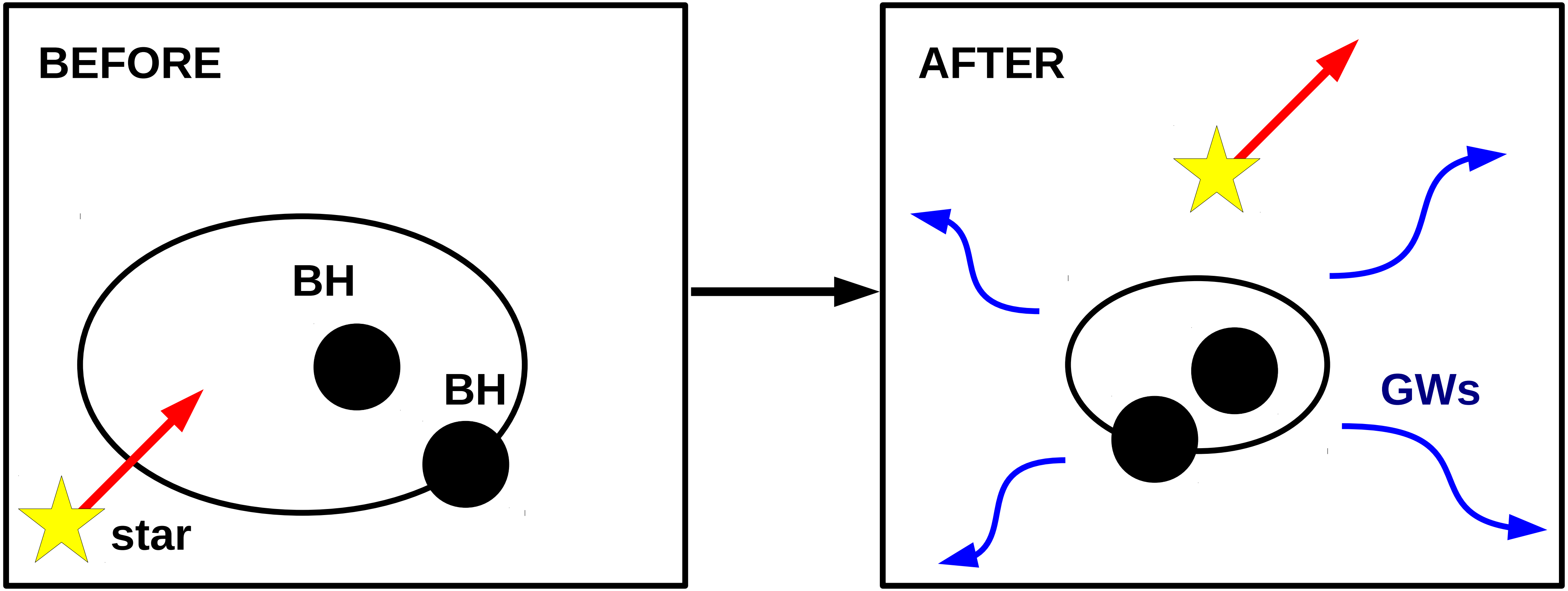
Michela Mapelli

Dynamics of Stars and Black Holes in Dense Stellar Systems II

Innsbruck, January 16 2018

**Based on last lecture,
WHAT are the possible effects of
dynamics on BH binaries?**

1. HARDENING:



After 3-body encounters, the semi-major axis shrinks and the BH-BH (or BH-NS or NS-NS) binary becomes important as gravitational wave (GW) source

HARDENING TIMESCALE

$$t_h = \left|\frac{a}{\dot{a}}\right| = \frac{1}{2\,\pi\,G\,\xi}\,\frac{\sigma}{\rho}\,\frac{1}{a}$$

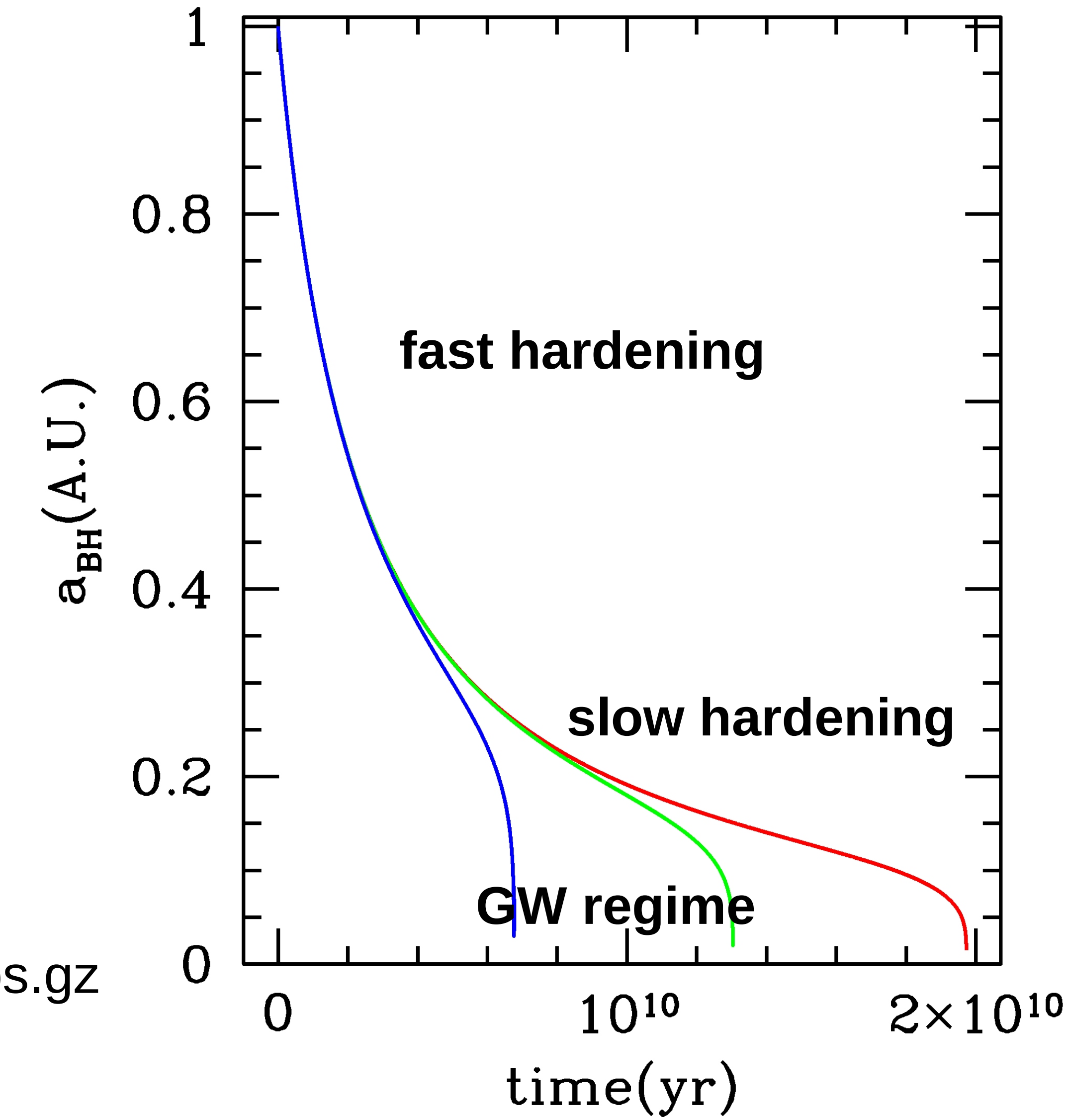
GRAVITATIONAL WAVE (GW) TIMESCALE

$$t_{GW} = \frac{5}{256}\,\frac{c^5\,a^4\,(1-e^2)^{7/2}}{G^3\,m_1\,m_2\,(m_1+m_2)}$$

Combining 1) and 2) we can find the maximum semi-major axis for GWs to dominate evolution

$$a_{GW} = \left[\frac{256}{5}\,\frac{G^2\,m_1\,m_2\,(m_1+m_2)\,\sigma}{2\,\pi\xi\,(1-e^2)^{7/2}\;c^5\,\rho}\right]^{1/5}$$

Gravitational wave (GW) progenitors



- * blue
  m_1=200 $M_\odot$ m_2=10 $M_\odot$
- * green
  m_1=50 $M_\odot$ m_2=10 $M_\odot$
- * red
  m_1=30 $M_\odot$ m_2=3 $M_\odot$

Figure and calculation
from page 200 of M. Mapelli's thesis
http://web.pd.astro.it/mapelli/images/tesi.ps.gz

$$\frac{da}{dt} = \underbrace{-2\,\pi\,\xi\,\frac{G\,\rho}{\sigma}\,a^2}_{\text{Binary shrinking by hardening}} - \underbrace{\frac{64}{5}\,\frac{G^3\,m_1\,m_2\,(m_1+m_2)}{c^5\,(1-e^2)^{7/2}}\,a^{-3}}_{\text{Binary shrinking by GWs (Peters 1964)}}$$

Binary shrinking by hardening

Binary shrinking by GWs (Peters 1964)

Number of encounters before GW regime:

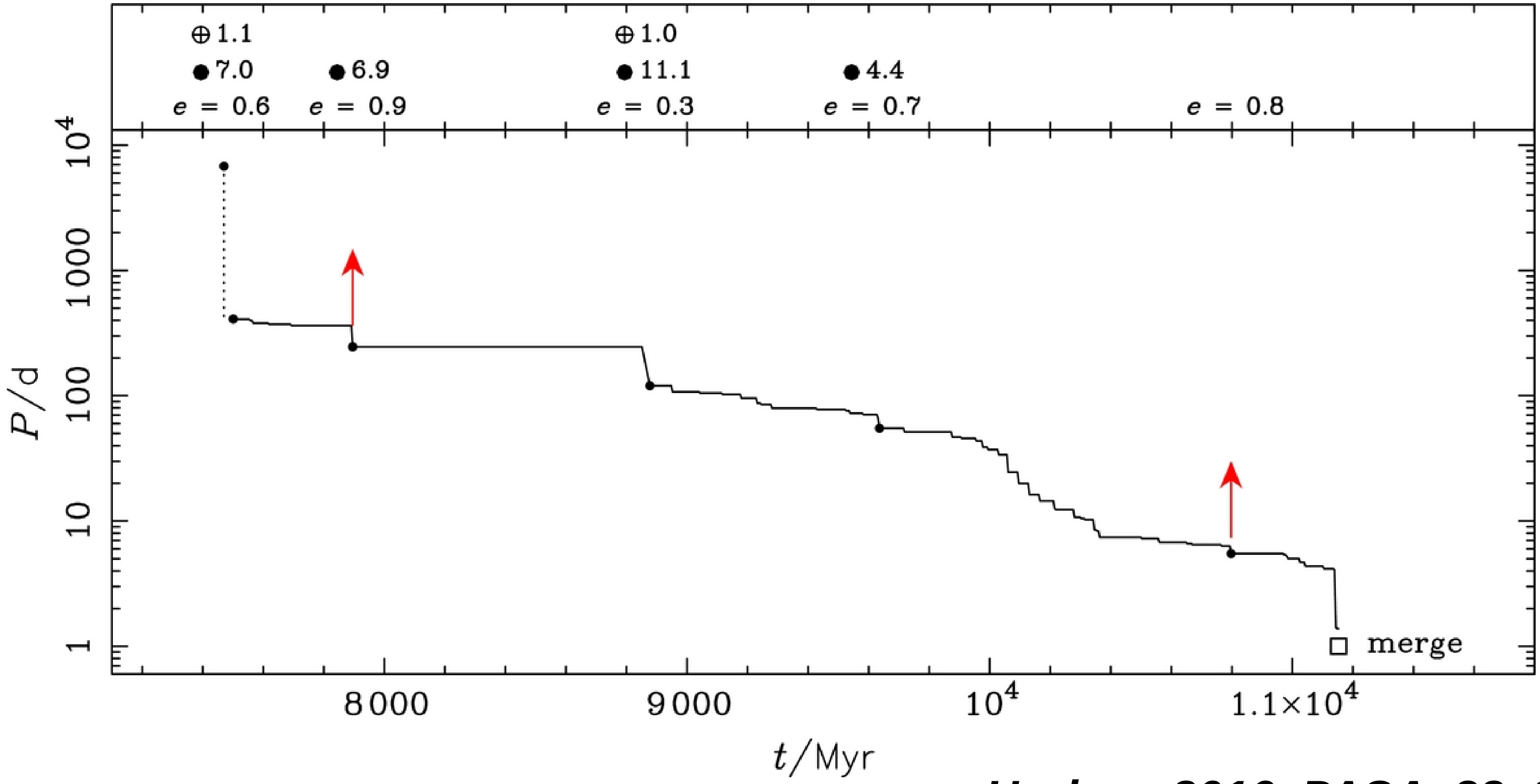
interaction rate

$$N_{int} = \int_0^t R\,dt = \int_0^t \frac{2\,\pi\,G\,m_T\,n\,a}{\sigma}\,dt$$

$$= \int_{a_0}^{a(t)} \frac{2\,\pi\,G\,m_T\,n\,a}{\sigma}\,\frac{\sigma\,da}{-2\,\pi G\,\xi\rho\,a^2} = \int_{a(t)}^{a_0} \frac{1}{\xi}\,\frac{m_T}{\langle m\rangle}\,\frac{da}{a}$$

$$\frac{da}{dt} = -2\,\pi\,G\,\xi\,\frac{\rho}{\sigma}\,a^2$$

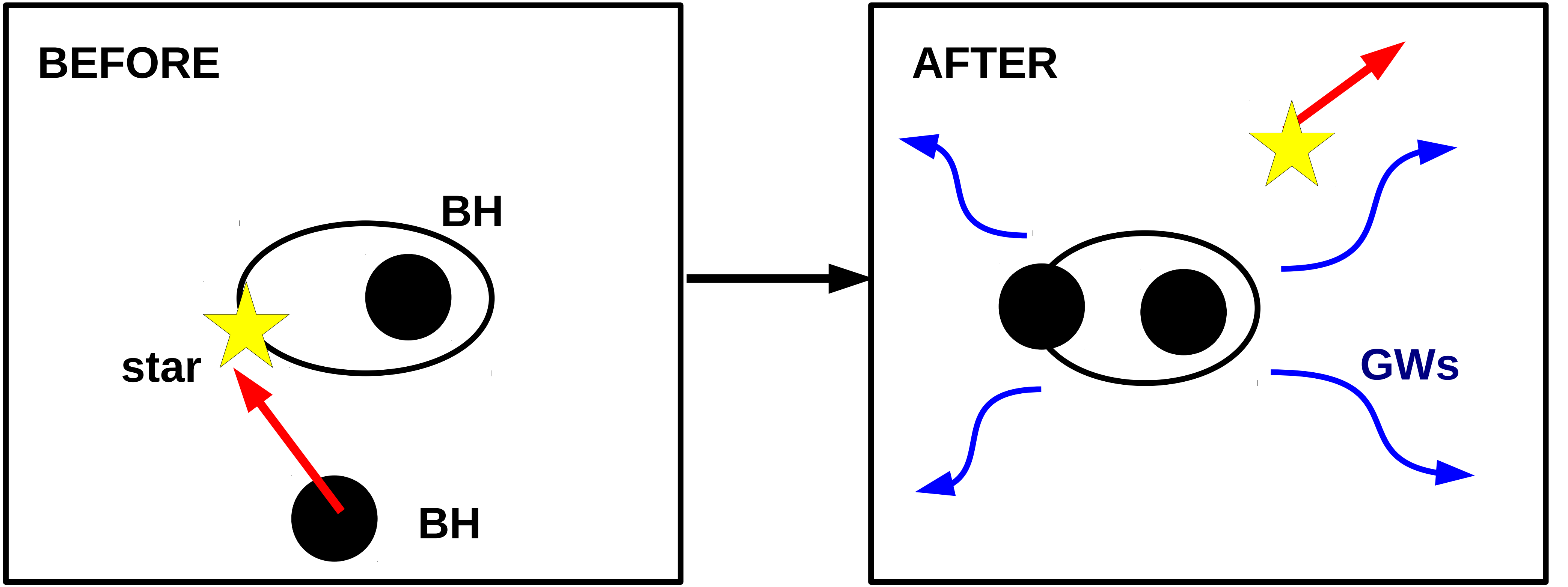
$$= \frac{1}{\xi}\,\frac{m_T}{\langle m\rangle}\,\ln\left(\frac{a_0}{a(t)}\right)$$



Hurley+ 2016, PASA, 33, 36

Hills 1992, AJ, 103, 1955; Kulkarni+ 1993, Nature, 364, 421; Sigurdsson & Hernquist 1993, Nature, 364, 423; Portegies Zwart & McMillan 2000, ApJ, 528, L17; Aarseth 2012, MNRAS, 422, 841; Breen & Heggie 2013, MNRAS, 432, 2779 ETC ETC...

