How to be ready for multi-messenger astronomy:

Gravitational wave sources in the frequency range of Advanced LIGO and VIRGO

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Jena, September 1st 2015

OUTLINE:

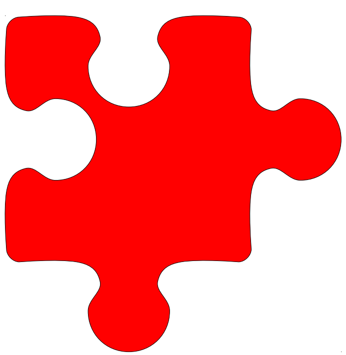
1. gravitational wave (GW) sources for LIGO/Virgo: merging black hole (BH) and neutron star (NS) binaries

2. possible electromagnetic counterparts

3. how to estimate the merger rate of BH and NS binaries

4. impact of environment on merger rate

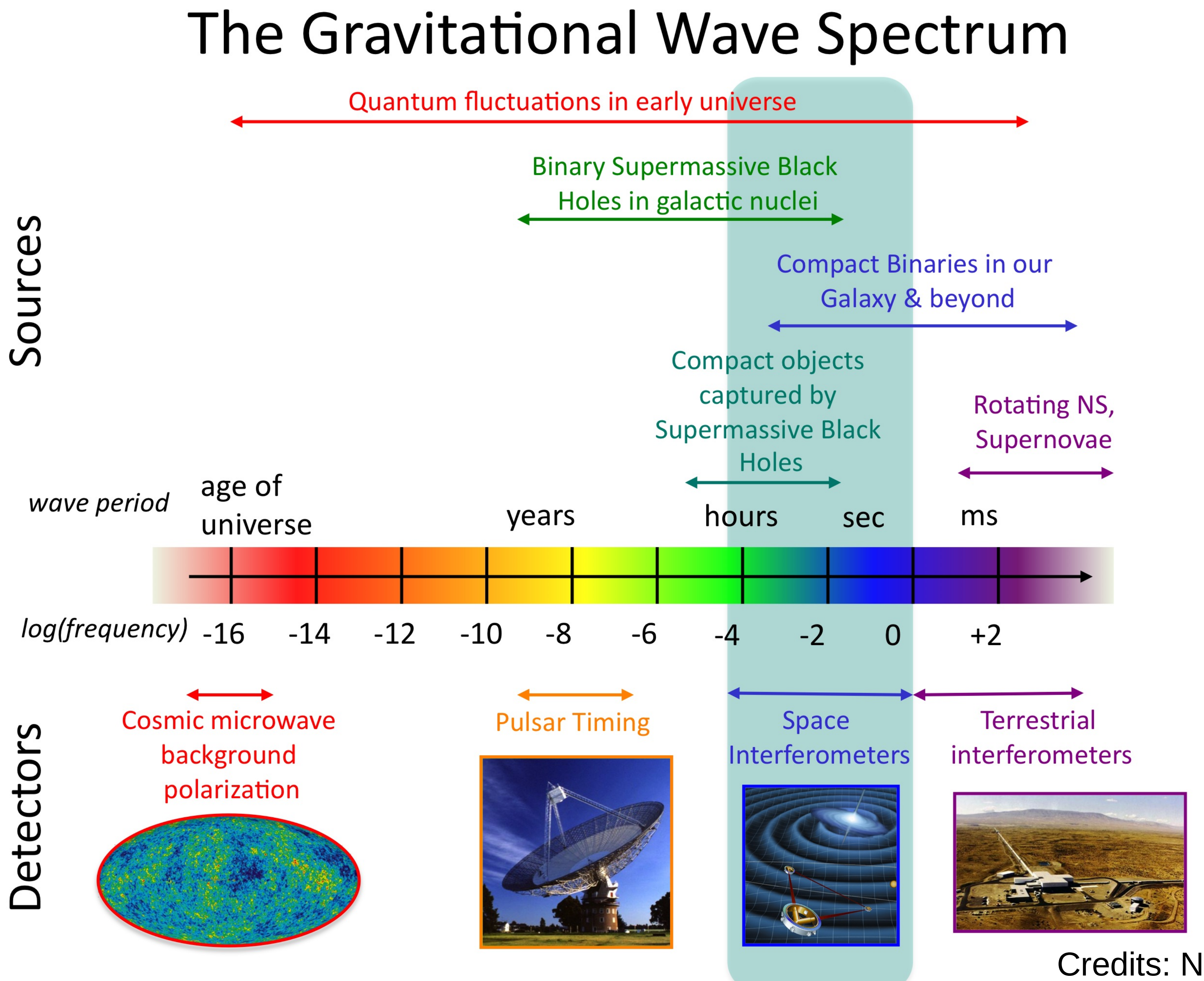
NOTE: MIND THE SLIDES WITH THIS FLAG
THEY ARE SIMPLE SUGGESTIONS FOR
TEACHING TO HIGH-SCHOOL STUDENTS!!!



1. gravitational wave sources for LIGO/Virgo

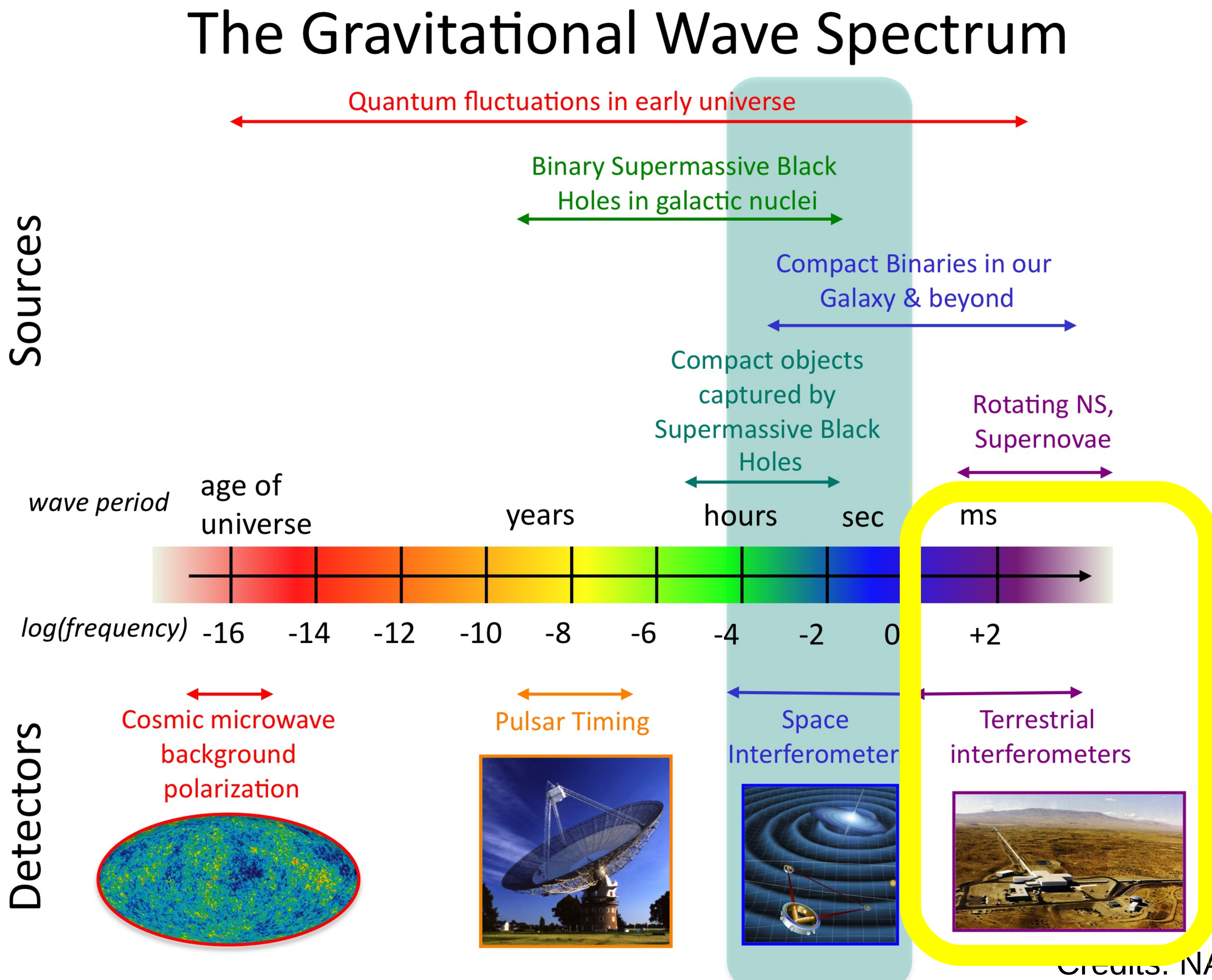
Virgo (Santo Stefano a Macerata, Cascina, Italy)

1. gravitational wave sources for LIGO/Virgo



Credits: NASA

1. gravitational wave sources for LIGO/Virgo



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1. gravitational wave sources for LIGO/Virgo

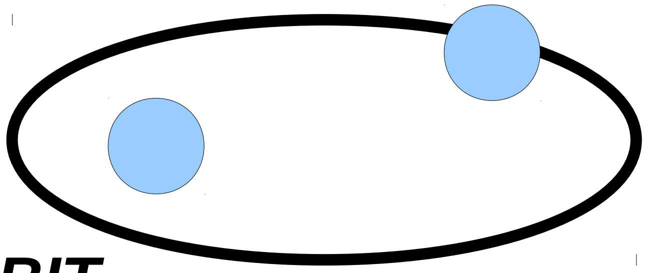
Focus on MERGING double compact-object binaries because LIGO-VIRGO sources

black hole – black hole (BH-BH) binaries

neutron star-neutron star (NS-NS) binaries

black hole – neutron star (BH-NS) binaries

For BH-BH, BH-NS and NS-NS binary I mean KEPLERIAN binary: BOUND SYSTEM on ELLIPTICAL ORBIT composed of 2 BHs, or 2 NSs or 1 BH + 1 NS



1. gravitational wave sources for LIGO/Virgo

QUESTIONS TO ADDRESS IN THIS LECTURE FROM A SIMPLE POINT OF VIEW

1 → HOW DO BHs and NSs form?

2 → WHY DO GWs cause BH- and NS-binaries to merge (GW frequencies)?

3 → Are there electromagnetic (EM) counterparts (if any)?

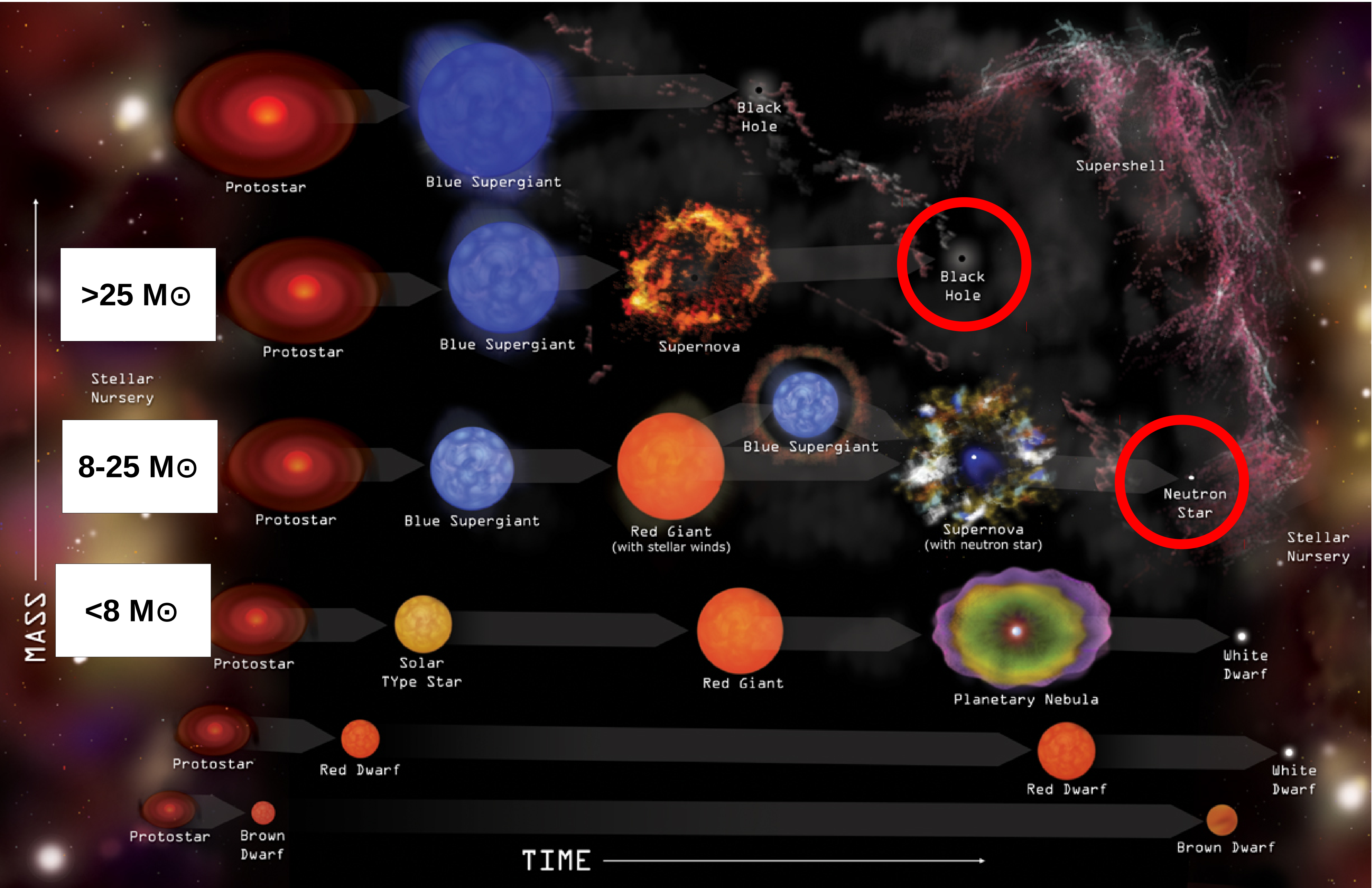
4 → WHAT IS THE RATE of MERGERS?

5 → WHAT IS THE ENVIRONMENT EFFECT ON THE RATE?

1. gravitational wave sources

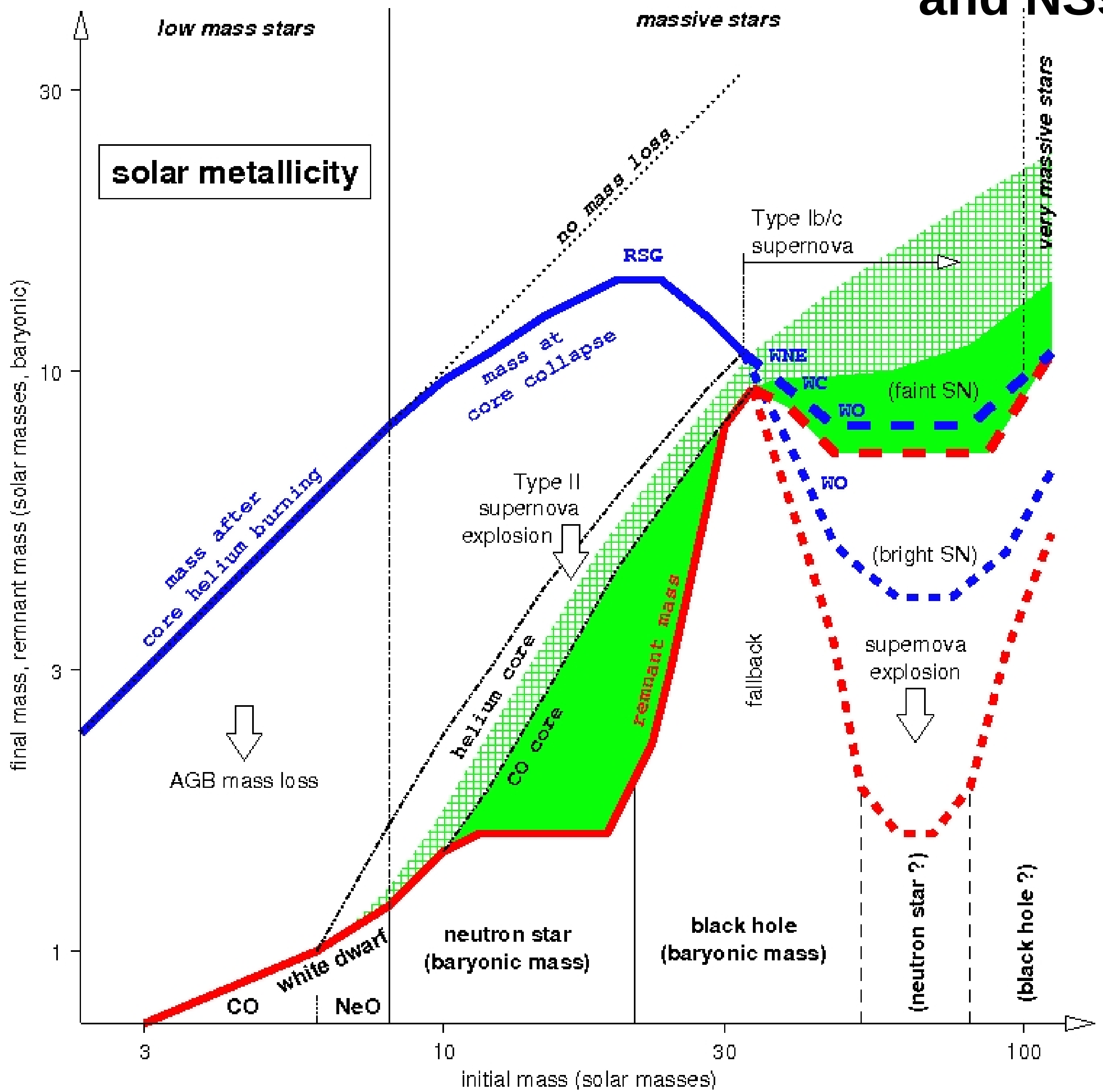
1 → HOW DO BHs and NSs form?

