블랙홀 쌍성의 형성과 진화 …

배영복 (중앙대)
2024 수치상대론 및 중력파여름학교
2024. 08. 01

Introduction

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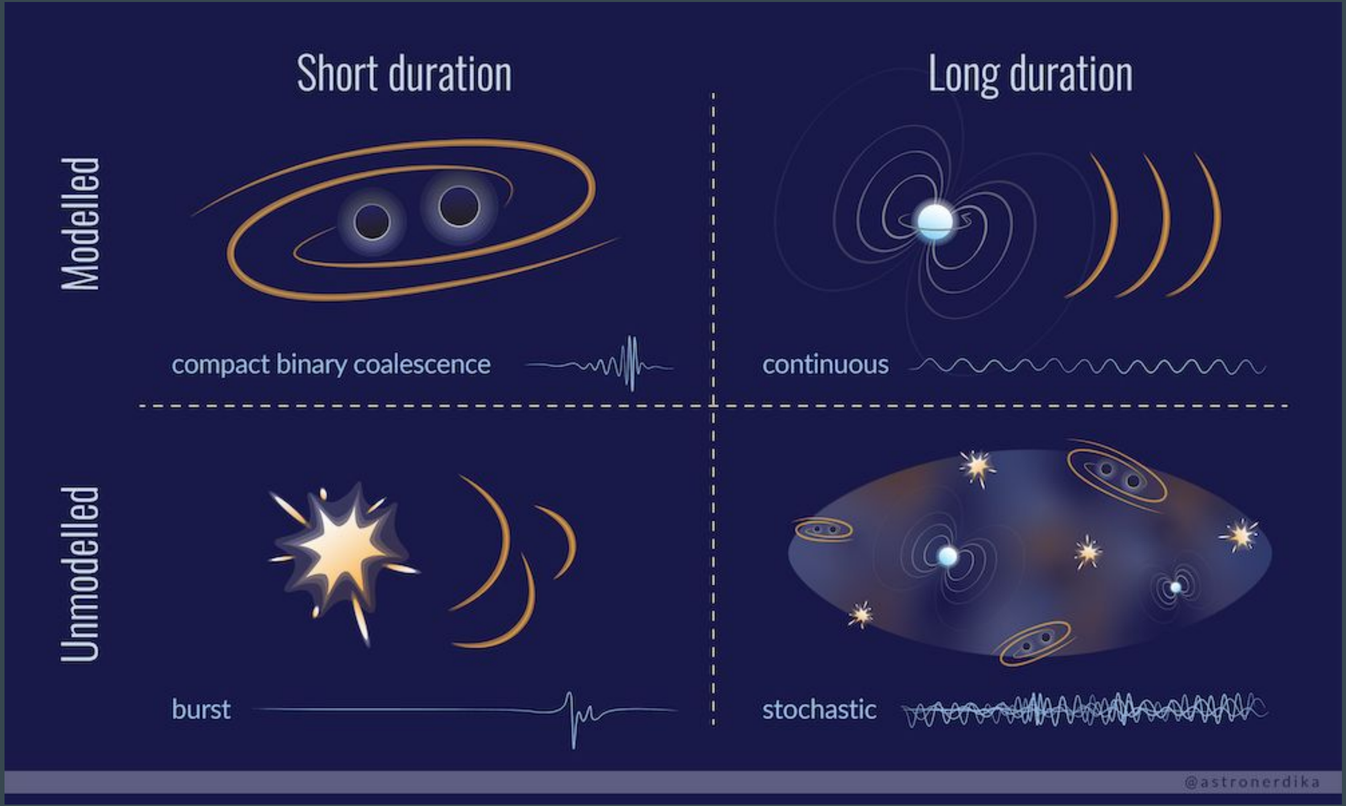
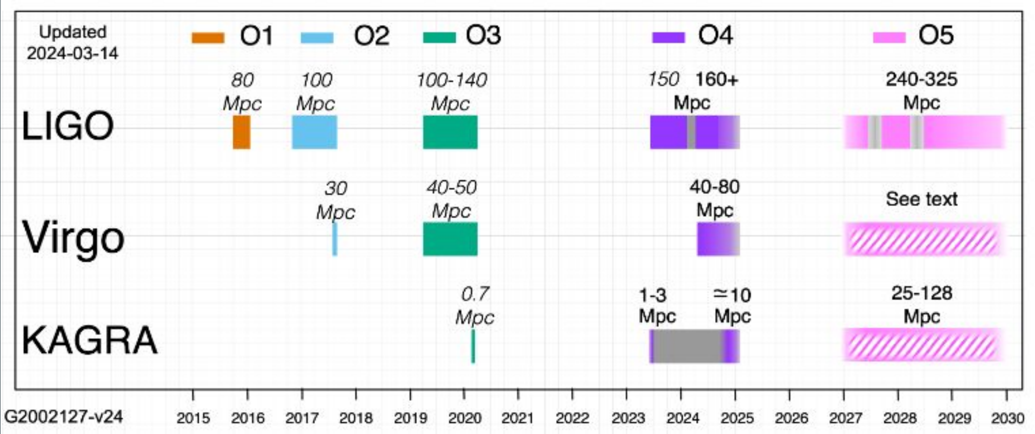
GW sources



Credit:
Shanika Galaudage

Observation of Gravitational Waves (GWs)

- GWTC-1 (Gravitational-Wave Transient Catalog)
  - O1 (Sep. 12, 2015 - Jan. 19, 2016)
    - First detection of GWs
  - O2 (Nov. 30, 2016 - Aug. 25, 2017)
    - First detection of a binary neutron star inspiral
  - 11 GW sources
- GWTC-2, GWTC-2.1
  - O3a (Apr. 01, 2019 - Oct. 01, 2019)
  - 44 GW sources
- GWTC-3
  - O3b (Nov. 01, 2019 - Mar. 27, 2020)
  - 35 GW sources
- GWTC-4 ?
  - O4a (May. 24, 2023 - Jan. 16, 2024)
  - O4b (Apr. 10, 2024 - Jun. 9, 2025)
  - Hundreds of GW sources?