2. EXCHANGE:

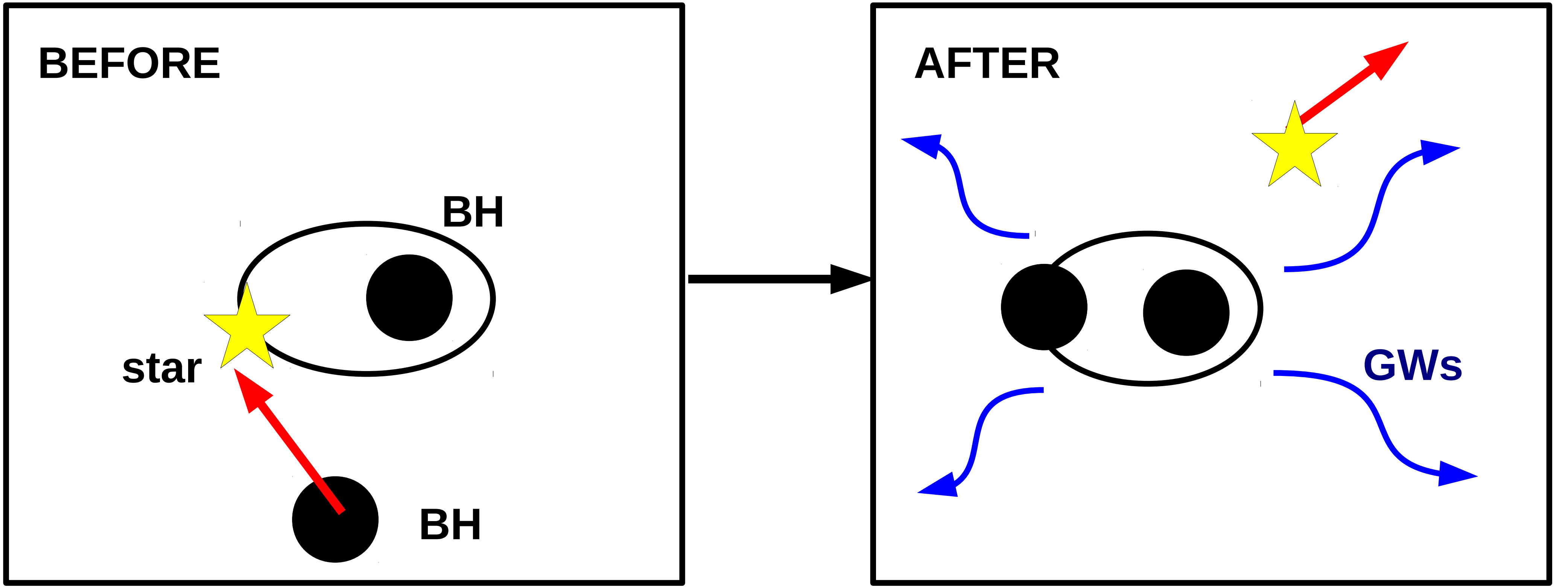


Exchanges are very important: bring BHs in binaries

BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!

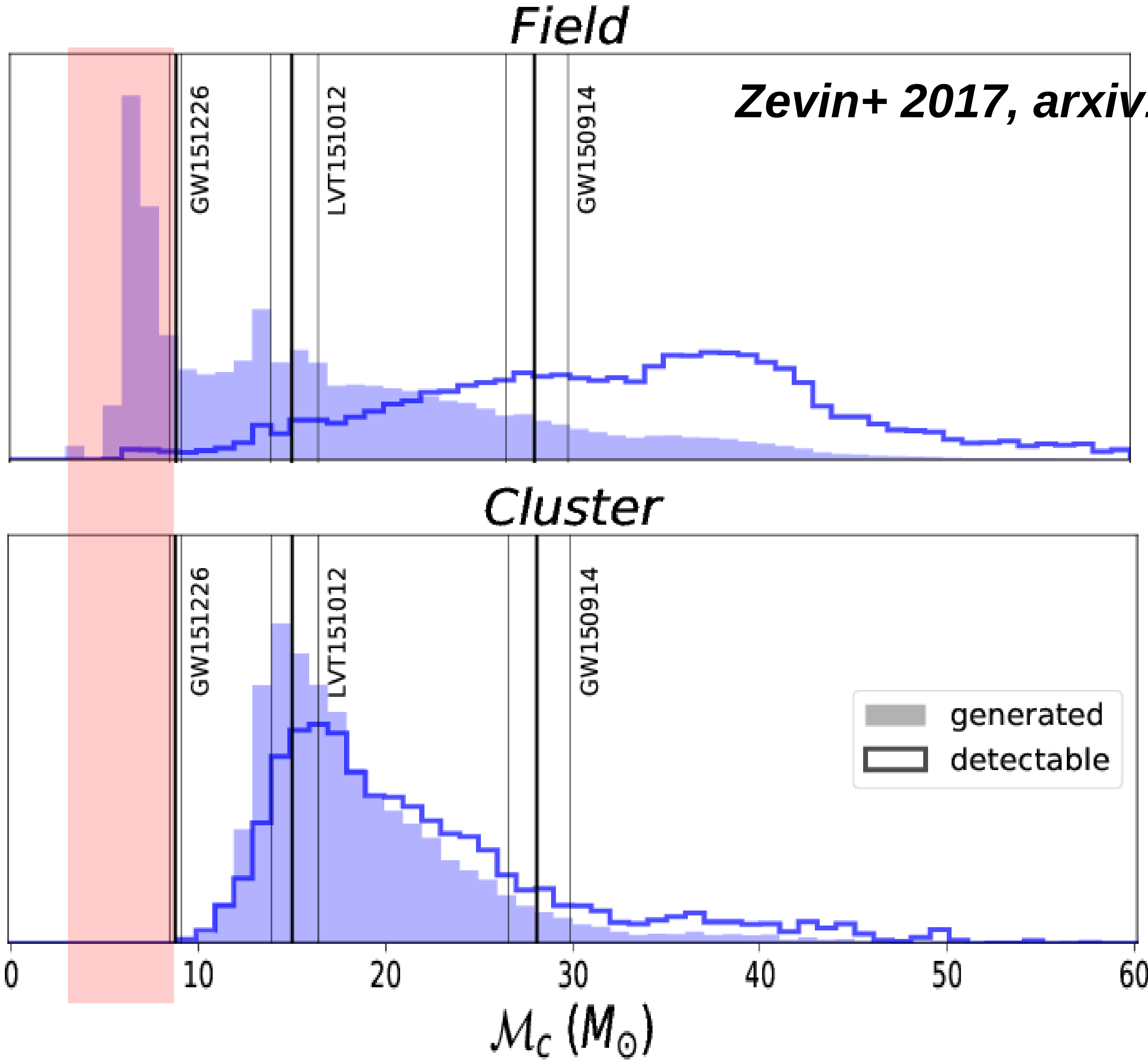
BH born from single star in the field never acquires a companion
BH born from single star in a sc likely acquires companion from dynamics

2. EXCHANGE:



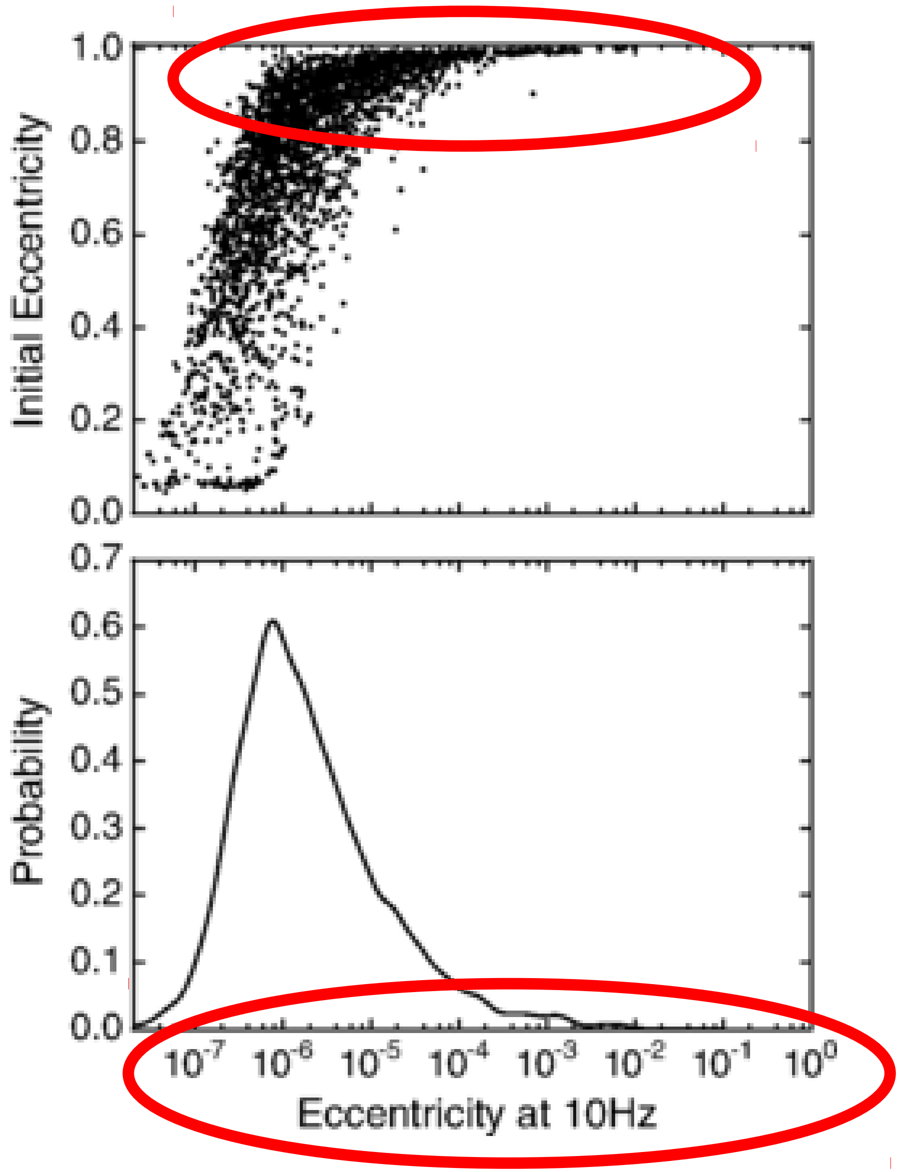
>90% BH-BH binaries in young star clusters form by exchange
(Ziosi+ 2014)

EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH
- *THE MOST MASSIVE BHs*
- *HIGH ECCENTRICITY*
- *MISALIGNED BH SPINS*



Zevin+ 2017, arxiv1704.07379

Ziosi, MM+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, Phys. Review Letter, 115, 1101; Rodriguez+ 2016, PhRvD, 93, 4029; Askar+ 2017, MNRAS, 464, L36; Banerjee 2017, MNRAS, 467, 524 and many others



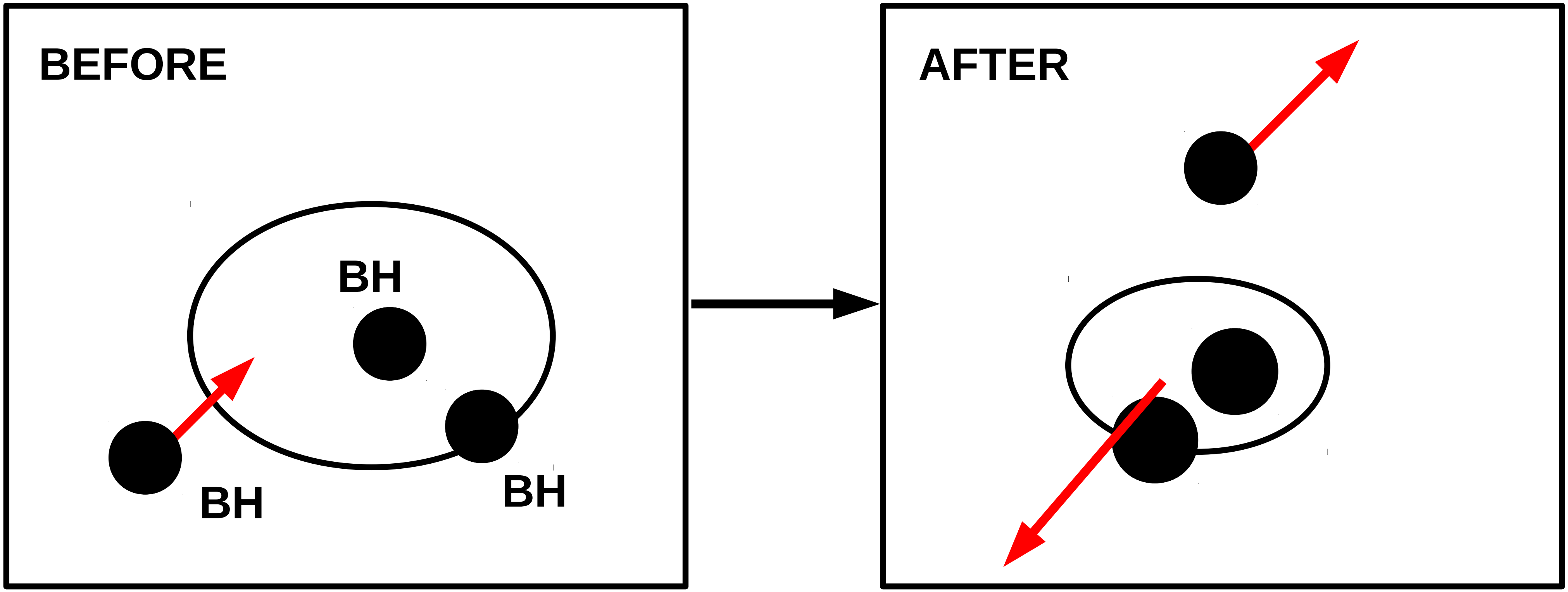
Rodriguez+ 2016, PhRvD, 93, 4029

- high eccentricity at formation

- small eccentricity when reaching LIGO-Virgo range

Ziosi, MM+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, Phys. Review Letter, 115, 1101; Hurley+ 2016, PASA, 33, 36; Askar+ 2017, MNRAS, 464, L36; Banerjee 2017, MNRAS, 467, 524 and many others

