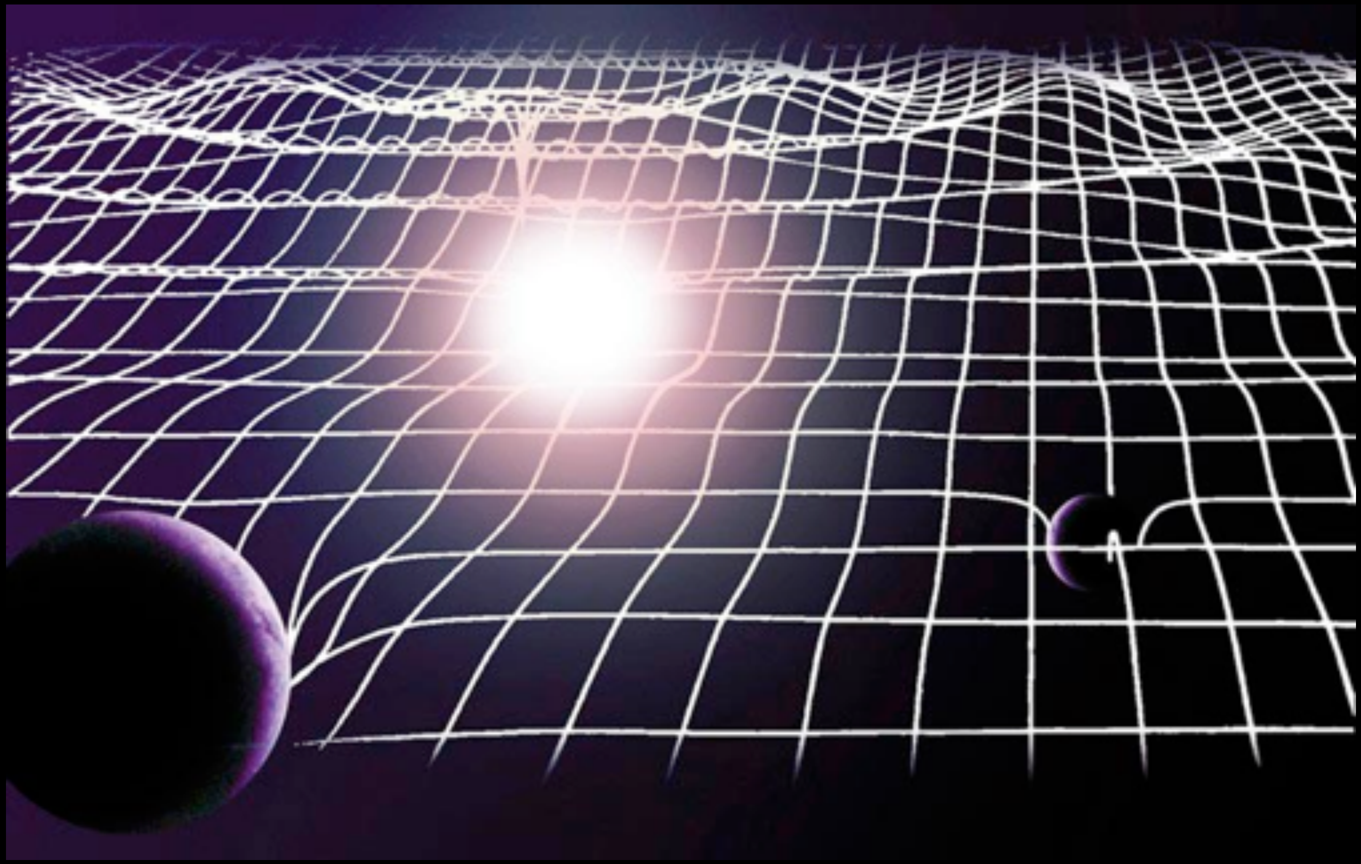
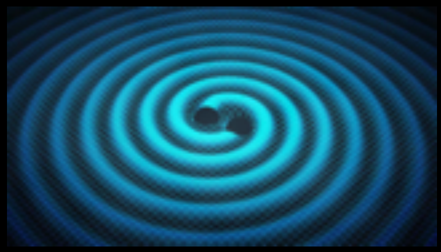
Gravitational Wave Astrophysics

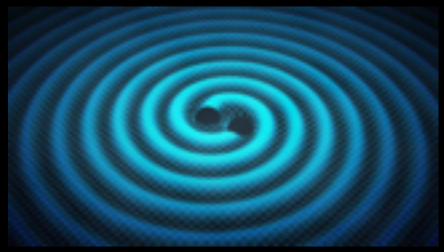
Johan Samsing
Princeton University



Part I



Gravitational Wave Properties



Frequency:

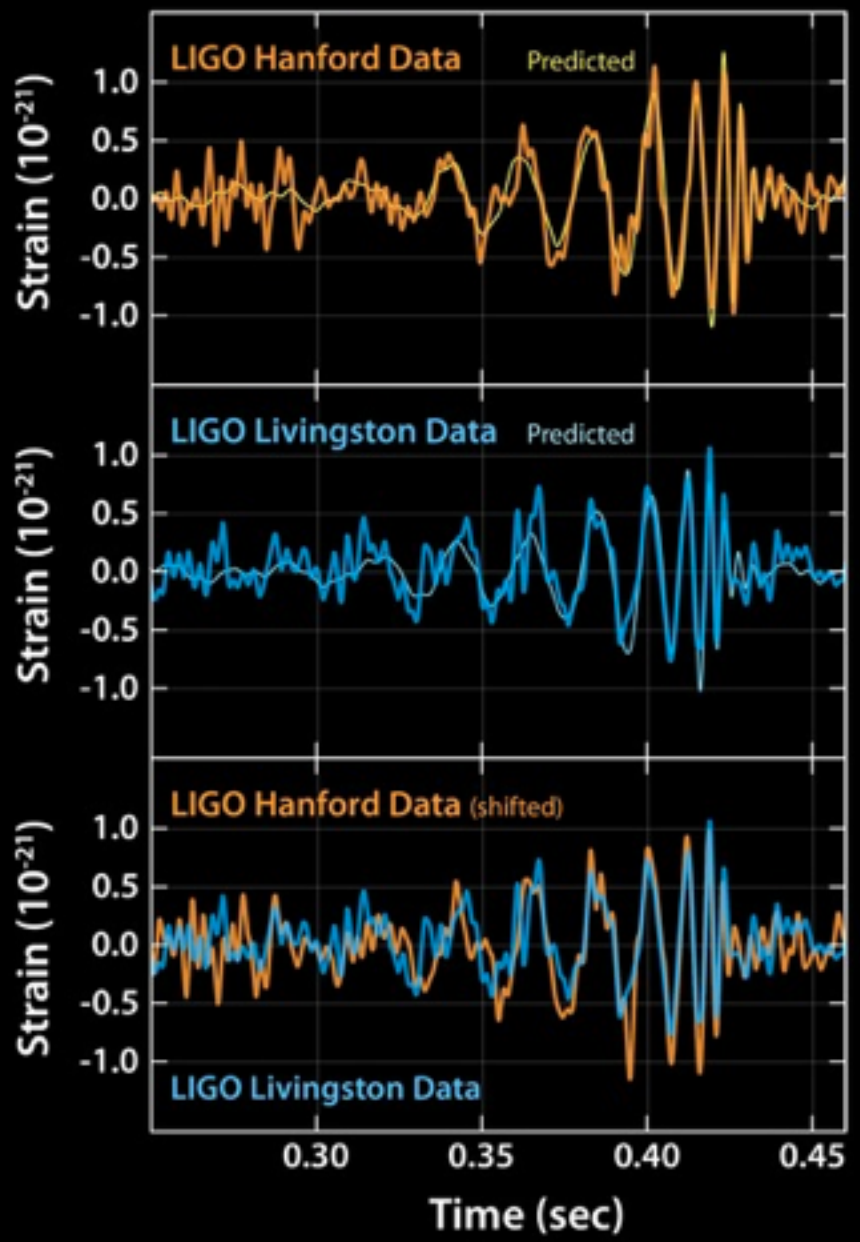
$$f_{GW} \sim 2 f_{orb}$$

Strain:

$$h = 5 \times 10^{-22} \left(\frac{M}{2.8 M_\odot}\right)^{2/3} \left(\frac{\mu}{0.7 M_\odot}\right) \left(\frac{f}{100\text{Hz}}\right)^{2/3} \left(\frac{15\text{Mpc}}{r}\right)$$

Merger time:

$$t_{life} \propto a^4 m^{-3} (1 - e^2)^{7/2}$$



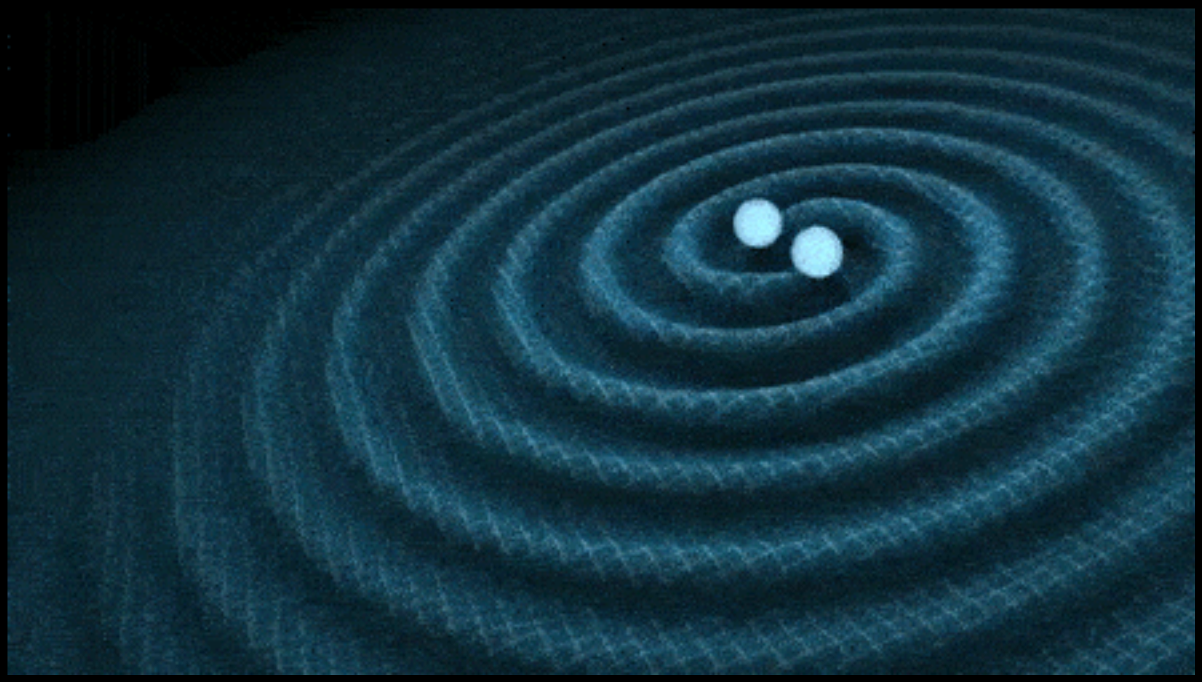
Objects:

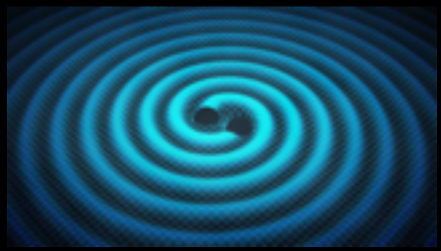
NS Binary: $f_{GW}(NS) \sim 10^3$ Hz

WD Binary: $f_{GW}(WD) \sim 10^{-1}$ Hz

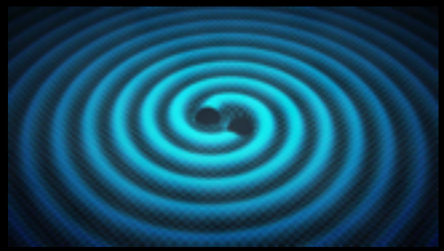
Solar Binary: $f_{GW}(sun) \sim 10^{-4}$ Hz

In an expanding U: redshift, (1+z)





Gravitational Wave Properties



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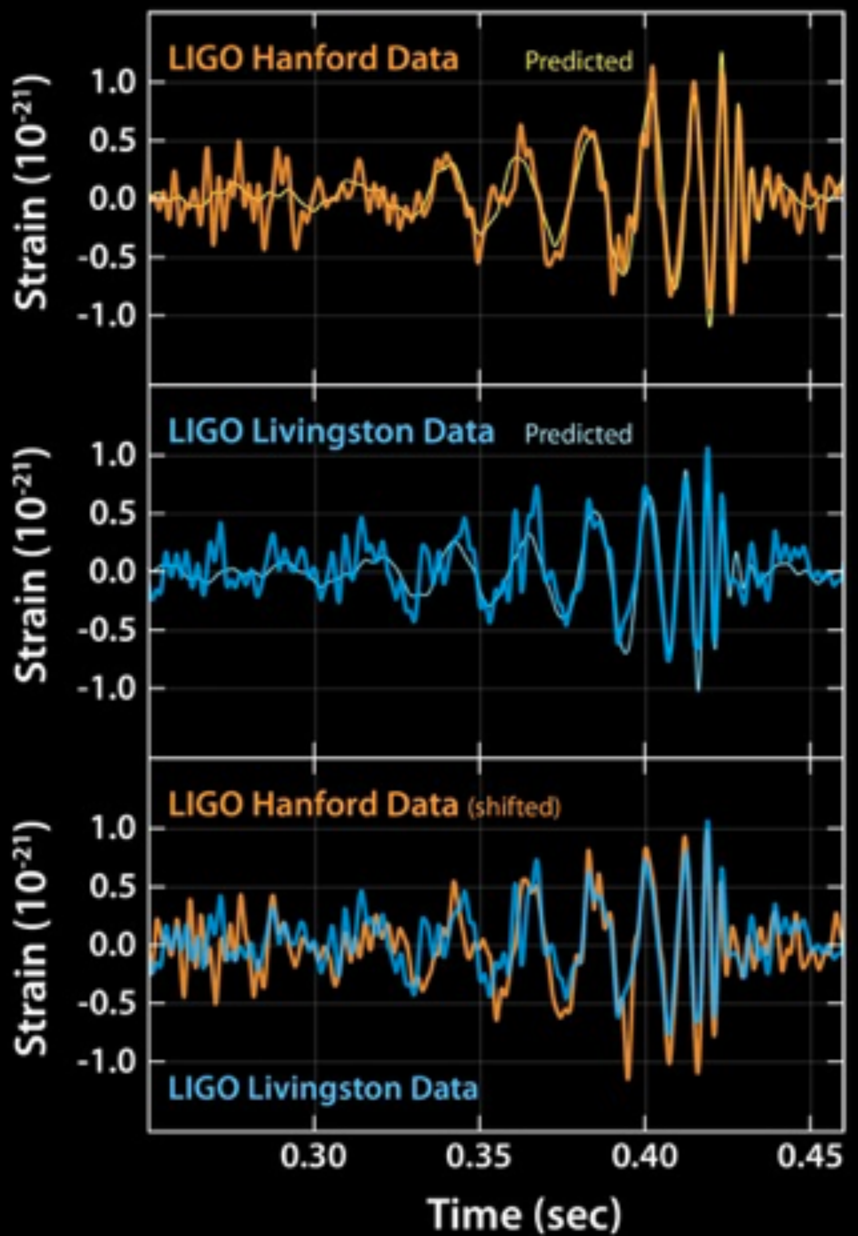
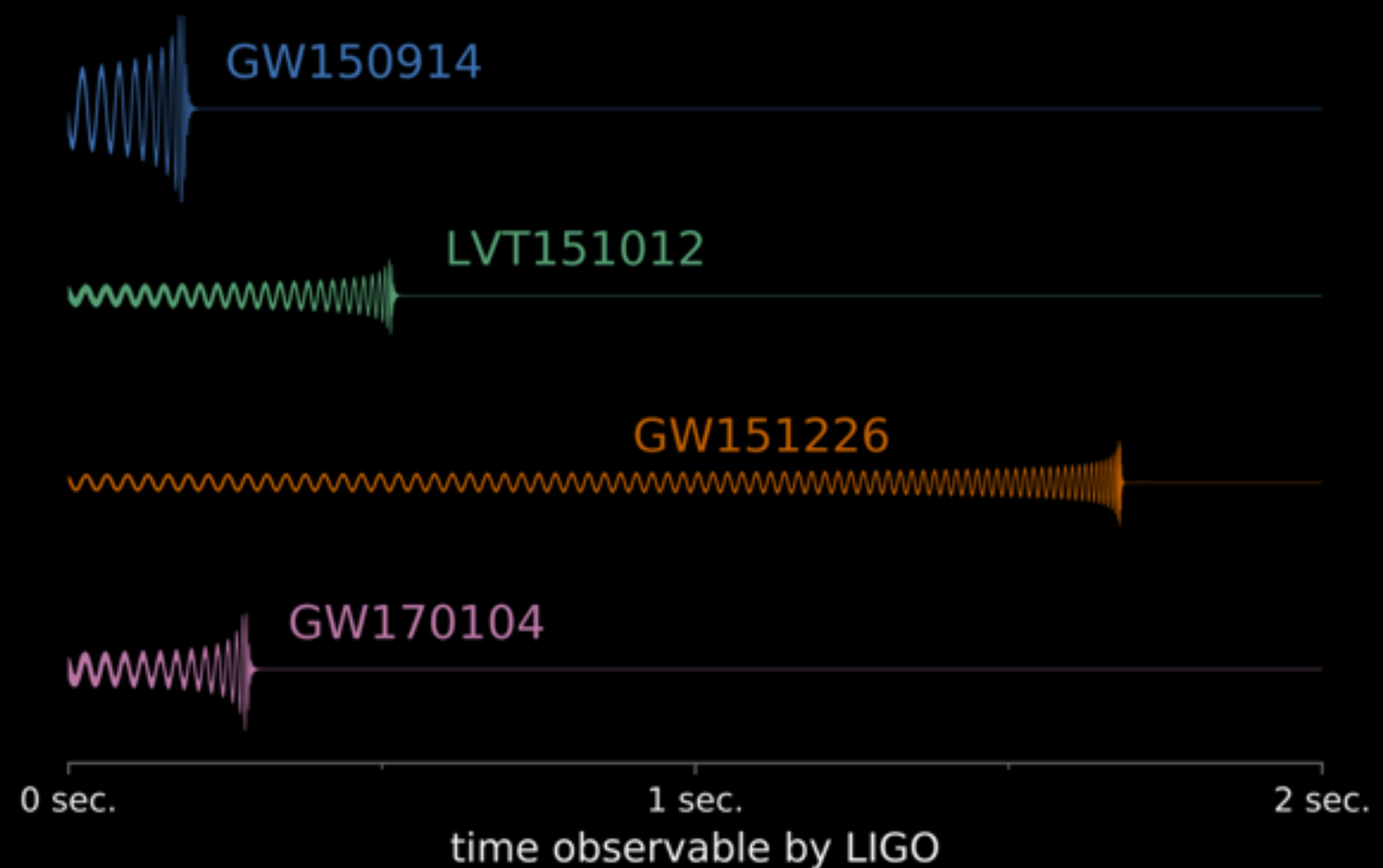
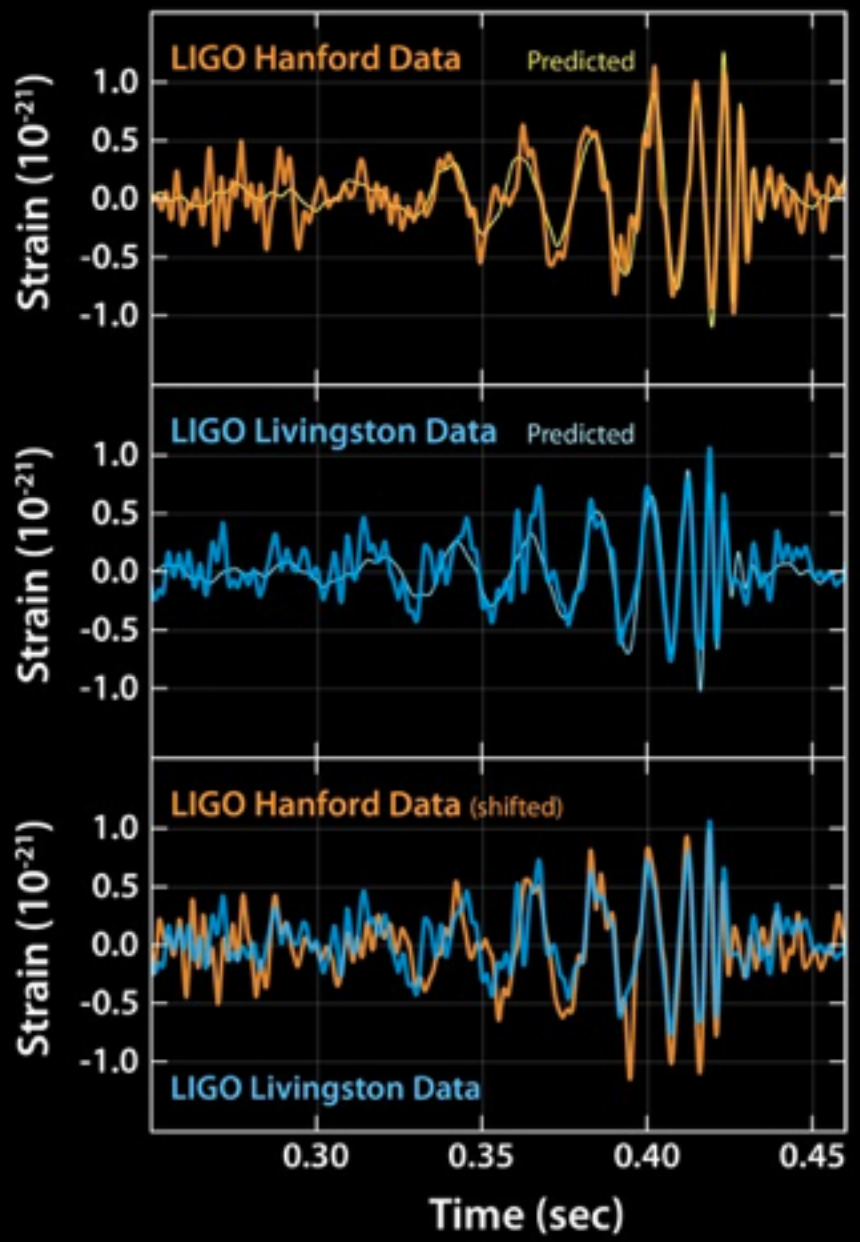


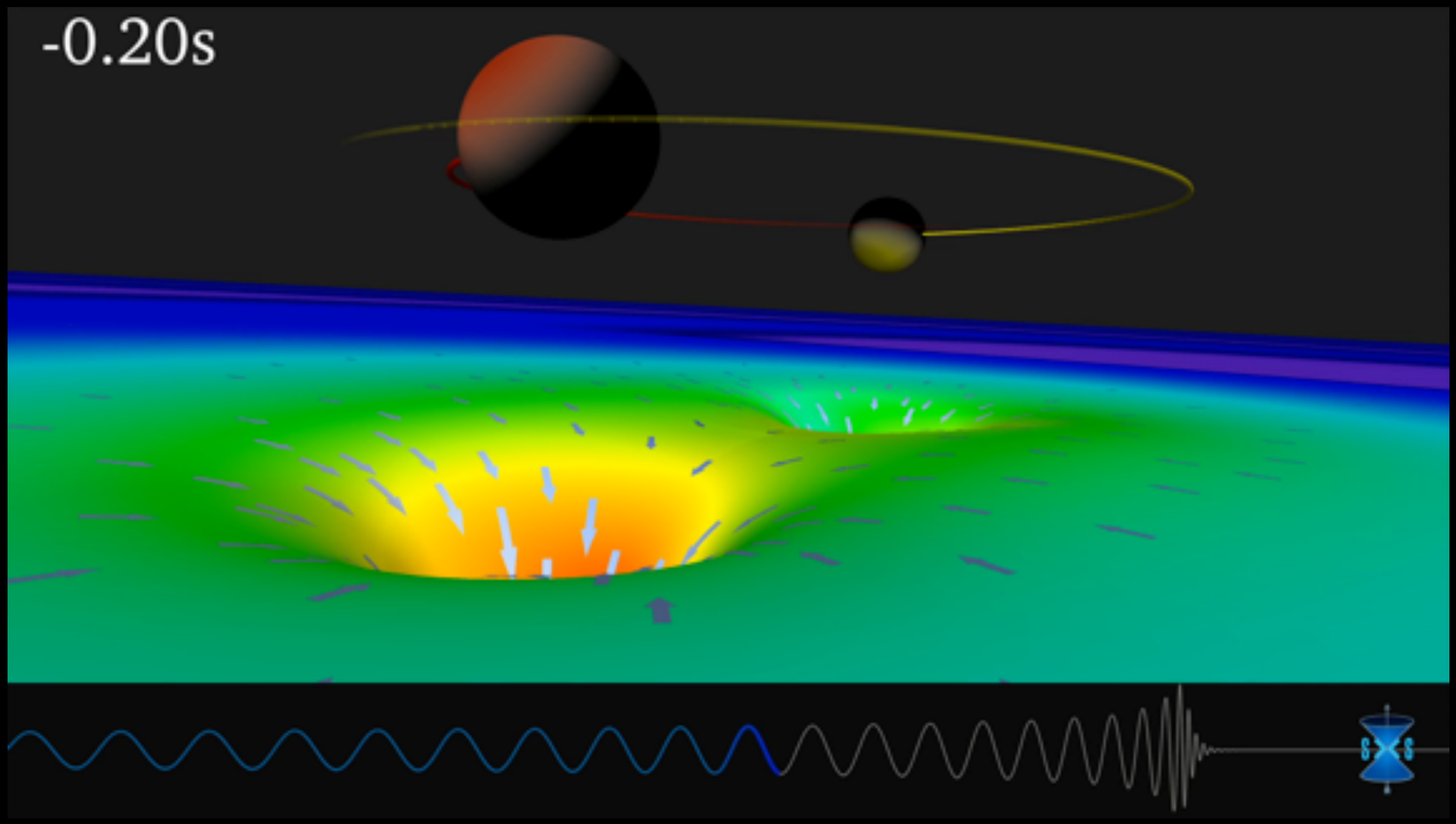


Gravitational Waves have now been observed!

Real Signal:



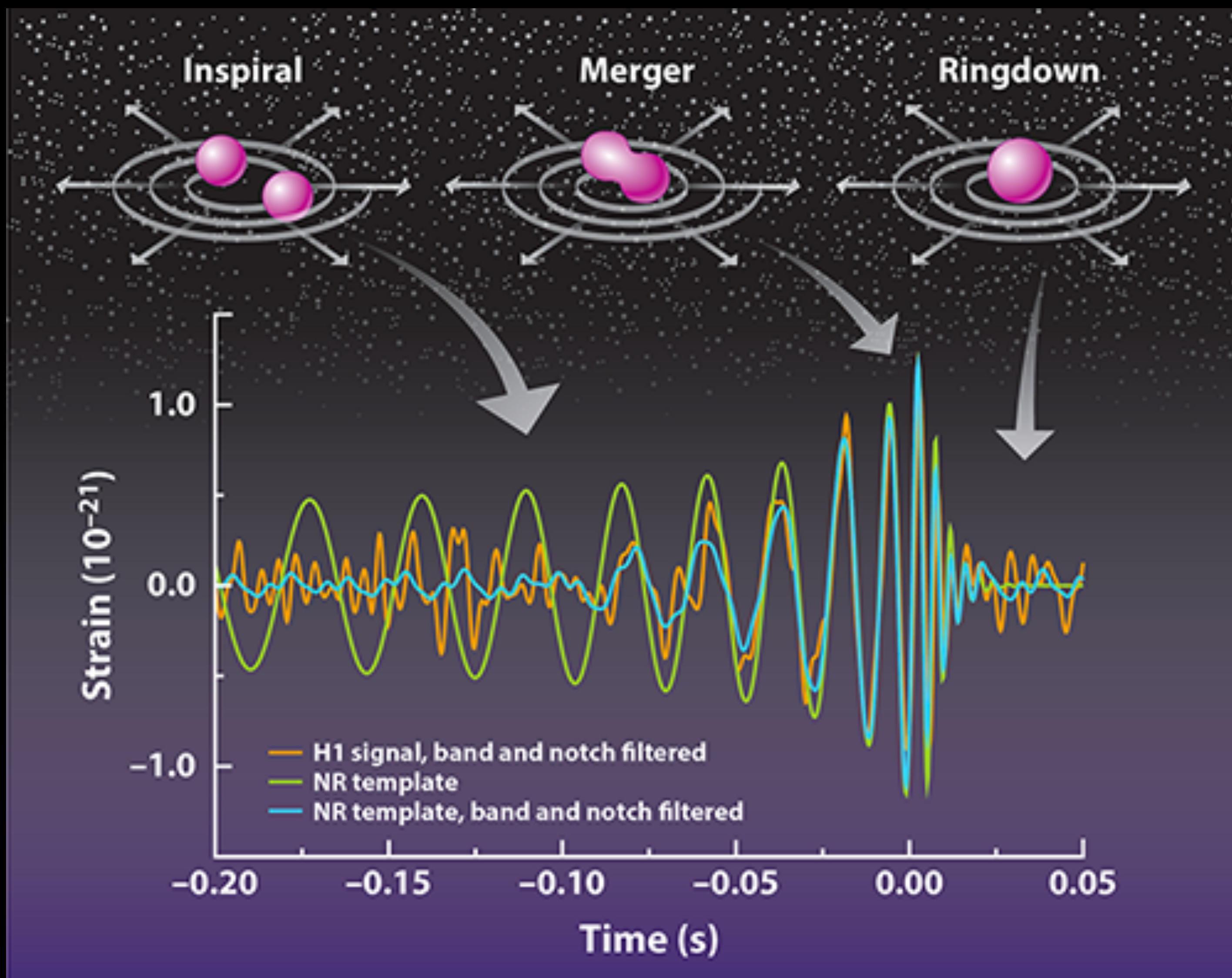
Animation:

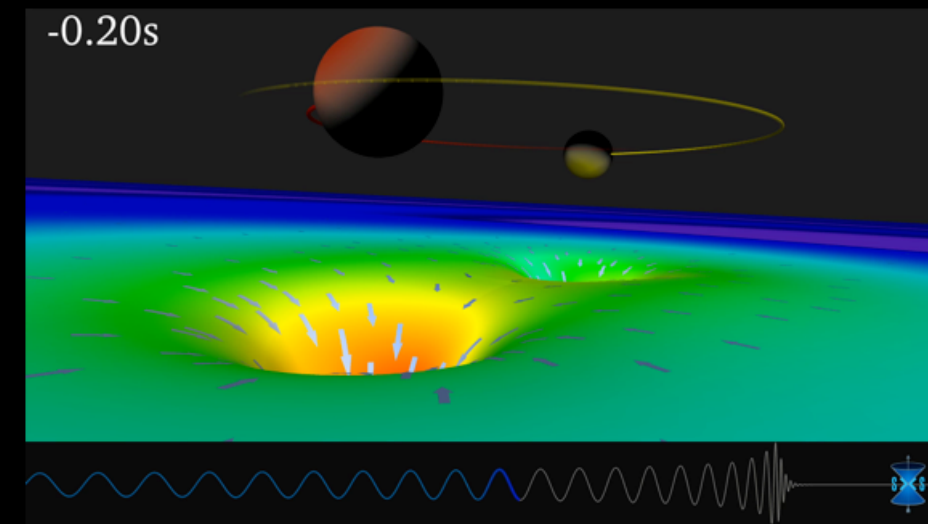


Nobel Prize: 2017

Dynamics, Merger, and Simulation

The three stages of merger:

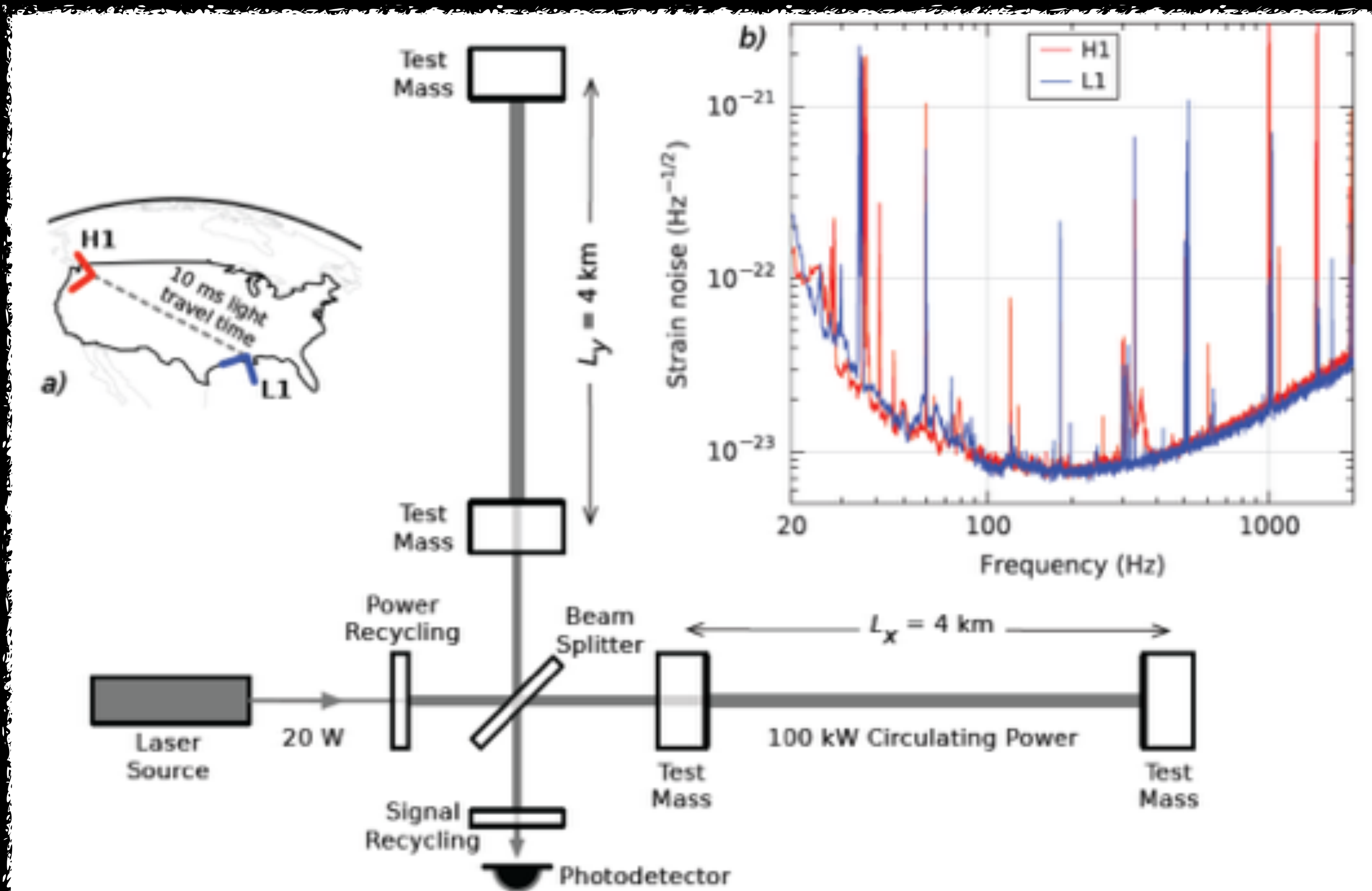


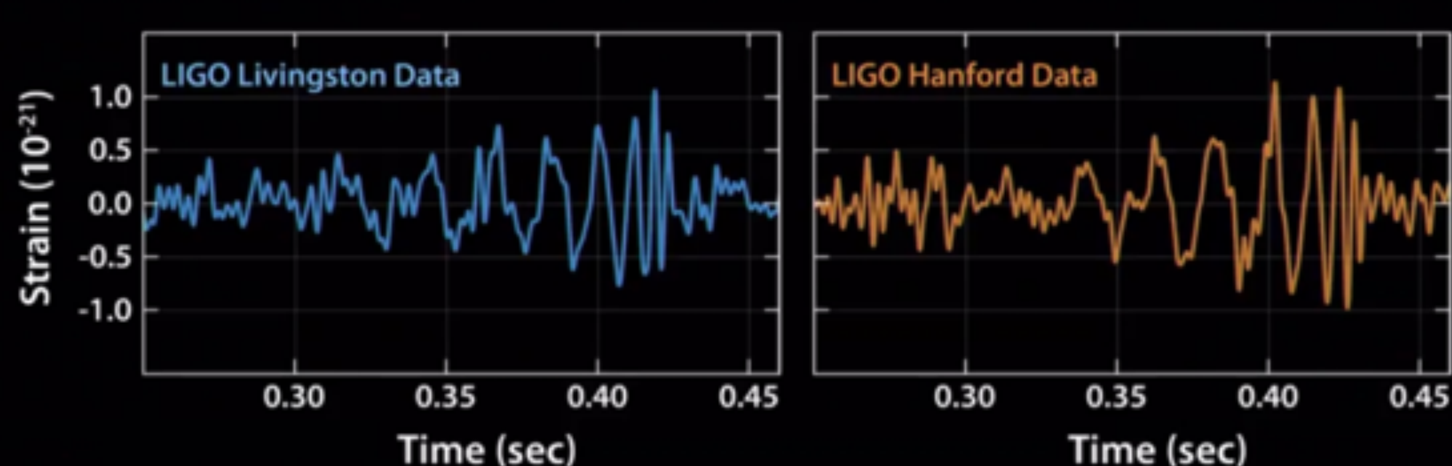


First GR sim.

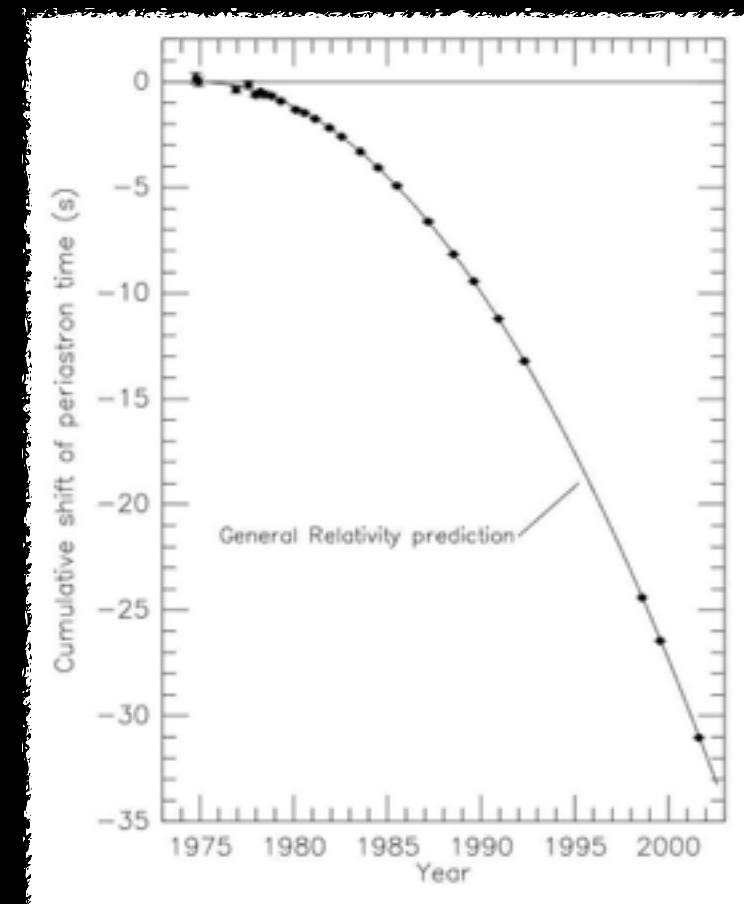
How Gravitational Waves are Detected

Direct:

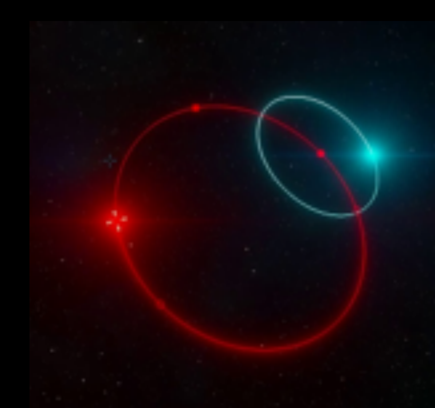


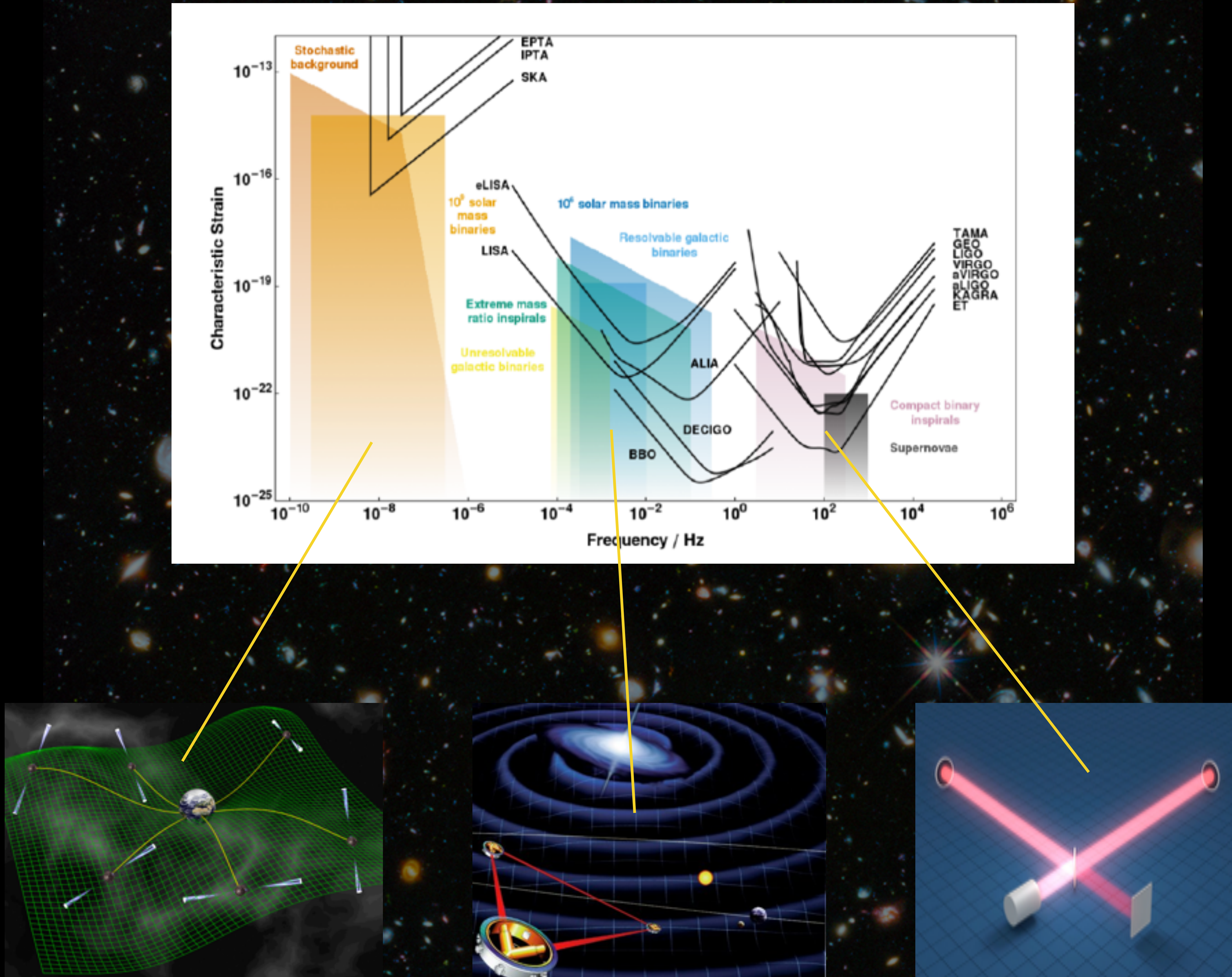


Indirect:



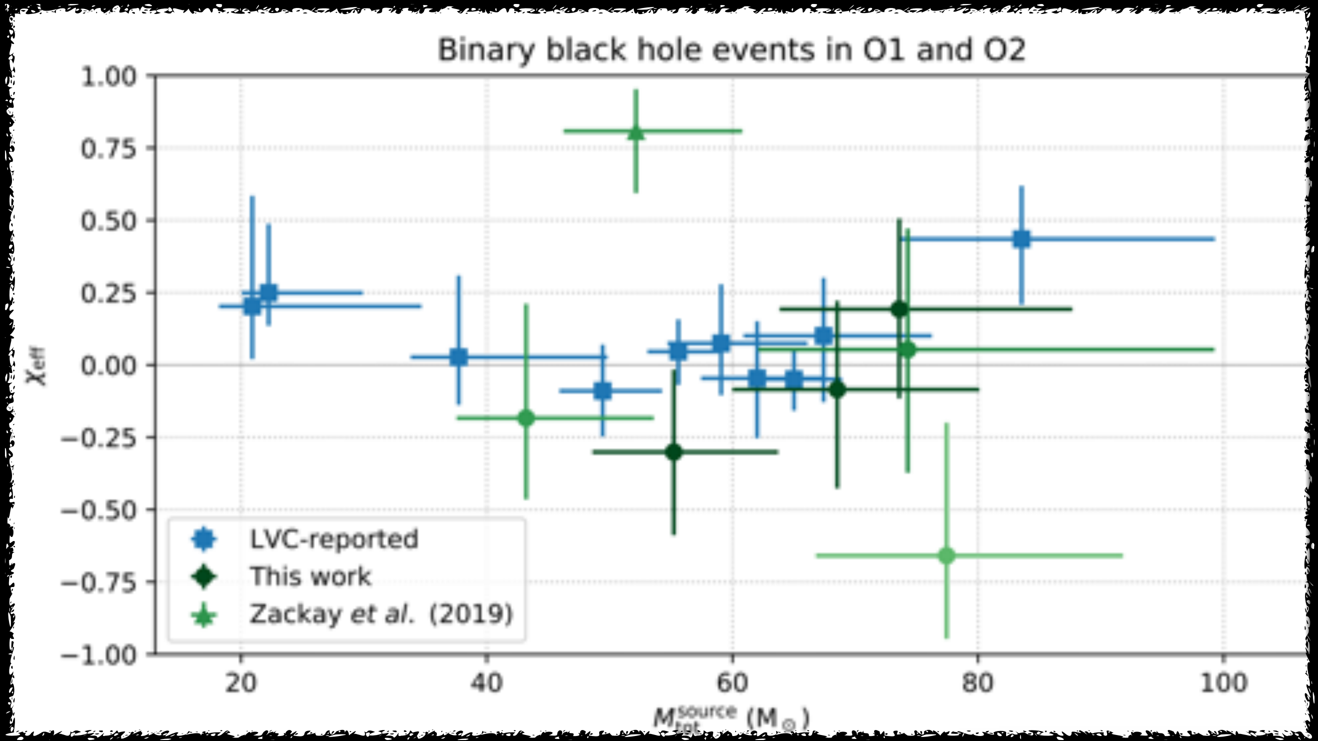
Hulse-Taylor Pulsar



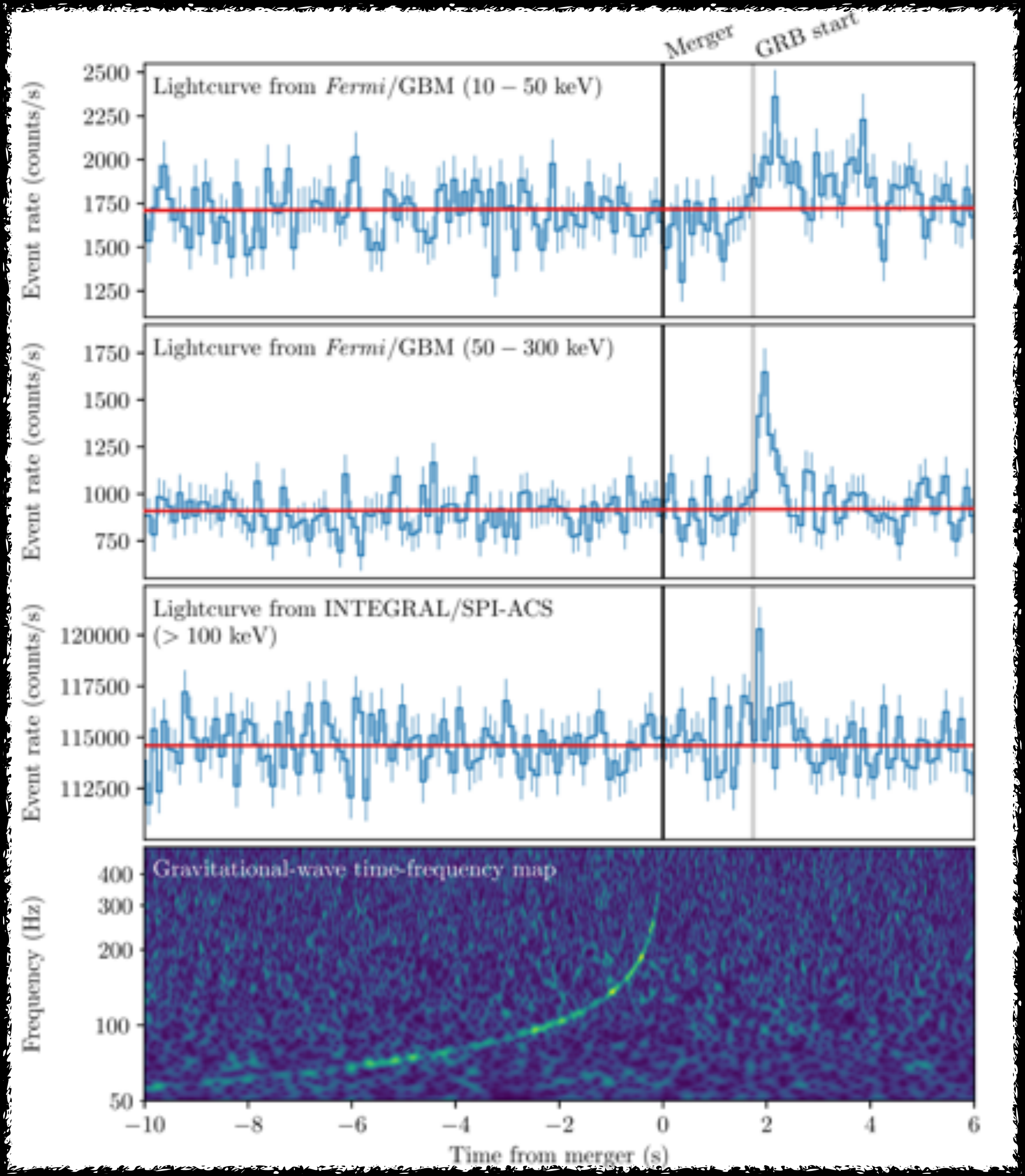

Stochastic background
EPTA
IPTA
SKA
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
Characteristic Strain
eLISA
10^9 solar mass binaries
LISA
10^6 solar mass binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
ALIA
DECIGO
BBO
TAMA
GEO
LIGO
VIRGO
aVIRGO
aLIGO
KAGRA
ET
Compact binary inspirals
Supernovae
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Frequency / Hz

Current Status: Any Surprises yet?

