY from the binary

or lose a fraction of its kinetic energy, which is converted into internal energy of the binary.



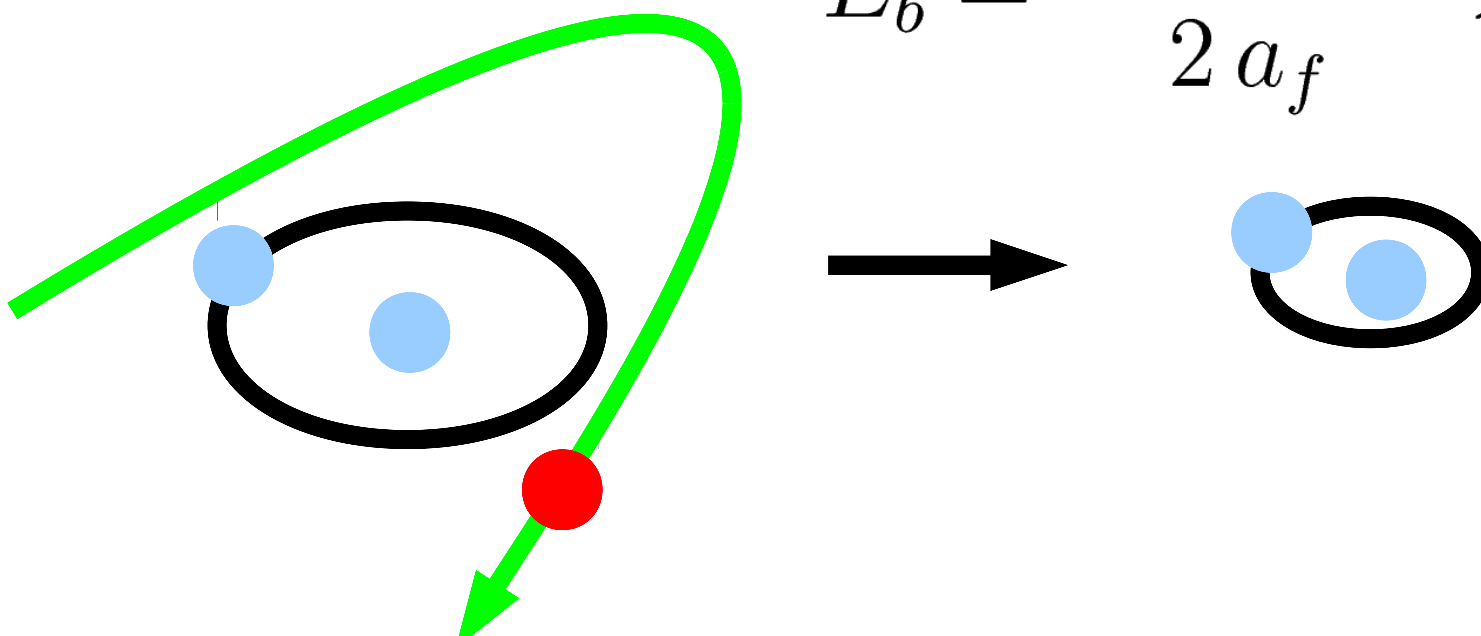
BINARIES as ENERGY RESERVOIR

If the star extracts E_{int} from the binary, its final kinetic energy (K_f) is higher than the initial kinetic energy (K_i).
We say that the STAR and the BINARY acquire RECOIL VELOCITY.

E_{int} becomes more negative, i.e. E_b higher: the binary becomes more bound (e.g. a decreases or m_1 and m_2 change).

$a_f < a_i$

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



CARTOON of a FLYBY ENCOUNTER where $a_f < a_i \rightarrow E_b$ increases

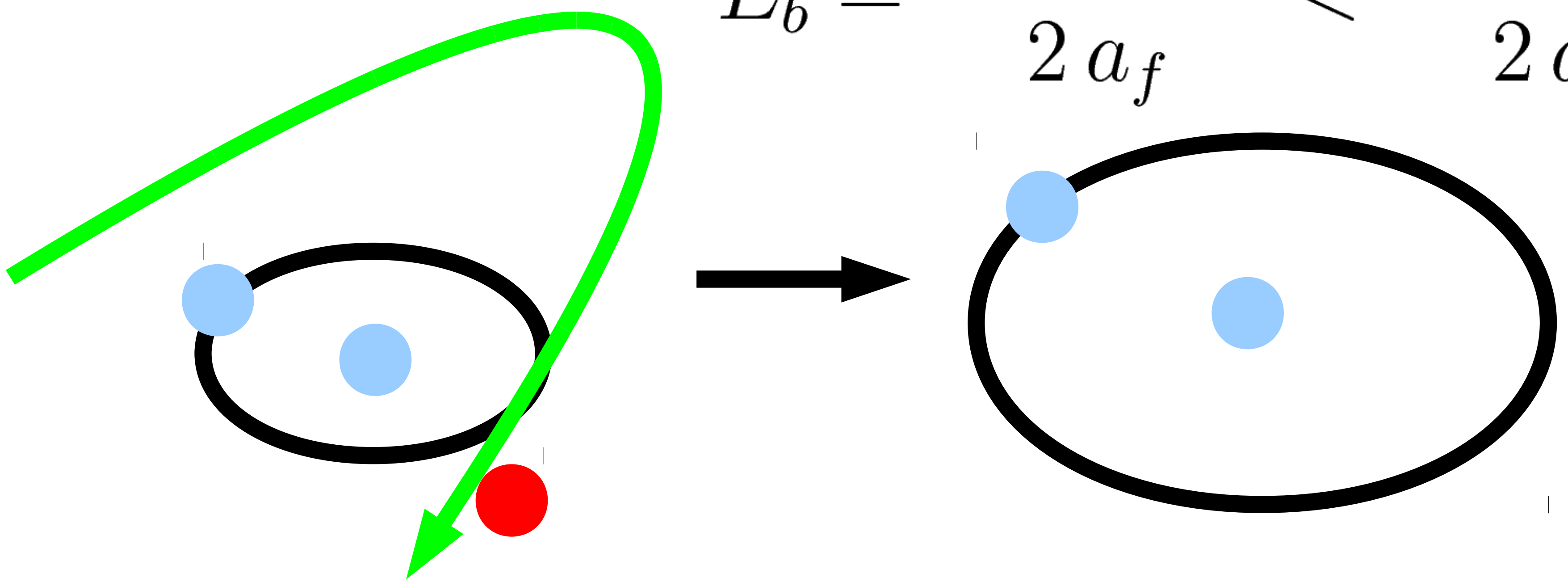
BINARIES as ENERGY RESERVOIR

If the star transfers kinetic energy to the binary, its final kinetic energy (K_f) is obviously lower than the initial kinetic energy (K_i).

E_{int} becomes less negative, i.e. E_b smaller: the binary becomes less bound (e.g. a increases) or is even IONIZED (:= becomes UNBOUND).

$a_f > a_i$

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



CARTOON of a FLYBY ENCOUNTER where $a_f > a_i \rightarrow$ E_b decreases

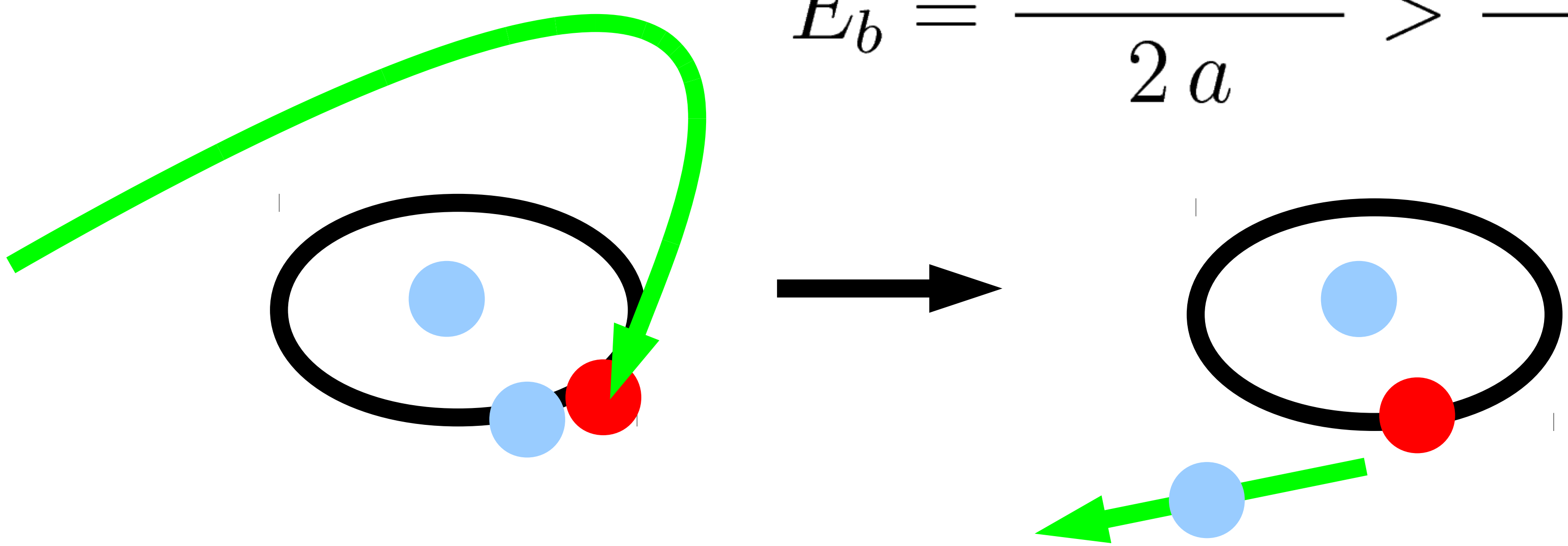
BINARIES as ENERGY RESERVOIR

An alternative way for a binary to transfer internal energy to field stars and increase its binding energy E_b is an **EXCHANGE**:
the single star replaces one of the former members of the binary.