3. EJECTIONs:



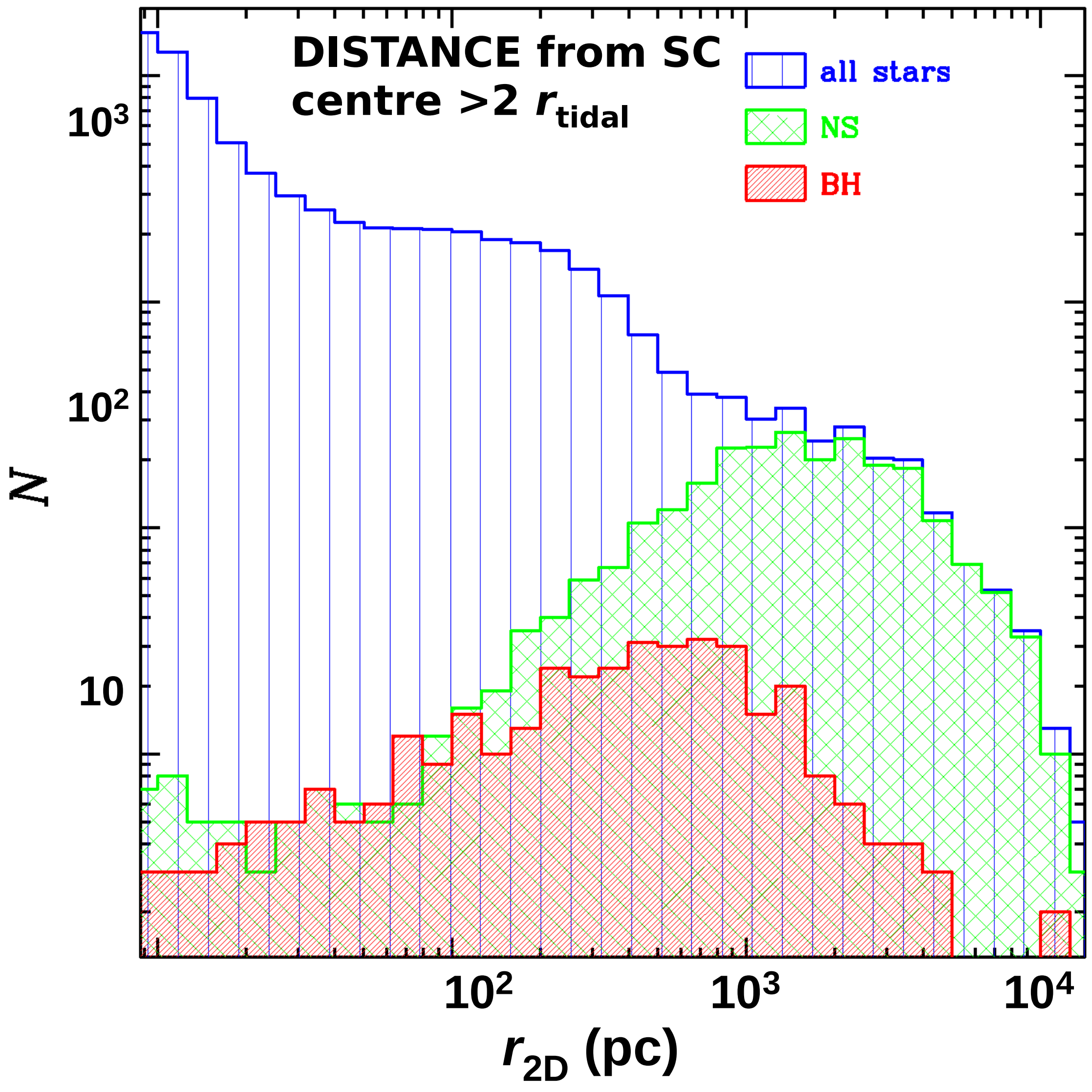
Internal energy is extracted from the binary

→ **converted into KINETIC ENERGY of the INTRUDER AND of the centre-of-mass of the BINARY**

→ **BOTH RECOIL and can be ejected from star cluster**

BHs and NSs are ejected from host star clusters by DYNAMICS and NATAL (SN) KICKS

Simulations of young star clusters @ t=100 Myr



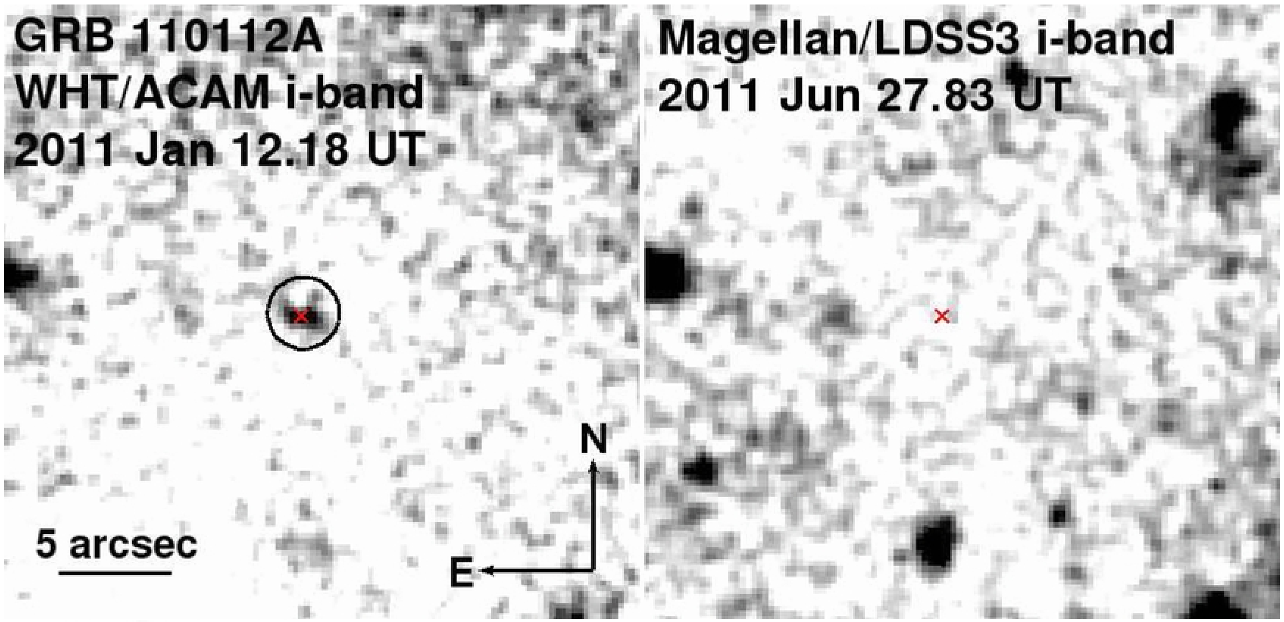
~80-90% NS is ejected (mainly by SN)

~40% BH is ejected (1/2 by SN, 1/2 by 3body)

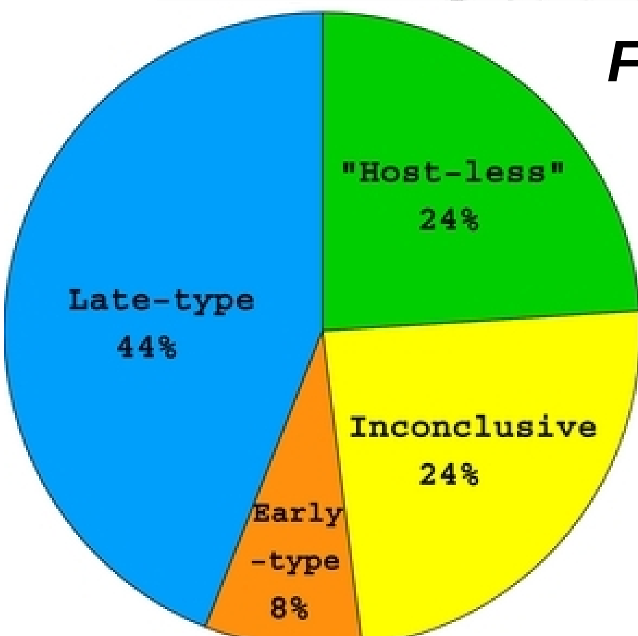
PREDICTED MERGERS OCCUR MOSTLY IN THE FIELD

Downing+ 2011, MNRAS, 416, 133
MM + 2013, MNRAS, 429, 2298

Are host-less short GRBs associated with dynamical ejections?



Fong+ 2013, ApJ, 769, 56



ISSUE: dynamical kicks 0 – 200 km/s

not enough to unbind system from host galaxy

4. KOZAI-LIDOV RESONANCE:

Discovered by Kozai and Lidov in ~ 1962

I need a HIERARCHICAL TRIPLE:

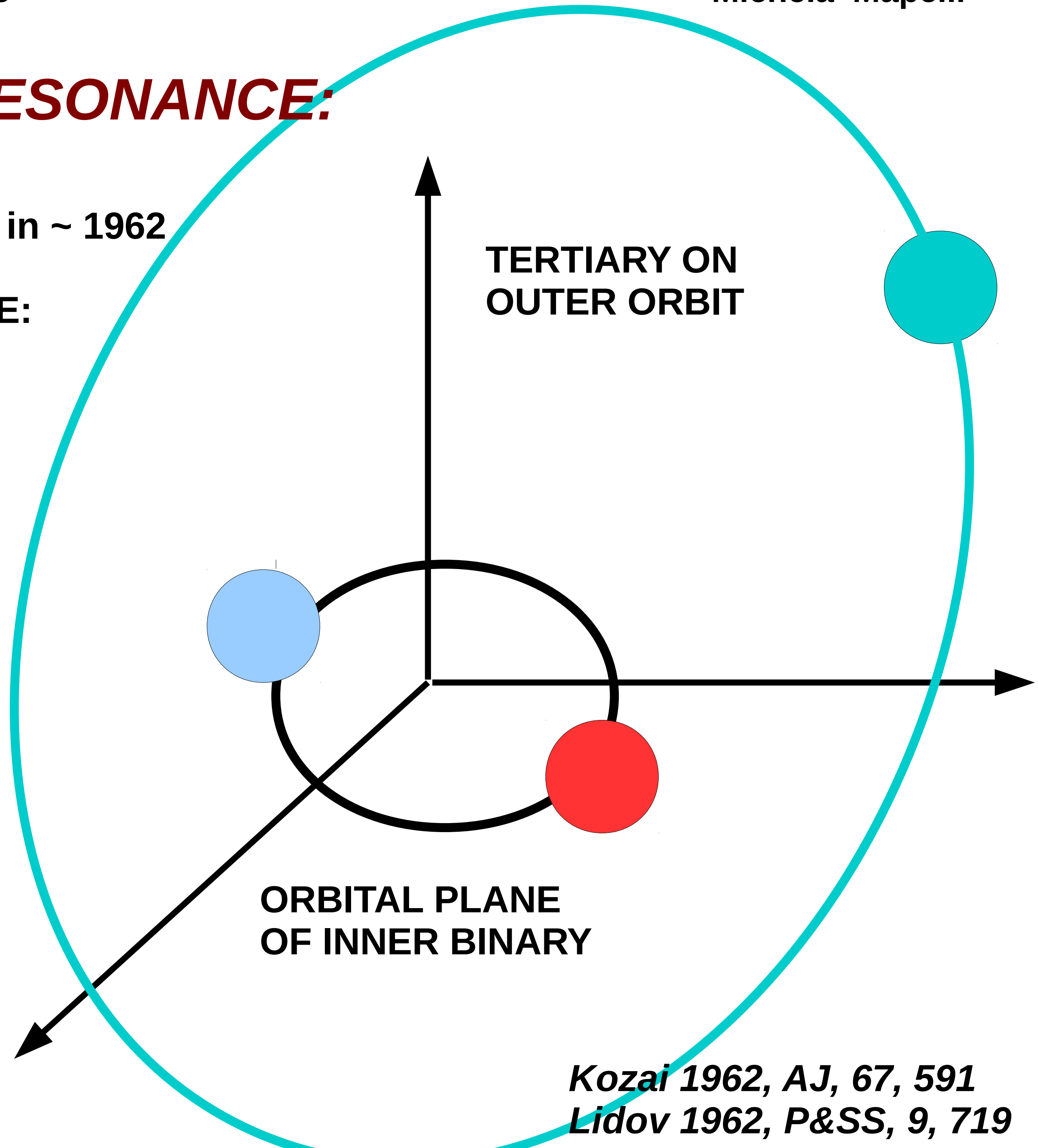
- Inner tight binary

- Outer body whose motion about the binary can be approximated with outer binary (CM + 3rd body)