https://observing.docs.ligo.org/plan/

Name	Version	Release	GPS	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)
GW200322_091133	v1	GWTC-3-confident	1268903511.3	38^{+130}_{-22}	$11.3^{+24.3}_{-6.0}$	$4.5^{+2.7}_{-3.0}$	3500^{+12500}_{-2200}	$0.27^{+0.54}_{-0.58}$	50^{+132}_{-22}
GW200316_215756	v1	GWTC-3-confident	1268431094.1	$13.1^{+10.2}_{-2.9}$	$7.8^{+2.0}_{-2.9}$	$10.3^{+0.4}_{-0.7}$	1120^{+480}_{-440}	$0.13^{+0.27}_{-0.10}$	$21.2^{+7.2}_{-2.0}$
GW200311_115853	v1	GWTC-3-confident	1267963151.3	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$	$17.8^{+0.2}_{-0.2}$	1170^{+280}_{-400}	$-0.02^{+0.16}_{-0.20}$	$61.9^{+5.3}_{-4.2}$
GW200308_173609	v1	GWTC-3-confident	1267724187.7	60^{+166}_{-29}	24^{+36}_{-13}	$4.7^{+2.5}_{-2.9}$	7100^{+13900}_{-4400}	$0.16^{+0.58}_{-0.49}$	$92.0^{+169.0}_{-48.0}$
GW200306_093714	v1	GWTC-3-confident	1267522652.1	$28.3^{+17.1}_{-7.7}$	$14.8^{+6.5}_{-6.4}$	$7.8^{+0.4}_{-0.6}$	2100^{+1700}_{-1100}	$0.32^{+0.28}_{-0.46}$	$43.9^{+11.8}_{-7.5}$
GW200302_015811	v1	GWTC-3-confident	1267149509.5	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$	$10.8^{+0.3}_{-0.4}$	1480^{+1020}_{-700}	$0.01^{+0.25}_{-0.26}$	$57.8^{+9.6}_{-6.9}$
GW200225_060421	v1	GWTC-3-confident	1266645879.3	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$	$12.5^{+0.3}_{-0.4}$	1150^{+510}_{-530}	$-0.12^{+0.17}_{-0.28}$	$33.5^{+3.6}_{-3.0}$
GW200224_222234	v1	GWTC-3-confident	1266618172.4	$40.0^{+6.7}_{-4.5}$	$32.7^{+4.8}_{-7.2}$	$20.0^{+0.2}_{-0.2}$	1710^{+500}_{-650}	$0.10^{+0.15}_{-0.16}$	$72.3^{+7.2}_{-5.3}$
GW200220_124850	v1	GWTC-3-confident	1266238148.1	$38.9^{+14.1}_{-8.6}$	$27.9^{+9.2}_{-9.0}$	$8.5^{+0.3}_{-0.5}$	4000^{+2800}_{-2200}	$-0.07^{+0.27}_{-0.33}$	67^{+17}_{-12}
GW200220_061928	v1	GWTC-3-confident	1266214786.7	87^{+40}_{-23}	61^{+26}_{-25}	$7.2^{+0.4}_{-0.7}$	6000^{+4800}_{-3100}	$0.06^{+0.40}_{-0.38}$	148^{+55}_{-33}
GW200219_094415	v1	GWTC-3-confident	1266140673.1	$37.5^{+10.1}_{-6.9}$	$27.9^{+7.4}_{-8.4}$	$10.7^{+0.3}_{-0.5}$	3400^{+1700}_{-1500}	$-0.08^{+0.23}_{-0.29}$	$65.0^{+12.6}_{-8.2}$
GW200216_220804	v1	GWTC-3-confident	1265926102.8	51^{+22}_{-13}	30^{+14}_{-16}	$8.1^{+0.4}_{-0.5}$	3800^{+3000}_{-2000}	$0.10^{+0.34}_{-0.36}$	81^{+20}_{-14}
GW200210_092254	v1	GWTC-3-confident	1265361792.9	$24.1^{+7.5}_{-4.6}$	$2.83^{+0.47}_{-0.42}$	$8.4^{+0.5}_{-0.7}$	940^{+430}_{-340}	$0.02^{+0.22}_{-0.21}$	$27.0^{+7.1}_{-4.3}$
GW200209_085452	v1	GWTC-3-confident	1265273710.1	$35.6^{+10.5}_{-6.8}$	$27.1^{+7.8}_{-7.8}$	$9.6^{+0.4}_{-0.5}$	3400^{+1900}_{-1800}	$-0.12^{+0.24}_{-0.30}$	$62.6^{+13.9}_{-9.4}$

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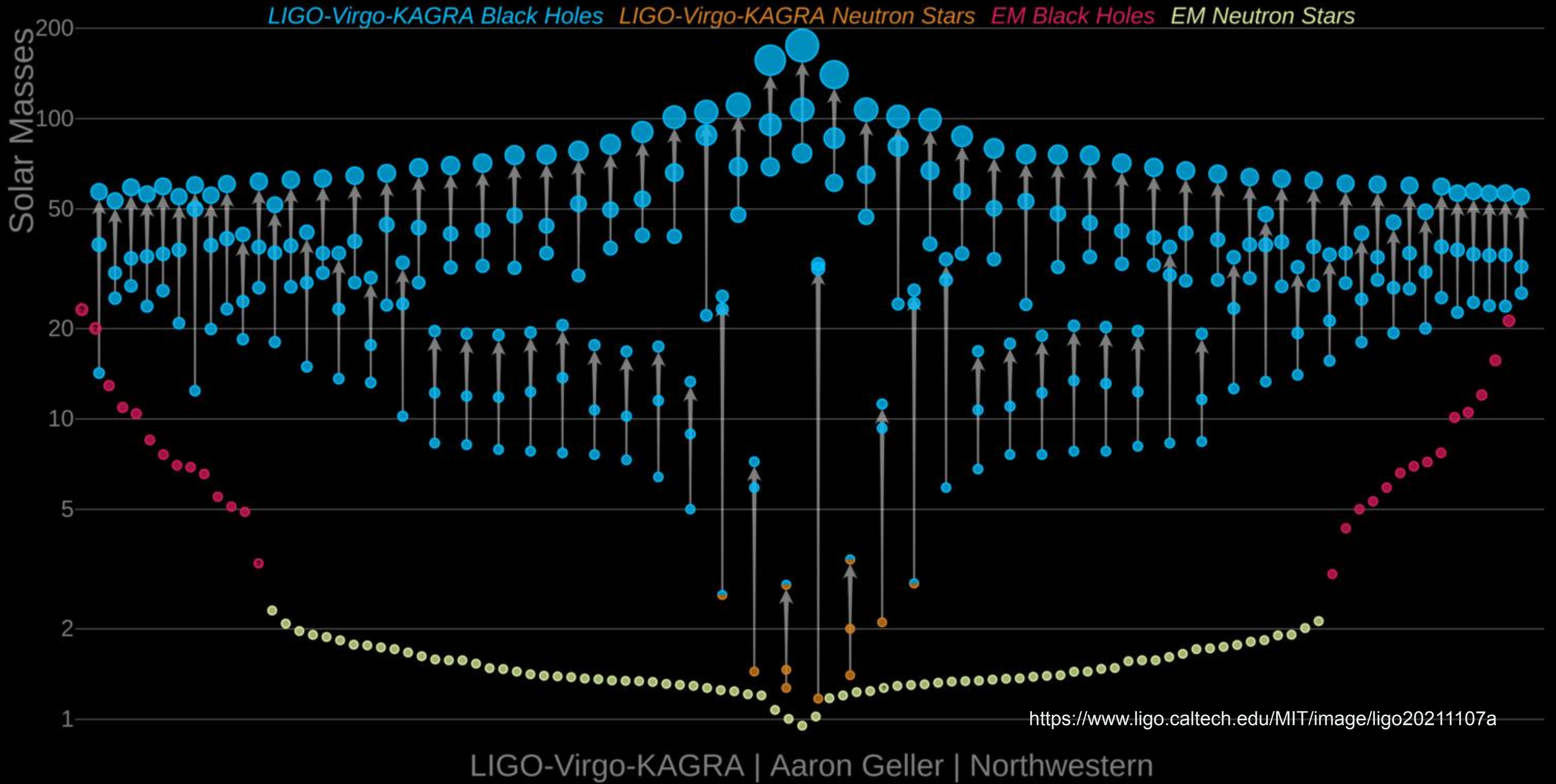
https://gwosc.org/eventapi/html/GWTC/