An exchange interaction is favoured when the mass of the single star m_3 is HIGHER than the mass of one of the members of the binary so that the new E_b of the binary is higher than the former:

$m_3 > m_2$

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

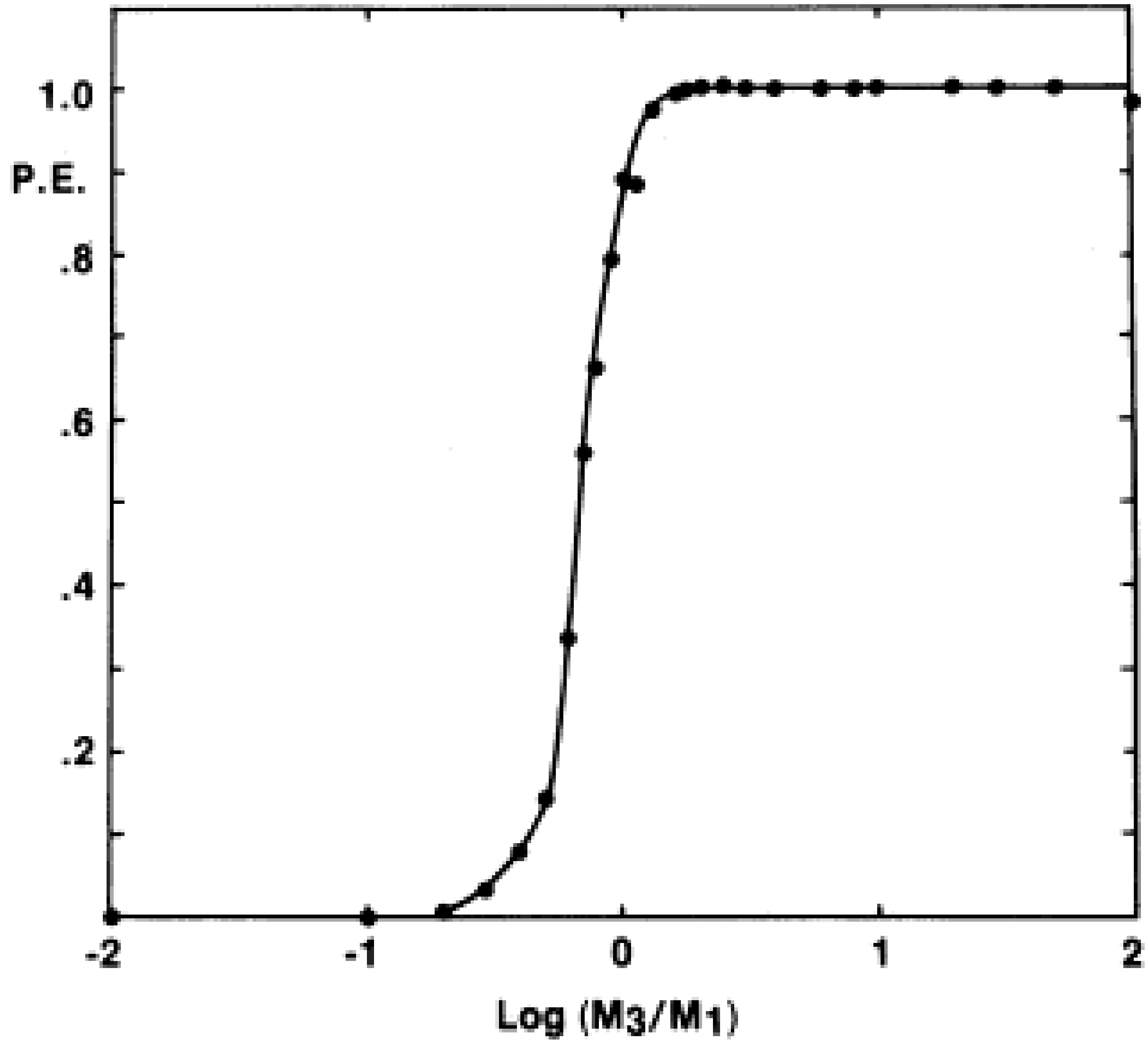


CARTOON of a EXCHANGE ENCOUNTER where $m_3 > m_2 \rightarrow$ E_b increases

EXCHANGE PROBABILITY

Probability increases dramatically if
$m_3 \geq m_1$

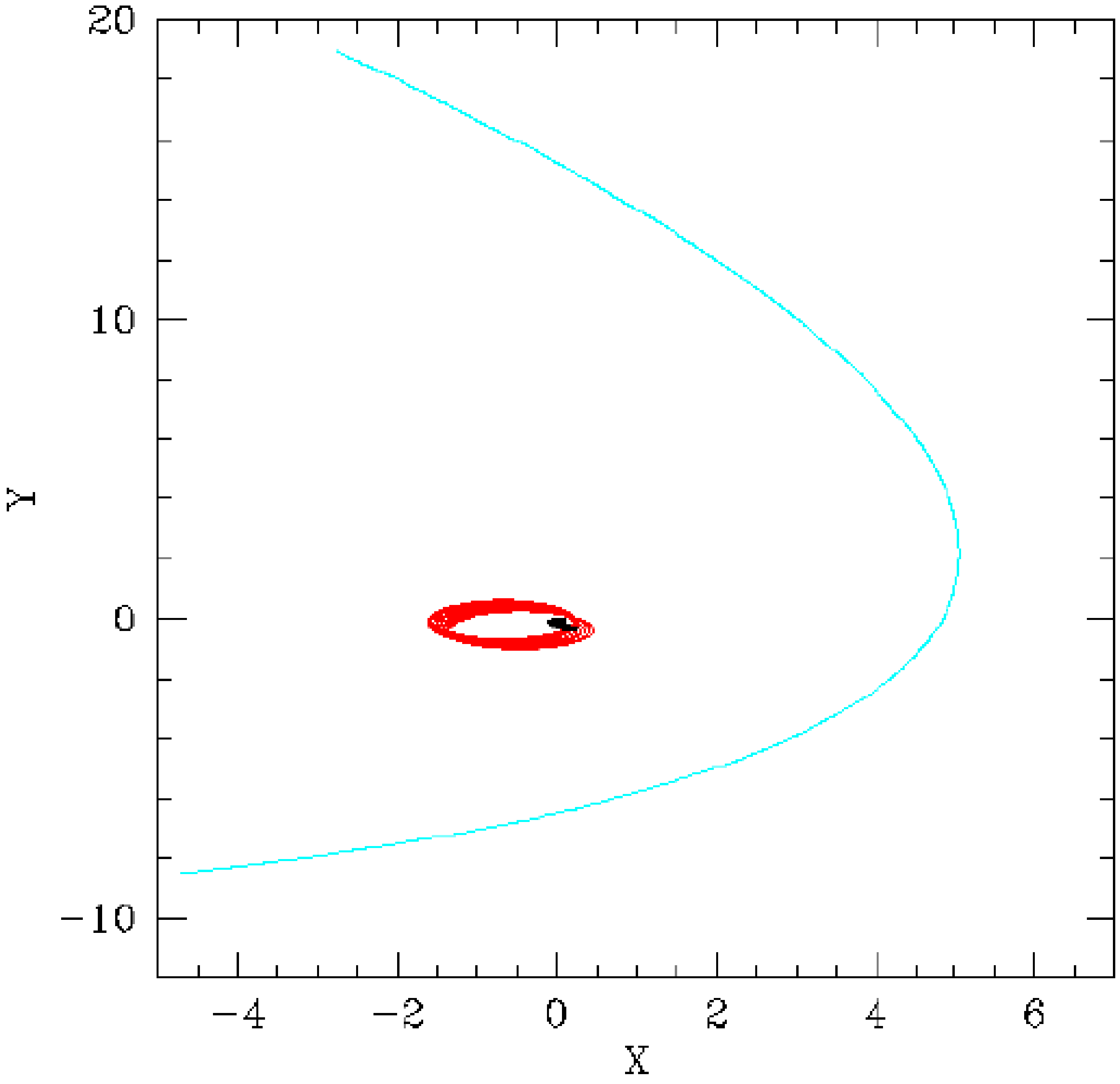
EXCHANGES TEND TO BUILD MORE AND MORE MASSIVE BINARIES!!!



Hills & Fullerton 1980, AJ, 85, 1281

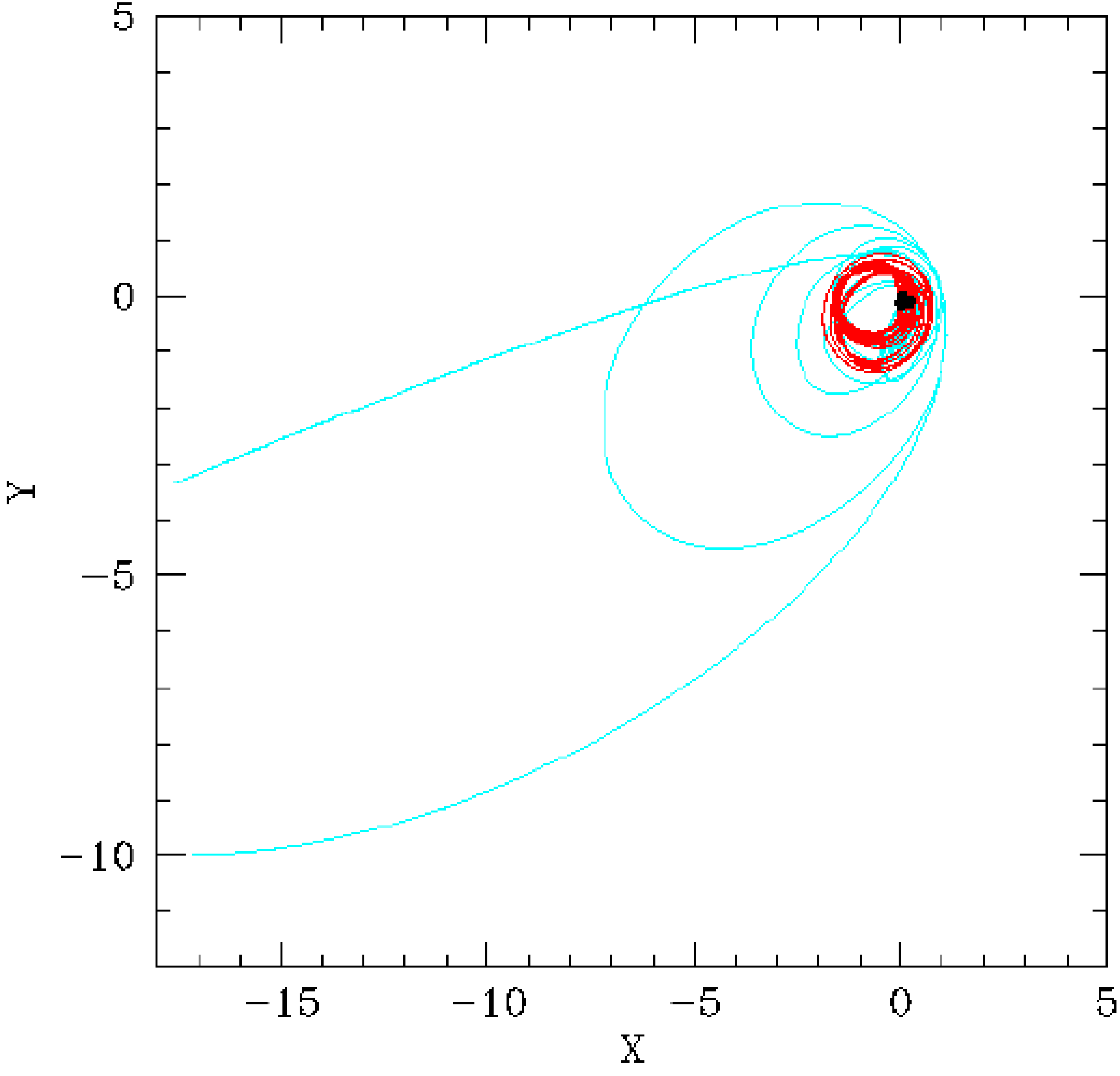
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT FLYBY:



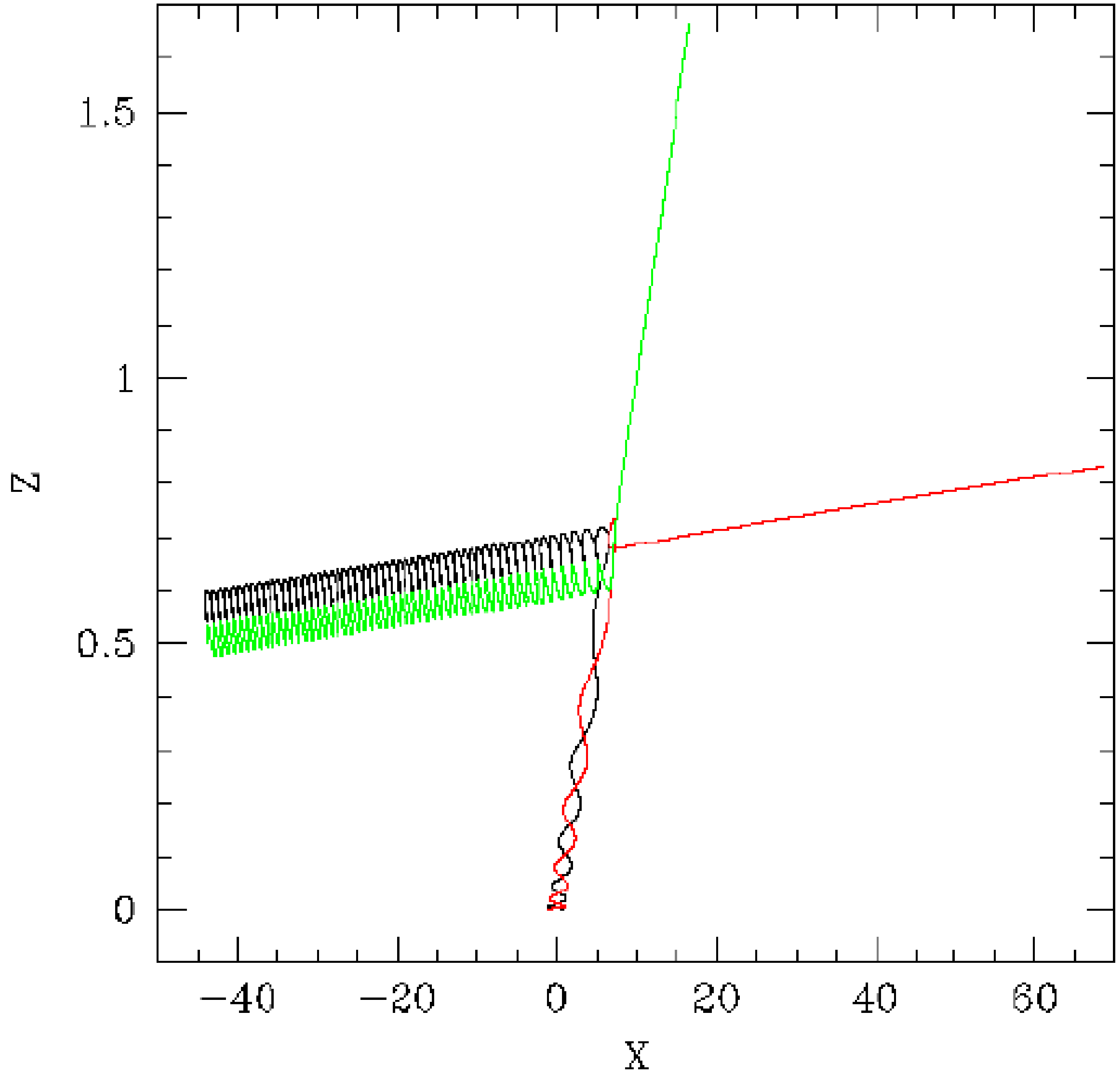
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT FLYBY:



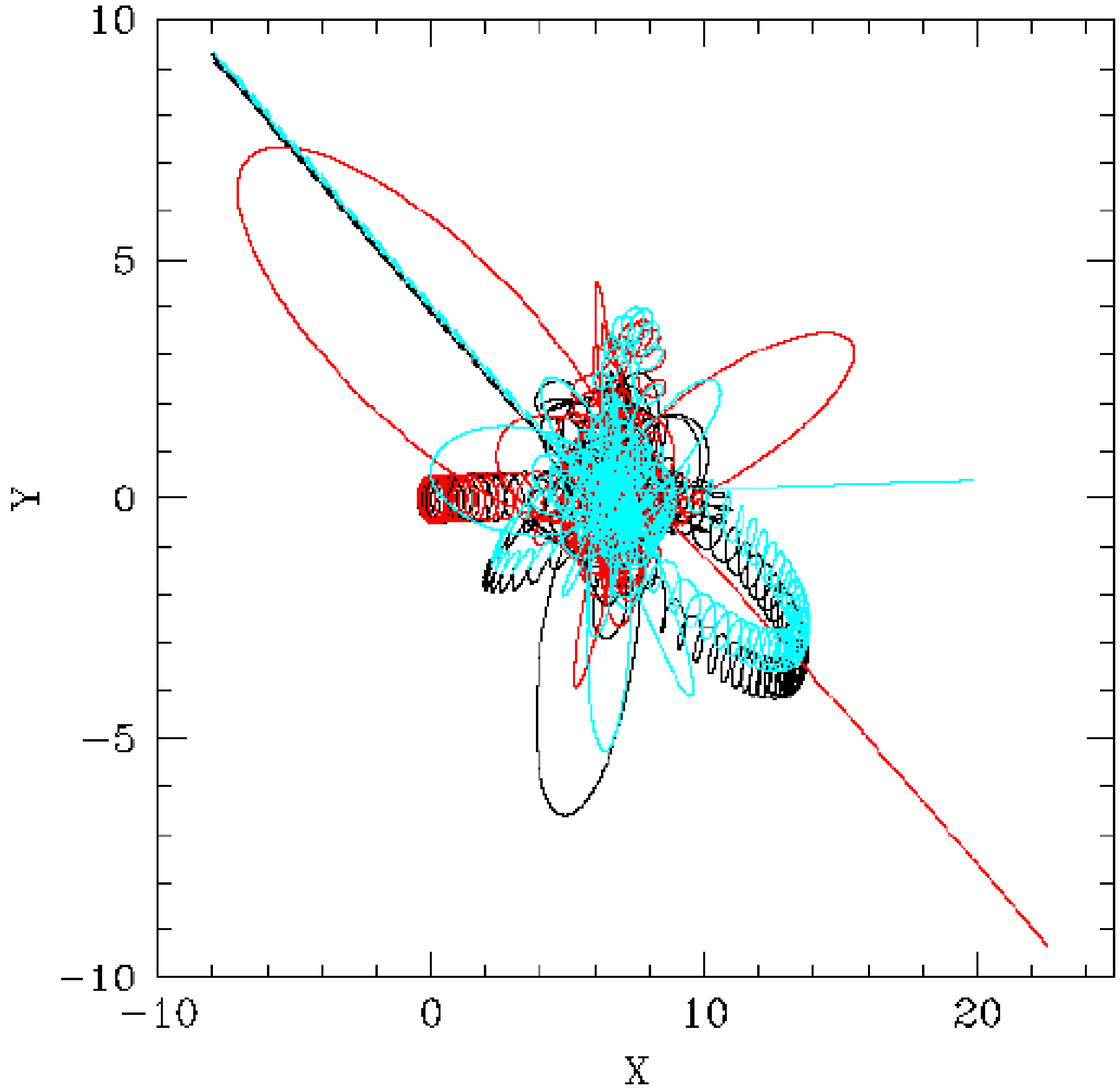
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT
EXCHANGE:



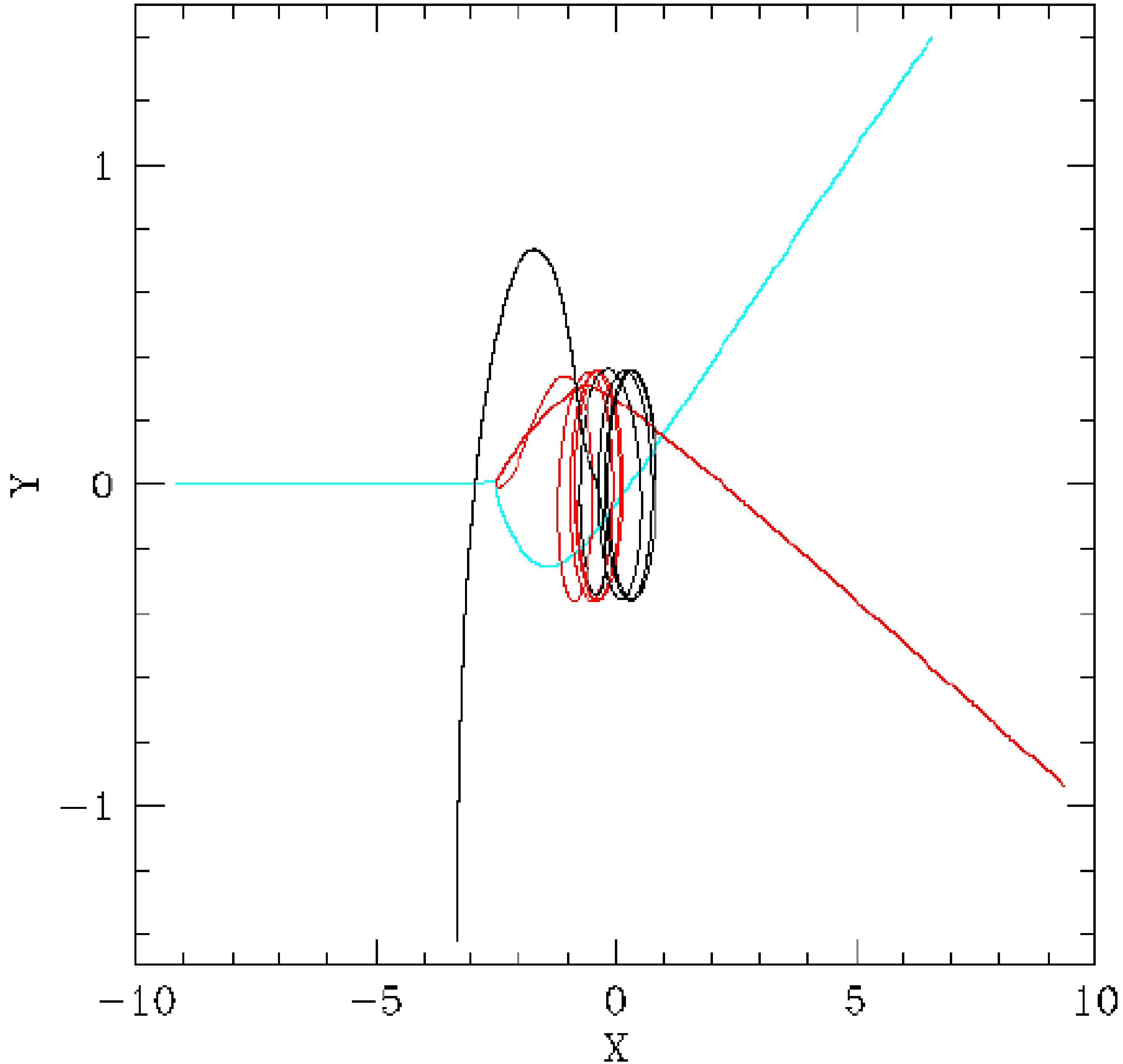
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT EXCHANGE:



EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

IONIZATION:



IMPORTANT INFORMATION about 3-body encounters

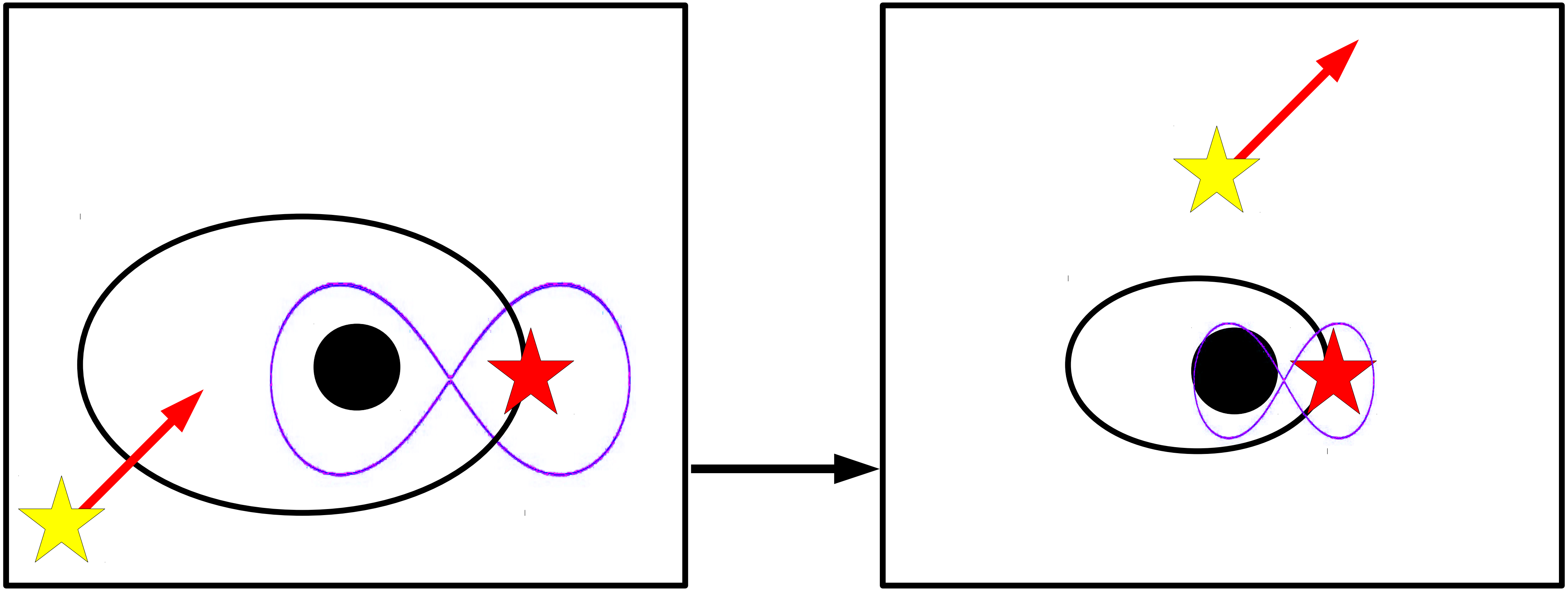
1 → If star extracts E_{int} from the binary,
the binary SHRINKS: semi-major axis decreases

2 → EXCHANGES bring to formation of
more and more massive binaries

3 → If star extracts E_{int} from the binary, the binary and the
star RECOIL: may be ejected from the SC

2. 3-body encounters enhance ULX formation

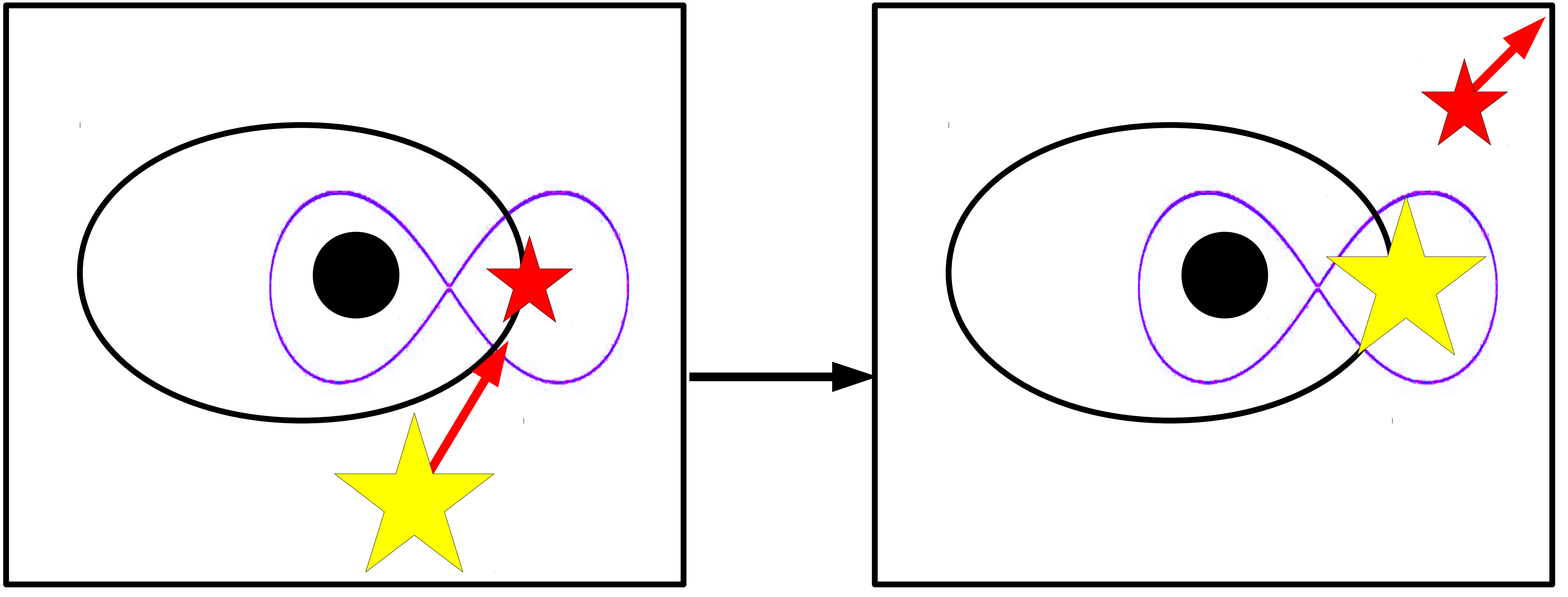
Which is the effect of 3-body encounters on X-ray binaries?