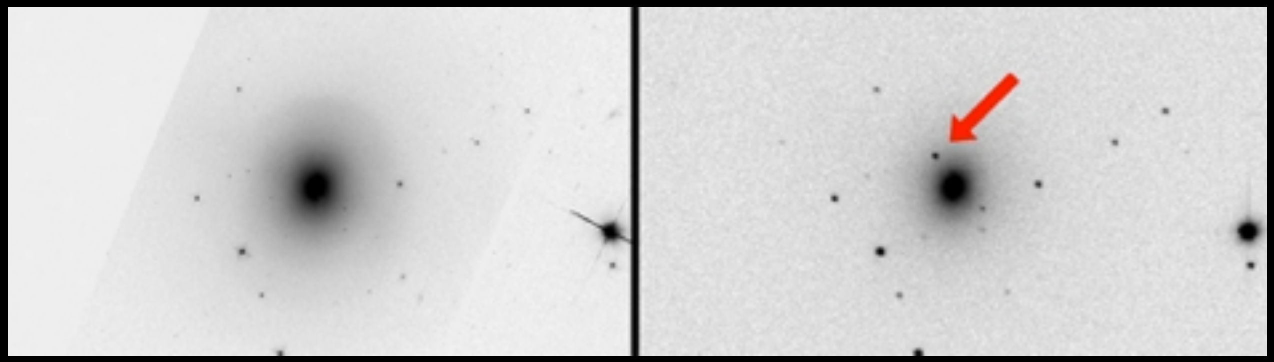
Black Holes:



Neutron Stars:



NS-NS optical signal:



What observations are we waiting for?

How do we know its Black Holes?

Solar Binary: $f_{GW}(sun) \sim 10^{-4}$ Hz

WD Binary: $f_{GW}(WD) \sim 10^{-1}$ Hz

NS/BH Binary: $f_{GW}(NS) \sim 10^{3}$ Hz

What can we learn from Gravitational Waves?

- What we measure:
  - Masses
  - Spins
  - Eccentricity
  - Dist./Pos./Redshift
  - Acceleration

- What we can learn about:
  - Gravity
  - Space time: Extra Dim?
  - Cosmology: Expansion
  - Nuclear Physics
  - Astrophysics

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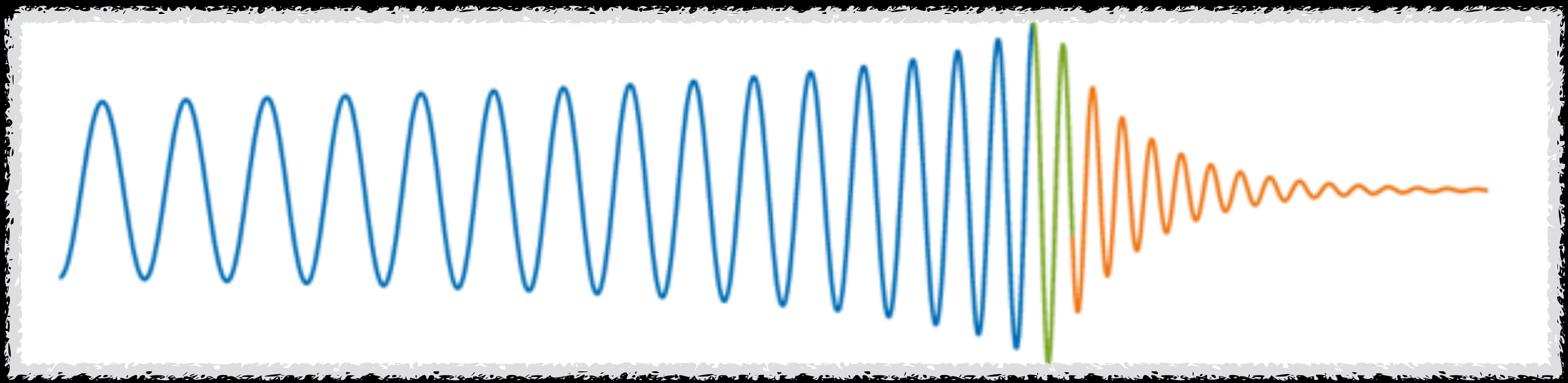
Generic Inspiral:



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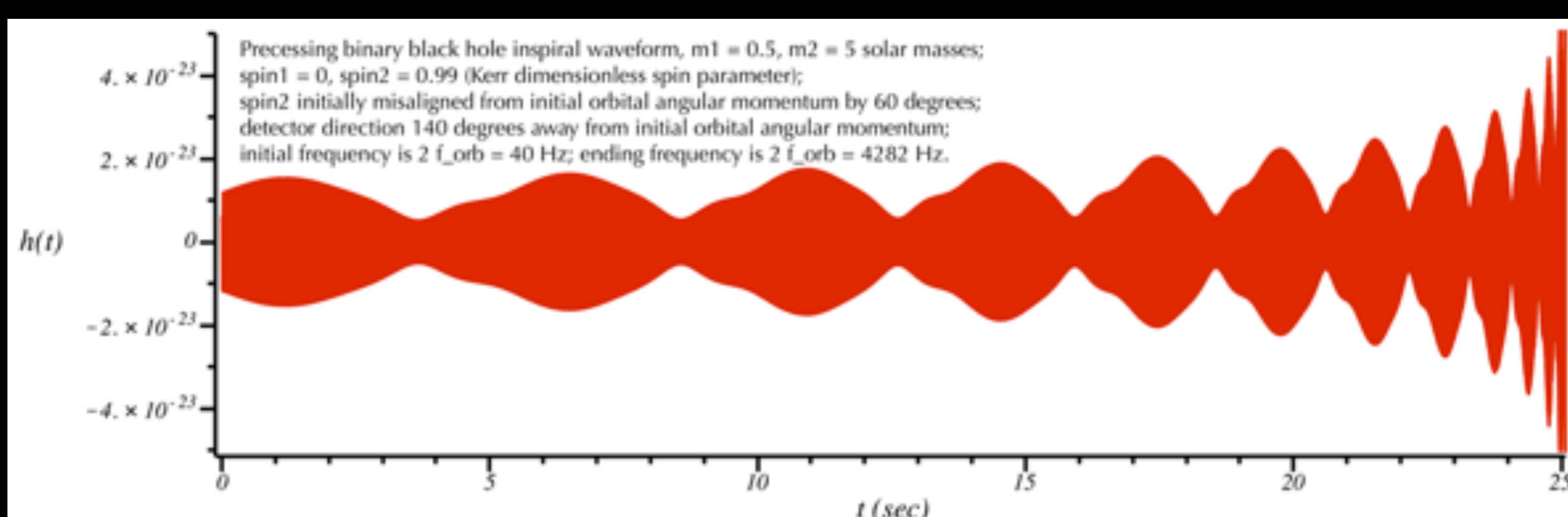
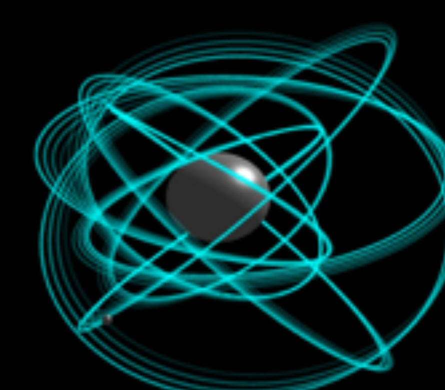
Highly Spinning:





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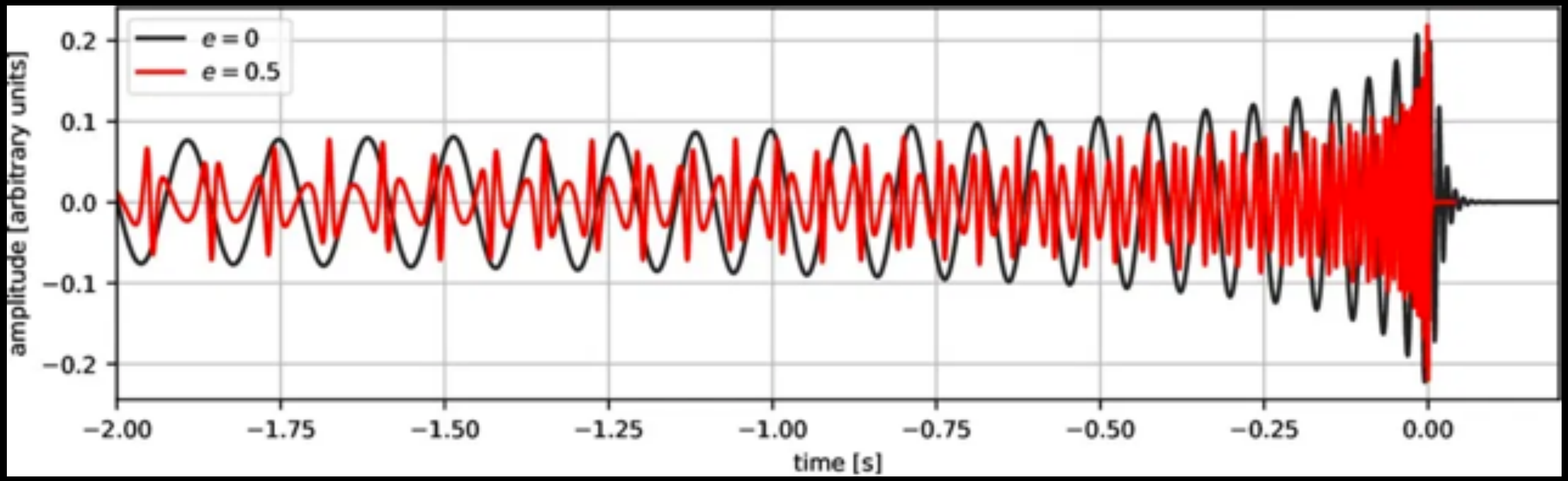
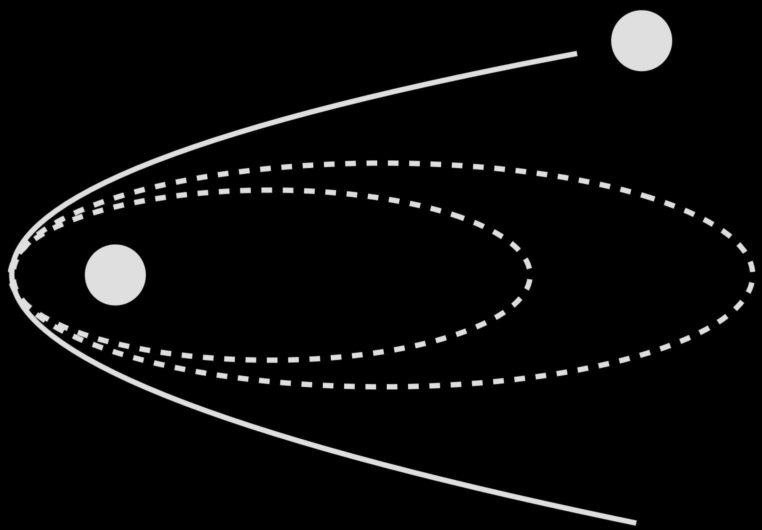
Highly Eccentric:





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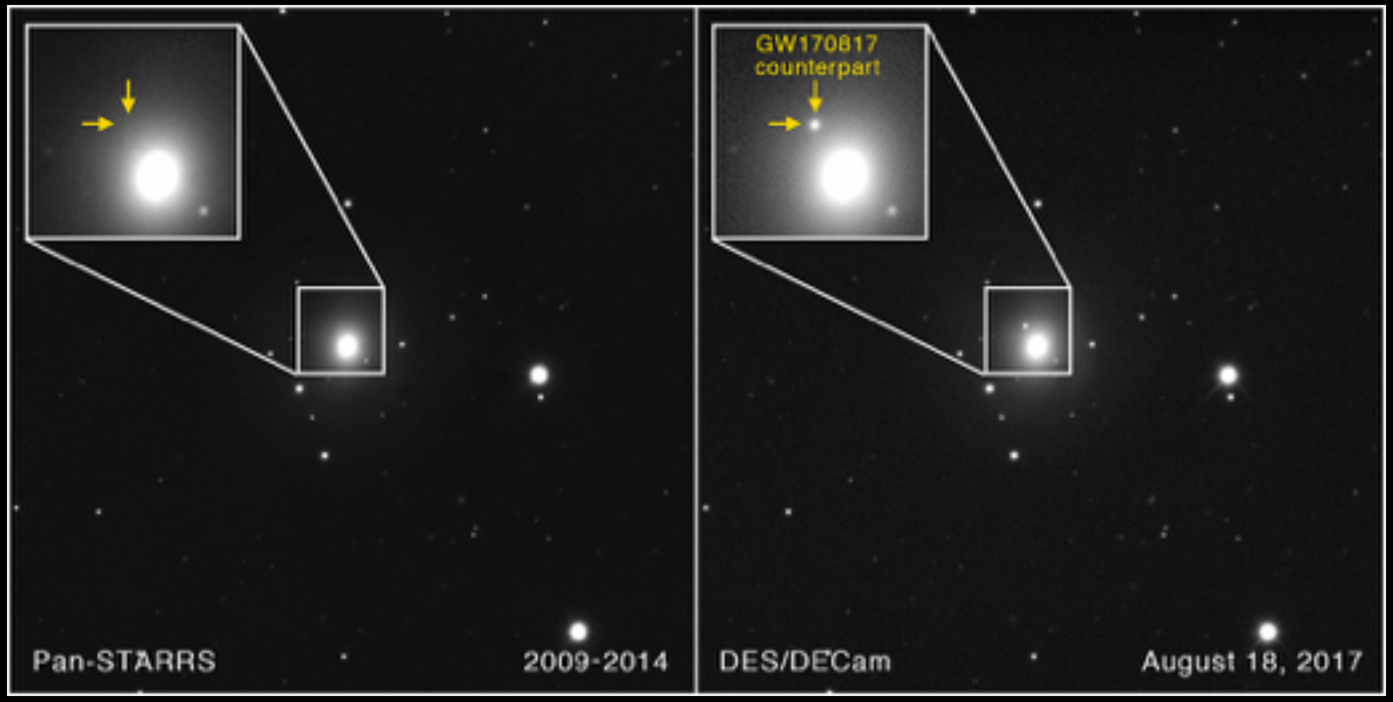
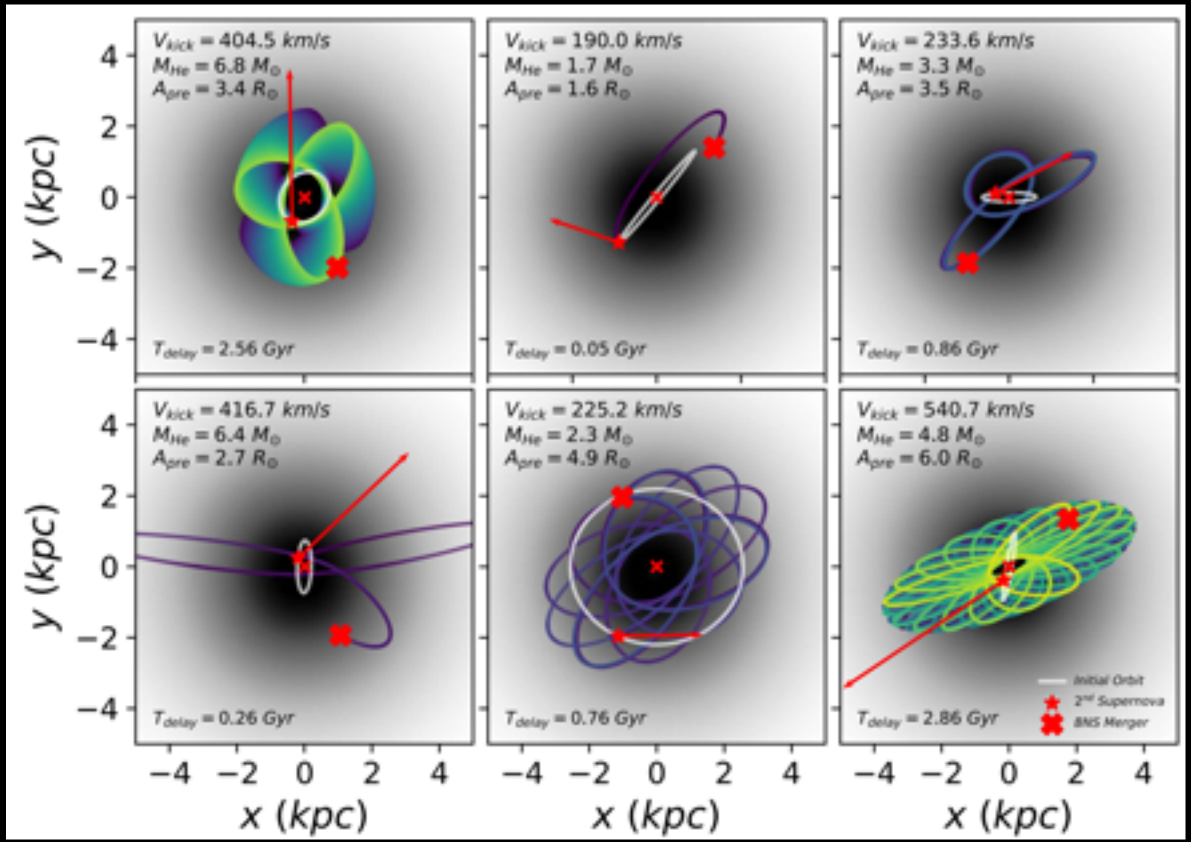
Observation:



Simulation:



What can we learn from Gravitational Waves?

- What we measure:

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- Spins
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- **Acceleration**

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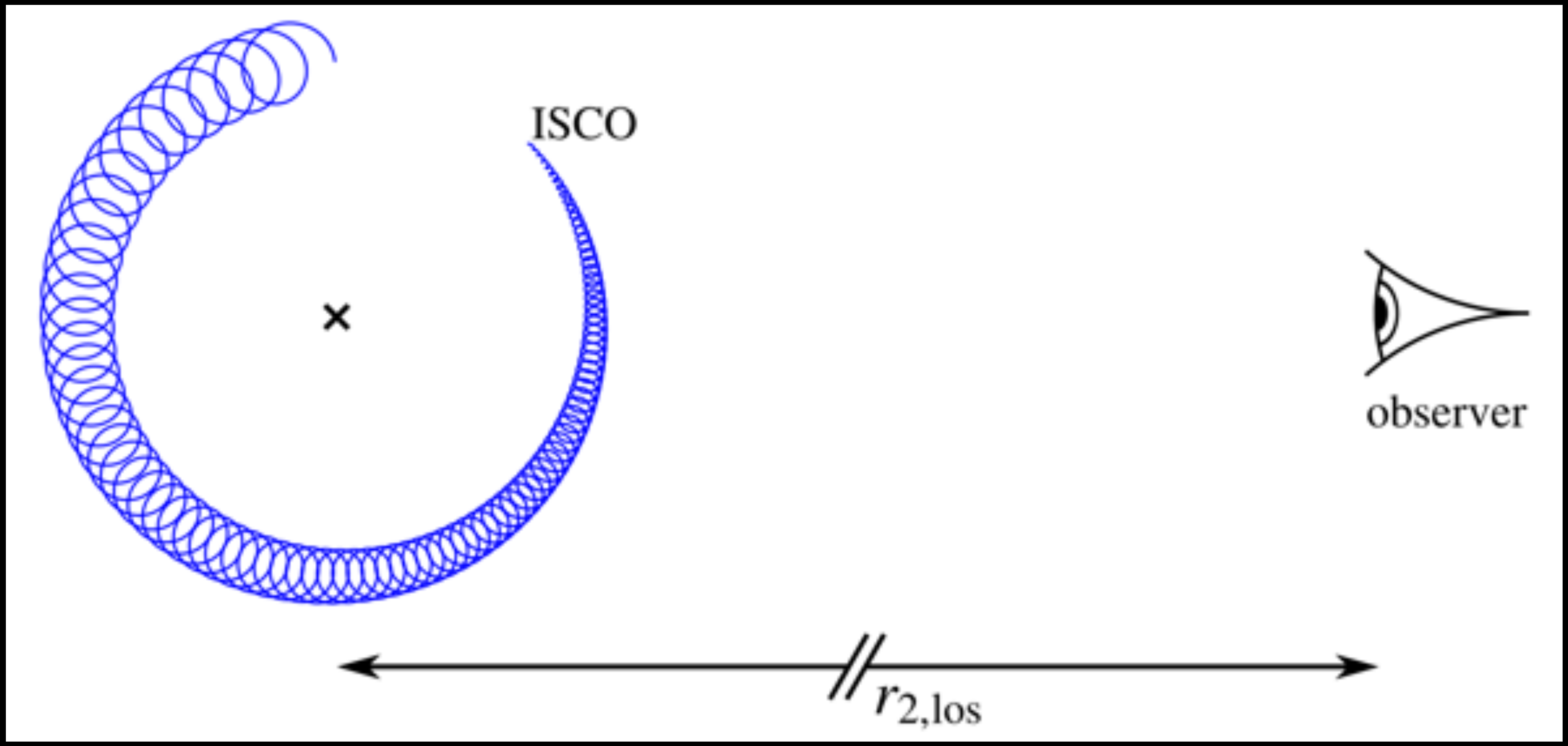

What can we learn from Gravitational Waves?

- What we measure:

- Masses
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- Dist./Pos./Redshift
- Acceleration

- What we can learn about:

- **Gravity (modify waveform)**
- **Space time: Extra Dim?**
- Cosmology: Expansion
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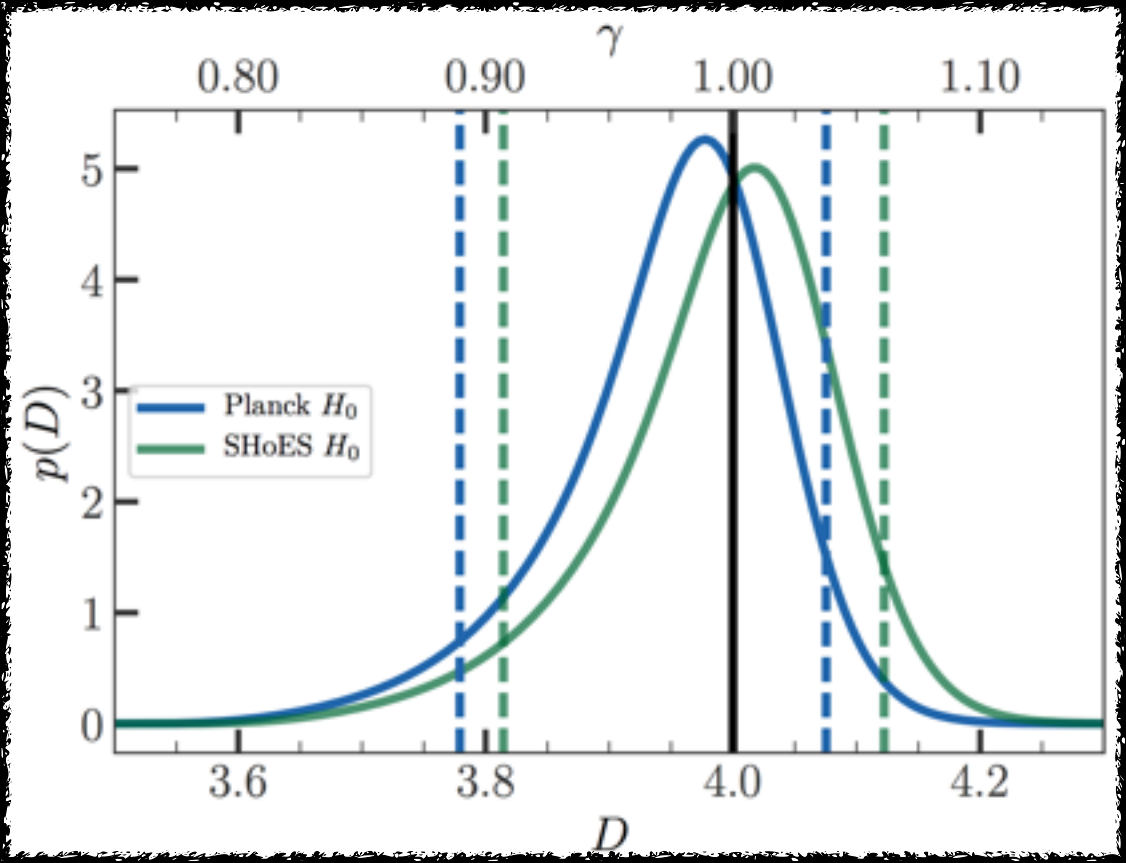
Constraining the number of space-time dimensions:

$$h \propto \frac{1}{d_L^{\gamma}}$$



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- **Cosmology: Expansion**
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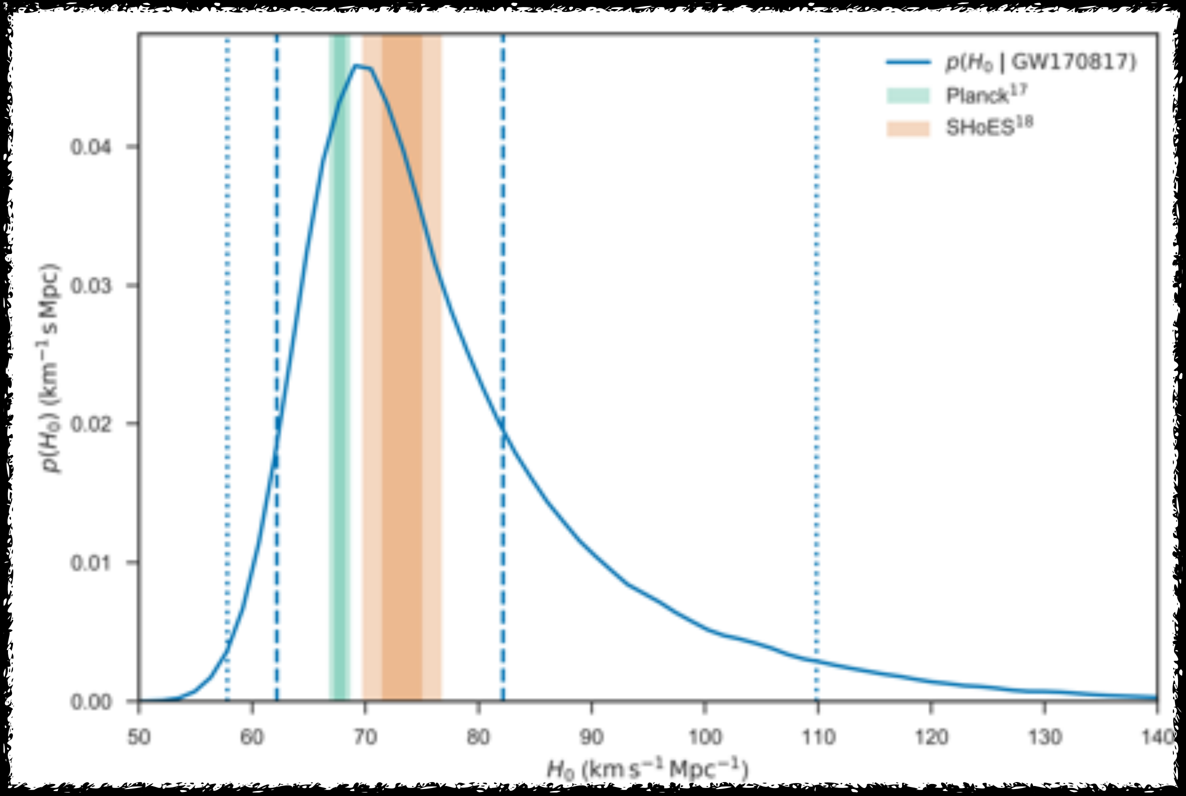
Hubble's law:

$$v_H = H_0 d$$

The cosmological params.
can also be measured!

$$D_L(z) = \frac{c\,(1+z)}{H_0\sqrt{\Omega_K}} \sinh\left[\sqrt{\Omega_K}\int_0^z \frac{H_0}{H(z')}\,dz'\right]$$



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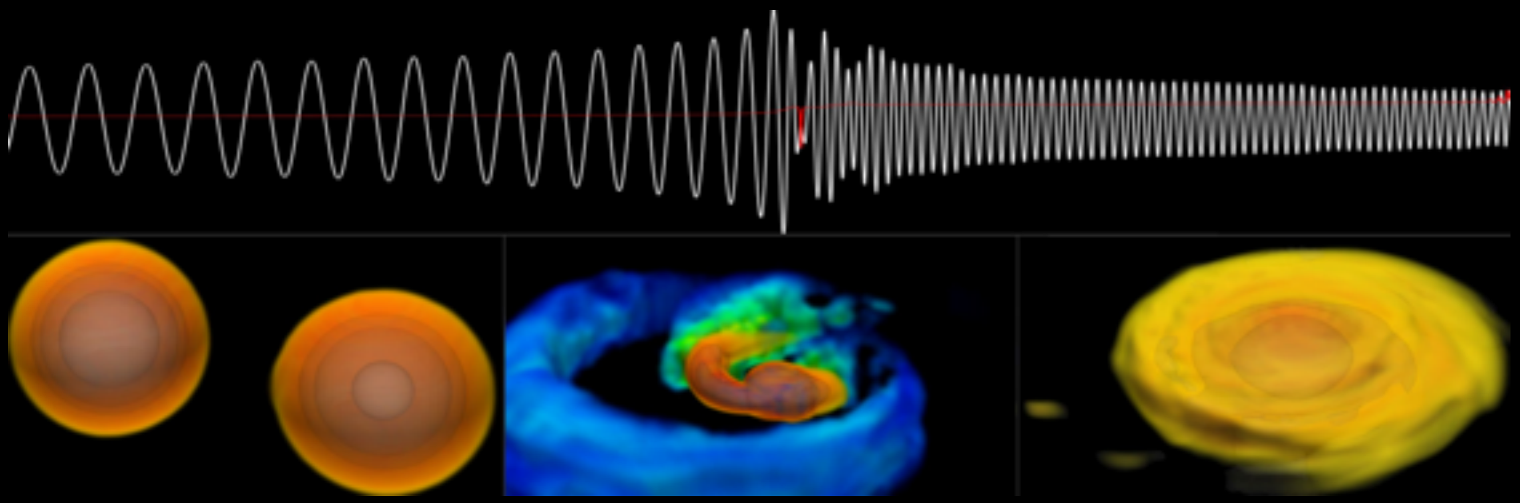
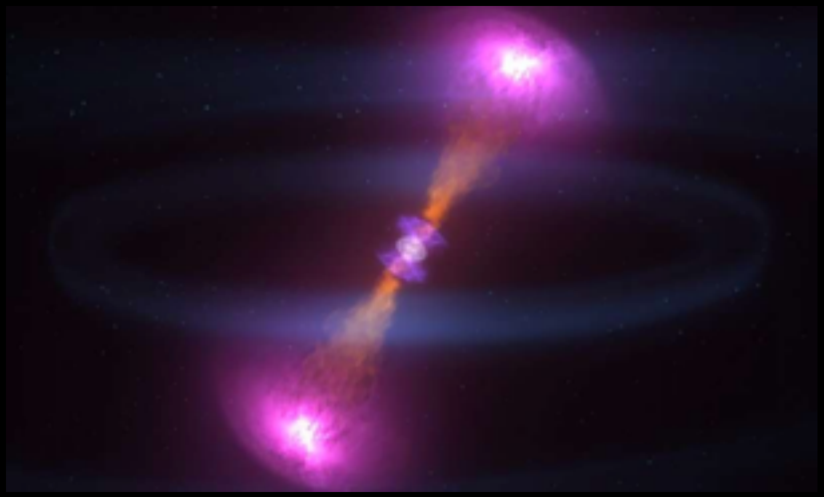
  - **Nuclear Physics**
  - Astrophysics

Tidal coupling and disruption:



Jet/Enrichment:



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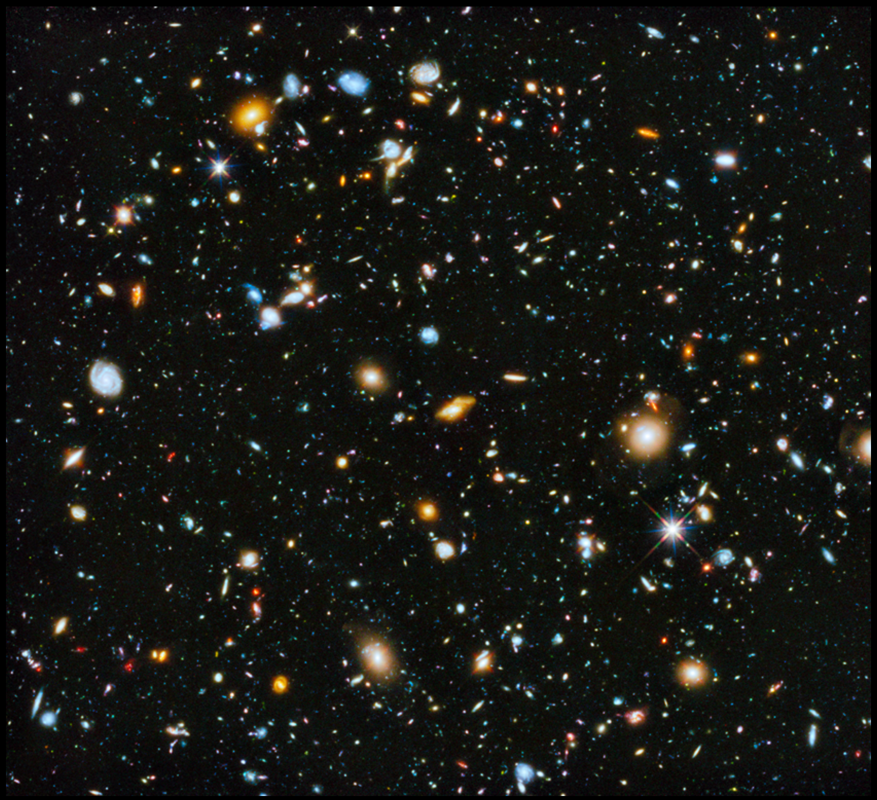
  - **Nuclear Physics**
  - **Astrophysics**

Astrophysics: How do Black Holes Form and Merge?

- *Primordial BHs*
- *Galactic Nuclei*
- *Supernovae*
- *Isolated BSE*
- *3,4-body BSE*
- *AGN Disk*
- *NS Mountains*
- *… ?*



Gravitational Wave Astrophysics

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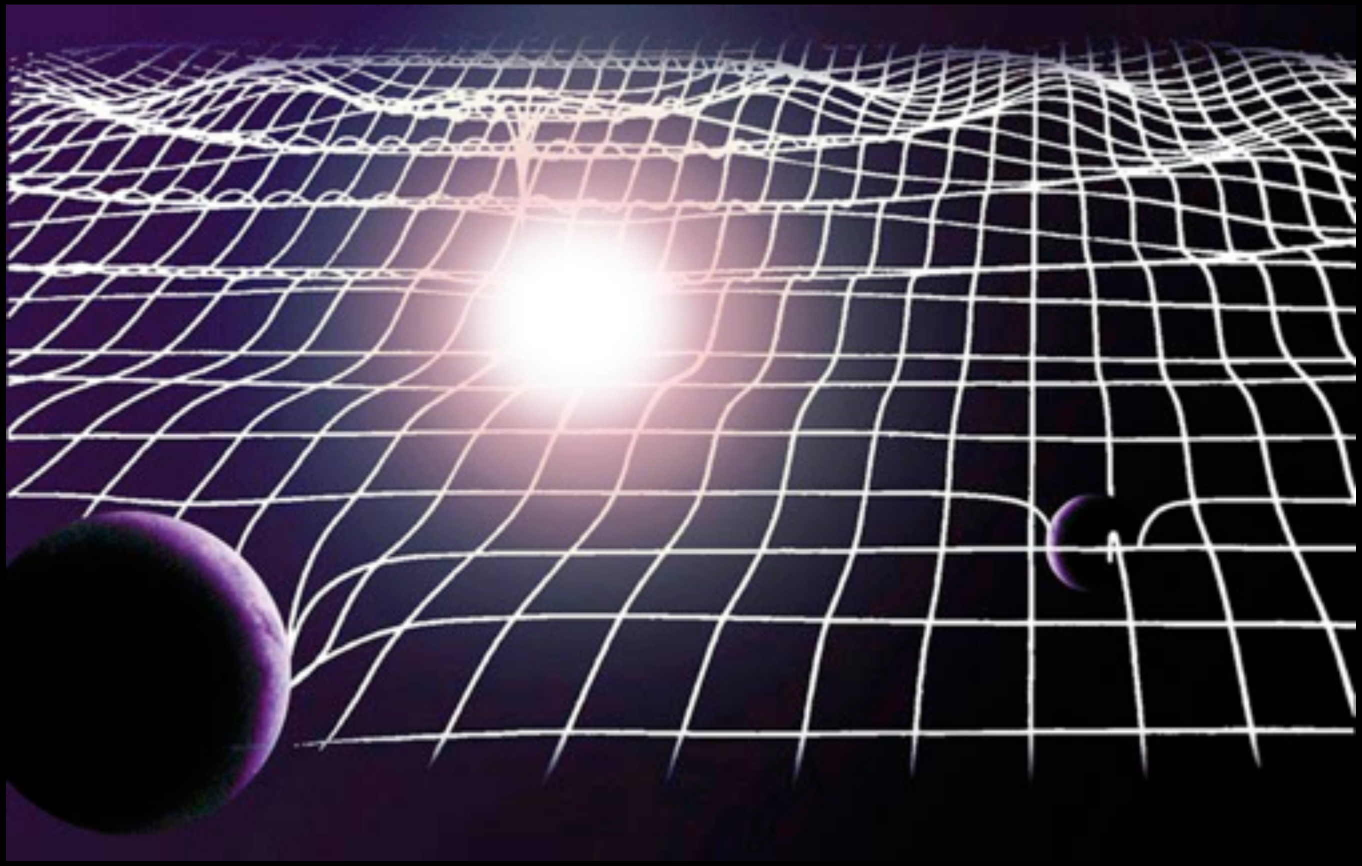
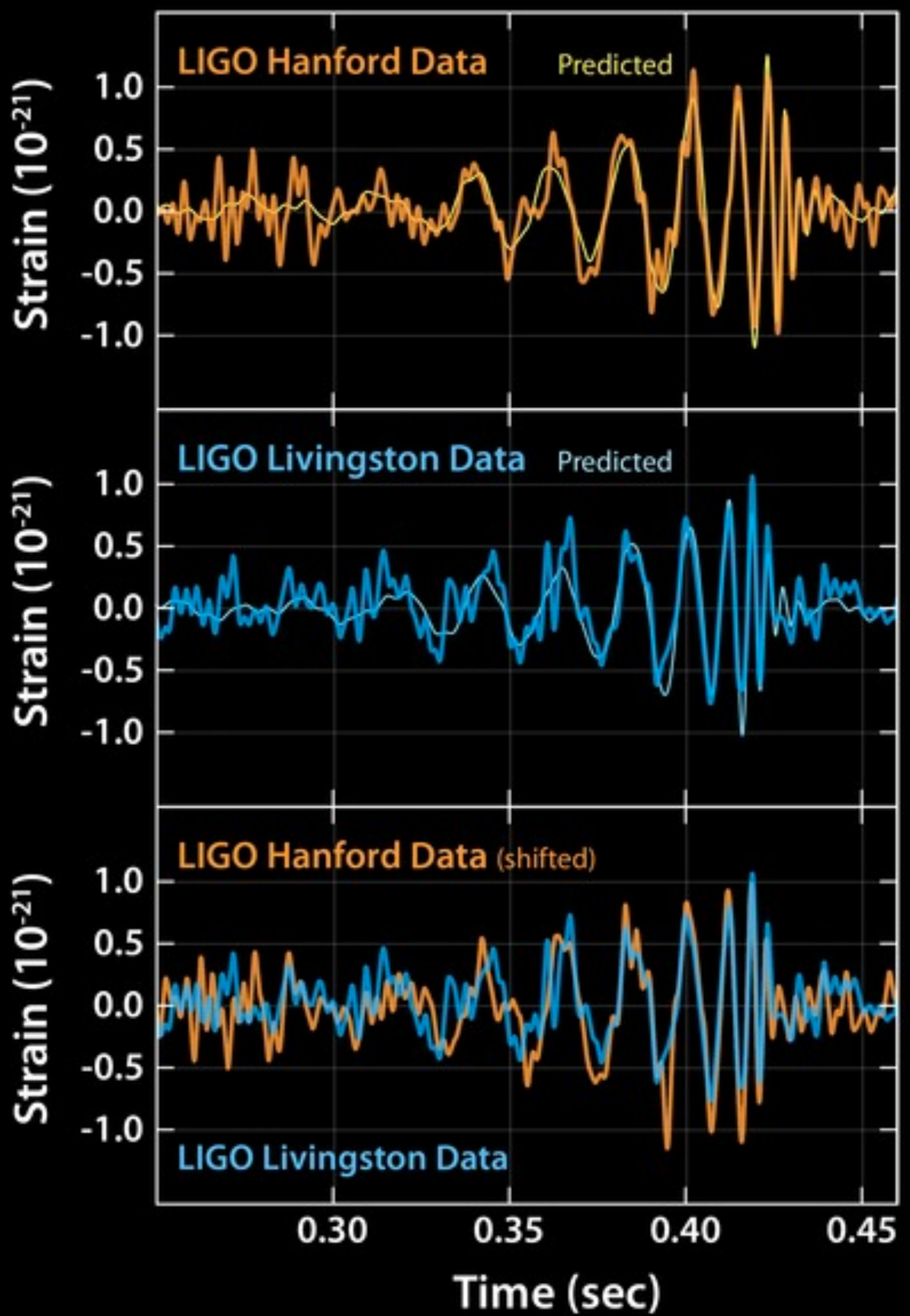
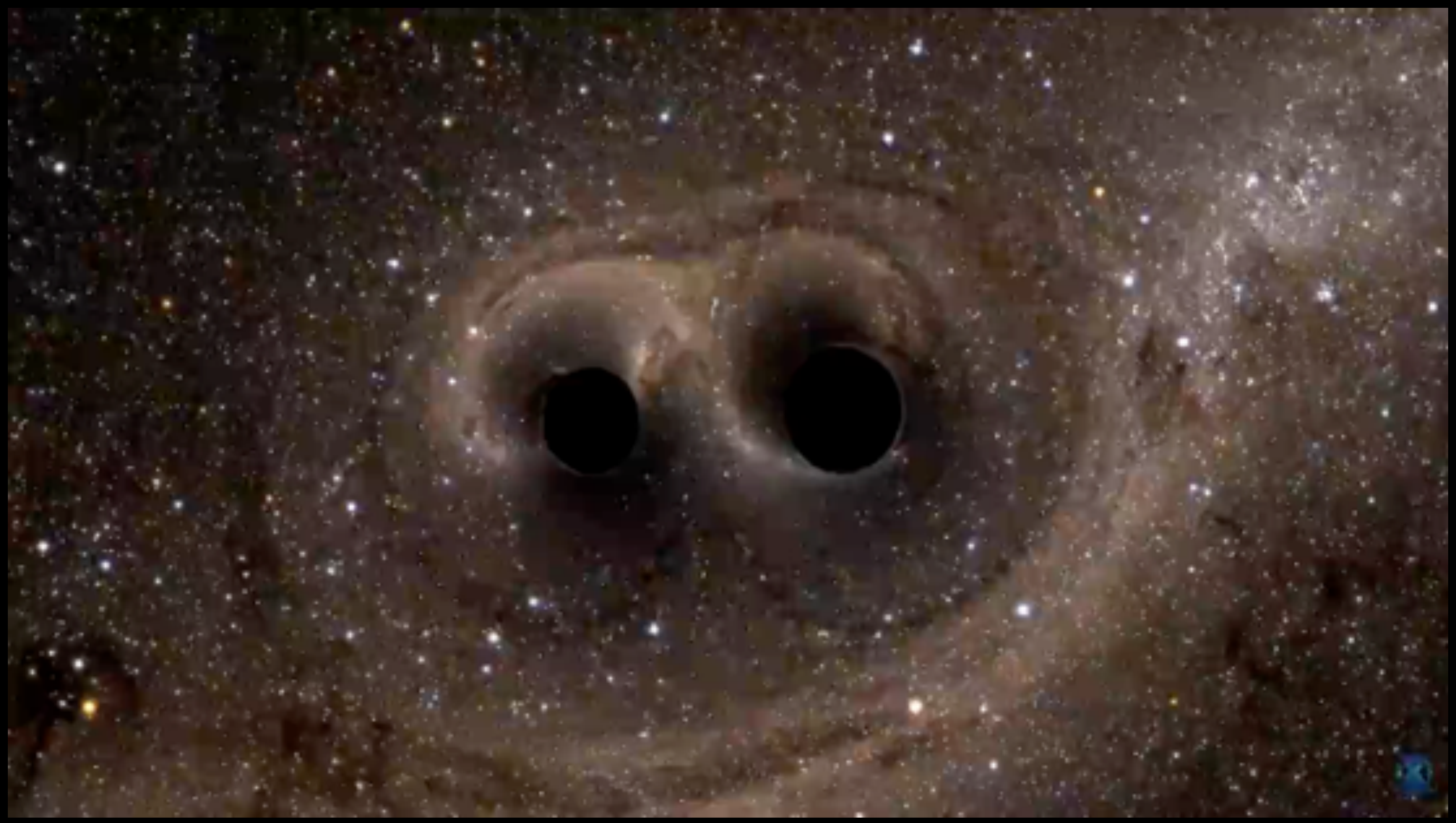


Part II

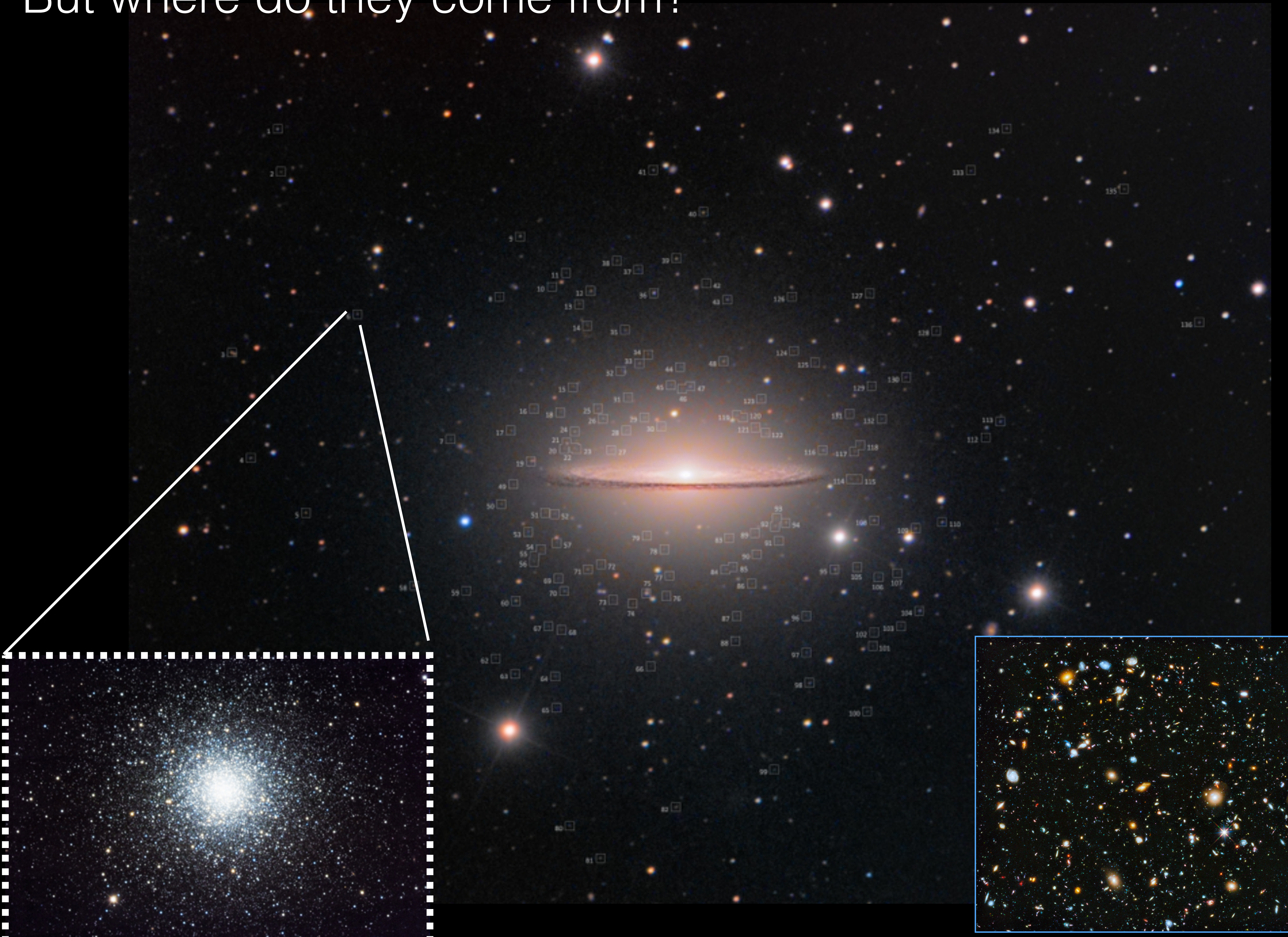
Observation:

Simulation:



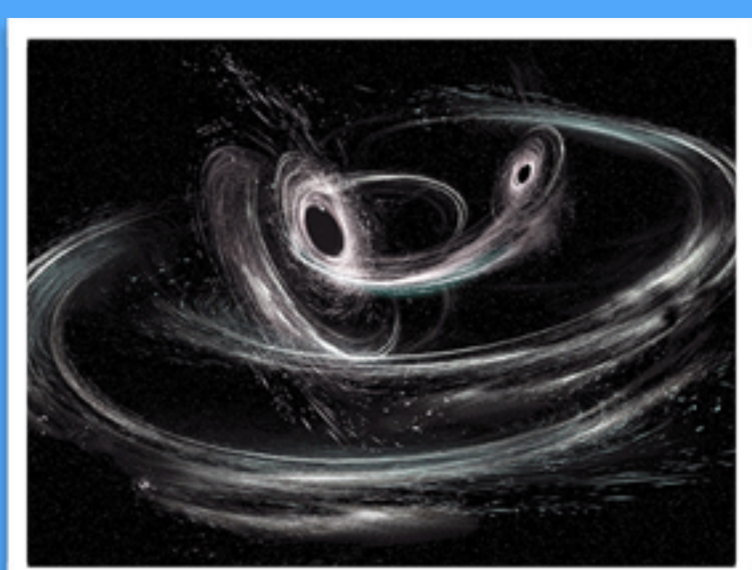


But where do they come from?