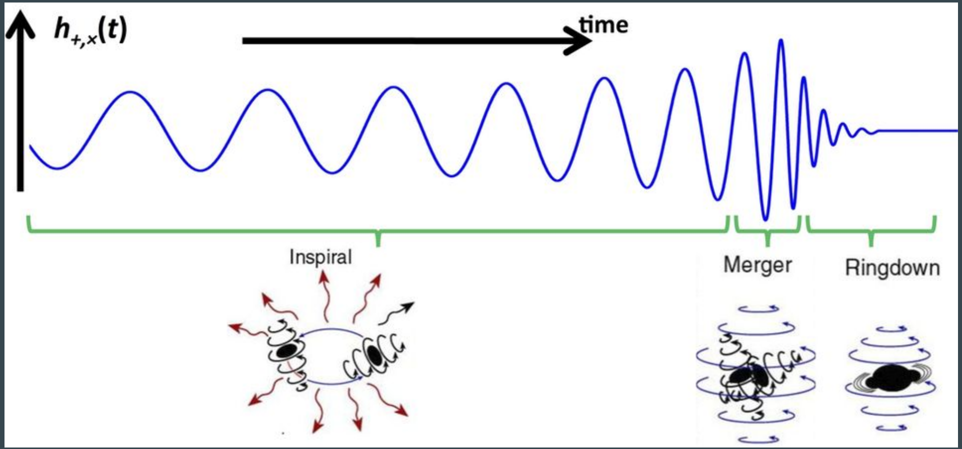
Masses in the Stellar Graveyard



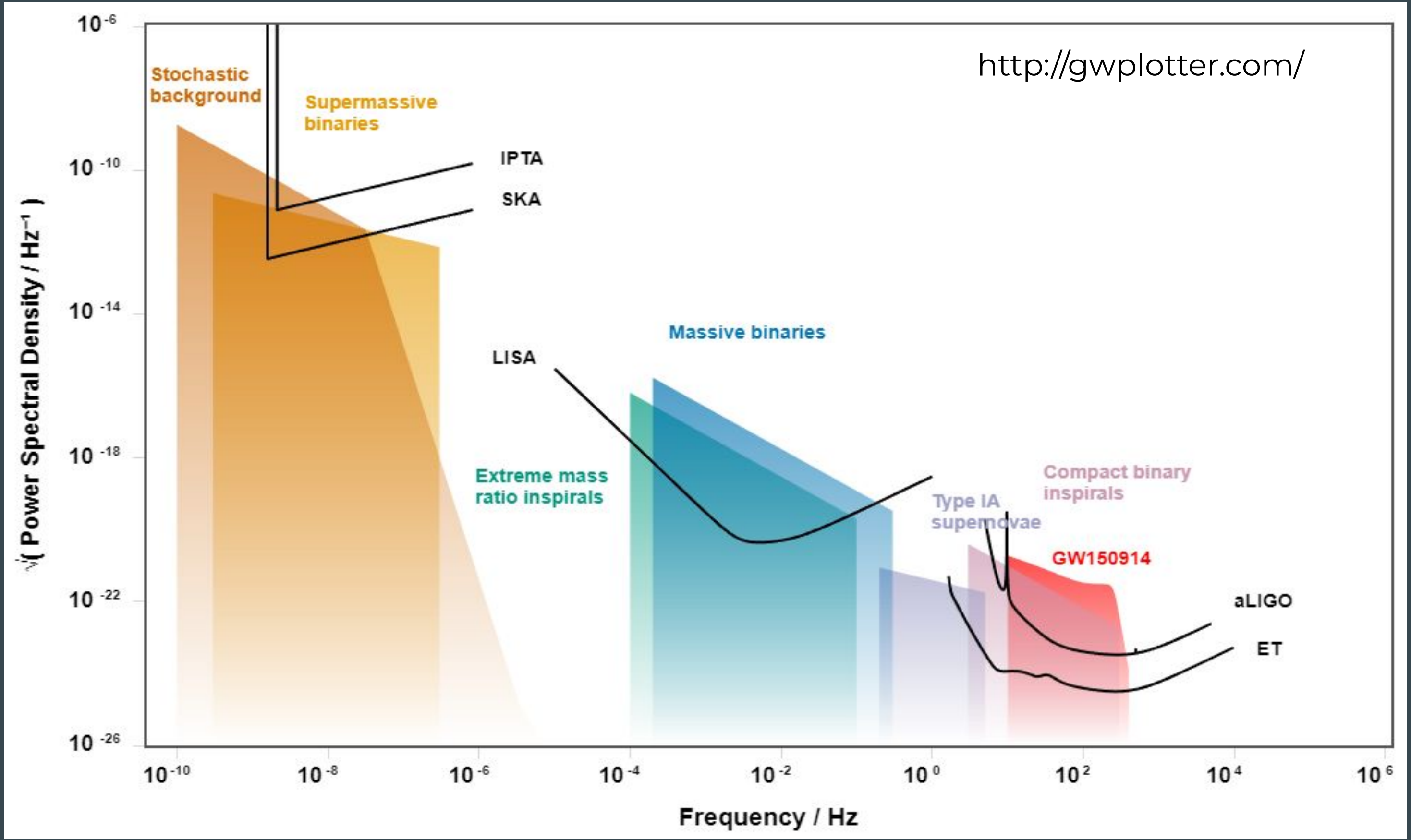
https://www.ligo.caltech.edu/MIT/image/ligo20211107a

Binary black holes (BBHs)

- More than 90% of GW sources ever detected
- Strong GW signal
- Detectable frequency for current interferometric GW detectors
- Predictable waveforms
- Coalescence
  - Inspiral - Merger - Ringdown



M. Favata/SXS/K. Thorne

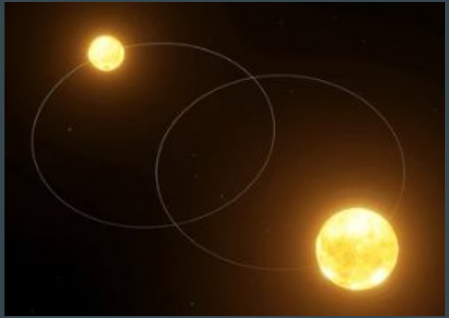


Supermassive BH	Intermediate mass BH	Stellar mass BH	Neutron star, Primordial BH?

