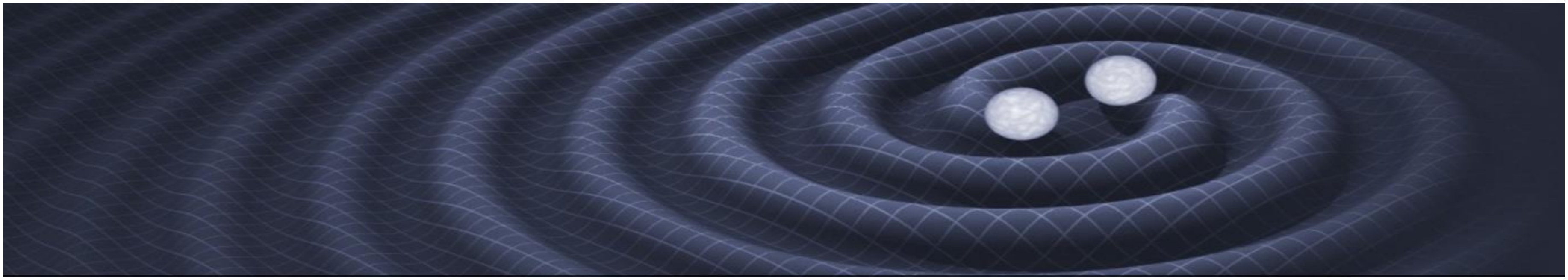
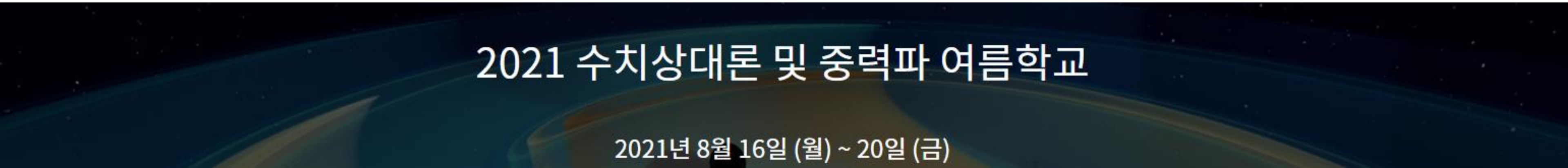


중력파 천체물리학 I,II,III

김정리
(이화여자대학교)



강의 개요

- 강의 1: 정의, 개념 소개 + **중력파 천문학**
- 강의 2: **중력파 천체물리학**
- 강의3: **중력파 천체물리학 (보충) + 중력파 관측**

참고문헌

GW transient catalogue -1 https://arxiv.org/abs/1811.12907

GW transient catalogue -2” https://arxiv.org/abs/2010.14527

과 이 논문에 기재된 참고문헌들

(+) 천문학, 천체물리학 교과서

universe, astrophysics 주제 TED 강연

중력파 천체물리학 Gravitational-Wave Astrophysics

- 밀집성의 형성과 진화 (단일별, 쌍성)
  Formation and evolution of compact stars

- 무거운 블랙홀의 형성과 진화 (배영복 박사님 강의)

관측 예) 블랙홀-블랙홀 병합(GW150914), 중성자별-중성자별 병합(GW170817)

블랙홀-중성자별 병합(GW200105) 은 지구상 중력파 검출기로 중력파 신호 관측 성공.

다중신호 천문학 Multimessenger Astronomy

- 우주에서 오는 빛, 입자, 중력파 등 다양한 "신호"를 종합적으로 활용하여 관측하자 ➔ 다각적이고 보다 깊은 이해 가능

- 조건: 다양한 신호 방출 + 이들 신호가 관측 가능

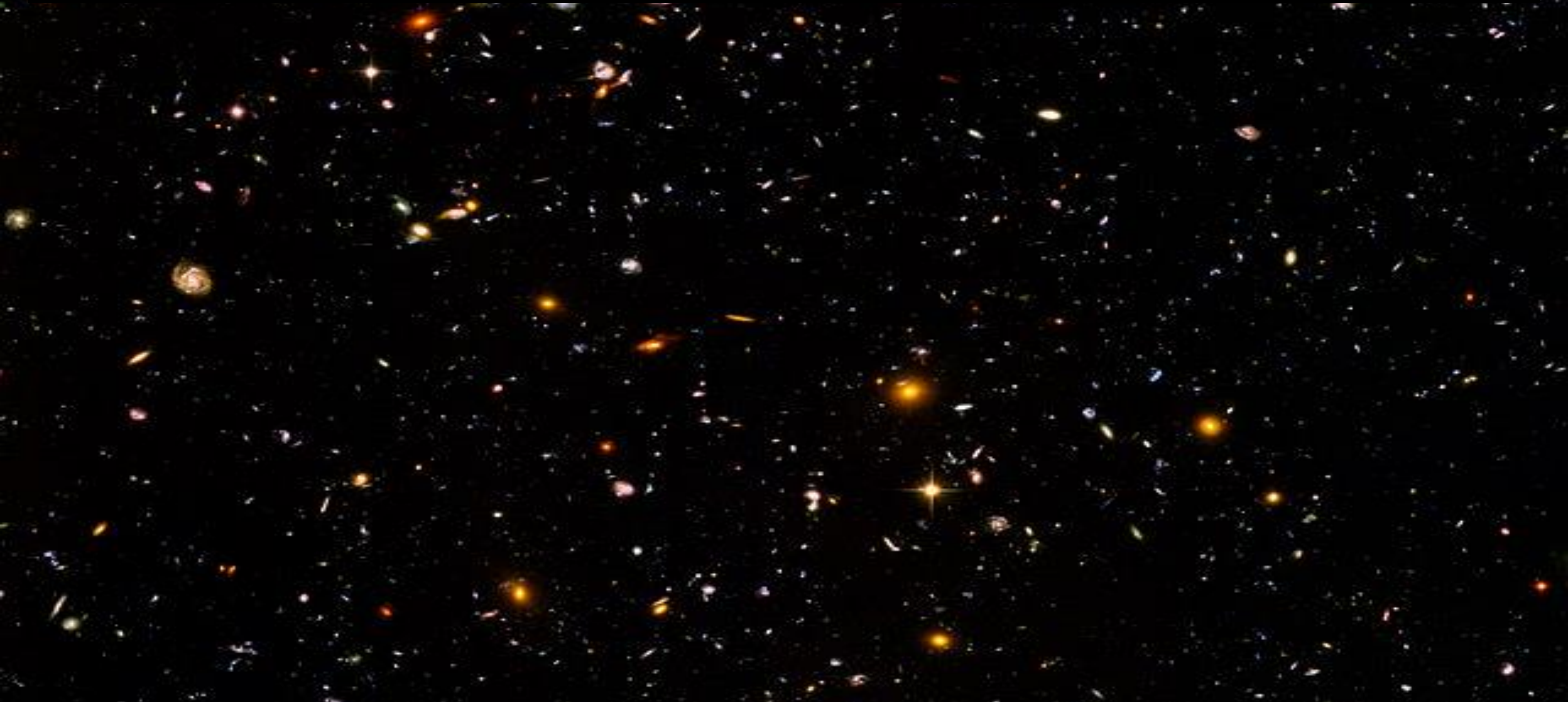
- 다중신호 천문학을 활용한 허블상수 측정, 우주론 검증 (이형목 교수님 강의)

관측 예) SN1987A (빛 + 중성미자) 거대마젤란은하에서 발생한 초신성폭발

GW170817 (중력파) 외부은하에서 일어난 중성자별-중성자별(NS-NS) 병합 최초 관측,
NS-NS 병합 ➔ 감마선폭발 ➔ 킬로노바 발생 (이론 예측)이 관측으로 확인

IceCube-170922A (빛 + 중성미자) "천체물리학적으로 근원이 규명된"
중성미자 관측.

빛으로 본 우주



We cannot see a light source if it is too far, too faint, or blocked by something.

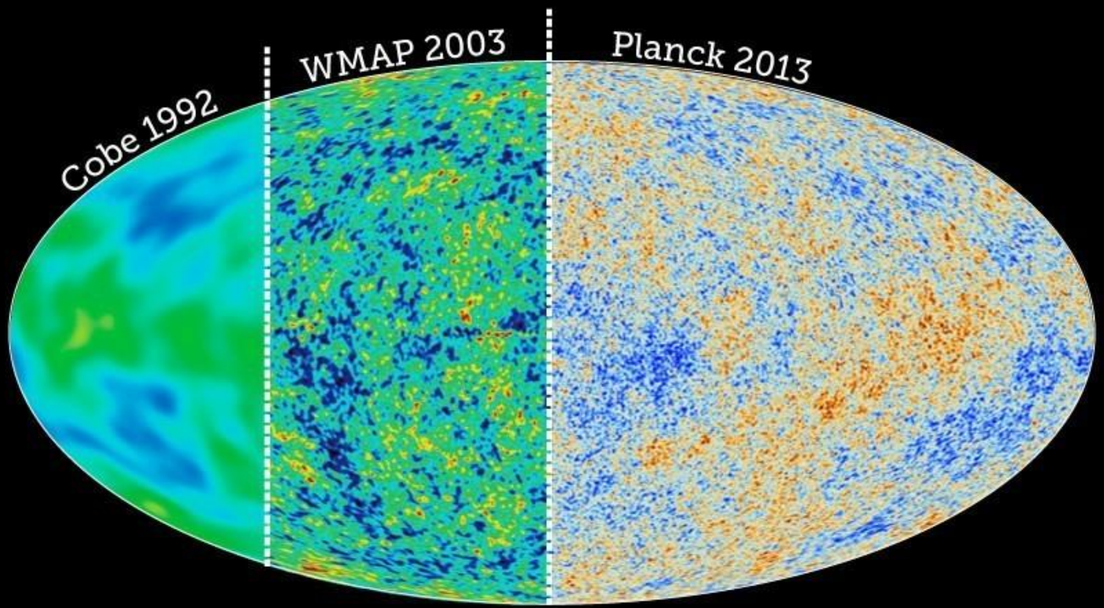
Some objects in the universe do not emit light at all.

감마선으로 본 우주
(“transients” = one-time strong emission of lights 섬광?)

GW sources are typically observable as transients in 10-2000 Hz
“binary inspirals” or “mergers”

Cosmic microwave background

“black body radiation (T=2.7 K)”

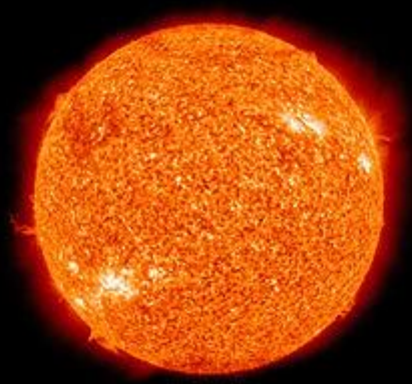


“GW background” are expected in all frequencies

lowest frequencies: early universe “inflation signature”

higher frequencies: astrophysical origin
(superposition of GWs from astrophysical objects)

Some astronomical objects are observable at all times
“continuous sources”



Supermassive BH binaries would orbit very slowly

(period ~ billion yrs, dP/dt is very small, amplitude barely changes)

➔ emitting GWs at a constant frequency

➔ “continuous sources”

관련 용어

- **초신성 supernova**

  태양보다 수십 배 무거운 별의 진화 후기 단계에서 발생하기도 하는 별의 폭발 현상
  강한 가시광선 방출 ➔ 이어서 점차 낮은 에너지의 빛이 방출되는 것을 afterglow라고 부름

- **White dwarf (WD), Neutron star (NS)** and **Black hole (BH)**

  end phases of massive stars 밀집성(고중력천체) : 백색왜성, 중성자별, 블랙홀

- **짧은 감마선폭발(섬광?) short gamma-ray burst (sGRB)**

  감마선 빛이 몇 초 정도로 짧게 방출되는 현상. 우주 전역에서 관측되고 있음. 1일~1회 정도
  감마선 폭발 현상에 이어서 점차 낮은 에너지의 빛이 방출되는 것을 afterglow라고 부름
  burst of gamma-rays in seconds
  central engine is still not well known, but NS-NS merger is confirmed to be a short GRB progenitor (GW170817)

관련 용어 “전파 천문학과 중력파 천체물리학” “펄서와 중력파 관측”

- **Pulsar (PSR) 펄서**

 중성자별 중에서 강한 표면 자기장을 띄고, 전파빔을 방출하는 천체. 우리 은하내 수천 개 관측
 우리가 알고 있는 중성자별은 대부분 우리 은하내 전파빔을 내는 펄서로 관측되어 존재가 확인됨.
 일부는 엑스선이나 감마선을 내기도 함.
 rapidly spinning highly magnetized neutron stars

- **Millisecond pulsar (MSP)** 밀리초 펄서, 자전주기가 ms인 펄서. 우리 은하내에서 수십 개 관측

 밀리초 펄사는 쌍성을 이루고 있거나 단독으로 존재.
 ➔ 쌍성으로 존재하는 밀리초 펄사는 짝이 종류에 따라 상대성이론 검증의 도구로 활용
 (헐스-테일러펄사 1974 발견, 1993 노벨물리학상 수상. 최초로 발견된 우리 은하내 NS-NS 쌍성)
 ➔ 단독으로 존재하는 밀리초 펄사를 펄서 타이밍 어레이에 활용
 pulsars spinning several hundreds times per second
 spin period ~ millisecond

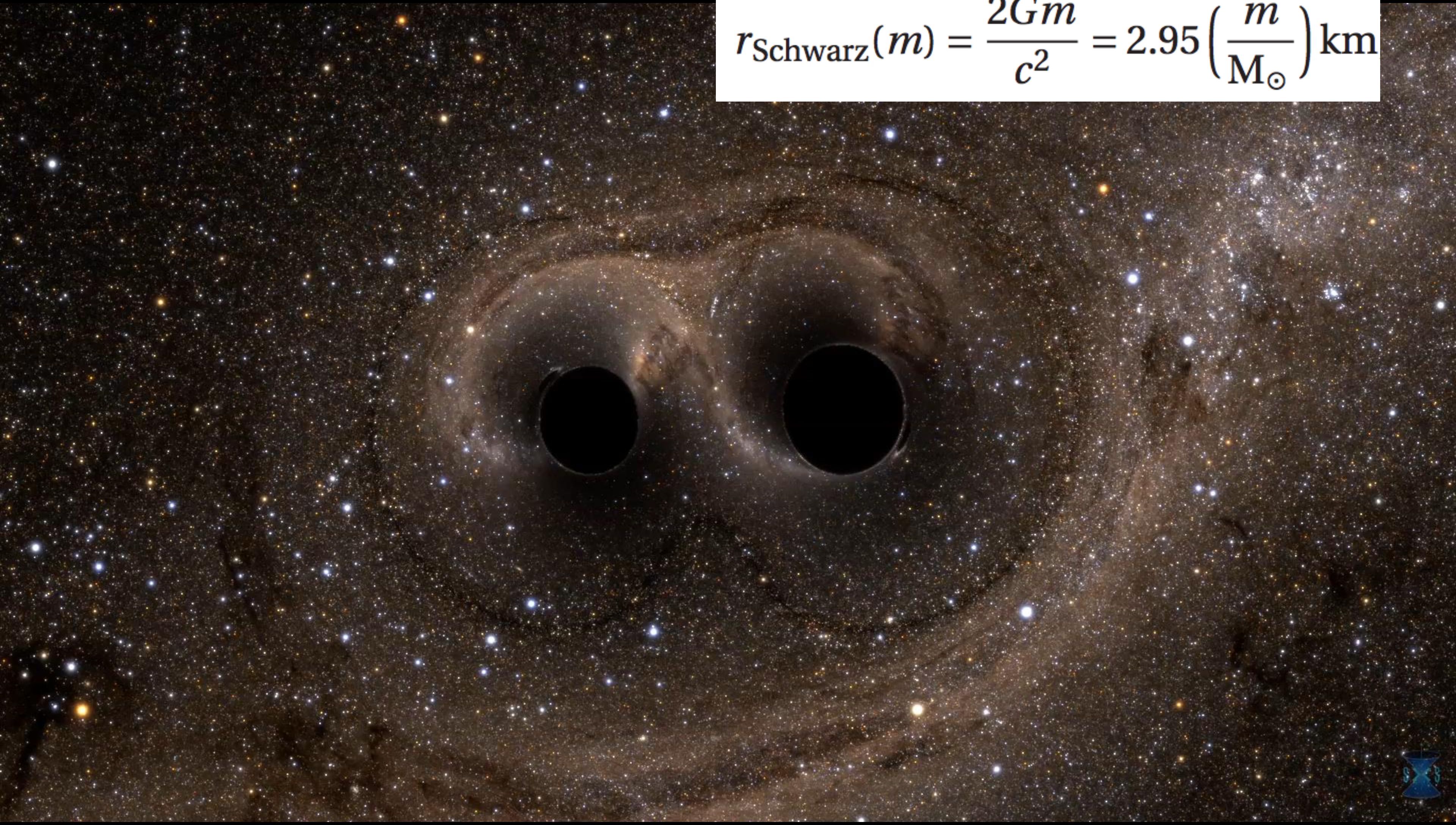
Black Holes (BHs)

BBH = binary black holes

not observable with light

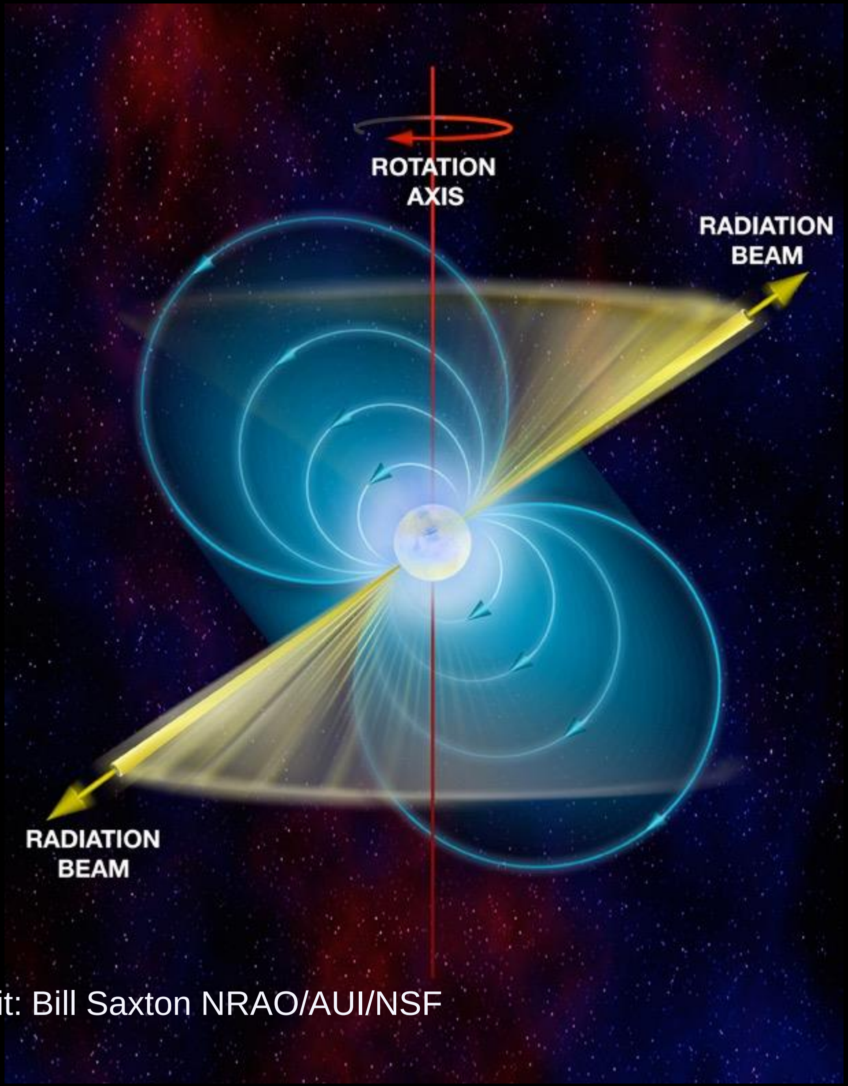
BBHs are strong sources of GWs

$$r_{\mathrm{Schwarz}}(m) = \frac{2Gm}{c^2} = 2.95\left(\frac{m}{\mathrm{M}_\odot}\right)\mathrm{km}$$

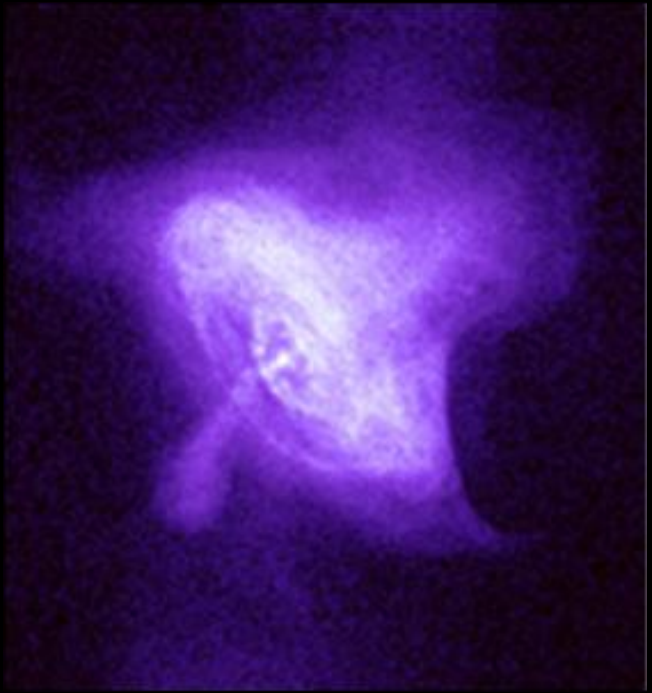


A radio pulsar: a cosmic light house

a rapidly rotating, highly magnetized neutron star
spin period : milliseconds up to O(10) seconds, ~3000 radio pulsars in MW

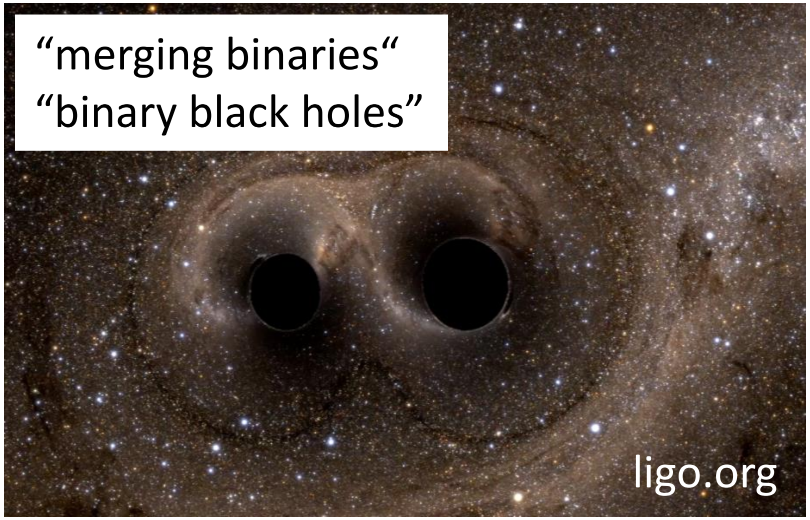


Credit: Bill Saxton NRAO/AUI/NSF



X-ray image
of a Crab pulsar
(NASA)

