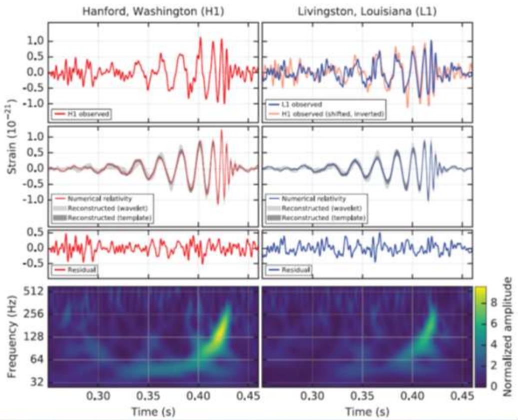
제8차 카그라 국제 워크숍
(2021/7/8, 한국천문연구원, 온라인)

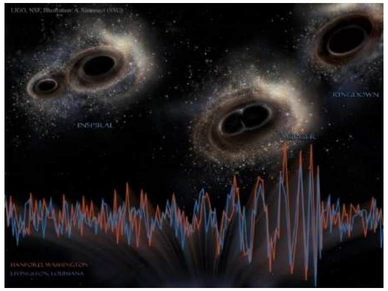
중력파에 대한 10가지 질문
(Ten Questions for Gravitational Waves and Outlook)

강 궁 원

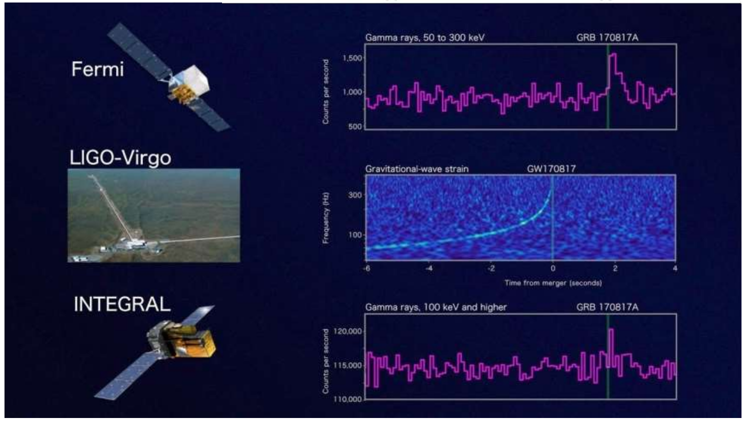
(중앙대, 문의: gwkang@cau.ac.kr)

• 중력파:





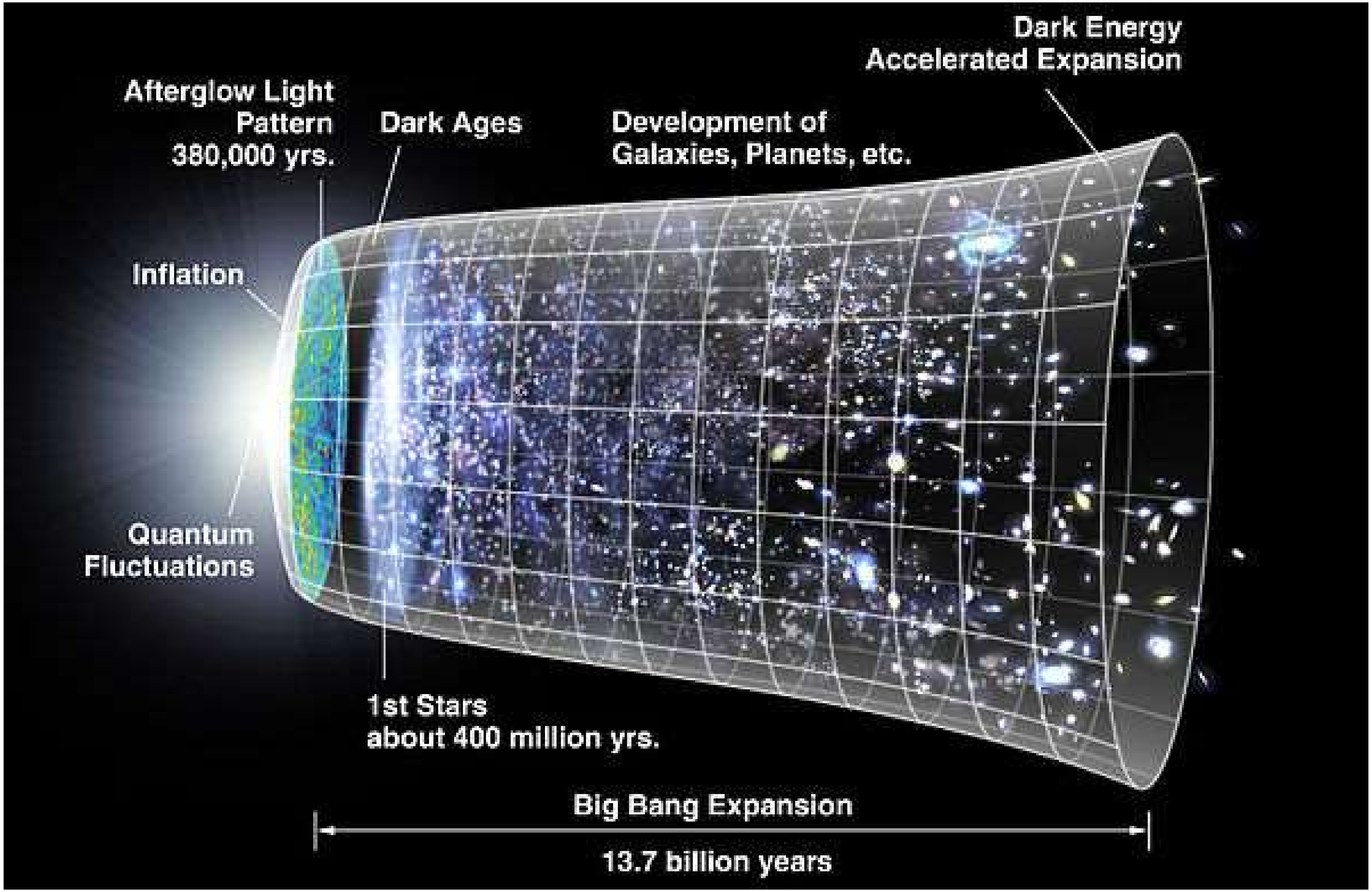
(Credit: Aurore Simonnet)



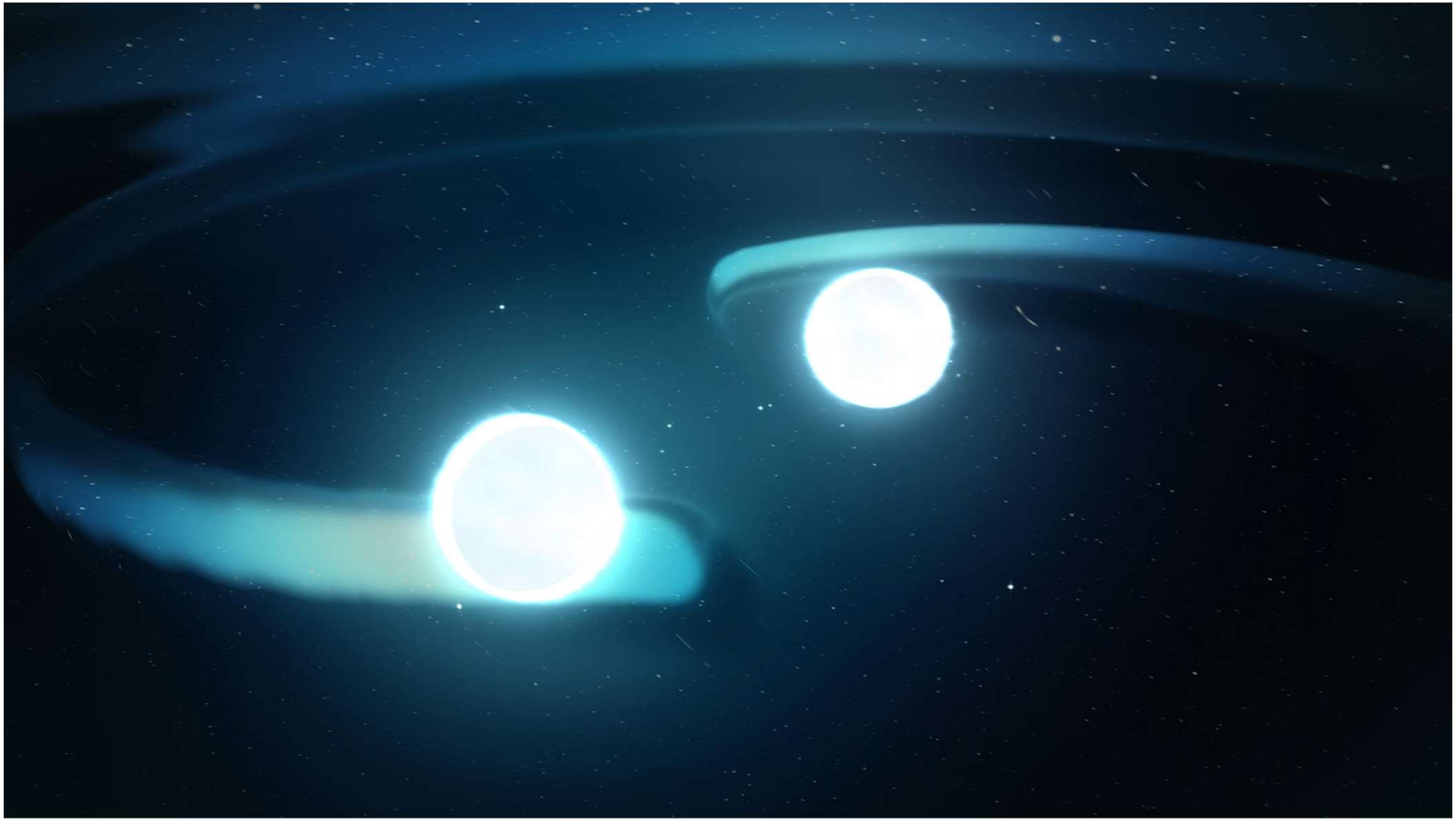
- 2015.09.14 LIGO에서 최초 검출, 2016년 2월 발표
- 1차~3차 관측 가동: 52건 검출, 중력파 천문학/다중신호 천문학 시대 도래

➔ “중력파”의 과학사적 의미, 최근 현황, 그리고 전망

Mars, left, and the Milky Way are visible in the clear night sky as photographed near Salgotarjan, some 110 kms northeast of Budapest, Hungary, Aug. 03, 2018. (MTVA - Media Service Support and Asset Management Fund)



Credit courtesy: NASA/WMAP Science Team



중성자별 병합과 중력파-전자기파 발생(Credit: LIGO/SXS/R.Hurt and T. Pyle)

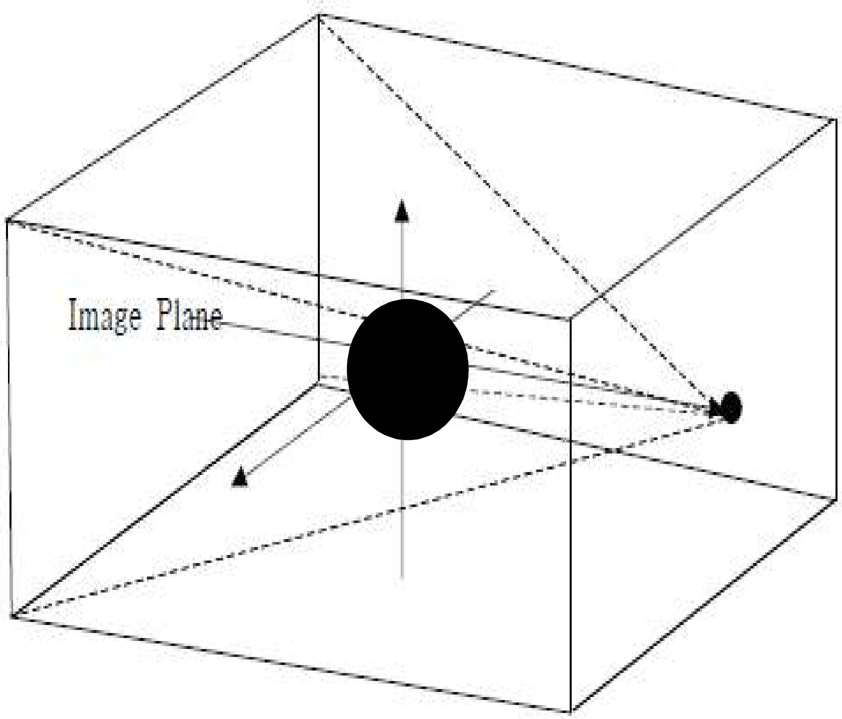
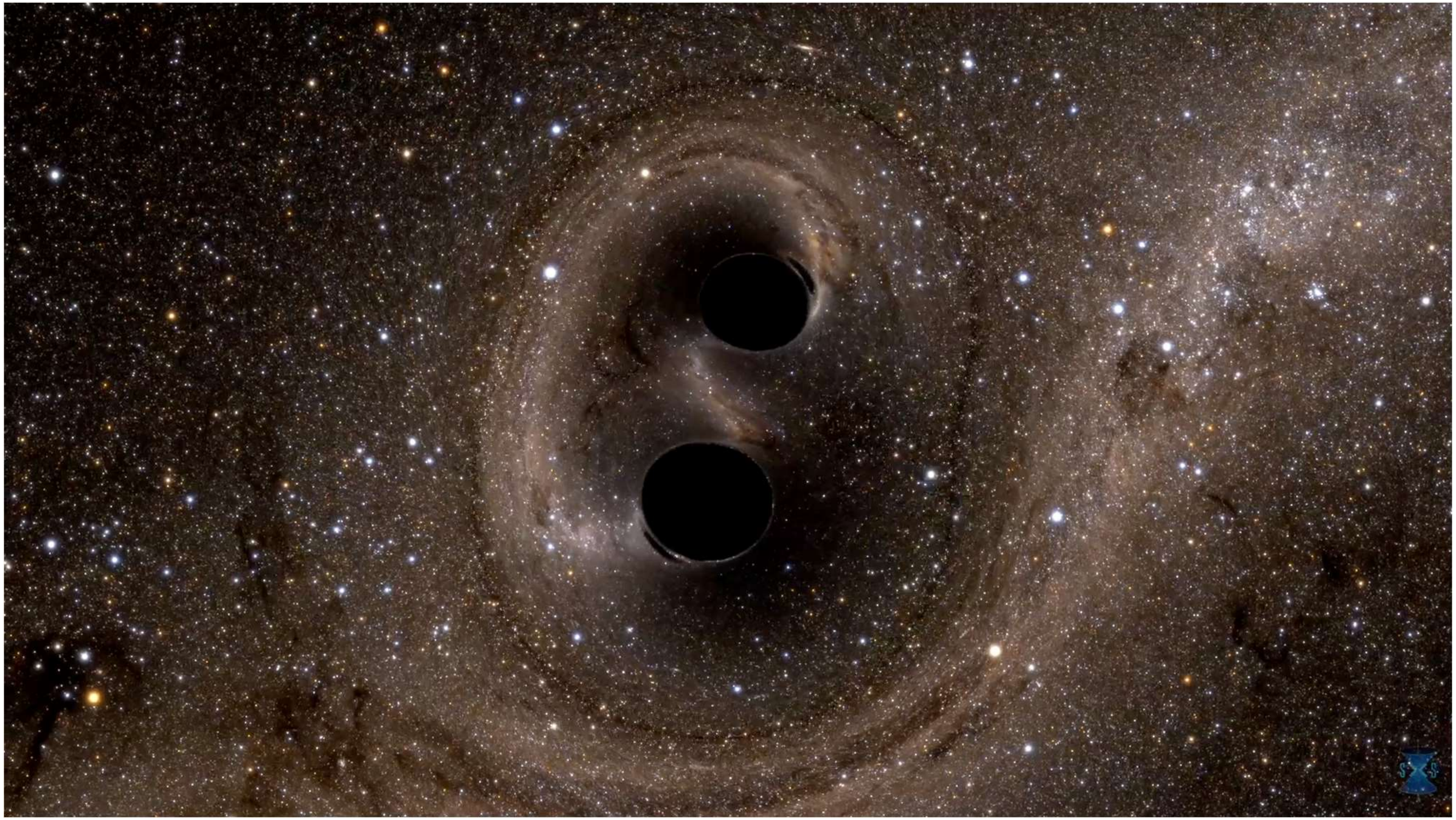