Formation

Formation of BBH

- Massive binary star → Binary black hole



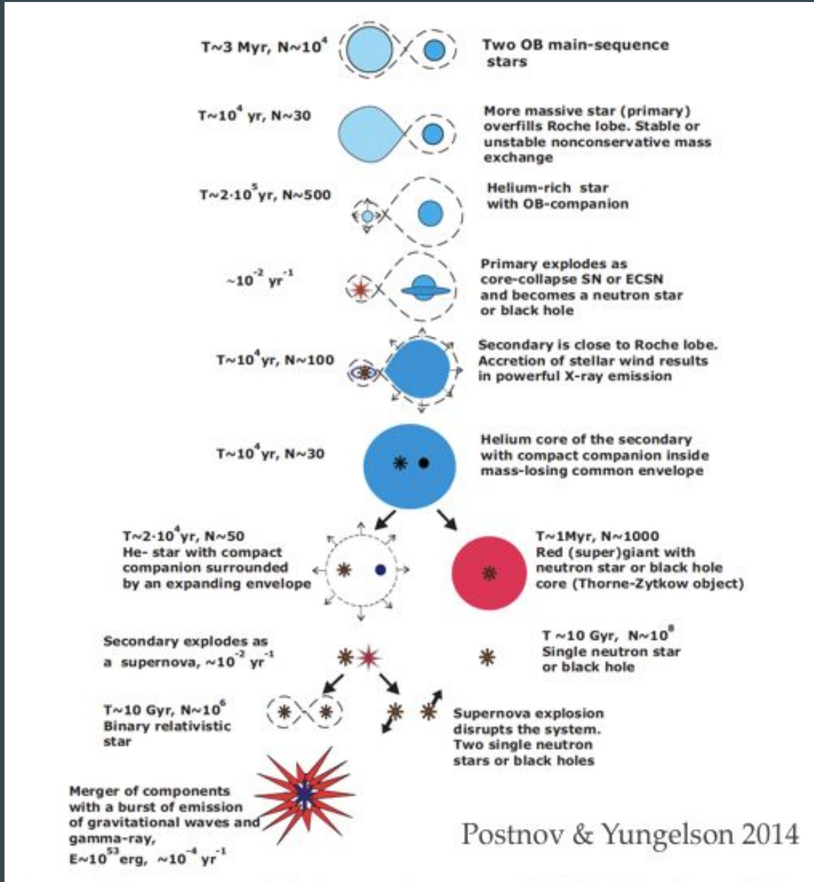


Figure 7: Evolutionary scenario for the formation of neutron stars or black holes in close binaries. T is the typical time scale of an evolutionary stage, N is the estimated number of objects in the given evolutionary stage.

Formation of BBH

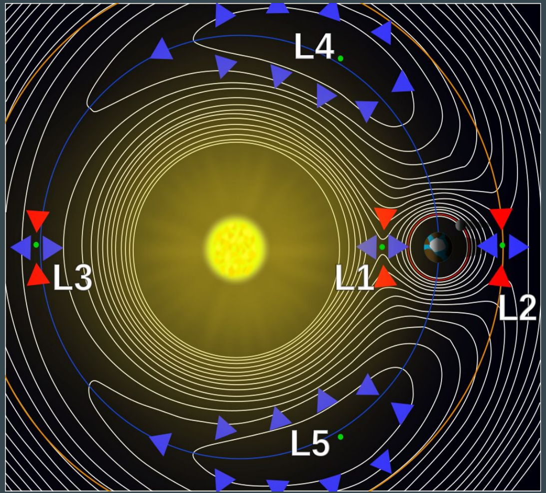
- Dynamical evolution of star cluster
  - Self-gravitating system
  - Core collapse
  - Mass segregation
- Dynamical formation of BBH
  - Three-body process
  - Dynamical capture

M80 (NGC 6093)
NASA, The Hubble Heritage Team, STScI, AURA - Great Images in NASA Description

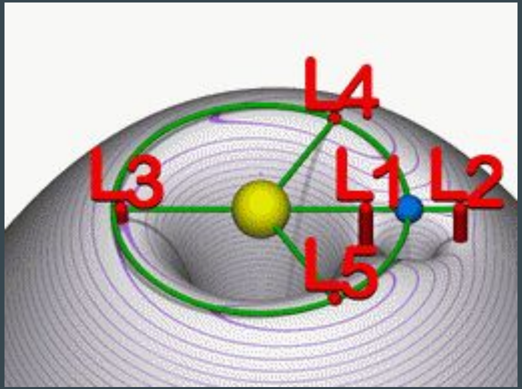
Nuclear star cluster of Milky Way
Stefan Gillessen, Reinhard Genzel, Frank Eisenhauer - http://www.eso.org/public/outreach/press-rel/pr-2008/pr-46-08.html