Many stars in the universe are in binaries



compact binary coalescences (CBCs) 밀집 쌍성 병합

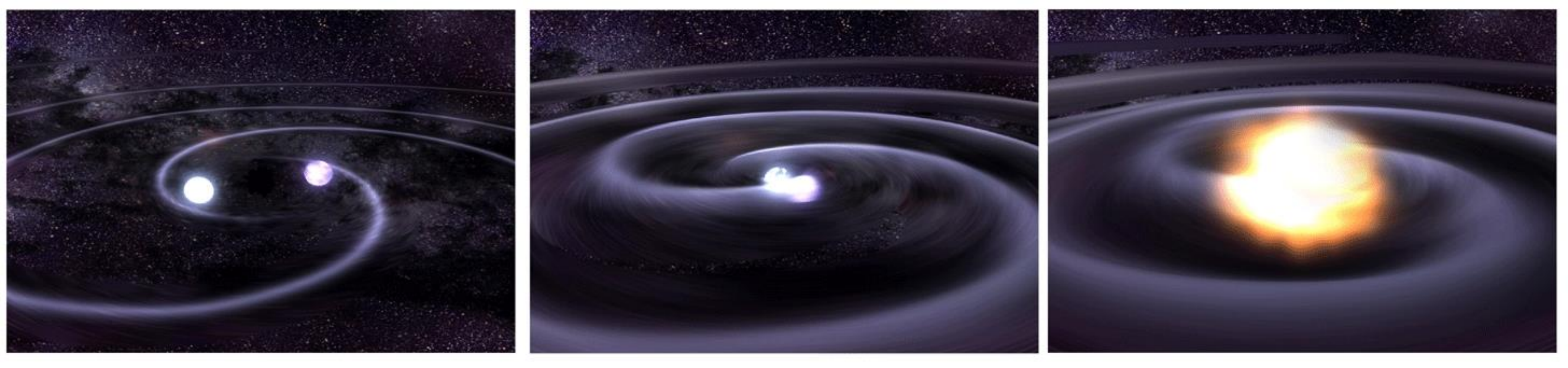
merging binaries consisting of WD/NS/BH

➔ 조건: 중력파 방출로 인한 da/dt (anow ➔ 충돌) 시간이
허블시간 보다 작으면 “병합 쌍성 " 으로 구분

$$\tau_{\mathrm{mrg}} = 9.83 \times 10^6\,\mathrm{yr} \left(\frac{P_b}{\mathrm{hr}}\right)^{8/3} \left(\frac{\mu}{\mathrm{M}_\odot}\right)^{-1} \left(\frac{m_1 + m_2}{\mathrm{M}_\odot}\right)^{-2/3}$$

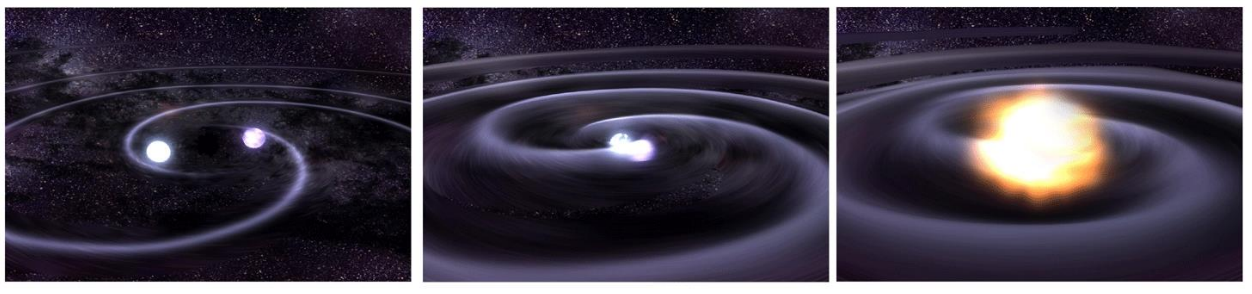
$$\mu = m_1 m_2/(m_1 + m_2)$$

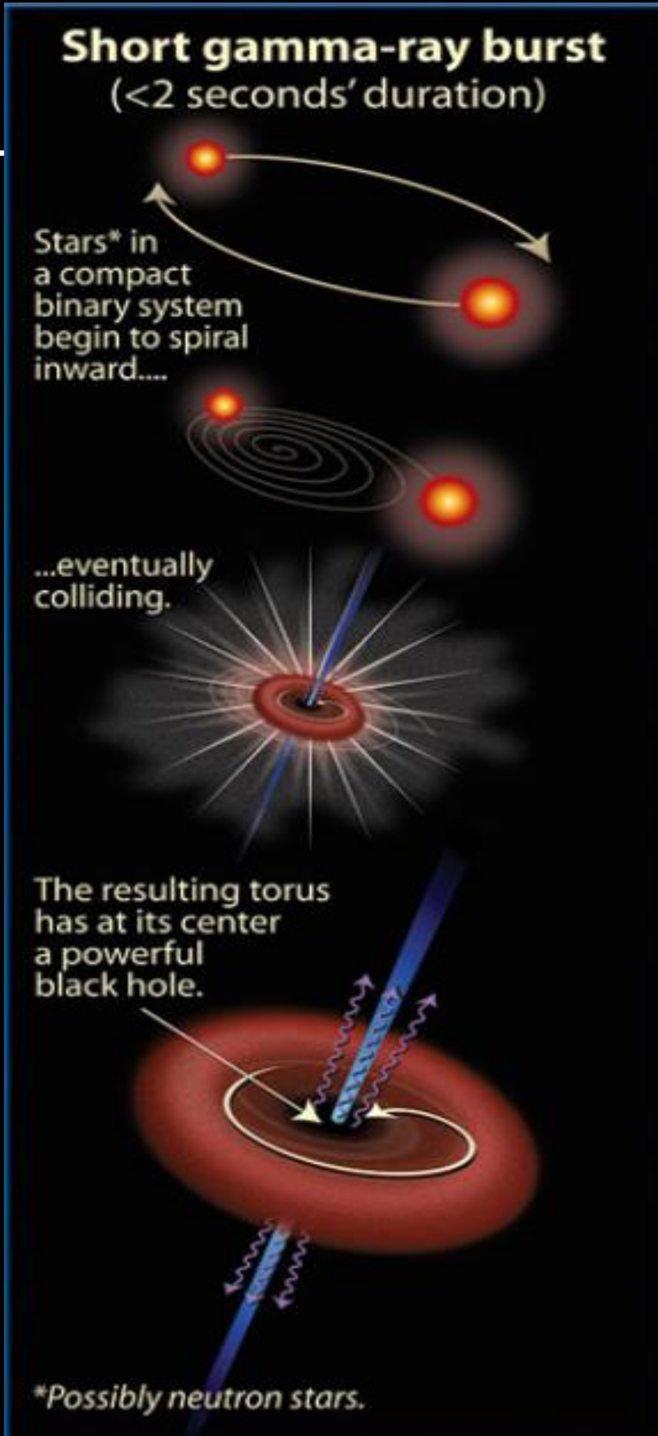
https://arxiv.org/pdf/astro-ph/0402162.pdf (following Peters (1964))



gamma-ray bursts

short emission (within 2 seconds) of light
in gamma-rays may occur right after
the collision of two neutron stars

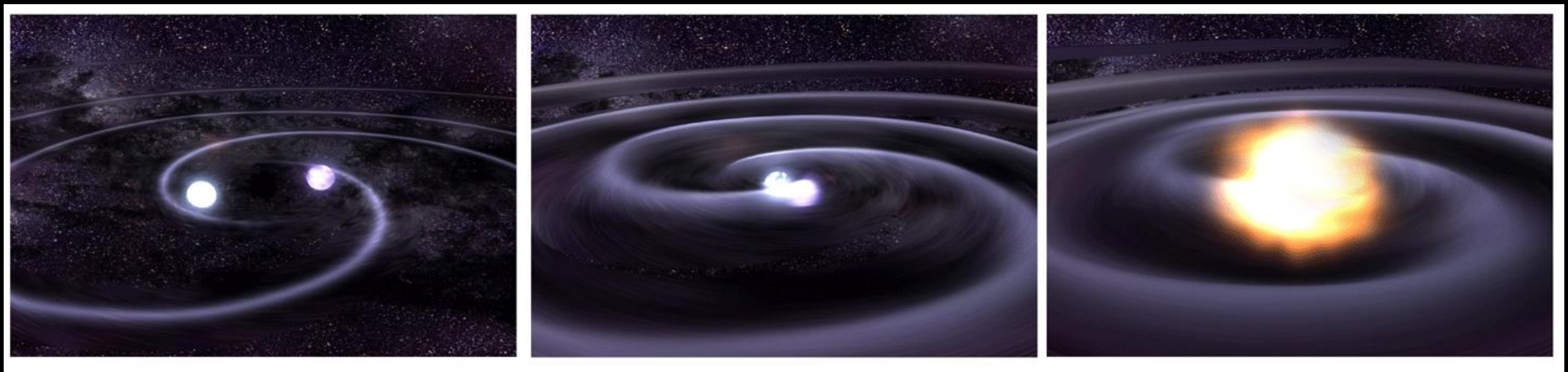




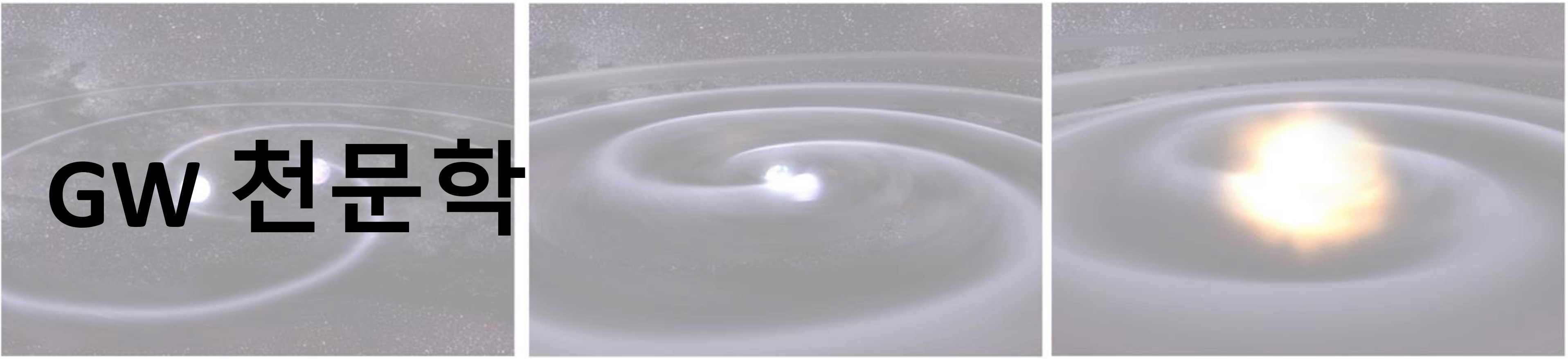
compact binary coalescences (CBCs) 밀집 쌍성 병합

3 phases of a CBC = inspiral + merge + ringdown

➔ 편의상 병합 과정을 3단계로 나누어 중력파 파형을 계산하거나 신호를 분석한다.
지상 중력파 검출기를 사용한 자료분석의 경우
- 별질량 블랙홀의 병합 : IMR (insrpial-merge-ringdown) 중력파 파형이 유리
- NS-NS 병합: 나선근접운동을 기술하는 중력파 파형 + 중성자별 크기 변형 효과



GW 천문학



GW frequency ~ 1/(source mass)$^{\alpha}$

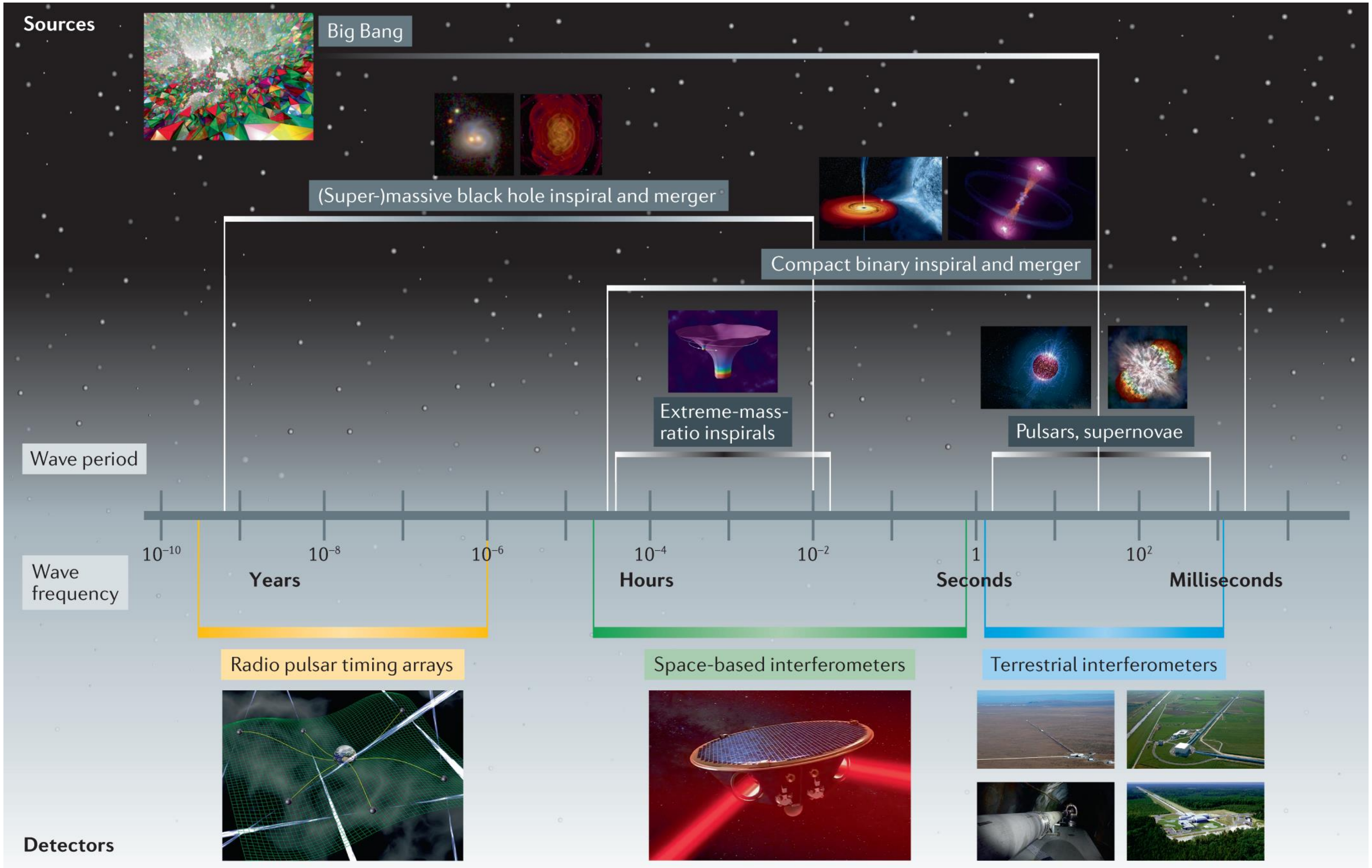
- massive source emits GW signals at lower frequencies
- different frequencies require different observational technique

Successful technique to observe GW signals:

- laser interferometry (on Earth, in space)
- pulsar timing array (radio observation using fast-rotating radio pulsars)

중력파 천문학과 중력파원

관측 주파수(Hz) 🡐 🡒 중력파원의 “특징적인 시간 " 기준 🡒 중력파원의 질량



https://www.nature.com/articles/s42254-021-00303-8/figures/2

중력파 관측 ➔ 밀집성의 질량 ➔ 밀집성의 형성과 진화

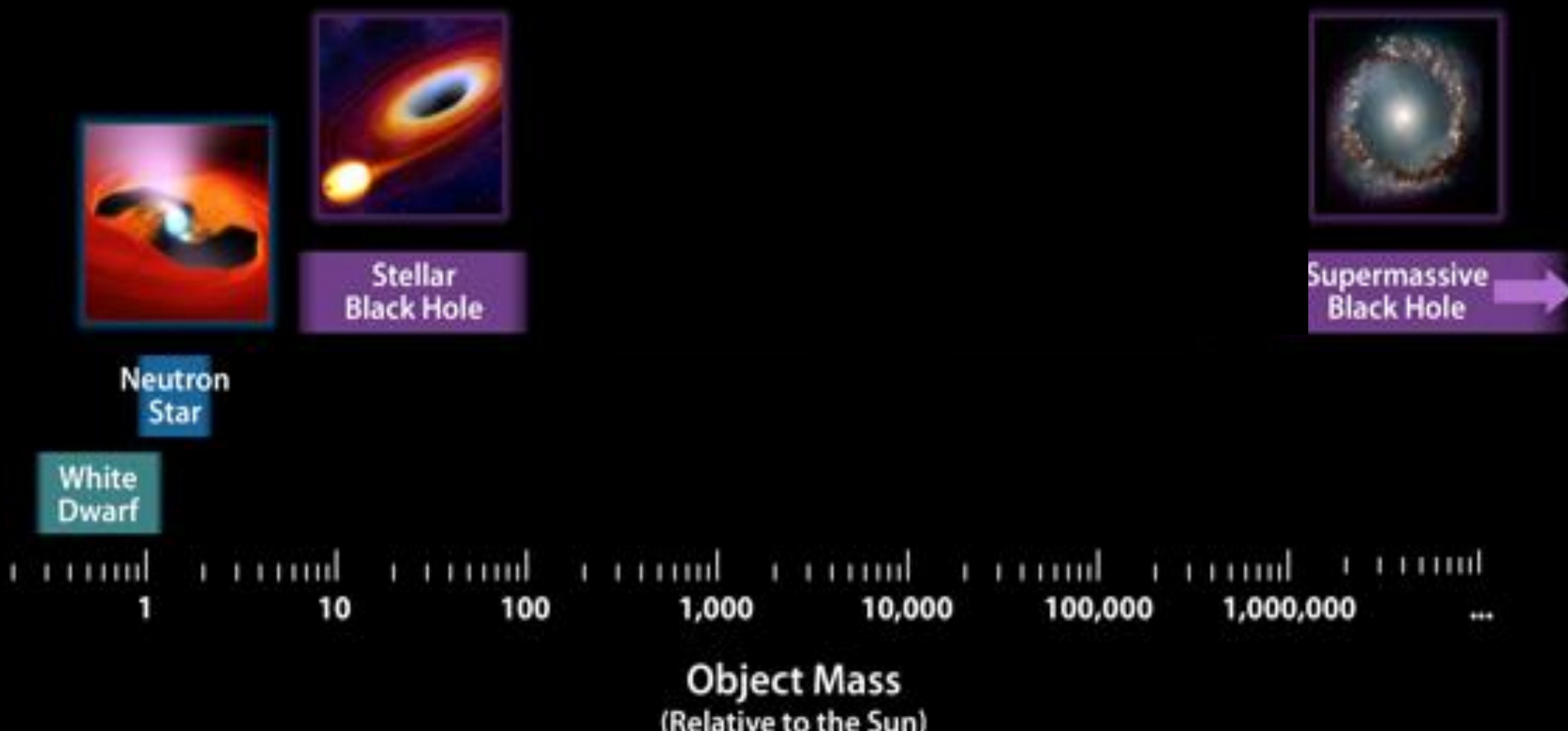
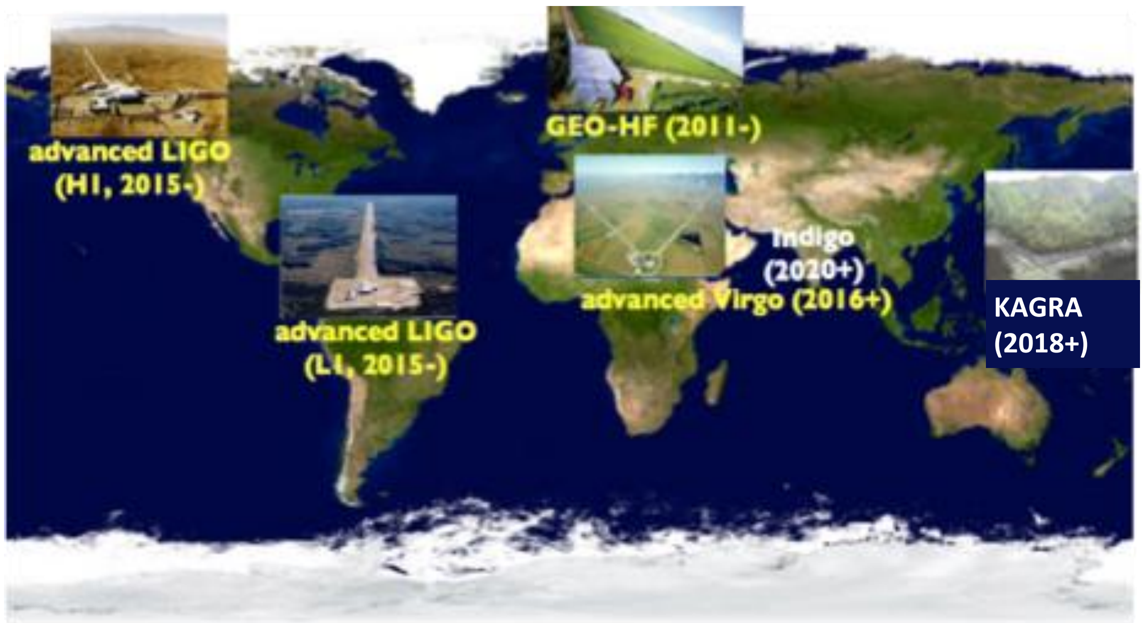


