블랙홀 쌍성의 형성과 진화

배영복 (중앙대)

2025 수치상대론 및 중력파 여름학교

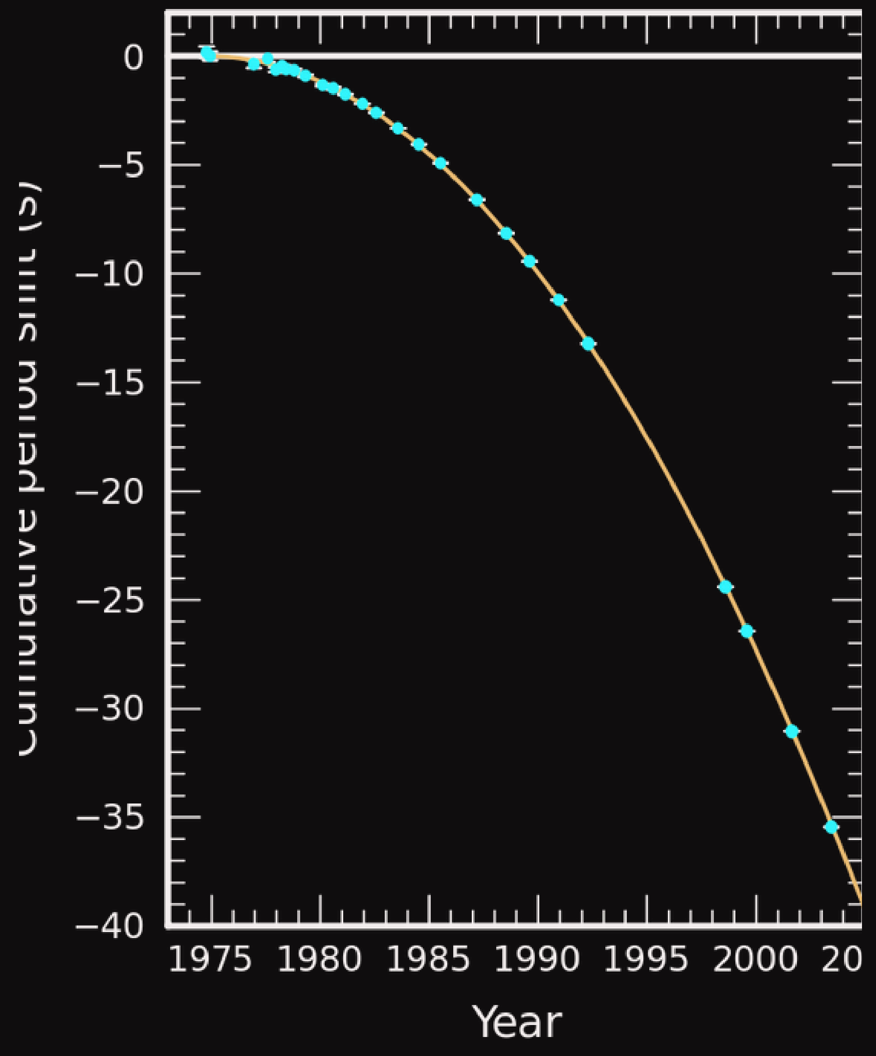
2025. 07. 28

OUTLINE

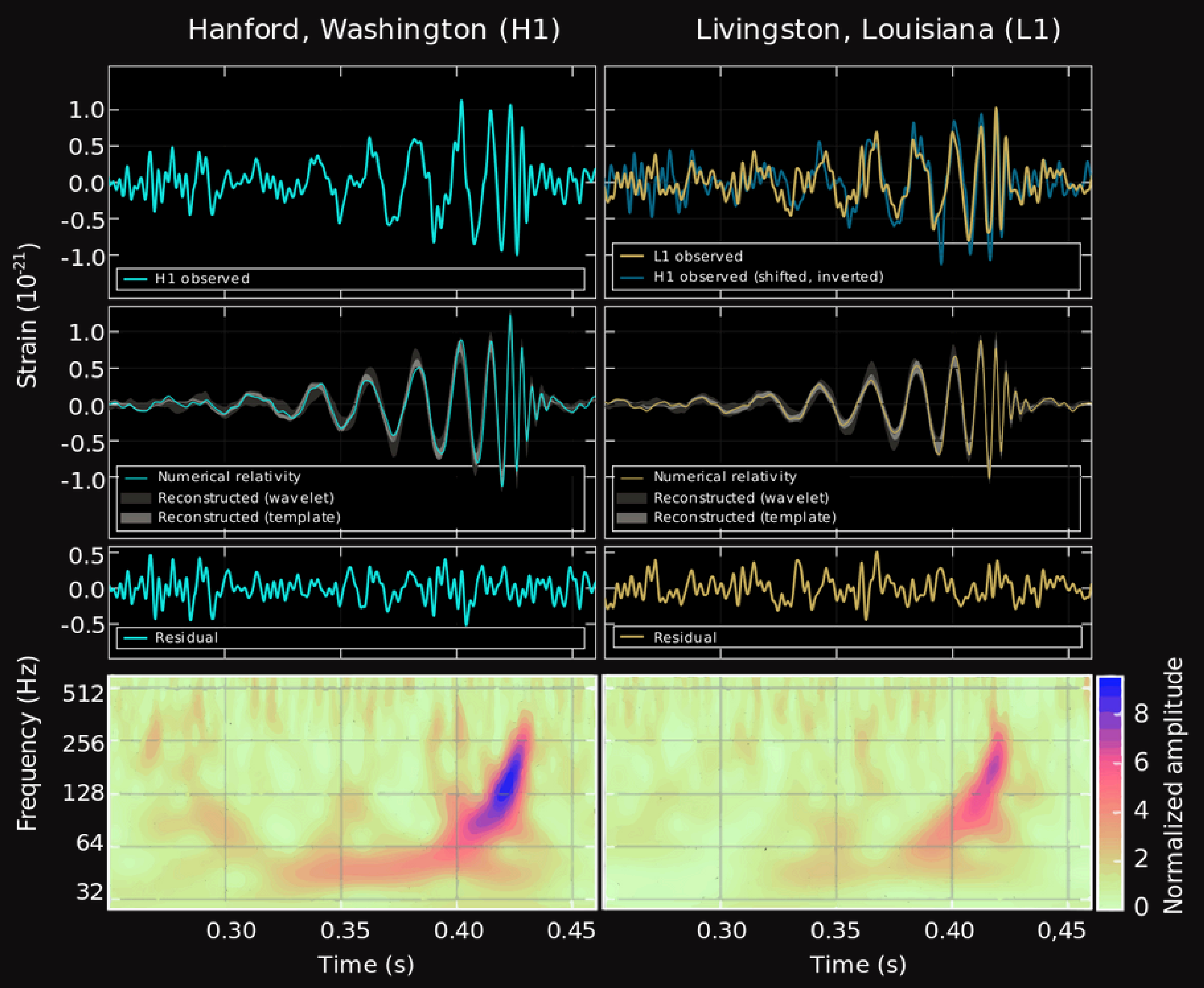
Introduction
Formation
Evolution
GW Transient Catalog

INTRODUCTION

Introduction



https://en.wikipedia.org/wiki/Hulse%E2%80%93Taylor_binary#/media/File:PSR_B1913+16_period_shift_graph.svg



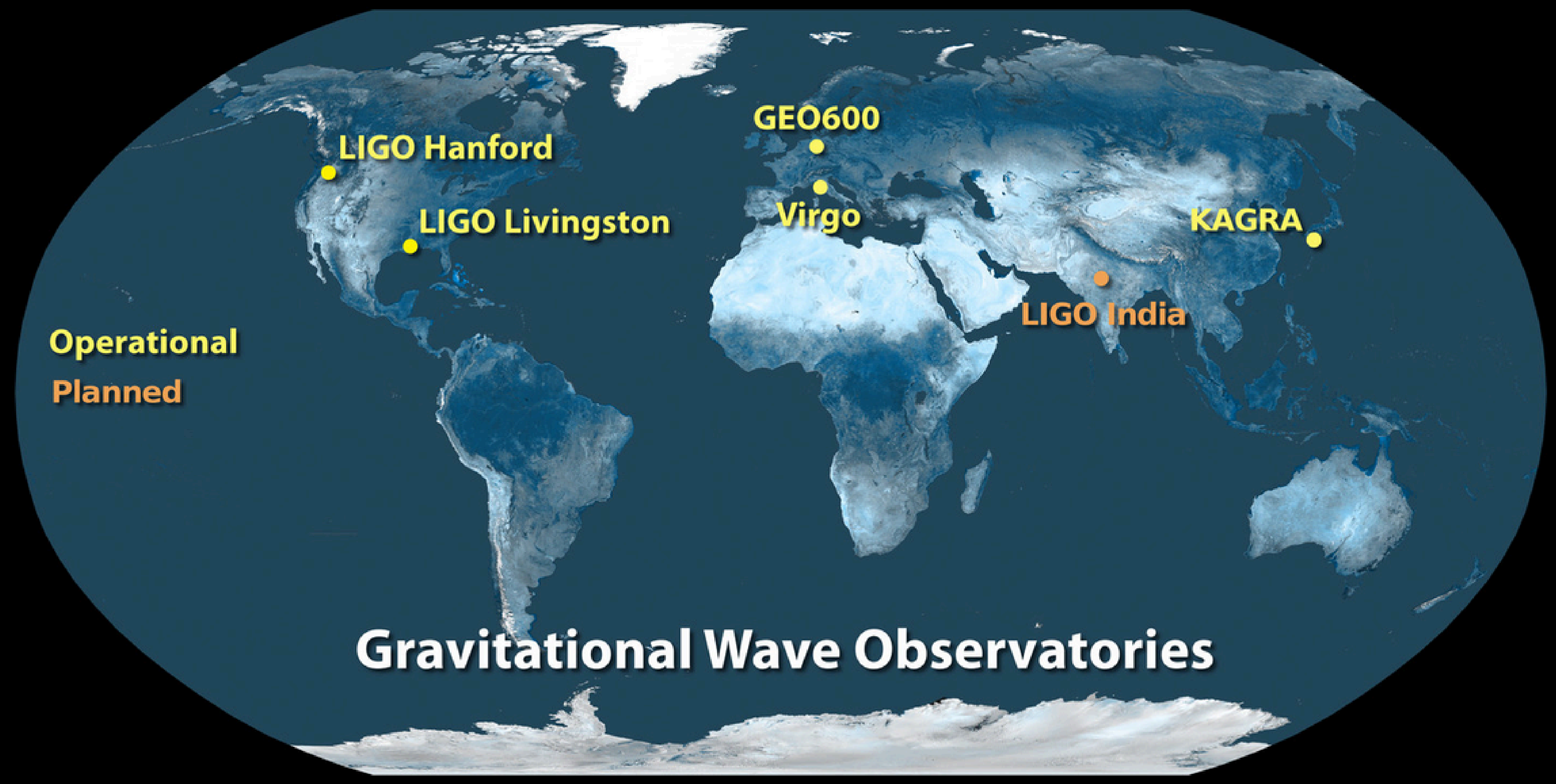
https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves#/media/File:LIGO_measurement_of_gravitational_waves.svg

Gravitational-Waves (GWs)

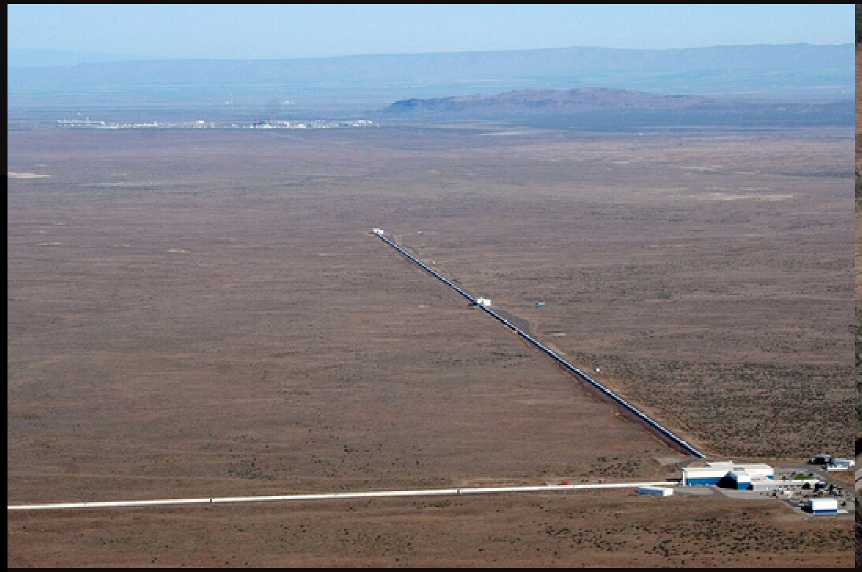
- Ripples of spacetime curvature that propagates as waves
- Indirect detection - PSR 1913+16 (Hulse & Taylor 1974, Weisberg & Taylor 2005)
- Direct detection - GW150914 by aLIGO
- Multi-messenger astronomy

Introduction

Interferometric GW detectors



Caltech/MIT/LIGO Lab



LIGO Hanford / Livingston

Virgo

KAGRA

(By Christopher Berry - http://cplberry.com/2015/07/26/whats-up-doc/, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=45370733)

Introduction
Interferometric GW detectors

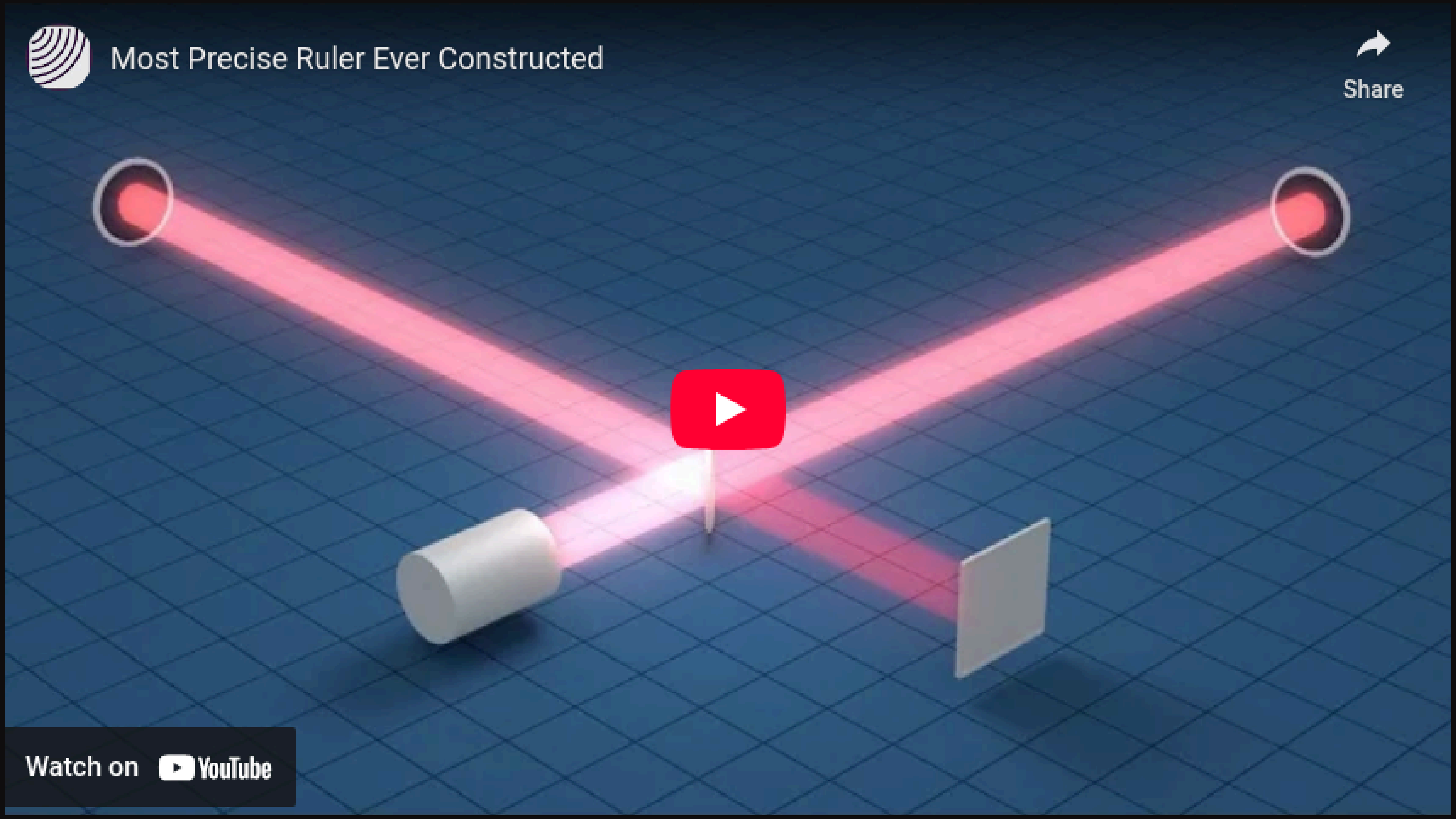
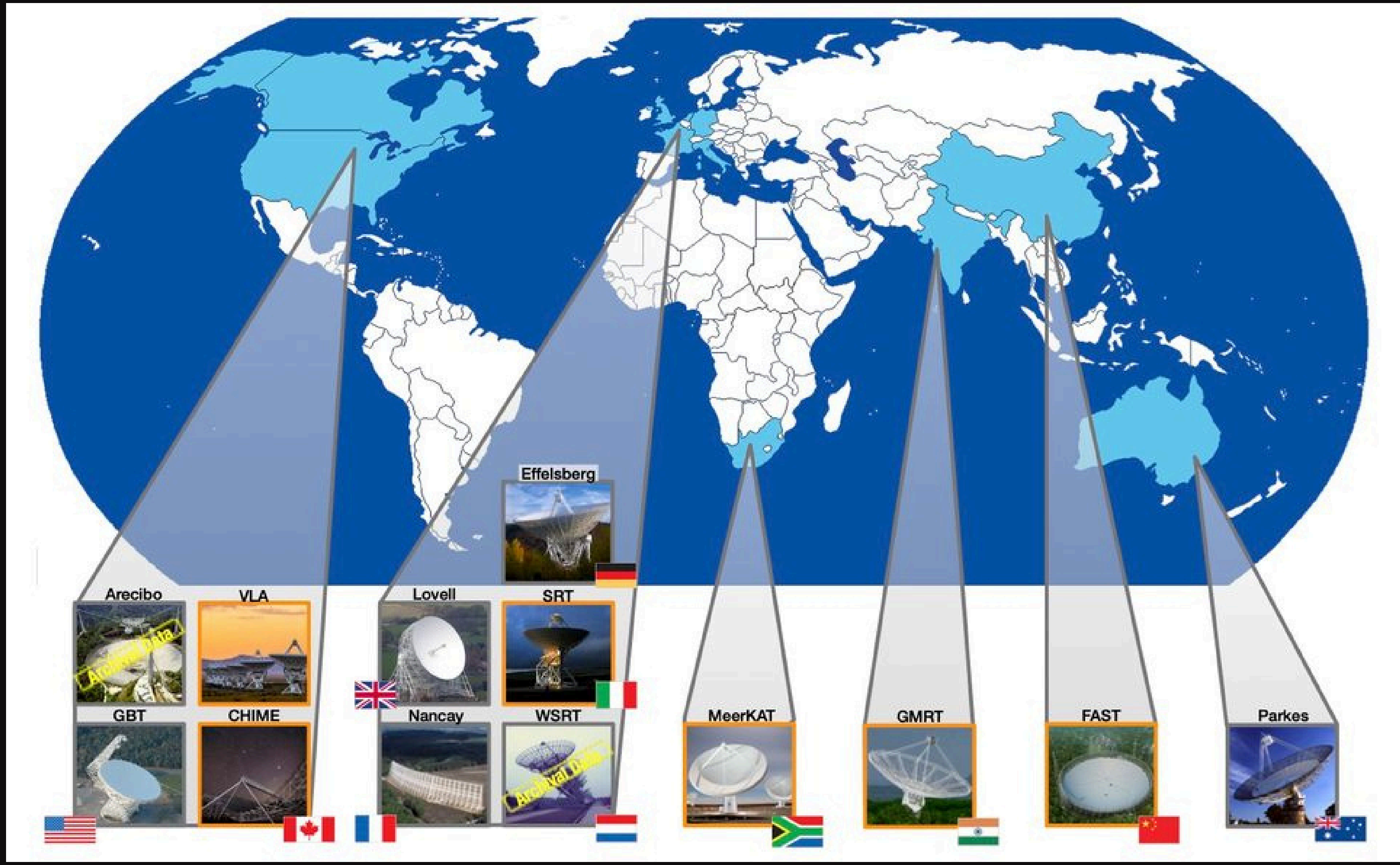
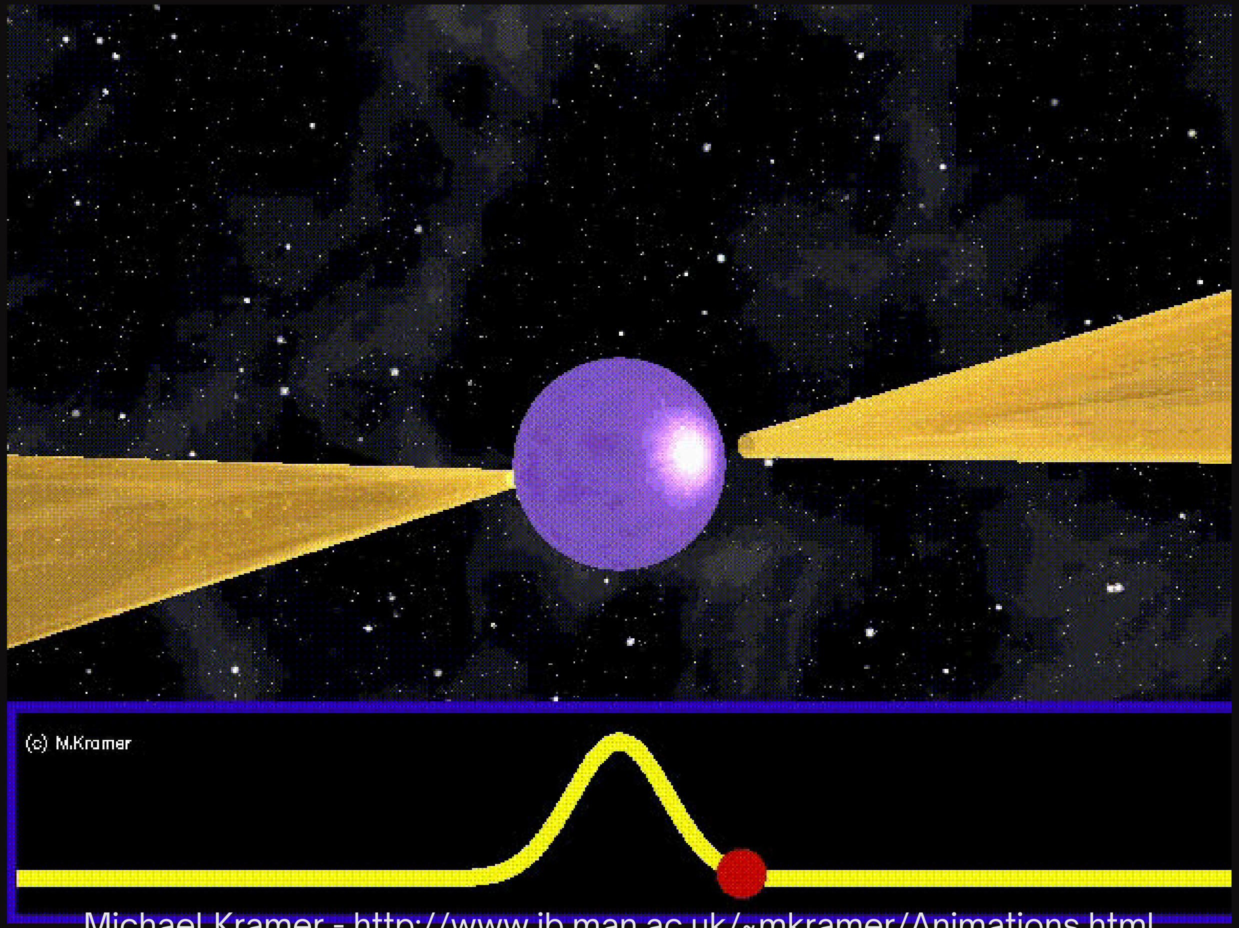