- if inclination between 2 orbital planes is not 0

→ KOZAI RESONANCE

ECCENTRICITY AND INCLINATION OSCILLATE



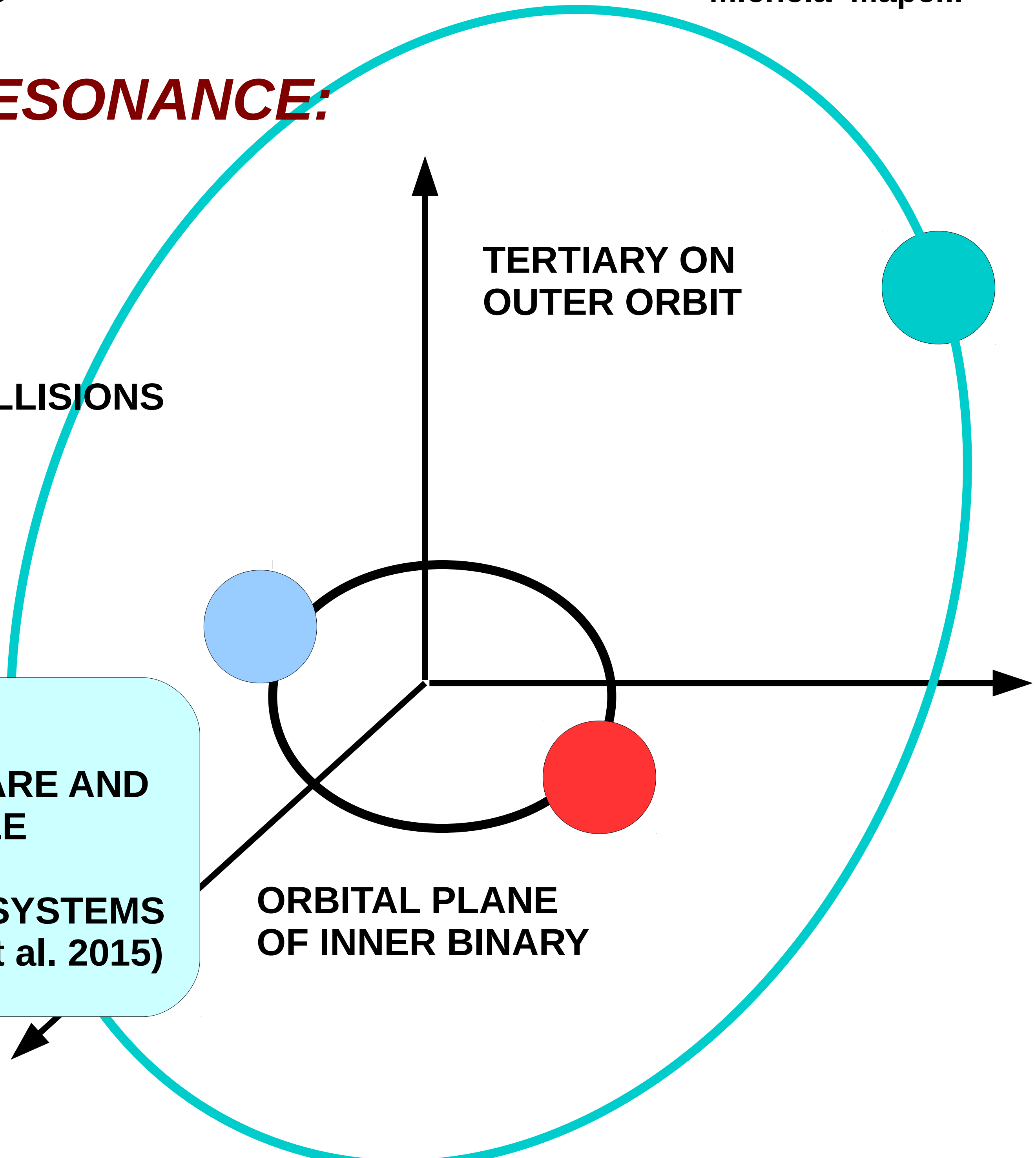
Kozai 1962, AJ, 67, 591
Lidov 1962, P&SS, 9, 719

4. KOZAI-LIDOV RESONANCE:

ECCENTRICITY AND INCLINATION OSCILLATE

TRIGGERING MERGERS / COLLISIONS between binary members

→ IMPORTANT FOR GRAVITATIONAL WAVES



YOU MIGHT SAY:
TRIPLES SHOULD BE VERY RARE AND KL RESONANCE IS NEGLIGIBLE INSTEAD
~ 10 % STARS ARE IN TRIPLE SYSTEMS (Raghavan et al. 2010; Riddle et al. 2015)

4. KOZAI-LIDOV RESONANC

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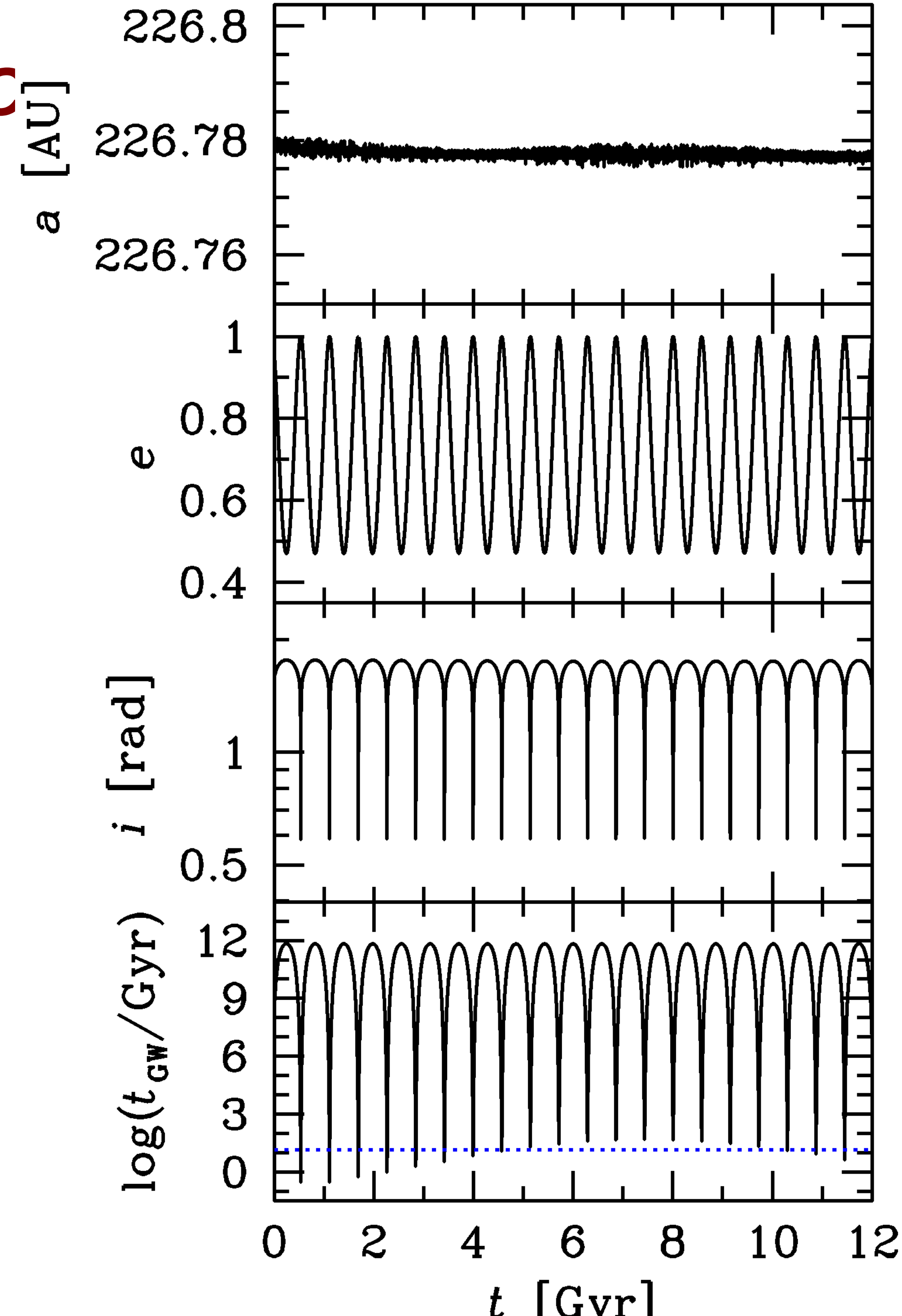
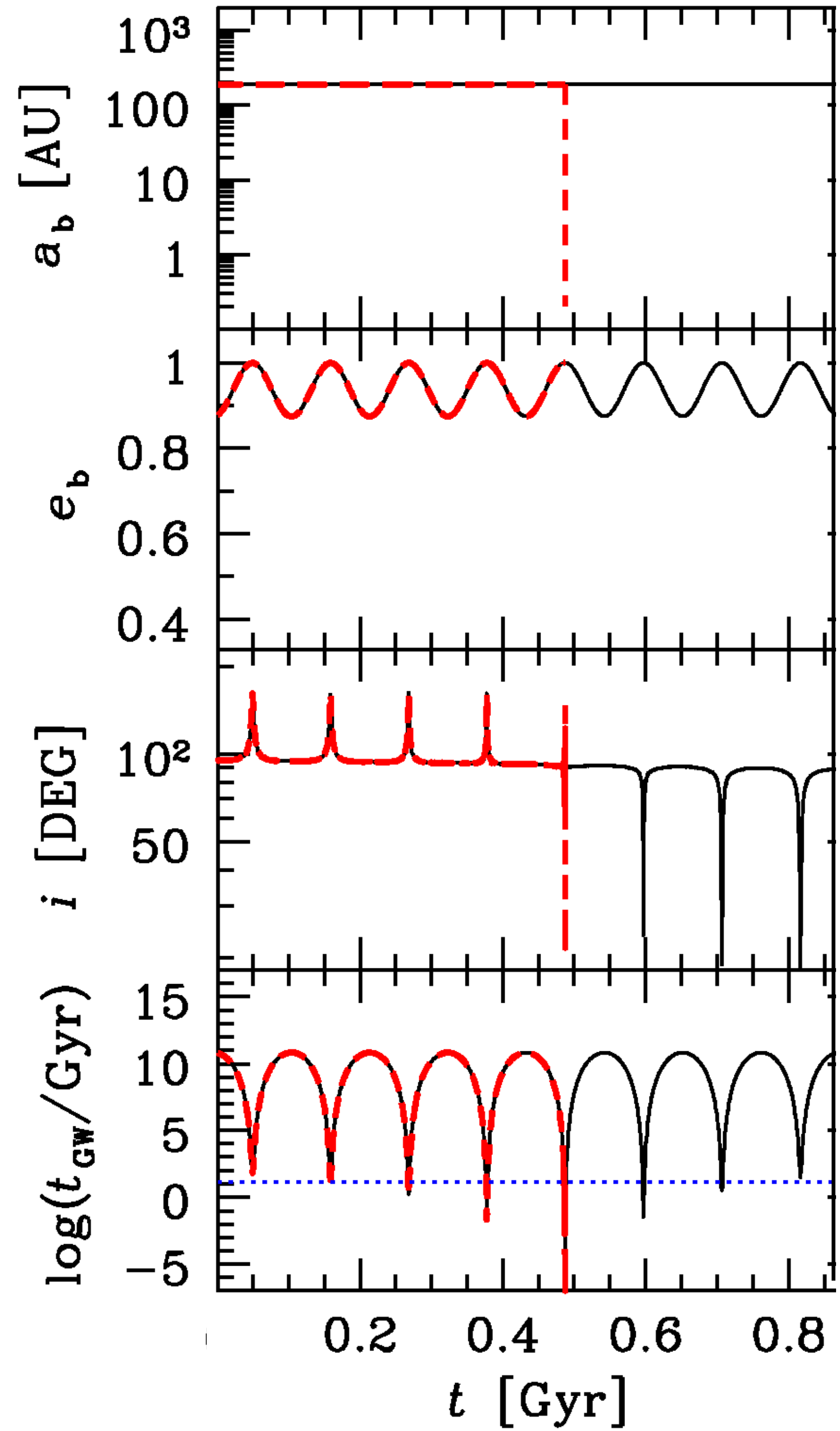


Kimpson+ 2016

4. KOZAI-LIDOV RESONANCE:

No post-Newtonian (PN) (solid line)

With 2.5 PN term (dashed line)



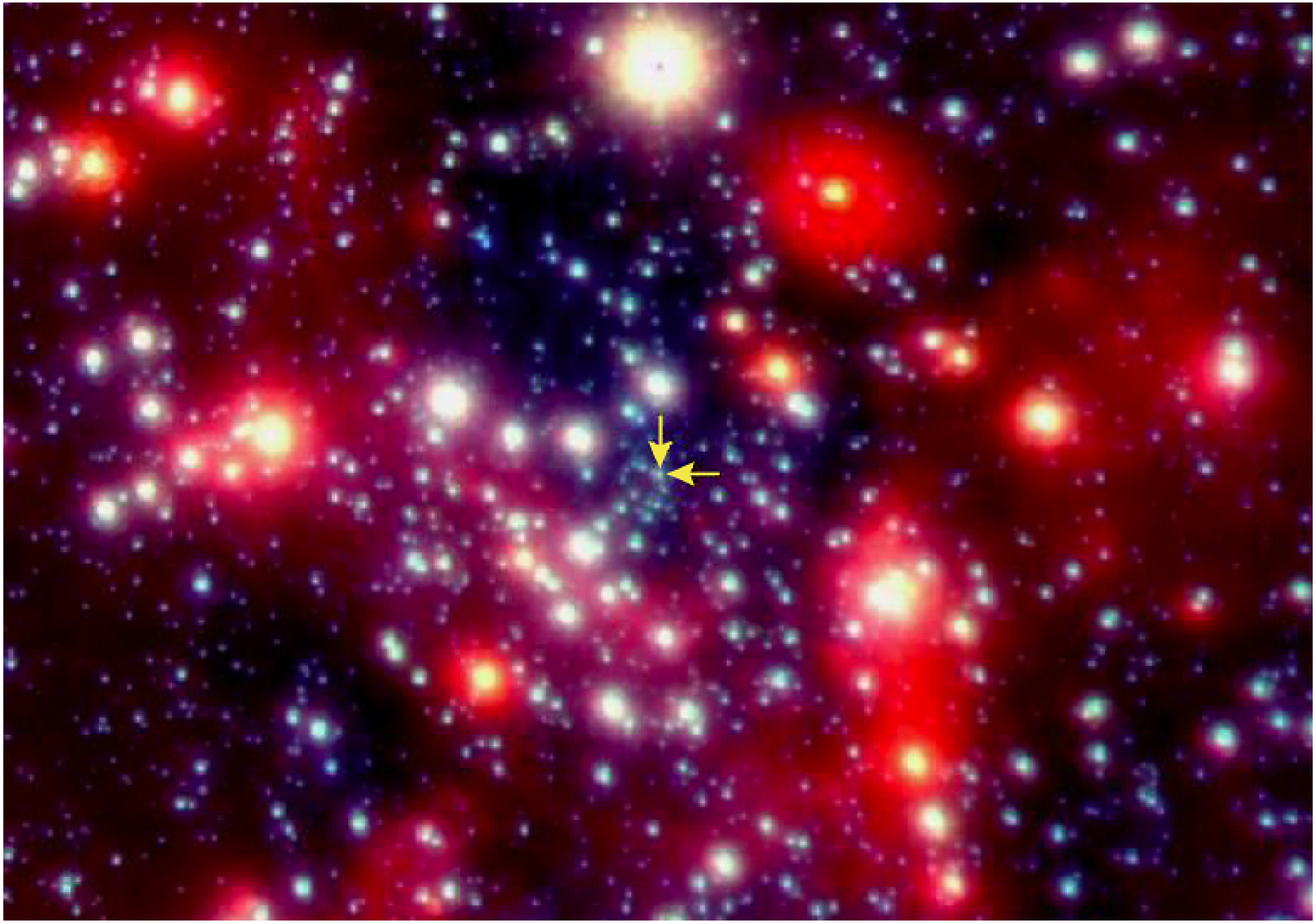
PN: treatment of Einstein's non-linear equations as lowest-order deviations from Newton's equation

~ 50% more MERGERS
of BH-BH binaries
in young dense star clusters
If Kozai accounted for