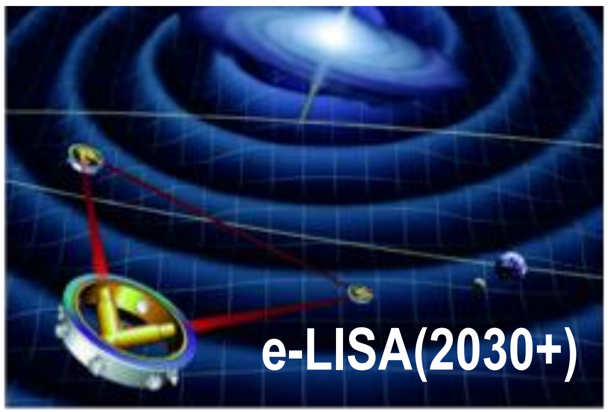
Image credit: NASA/JPL-Caltech

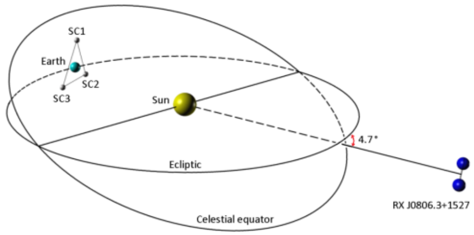
International GW observatory network

laser interferometry

- 2017 - present aLIGO(USA), aVirgo(Europe) ← "a" = advanced
- 2020, 2021 aLIGO, aVirgo, KAGRA(Japan)
- 2030+ aLIGO, aVirgo, KAGRA, and LIGO-India(India) : on Earth
  LISA (Europe/USA) , Chinese concept (2030+) : in Space







기기 감도 향상 ➔ 더 먼 우주 관측 가능 ➔ 관측 부피 증가

중력파원의 갯수밀도 (per Gpc^3) x 중력파원 방출 빈도 (per yr) x 관측 가능한 우주 부피 (Gpc^3)

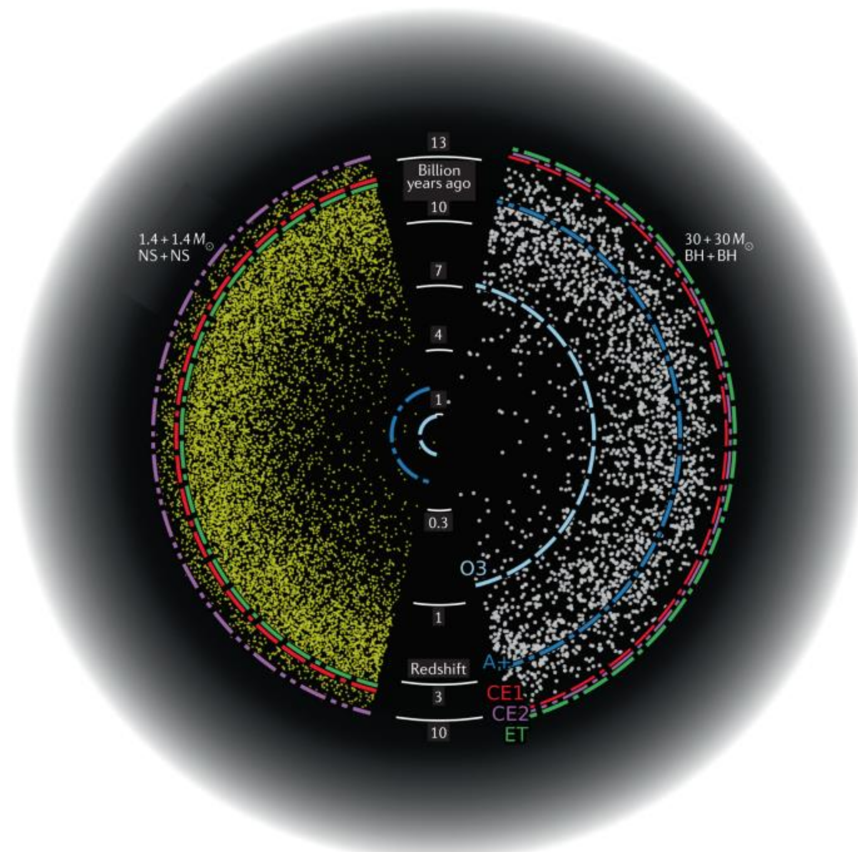
~ 년당 중력파 관측 빈도수 혹은 빈도율 추정 가능 “detection rate”

➔ 갯수밀도 추정: 중력파원의 공간 분포

➔ 방출 빈도 추정: 중력파원의 형성과 진화,
중력파 방출 기작

➔ 관측 가능한 우주 부피: 기기 감도,
잡음 특성

관측빈도 = figure-of-merit 성능지수 for
GW detection

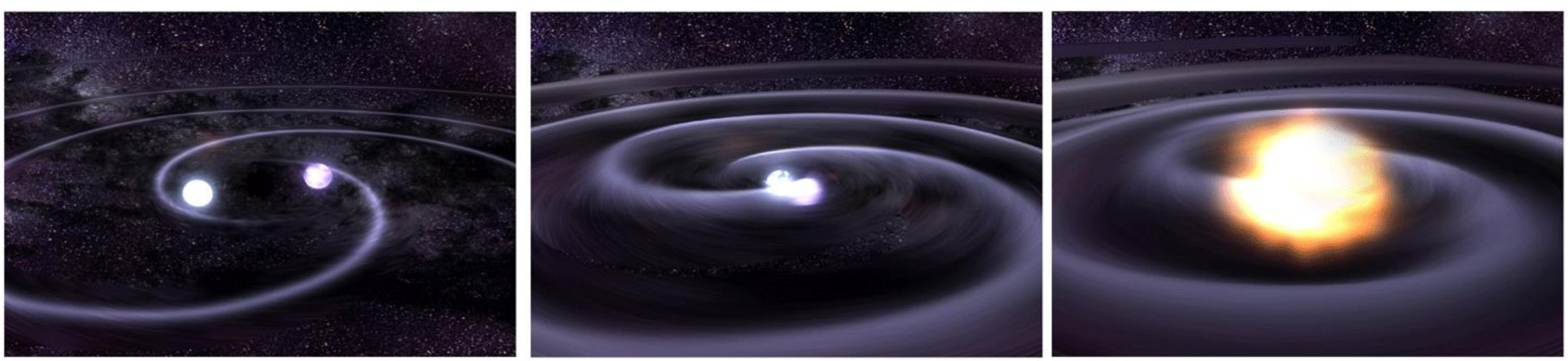


Definition of *figure of merit*

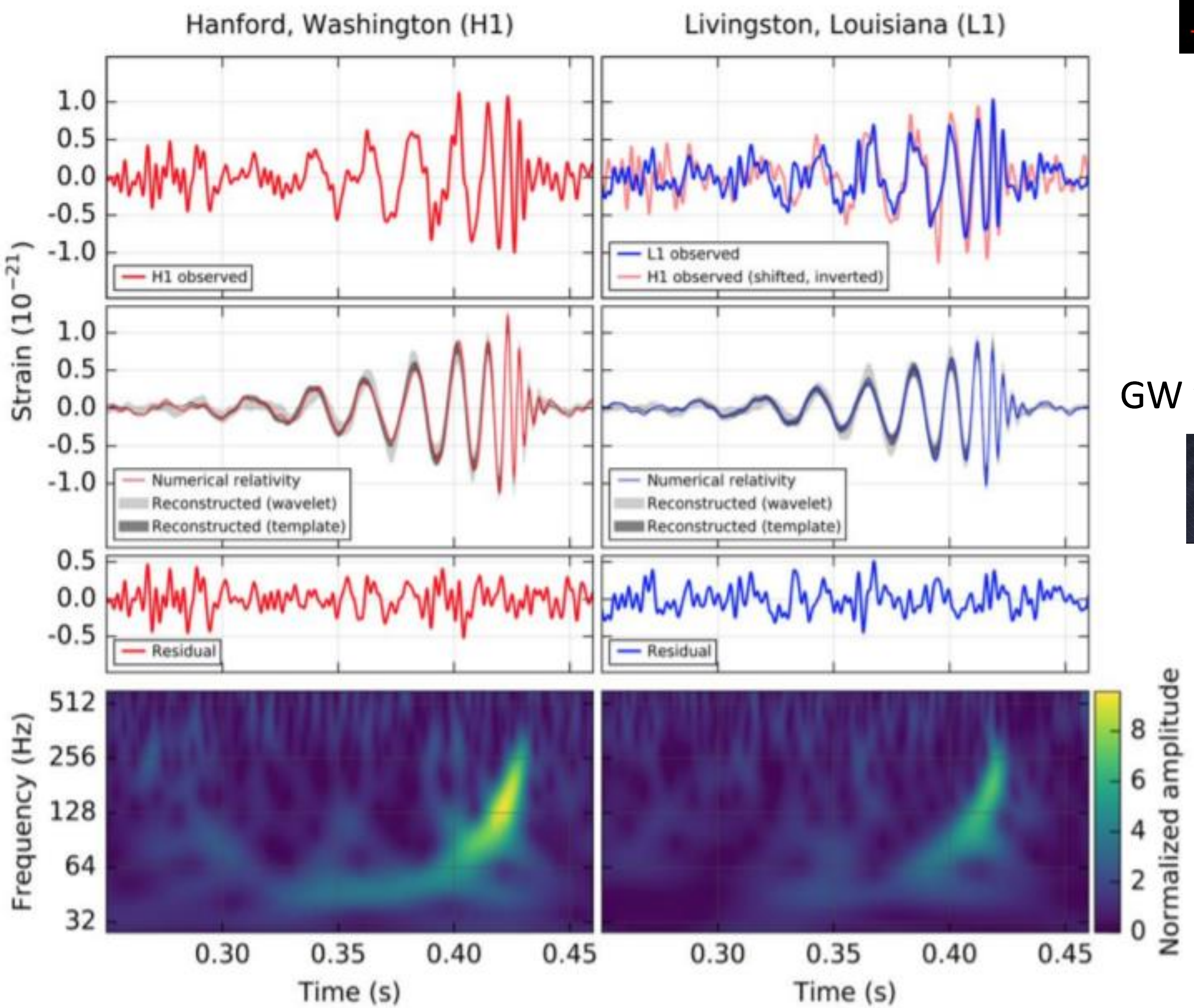
: a numerical quantity based on one or more characteristics of a system or device that represents a measure of efficiency or effectiveness

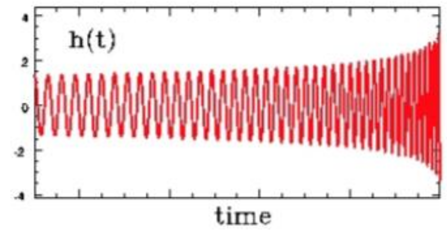
https://www.nature.com/articles/s42254-021-00303-8/figures/2

compact binary coalescences (CBCs) 밀집 쌍성 병합

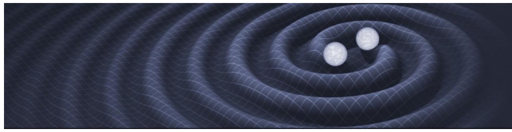


“chirp” 블랙홀-블랙홀 병합
GW150914 중력파





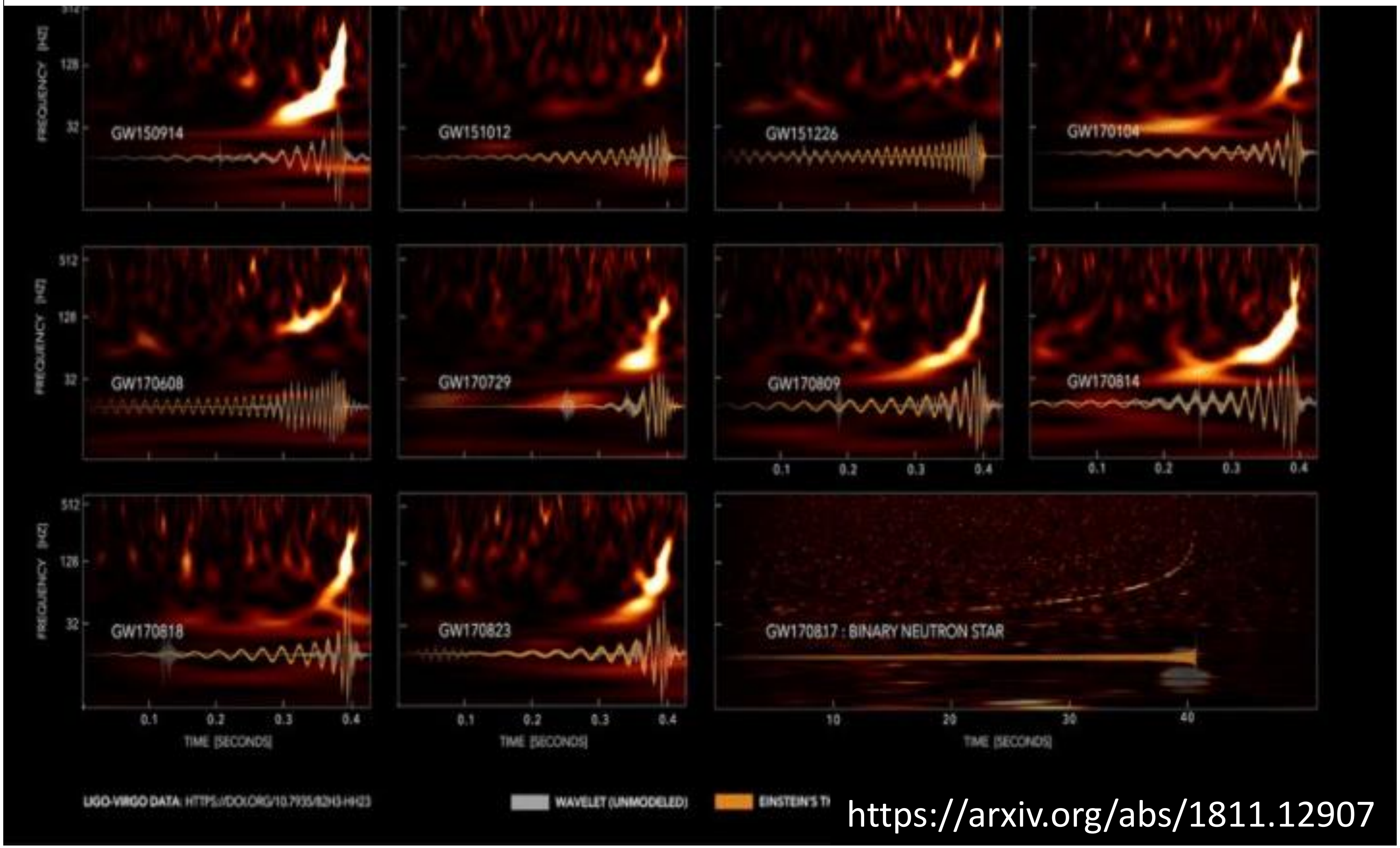
GW waveform of GW150914



www.gw-openscience.org

Gravitational Wave Open Science Center

The **Gravitational Wave Open Science Center** provides data from gravitational-wave observatories, along with access to tutorials and software tools.



https://www.ligo.caltech.edu/page/detection-companion-papers

PHYSICAL REVIEW X **9**, 031040 (2019)

GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 14 December 2018; revised manuscript received 27 March 2019; published 4 September 2019)

1 NS-NS (GW170817)
10 BH-BH (including GW150914)

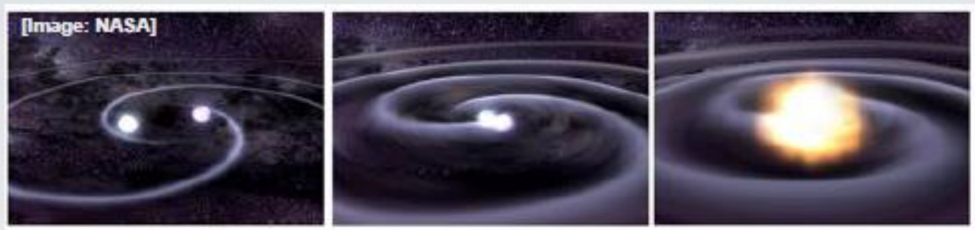
GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run

arXiv:2010.14527v1
(posted on Oct 27, 2020)

- **47 compact binary mergers** detected with a false-alarm rate (FAR) < 1 yr^{-1} in GWTC-2
- **Advanced LIGO–Virgo observing runs O3a**
- **multiple detections on the same date**

- **search space : individual mass = [2, 100] M_{sun}, z up to 2.3, also**
- **individual mass = [1, 400] M_{sun}, total mass = [2, 758] M_{sun}**

중력파 천문학과 중력파 천체물리학



inspiral

merge

ringdown

개별질량
거리
천구상의 위치
궤도 방향
블랙홀 스핀

중성자별 구조

상태방정식(nuclear eq. of state)

중성자별 내/외부 자기장 효과

블랙홀-블랙홀 쌍성계에서
블랙홀간 상호작용

충돌후 생성된 천체의 성질

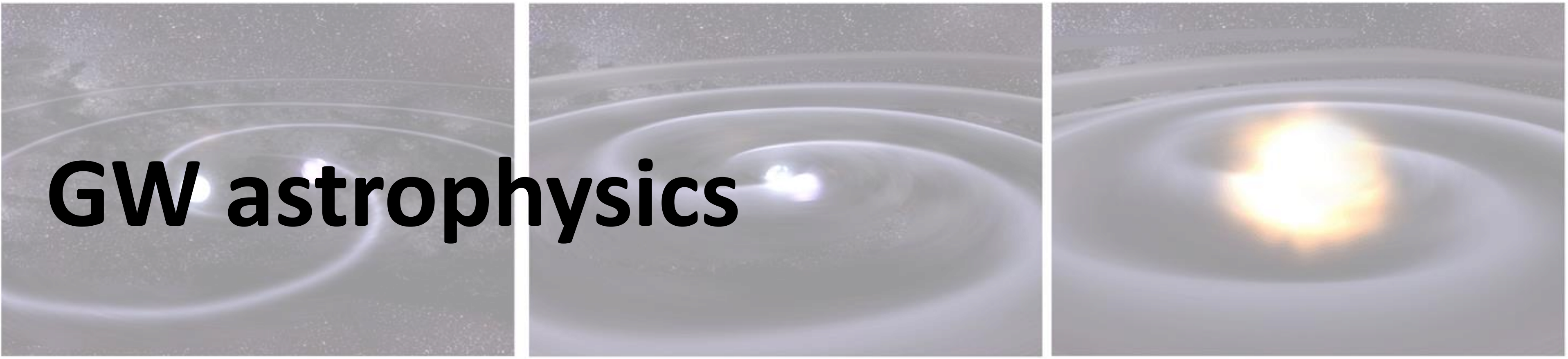
중력파 최초검출
중력파 천문학

강한 중력장에서의 물리현상

천체물리학
관측천문학

⟷

중력파 모수추정
중력파 검출



GW astrophysics

We can trace down or reconstruct the formation and evolutionary "history" of a source by GW observation

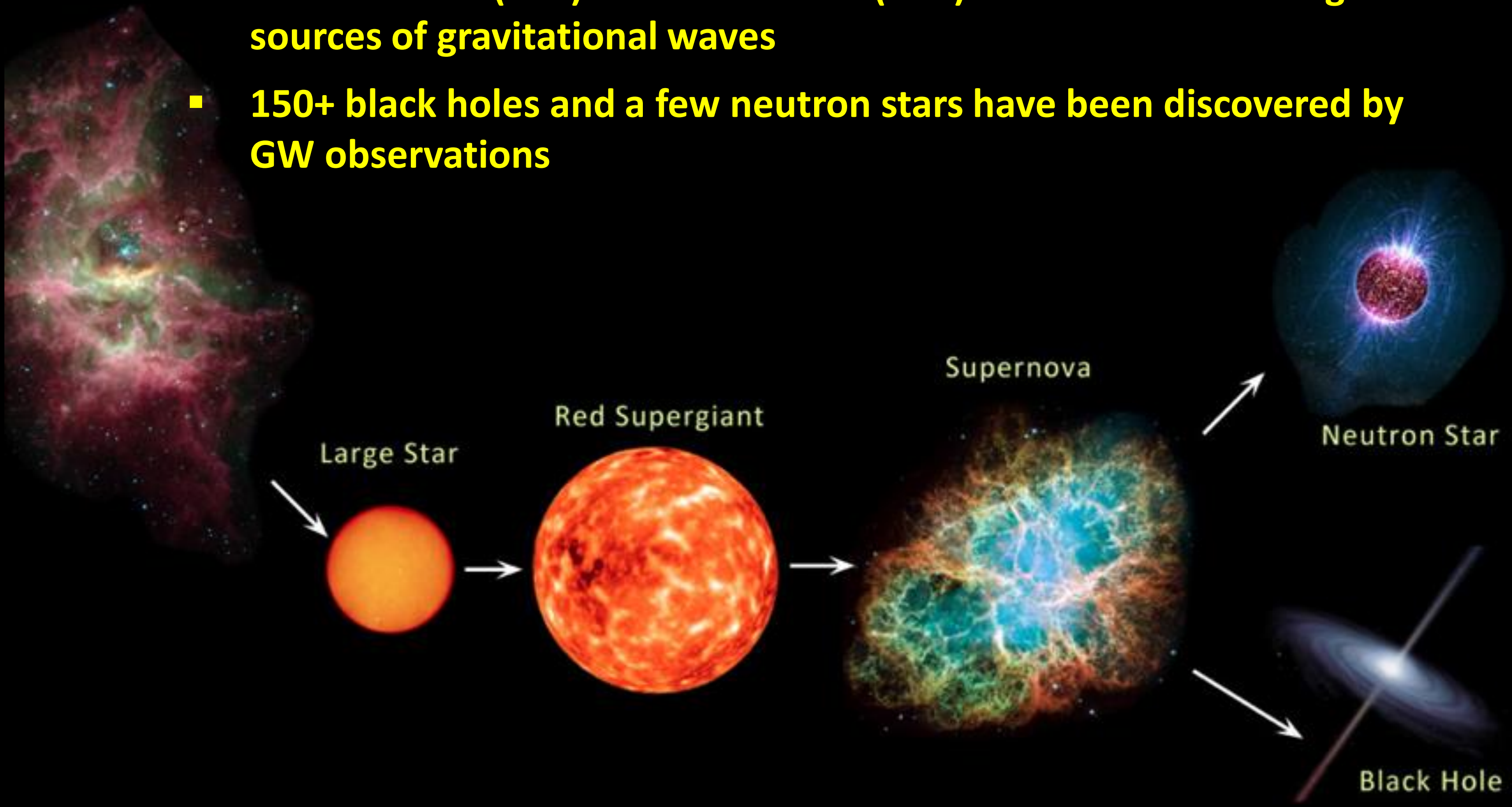
requirement: good data (strong signal, less noise or identified noises)
accurate GW waveform (model)

method: matched filtering + Bayesian inference "parameter estimation"
➔ 15 parameters to determine GW signal h(t)

a priori knowledge helps ! (constraints, independent observations)