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

2. 3-body encounters enhance ULX formation

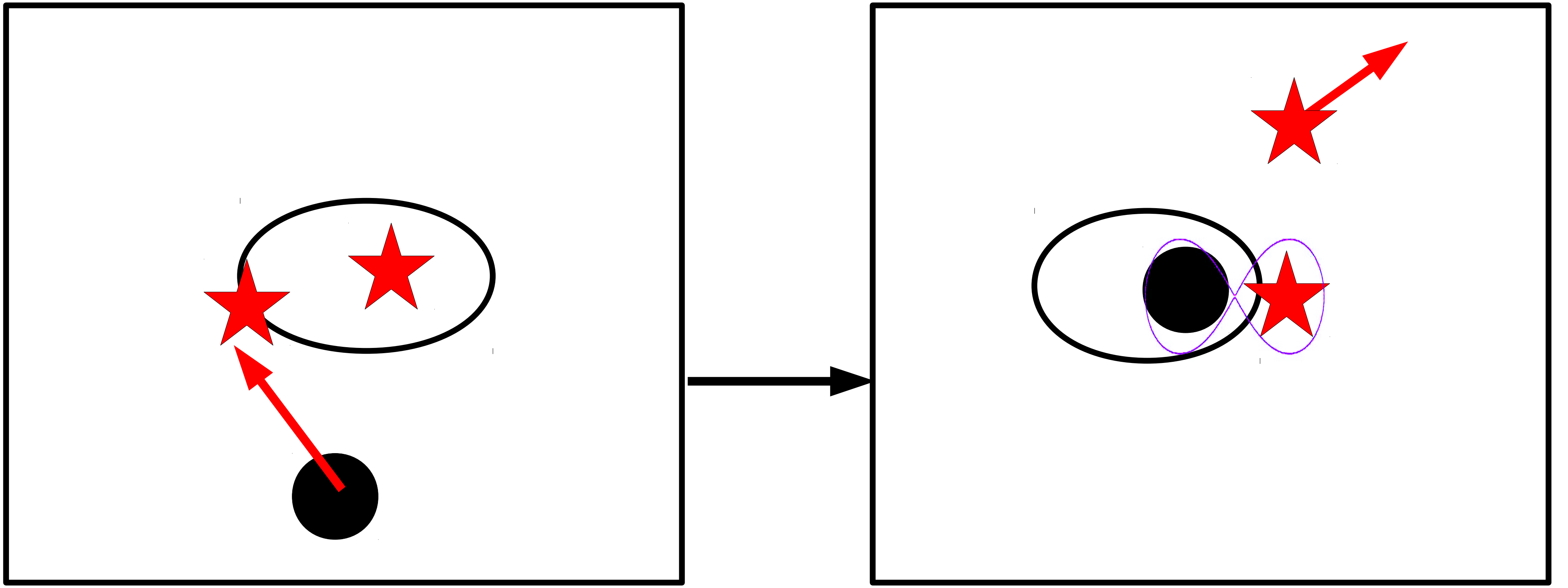
Which is the effect of 3-body encounters on X-ray binaries?



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

2. 3-body encounters enhance ULX formation

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



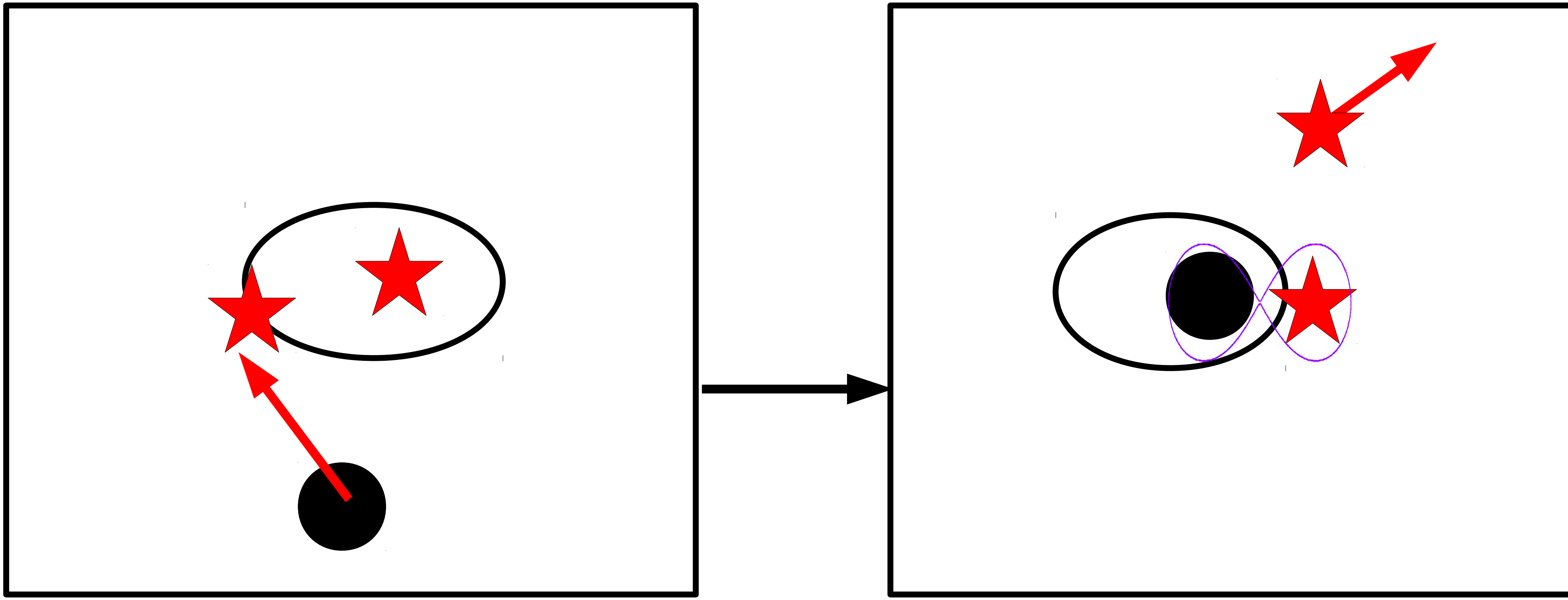
Exchanges are very important: (2) bring single BHs in binaries