Image Plane



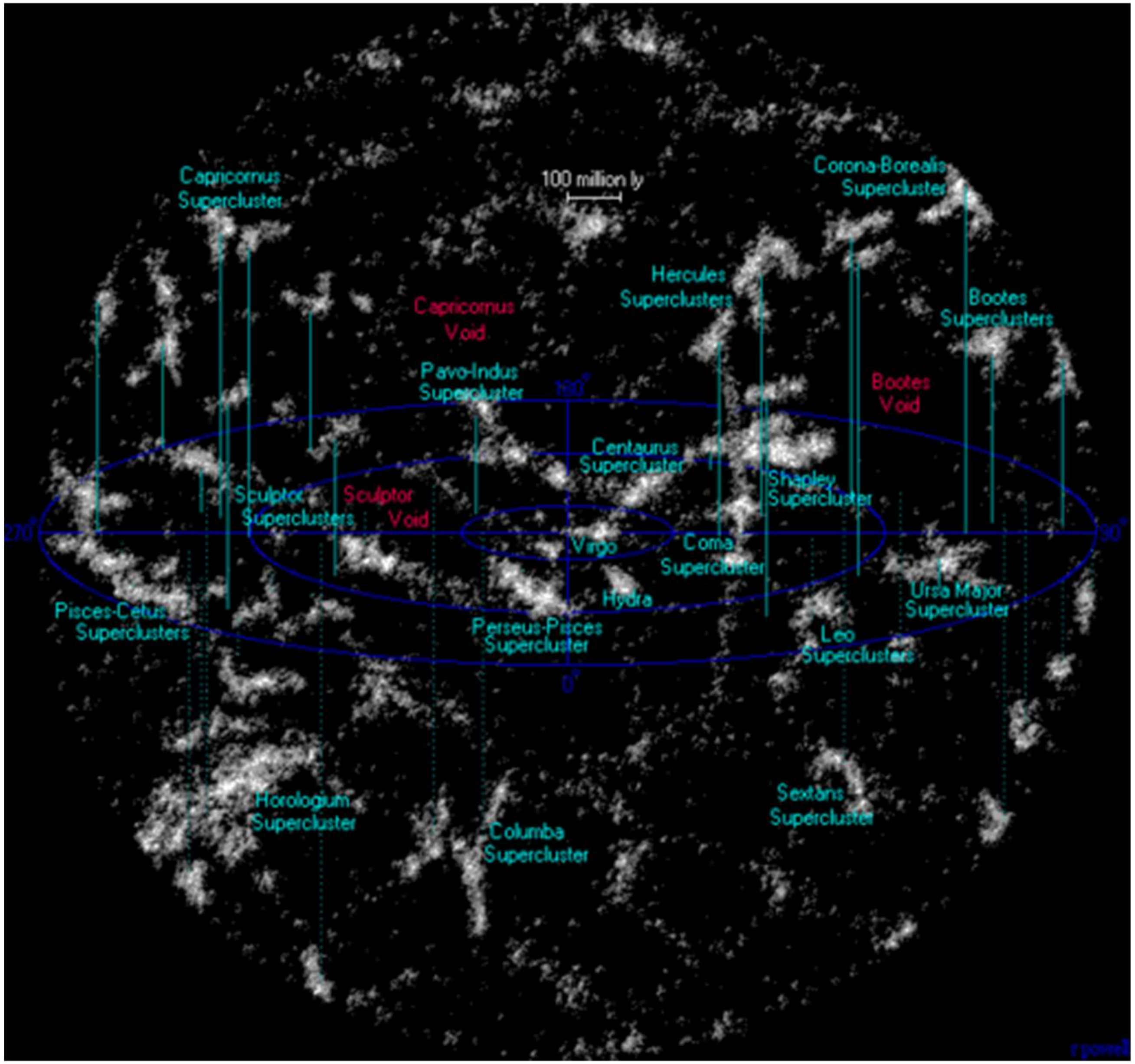
블랙홀 쌍성 병합

✓ **블랙홀 쌍성병합 발생(GW150914):**

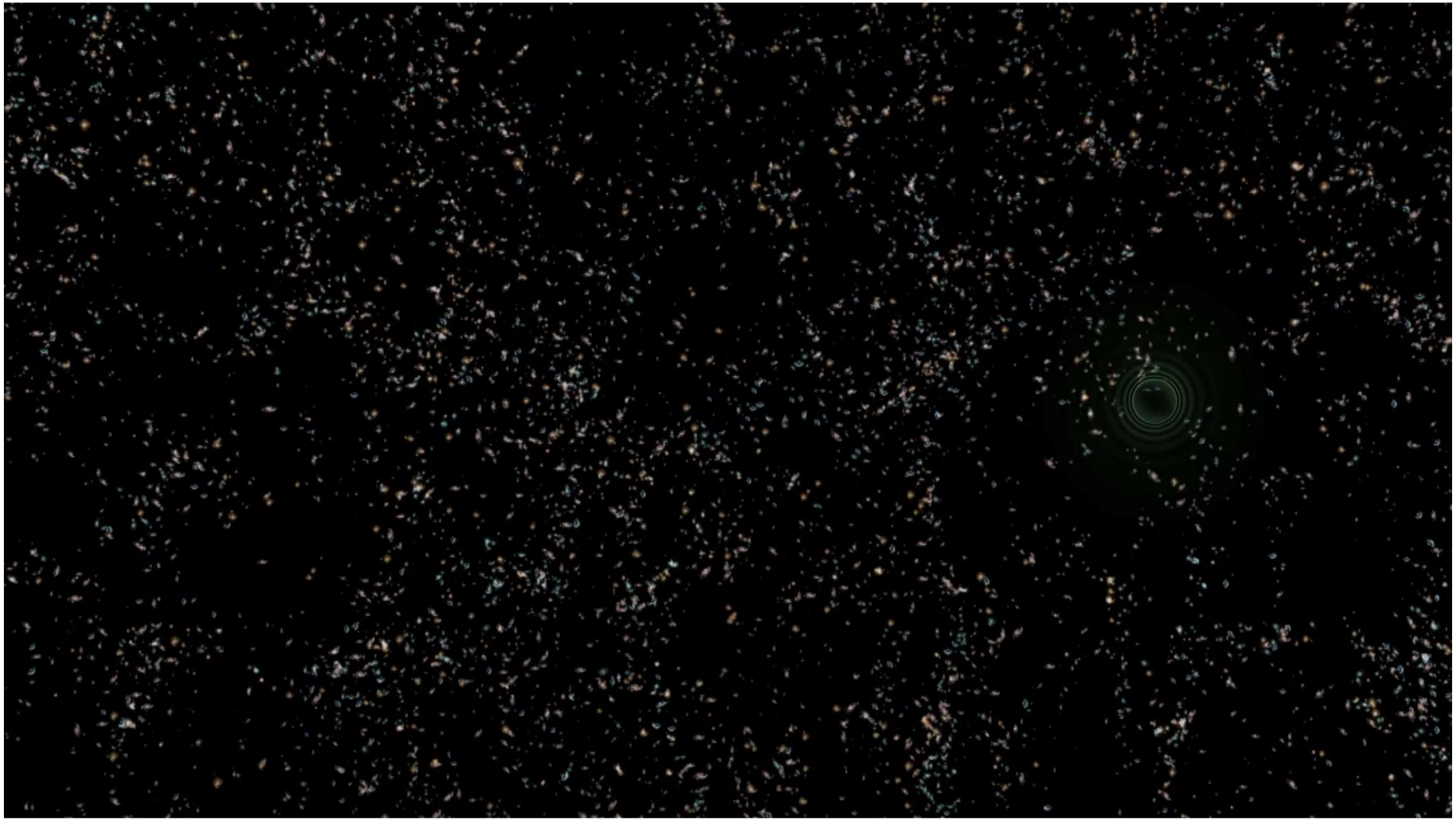
- 거리: 410^{+160}_{-180} Mpc

  (7.5~18.6 억광년)

- 질량: $36^{+5}_{-4}M_{\odot} + 29^{+4}_{-4}M_{\odot}$

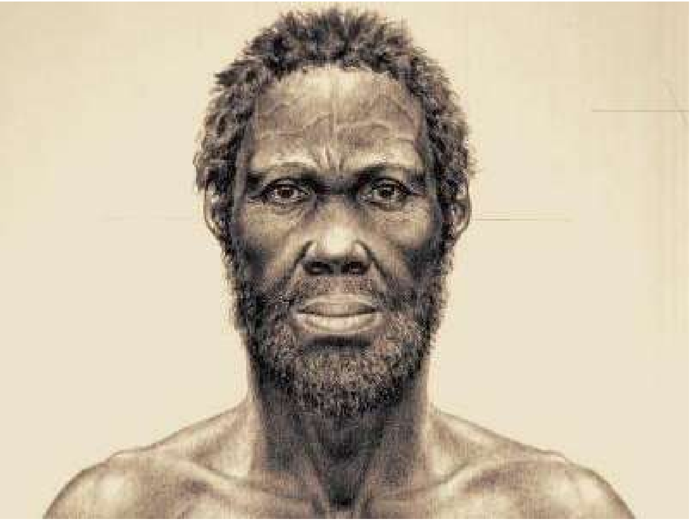


시공간 곡률의 파동



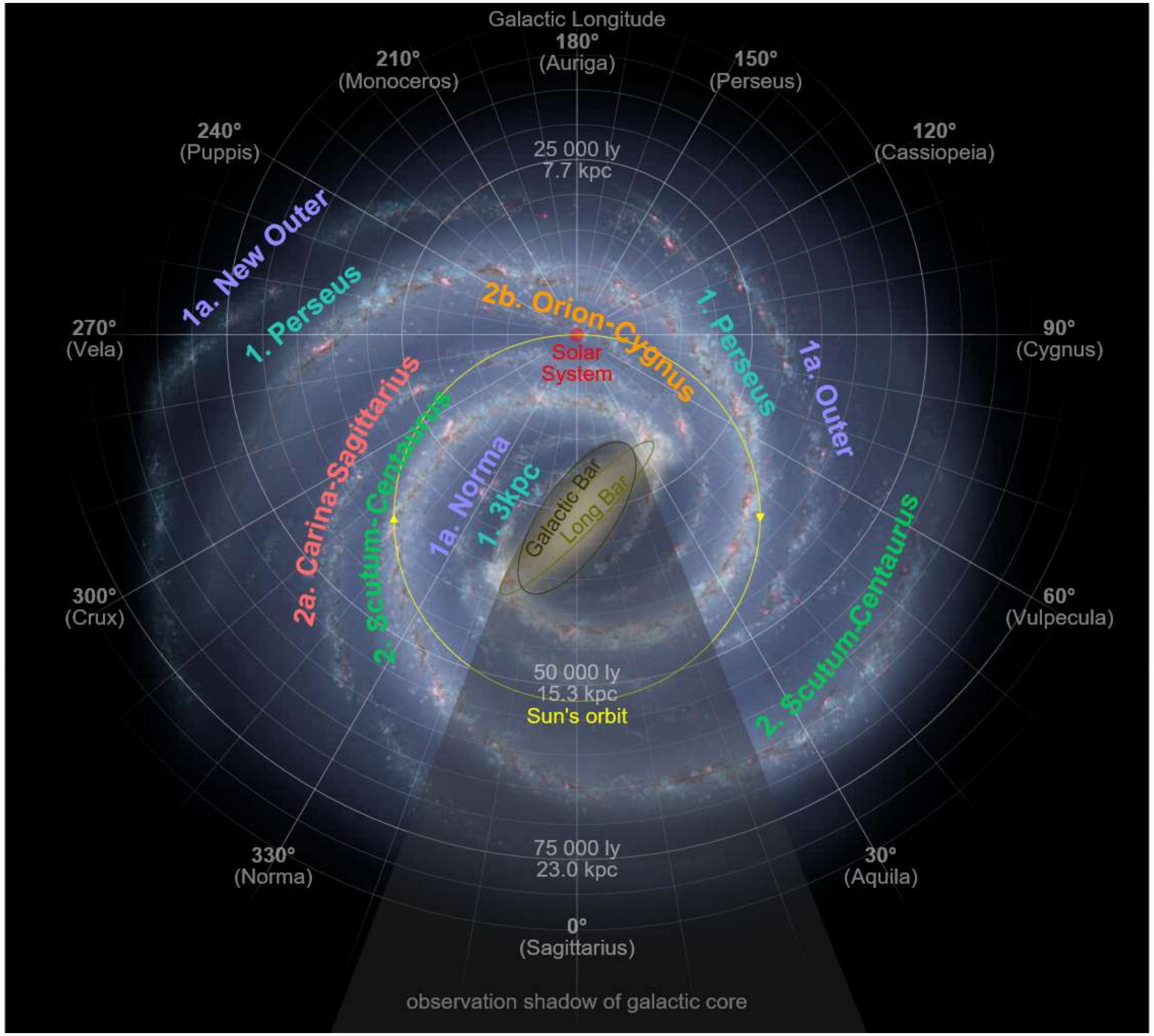
(Credit: LIGO/SXS/R.Hurt and T. Pyle)

✓ 약 10만년 전 우리 은하 진입



현생인류

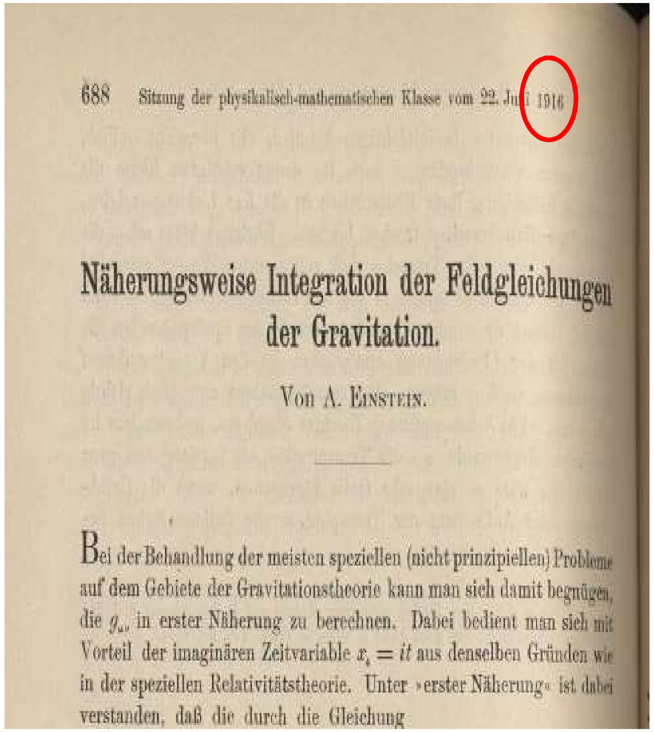
(Credit: 오정근 (천문학회 ’16))



(Credit: Andrew Z. Colvin)

https://commons.wikimedia.org/w/index.php?curid=14646767

- ✓ **1905년: 특수상대론**
- ✓ **1915년: 일반상대론**
- ✓ **1916년: 중력파 예견**



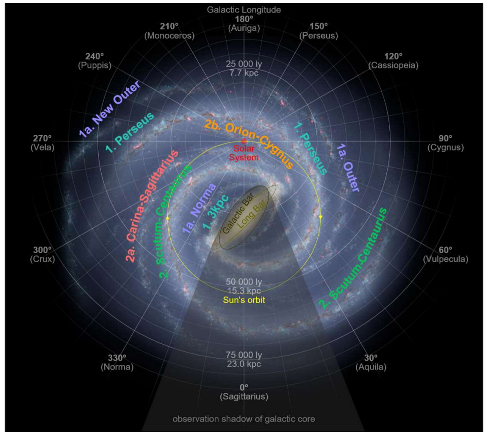
688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

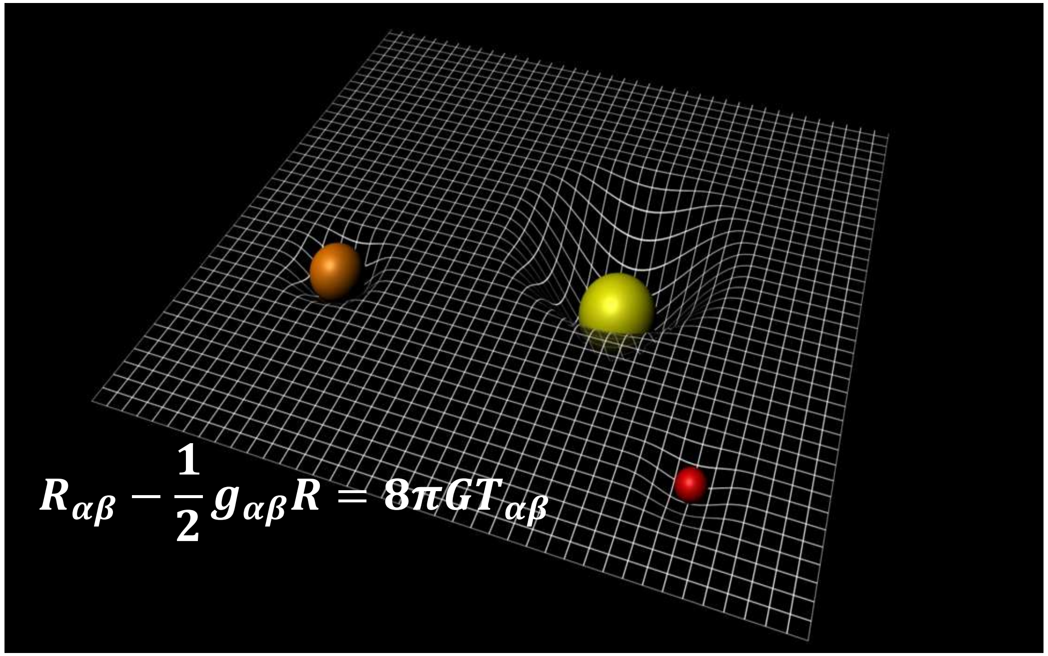
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

A. Einstein (1916)

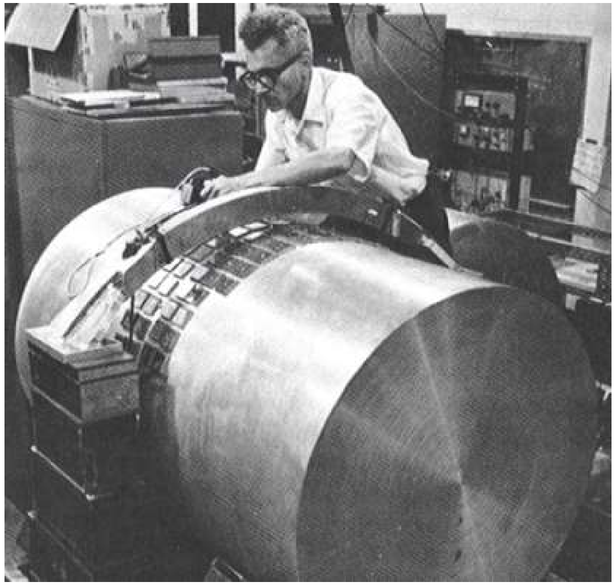




$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = 8\pi G T_{\alpha\beta}$$

(Credit: ESA–C.Carreau)

- ✓ Weber at U. of Maryland (1960s)



- ✓ MIT Technical Report in 1972: “LIGO concept paper”

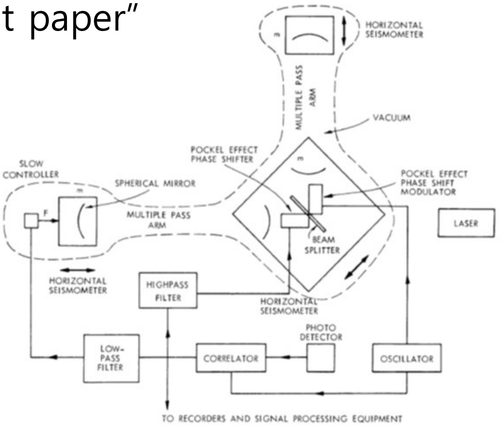
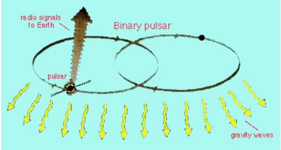


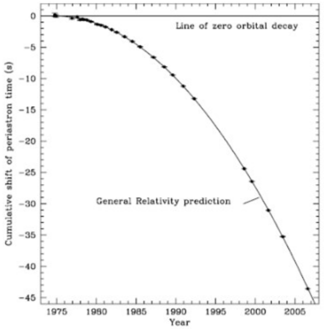
Fig. V-20. Proposed antenna.