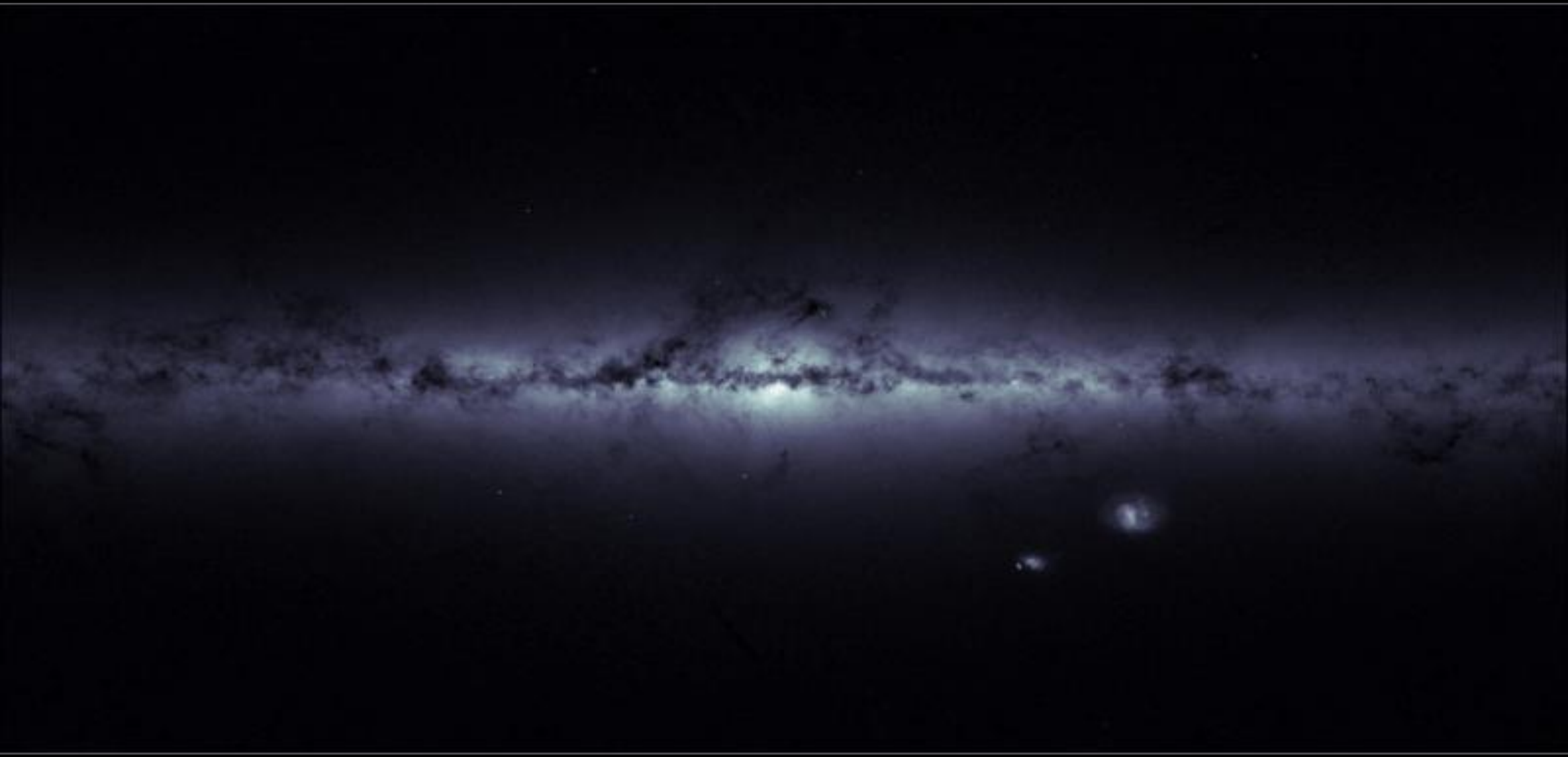
Evolution of a massive star "single star evolution"

- **neutron stars (NSs) and black holes (BHs) in binaries are strong sources of gravitational waves**
- **150+ black holes and a few neutron stars have been discovered by GW observations**



http://essayweb.net/astronomy/images/Stellar_Evolution_large.jpg

typically, BBHs and NS-NS binaries reside in a galactic disk

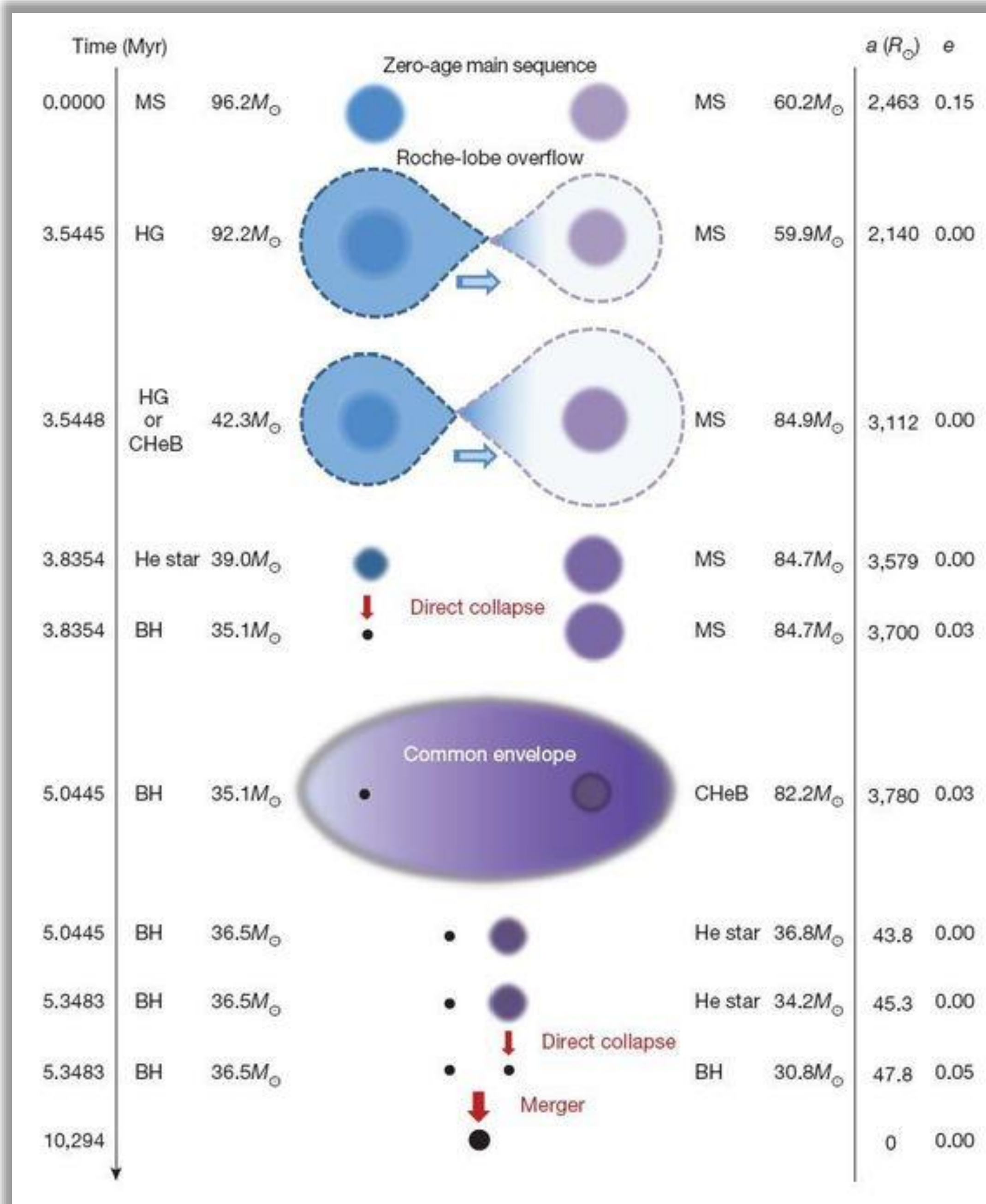


Credit: ESA/Gaia

Evolution of a binary

"standard" binary evolution
in the Galactic disk

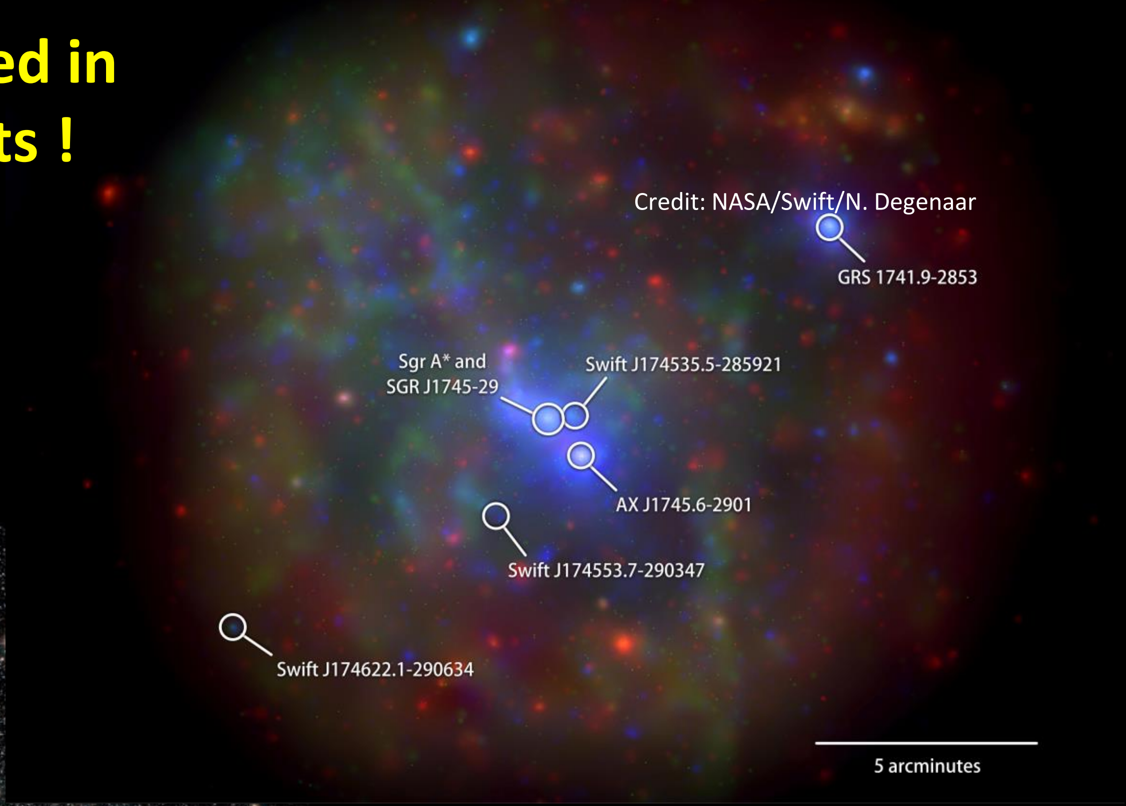
- initial conditions
  (mass ratio, separation, metallicity)
- common envelope
- supernovae
- mass/angular momentum transfer



https://www.nature.com/articles/nature18322

Some binaries can be formed in dense stellar environments !

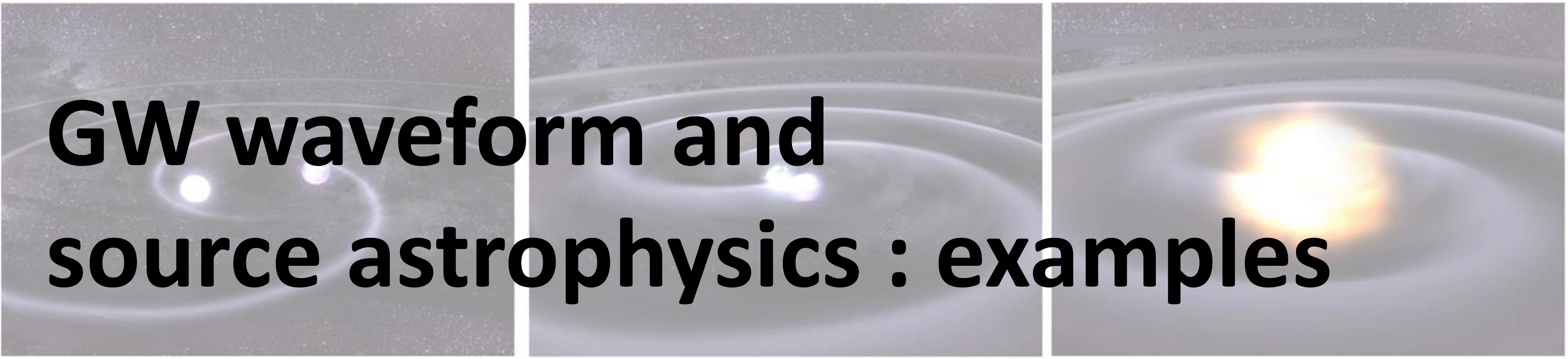
(구상성단, 은하중심)



CBC location

➔ ejected from a cluster
➔ “offset” from the host galaxy

GW waveform and source astrophysics : examples



a typical post-Newtonian “inspiral” waveform in the frequency domain

$$\tilde{h}(f) = \mathcal{A} e^{i\Psi} \qquad \tilde{h}(f) \equiv \int_{-\infty}^{\infty} h(t) e^{2\pi i f t}\, dt$$

$$\mathcal{A} = -M \sqrt{\frac{5\pi}{96}} \left(\frac{M}{D}\right) \sqrt{\eta} (\pi M f)^{-7/6} \quad \left[(1+C^2)^2 F_+^2 + 4C^2 F_\times^2\right]^{1/2}$$

$$\Psi(f) = \phi_c + 2\pi f t_c + \frac{3}{128 \eta v^5} \left(1 + \Delta\Psi^{\text{circ.}}_{3.5\text{PN}} + \Delta\Psi^{\text{spin, circ.}}_{4\text{PN}} + \Delta\Psi^{\text{ecc.}}_{3\text{PN}}\right)$$

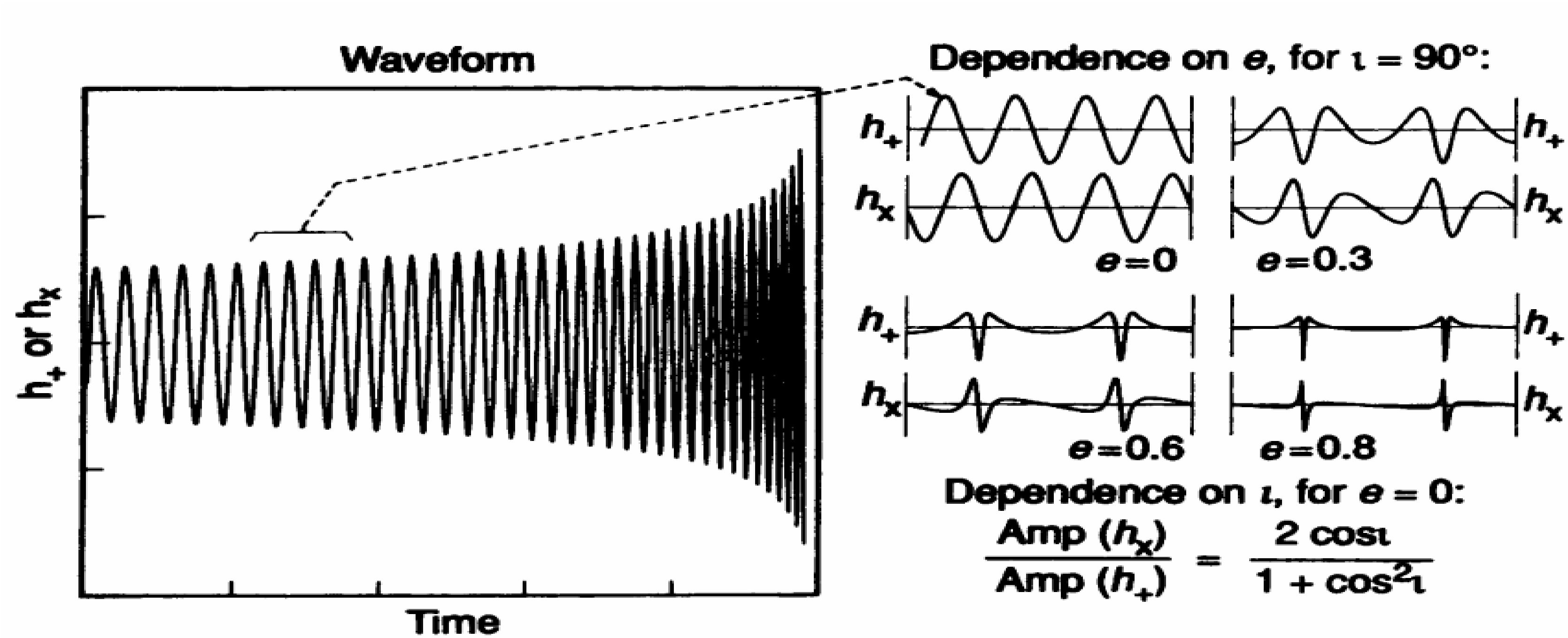
where t_c and ϕ_c are the coalescence time and phase, and $v \equiv (\pi M f)^{1/3}$ is the PN orbital velocity parameter. Note that the angle β is absorbed into a constant shift to ϕ_c.

The standard 3.5PN circular contribution is $\Delta\Psi^{\text{circ.}}_{3.5\text{PN}} = \sum_{n=2}^{7} c_n(\eta) v^n$, where the $c_n(\eta)$ can be read off of Eq. (3.18) of [93], and the 2.5PN and 3PN coefficients also depend on $\ln v$.

https://arxiv.org/pdf/2108.05861.pdf

Example: Effects of eccentricity

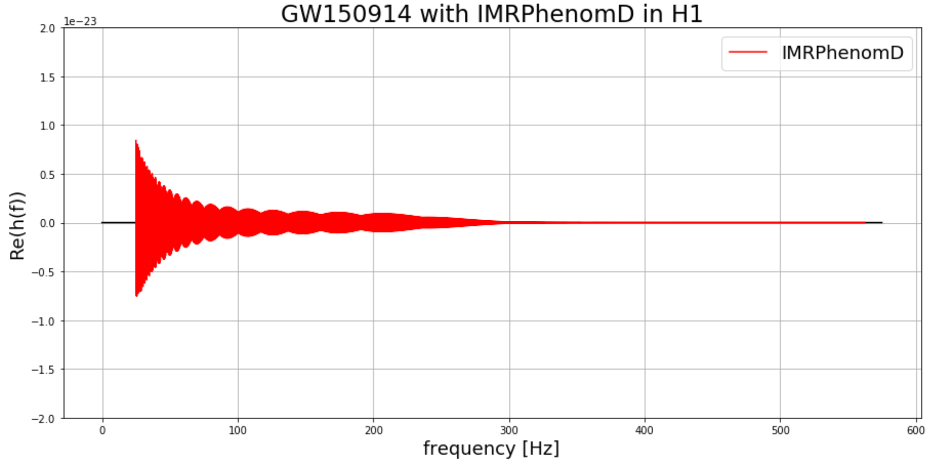
- strong circularization due to GW emission
- eccentricity & spin information is useful to determine the formation mechanis m and location (galactic disk vs cluster)
- important for future detectors sensitive in lower frequencies



inspiral signal vs inspiral-merge-ringdown signal (ex) GW150914

<Frequency Domain>

IMRPhenomD
25Hz ~ 562.4Hz
(SNR 20.74)



TaylorF2
25Hz ~ 60.9Hz
(SNR 20.00)

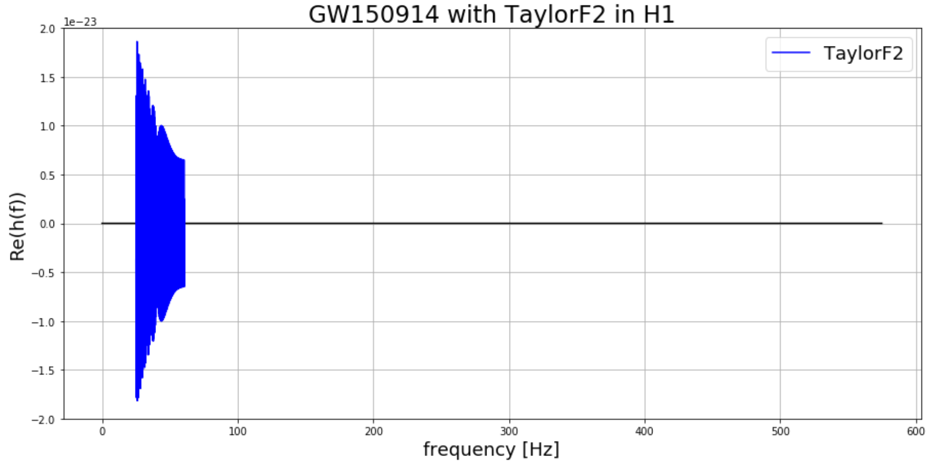
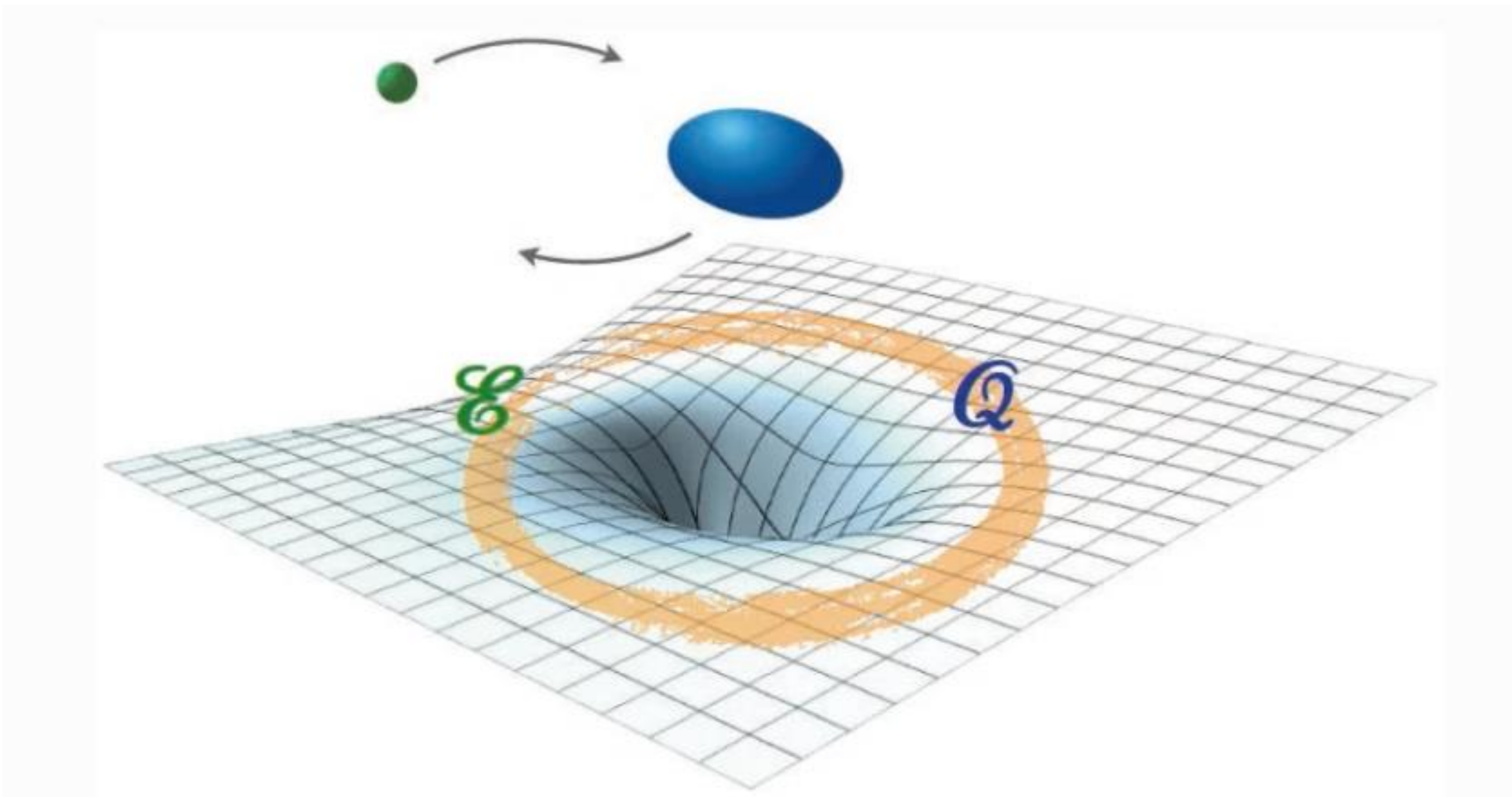