Image credit: LIGO/T. Pyle
https://www.youtube.com/watch?v=tQ_teIUb3tE&t=56s

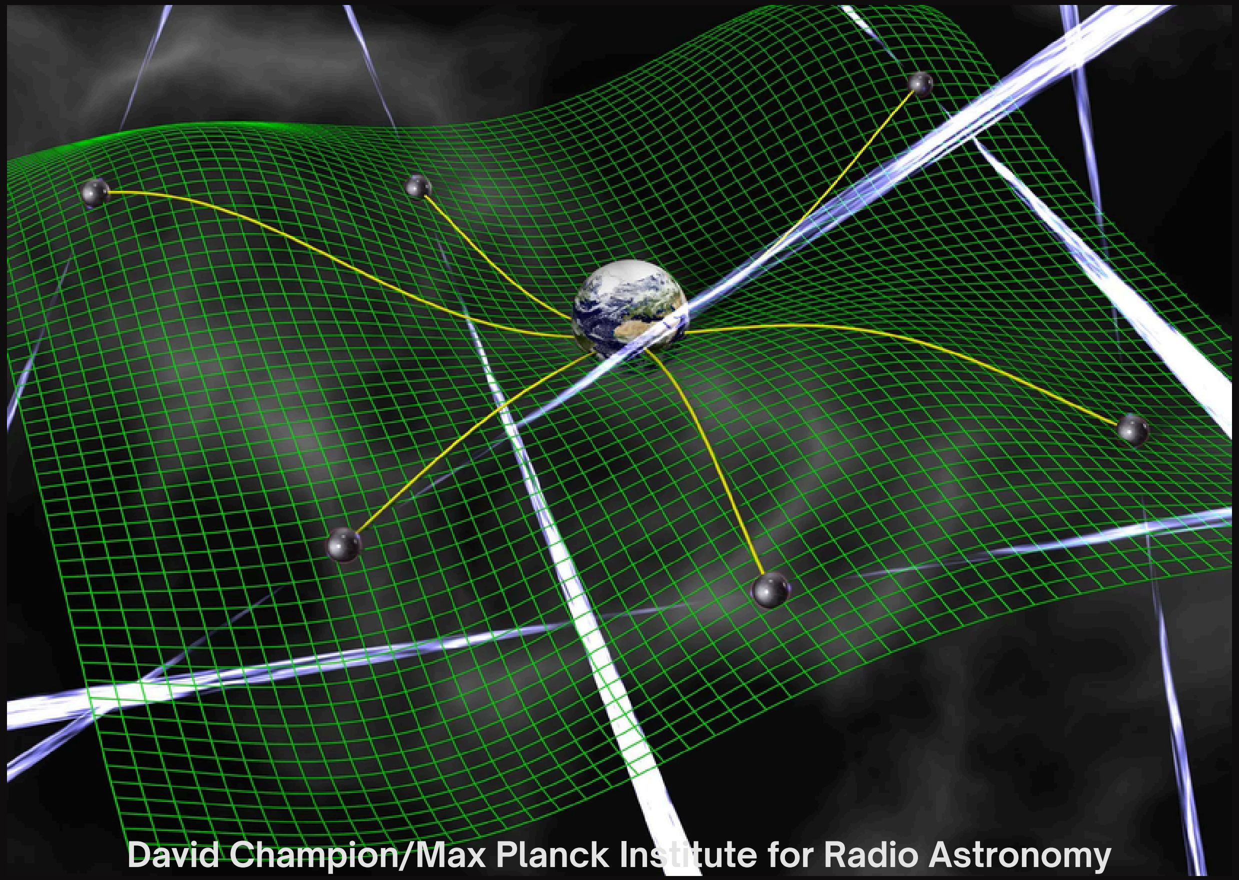
Introduction

Pulsar Timing Array





Michael Kramer - http://www.jb.man.ac.uk/~mkramer/Animations.html



David Champion/Max Planck Institute for Radio Astronomy

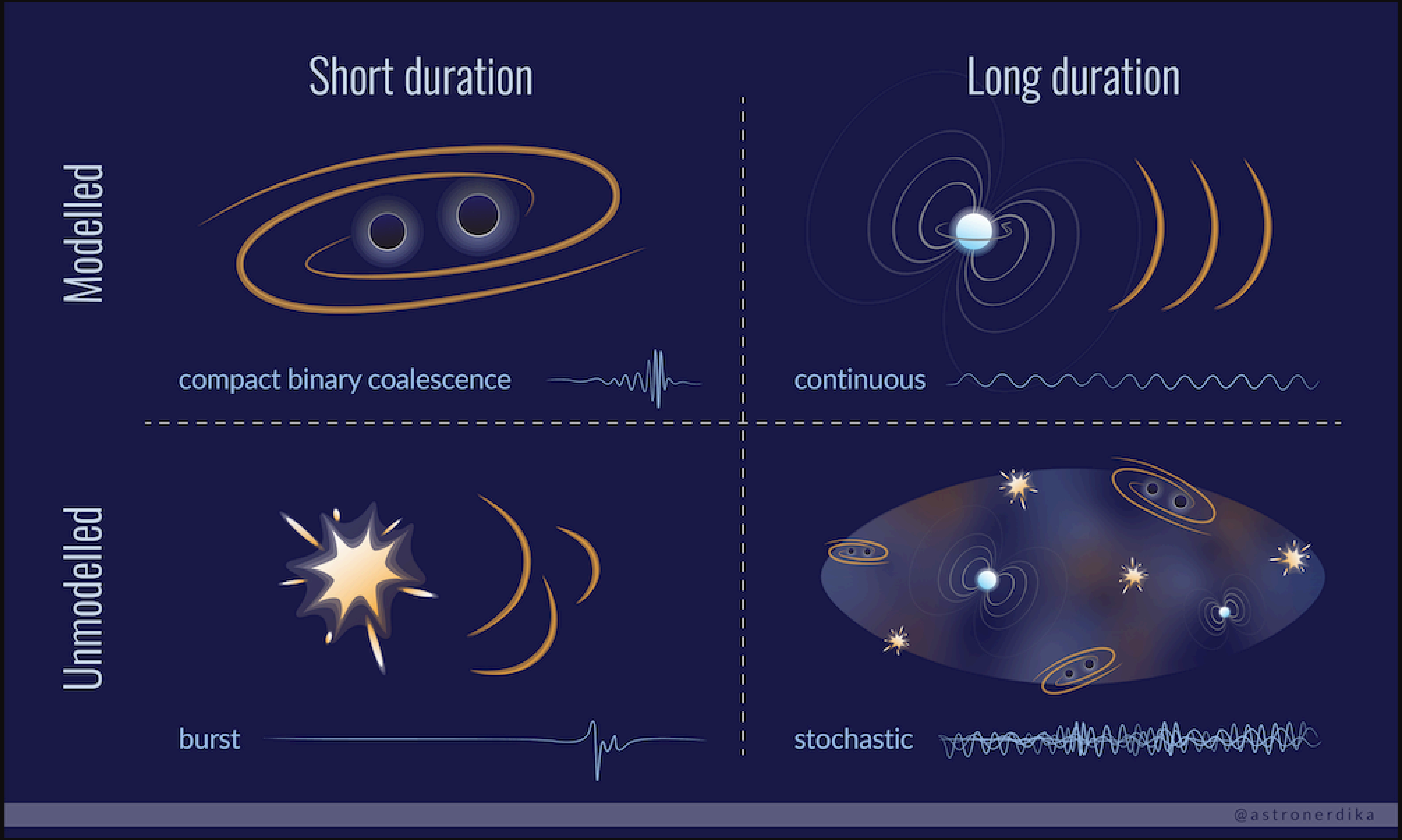
Introduction

EM wave vs. GW

Property	Electromagnetic waves	Gravitational waves
Nature	Electromagnetic radiation	Ripples in spacetime curvature
Radiation mechanism	Dipole radiation	Quadrupole radiation
Propagation speed	Speed of light	Speed of light
Interaction with matter	Easily absorbed, scattered, or emitted by matter	Extremely weakly interacting, pass through matter almost unaffected
Polarization	Linear, circular, elliptic (continuous states from 2 basis vectors)	Plus, cross (2 fixed geometric modes)
Observable quantity	Intensity ($\propto 1/r^2$)	Strain amplitude ($\propto 1/r$)
Gravitational Lensing	Yes	Yes

Introduction

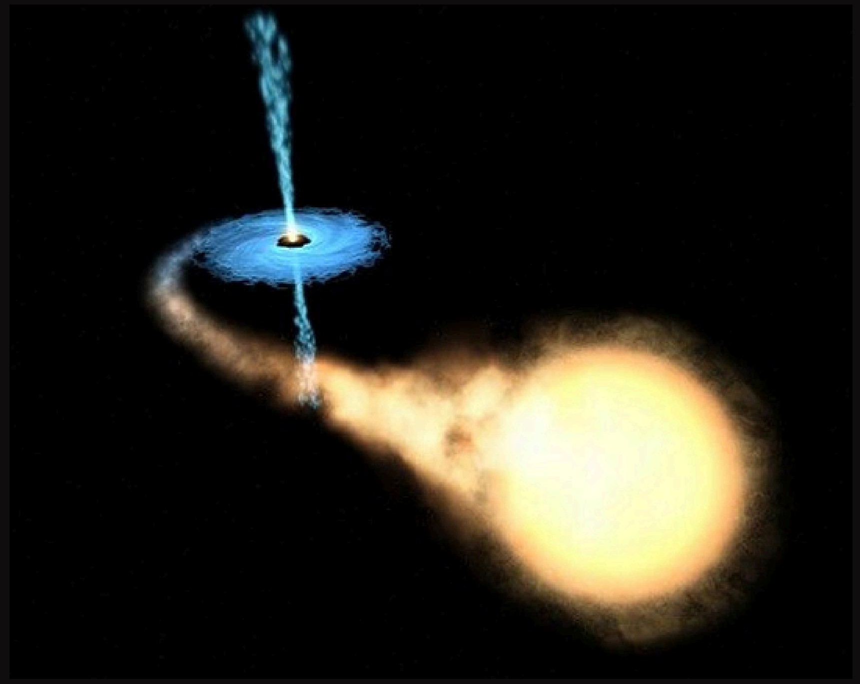
GW sources



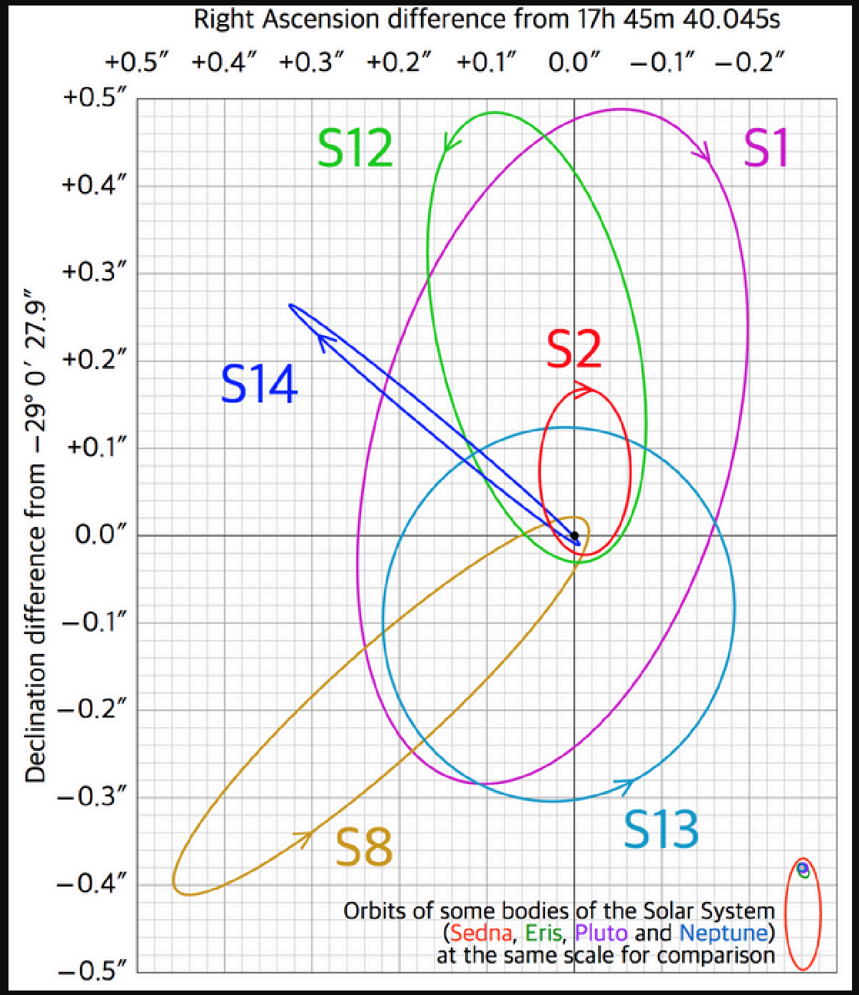
Credit:
Shanika Galaudage

Introduction
Black hole

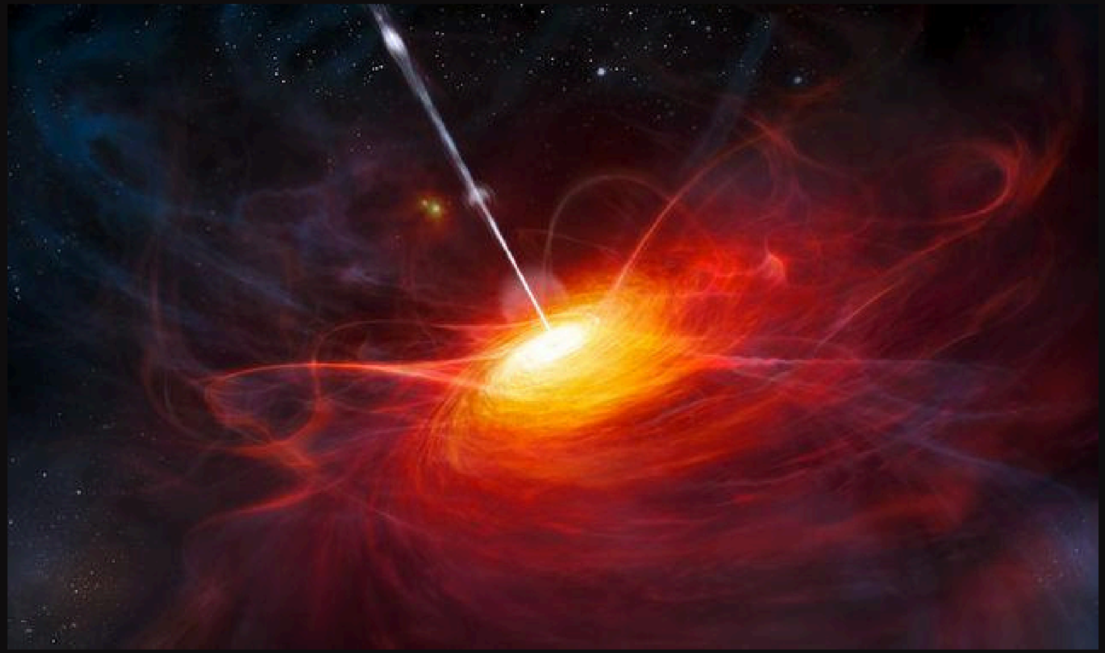
- **Black hole (BH)**
  - Solution of Einstein equation
  - Schwarzschild (1916), Kerr (1963)
  - Observations
    - X-ray binaries
    - Quasar
    - Stars orbiting Sagittarius A*
    - Gravitational waves
    - EHT
    - ...



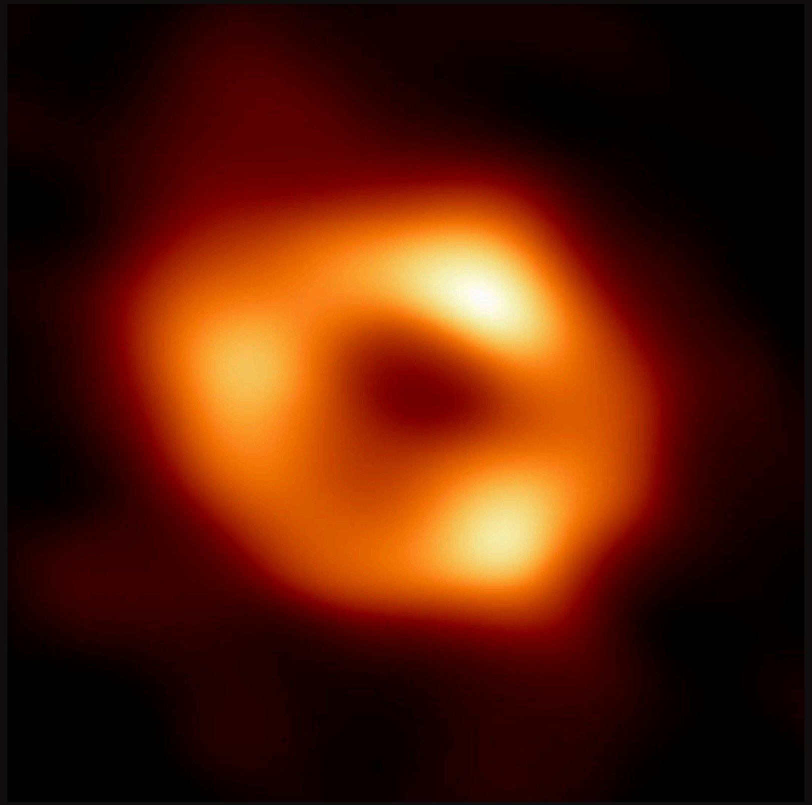
Wikipedia: X-ray binary



Wikipedia: Sagittarius A*



Wikipedia: Quasar



https://www.eso.org/public/images/eso2208-eht-mwa/

Introduction
Black hole

- **Black hole (BH)**
  - Subsolar mass BH
    - Primordial
      - Early universe
      - Candidate of dark matter
  - Stellar mass BH
    - stellar evolution
      - initial mass function of stars, metallicity, mass gap
    - Merger of neutron stars
  - Intermediate mass BH
  - Supermassive BH
    - M-σ relation