TAMA 300 m (NAOJ, Tokyo area, 2008)

(credit: Shinkai ('21))

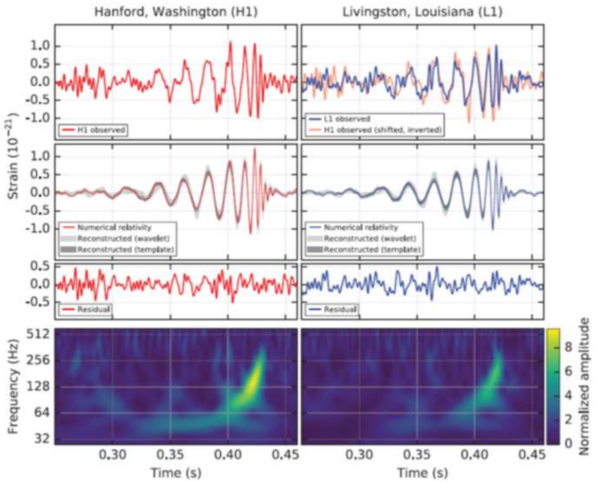
- ✓ PSR B1913+16 Hulse & Taylor (1974)



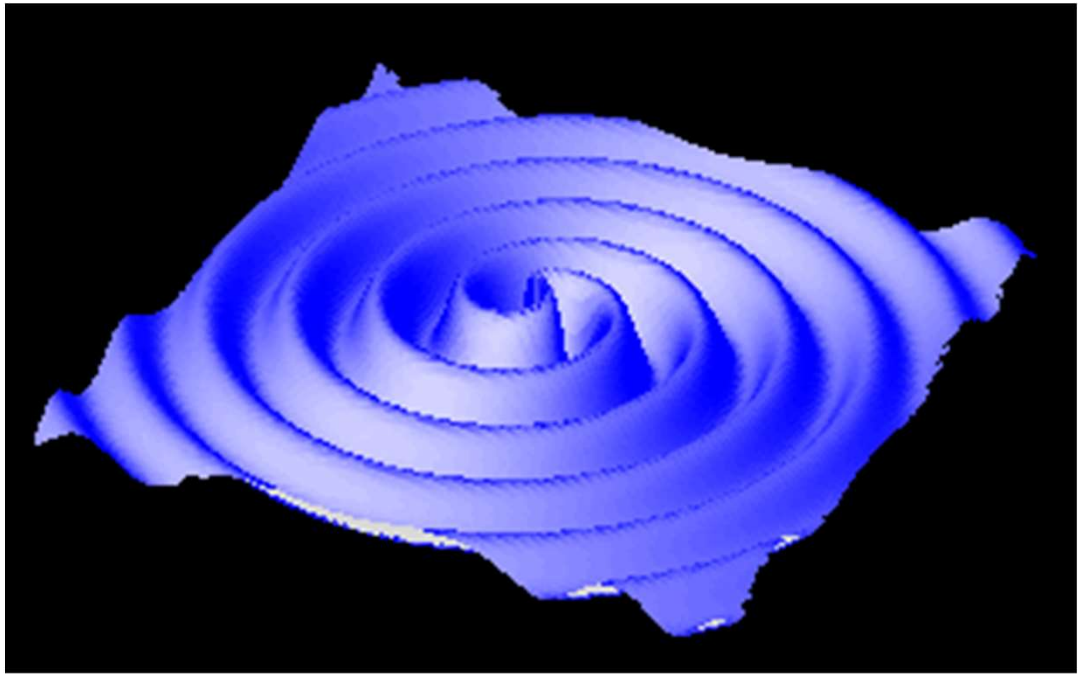


- ✓ **LIGO: 1990~**

- ✓ **2015.09.14: 첫 검출!**

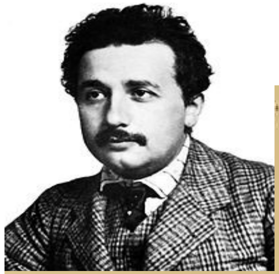


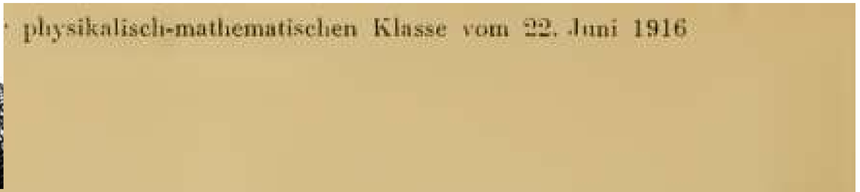
1. 중력파란 무엇인가?



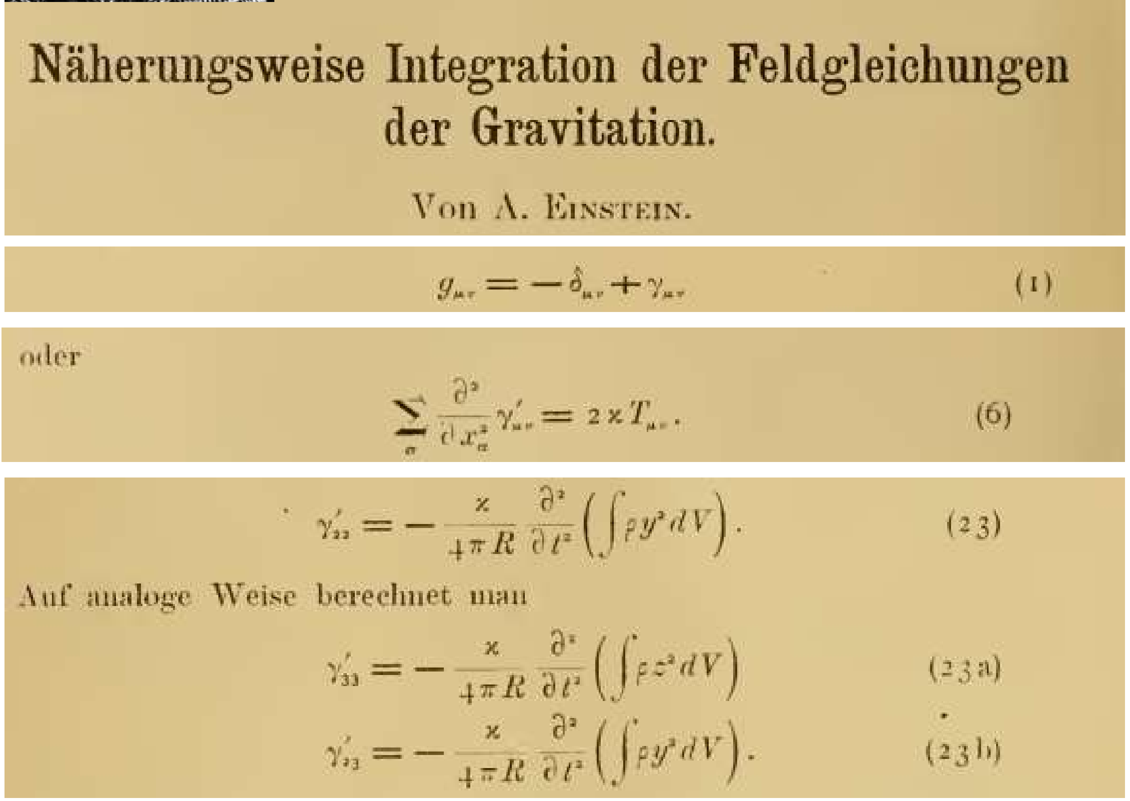
- 가속하는 전하가 전자기파를 발생시키듯이 질량의 요동이 중력파 발생
- 시공간 자체의 파동
- 물질의 요동이 주위의 시공간을 변형시키고 이 시공간의 주름이 빛의 속도로 퍼져 나감

• 1916년 아인슈타인이 예측





physikalisch-mathematischen Klasse vom 22. Juni 1916



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

oder

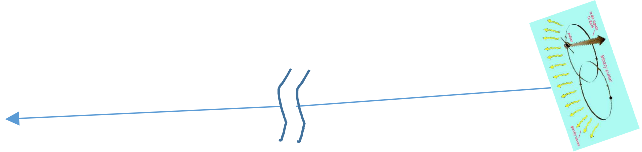
$$\sum_{\sigma} \frac{\partial^2 \gamma'_{\mu\nu}}{\partial x_\sigma^2} = 2\varkappa T_{\mu\nu}. \qquad (6)$$

$$\gamma'_{22} = -\frac{\varkappa}{4\pi R}\frac{\partial^2}{\partial t^2}\left(\int \rho y^2 dV\right). \qquad (23)$$

Auf analoge Weise berechnet man

$$\gamma'_{33} = -\frac{\varkappa}{4\pi R}\frac{\partial^2}{\partial t^2}\left(\int \rho z^2 dV\right) \qquad (23\text{a})$$

$$\gamma'_{23} = -\frac{\varkappa}{4\pi R}\frac{\partial^2}{\partial t^2}\left(\int \rho yz\, dV\right). \qquad (23\text{b})$$



g_{ab}

$= \eta_{ab} + h_{ab}$

$with\ \ |h_{ab}| \ll 1$

- **선형 근사:** "편평한 시공간의 미약한 섭동"

$$R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab}$$

$$\to \left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \vec{\nabla}^2\right) h_{ab} = 0$$

in vacuum with TT- gauge

- **우주론적 중력파:**

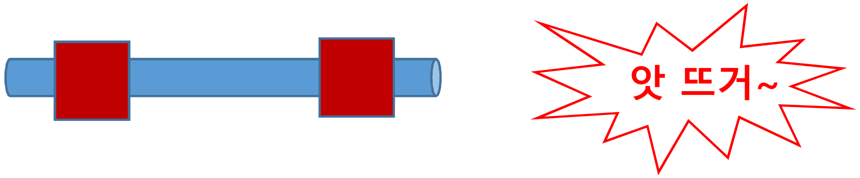
$$ds^2 = -dt^2 + a^2(t)\left(\delta_{ij} + h_{ij}\right) dx^i dx^j$$

- In general, $g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu}$

- Lots of confusions and contraversals for the reality of GWs till 1950s
- **"Sticky bead" argument:** Chapel Hill meeting in 1957

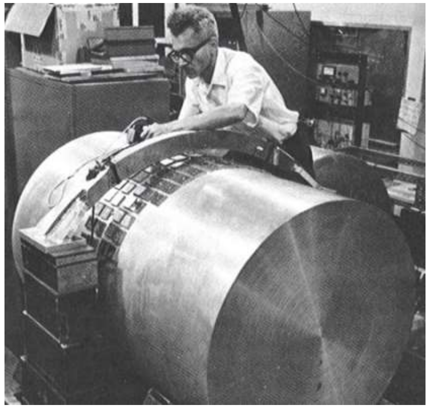
$$\frac{d^2\eta^i}{d\tau^2} = -R_{0j0}{}^{i}\eta^j = \frac{1}{2}\frac{d^2h_{ij}^{\mathrm{TT}}}{dt^2}\xi^j.$$

(Pirani '57)



- It was **J. Weber ('63)** who tried for the first time the detection experiment by using a resonant-mass cylindrical bar **at 1660Hz**.
- It was very sensitive $\boldsymbol{h \sim 10^{-16}}$, but still far from $\sim 10^{-22}$.

UMD

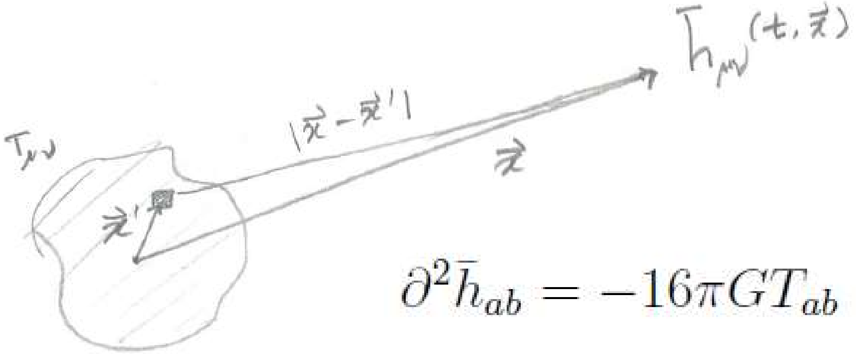


➔ ALEGRO: $h \sim 10^{-19}$ in 1990s

LSU ('09)

2. 중력파의 발생원과 세기는?

$$I^{ij} = \int \rho x^i x^j d^3x$$



$$\partial^2 \bar{h}_{ab} = -16\pi G T_{ab}$$

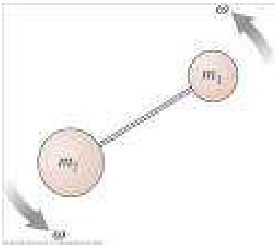
$$h_{ij}(t, \vec{x}) = \frac{2G}{c^4}\frac{1}{r}\ddot{I}_{ij}\left(t - \frac{r}{c}\right)$$

$$\sim \frac{1}{r} \times \omega^2 \times M_{source} \times R_{source}^2 \times \vartheta(1)$$

$$\sim 1.6 \times 10^{-4} \ \frac{s^2}{kg\ m}$$

$M_{\odot} \sim 10^{30}\ kg$!!

