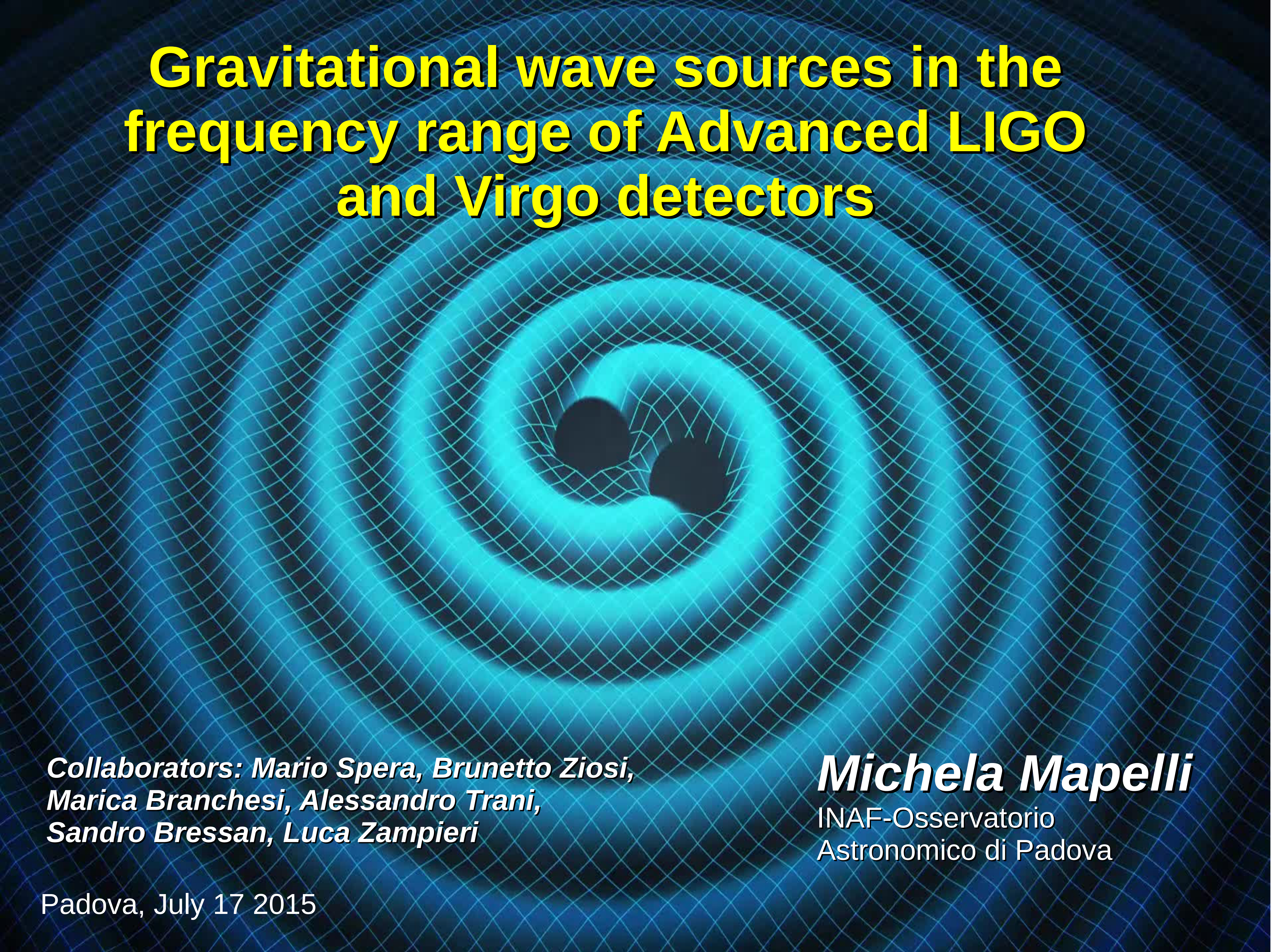
Gravitational wave sources in the frequency range of Advanced LIGO and Virgo detectors



Collaborators: Mario Spera, Brunetto Ziosi, Marica Branchesi, Alessandro Trani, Sandro Bressan, Luca Zampieri

Michela Mapelli
INAF-Osservatorio Astronomico di Padova

Padova, July 17 2015

OUTLINE:

1. gravitational waves for dummies

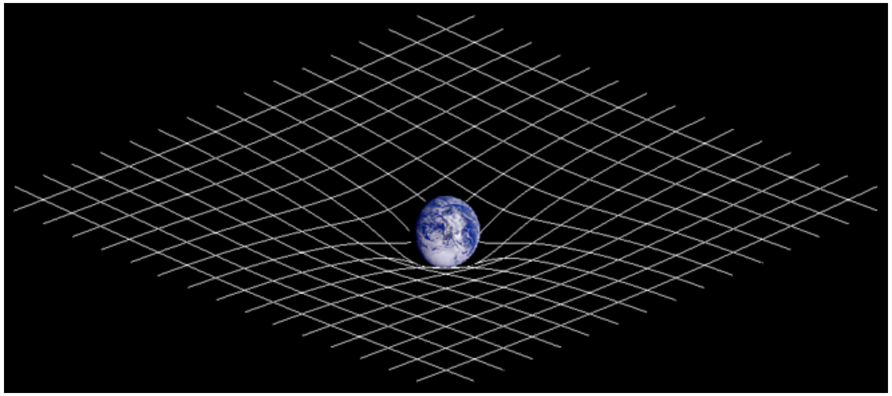
2. a couple of words about detectors

3. gravitational wave sources (for LIGO/Virgo)

4. how to estimate the merger rate

5. impact of environment on merger rate

1. Gravitational waves for dummies



Browsing wikipedia `gravitational waves are ripples in the curvature of spacetime which propagate as waves, travelling outward from the source'

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Weak field (far from source)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad with\, |h_{\mu\nu}| \ll 1$$

Using gauge invariance and assuming vacuum (*T*=0 no mass no energy)

$$\Box h = -\frac{16\pi G}{c^4} T_{\mu\nu} = 0$$

Equation of WAVES!!

1. Gravitational waves for dummies

By integrating equation

$$\Box h = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

$$h^{ij}(t, \vec{x}) \sim \frac{2\,G}{r\,c^4} \frac{d^2}{dt^2} I^{ij}(t - r/c)$$

Distance source-observer

Moment of inertia, or second mass moment, or quadrupole moment of mass $I^{ij} = \int dx^3 \, \rho(t, \vec{x}) \, x^i \, x^j$

Retarded time

→ not all accelerating masses do this job but only those with <u>QUADRUPOLE</u>

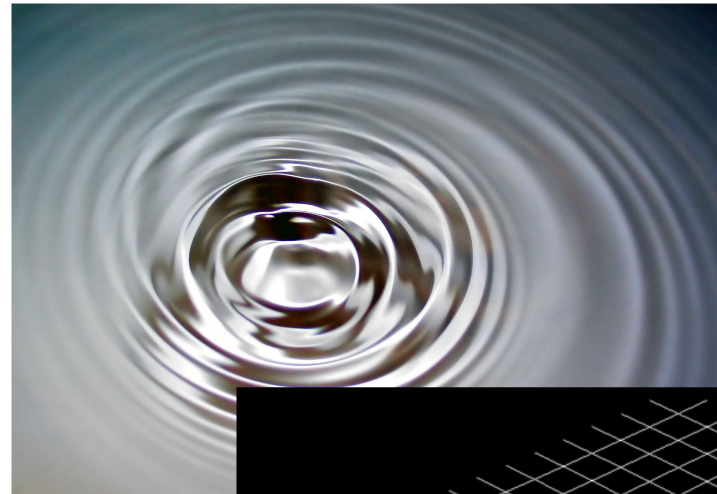
If you do calculation, monopole and dipole disappear

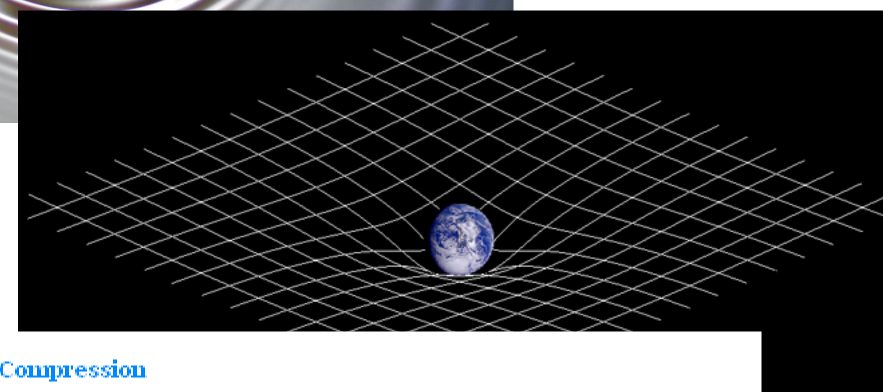
→ for a gravitational wave to form, there must be an ASYMMETRY IN MASS DISTRIBUTION

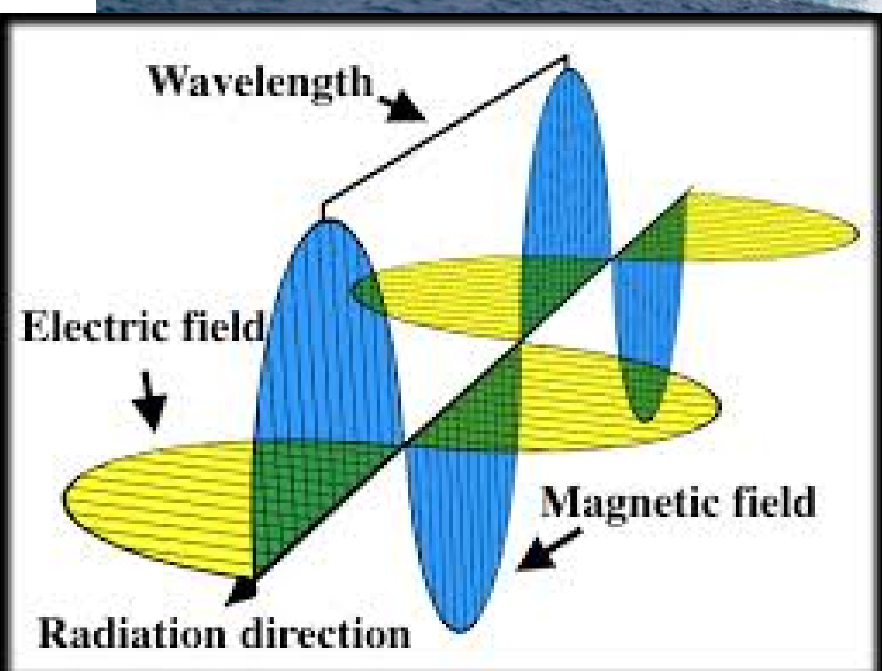
1. Gravitational waves for dummies

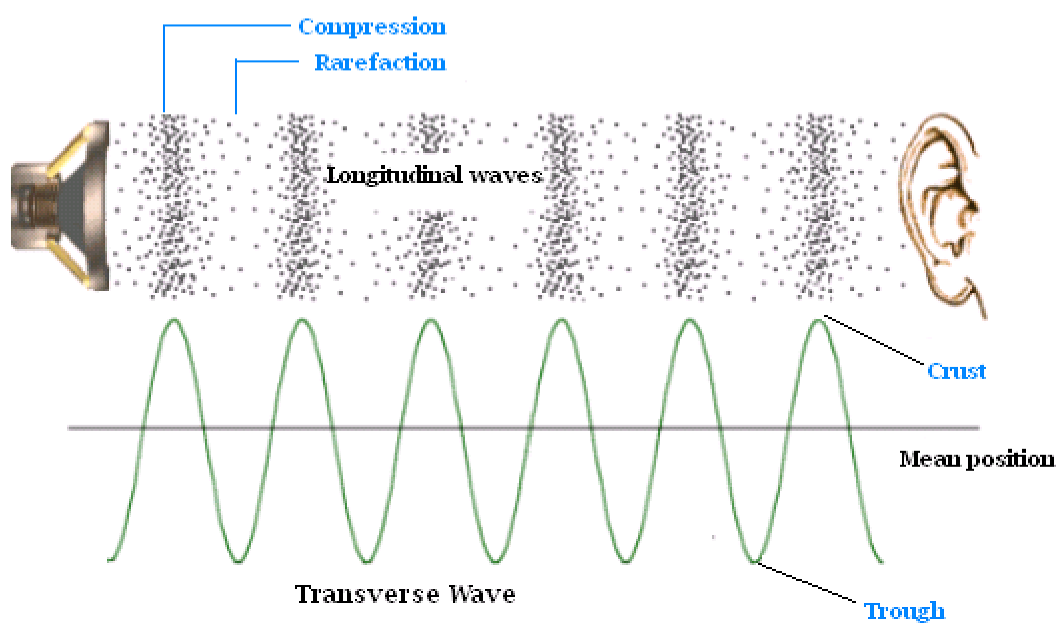
TO EXPLAIN TO HIGH-SCHOOL STUDENTS

Nature is full of waves...









1. Gravitational waves for dummies

TO EXPLAIN TO HIGH-SCHOOL STUDENTS

Analogy with electromagnetic field

- an accelerating charge produces a perturbation in electromagnetic field that propagates as wave

1. Gravitational waves for dummies

TO EXPLAIN TO HIGH-SCHOOL STUDENTS

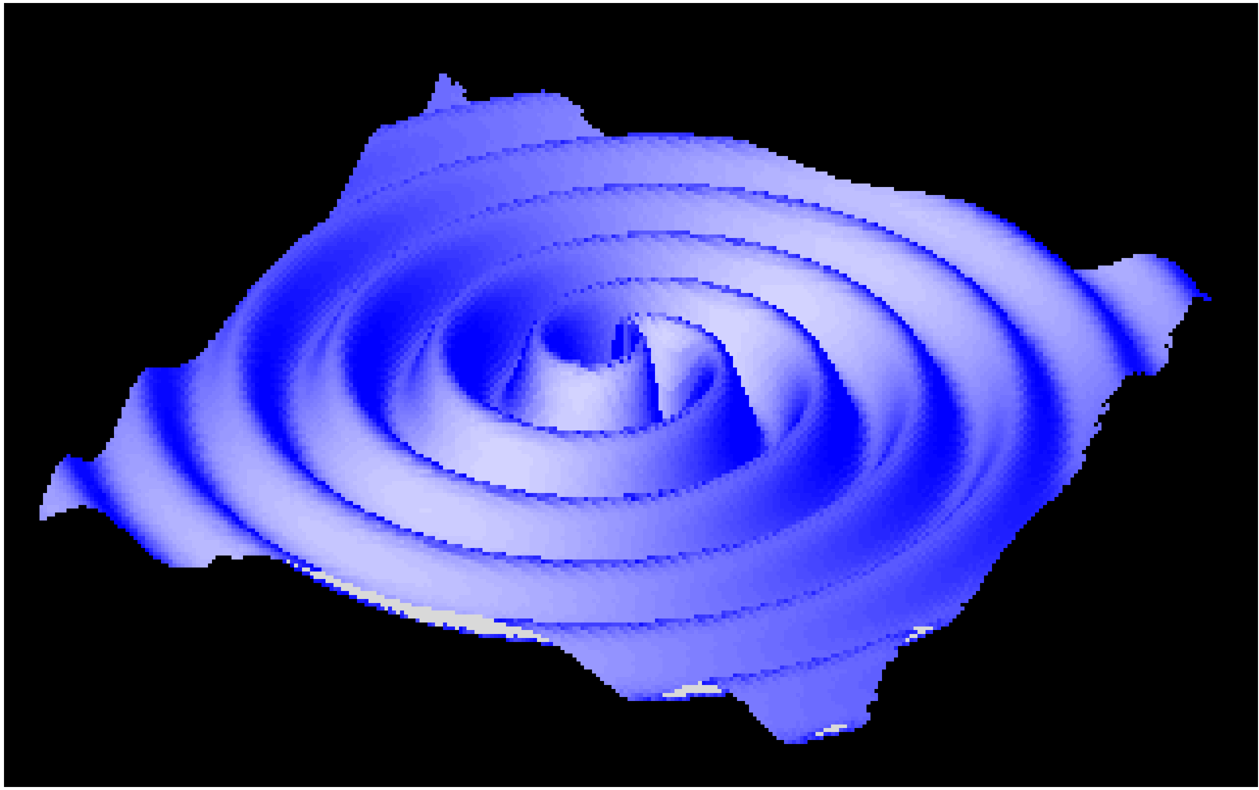
Analogy with electromagnetic field

a mass is source of gravitational field as a charge is source of electromagnetic field

→ an accelerating mass should produce perturbations in gravitational field,

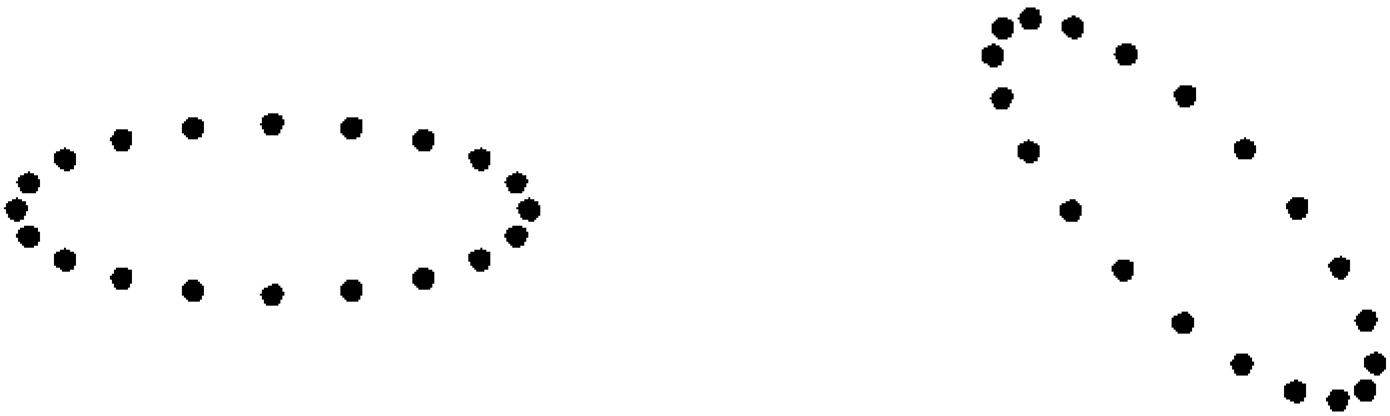
i.e. intrinsic perturbations of space-time that propagate as waves:

do not move in space-time but MOVE SPACE-TIME at speed of light (i.e. lead deformation in space time – squeeze stretch)



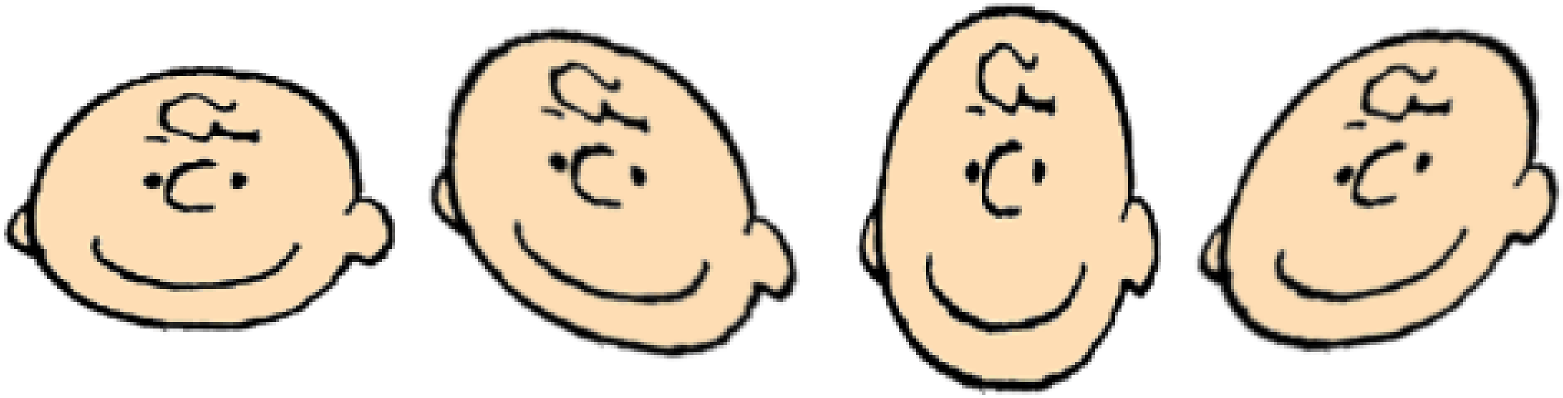
1. Gravitational waves for dummies

When GW passes through space deforms it



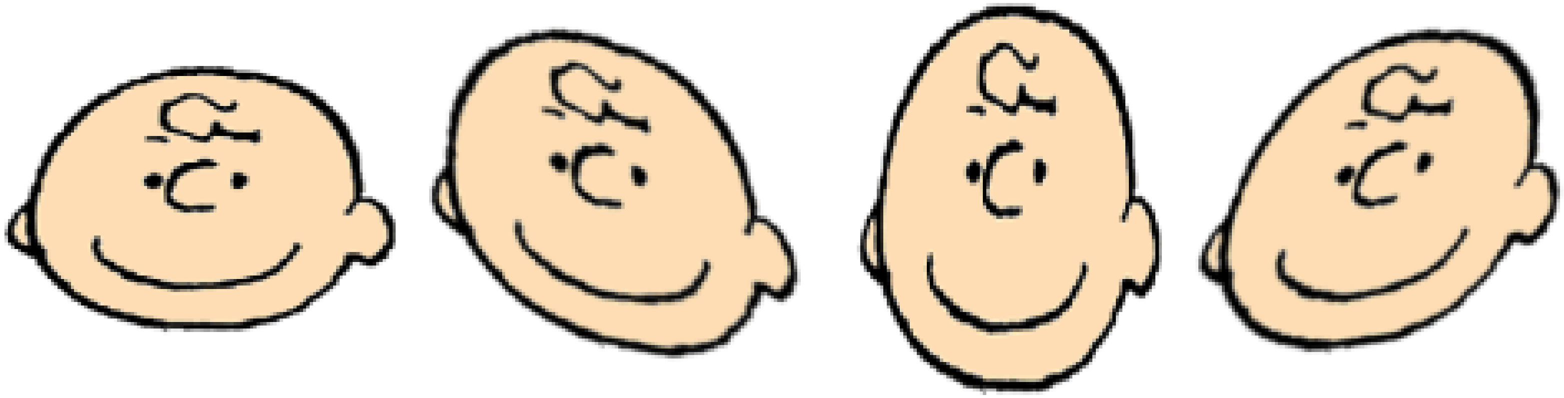
1. Gravitational waves for dummies

When GW passes through space deforms it



1. Gravitational waves for dummies

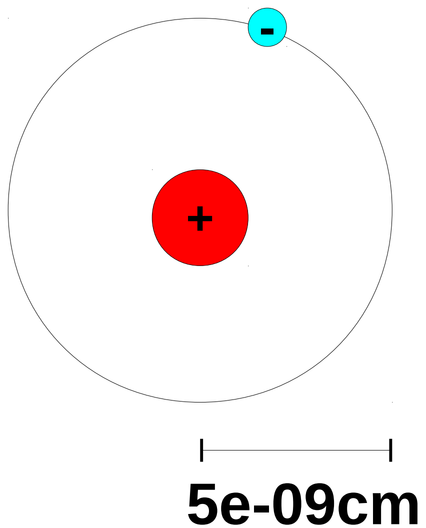
When GW passes through space deforms it



But deformations are very small:
strain=relative deformation

$$h \sim 1e\text{-}21$$

For $l_{Sun\text{-}Earth}$ ~ 1.5e13 cm
$h\ l_{Sun\text{-}Earth}$ ~ 1e-21 x 1.5e13 ~ 1.5e-08cm
< size of H atom at distance Sun-Earth



2. a couple of words about detectors

Michelson interferometers

2. a couple of words about detectors

Michelson interferometers

2 LIGO detectors in the US

1 Virgo (Italy)

LIGO Lab/Virgo

Design started in the '90s

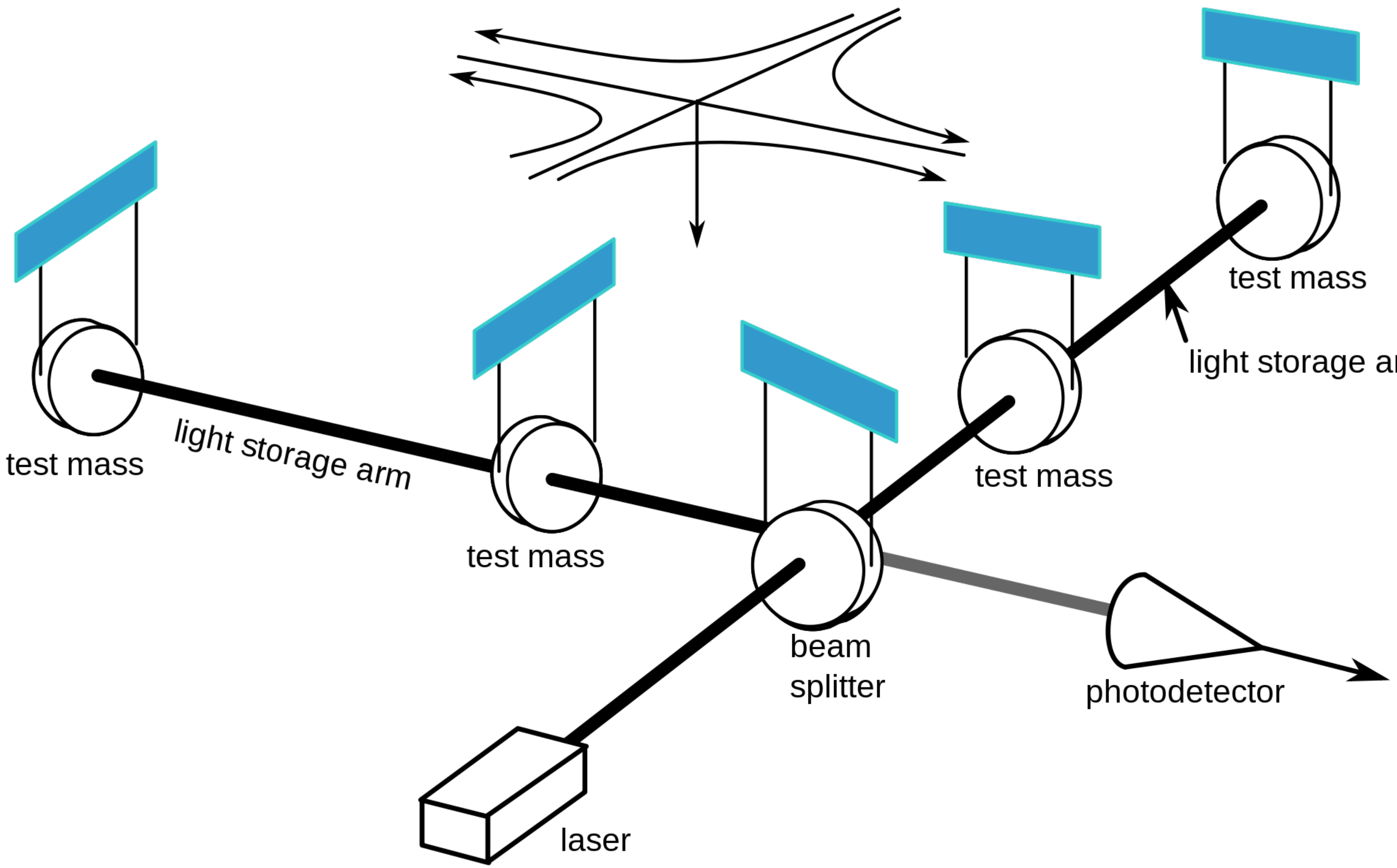
First science runs ~ 2007 (no detection)

Now being upgraded

Next runs ~2016

2. a couple of words about detectors

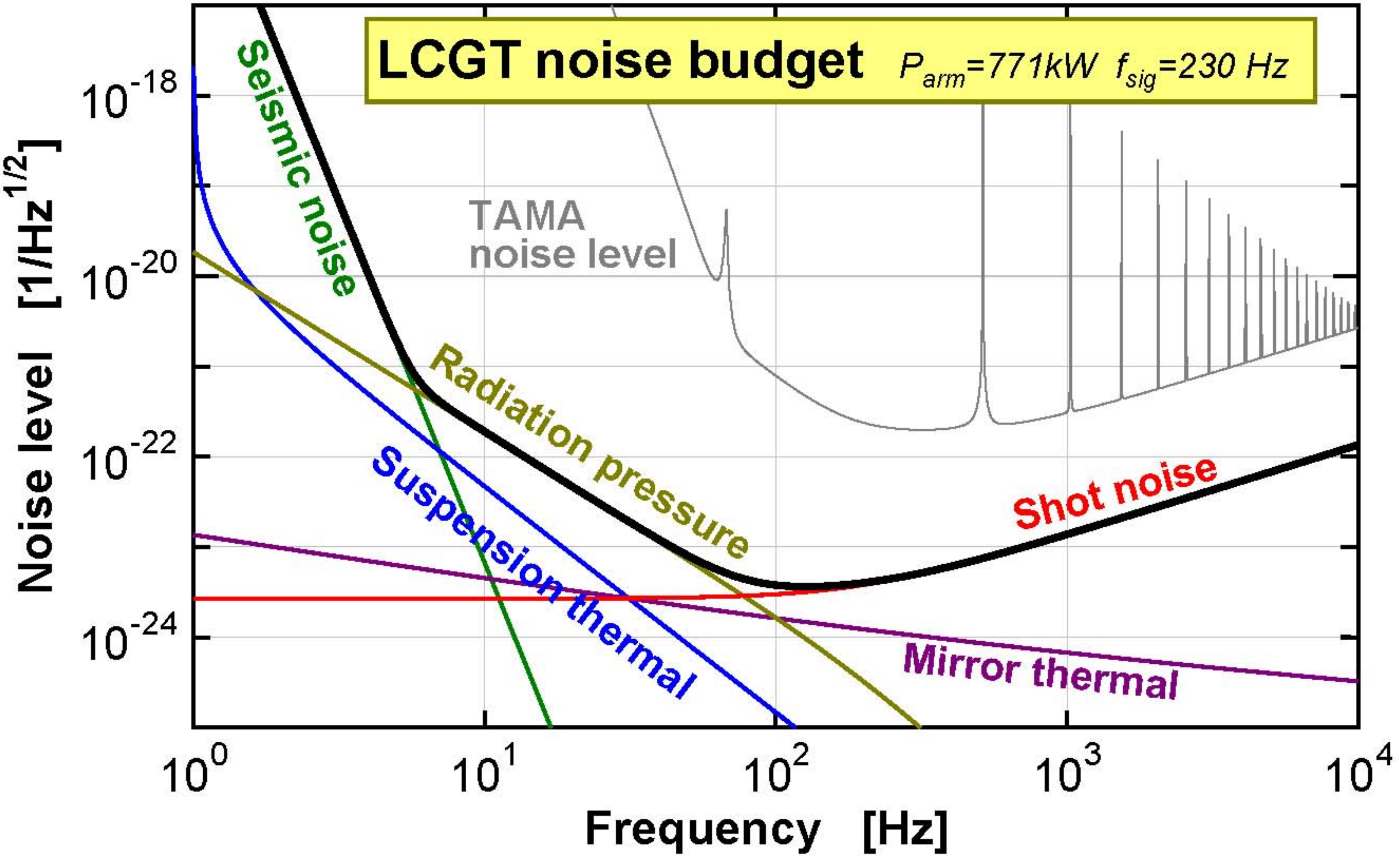
Michelson interferometers



Two arms of ~ 4 km – At least 100 km requested for detection → laser is bounced back and forth

2. a couple of words about detectors

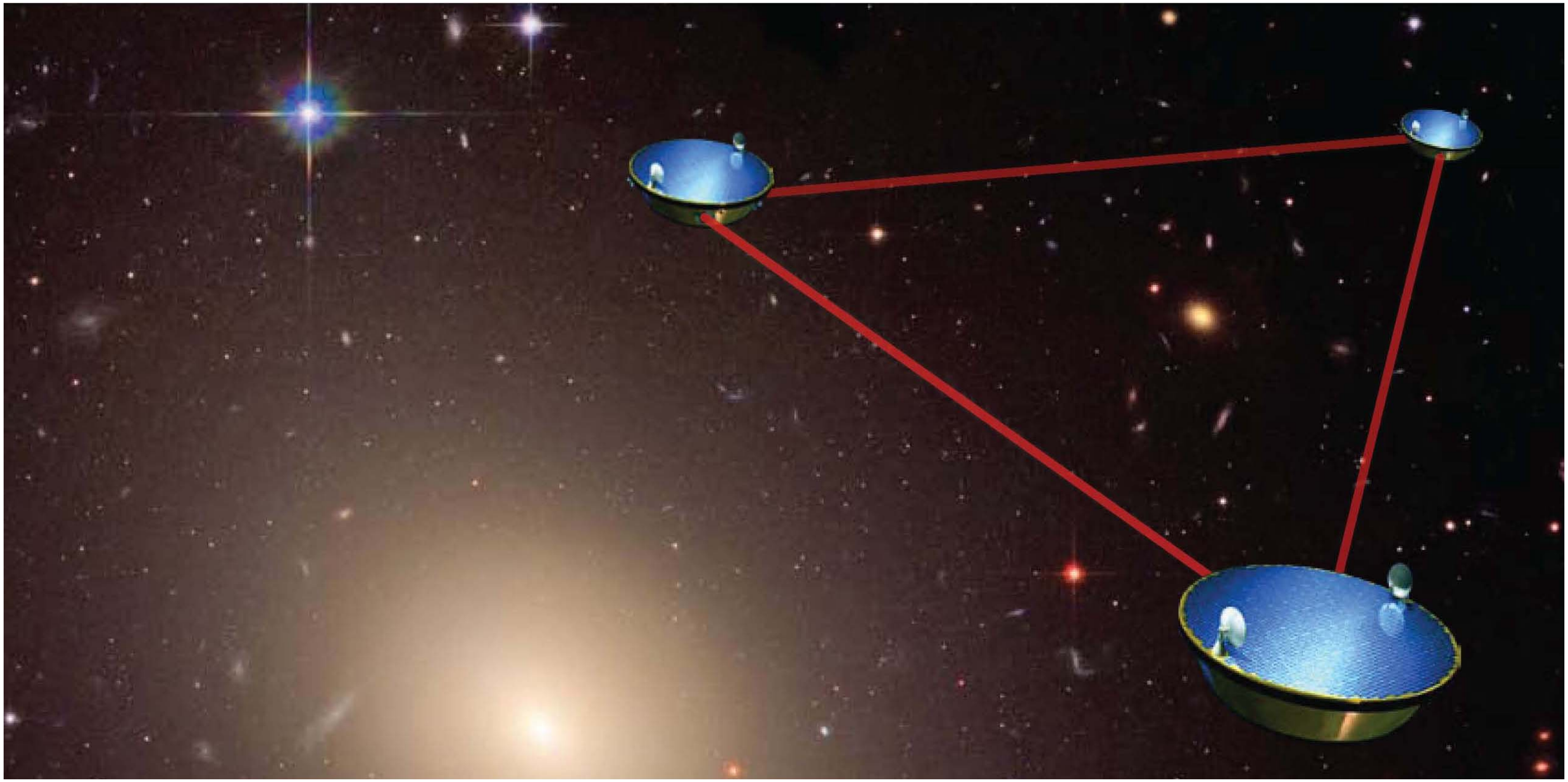
NOISE is the problem!



2. a couple of words about detectors

To go to lower frequency we need flying detectors!