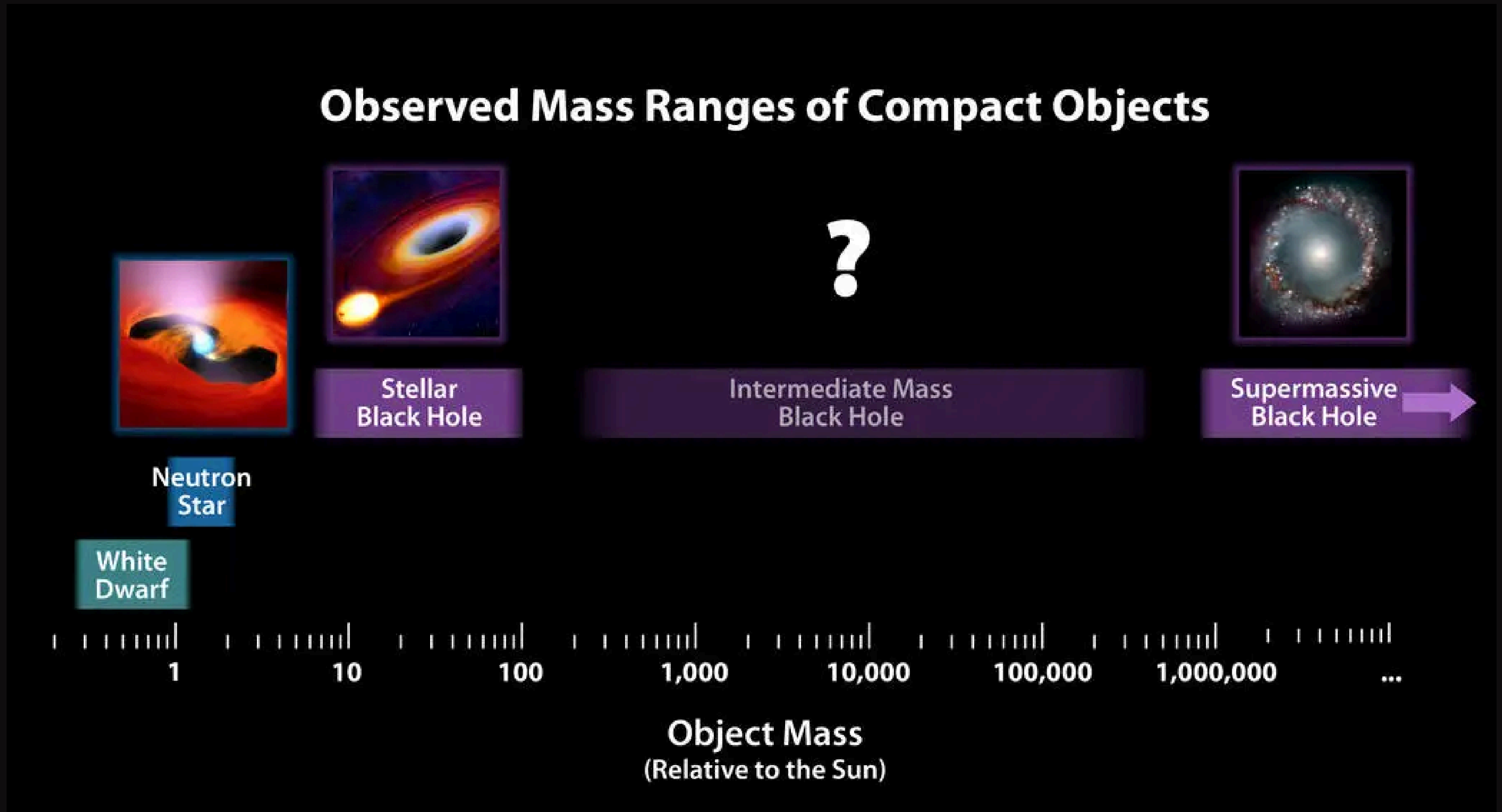
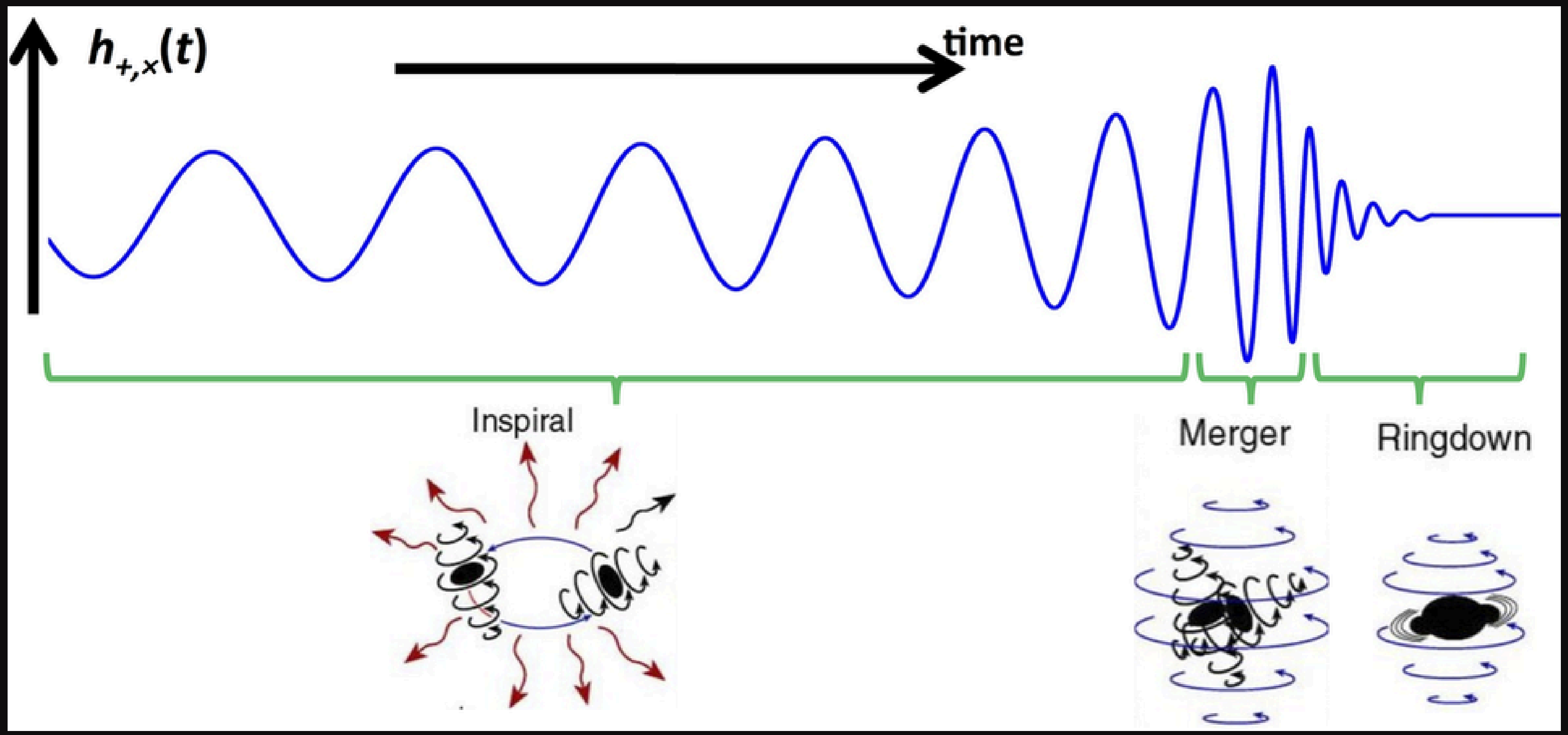


Image credit: NASA/JPL-Caltech

Introduction
Binary Black Holes

- **Binary Black holes (BBHs)**
    - Pair of two black holes
    - More than 90% of GW sources ever detected
    - Strong GW signal
    - Detectable frequency for current interferometric GW detectors - Stellar mass BBH
    - Predictable waveforms
    - Coalescence
        - Inspiral - Merger - Ringdown

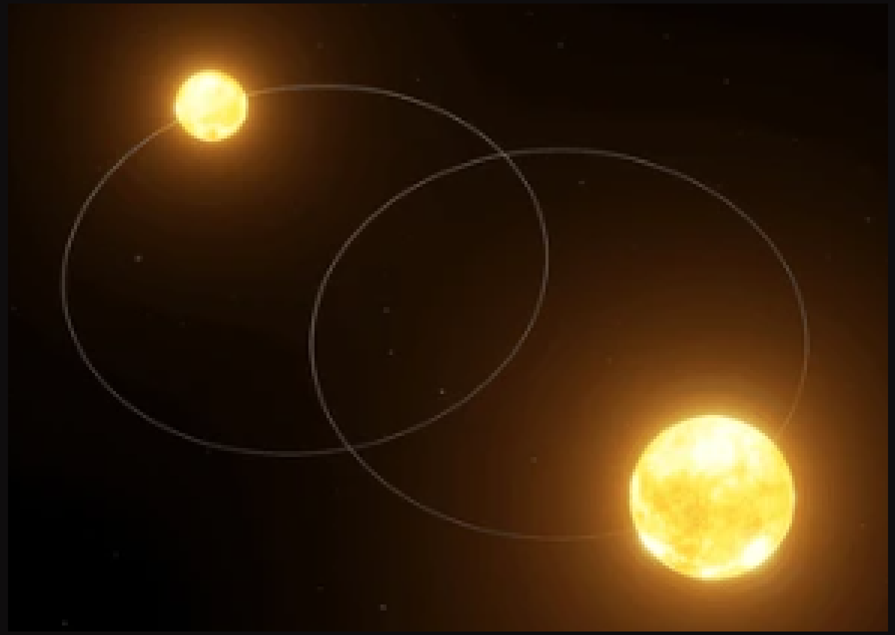


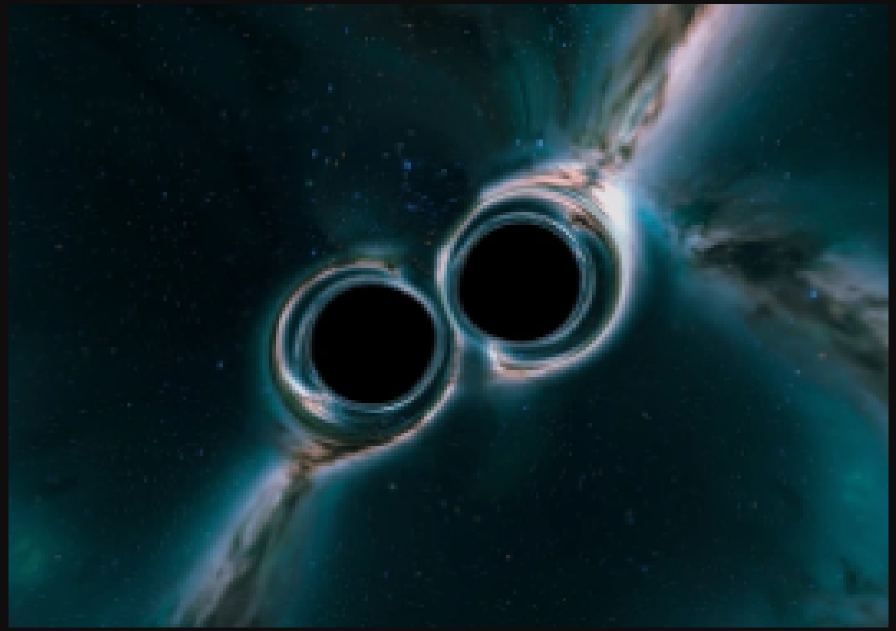
M. Favata/SXS/K. Thorne

FORMATION

Formation

Massive Binary Star → Binary Black Hole





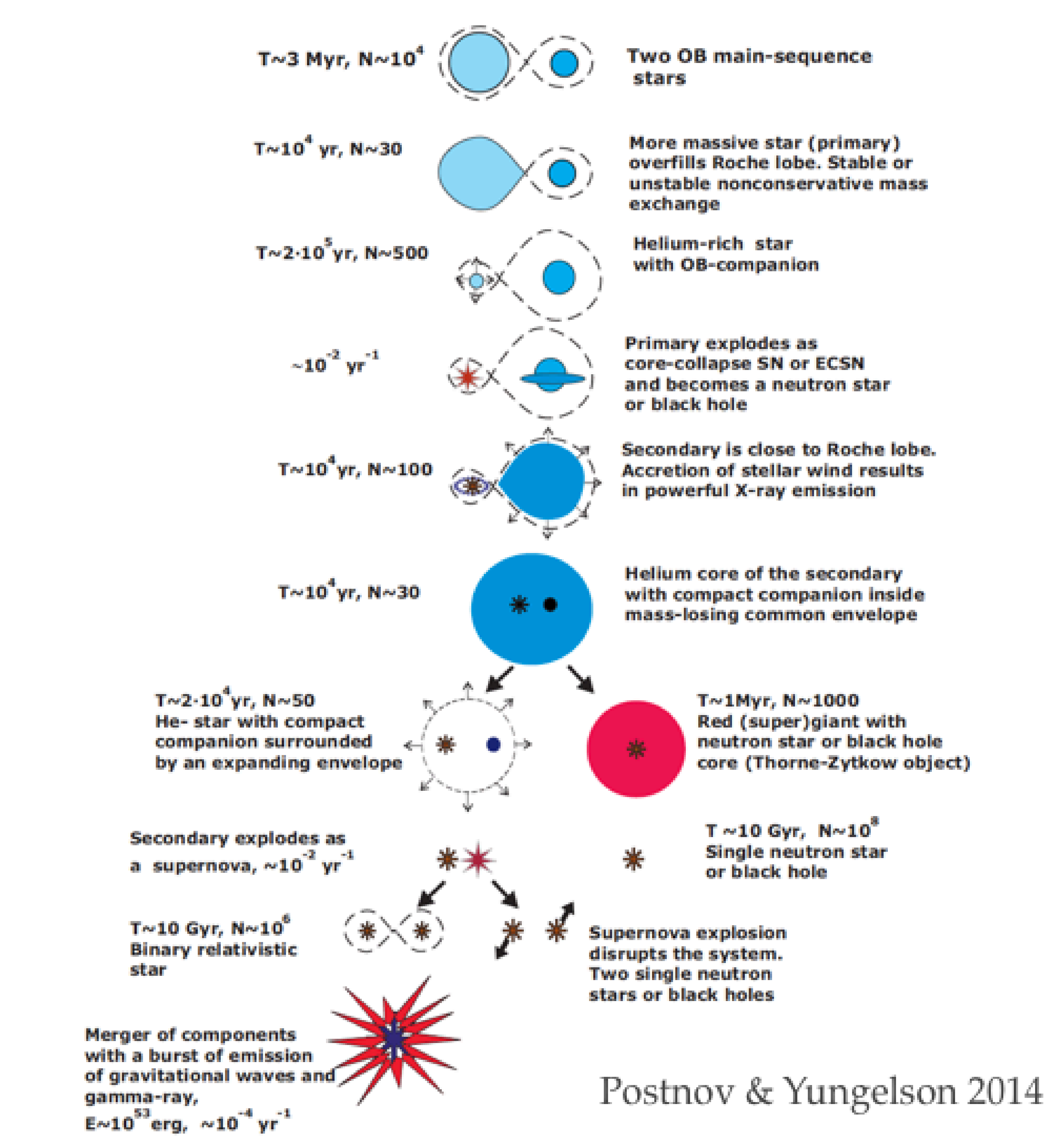
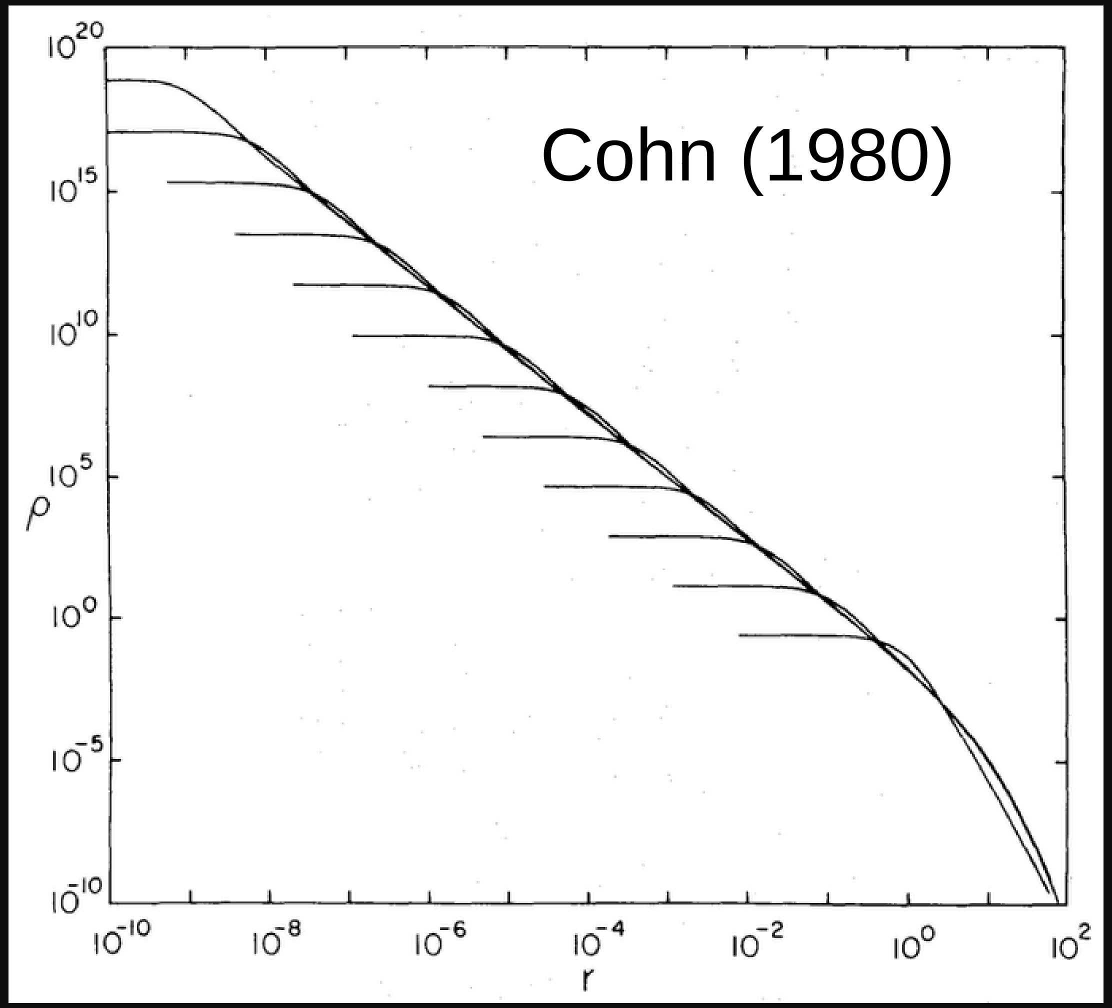
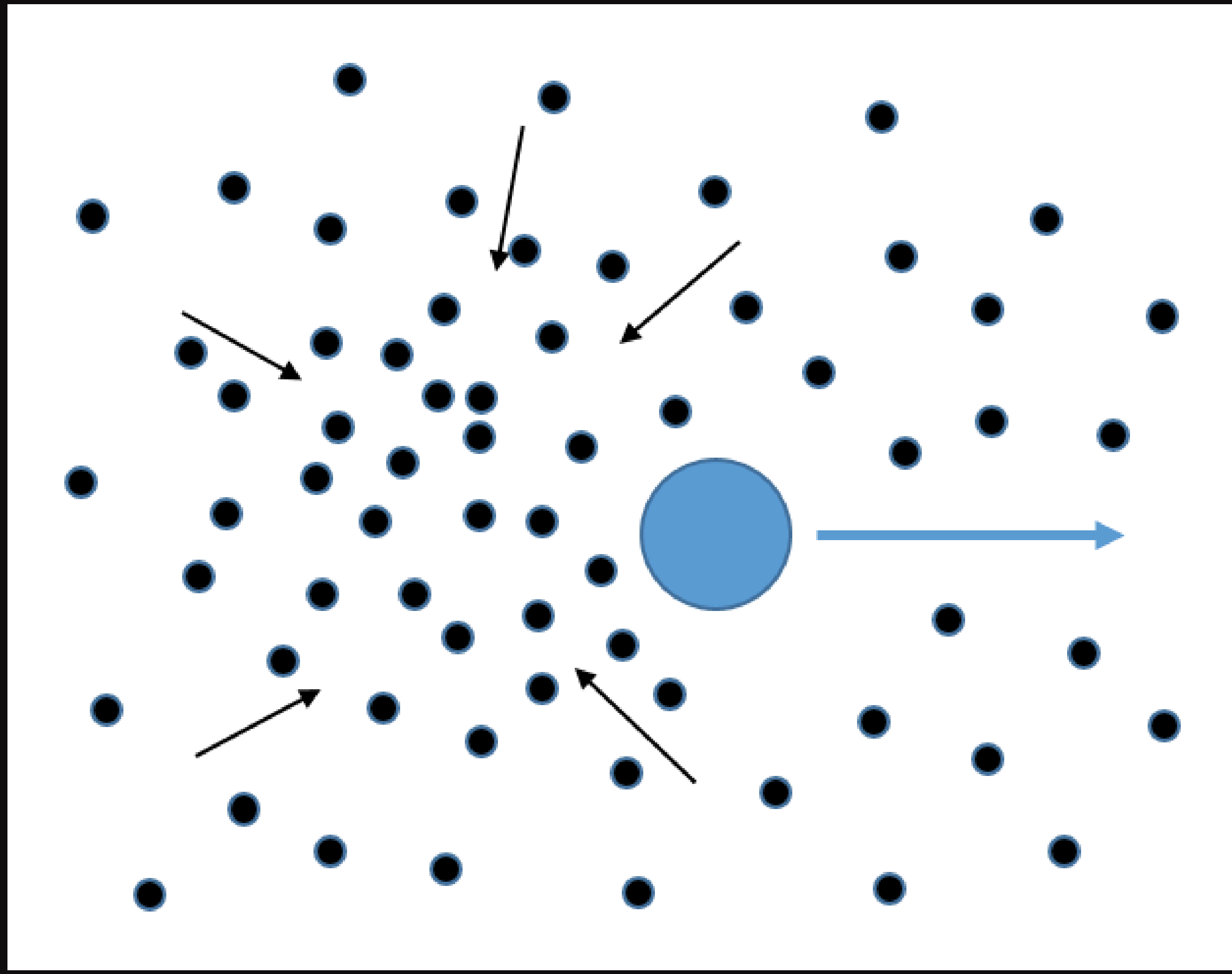


Figure 7: Evolutionary scenario for the formation of neutron stars or black holes in close binaries. T is the typical time scale of an evolutionary stage, N is the estimated number of objects in the given evolutionary stage.