- 주먹을 흔들어도 발생하나 지극히 약함:



$1\ ton \times 2,\ 2\ m\ \ \&\ \ 1\ kHz$

➔ $\boldsymbol{h_{GW} \sim 9 \times 10^{-39}}$

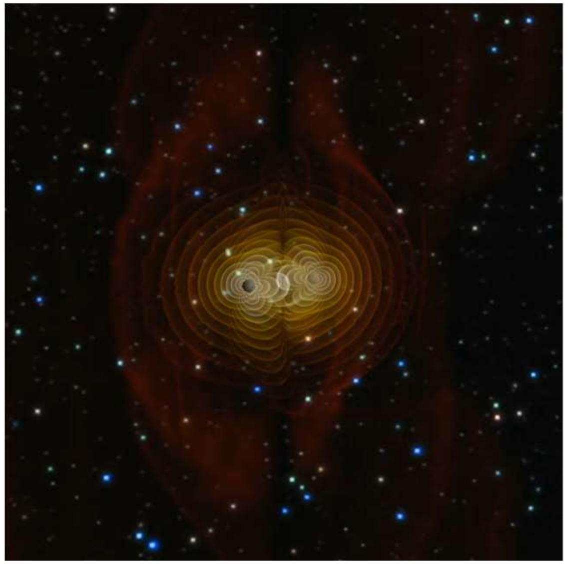
at $r \sim \lambda = 300\ km$

$\sim 10^{11}$ protons at $v \sim 0.999999991c$

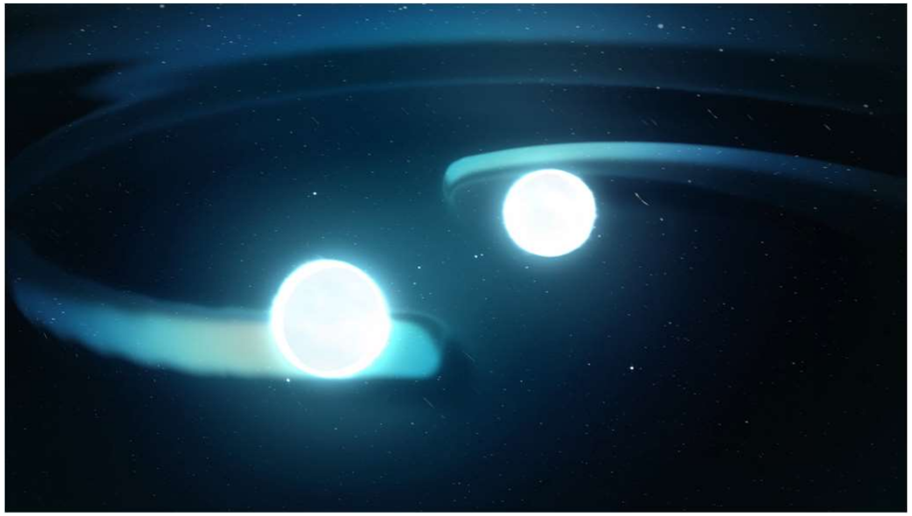
➔ $\boldsymbol{h_{GW} \sim 10^{-43}}$

- 격렬한 천체현상에서 강력한 중력파 발생:

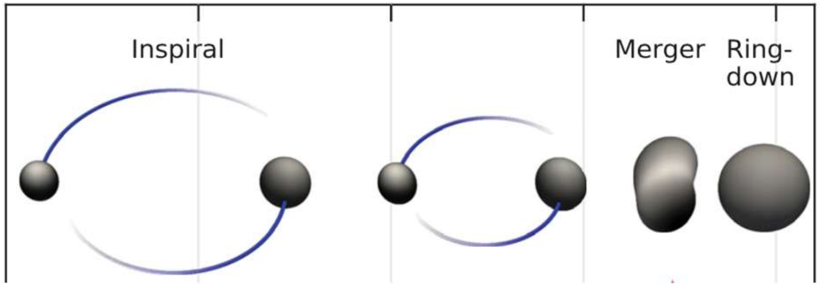
$$h_{\mathrm{BM}} \sim 10^{-20} \frac{\mathrm{Mpc}}{r} \frac{M}{\mathrm{M}_\odot} \left(\frac{M}{\mathrm{M}_\odot} \frac{f}{\mathrm{kHz}}\right)^{2/3}$$



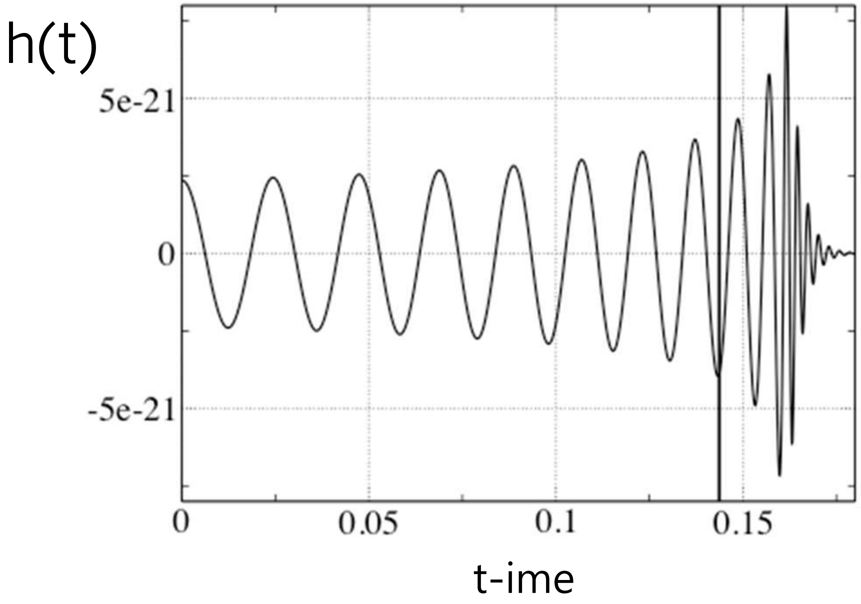
블랙홀 병합과 중력파 발생 (Credit: NASA/C. Henze)

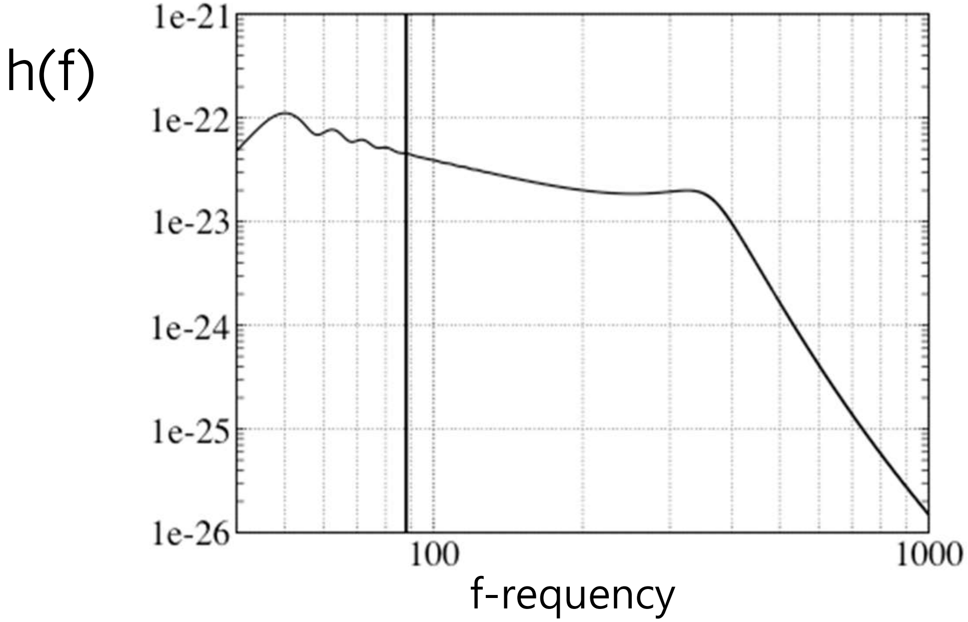


중성자별 병합과 중력파-전자기파 발생
(Credit: LIGO/SXS/R.Hurt and T. Pyle)

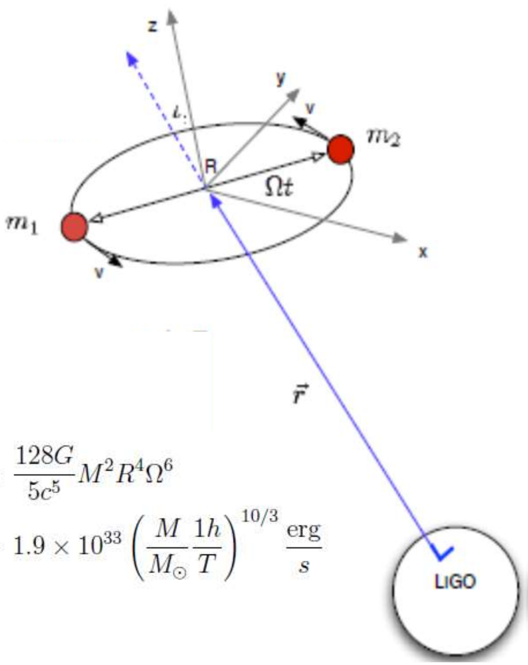


- Binaries emit GWs, resulting in decays of orbit.
- Eventually collide or merge
- Quickly becomes quite, e.g., a stationary single spinning BH which is probably described by the Kerr metric
- PN gives waveforms for inspiral and ringdown phases





Abadie et al. arXiv:1102.3781



$$P = \frac{128G}{5c^5} M^2 R^4 \Omega^6$$
$$= 1.9 \times 10^{33} \left(\frac{M}{M_\odot} \frac{1h}{T} \right)^{10/3} \frac{\text{erg}}{s}$$

$$\bar{h}^{ij}_{\mathrm{TT}} \sim -\frac{G}{c^4} \frac{8\Omega^2 M R^2}{r} \begin{pmatrix} \cos[2\Omega(t-r)] & \sin[2\Omega(t-r)] & 0 \\ \sin[2\Omega(t-r)] & -\cos[2\Omega(t-r)] & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$h \sim \frac{1}{r} M R^2 f^2 \cos 4\pi f (t-r)$$

$$f \to f(t): ? \qquad \frac{1}{R^2} \sim \frac{v^2}{R} \sim f^2 R \to f^2 \sim \frac{1}{R^3} \to \frac{\dot{f}}{f} = -\frac{3}{2} \frac{\dot{R}}{R}$$

$$E \sim -\frac{G m_1 m_2}{2R} \sim f^{\frac{2}{3}} \to \dot{E} \sim f^{-1/3} \dot{f} \sim -P \sim -f^{10/3}$$

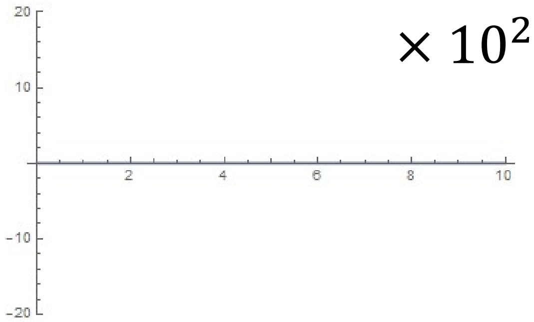
$$\Rightarrow f(t) \sim (t_{coal} - t)^{-3/8}$$

$$h_{+(t)} \sim -\frac{G\mathcal{M}/c^2}{r} \frac{1+\cos^2 \iota}{2} \left(\frac{5G\mathcal{M}/c^3}{t_c - t} \right)^{1/4} \cos\left[\left(\frac{t_c - t}{5G\mathcal{M}/c^3} \right)^{5/8} - 2\phi_c \right]$$

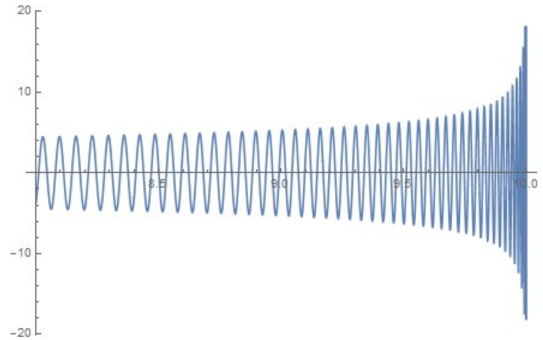
Ex) m1=36Msun, m2=29Msun, r=410Mpc

$$\Rightarrow \quad M_{Chirp} = \frac{(m1 * m2)^{3/5}}{(m1 + m2)^{1/5}} \sim 28 \text{ Msun}$$

$$h(f) \sim e^{i\psi(f)} f^{-7/6}$$



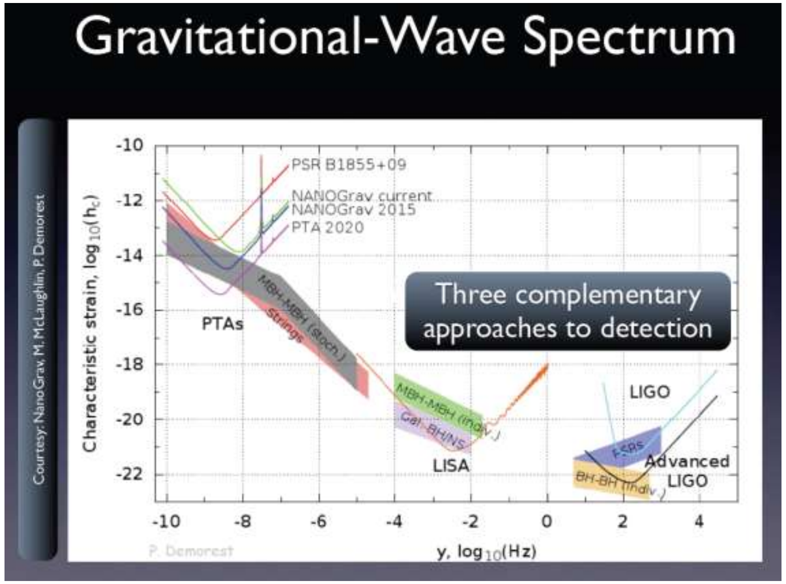
$\times 10^{22}$ ➔



- Astronomical sources:
  - BH-BH, BH-NS, NS-NS coalescences
  - Supernova explosions: GW+Neutrino+…
  - Stochastic signals
  - Cosmic string kinks
  - Etc.

  - Galaxies ~1,000억 개/Universe. Stars ~1,000억 개/Galaxy.

- Bandwidths and significances of sources: (Cutler & Thorne ‘02)
  - Extremely Low Freq. band (ELF, $\mathbf{10^{-15}\sim10^{-18}}\ \boldsymbol{Hz}$):
    - Primordial GWs
    - Imprint on the polarization of CMB radiations
    - Quantum origin at big bang subsequently amplified by inflation
    - Great potential for probing the physics of inflation
  - Very Low Freq. band (VLF, $\mathbf{10^{-7}\sim10^{-9}}\ \boldsymbol{Hz}$):
    - Emitted by pulsars (e.g., Hulse-Taylor ‘75)
    - via pulsar timing array, or indirectly by pulses at earth
    - Extremely massive BH binary or violent processes in 0.1 second of the early universe
  - Low Freq. band (LF, $\mathbf{10^{-4}\sim0.1}\ \boldsymbol{Hz}$):
    - From massive (10^5~10^7M⊙) BH binaries out to cosmological distances (CD)
    - From small BHs, NSs and WDs spiraling into massive BHs out to CDs
    - From orbital motions of WDB, NSB, and stellar-mass BHB in our own galaxy
    - And possibly from violent processes in the very early universe
    - To be observed by the space-based detector, LISA
  - **High Freq. band (HF, $\mathbf{10\sim10^{3}}\ \boldsymbol{Hz}$):**
    - From a spinning slightly deformed NS in our Milky Way galaxy
    - From a variety of sources in the more distance:
      - Final inspiral and collisions of NSB and stellar-mass BHB (up to ~100M⊙)
      - Tearing apart of a NS by a companion BH
      - Supernovae, Triggers of GRBs, etc.
    - **To be measured by earth-based detectors such as LIGO, Virgo, KAGRA, and resonant-mass bar**

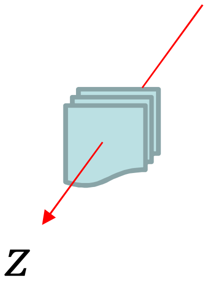


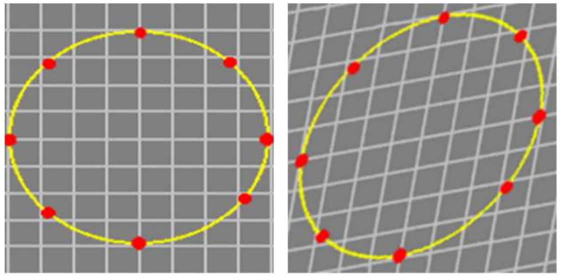
3. 중력파가 지나가면 어떻게 되는가?

- 시공간 자체가 변함: $ds^2 = -dt^2 + (1 + h_+)dx^2 + (1 - h_+)dy^2 + 2h_\times dxdy + dz^2$
- 물체의 변형 및 길이 변화 일으킴

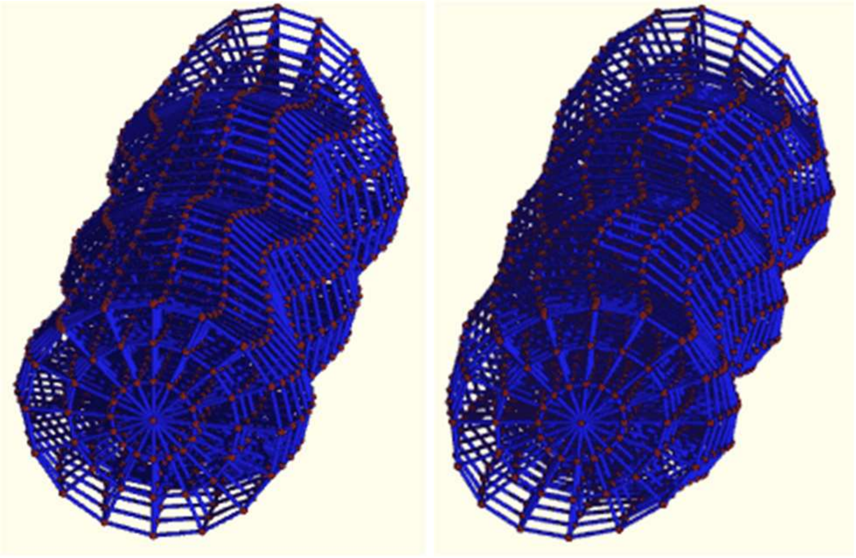
$$\begin{aligned} L'_x &= \int \sqrt{1 + h_{xx}}dx \\ &\sim \int (1 + \frac{1}{2}h_{xx})dx \\ &= (1 + \frac{1}{2}h\sin(\omega t)) \int dx \\ &= L + \frac{1}{2}Lh\sin(\omega t) \end{aligned}$$