LISA – eLISA (>> 2020)



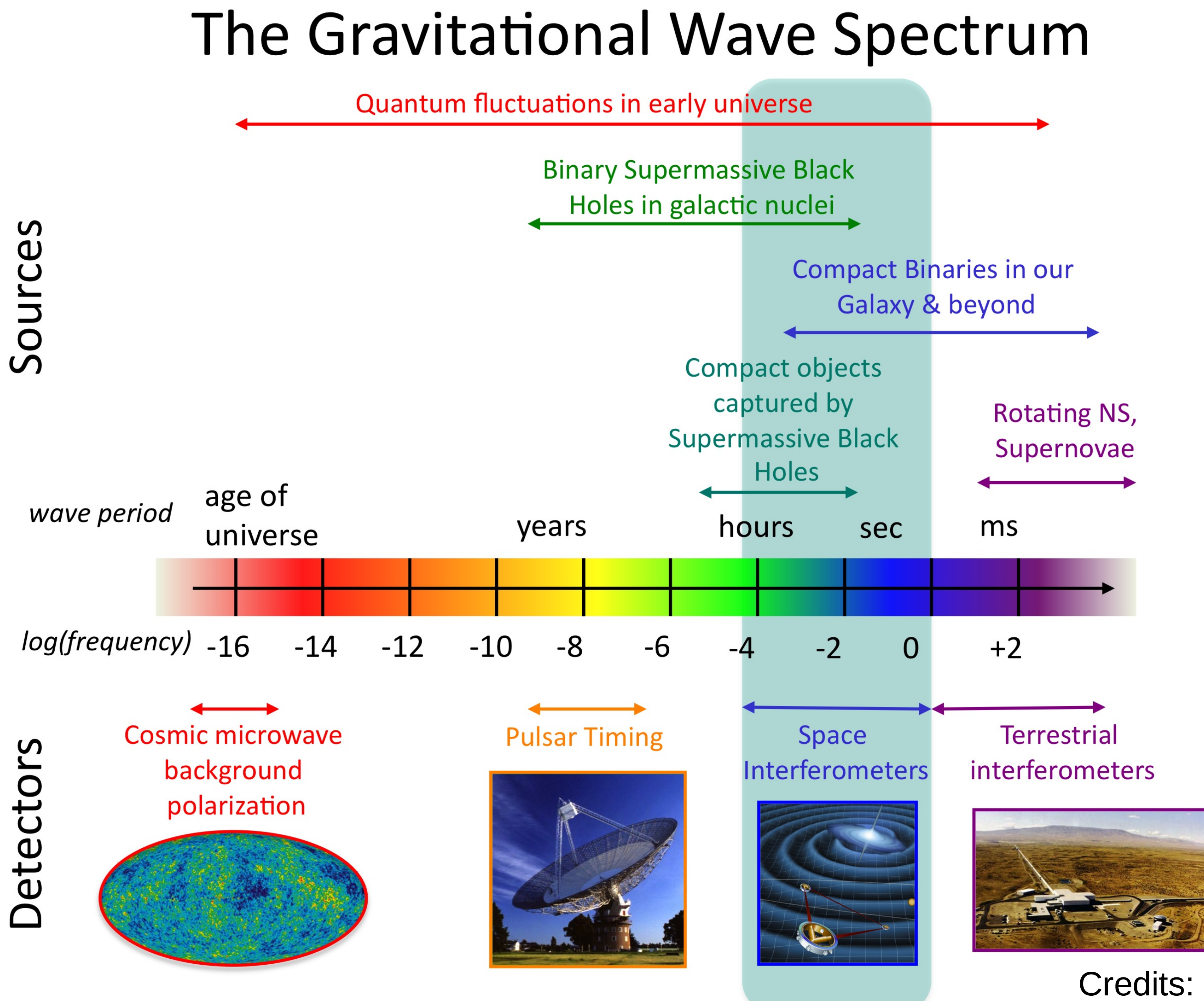
From http://lisa.nasa.gov/mission/index.html)

2. a couple of words about detectors

PLAY AT BUILDING YOUR OWN DETECTOR
https://www.youtube.com/watch?v=lAvJrePR7F4

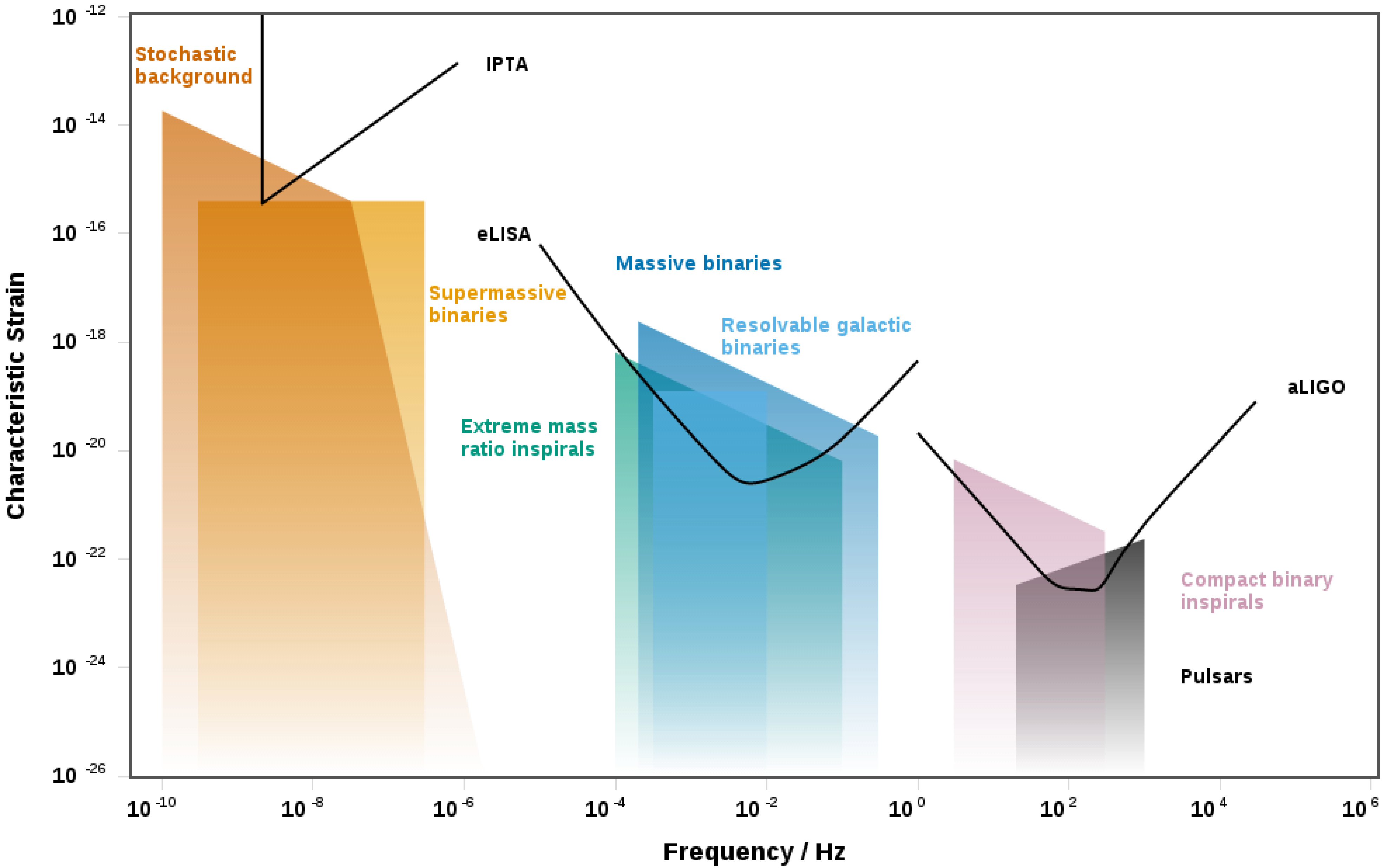
http://www.gwoptics.org/processing/space_time_quest/

2. a couple of words about detectors



Credits: NASA

2. a couple of words about detectors



http://rhcole.com/apps/GWplotter/
Christopher Berry

3. gravitational wave sources (for LIGO/Virgo)

Focus on double compact-object binaries because LIGO-VIRGO sources

black hole – black hole (BH-BH) binaries

neutron star-neutron star (NS-NS) binaries

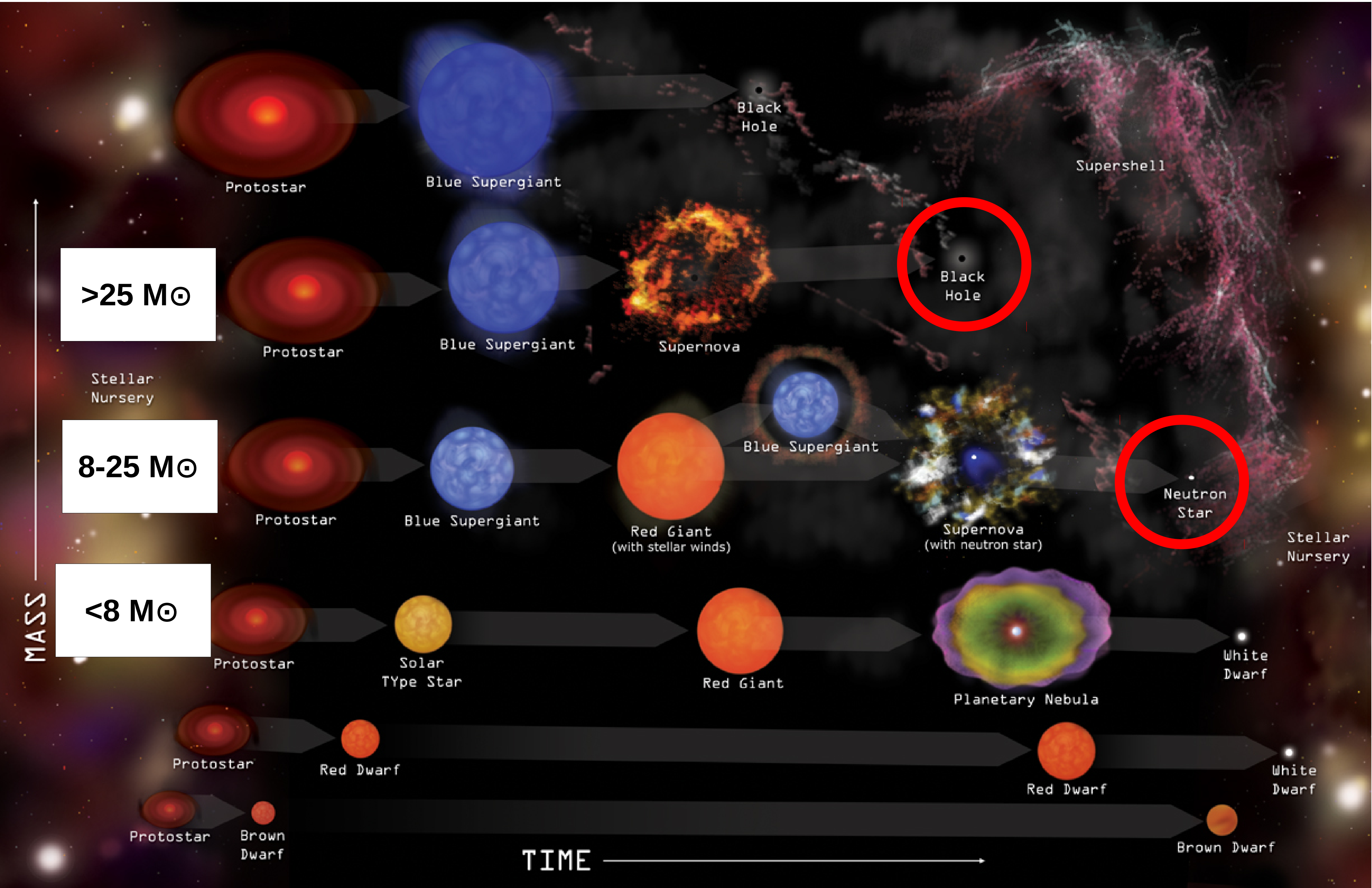
black hole – neutron star (BH-NS) binaries

HOW DO BHs and NSs form?

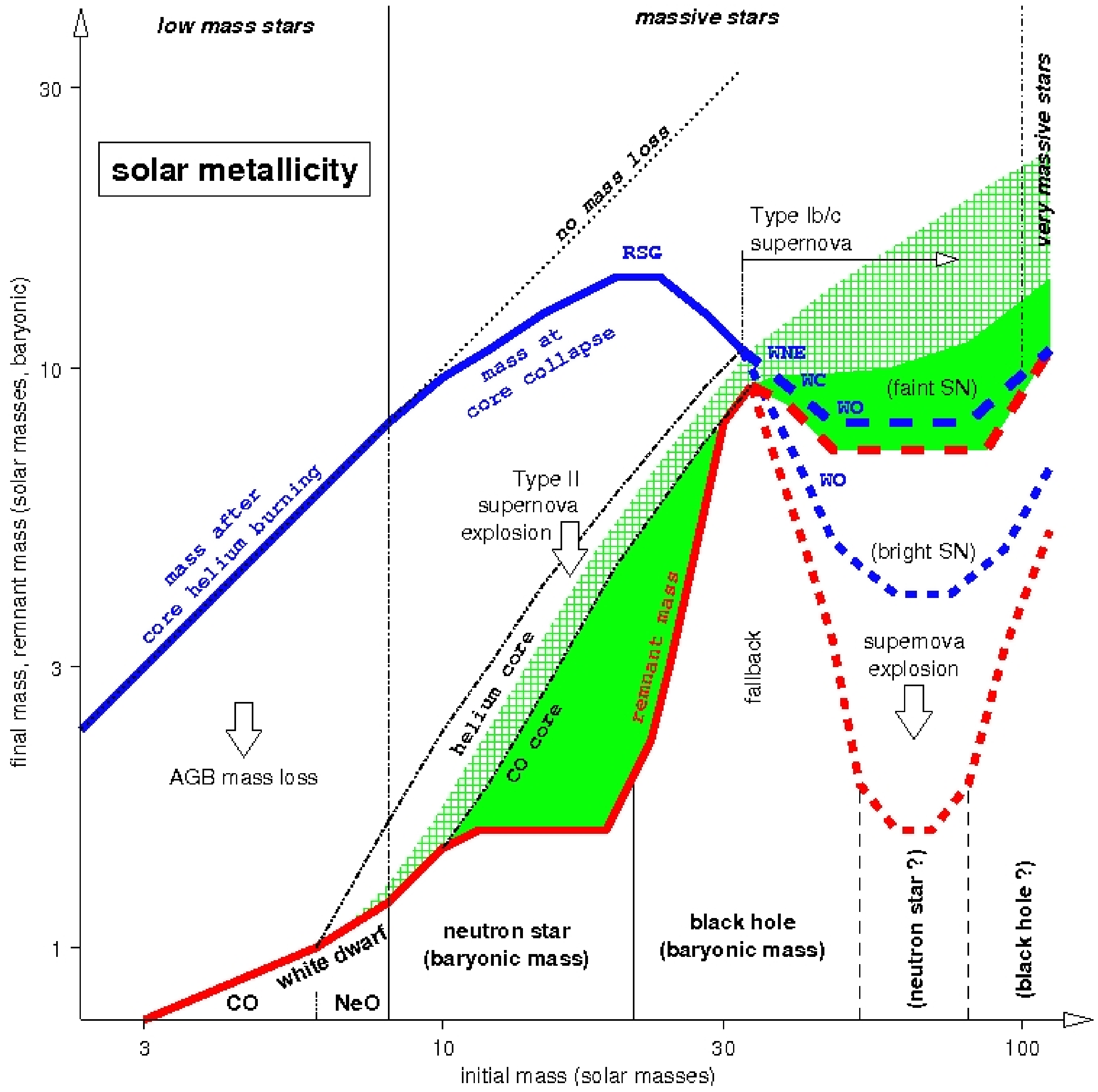
3. gravitational wave sources

HOW DO BHs and NSs form?

Credits: Chandra



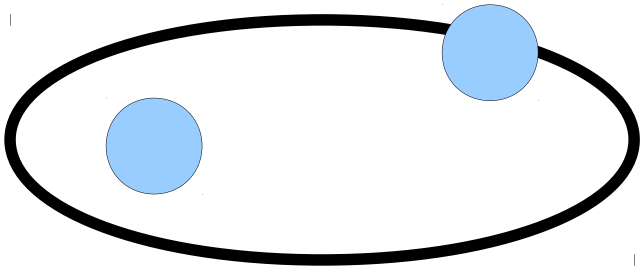
3. gravitational wave sources



Heger et al. (2003)

3. gravitational wave sources

For BH-BH, BH-NS and NS-NS binary I mean KEPLERIAN binary



CARTOON OF NS-NS MERGER

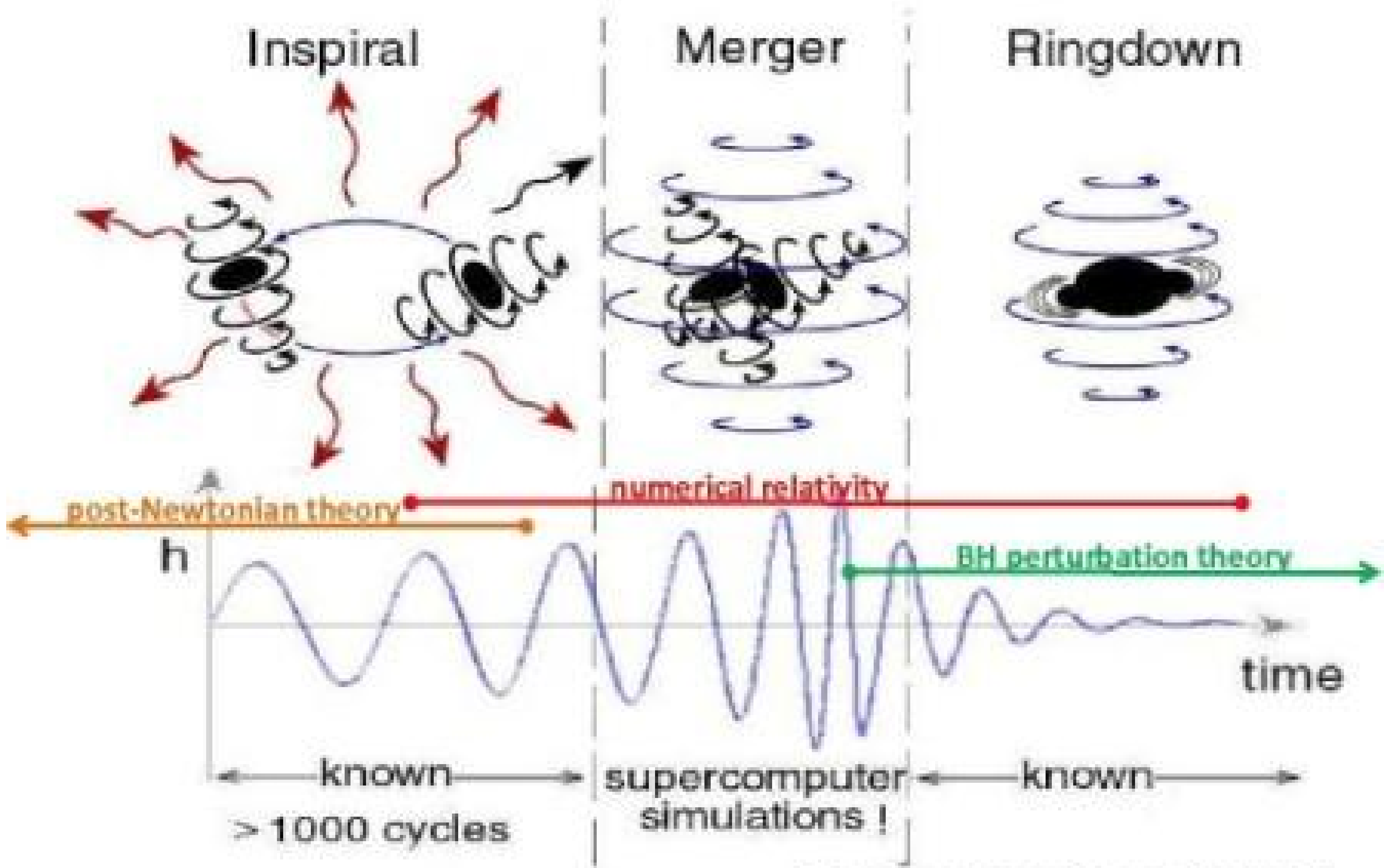
<u>What differences if BH-BH merger?</u>

https://www.youtube.com/watch?v=g8s81MzzJ5c

Credits: NASA

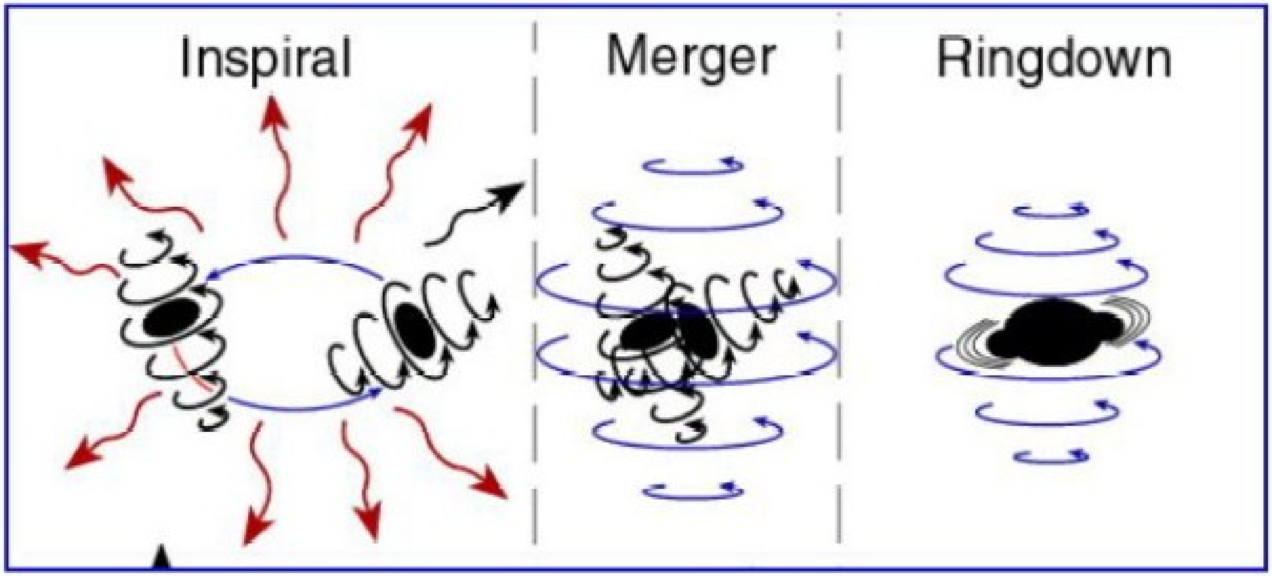
3. gravitational wave sources

Cartoon of BH coalescence:



[slide adapted from Thorne, Centrella]

3. gravitational wave sources



Some back of the envelope calculations:

- frequency of gravitational waves $$\boxed{\omega_{\rm GW} = 2\,\omega_{\rm orb}}$$

- last stable orbit $$r_{\rm LSO} = 6\,G\,M/c^2$$

- GW frequency at last stable orbit (=end of inspiral)

$$\omega_{\rm GW,\,LSO} = 2\sqrt{\frac{G\,M}{r_{LSO}^3}} = \frac{2\,c^3}{6^{3/2}\,(G\,M)}$$

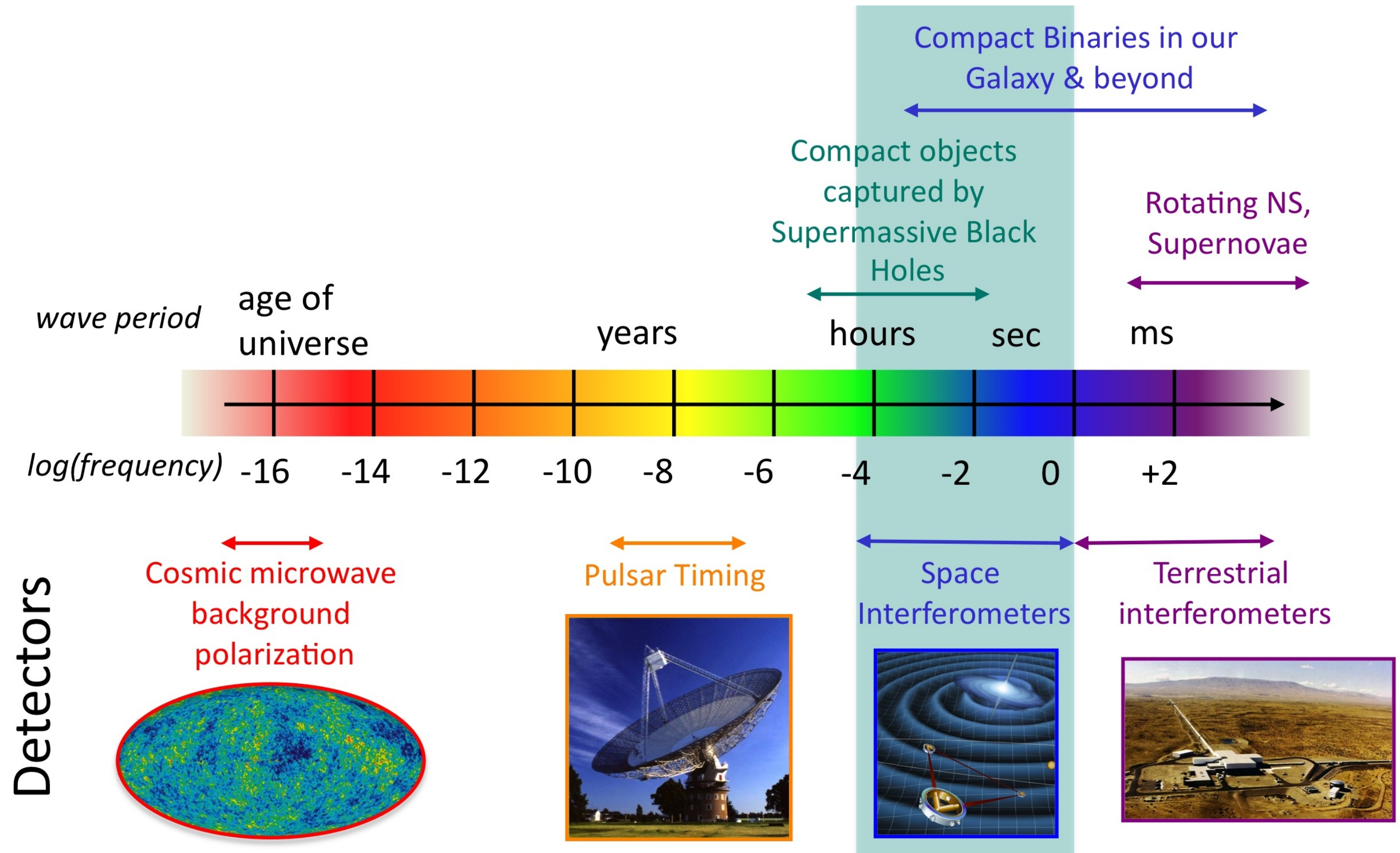
3. gravitational wave sources

Some back of the envelope calculations:

- GW frequency at last stable orbit (=end of inspiral)

$$\omega_{\mathrm{GW,\,LSO}} = 2\sqrt{\frac{G\,M}{r_{LSO}^3}} = \frac{2\,c^3}{6^{3/2}\,(G\,M)} \sim 2771\,\mathrm{s}^{-1}\,(10\,M_\odot/M)$$

$$\nu_{\mathrm{GW}} \sim 440\,\mathrm{Hz}\,(10\,M_\odot/M)$$



3. gravitational wave sources

Some more back of the envelope calculations:

- **amplitude**

From $$h^{ij}(t,\vec{x}) \sim \frac{2\,G}{r\,c^4}\frac{d^2}{dt^2} I^{ij}(t-r/c)$$

In the specific case of a binary, in spherical coordinates, for the inspiral

$$h_+ = \frac{1}{r}\left(\frac{4\,G\,\mu\,\omega_{\mathrm{orb}}^2\,a^2}{c^4}\right)\left(\frac{1+\cos^2\theta}{2}\right)\cos\left(2\,\omega_{\mathrm{orb}}\,t_{\mathrm{ret}}+\phi\right)$$

$$h_\times = \frac{1}{r}\left(\frac{4\,G\,\mu\,\omega_{\mathrm{orb}}^2\,a^2}{c^4}\right)\cos\theta\,\sin\left(2\,\omega_{\mathrm{orb}}\,t_{\mathrm{ret}}+\phi\right)$$

$$|h| = \frac{1}{2}\sqrt{h_+^2+h_\times^2} = \frac{1}{r}\left(\frac{2\,G\,\mu\,\omega_{\mathrm{orb}}^2\,a^2}{c^4}\right)\sqrt{\frac{(1+\cos^2\theta)^2}{4}+\cos^2\theta}$$

3. gravitational wave sources

Some more back of the envelope calculations:

- strain (same as amplitude)

$$h \sim 10^{-21} \left(\frac{m_{\rm chirp}}{M_\odot} \right)^{5/3} \left(\frac{P}{\rm hour} \right)^{-2/3} \left(\frac{r}{1\,\rm kpc} \right)^{-1}$$

- chirp mass

$$m_{\rm chirp} = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- coalescence timescale (Peters 1964)

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

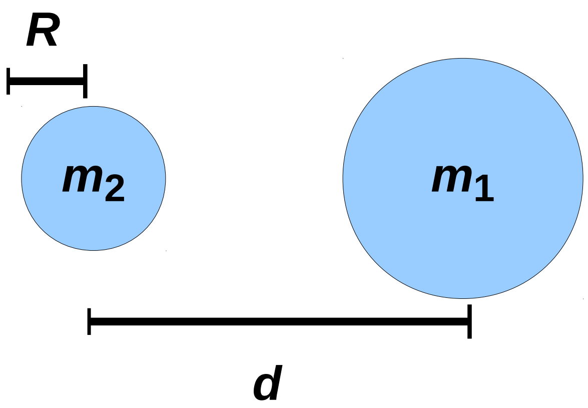
(to derive this timescale: GWs lead to energy loss → change in semi-major axis)

3. gravitational wave sources

WHY 'normal' stars in binaries are not sources of gravitational waves?

3. gravitational wave sources

WHY 'normal' stars in binaries are not sources of GWs?



Mind the definition of tidal radius

$$r_{\rm t} \sim d \left(\frac{m_2}{3\,m_1}\right)^{1/3}$$

If $R >= r_t$ the star is tidally disrupted

$$\omega_{\rm GW} = 2\,\omega_{\rm orb} = 2\left[\frac{G\,(m_1+m_2)}{d^3}\right]^{1/2} \sim 2\left[\frac{G\,(m_1+m_2)\,m_2}{3\,m_1\,r_t^3}\right]^{1/2}$$

If $r_t = R$ = 1 Rsun=6e10 cm, $m_1 = m_2$=1 Msun,
the maximum GW frequency that can be emitted by 2 sun-like stars (before tidal disruption) is

$$\omega_{\rm GW} \sim 3 \times 10^{-4}\,{\rm Hz}$$

MUCH LOWER THAN LIGO-VIRGO range!!!