figure credit: Chaeyeon Jeon

중성자별-중성자별 병합 중력파 모델링에서는

- 중성자별의 변형(tidal distortion ➔ NS 상태방정식)
- 나선궤도의 정확한 모양 (원궤도? 타원궤도?)을 고려해야

보다 정확한 관측(물리량 측정)이 가능하다

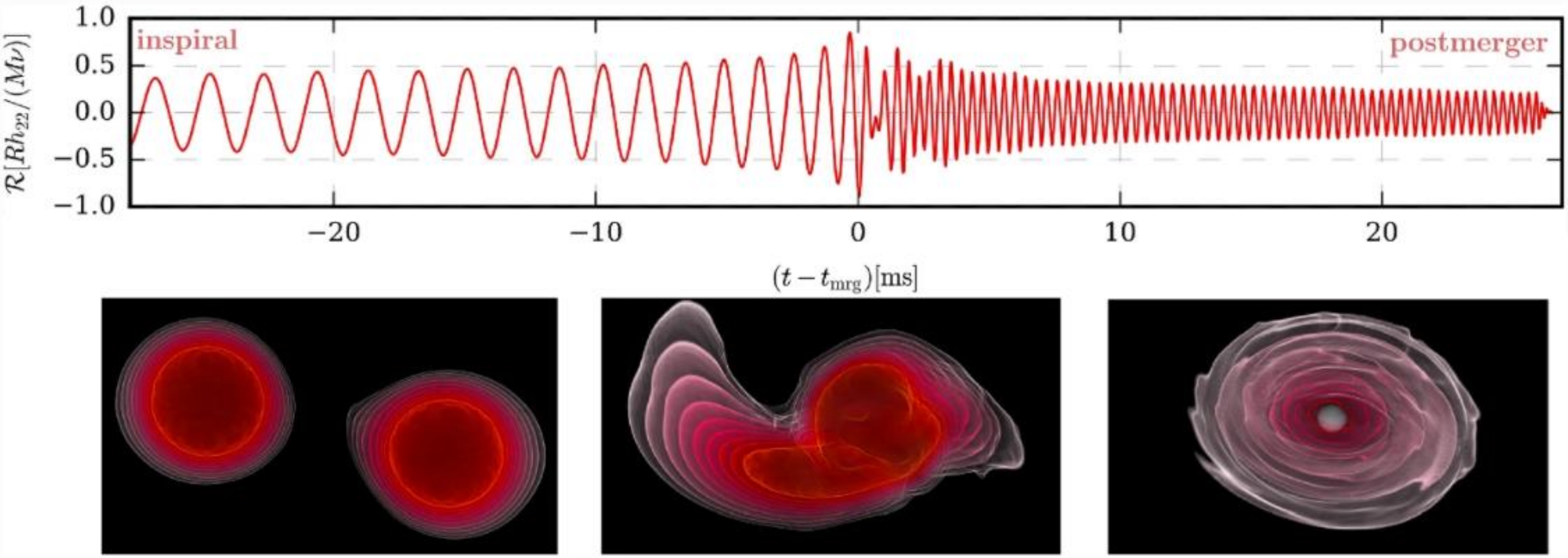


https://link.springer.com/article/10.1007/s10714-020-02751-6/figures/3

중성자별-중성자별 병합에서 방출된 중력파 시뮬레이션

Fig. 1

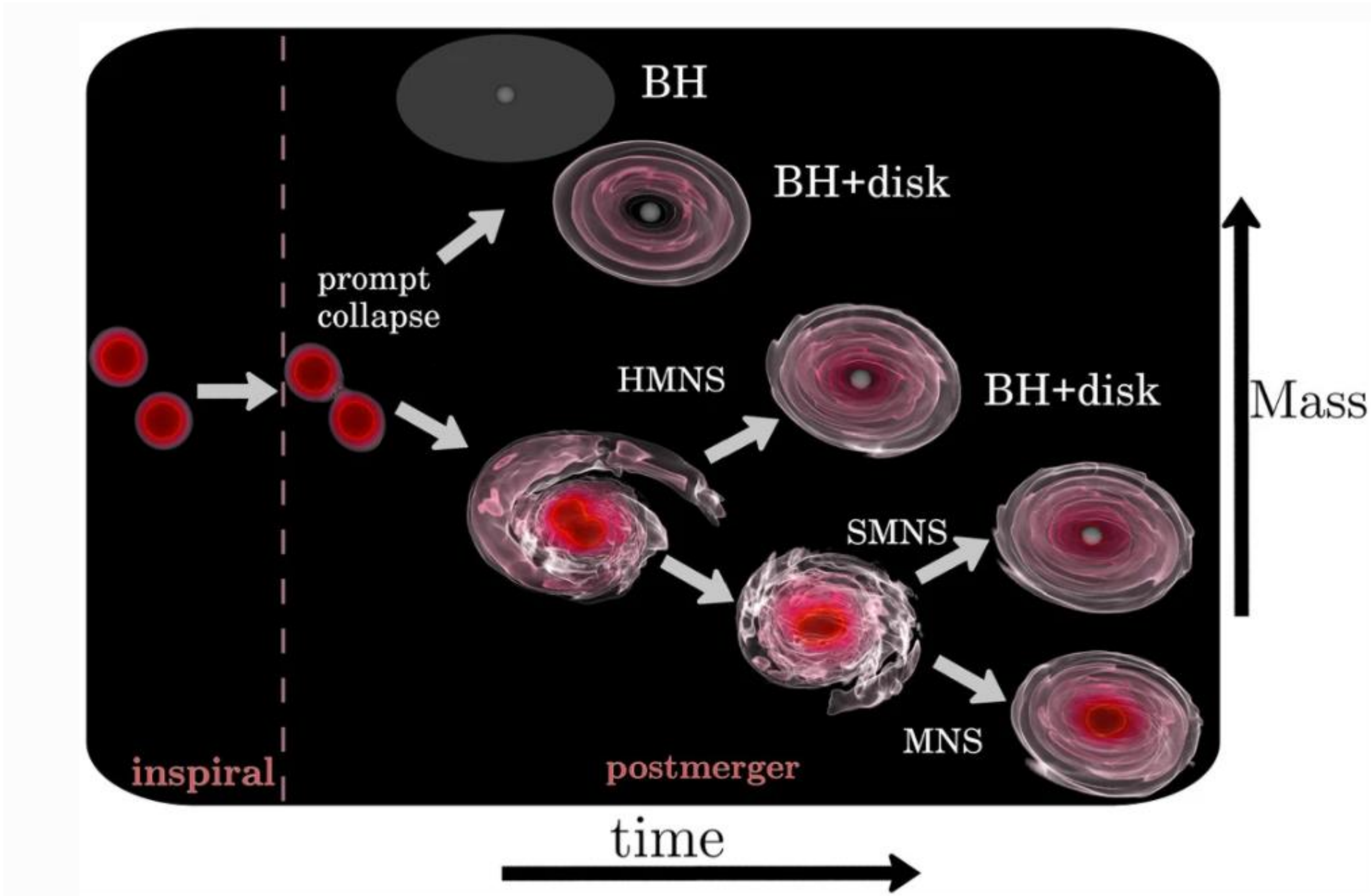
From: Interpreting binary neutron star mergers: describing the binary neutron star dynamics, modelling gravitational waveforms, and analyzing detections



NR simulation of a BNS merger showing the GW signal and the matter evolution. Top panel: GW signal emitted during the last orbits before the merger (late-inspiral phase) and during the postmerger phase of the BNS coalescence. Bottom panel: Rest-mass density evolution for the inspiral (first panel), the merger (second panel) and the postmerger phase after the formation of the black hole (third panel)

https://link.springer.com/article/10.1007/s10714-020-02751-6/figures/1

중성자별-중성자별 병합 (중력파 방출) 이후 빛, 중성미자도 방출 ?
➔ 다중신호 천문학 multimessenger astronomy



https://link.springer.com/article/10.1007/s10714-020-02751-6/figures/4

GW observation and astrophysics

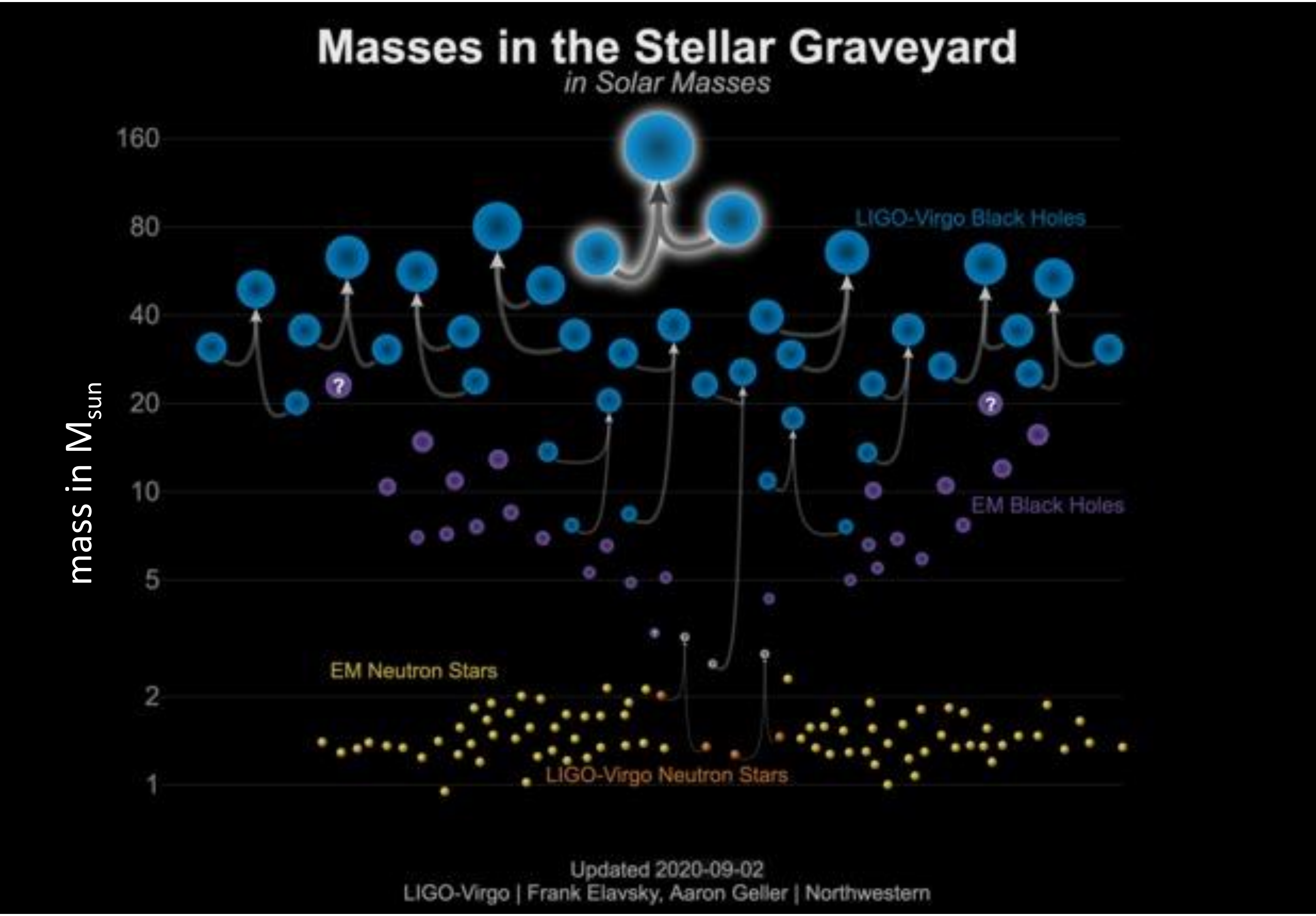
matched filter

“template h(t), h(f)” ➔ find the best template that matches the GW signal embedded in the data

data = signal + noise   (if signal exists)

How to “measure” astrophysical quantities about the source in GW observation?

➔ parameter estimation (statistical inference)



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
mass in M_sun

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run

BH data with advanced LIGO-Virgo

+ KAGRA from Y2021

+ LIGO India from Y2030s(?)

1 GW detection ➔ 3 masses + 1 spin

- individual masses (m_1,m_2) ➔ mass ratio
- individual spins (s_1,s_2)
- distance
- sky location (RA, dec)

$$T^2 = \frac{4\pi^2}{G(M+m)} a^3$$

- remnant mass (m_f)
- remnant spin (s_f)

Event	$m_1 [M_\odot]$	$m_2 [M_\odot]$	FAR [yr^{-1}]
GW150914	$35.7^{+4.8}_{-3.1}$	$30.6^{+3.1}_{-4.4}$	$< 1.0 \times 10^{-7}$
GW151012	$23.3^{+14.7}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	7.9×10^{-3}
GW151226	$13.7^{+8.7}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$< 1.0 \times 10^{-7}$
GW170104	$31.0^{+7.3}_{-5.7}$	$20.0^{+4.9}_{-4.6}$	$< 1.0 \times 10^{-7}$
GW170608	$11.0^{+5.6}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$< 1.0 \times 10^{-7}$
GW170729	$50.7^{+16.5}_{-10.5}$	$34.0^{+9.3}_{-10.2}$	2.0×10^{-2}
GW170809	$35.1^{+8.4}_{-5.9}$	$23.8^{+5.2}_{-5.2}$	$< 1.0 \times 10^{-7}$
GW170814	$30.6^{+5.6}_{-3.0}$	$25.3^{+2.8}_{-4.1}$	$< 1.0 \times 10^{-7}$
* GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$< 1.0 \times 10^{-7}$
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	4.2×10^{-5}
GW170823	$39.7^{+11.2}_{-6.7}$	$29.0^{+6.8}_{-7.7}$	$< 1.0 \times 10^{-7}$
GW190408_181802	$24.5^{+5.1}_{-3.4}$	$18.3^{+3.2}_{-3.5}$	1.0×10^{-5}
GW190412	$30.0^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	1.0×10^{-5}
GW190413_052954	$33.4^{+12.4}_{-7.4}$	$23.4^{+6.7}_{-6.3}$	7.2×10^{-2}
GW190413_134308	$45.4^{+13.6}_{-9.6}$	$30.9^{+10.2}_{-9.6}$	4.4×10^{-2}
GW190421_213856	$40.6^{+10.4}_{-6.6}$	$31.4^{+7.5}_{-8.2}$	7.7×10^{-4}
GW190424_180648	$39.5^{+10.9}_{-6.9}$	$31.0^{+7.4}_{-7.3}$	7.8×10^{-1}
* GW190425	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	7.5×10^{-4}
GW190503_185404	$42.9^{+9.2}_{-7.8}$	$28.5^{+7.5}_{-7.9}$	1.0×10^{-5}
GW190512_180714	$23.0^{+5.4}_{-5.7}$	$12.5^{+3.5}_{-2.5}$	1.0×10^{-5}
GW190513_205428	$35.3^{+9.6}_{-9.0}$	$18.1^{+7.3}_{-4.2}$	1.0×10^{-5}
GW190514_065416	$36.9^{+13.4}_{-7.3}$	$27.5^{+8.2}_{-7.7}$	5.3×10^{-1}
GW190517_055101	$36.4^{+11.8}_{-7.8}$	$24.8^{+6.9}_{-7.1}$	5.7×10^{-5}
[illegible]	$64.5^{+11.3}_{-13.2}$	$39.9^{+11.0}_{-10.6}$	1.0×10^{-5}
[illegible]	$91.4^{+29.3}_{-17.5}$	$66.8^{+20.7}_{-20.7}$	2.0×10^{-4}
GW190521_074359	$42.1^{+5.9}_{-4.9}$	$32.7^{+5.4}_{-6.2}$	1.0×10^{-5}

With better sensitivity.

we can "determine" orbital configuration

(inclination, eccentricity)

➔ better distance measure

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run

chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

effective spin $\chi_{\text{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot \hat{L}_{\text{N}}}{m_1 + m_2}$

Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_{L} (Gpc)	z	M_{f} ($M_\odot$)	χ_{f}	$\Delta\Omega$ (deg^2)	SNR
GW190408_181802	$42.9^{+4.1}_{-2.9}$	$18.3^{+1.8}_{-1.2}$	$24.5^{+5.1}_{-3.4}$	$18.3^{+3.2}_{-3.5}$	$-0.03^{+0.13}_{-0.19}$	$1.58^{+0.40}_{-0.59}$	$0.30^{+0.06}_{-0.10}$	$41.0^{+3.8}_{-2.7}$	$0.67^{+0.06}_{-0.07}$	140	$15.3^{+0.2}_{-0.3}$
GW190412	$38.4^{+3.8}_{-3.7}$	$13.3^{+0.4}_{-0.3}$	$30.0^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$0.25^{+0.08}_{-0.11}$	$0.74^{+0.14}_{-0.17}$	$0.15^{+0.03}_{-0.03}$	$37.3^{+3.9}_{-3.9}$	$0.67^{+0.05}_{-0.06}$	21	$18.9^{+0.2}_{-0.3}$
GW190413_052954	$56.9^{+13.1}_{-8.9}$	$24.0^{+5.4}_{-3.7}$	$33.4^{+12.4}_{-7.4}$	$23.4^{+6.7}_{-6.3}$	$0.01^{+0.29}_{-0.33}$	$4.10^{+2.41}_{-1.89}$	$0.66^{+0.30}_{-0.27}$	$54.3^{+12.4}_{-8.4}$	$0.69^{+0.12}_{-0.13}$	1400	$8.9^{+0.4}_{-0.8}$
GW190413_134308	$76.1^{+15.9}_{-10.6}$	$31.9^{+7.3}_{-4.6}$	$45.4^{+13.6}_{-9.6}$	$30.9^{+10.2}_{-9.6}$	$-0.01^{+0.24}_{-0.28}$	$5.15^{+2.44}_{-2.34}$	$0.80^{+0.30}_{-0.31}$	$72.8^{+15.2}_{-10.3}$	$0.69^{+0.10}_{-0.12}$	520	$10.0^{+0.4}_{-0.5}$
GW190421_213856	$71.8^{+12.5}_{-8.6}$	$30.7^{+5.5}_{-3.9}$	$40.6^{+10.4}_{-6.6}$	$31.4^{+7.5}_{-8.2}$	$-0.05^{+0.23}_{-0.26}$	$3.15^{+1.37}_{-1.42}$	$0.53^{+0.18}_{-0.21}$	$68.6^{+11.7}_{-8.1}$	$0.68^{+0.10}_{-0.11}$	1000	$10.7^{+0.2}_{-0.4}$
GW190424_180648	$70.7^{+13.4}_{-9.8}$	$30.3^{+5.7}_{-4.2}$	$39.5^{+10.9}_{-6.9}$	$31.0^{+7.4}_{-7.3}$	$0.15^{+0.22}_{-0.22}$	$2.55^{+1.56}_{-1.33}$	$0.45^{+0.22}_{-0.21}$	$67.1^{+12.5}_{-9.2}$	$0.75^{+0.08}_{-0.09}$	26000	$10.4^{+0.2}_{-0.4}$
GW190425	$3.4^{+0.3}_{-0.1}$	$1.44^{+0.02}_{-0.02}$	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	$0.06^{+0.11}_{-0.05}$	$0.16^{+0.07}_{-0.07}$	$0.03^{+0.01}_{-0.02}$	–	–	9900	$12.4^{+0.3}_{-0.4}$
GW190426_152155	$7.2^{+3.5}_{-1.5}$	$2.41^{+0.08}_{-0.08}$	$5.7^{+4.0}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.33}_{-0.30}$	$0.38^{+0.19}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	–	–	1400	$8.7^{+0.5}_{-0.6}$
GW190503_185404	$71.3^{+9.3}_{-8.0}$	$30.1^{+4.2}_{-4.0}$	$42.9^{+9.2}_{-7.8}$	$28.5^{+7.5}_{-7.9}$	$-0.02^{+0.20}_{-0.26}$	$1.52^{+0.71}_{-0.66}$	$0.29^{+0.11}_{-0.11}$	$68.2^{+8.7}_{-7.5}$	$0.67^{+0.09}_{-0.12}$	94	$12.4^{+0.2}_{-0.3}$
GW190512_180714	$35.6^{+3.9}_{-3.4}$	$14.5^{+1.3}_{-1.0}$	$23.0^{+5.4}_{-5.7}$	$12.5^{+3.5}_{-2.5}$	$0.03^{+0.13}_{-0.13}$	$1.49^{+0.53}_{-0.59}$	$0.28^{+0.09}_{-0.10}$	$34.2^{+3.9}_{-3.4}$	$0.65^{+0.07}_{-0.07}$	230	$12.2^{+0.2}_{-0.4}$
GW190513_205428	$53.6^{+8.6}_{-5.9}$	$21.5^{+3.6}_{-1.9}$	$35.3^{+9.6}_{-9.0}$	$18.1^{+7.3}_{-4.2}$	$0.12^{+0.29}_{-0.18}$	$2.16^{+0.94}_{-0.80}$	$0.39^{+0.14}_{-0.13}$	$51.3^{+8.1}_{-5.8}$	$0.69^{+0.14}_{-0.12}$	490	$12.9^{+0.3}_{-0.4}$
GW190514_065416	$64.2^{+16.6}_{-9.6}$	$27.4^{+6.9}_{-4.3}$	$36.9^{+13.4}_{-7.3}$	$27.5^{+8.2}_{-7.7}$	$-0.16^{+0.28}_{-0.32}$	$4.93^{+2.76}_{-2.41}$	$0.77^{+0.34}_{-0.33}$	$61.6^{+16.0}_{-9.2}$	$0.64^{+0.11}_{-0.14}$	2400	$8.2^{+0.3}_{-0.6}$
GW190517_055101	$61.9^{+10.0}_{-9.6}$	$26.0^{+4.2}_{-4.0}$	$36.4^{+11.8}_{-7.8}$	$24.8^{+6.9}_{-7.1}$	$0.53^{+0.20}_{-0.19}$	$2.11^{+1.79}_{-1.00}$	$0.38^{+0.26}_{-0.16}$	$57.8^{+9.4}_{-9.1}$	$0.87^{+0.05}_{-0.07}$	460	$10.7^{+0.4}_{-0.6}$
GW190519_153544	$104.2^{+14.5}_{-14.9}$	$43.5^{+6.8}_{-6.8}$	$64.5^{+11.3}_{-13.2}$	$39.9^{+11.0}_{-10.6}$	$0.33^{+0.19}_{-0.22}$	$2.85^{+2.02}_{-1.14}$	$0.49^{+0.27}_{-0.17}$	$98.7^{+13.5}_{-14.2}$	$0.80^{+0.07}_{-0.12}$	770	$15.6^{+0.2}_{-0.3}$
GW190521	$157.9^{+37.4}_{-20.9}$	$66.9^{+15.5}_{-9.2}$	$91.4^{+29.3}_{-17.5}$	$66.8^{+20.7}_{-20.7}$	$0.06^{+0.31}_{-0.37}$	$4.53^{+2.30}_{-2.13}$	$0.72^{+0.29}_{-0.29}$	$150.3^{+35.8}_{-20.0}$	$0.73^{+0.11}_{-0.14}$	940	$14.2^{+0.3}_{-0.3}$