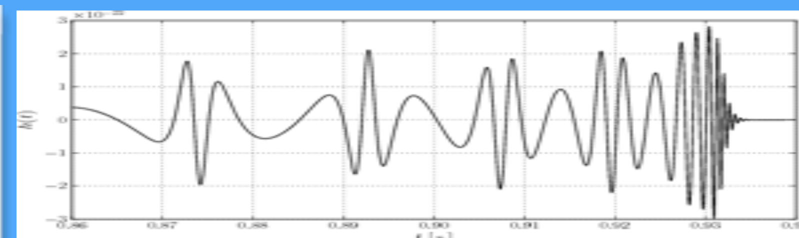


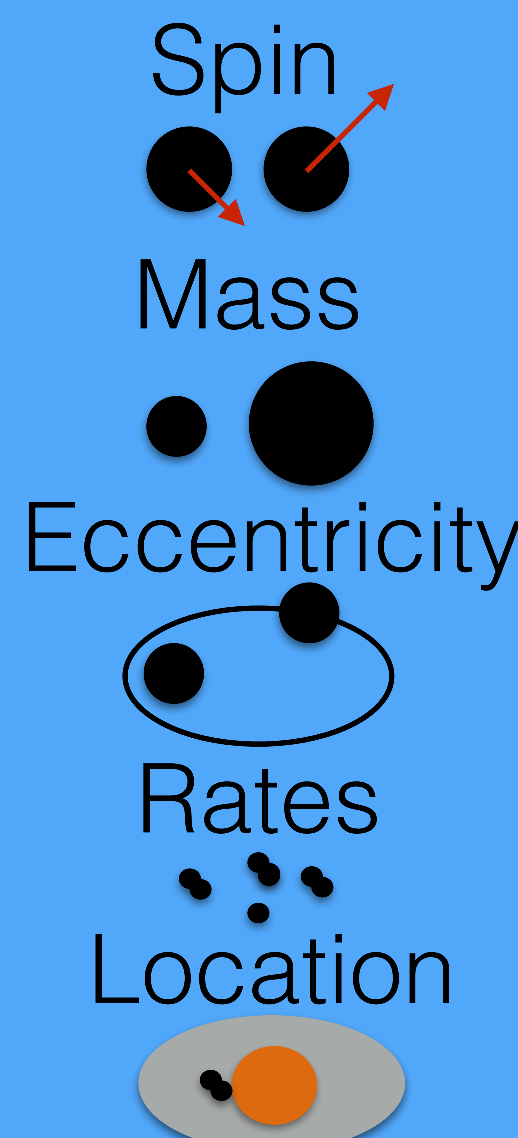
What is the origin of BBH mergers?

Clusters

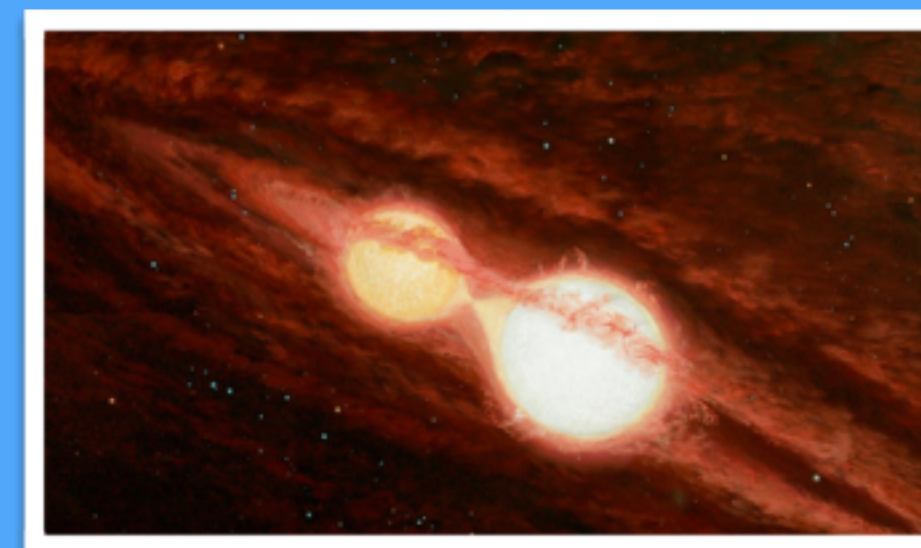


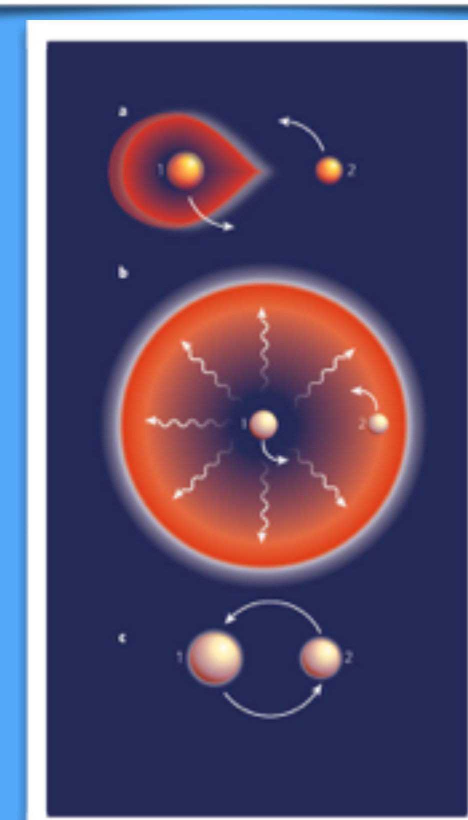
parameters





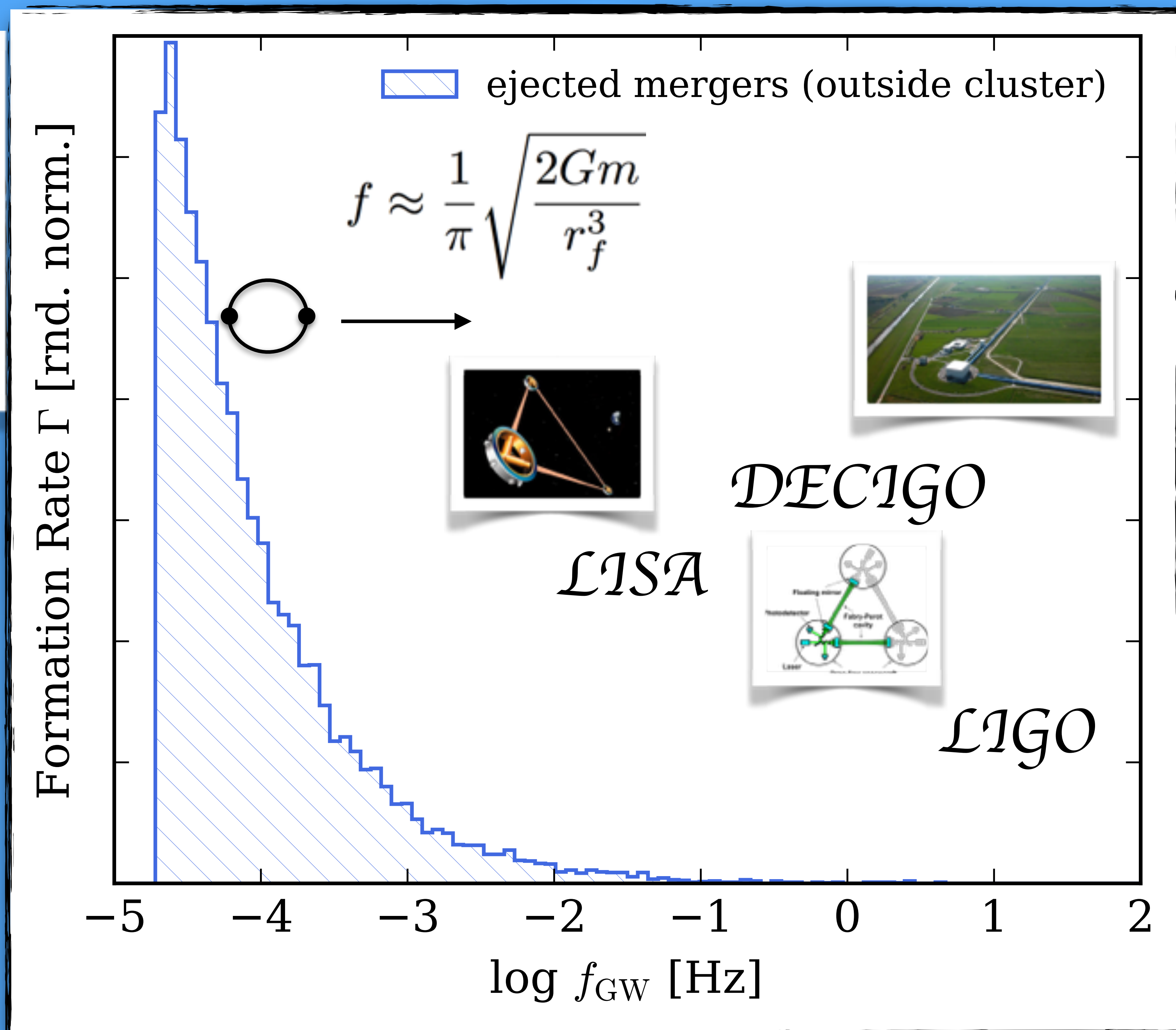
Field





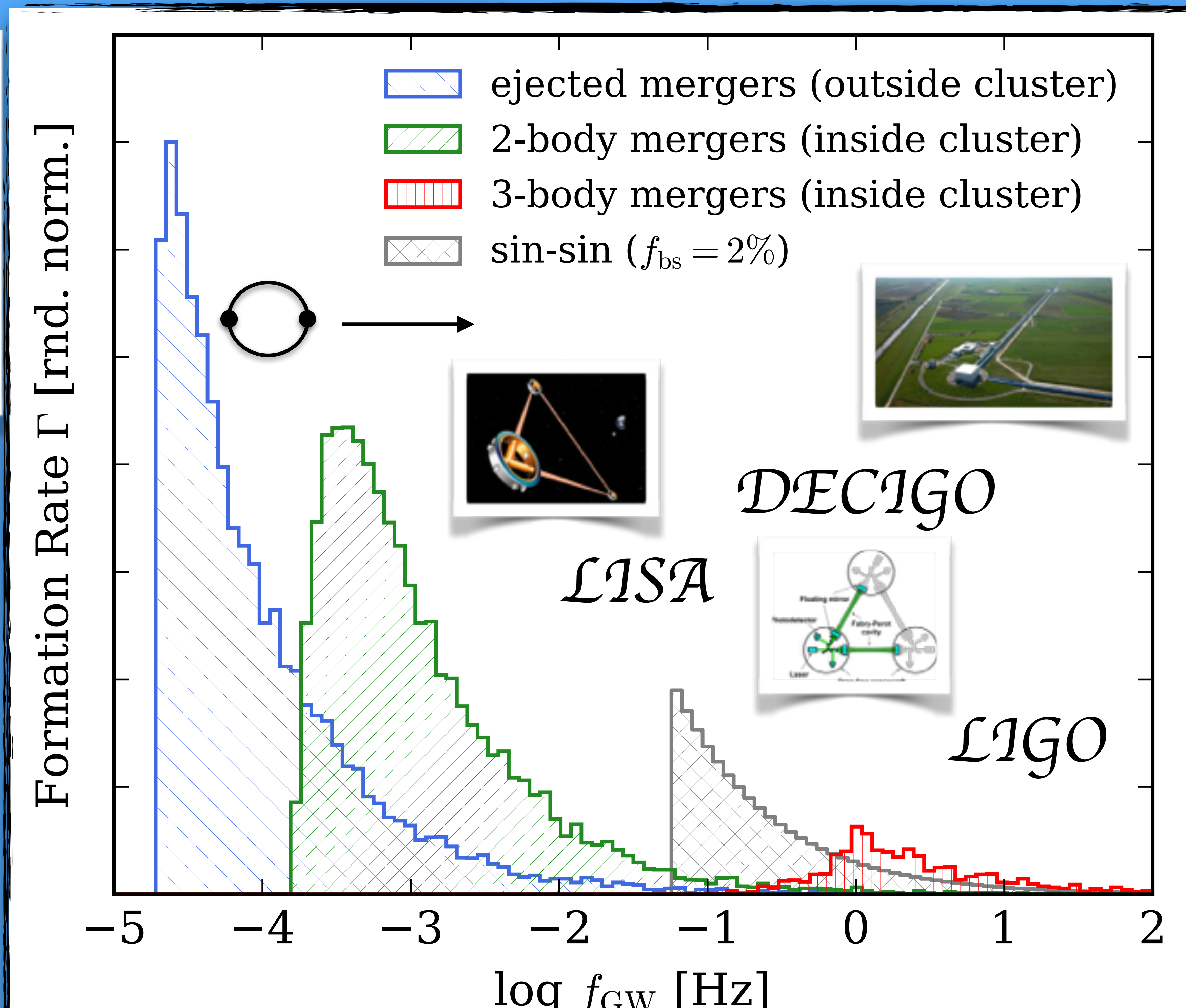
Old Newtonian Studies

< 2017

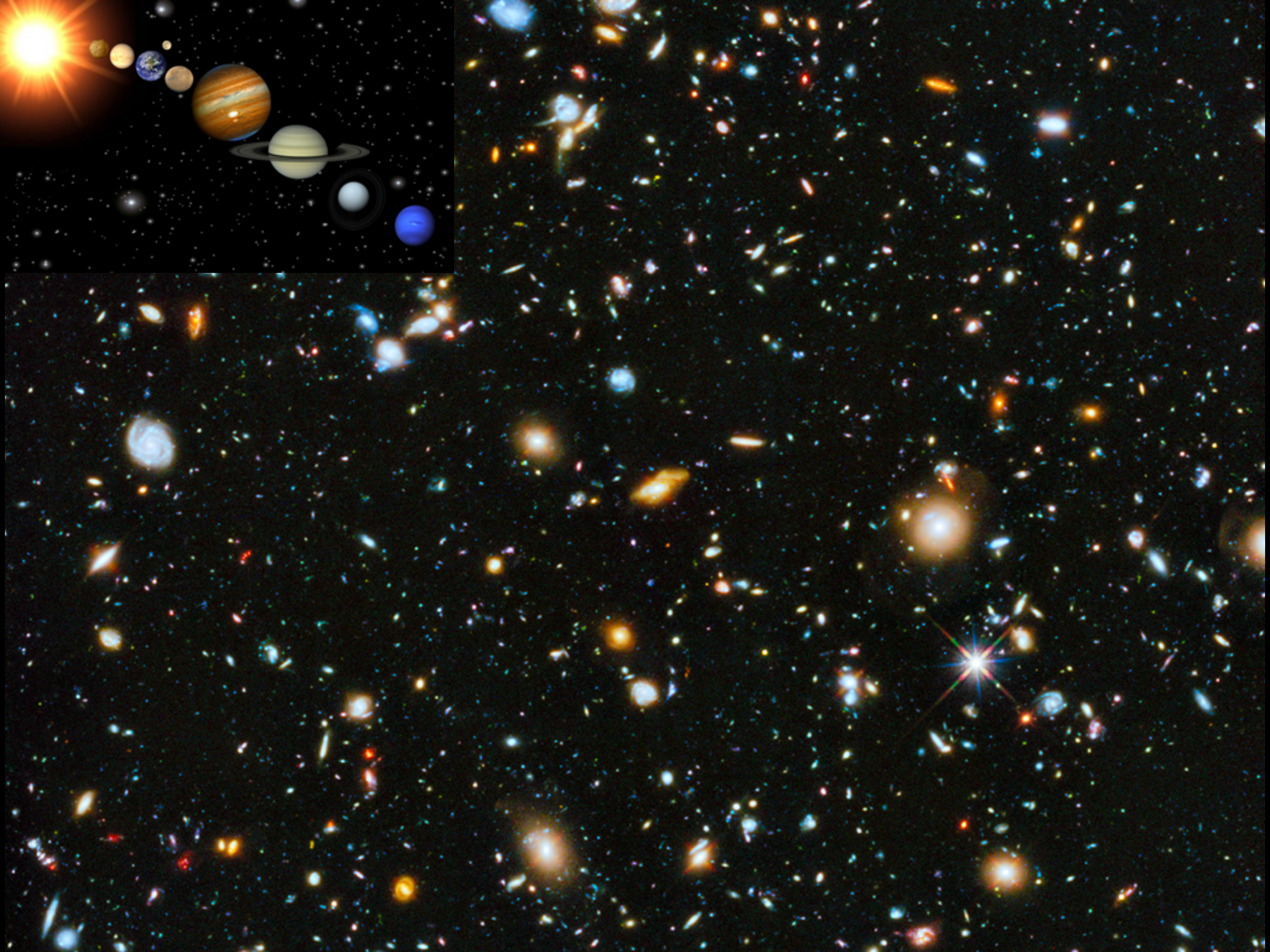


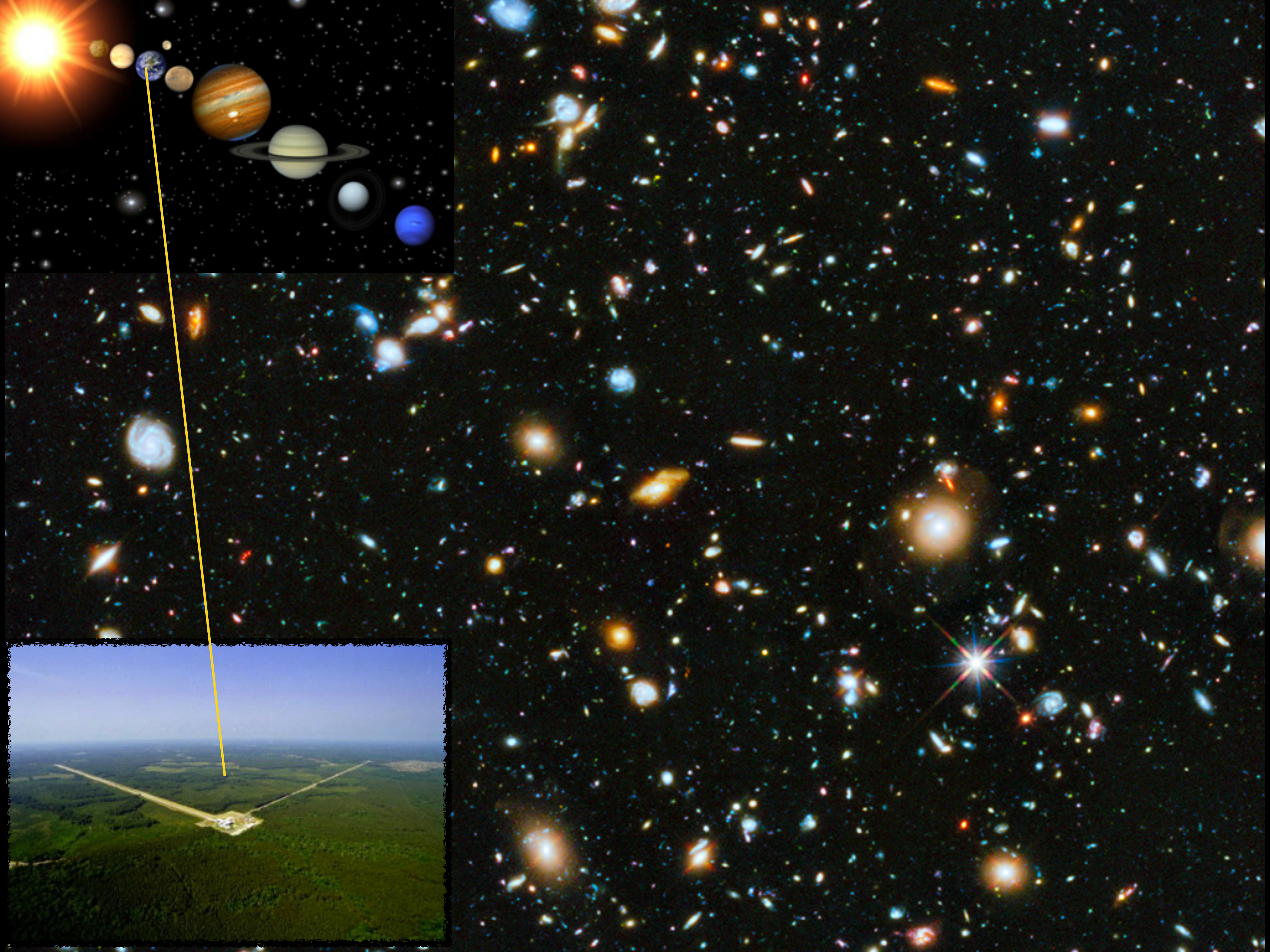
New Post-Newtonian Studies

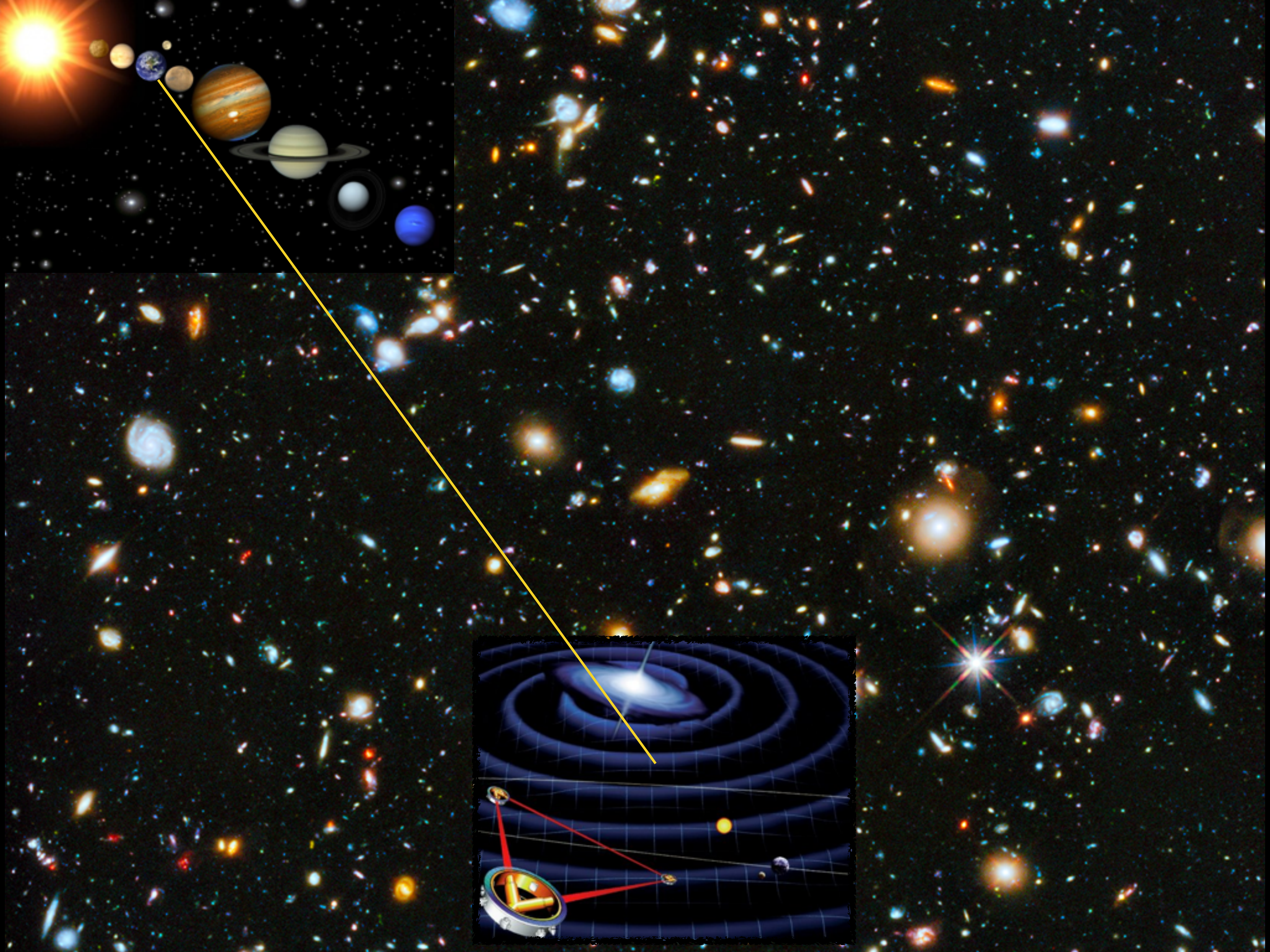
> 2017

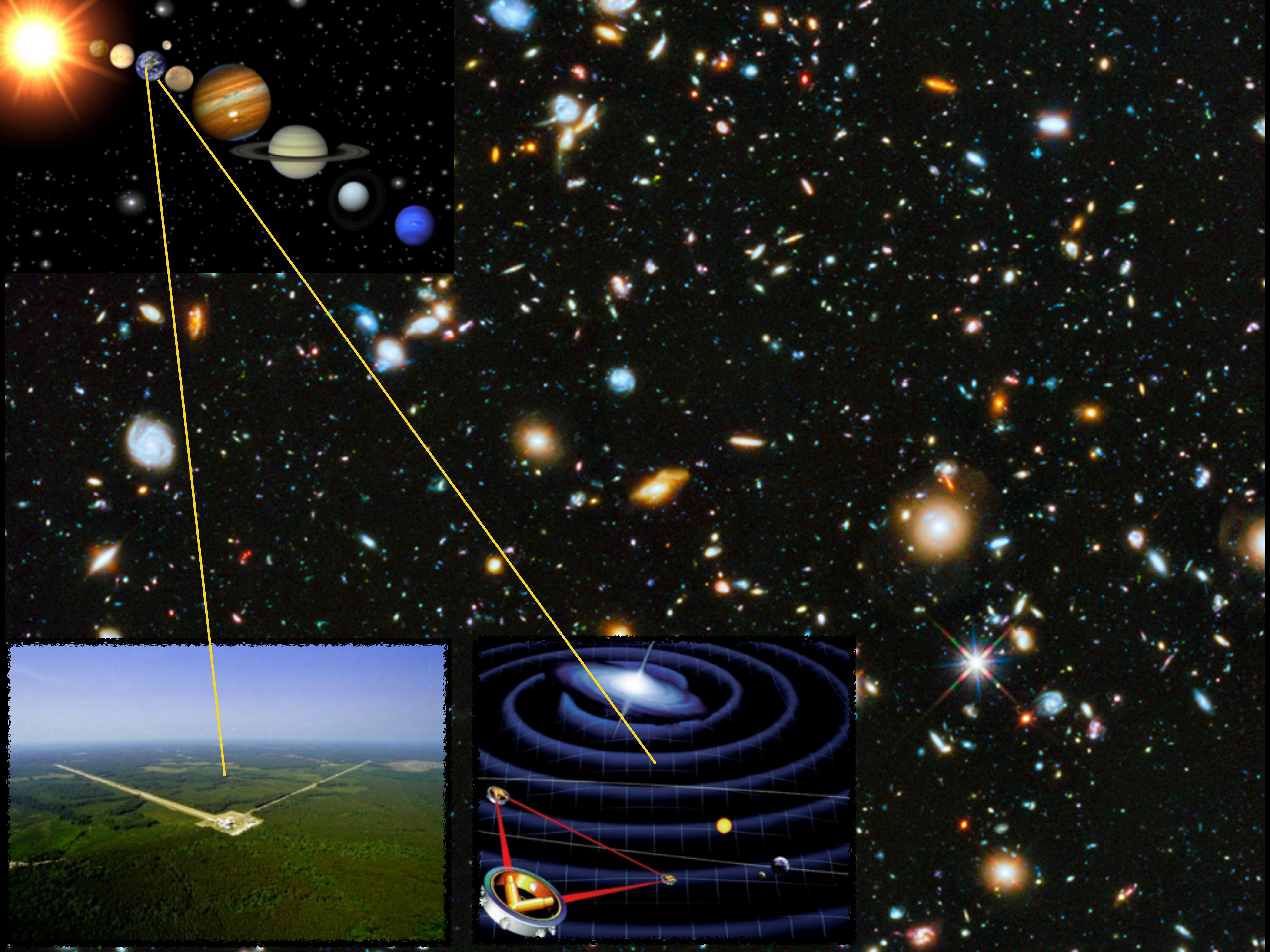


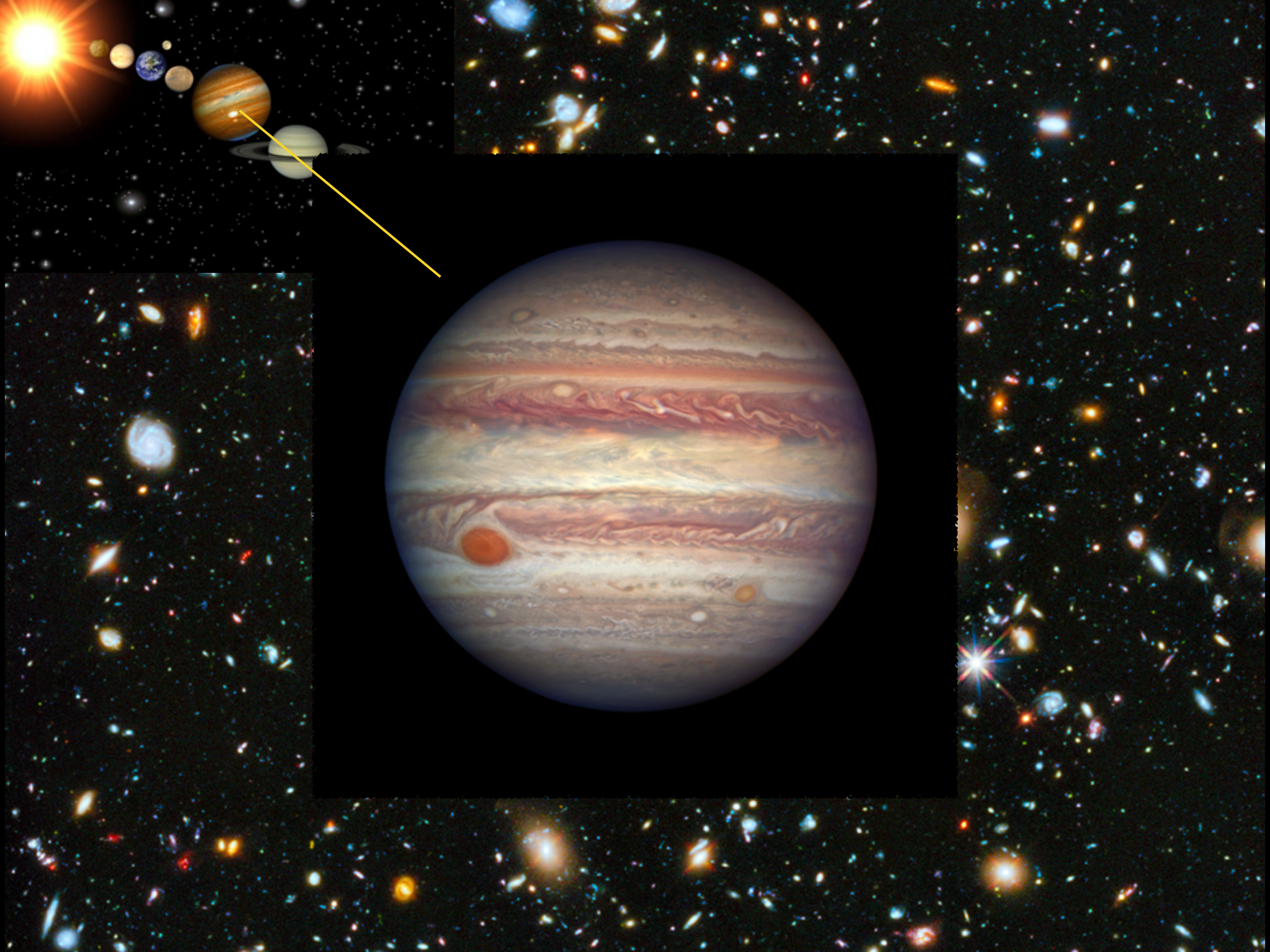
THESE are real 'useful' predictions…

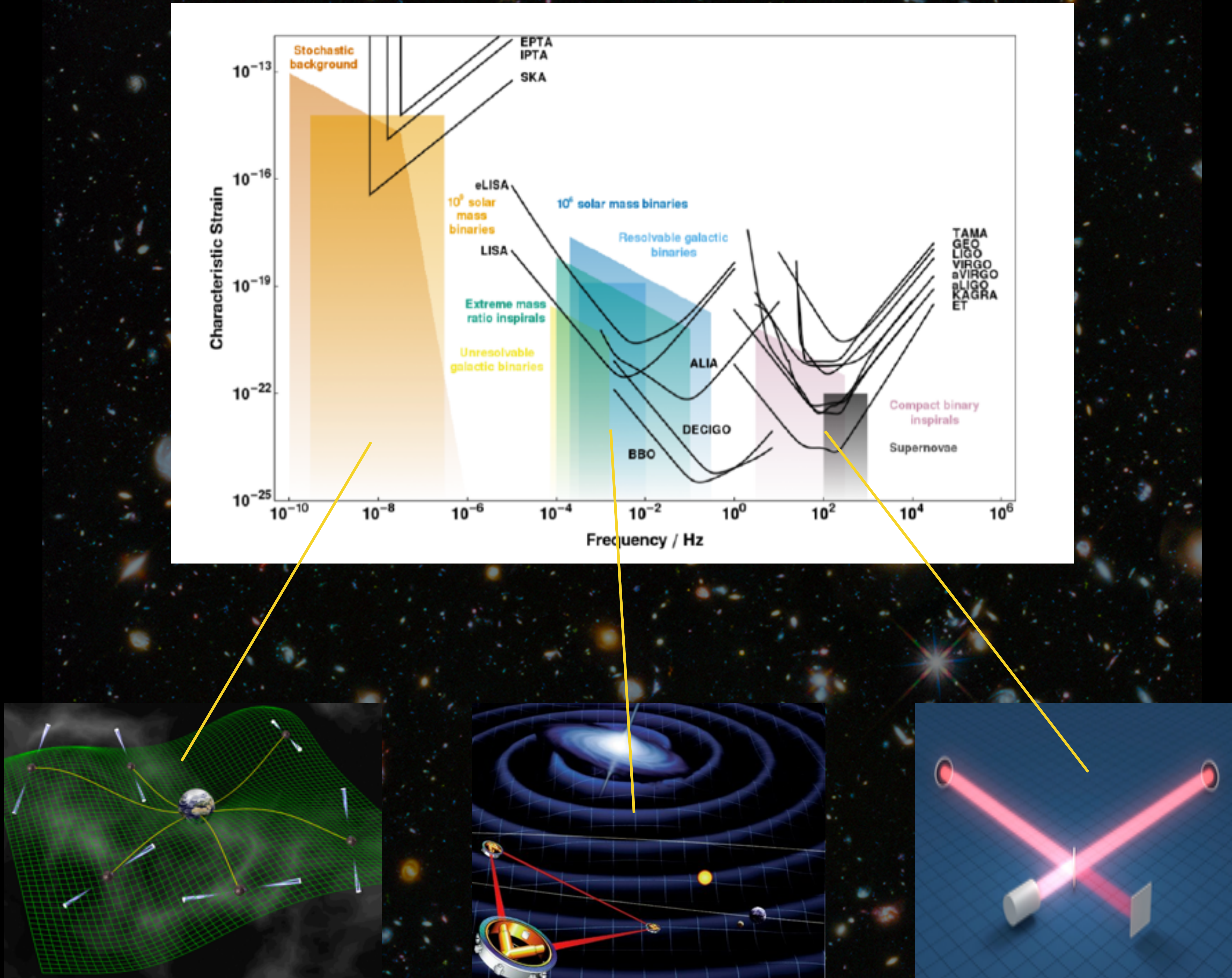












Stochastic background
EPTA
IPTA
SKA
eLISA
10^{9} solar mass binaries
10^{6} solar mass binaries
Resolvable galactic binaries
LISA
Extreme mass ratio inspirals
Unresolvable galactic binaries
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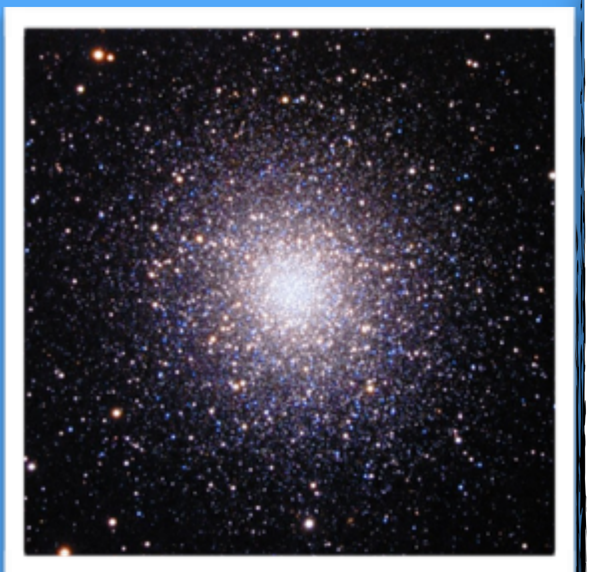
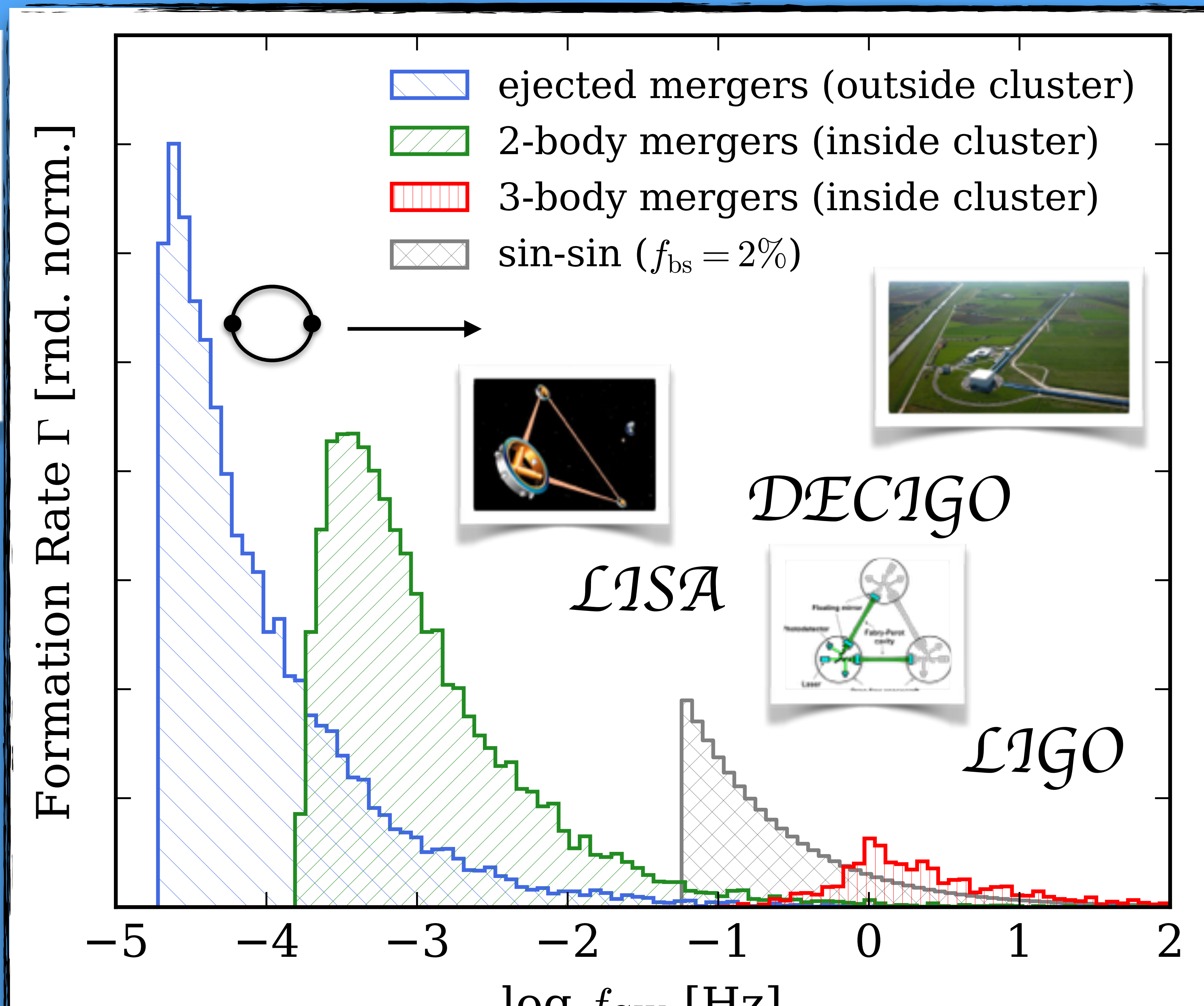
Frequency / Hz

New Post-Newtonian Studies

> 2017





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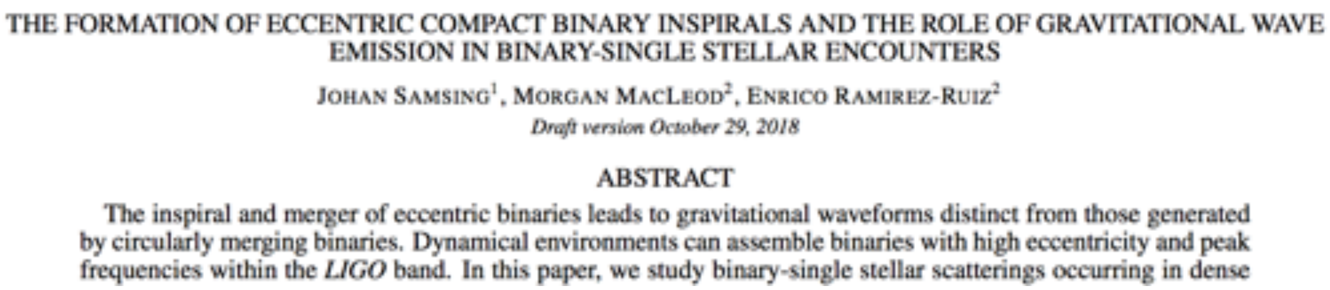
Background



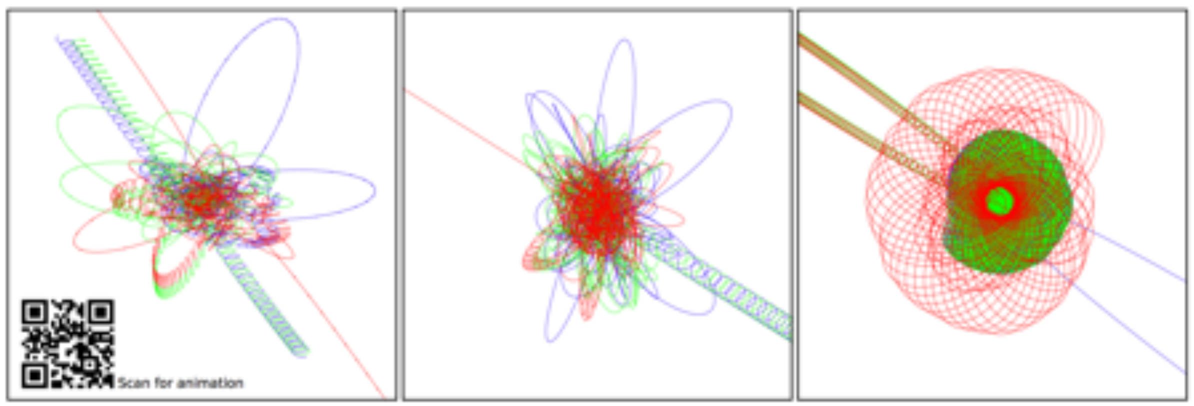
THE FORMATION OF ECCENTRIC COMPACT BINARY INSPIRALS AND THE ROLE OF GRAVITATIONAL WAVE EMISSION IN BINARY-SINGLE STELLAR ENCOUNTERS

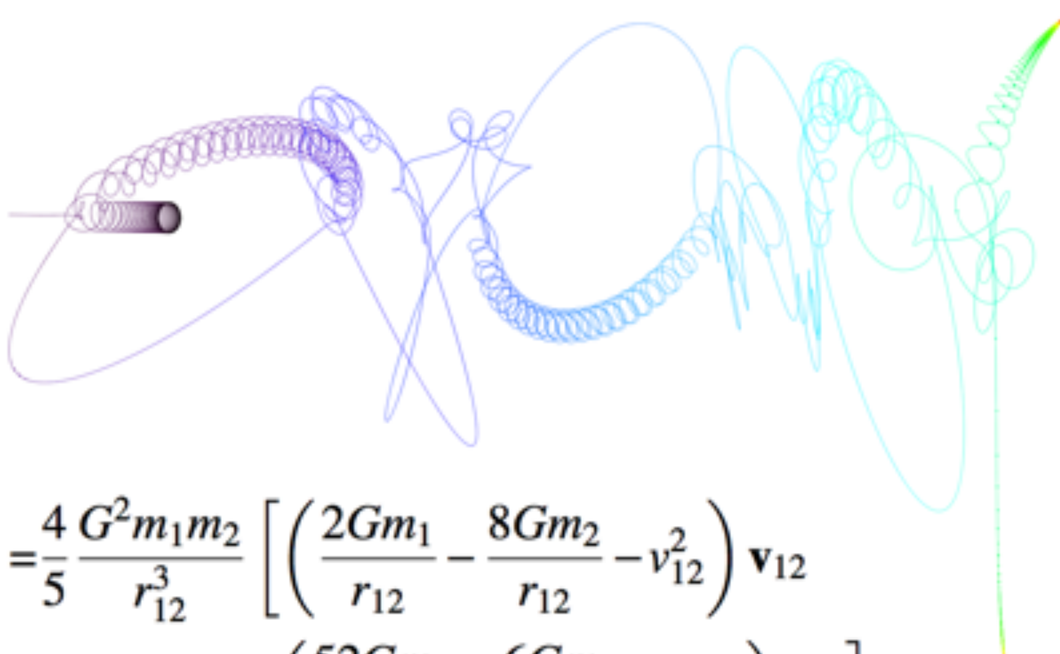
JOHAN SAMSING[1], MORGAN MACLEOD[2], ENRICO RAMIREZ-RUIZ[2]

Draft version October 29, 2018

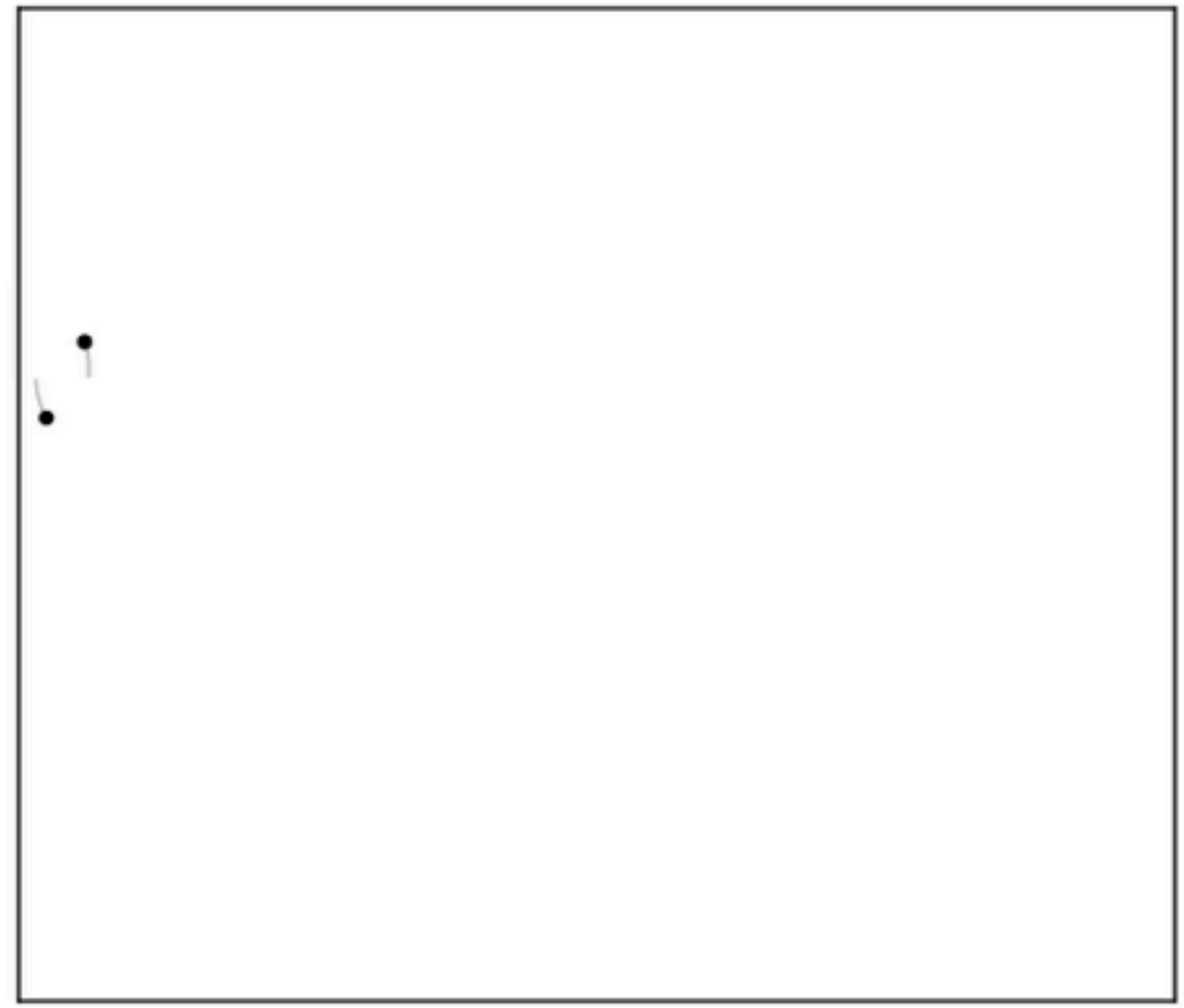
ABSTRACT

The inspiral and merger of eccentric binaries leads to gravitational waveforms distinct from those generated by circularly merging binaries. Dynamical environments can assemble binaries with high eccentricity and peak frequencies within the *LIGO* band. In this paper, we study binary-single stellar scatterings occurring in dense





$$\mathbf{a}_5 = \frac{4}{5}\frac{G^2 m_1 m_2}{r_{12}^3}\left[\left(\frac{2Gm_1}{r_{12}} - \frac{8Gm_2}{r_{12}} - v_{12}^2\right)\mathbf{v}_{12} + (\hat{\mathbf{r}}_{12}\cdot\mathbf{v}_{12})\left(\frac{52Gm_2}{3r_{12}} - \frac{6Gm_1}{r_{12}} + 3v_{12}^2\right)\hat{\mathbf{r}}_{12}\right]$$



eccentric black hole mergers forming in globular clusters Samsing, 18.