4. how to estimate the merger rate (and detection rate)

FROM OBSERVATIONS

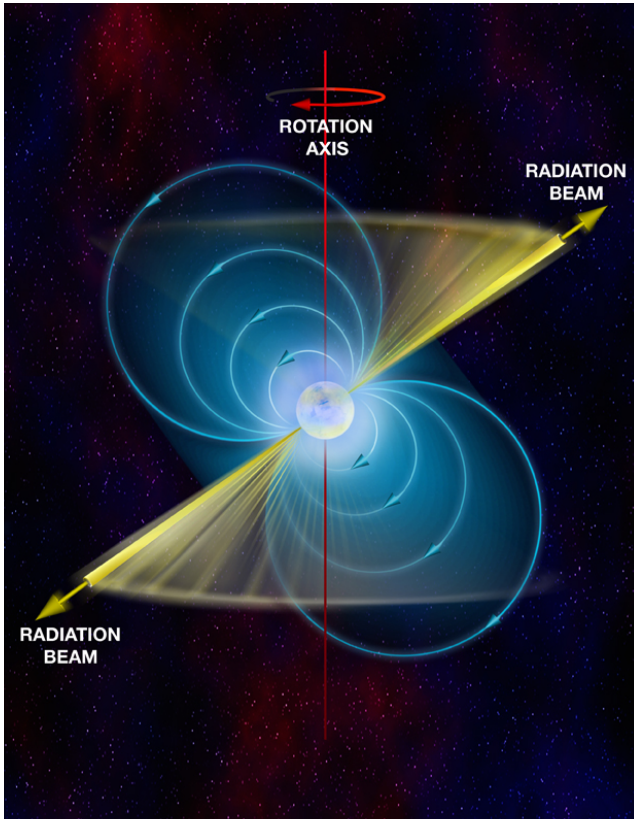
observable	NS-NS merger	BH-NS merger	BH-BH merger
1- number of observed NS-NS	YES	NO	NO
2- short gamma-ray burst rate	YES	MAYBE	NO
3- number of observed BH-WR	NO	MAYBE	YES

4. how to estimate the merger rate (and detection rate)

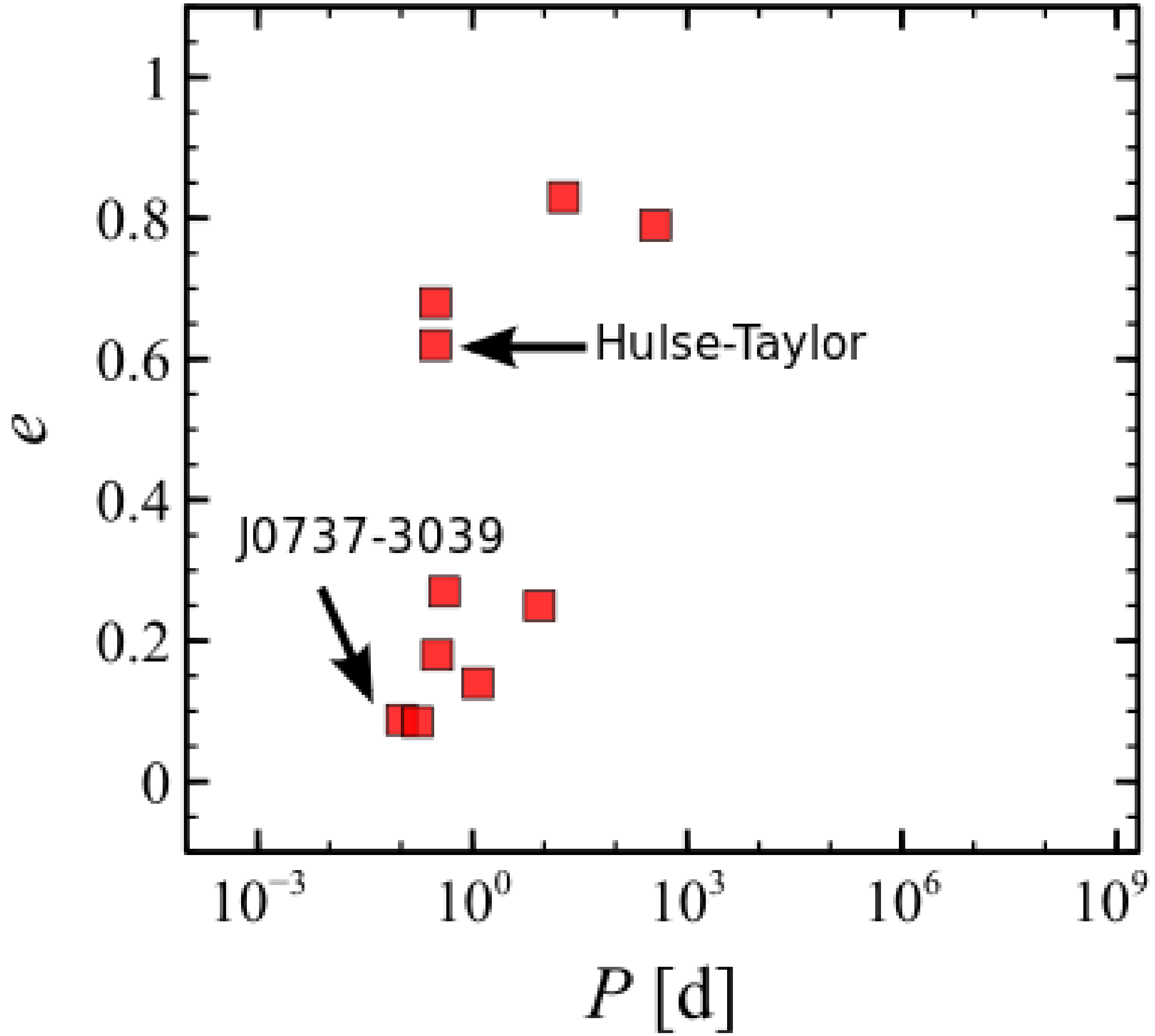
From observations

1- number of observed NS NS binaries:

D. R. Lorimer 2008,
Binary and Millisecond Pulsars,
arxiv.org/pdf/0811.0762v1.pdf



CREDIT: Bill Saxton, NRAO/AUI/NSF



From Ziosi, PhD thesis

4. how to estimate the merger rate (and detection rate)

From observations

1- number of observed NS-NS binaries:

1. take properties of observed NS-NS (semi-major axis, mass, eccentr.)
2. estimate GW merger timescale t_{GW} for each of them
3. sum 1/ t_{GW} over all NS NS binaries in Milky Way (MW)
4. normalize to MW star formation rate (SFR_{MW}~0.25 Msun yr^{-1}) and multiply by density of star formation rate in the local Universe (ρ_{SFR}~0.015 Msun yr^{-1} Mpc^{-3}, Hopkins & Beacom 2006)
5. multiply by instrumental horizon of Adv LIGO/Virgo for NS-NS
   $V \sim 4/3\, \pi\, L^3$ (with L=200 Mpc)

YOU GET THE DETECTION RATE:

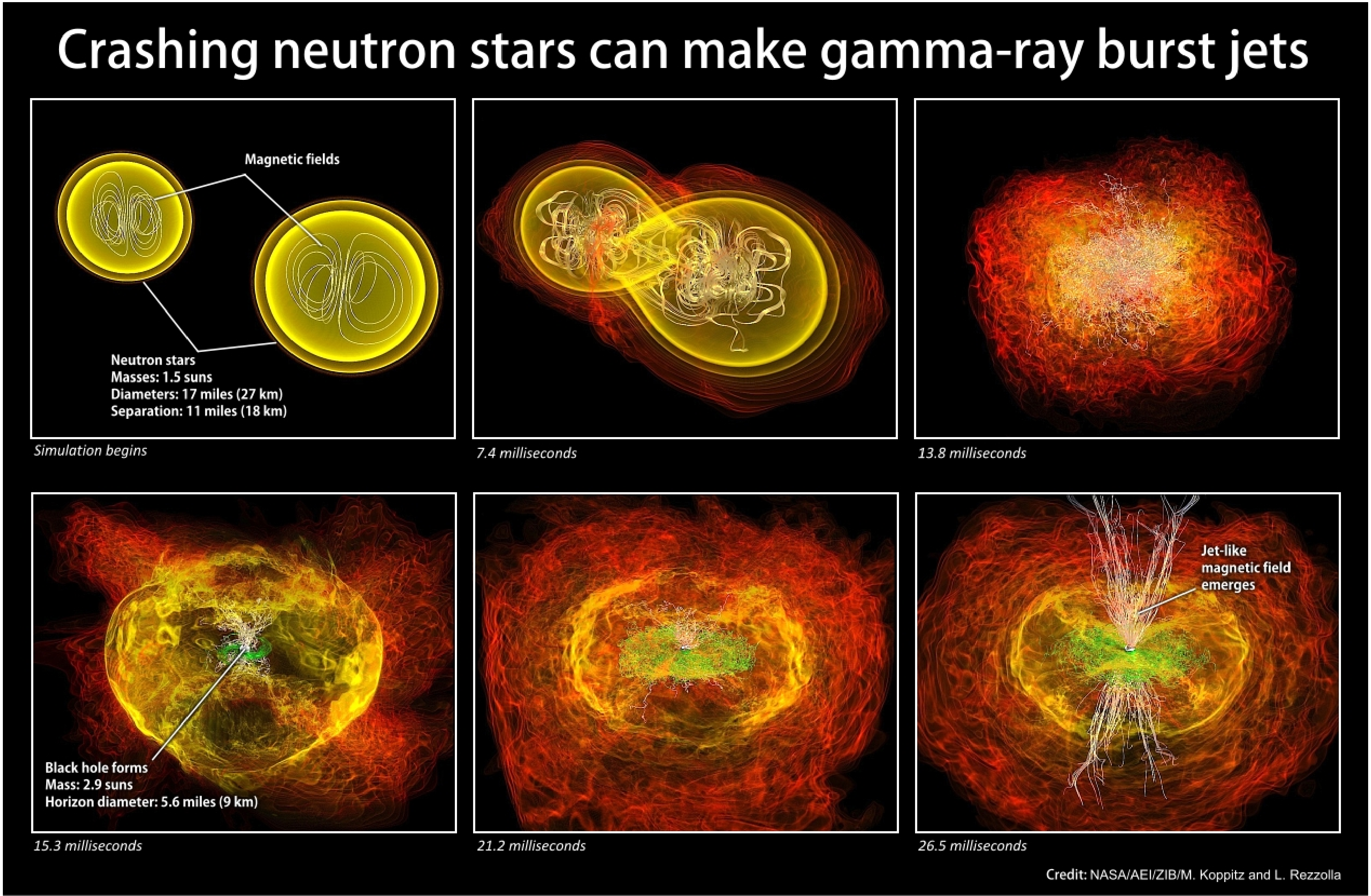
$$R = \sum_i \frac{1}{t_{\rm GW,\,i}}\,\frac{\rho_{\rm SFR}}{\rm SFR_{MW}}\,\frac{4}{3}\,\pi L^3$$

THERE ARE SEVERAL PROCEDURES SIMILAR TO THIS ONE!!!

4. how to estimate the merger rate (and detection rate)

From observations

2- short gamma ray burst rate



4. how to estimate the merger rate (and detection rate)

From observations

2- short gamma ray burst rate

gamma ray burst <2 s thought to be produced by NS-NS or NS-BH merger

1. take observed short gamma-ray burst rate $R_{\rm GRB}$

2. correct for beaming (we see only short γ-ray bursts pointing toward us)

$\sim(1 - \cos\theta)^{-1}$

3. multiply by instrumental horizon of Adv LIGO/Virgo for NS-NS

V~ 4/3 π L^3 (with L=200 Mpc)

YOU GET THE DETECTION RATE:

$$R = R_{\rm GRB}\,(1-\cos\theta)^{-1}\,\frac{4}{3}\,\pi L^3$$

EASY BUT ASSUMPTION that gamma-ray burst means merger

(e.g. Coward+2012; Siellez+ 2014)

4. how to estimate the merger rate (and detection rate)

From observations

3- BH-WR binaries:

WR stars are naked Helium stars that will end as BH or NS
→ BH-WR are precursor of BH-BH (or possibly BH-NS)

The Galactic WR star WR124 and its nebula

Cartoon of a BH-WR

4. how to estimate the merger rate (and detection rate)

From observations

3- BH-WR binaries:

WR stars are naked Helium stars that will end as BH or NS
→ BH-WR are precursor of BH-BH (or possibly BH-NS)

Calculation similar to NS-NS binaries:

1. take properties of observed BH-WR (semi-major axis, mass, eccentr.)
2. estimate GW merger timescale $t_{GW,i}$ for each of them
3. normalize to star formation rate of their host galaxy (SFR_i)
3. sum $1/(SFR_i\, t_{GW,i})$ over all BH-WR in local Universe
4. multiply by density of star formation rate in the local Universe (ρ_{SFR}~0.015 Msun yr^{-1} Mpc^{-3}, Hopkins & Beacom 2006)
5. multiply by instrumental horizon of Adv LIGO/Virgo for BH-BH $V \sim 4/3\, \pi\, L^3$ (with L=1 Gpc)

$$R = \sum_i \frac{1}{t_{\rm GW,\,i}\,{\rm SFR}_i}\,\rho_{\rm SFR}\,\frac{4}{3}\,\pi L^3$$

4. how to estimate the merger rate (and detection rate)

From theory

Method	NS-NS merger	BH-NS merger	BH-BH merger
1- population synthesis simulations	YES	YES	YES
2- dynamical simulations (Monte Carlo or N-body)	YES	YES	YES

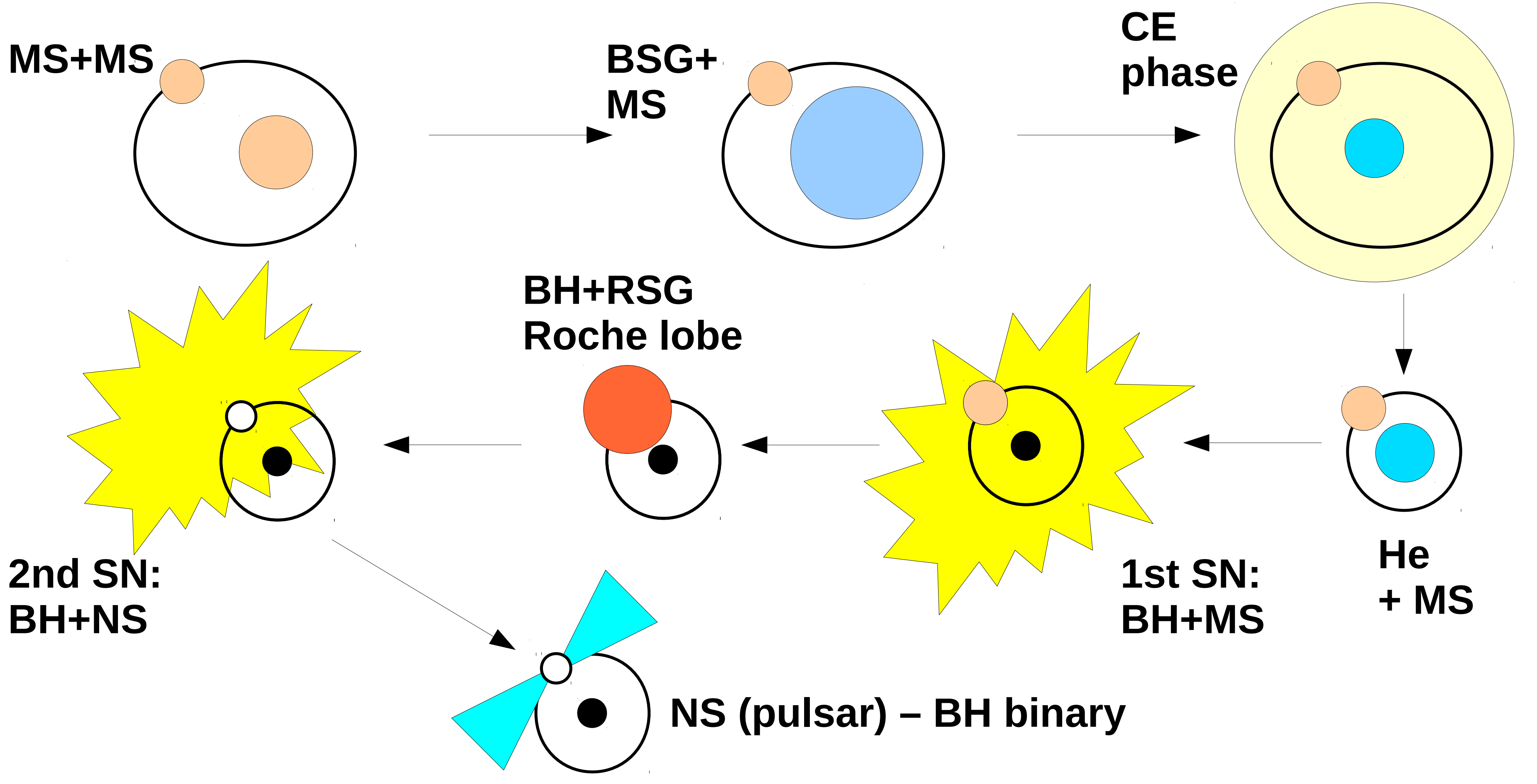
Theory seems better than observations, but........

4. how to estimate the merger rate (and detection rate)

From theory

1- population synthesis simulations

Codes that evolve a binary of massive stars (stellar evolution + orbital evolution) until it forms a NS-NS or NS-BH or BH-BH



4. how to estimate the merger rate (and detection rate)

From theory

1- population synthesis simulations

Codes that evolve a binary of massive stars (stellar evolution + orbital evolution) until it forms a NS-NS or NS-BH or BH-BH

1. **simulate a large grid of ISOLATED binaries (e.g. equal to total stellar mass of the Milky Way)**

2. **extract the number of mergers of NS-NS, NS-BH or BH-BH in the simulations in a Hubble time:**
   this gives the merger rate of the Milky Way

3. **either normalize to the SFR of the MW and multiply by the SFR density (see description about NS-NS observations)**
   or normalize to the MW mass and multiply by the mass density of galaxies in the local Universe

4. **multiply by instrumental horizon of Adv LIGO/Virgo for NS-NS, NS-BH, BH-BH**

4. how to estimate the merger rate (and detection rate)

From theory

2- dynamical simulations (Monte Carlo or N-body)

WHY DYNAMICS????????

5. impact of environment on merger rate

WHY DYNAMICS???????

COLLISIONAL/COLLISIONLESS

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

When is a stellar system collisional/collisionless?

RELAXATION TIMESCALE

Gravity is a LONG-RANGE force

→ 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

5. impact of environment on merger rate

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:

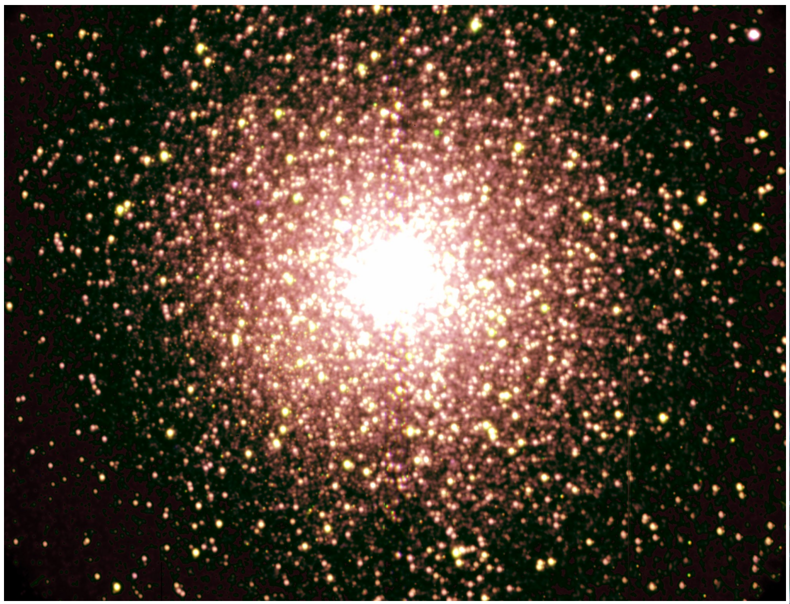
$$t_{\rm rlx} = 10\,{\rm Myr}\,\left(\frac{M_{\rm TOT}}{3500\,{\rm M}_\odot}\right)^{1/2}\,\left(\frac{r_{\rm hm}}{1\,{\rm pc}}\right)^{3/2}$$

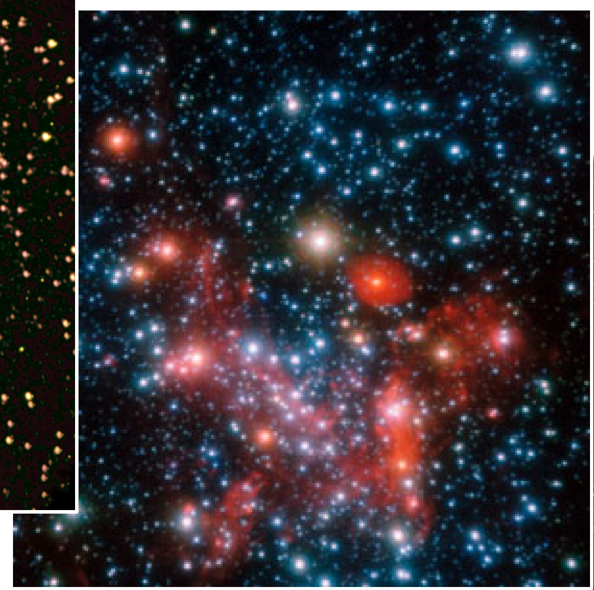
5. impact of environment on merger rate

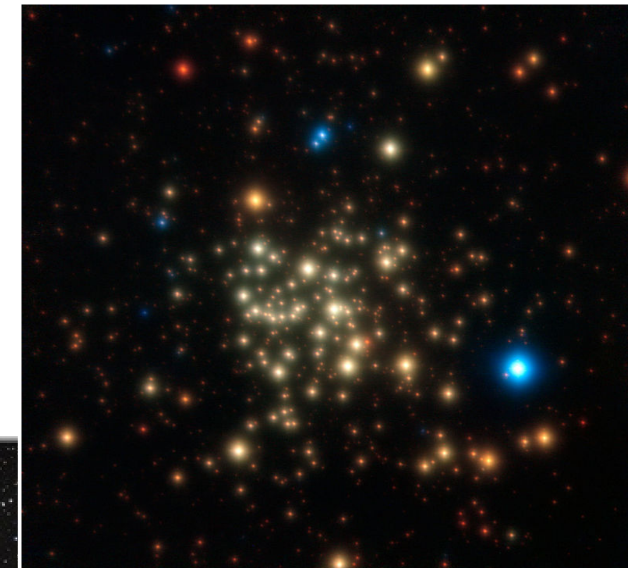
*** globular clusters, dense young star clusters, nuclear star clusters**

R~1-10 pc, N~10^{3-7} stars, v~1-10 km/s

→ **t_{rlx}~10^{7-10} yr** → **COLLISIONAL**







*** galaxy field/discs**

R~10 kpc, N~10^{10} stars, v~100-500 km/s

→ **t_{rlx} >> Hubble time** → **COLLISIONLESS**

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.

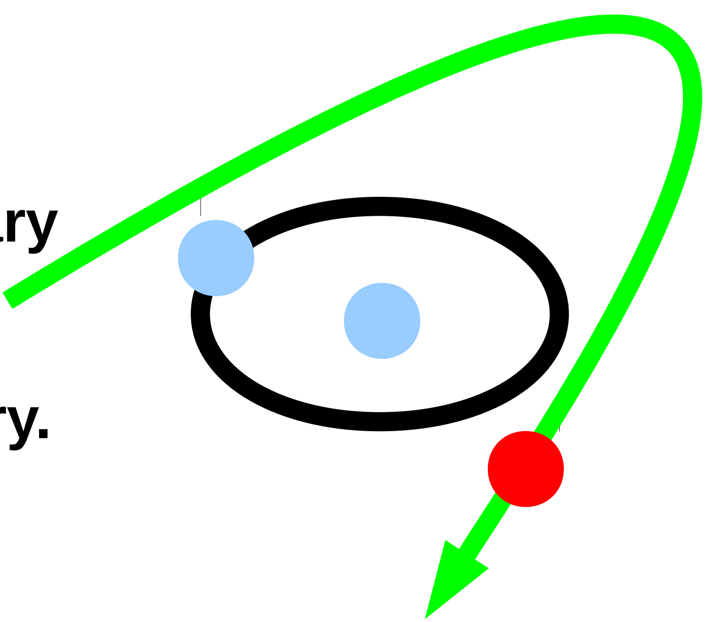
THE ENERGY RESERVOIR of BINARIES can be EXCHANGED with stars:

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

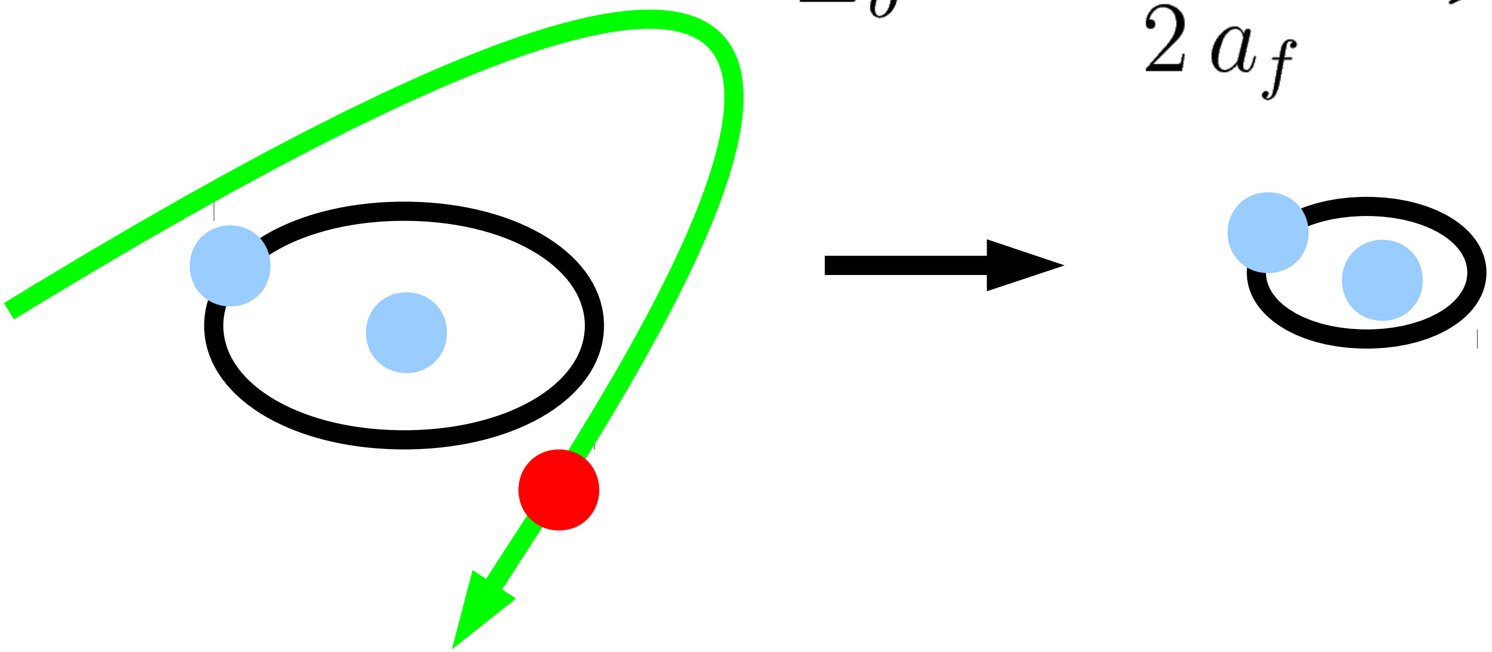
If the star extracts E_{int} from the binary,

1) final kinetic energy of star > initial kinetic energy.
STAR and BINARY acquire RECOIL VELOCITY

2) E_{int} becomes more negative, i.e. E_b higher:
the binary becomes more bound.

$a_f < a_i$

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



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

BINARIES as ENERGY RESERVOIR

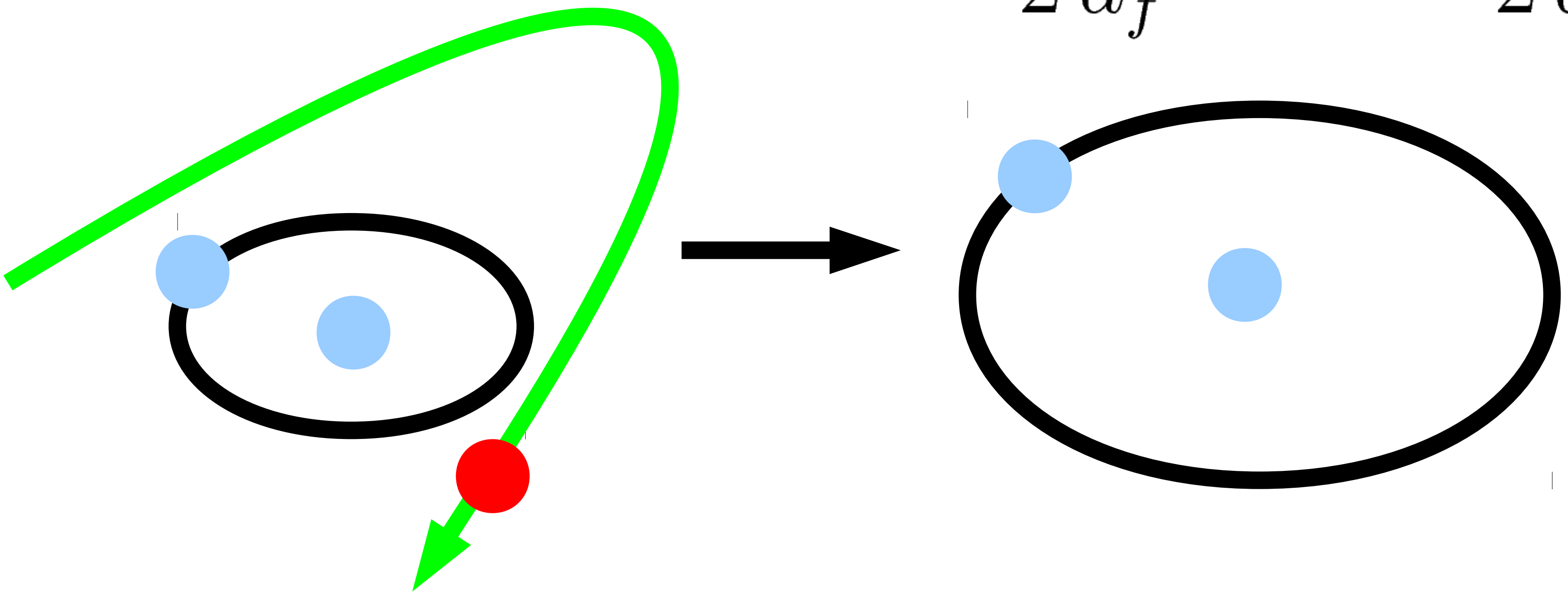
If the star transfer kinetic energy to the binary,

1) final kinetic energy of star < initial kinetic energy.

2) E_{int} becomes less negative, i.e. E_b smaller:
the binary becomes less bound
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 $a_f > a_i$ → E_b decreases

BINARIES as ENERGY RESERVOIR

Alternative way for a binary to transfer internal energy to field stars:

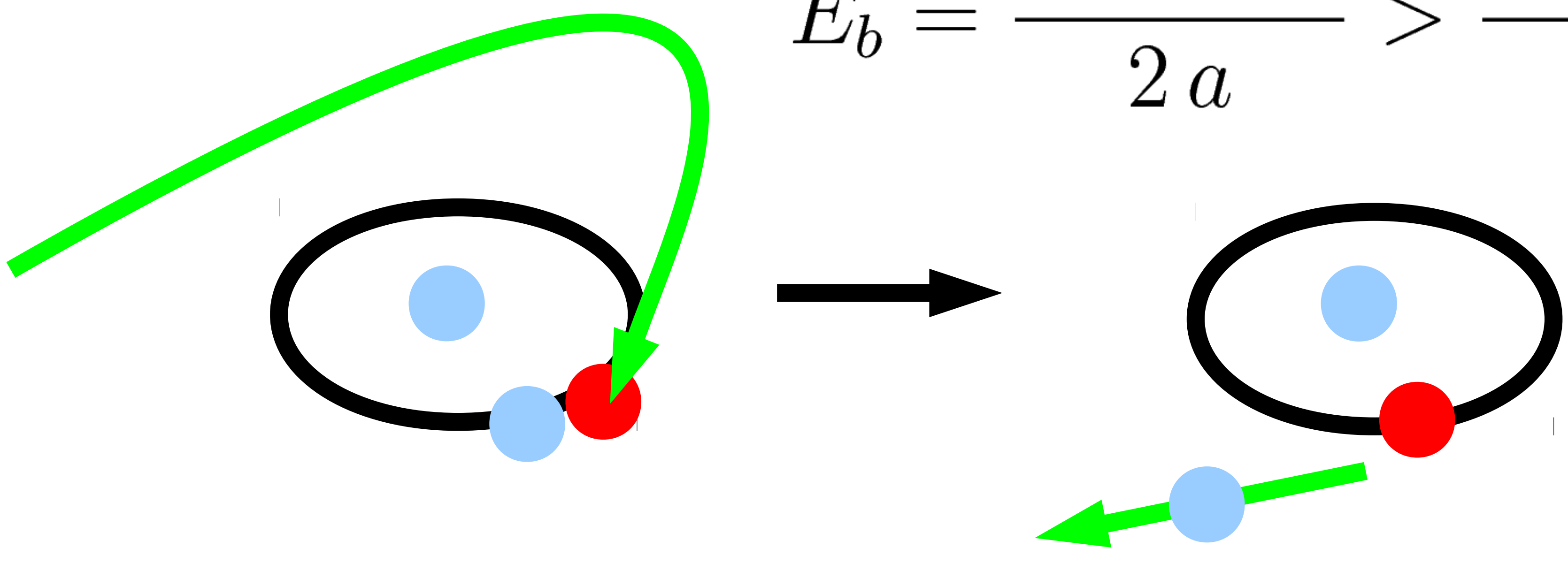
EXCHANGE

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:

$m_3 > m_2$

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

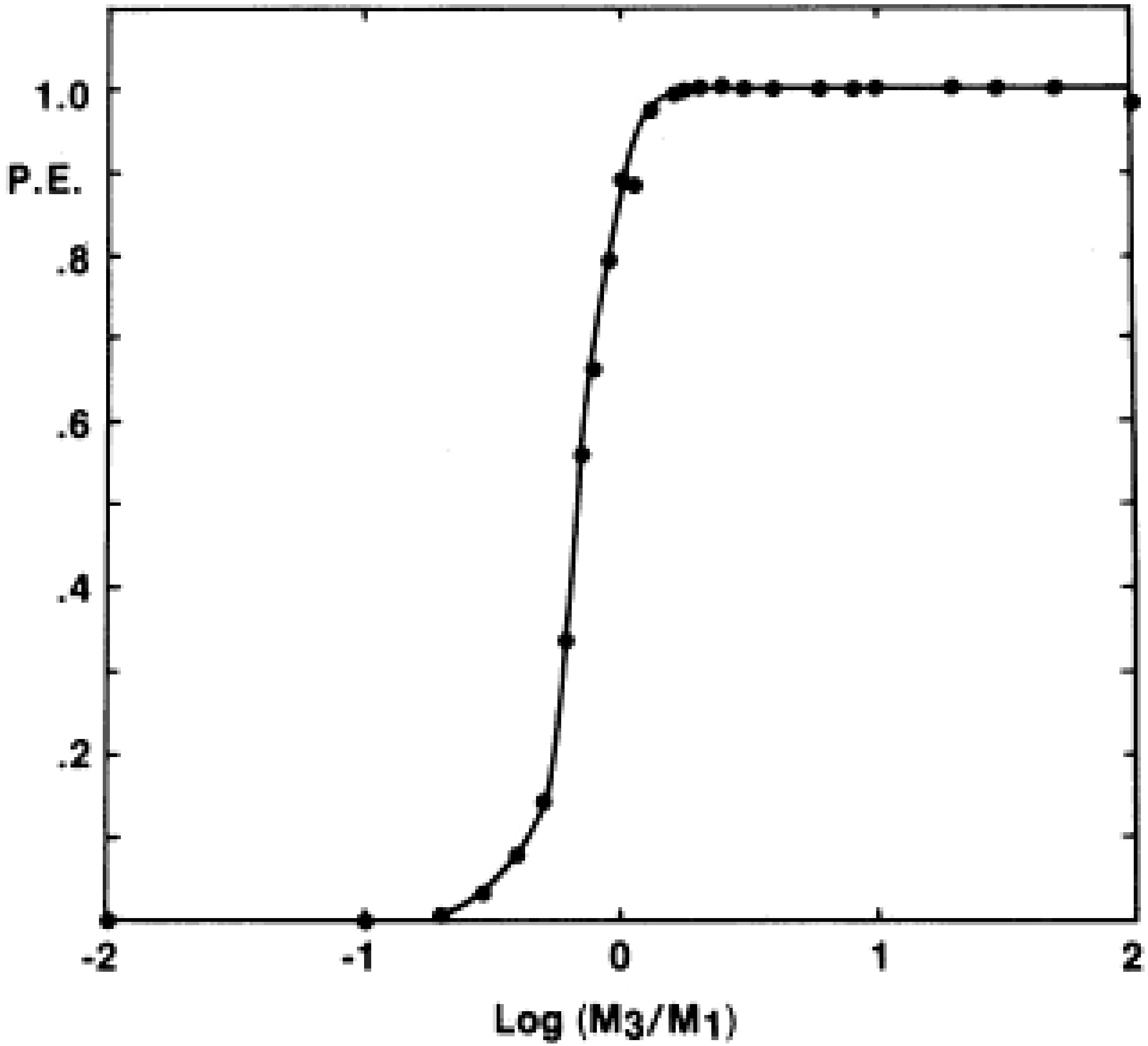


CARTOON of a EXCHANGE ENCOUNTER where $m_3 > m_2 \rightarrow$ E_b increases

EXCHANGE PROBABILITY

Probability increases dramatically if $m_3 \geq m_1$

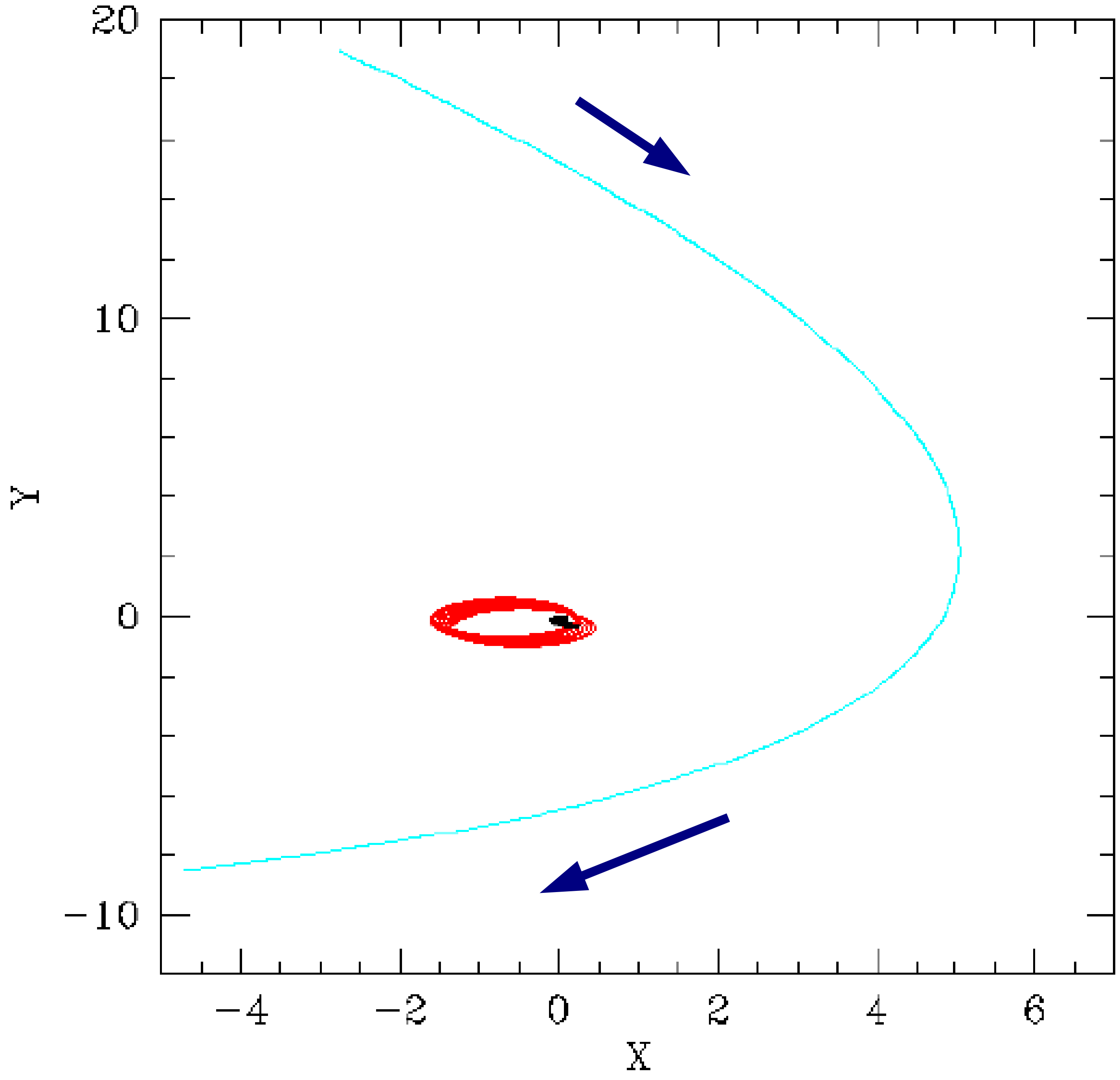
EXCHANGES TEND TO BUILD MORE AND MORE MASSIVE BINARIES!!!