Credits: Chandra



1. gravitational wave sources

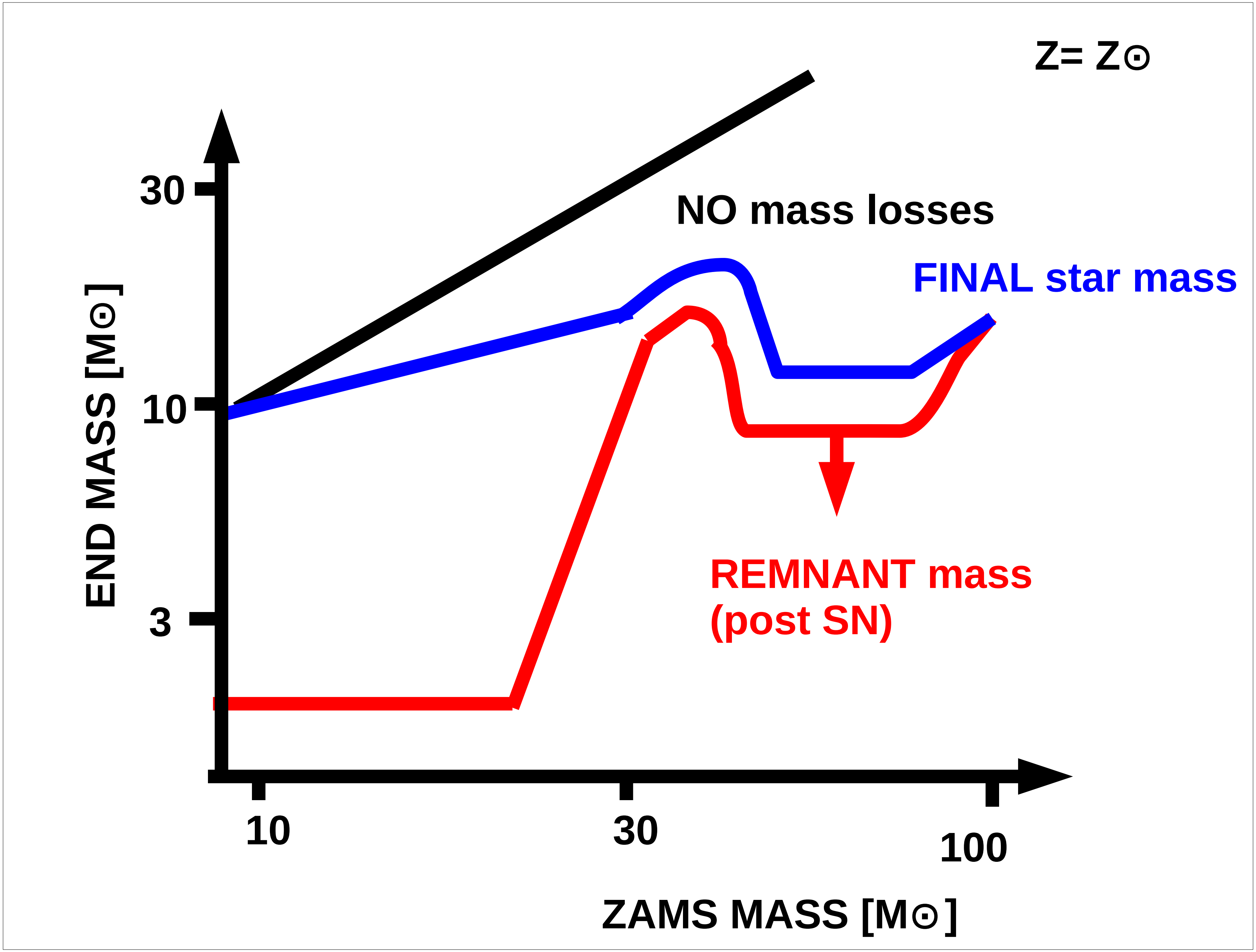
1 → HOW DO BHs and NSs form?



Heger et al. (2003)

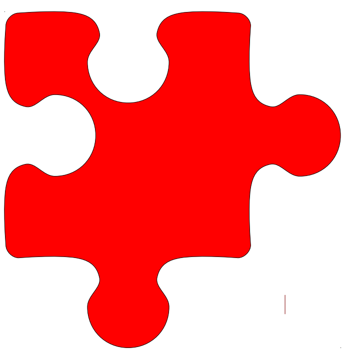
1. gravitational wave sources

1 → HOW DO BHs and NSs form?



1. gravitational wave sources

CARTOON OF NS-NS MERGER



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

Credits: NASA

Movies by NASA are a perfect reservoir for high-school students

2 → WHY DO GWs cause BH- and NS-binaries to merge?

1. gravitational wave sources

2 → WHY DO GWs cause BH- and NS-binaries to merge?

From yesterday talks:

- GW emission only from QUADRUPOLE
A binary has a non-zero mass QUADRUPOLE
Thus emits GW

- GW emission implies energy loss

Binary's energy = $$E_{\rm int} = -\frac{G\, m_1\, m_2}{2\, a}$$

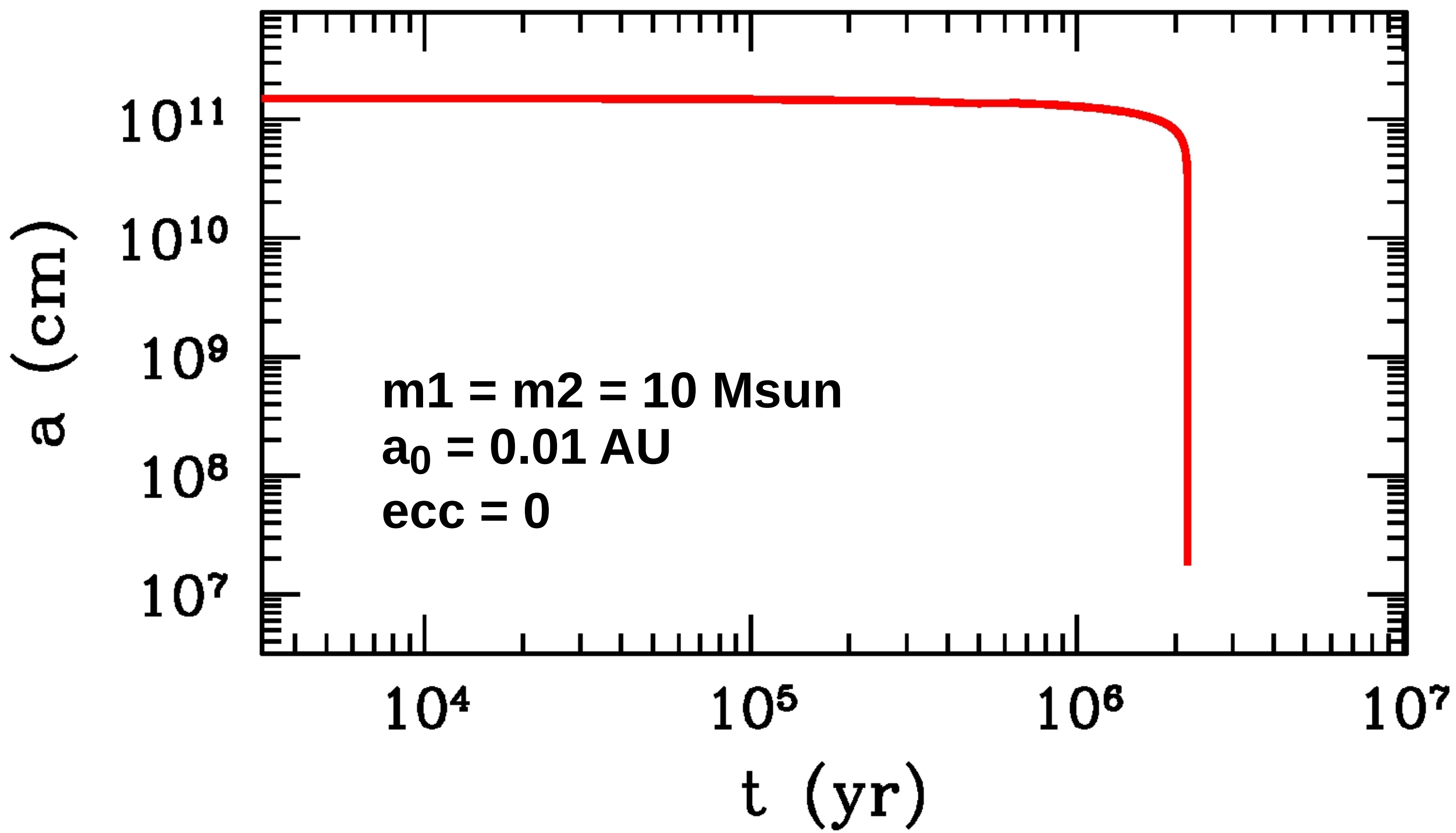
Semi-major axis of Kepler binary changes as

$$\frac{\mathrm{d}a}{\mathrm{d}t} \sim -\frac{64}{5}\frac{G^3\, m_1\, m_2\, (m_1 + m_2)}{c^5\, a^3\, (1-e^2)^{7/2}}$$

Peters (1964)

1. gravitational wave sources

$$a(t) = a_0 \left[1 - \frac{256/5\, G^3\, m_1\, m_2\, (m_1 + m_2)\, t}{c^5\, (1-e^2)^{7/2}\, a_0^4}\right]^{1/4}$$



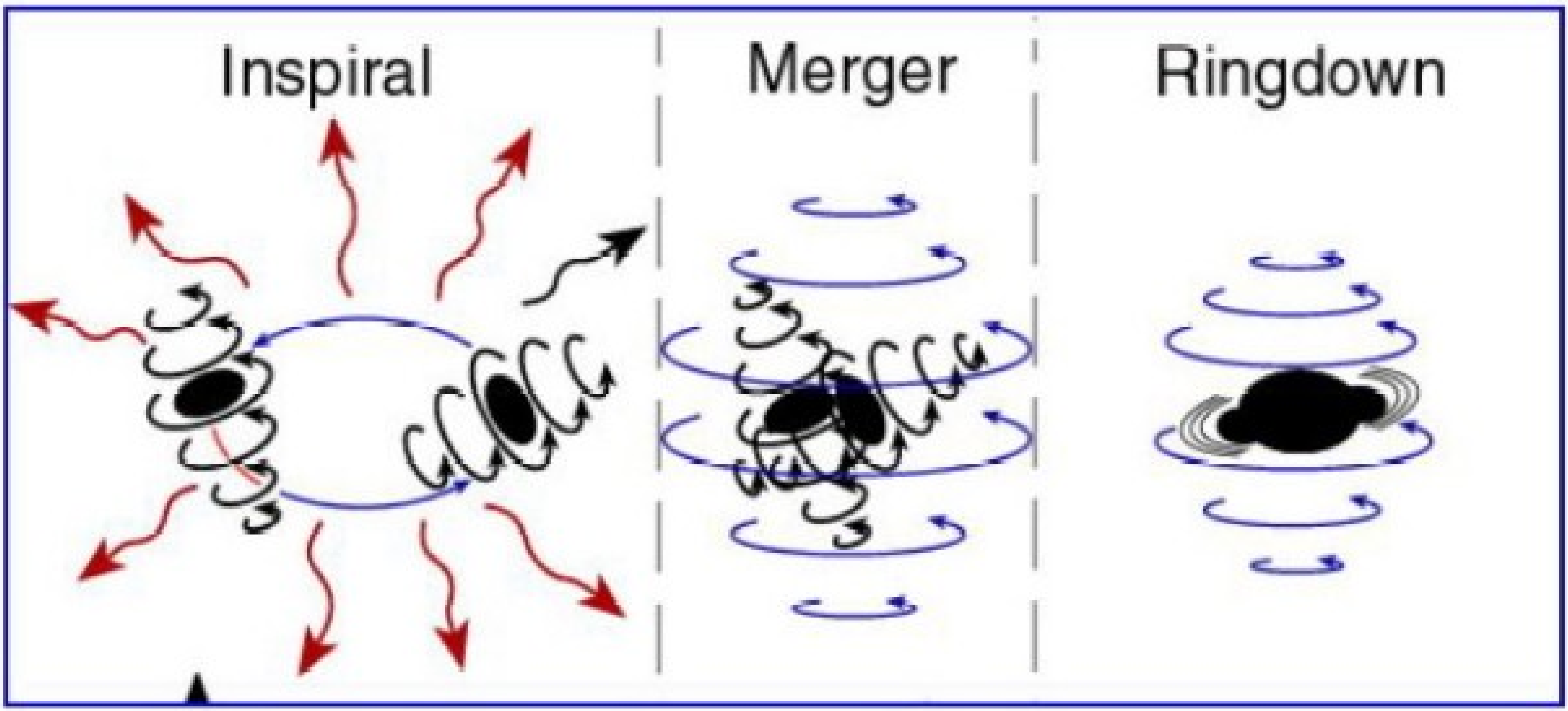
1. gravitational wave sources

$$a(t) = a_0 \left[1 - \frac{256/5\, G^3\, m_1\, m_2\, (m_1 + m_2)\, t}{c^5\, (1 - e^2)^{7/2}\, a_0^4} \right]^{1/4}$$

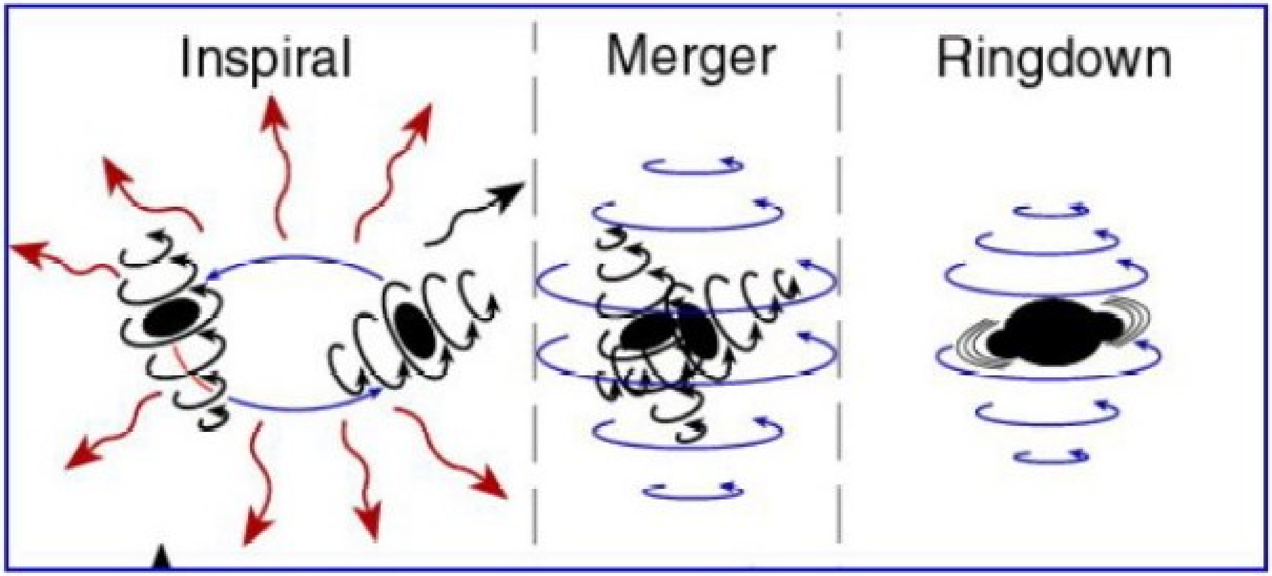
→ **MERGER TIMESCALE: time for the semi-major axis to shrink to zero due to GW emission**

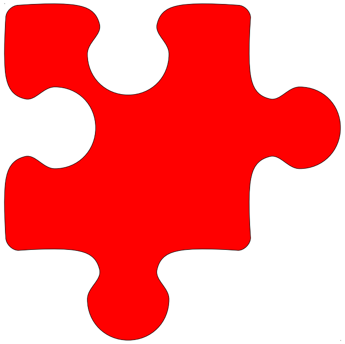
$$t_{\mathrm{GW}} = \frac{5}{256} \frac{c^5\, (1 - e^2)^{7/2}\, a_0^4}{G^3\, m_1\, m_2\, (m_1 + m_2)}$$

1. gravitational wave sources



1. gravitational wave sources





Some back of the envelope calculations:

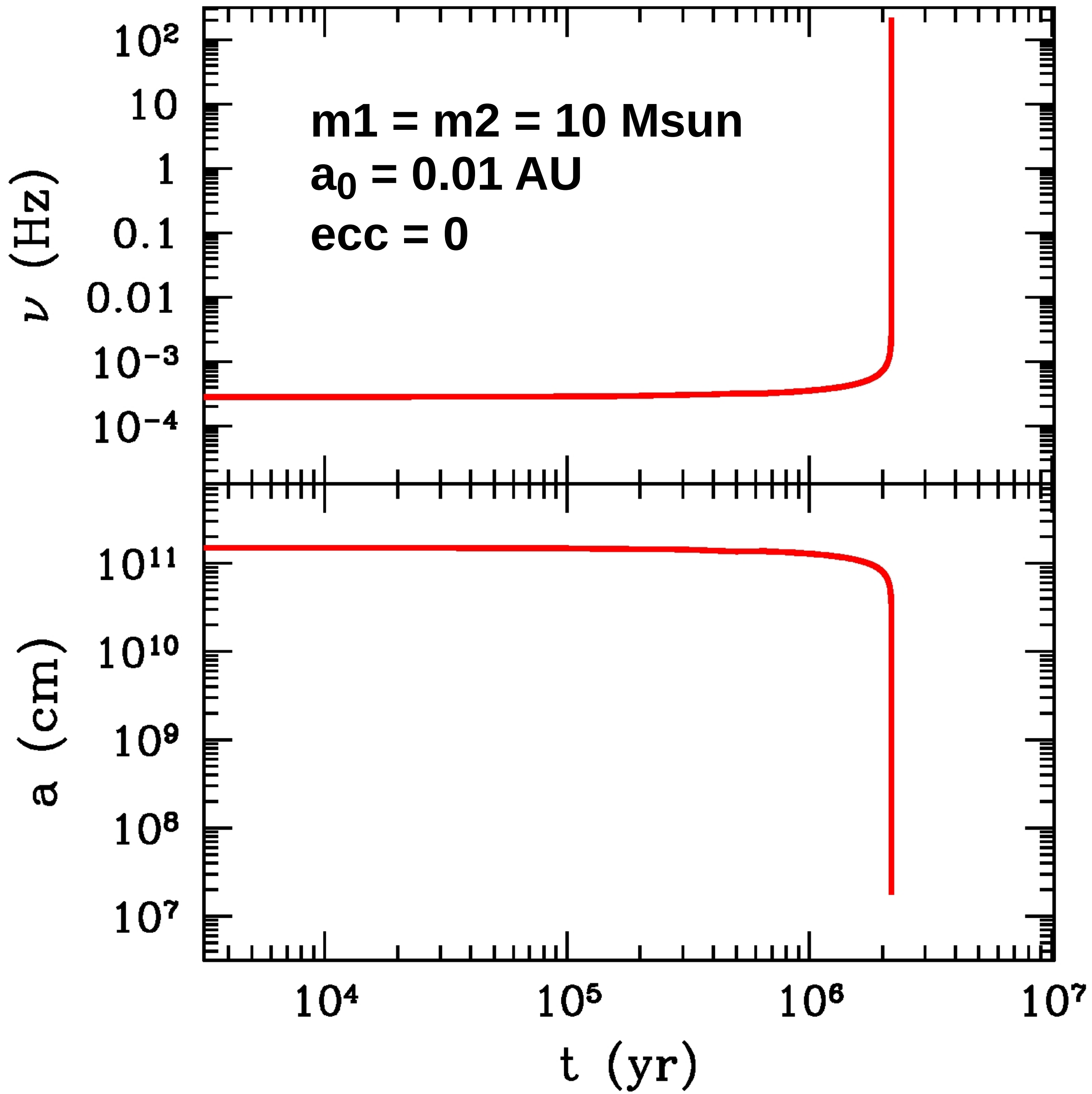
- frequency of gravitational waves

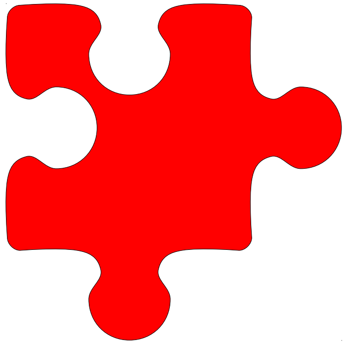
$$\omega_{\mathrm{GW}} = 2\,\omega_{\mathrm{orb}}$$