Formation

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





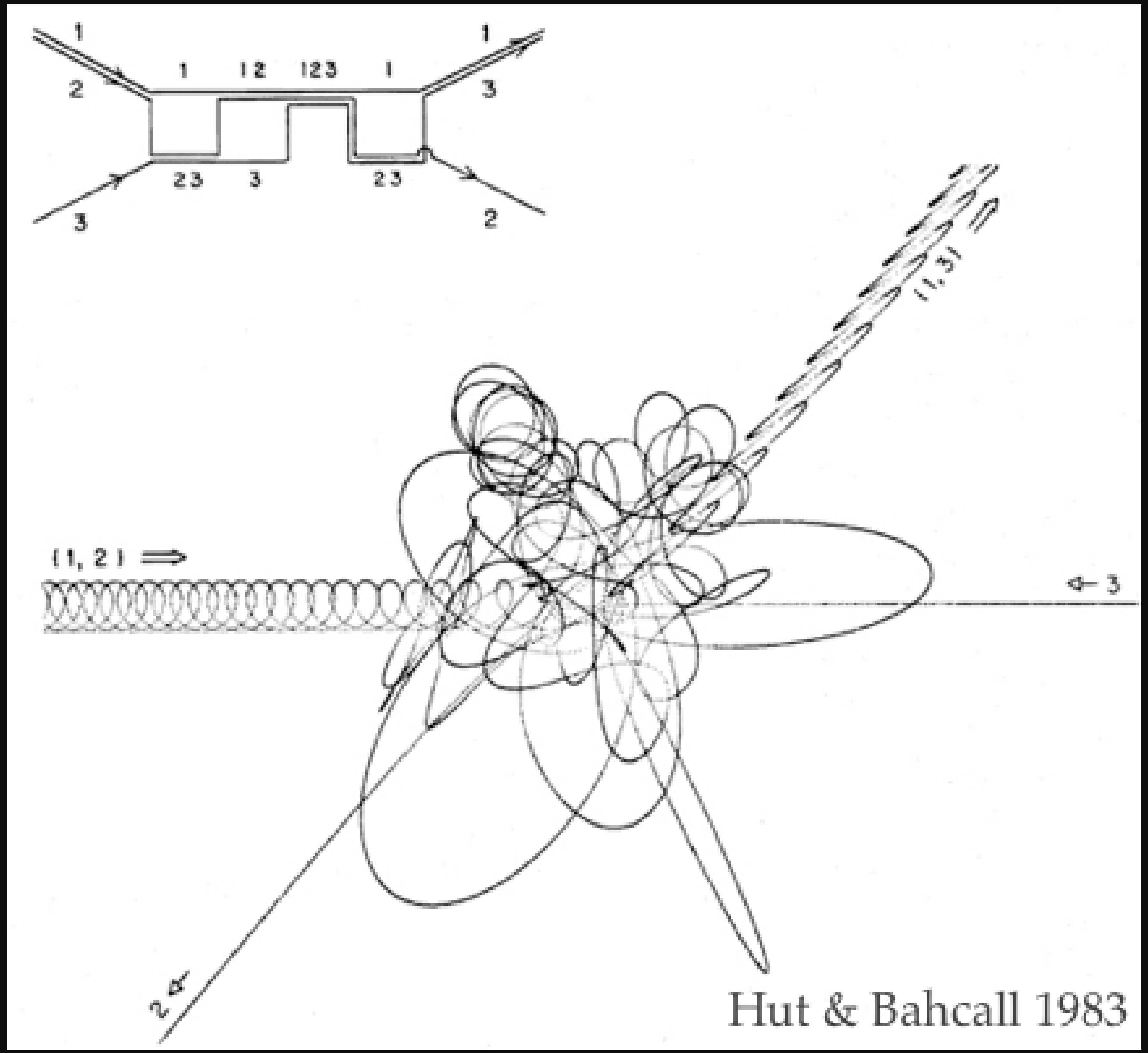
M80 (NGC 6093)
NASA, The Hubble Heritage Team, STScI, AURA - Great Images in NASA Description

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

Formation

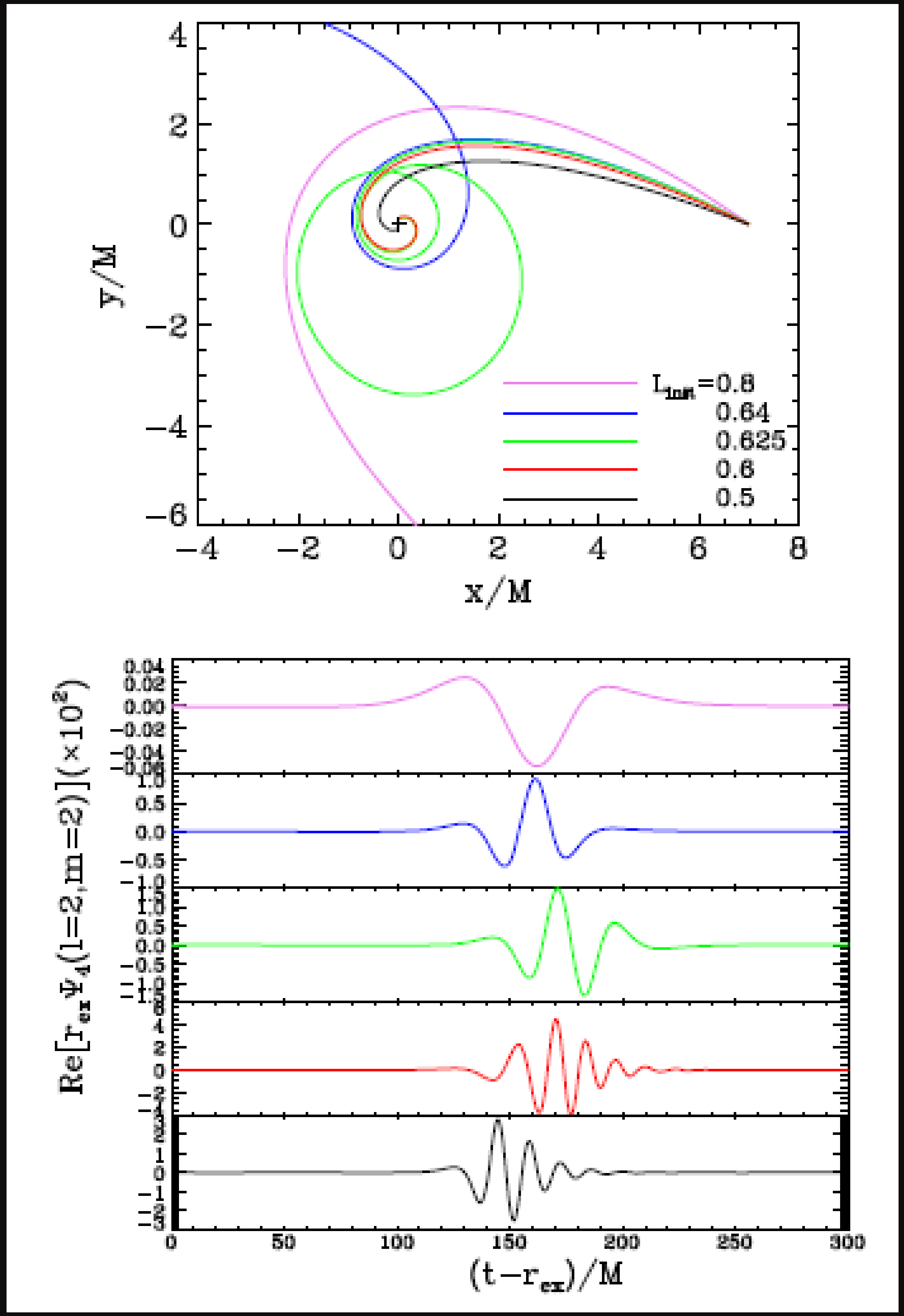
Three-body process

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



Formation

- **Dynamical capture**
  - Gravitational radiation driven capture (GR capture), or Gravitational wave capture (GW capture)
  - Two body process
  - Unbound orbit to bound orbit by emitting GWs
  - Energy radiation > orbital energy

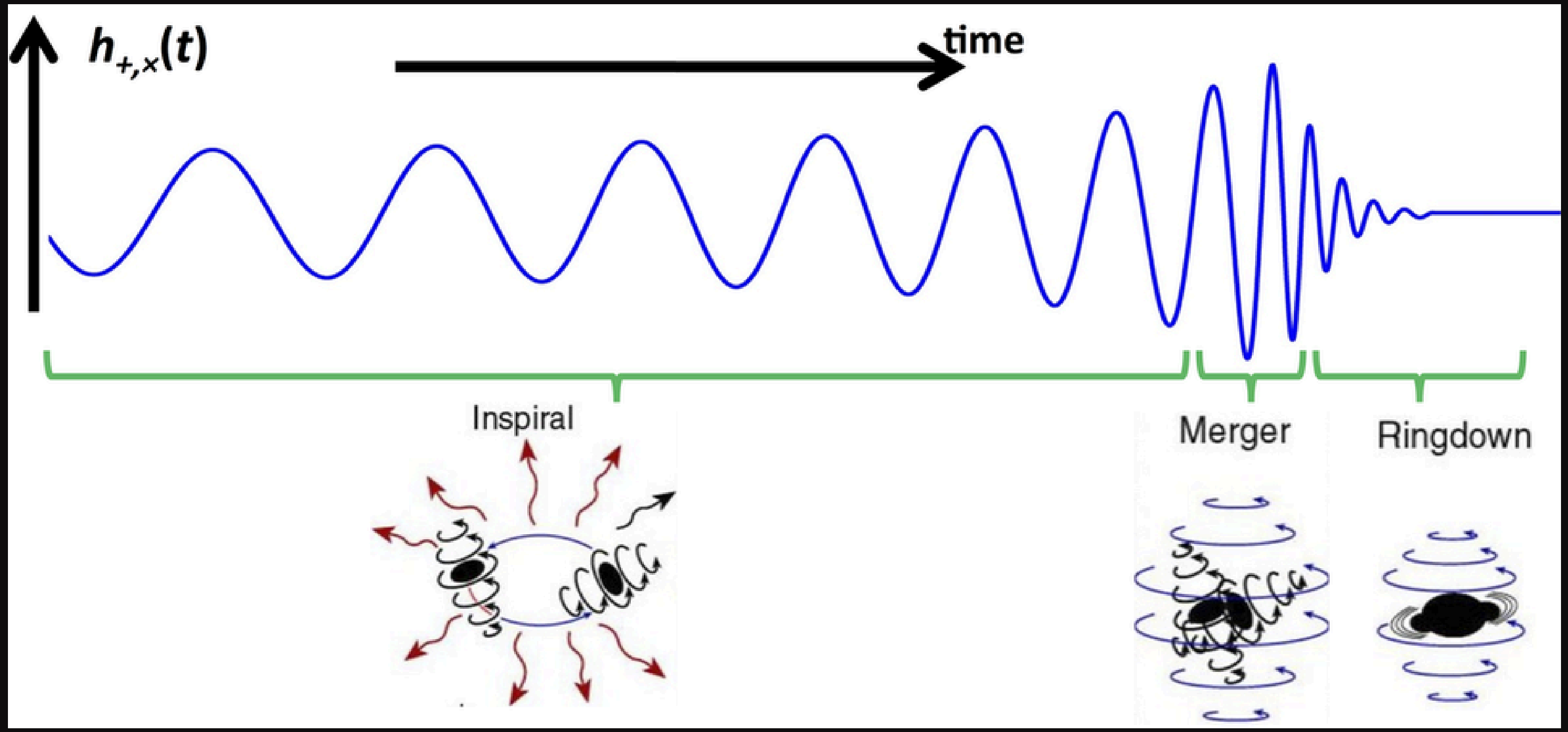


Bae et al. (2017) PRD 96, 084009

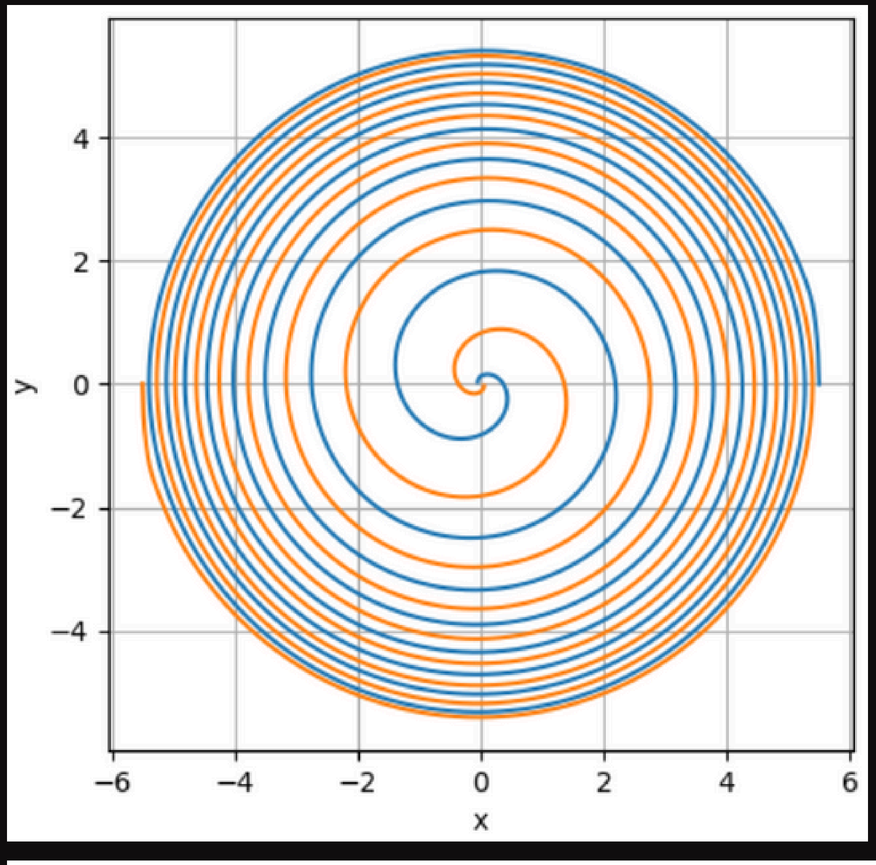
EVOLUTION

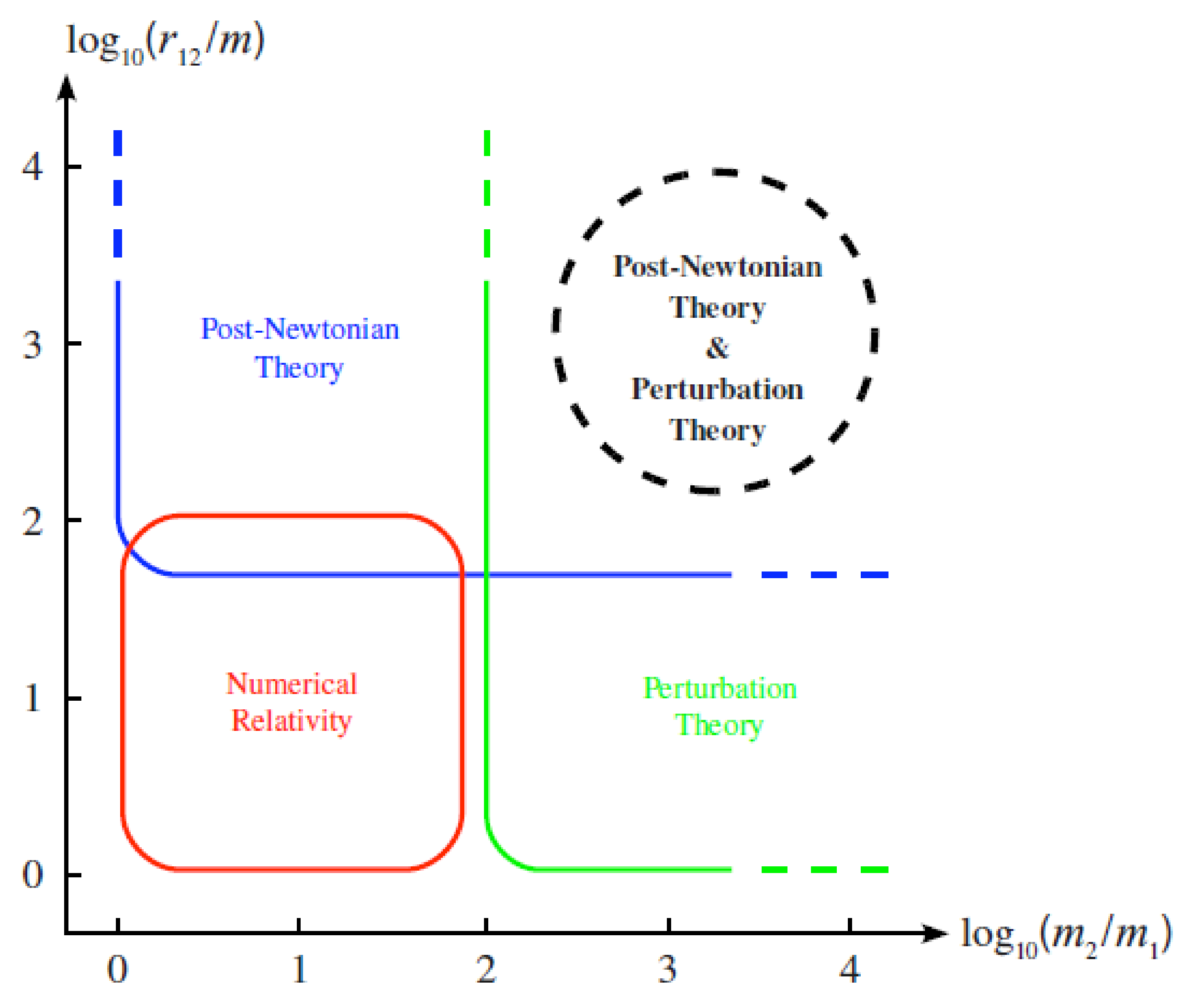
Evolution Phase

- **Inspiral - Merger - Ringdown**



M. Favata/SXS/K. Thorne





Blanchet, L. 2014, Living Review in Relativity, 17, 2

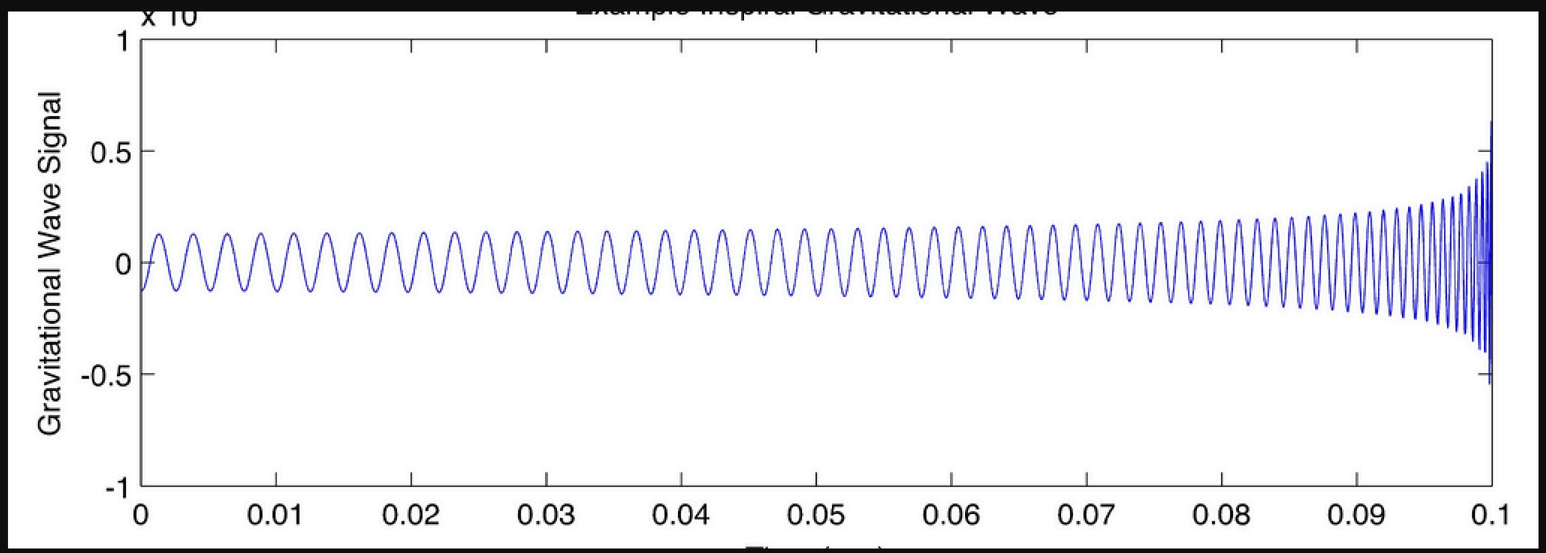
Inspiral

GW Strain from quasi-circular binary

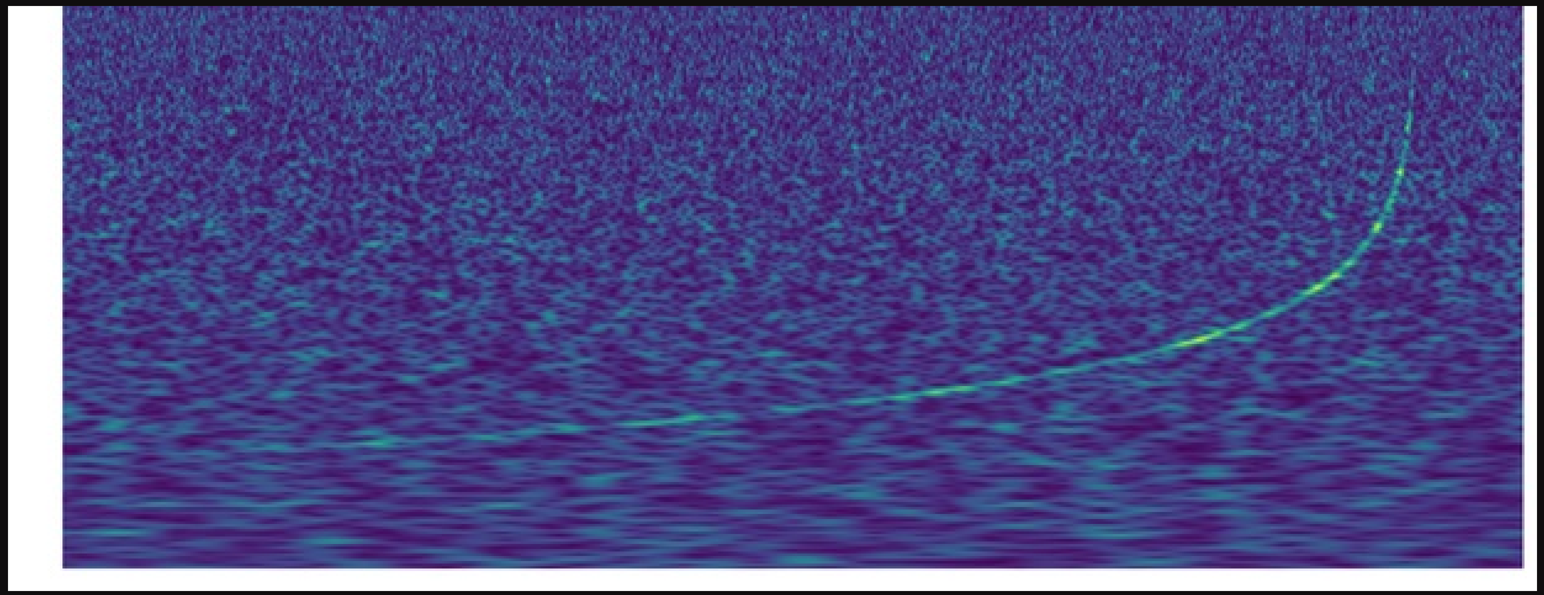
$$h_+ = \frac{G^{5/3}}{c^4}\frac{2}{r}(1+\cos^2 i)(\pi f M)^{2/3}\mu\cos(2\pi f t)$$

$$h_\times = \frac{G^{5/3}}{c^4}\frac{4}{r}\cos i(\pi f M)^{2/3}\mu\sin(2\pi f t)$$