Hills & Fullerton 1980, AJ, 85, 1281

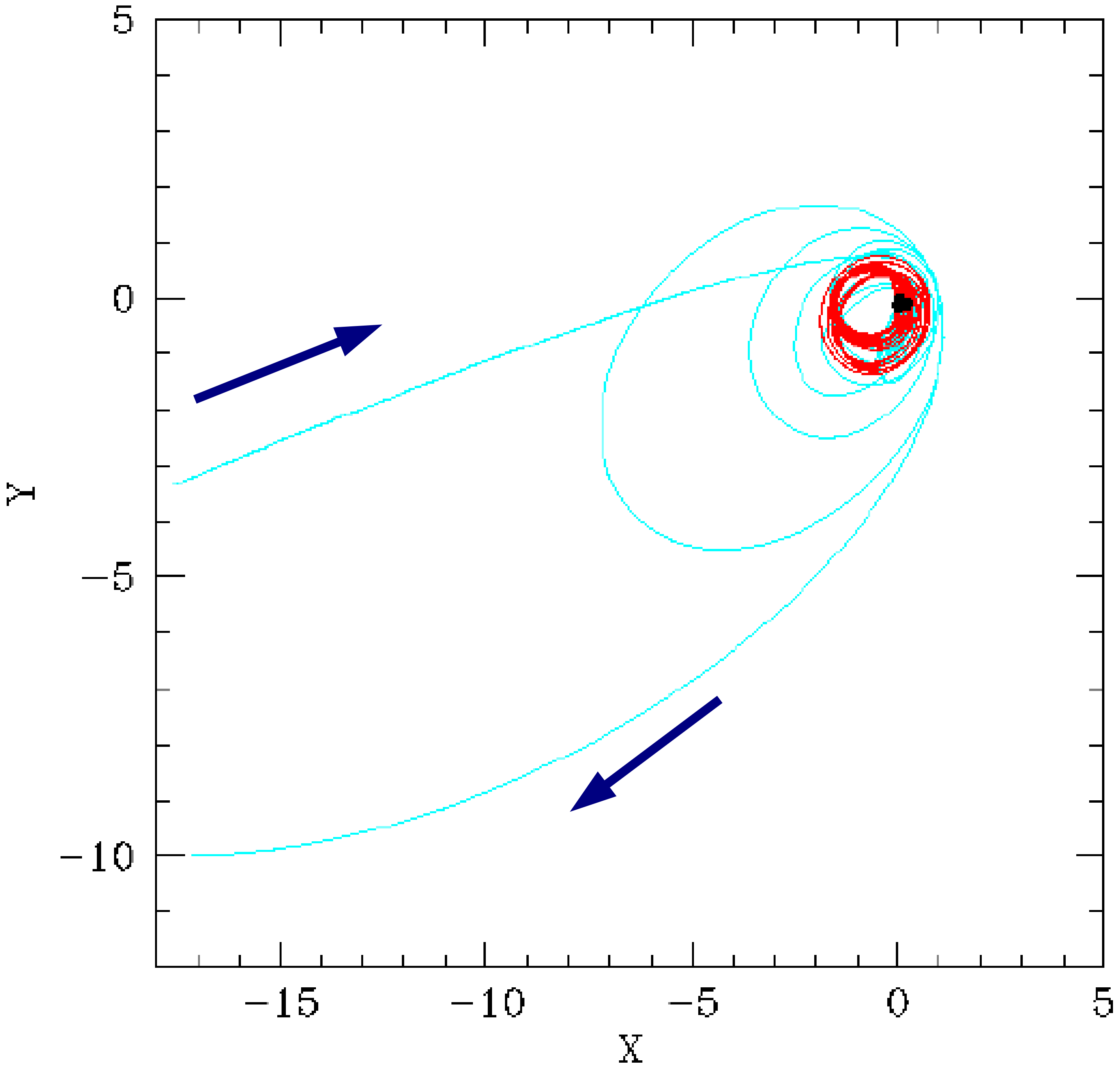
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT
FLYBY:



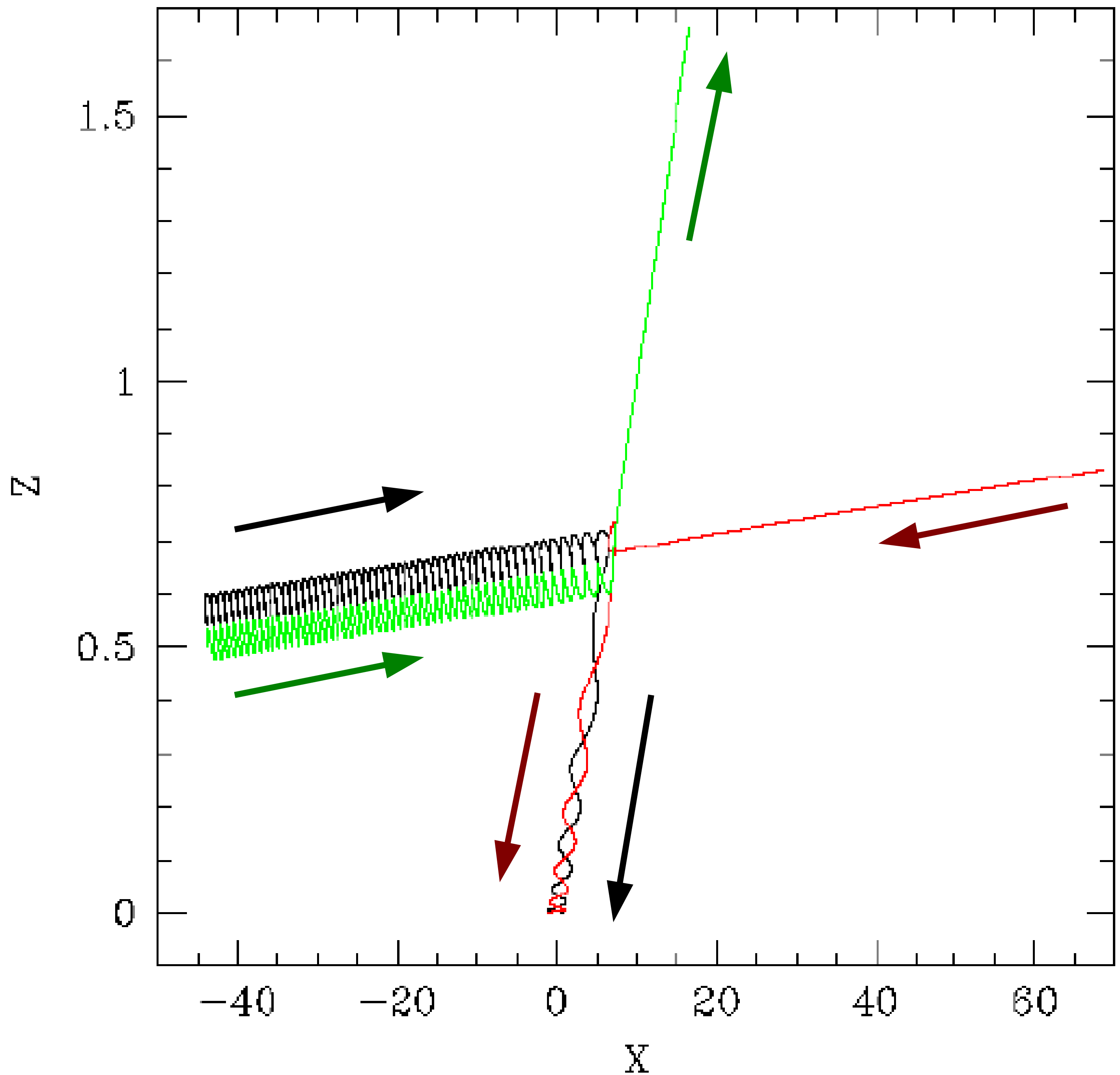
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT
FLYBY:



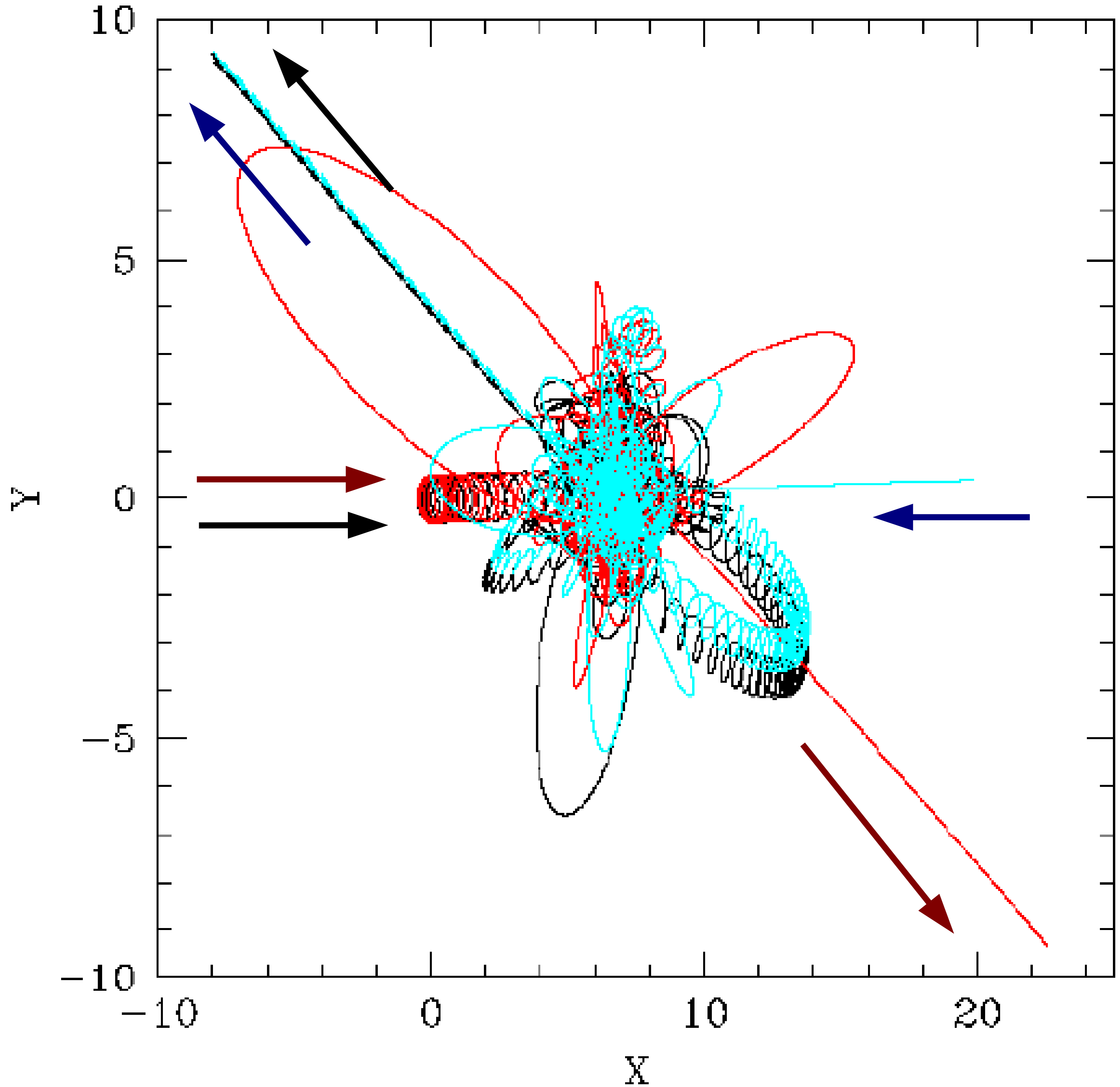
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT
EXCHANGE:



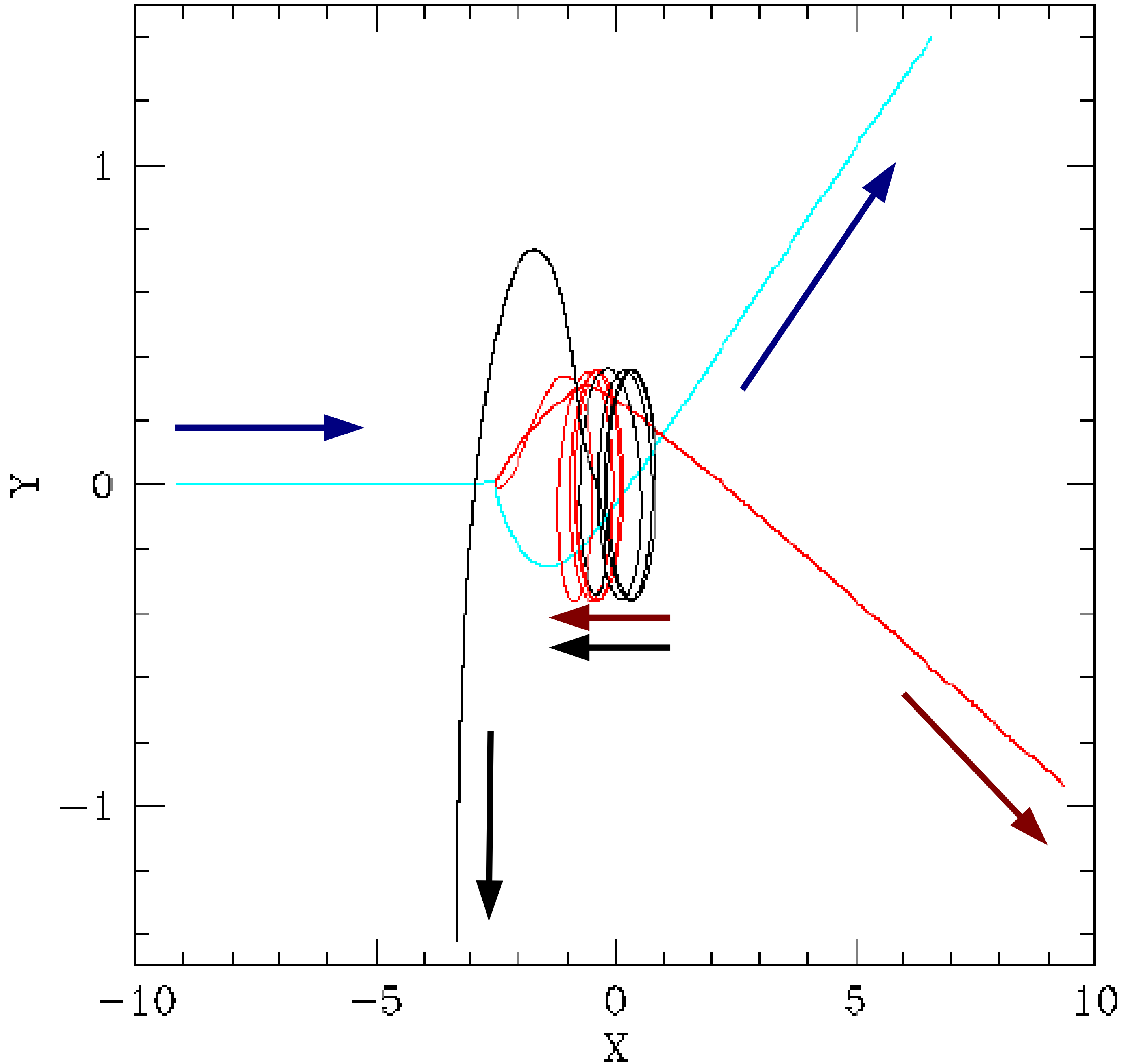
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT
EXCHANGE:



EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

IONIZATION:



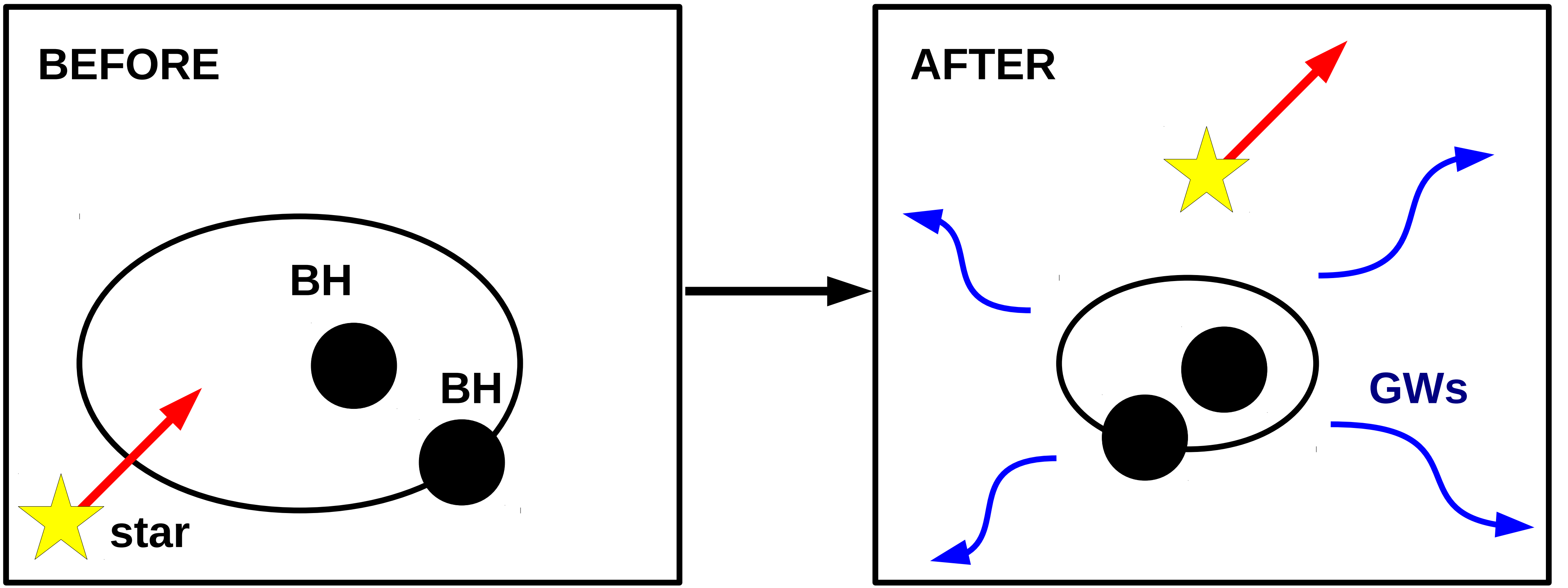
IMPORTANT INFORMATION to understand importance of 3-body encounters for GRAVITATIONAL WAVES

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

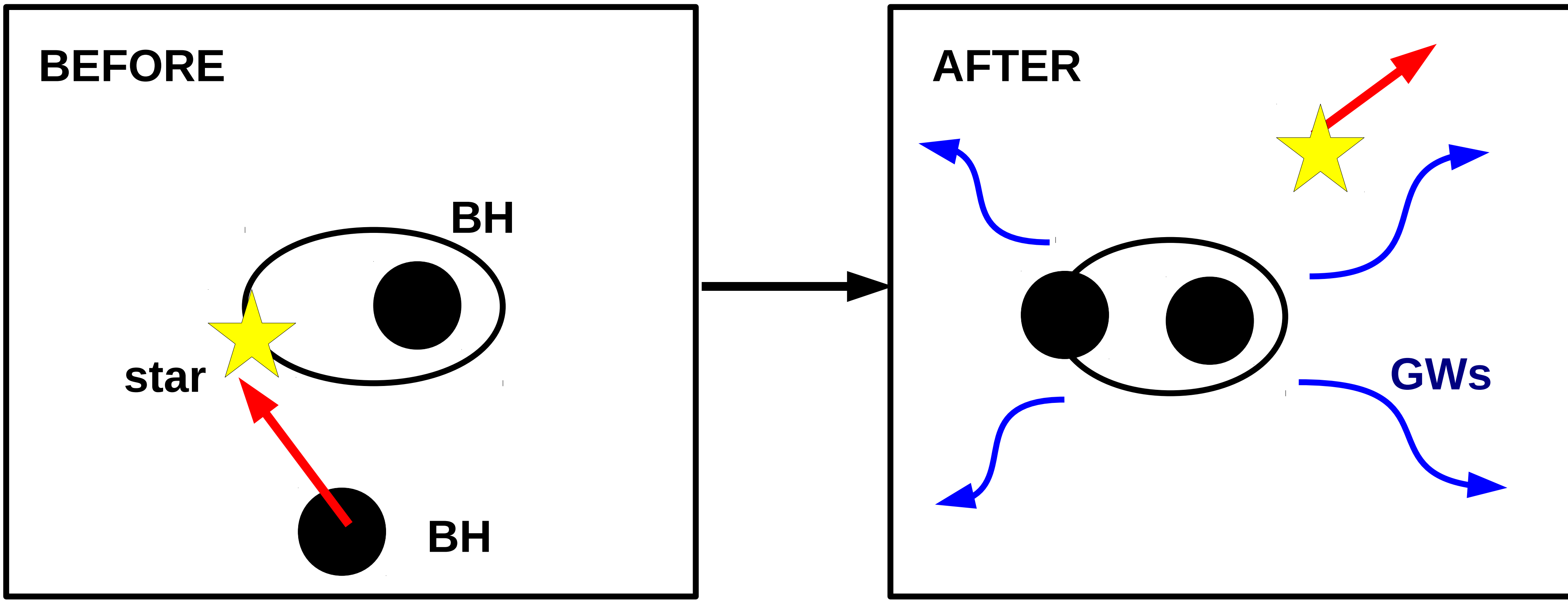
3→ If star extracts E_{int} from the binary, the binary and the star RECOIL: may be ejected from the SC

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



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

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

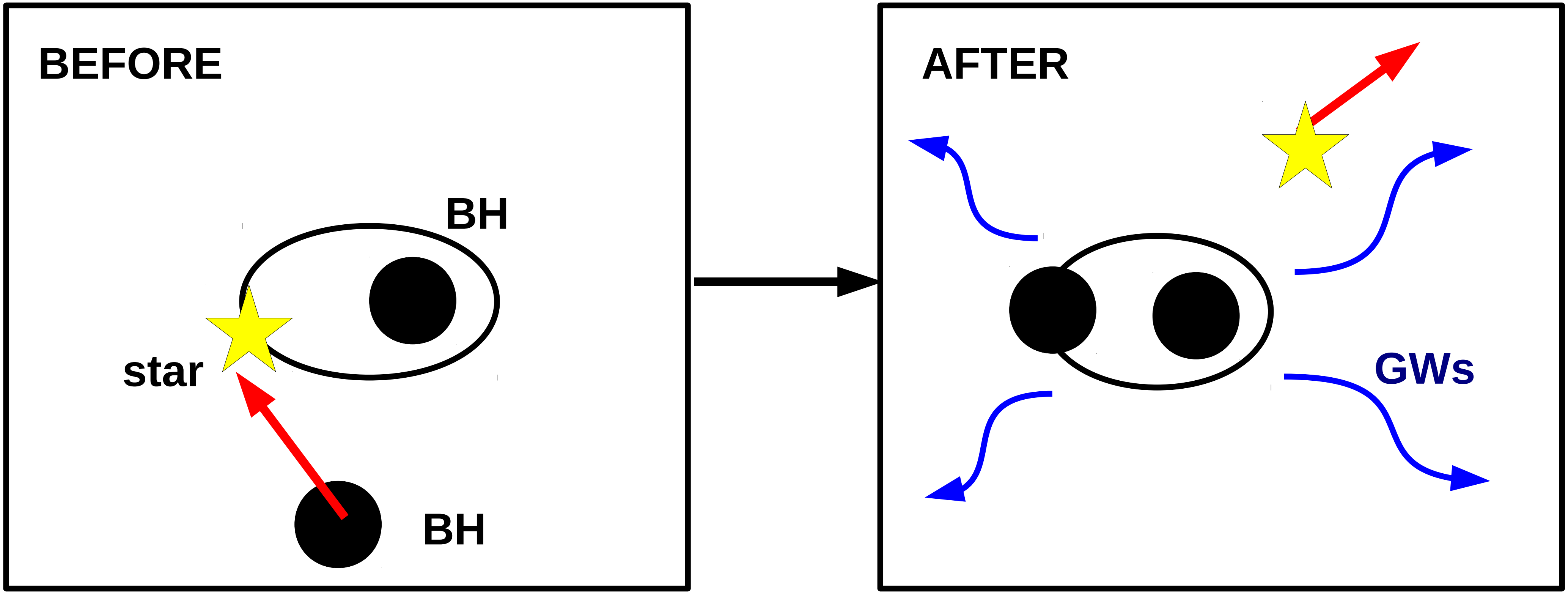


Exchanges are very important: bring BHs in binaries

BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!

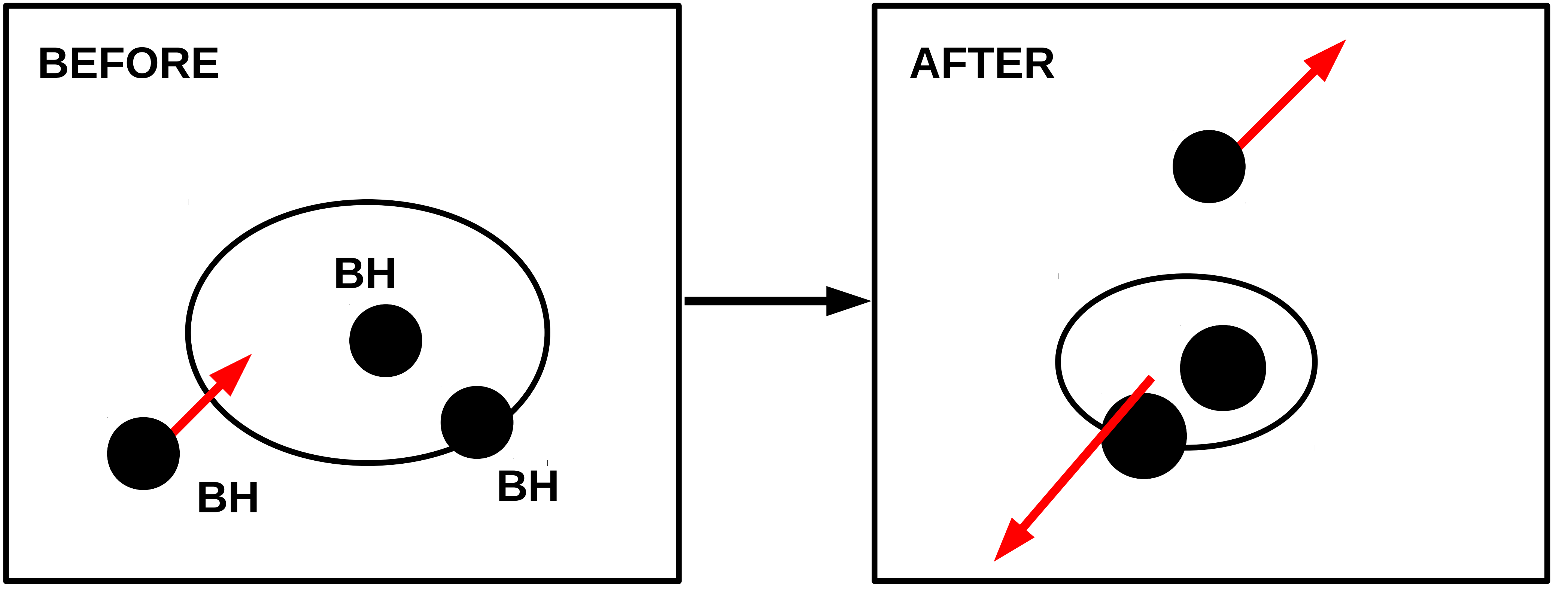
BH BORN FROM SINGLE STAR IN THE FIELD NEVER ACQUIRES A COMPANION
BH BORN FROM SINGLE STAR IN A SC LIKELY ACQUIRES COMPANION FROM DYNAMICS

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



EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH THE MOST MASSIVE BHs !!

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



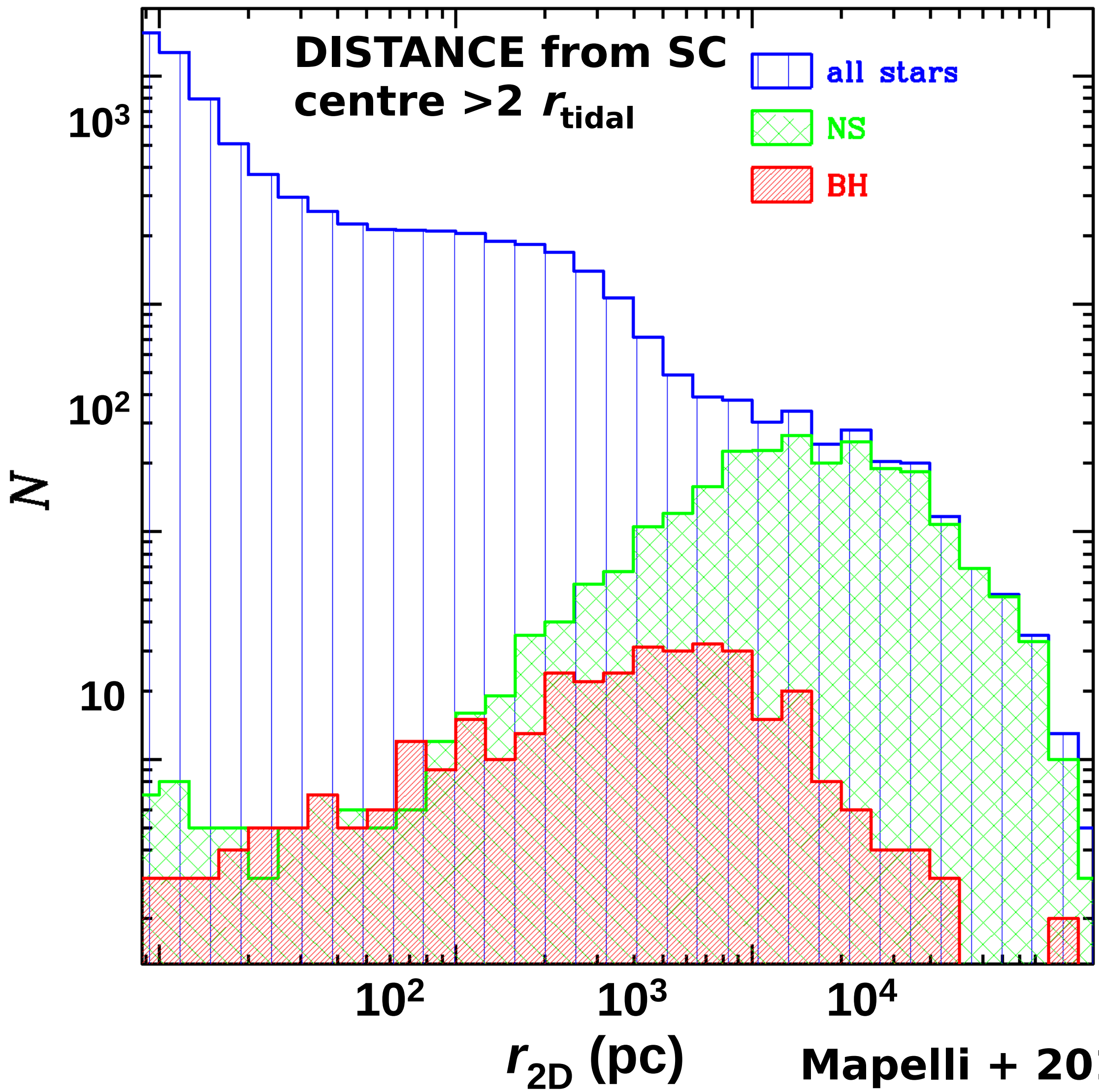
Internal energy is extracted from the binary

→ **converted into KINETIC ENERGY of the INTRUDER AND of the CM of the BINARY**

→ **BOTH RECOIL and can be ejected from SC**

Star clusters lose large fraction of mass by

1. **high-speed EJECTIONS (caused by SN kick and 3-body, enhanced by Spitzer instability)**
2. **low-speed evaporation (less bound stars leave the star cluster)**
3. **tidal fields**



Mapelli + 2013

Simulation of young SC @ 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 after young SC death by disruption!

WE EXPECT THAT

GLOBULAR CLUSTERS:

- dynamics enhances formation of BH-BH binaries (with respect to NS-NS)
- some (?) BH-BH and NS-NS are ejected due to SN kicks and/or 3-body encounters

YOUNG STAR CLUSTERS AND OPEN CLUSTERS:

- dynamics enhances formation of BH-BH binaries (with respect to NS-NS)
- MOST (all?) BH-BH and NS-NS are ejected due to SN kicks, 3-body encounters and evaporation

FIELD:

- more NS-NS than BH-BH because no dynamics

DOES THIS AGREE with MODELS/SIMULATIONS OF MERGER RATE?

HOW DO WE MODEL/SIMULATE THIS?

STAR CLUSTERS:

1. MONTE CARLO simulations (dynamics only or coupled with stellar and binary evolution)

PROS:
- very fast treatment of dynamics (N logN)
- large number of objects

CONS:
- assume equilibrium and spherical symmetry

→ GLOBULAR CLUSTERS

2. DIRECT N-BODY simulations (dynamics only or coupled with stellar and binary evolution)

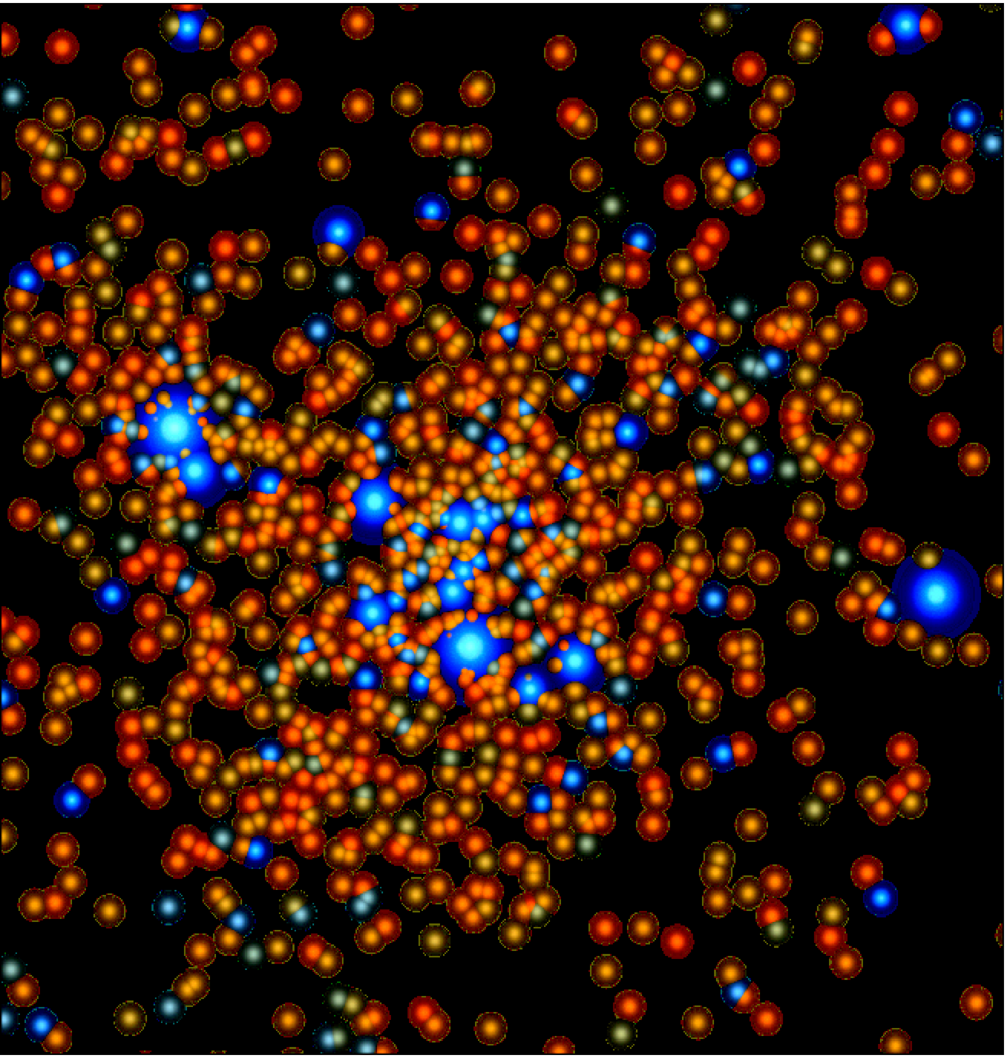
PROS:
- very accurate treatment of dynamics
- each particle is a single star with physical mass, radius
- no necessary assume equilibrium and symmetry

CONS:
- slow (N^2, but GRAPHICS PROCESSING UNITS)

→ YOUNG STAR CLUSTERS

HOW DO WE MODEL/SIMULATE THIS?