HIGH-SCHOOL STUDENTS CAN CALCULATE KEPLERIAN FREQUENCY!!!

$$\omega_{\mathrm{orb}} = \sqrt{\frac{G\,m_{\mathrm{TOT}}}{a^3}}$$

1. gravitational wave sources

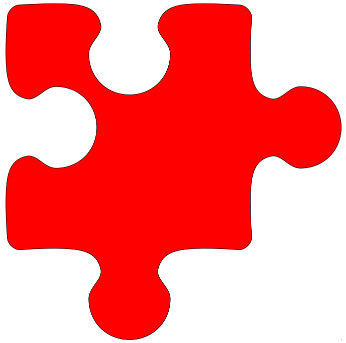


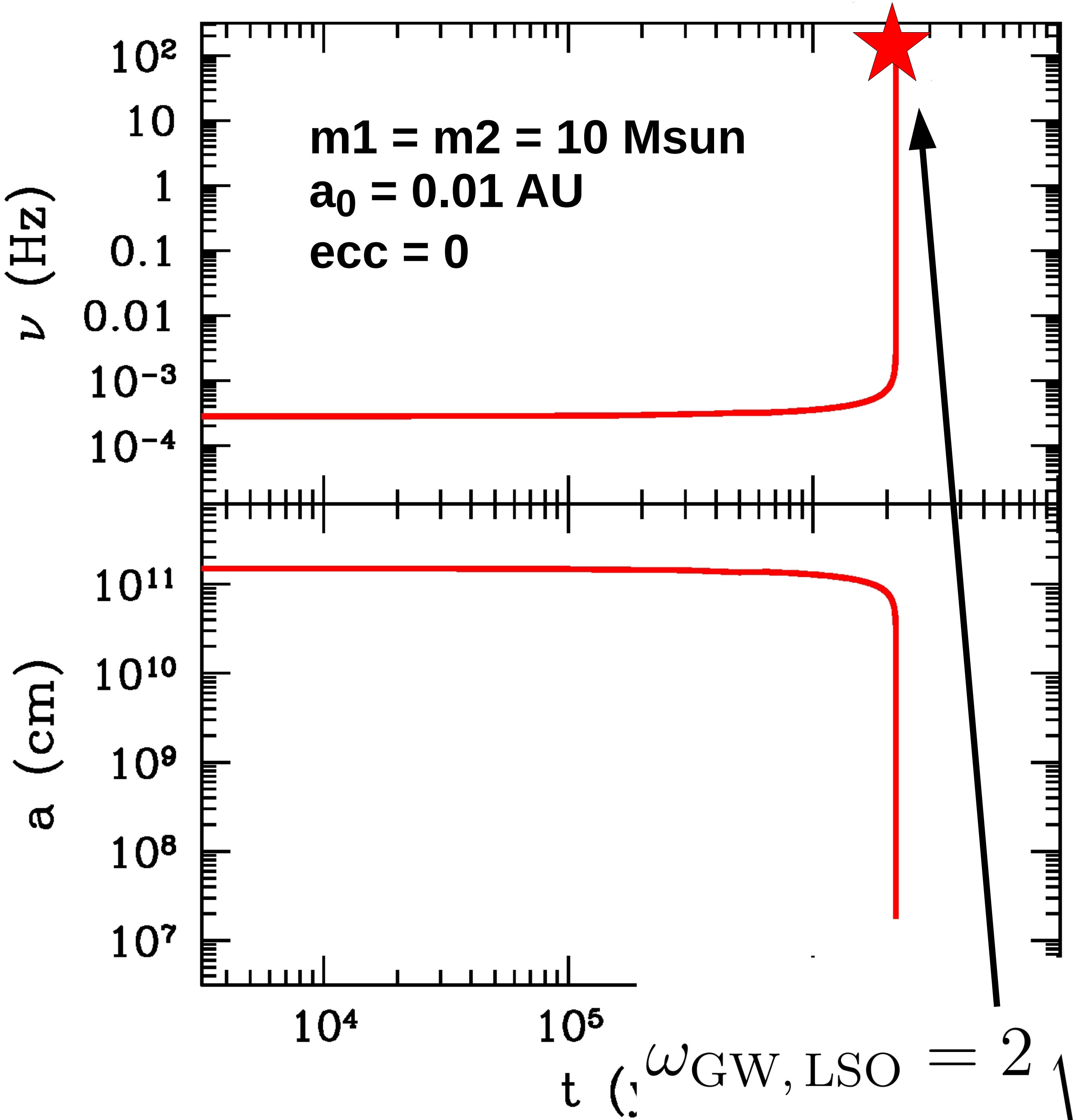


$$\omega_{\rm GW} = 2\,\omega_{\rm orb}$$

means that when two objects are FAR away GW frequency is LOWER

1. gravitational wave sources





→ **higher frequency just before merger**

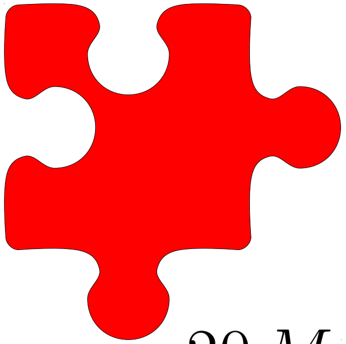
- last stable orbit

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

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

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

1. gravitational wave sources

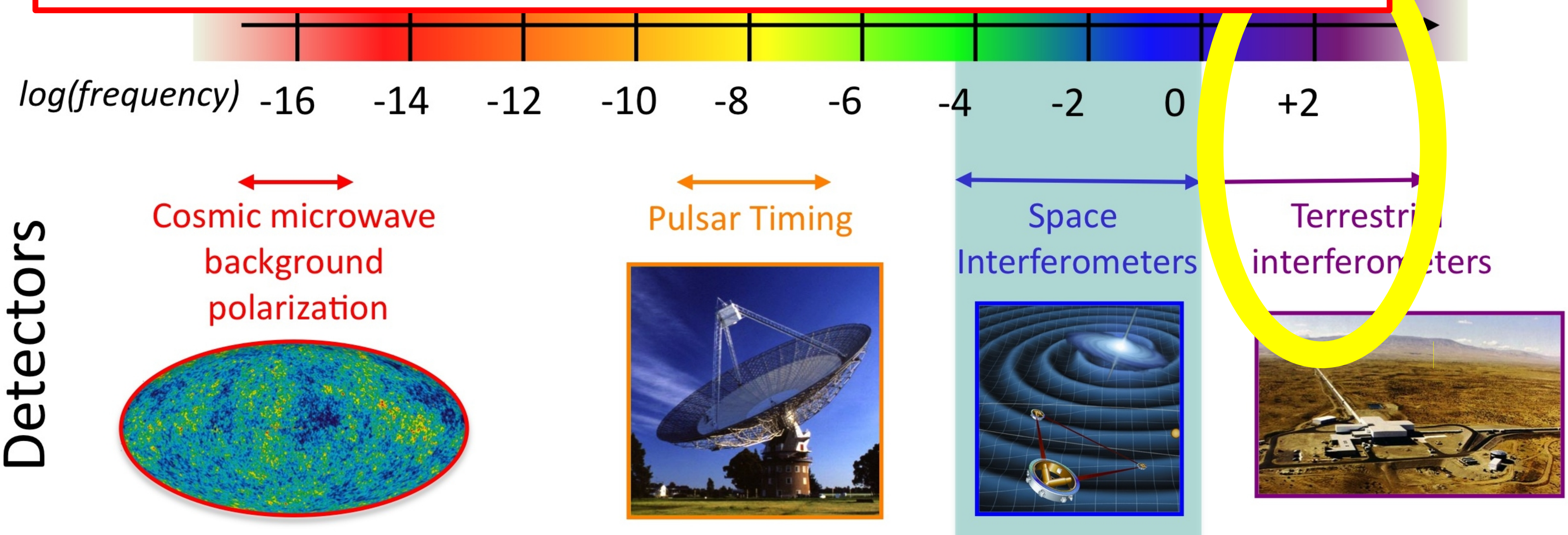


Some back of the envelope calculations:

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

$$\omega_{\mathrm{GW,LSO}} = 2\sqrt{\frac{G\,(m_1+m_2)}{r^3_{\mathrm{LSO}}}} = \frac{2\,c^3}{6^{3/2}\,G\,(m_1+m_2)} \sim 1385\,\mathrm{s}^{-1}\,\frac{20\,M_\odot}{m_1+m_2}$$

$$\nu_{\mathrm{GW,LSO}} \sim 220\,\mathrm{Hz}\,\frac{20\,M_\odot}{m_1+m_2}$$



1. gravitational wave sources

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

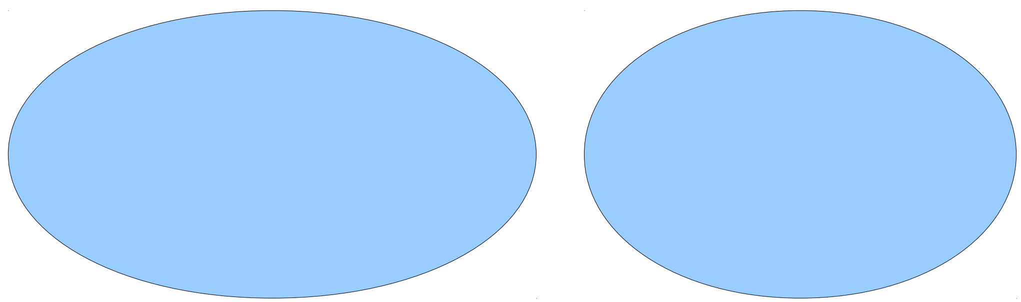
1. gravitational wave sources

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

Stars have a much larger radius than NSs and BHs

→

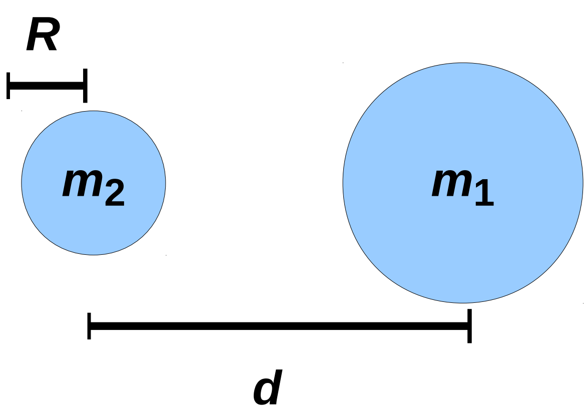
When 2 stars are too close, tidal forces between them SQUEEZE and DISRUPT THEM



The 2 stars merge before they emit GWs in the LIGO/VIRGO range

1. gravitational wave sources

WITH THE PROPER FORMALISM



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

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

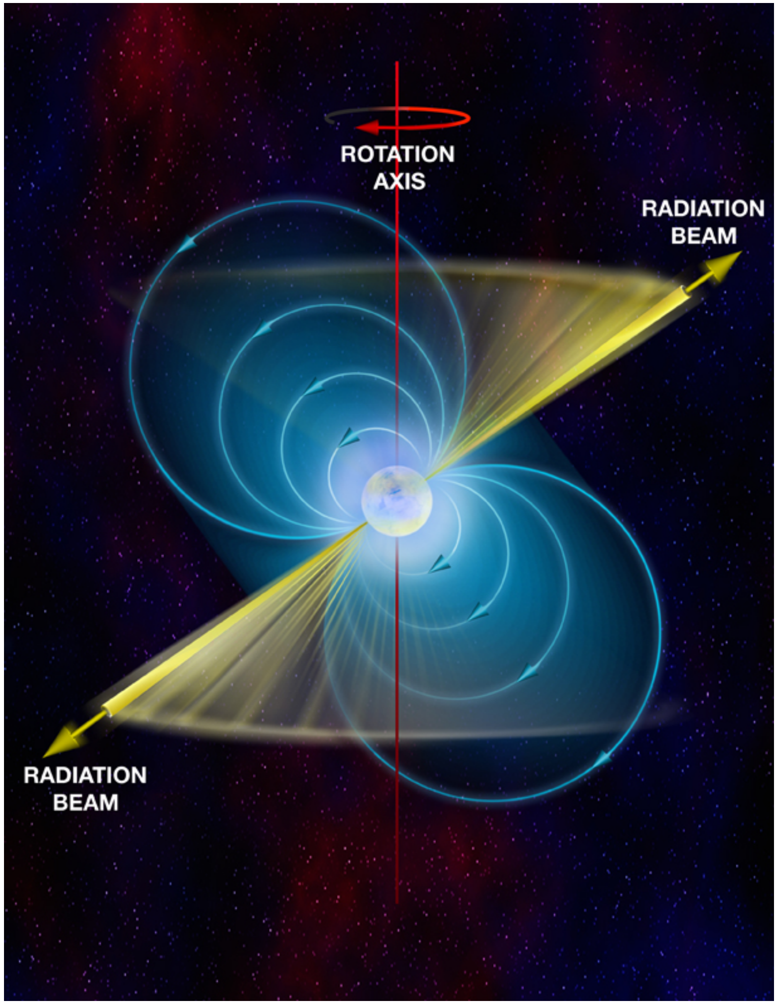
MUCH LOWER THAN LIGO-VIRGO range!!!

2. possible electromagnetic ~~counterparts~~ precursors

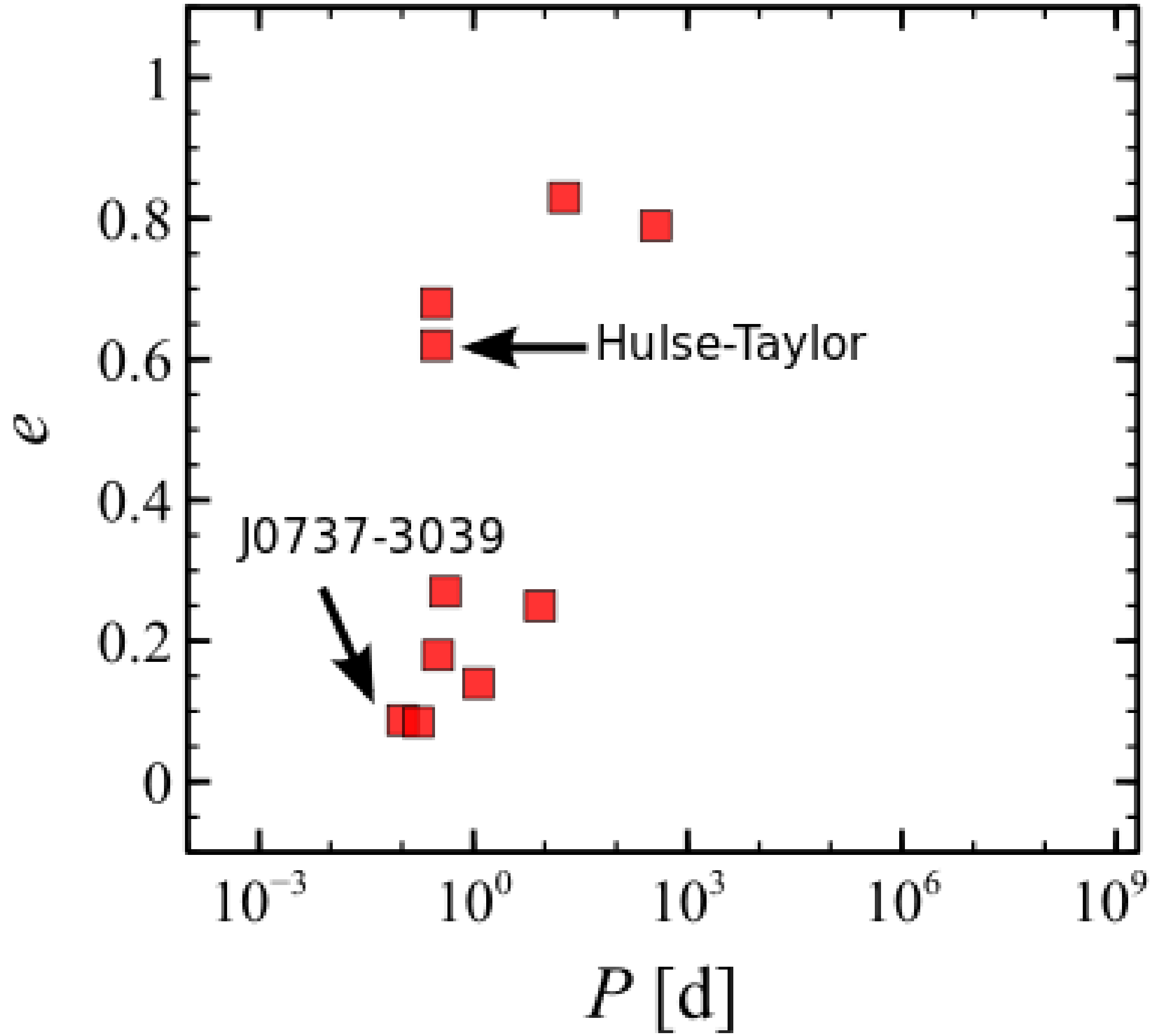
- **OBSERVATION OF ~10 NS-NS systems**

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

See Niccolò's talk!