Background

THE FORMATION OF ECCENTRIC COMPACT BINARY INSPIRALS AND THE ROLE OF GRAVITATIONAL WAVE EMISSION IN BINARY-SINGLE STELLAR ENCOUNTERS

JOHAN SAMSING[1], MORGAN MACLEOD[2], ENRICO RAMIREZ-RUIZ[2]

Draft version October 29, 2018

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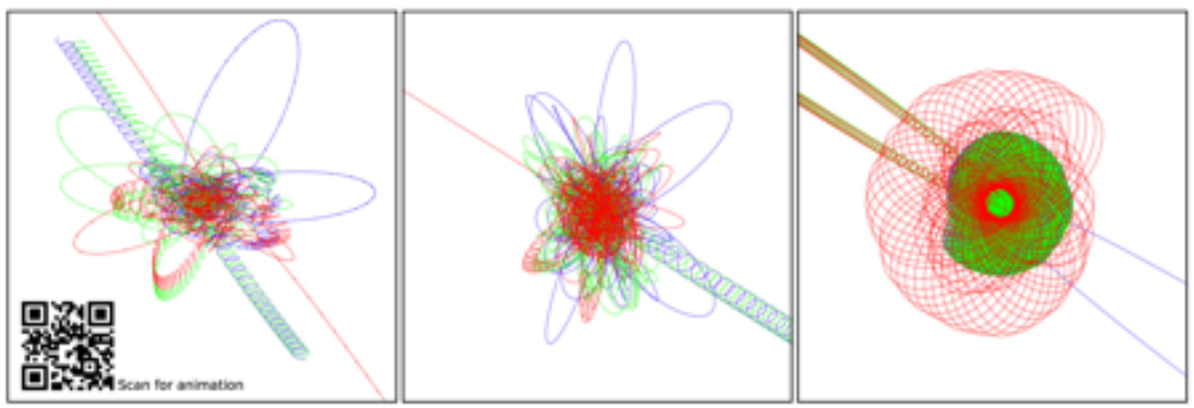


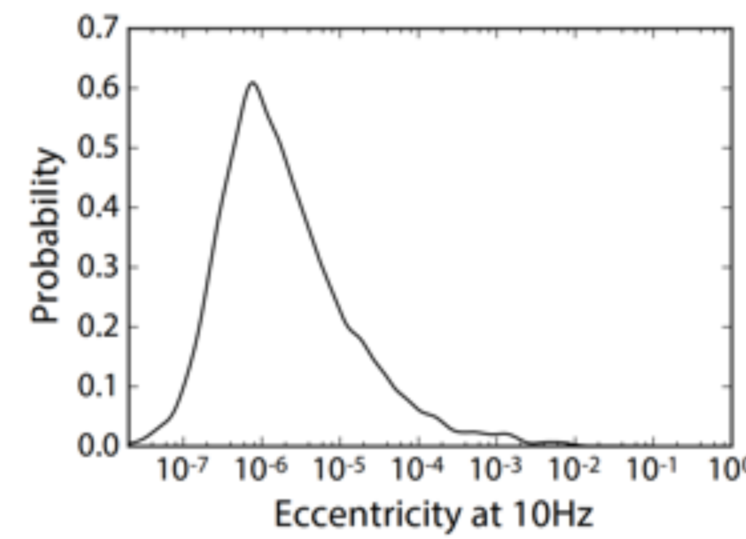
Binary Black Hole Mergers from Globular Clusters: Masses, Merger Rates, and the Impact of Stellar Evolution

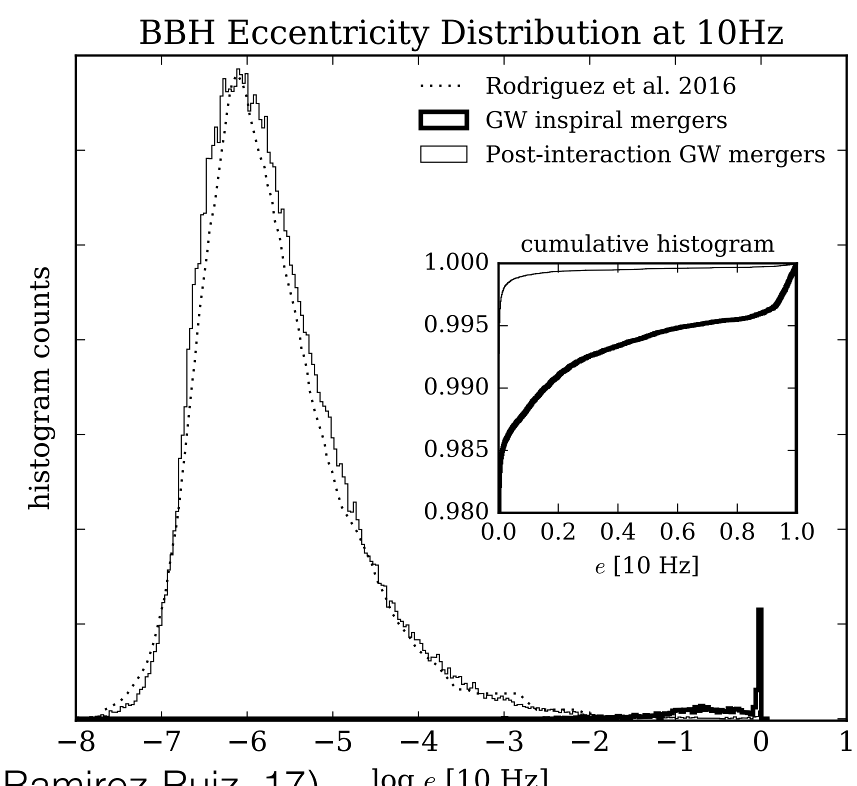
Carl L. Rodriguez,[1] Sourav Chatterjee,[1] and Frederic A. Rasio[1]

[1] *Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Dept. of Physics and Astronomy, Northwestern University, 2145 Sheridan Rd, Evanston, IL 60208, USA*

(Dated: March 25, 2016)

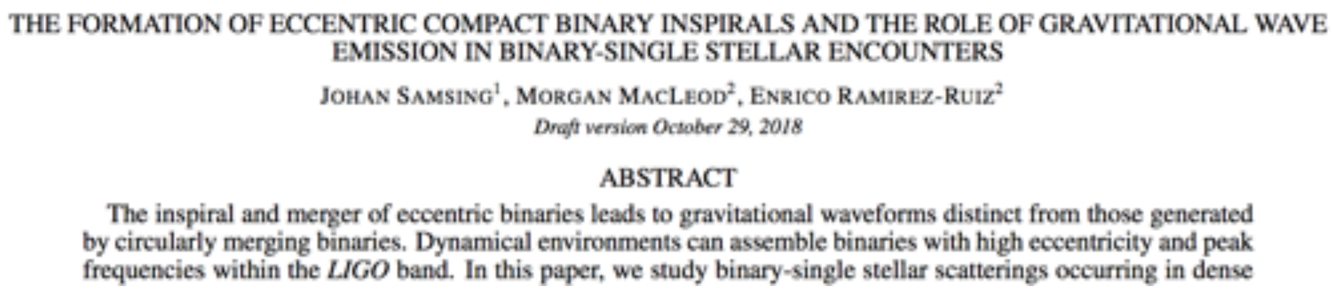
The recent discovery of GW150914, the binary black hole merger detected by Advanced LIGO,





(Samsing, Ramirez-Ruiz, 17)

Background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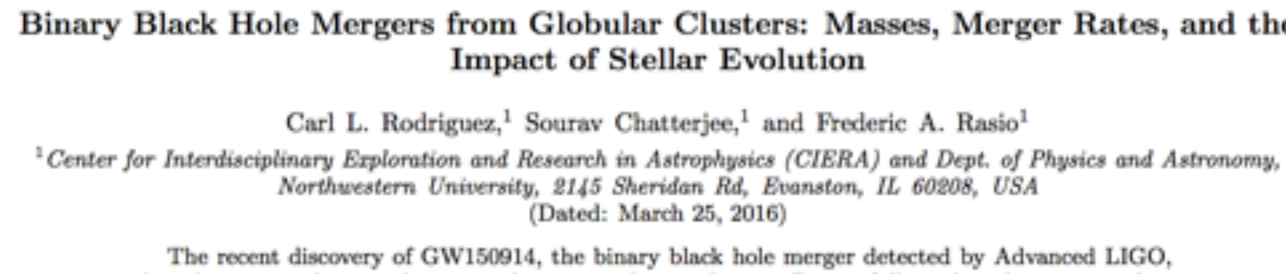
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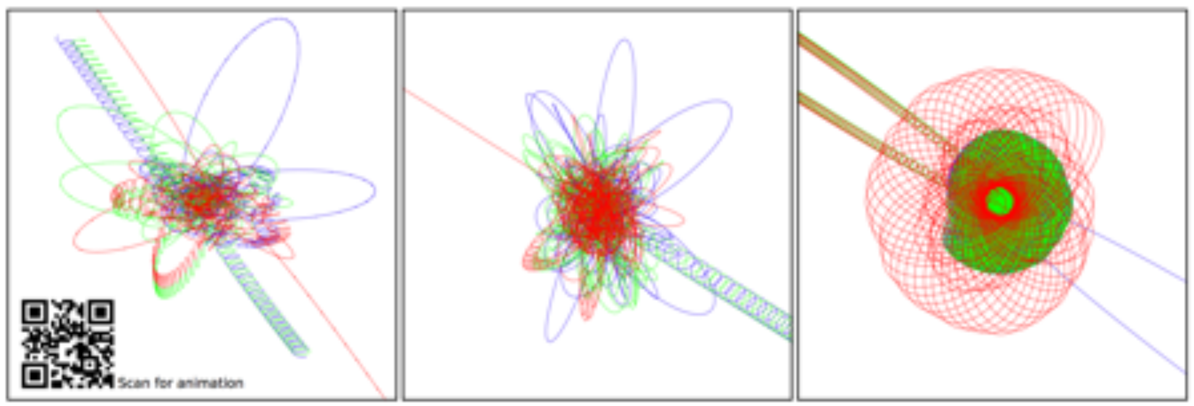
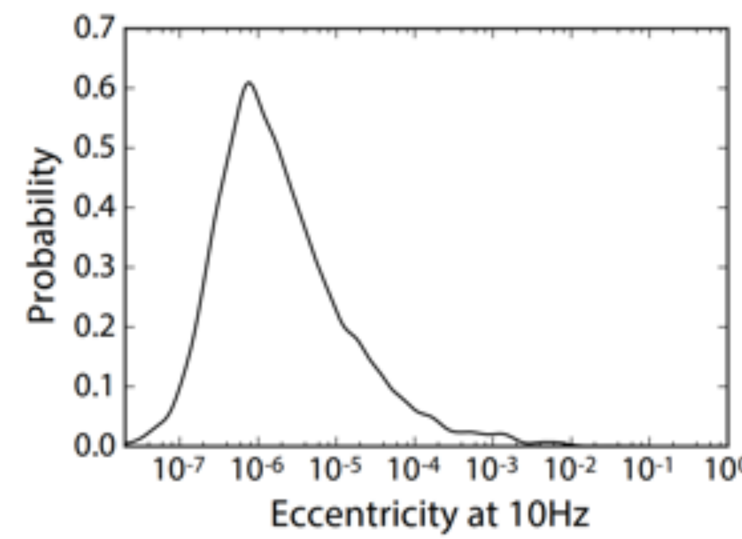
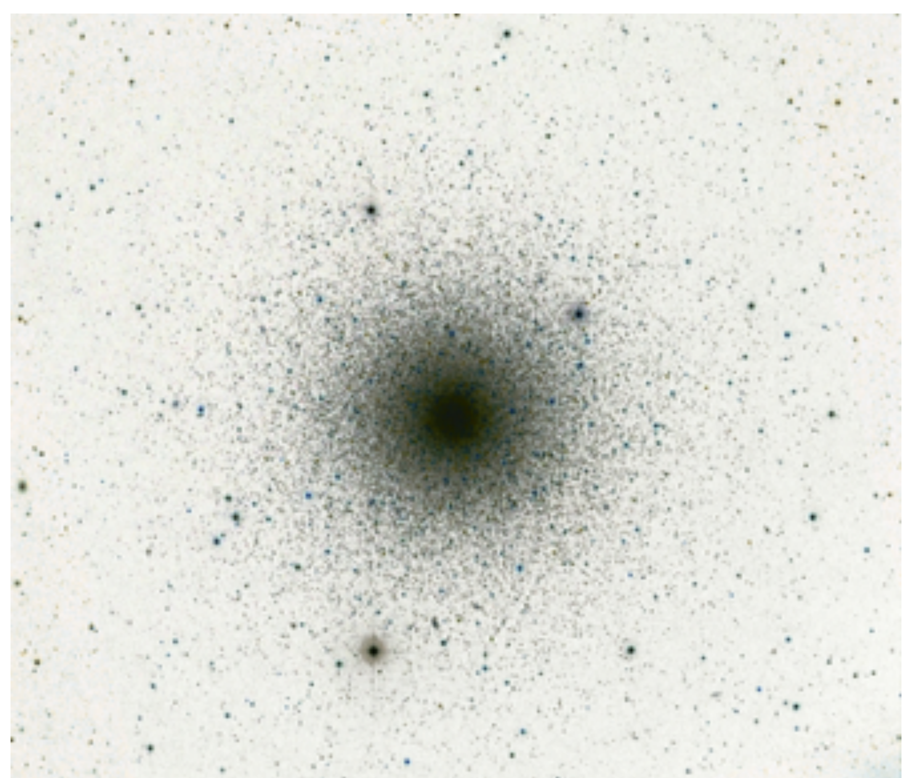




Why is it so difficult?



Background

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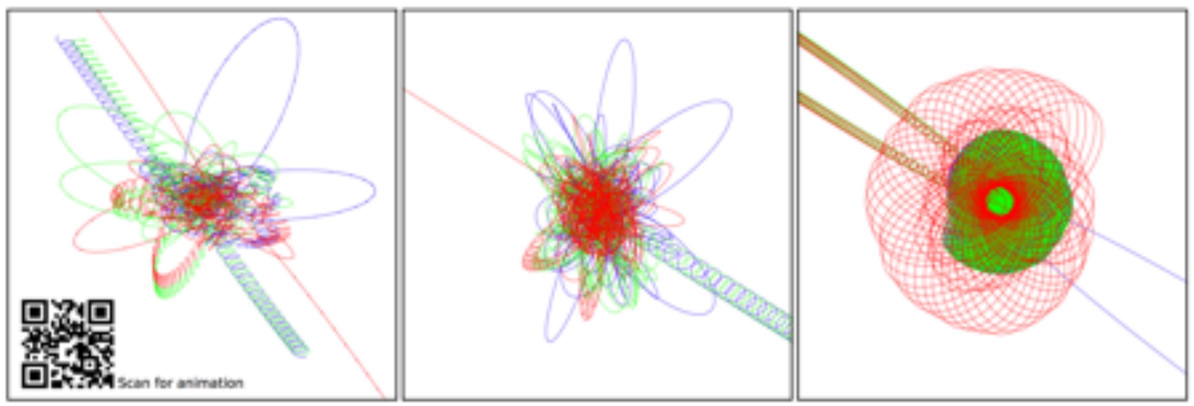
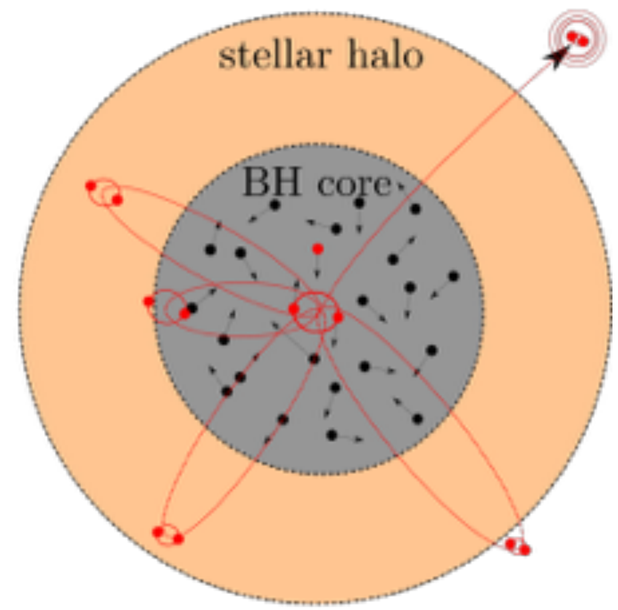
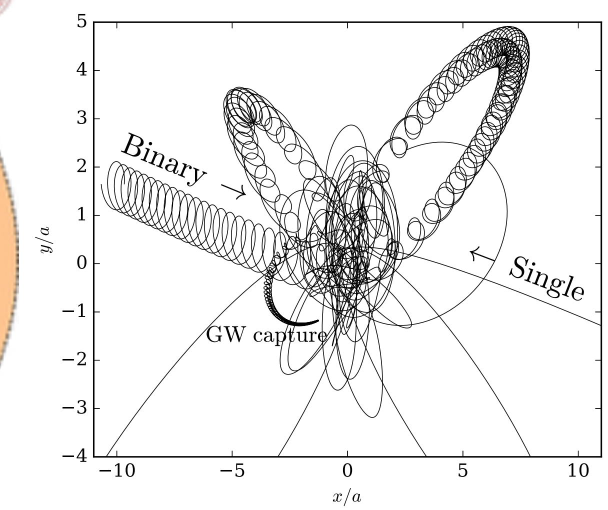


Eccentric Black Hole Mergers Forming in Globular Clusters

Johan Samsing*
Department of Astrophysical Sciences, Princeton University, Peyton Hall, 4 Ivy Lane, Princeton, NJ 08544, USA.

We derive the probability for a newly formed binary black hole (BBH) to undergo an eccentric gravitational wave (GW) merger during binary-single interactions inside a stellar cluster. By integrating over the hardening interactions such a BBH must undergo before ejection, we find that the observable rate of BBH mergers with eccentricity > 0.1 at 10 Hz relative to the rate of circular mergers can be as high as $\sim 5\%$ for a typical globular cluster (GC). This further suggests that BBH mergers forming through GW captures in binary-single interactions, eccentric or not, are likely to constitute $\sim 10\%$ of the total BBH merger rate from GCs. Such GW capture mergers can only





Clusters give rise to predictable outcomes.

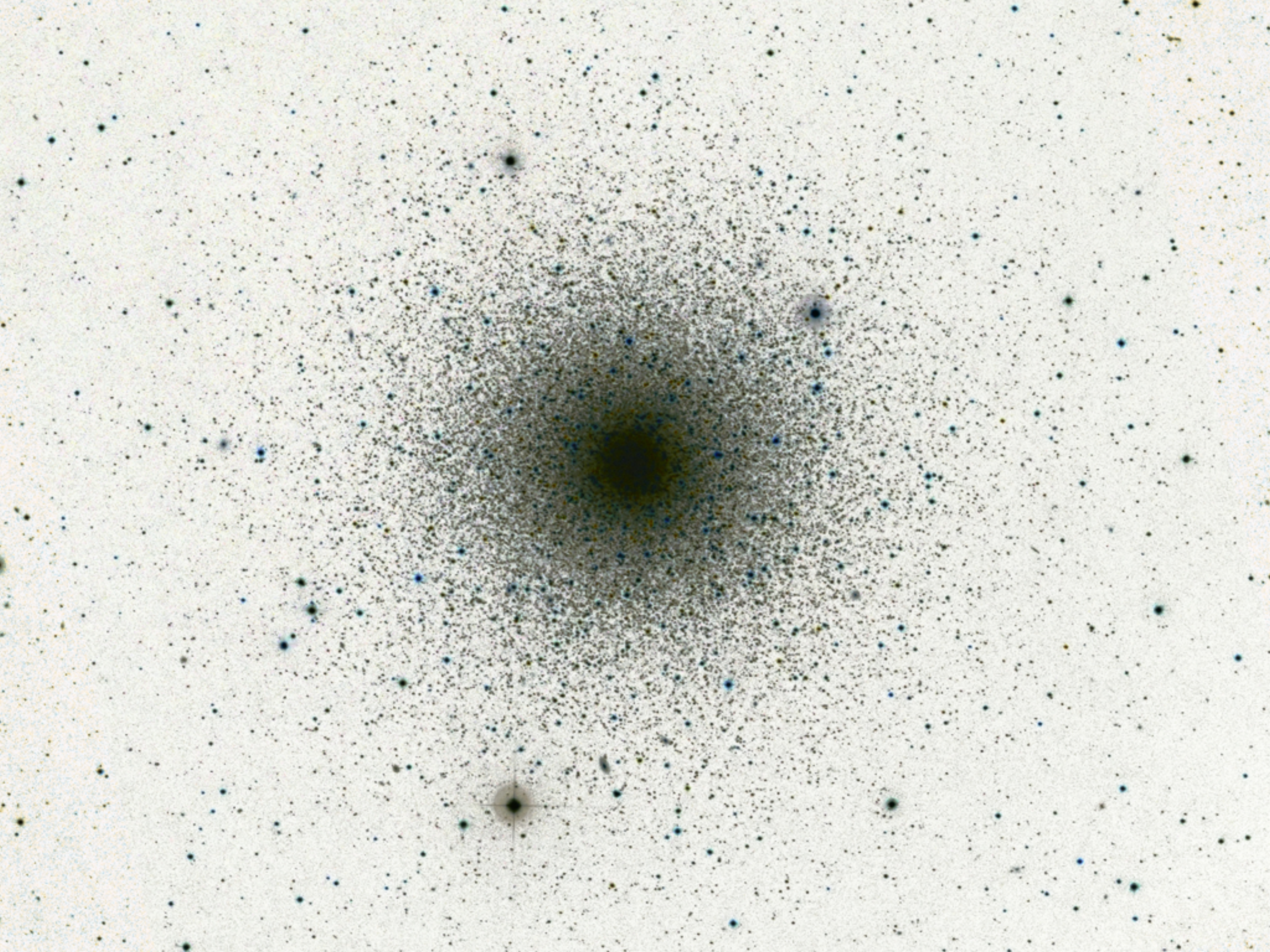
Pen and paper can reach percent precision!

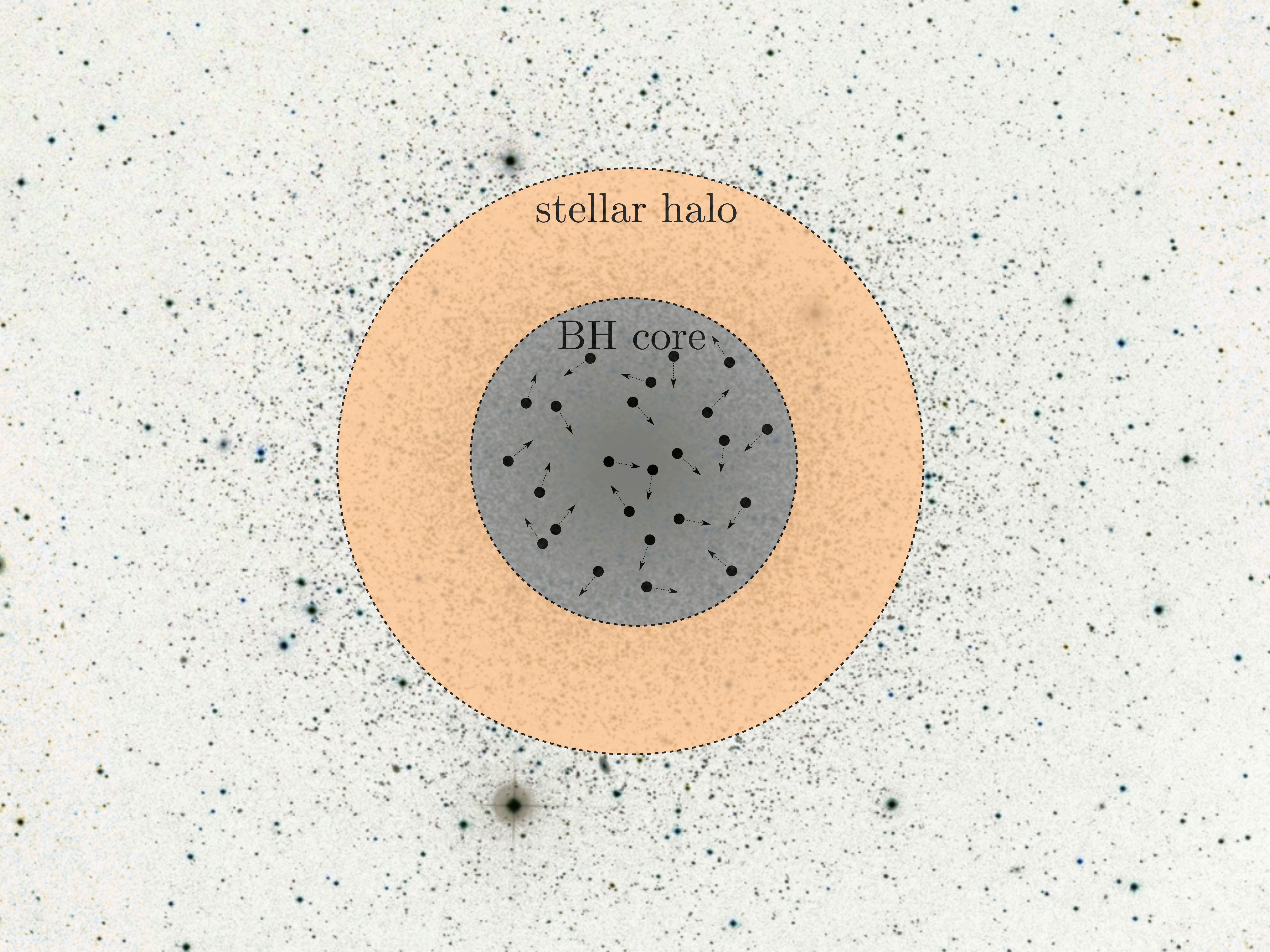
Our two methods greatly complement each other!

Post-Newtonian Dynamics in Dense Star Clusters: Formation, Masses, and Merger Rates of Highly-Eccentric Black Hole Binaries

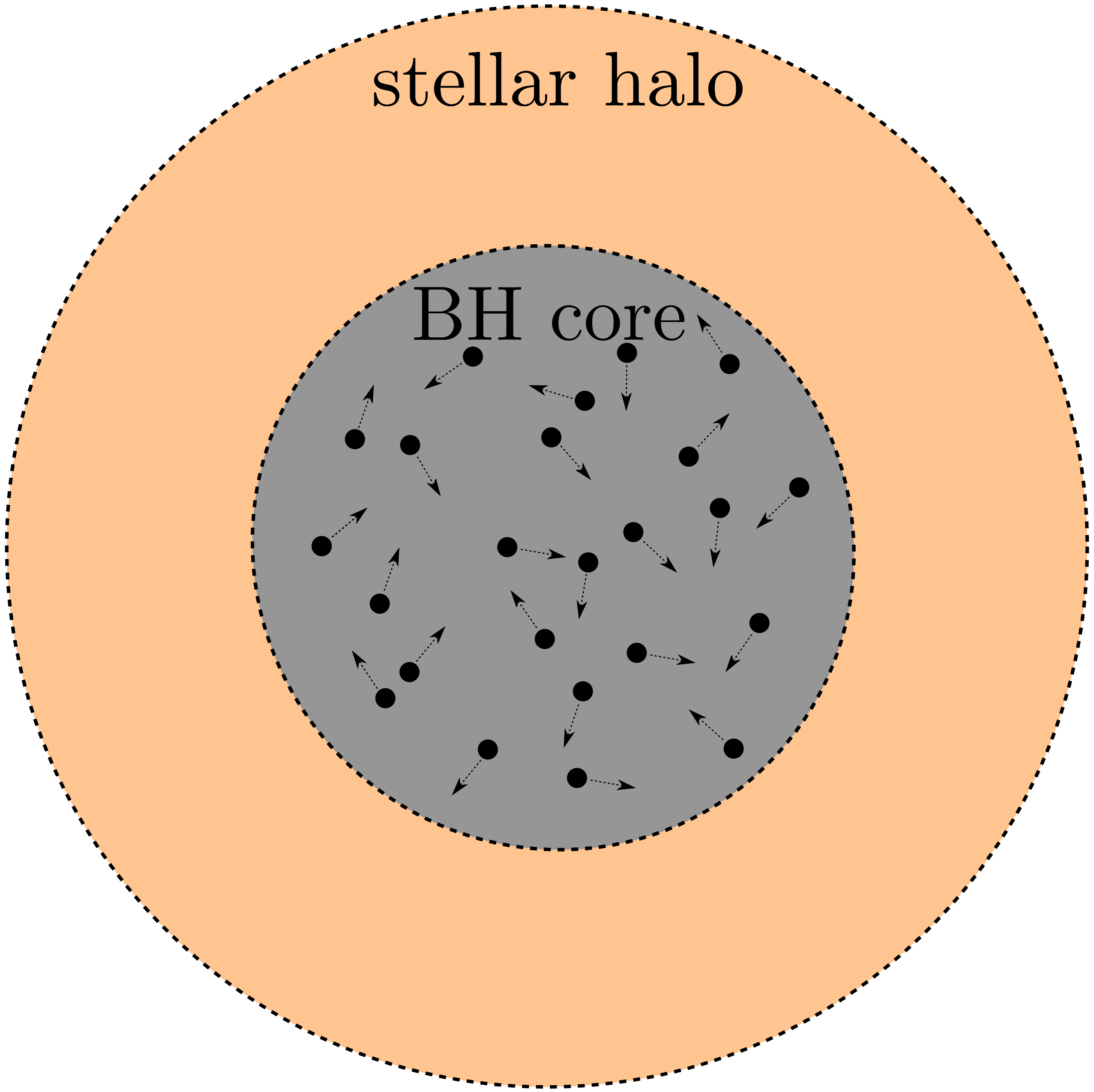
Carl L. Rodriguez,[1] Pau Amaro-Seoane,[2] Sourav Chatterjee,[3] Kyle Kremer,[4] Frederic A. Rasio,[4] Johan Samsing,[5] Claire S. Ye,[4] and Michael Zevin[4]

Using state-of-the-art dynamical simulations of globular clusters, including radiation reaction during black hole encounters and a cosmological model of star cluster formation, we create a realistic population of dynamically-formed binary black hole mergers across cosmic space and time. We show that in the local universe, 10% of these binaries form as the result of gravitational-wave emission between unbound black holes during chaotic resonant encounters, with roughly half of those events having eccentricities detectable by current ground-based gravitational-wave detectors. The mergers



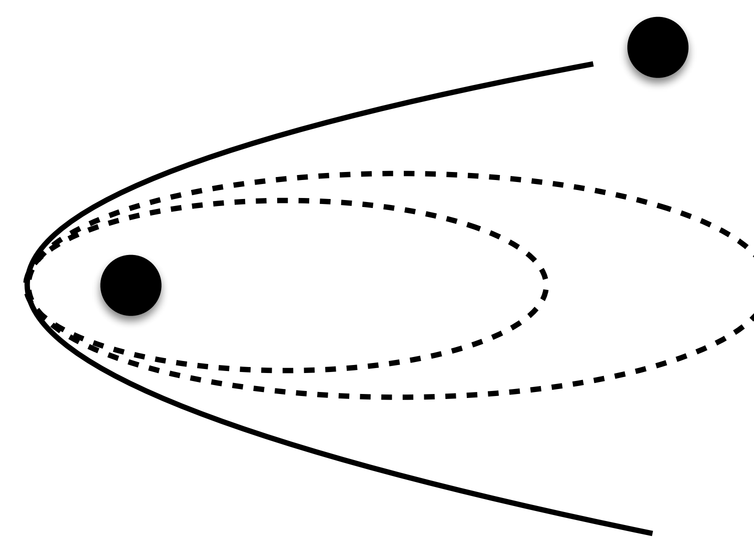

stellar halo
BH core

MODEL:



$$f \approx \frac{1}{\pi}\sqrt{\frac{2Gm}{r_f^3}}$$

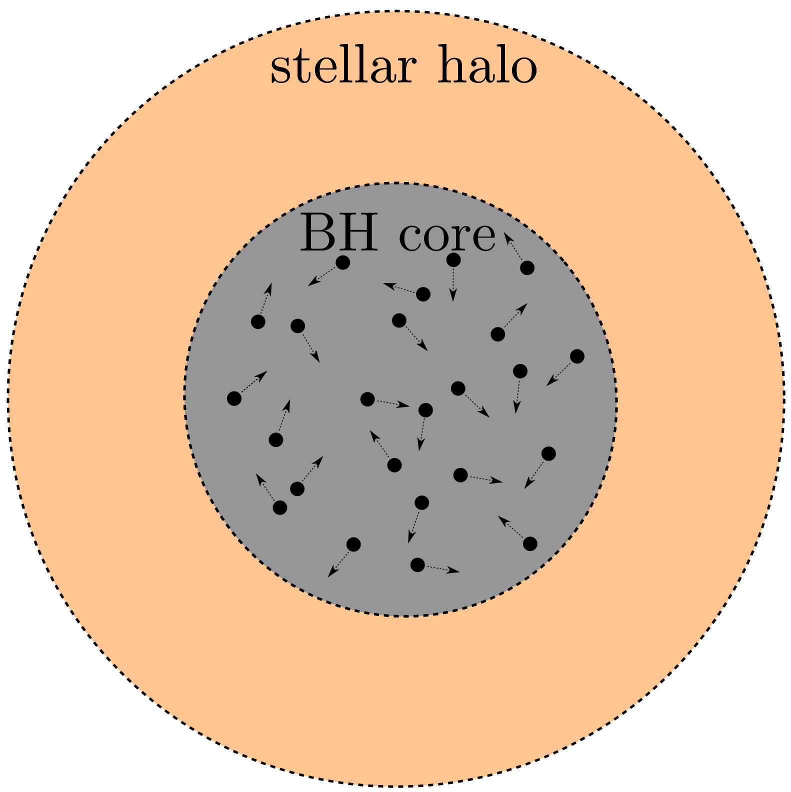
$$r_f \approx \left(\frac{2Gm}{f^2\pi^2}\right)^{1/3}$$

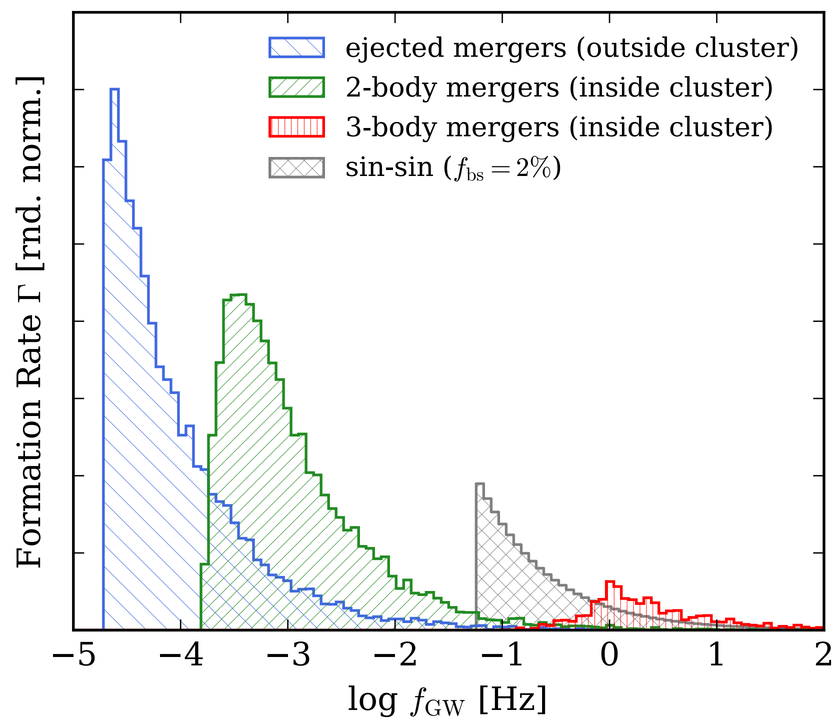


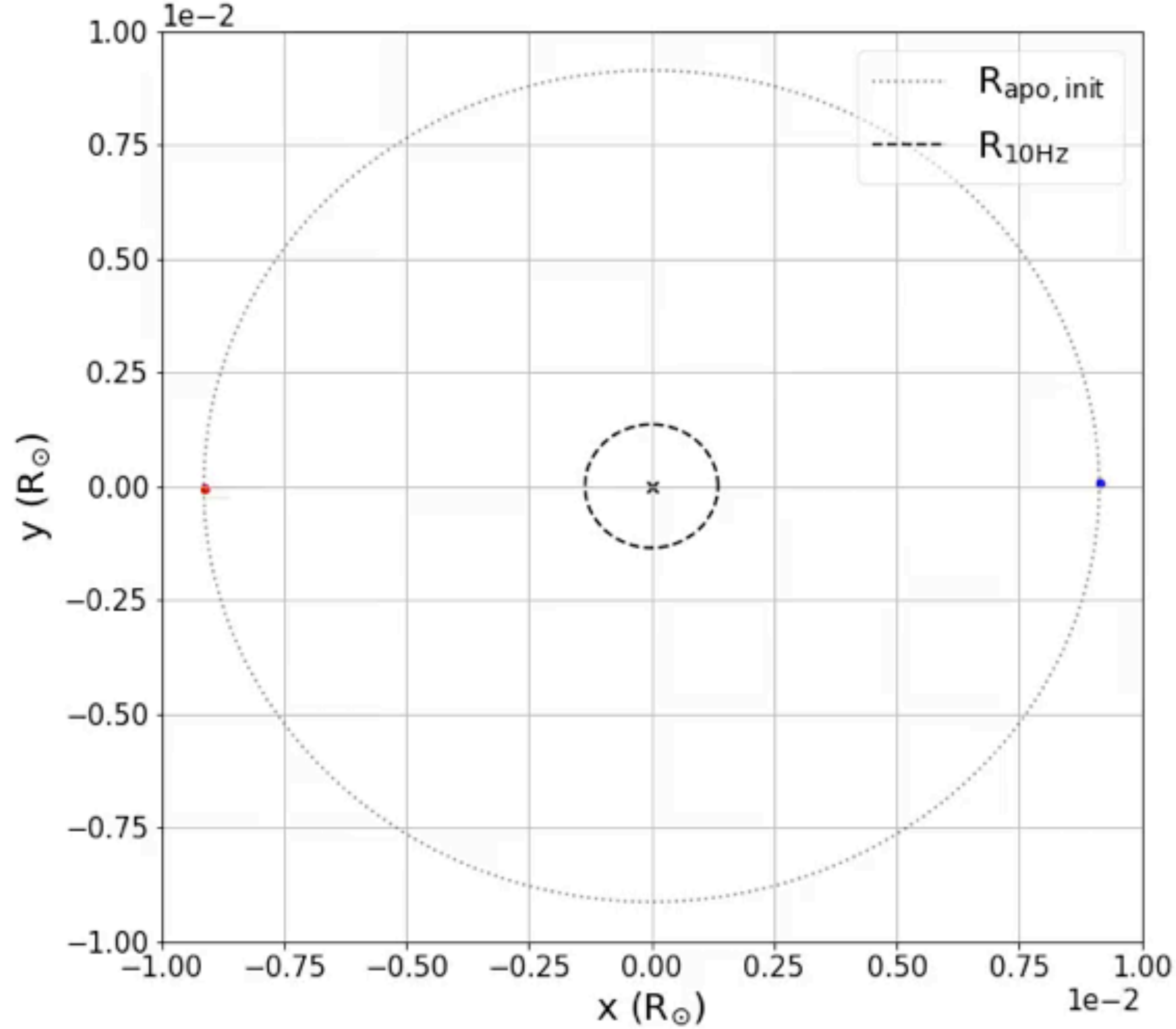
How do BBHs form and merge?

What is the peak freq. dist?
Correlate this with e!