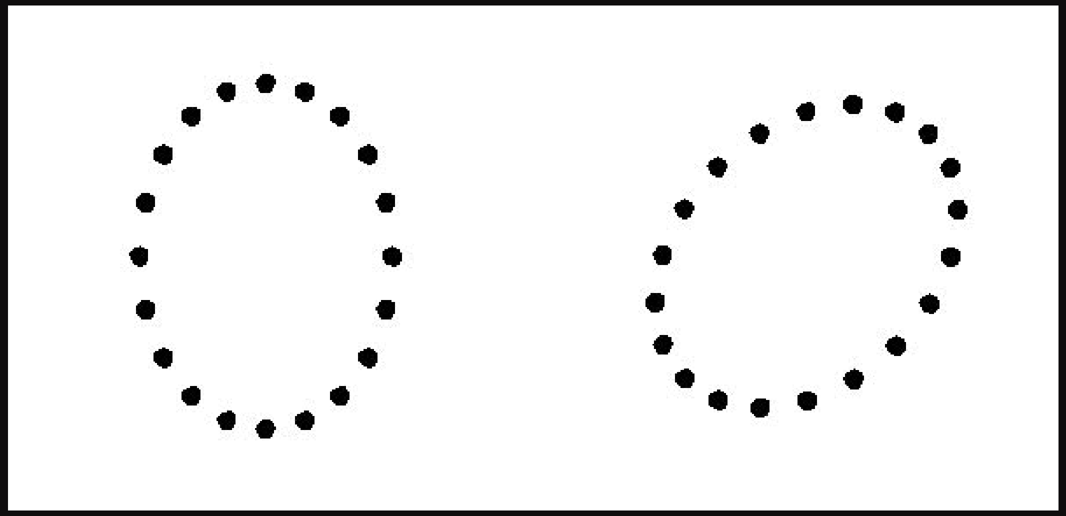
$$h = (\langle h_+^2\rangle + \langle h_\times^2\rangle)^{1/2} = \left(\frac{32}{5}\right)^{1/2}\frac{G^{5/3}}{c^4}\frac{M_c^{5/3}}{r}(\pi f)^{2/3}$$



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



Credit: LSC/Alex Nitz, https://www.ligo.caltech.edu/WA/image/ligo20171016f



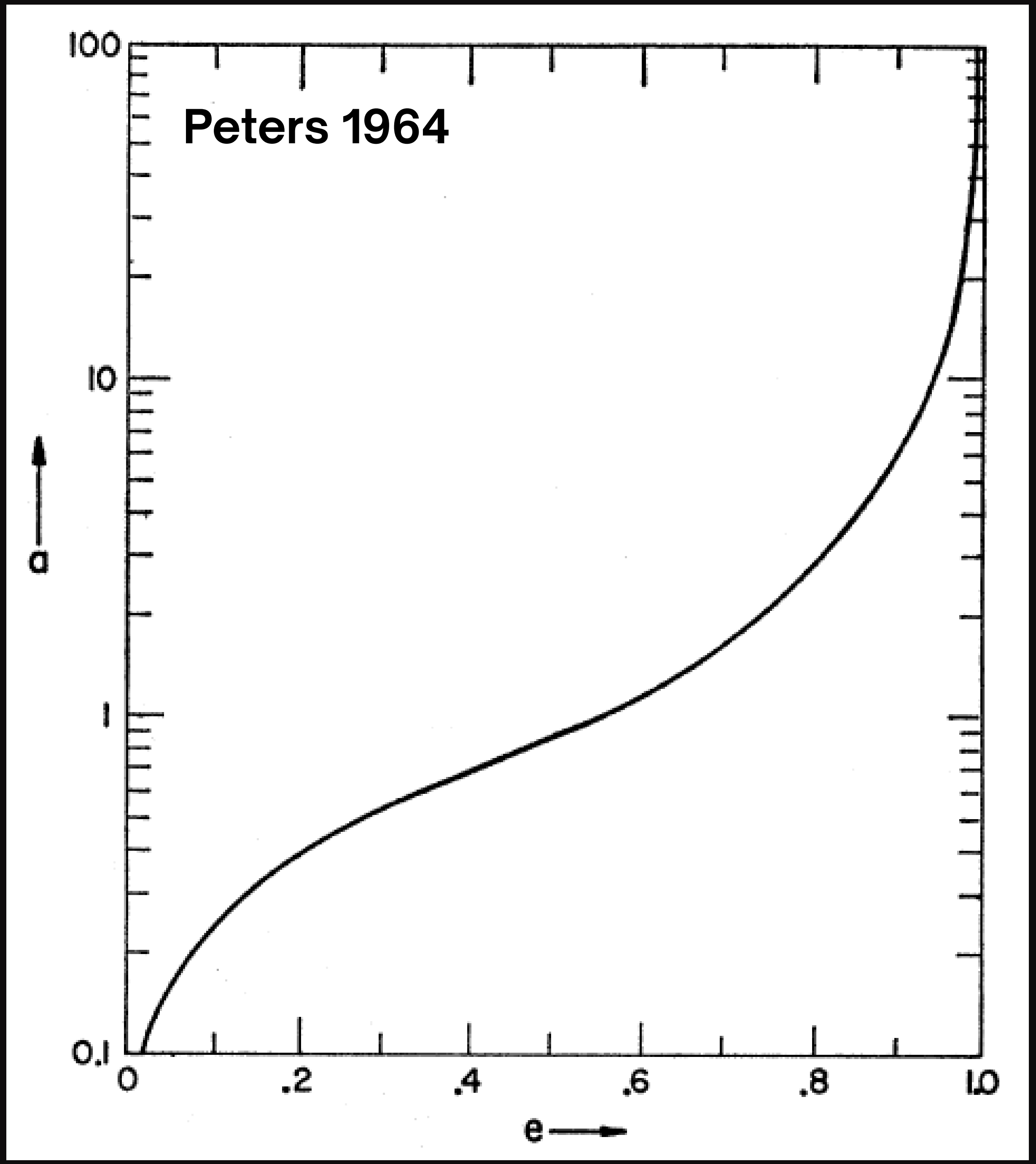
Inspiral

Circularization

- Energy & Angular momentum radiation (Peters 1964)

$$\left\langle \frac{dE}{dt} \right\rangle = -\frac{32}{5}\frac{G^4 m_1^2 m_2^2 (m_1+m_2)}{c^5 a^5 (1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

$$\left\langle \frac{dL}{dt} \right\rangle = -\frac{32}{5}\frac{G^{7/2} m_1^2 m_2^2 (m_1+m_2)}{c^5 a^{7/2} (1-e^2)^{2}}\left(1+\frac{7}{8}e^2\right)$$



Inspiral

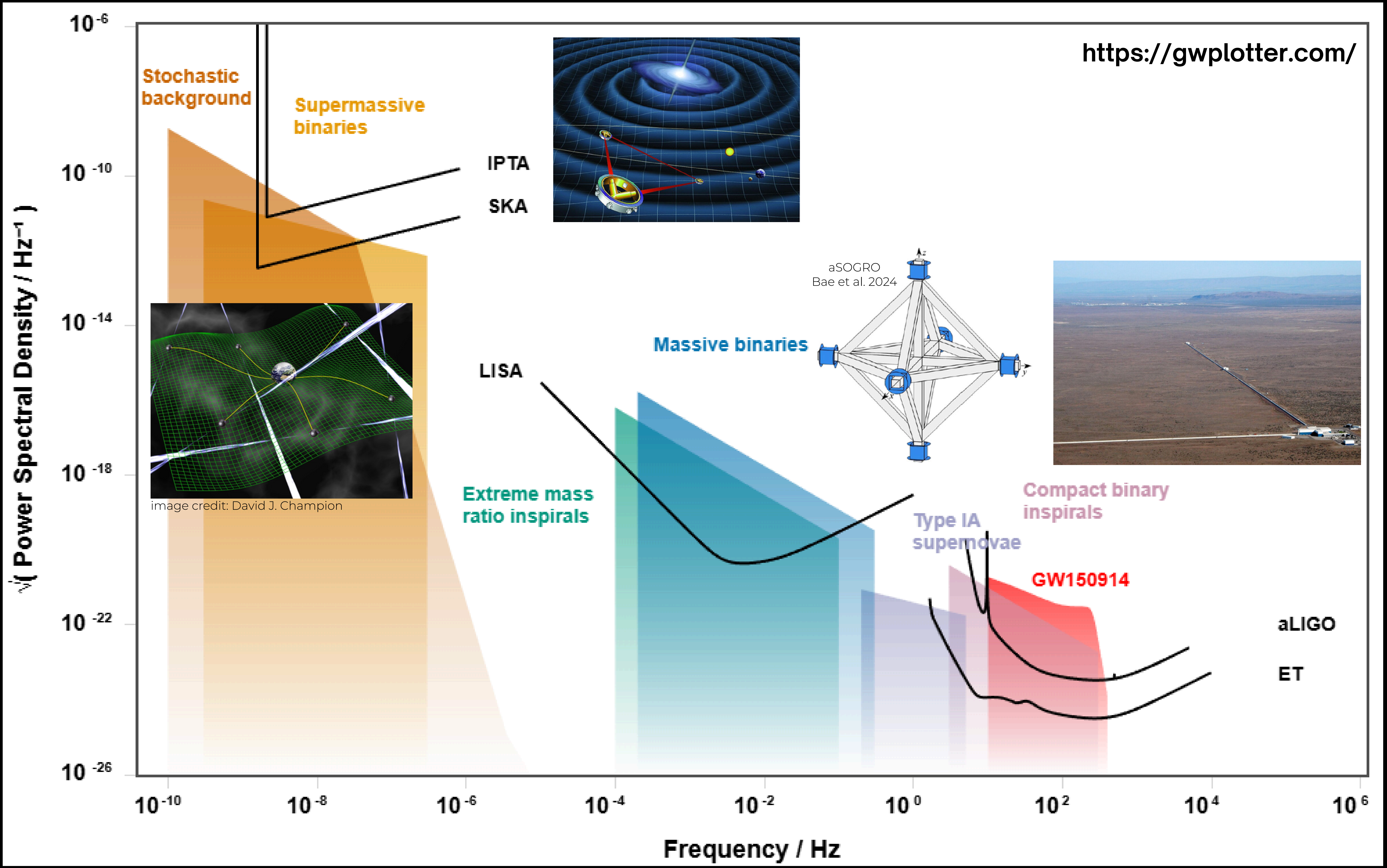
- **Innermost Stable Circular Orbit (ISCO)**
  - ISCO of test particle in Schwarzschild metric

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

  - Highest GW frequency of inspiral phase

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

  - The location of the ISCO varies with black hole spin and is less well-defined in comparable-mass binaries.
  - However, it typically marks the end of the inspiral and the onset of the plunge.



Supermassive BH	Intermediate mass BH	Stellar mass BH	Neutron star / Primordial BH

Inspiral

Highly Eccentric orbit

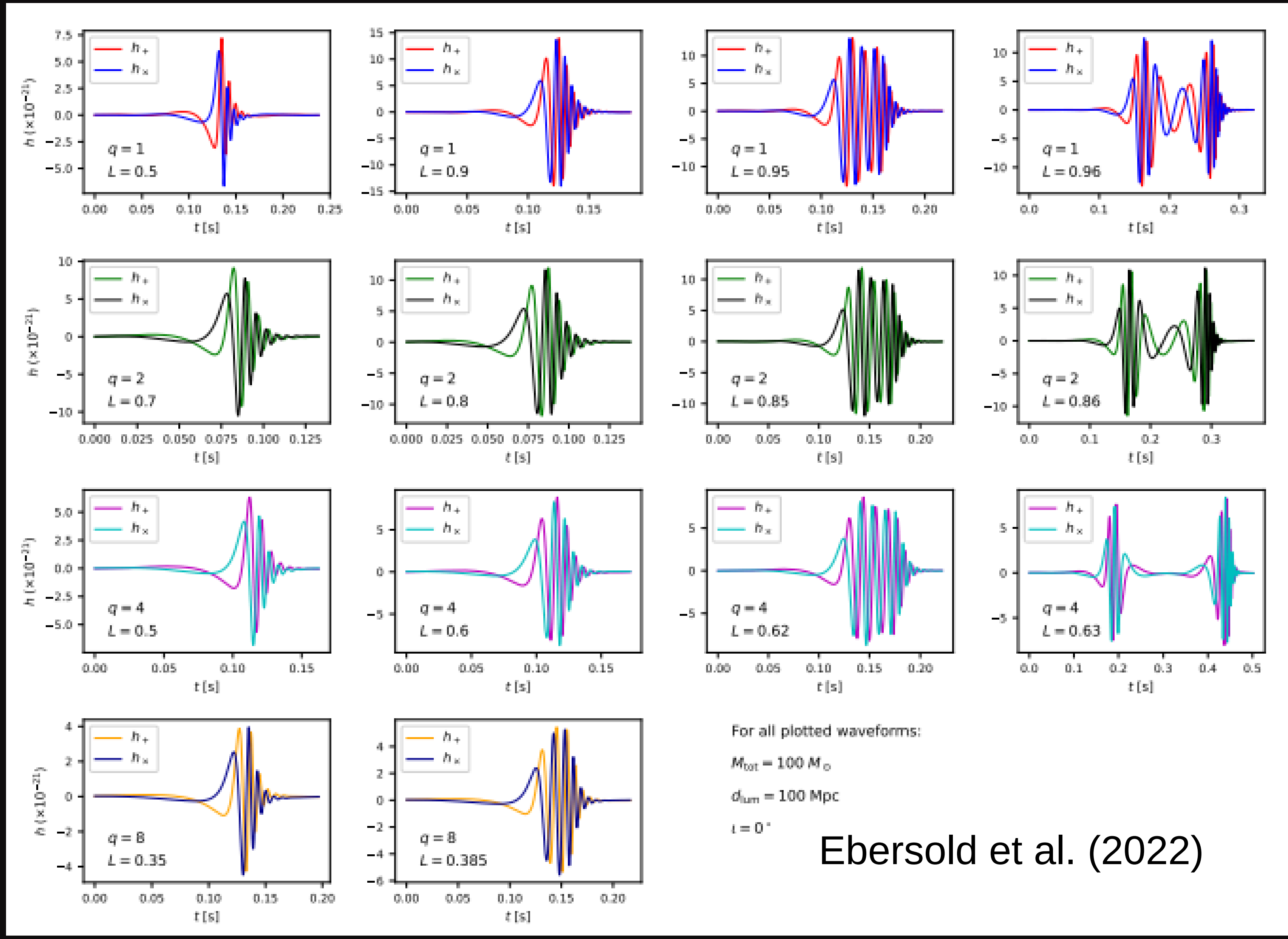
- Very close encounter of BHs
- Kozai-Lidov mechanism
- Primordial BHs

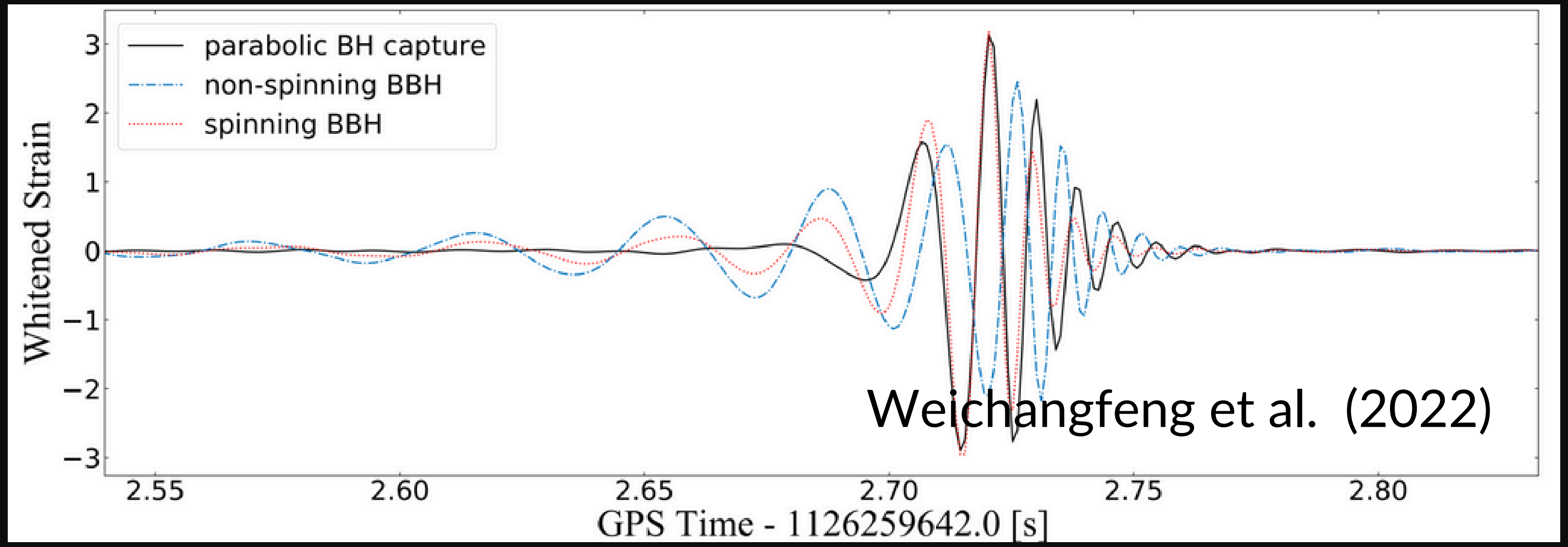
Waveform

- Sporadic burst
- Merger-Ringdown without inspiral
- Repeated burst in a short time

GW190521

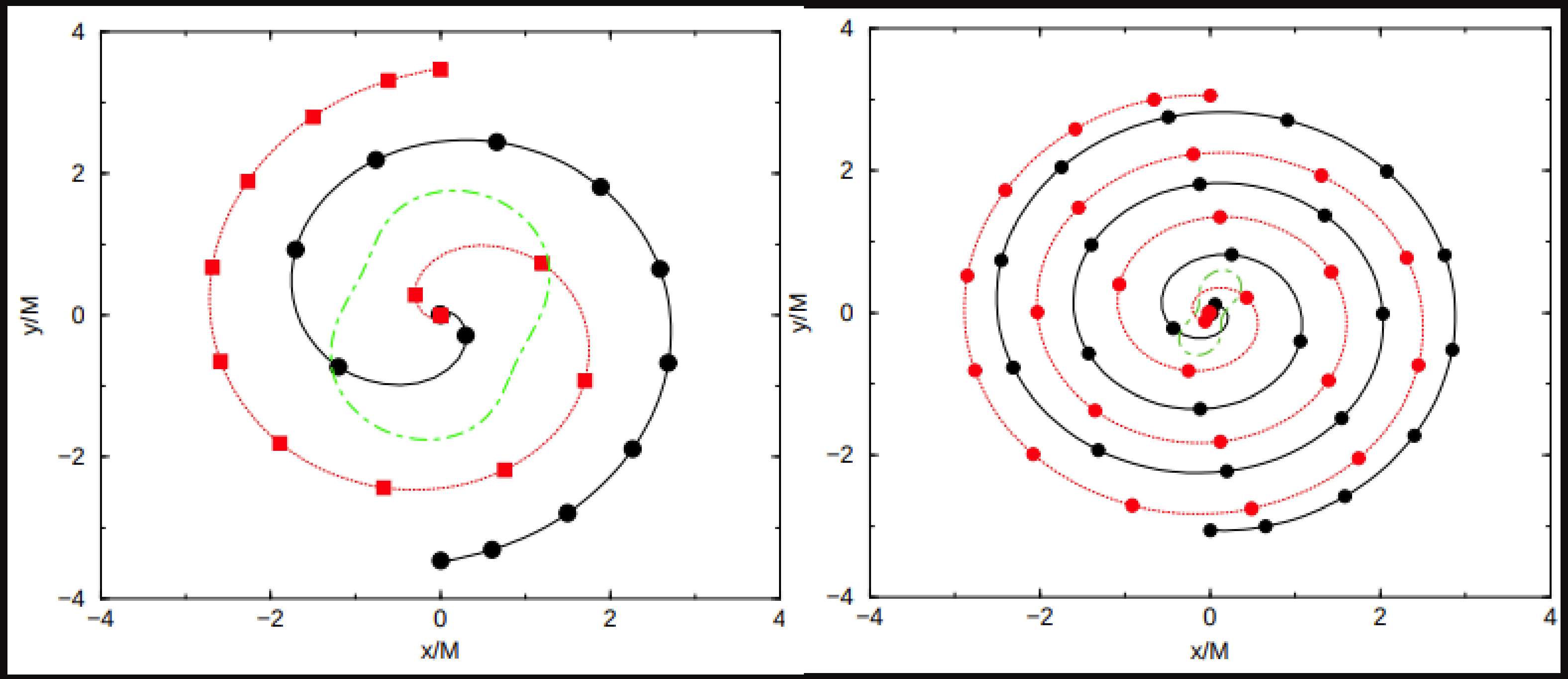
- Quasi-circular (Abbott et al. 2020)
- e~0.1 (Romero-Shaw et al. 2020)
- e~0.69 (Gayathri et al. 2022)
- Dynamical capture (e≳1) (Gamba et al. 2022)
- Head-on collision (Bustillo et al. 2021)