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 SC LIKELY ACQUIRES COMPANION FROM DYNAMICS

2. 3-body encounters enhance ULX formation

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

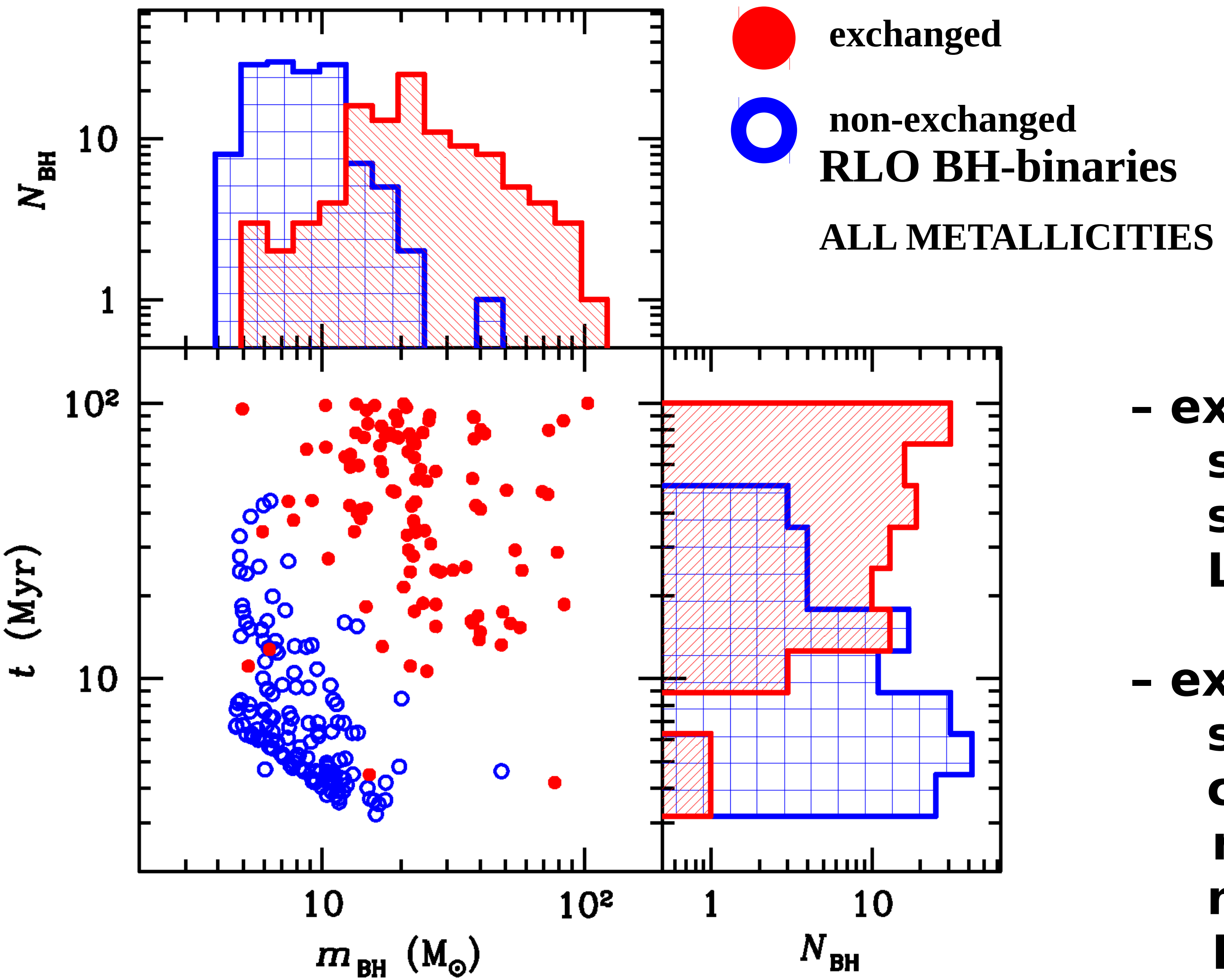


EXCHANGES FAVOUR THE FORMATION of X-RAY BINARIES WITH THE MOST MASSIVE BHs

BHs with Ledd>10^39 erg s^-1

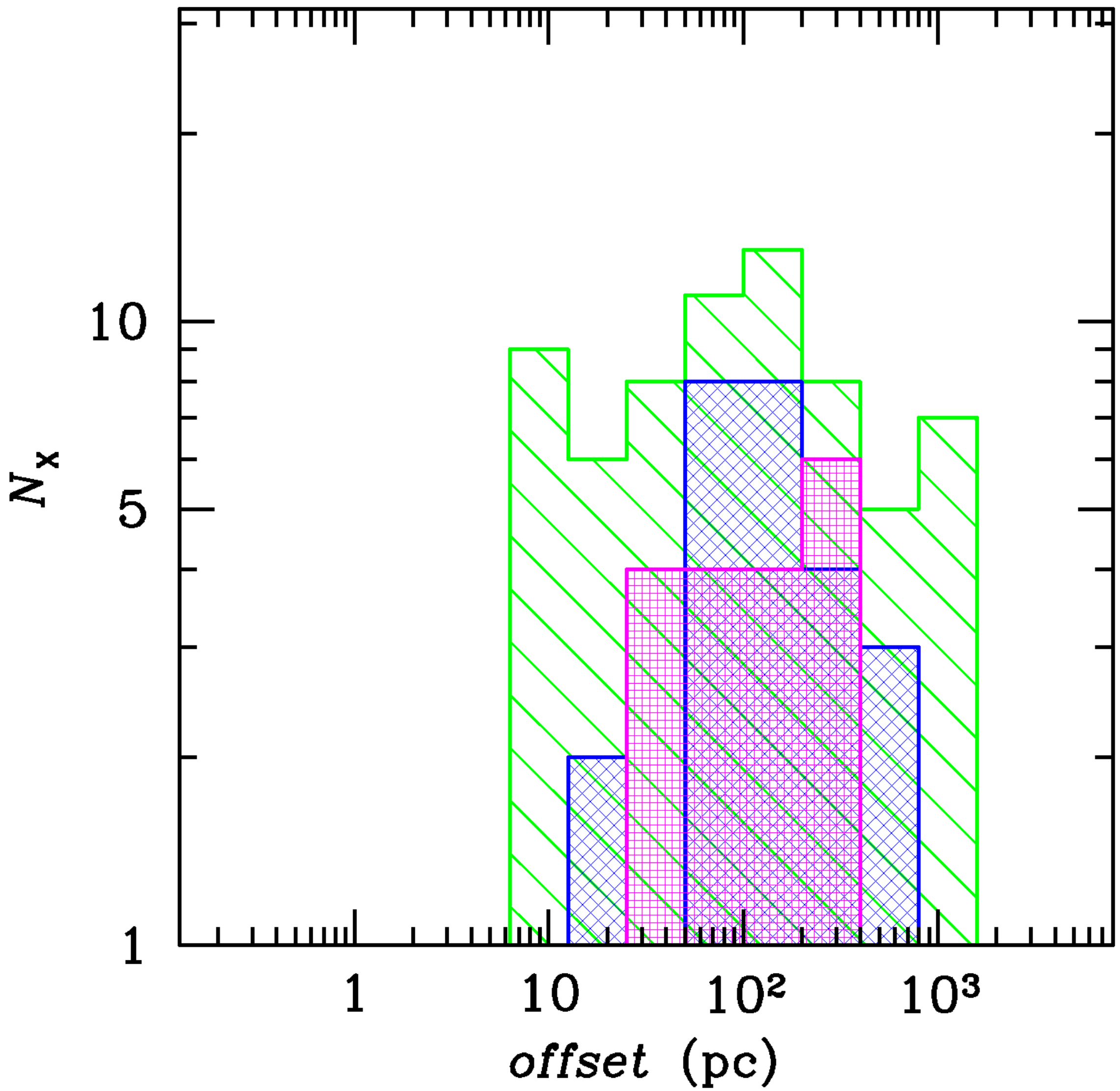
→ produce ULXs with no or mild super-Eddington

FROM N-Body simulations with STARLAB (MM+ 2011, 2013, 2014)
Bachelor, Master and PhD thesis available on this topic (ASK ME!)



- **exchanged systems start RLO LATER**
- **exchanged systems contain more massive BHs**

OBSERVED OFFSET of X-ray binaries with respect to the closest YSC:



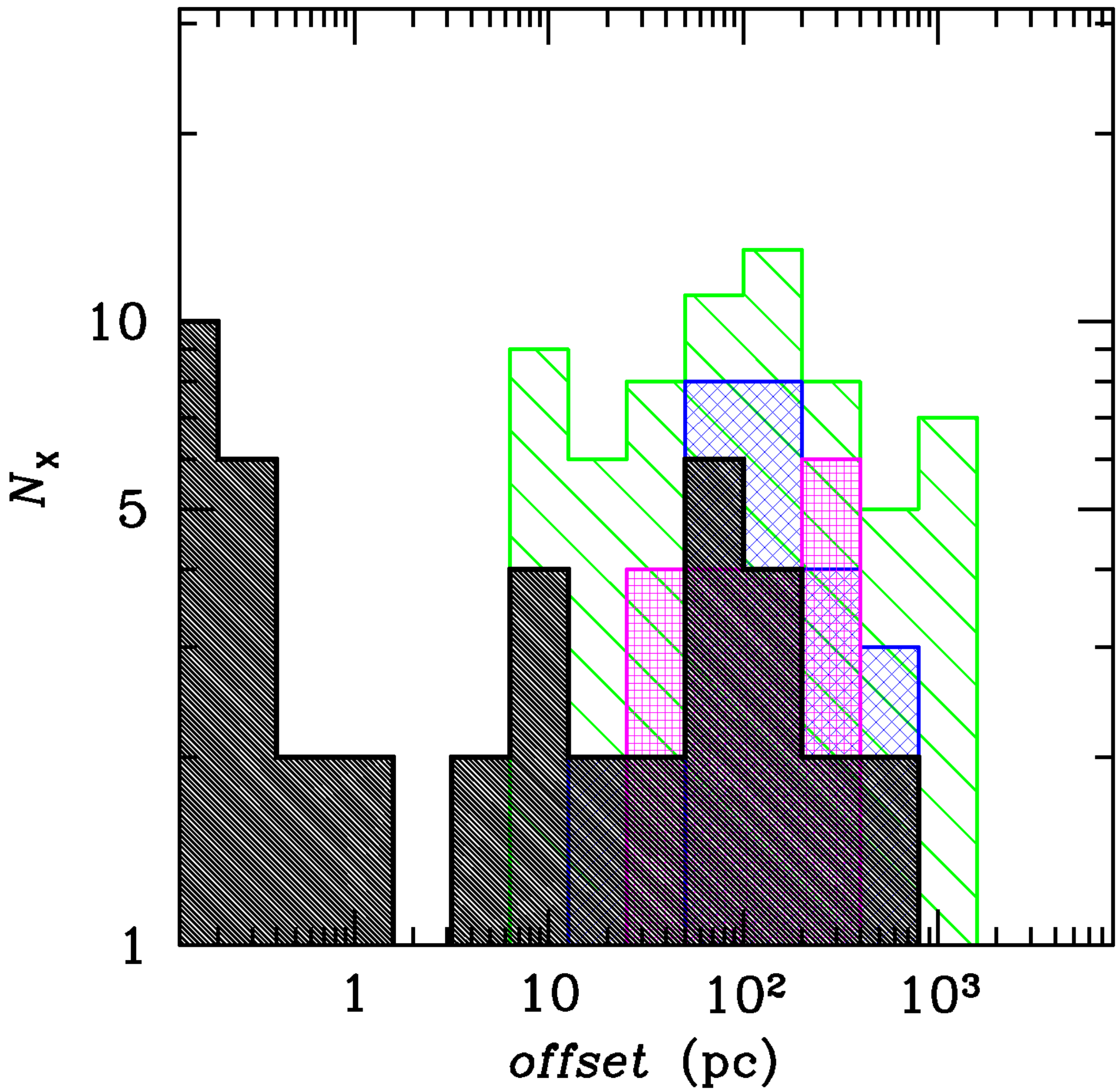
Kaaret et al. 2004 (bright X-ray binaries in M82, NGC1569, NGC5253)

Berghea, PhD Thesis, 2009 (ULXs in nearby galaxies)

Poutanen et al. 2013 (bright X-ray binaries in the Antennae)