✓ **Strain:** $\frac{\Delta L}{L} \cong h_{GW}(t)$



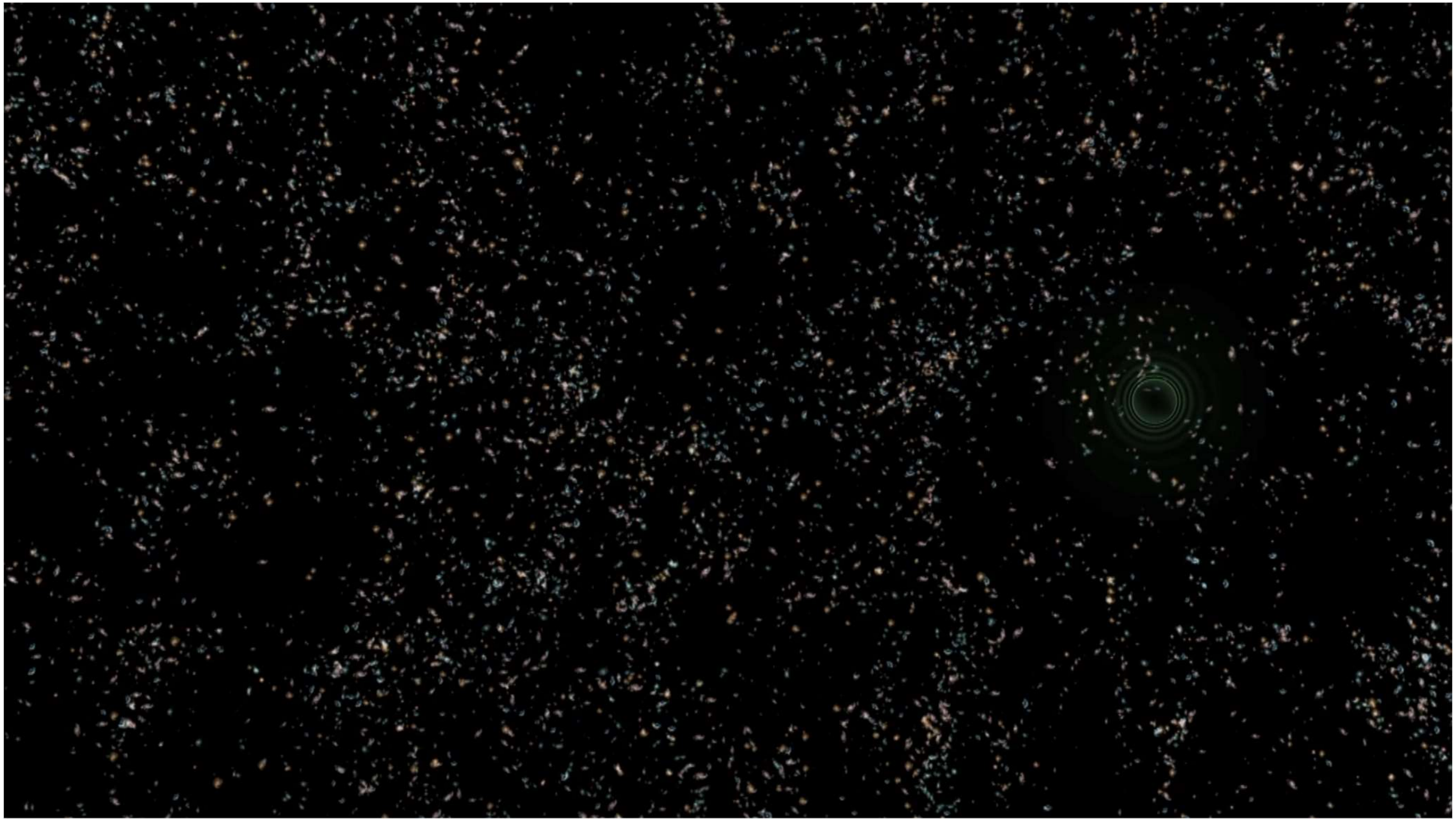


플러스(좌), 크로스(우) 편극된 중력파



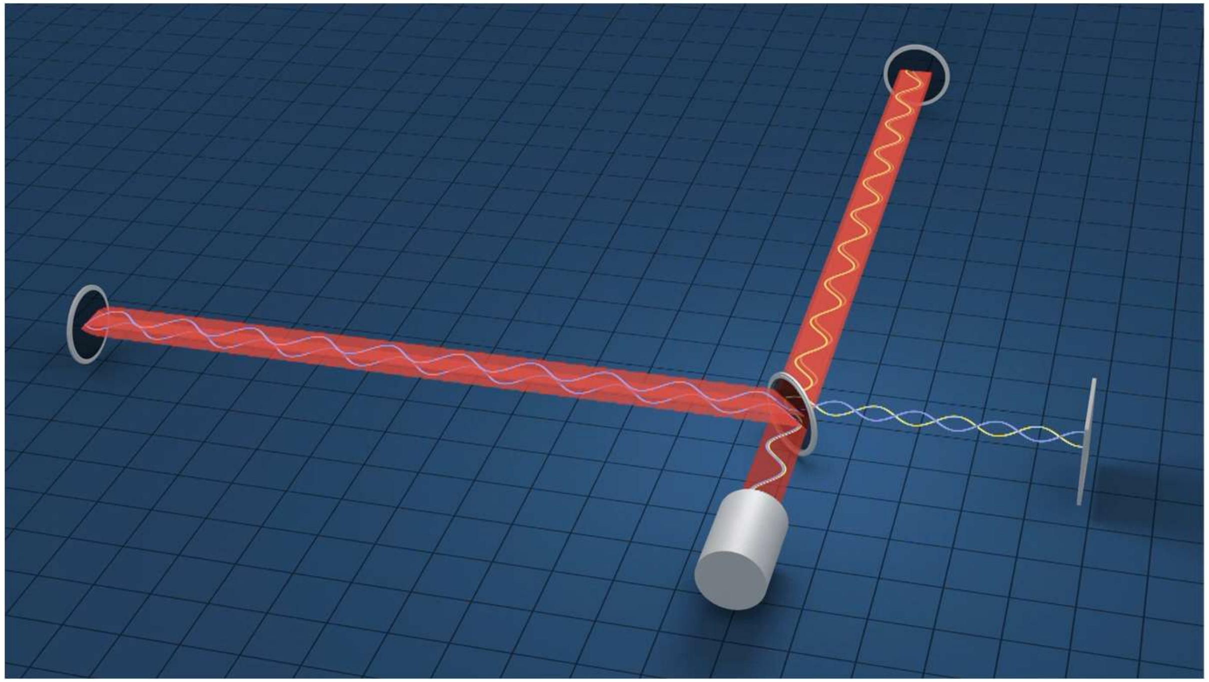
Credit: Ravikumar Kopparapu

중력파의 퍼져 나감과 시공간의 변화



(Credit: LIGO/SXS/R.Hurt and T. Pyle)

4. 중력파 검출의 원리는?

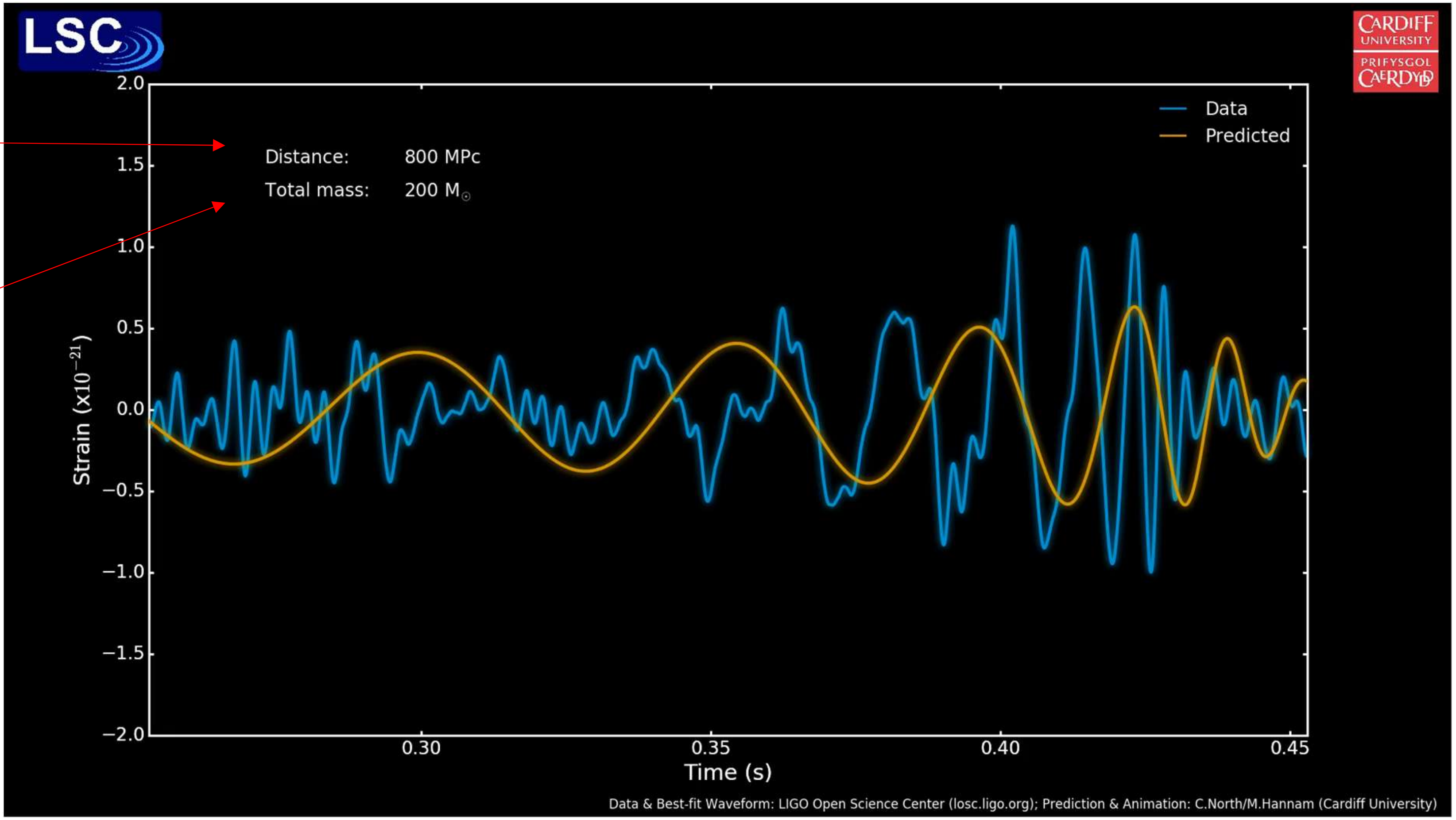


(Credit: LIGO/T. Pyle)

- 중력파 통과로 간섭계 팔의 길이 진동
- 빛의 간섭현상 발생
- 빛의 강도변화를 정밀히 측정하여 중력파 정보 추출

거리

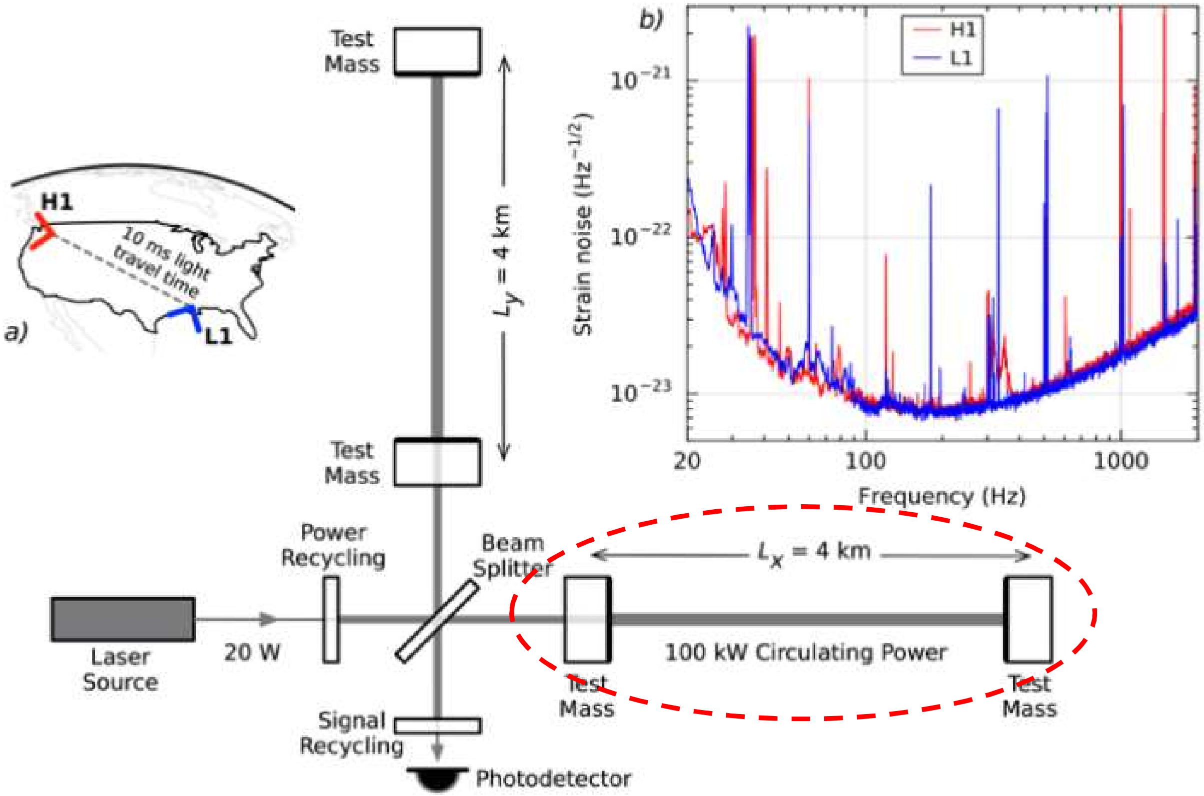
총질량



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

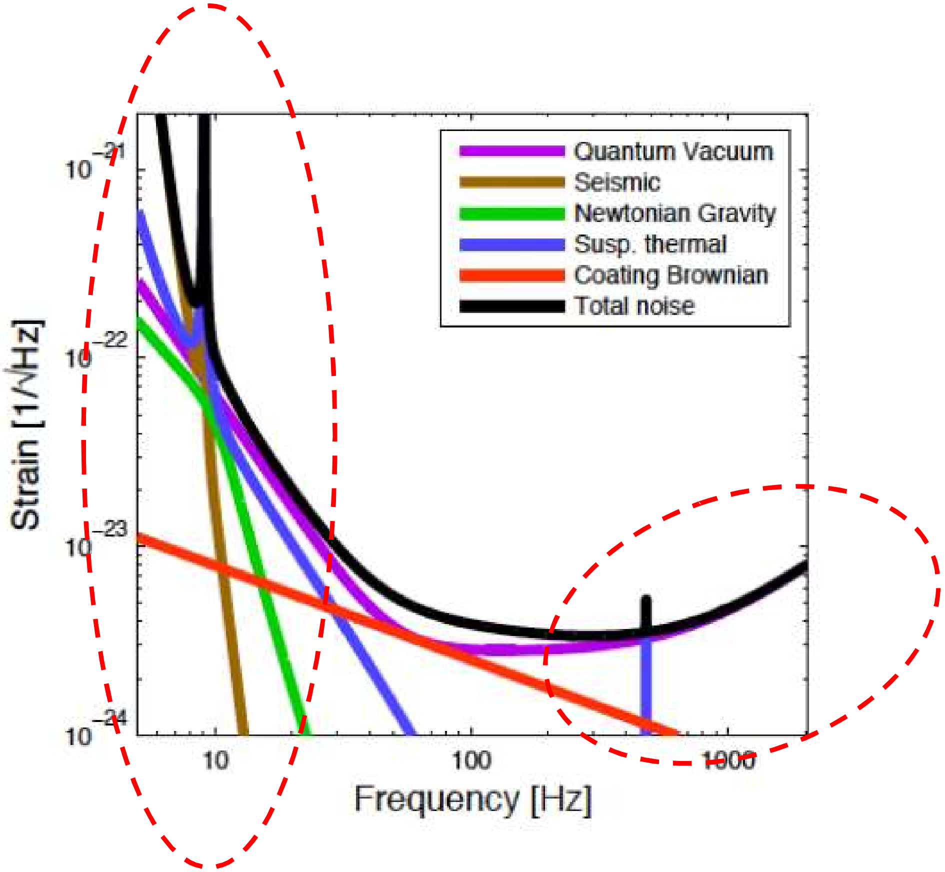
✓ 검출 데이터로 중력파 파원 천체의 질량, 거리, 스핀 등 모수 추정

LIGO and Current Sensitivity



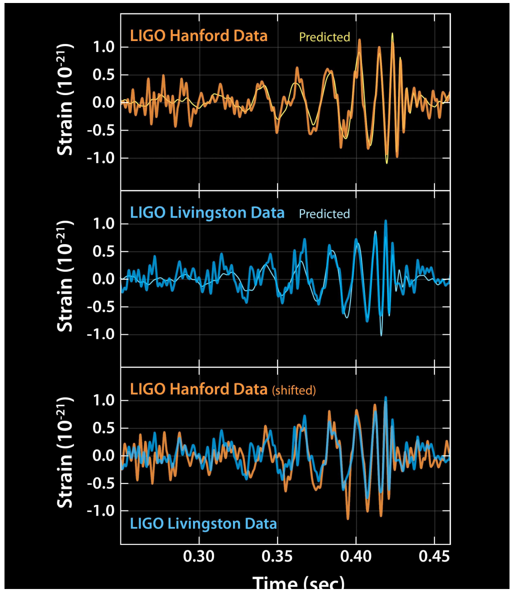
Sources of Noises

- Laser shot noise
  - Inrcrease laser power, resonant cavity, power recycling
- Radiation pressure noise
  - Make mirrors heavierSuspension thermal noise/ mirror coating brownian noise
  - Increase beam size, monolithic suspension structure
- Seismic noise
  - Multi-stage suspension, underground
- Newtonian Noise
  - So far difficult to avoid. Seismic and wind measurement and careful modeling



5,6. 실제 중력파 검출과 현황은?