TABLE VI. Median and 90% symmetric credible intervals on selected source parameters

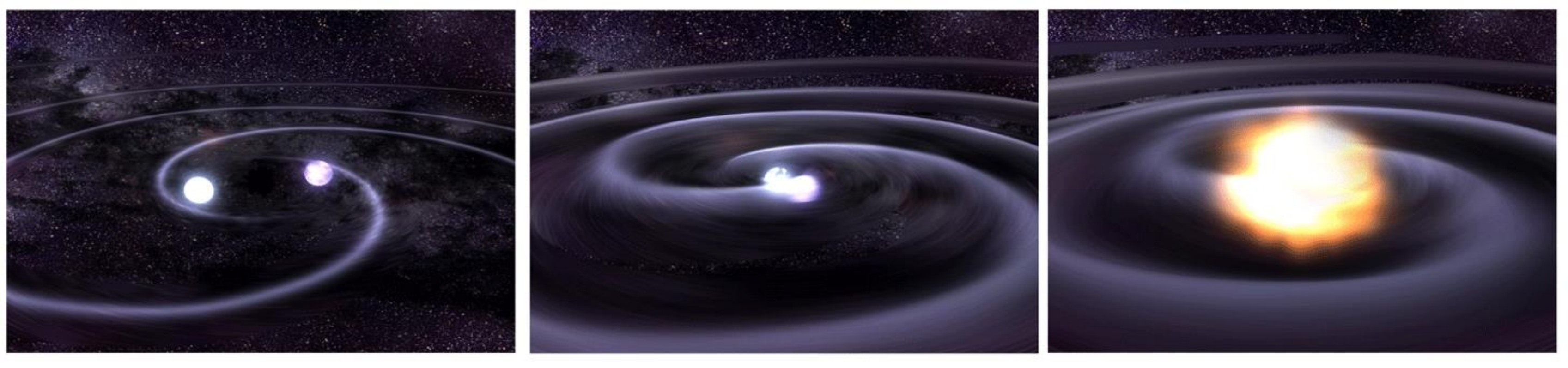
compact binary coalescences (CBCs) 밀집 쌍성 병합

inspiral motion 나선근접궤도 운동

matched filter + 중력파 파형 h(t) ➔ 중력파원의 물리량

{m1,m2,s1,s2, a, d, RA, dec} ➔ "관측가능한 물리량"
+ eccentricity observables

단, 중력파 자료 분석 ➔ "통계적 추정" inferences



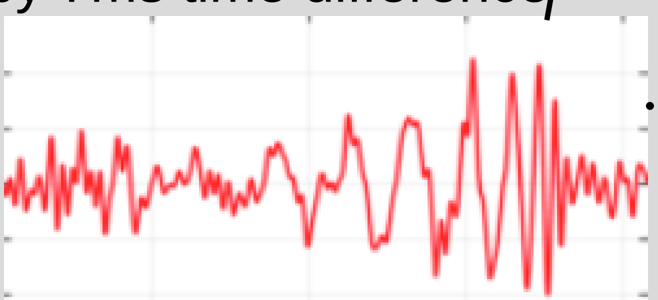
parameter estimation

GW detection

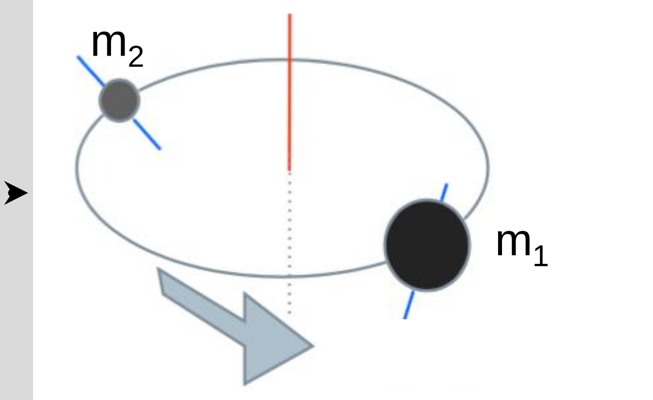
Measuring observables

- m1, m2, s1, s2
- 거리 d
- 천구상의 위치 sky location
- 궤도 모양

two sites of LIGO
on Earth detect GWs
by 7ms time difference



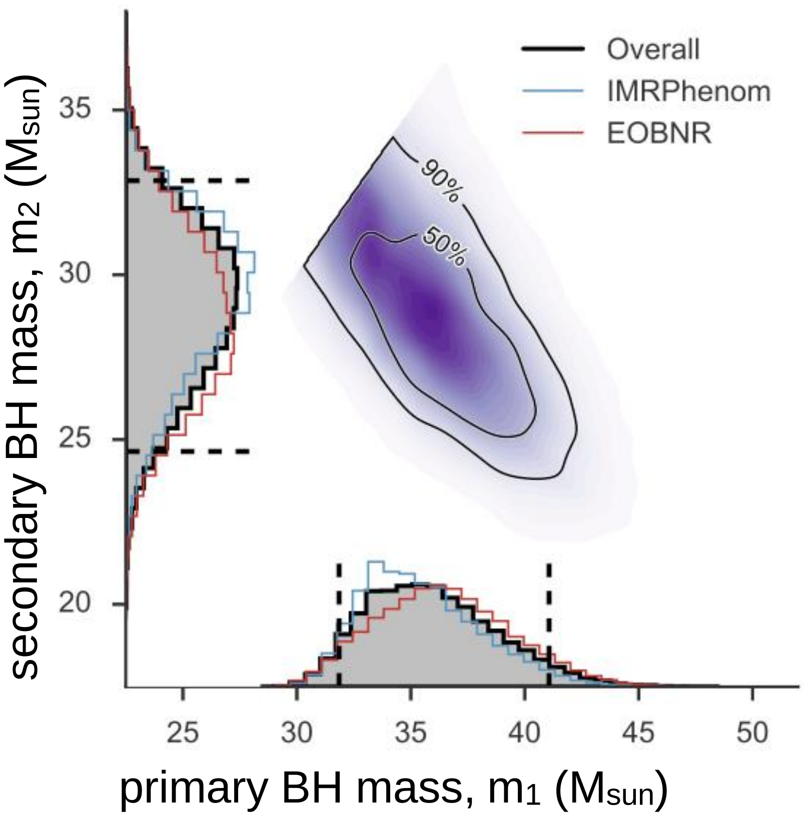
Bayesian inference
"parameter estimation"



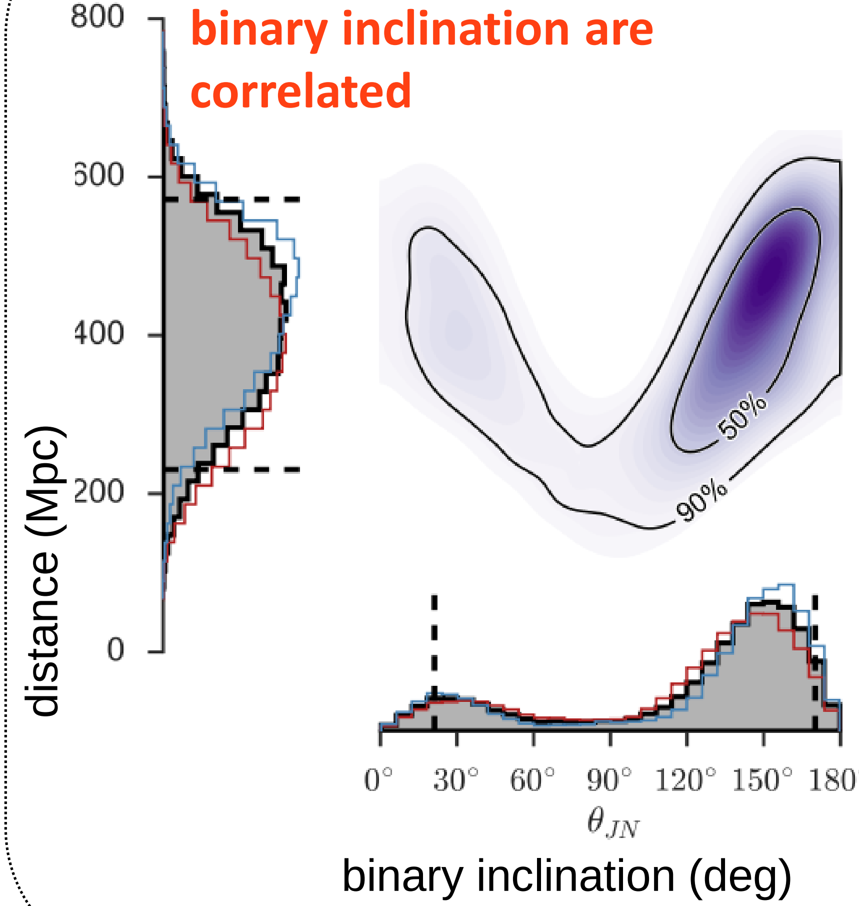
example of parameter estimation: GW150914

two GW waveform models for BH-BH binaries
(IMRPhenom and EOBNR)

individual masses are measured



distance and binary inclination are correlated



mass and spin of the final, single BH remnant formed after the merger of two BHs (GW150914)

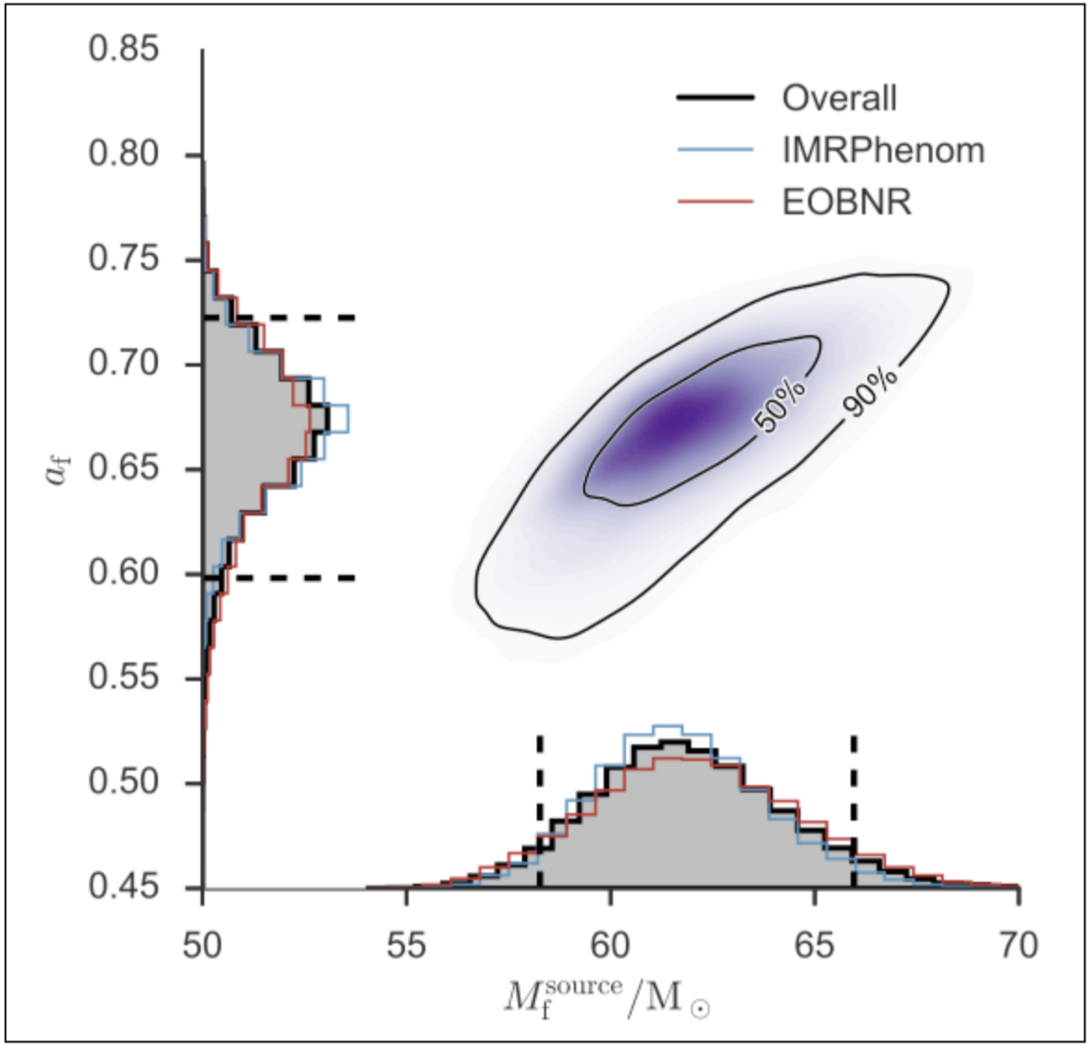
GW energy ~ three Suns ($E=mc^2$)

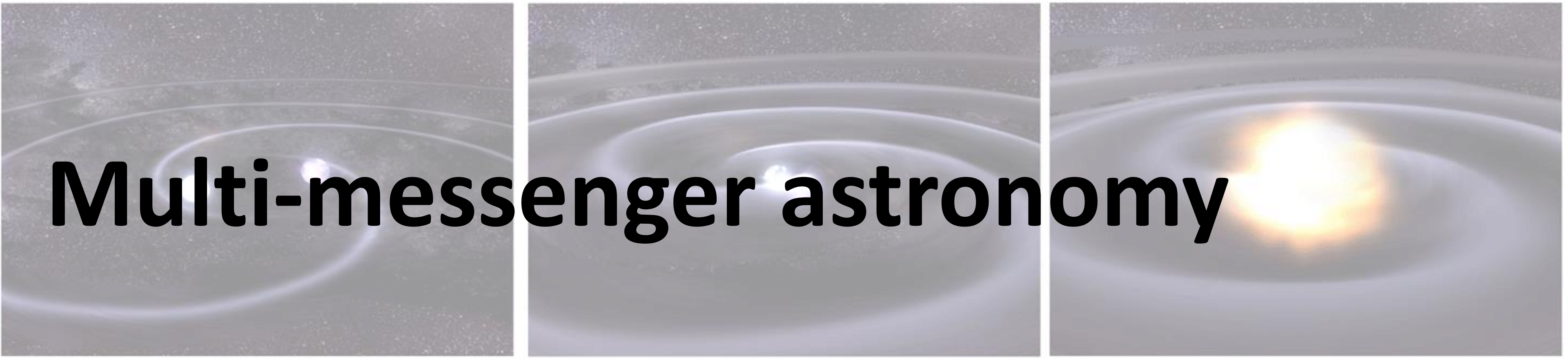
$m_1 + m_2 = m_{final}$ + GW energy

First concrete measurement of a BH spin ~ 0.65

dimensionless spin parameter
(0 =< a =< 1)

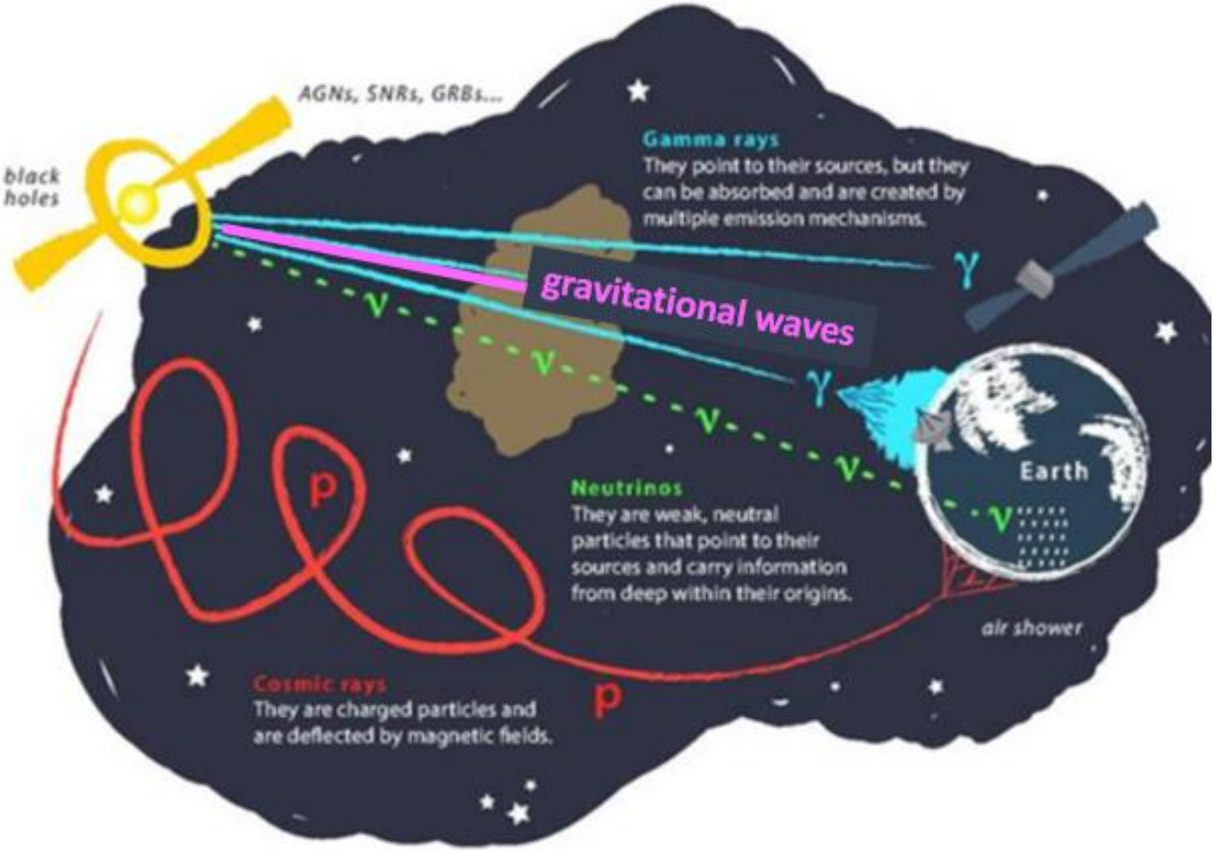
$$a = \frac{cJ}{GM^2}$$





Multi-messenger astronomy

light + particles (neutrinos, cosmic rays) + gravitational waves



Detection of the first “astrophysical” neutrinos from another galaxy (“blazer”) by

the IceCube Neutrino Observatory

[original URL:
https://www.youtube.com/watch?v=wfVM6To7XfE](https://www.youtube.com/watch?v=wfVM6To7XfE)

IceCube Neutrino Observatory
1.85K subscribers

Korean science news article
https://bit.ly/2Wyk8g4

외계 중성미자 발원지 찾았다

"멀티메신저 우주물리학 시대 도래"

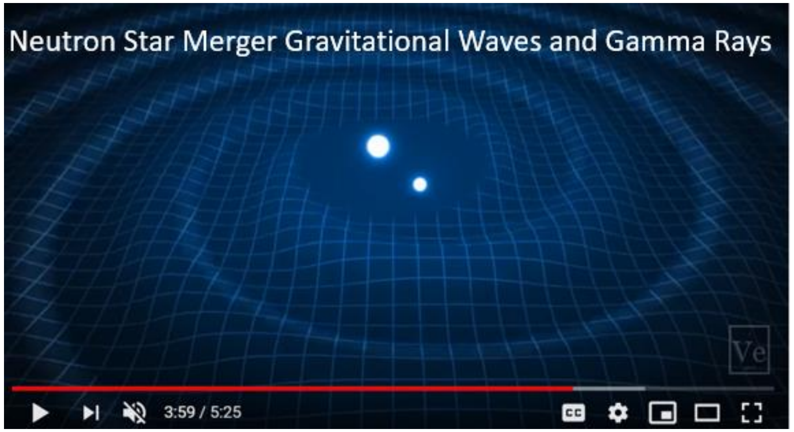
2018.07.13 03:38 | 김병희 객원기자

Example of MMA: **GW170817 “GW + light”**

neutrino is also expected but not detected

[original URL:](https://www.youtube.com/watch?v=txpIT0PW02E)
https://www.youtube.com/watch?v=txpIT0PW02E

Chandra X-ray Observatory
28.6K subscribers



[original URL:](https://www.youtube.com/watch?v=EAyk2OsKvtU)
https://www.youtube.com/watch?v=EAyk2OsKvtU