Kimpson, Spera, MM, Ziosi 2016, MNRAS, 463, 2443

Antognini+ 2014, MNRAS, 439, 1079;
Antonini+ 2016, ApJ, 816, 65;
Antognini+ 2016, MNRAS, 456, 4219;
Kimpson+ 2016, MNRAS, 463, 2443;
Antonini+ 2017arXiv170306614A

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:

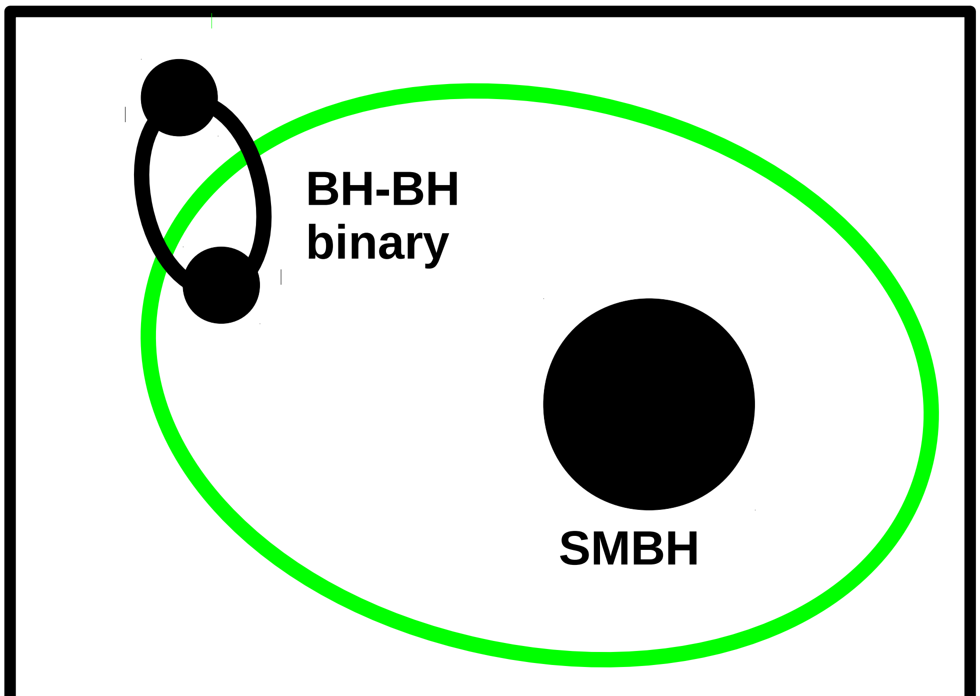


Schoedel et al. 2002, Nature, 419, 694

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:

* high escape velocity
(BHs are retained)

* triple might be with SMBH



Antonini & Perets 2012, ApJ, 757, 27

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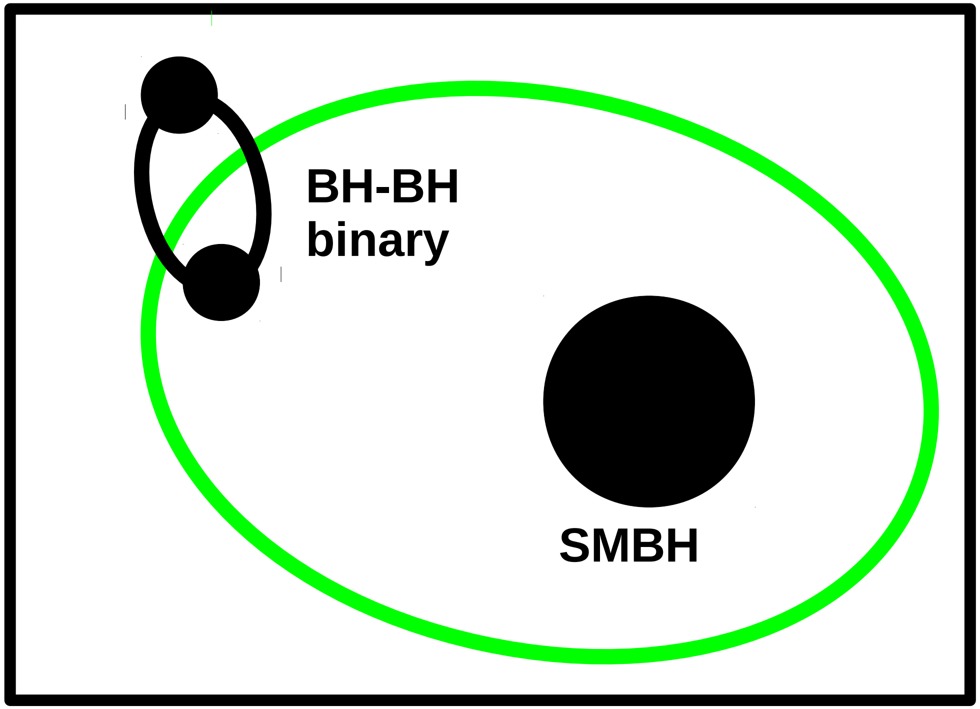
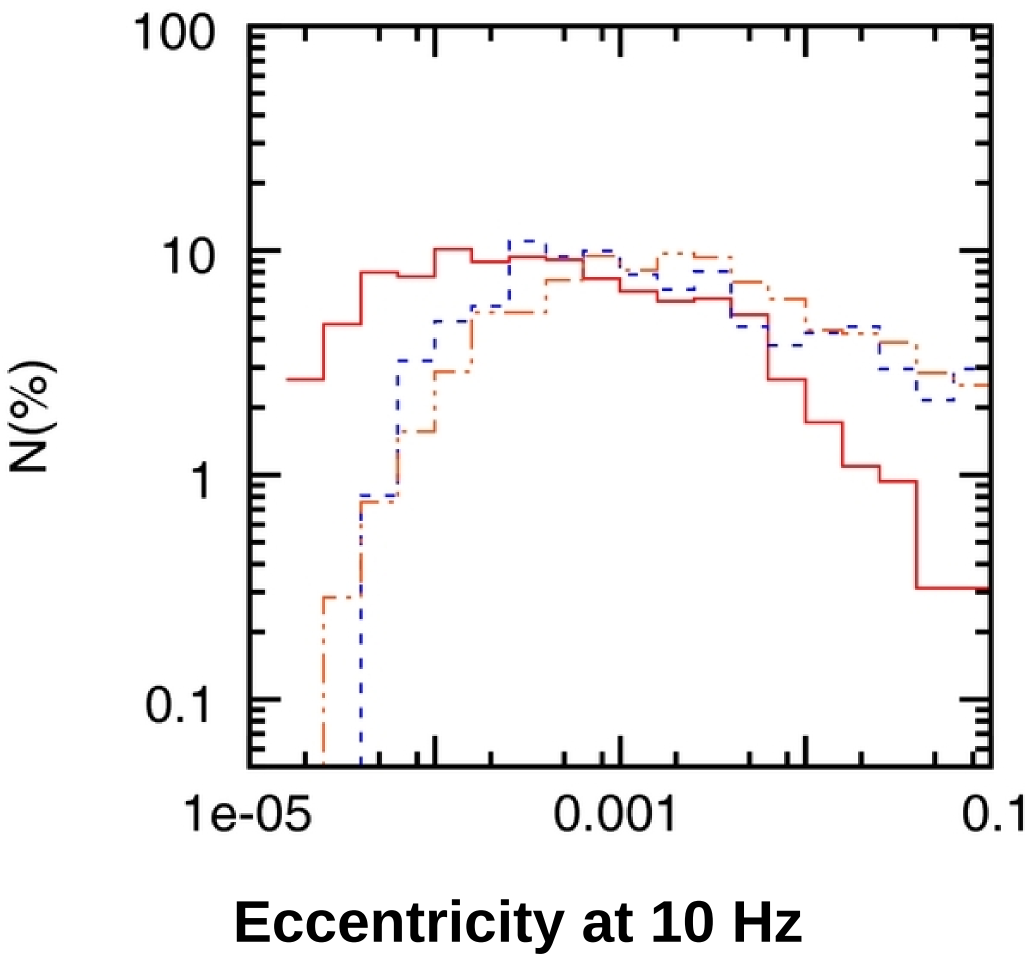




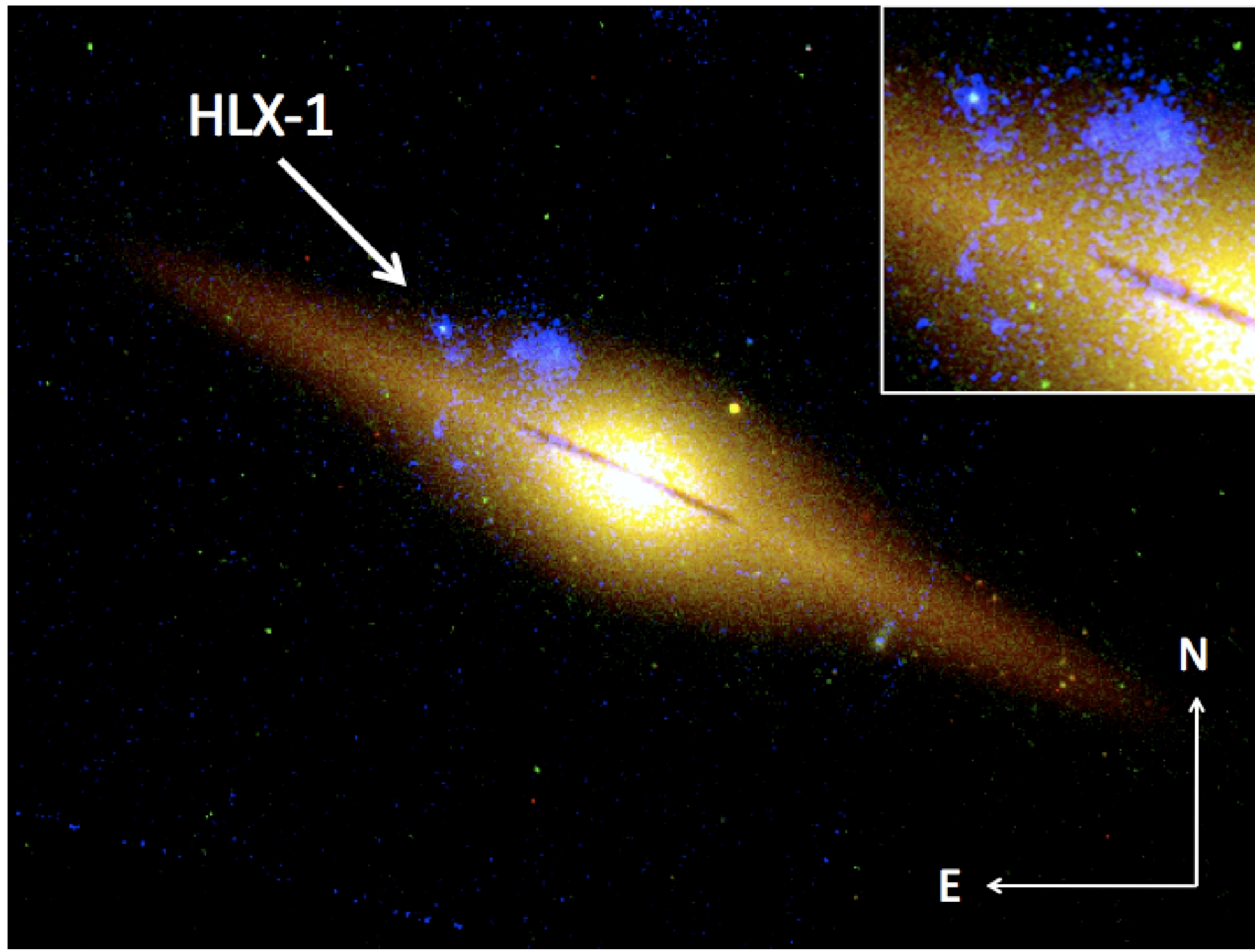
Antonini & Perets 2012, ApJ, 757, 27

5. Intermediate-mass black holes (IMBHs): 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~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

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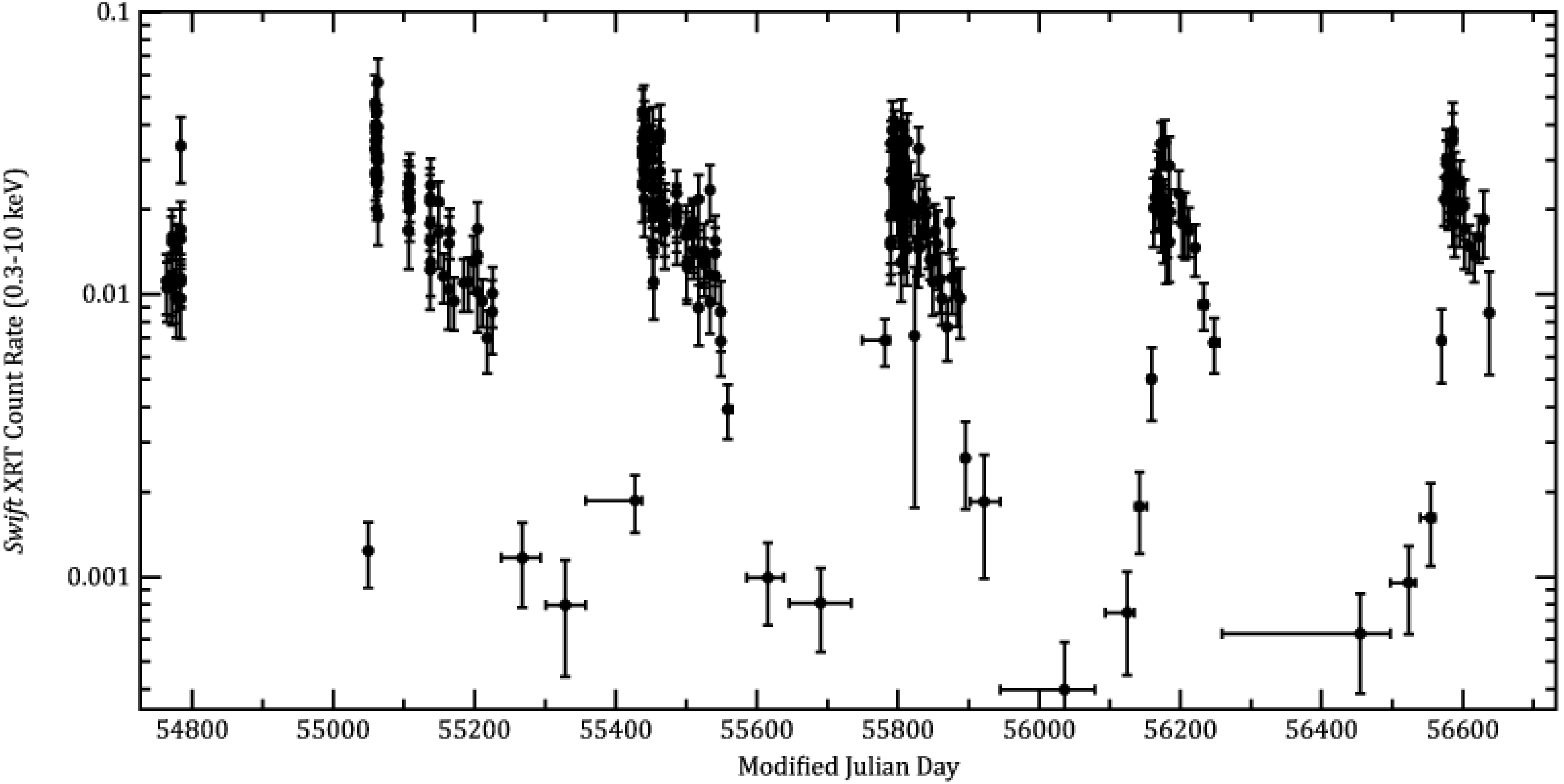
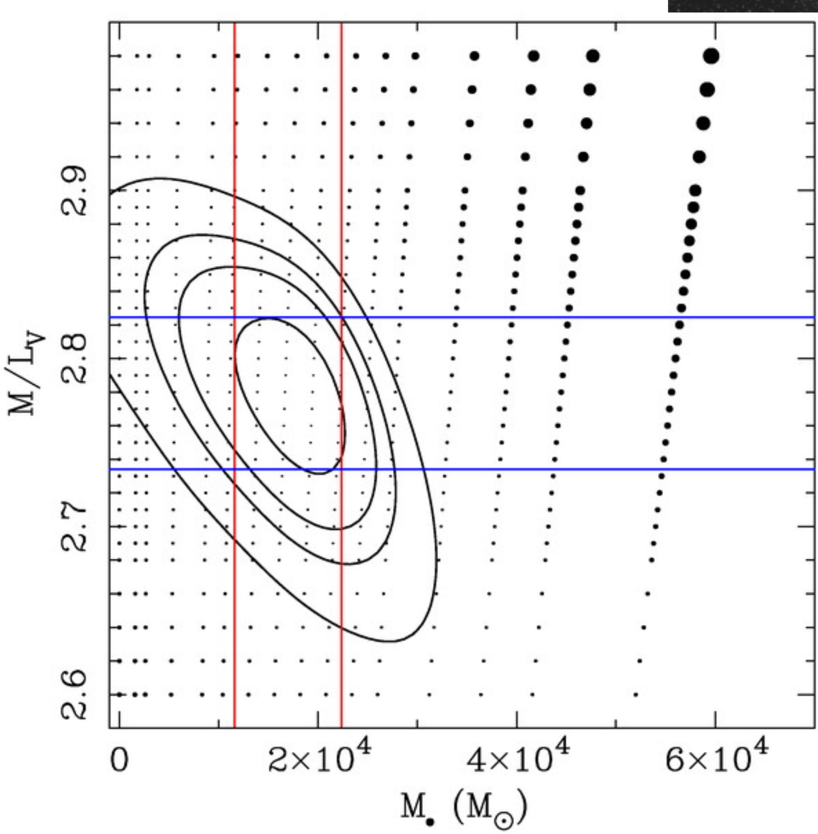