- 2015년 9월 14일 라이고(LIGO)에서 처음으로 검출



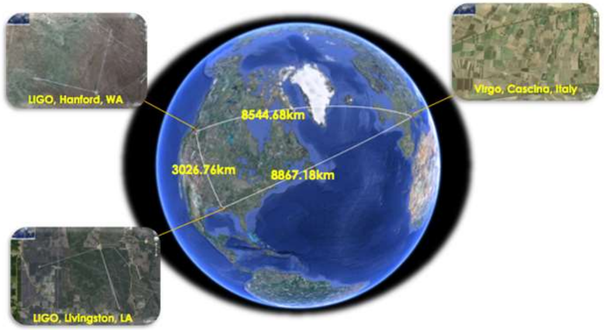
(Credit: LIGO)

- GW150914:

  - ~13억 광년
  - 블랙홀 병합

$$(36M_\odot - 29M_\odot) \rightarrow 62M_\odot$$

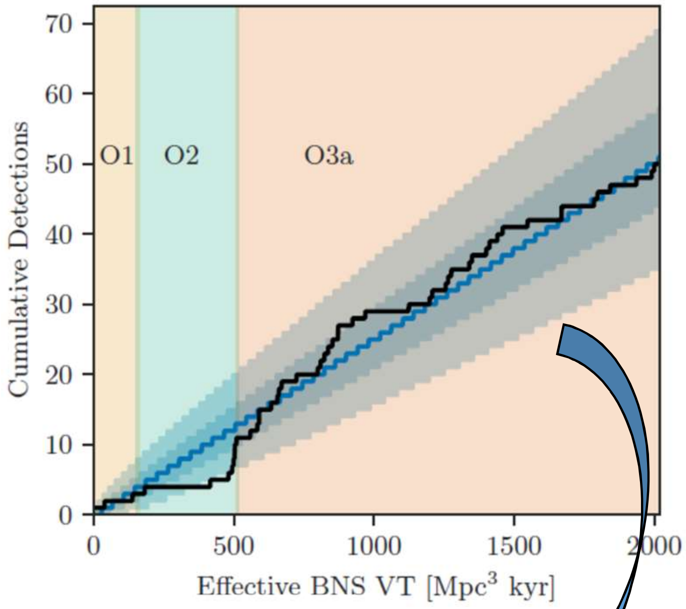
GW $3M_\odot$



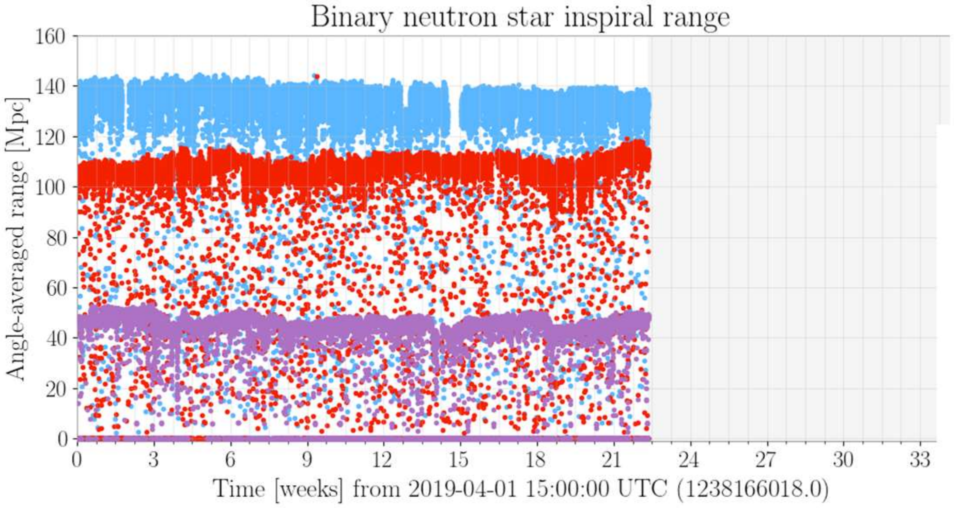
라이고(LIGO): Laser Interferometer Gravitational-wave Observatory

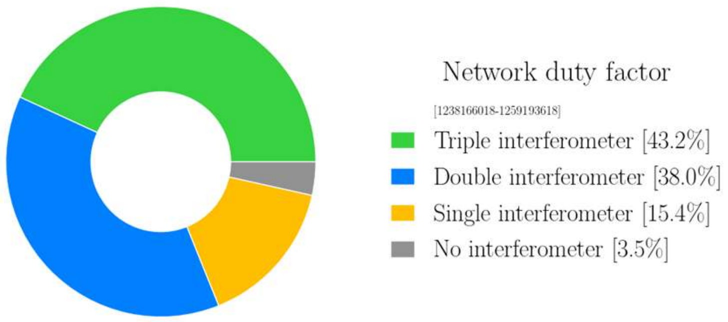
- **관측 가동 3회:** 총 52건 검출!
  - O1 (2015.9.12~2016.1.19): 3 BBH
  - O2 (2016.11.30~2017.8.25): 7 BBH & 1 BNS
  - O3a (2019.4.1~9.31): 36 BBH & 3 others,
    O3b (2019.11.2~2020.3.27): 2 NSBH+??
  - Virgo: 2017.8.1~ , KAGRA: 2020.4~

GWTC-2 ('20)



- **~8 events per month!**
- Duty cycle: ~40% (?)



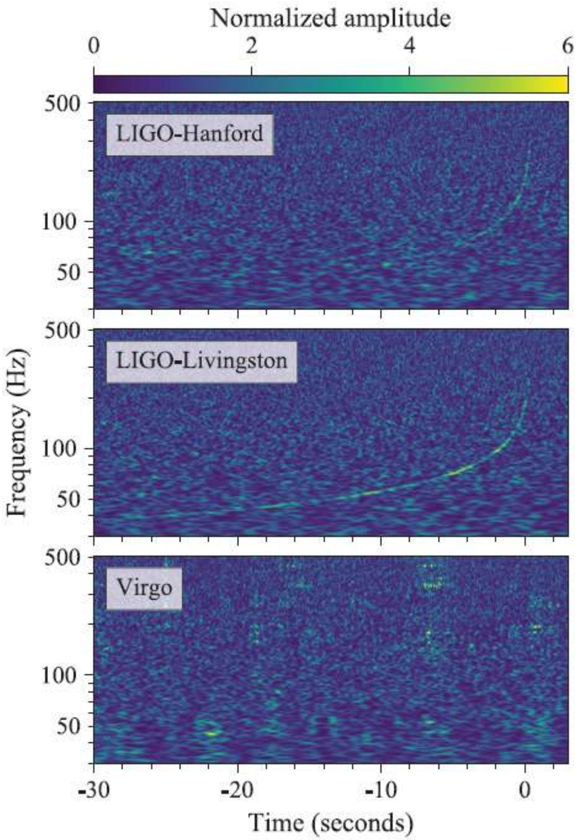


- Detections of GWs: GW150914, …, GW170817, ⋯
    - 52 observations in total
    - Mostly from BBH (binary black hole) mergers, e.g., 46 events
    - No signals other than GWs have been observed from them.
- Merger events with “neutron” star(s): GW170817 (BNS $(1.46,1.27)M_{\odot}$), GW190425 (‘BNS’ $(2.0,1.4)M_{\odot}$), GW190426_152155 (BBH/NSBH $(5.7,1.5)M_{\odot}$), GW190814 (BH-NS/BH $(23.2,2.59)M_{\odot}$), GW200105 (NSBH $(8.9,1.9)M_{\odot}$), GW200115 (NSBH $(5.7,1.5)M_{\odot}$)
- GW170817:
    - Both GW & EM signals were observed.
    - True beginning of the multi-messenger astrophysics/astronomy!

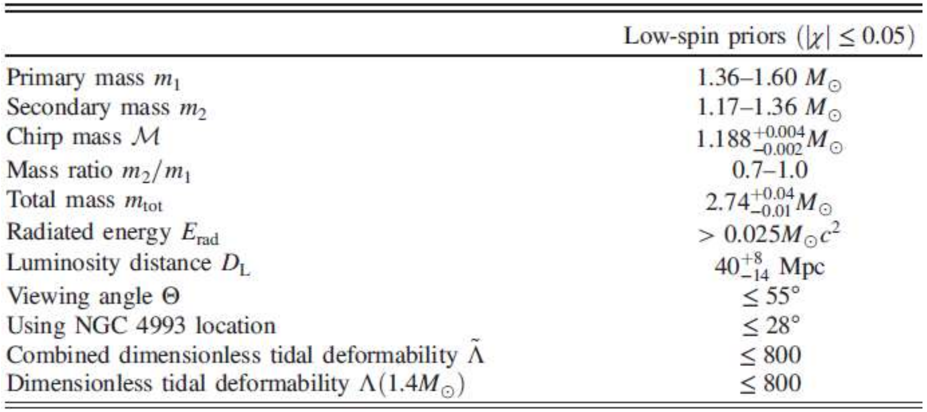
- # GW170817:

https://www.youtube.com/watch?v=aWX-BY-A9CY

- First observation of a BNS inspiral on Aug. 17, 2017 at 12:41:04 UTC in O2 (2016.11.30 ~ 2017.8.25)
- Duration: ~100 s, SNR: 32.4, FAR: ≤ One per 80,000 years

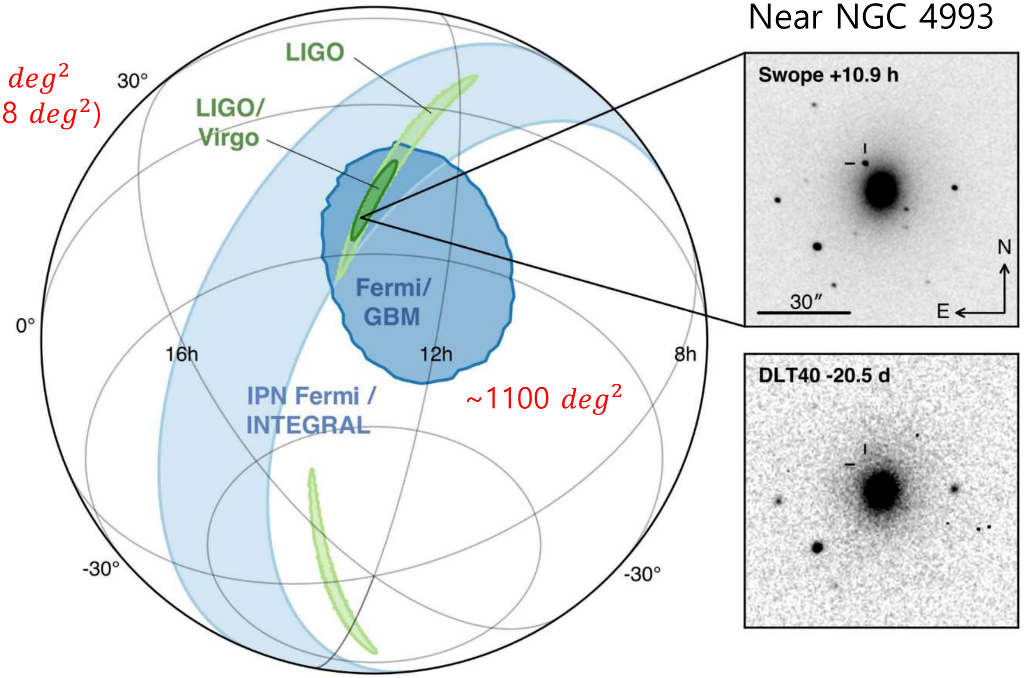


PRL **119**, 161101 (2017)



	Low-spin priors ($\lvert\chi\rvert \le 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc
Viewing angle Θ	$\le 55°$
Using NGC 4993 location	$\le 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

✓ Sky localization and EM follow-up observation:



190 deg^2

31 deg^2
(➔ 28 deg^2)

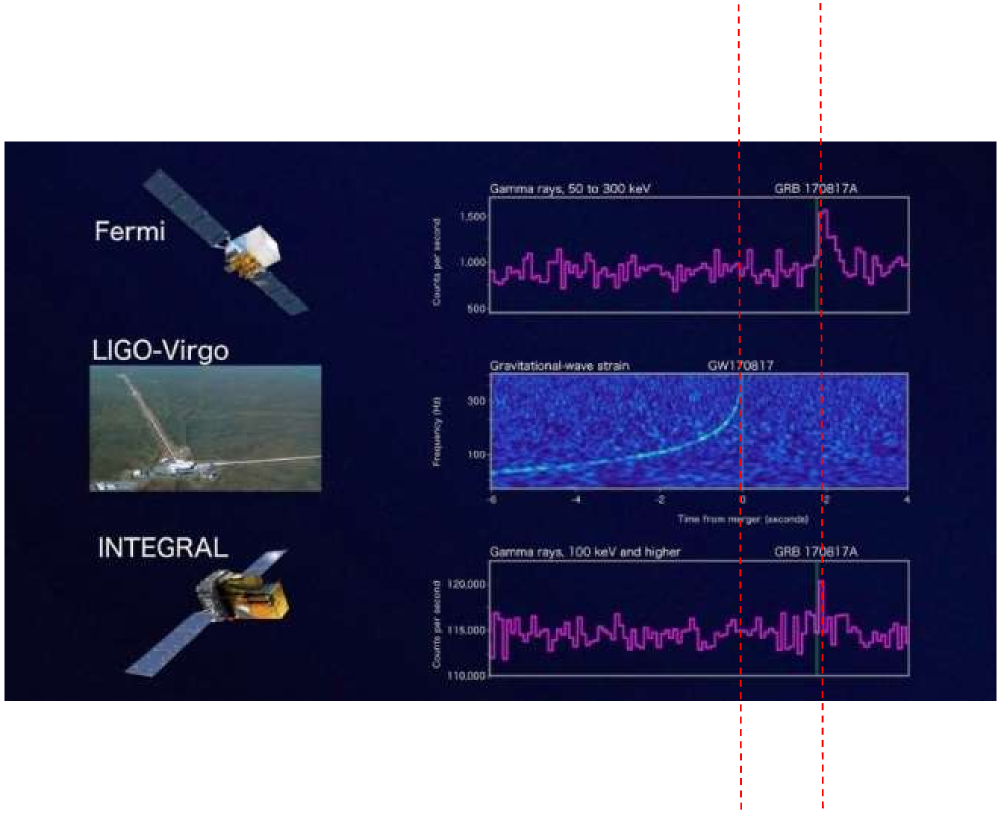
~1100 deg^2

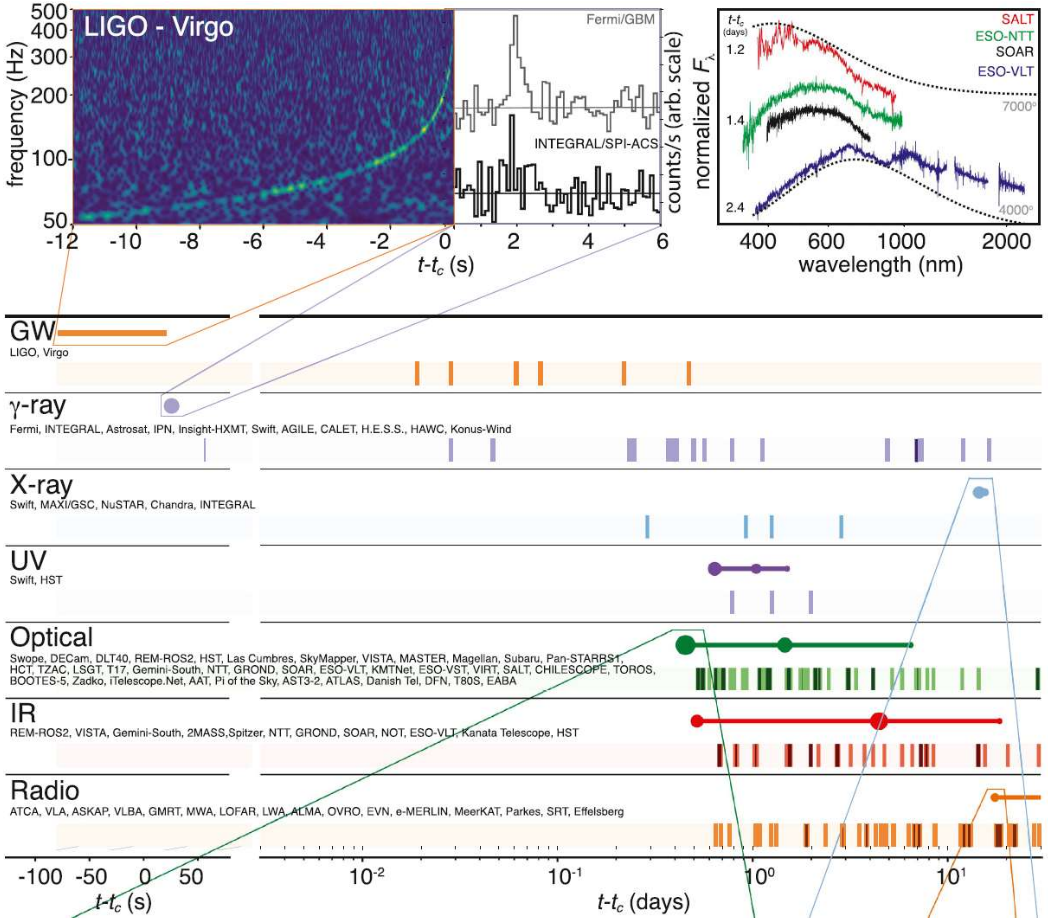
Near NGC 4993

Centered around $(12^h 57^m, -17^{\circ} 51')$

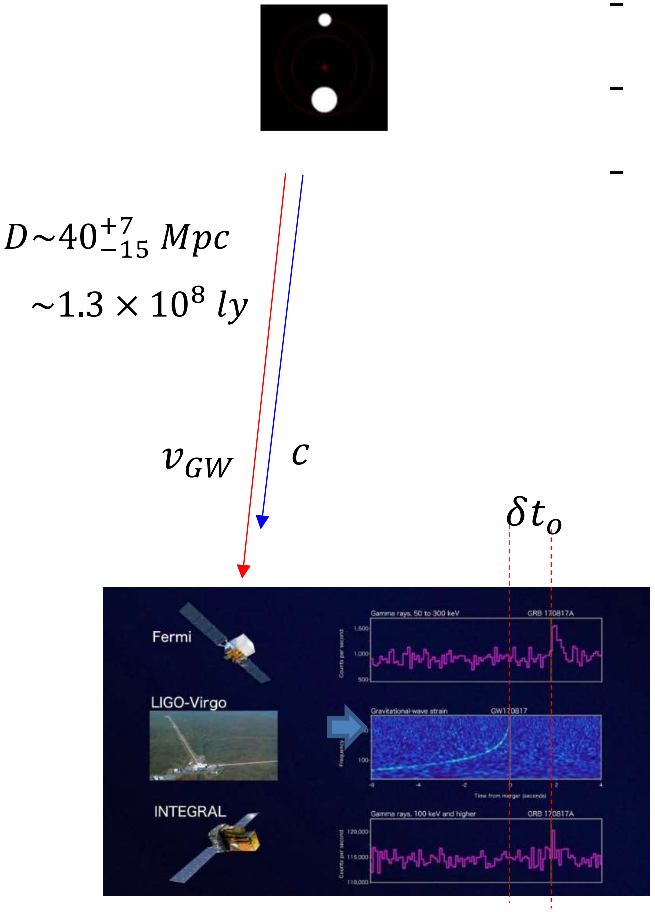
ApJL ('17)