Three-body problem

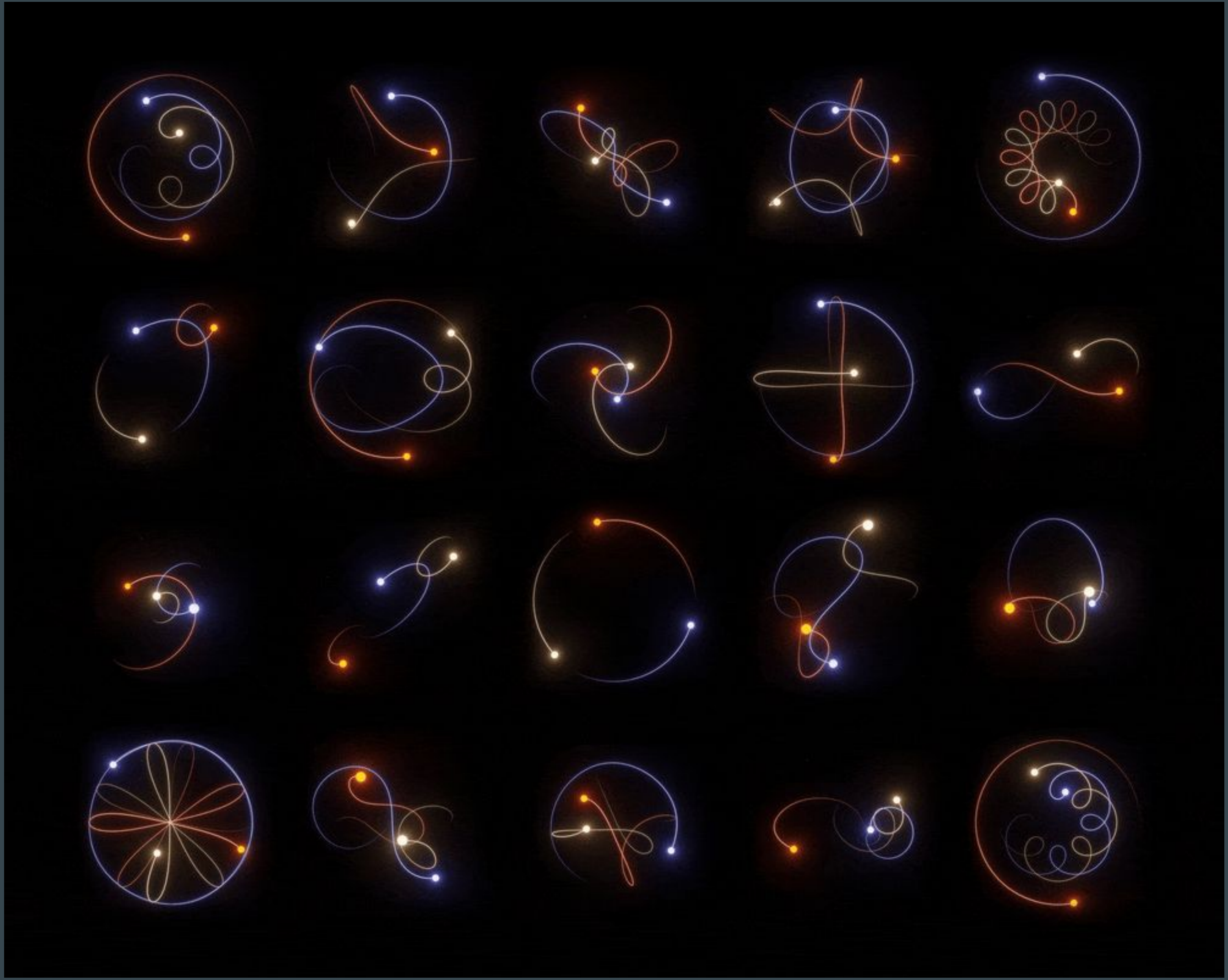
- No general closed-form solution exists, generally chaotic.
  - Series solution by Sundman (1912)
- Restricted three-body problem
  - one negligible mass under two massive bodies
  - Lagrange points
- Special case solutions
  - Euler's collinear solution, Figure-eight shape, ...
- Numerical methods are required in general.



https://en.wikipedia.org/wiki/Lagrange_point#/media/File:Lagrange_points2.svg



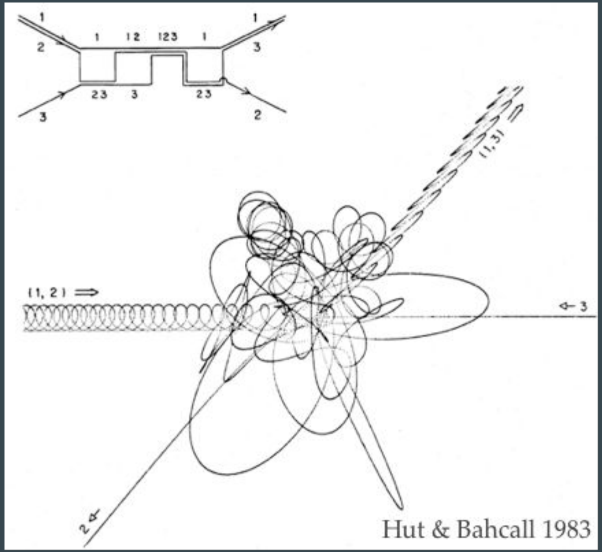
https://en.wikipedia.org/wiki/File:Lagrangian_points_equipotential.gif



https://en.wikipedia.org/wiki/Three-body_problem#/media/File:5_4_800_36_downscaled.gif