OBSERVED OFFSET of X-ray binaries with respect to the closest YSC

+ SIMULATIONS: BH binaries ejected by 3 BODY ENCOUNTERS



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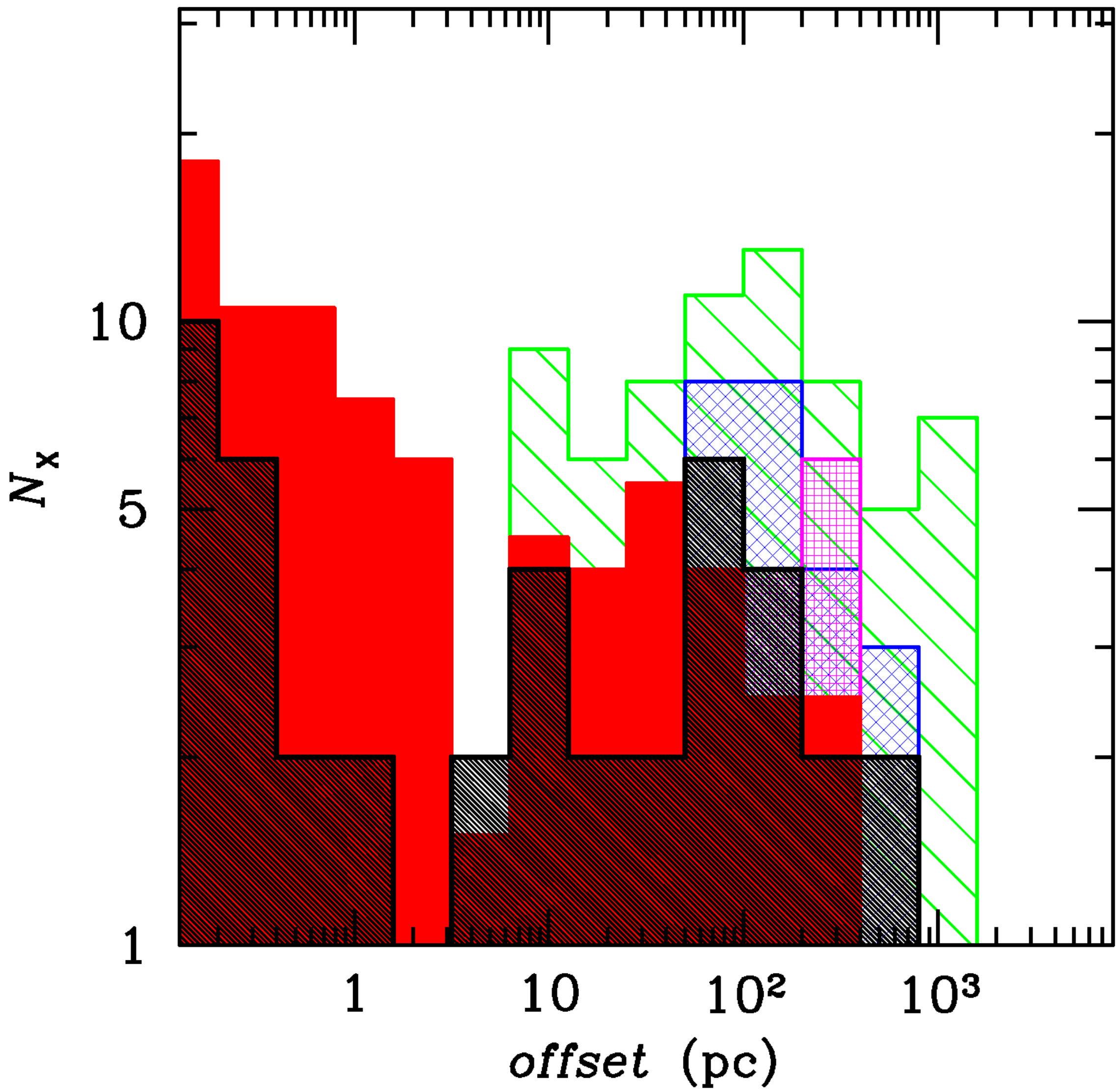
MM et al. 2011 simulated BH binaries in YSC – NO stellar evolution

OBSERVED OFFSET of X-ray binaries with respect to the closest YSC

+ SIMULATIONS: BH binaries ejected by 3 BODY ENCOUNTERS



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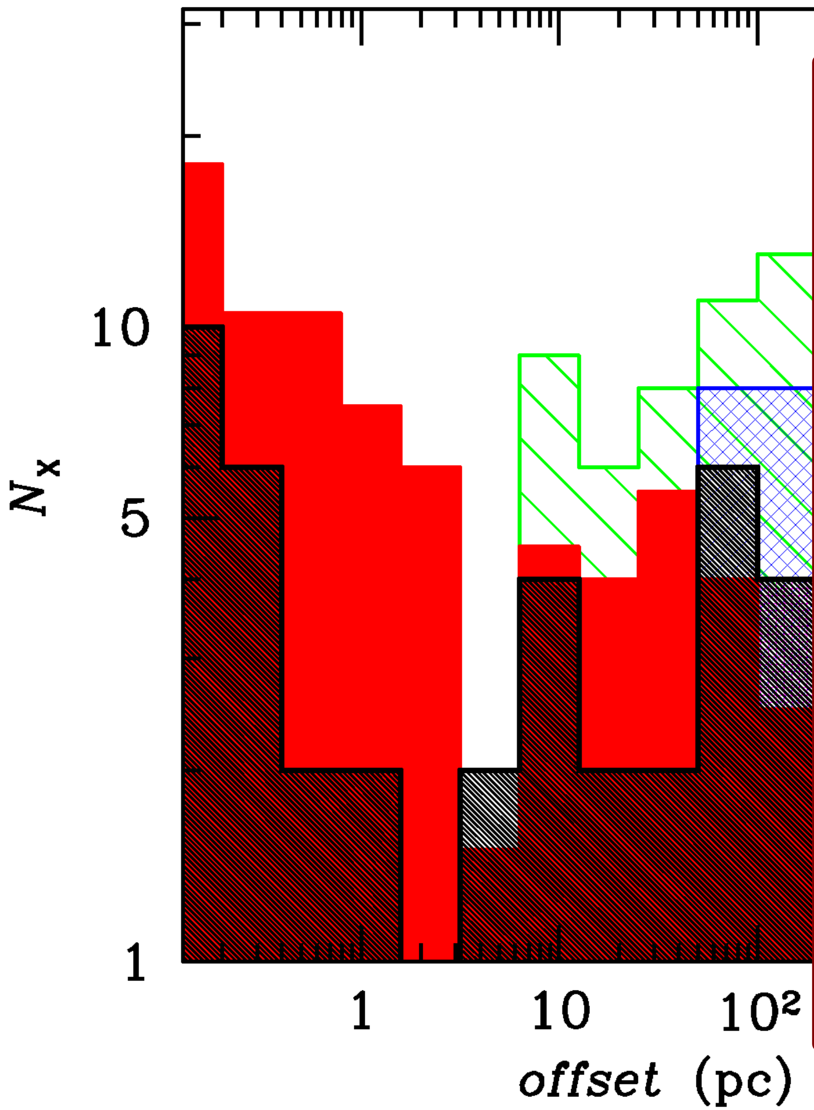
MM et al. 2011 simulated BH binaries in YSC – NO stellar evolution

MM et al. 2013 simulated RLO binaries in YSC – with stellar evolution

3. 3-body encounters trigger ULX ejection

Possible explanations for the discrepancy (to be checked):



- **SN kicks stronger than we assumed (Hartman 1997 rescaled for BH mass)**
- **YSCs were most X-ray binary form are DENSER than our simulated YSCs (more dynamical ejections)**
- **evaporation of YSCs by tidal fields (not present in our simulations) !!!**
- **complete and unbiased data sample**

→ **WORK IN PROGRESS!**

Bachelor, Master, PhD thesis available on this topic (ask me!)

MASS SEGREGATION??
Consequence of equipartition theorem:

PARTICLES TEND TO HAVE THE SAME AVERAGE KINETIC ENERGY

If stars are equal mass → equipartition implies that have the same average VELOCITY

If stars have different masses, this has a relevant consequence:

$$m_i \langle v_i^2 \rangle = m_j \langle v_j^2 \rangle$$

$$\text{if} \quad m_i > m_j \Rightarrow \langle v_i^2 \rangle < \langle v_j^2 \rangle$$

During two-body encounters, massive stars transfer kinetic energy to light stars. Massive stars slow down, light stars move to higher velocities.

Equipartition in multi-mass systems is reached via ***dynamical friction***

This means that **heavier stars drift to the centre of the cluster**, producing **MASS SEGREGATION**
(i.e. local mass function different from IMF)

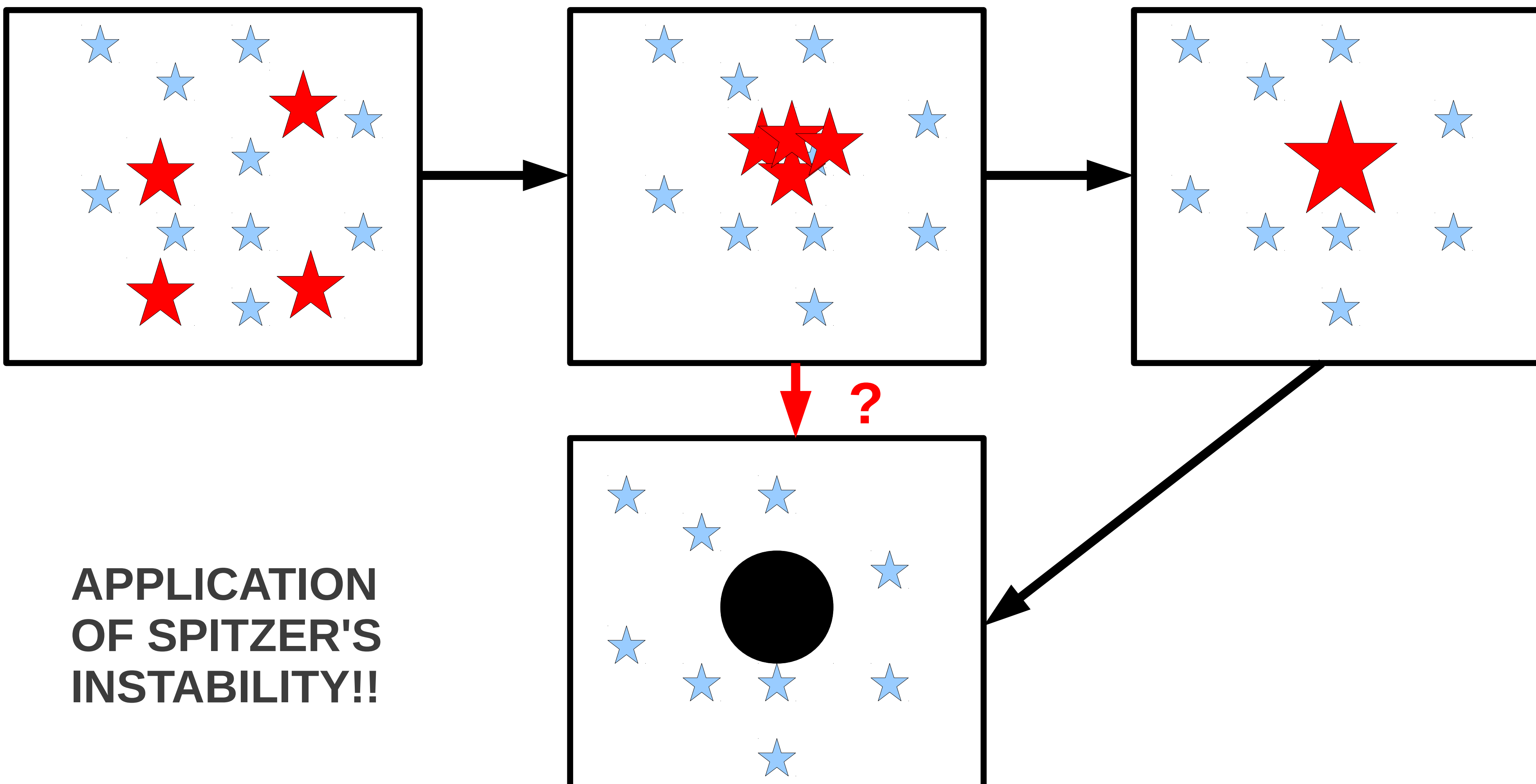
1- runaway collapse of stars at centre of star cluster