✓ Multi-messenger observations for GW170817: ApJL ('17)





✓ Propagation speed of a GW vs Speed of a light:



$D{\sim}40^{+7}_{-15}\ Mpc$

$\sim 1.3 \times 10^{8}\ ly$

v_{GW}

c

δt_o

- In GR, $v_{GW} = c$.
- From the time difference at two LIGOs: $0.55\,c < v_{GW} < 1.42\,c$
- Use the arrival times of GWs and lights with distance for GW170817

$$v_{\rm GW} = D/(t_{\rm o} - t_{\rm e}) \qquad c = D/\left[(t_{\rm o} + \delta t_{\rm o}) - (t_{\rm e} + \delta t_{\rm e})\right].$$

$$\delta t_{\rm e,\,o} \sim \text{few seconds} \Rightarrow \frac{\delta v}{c} = \frac{v_{\rm GW} - c}{c} = \frac{\delta t_{\rm o} - \delta t_{\rm e}}{t_{\rm o} - t_{\rm e}} \simeq \frac{c(\delta t_{\rm o} - \delta t_{\rm e})}{D}$$

$$\delta t_{\rm e,\,o}/(t_{\rm o} - t_{\rm e}) \ll 1. \qquad = 6.5 \times 10^{-16}\,\frac{26\ \text{Mpc}}{D}\left(\frac{\delta t_{\rm o}}{1.74\ \text{s}} - 5.7 \times \frac{\delta t_{\rm e}}{10\ \text{s}}\right).$$

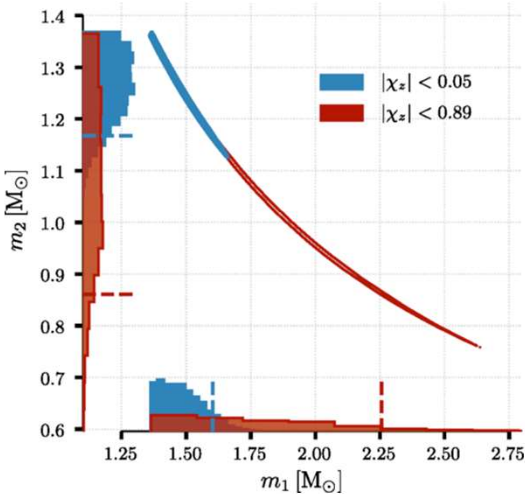
$$0 \leq \delta t_{\rm e} \leq 10\ \text{s}$$

$$\Downarrow$$

$$\boxed{-3 \times 10^{-15} \leq \frac{\delta v}{c} \leq 7 \times 10^{-16}}$$

$$\left(-0.45 < \frac{\delta v}{c} < 0.42\right)$$

- BNS masses consistent with galactic binaries
- Justifies the ‘kilonova’ model: BNS mergers create many heavy elements including Ag!



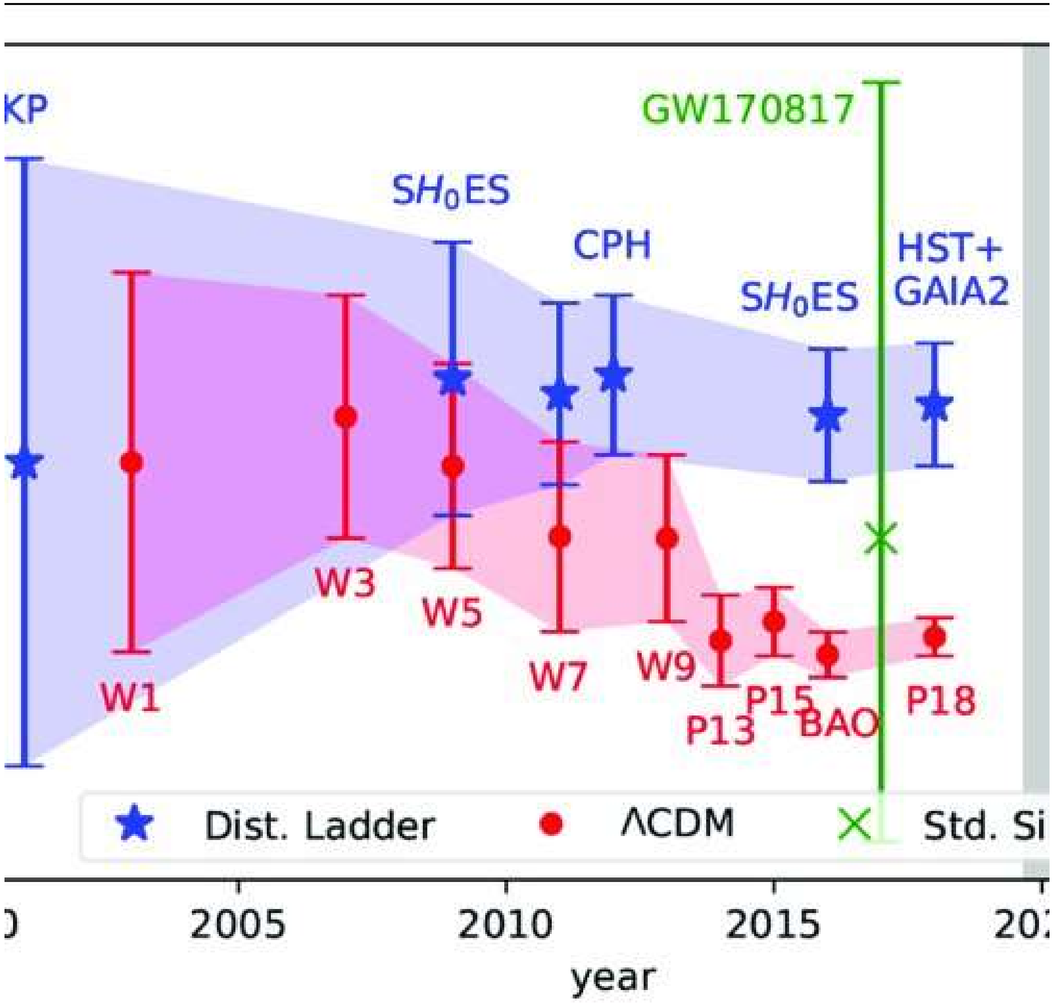
- This simultaneous observation in different forms of radiation gave a firm evidence of GW detection, marking an exciting new chapter in multi-messenger astronomy!

- Hubble’s Law: $v = H_0 \times D$
  - Amplitude of GW $\Rightarrow$ distance estimate
  - Host galaxy ID $\Rightarrow$ redshift
  - Independent estimate of Hubble constant !

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Credit: T. Dent (’19)

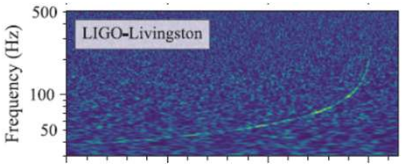
- Hubble tension problem:



- GWs from a compact binary coalescence in inspiral phase:

$$h_+ = \frac{2\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}}{D_L}\left[1+(\hat{L}\cdot\hat{n})^2\right]\cos[\Phi(t)],$$

$$h_\times = \frac{4\mathcal{M}_z^{5/3}[\pi f(t)]^{2/3}(\hat{L}\cdot\hat{n})}{D_L}\sin[\Phi(t)].$$



$$f_{\mathrm{GW}}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}(t_c - t), \Rightarrow \mathcal{M} = \frac{c^3}{G}\left(\left(\frac{5}{96}\right)^3 \pi^{-8}\,(f_{\mathrm{GW}})^{-11}\left(\dot{f}_{\mathrm{GW}}\right)^3\right)^{1/5}$$

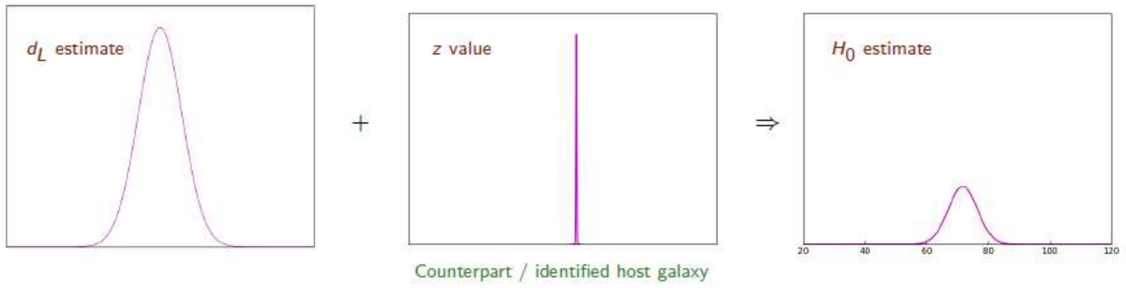
Then, we can estimate the luminosity distance $D_L(z)$ though degenerate with inclination.

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')}\ ,\ H(z') = H_0\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$

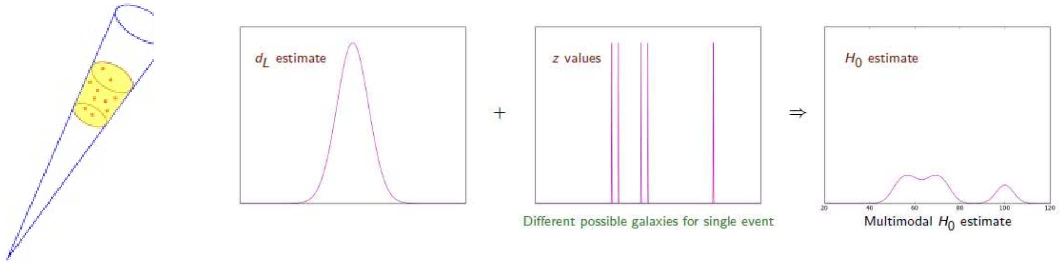
Thus, the Hubble constant H_0 can be estimated provided that the redshift z is measured separately, e.g., from the EM measurement of the host galaxy.

Lots of BBH merger events, but BBHs do not have such luminous object!

- Schutz’s method:

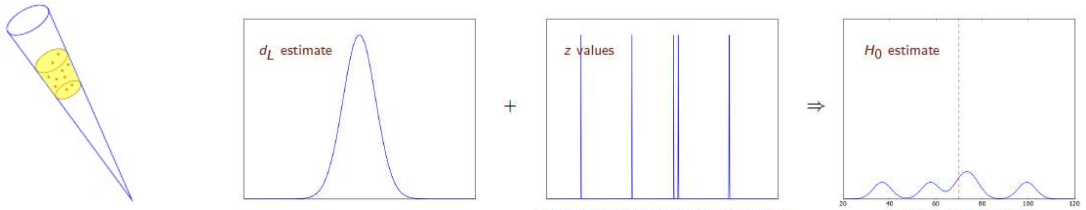


Counterpart / identified host galaxy



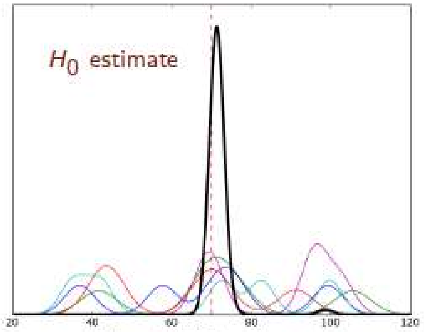
Different possible galaxies for single event

Multimodal H_0 estimate



Different possible galaxies for single event

Multimodal H_0 estimate



Unimodal joint H_0 result

…… ……

Slide credit: A. Askar ‘19

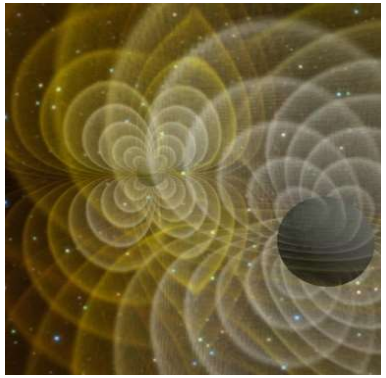
7. 중력파 검출의 의의는?

- 이론 및 천체물리학/천문학 모델 검증
- 최초의 성과들: 중력파 검출, 블랙홀 병합 관측,중성자별 병합 관측, 킬로노바 모델 검증, 중력파 속도 관측, 중성자별-블랙홀 쌍성 관측, ……

Ex) $-3 \times 10^{-15} \leq \frac{v_{GW}-c}{c} \leq 7 \times 10^{-16}$, $H_0 = 68^{+14}_{-7} km/s/Mpc$