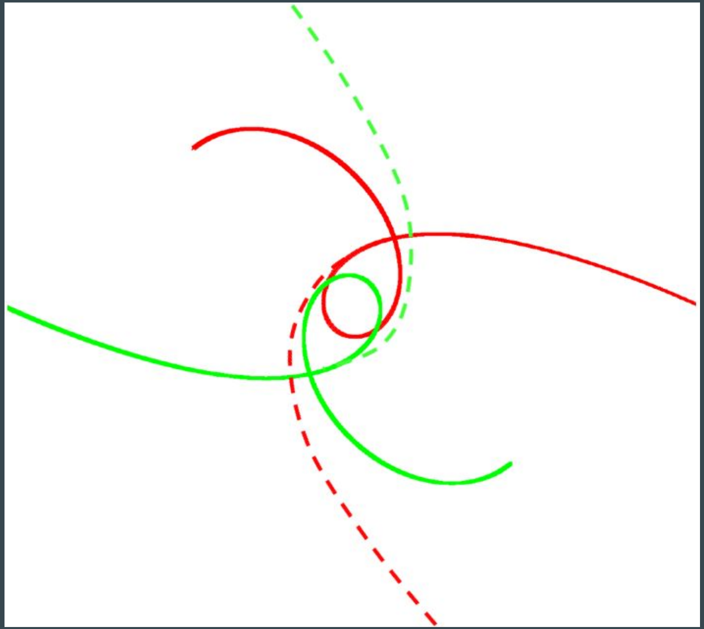
Three-body process

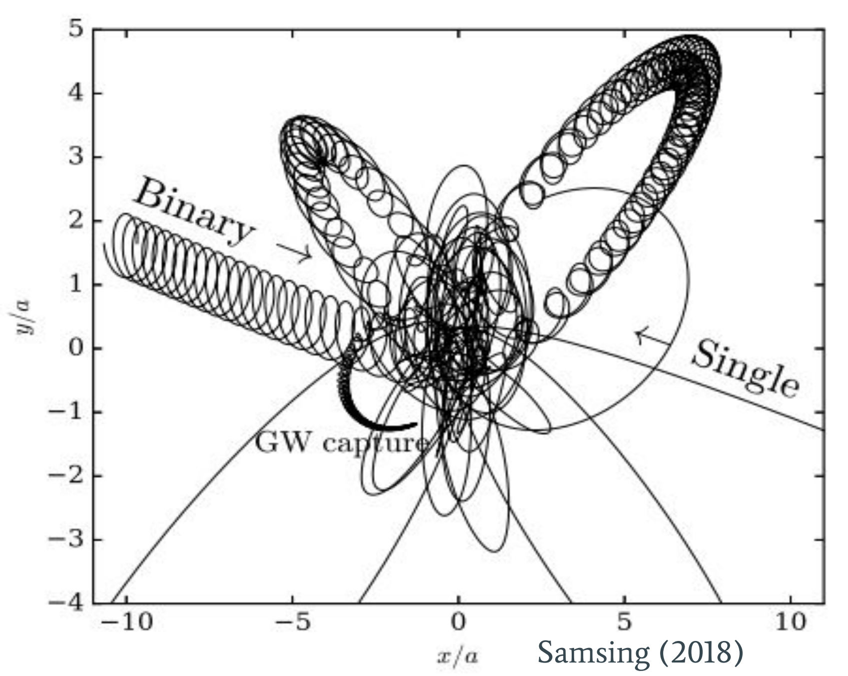
- Three-body process
  - Binary formation through the interactions of three or more bodies



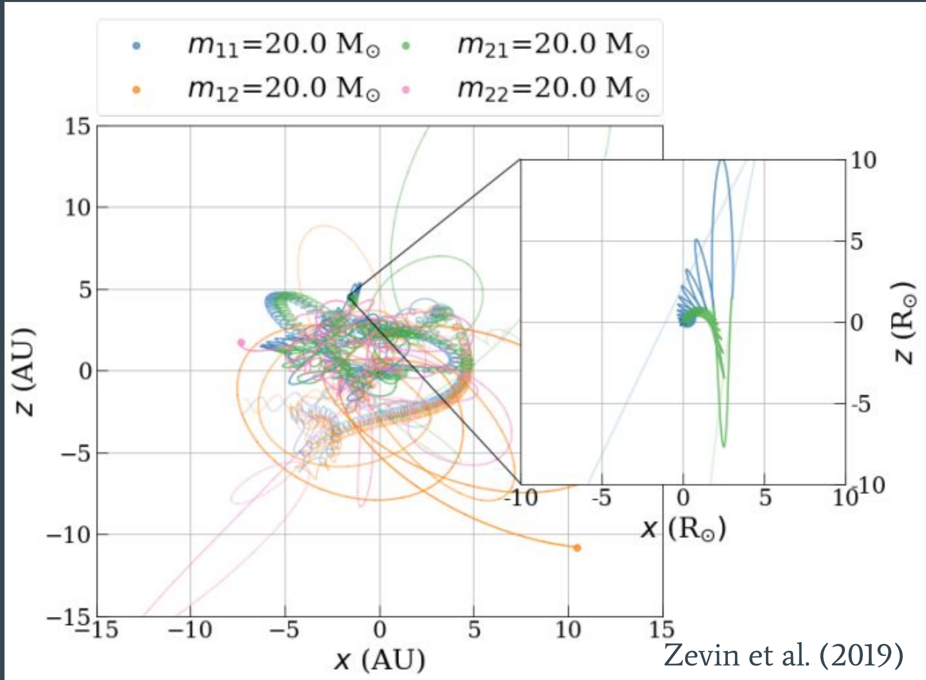
Dynamical capture

- Orbital energy loss through GW emission
- Energy radiation > orbital energy
- Hyperbolic → Elliptic orbit





Samsing (2018)



Zevin et al. (2019)

https://content.cld.iop.org/journals/0004-637X/871/1/91/revision1/apjaaf6ecf8_video.mp4?Expires=1723030060&Signature=i8Mdkfu7WvBQikyTT3ixHxD2-D4yRWGT4z5VlFwBorgYxjxLuMb~8mc550EEqLjBwK0y-3kkNmcL41P385O75CPkaNdcfeChMCPUqxrob6GFAGZjaiIsvKzUEca-j7FB5FWaV9auI~36pvbqDO0No3KS0x01NBf2-PVHHfOK5O5SFDUCeClQ-sphxKcTKX5k4yWmeJWvo4L6RL4jJoivI84KtOmpxP5aa47vq-agfbnL0CN5tsMpzQgQf~H6Qil982GFAYmCTpnybAnnNIYvcrdnkZe8Zs-GbaoUfUsoRM9bEv2LLLpTDzODUG5bZrGoHoaI-MgS-2M3uErAUohTPA__&Key-Pair-Id=KL1D8TIY3N7T8

Evolution

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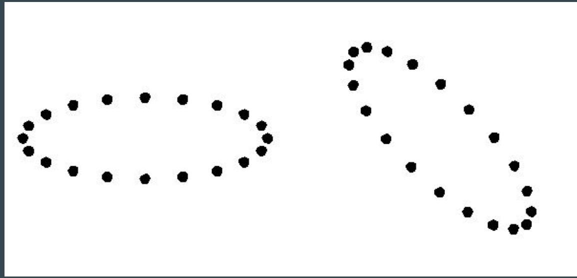
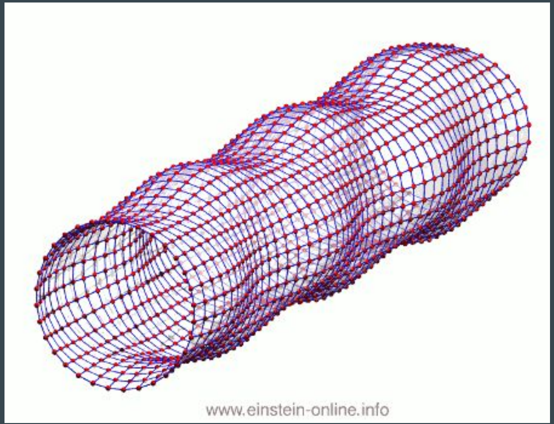
Inspiral