CREDIT: Bill Saxton, NRAO/AUI/NSF



From Ziosi, PhD thesis

2. possible electromagnetic ~~counterparts~~ precursors

- NO OBSERVATIONS OF STELLAR BH-BH BINARIES
in principle possible only from dynamics signatures (eg a pulsar in a triple BH-BH-NS system)

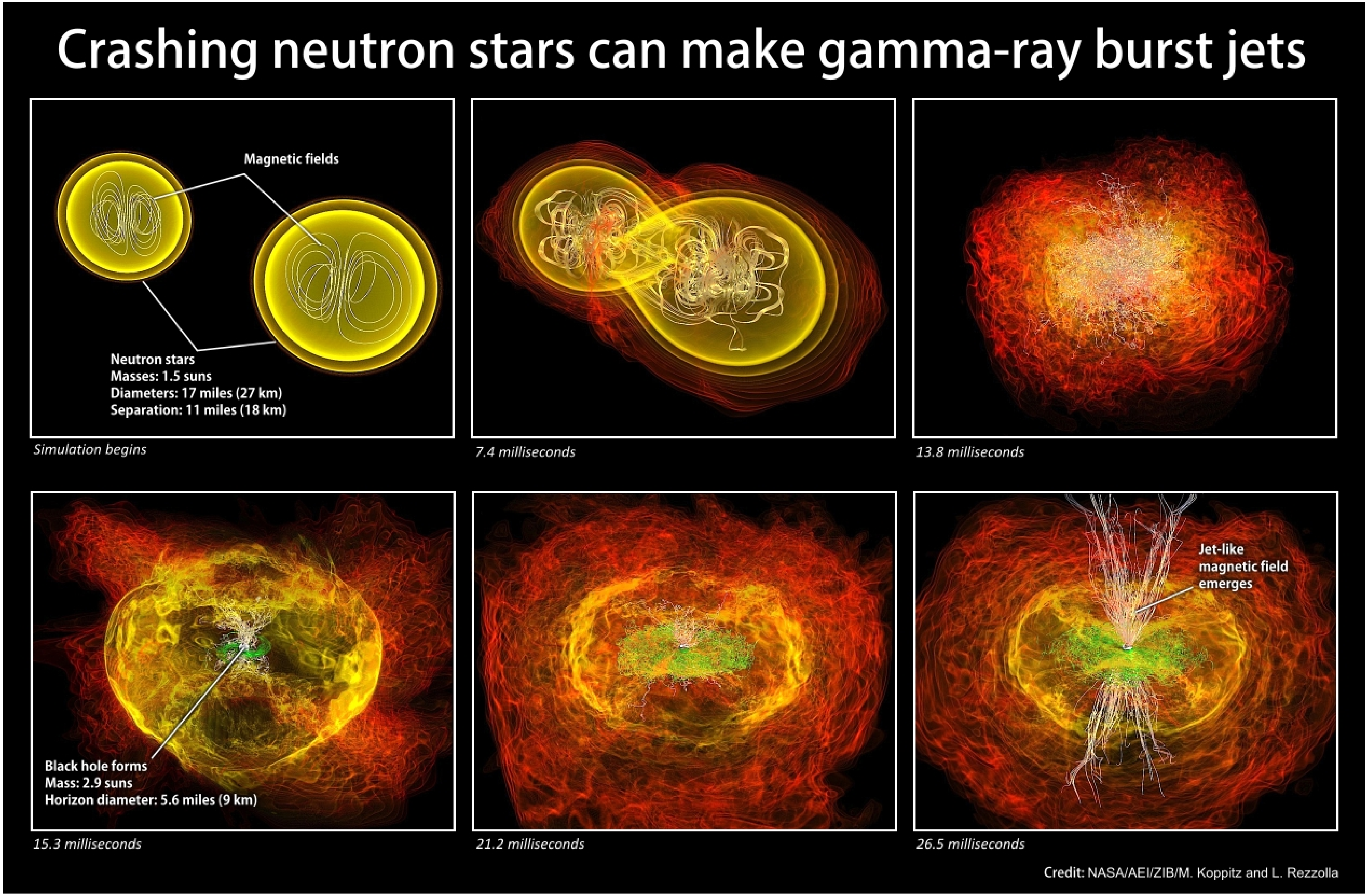
- BH-WR binaries:

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

Cartoon of a BH-WR

2. possible electromagnetic counterparts

The 'Genuine' EM counterparts of NS-NS and NS-BH are SHORT GRBs..

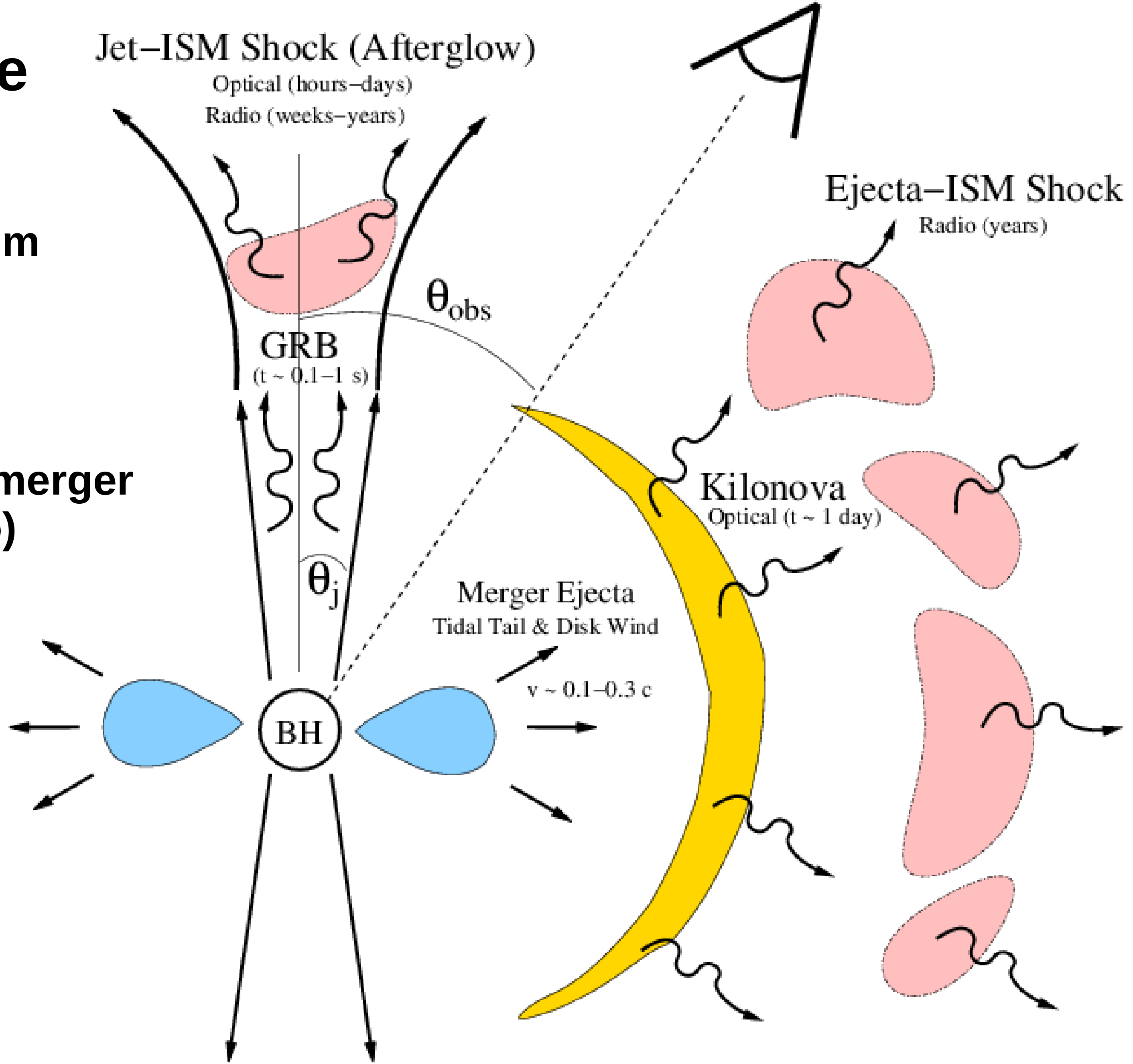


2. possible electromagnetic counterparts

...and/or kilonovae

GRB afterglow comes from shocks with ISM

Kilonova comes from radioactive decay of merger ejecta (optical – radio)



Mezger & Berger 2011

2. possible electromagnetic counterparts

...and/or kilonovae

Short GRB:	Kilonova:
- gamma-rays (<2 sec) come from relativistic jet (BEAMED!)	- comes from radioactive decay of merger ejecta (optical – radio)
- GRB (X-ray to optical) afterglow comes from shocks with ISM	- expected high speed (~10^4 km/s, Kasen+ 2015)
- optical (isotropic) luminosity up to ~10^{43} erg/s for hours-days	- optical – NIR luminosity up to ~10^{41} erg/s lasts for ~1 day
- radio emission lasts for weeks-yrs	- radio emission lasts for years
- ~50 short GRBs with afterglows observed since 2005	- maybe associated with NIR excess observed in some GRB (Tanvir+ 2013, Berger+ 2013)

2. possible electromagnetic counterparts

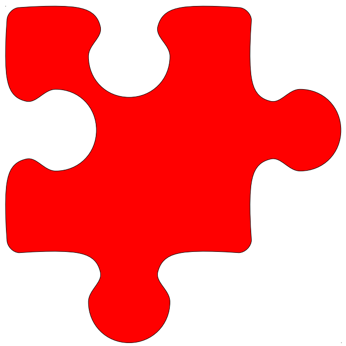
IMPORTANCE of COUNTERPARTS:

1. **COLLECT MORE INFORMATION ON OBJECTS THAT EMIT GWs (e.g. space location)**
   → **see other talks**

2. **HELP ESTIMATING THE MERGER RATE**
   → **next slides**

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

CALCULATE RATES IS IMPORTANT FOR EVERYDAY LIFE
(even of high-school students)

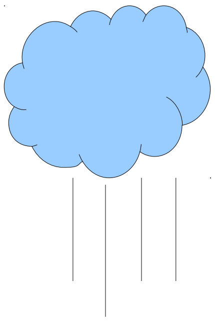


RATE of RAINY DAYS

e.g. number of rainy days per year in Italy

A limited time: I have 1 week to do my measurements

M	T	W	T	F	S	S



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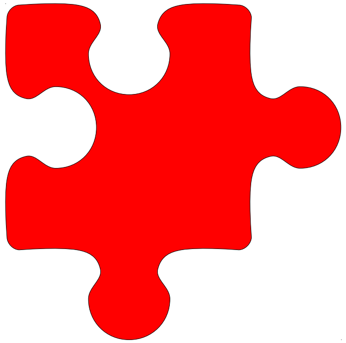

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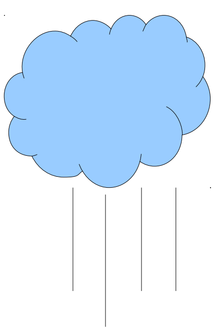

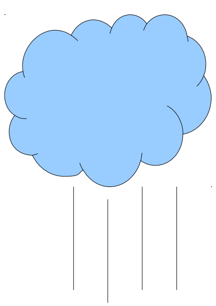

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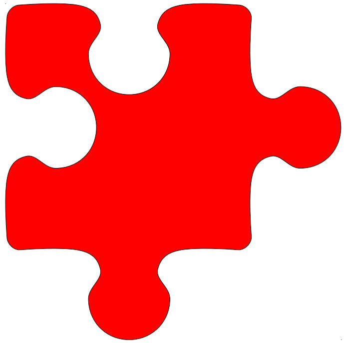

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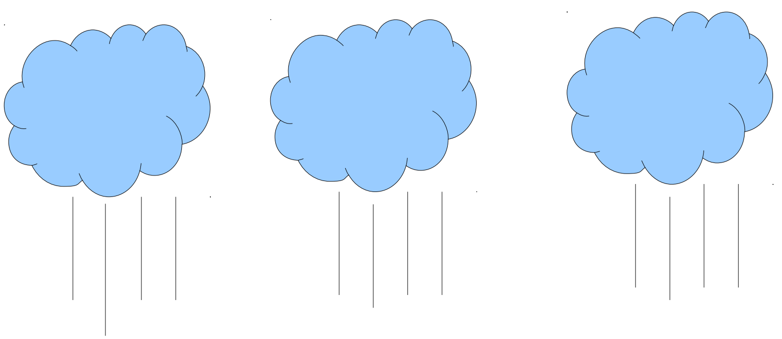

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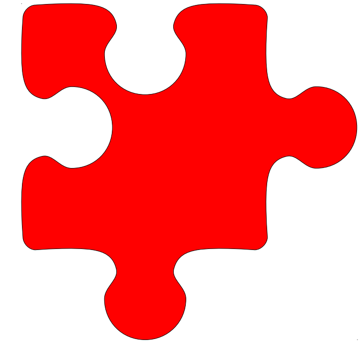

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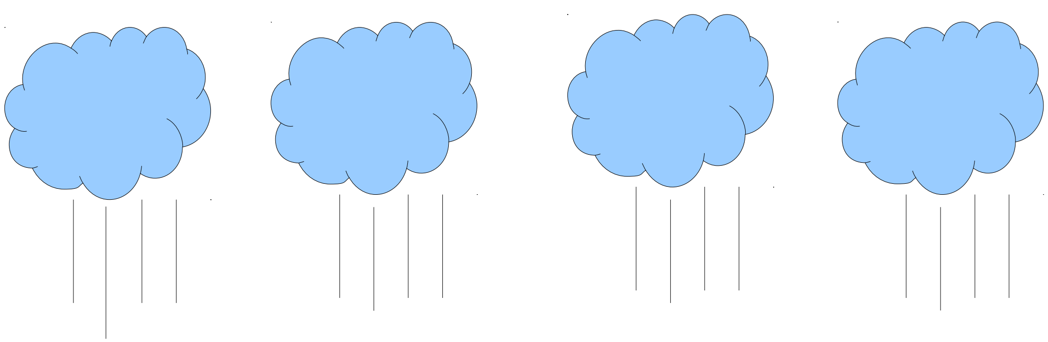

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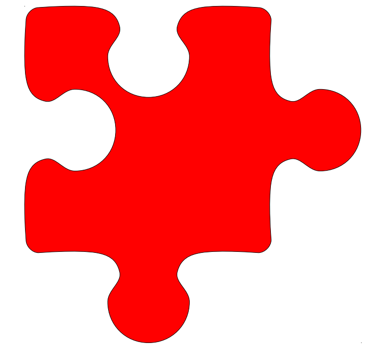

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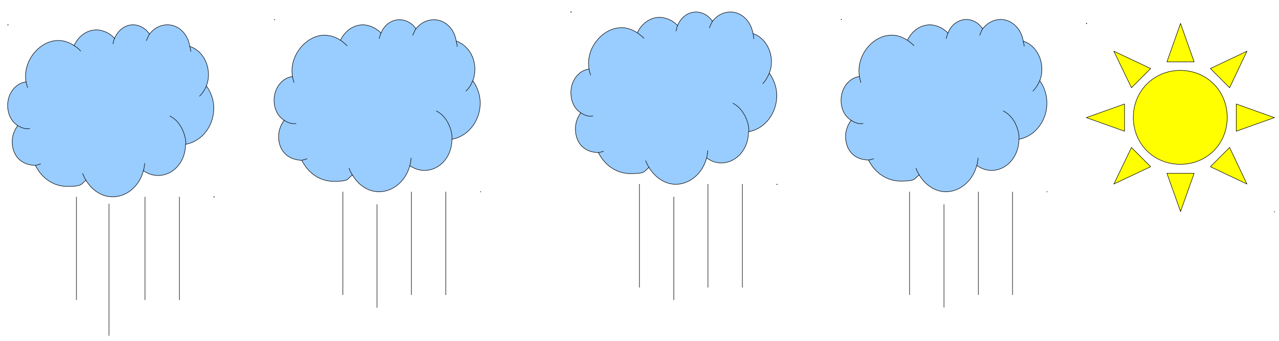

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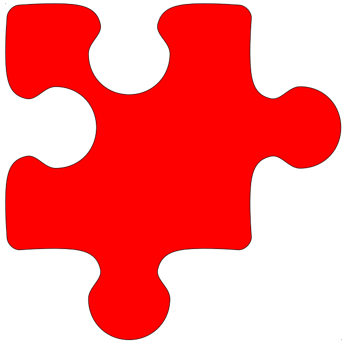

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e.g. number of rainy days per year in Italy

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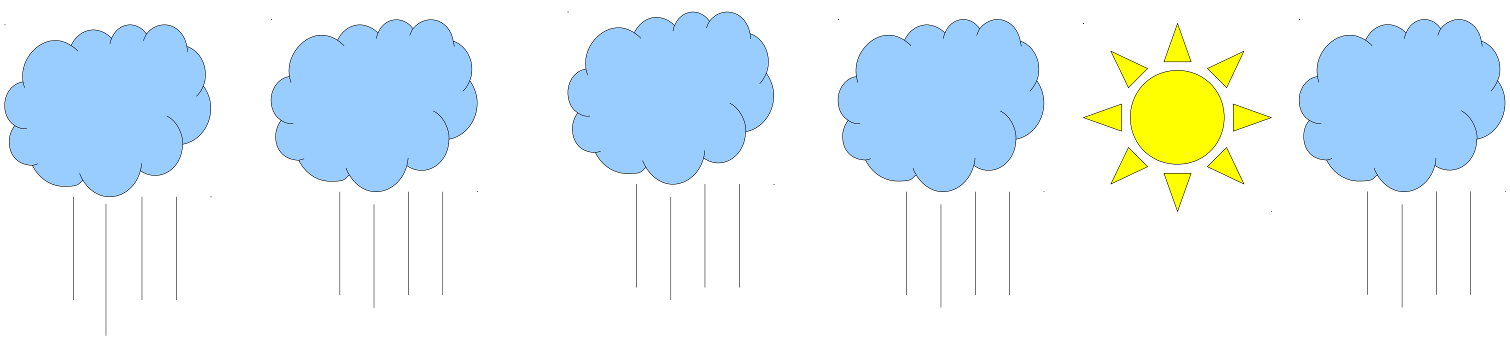