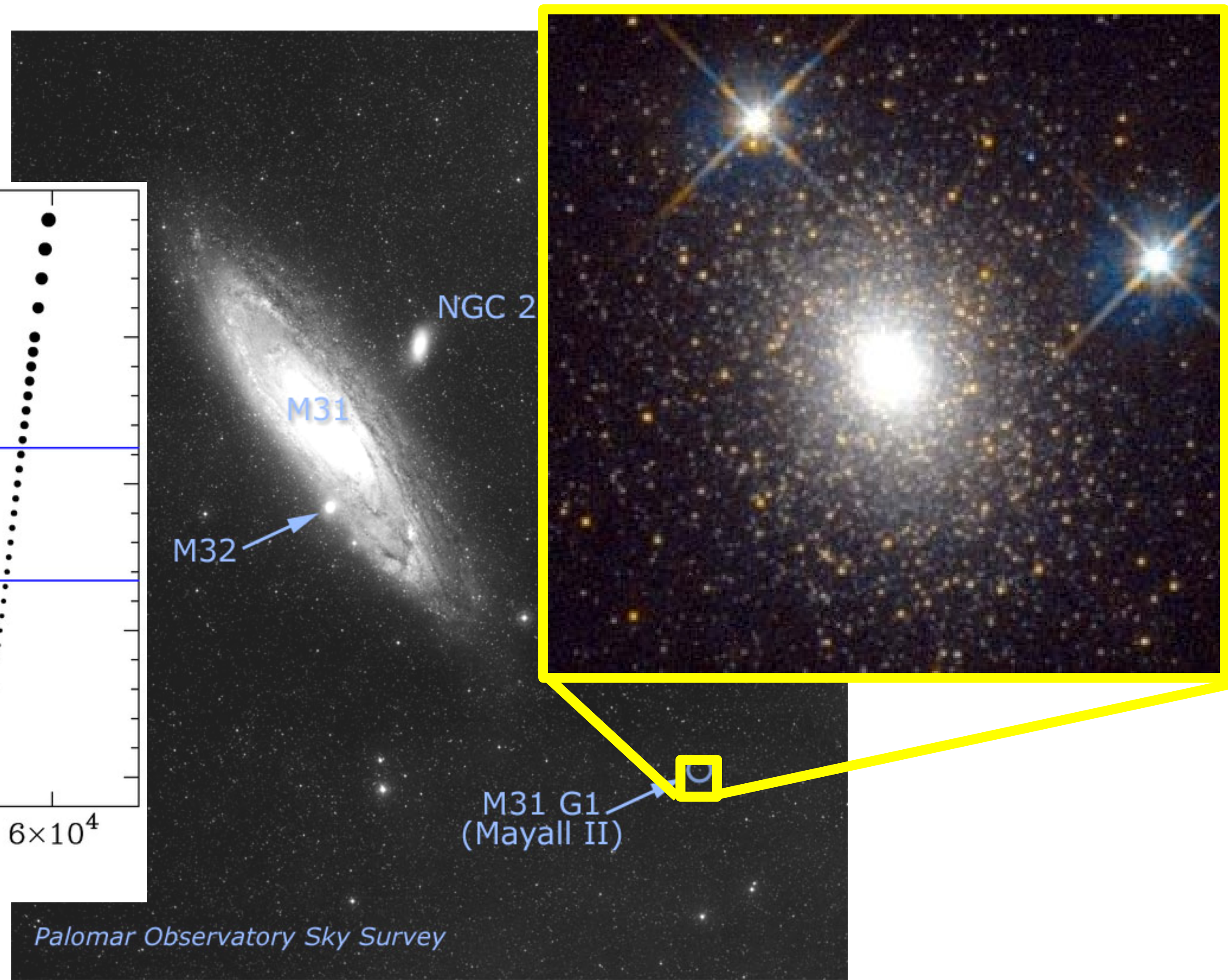
Webb+ 2014, arXiv:1401.1728

5. Intermediate-mass black holes (IMBHs): 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

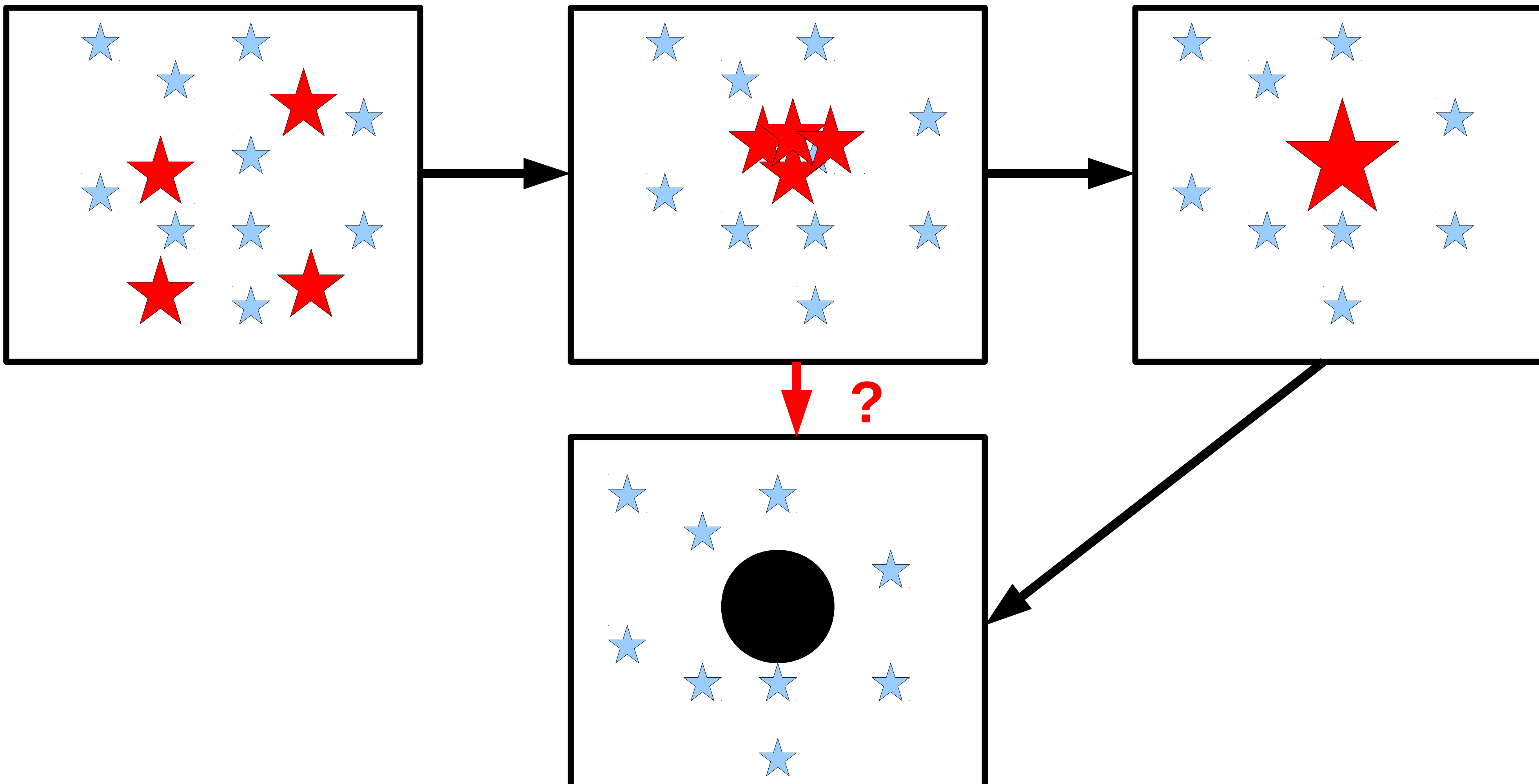
5. Intermediate-mass black holes (IMBHs): BHs with mass 10^{2-5} $M_\odot$

How do IMBHs form?	***Requires dynamics?***
1- runaway collisions of stars	***yes***
2- repeated mergers of BHs	***yes***
3- remnants of very massive (>260 Msun) extremely metal-poor stars (stellar BHs)	***No*** ***(unless very massive star was dynamically formed)***
4- low mass end of super-massive BHs (not part of this course)	***maybe***

5.1 IMBHs from Runaway collisions

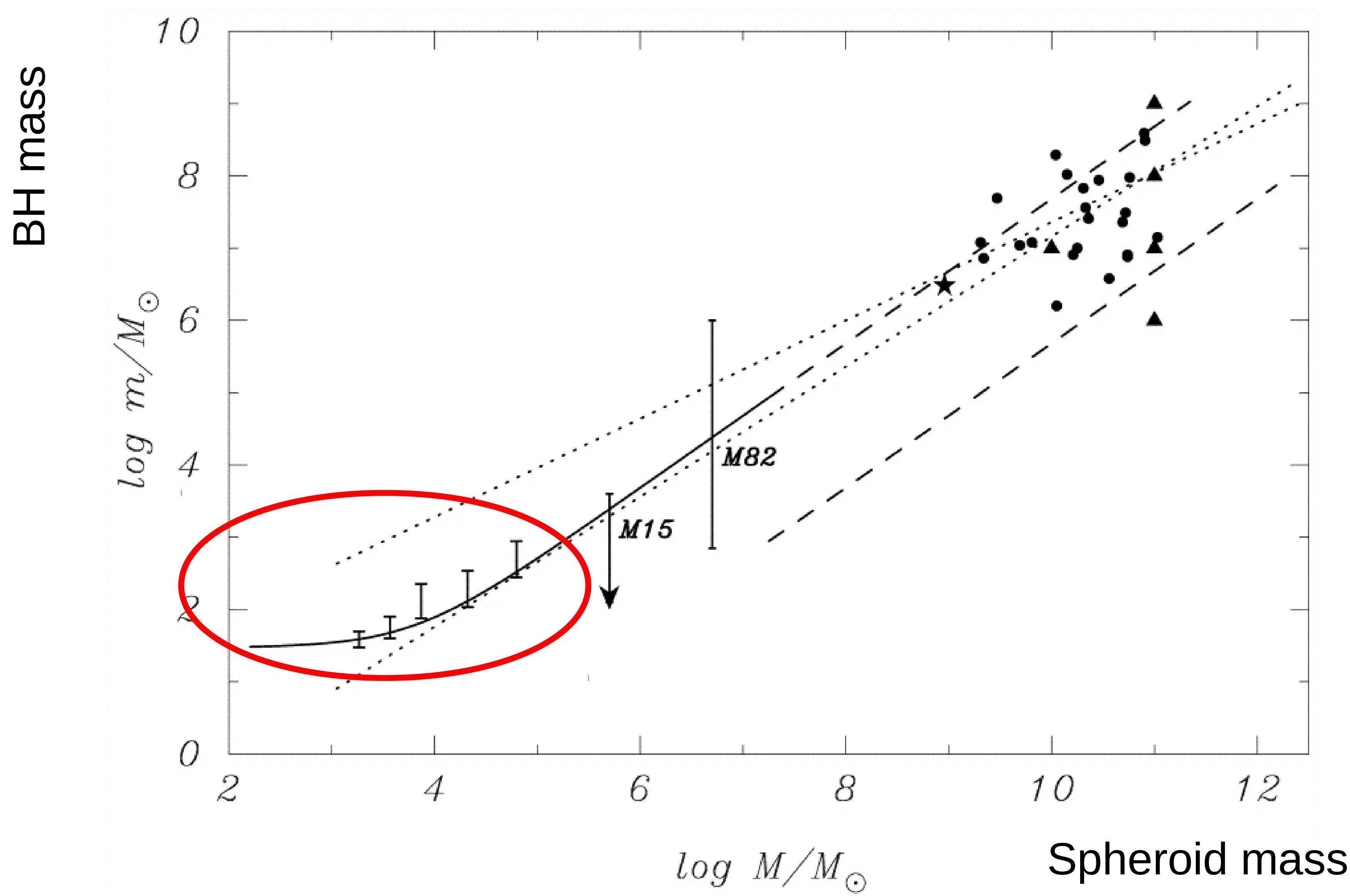
IDEA: mass segregation brings very massive stars to the centre