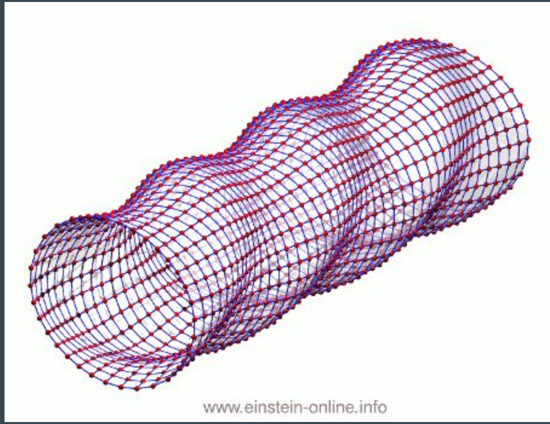


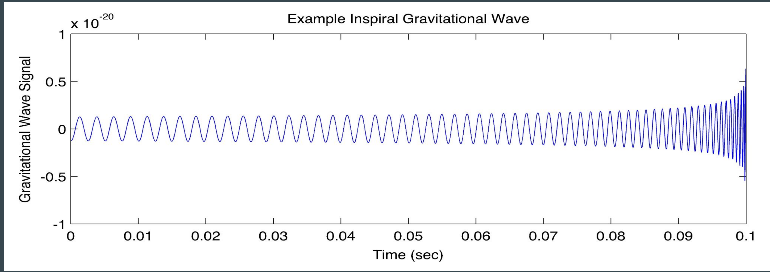
- Two polarization

$$h_+ = \frac{A}{r}(1+\cos^2 i)\cos(2\pi f t) f^{2/3}$$

$$h_\times = \frac{2A}{r}\cos i \sin(2\pi f t) f^{2/3}$$

$$A = 2\frac{G^{5/3}}{c^4}\pi^{2/3}M_c^{5/3}, \quad M_c \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$





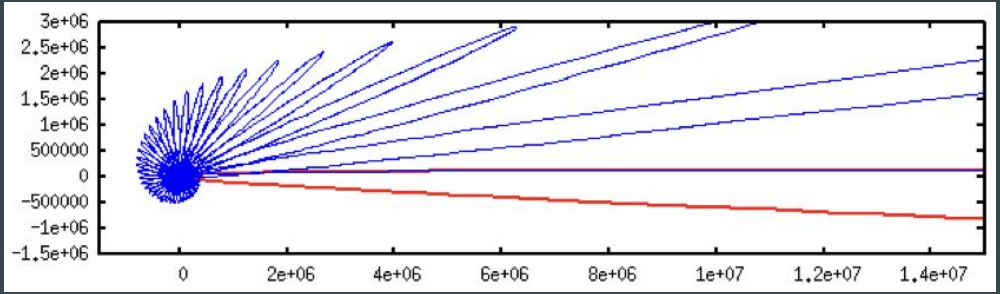
A. Stuver/LIGO, https://www.ligo.org/science/GW-Inspiral.php

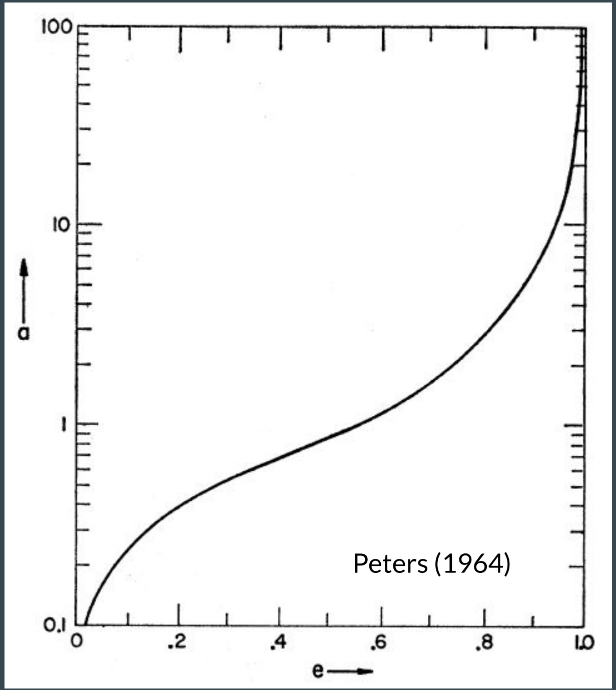
Inspiral

- Circularization

$$\langle\frac{da}{dt}\rangle = -\frac{64}{5}\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^3 (1-e^2)^{7/2}}(1+\frac{73}{24}e^2+\frac{37}{96}e^4)$$

$$\langle\frac{de}{dt}\rangle = -\frac{304}{15}e\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^4 (1-e^2)^{5/2}}(1+\frac{121}{304}e^2)$$





Inspiral

- Innermost Stable Circular Orbit (ISCO)
- ISCO of test particle in Schwarzschild metric

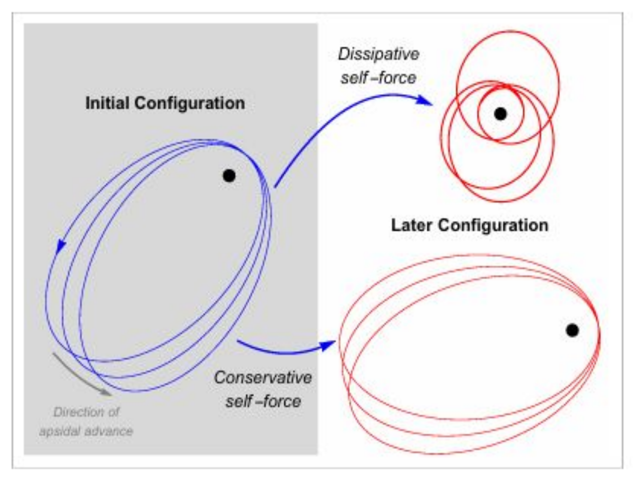
$$r_{ISCO} = \frac{6GM}{c^2}$$

- Highest GW frequency of inspiral phase

$$f_{ISCO,GW} = \frac{1}{\pi}\left(\frac{1}{6}\right)^{3/2}\frac{c^3}{G(m_1+m_2)} \approx \frac{4396}{M/M_\odot}\text{Hz}$$

Inspiral

- Eccentricity



Osburn et al. (2016)