STAR CLUSTERS:



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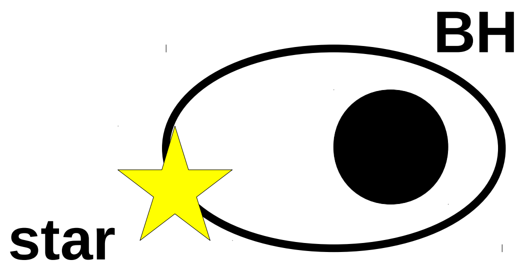
→ YOUNG STAR CLUSTERS

HOW DO WE MODEL/SIMULATE THIS?



FIELD BINARIES:

Population synthesis models, i.e. stellar and binary evolution of isolated binaries

PROS:
fast → large statistical sample

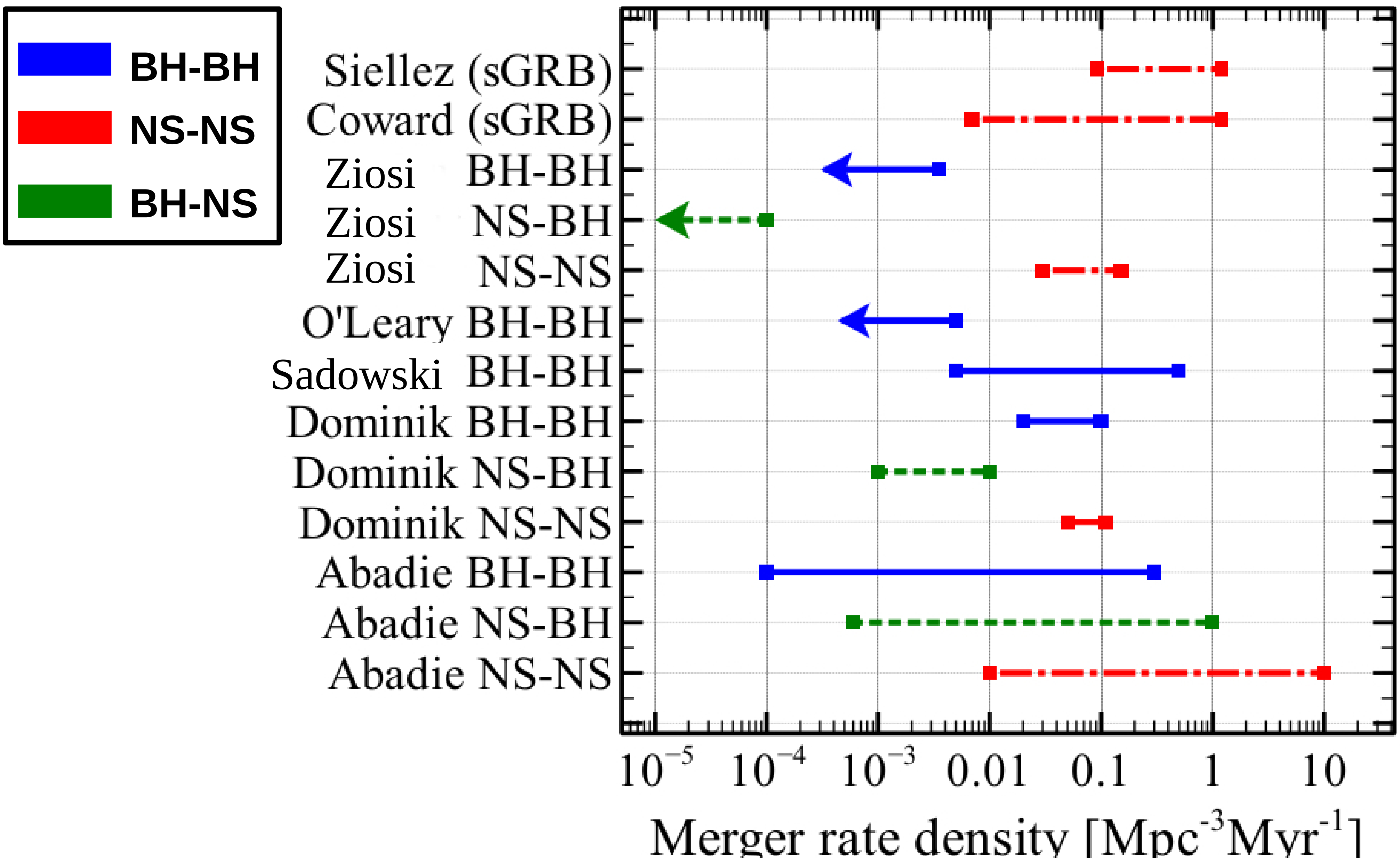
CONS:
NO dynamics, while we know that stars form in clusters

SOMETIMES COMPLEMENTED BY (or TUNED on the basis of) THE EMPIRICAL APPROACH (see Andrea Possenti's talk):

extrapolation of NS-NS merger rate from observed NS-NS binaries and/or from short gamma-ray burst rate

5. impact of environment on merger rate

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



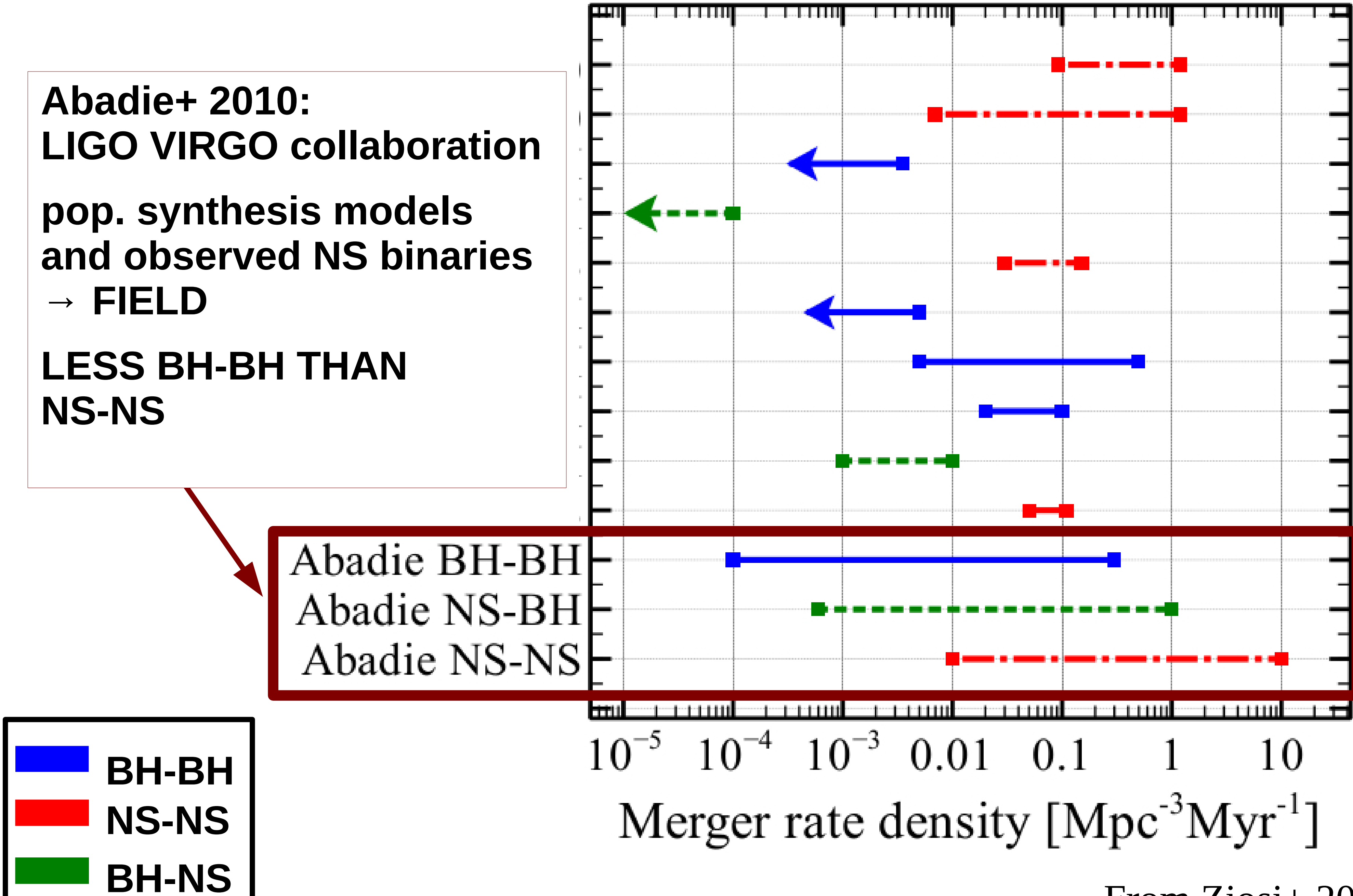
From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:

Abadie+ 2010:
LIGO VIRGO collaboration

pop. synthesis models and observed NS binaries → FIELD

LESS BH-BH THAN NS-NS



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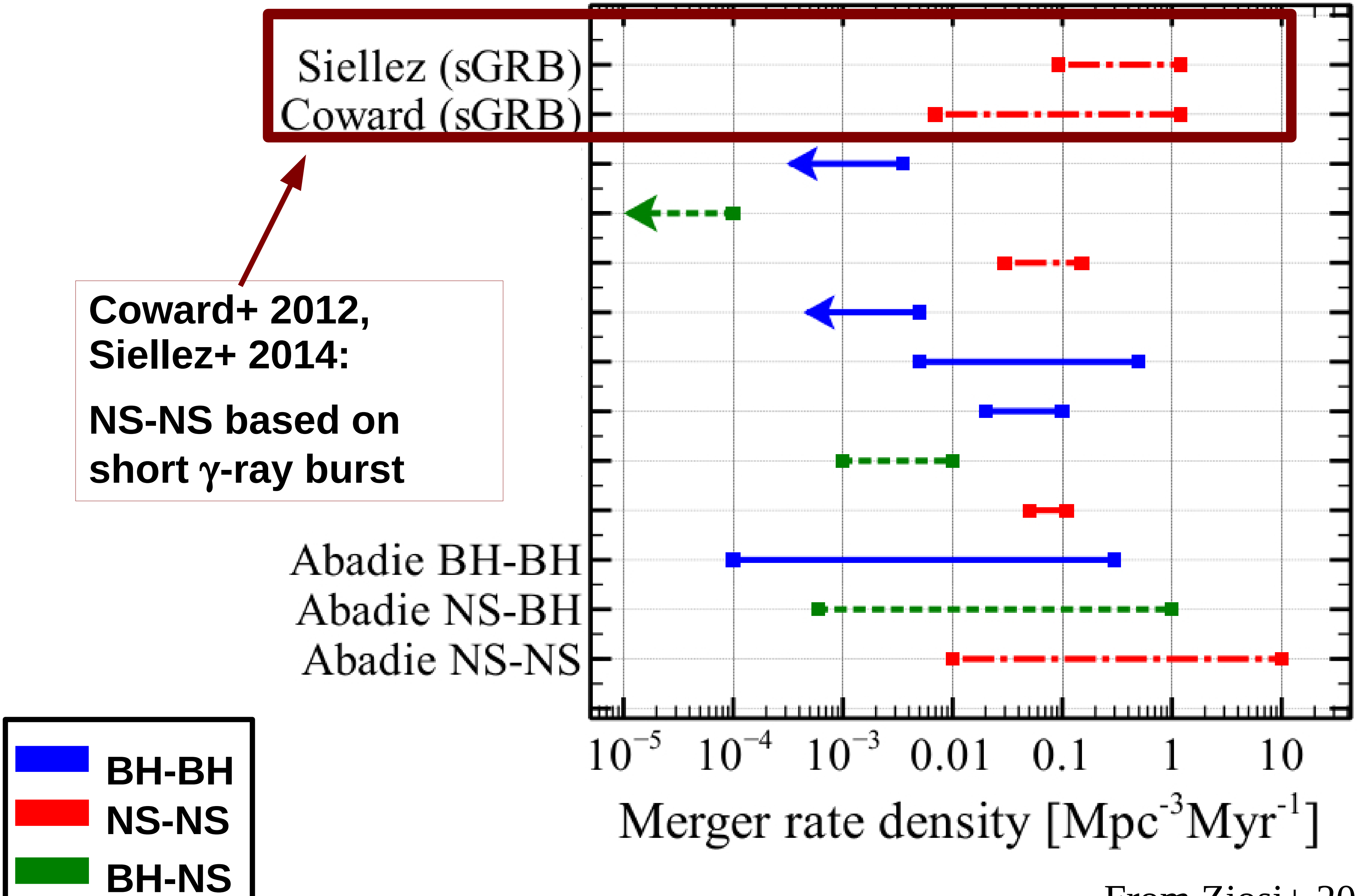
Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



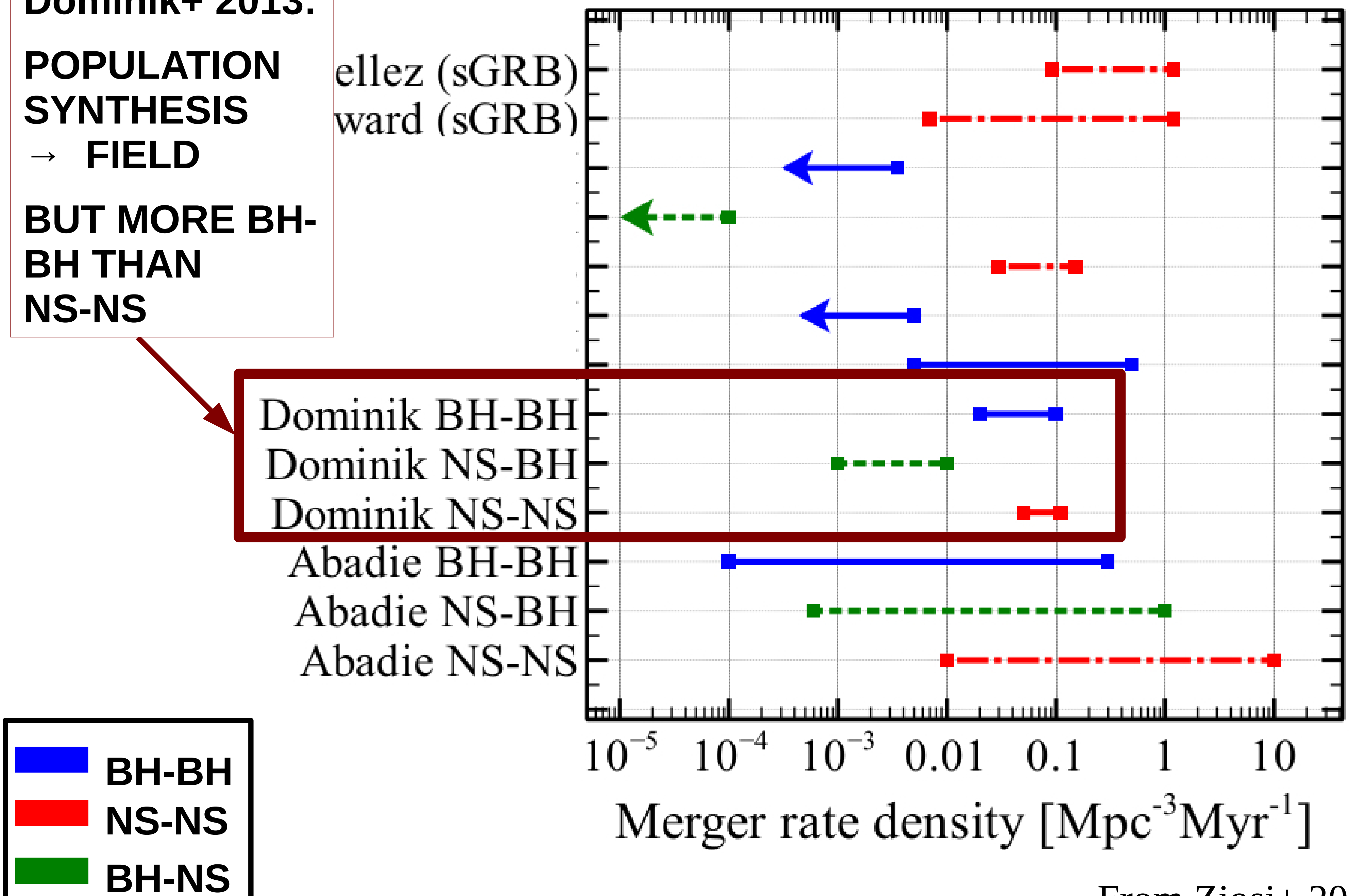
From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:

Dominik+ 2013:

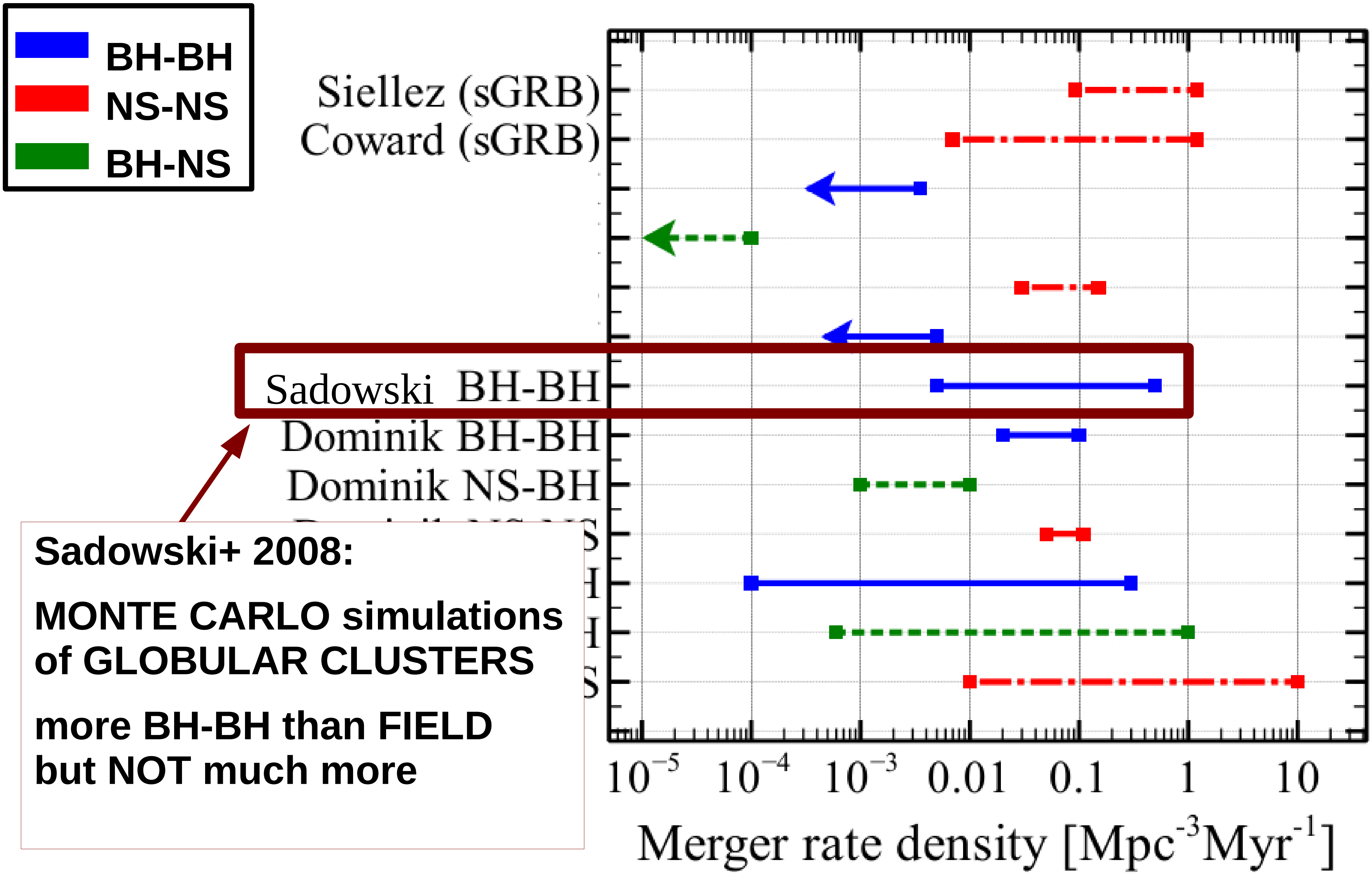
POPULATION SYNTHESIS → FIELD

BUT MORE BH-BH THAN NS-NS



From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



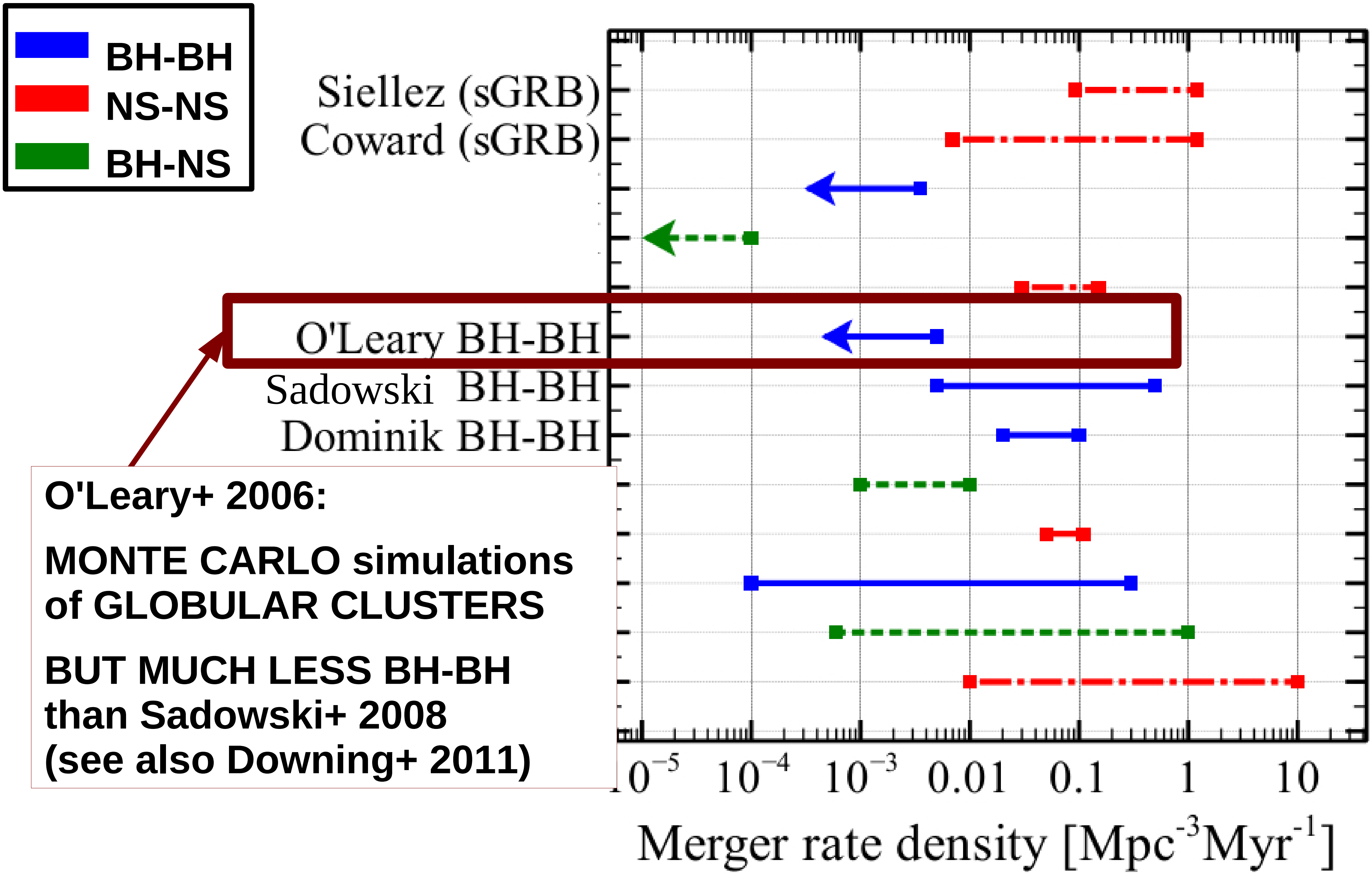
Sadowski+ 2008:

MONTE CARLO simulations of GLOBULAR CLUSTERS

more BH-BH than FIELD but NOT much more

From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



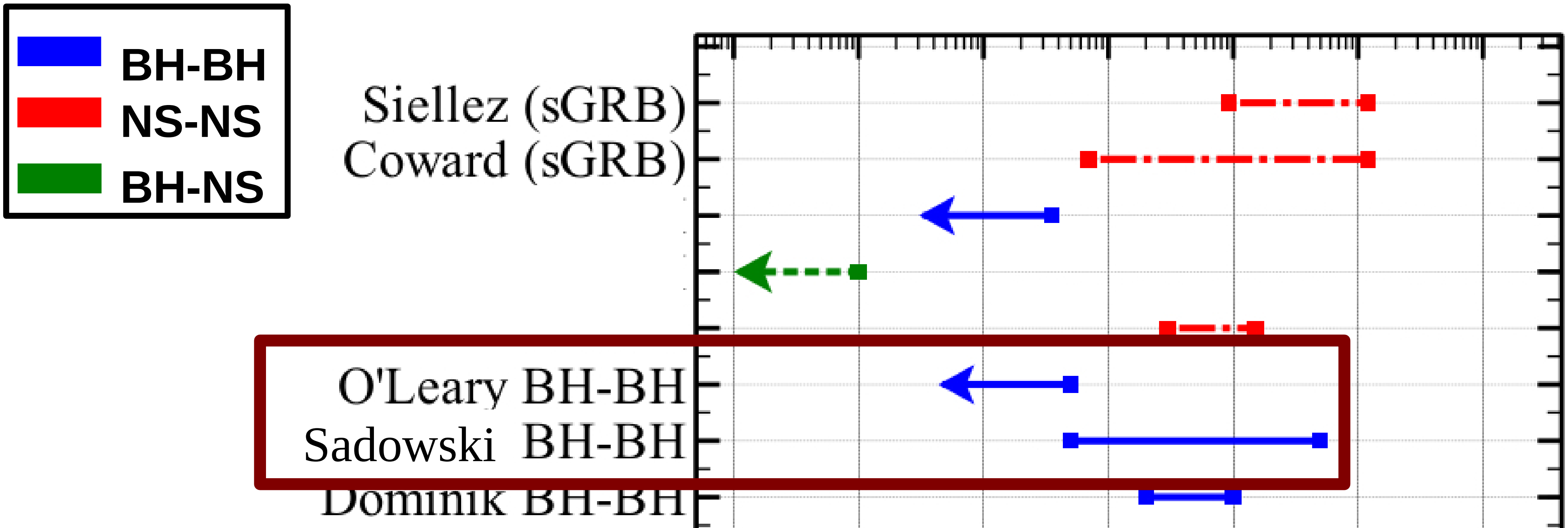
O'Leary+ 2006:

MONTE CARLO simulations of GLOBULAR CLUSTERS

BUT MUCH LESS BH-BH than Sadowski+ 2008 (see also Downing+ 2011)

From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



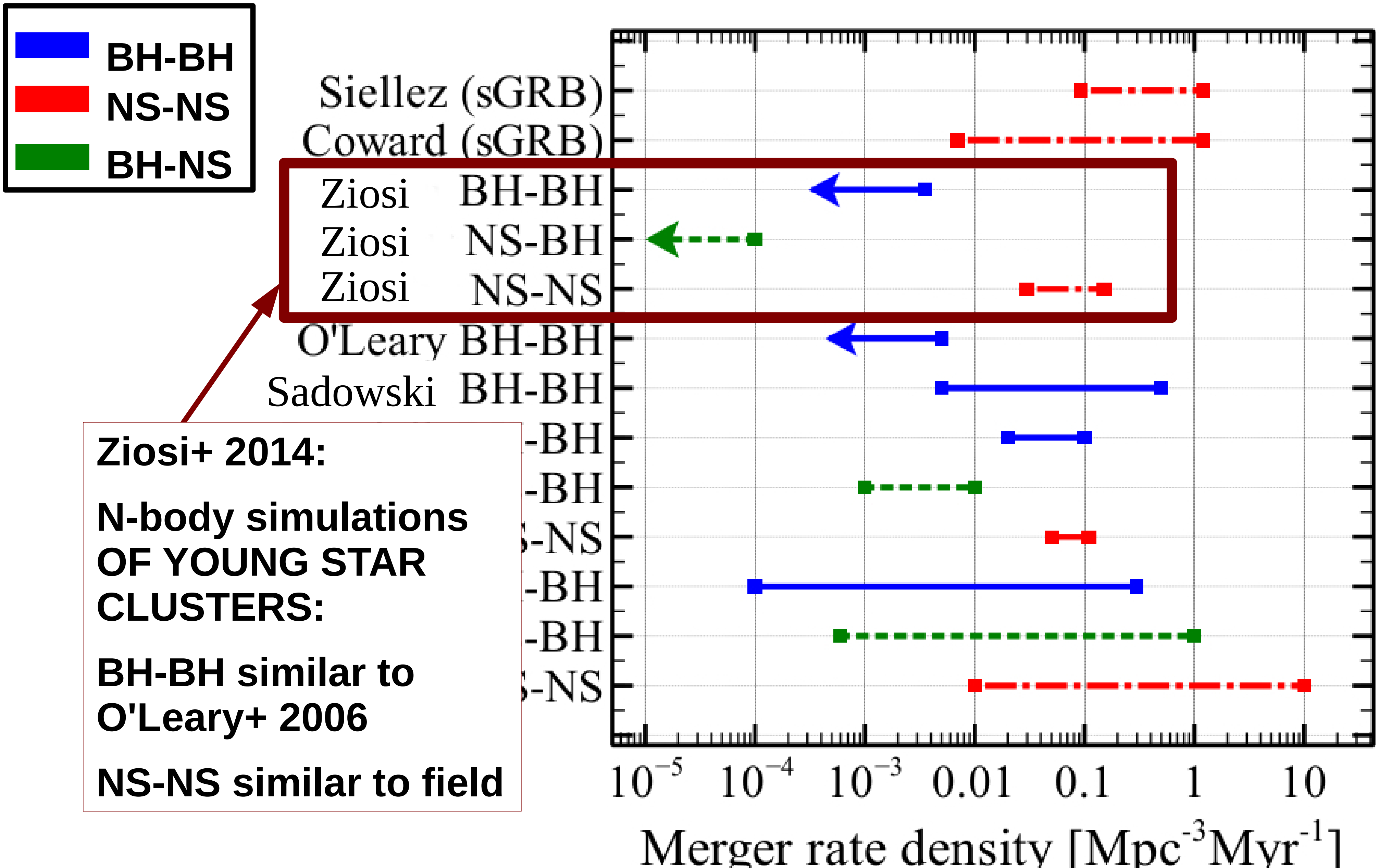
MONTE CARLO SIMULATIONS of globular clusters:

O'Leary+ 2006 assume SPITZER's INSTABILITY LEADS TO EJECTION OF MOST BHs before BH-BH binaries are important for GW (see also Downing+ 2011)

Sadowski+ 2008 assume Spitzer's instability never occurs, BHs remain in equilibrium with other stars

From Ziosi+ 2014

Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



Ziosi+ 2014:

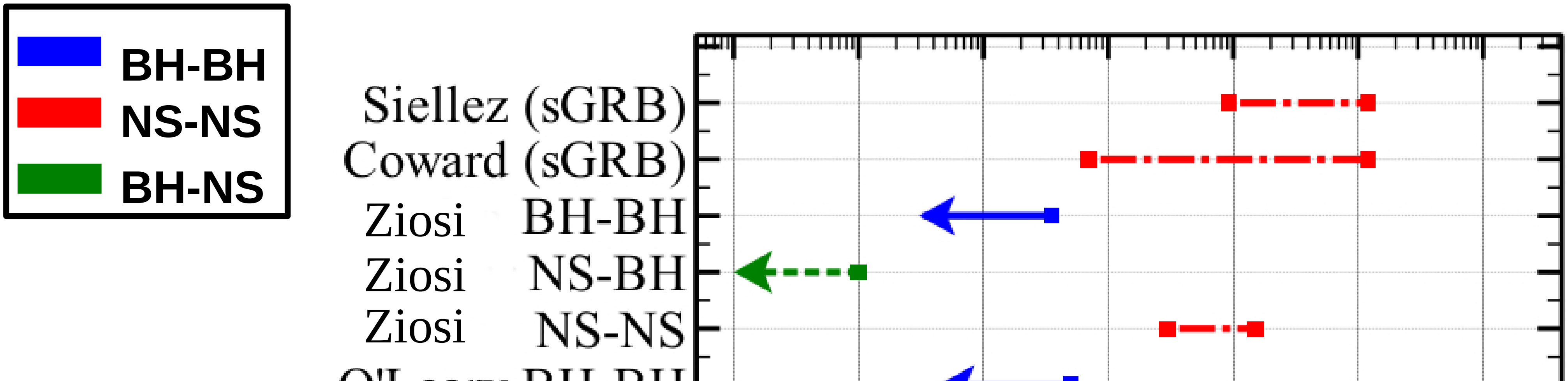
N-body simulations OF YOUNG STAR CLUSTERS:

BH-BH similar to O'Leary+ 2006

NS-NS similar to field

From Ziosi+ 2014

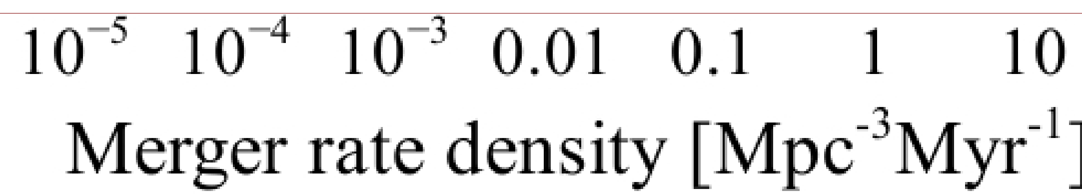
Recent estimates of the MERGER RATE of BH-BH, BH-NS and NS-NS:



TAKE HOME MESSAGE:

– **INTERPLAY BETWEEN DYNAMICS, STELLAR EVOLUTION, BH FORMATION THEORY AND ENVIRONMENT MUCH MORE COMPLICATED THAN EXPECTED!!!**

– **LARGE UNCERTAINTIES IN ALL MODELS**



From Ziosi+ 2014

WHAT TO DO NEXT

Possible themes to investigate for Jena:

- detectors (build one ;))

- population synthesis or N-body simulation to investigate effect of environment

- follow stellar evolution in a binary to see if it forms a 'good' BH-BH, NS-NS or NS-BH binary

- census of gamma ray bursts, or black hole – WR binaries → indicators of GW sources

- calculate merger and detection rate in alternative way to the one I suggested

- your ideas (but discuss them with me before Jena if you need help..)