MODEL:



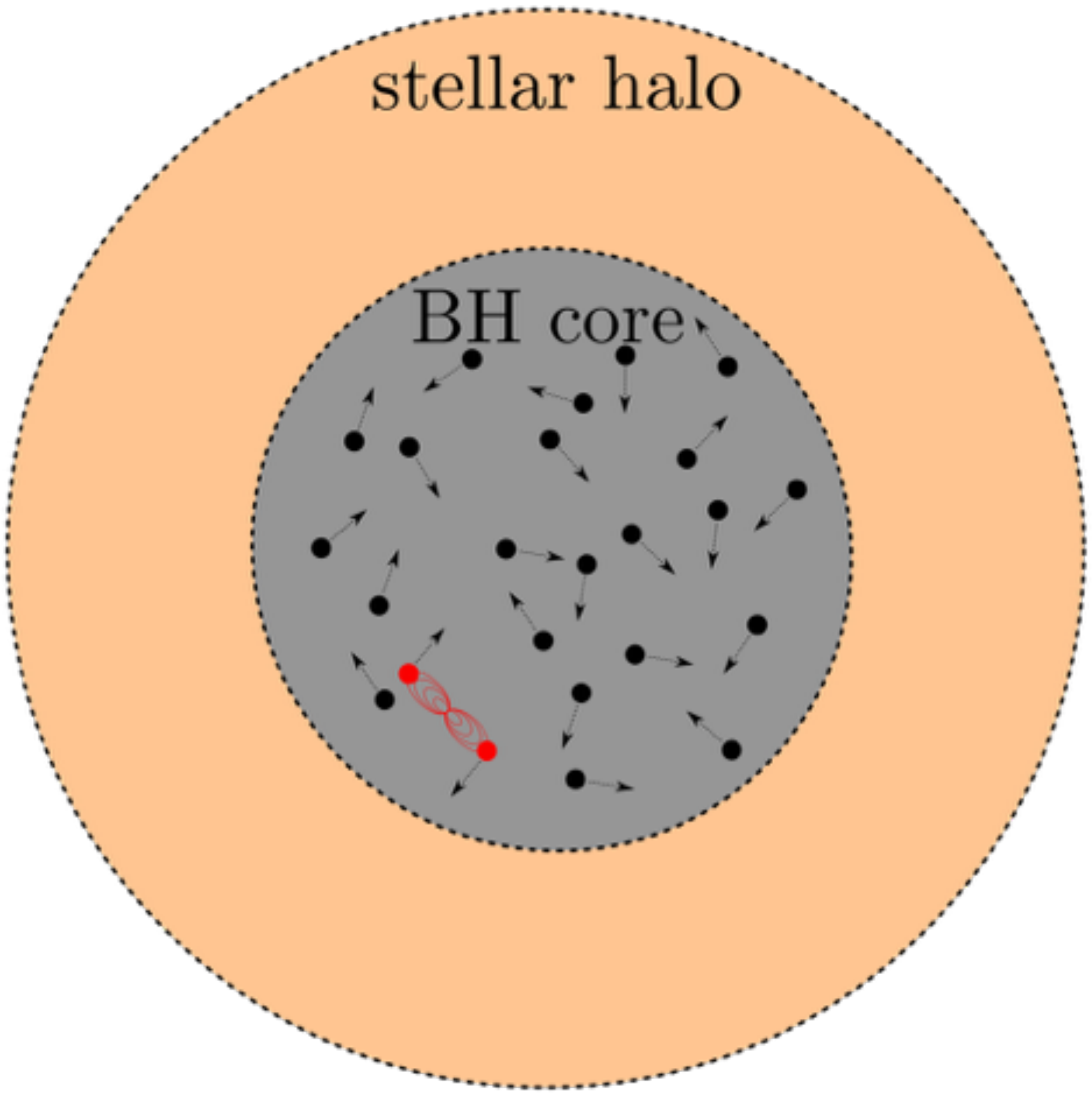


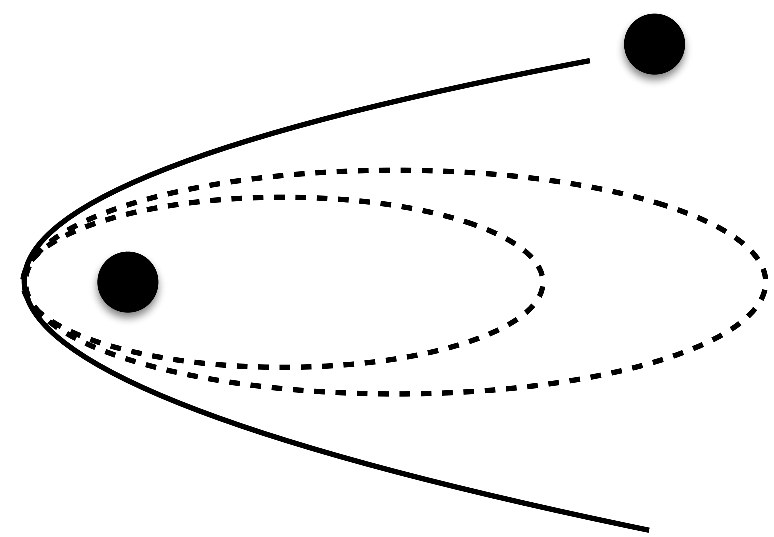


$$f \approx \frac{1}{\pi}\sqrt{\frac{2Gm}{r_f^3}}$$

Merger Type: Single-Single

Capture:



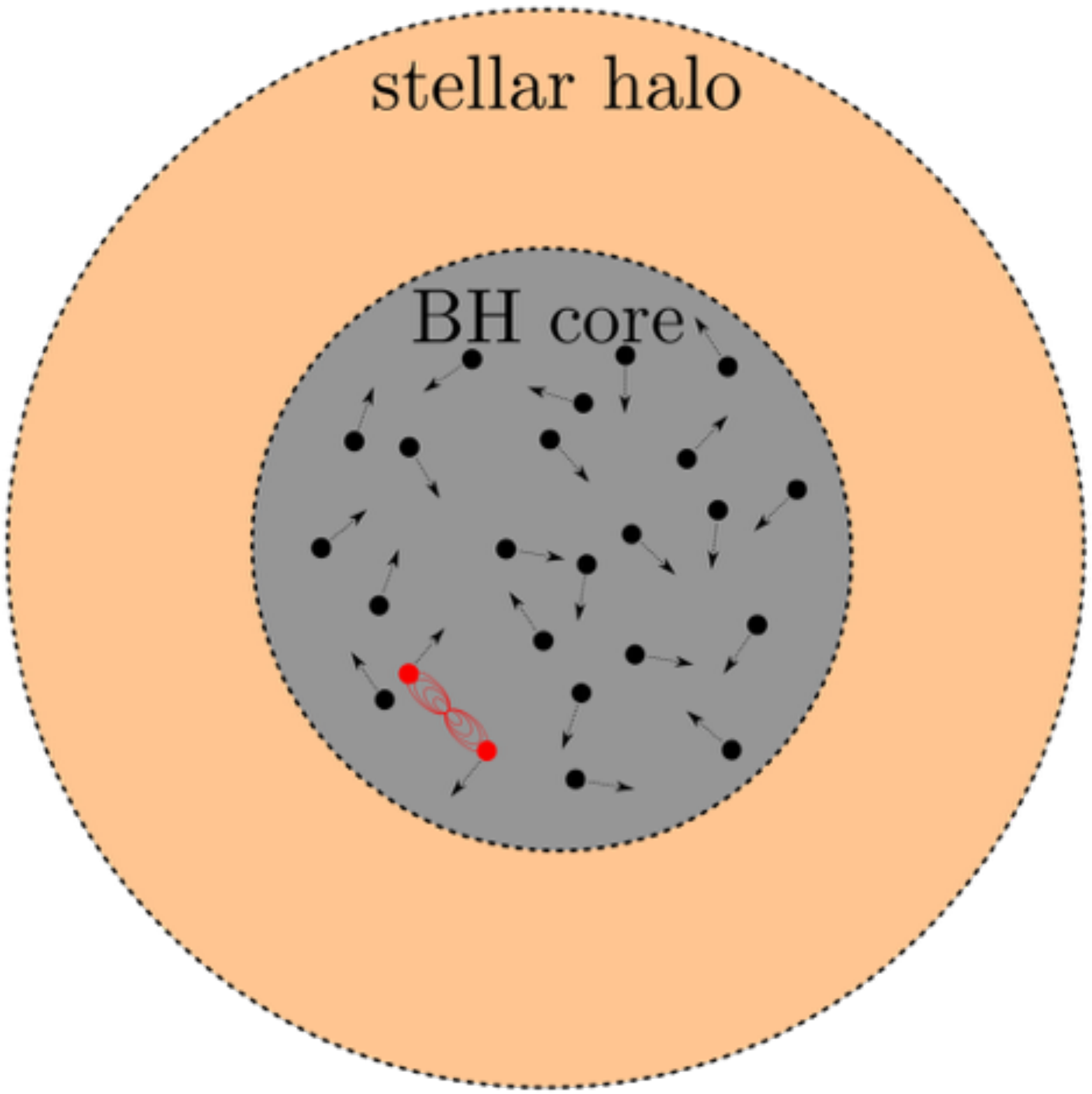


$$\Delta E_{\mathrm{p}} \approx (85\pi/12) G^{7/2} c^{-5} m^{9/2} r_{\mathrm{p}}^{-7/2}$$

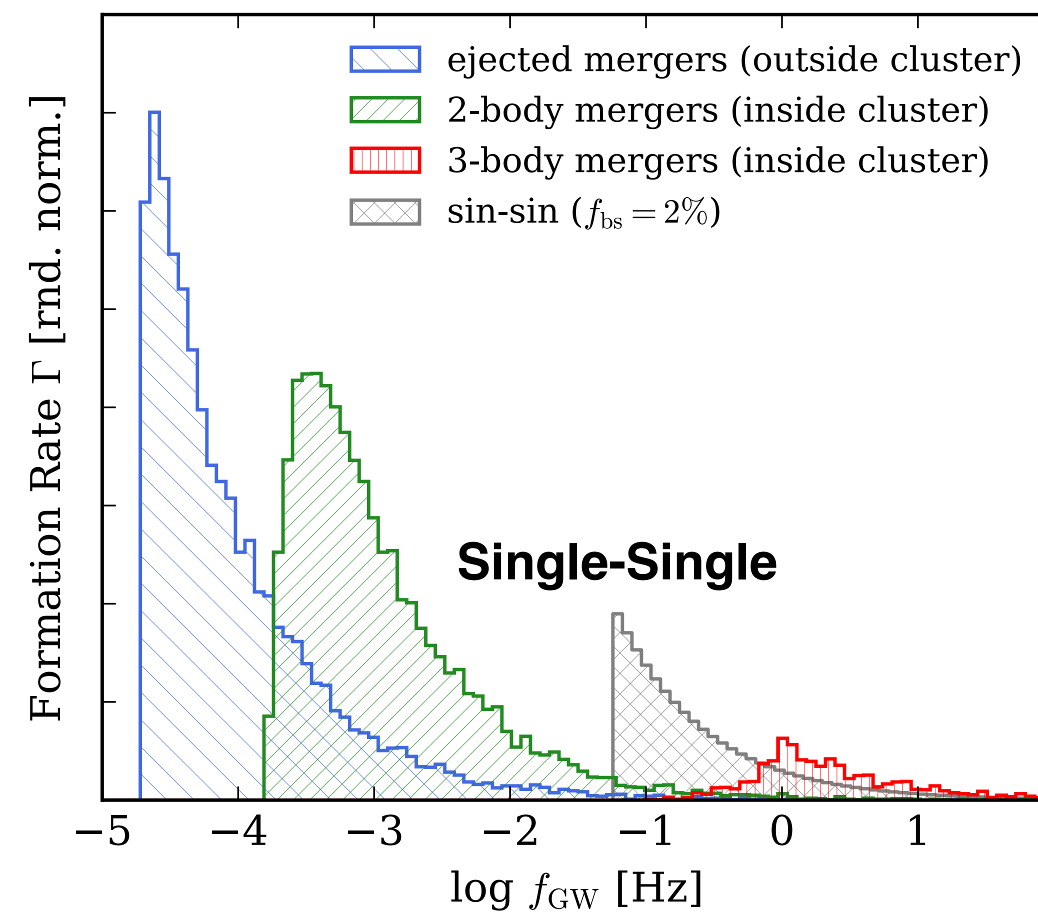
$$E_{\mathrm{ss}} \approx \mu v^2/2$$

$$\mathcal{R}_{\mathrm{ss}} = \left(\frac{85\pi}{24\sqrt{2}}\right)^{2/7} \times \mathscr{R}_{\mathrm{m}} \left(\frac{c^2}{v^2}\right)^{2/7}$$

Merger Type: Single-Single



S-S captures do not only operate in Galactic Nuclei!



$$\mathcal{R}_{\rm ss} = \left(\frac{85\pi}{24\sqrt{2}}\right)^{2/7} \times \mathscr{R}_{\rm m} \left(\frac{c^2}{v^2}\right)^{2/7} \qquad f \approx \frac{1}{\pi}\sqrt{\frac{2Gm}{r_f^3}}$$

Distribution depends on:

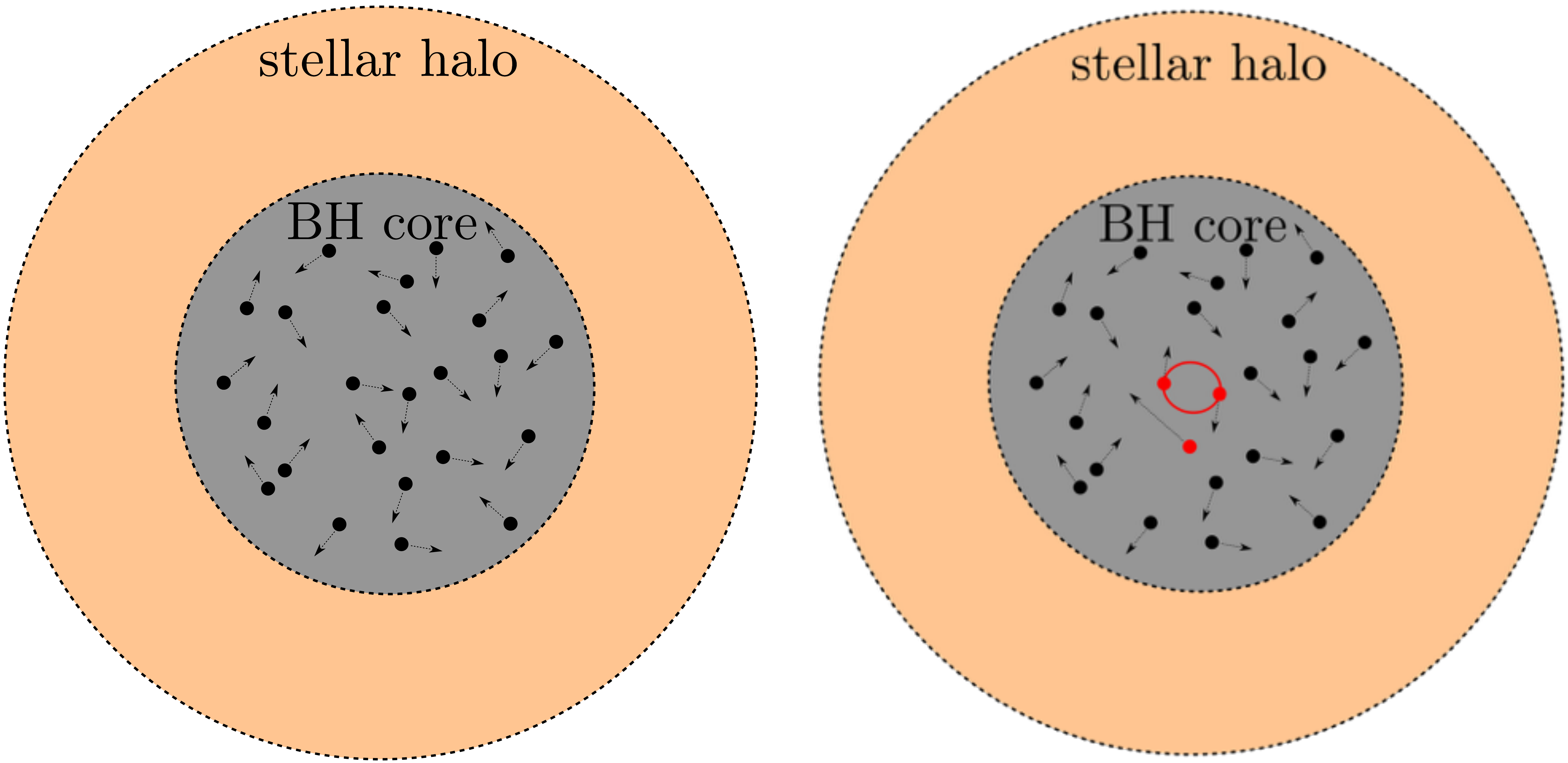
BH distribution (Plummer/Uniform..)

Binary Fraction

<u>see our new paper:</u>

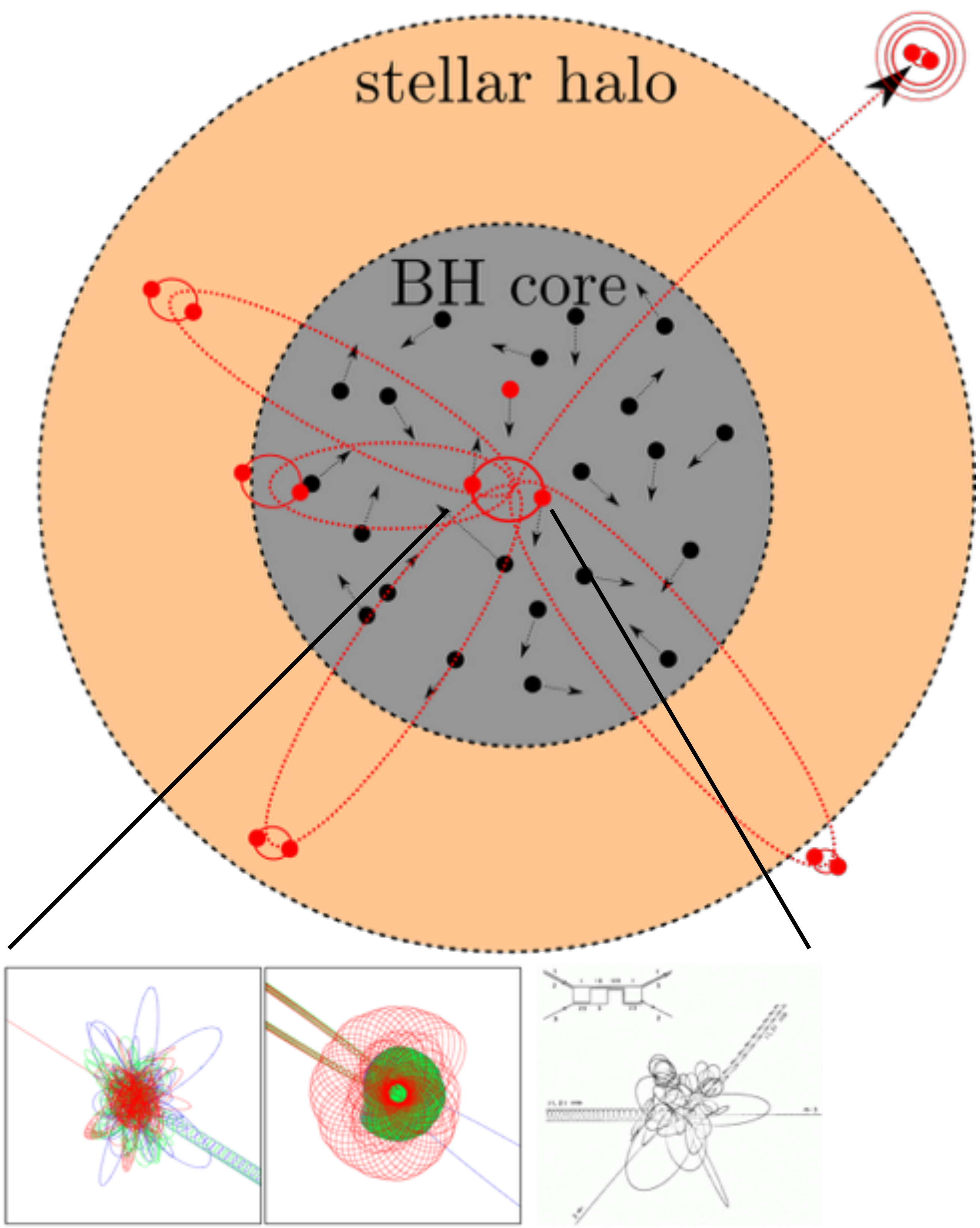
'GW captures of single BHs in GCs'
(Samsing, et al. 2019)

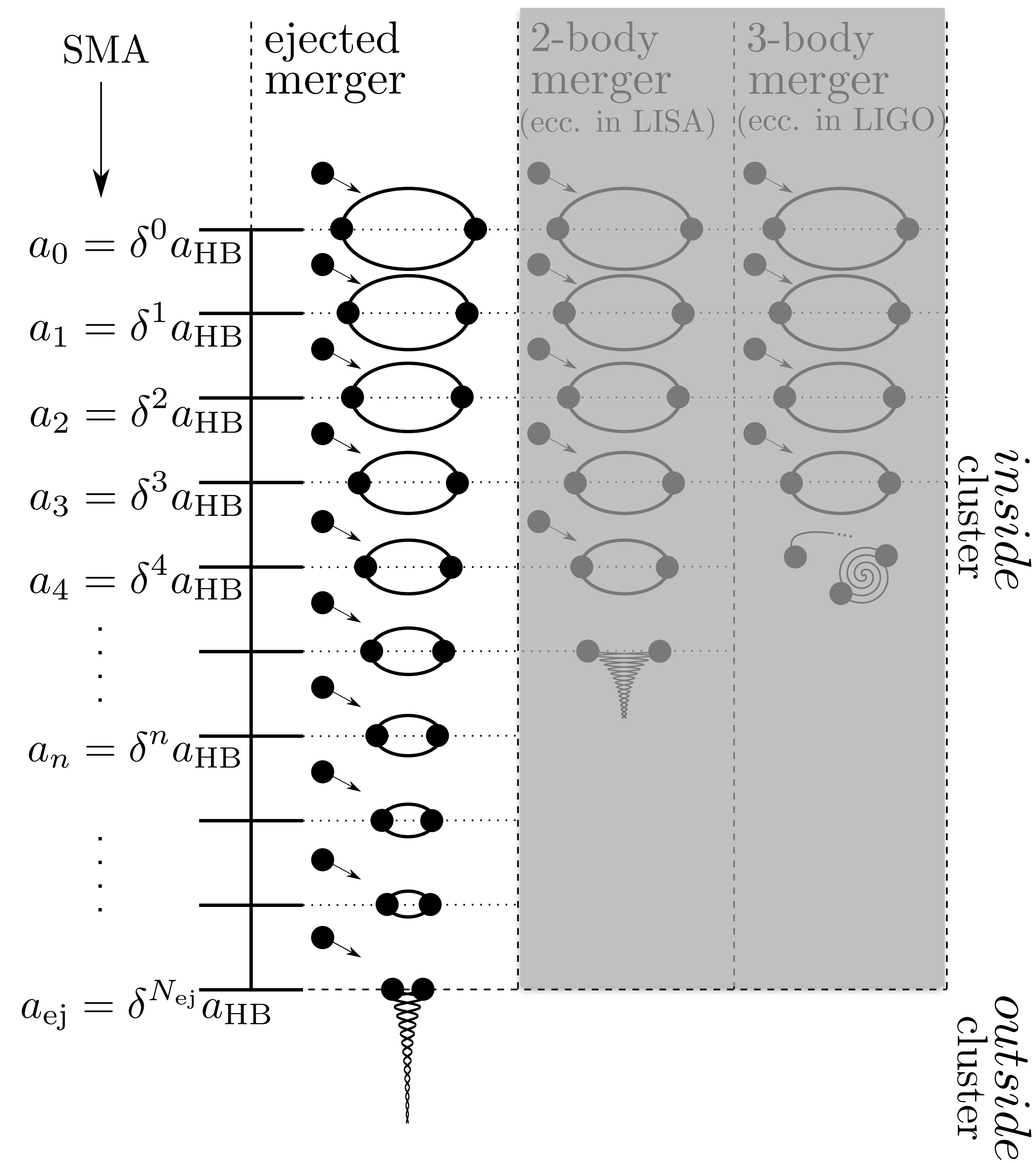
Few-body BBH mergers: Formation of a BBH



$$a_{\rm HB} = \frac{3}{2}\frac{Gm_{\rm BH}}{v_{\rm dis}^2}$$

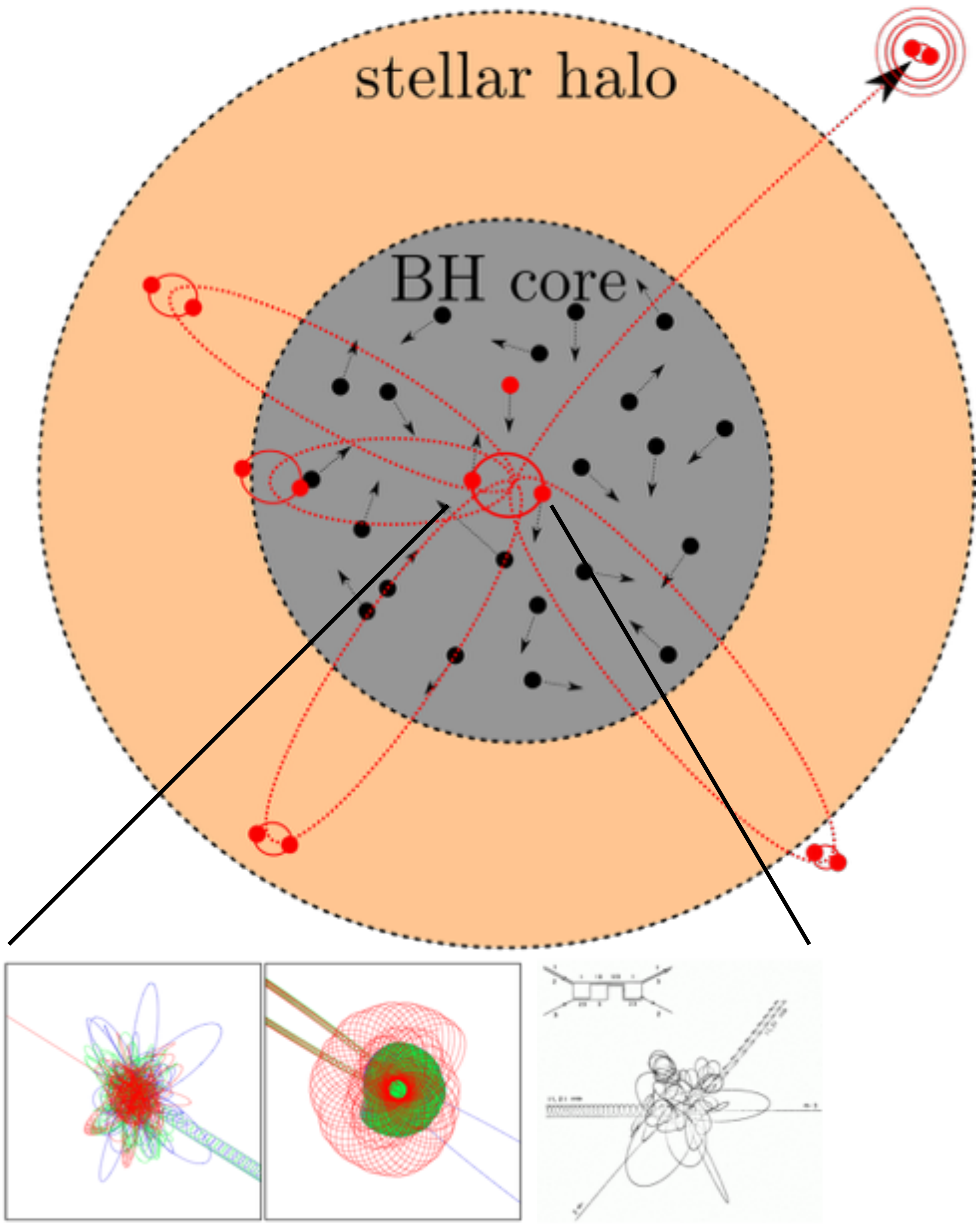
Merger Type: Ejected Merger

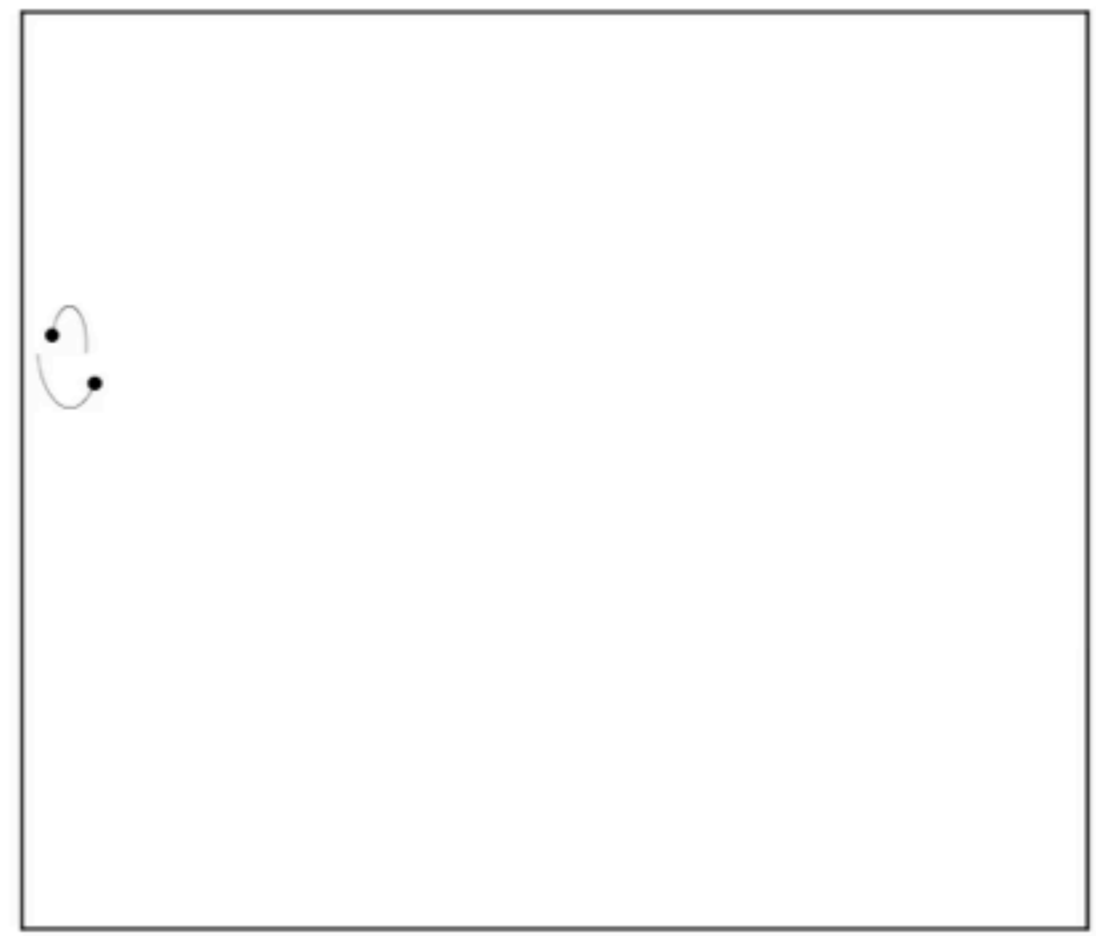




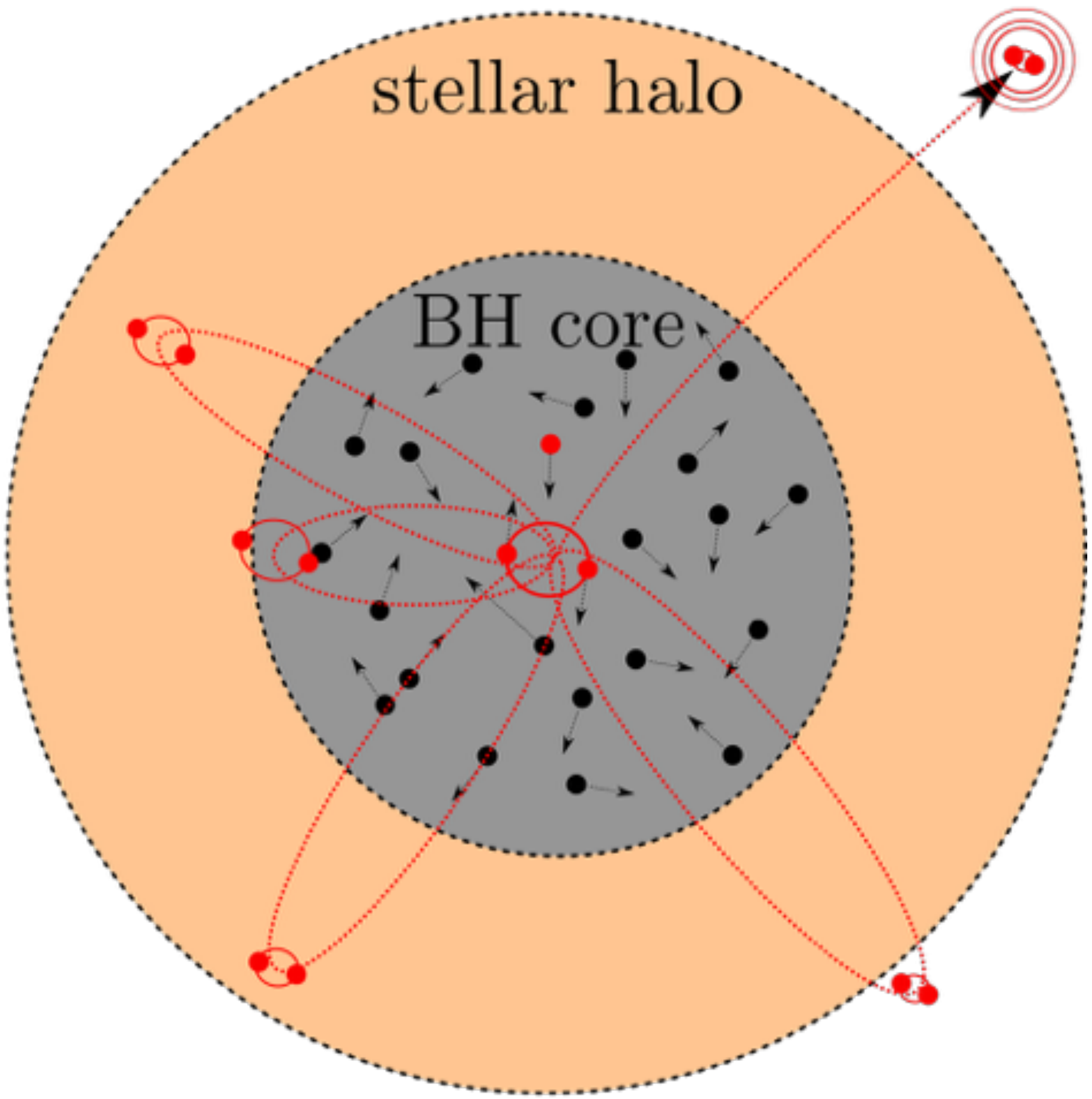
Samsing, D’Orazio. 18.

Merger Type: Ejected Merger

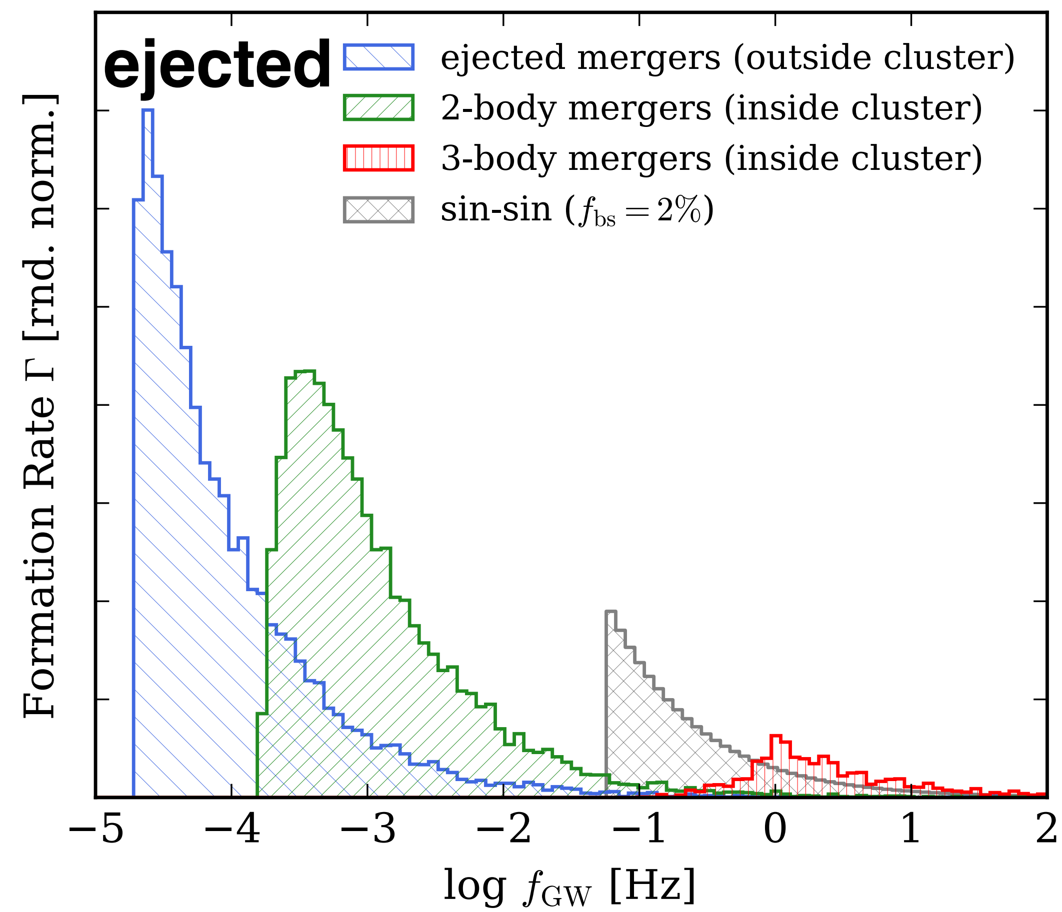




Merger Type: Ejected Merger



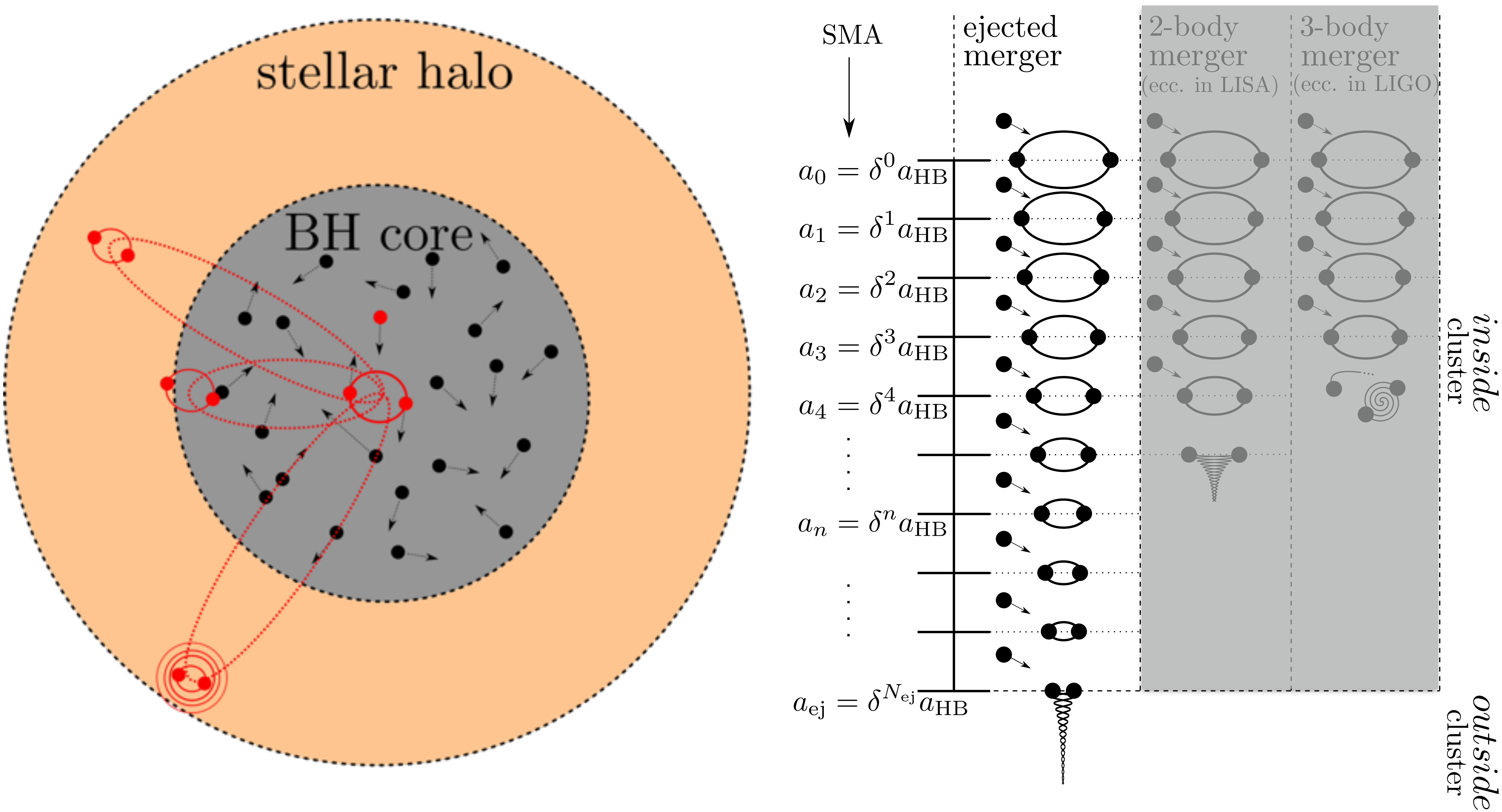
Circular GW sources



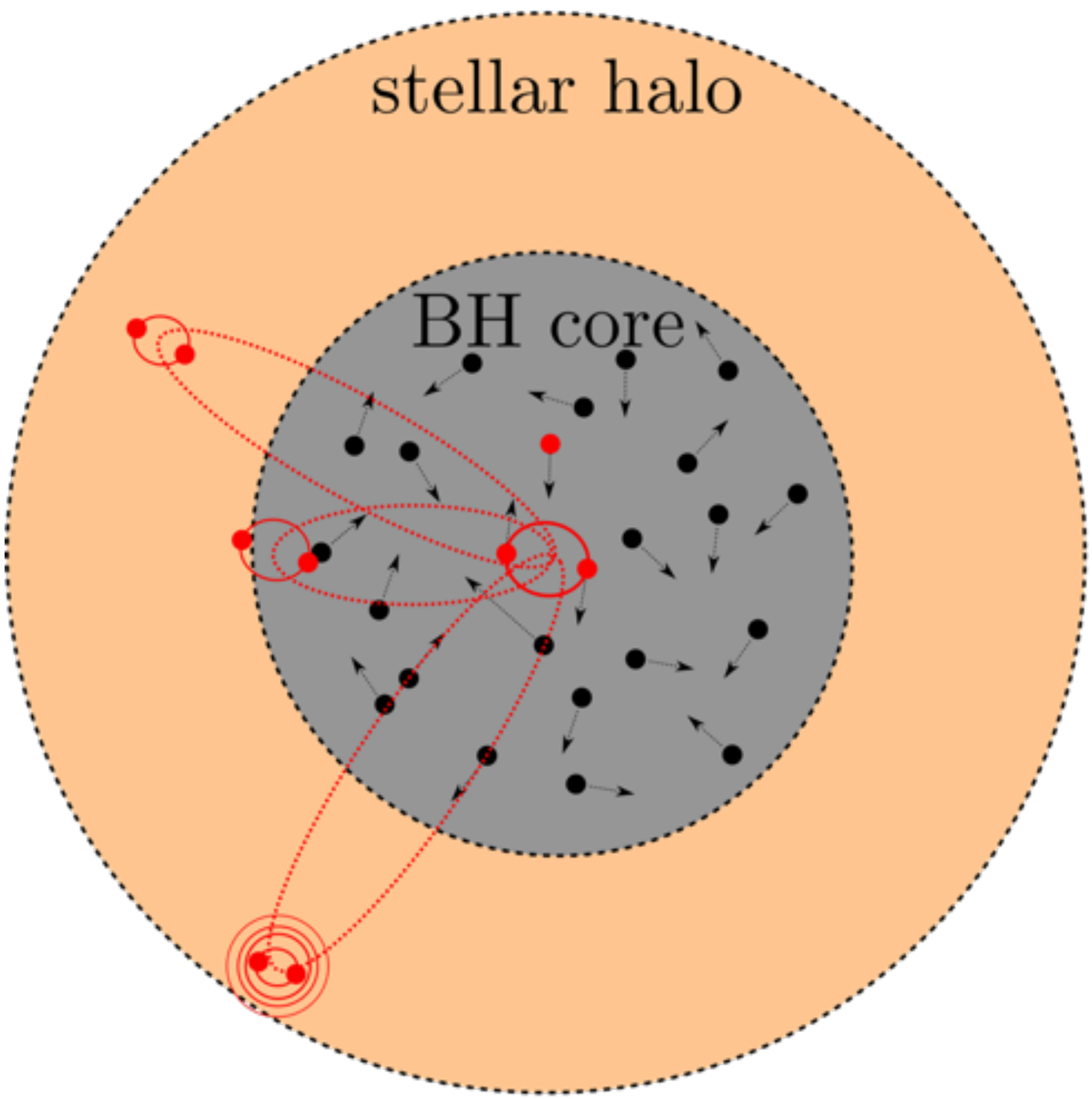
Important point: It is all about characteristic time scales!

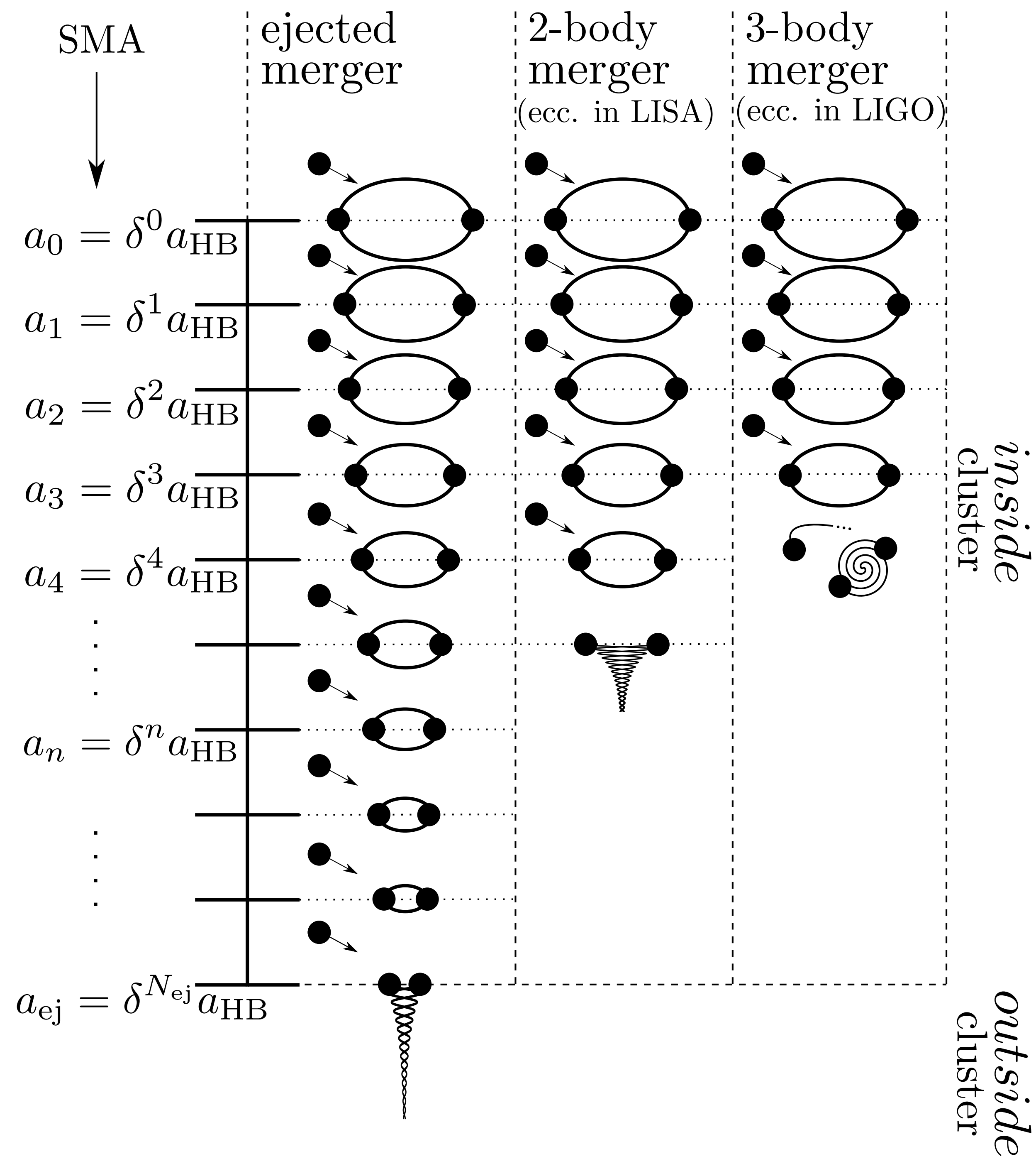
$$f_{r,0}^{\rm peak}(\mathcal{T}) \approx 2 \cdot 10^{-5}\ {\rm Hz} \left(\frac{\mathcal{T}}{10^{10}{\rm yrs}}\right)^{-3/7} \left(\frac{a}{0.5{\rm au}}\right)^{3/14} \left(\frac{m}{30M_{\odot}}\right)^{-11/14}$$

Merger Type: 2-body Merger



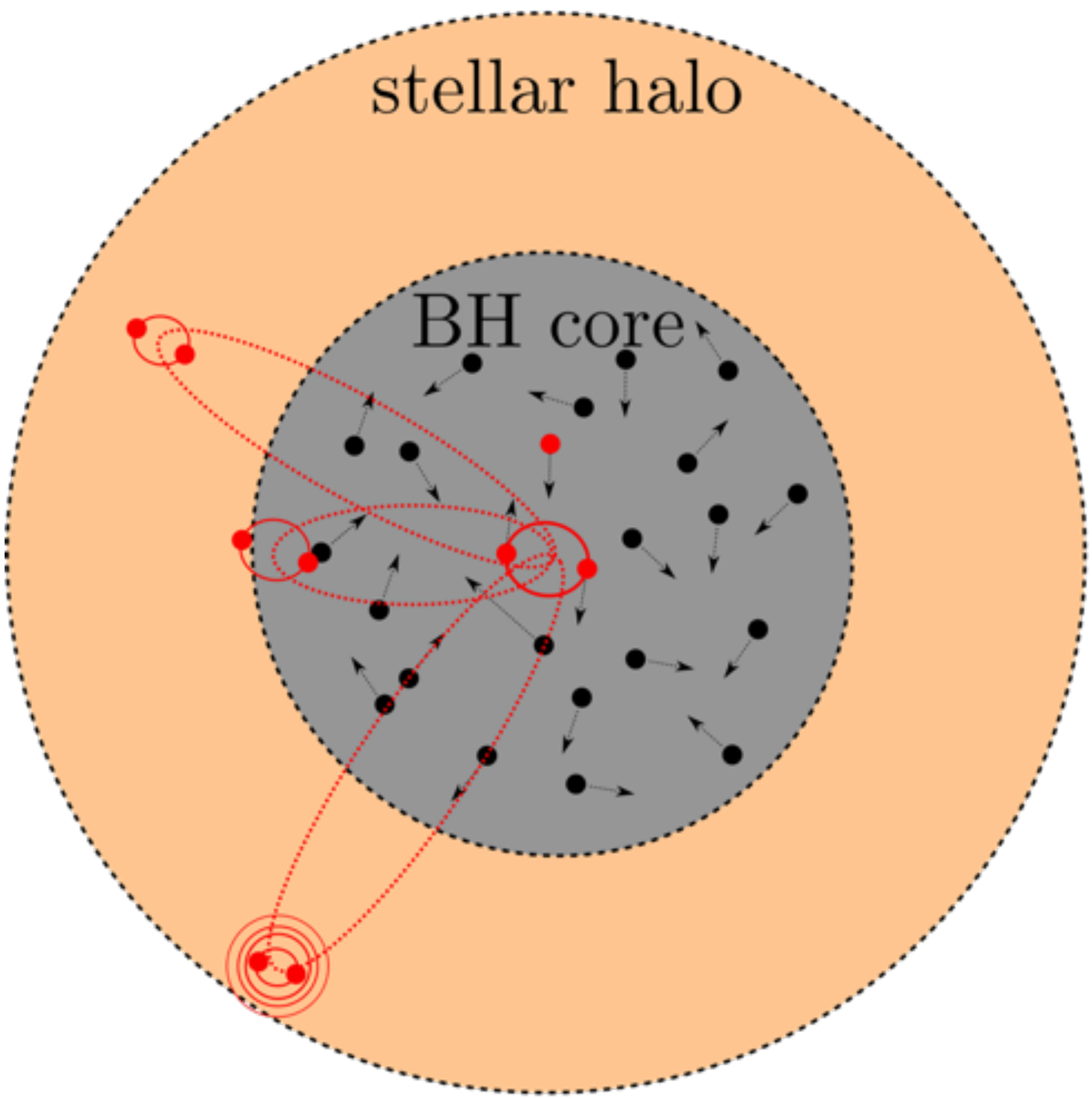
Merger Type: 2-body Merger

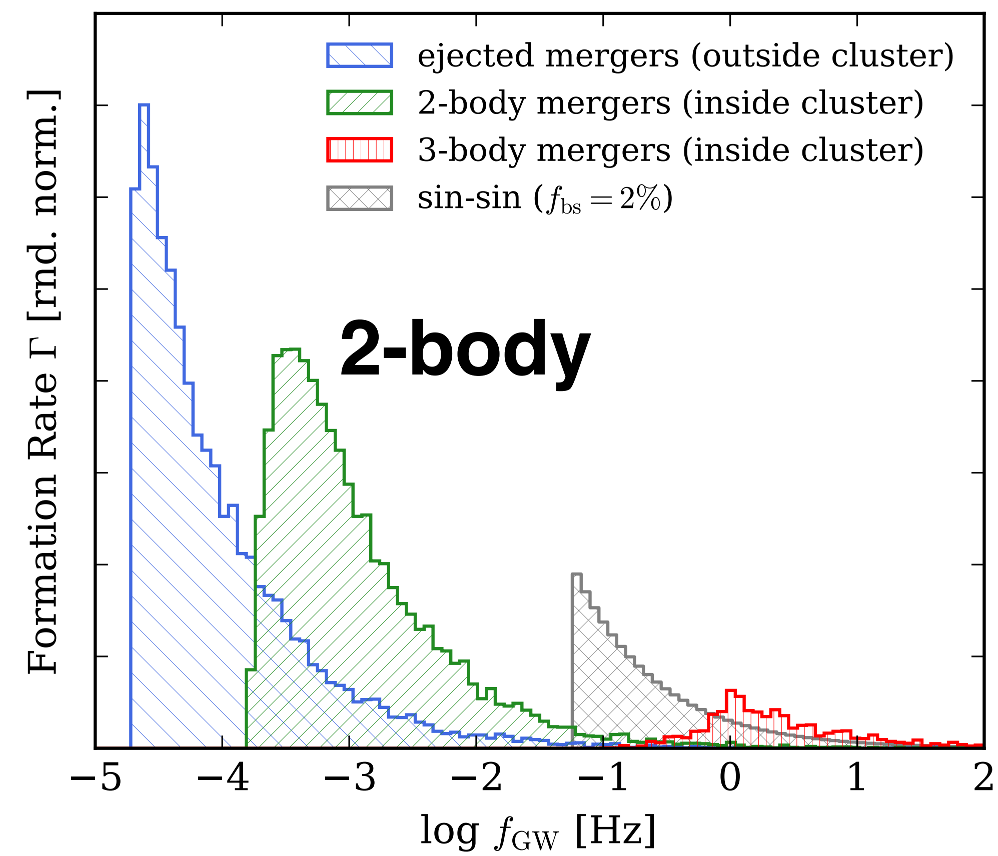


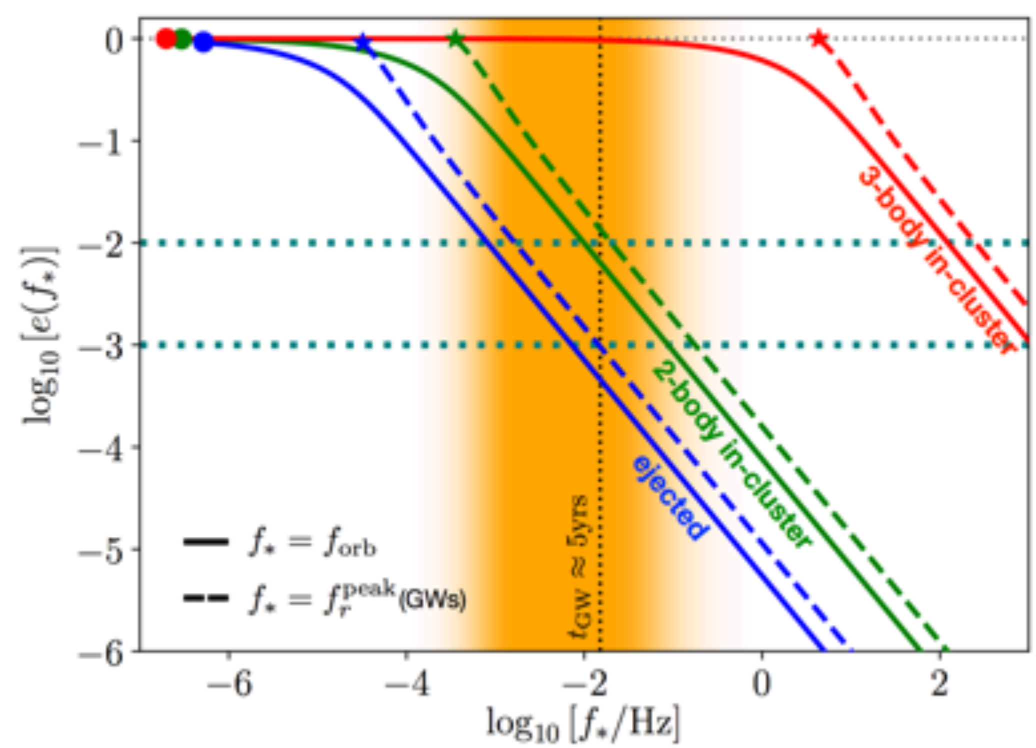


Merger Type: 2-body Merger

Eccentric LISA sources





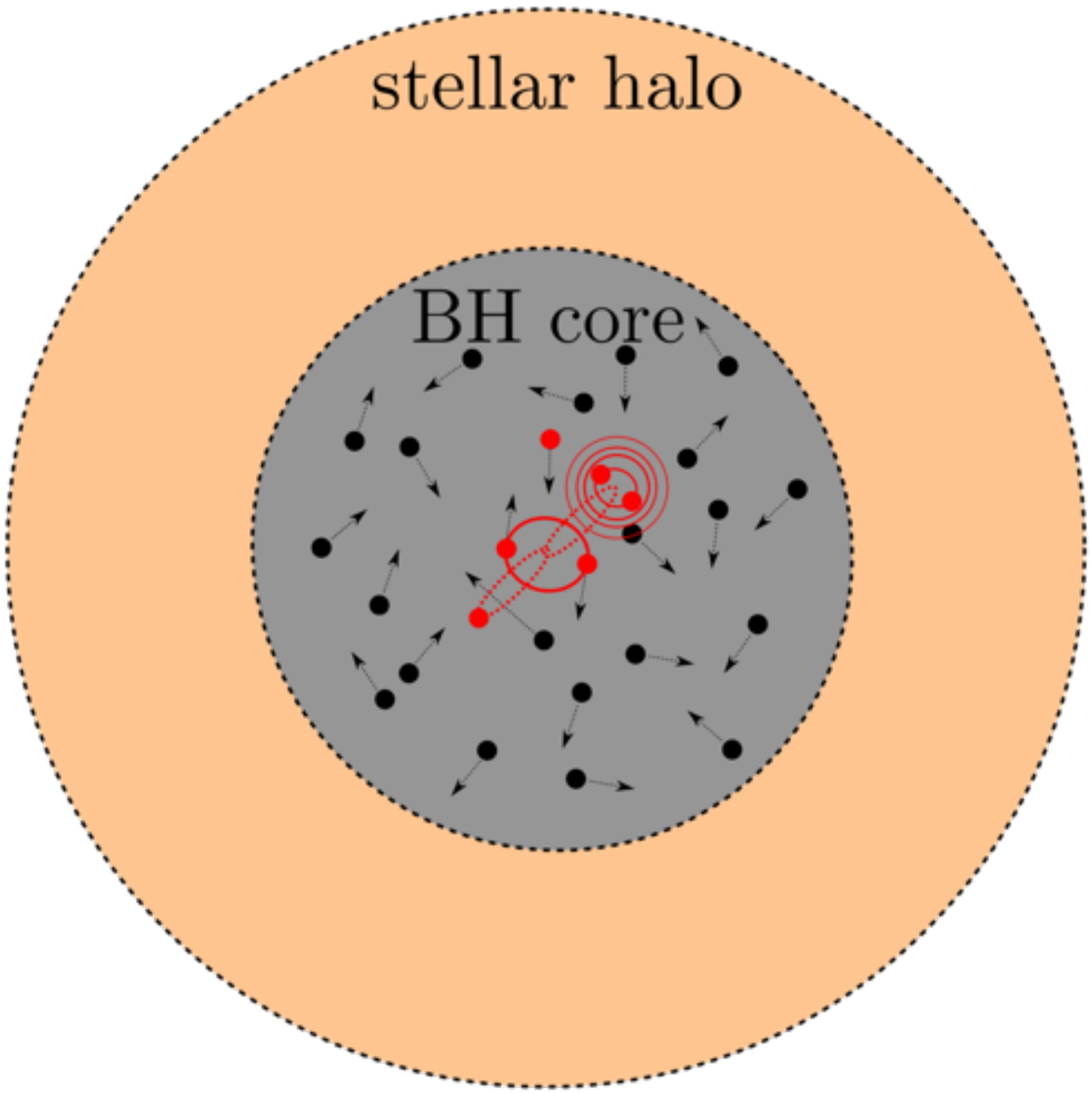


Consider again the characteristic time-scale argument:

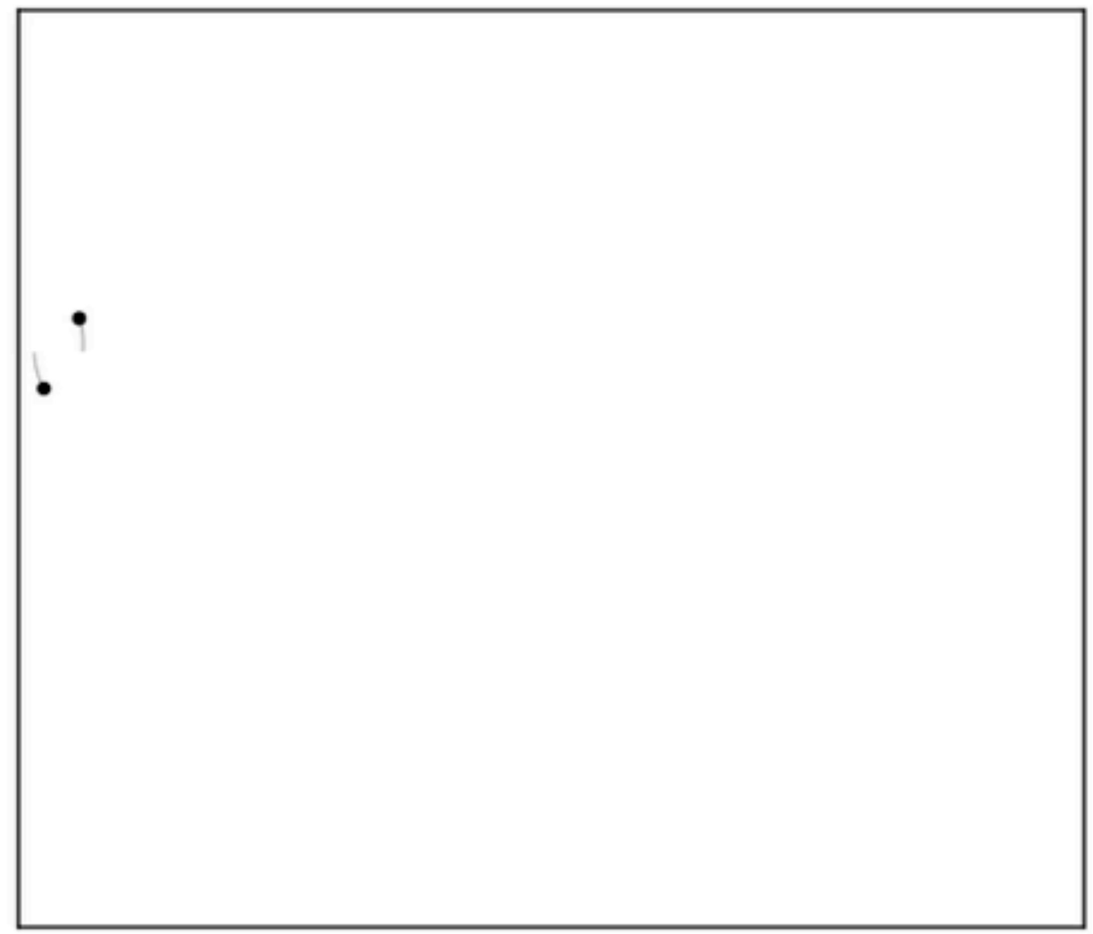
$$f_{r,0}^{\rm peak}(\mathcal{T}) \approx 2{\cdot}10^{-5}\,{\rm Hz}\left(\frac{\mathcal{T}}{10^{10}{\rm yrs}}\right)^{-3/7}\left(\frac{a}{0.5{\rm au}}\right)^{3/14}\left(\frac{m}{30M_{\odot}}\right)^{-11/14}$$

series of papers: Samsing, D'Orazio

Merger Type: 3-body Merger

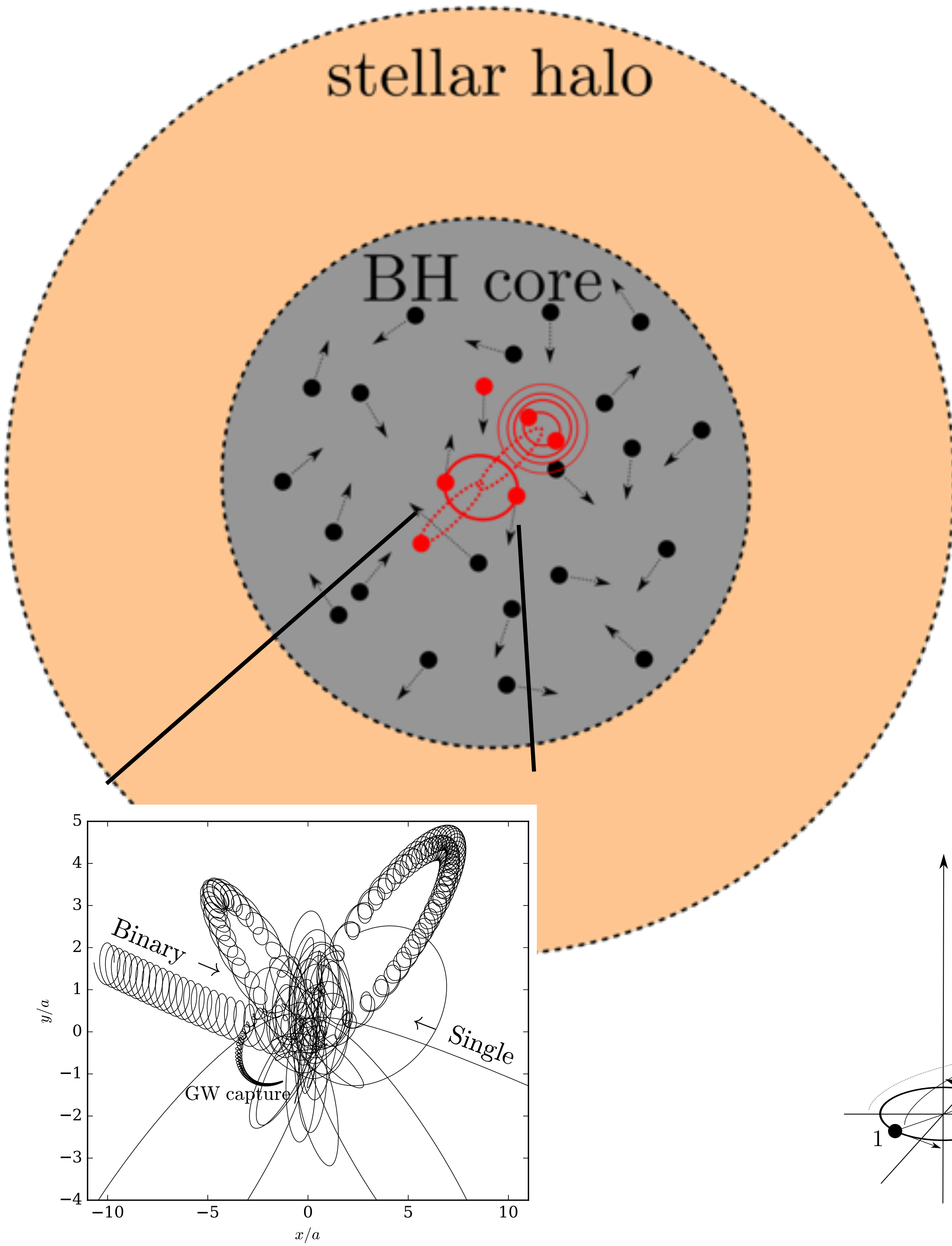


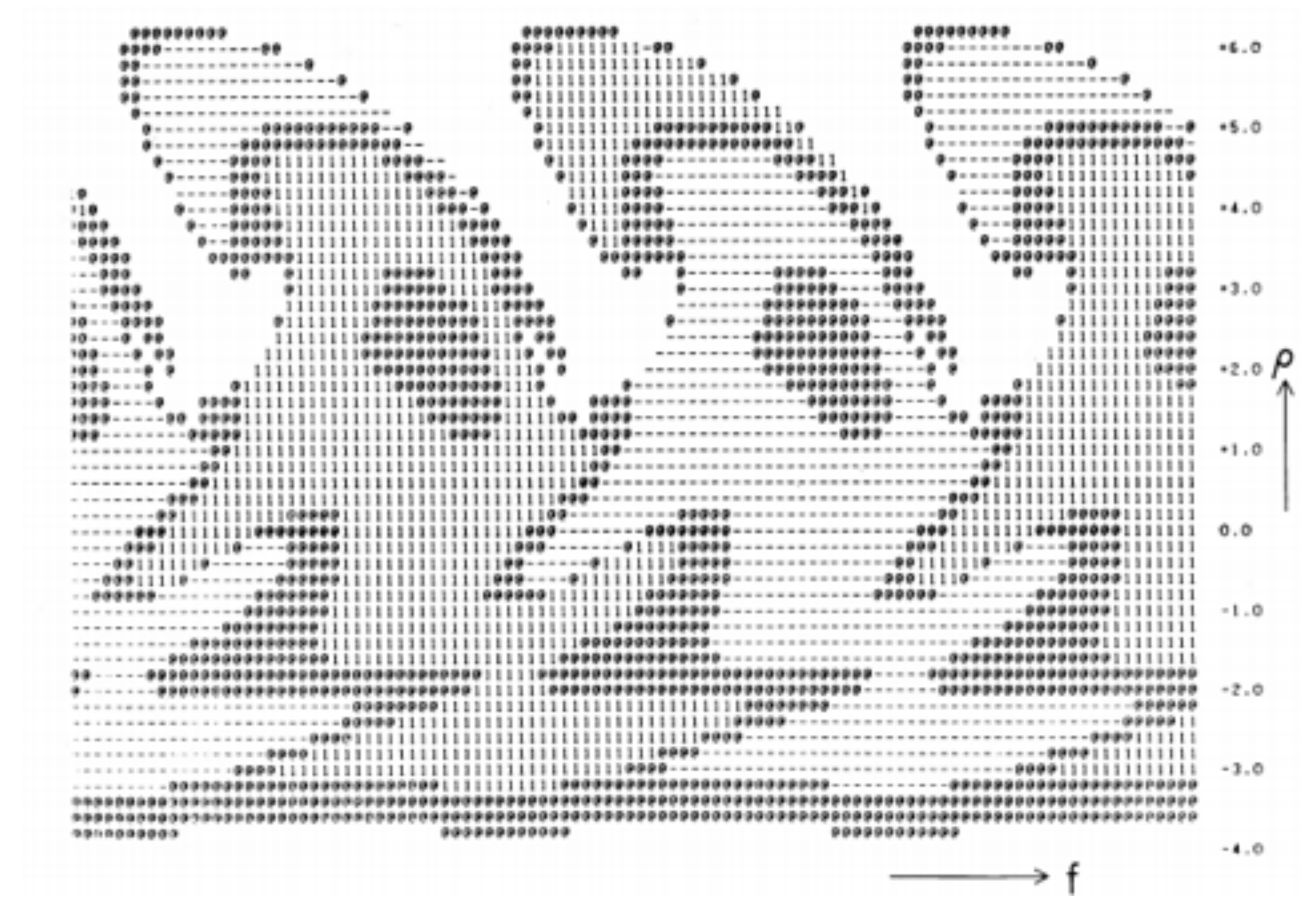
Post-Newtonian

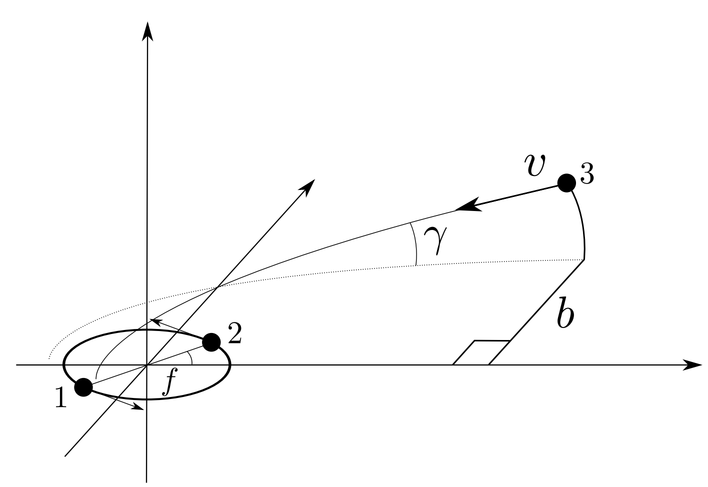


Merger Type: 3-body Merger

Topology







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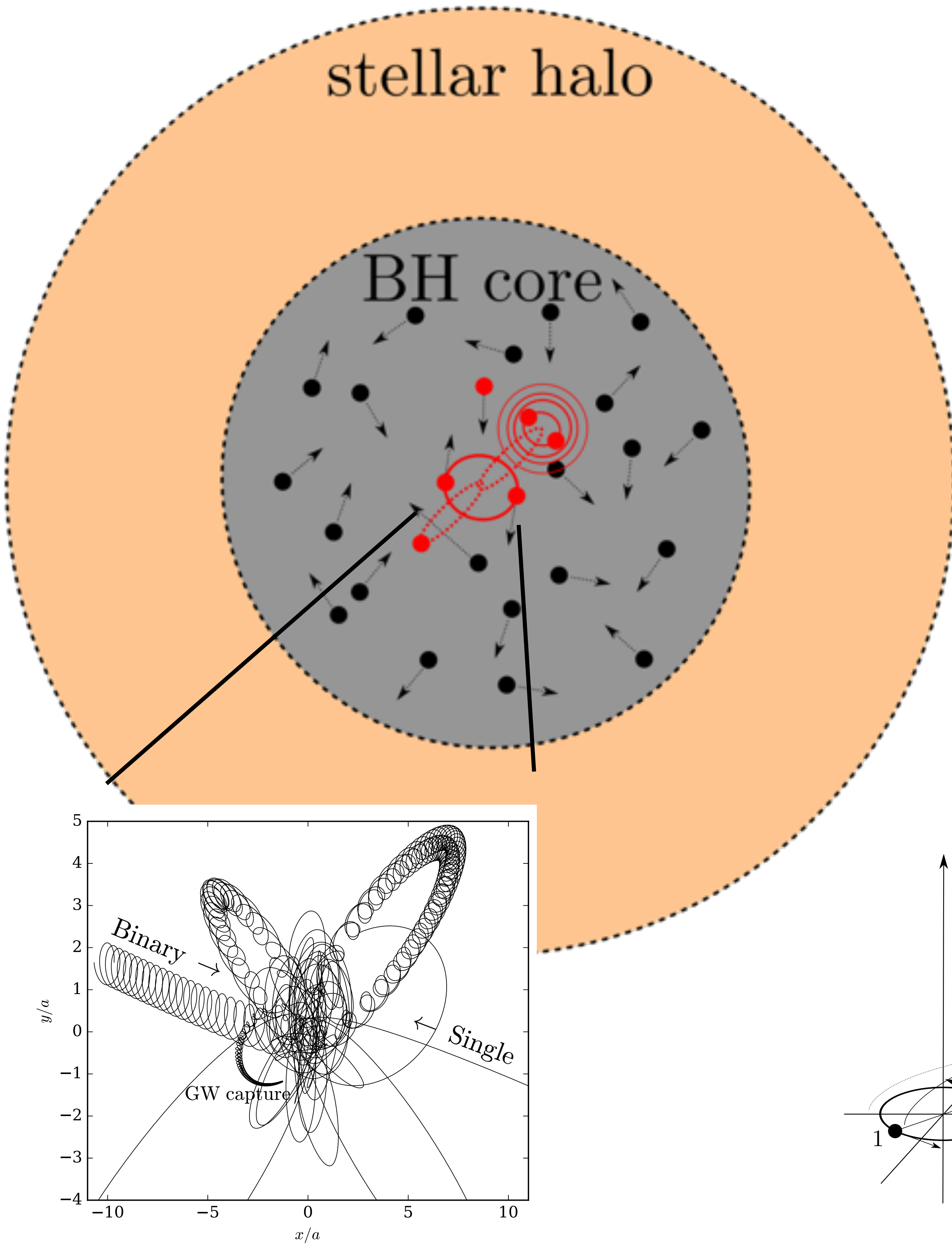
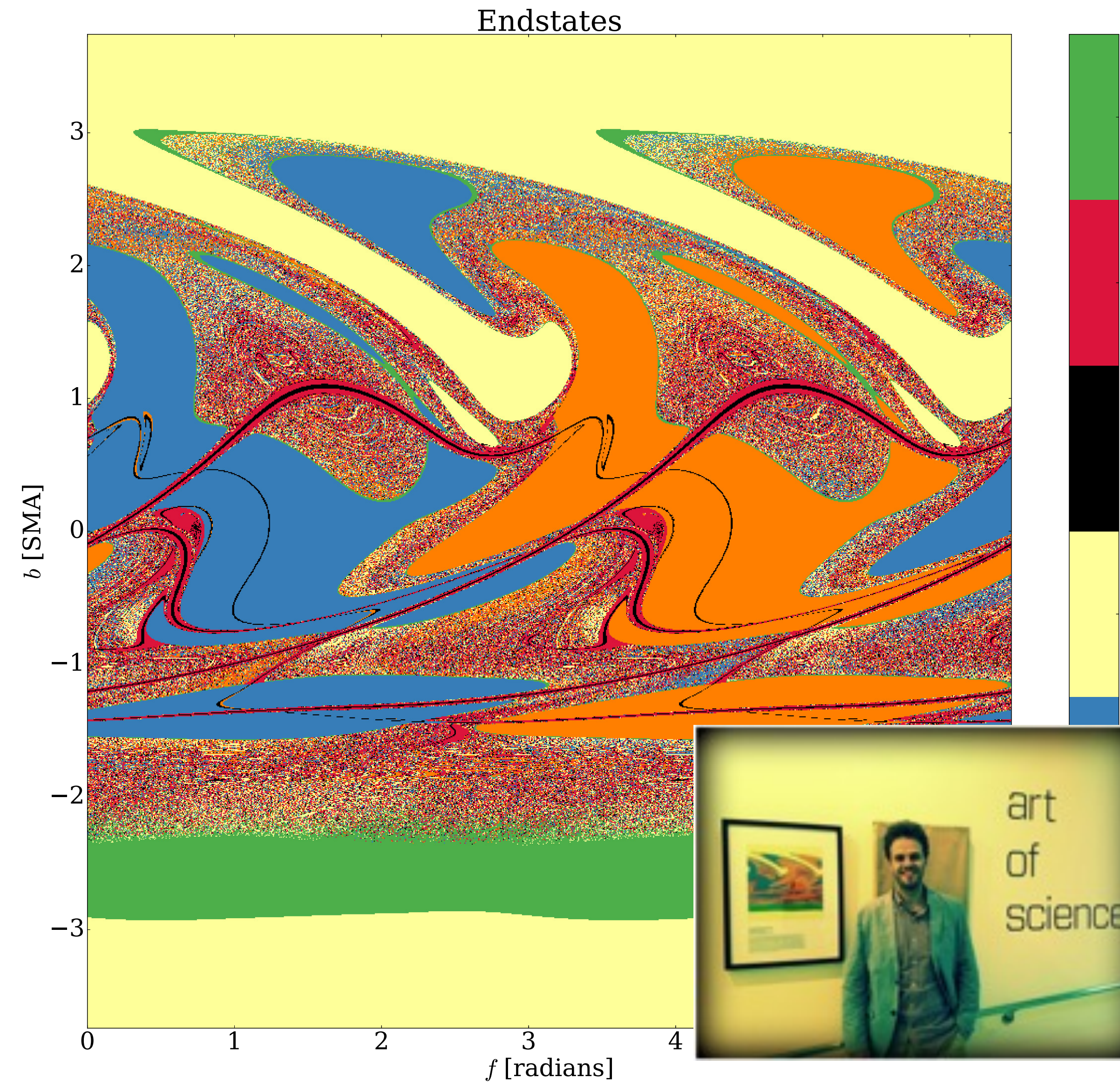
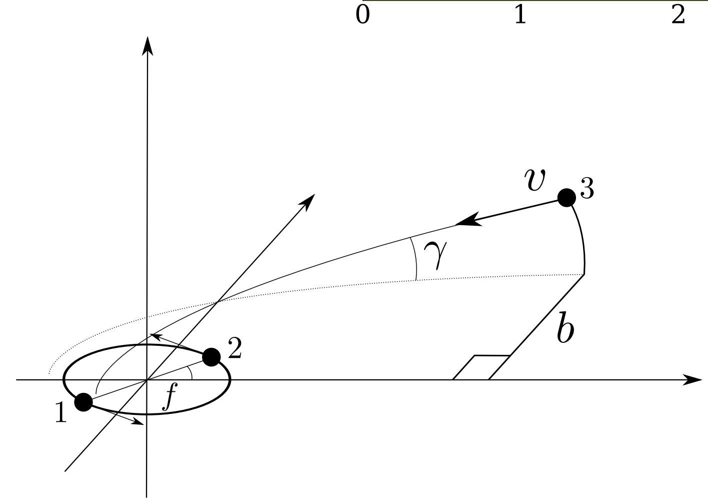
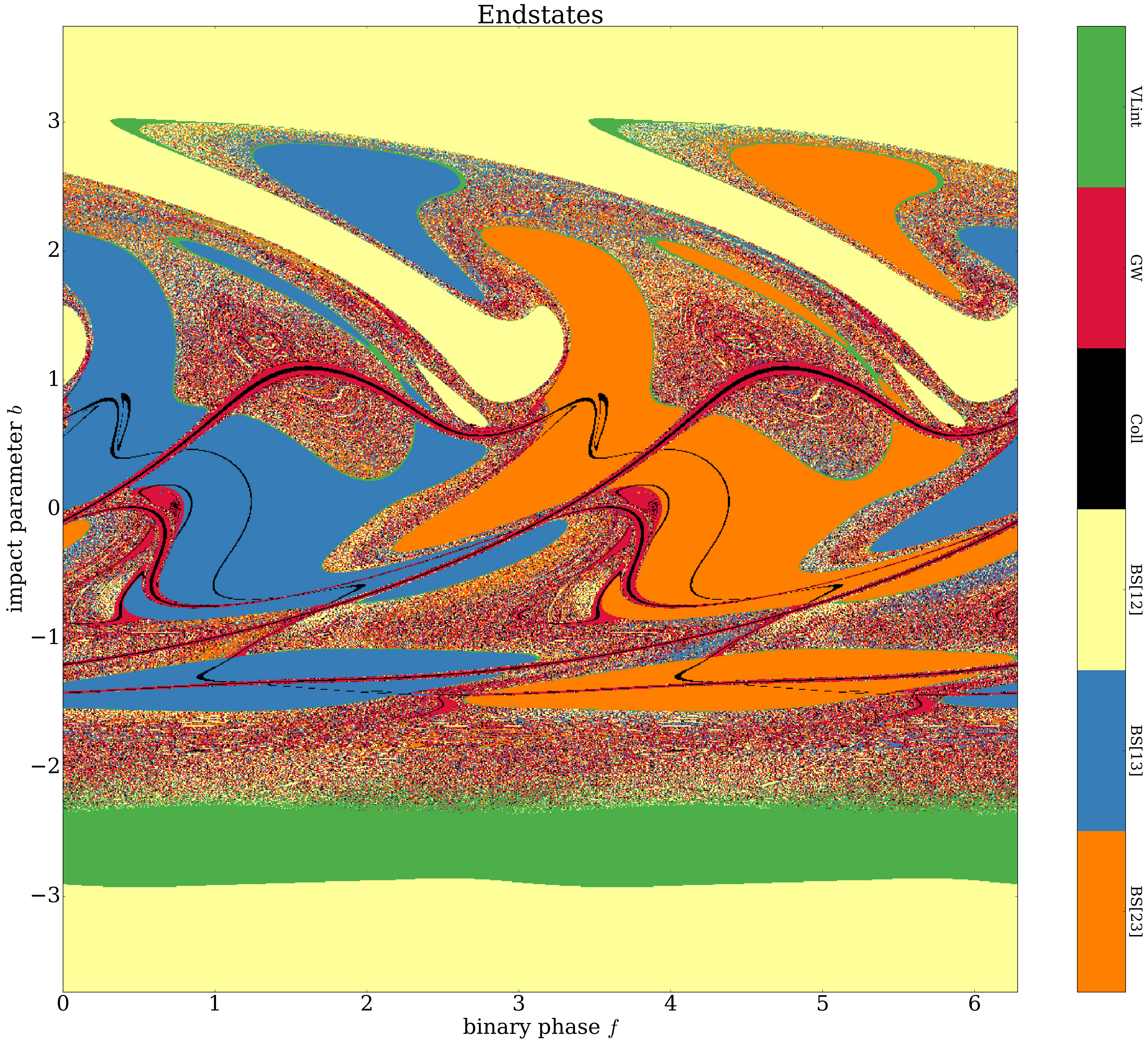


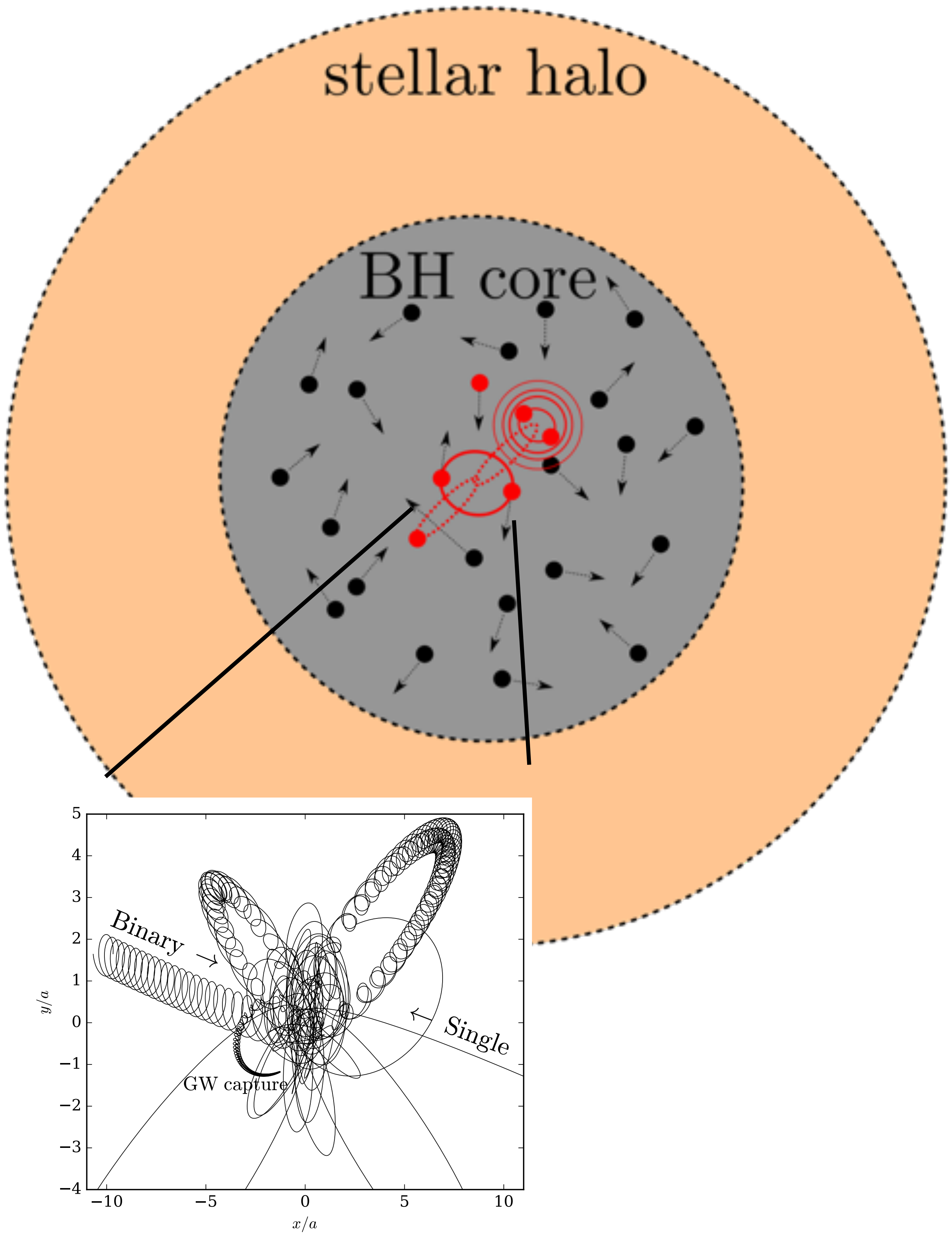




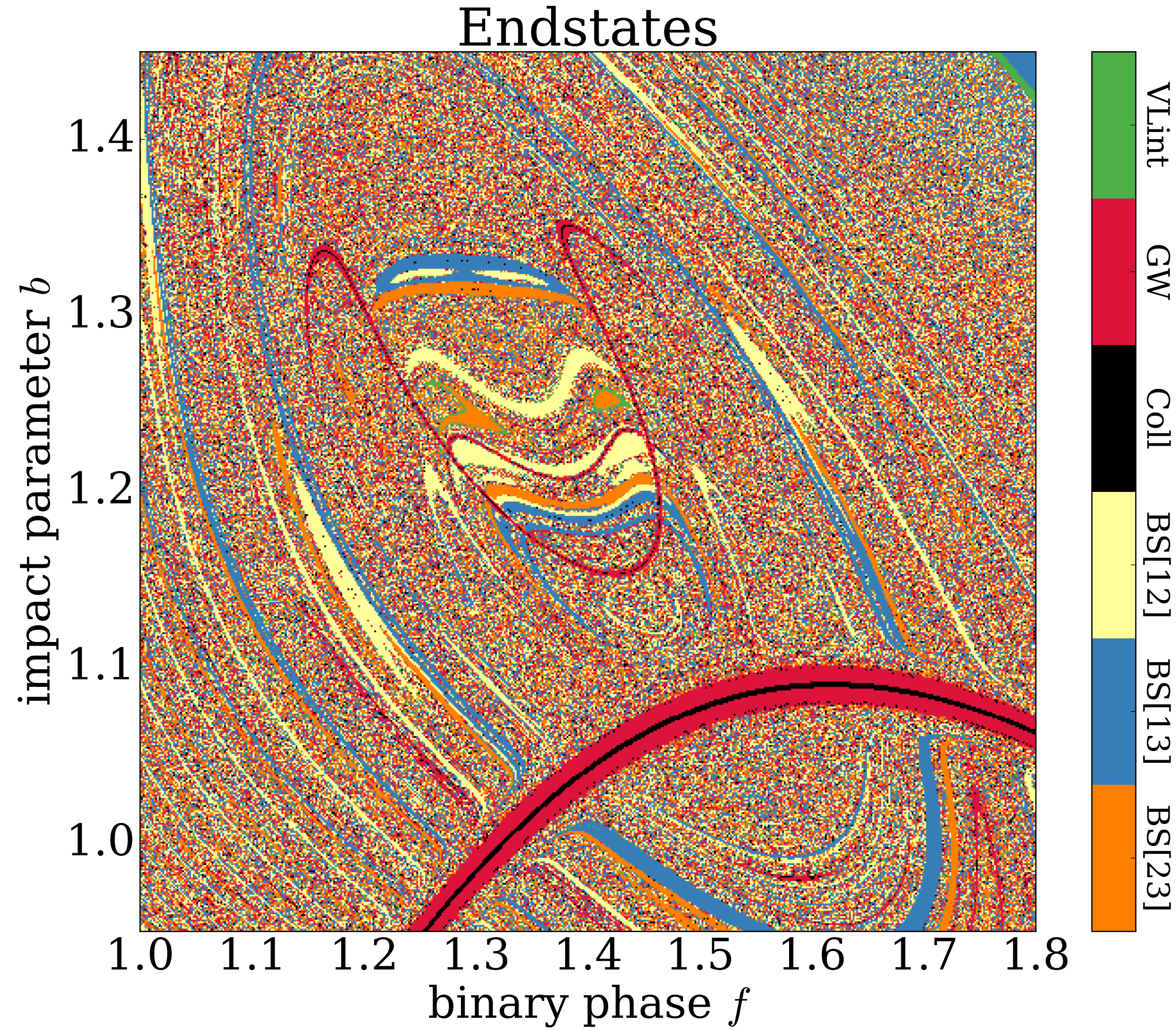


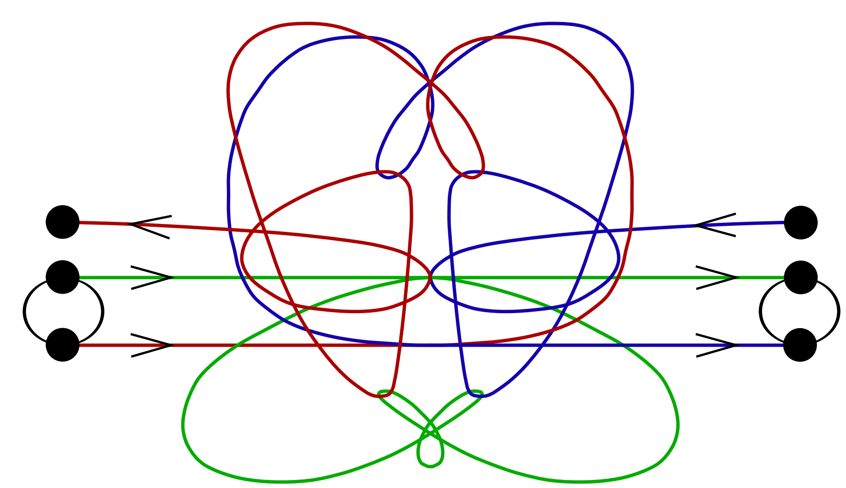
Endstates
impact parameter b
binary phase f
VLint
GW
Coll
BS[12]
BS[13]
BS[23]

Merger Type: 3-body Merger



Topology





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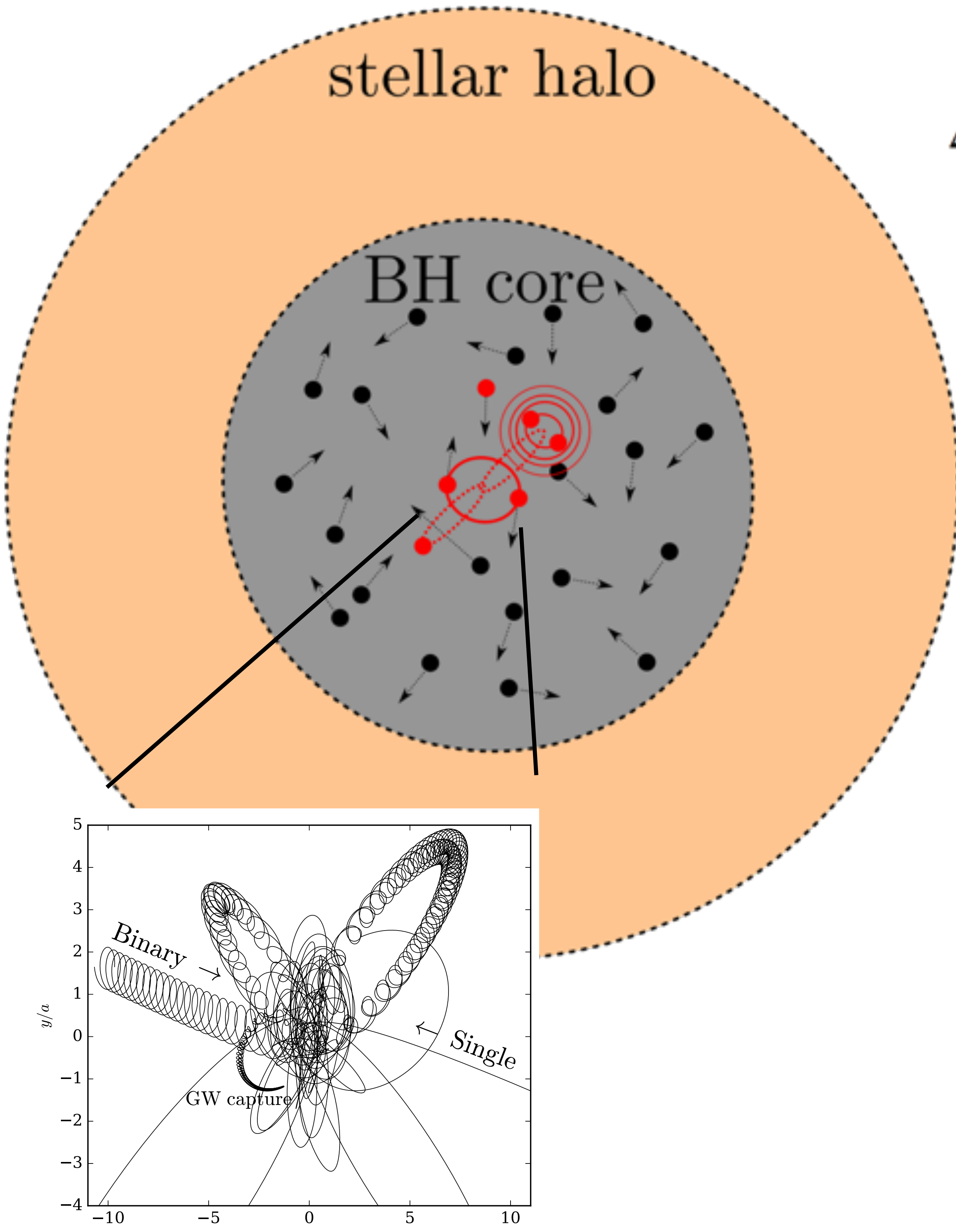
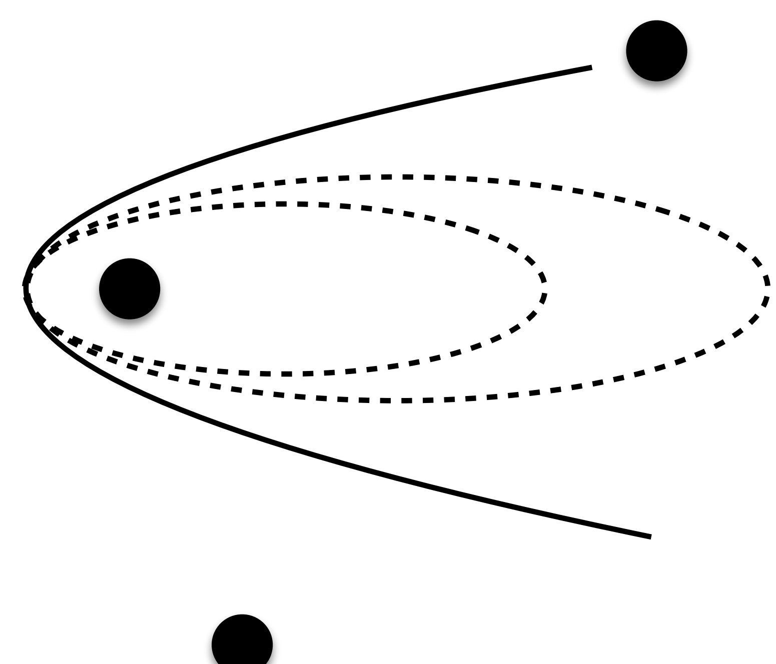


3-body GW capture:

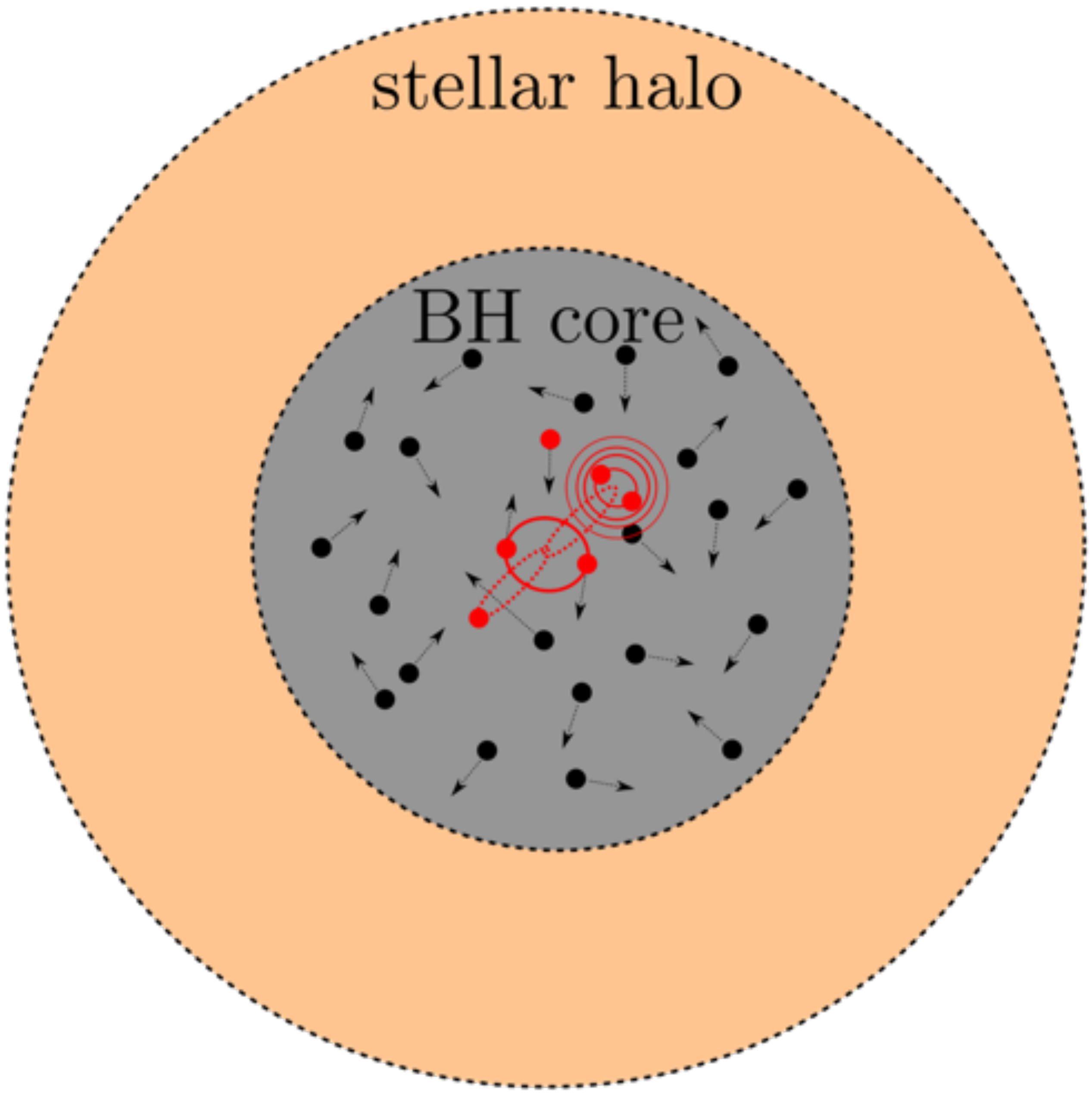
$$E_{\mathrm{B}} \approx Gm^2/(2a)$$

$$\Delta E_{\mathrm{p}} \approx (85\pi/12) G^{7/2} c^{-5} m^{9/2} r_{\mathrm{p}}^{-7/2}$$

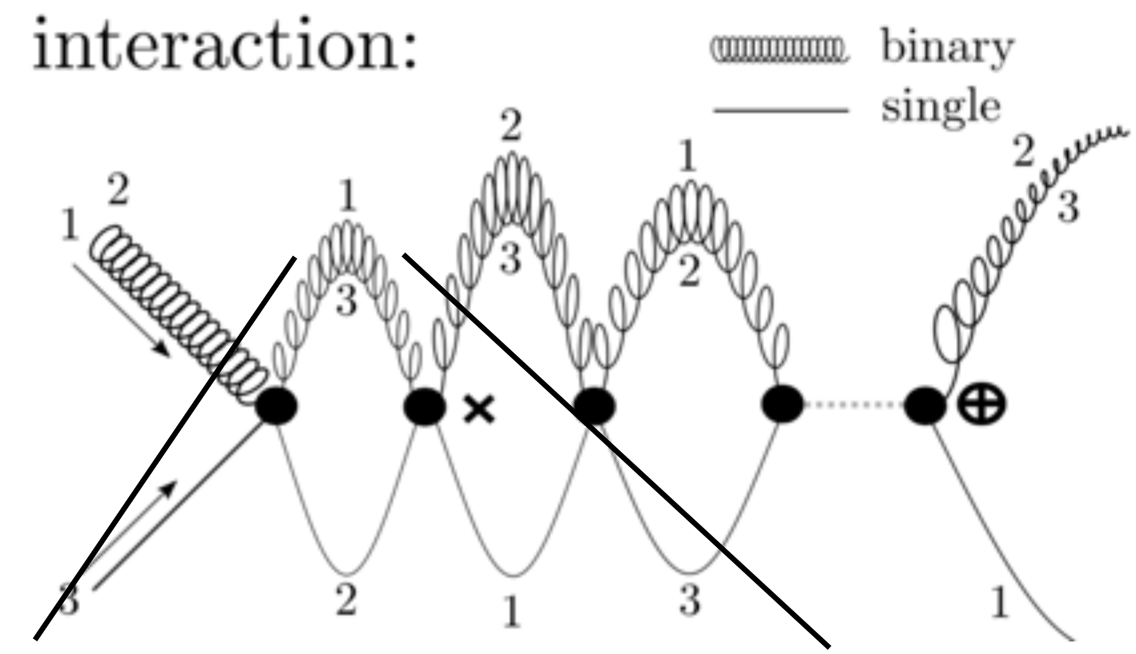
$$\mathcal{R}_{\mathrm{bs}} \approx \left(\frac{85\pi}{24\sqrt{2}}\right)^{2/7} \times \mathscr{R}_{\mathrm{m}} \left(\frac{a}{\mathscr{R}_{\mathrm{m}}}\right)^{2/7}$$



Merger Type: 3-body Merger



3-body Ecc. Probability:



$$r_{\mathrm{p}} = a(1-e) \quad P(e) = 2e$$

$$P_{\mathrm{EM}}(a) \approx \frac{2r_{\mathrm{EM}}}{a} \times N_{\mathrm{IMS}}$$

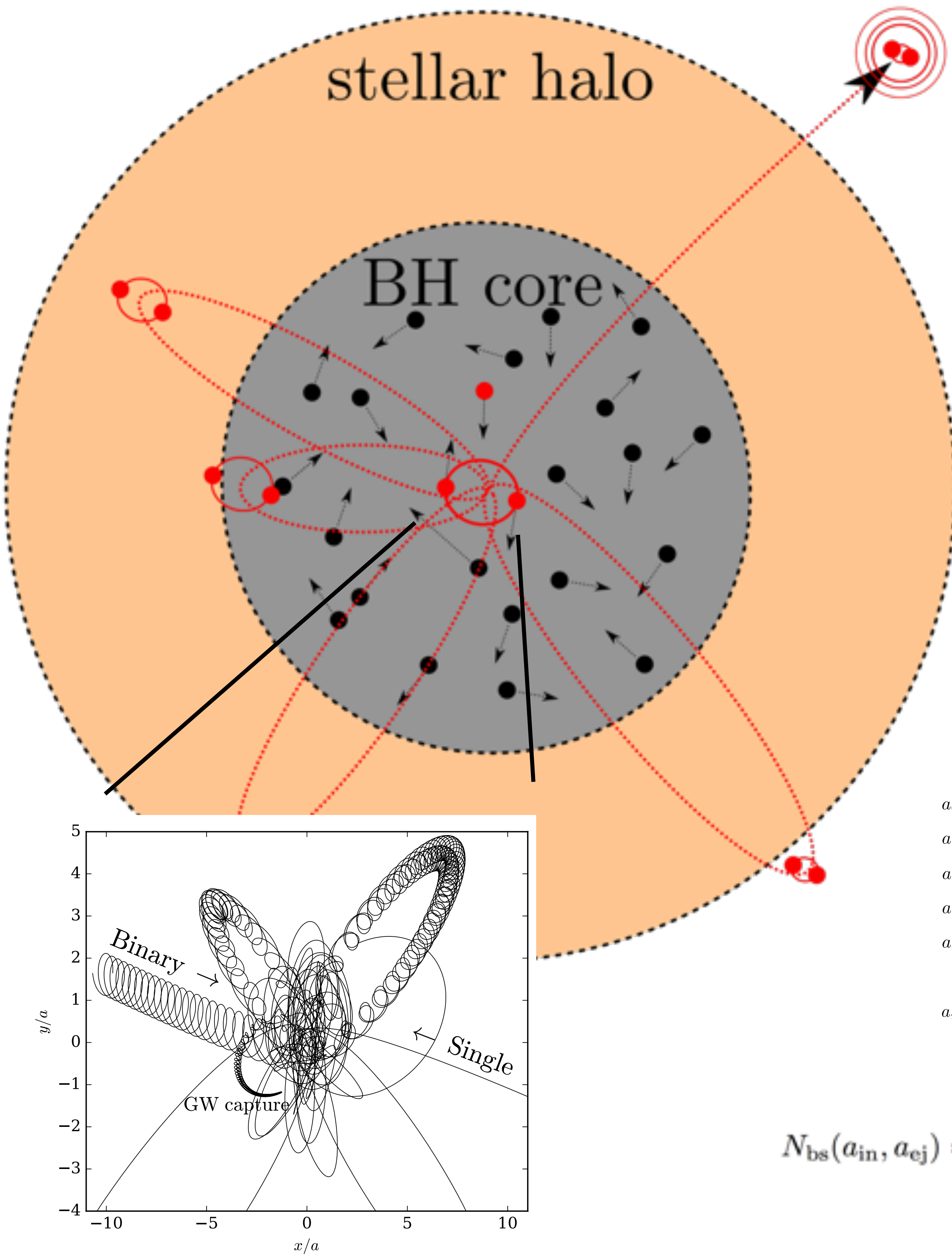
$$r_{\mathrm{EM}} \approx \left(\frac{2Gm}{f^2\pi^2}\right)^{1/3} \frac{1}{2}\frac{1+e_f}{e_f^{12/19}}\left[\frac{425}{304}\left(1+\frac{121}{304}e_f^2\right)^{-1}\right]^{870/2299}$$

$$P_{\mathrm{EM}}(a_{\mathrm{in}}, a_{\mathrm{ej}}) = \frac{1}{1-\delta}\int_{a_{\mathrm{ej}}}^{a_{\mathrm{in}}} \frac{P_{\mathrm{EM}}(a)}{a} da \approx \frac{P_{\mathrm{EM}}(a_{\mathrm{ej}})}{1-\delta}$$

Merger Type: 3-body Merger

Eccentric Black Hole Mergers Forming in Globular Clusters
Authors: Johan Samsing

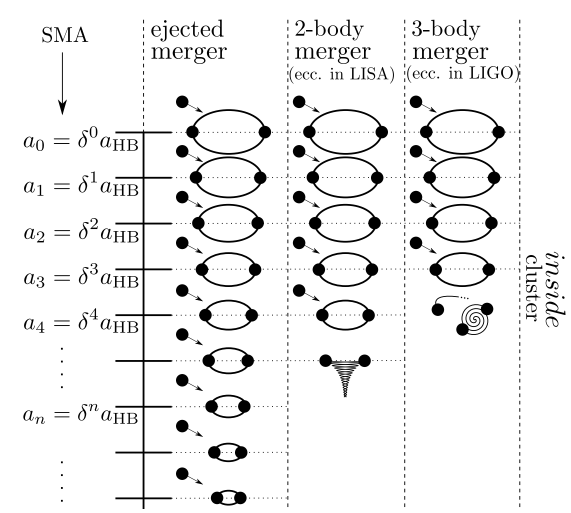
Newtonian codes underestimate the rate by more than a factor of 100!