If timescale for mass segregation < timescale for SN explosion
+ encounter rate sufficiently high
→ massive stars collide, merge and form a super-massive star, which collapses to a BH



5.1 IMBHs from Runaway collisions

"Analytic" *formalism by Portegies Zwart & McMillan 2002, ApJ, 576,899* confirmed by their simulations

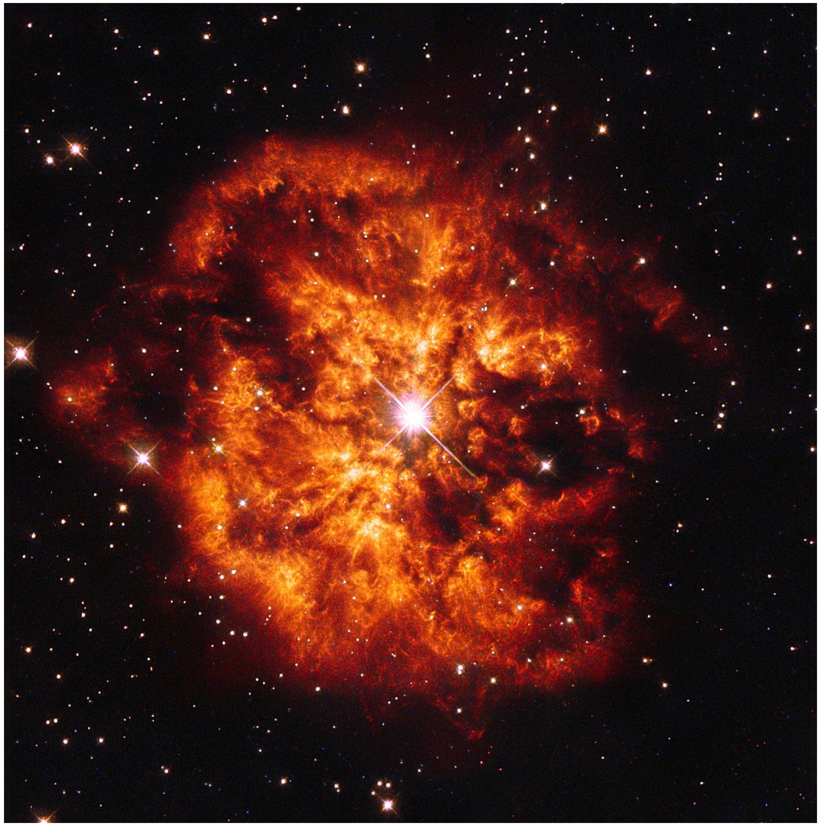


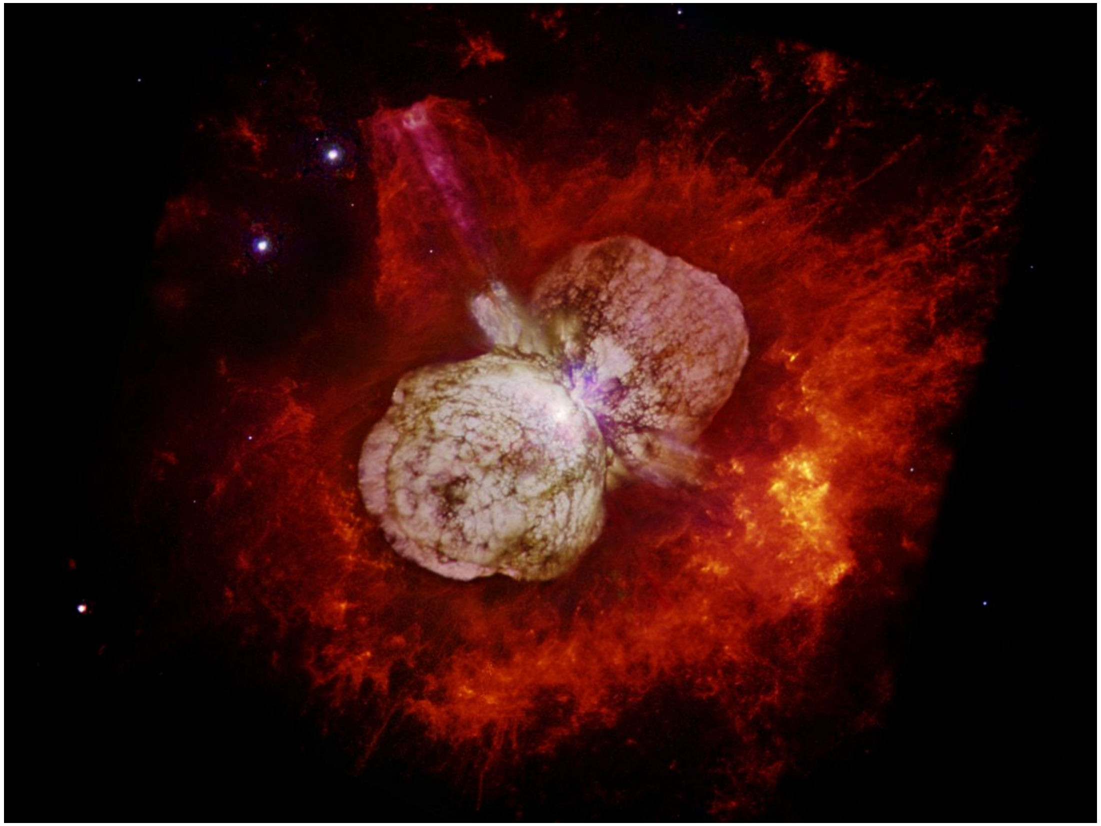
5.1 IMBHs from Runaway collisions

MAIN ISSUE: MASS LOSS!!!

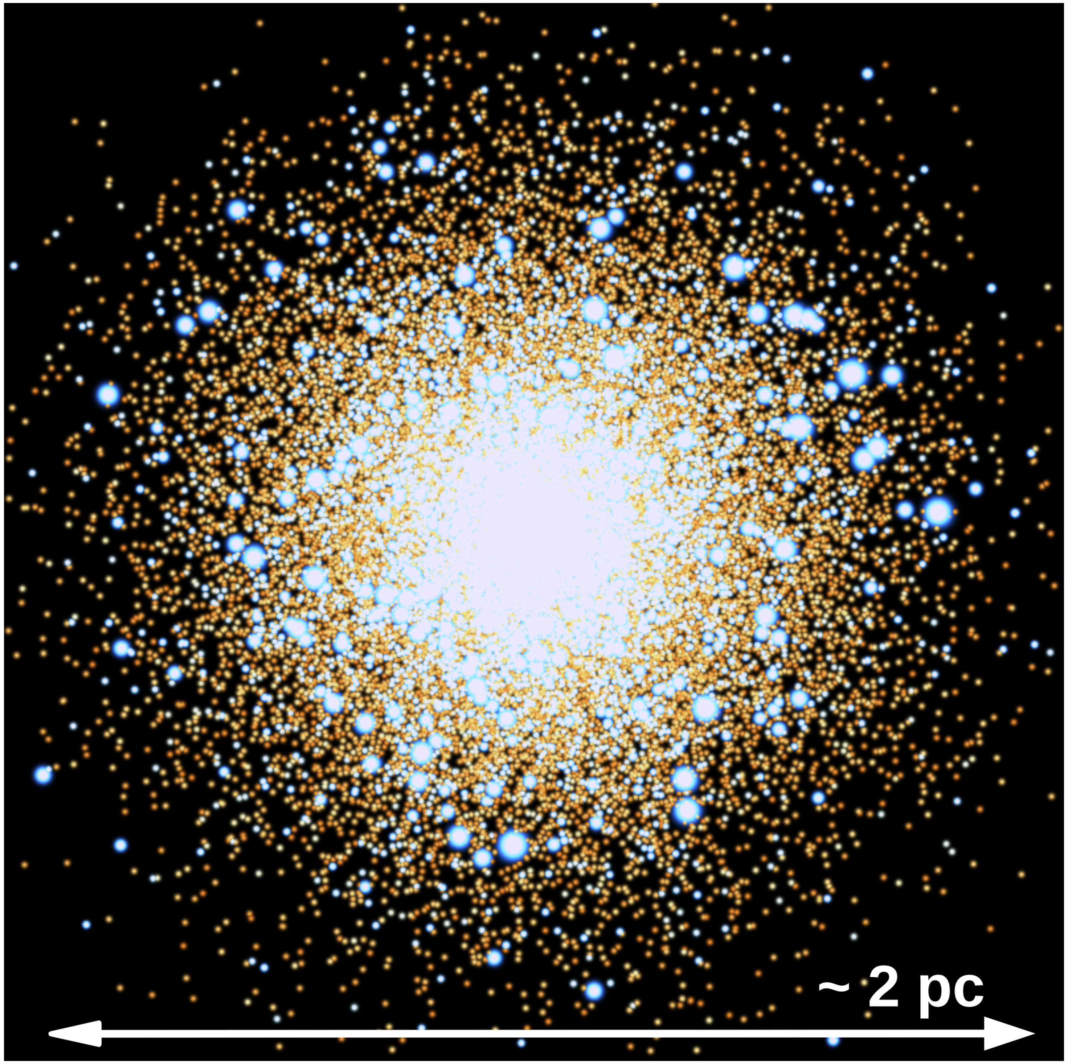
(1) during merger
simulations show mass loss up to 25% of total mass
(Gaburov et al. 2010, MNRAS, 402, 105)

(2) after merger, by stellar winds
the super-massive star will be very unstable (radiation pressure dominated)
e.g. MM 2016, MNRAS, 459, 3432





5.1 IMBHs from Runaway collisions



N-body simulations of collisional systems (direct summation N-body)

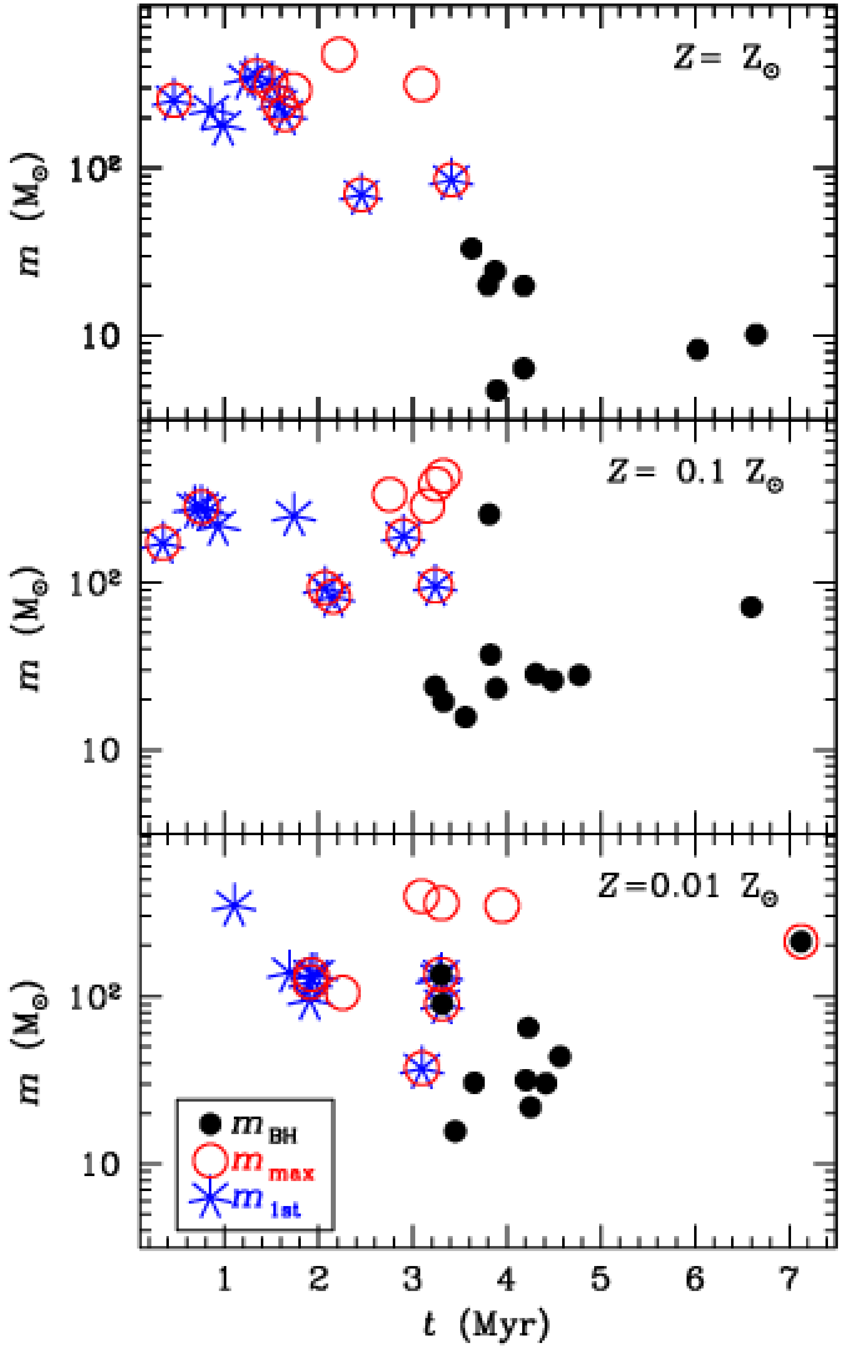
+

stellar and binary evolution (population synthesis) embedded in N-body

=

can be used to study IMBH formation accounting for mass loss

5.1 IMBHs from Runaway collisions



Mass loss by stellar winds prevents formation of IMBHs from runaway collisions UNLESS METALLICITY < 0.1 Zsun