USEFUL REFERENCES

- Michele Maggiore 2007, Gravitational Waves
Volume 1. Theory and Experiments, Oxford University Press

- Christopher Berry's website, http://cplberry.com/2015/01/10/1408-0740/

- Space Time Quest, the interferometer game,
http://www.gwoptics.org/processing/space_time_quest/

- Abadie+ 2010 (LIGO/Virgo paper on sources), http://arxiv.org/abs/1003.2480

- Coward+ 2012 (GW rate from γ-ray bursts), http://arxiv.org/abs/1202.2179

- Ziosi+ 2014 (dynamics of BH-BH, NS-NS), http://arxiv.org/abs/1404.7147

- Lorimer 2008 (pulsar binary census and pulsar physics),
http://relativity.livingreviews.org/Articles/lrr-2008-8/

- N-body codes to play with : starlab (http://www.sns.ias.edu/~starlab/),
HiGPUs (http://astrowww.phys.uniroma1.it/dolcetta/HPCcodes/HiGPUs.html),
Nbody6 (http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm)
ASK ME IF YOU WANT TO PLAY WITH N-BODY!

- stellar and binary evolution codes: MESA (http://mesa.sourceforge.net/)
ASK ME IF YOU WANT TO PLAY WITH MESA!

3. gravitational wave sources

WHY 'normal' stars in binaries are not sources of gravitational waves?

WHY 'normal' stars in binaries are not sources of gravitational waves?

5. impact of environment on merger rate

5. impact of environment on merger rate

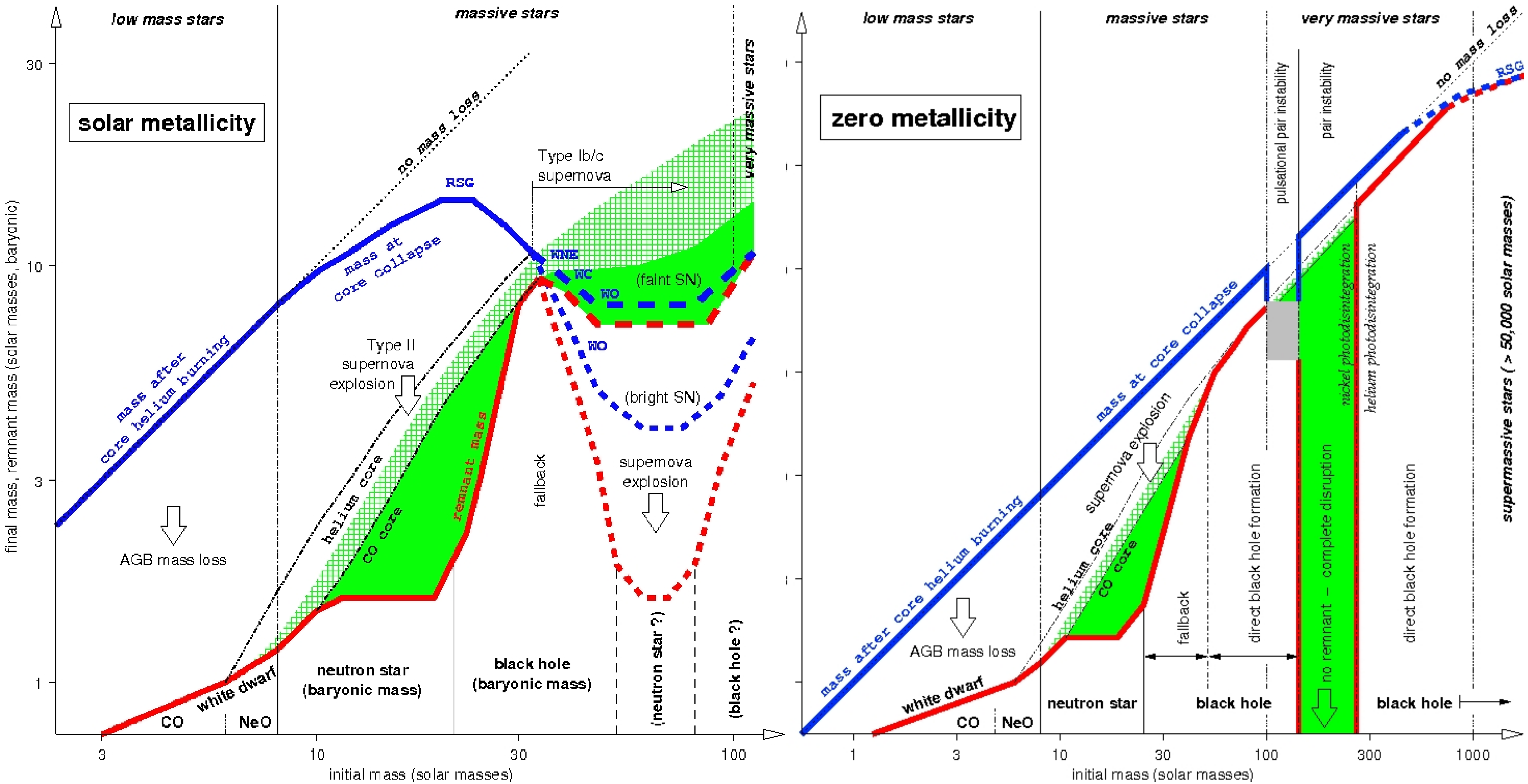
WHY DYNAMICS???????

5. impact of environment on merger rate

WHY DYNAMICS????????

3. gravitational wave sources

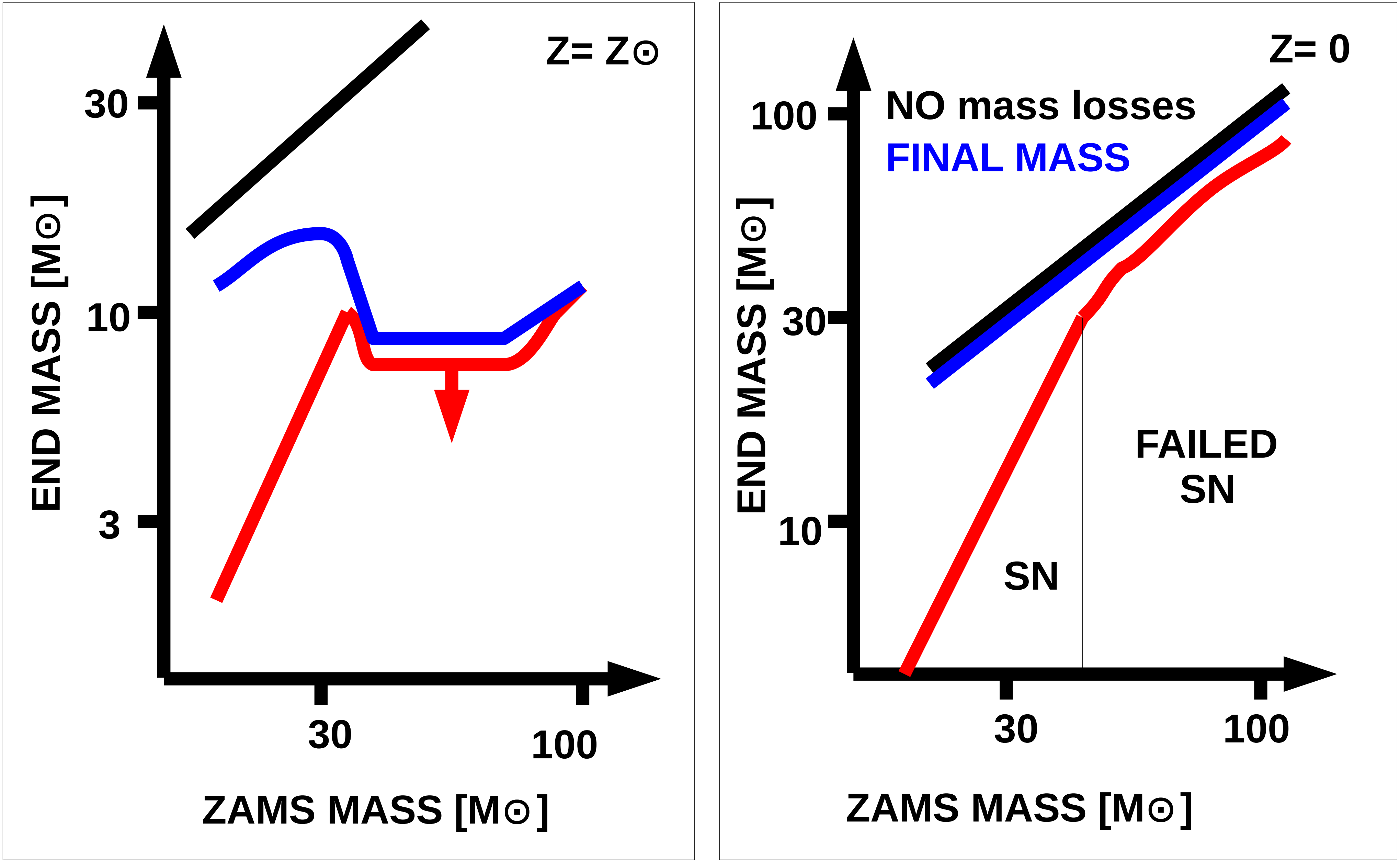
HOW DO BHs and NSs form?



Heger et al. (2003)

3. gravitational wave sources

HOW DO BHs and NSs form?



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

→ 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 (Δv/v ~ 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

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

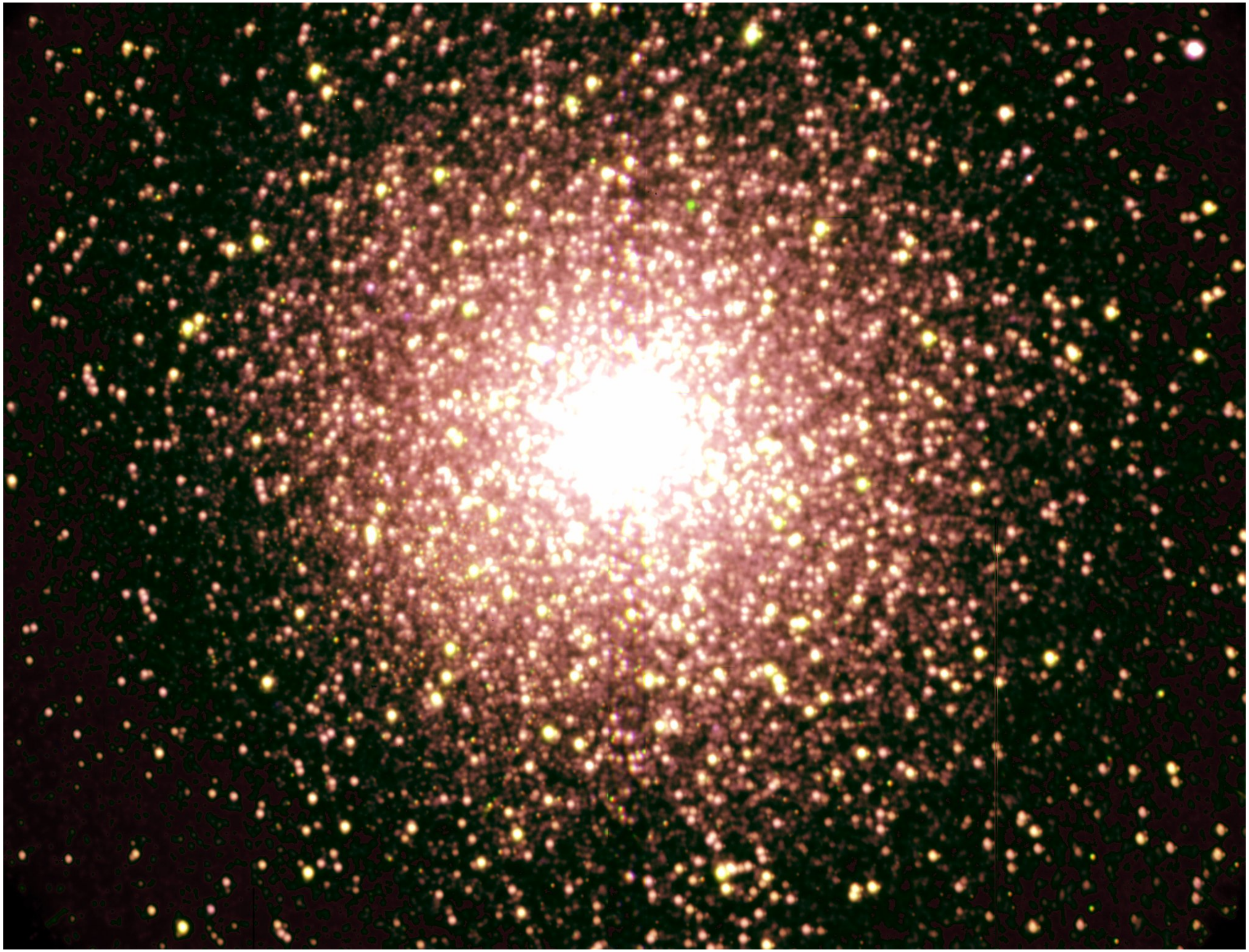
→ **COLLISIONAL**

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

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

→ **COLLISIONLESS**

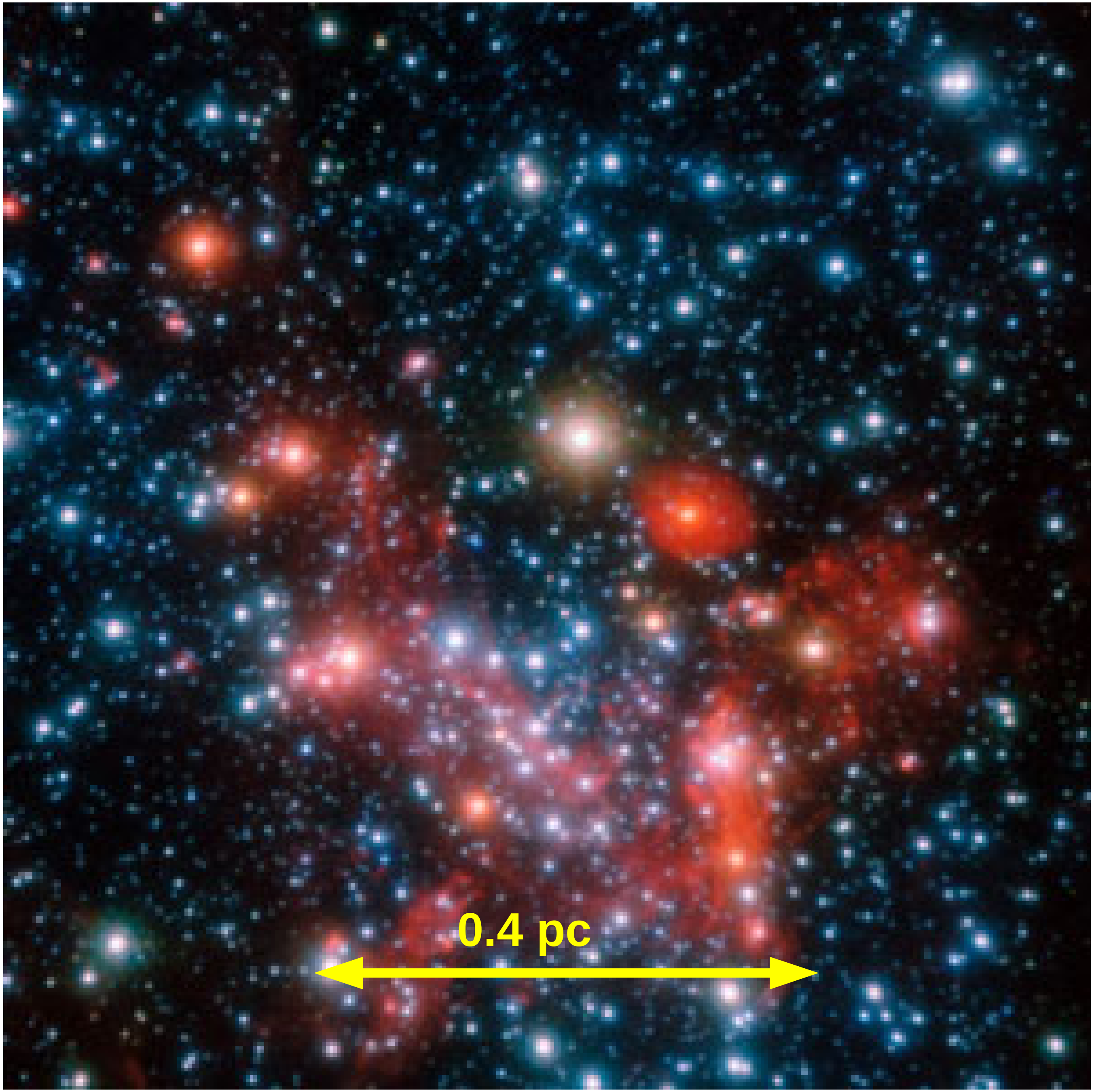
EXAMPLES of COLLISIONAL stellar systems



t_{rlx}~ 1 Gyr

Globular clusters (47Tuc)

EXAMPLES of COLLISIONAL stellar systems



t_{rlx}~ 0.1 Gyr

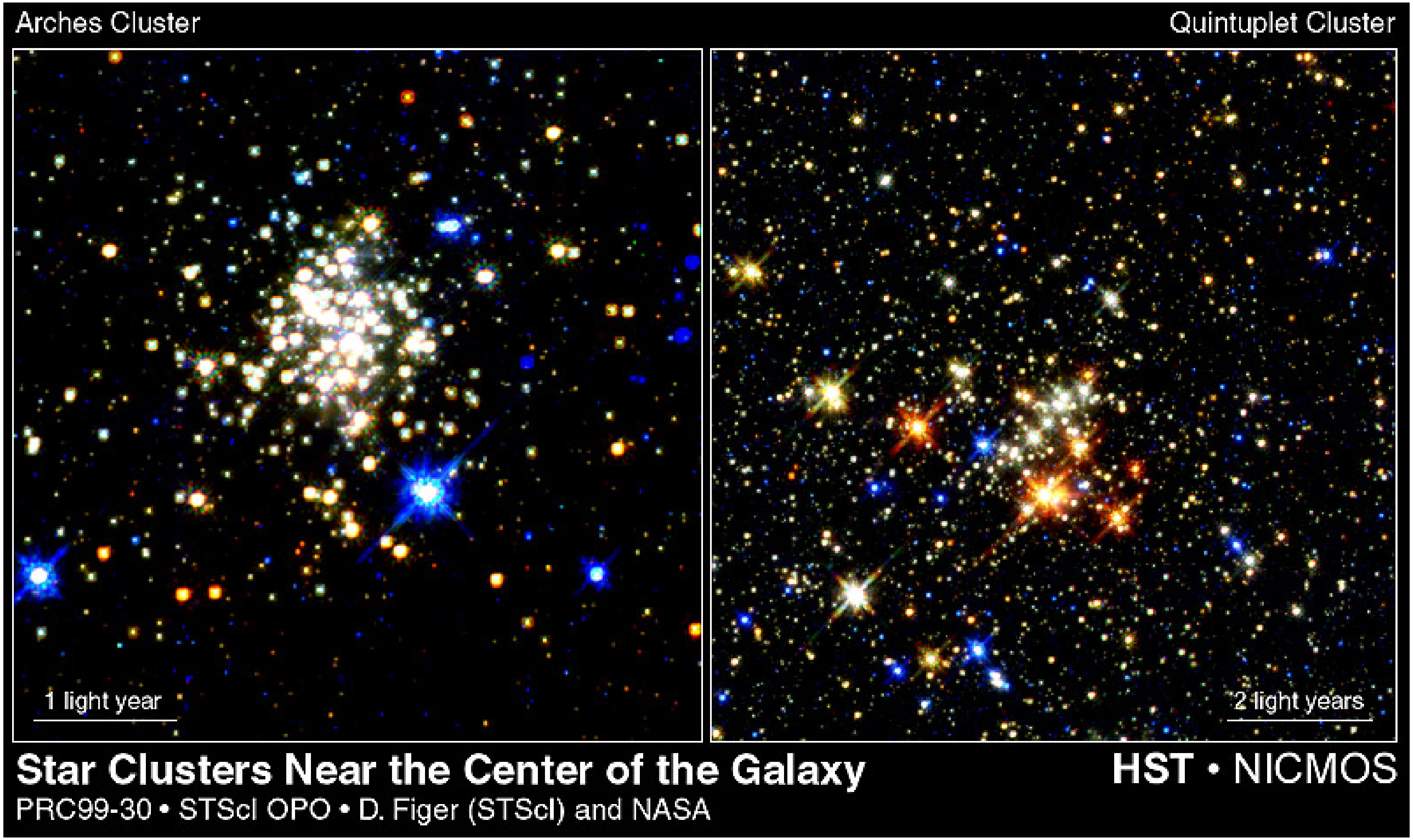
Nuclear star clusters (MW)
NaCo @ VLT
Genzel+2003

EXAMPLES of COLLISIONAL stellar systems

Open clusters (M67)
Courtesy Bob Franke

$t_{\mathrm{rlx}} \sim 100$ **Myr**

EXAMPLES of COLLISIONAL stellar systems

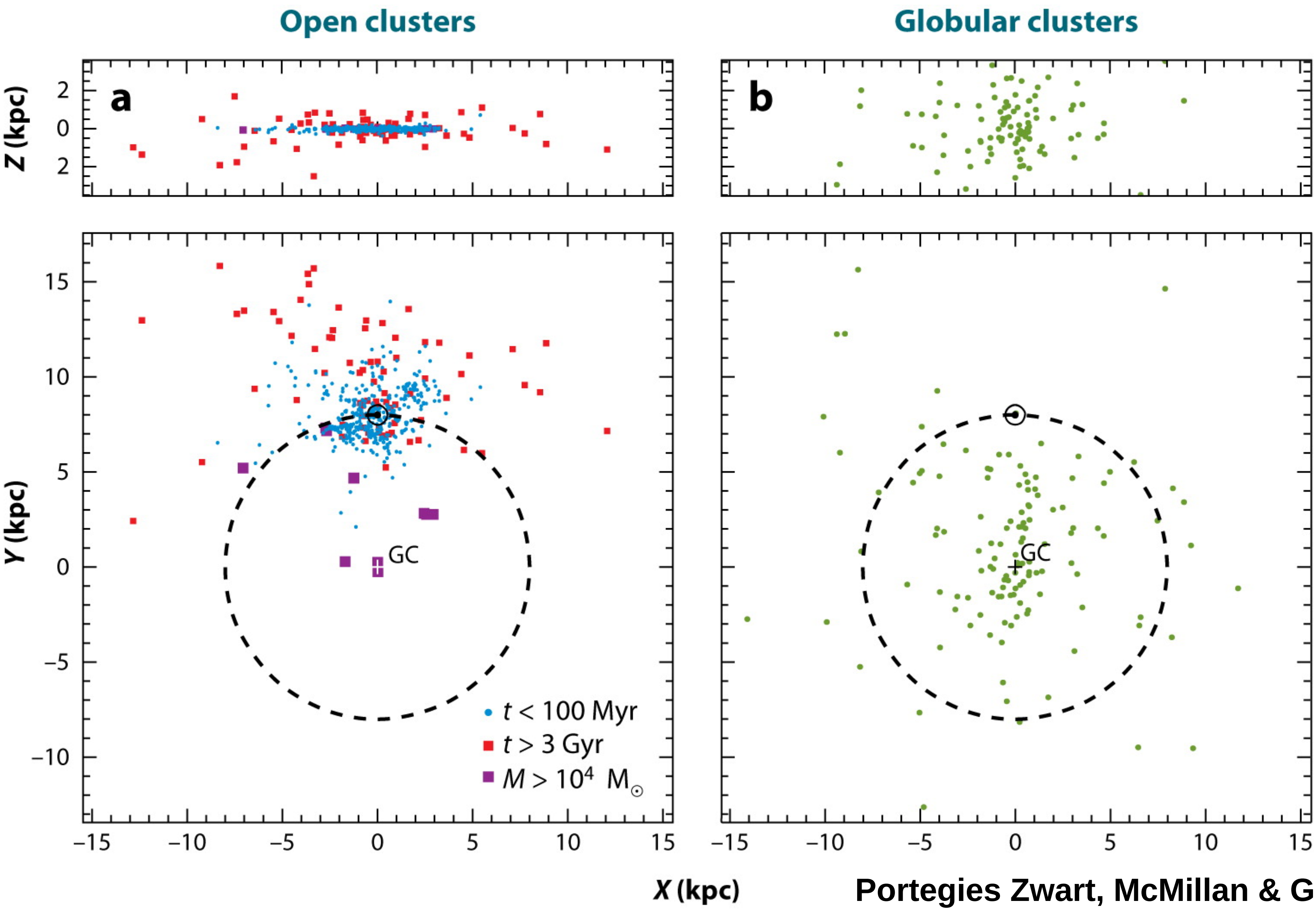


Young dense star clusters (Arches, Quintuplet)

t_{rlx} **~ 10-100 Myr**

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

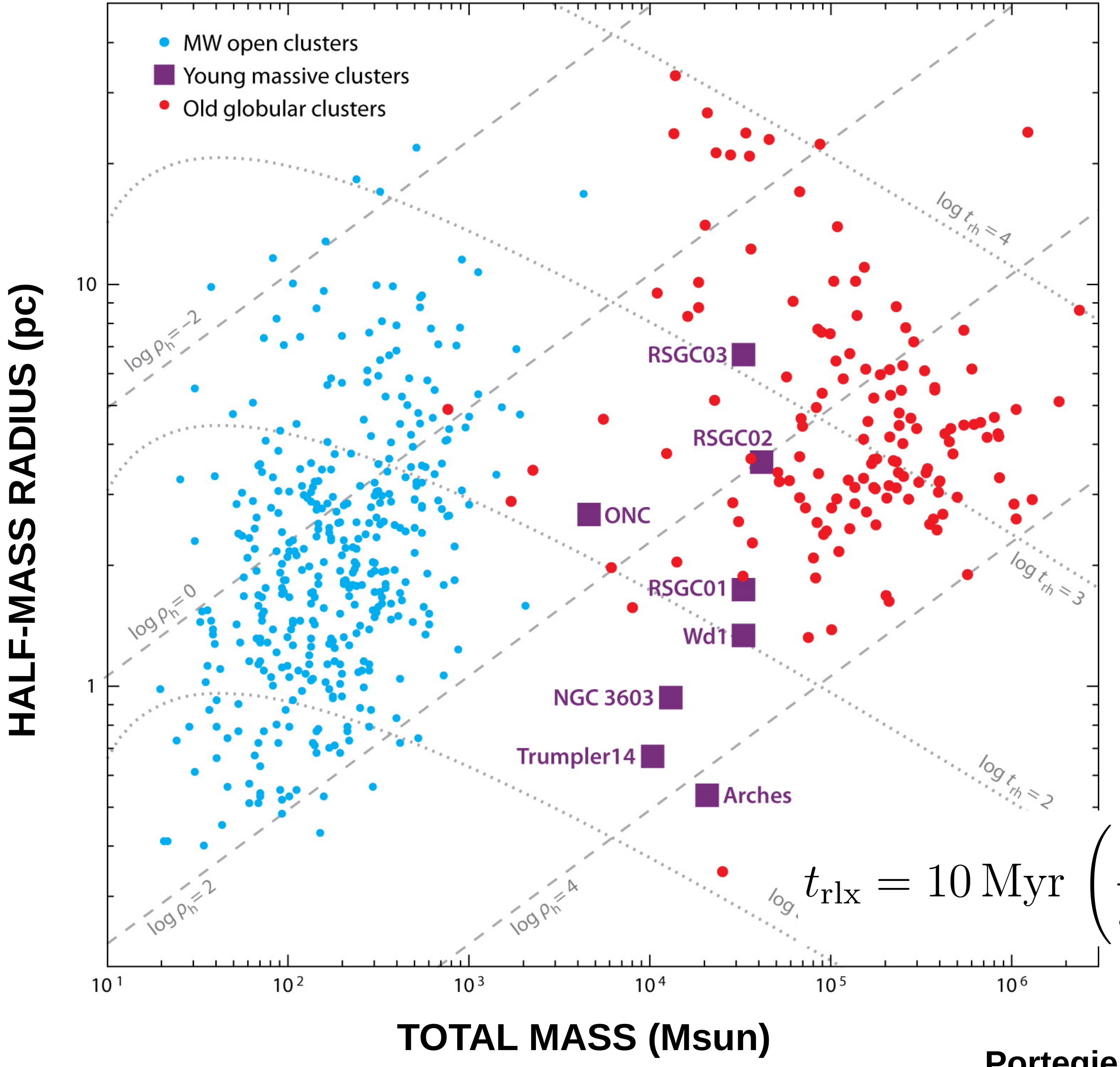
DISTRIBUTION of COLLISIONAL stellar systems in the MILKY WAY



Portegies Zwart, McMillan & Gieles 2010

GLOBULAR CLUSTERS ARE A HALO POPULATION
YOUNG and OPEN CLUSTERS ARE A DISC POPULATION

MAIN PROPERTIES of COLLISIONAL stellar systems in the MILKY WAY



Open clusters

Globular clusters

Young dense star clusters

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

Portegies Zwart, McMillan & Gieles 2010

MAIN PROPERTIES of COLLISIONAL stellar systems in the MILKY WAY

cluster	age [Gyr]	m_{to} [$M_\odot$]	M [$M_\odot$]	r_{vir} [pc]	ρ_c [$M_\odot/pc^3$]	Z [$Z_\odot$]	location	t_{dyn} [Myr]	t_{rh} [Myr]
OC	$\lesssim$ 0.3	$\lesssim 4$	$\lesssim 10^3$	1	$\lesssim 10^3$	~ 1	disk	~ 1	$\lesssim 100$
GC	$\gtrsim 10$	~ 0.8	$\gtrsim 10^5$	10	$\gtrsim 10^3$	< 1	halo	$\gtrsim 1$	$\gtrsim 1000$
YMC	$\lesssim$ 0.1	$\gtrsim 5$	$\gtrsim 10^4$	1	$\gtrsim 10^3$	$\gtrsim 1$	galaxy	$\lesssim 1$	$\lesssim 100$

Portegies Zwart, McMillan & Gieles 2010

ONE OF THE MAIN PROPERTIES OF COLLISIONAL SYSTEMS IS THAT

THREE-BODY ENCOUNTERS
(= CLOSE GRAVITATIONAL ENCOUNTERS BETWEEN A BINARY AND A SINGLE STAR)

ARE FREQUENT IN COLLISIONAL SYSTEMS

SPITZER INSTABILITY: – ENHANCES EJECTIONS –

MASS SEGREGATION
Consequence of equipartition theorem (for two-body encounters):

PARTICLES TEND TO HAVE THE SAME AVERAGE KINETIC ENERGY

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

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

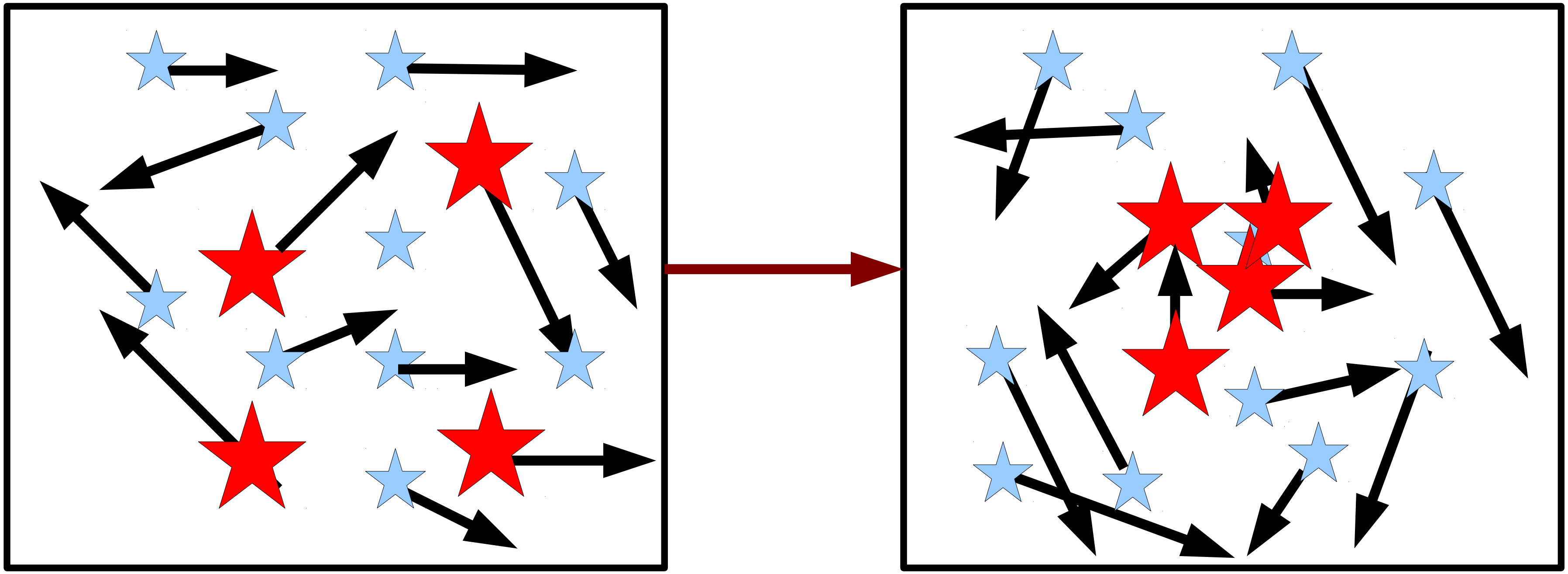
If stars have different masses, this has a relevant consequence:

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

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

SPITZER INSTABILITY:

MASS SEGREGATION



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

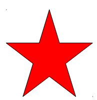
This means that **heavier stars drift to the centre of the cluster**, producing **MASS SEGREGATION**
(i.e. local mass function different from IMF)

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

SPITZER INSTABILITY (or mass stratification instability):

It is not always possible to reach equipartition in a multi-mass system.