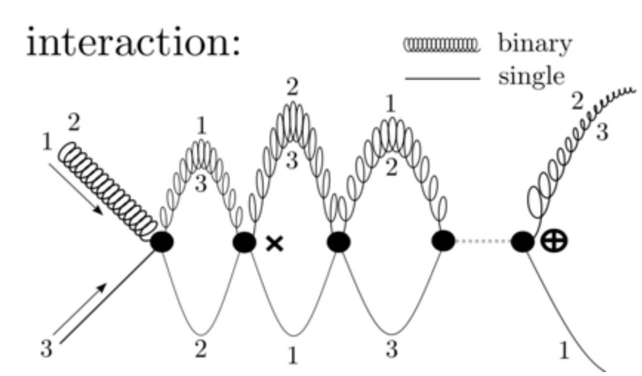
number of tries

- GR: **1x1 = 1**

+GR: **20x20 = 400**



X

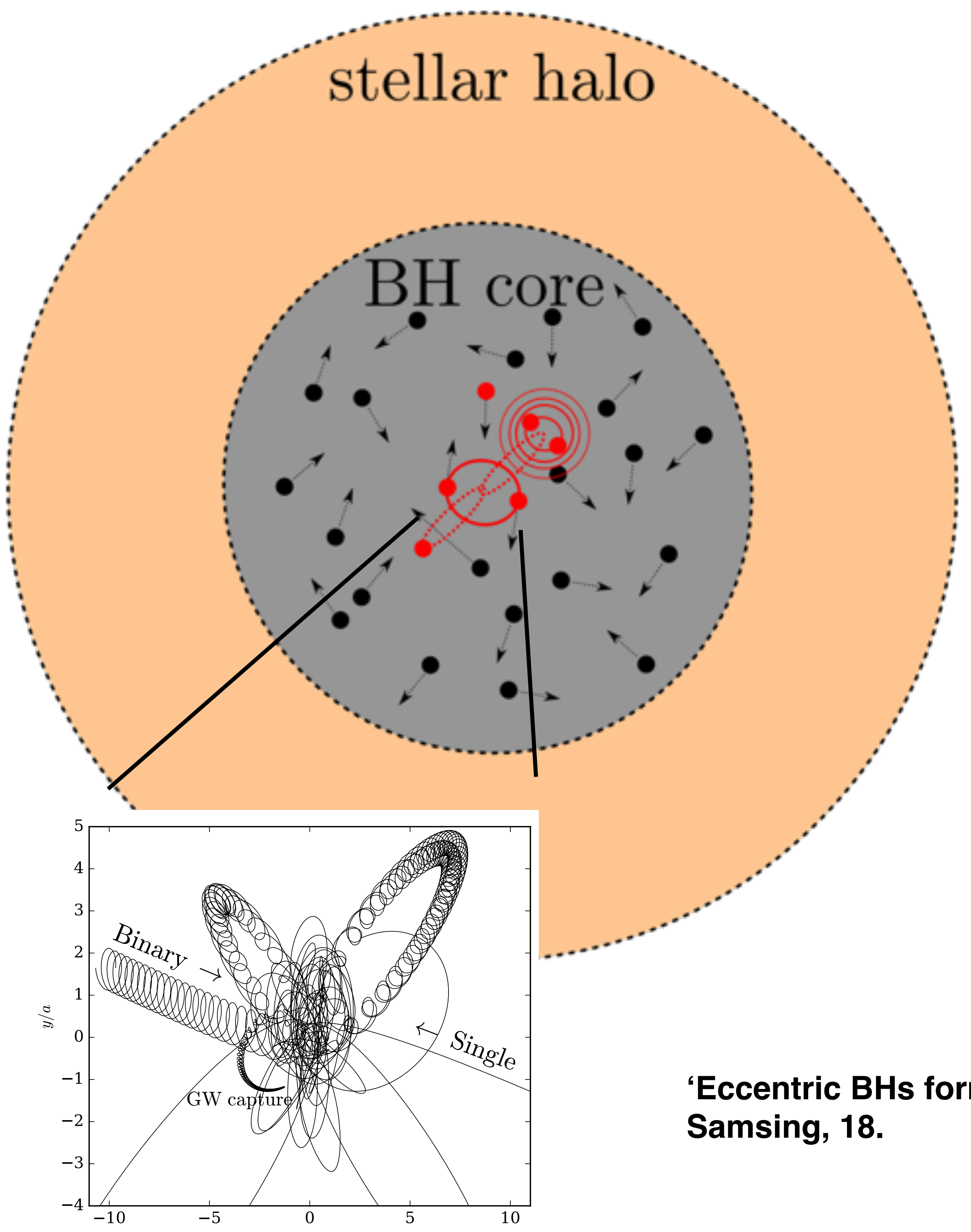


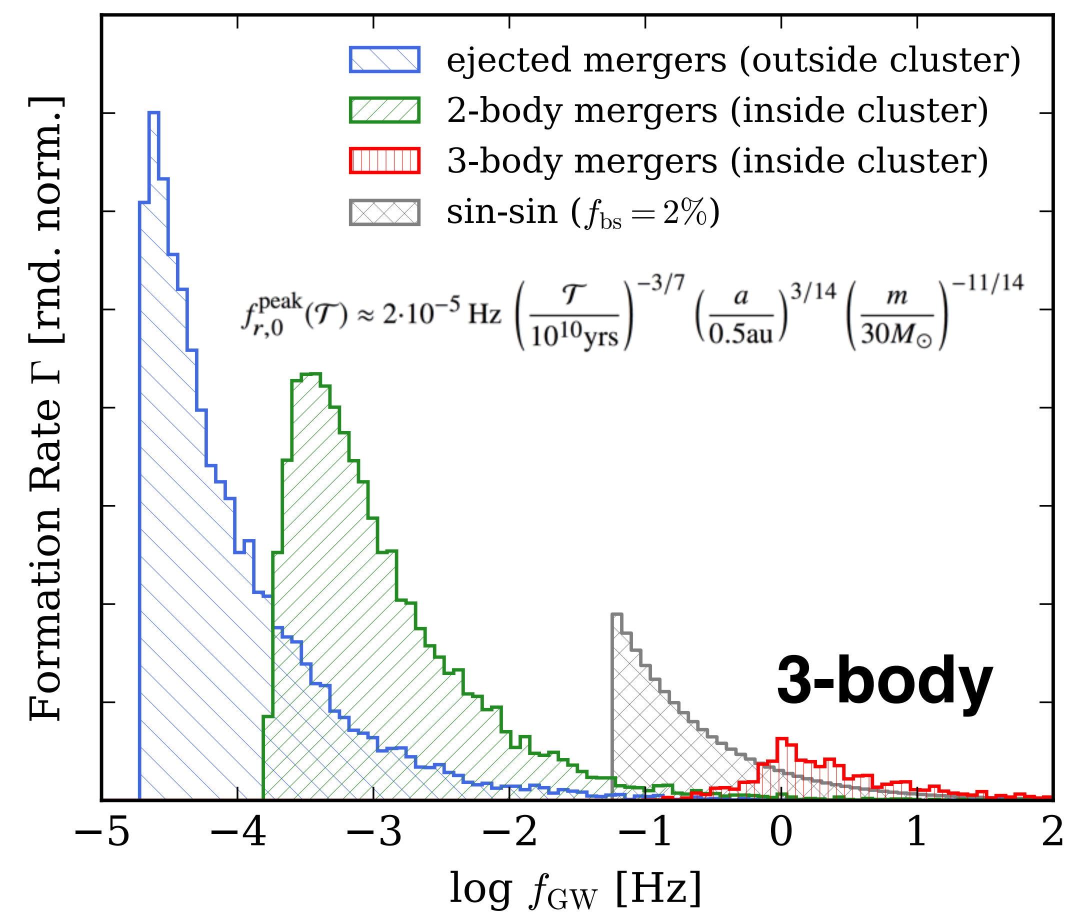
$$N_{\rm bs}(a_{\rm in}, a_{\rm ej}) = \int_{a_{\rm ej}}^{a_{\rm in}} \frac{1}{1-\delta}\frac{1}{a}da = \frac{1}{1-\delta}\ln\left(\frac{a_{\rm in}}{a_{\rm ej}}\right)$$

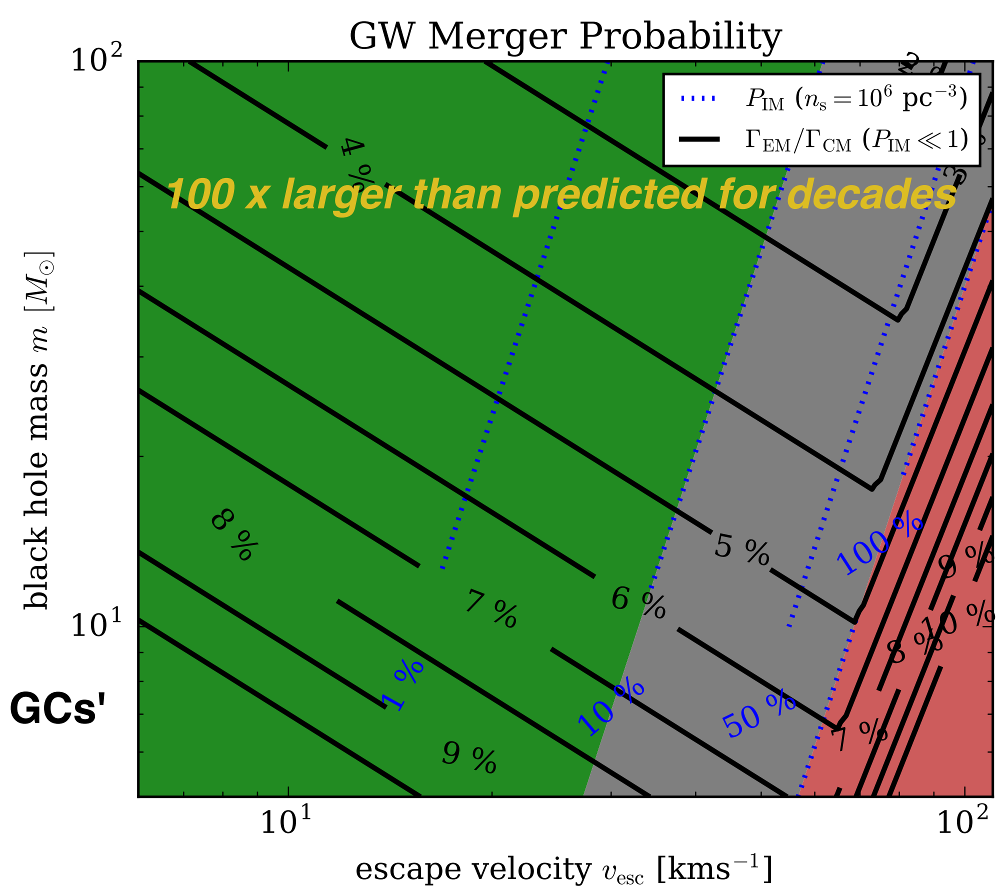
$$N_{\rm IMS} \approx (\max(a_{\rm IMS})/a)^{7/2}$$

Merger Type: 3-body Merger

Eccentric LIGO sources

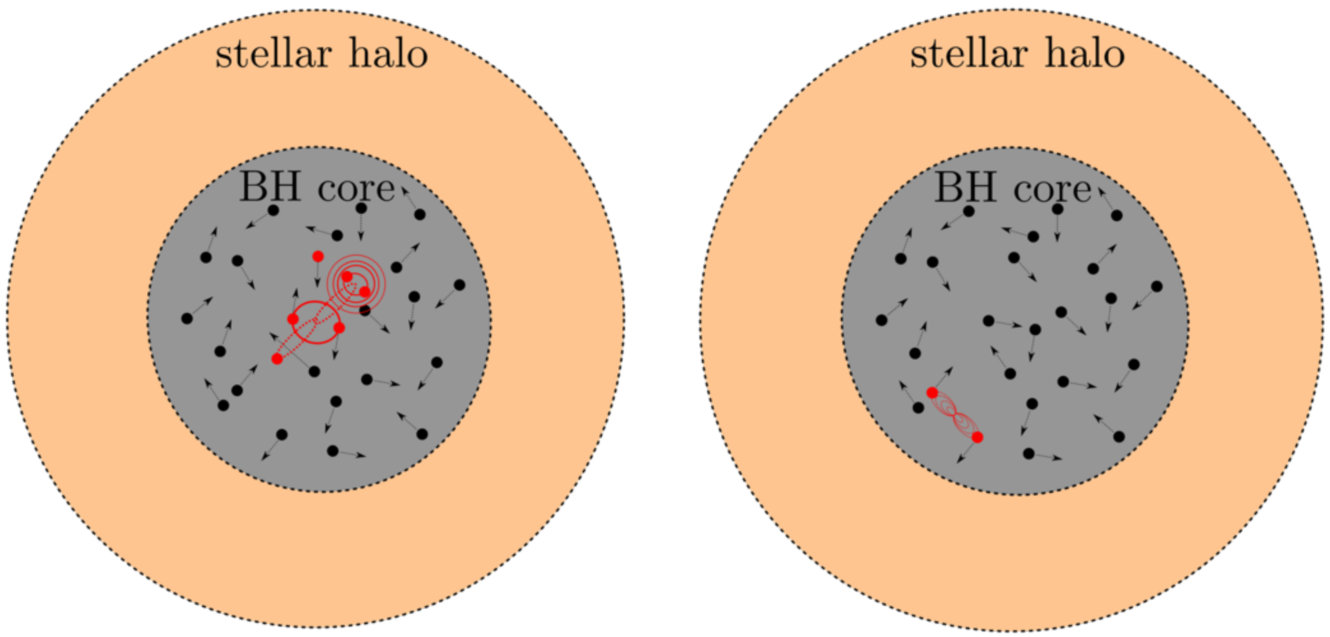




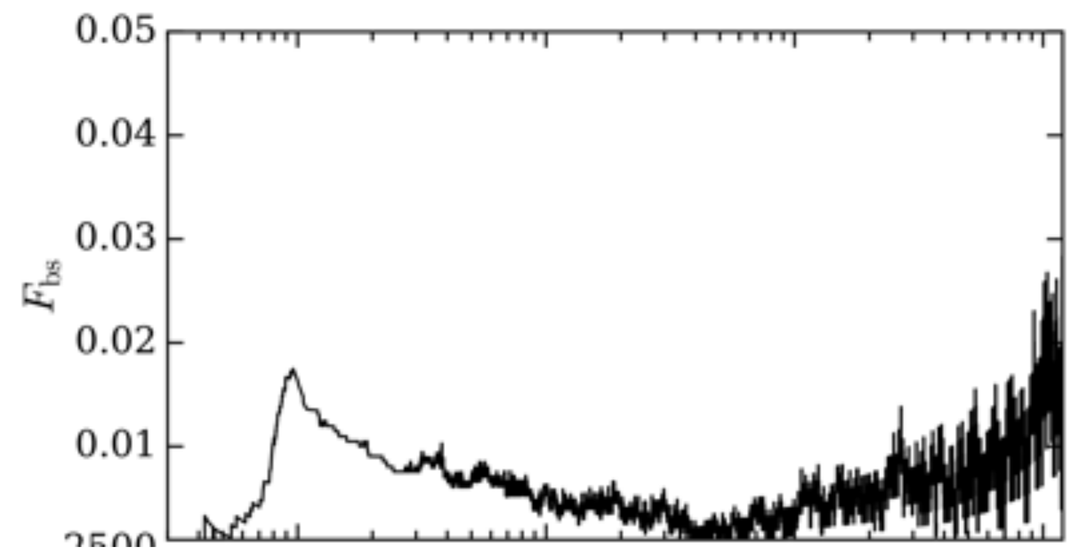


'Eccentric BHs forming in GCs'
Samsing, 18.

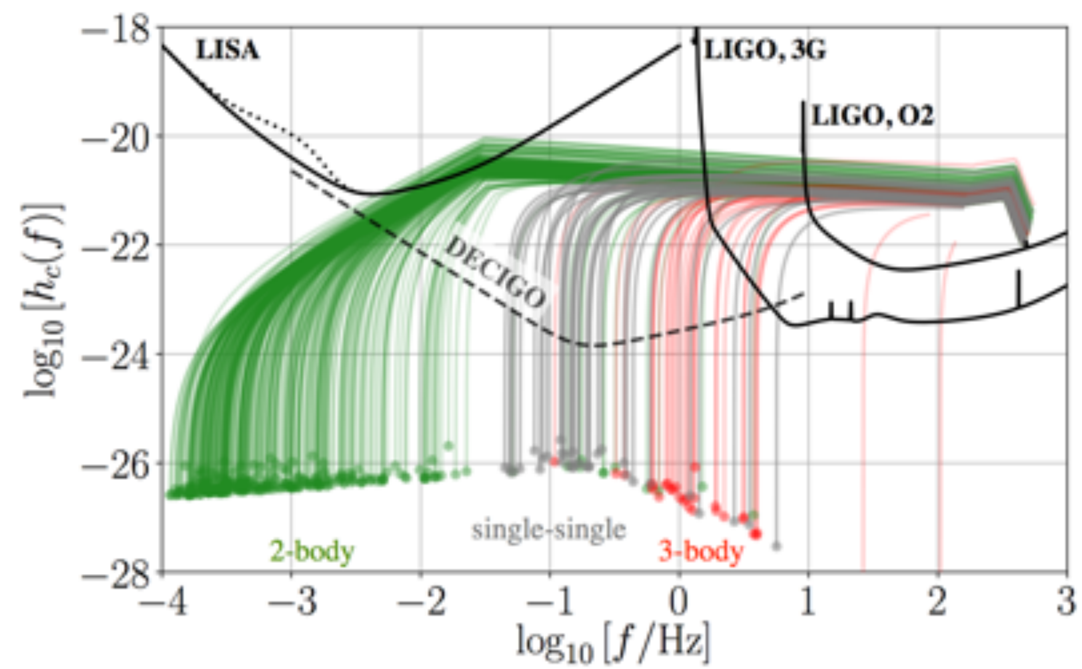
Comparing binary-single and single-single:



binary fraction



f distribution

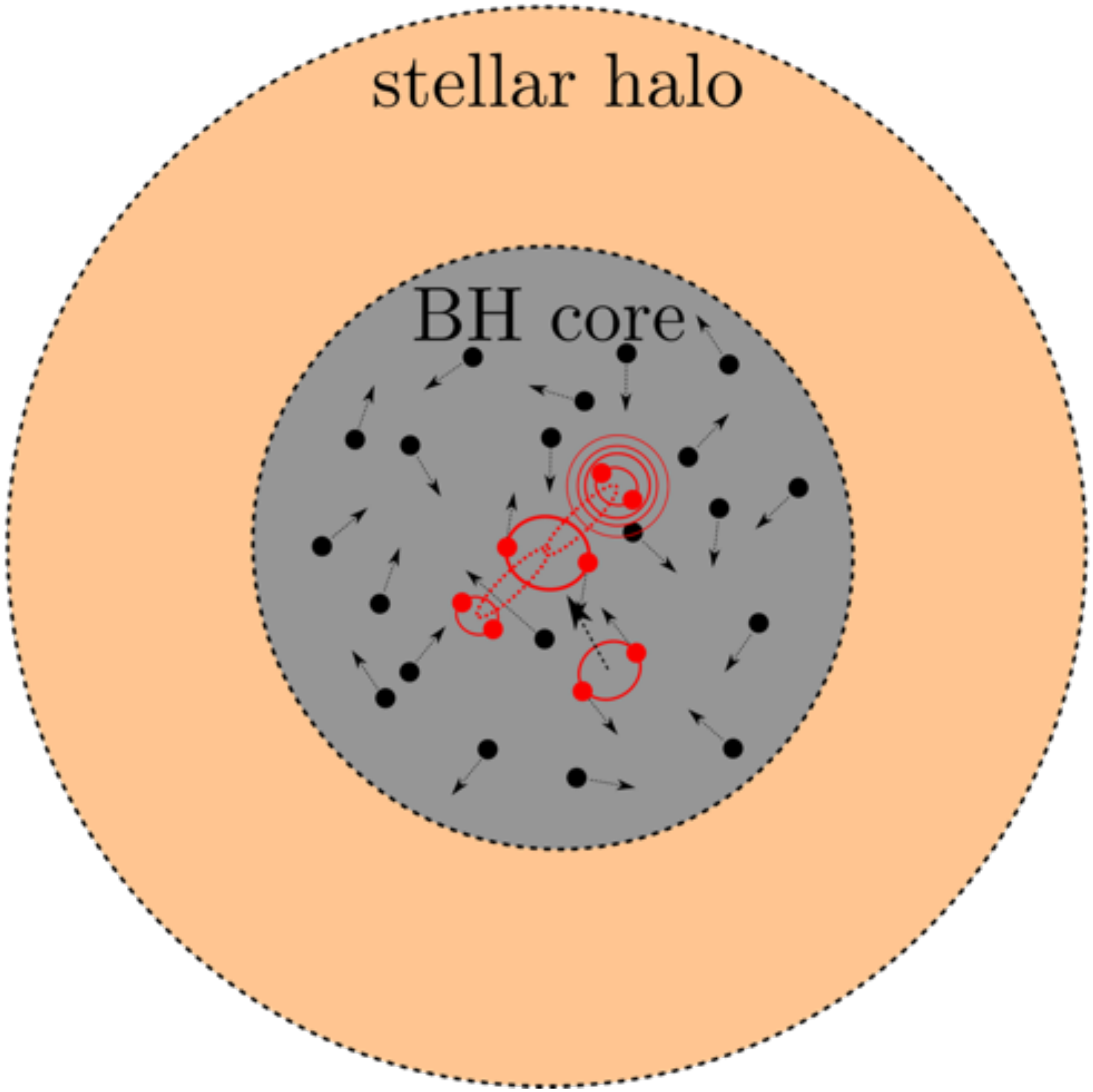


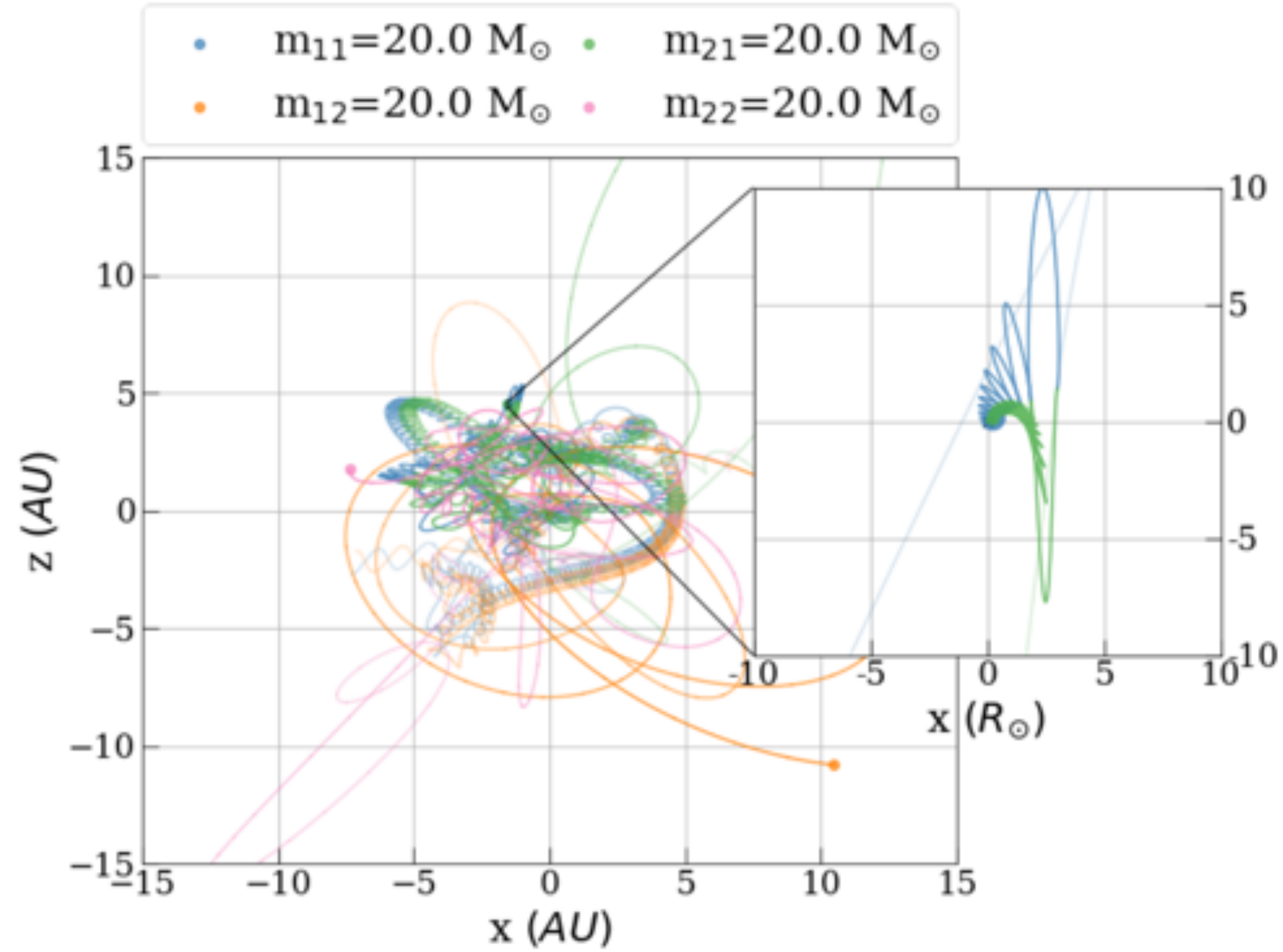
uniform sphere:

$$\frac{\Gamma_{\rm bs}}{\Gamma_{\rm ss}} \approx 6 F_{\rm bs} \mathcal{N} \times \left(\frac{\phi - 1}{12 f_{\rm ed}^2} \right)^{2/7} \frac{7}{5}$$

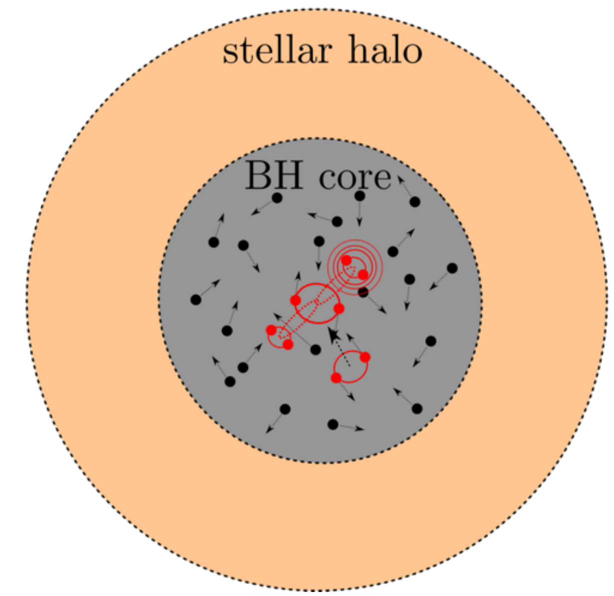
Can we here probe the BH core properties?

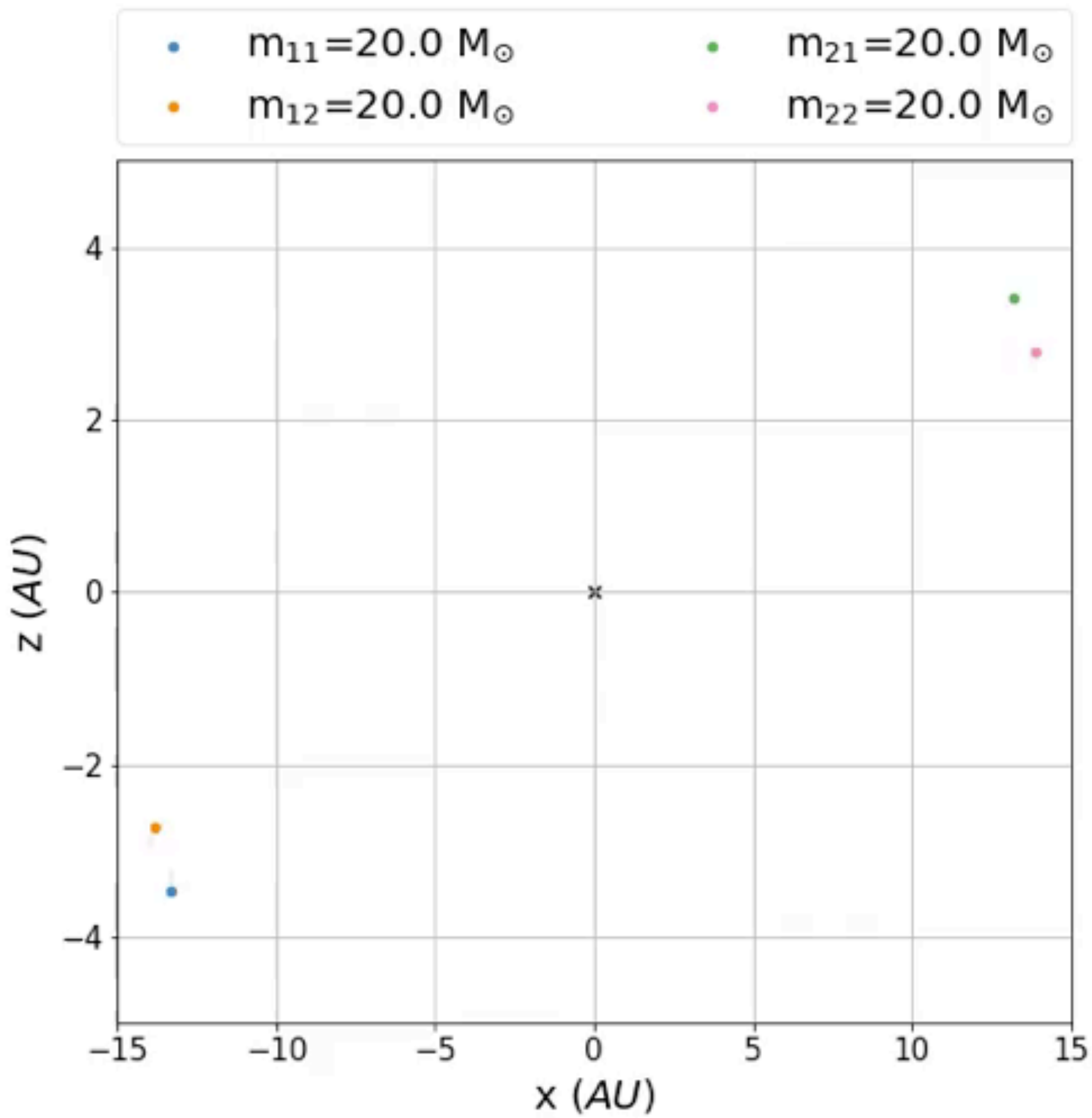
Merger Type: 4-body Merger

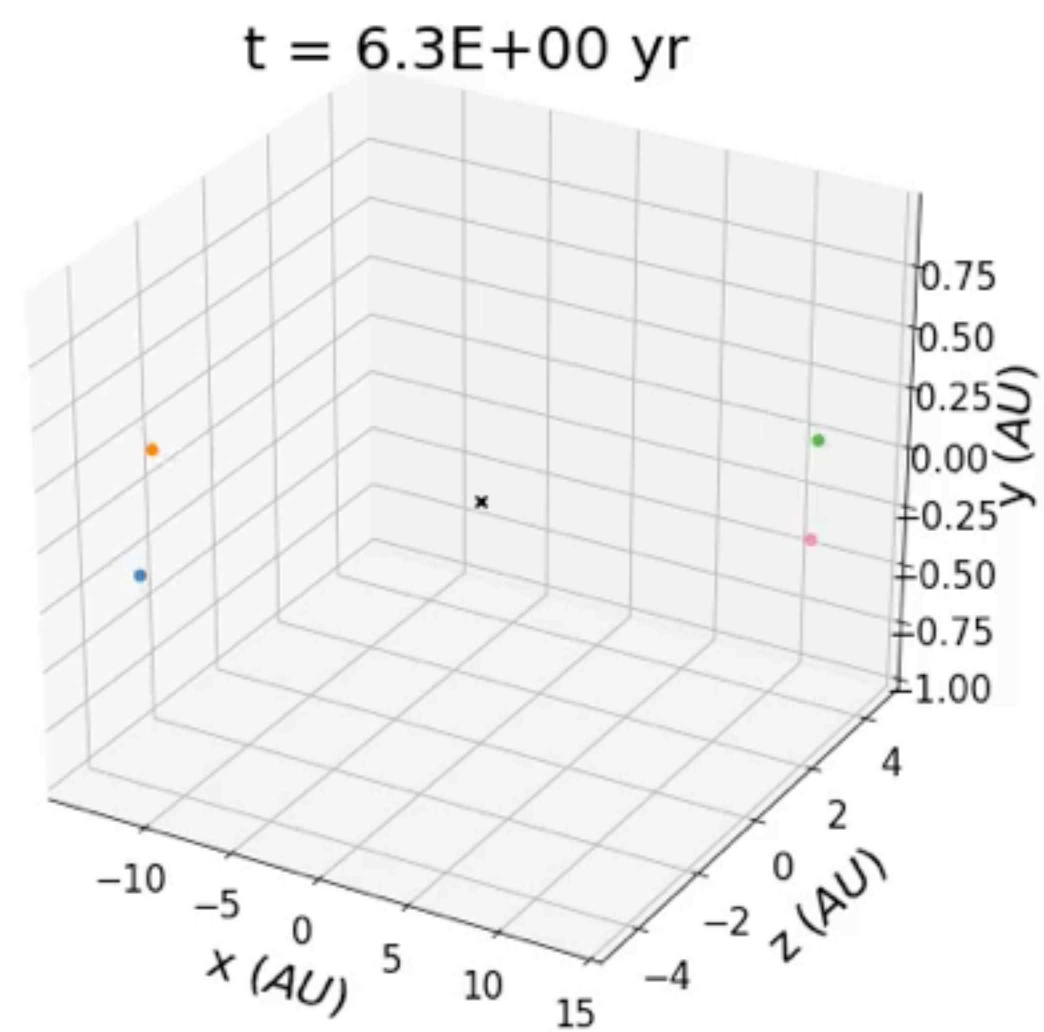




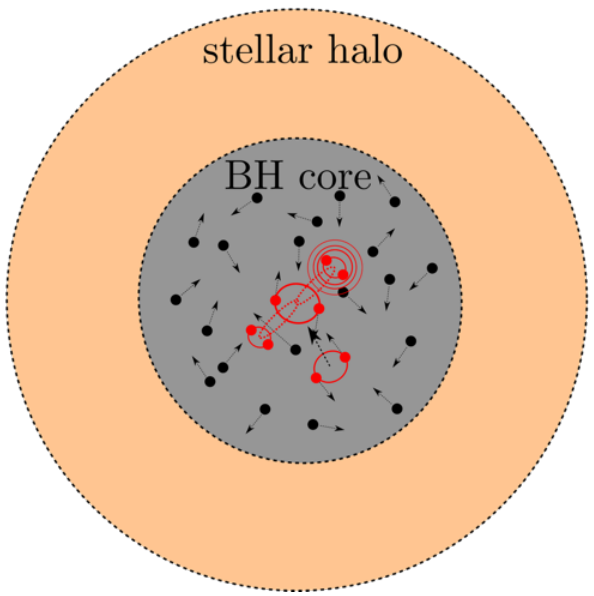
Merger Type: 4-body Merger

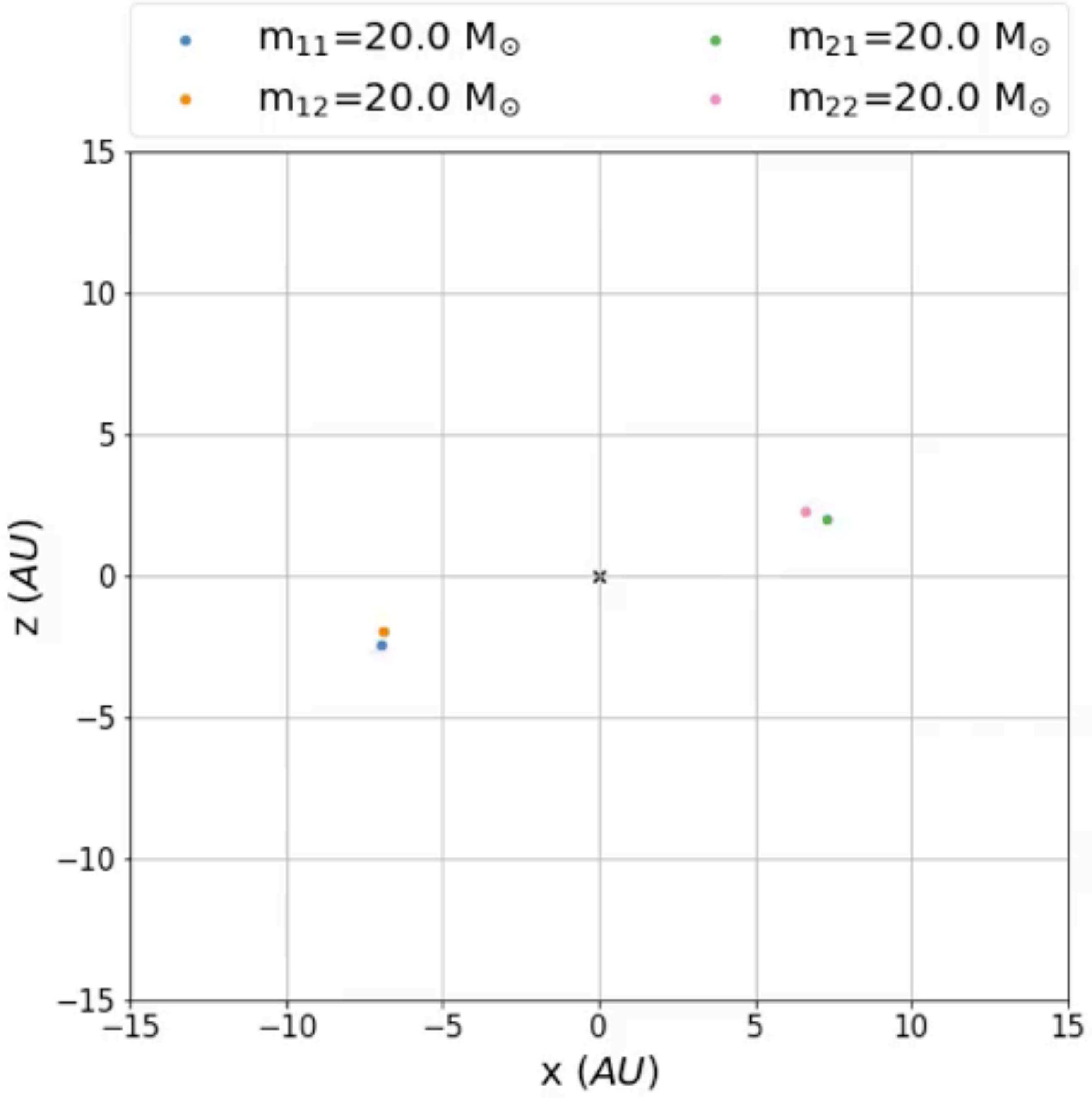


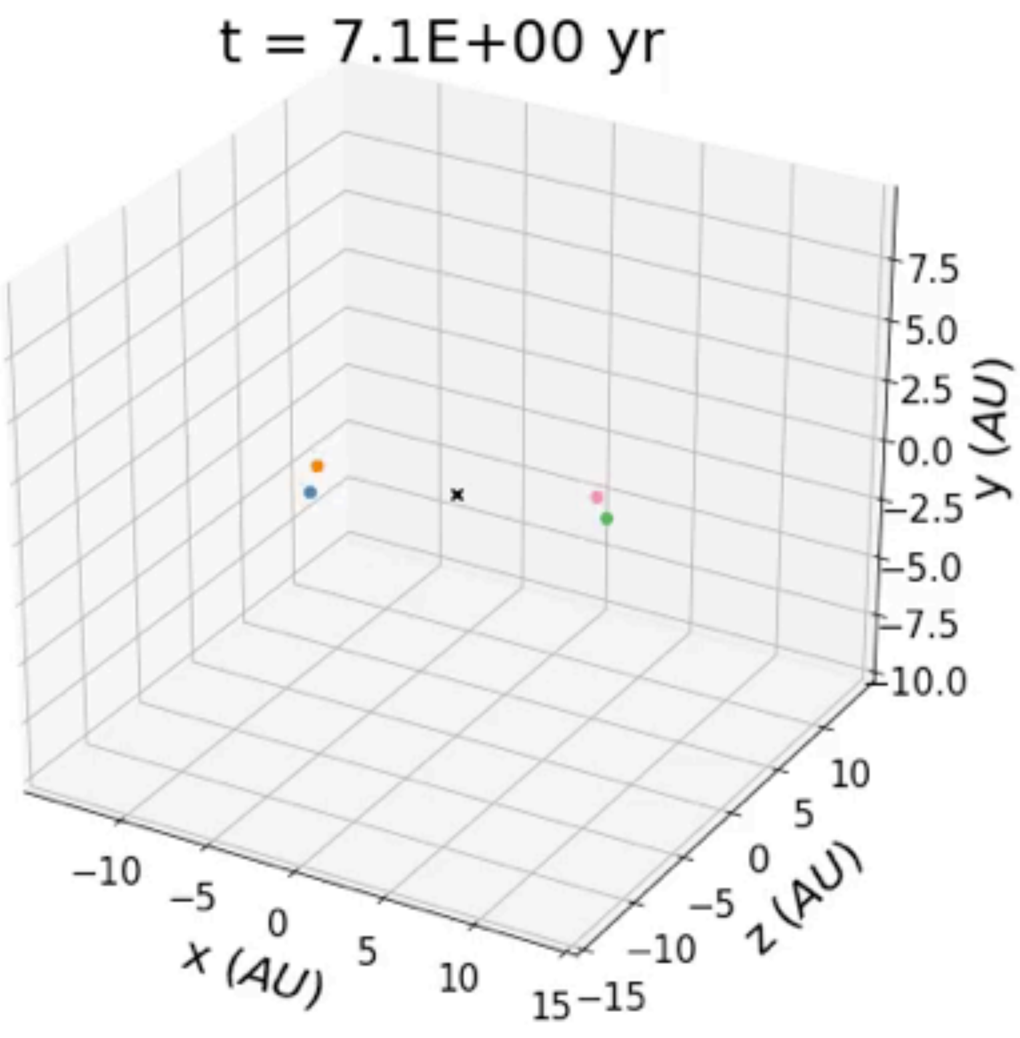




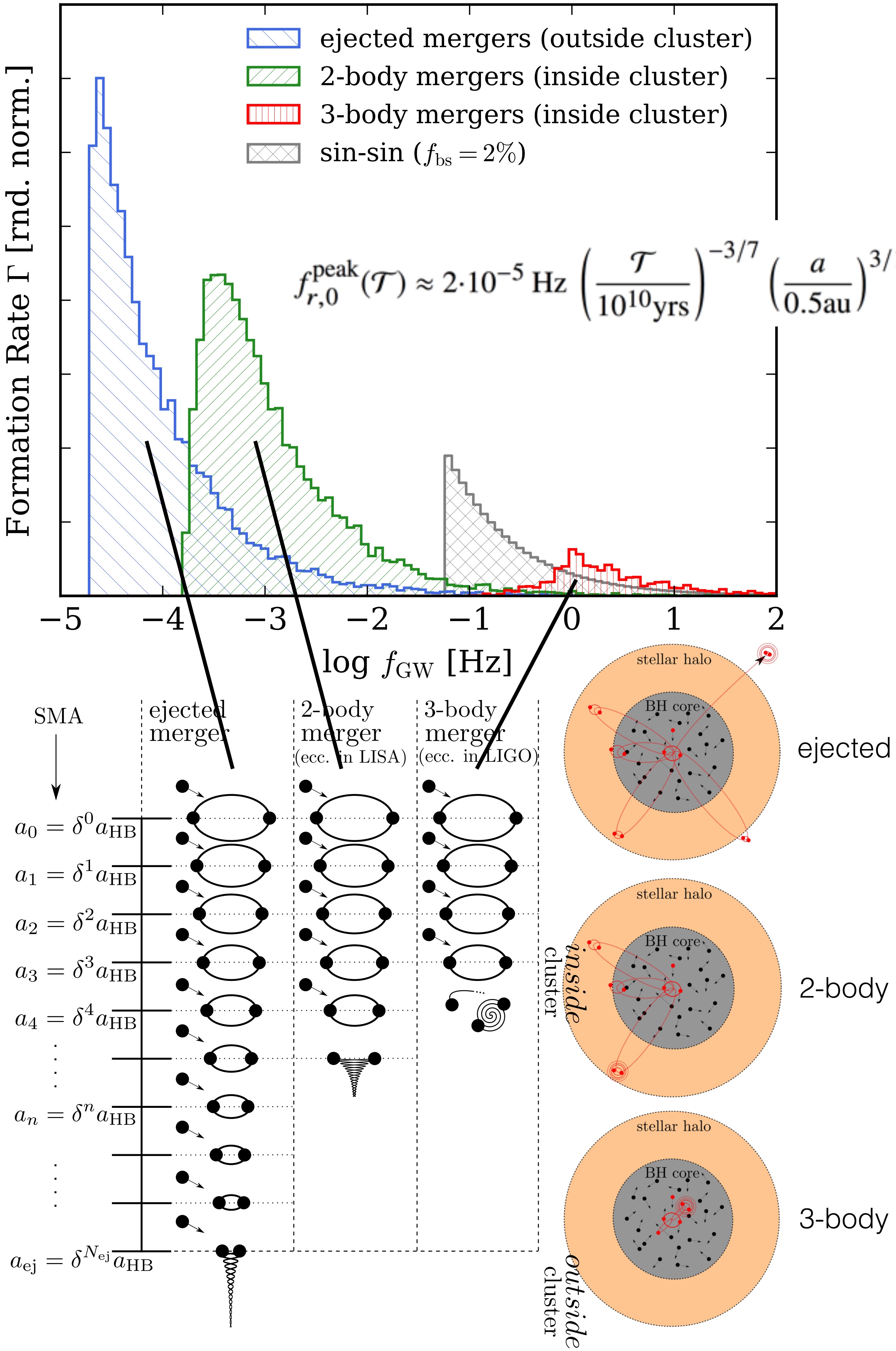
Merger Type: 4-body Merger







Peak Normalizations:



$$f_{r,0}^{\rm peak}(\mathcal{T}) \approx 2{\cdot}10^{-5}\,{\rm Hz} \left(\frac{\mathcal{T}}{10^{10}{\rm yrs}}\right)^{-3/7} \left(\frac{a}{0.5{\rm au}}\right)^{3/14} \left(\frac{m}{30M_\odot}\right)^{-11/14}$$

$$P_i \approx F_i \times \left(\frac{\tau_i(a_{\rm ej})}{t_{\rm GW}^{e=0}(a_{\rm ej})}\right)^{2/7}$$

$$F_{\rm in} \approx (7/10)/(1-\delta) \approx 3$$

$$F_{\rm GW} \approx (7/5)/(1-\delta) \times N_{\rm MS} \approx 120$$

$$a_{\rm ej} \sim 0.5\ {\rm AU} \qquad M \sim 30 M_\odot$$

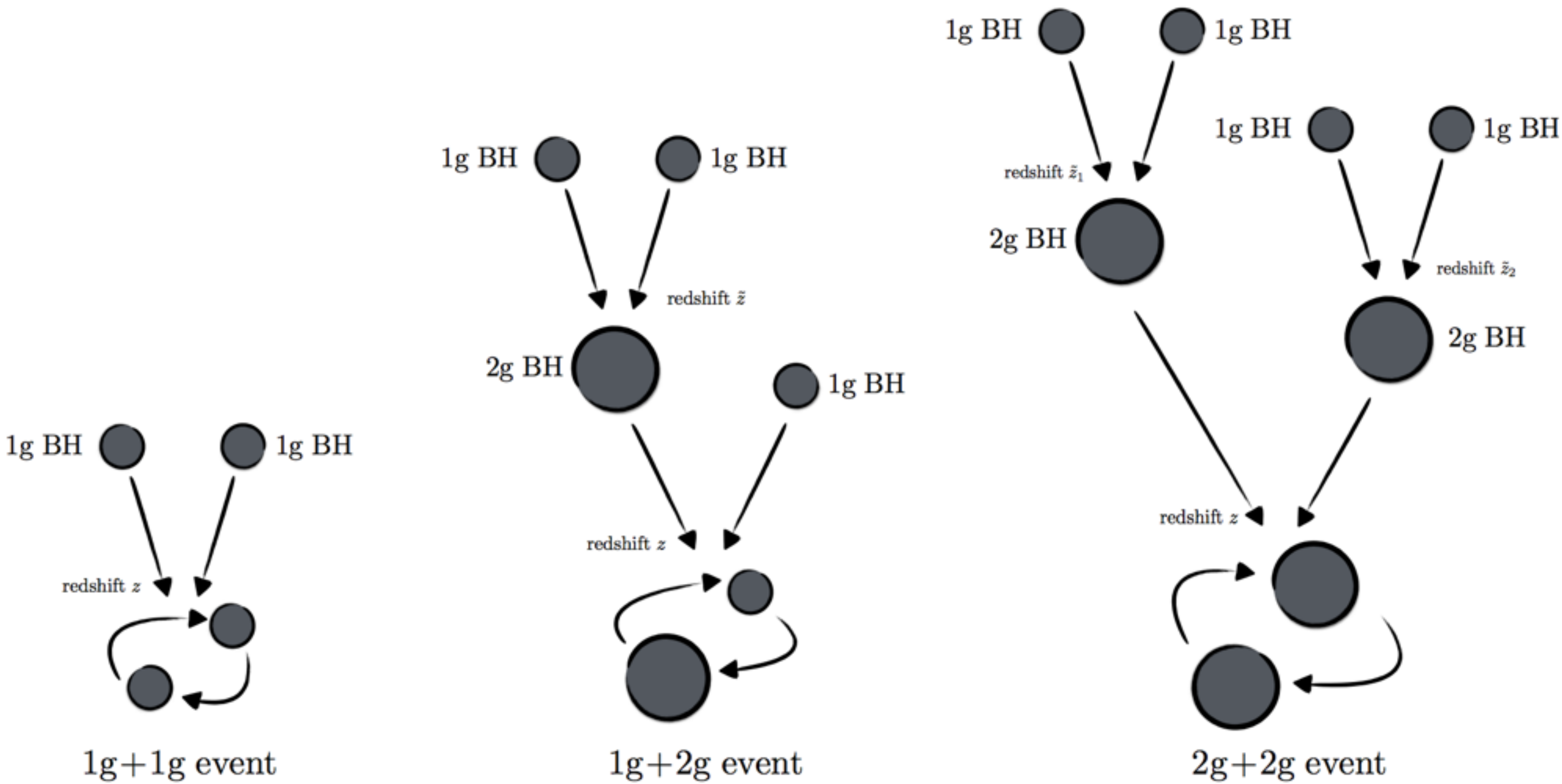
$$\tau_{\rm in} \sim 10^7\ {\rm years} \qquad \tau_{\rm GW} \sim 0.1\ {\rm year}$$

$$P_{\rm in} \approx 0.15 \quad P_{\rm GW} \approx 0.03$$

$$P(t_{\rm GW}(a_{\rm ej}) < T_{\rm H}) \approx 0.35$$

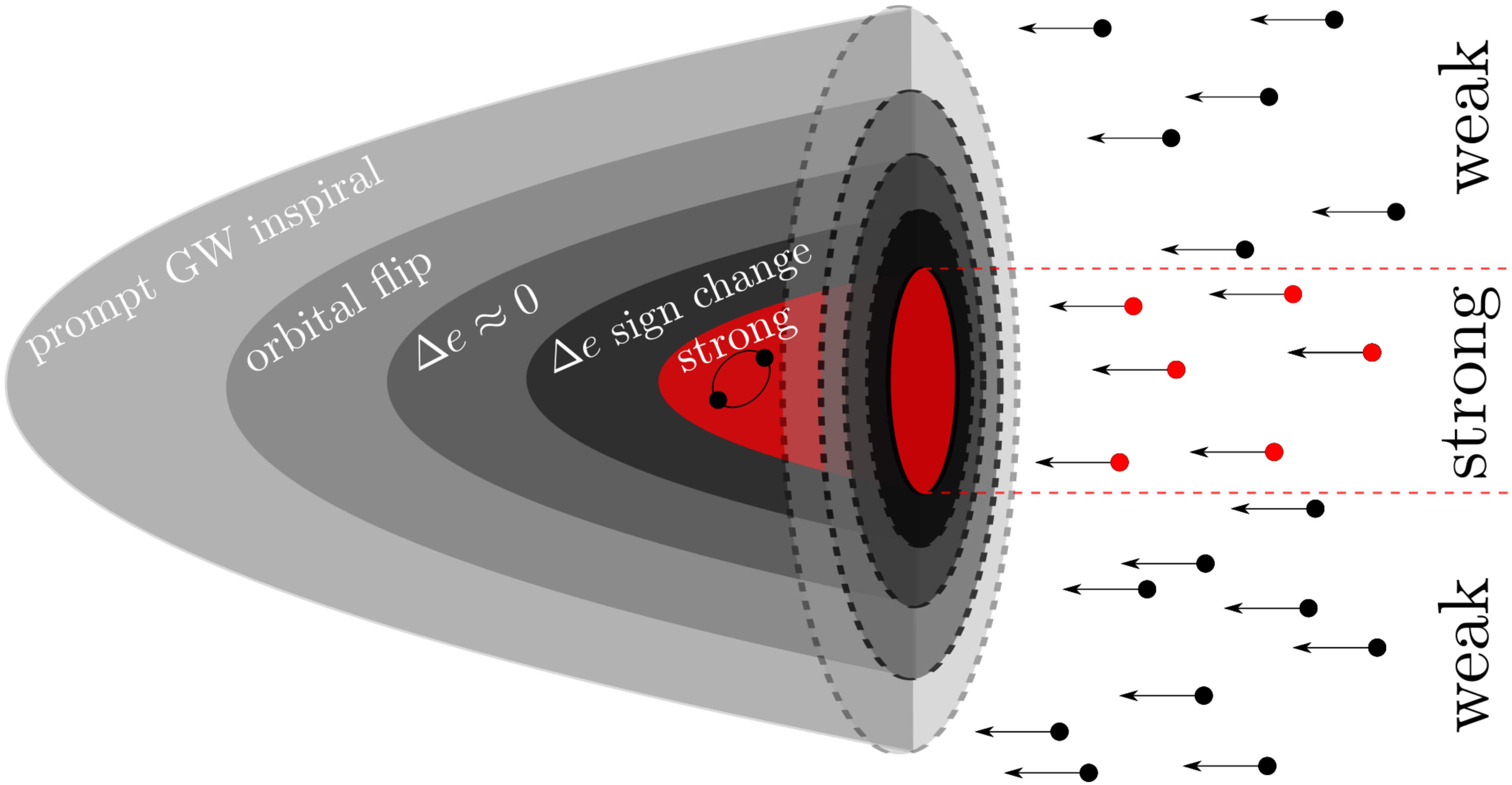
$$0.82 \times 0.35 \approx 0.3$$

start to reach 10% high ecc. LIGO mergers


1g BH
1g BH
redshift z
1g+1g event
1g BH
1g BH
redshift $\tilde{z}$
2g BH
1g BH
redshift z
1g+2g event
1g BH
1g BH
redshift $\tilde{z}_1$
2g BH
1g BH
1g BH
redshift $\tilde{z}_2$
2g BH
redshift z
2g+2g event

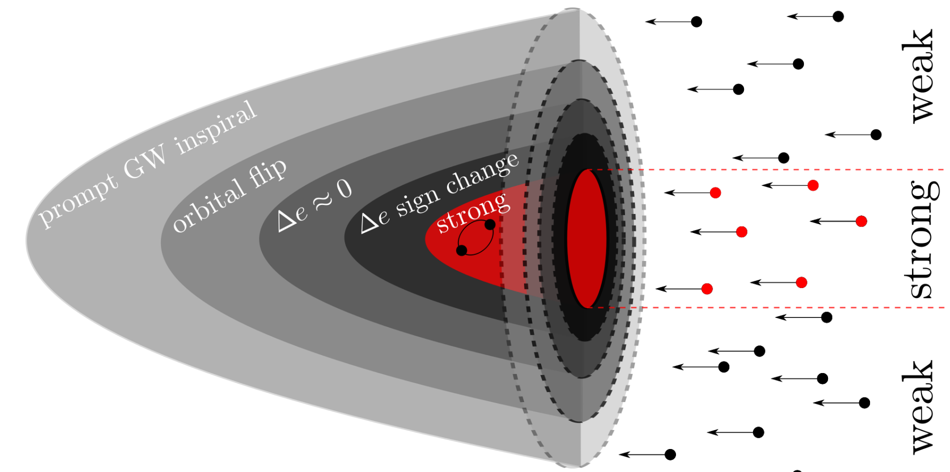
Merger Type: Secular-processes

- work done with Adrian Hamers (IAS)



Merger Type: Secular-processes

Why is this important?

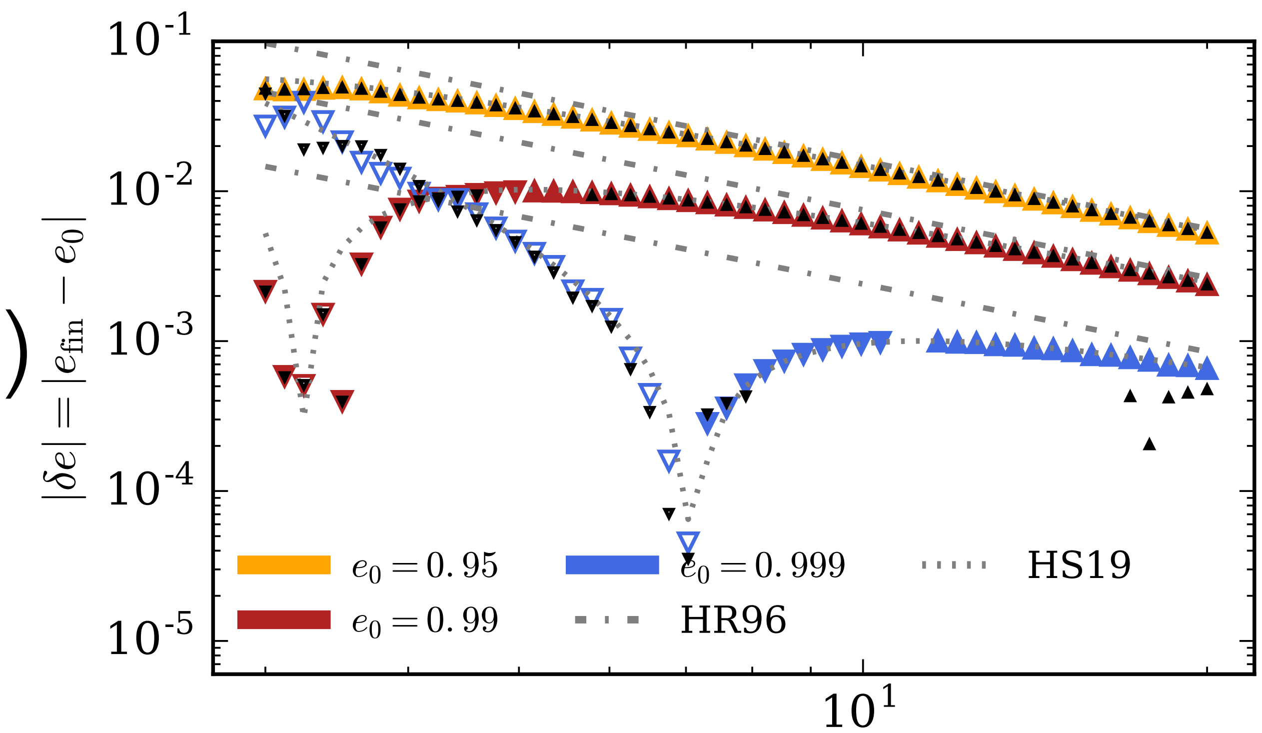


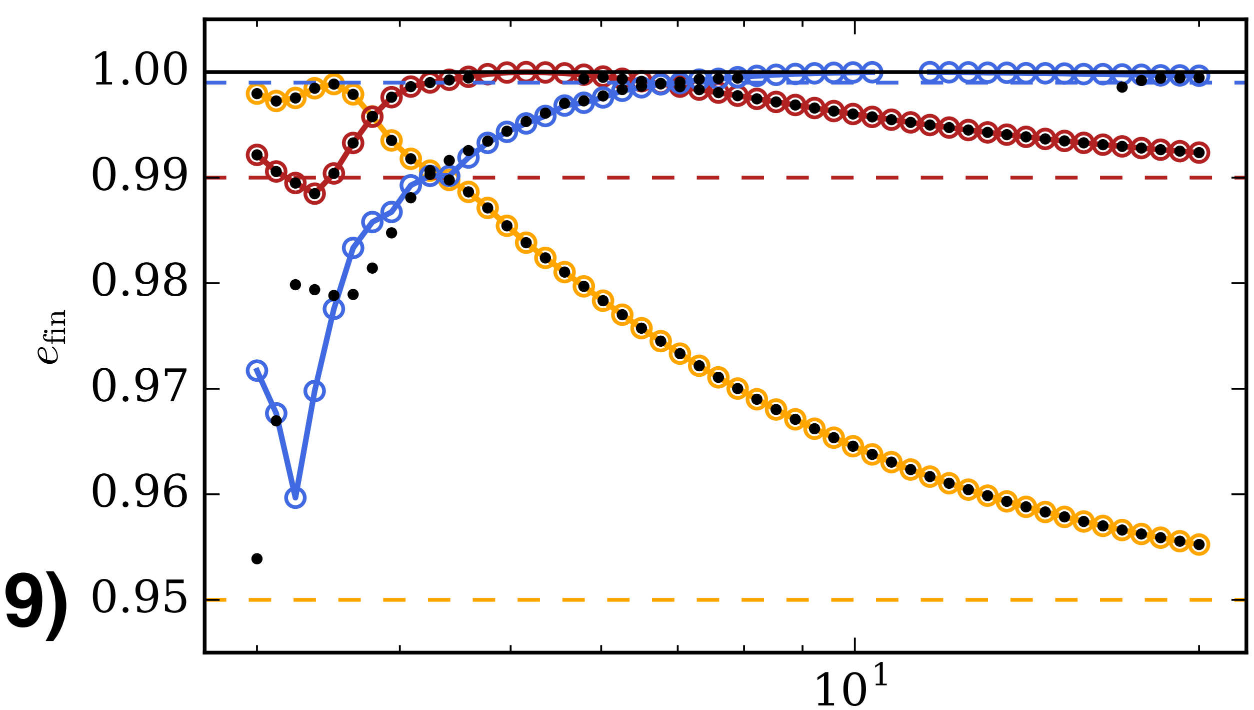
1.order (Heggie, Rasio 96)

$$\delta e = -\frac{15\pi}{16}\left(\frac{2m_3^2 a^3}{M_{123}M_{12}r_p^3}\right)^{1/2} e\sqrt{1-e^2}\sin 2\Omega \sin^2 i$$

2.order 2x(Hamers, Samsing 19)

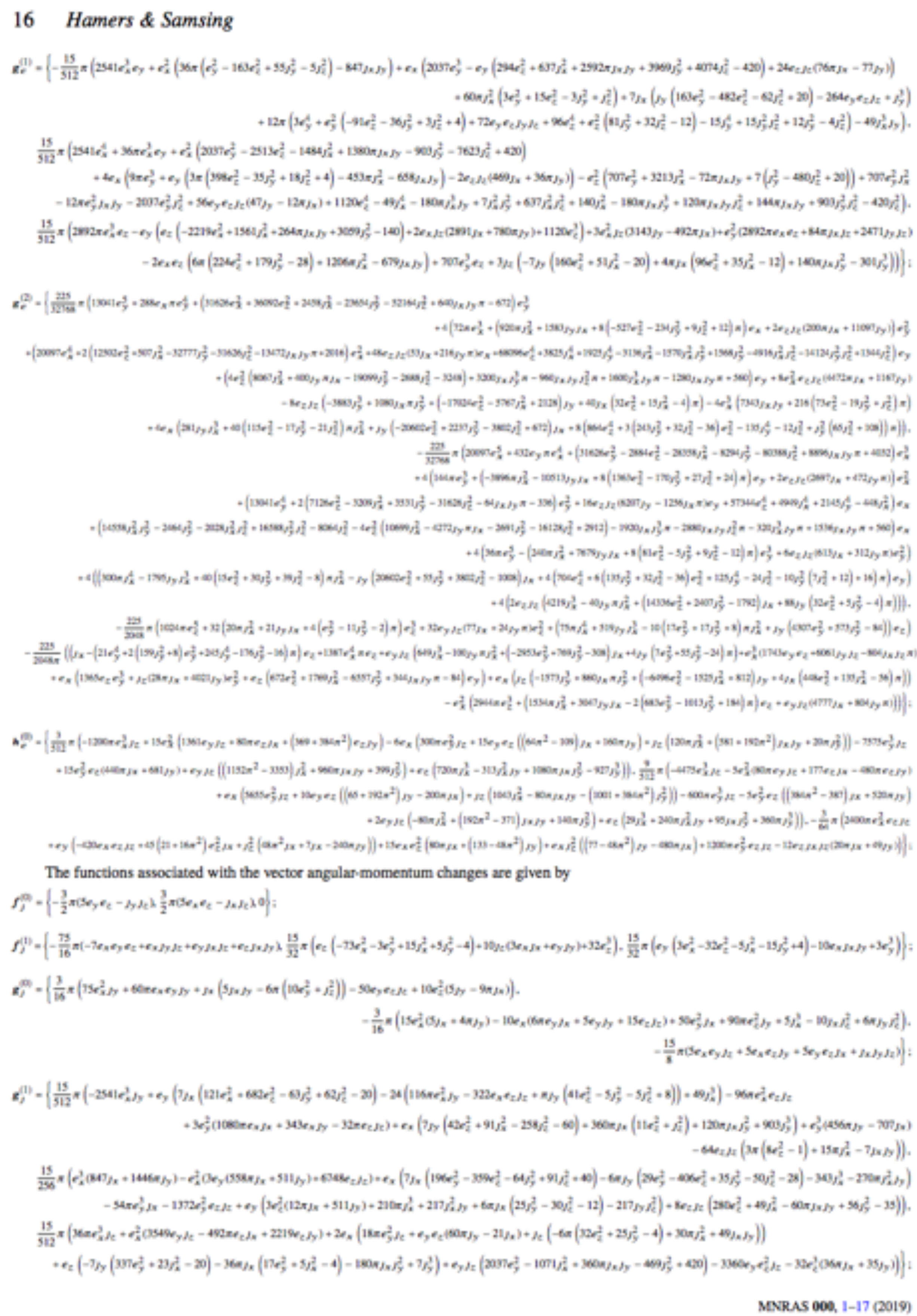
$$\begin{aligned}\Delta e_{\mathrm{SO}} =& \Delta e_{\mathrm{FO}} + \epsilon^2 \frac{3}{512}\pi e_0 \Big[-100\left(1-e_0^2\right)\sin 2\Omega \\ & \left\{(5\cos i + 3\cos 3i)\cos 2\omega + 6\sin i \sin 2i\right\} \\ & + 4\cos 2i \Big\{ 3\pi\left(81e_0^2 - 56\right) - 200\left(1-e_0^2\right) \\ & \cos 2\Omega \sin 2\omega \Big\} + 3\pi \Big\{ 200 e_0^2 \sin^4 i \cos 4\Omega \\ & + 8\left(16e_0^2 + 9\right)\sin^2 2i \cos 2\Omega \\ & + \left(39e_0^2 + 36\right)\cos 4i - 299e_0^2 + 124 \Big\}\Big],\end{aligned}$$





and 1x(Samsing, Hamers, Types 19)

non-parabolic limit…


16 *Hamers & Samsing*

The functions associated with the vector angular-momentum changes are given by

MNRAS 000, 1–17 (2019)

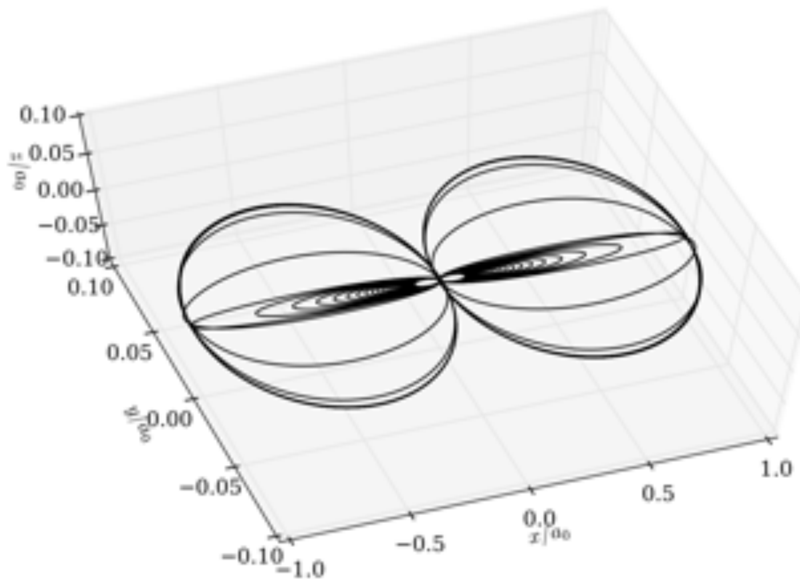
2 *Hamers & Samsing*

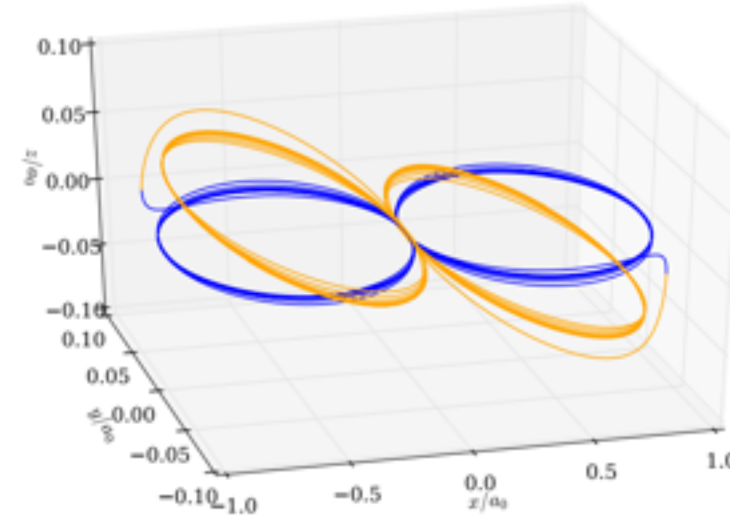
Terms of order	Number of terms in Δe $E = 1$	$E > 1$
ϵ_{SA} (all)	16	60
ϵ_{SA}	2	8
$\epsilon_{\mathrm{SA}}\epsilon_{\mathrm{oct}}$	14	52
ϵ_{SA}^2 (all)	193	55,895
ϵ_{SA}^2	17	1,871
$\epsilon_{\mathrm{SA}}^2\epsilon_{\mathrm{oct}}$	60	16,035
$\epsilon_{\mathrm{SA}}^2\epsilon_{\mathrm{oct}}^2$	116	37,989
ϵ_{SA}^3 (all)	1,146	2,931,541
ϵ_{SA}^3	54	38,366
$\epsilon_{\mathrm{SA}}^3\epsilon_{\mathrm{oct}}$	175	289,496
$\epsilon_{\mathrm{SA}}^3\epsilon_{\mathrm{oct}}^2$	311	856,072
$\epsilon_{\mathrm{SA}}^3\epsilon_{\mathrm{oct}}^3$	606	1,747,607

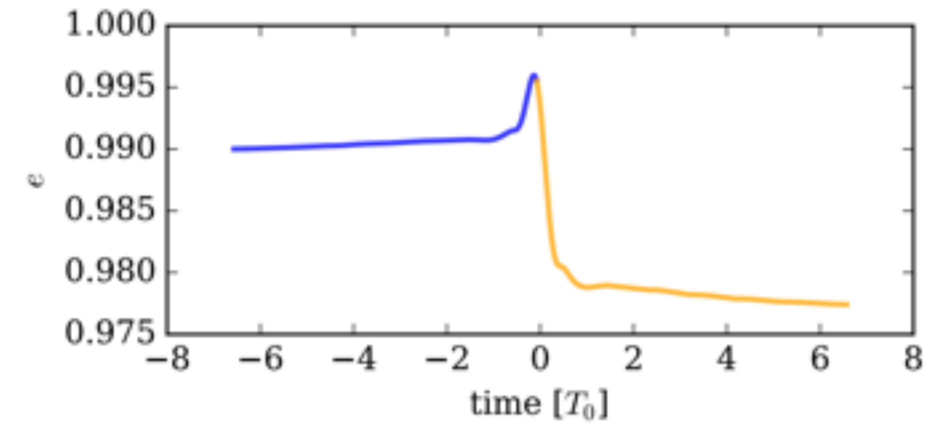
Merger Type: Secular-processes

PN effects?

2.5

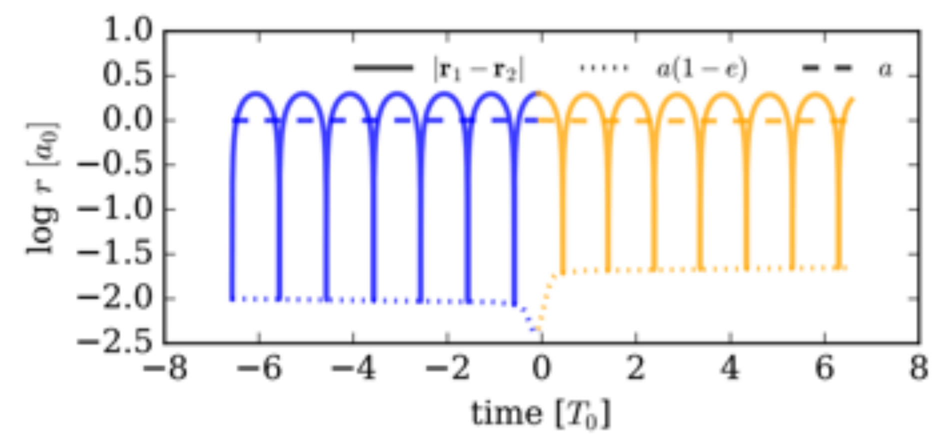




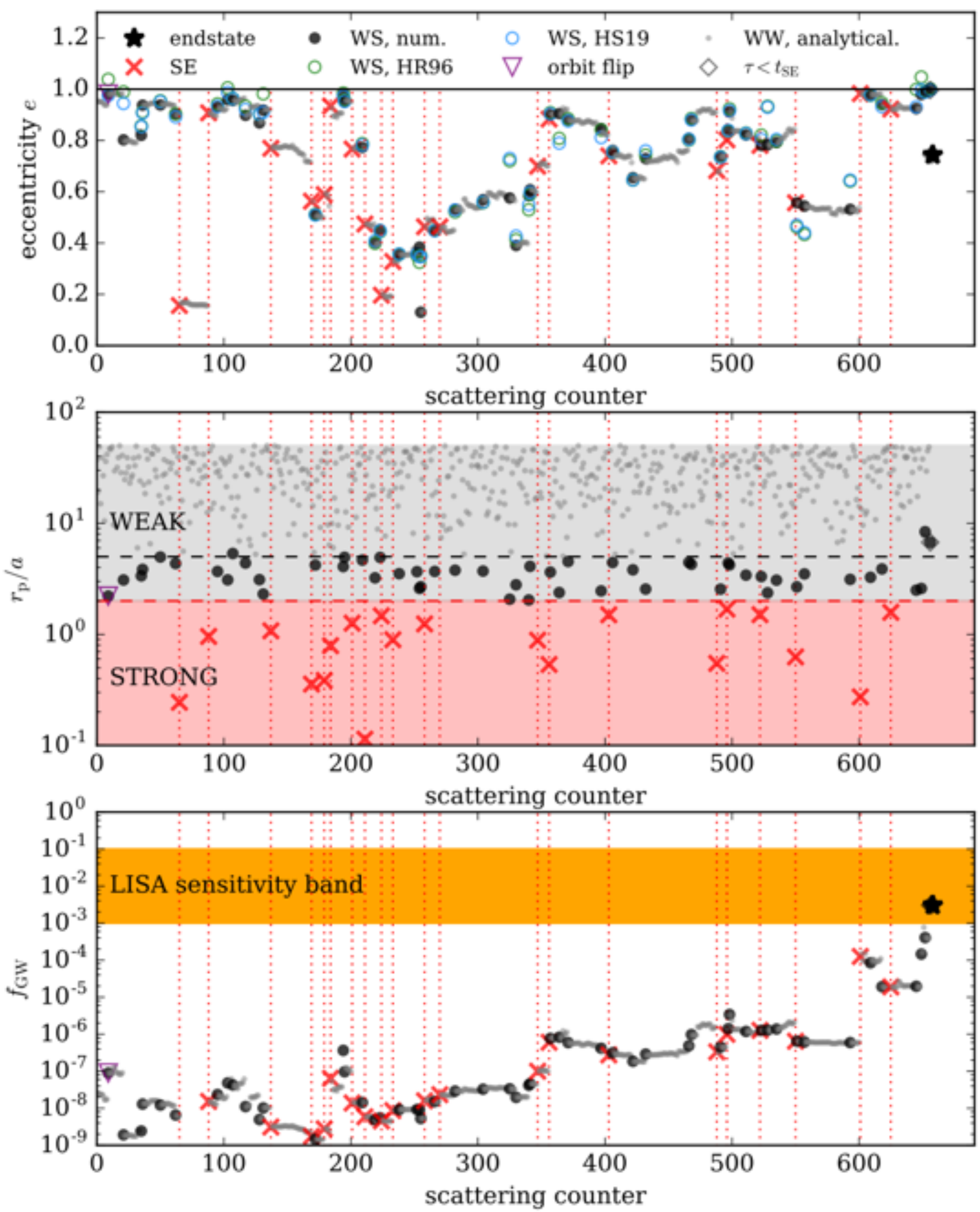


1,2

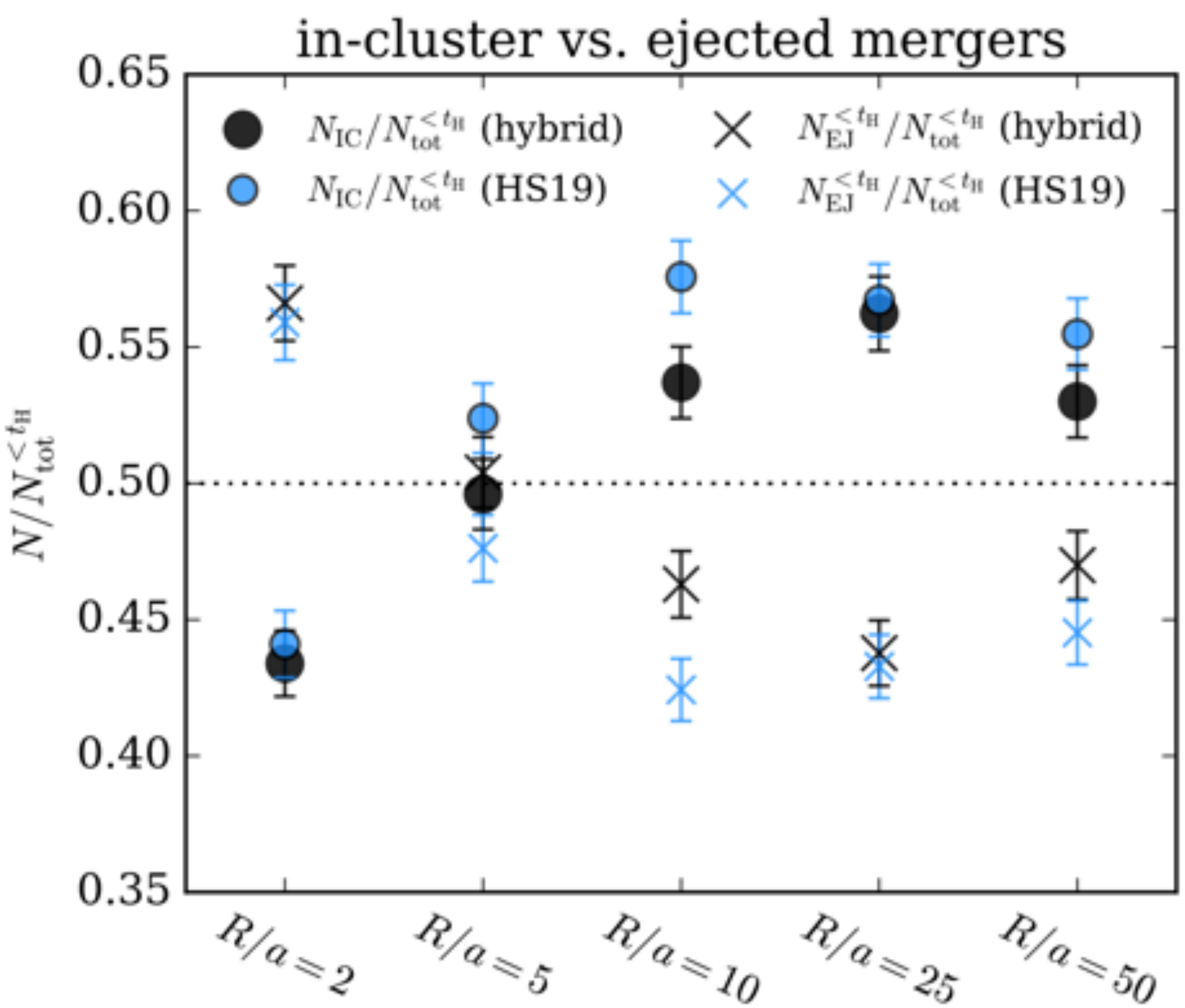
$$\frac{r_p}{a_0} \gtrsim \frac{a_0^{2/3}}{\mathscr{R}_m^{2/3}}(1-e_0^2)^{2/3}$$
$$\gtrsim 10^3 \times \left(\frac{a_0}{0.5\mathrm{AU}}\right)^{2/3}\left(\frac{m}{20M_\odot}\right)^{-2/3}\left(1-(e_0/0.99)^2\right)^{2/3}$$

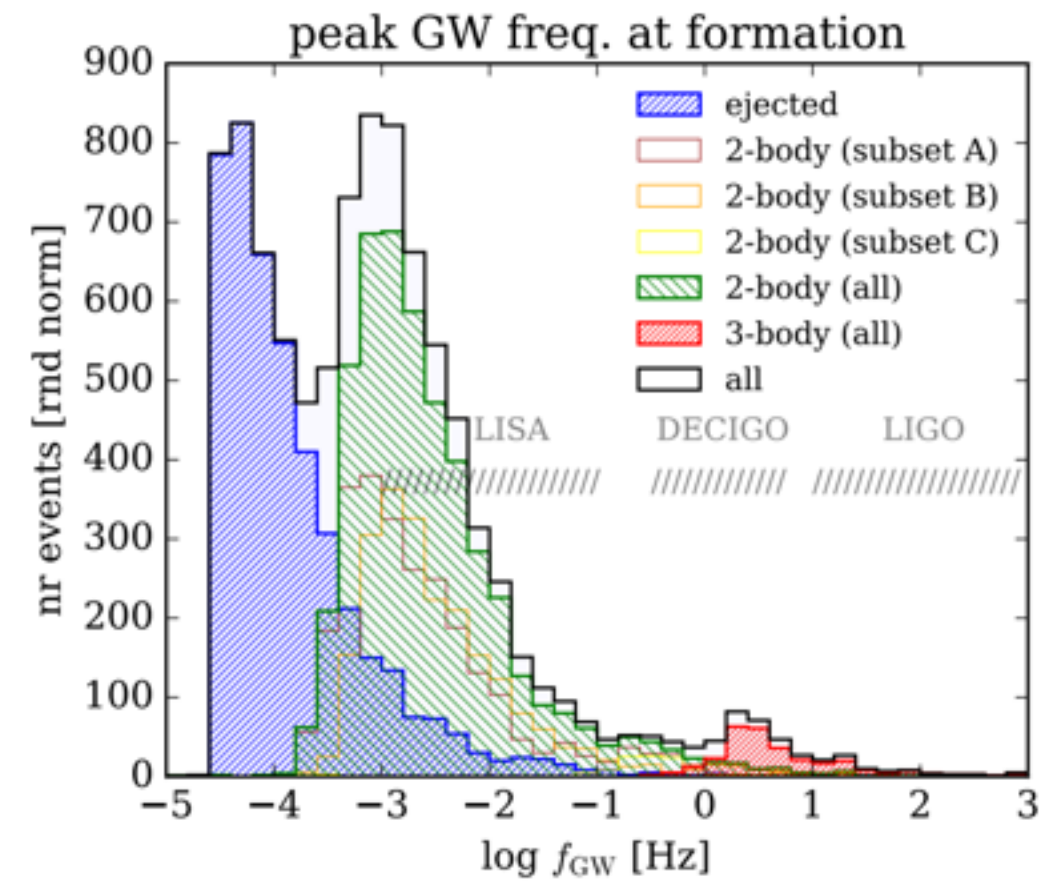


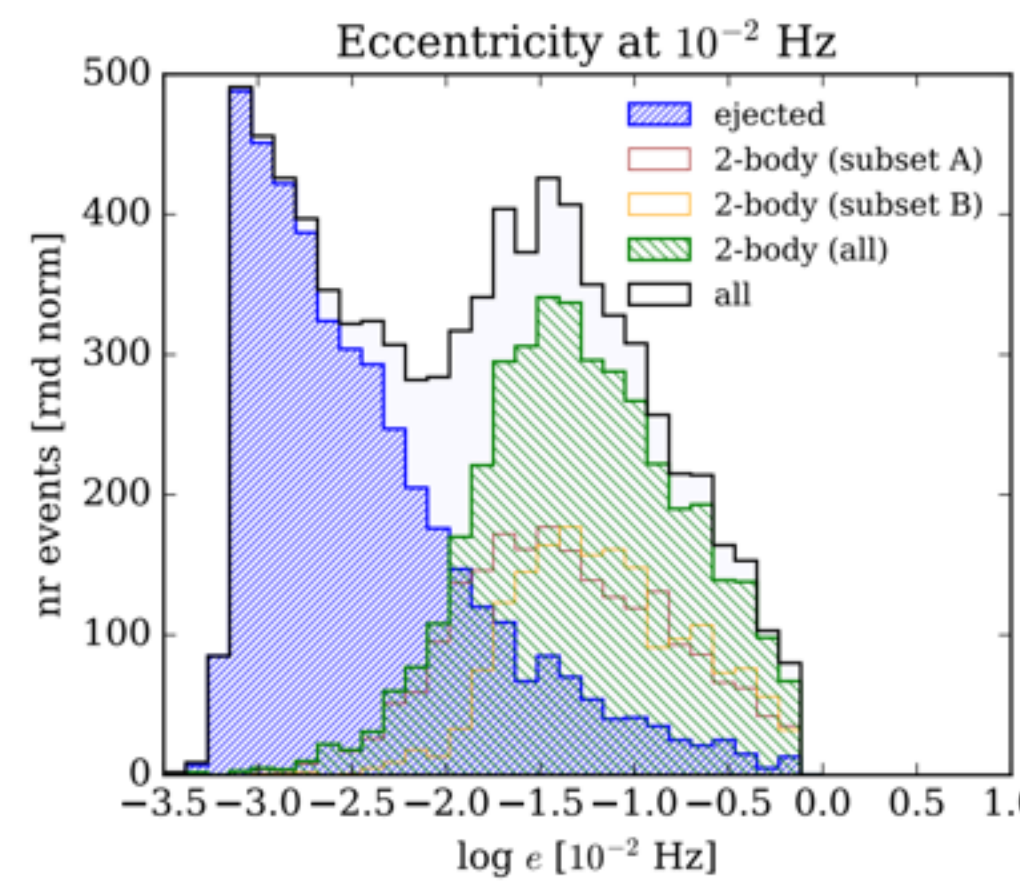
Merger Type: Secular-processes



Results from our MC code

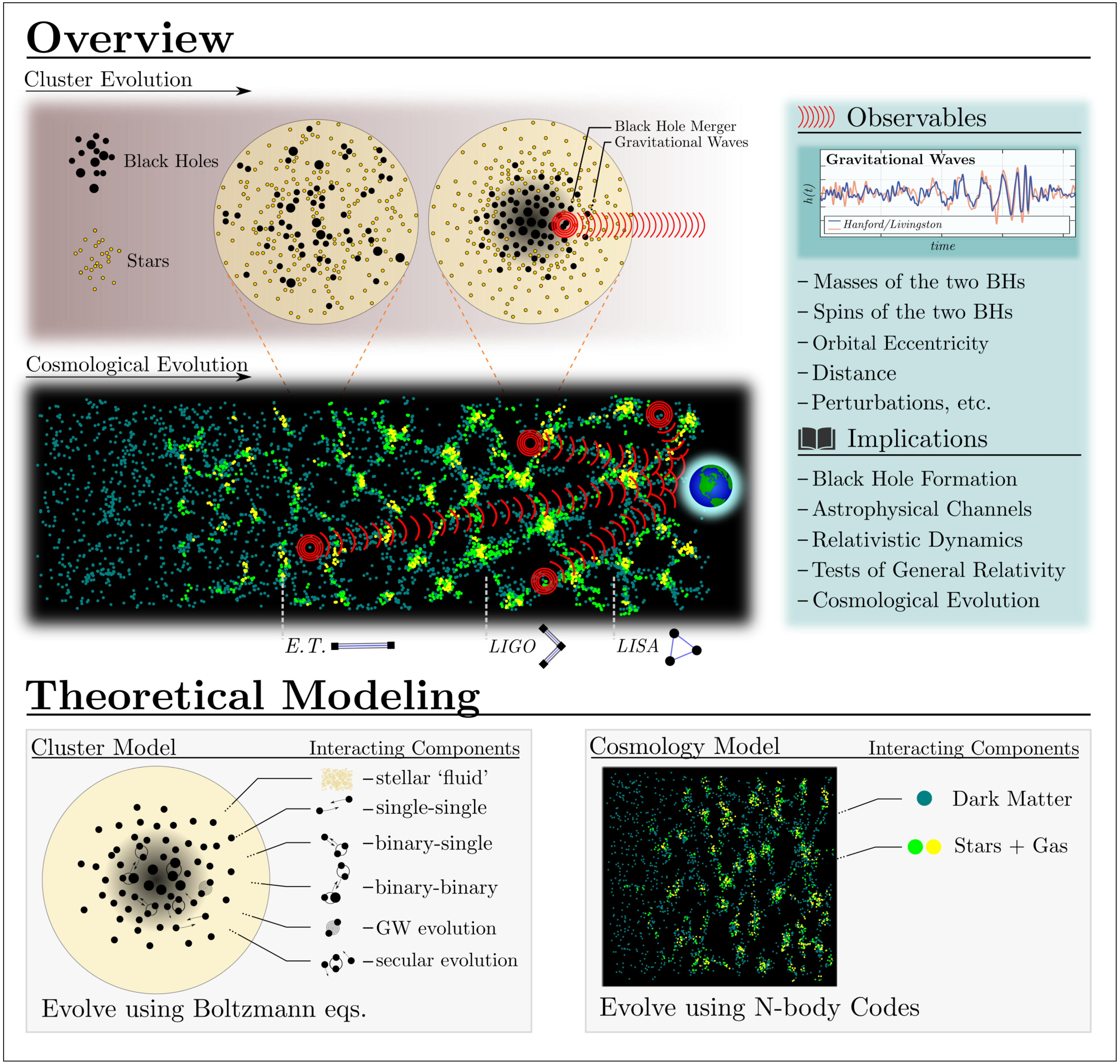






more BBHs are driven to merger!

Future



Overview
Cluster Evolution
Black Holes
Stars
Black Hole Merger
Gravitational Waves
Cosmological Evolution
E.T.
LIGO
LISA
Observables
Gravitational Waves
h(t)
Hanford/Livingston
time
– Masses of the two BHs
– Spins of the two BHs
– Orbital Eccentricity
– Distance
– Perturbations, etc.
Implications
– Black Hole Formation
– Astrophysical Channels
– Relativistic Dynamics
– Tests of General Relativity
– Cosmological Evolution
Theoretical Modeling
Cluster Model
Interacting Components
– stellar 'fluid'
– single-single
– binary-single
– binary-binary
– GW evolution
– secular evolution
Evolve using Boltzmann eqs.
Cosmology Model
Interacting Components
Dark Matter
Stars + Gas
Evolve using N-body Codes


THANK YOU