Inspiral

Eccentricity & Spin effect



Campanelli et al. (2006)
Orbits with anti-aligned (left) and aligned (right) spins with the direction of orbital angular momentum

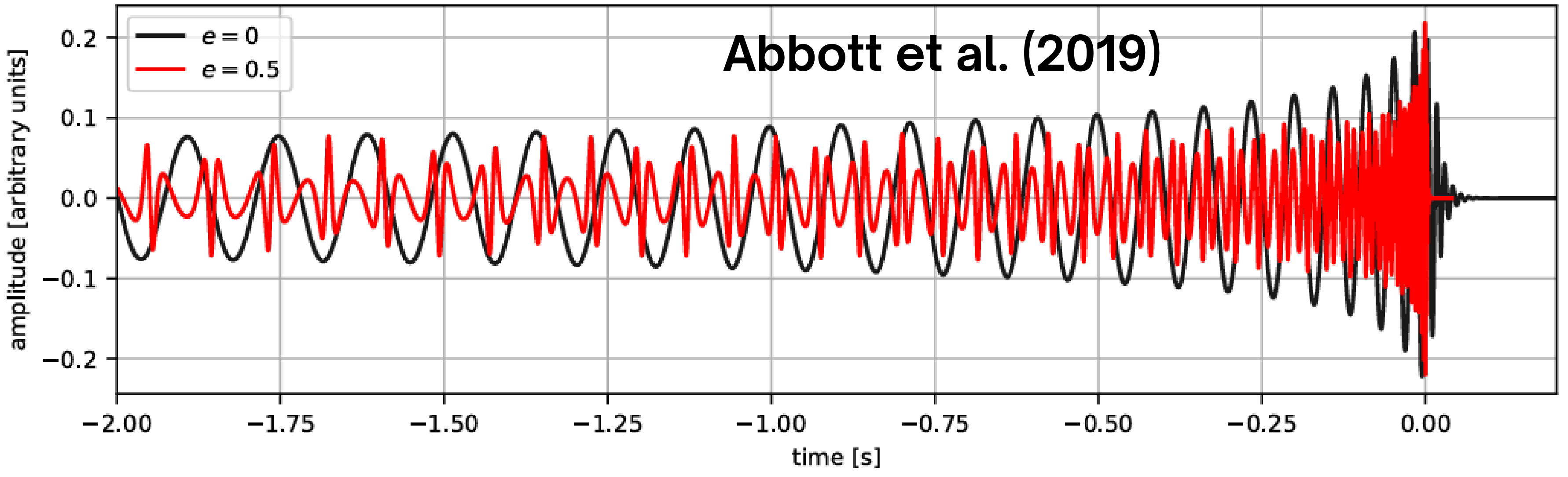
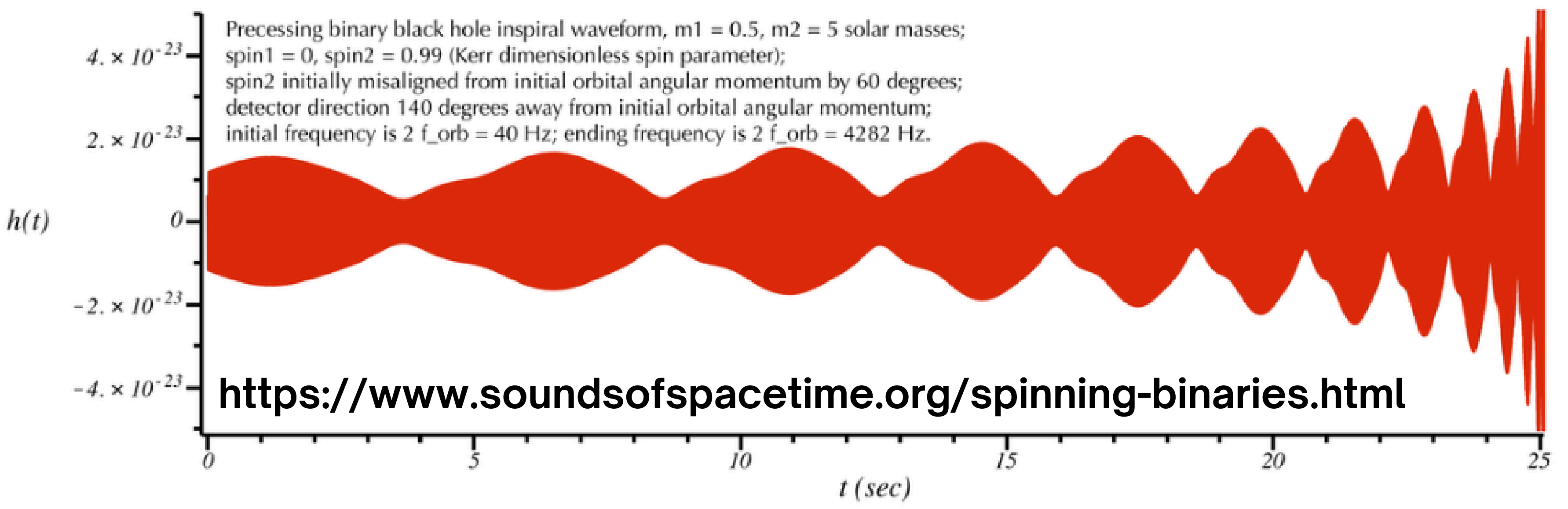


Figure 1. Examples of gravitational waveforms for a $10\,M_\odot - 10\,M_\odot$ BBH system with eccentricities 0 (black) and 0.5 (red).



Inspiral signal of two black holes showing extreme precession. System parameters are listed on the plot. Only one black hole is spinning (at close to the maximum rate). Notice the large modulations to the amplitude of the signal.

Merger

- **Each BH reaches very high speed just before merger.**
- **GW emission peak**
- **Common horizon forms**
- **Recoil (Kick)**
  - Asymmetric GW emission
  - Unequal mass / Spin
  - Up to ~10,000 km/s (Healy et al. 2009)
- **Numerical Relativity**
  - 3+1 formalism
  - Accurate, but slow and expensive

Numerical Relativity

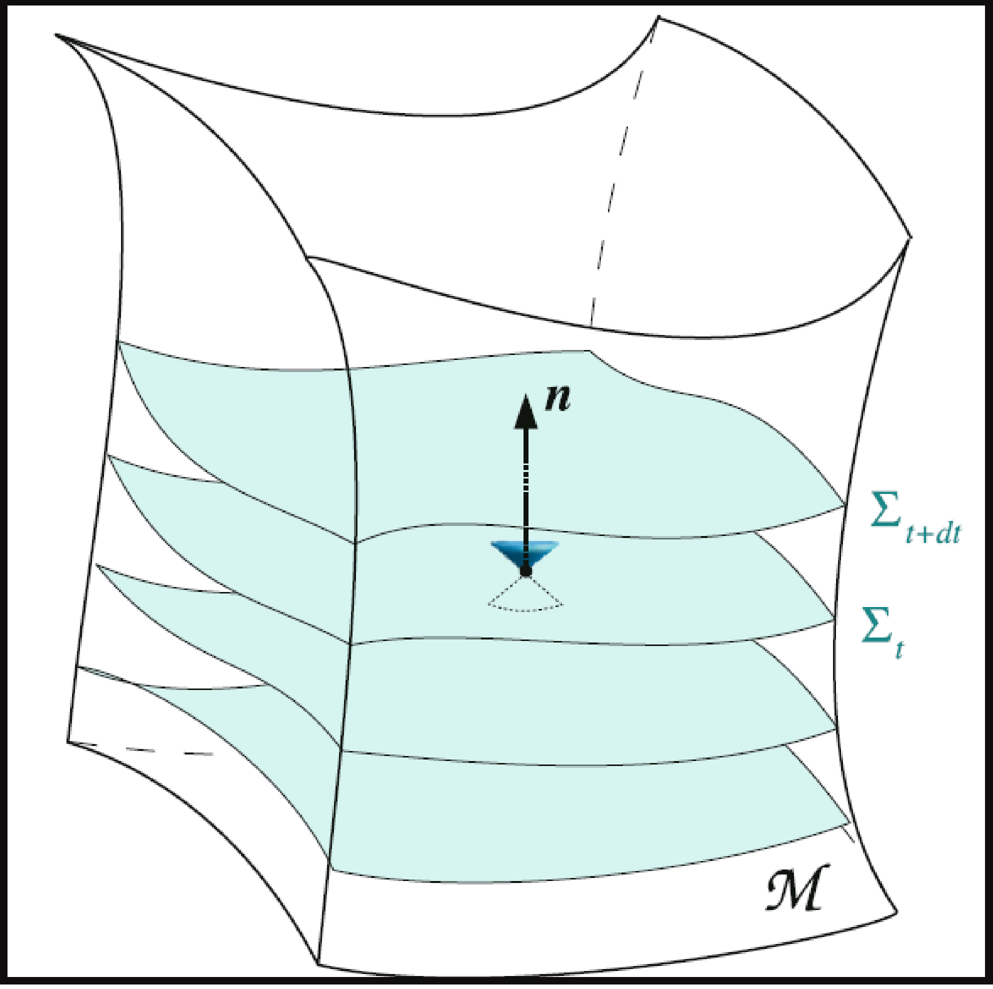
Einstein equations

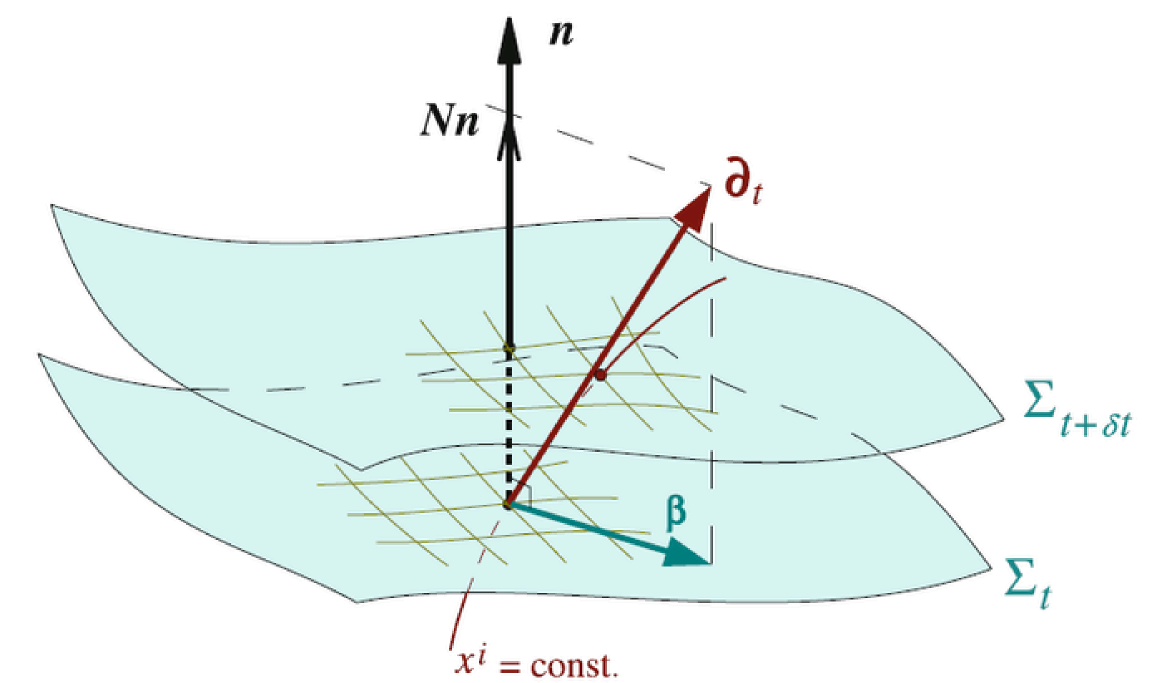
$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

3+1 formalism

- 4 dimensional space time → 3+1 dimension
- Constraint & Evolution equations
- Gauge choice

Metric	$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$
Hamiltonian Constraint	$R + K^2 - K_{ij}K^{ij} = 16\pi\rho$
Momentum Constraint	$D_j(K^{ij} - \gamma^{ij}K) = 8\pi S^i$
Evolution equation of spatial metric	$\partial_t \gamma_{ij} = -2\alpha K_{ij} + D_i\beta_j + D_j\beta_i$
Evolution equation of extrinsic curvature	$\partial_t K_{ij} = \alpha(R_{ij} - 2K_{ik}K^k_j + KK_{ij}) - D_iD_j\alpha - 8\pi\alpha(S_{ij} - \frac{1}{2}\gamma_{ij}(S-\rho)) + \beta^k\partial_k K_{ij} + K_{ik}\partial_j\beta^k + K_{kj}\partial_i\beta^k$
$\rho = n_a n_b T^{ab}, \quad S^i = -\gamma^{ij} n^a T_{aj}, \quad S_{ij} = \gamma_{ia}\gamma_{jb}T^{ab}, \quad S = \gamma^{ij}S_{ij}$	





Gourgoulhon, E. 2012, 3+1 Formalism in General Relativity: Bases of Numerical Relativity, Lecture Notes in Physics, Volume 846

Ringdown

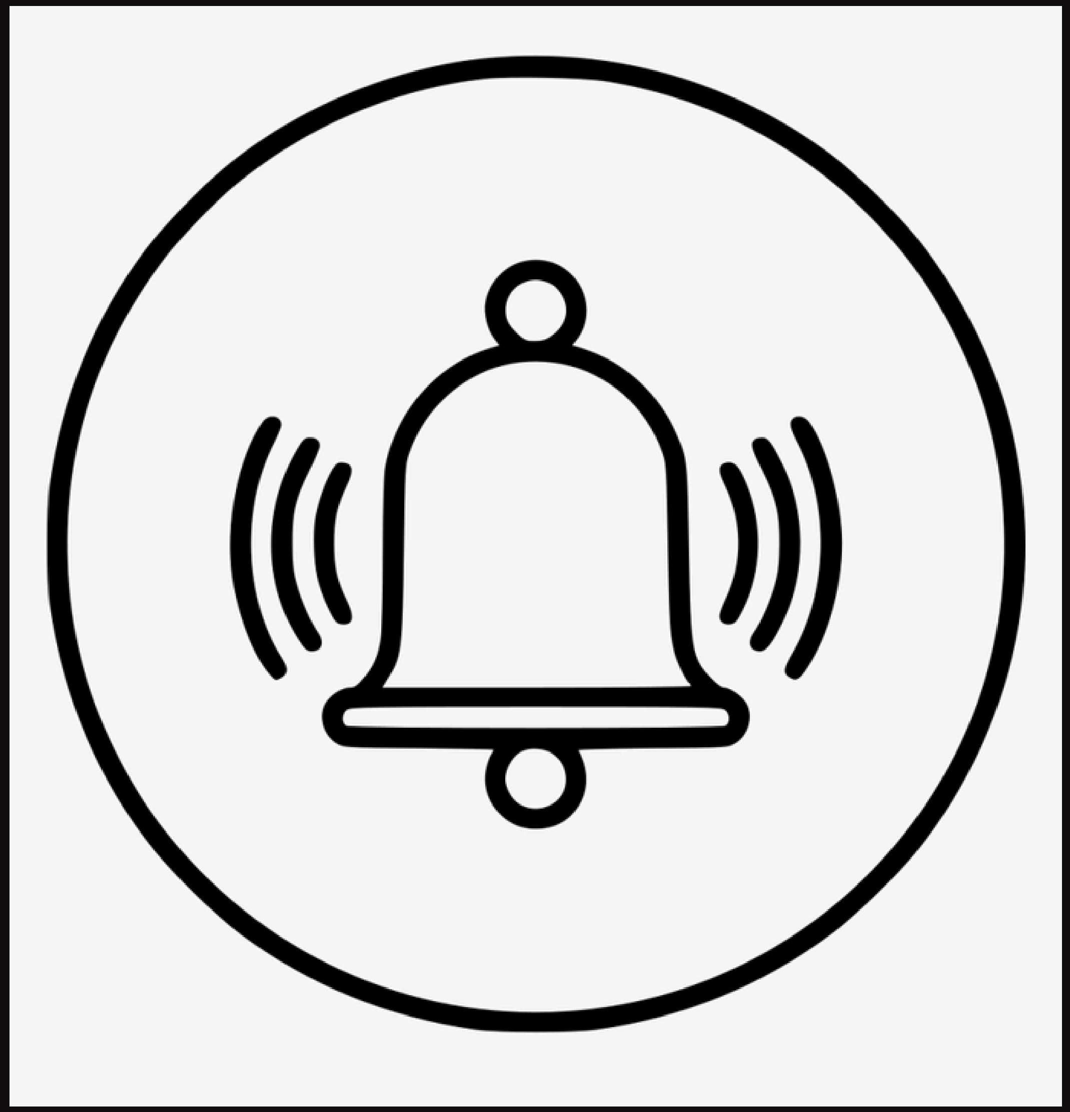
- **Love number**
  - Parameter that measures the rigidity or deformability of a body (planet/star) in response to the tidal forces exerted by another body
  - Higher Love number - less rigid / Lower Love number - more rigid
  - For static external tidal field:
    - Schwarzschild BH - zero Love number (e.g. Binnington & Poisson 2009)
    - Kerr BH - Small, but non-zero Love number (e.g. Le Tiec & Casals 2021)
  - How about that in dynamical situation?

Ringdown

- **Ringing of merged black hole**
  - Gradually settling into a stable Kerr black hole
  - Damped oscillation after the merger
- **Higher GW frequency than inspiral**
- **Perturbation theory**
- **Astrophysical information - mass, spin**
- **Quasi-normal mode (Berti et al. 2006, …)**

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

- **Testing general relativity**



Ringdown

TABLE II. First three overtones for $l = 2$. A comma separates the real part from the imaginary part of $M\omega$. To save space, in this and the following Tables we omit leading zeros.

j	$m = 2$	$m = 1$	$m = 0$	$m = -1$	$m = -2$
			$l = 2$, $n = 0$		
0.00	.3737,.0890	.3737,.0890	.3737,.0890	.3737,.0890	.3737,.0890
0.10	.3870,.0887	.3804,.0888	.3740,.0889	.3678,.0890	.3618,.0891
0.20	.4021,.0883	.3882,.0885	.3751,.0887	.3627,.0889	.3511,.0892
0.30	.4195,.0877	.3973,.0880	.3770,.0884	.3584,.0888	.3413,.0892
0.40	.4398,.0869	.4080,.0873	.3797,.0878	.3546,.0885	.3325,.0891
0.50	.4641,.0856	.4206,.0862	.3833,.0871	.3515,.0881	.3243,.0890
0.60	.4940,.0838	.4360,.0846	.3881,.0860	.3489,.0876	.3168,.0890
0.70	.5326,.0808	.4551,.0821	.3941,.0845	.3469,.0869	.3098,.0887
0.80	.5860,.0756	.4802,.0780	.4019,.0822	.3454,.0860	.3033,.0885
0.90	.6716,.0649	.5163,.0698	.4120,.0785	.3444,.0849	.2972,.0883
0.98	.8254,.0386	.5642,.0516	.4223,.0735	.3439,.0837	.2927 − .0881
			$l = 2$, $n = 1$		
j	$m = 2$	$m = 1$	$m = 0$	$m = -1$	$m = -2$
0.00	.3467,.2739	.3467,.2739	.3467,.2739	.3467,.2739	.3467,.2739
0.10	.3619,.2725	.3545,.2731	.3472,.2737	.3400,.2744	.3330,.2750
0.20	.3790,.2705	.3635,.2717	.3486,.2730	.3344,.2744	.3206,.2759
0.30	.3984,.2680	.3740,.2698	.3511,.2718	.3296,.2741	.3093,.2765
0.40	.4208,.2647	.3863,.2670	.3547,.2700	.3256,.2734	.2989,.2769
0.50	.4474,.2602	.4009,.2631	.3594,.2674	.3225,.2723	.2893,.2772
0.60	.4798,.2538	.4183,.2575	.3655,.2638	.3201,.2708	.2803,.2773
0.70	.5212,.2442	.4399,.2492	.3732,.2585	.3184,.2686	.2720,.2773
0.80	.5779,.2281	.4676,.2358	.3826,.2507	.3173,.2658	.2643,.2772
0.90	.6677,.1953	.5059,.2097	.3935,.2385	.3167,.2620	.2570,.2770
0.98	.8249,.1159	.5477,.1509	.4014,.2231	.3164,.2581	.2515,.2768
			$l = 2$, $n = 2$		
j	$m = 2$	$m = 1$	$m = 0$	$m = -1$	$m = -2$
0.00	.3011,.4783	.3011,.4783	.3011,.4783	.3011,.4783	.3011,.4783
0.10	.3192,.4735	.3104,.4756	.3017,.4778	.2932,.4801	.2846,.4825
0.20	.3393,.4679	.3214,.4719	.3038,.4764	.2866,.4811	.2697,.4862
0.30	.3619,.4613	.3342,.4671	.3074,.4739	.2813,.4814	.2559,.4895
0.40	.3878,.4533	.3492,.4607	.3124,.4701	.2772,.4808	.2433,.4925
0.50	.4179,.4433	.3669,.4522	.3190,.4647	.2741,.4794	.2316,.4952
0.60	.4542,.4303	.3878,.4407	.3273,.4571	.2721,.4768	.2207,.4977
0.70	.4999,.4123	.4133,.4241	.3374,.4464	.2709,.4729	.2107,.4999
0.80	.5622,.3839	.4451,.3984	.3488,.4307	.2703,.4674	.2013,.5019
0.90	.6598,.3275	.4867,.3502	.3591,.4067	.2697,.4600	.1925,.5038
0.98	.8238,.1933	.5201,.2331	.3599,.3808	.2686,.4527	.1858,.5051