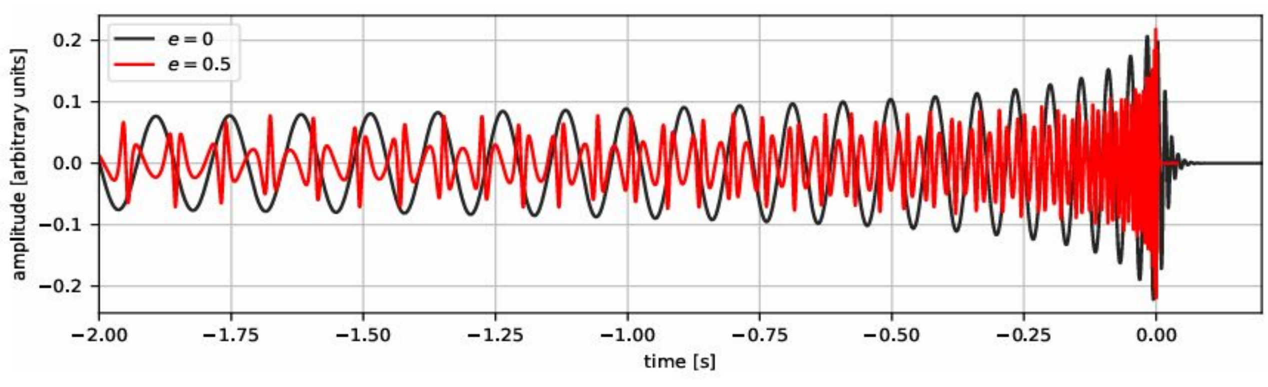
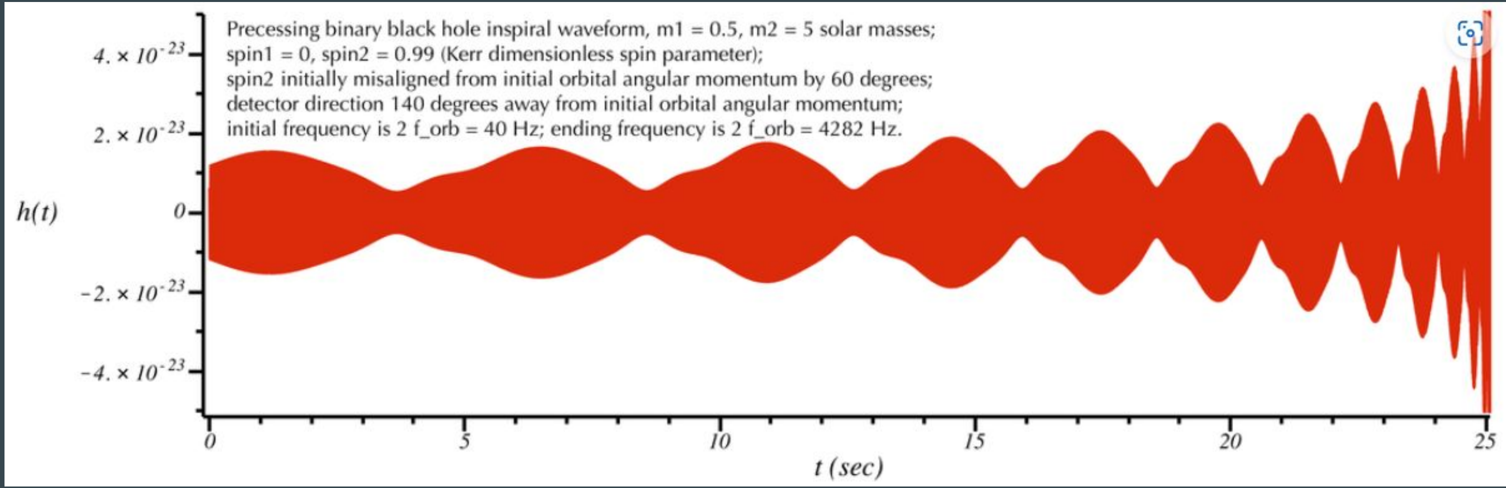


Figure 1. Examples of gravitational waveforms for a $10\,M_\odot - 10\,M_\odot$ BBH system with eccentricities 0 (black) and 0.5 (red).

Abbott et al. (2019)

Inspiral

- Spin



https://www.soundsofspacetime.org/spinning-binaries.html

Merger

- GW emission peak
- Numerical relativity
- Recoil (Kick)
    - Asymmetric GW emission
    - Unequal mass, Spin
    - Up to ~10,000 km/s (Healy et al. 2009)

Campanelli et al. (2007)

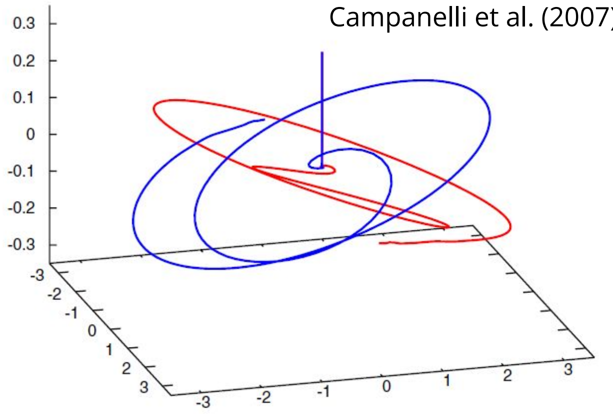


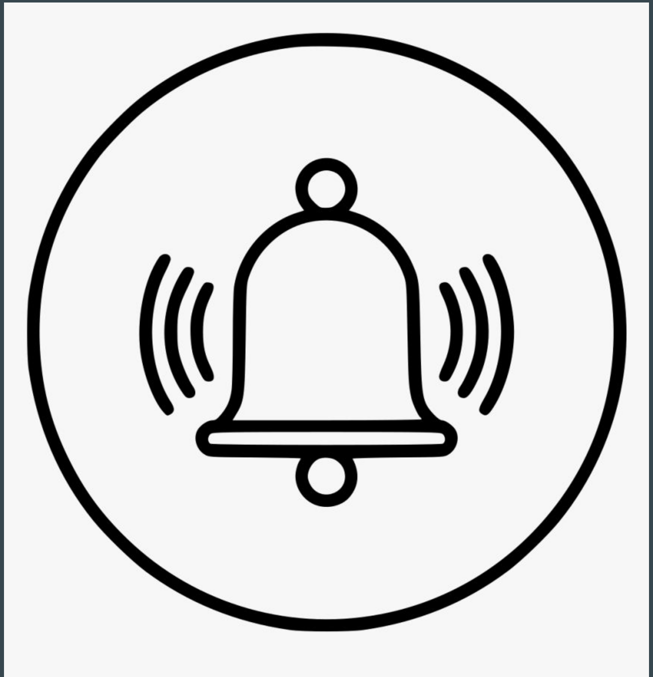
FIG. 4 (color online). The three-dimensional trajectories of the punctures showing the orbital precession and the final recoil for the SP2 configuration. Note that the scale of the z axis is 1/10 that of the x and y axes.

Ringdown

- Ringing of merged BH
  - Gradually settling into a stable Kerr BH
  - Damped oscillation after the merger
- Higher GW frequency than inspiral
- Astrophysical information - mass, spin
- Quasi-normal mode (Berti et al. 2006, ...)
  - Quasi: damping by emitting GWs

$$h(t) \sim A \exp[i(f_R + i f_I)t]$$

- Testing general relativity



Summary

- Binary black holes are the main targets of current GW detectors.
- Formation
    - Evolution of stellar binary
    - Dynamical formation in star cluster
- Coalescence
    - Inspiral-Merger-Ringdown