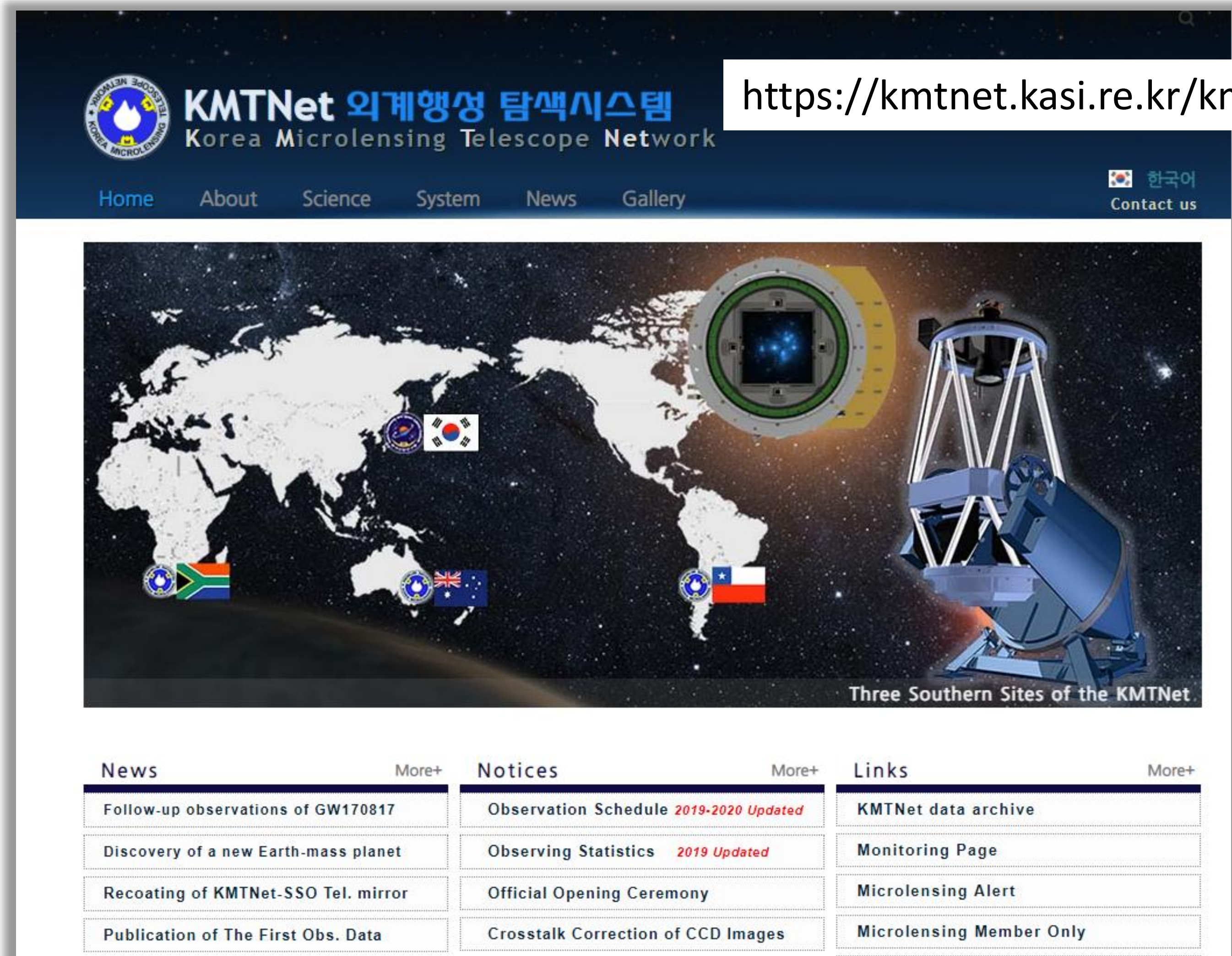
Veritasium
6.96M subscribers

further reading (in Korean)

천체에서 오는 중력파와 감마선, X-선, 가시광선 등 전자기파 신호의 동시 관측 최초 성공

https://www.kasi.re.kr/kor/research/post/mainResearch/10215

KASI 한국천문연구원 Korea Astronomy & Space Science Institute https://kmtnet.kasi.re.kr/kmtnet-eng/



size: 1.6 m (diameter)

3 optical telescopes

in
Chile,
Australia,
Republic of South Africa

GW170817 success story

- GW signals from neutron star – neutron star inspiral is observed
- Fermi gamma-ray satellite telescope independently detected gamma-ray burst signals 1.7 s after the GW "trigger"
- temporal & spatial coincidence can be explained if
  both GW and γ-ray light are emitted from the same source

- GW observation ➔ individual masses, distance "m_1, m_2, d"
- gamma-ray burst + follow-up light observation
  ➔ host galaxy ➔ redshift "z" "후퇴속도"
- Hubble's law

$$v = H_0 d$$

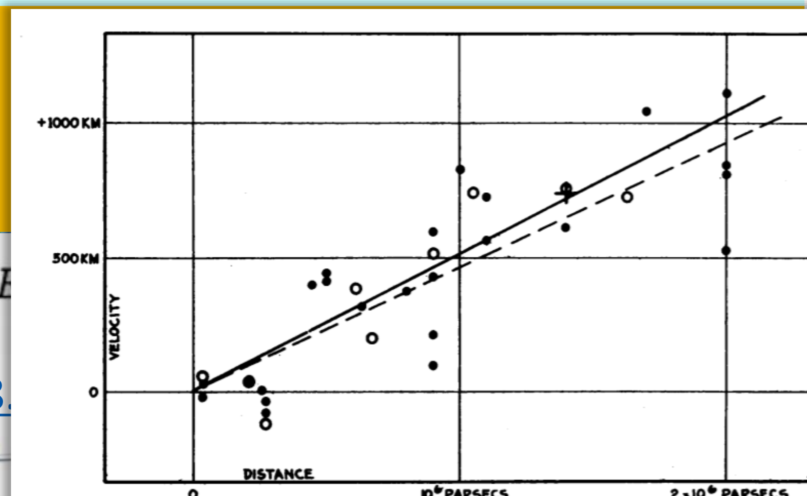
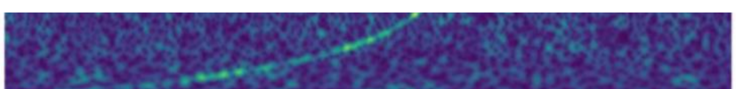


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

A RELATION BETWEEN DISTANCE AND RADIAL VE
AMONG EXTRA-GALACTIC NEBULAE

https://www.pnas.org/content/pnas/15/3/168.



Hubble constant by GW observation

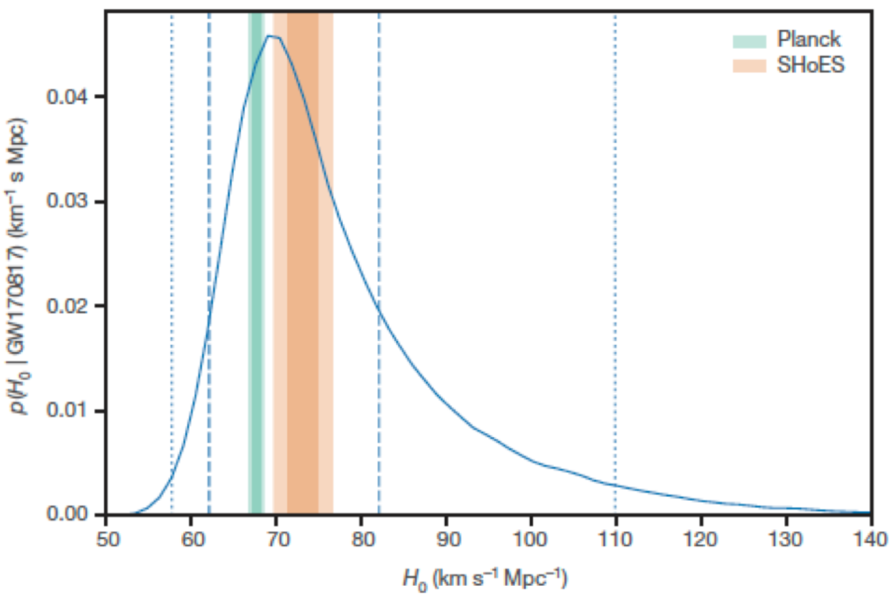
$$v = H_0 d$$ **(v : 후퇴속도, d : 거리, H_0 : 허블 상수)**

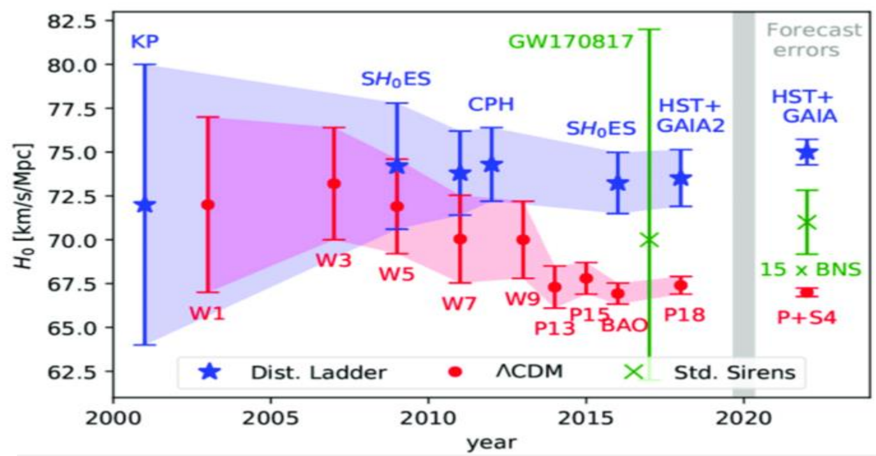
- **근거리 관측을 통한 허블 상수 측정 (기존 방법): ' 표준 광원 ' 을 활용**

- **원거리 관측을 통한 허블 상수 측정: 우주배경복사 관측**

최신 정밀 관측으로 근거리 허블 상수와 원거리 허블 상수 측정값 사이에 오차 범위를 훨씬 벗어나는 차이가 있다는 것이 발견됨 → 새로운 허블상수 갈등의 등장

Hubble constant can be measured by GW observations (NSNS and BBHs)





2001년-현재 H_0 의 원거리 측정(붉은색) vs 근거리 측정(보라색).
두 측정간 오차 범위를 훨씬 벗어나는 차이가 보임.
(Freedman 2017, Nature Astronomy)

[요약] Compact objects as GW sources

- compact binary coalescences (CBCs)
  merging binaries consisting of WD/NS/BH

  3 phases of a CBC = inspiral + merger + ringdown

Types of known CBCs in GW transient catalogue (GWTC-1, 2)

NS-NS “extragalactic population” “EM is not required”

BH-BH (binary black holes = BBHs) “stellar-mass” black holes

NS-BH (not included in GWTC-2) GW200105, GW200115

GW detections so far

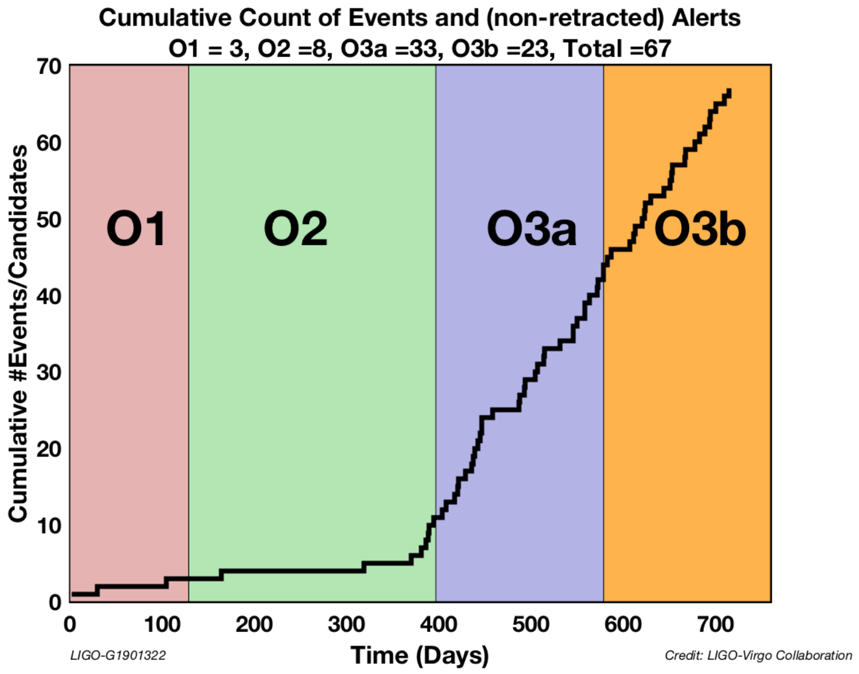
better sensitivities ➔ more detections, many surprises!

O1 : GW150914
O2: GW170817 (NS-NS binary merger)
O3: GW190814 (NS-BH candidate)
GW190521 (Intermediate-mass BH)

56 detections from O3

5-times more O1+O2
(total 11 detections)

Image credit:
LIGO-Virgo
Collaboration.



prospects for BH astronomy with GW/EM observations

Stellar-mass BBHs

- **advanced LIGO + advanced Virgo + KAGRA** (from the year 2021)

  Korea contribute in KAGRA data analysis (Ewha, Inje, UNIST) &

  LIGO data analysis → Korea GW group (KGWG)

- develop **accurate/fast/realistic waveform models**

  - higher modes, eccentricity

  - important for better distance measure → "standard sirens"

- **realtime parameter estimation** for mass, distance, sky location

  - important for EM follow-ups

- compare **model predictions with GW/EM observation**

GW science goes on !

LIGO Hanford Observatory control room. Credit: Caltech/MIT/LIGO Lab.

LIGO-Virgo-KAGRA Webinar to Discuss New Results on the Gravitational-wave Background

News Release • February 2, 2021

On Thursday 4 February, at 10:00 Eastern US (other time zones below), the LVK will host an online webinar entitled "Constraining astrophysical and cosmological gravitational-wave backgrounds with Advanced LIGO and Virgo's third observing run." We will present results from our recent papers: **arxiv.org/abs/2101.12248** and **arxiv.org/abs/2101.12130**. The webinar is open to all.

Register for the webinar.

LIGO-Virgo-KAGRA Webinar
Thu, 4 Feb at 10:00 Eastern Time (US and Canada)
Thu, 4 Feb at 07:00 (US PST/Los Angeles)
Thu, 4 Feb at 09:00 (US CST/Chicago)
Thu, 4 Feb at 16:00 (CET/Pisa, Italy)
Thu, 4 Feb at 20:30 (IST/Pune, India)
Fri, 5 Feb at 00:00 (JST/Tokyo)
Fri, 5 Feb at 02:00 (AEDT/Sydney)

A recording will be posted after the seminar for those who cannot attend the live event.

Update: View the webinar:

GW observation will be resumed hopefully soon!

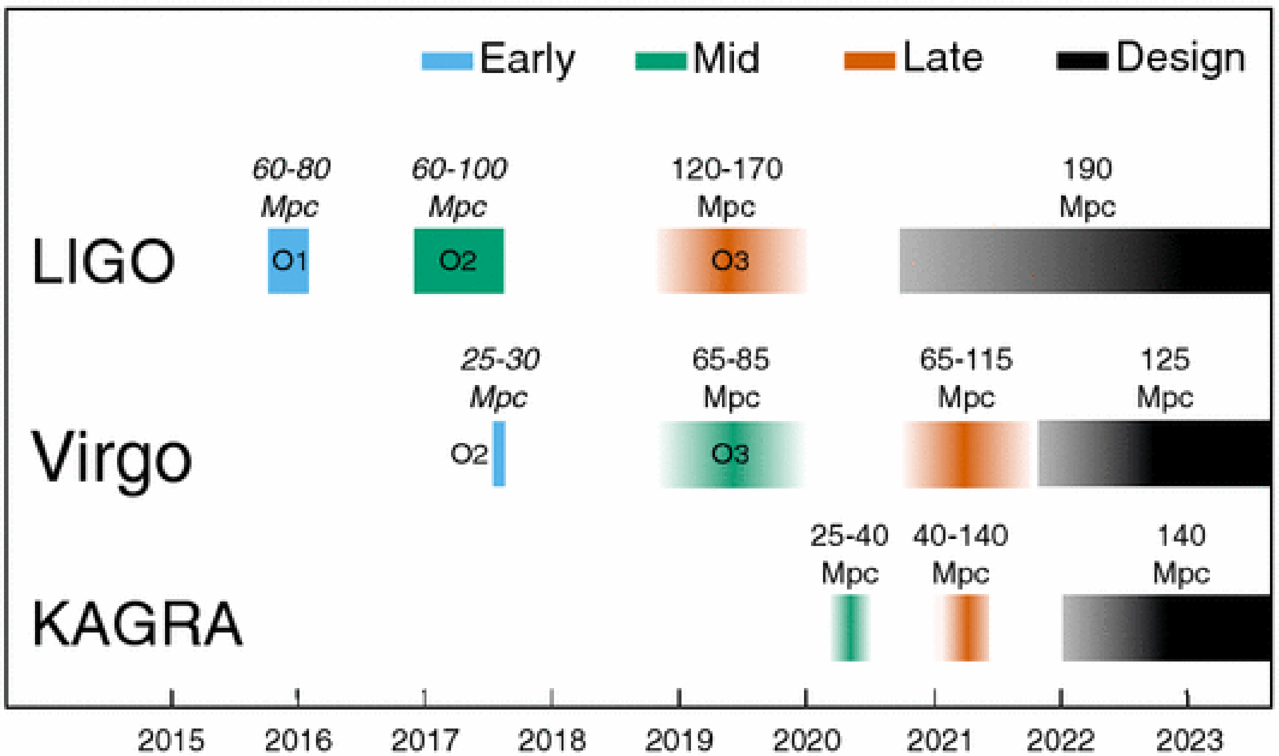
Review Article | Open Access | Published: 26 April 2018

Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA

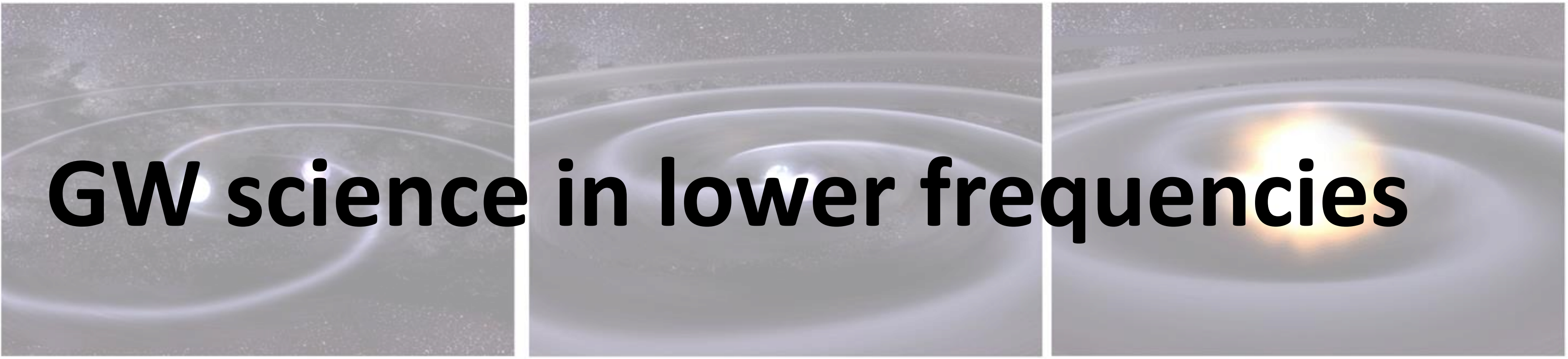
B. P. Abbott, R. Abbott, [...] KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration

Living Reviews in Relativity **21**, Article number: 3 (2018) | Cite this article

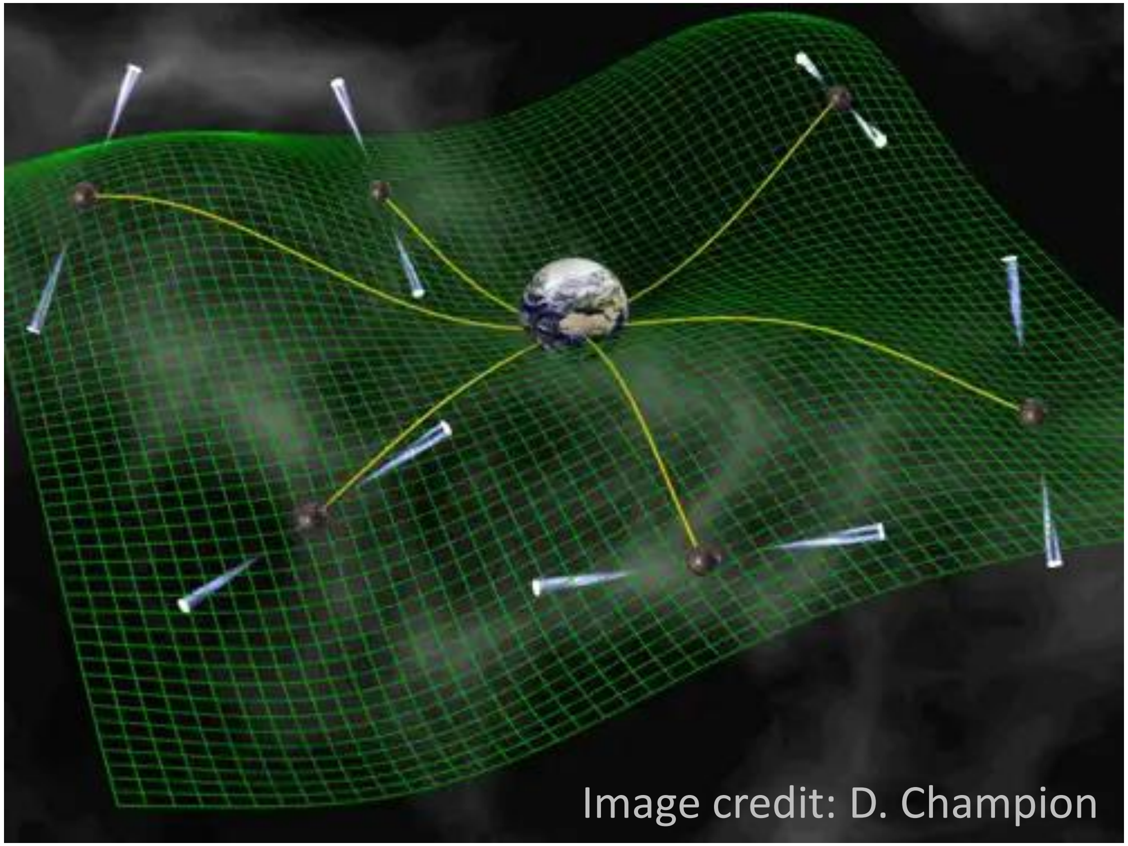
https://link.springer.com/article/10.1007/s41114-018-0012-9



GW science in lower frequencies



Pulsar timing array and search for supermassive BH binaries



Pulsar timing array (PTA) collaborations (alphabetical order)

- **European Pulsar Timing Array (EPTA)**
  Europe: Effelsberg, Lovell, Nancay, Sardinia, and Westerbork Radio Synthesis Telescope

- **North American Nanohertz Observatory for Gravitational Waves (NANOGrav, 2007-)**
  USA/Canada: Arecibo Telescope, Green Bank Telescope (GBT)

- **Parkes Pulsar Timing Array (PPTA, 2004-)**
  Australia: Parkes Radio Telescope

arXiv.org > astro-ph > arXiv:1602.03640

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 11 Feb 2016]

The International Pulsar Timing Array: First Data Release

J. P. W. Verbiest, L. Lentati, G. Hobbs, R. van Haasteren, P. B. Demorest, G. H. Janssen,

THE NANOGRAV 11-YEAR DATA SET: HIGH-PRECISION TIMING OF 45 MILLISECOND PULSARS

High-precision timing of millisecond pulsars offers the promise of detecting gravitational waves with periods of a few years, i.e., in the nanohertz (nHz) band of the gravitational-wave spectrum

Main science target:

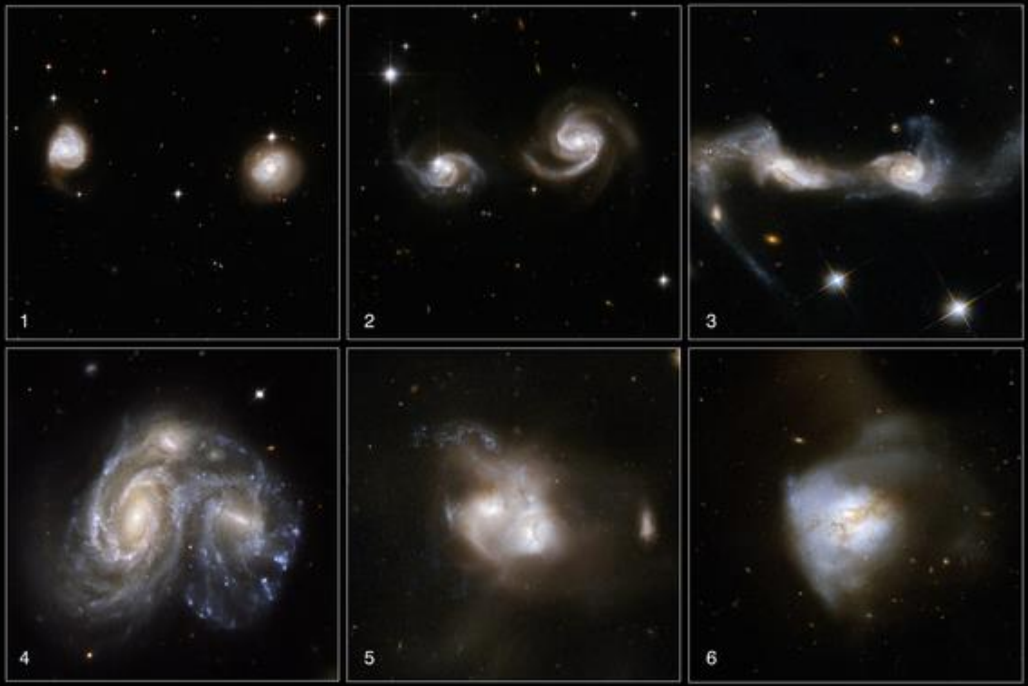
- direct detection of gravitational waves using pulsar timing
- incoherent superposition of GWs from the cosmic merger history of supermassive black hole binaries ➔ GW background
- detection of a SMBHB ? "resolvable sources" "continuous signal"

[on-going] in collaboration with Hyosun Park, Andrea Lommen (Haverford), and Juhan Kim (KIAS)

unanswered questions:

1) Would merging galaxies result in supermassive BH binaries ?