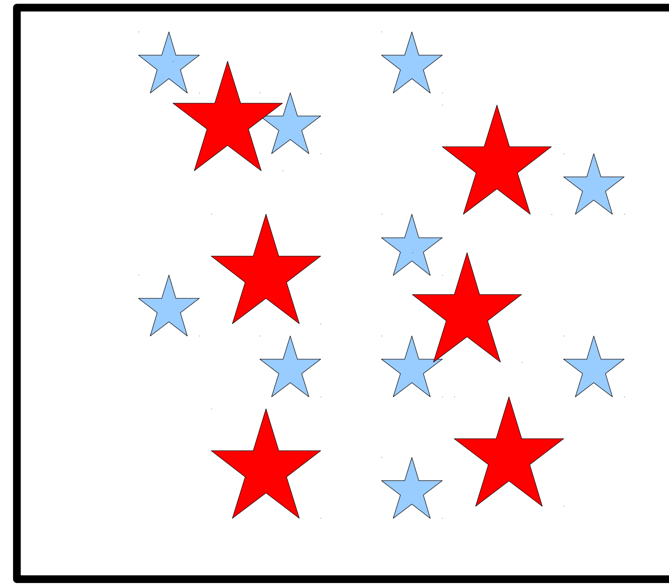
Let us suppose that there are two populations with two different masses:



HEAVY POPULATION
m_2 (total mass M_2)

LIGHT POPULATION
m_1 (total mass M_1)

$m_2 > m_1$



$M_2 \sim M_1$

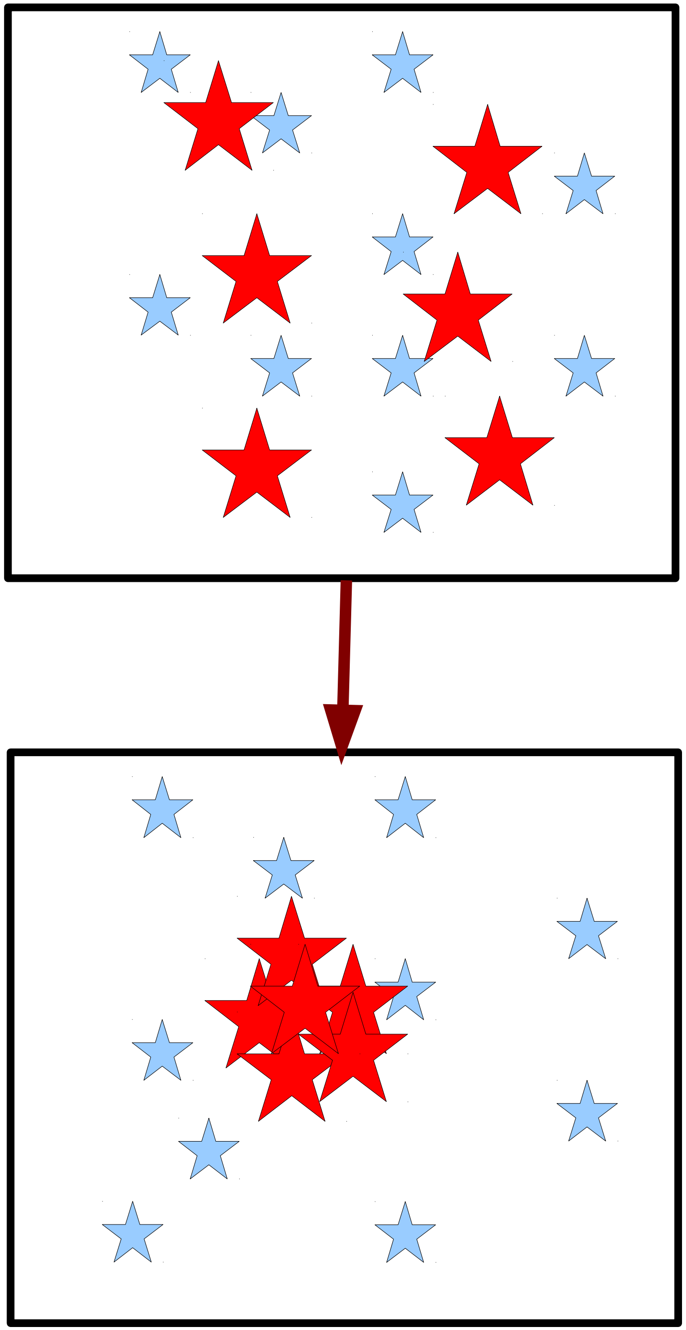
If the total mass of the heavy population is similar to the total mass of the light population, equipartition is not possible:

$M_2 \langle v_2^2 \rangle >> M_1 \langle v_1^2 \rangle$

THE LIGHT POPULATION CANNOT ABSORB ALL THE KINETIC ENERGY THAT MUST BE TRANSFERRED FROM THE HEAVY POPULATION TO REACH EQUIPARTITION

SPITZER INSTABILITY (or mass stratification instability):

The heavy population forms a
CLUSTER WITHIN THE CLUSTER
(sub-cluster at the centre of the cluster),
DYNAMICALLY DECOUPLED
from the rest of the cluster.



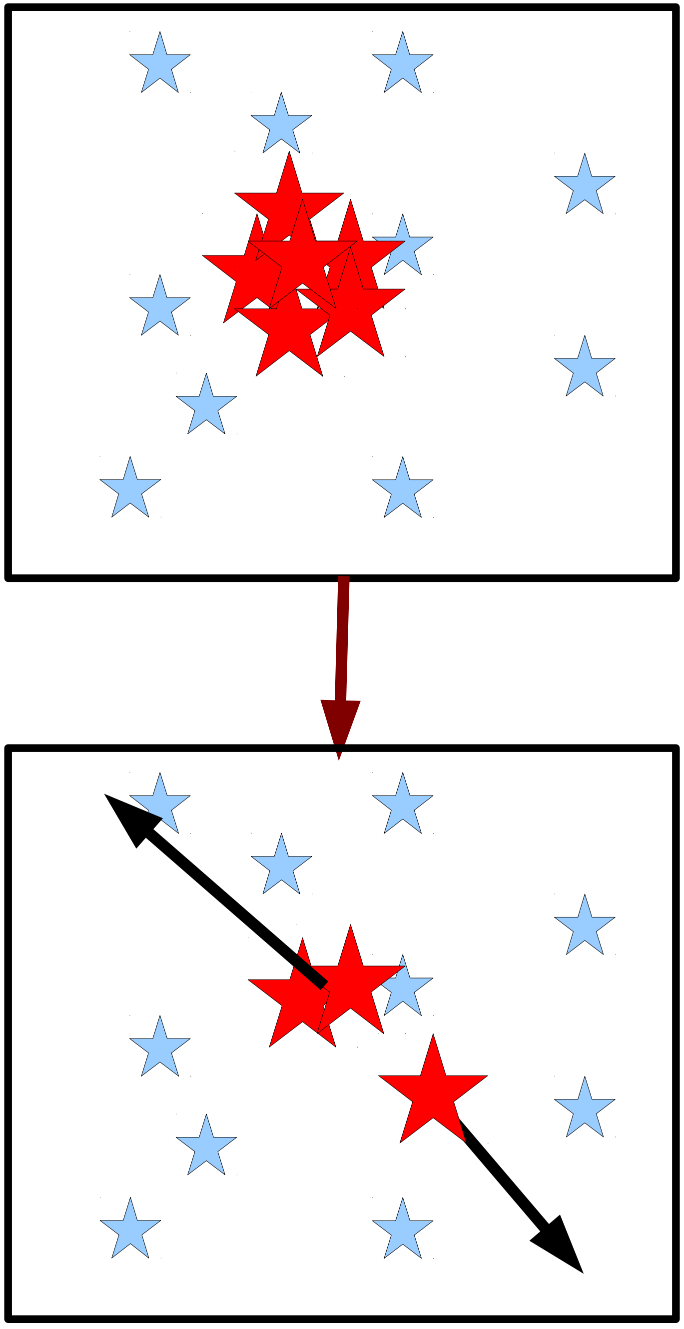
The massive stars in the sub-cluster keep transferring kinetic energy to the lighter stars but cannot reach equipartition:
the core of massive stars continues to CONTRACT TILL INFINITE DENSITY!

SPITZER INSTABILITY (or mass stratification instability):

The contraction stops

– when most of the massive stars eject each-other from the SC by 3-body encounters

SPITZER INSTABILITY ENHANCES THE EJECTION OF MASSIVE OBJECTS (E.G. BLACK HOLES) FROM SCs !!!!



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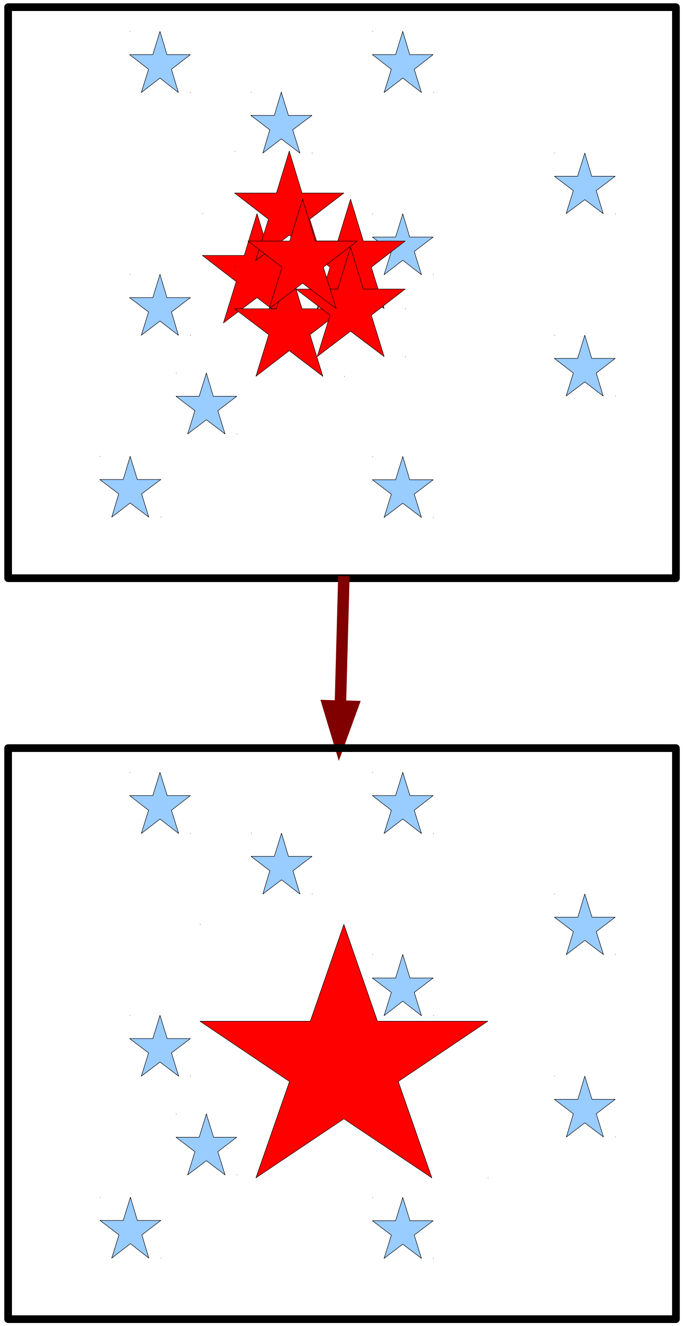
SPITZER INSTABILITY ENHANCES THE EJECTION OF MASSIVE OBJECTS (E.G. BLACK HOLES) FROM SCs !!!!

– or when most of the massive stars collapse into a single object



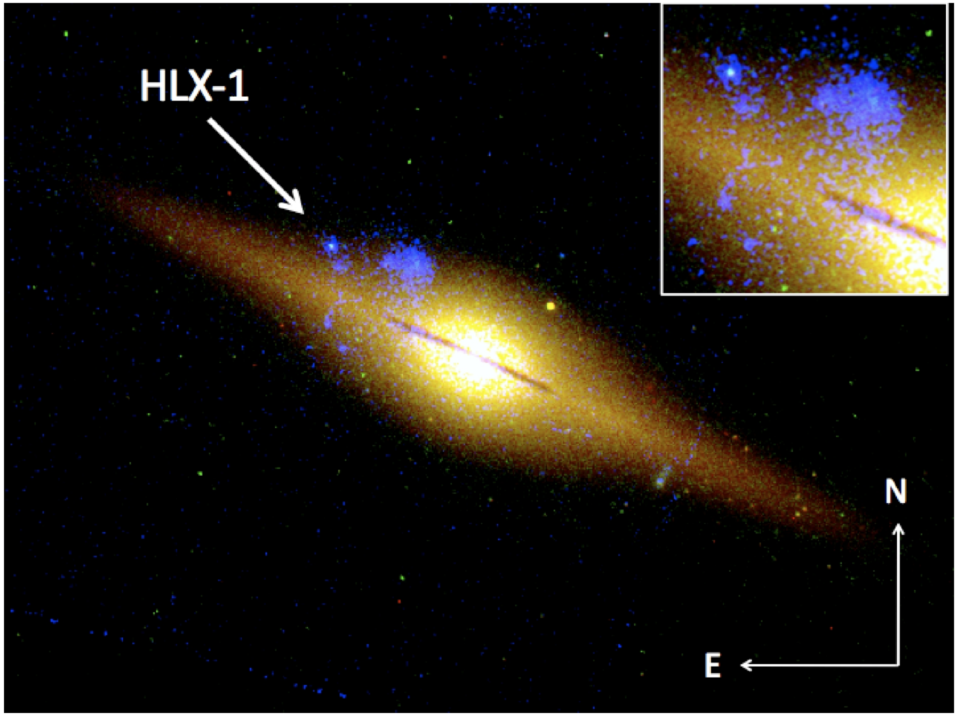
IMBHs are BHs with mass 10^2-10^5 Msun

→some limited observational signature

1* Hyper-luminous 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, 2014;
Soria+ 2010, 2012;
Mapelli+ 2012, 2013



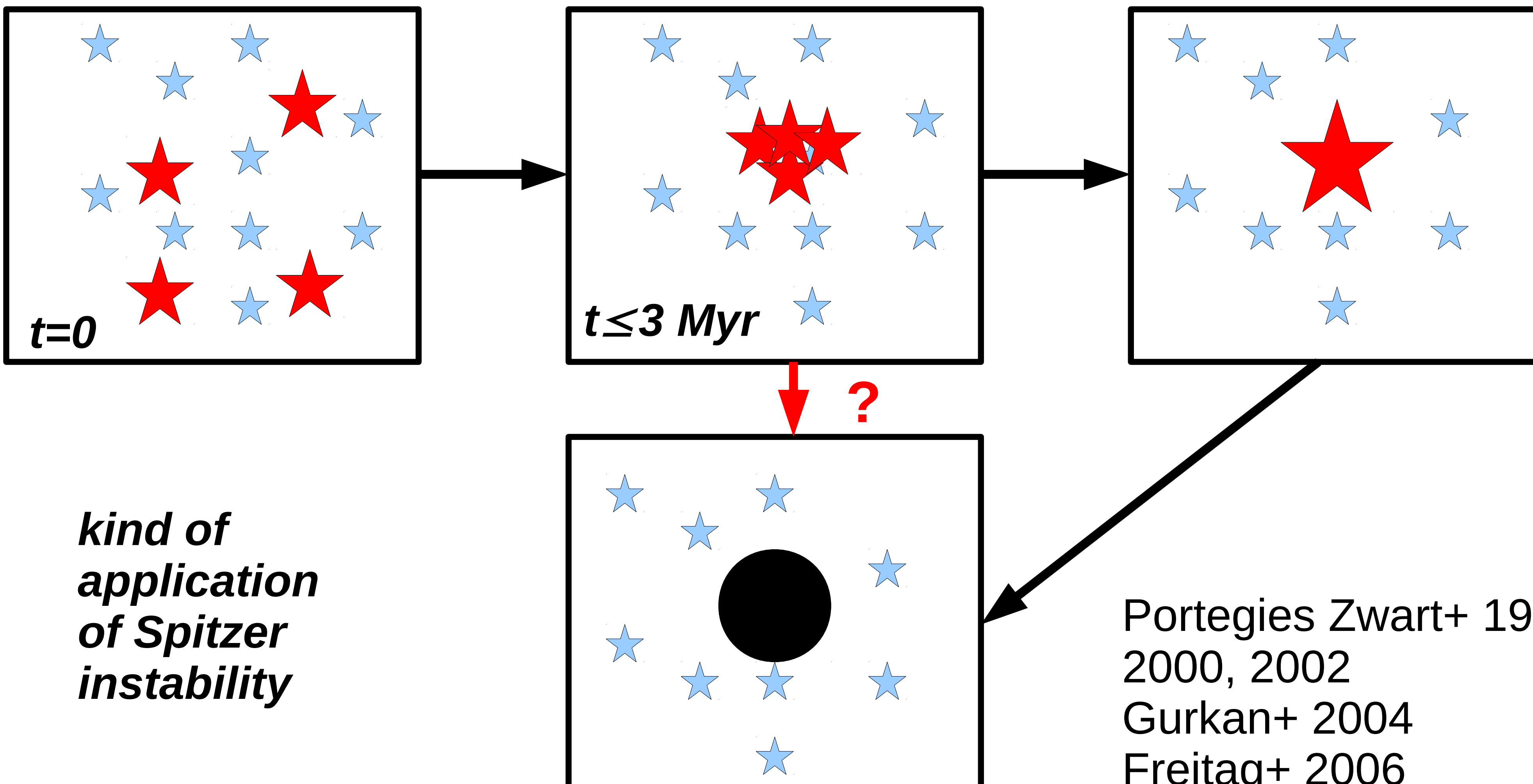
2* centre of G1 globular cluster (dwarf nucleus?) in Andromeda

→ cannot form through stellar evolution (at least in current Universe)

→ theoretical models predict formation through dynamics

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



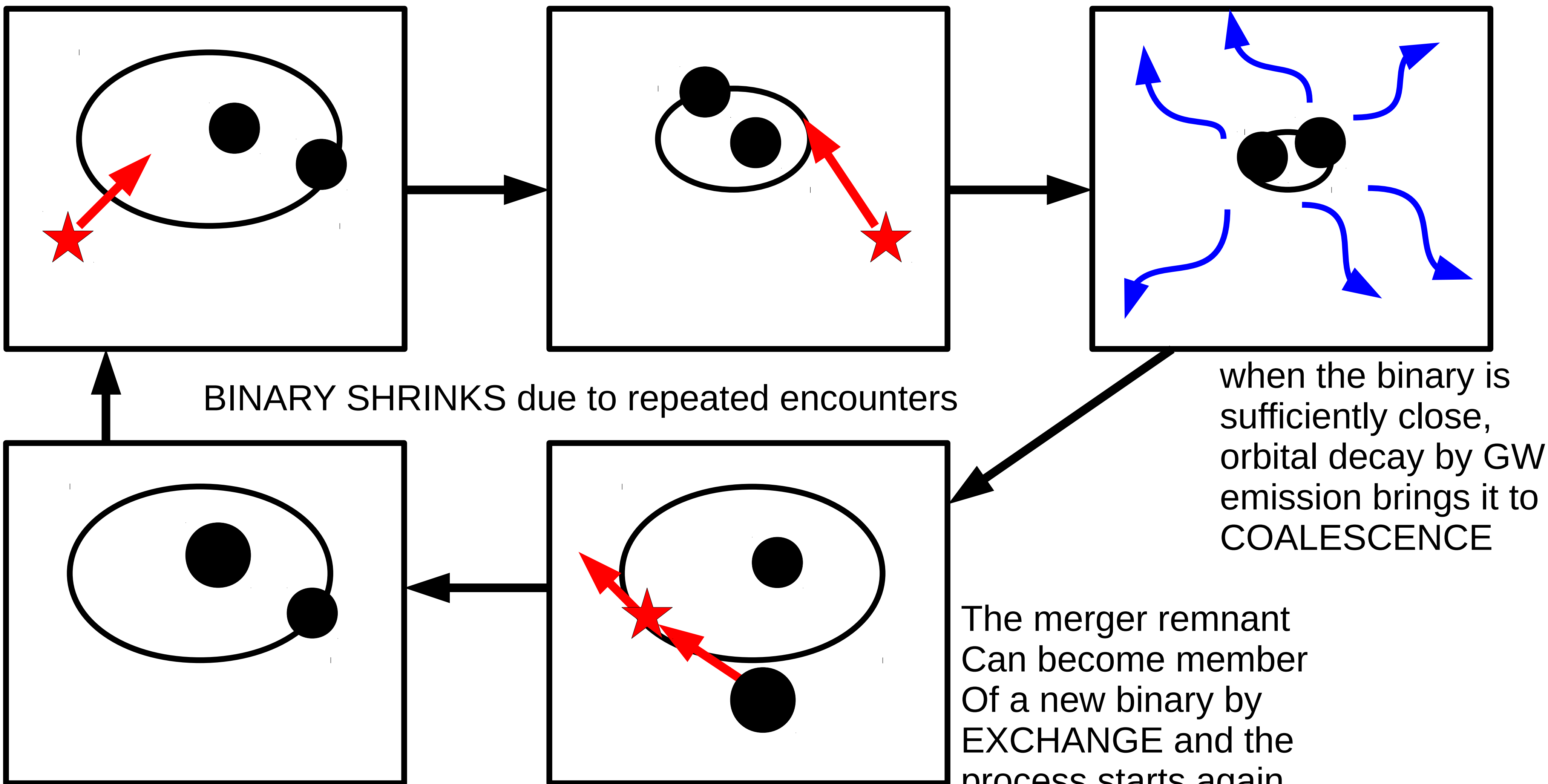
kind of application of Spitzer instability

Portegies Zwart+ 1999, 2000, 2002
Gurkan+ 2004
Freitag+ 2006

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



CONCLUSIONS:

COLLISIONAL SYSTEMS are very important for the evolution of BH and NS systems:

- **THREE-BODY ENCOUNTERS enhance formation of BH binaries**
- **BUT THREE-BODY ENCOUNTERS can also eject compact objects**
- **SPITZER INSTABILITY PLAYS A ROLE in enhancing ejections**
- **IMBHs might form dynamically**
- **INTERPLAY BETWEEN DYNAMICS, STELLAR EVOLUTION, BH FORMATION THEORY AND ENVIRONMENT MUCH MORE TRICKY THAN EXPECTED!!!**
- **LARGE UNCERTAINTIES IN ALL MODELS of BH and NS binaries**

3. dynamical ejection of NS-NS, NS-BH and BH-BH binaries

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

FROM ENERGY CONSERVATION:

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

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

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

3. dynamical ejection of NS-NS, NS-BH and BH-BH binaries

Star clusters lose large fraction of mass by

1. **high-speed EJECTIONS (caused by SN kick and 3-body)**
2. **low-speed evaporation**
3. **tidal fields**

FIELD:
NO dynamics

GLOBULAR CLUSTERS:
dynamics
long-lived

3. dynamical ejection of NS-NS, NS-BH and BH-BH binaries

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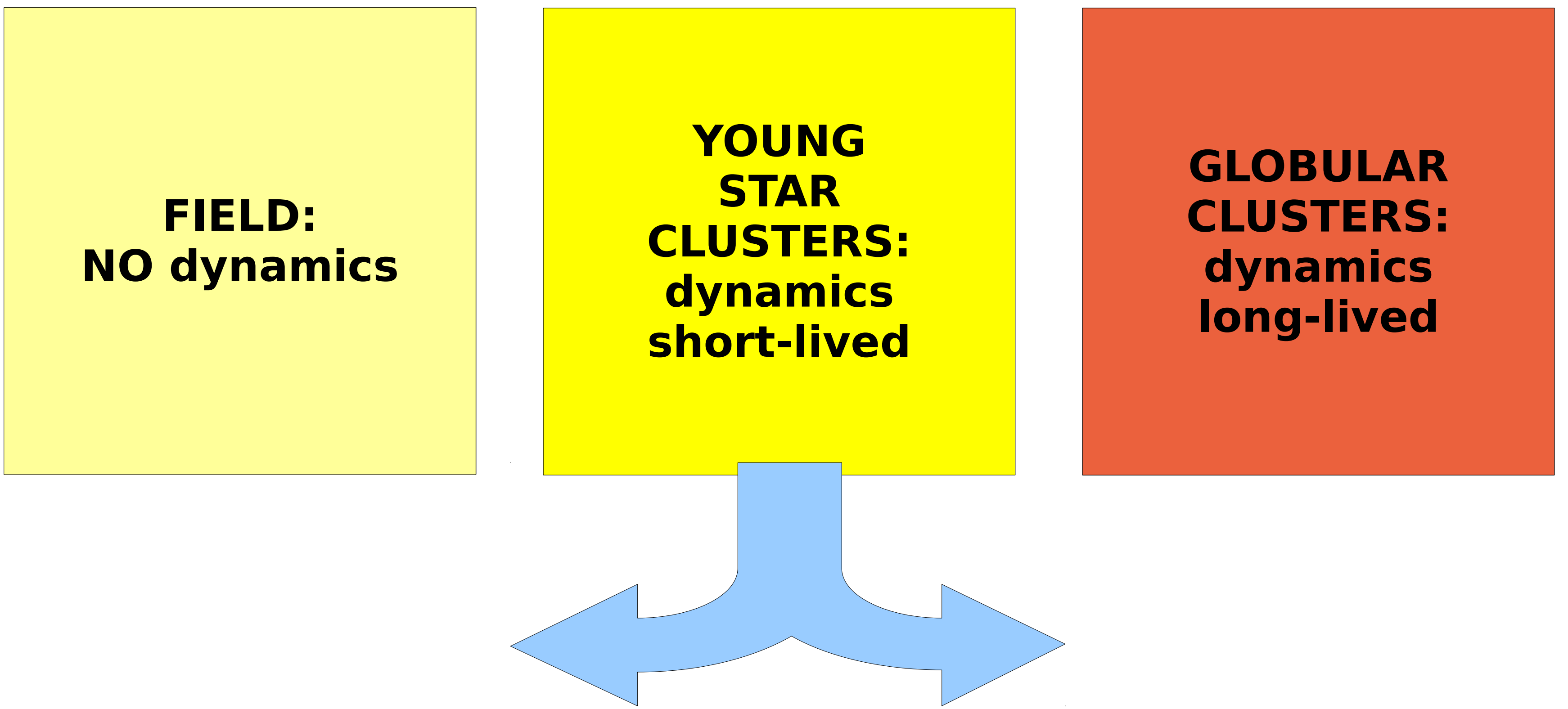

provide stars (and compact objects) to the field

share dynamical properties with globular clusters

SELECTED REFERENCES

* Spitzer L., Dynamical evolution of globular clusters, 1987, Princeton University Press

* Binney & Tremaine, Galactic Dynamics, First edition, 1987, Princeton University Press

* 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

SPITZER INSTABILITY (or mass stratification instability):

It is not always possible to reach equipartition in a multi-mass system.

Let us suppose that there are two populations with two different masses: m_1 (total mass M_1) and m_2 (total mass M_2), with $m_1 < m_2$.

We explore 2 limit cases where equipartition is impossible.

1) $M_2 >> M_1 \Rightarrow$ potential is dominated by massive stars

$\Rightarrow \langle v^2 \rangle$ of the massive stars is ~ ¼ $\langle v_{esc}^2 \rangle$

$\Rightarrow$ if $m_2/m_1 > 4$, the $\langle v^2 \rangle$ of light stars is higher than $\langle v_{esc}^2 \rangle$

$\Rightarrow$ ***ALL LIGHT STARS EVAPORATE FROM THE CLUSTER!!!***

Not very important in practice because IMF is not sufficiently top-heavy

SPITZER INSTABILITY (or mass stratification instability):

It is not always possible to reach equipartition in a multi-mass system.

Let us suppose that there are two populations with two different masses: m_1 (total mass M_1) and m_2 (total mass M_2), with $m_1 < m_2$.

2) $M_2 \sim M_1$ (the case of the so called Spitzer's instability)

If the total mass of the heavy population is similar to the total mass of the light population, equipartition is not possible:
the heavy population forms a cluster within the cluster,
i.e. a sub-cluster at the centre of the cluster,
dynamically decoupled from the rest of the cluster.
The sub-cluster of the heavy population tends to contract.

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

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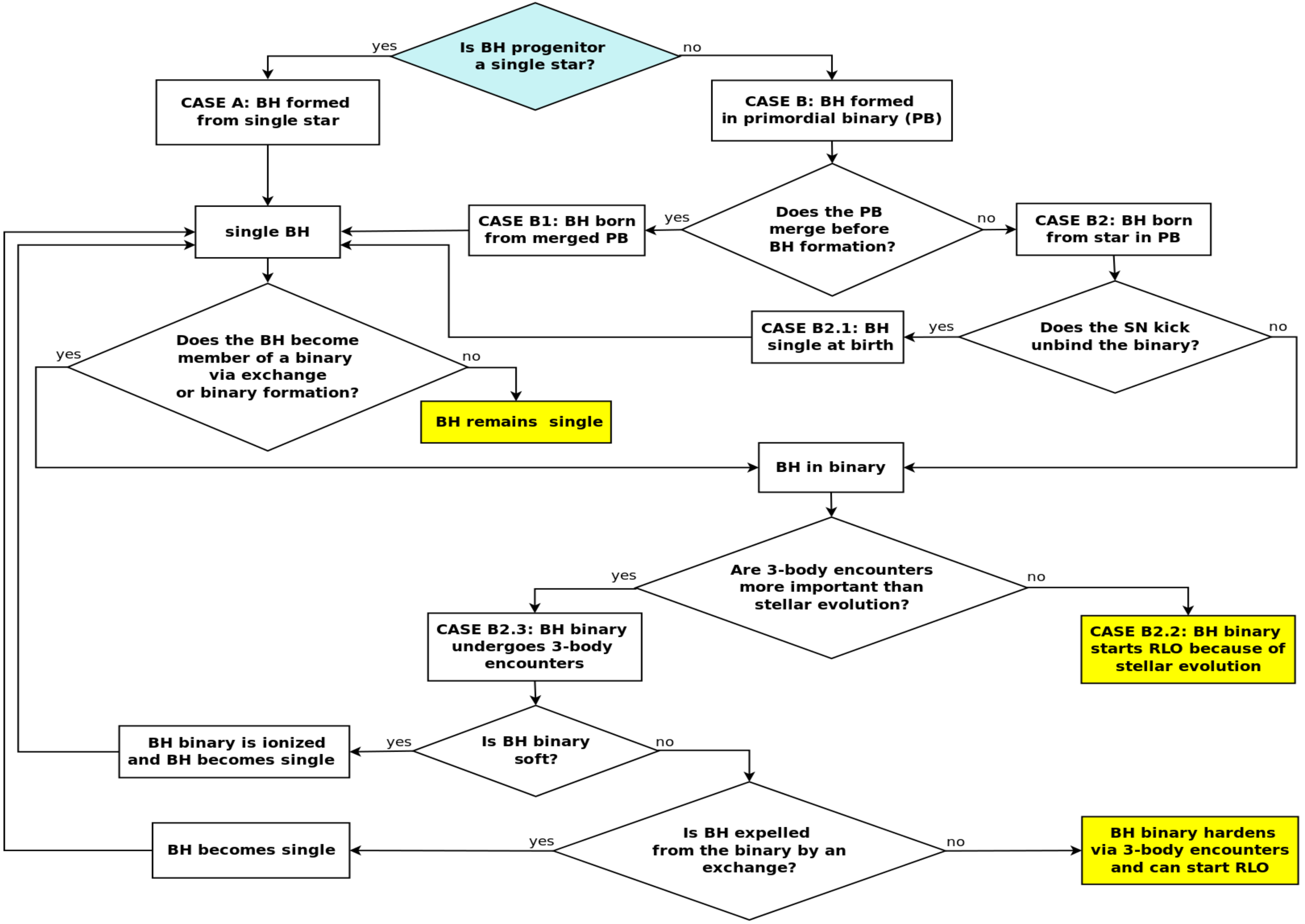
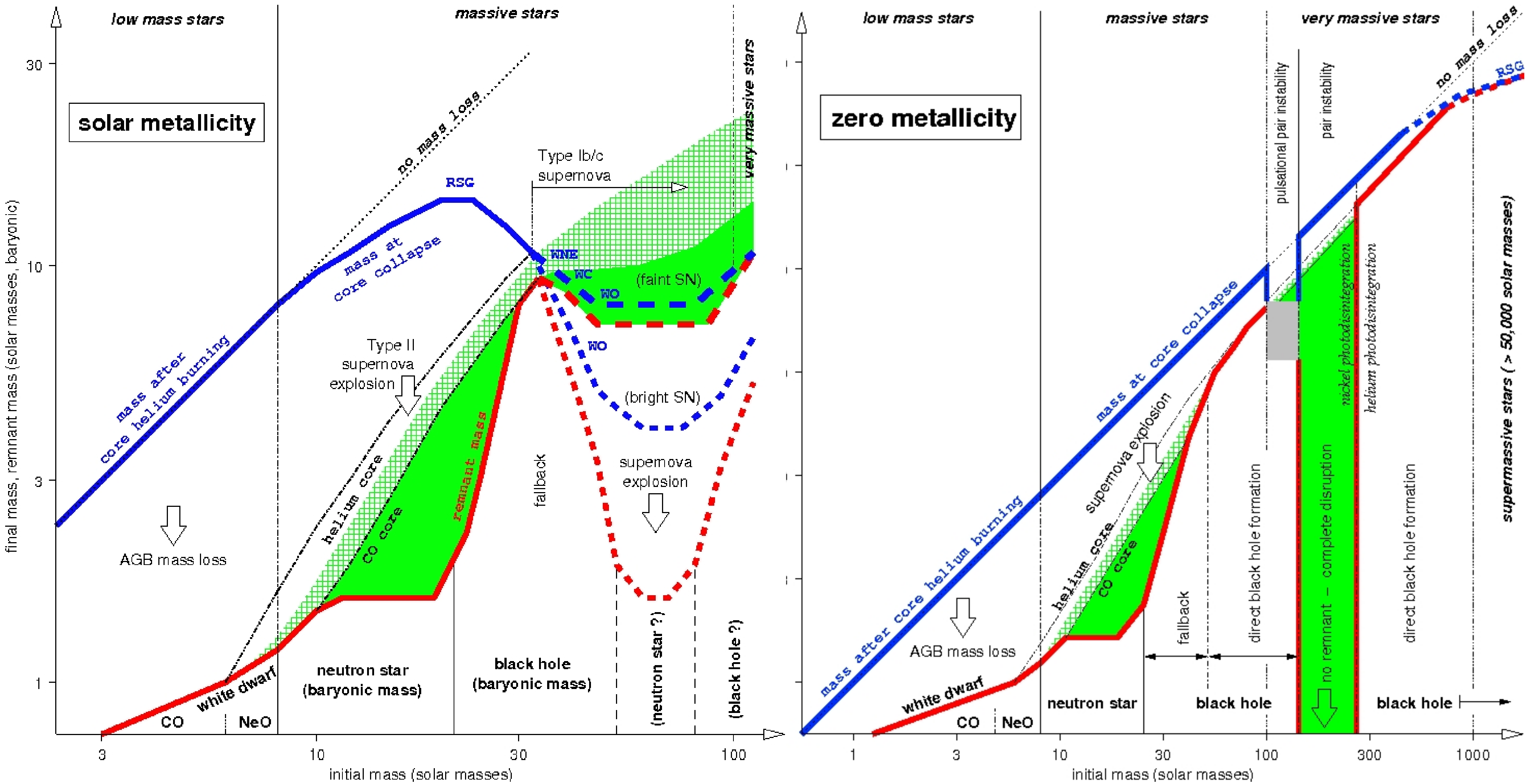
2. 3-body encounters enhance ULX formation



2. 3-body encounters enhance ULX formation

Formalism by Heger et al. (2003)