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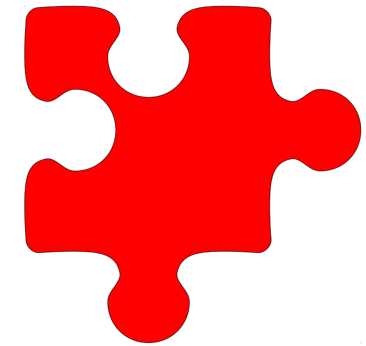

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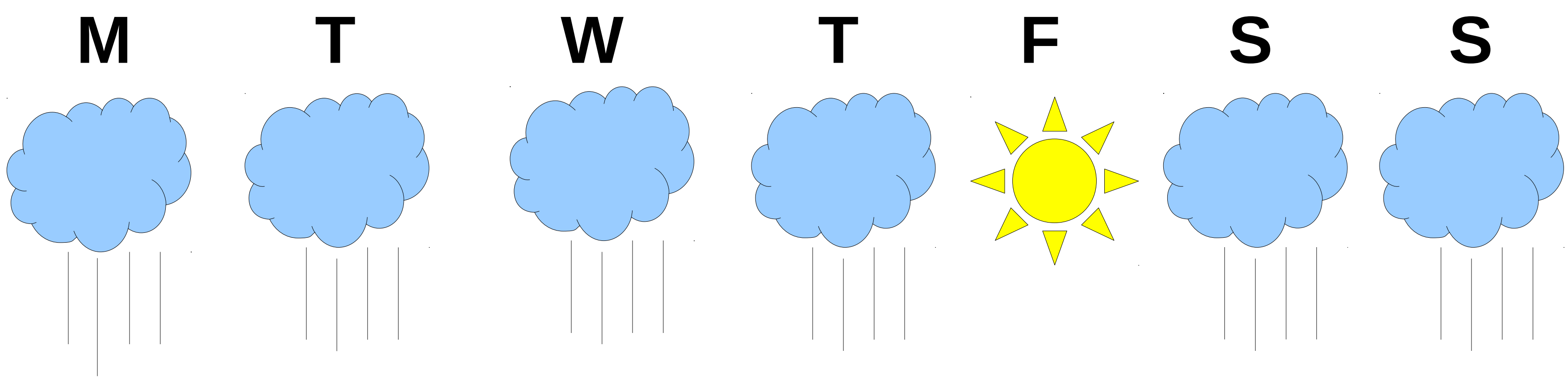
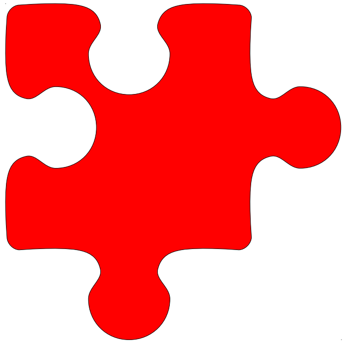


Rate : 6 over 7 days
I assume my week is representative of entire year
→ extrapolated rate = 312 raining days yr^-1
BIAS #1 : my week is in autumn (I can try to correct..)

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



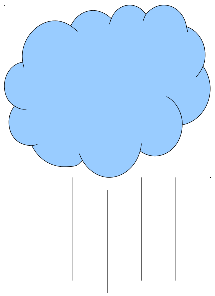
CALCULATE RATES IS IMPORTANT FOR EVERYDAY LIFE (even of high-school students)

RATE of RAINY DAYS

e.g. number of rainy days per year in Italy

A limited volume: I see only rain in my town, PADOVA

Padova



I assume Padova is representative of entire Italy

extrapolated rate = 312 raining days yr^-1 in Italy

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

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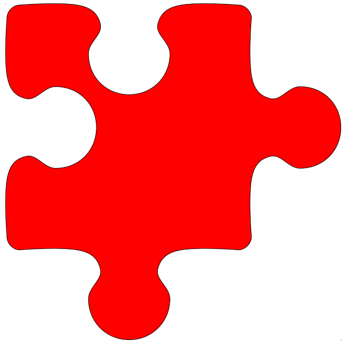

RATE of RAINY DAYS
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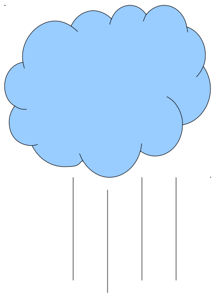
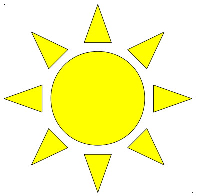


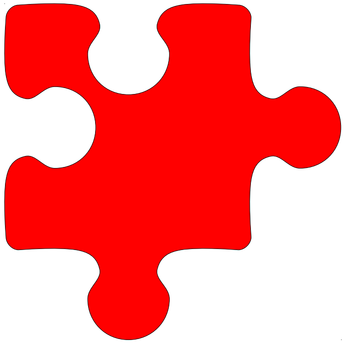
Palermo



I assume Padova is representative of entire Italy
extrapolated rate = 312 raining days yr^-1 in Italy

BIAS 2: my town is not representative of entire Italy (I might correct..)

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



Whenever I have to estimate a RATE

The problem is I can collect information only for

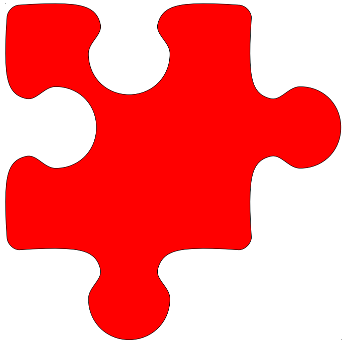
BIAS 1 - a limited time

BIAS 2 - a limited volume

→ I need to make some extrapolation / model

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

EXPECTED RATE of NS-NS MERGERS:
Number of NS-NS I expect to merge
per unit time per unit volume



The problem is I can collect information only for

BIAS 1 - a limited time

BIAS 2 - a limited volume

BIAS 3 - a proxy of the quantity I want to measure
(I cannot measure the quantity I am interested in, but something close to)

→ I need to make some extrapolation / model

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

FROM OBSERVATIONS

observable quantity	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

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

From observations

1- number of observed NS-NS binaries:

1. take the PROXY of NS-NS mergers:
   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)

$$R = \sum_i \frac{1}{t_{\mathrm{GW,i}}}$$

Units of Time^-1

Based on observations in a limited TIME (now) and VOLUME (MW)

How can I correct for larger Universe?
- I must do assumptions
- I can choose different approximations (differently affect results)

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

From observations

1- number of observed NS-NS binaries:

4. I assume number of NS-NS in a region of the Universe depends on the STAR FORMATION RATE (how many stars form in a place in a time)

→ 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)

$$R = \sum_i \frac{1}{t_{\rm GW,\,i}} \, \frac{\rho_{\rm SFR}}{\rm SFR_{MW}}$$

BUT I might have assumed the number of NS-NS scales with the TOTAL STAR MASS!!!!

→ Which differences do you expect?

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

From observations

1- number of observed NS-NS binaries:

4. I assume number of NS-NS in a region of the Universe depends on the STAR FORMATION RATE (how many stars form in a place in a time)

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$$R = \sum_i \frac{1}{t_{\rm GW,\,i}} \frac{\rho_{\rm SFR}}{\rm SFR_{MW}}$$

Units of Time^-1 Volume^-1

THIS IS A MERGER RATE PER UNIT VOLUME

HOW CAN I DERIVE THE DETECTION RATE (= how many of these mergers can be observed by LIGO/Virgo)?

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

From observations

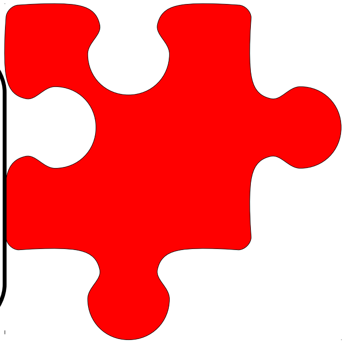
1- number of observed NS-NS binaries:

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:

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

CALCULATE *R* – EXERCISE FOR SCHOOL STUDENTS
(give them the properties of observed NS-NS to derive t_{GW}, ρ_{SFR}, SFR_{MW} and *L* are known values.)



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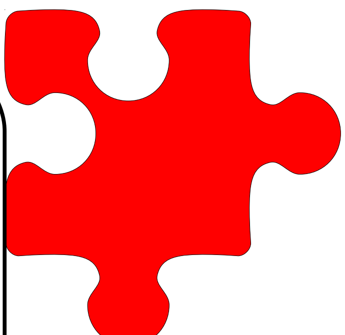
CALCULATE *R* – EXERCISE FOR SCHOOL STUDENTS
(give them the properties of observed NS-NS to derive t_{GW}, ρ_{SFR} , SFR_{MW} and *L* are known values.)

AND THE ANSWER IS …
0.4 yr^{-1} with ADVANCED LIGO/VIRGO!



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

From observations

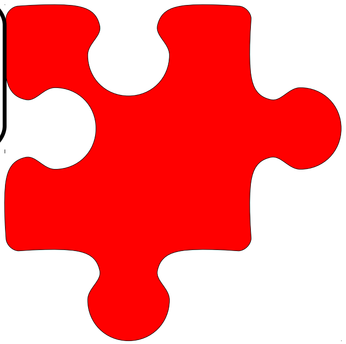
1- number of observed NS-NS binaries:

5. 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:

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

0.4 yr^{-1} with ADVANCED LIGO/VIRGO!



CLOSE TO PESSIMISTIC ESTIMATE FOR ADV. LIGO/VIRGO
(0.4 – 400 yr^{-1} – uncertainty of 3 orders of magnitude!!!!)

BUT THERE ARE MORE BIASES TO ACCOUNT FOR

AND THERE ARE SEVERAL PROCEDURES SIMILAR TO THIS ONE!!!

3. 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_{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
$V \sim 4/3\, \pi\, L^3$ (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)

3. 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 $t_{\mathrm{GW,i}}$ for each of them

$$R = \sum_i \frac{1}{t_{\mathrm{GW,i}}}$$

Units of Time^-1

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

From observations

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→ 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 $t_{\mathrm{GW,i}}$ for each of them**
3. **normalize to star formation rate of their host galaxy ($\mathrm{SFR_i}$)**

& sum $1/(\mathrm{SFR_i}\, t_{\mathrm{GW,i}})$ over all BH-WR in local Universe

$$R = \sum_i \frac{1}{t_{\mathrm{GW,\,i}}\,\mathrm{SFR}_i}$$

Units of Time^-1 Mass^-1 Time

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

From observations

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$$R = \sum_i \frac{1}{t_{\mathrm{GW,\,i}}\,\mathrm{SFR}_i}\,\rho_{\mathrm{SFR}}$$

Units of Time^-1 Volume^-1

THIS IS A MERGER RATE PER UNIT VOLUME

HOW CAN I DERIVE THE DETECTION RATE ?

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

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5. multiply by instrumental horizon of Adv LIGO/Virgo for BH-BH
   V~ $4/3\, \pi\, L^3$ (with L=1 Gpc)

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

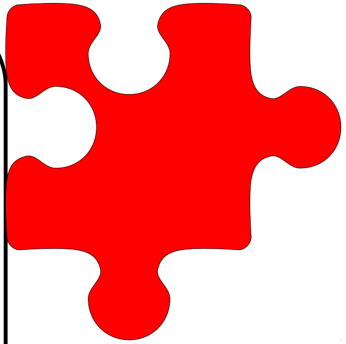
3. how to estimate the merger rate (and detection rate)

From observations

3- BH-WR binaries:

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

CALCULATE *R* – EXERCISE FOR SCHOOL STUDENTS
(give them the properties of observed BH-WR to derive t_{GW}, ρ_{SFR}, SFR_{MW} and *L* are known values.)



AND THE ANSWER IS.... $R < 10\ \mathrm{yr}^{-1}$

Upper limit because we assume SNe do not unbind binaries

See Esposito+ 2015 for details

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

From theory

Coming back to the rain metaphor:
I decide not to look at my windows,
sit down to my computer,
and develop a climate model of Italy!!!!!

1. no time limited

2. no volume limited

3. I can model what I really want to measure..

3. 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

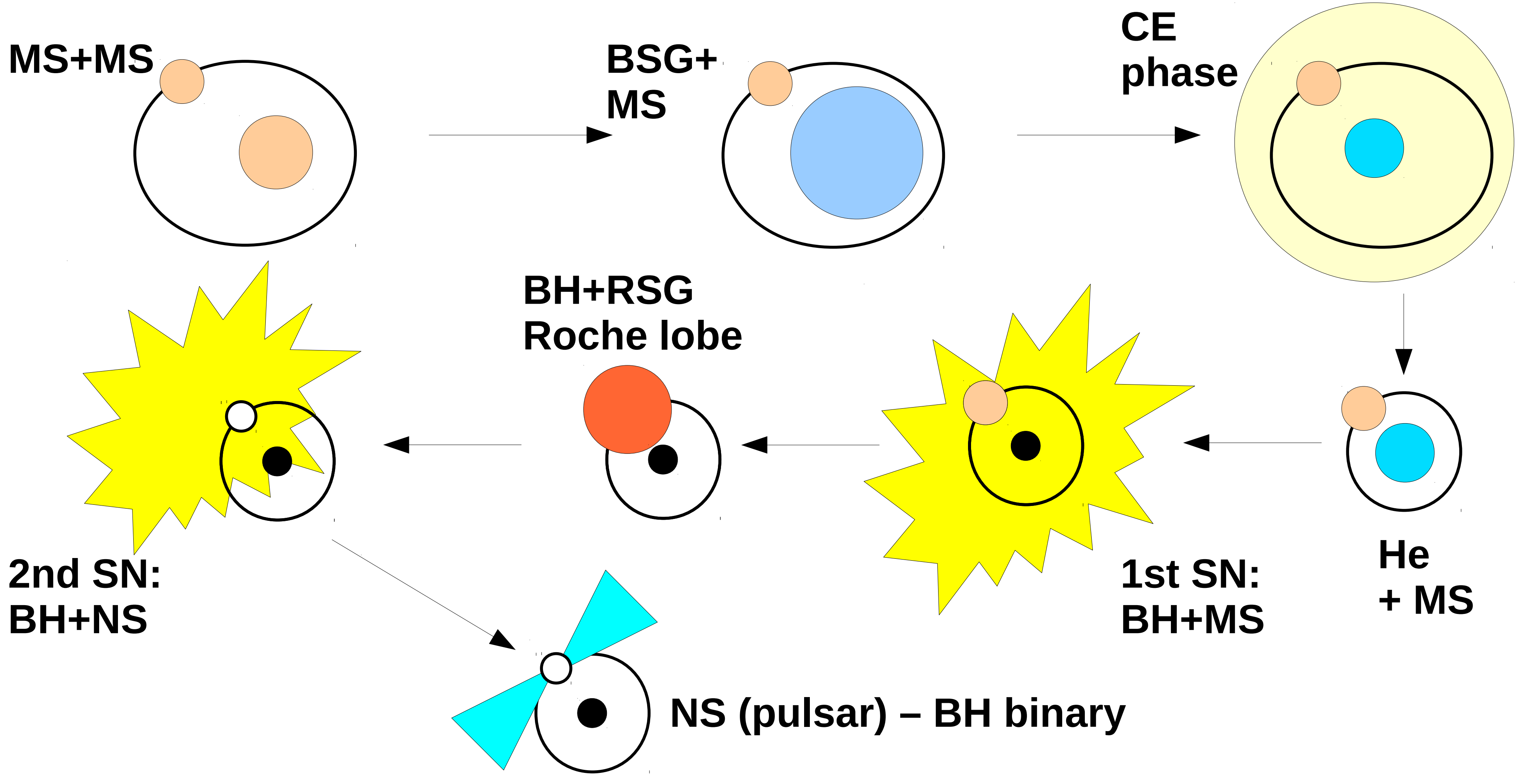
Theory seems better than observations, but........

3. 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



3. 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

3. 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**

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

From theory

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

WHY DYNAMICS????????

4. 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

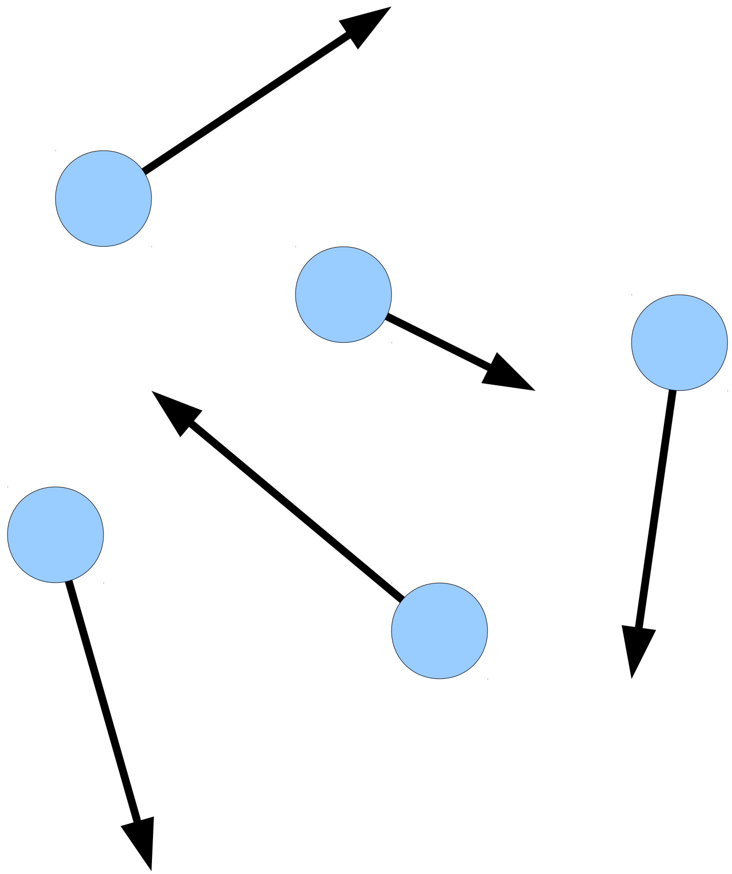
- **Collisionless systems** are systems where interactions are negligible

When is a stellar system collisional/collisionless?