2) Stellar-mass BBHs merge (like GW150914), do SMBHBs merge ?



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

$$f_{\mathrm{GW}} = \frac{1}{\pi}\sqrt{\frac{GM}{a^3}}$$

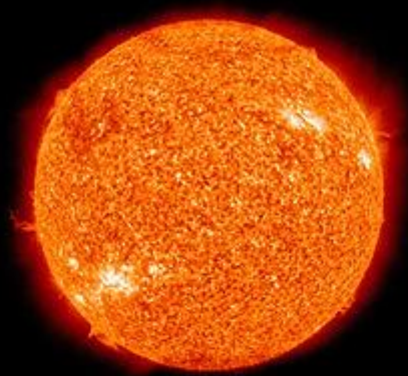
billion solarmass BBH
a = (1/1000) parsec !

"It takes hundreds of millions of years for one merger to complete"

➔ **GW signals from a SMBHB ~ nHz up to μHz**

https://sci.esa.int/web/hubble/-/42637-merger-stages-of-interacting-galaxies

GW signals emitted from “merging” supermassive BBHs are expected to be continuous ➔ narrow-band search



“It takes hundreds of millions of years for one merger to complete”

➔ GW signals from a SMBHB ~ nHz up to μHz

BBHs astronomy for the next decades

➔ nHz (PTA), micro Hz (LISA), ~100 Hz(LIGO)

stellar-mass BBHs,
supermassive BBHs,
BBHs with large mass ratio ➔ supermassive BH + stellar-mass BH

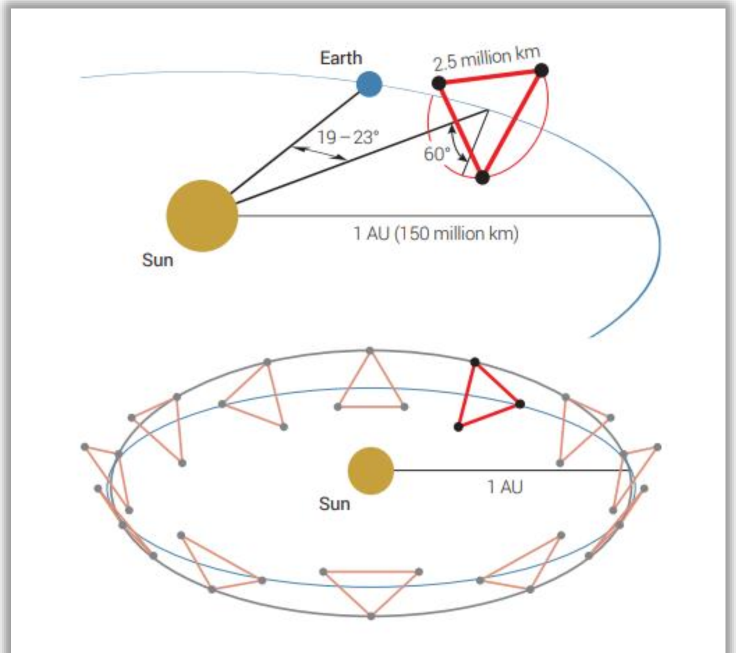
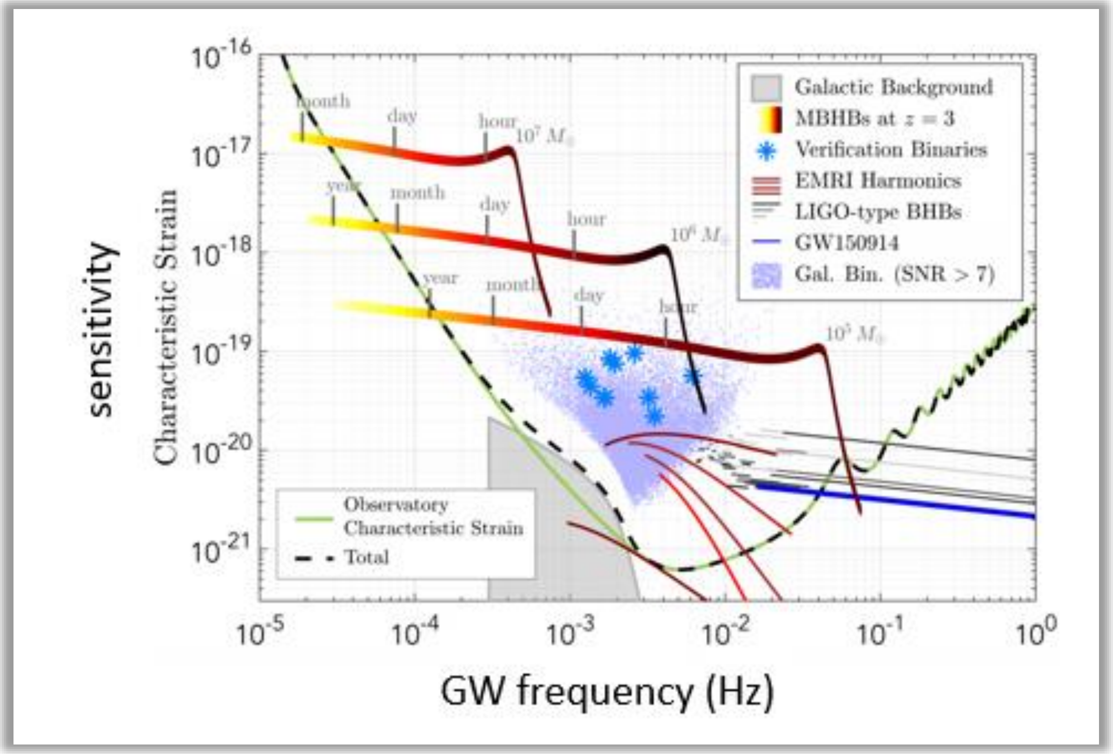


Figure 4: Depiction of the LISA Orbit.



https://arxiv.org/ftp/arxiv/papers/1702/1702.00786.pdf

백색왜성과 리사 중력파 망원경

WD-WD and NS-WD binaries are important GW sources in mHz frequencies

➔ some accreting WD-WD binaries in our Milky Way are **"LISA verification sources"**
(AM CVn = AM Canum Venaticorum = 사냥개자리 AM 변광성) "격변 변광성"

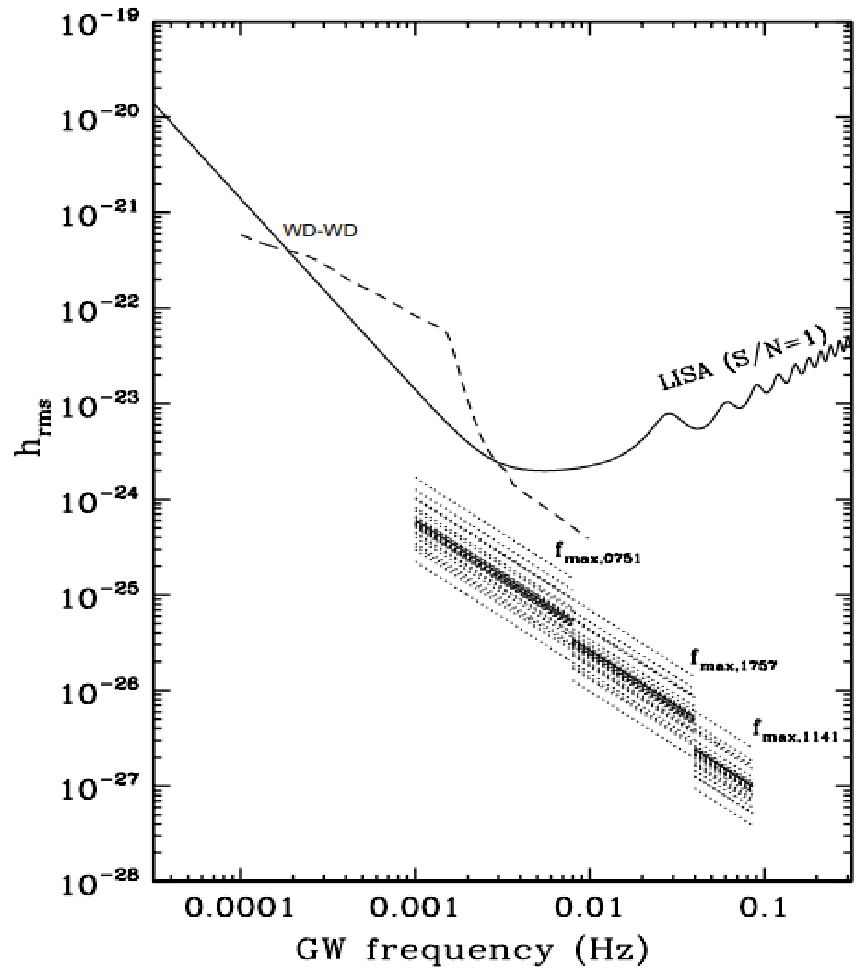
use eq. (16) in his paper to calculate $h_c(f)^5$, and find

$$h_{\rm rms}(f) \simeq 1.7 \times 10^{-26} \left(\frac{\mathcal{M}}{\rm M_\odot}\right)^{5/6} \left(\frac{f}{\rm mHz}\right)^{-7/6} \left(\frac{N_o}{\rm Mpc^{-3}}\right)^{1/2} \left(\frac{T_{\rm obs}}{\rm yr}\right)^{-1/2} , \quad (14)$$

where $\mathcal{M}$ is the "chirp mass" of a NS–WD binary defined by

$$\mathcal{M} \equiv \frac{(M_{\rm NS} M_{\rm WD})^{3/5}}{(M_{\rm NS} + M_{\rm WD})^{1/5}} , \quad (15)$$

and N_o is the comoving number density of NS–WD, i.e. the number of sources per $\rm Mpc^3$.



The effective GW amplitude for coalescing **NS–WD binaries** overlapped with the expected **LISA** sensitivity curve in 2004.

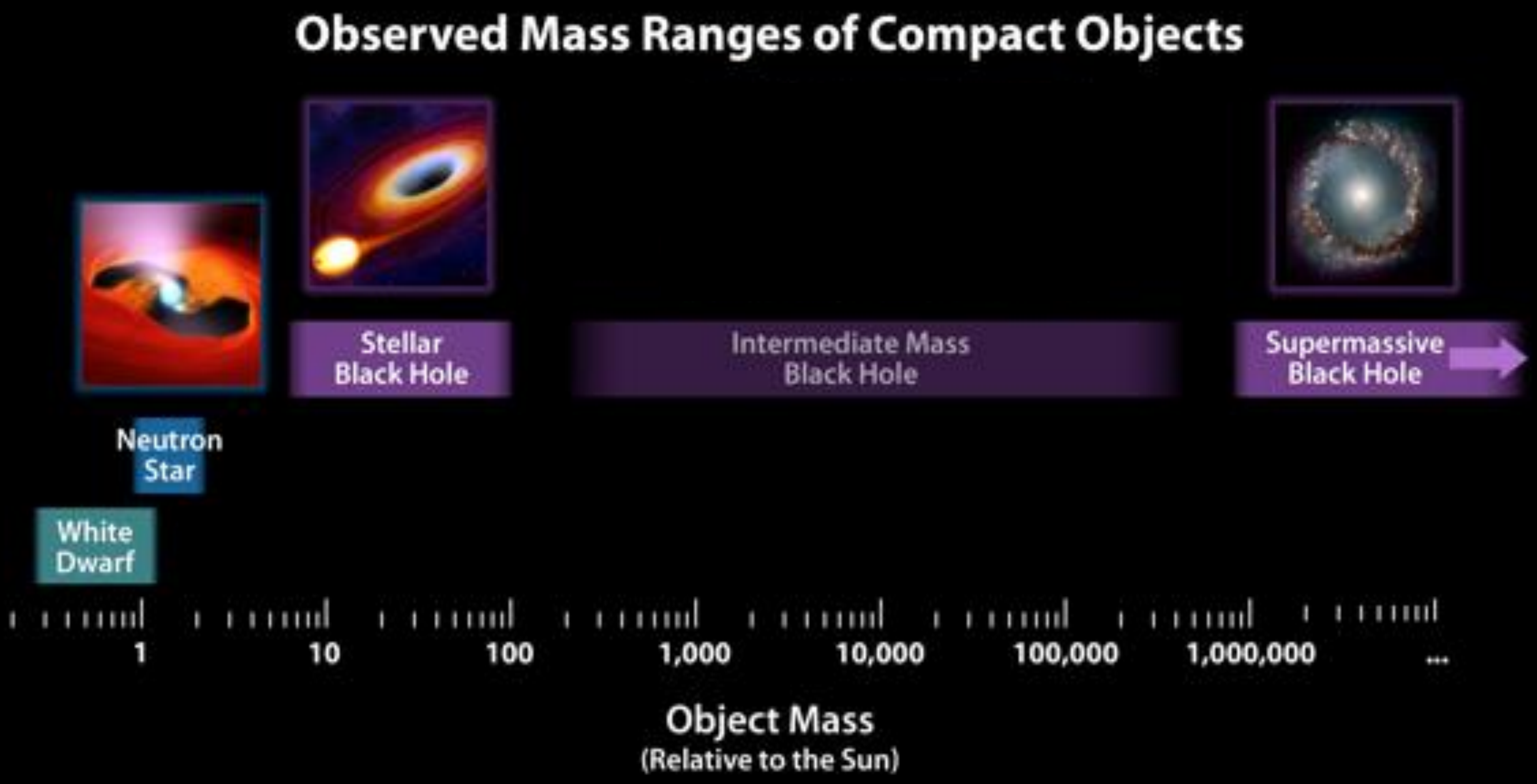
https://iopscience.iop.org/article/10.1086/424954/pdf

THE PROBABILITY DISTRIBUTION OF BINARY PULSAR COALESCENCE RATES. II. NEUTRON STAR–WHITE DWARF BINARIES

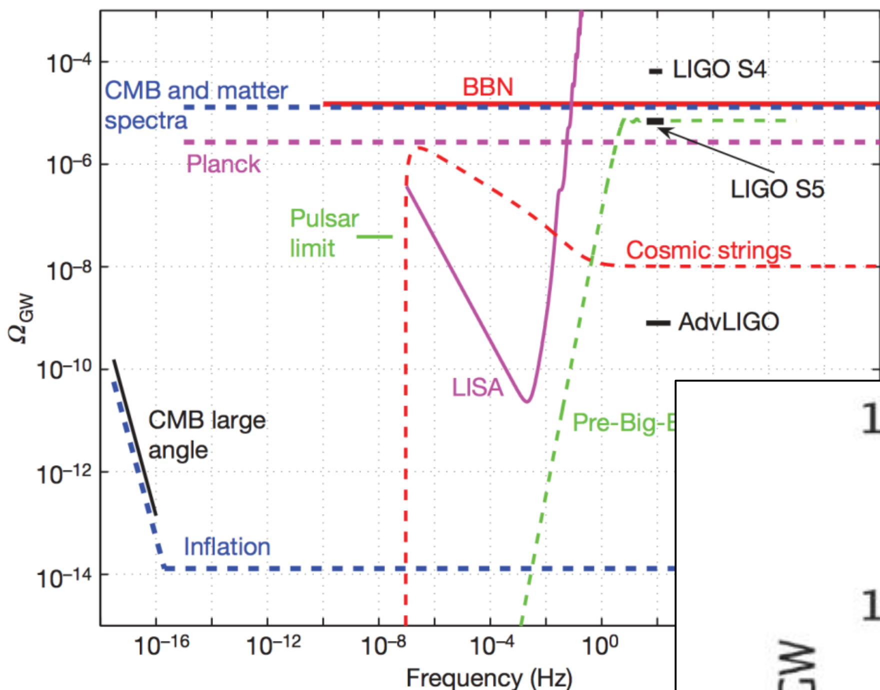
Chunglee Kim,[1] Vassiliki Kalogera,[1] Duncan R. Lorimer,[2] and Tiffany White[1]

Received 2004 February 5; accepted 2004 August 7

Multi-frequency GW observation will shed lights on the **BH mass spectrum** and **BH evolution**



Multi-frequency GW observation will shed lights on the GW background with astrophysical origin

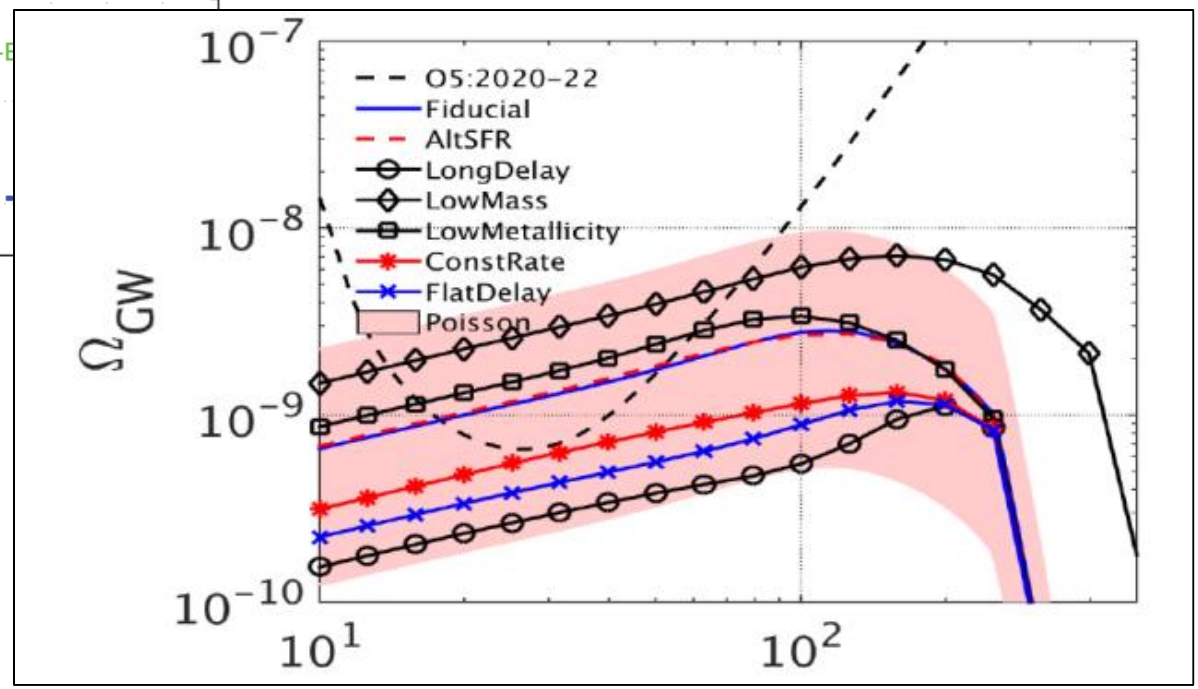


$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}(f)}{df}$$

energy density spectrum in GW

$$\Omega_{gw}(f,\theta) \quad \theta=(m_1,m_2,\chi_{eff})$$

BBH contribution



GW frequency (Hz)

BH astronomy and astrophysics in the next decades

Measuring observables from GW signals

m_1, m_2, $m_{\text{final BH}}$

spin, eccentricity

distance

sky location

Follow-up observations

(supermassive BHs are favored)

metallicity (of a host)

redshift (of a host)

empirical population study

evolution scenario

environment

Next decades will be a golden era for GW astronomy and astrophysics ! ➔ white dwarfs, neutron stars, black holes

GW astronomy and astrophysics

→

Gravitation

strong field gravity

Galaxy formation and evolution

large-scale structure

cosmology

Hubble constant
dark energy, standard model

2020+ : GW obs in 10-2000 Hz

2030+ : GW obs in 10-2000 Hz
in 0.03 mHz – 0.1 Hz
in nHz

Would more GW observations bring answers or more questions ?

감사합니다