Berti et al. 2006

Ringdown

- For a 10-solar-mass non-spinning BH, the physical scales of the (l=2,m=2,n=0) mode are as follows:

In geometrized unit system,

$$1M = \frac{GM}{c^3} \approx 4.926\ \mu\text{s} \times \left(\frac{M}{M_\odot}\right)$$

For 10 solar mass BH case:

$$M \approx 49.26\ \mu\text{s}$$

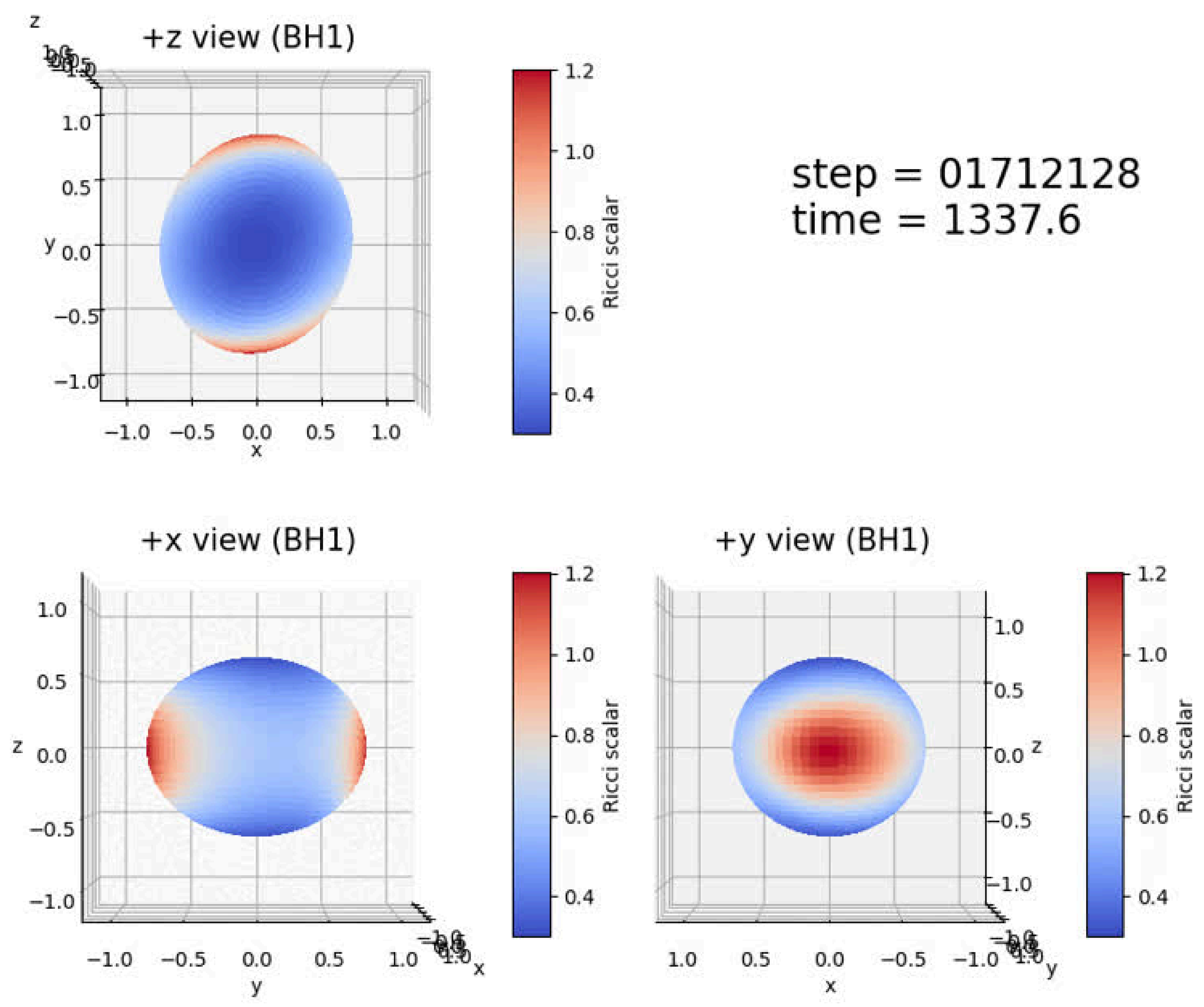
Oscallation frequency:

$$\omega_R M = 0.3737 \to \omega_R = \frac{0.3737}{M} \approx 7586\ \text{rad/s}$$

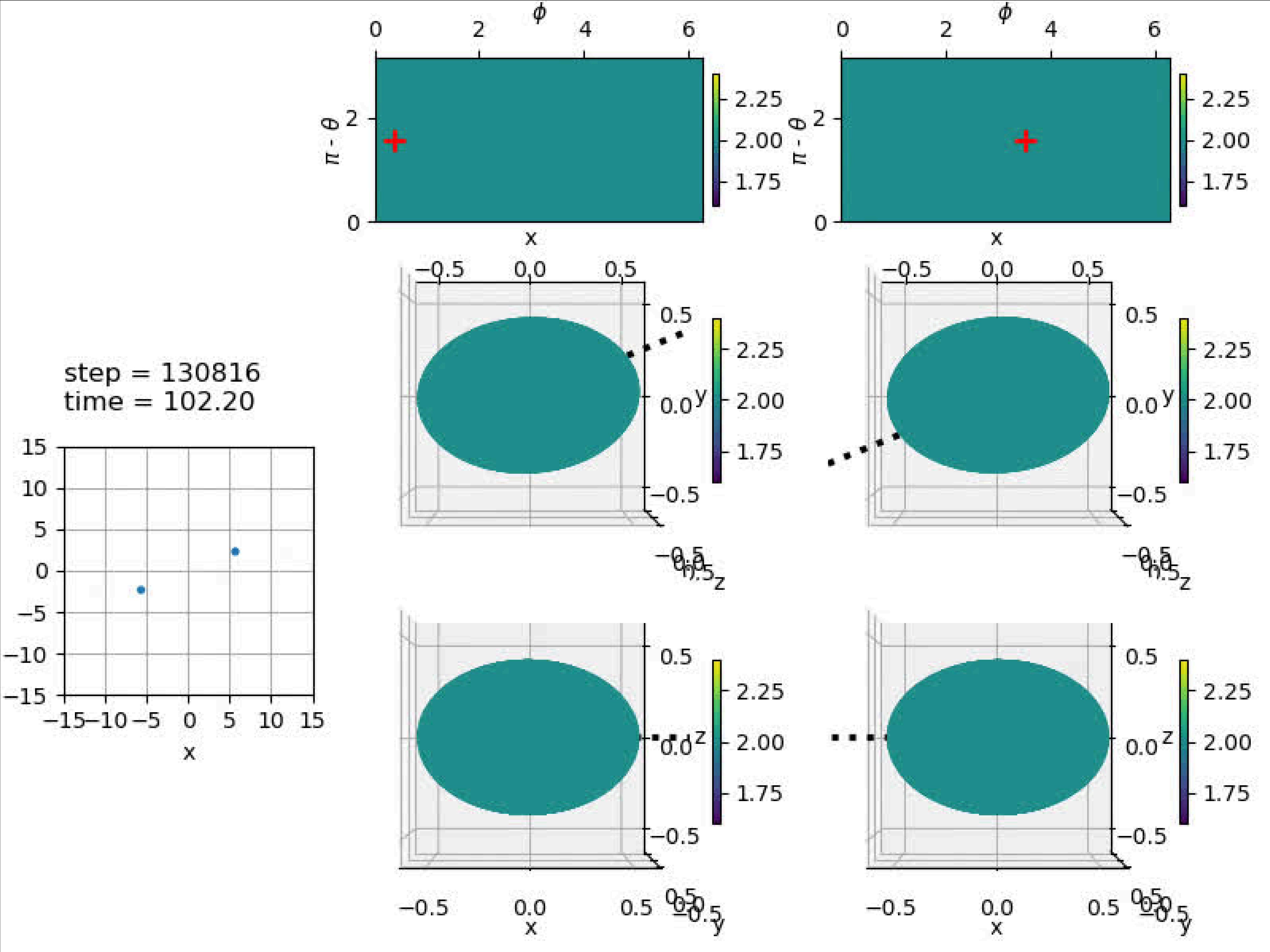
$$f = \frac{\omega_R}{2\pi} \approx 1207\ \text{Hz}$$

Damping time:

$$\omega_I M = 0.0890 \to \tau = \frac{1}{\omega_I} \approx 553.5\ \mu\text{s}$$



+z view (BH1)
+x view (BH1)
+y view (BH1)
Ricci scalar
step = 01712128
time = 1337.6
x
y
z



step = 130816
time = 102.20
x
ϕ
π - θ
x
y
z

GWTC

GRAVITATIONAL WAVE TRANSIENT CATALOG

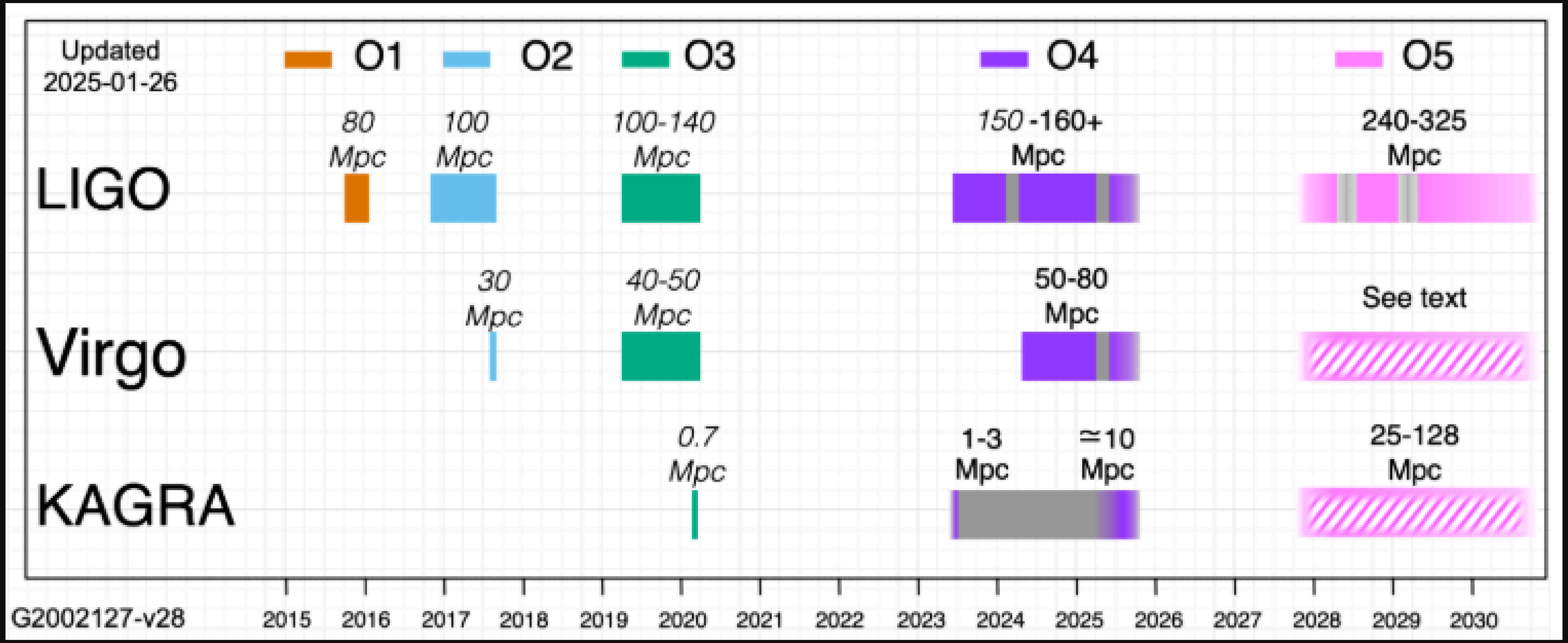
Modeled vs. Unmodeled search

- Modeled search
  - Assumes theoretical waveform templates
  - Uses matched filtering for signal extraction
  - Suitable for compact binary coalescence (CBC) events
  - Enables accurate parameter estimation
  - May miss poorly modeled or unexpected signals
- Unmodeled search
  - Makes no assumption about signal shape
  - Detects excess power in time-frequency domain
  - Requires coincident excess power triggers in two or more detectors to reject local glitches and confirm genuine signals
  - Uses algorithms like Coherent WaveBurst (cWB)
  - Designed to detect bursts, supernovae, unknown transients
  - Less precies; higher false-alarm rate

GWTC

Gravitational-Wave Transient Catalog

- **GWTC-1**
  - O1 (2015.09.12 - 2016.01.19)
    - First detection of GWs
  - O2 (2016.11.30 - 2017.08.25)
    - First detection of a binary neutron star inspiral
  - 11 GW sources
- **GWTC-2, GWTC-2.1**
  - O3a (2019.04.01 - 2019.10.01)
  - 44 GW sources
- **GWTC-3**
  - O3b (2019.11.01 - 2020.03.27)
  - 35 GW sources
- **GWTC-4 ?**
  - O4a (2023.05.24 - 2024.01.16)
  - O4b (2024.04.10 - 2025.01.28)
  - O4c (2025.01.28 - 2025.11.18)
  - More than 200 GW sources



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

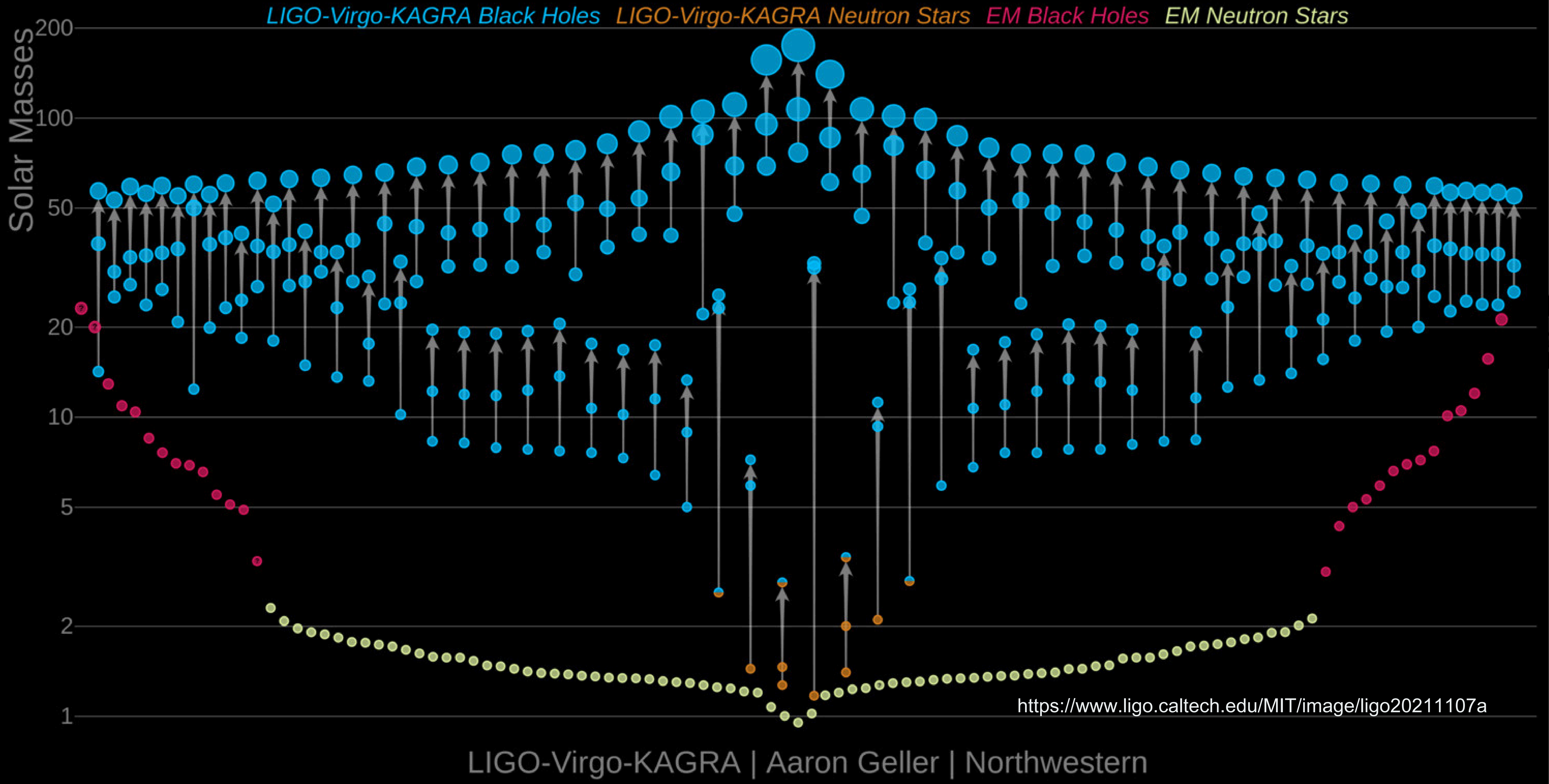
GWTC

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}	$-0.12^{+0.24}_{-0.30}$	$62.6^{+13.9}_{-9.4}$

...

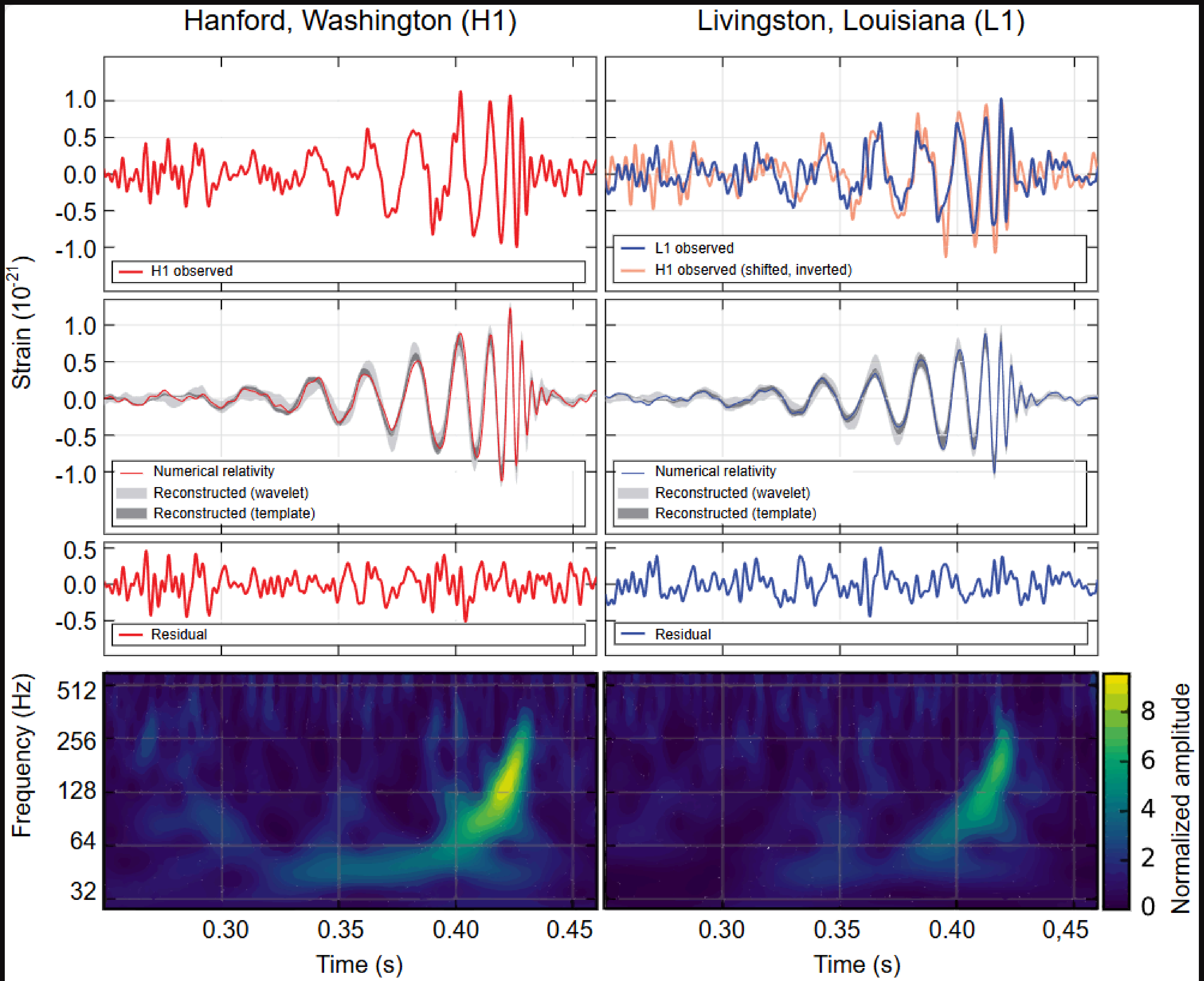
https://gwosc.org/eventapi/html/GWTC/

Masses in the Stellar Graveyard



GW150914

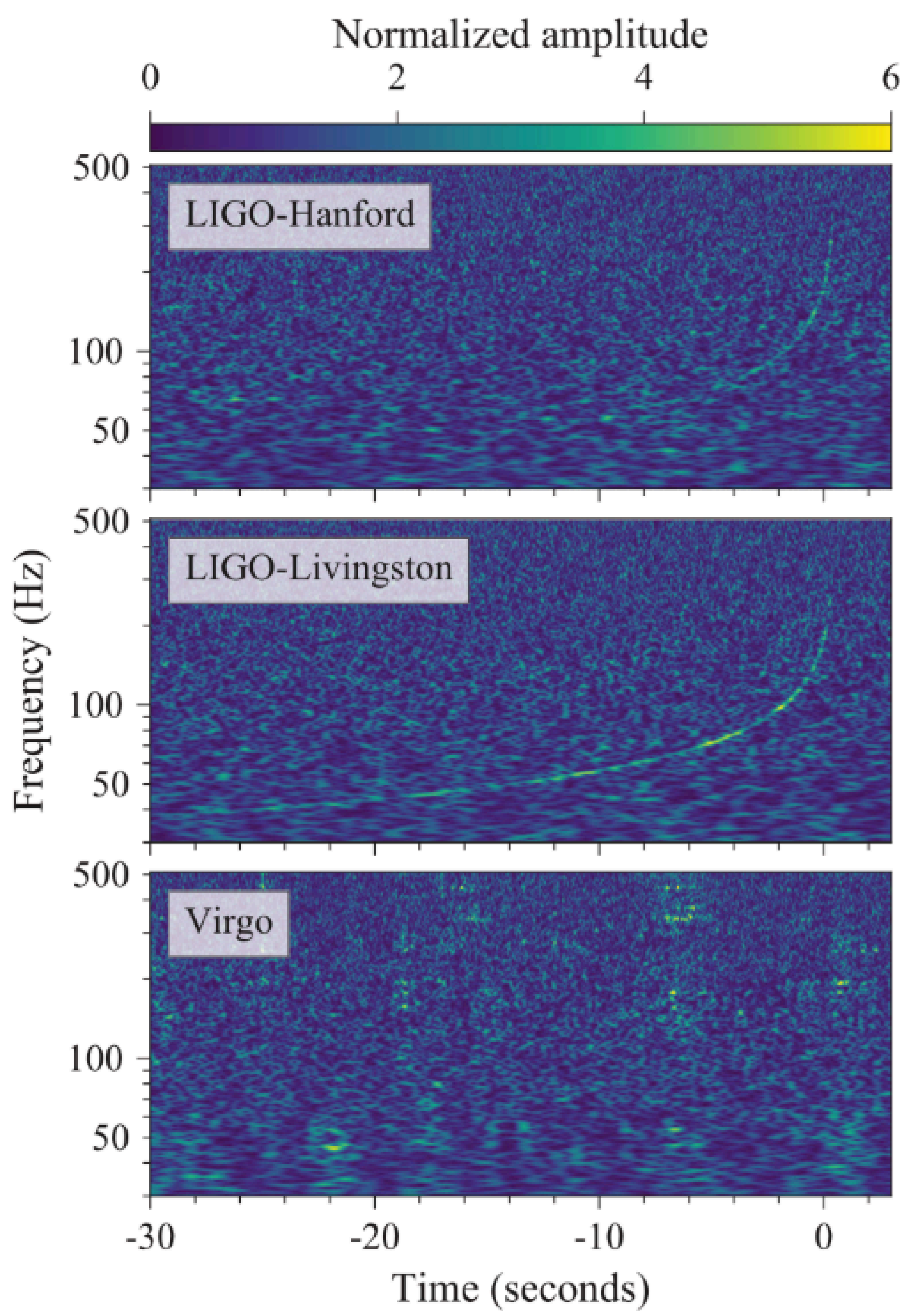
- First direct GW detection
- First observational confirmation of stellar-mass binary black hole mergers
- Source: Binary black hole merger
  - $m_1 \sim 36\ M_{\odot}$, $m_2 \sim 29\ M_{\odot}$
  - Final BH mass: $\sim 62 M_{\odot}$, Energy radiated: $\sim 3 M_{\odot}$
  - Distance ~ 440 Mpc
- Network SNR ~ 26, Duration ~ 0.2s
- 2017 Nobel Prize in physics



B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) — full list at the end of the article - http://physics.aps.org/featured-article-pdf/10.1103/PhysRevLett.116.061102 . See also the associated Jupyter notebook.