4. impact of environment on merger rate

COLLISIONAL/COLLISIONLESS

COLLISIONLESS systems:
astrophysical systems where the **stellar density is low**
→ gravitational interactions between stars are weak and rare, and do not affect the evolution of the system



Interaction
Rate
scales as

density / vel^3

4. impact of environment on merger rate

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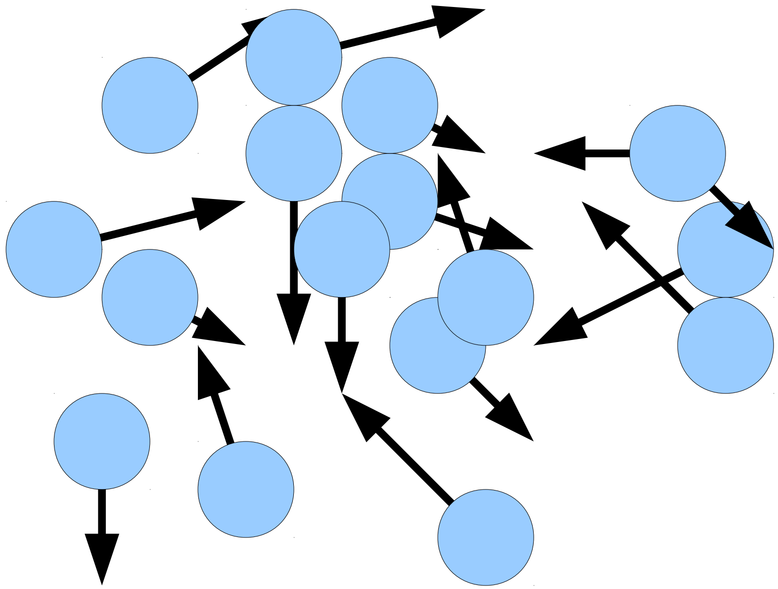
4. impact of environment on merger rate

COLLISIONAL/COLLISIONLESS

COLLISIONAL systems: SYSTEMS WHERE the stellar **DENSITY is so high that single gravitational interactions between particles are frequent**, strong and affect the overall evolution of system



Interaction Rate scales as

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4. impact of environment on merger rate

COLLISIONAL/COLLISIONLESS

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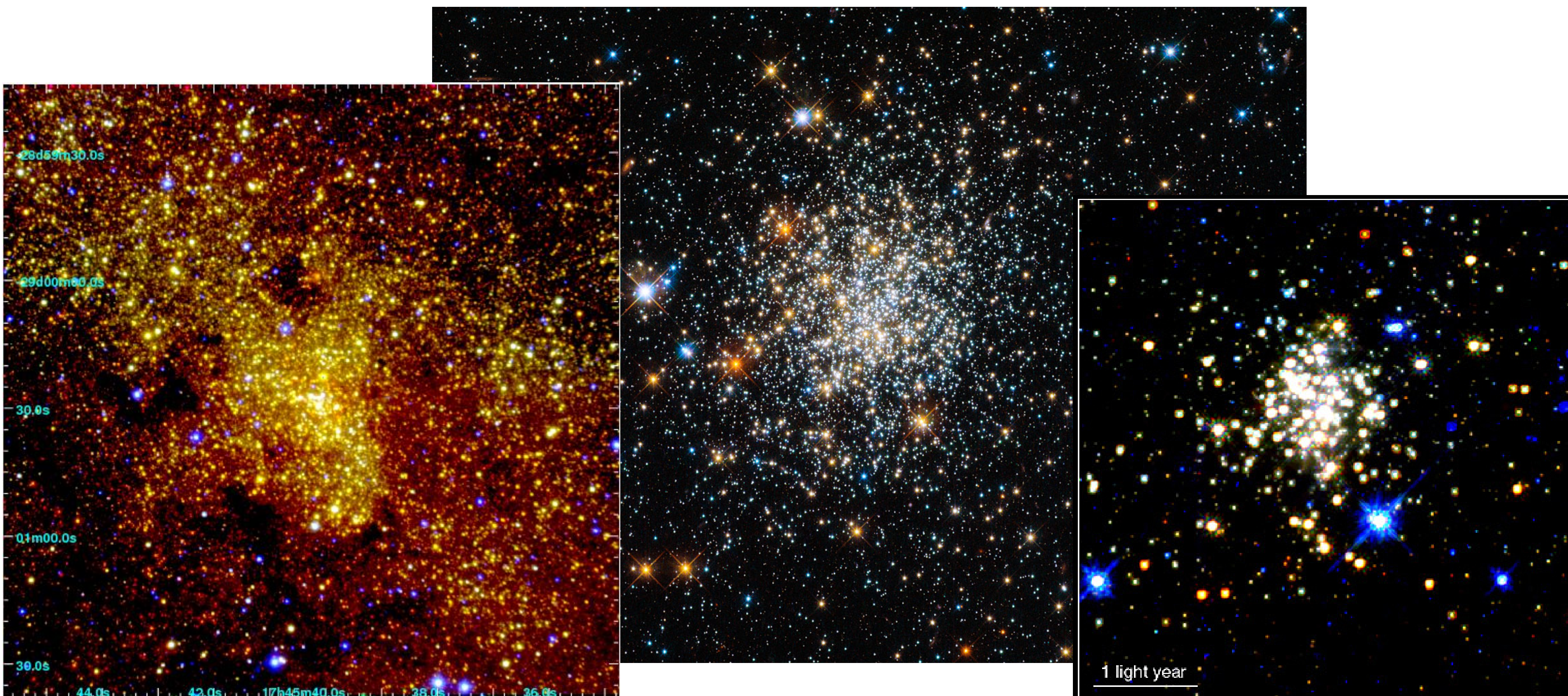
THE DENSEST STELLAR SYSTEMS: STAR CLUSTERS and GALACTIC NUCLEI



BINARIES as ENERGY RESERVOIR

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

INTERNAL ENERGY:

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

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

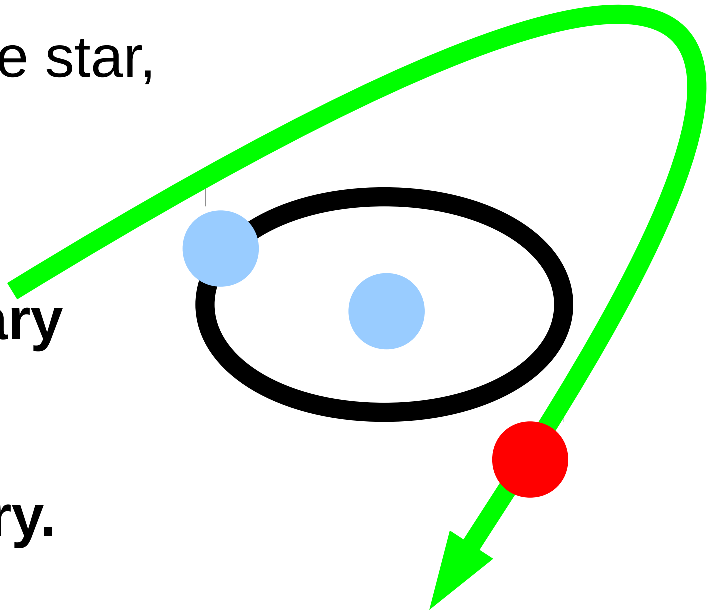
THE ENERGY RESERVOIR of BINARIES can be EXCHANGED with stars:

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

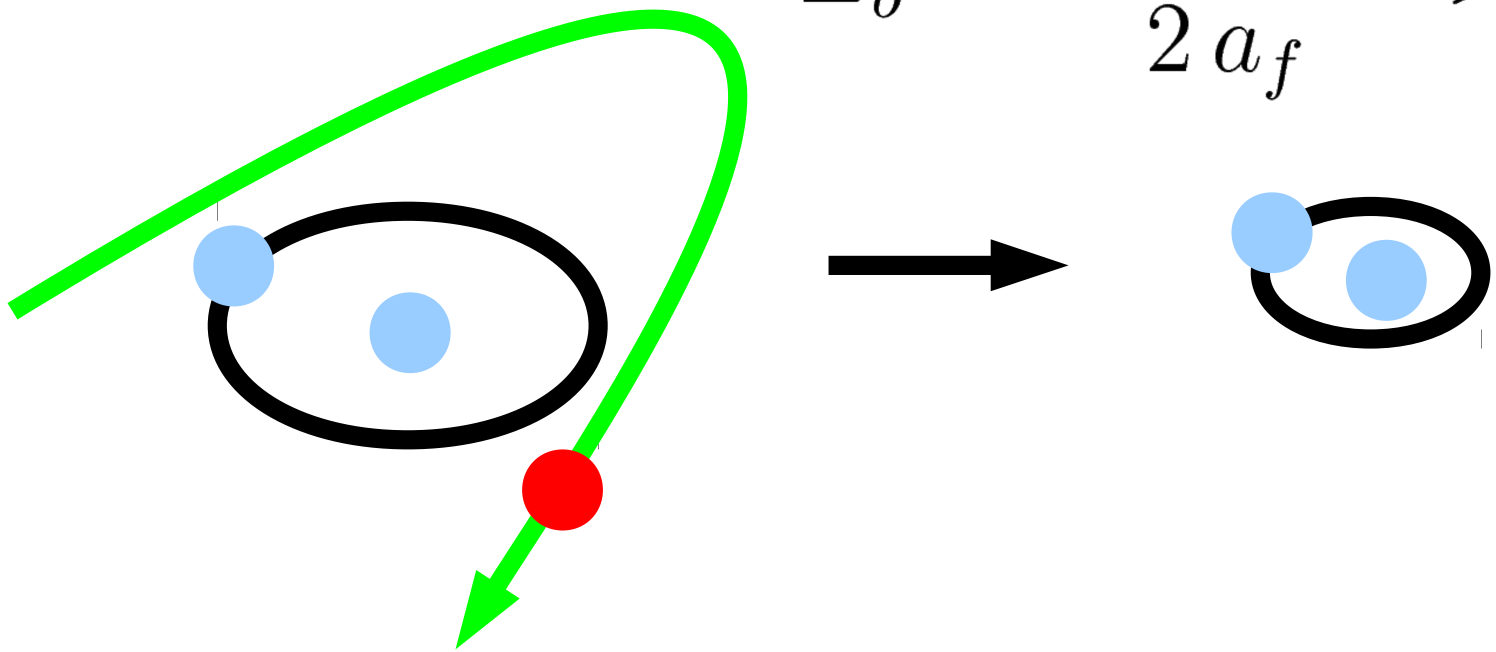
If the star extracts E_{int} from the binary,

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 $a_f < a_i \rightarrow E_b$ increases

BINARIES as ENERGY RESERVOIR

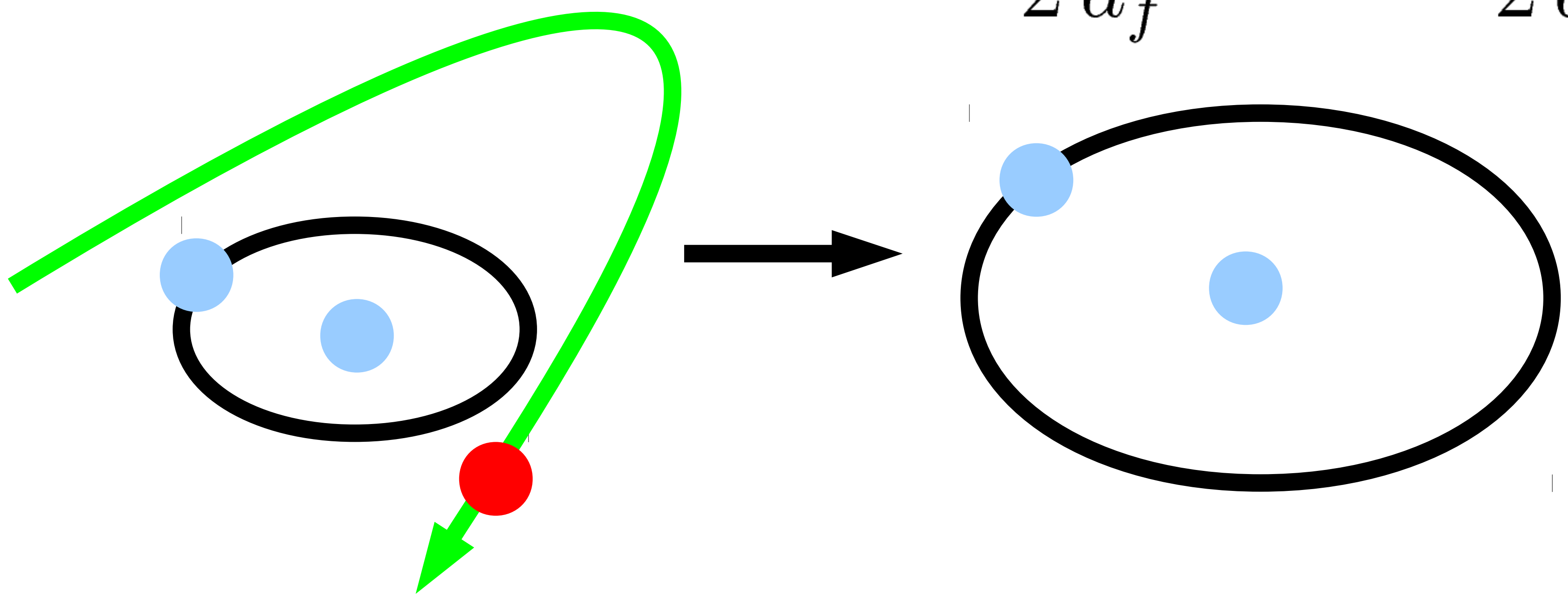
If the star transfer kinetic energy to the binary,

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 $a_f > a_i \rightarrow E_b$ decreases

BINARIES as ENERGY RESERVOIR

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

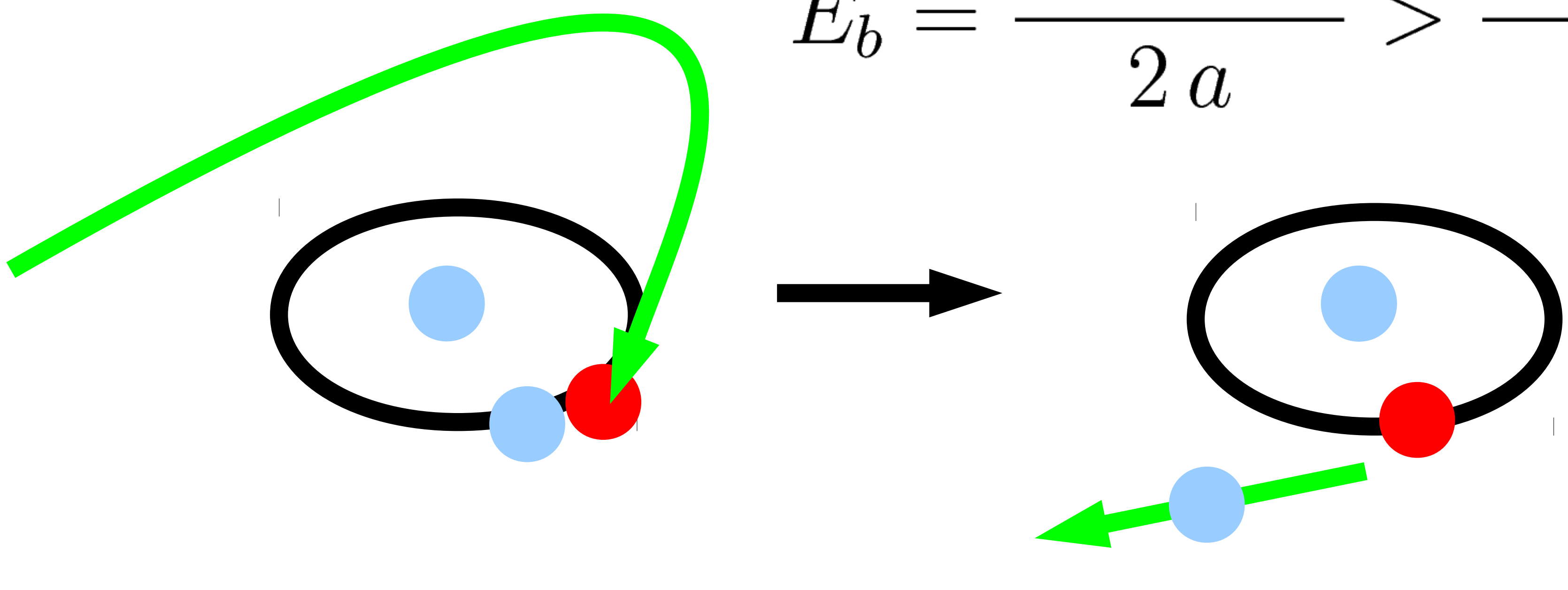
EXCHANGE

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:

$m_3 > m_2$

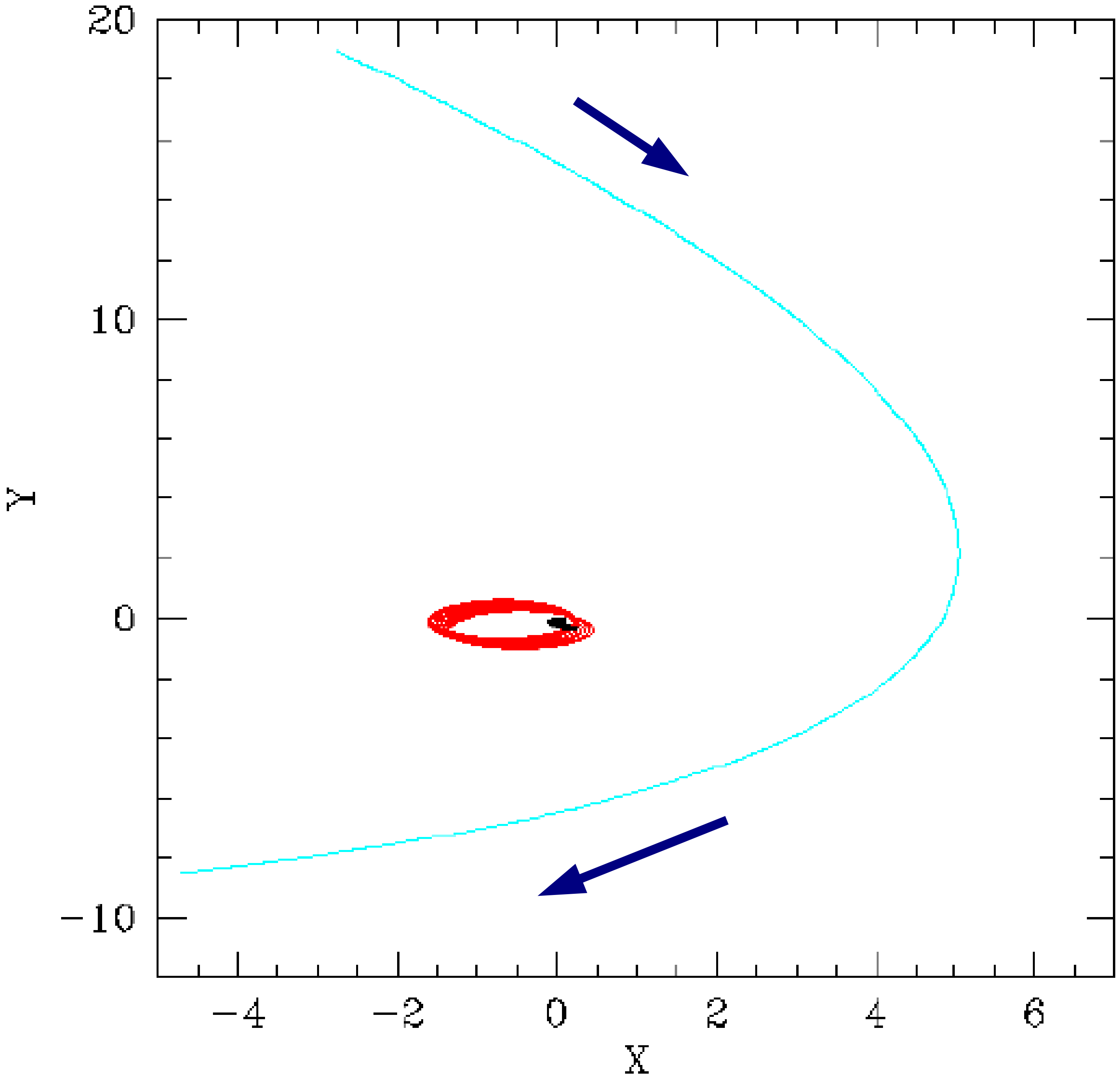
$$E_b = \frac{G\,m_1\,m_3}{2\,a} > \frac{G\,m_1\,m_2}{2\,a}$$



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

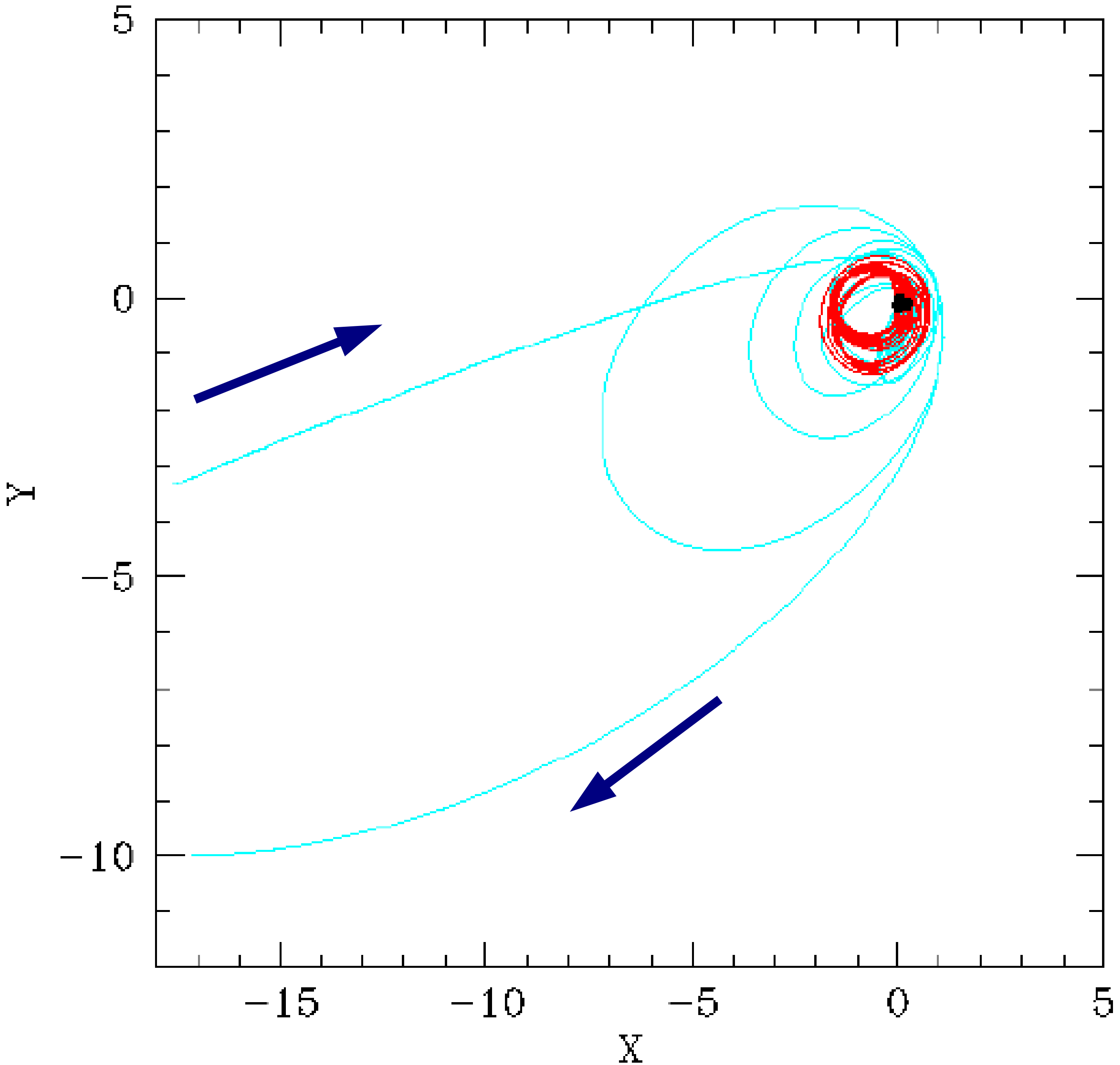
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT
FLYBY:



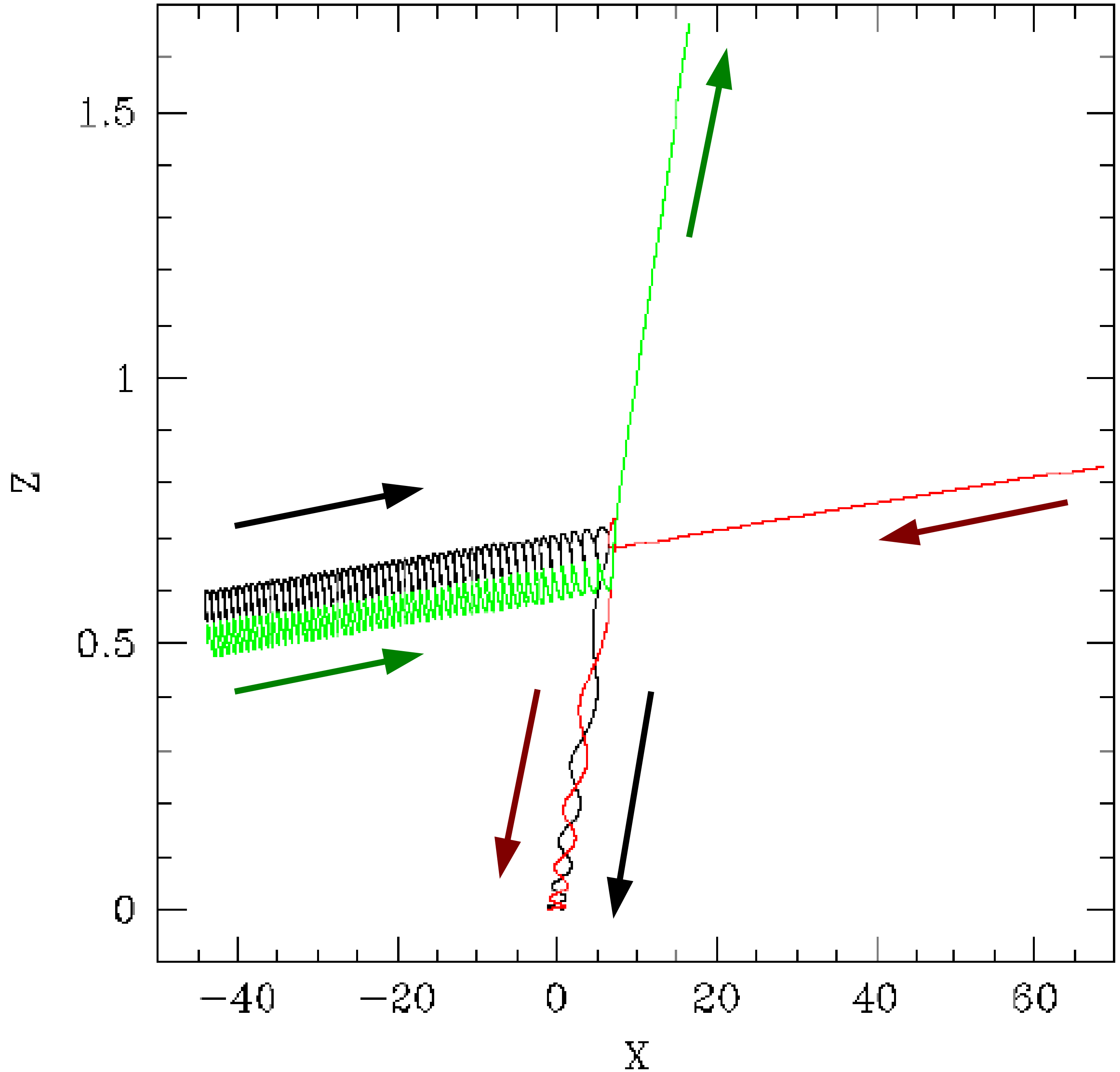
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT
FLYBY:



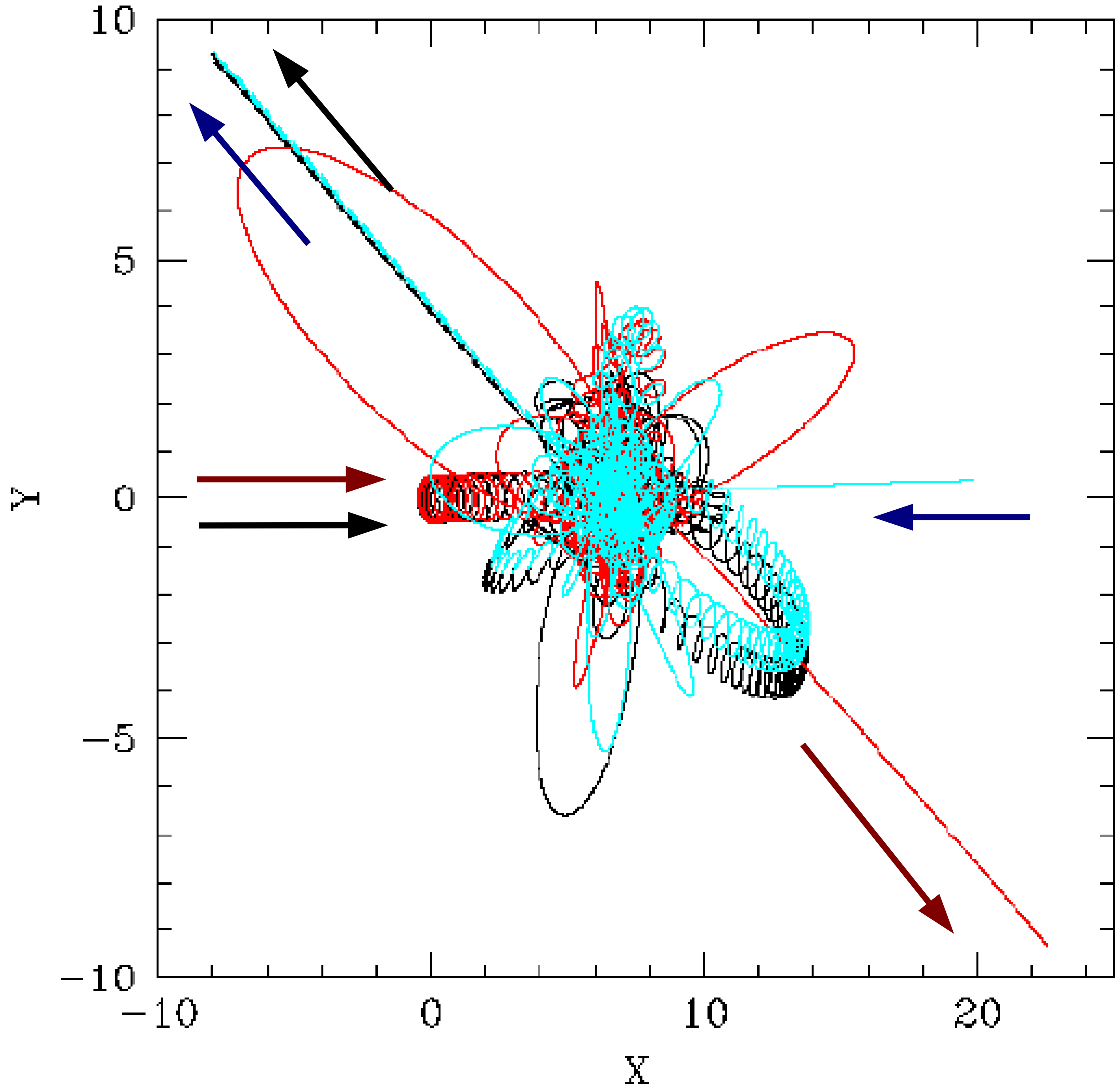
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

PROMPT
EXCHANGE:



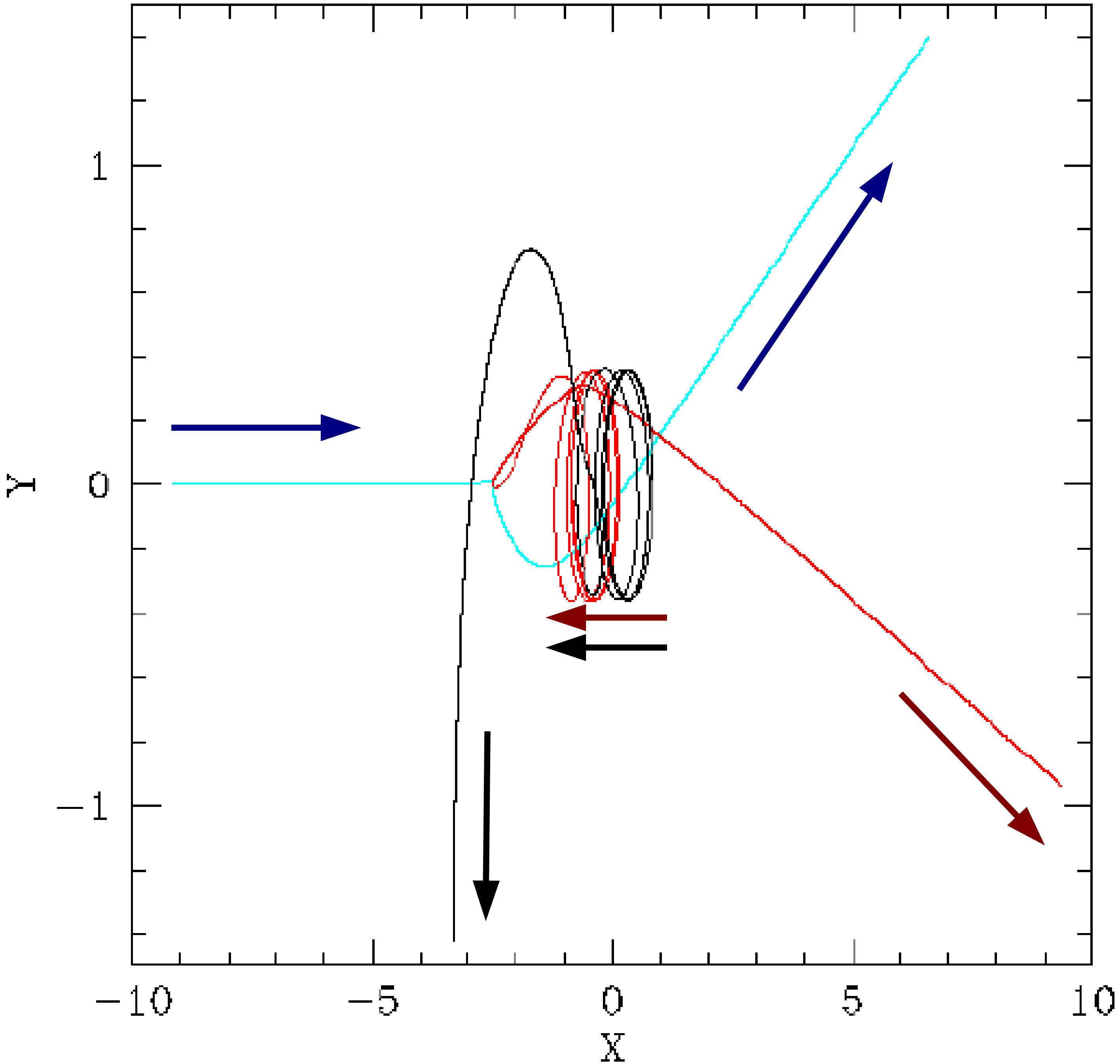
EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