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

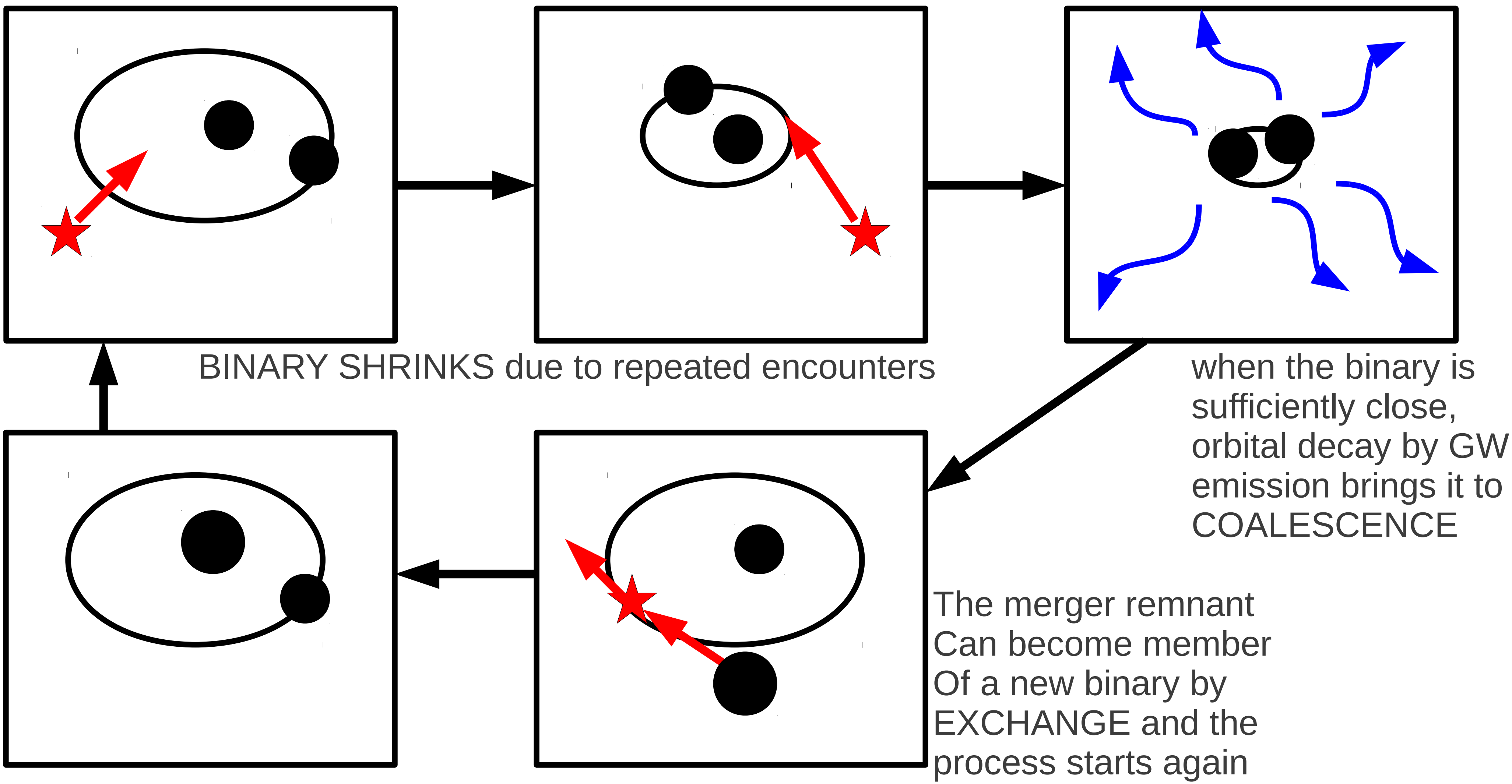


APPLICATION OF SPITZER'S INSTABILITY!!

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



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* Portegies Zwart & McMillan, 2002, ApJ, 576, 899

* Miller & Hamilton, 2002, MNRAS, 330, 232

* Kulkarni, Hut & McMillan 1993, Nature 364, 421

* Sigurdsson & Hernquist 1993, Nature 364, 42

* Mapelli et al. 2013, MNRAS, 429, 2298

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

Can we understand whether a binary will lose or acquire E_b?

YES, but ONLY in a STATISTICAL SENSE

We define **HARD BINARIES:** binaries with binding energy higher than the average kinetic energy of a star in the cluster

$$\frac{G\,m_1\,m_2}{2\,a} > \frac{1}{2}\,\langle m\rangle\,\sigma^2$$

$$\frac{G\,m_1\,m_2}{2\,a} < \frac{1}{2}\,\langle m\rangle\,\sigma^2$$

SOFT BINARIES: binaries with binding energy lower than the average kinetic energy of a star in the cluster

HEGGIE'S LAW (1975):

Hard binaries tend to become harder (i.e. increase E_b)

Soft binaries tend to become softer (i.e. decrease E_b)

as effect of three-body encounters

Recoil velocities

Most general expression of recoil velocity for the reduced particle (Sigurdsson & Phinney 1993)

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

m_a, m_b and m_e are the final mass of the primary binary member, the final mass of the secondary binary member and the final mass of the single star, respectively (these may be different from the initial ones in the case of an exchange).

This equation comes from (+) at slide 20:

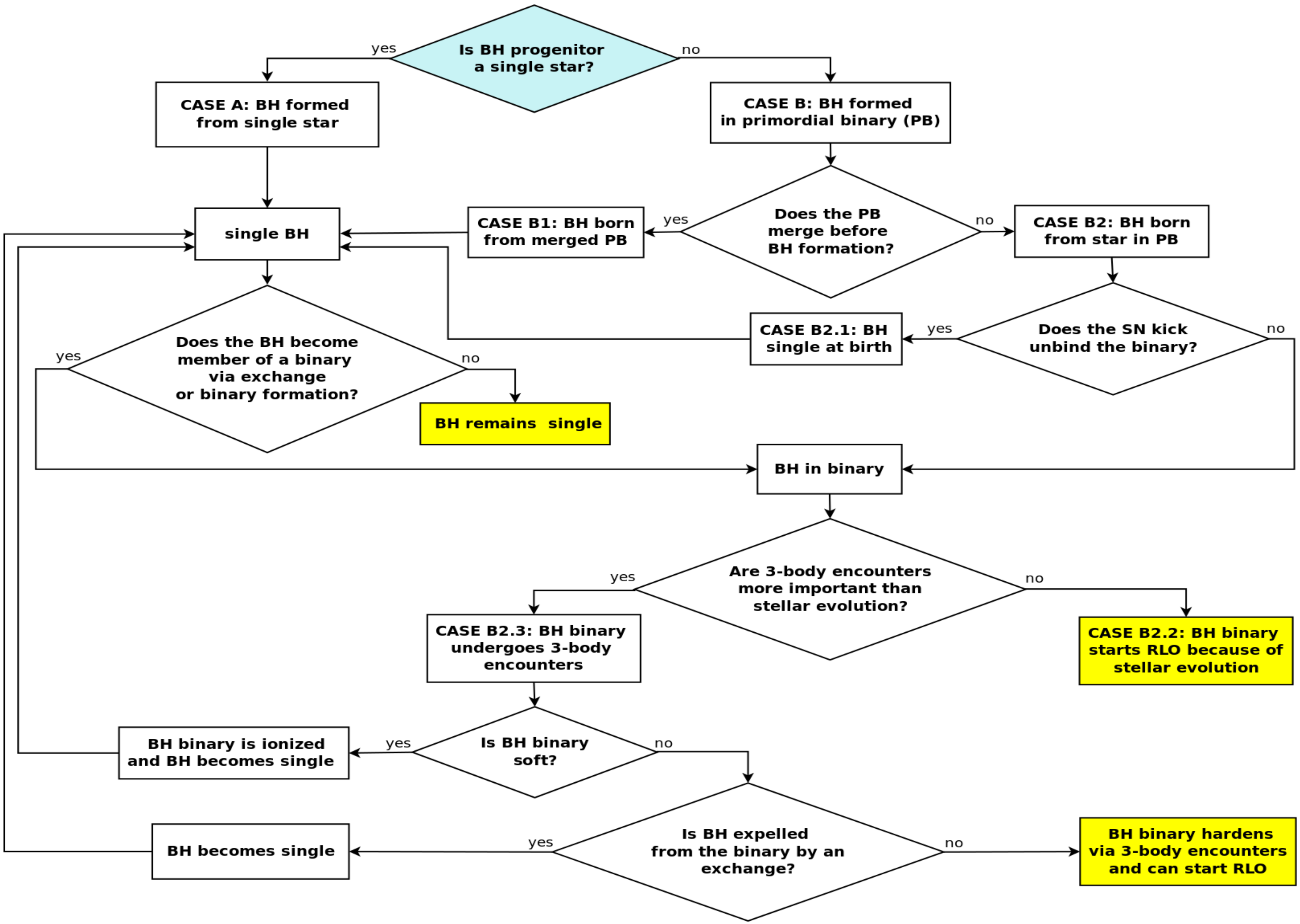
$$\frac{1}{2}\,\frac{m_3\,(m_1+m_2)}{m_T}\,v_\infty^2 + \Delta E_b = \frac{1}{2}\,\frac{m_e\,(m_a+m_b)}{m_T}\,v_{fin}^2$$

What happens to the binary, then?

The recoil of the binary (if the binary is more massive than the single star -i.e. the motion of the single star coincides almost with that of the reduced particles) follows from conservation of linear momentum

$$v_{rec} = \frac{m_e}{m_T}\,v_{fin}$$

2. 3-body encounters enhance ULX formation



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