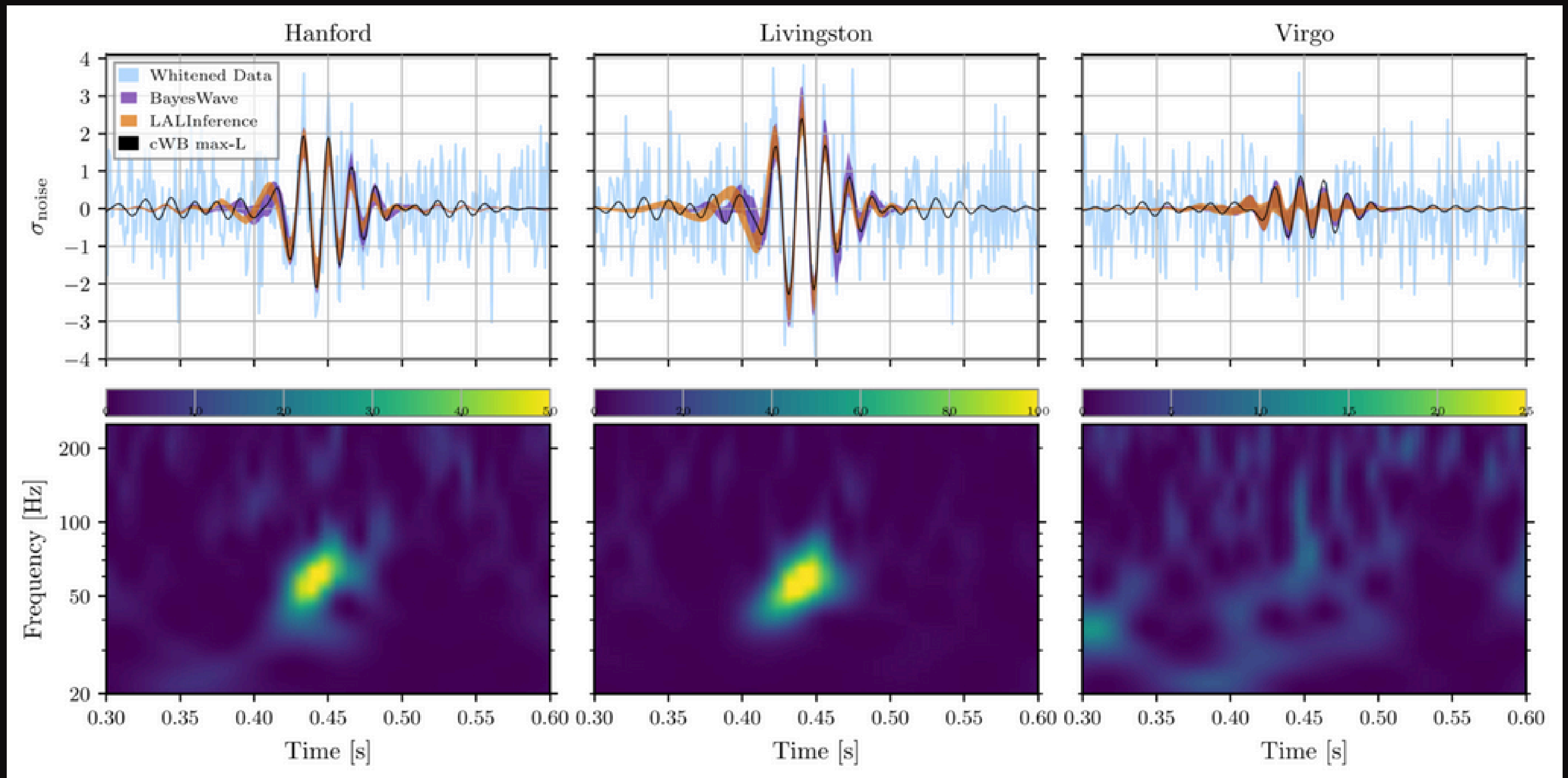
GW170817

- **First multimessenger astrophysics event**
  - Combined GW + EM observations
- **Source: Binary neutron star merger (inspiral)**
  - $m_1 \sim 1.46\ M_\odot$, $m_2 \sim 1.27\ M_\odot$
  - Distance ~ 40 Mpc
- **Network SNR ~ 33, Duration ~ 100s**
- **Electromagnetic counterparts**
  - Detected ~1.7s later: Gamma-ray burst (GRB 170817A)
  - Optical + infrared follow up: Kilonova
  - Over 70 observatories contributed
- **Used as a standard siren to measure Hubble constant ~70km/s/Mpc**



LIGO Scientific Collaboration and Virgo Collaboration

GW190521



R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration) - https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.101102 https://doi.org/10.1103/PhysRevLett.125.101102

- Source: Binary black hole merger
  - m_1 ~85 $M_\odot$, m_2 ~66 $M_\odot$
  - Final BH ~ 142 $M_\odot$: IMBH candidate
  - Distance ~ 5.3 Gpc
- Very short signal (~0.1s), peaking at low frequencies (~60Hz)
- BH fall into the upper mass gap (~60-120 $M_\odot$) & Resulting BH is in the IMBH range
- Hints at possible hierarchical mergers or new formation channels
- May have originated from an eccentric binary merger, potentially in a dense stellar environment

GW200105 / GW200115

- **Source: Neutron star - Binary black hole merger**
  - GW200105: $m_1 \sim 8.9\ M_\odot$, $m_2 \sim 1.9\ M_\odot$
  - GW200115: $m_1 \sim 5.7\ M_\odot$, $m_2 \sim 1.5\ M_\odot$
- **Confident detections of NS-BH mergers by LIGO-Virgo**
- **Secondary masses are consistent with NS.**
- **No electromagnetic counterpart detected.**
  - Likely due to high mass ratio and no tidal disruption of the NS
- **Added critical data to population models and merger rate estimates**

GWTC-3

Abbott et al. (2023) PRX 13, 011048

Merger rate

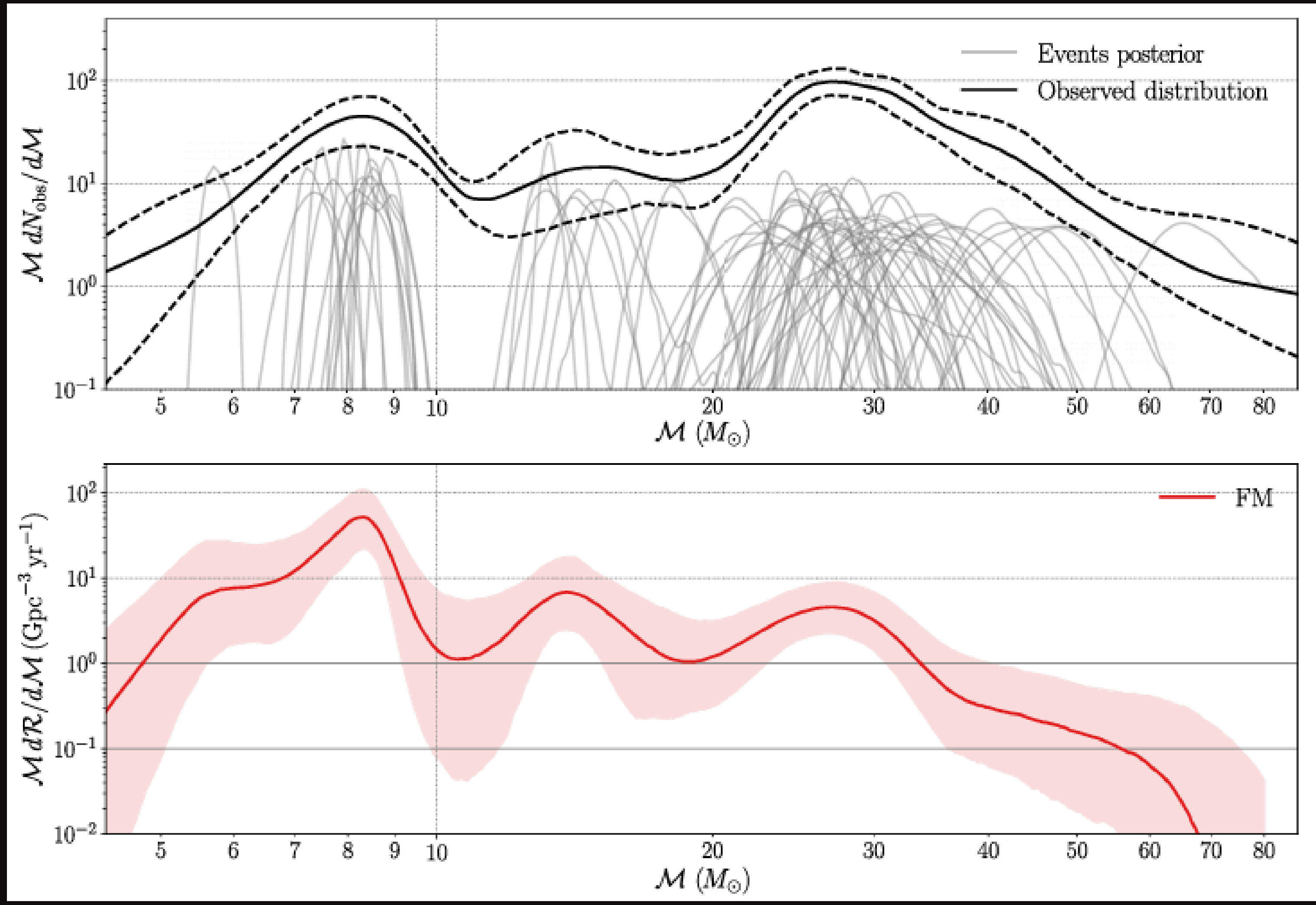
- BNS: 10-1700 Gpc^{-3} yr^{-1}
- NSBH: 7.8-140 Gpc^{-3} yr^{-1}
- BBH: 17.9-44 Gpc^{-3} yr^{-1} (at z=0.2)

Mass distribution

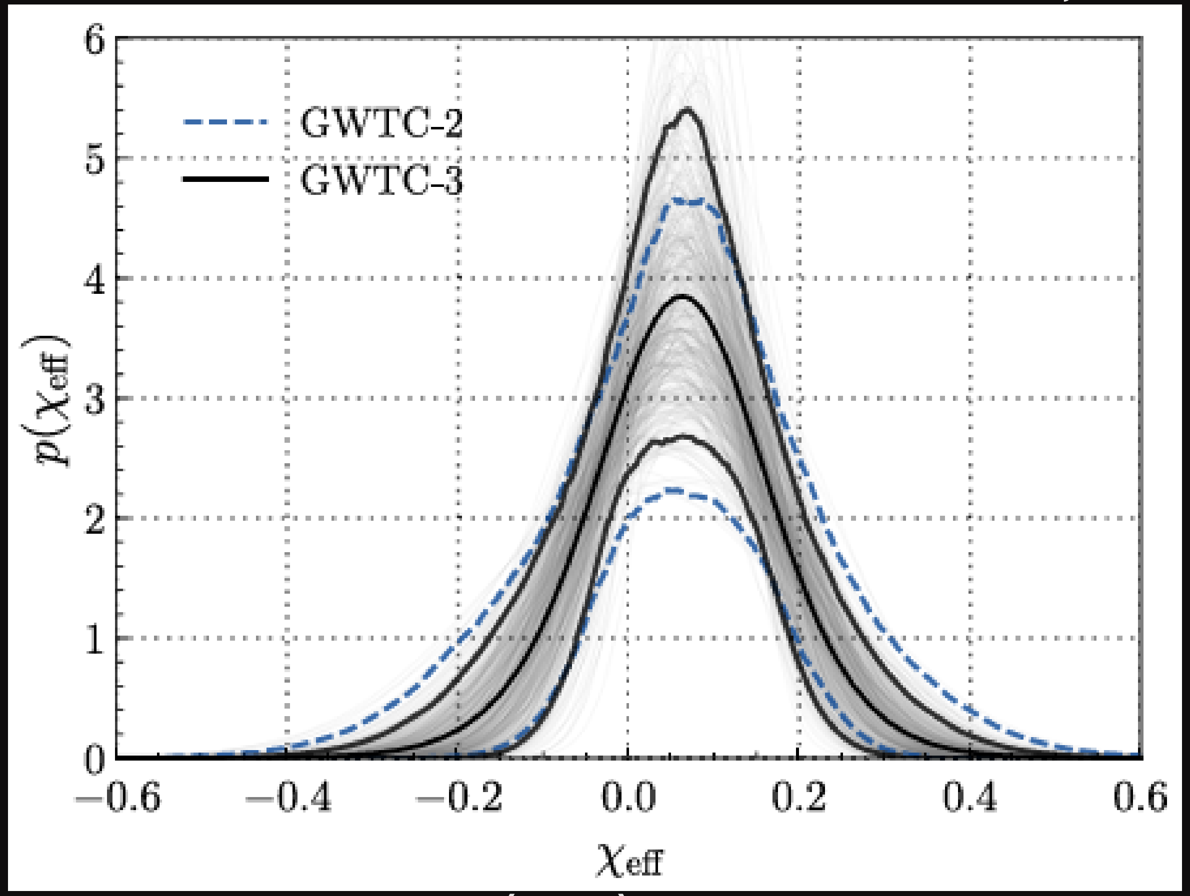
- NS: broad, relatively flat distribution from 1.2 $M_\odot$ to 2.0 $M_\odot$
- BBH: Peaks emerging at chirp masses of 8.3 $M_\odot$ and 27.9 $M_\odot$
- Primary mass distribution strongly decrease with mass; no clear evidence of an upper mass gap suppression above ~60 $M_\odot$

BH spin

- Typically small; half are below $\chi_i \simeq 0.25$
- Negative effective spin χ_{eff}~29%
- Increase in spin magnitude for systems with more unequal mass ratios



Abbott et al. (2023) PRX 13, 011048

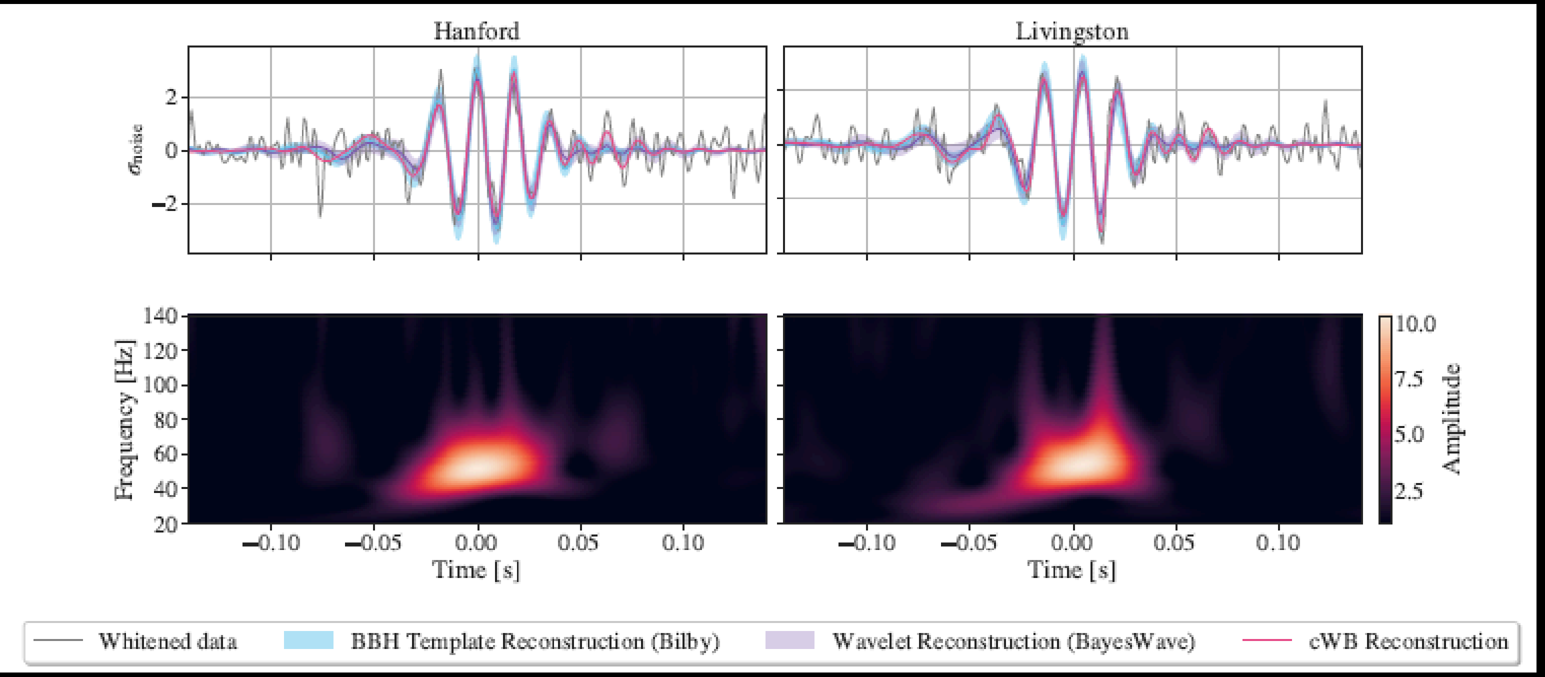


Abbott et al. (2023) PRX 13, 011048

GW231123

(arXiv:2507.08219)

- **Highest-mass** BBH observed to date (190-265 $M_\odot$ total remnant mass), featuring two BHs with **exceptionally high spins**.
- The primary BH's mass challenges the theorized upper mass gap, suggesting formation channels beyond standard stellar collapse, such as **hierarchical mergers**.



arXiv:2507.08219

Primary mass $m_1/\mathrm{M}_\odot$	137^{+22}_{-17}
Secondary mass $m_2/\mathrm{M}_\odot$	103^{+20}_{-52}
Mass ratio $q = m_2/m_1$	$0.75^{+0.22}_{-0.39}$
Total mass $M/\mathrm{M}_\odot$	238^{+28}_{-49}
Final mass $M_\mathrm{f}/\mathrm{M}_\odot$	225^{+26}_{-43}
Primary spin magnitude χ_1	$0.90^{+0.10}_{-0.19}$
Secondary spin magnitude χ_2	$0.80^{+0.20}_{-0.51}$
Effective inspiral spin χ_eff	$0.31^{+0.24}_{-0.39}$
Effective precessing spin χ_p	$0.77^{+0.17}_{-0.19}$
Final spin χ_f	$0.84^{+0.08}_{-0.16}$
Luminosity distance $D_\mathrm{L}/\mathrm{Gpc}$	$2.2^{+1.9}_{-1.5}$
Inclination angle $\theta_\mathrm{JN}/\mathrm{rad}$	$1.4^{+0.8}_{-1.1}$
Source redshift z	$0.39^{+0.27}_{-0.24}$
Network matched filter SNR ρ	$22.6^{+0.2}_{-0.3}$

arXiv:2507.08219

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