e.g. MM 2016, MNRAS, 459, 3432

* maximum star mass up to 500 Msun

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

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

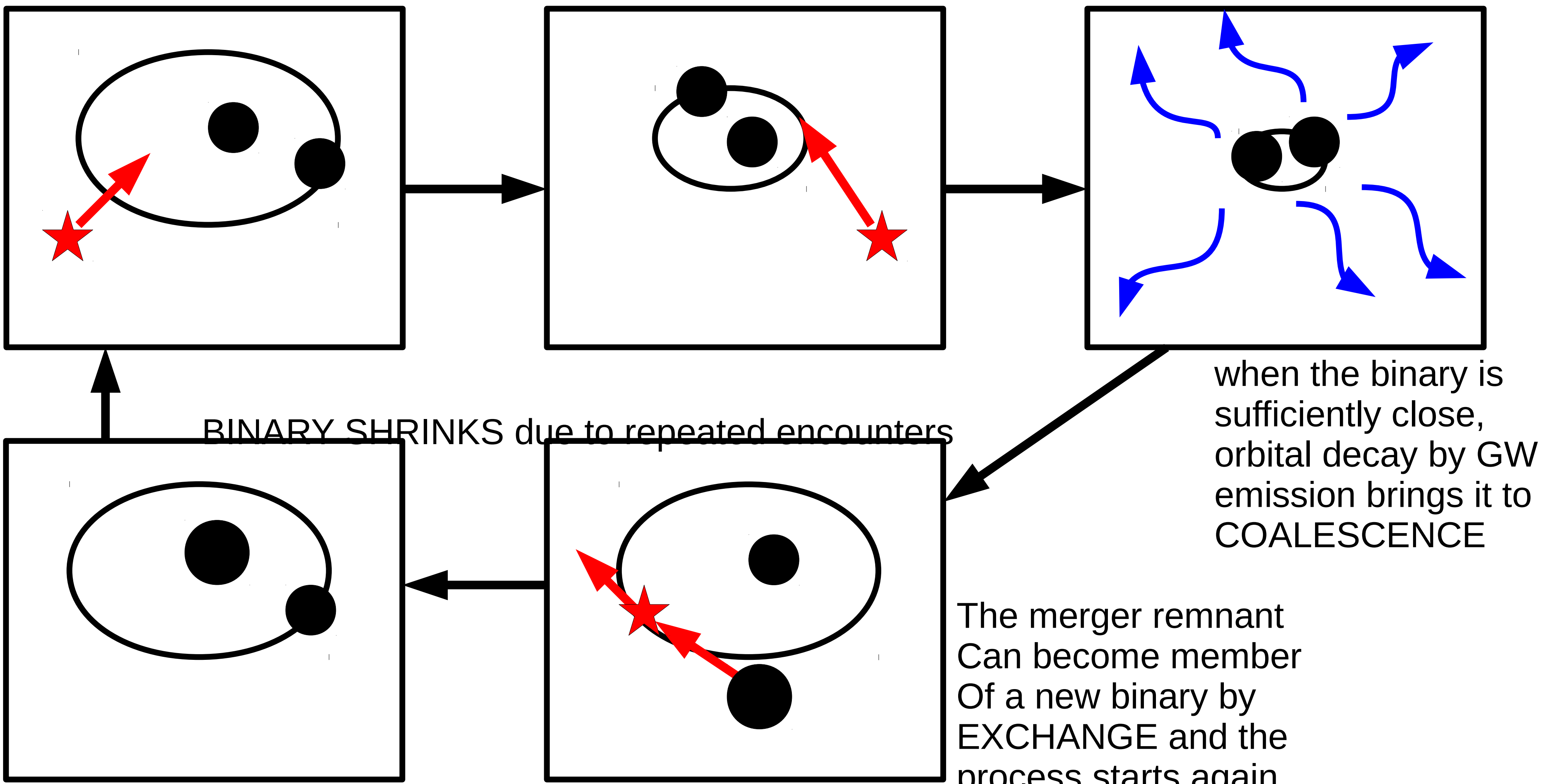
* CAVEAT 2: uncertainties in mass-loss during/after collisions

MM 2016, MNRAS, 459, 3432

5.2 IMBHs from 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



5.2 IMBHs from Repeated mergers

MAIN PROBLEM: seed BH must avoid ejection before merger

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

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

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

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 $m_1+m_2\sim m_T$

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

5.2 IMBHs from Repeated mergers

Orbital separation in gravitational wave merger regime:

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

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

5.2 IMBHs from Repeated mergers

ADDITIONAL PROBLEM: INEFFICIENT!

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

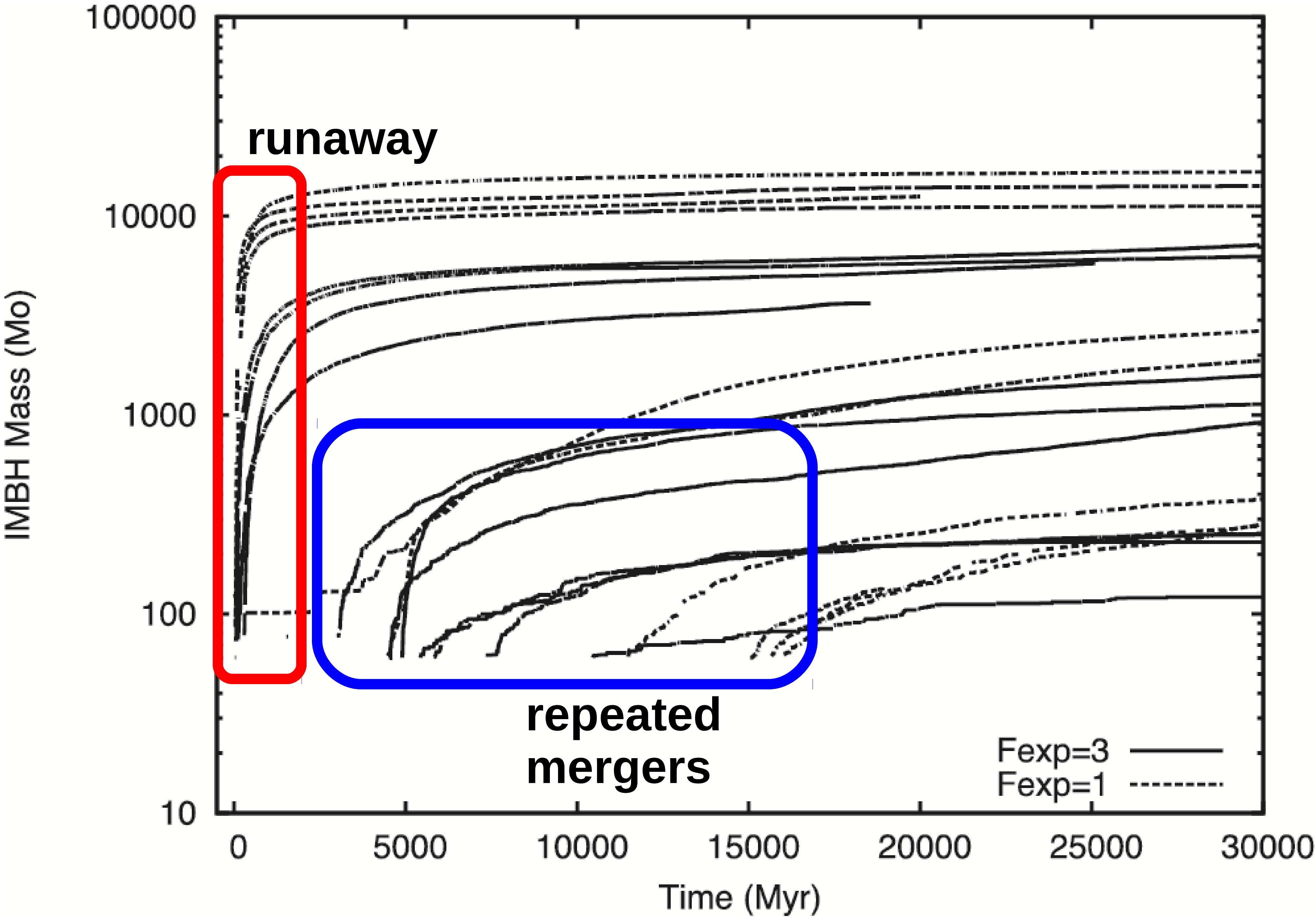
$$N_{merg} = \frac{1}{\xi}\,\frac{m_T}{\langle m\rangle}\,\ln\left(\frac{a_0}{a_{GW}}\right)$$

Time required for 1 merger:

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

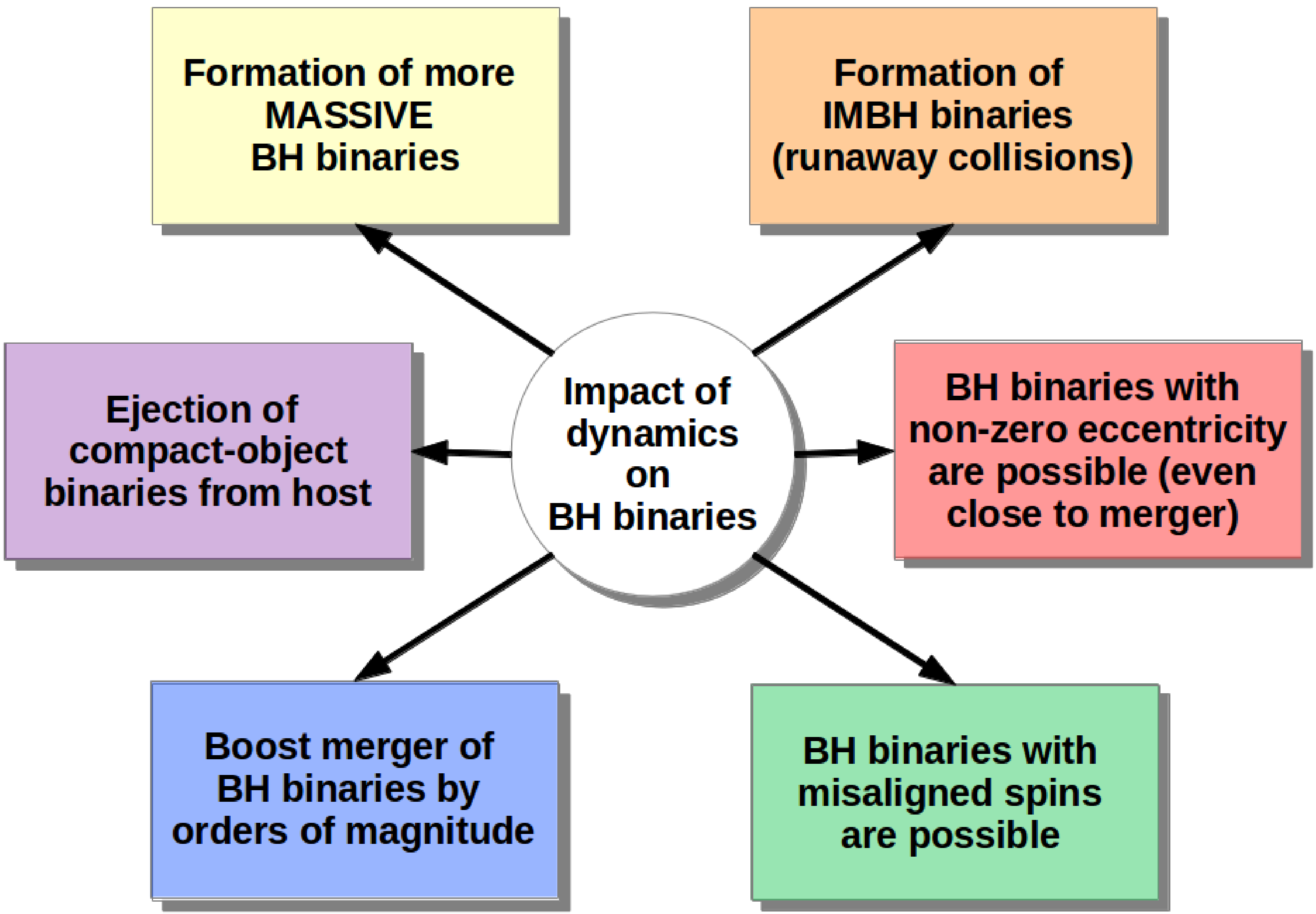
$$t_{GW} = \frac{\sigma}{2\,\pi\,G\,\xi\,\rho}\left(\frac{1}{a_{GW}} - \frac{1}{a_0}\right)$$

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



Giersz +2015, MNRAS, 454, 3150

SUMMARY of EFFECTs of DYNAMICS on BH binaries:



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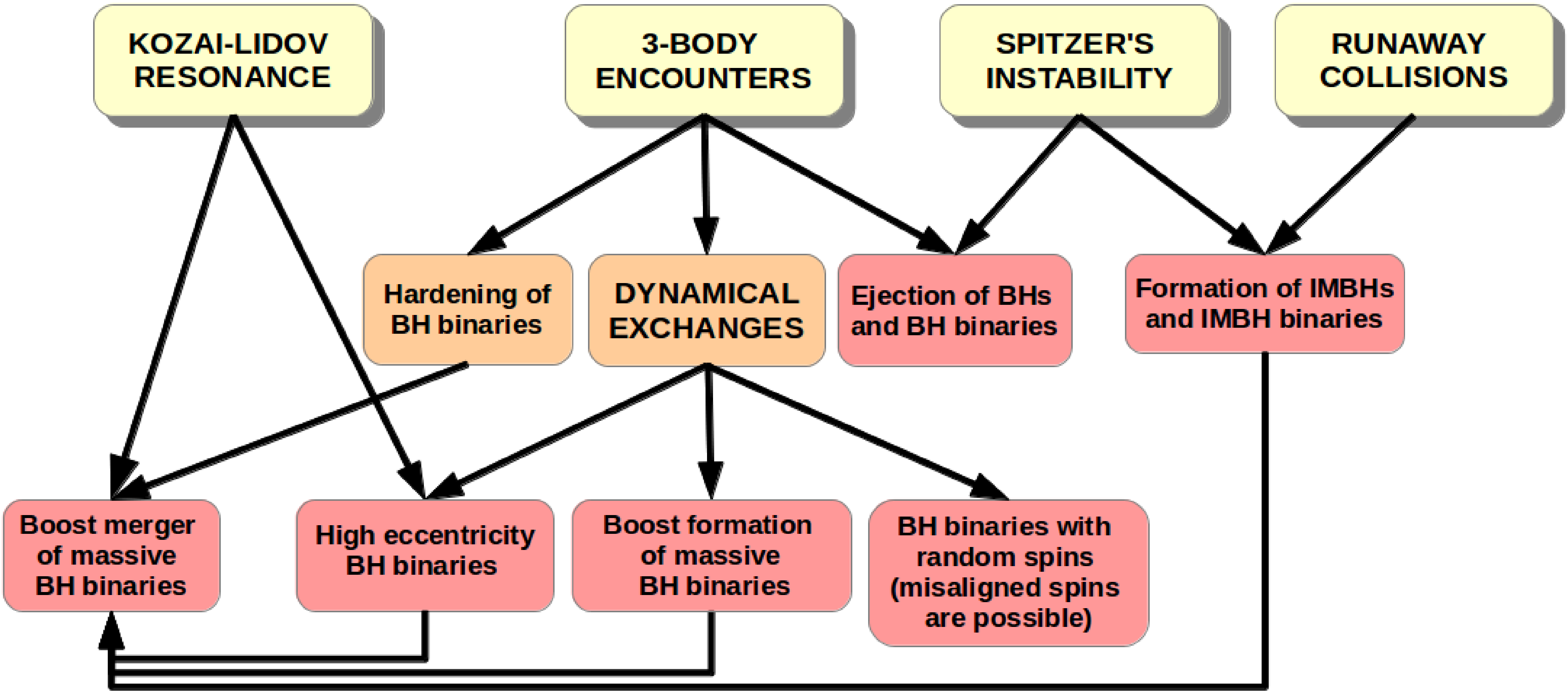

References:

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

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

* Heger et al. 2003, arXiv:astro-ph/0211062

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

* Sigurdsson & Hernquist 1993, Nature 364, 42

* Giersz et al. 2015, MNRAS, 454, 3150

* Mapelli 2016, MNRAS, 459, 3432

* Spera, Mapelli, Bressan 2015, MNRAS, 451, 4086

THANK YOU