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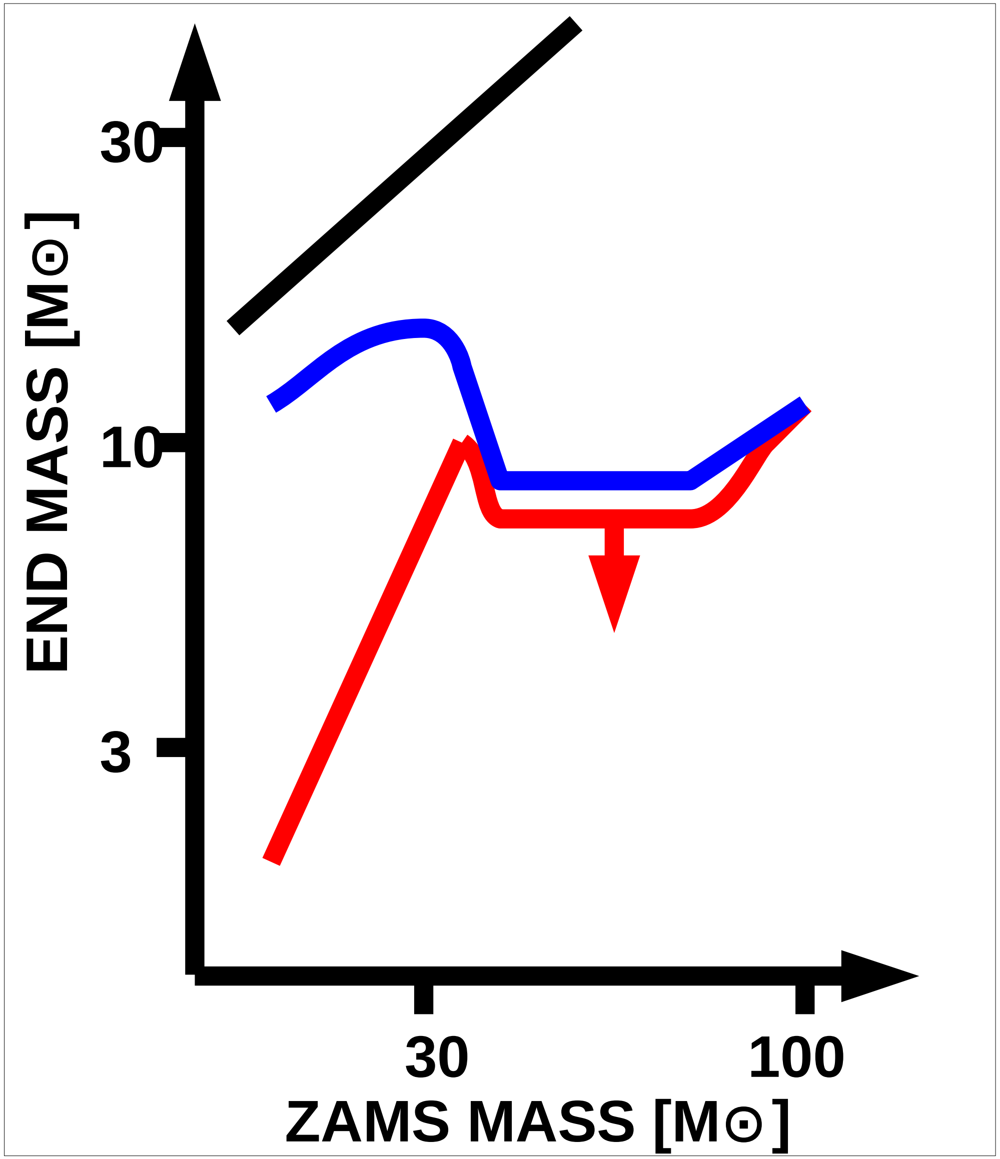
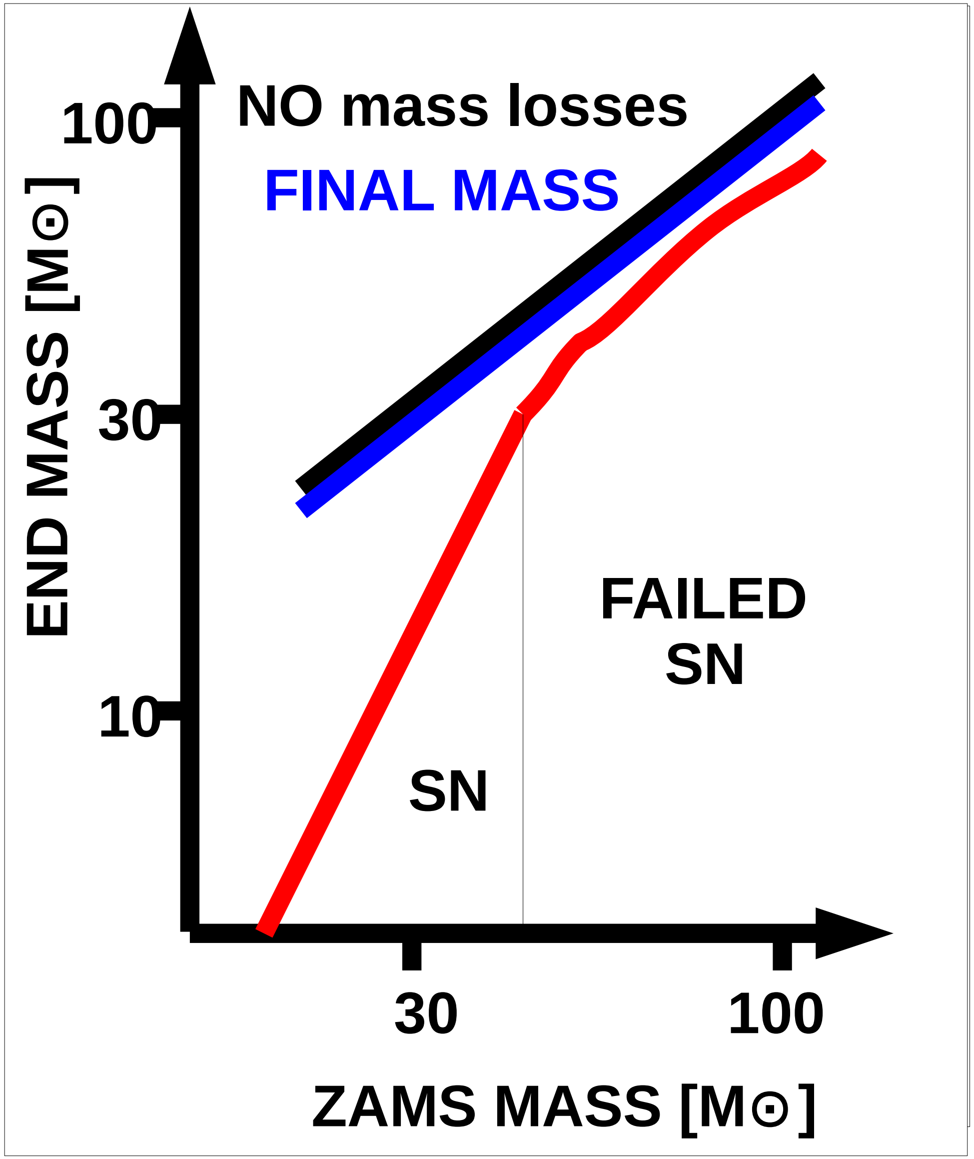
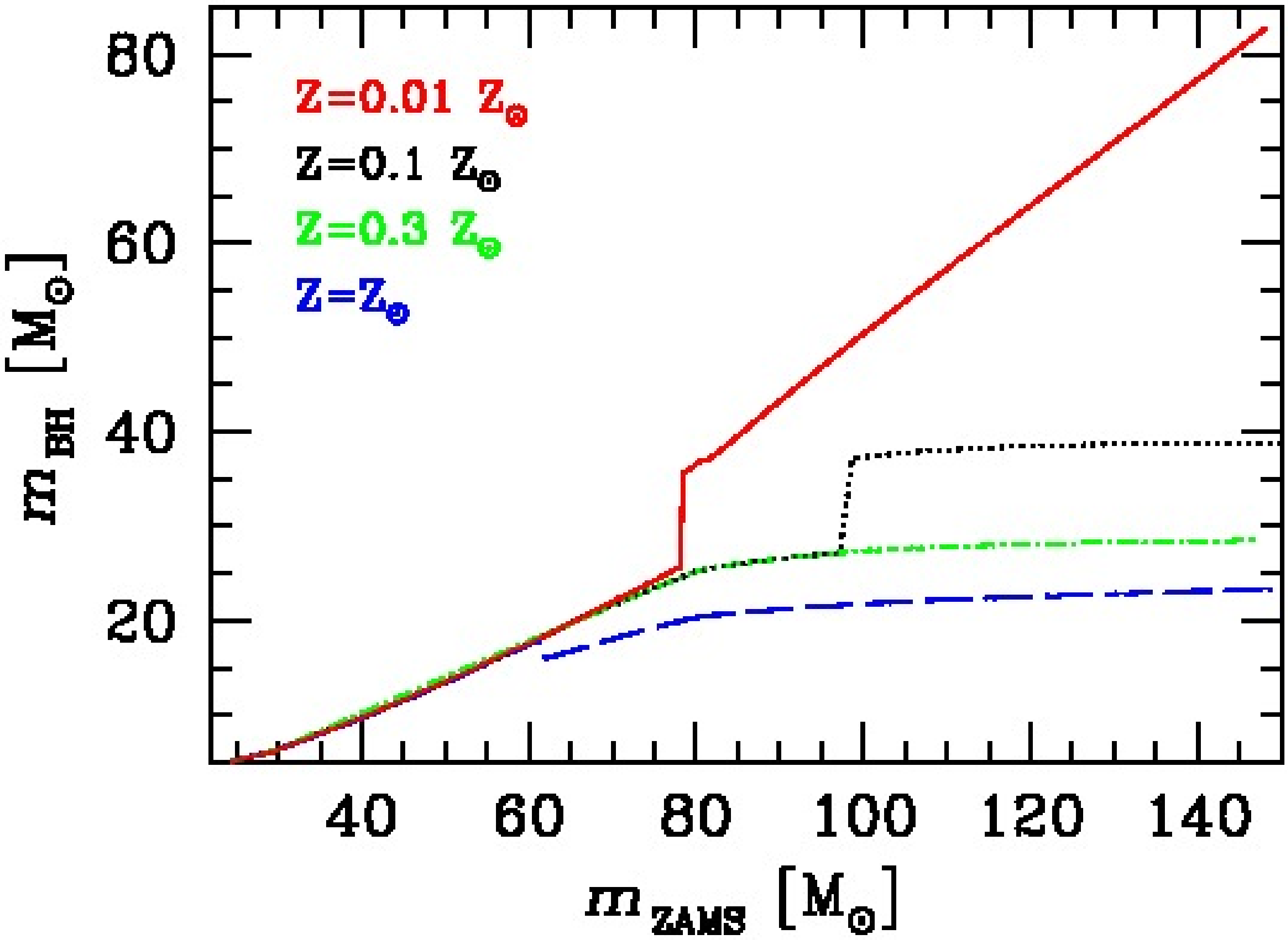
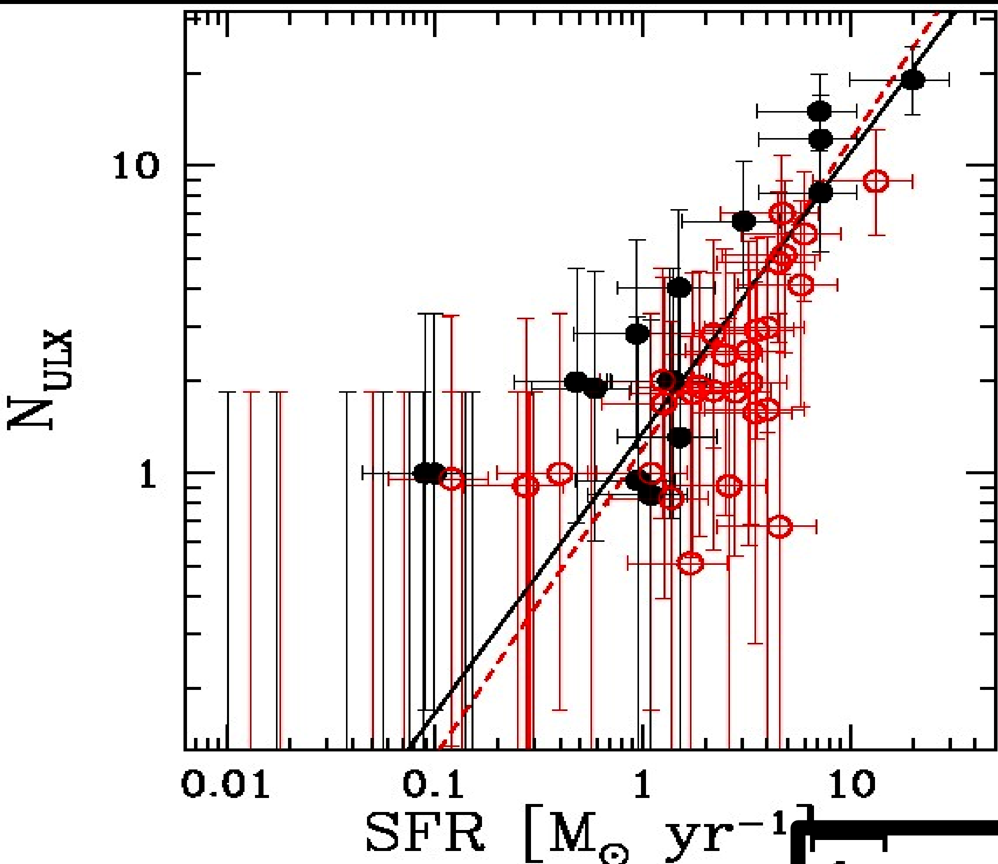


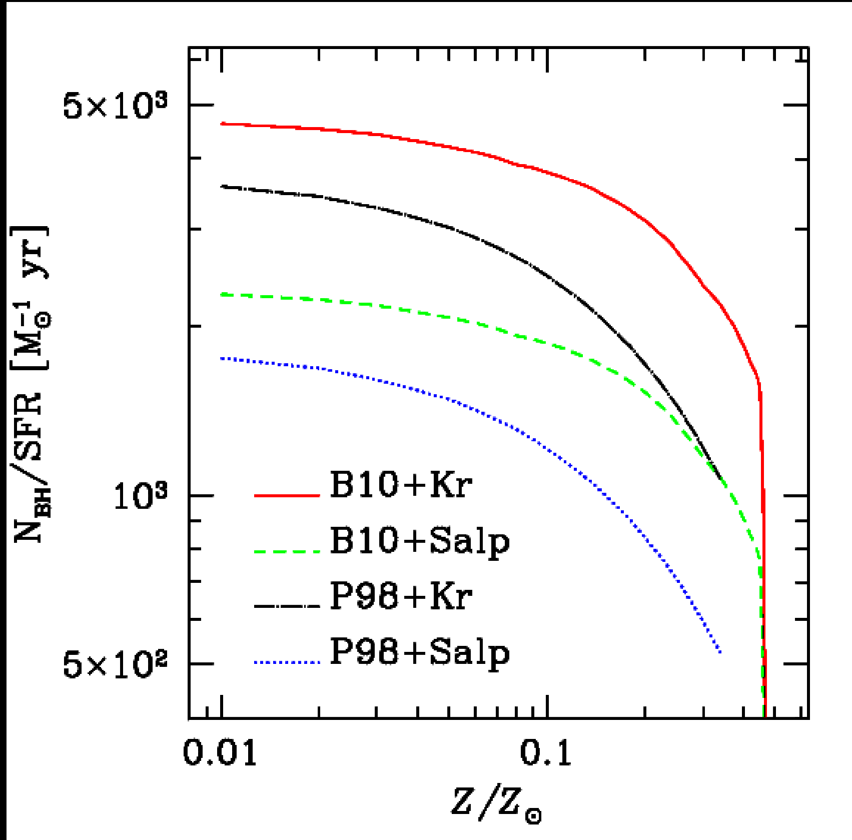


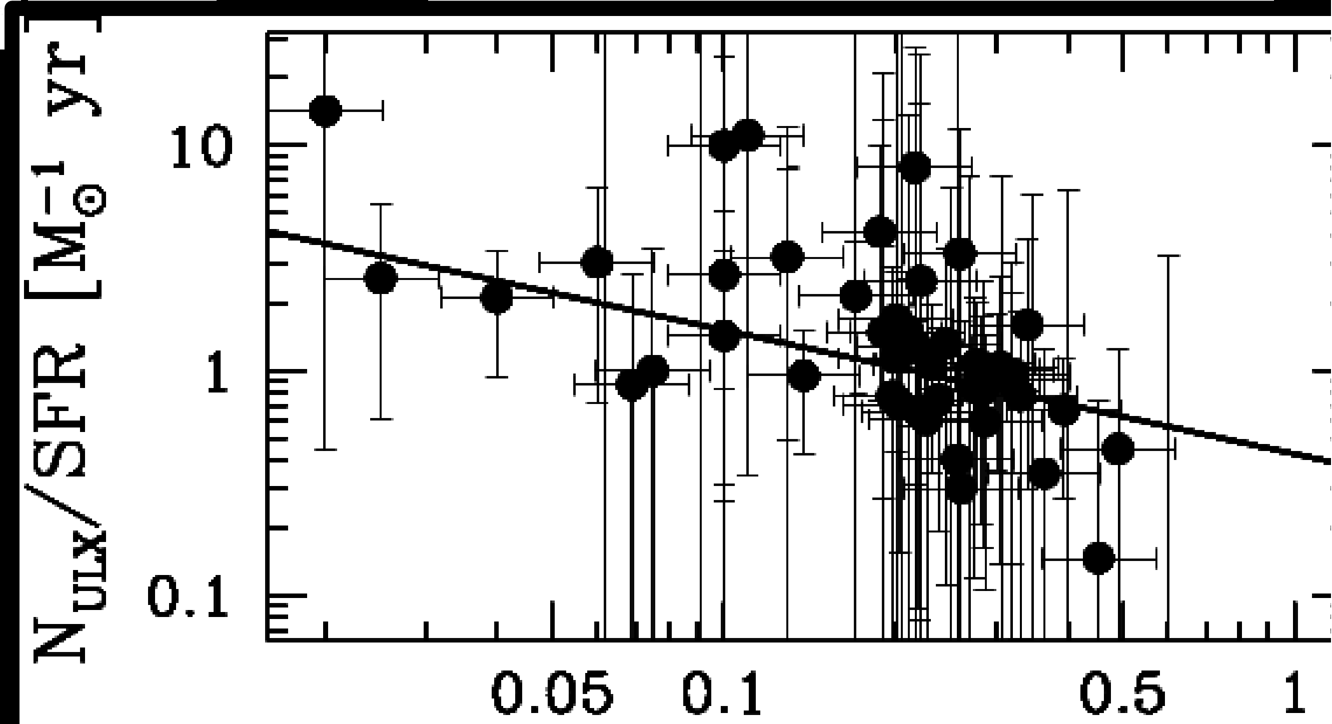
NOT ONLY AT ZERO METALLICITY



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

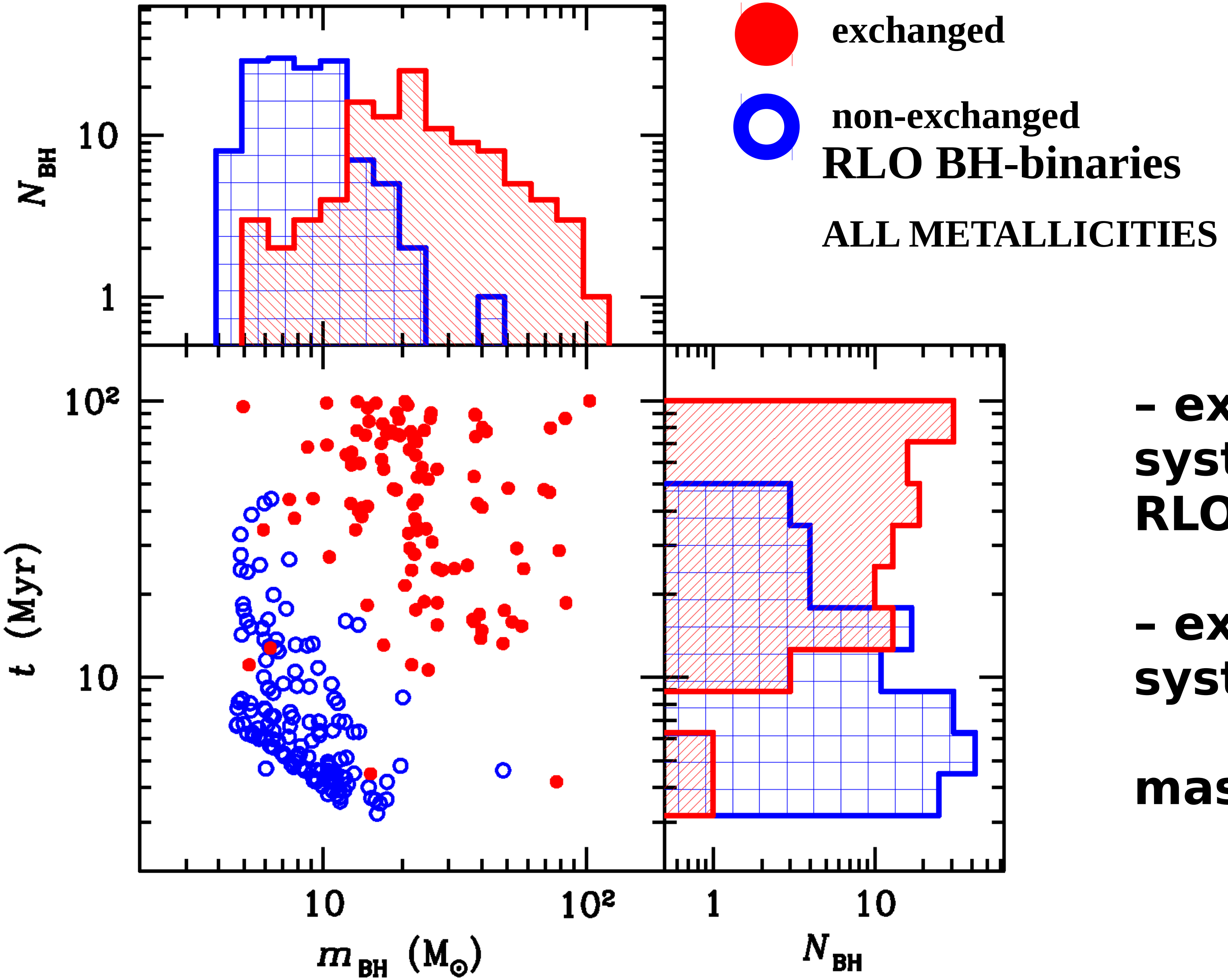






e.g.
Zampieri et al. 2004;
Soria et al. 2005;
Swartz et al. 2008;
MM, Colpi & Zampieri 2009;
Zampieri & Roberts 2009;
MM+ 2010, 2011;
Kaaret & Feng 2013

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 host more massive BHs

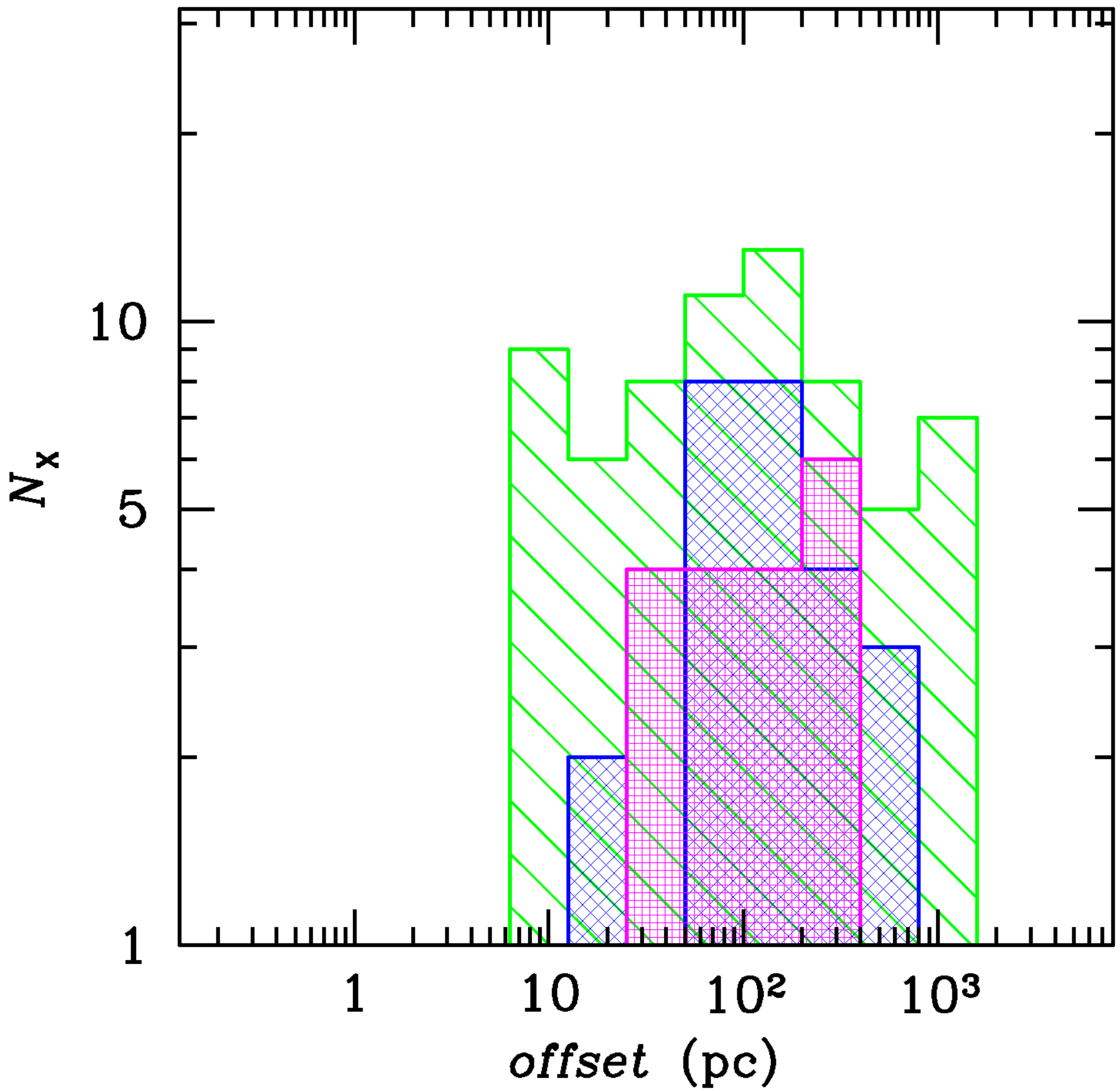
MAIN PROPERTIES of COLLISIONAL stellar systems in the MILKY WAY

ONE OF THE MAIN PROPERTIES OF COLLISIONAL SYSTEMS IS THAT

THREE-BODY ENCOUNTERS
(= CLOSE GRAVITATIONAL ENCOUNTERS BETWEEN A BINARY AND A SINGLE STAR)

ARE FREQUENT IN COLLISIONAL SYSTEMS

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



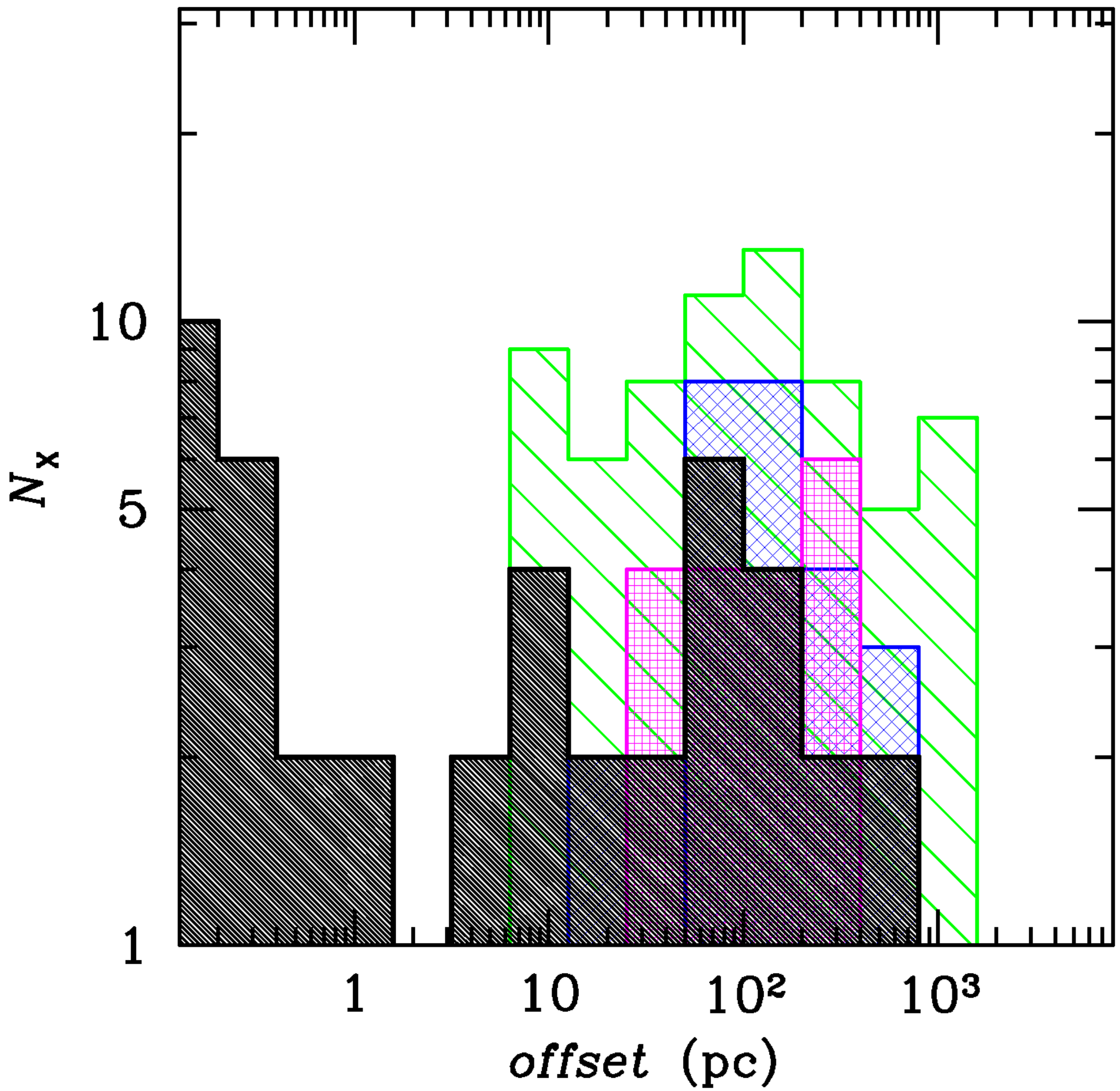
Kaaret et al. 2004 (bright X-ray binaries in M82, NGC1569, NGC5253)

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

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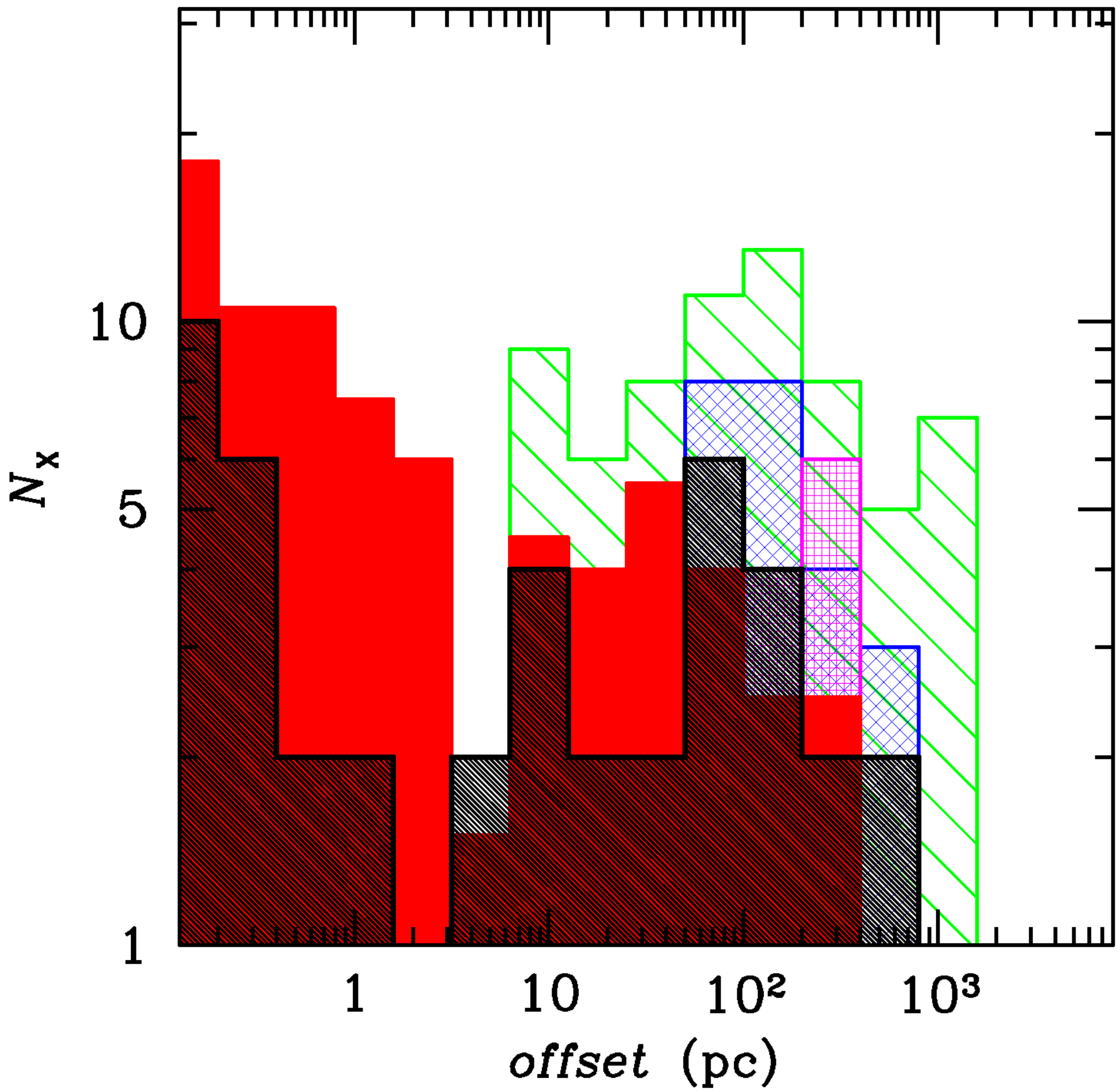

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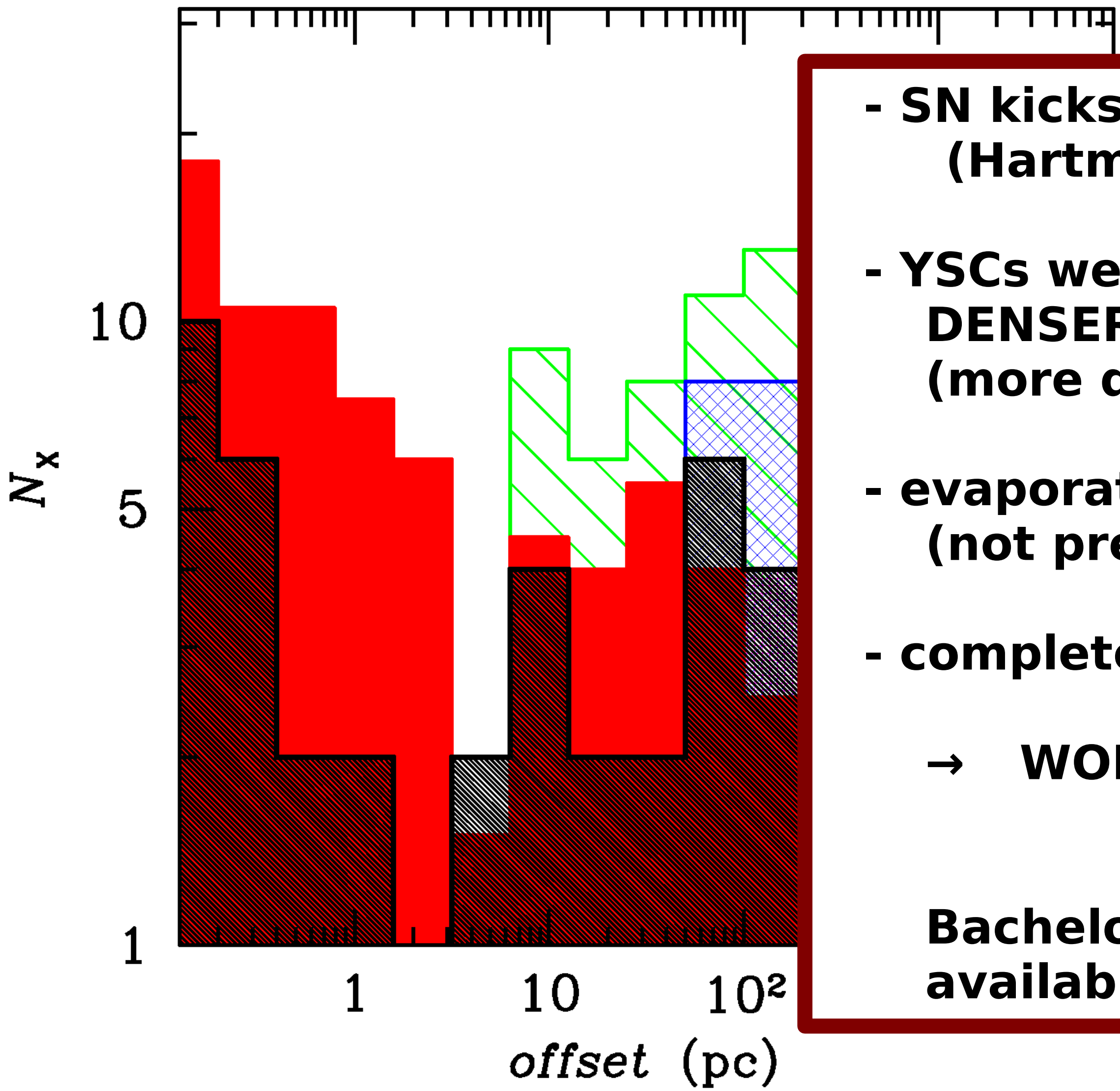
Poutanen et al. 2013 (bright X-ray binaries in the Antennae)

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

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

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!)