RESONANT EXCHANGE:

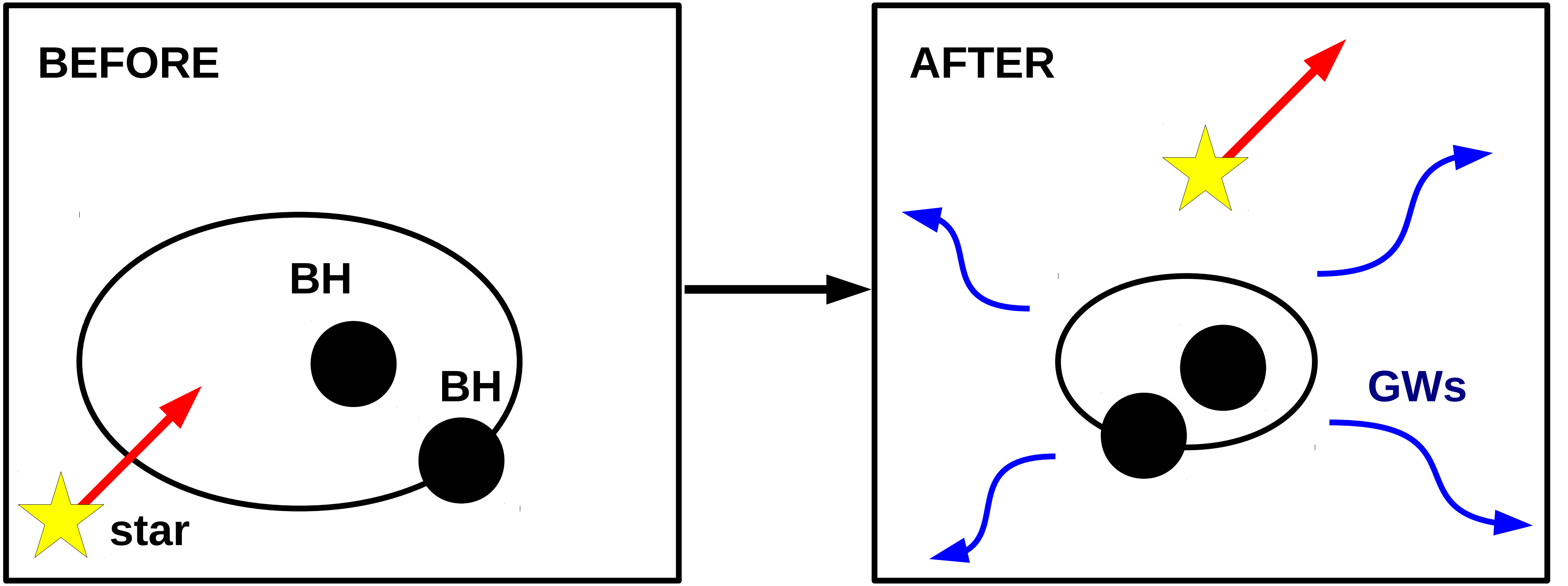


EXAMPLES of SIMULATED 3-BODY ENCOUNTERS

IONIZATION:

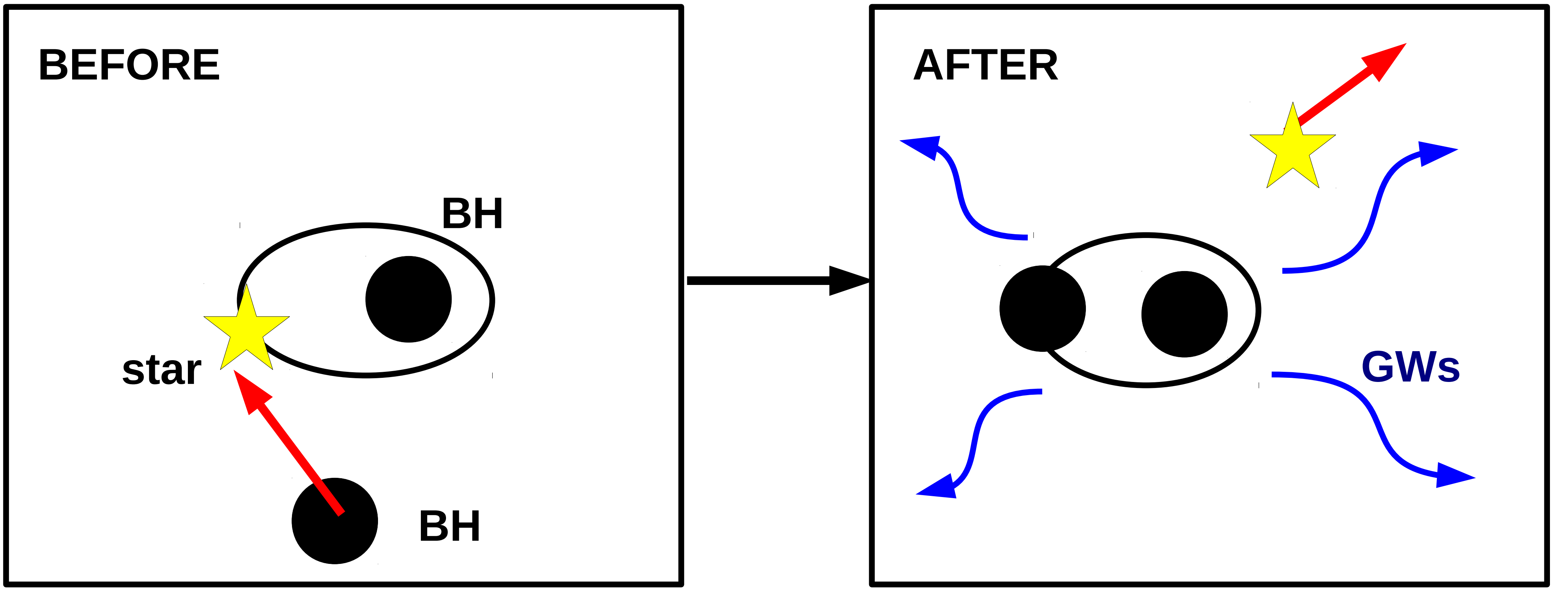


Which is the effect of 3-body encounters on BH-BH binaries?



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?

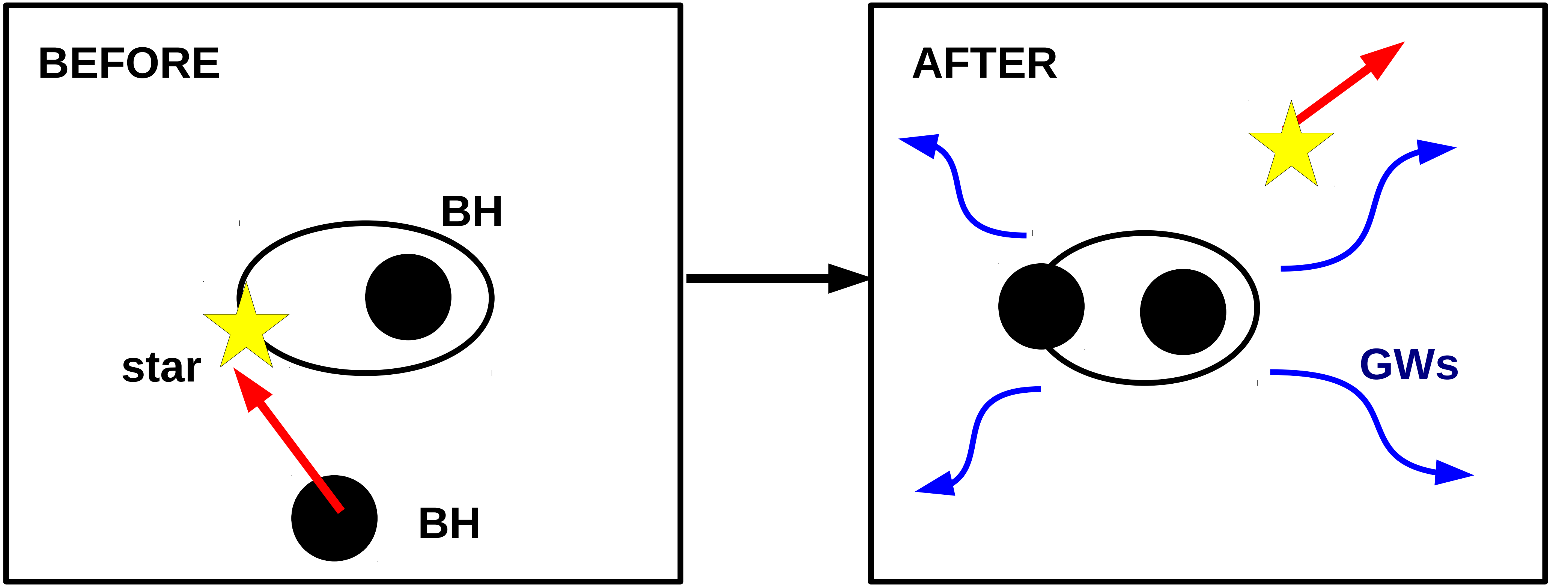


Exchanges are very important: bring BHs in binaries

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

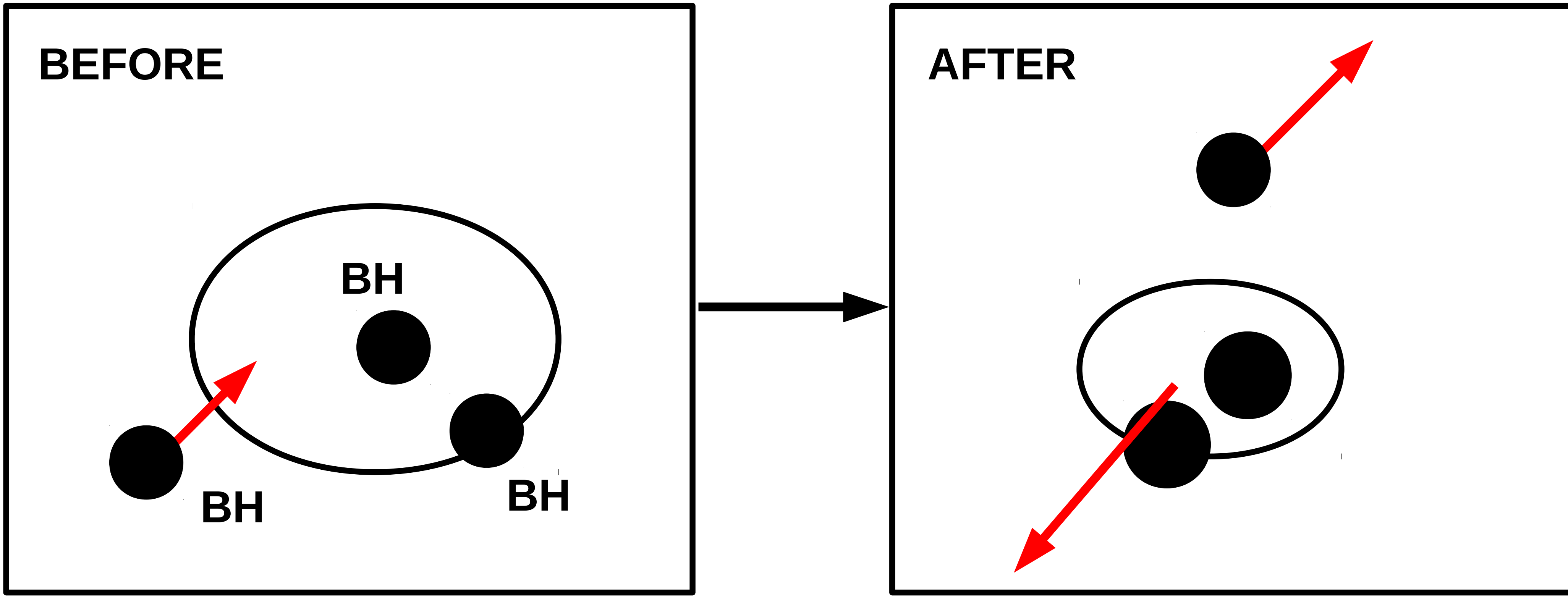
Which is the effect of 3-body encounters on BH-BH binaries?



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

4. impact of environment on merger rate

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**

What do we learn from dynamics?

If a BH or NS forms in a DENSE STELLAR SYSTEM (collisional system),
DYNAMICS CAN AFFECT

1. THE FORMATION OF BH-BH, NS-NS and BH-NS BINARIES

2. THEIR MERGER RATE

↓

DYNAMICAL SIMULATIONS ARE NEEDED to investigate MERGER RATE in STAR CLUSTERS!

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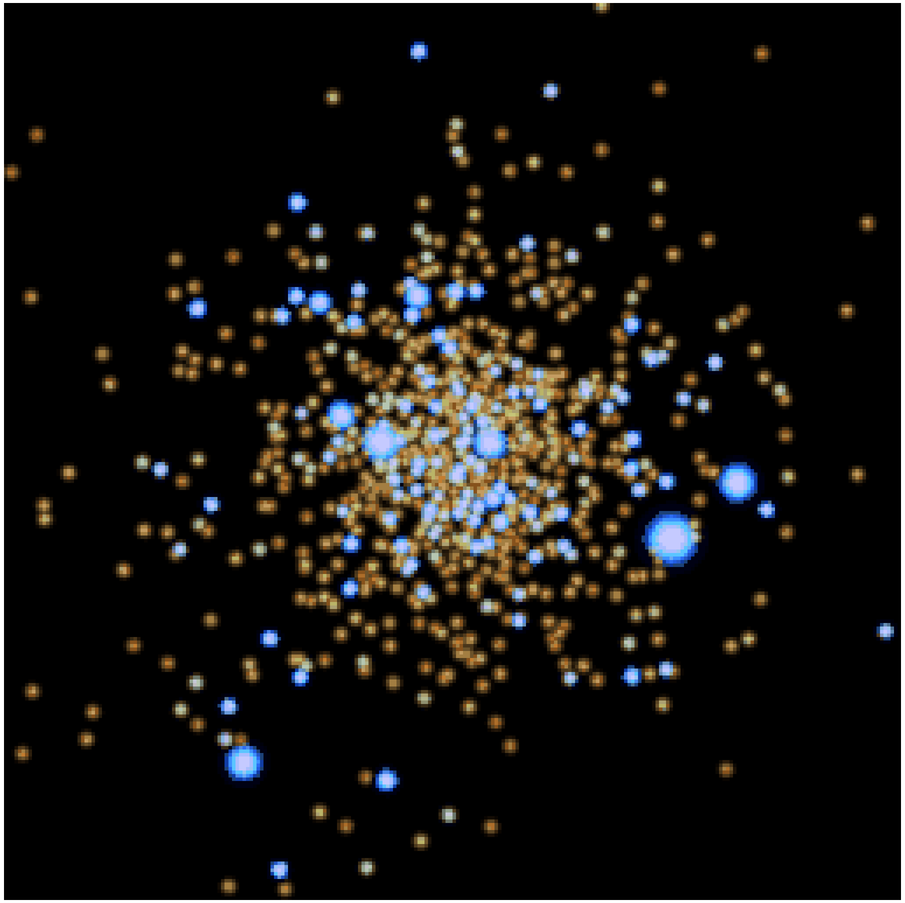

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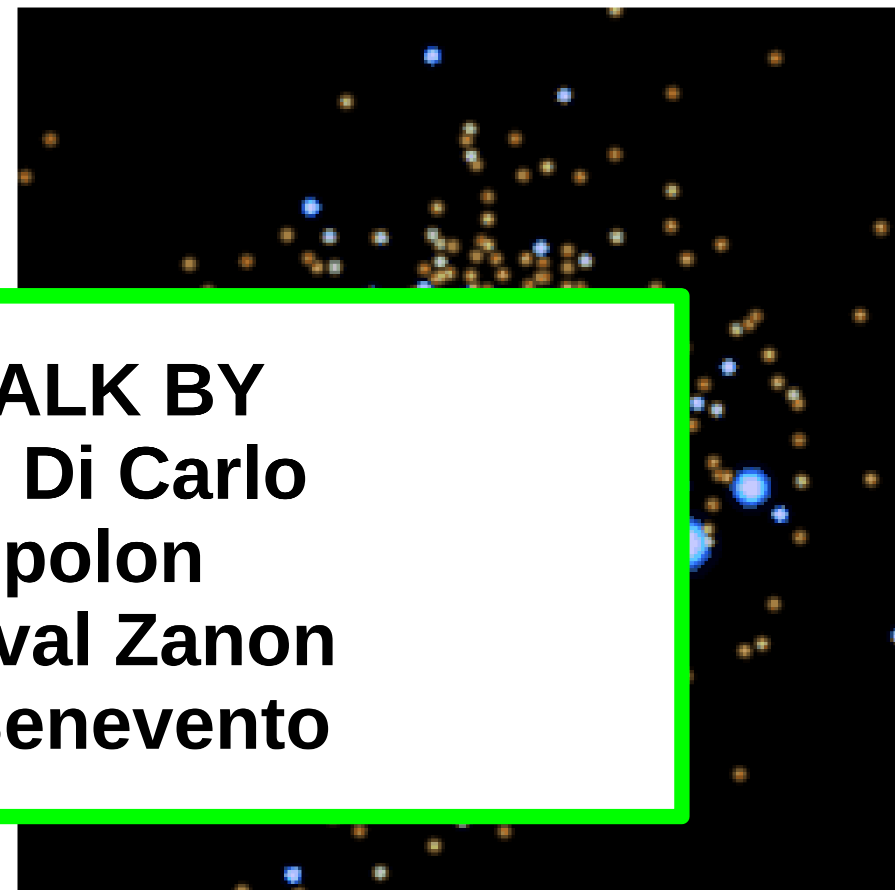

DYNAM
ARE NE
MERGE
CLUSTI

SEE THE TALK BY
Ugo Niccolò Di Carlo
Alessia Spolon
Arianna Miraval Zanon
Giampaolo Benevento

CONCLUSIONS:

- Advanced LIGO-Virgo detectors are about to start operating (2016) – frequency 10-10 000 Hz

- Double compact object binaries are one of the best GW sources in that range

- High-school students can estimate binary inspiral (semi-major axis shrinking, GW frequency)

- Main counterparts are short GRBs and kilonovae

- Estimate merger and detection rate is very important task, and a very dangerous/uncertain one

- The environment can affect the merger rate dramatically

THANK YOU