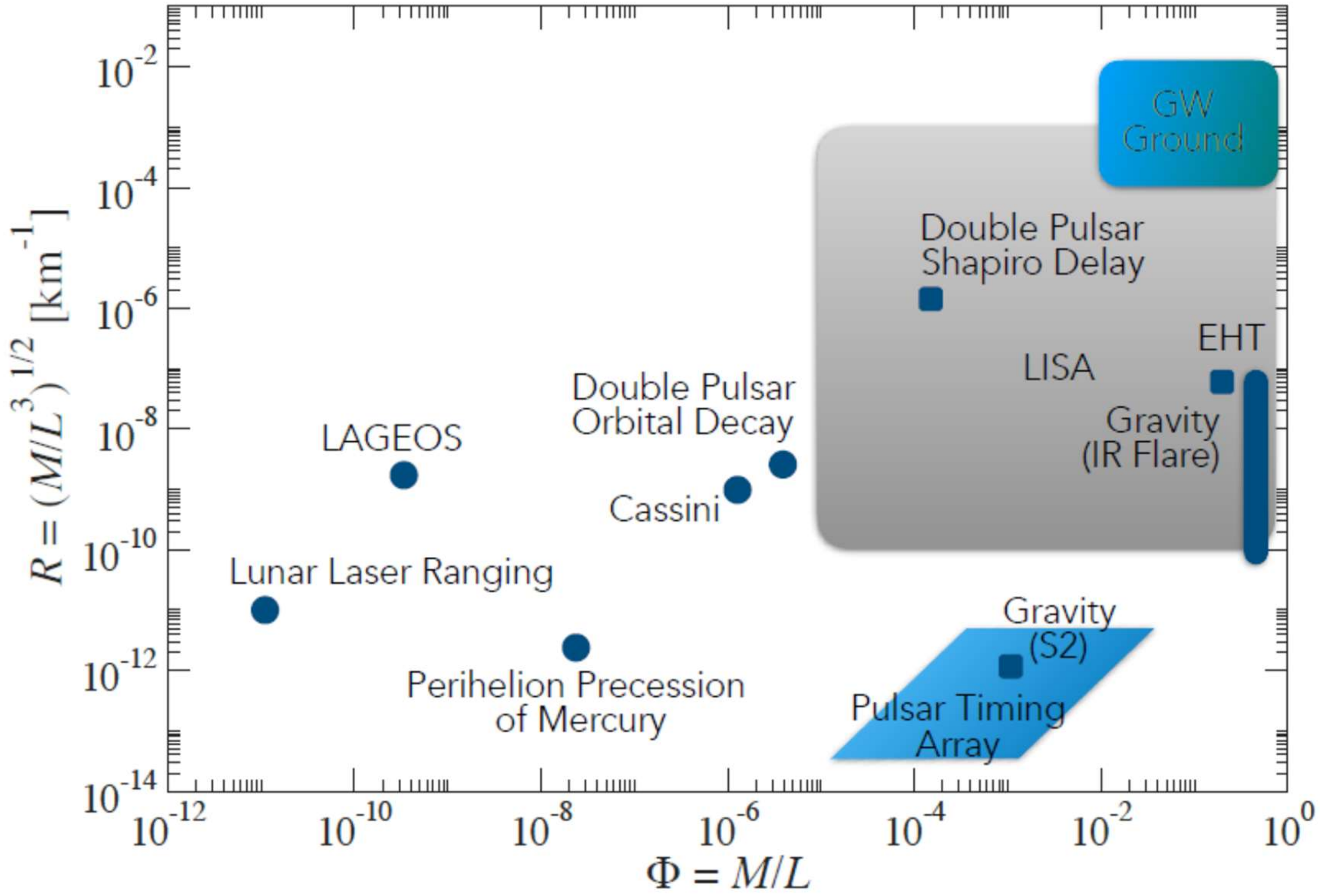
- **우주를 관측하는 또 다른 수단 획득**

➔ 중력파 천문학 시대 도래



중력파 관측소

✓Tests of General Relativity

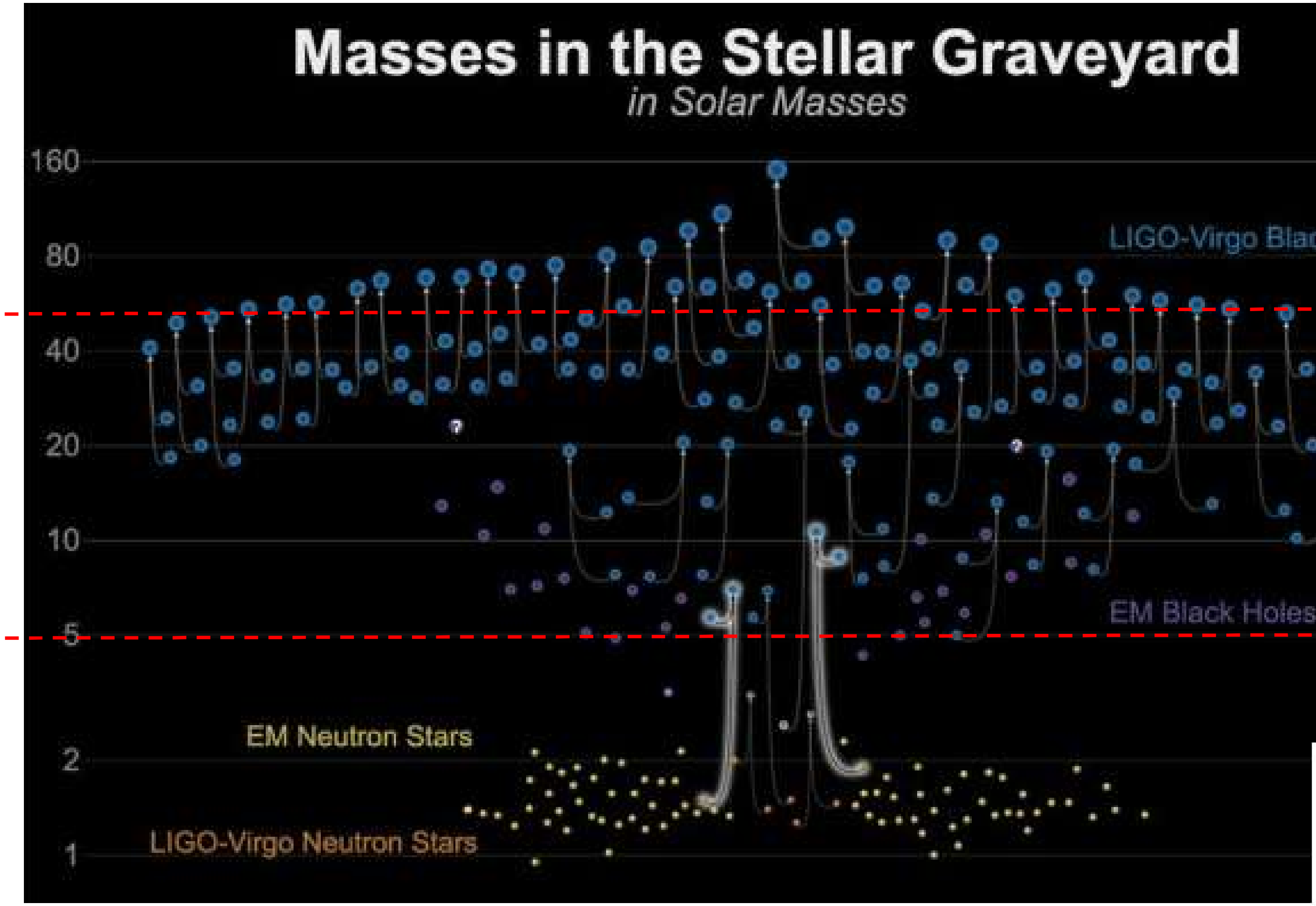


Probing gravity at all scales (arXiv: 1903.09221)

- But most of these are in weak field regions:
  Ex) For binary pulsars, $\dot{P}_{orb} \sim -(10^{-14} \sim 10^{-1})$. Even in the most relativistic one, J0737-3039, $v \sim 2 \times 10^{-3} c =$ $\mathbf{0.2\%\ c}$.

- By contrast, for GW150914, $\dot{P}_{orb} \sim -(0.1 \sim 1)$. $\boldsymbol{v \sim 0.5\ c}$ just before merger!
- In addition, coalescences of compact objects are in **highly nonlinear and strong field regime.**

✓ Masses in BBHs:

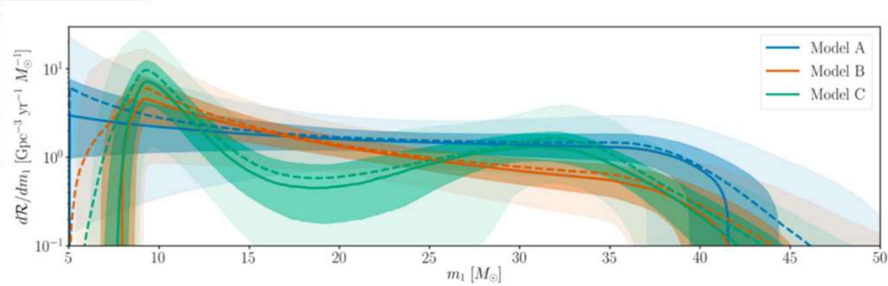


- No BBH of stellar origin > $50M_\odot$?
- Similarly, no BBH < $5M_\odot$?

➔ **"Mass Gaps" (?):**

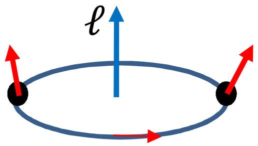
Belczynski+2011,
Sathya+2019

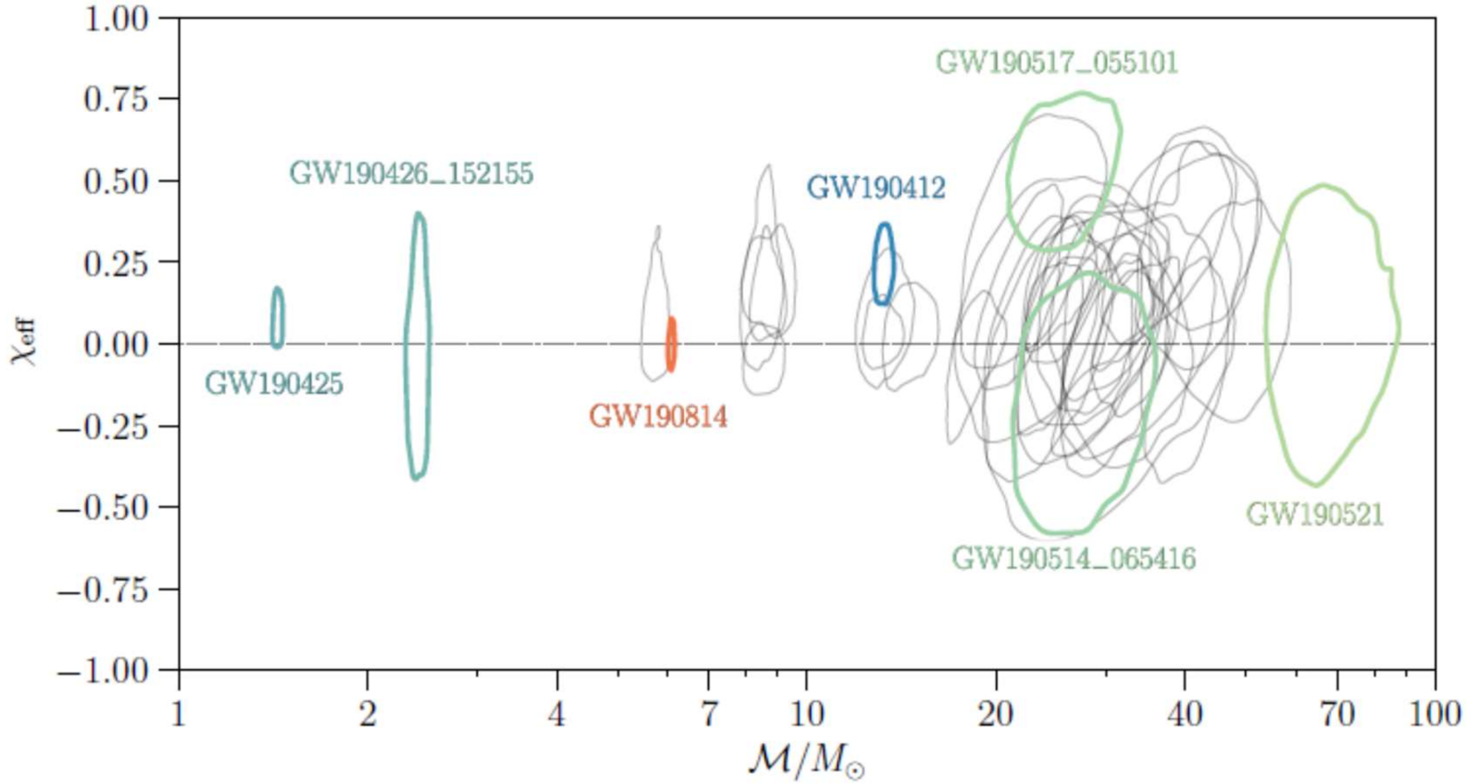
Abbott+19 (arXiv:1811.12940)



✓ Effective spins of binary objects:

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$$

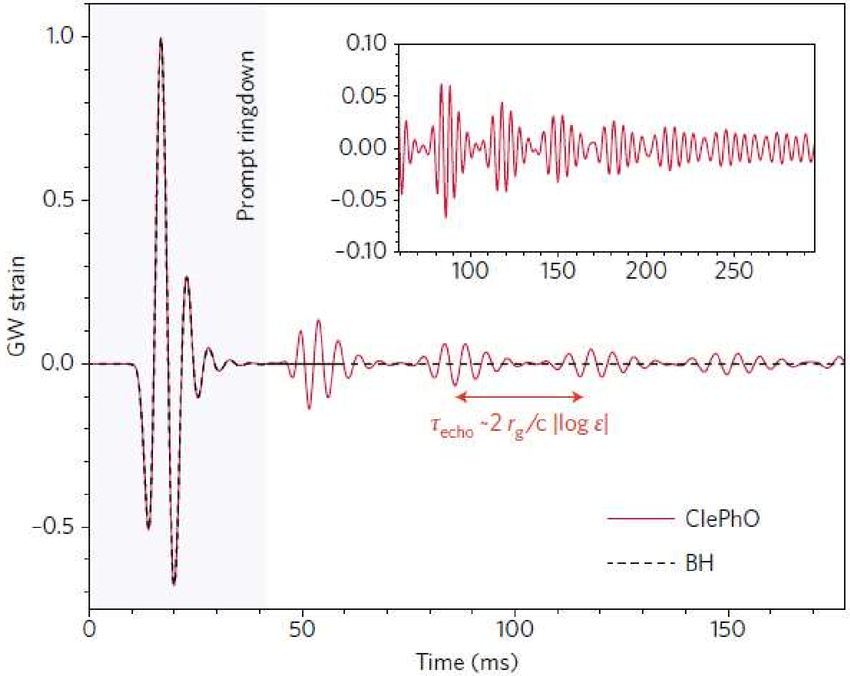




$\chi_{eff} \gtreqless 0$ **(??)**

➔ Implications on the origin of binary formations

✓ GW echo:



Credit: Cardoso, Pani (2016)

- Extremely compact objects instead of BH: ex) boson stars, strange stars, gravastars, …

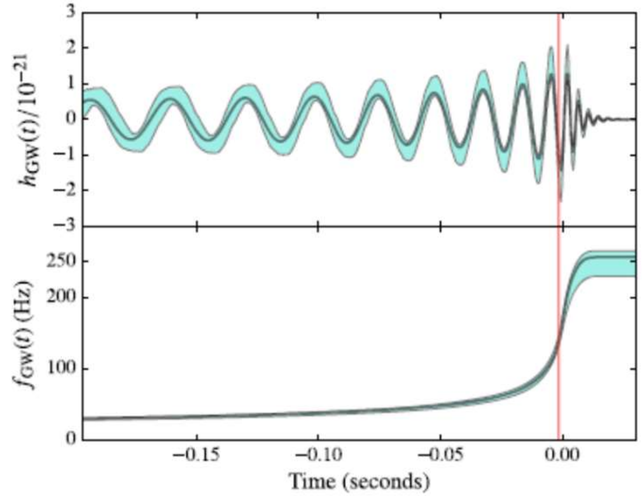
- Different nature of the event horizon: ex) fire-wall, ??

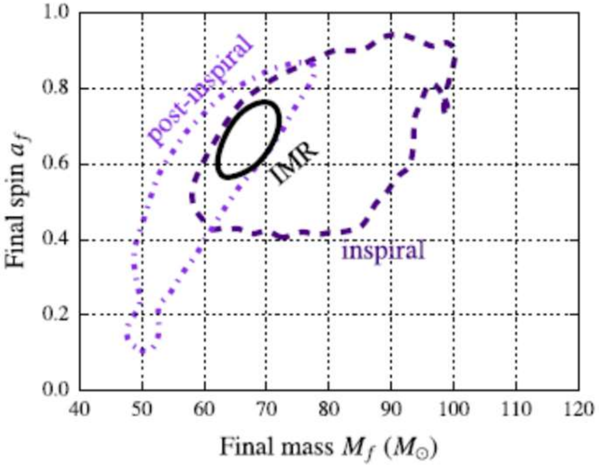
- Probe some parts of quantum gravity (?)

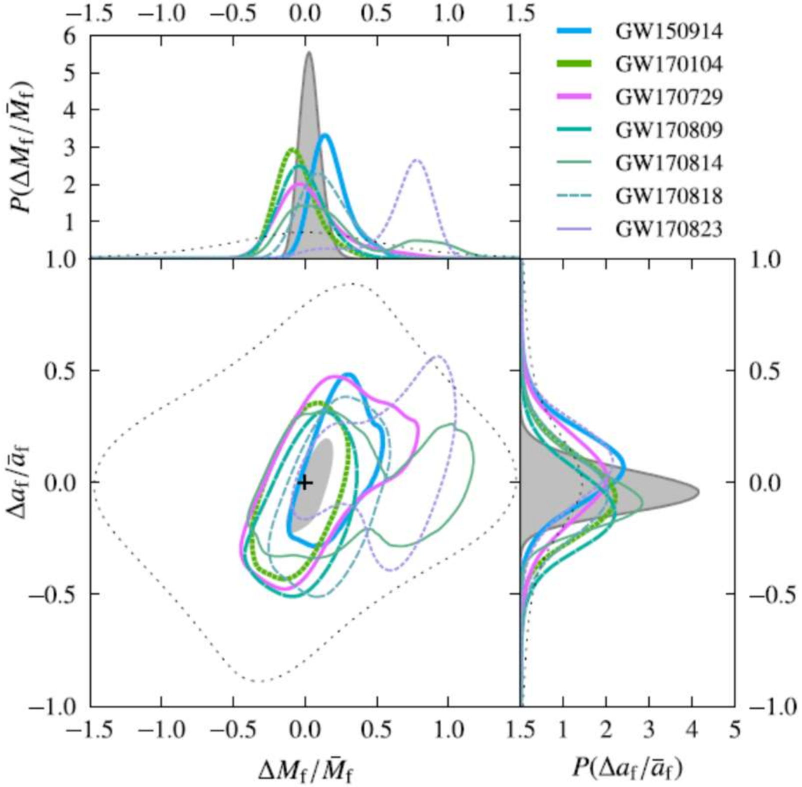
- **Inspiral-Merger-Ringdown (IMR) consistency test:**

$$\Delta M_{\mathrm{f}}/\bar{M}_{\mathrm{f}} := 2\left(M_{\mathrm{f}}^{\mathrm{insp}} - M_{\mathrm{f}}^{\mathrm{postinsp}}\right)/\left(M_{\mathrm{f}}^{\mathrm{insp}} + M_{\mathrm{f}}^{\mathrm{postinsp}}\right)$$

$$\Delta a_{\mathrm{f}}/\bar{a}_{\mathrm{f}} := 2\left(a_{\mathrm{f}}^{\mathrm{insp}} - a_{\mathrm{f}}^{\mathrm{postinsp}}\right)/\left(a_{\mathrm{f}}^{\mathrm{insp}} + a_{\mathrm{f}}^{\mathrm{postinsp}}\right)$$

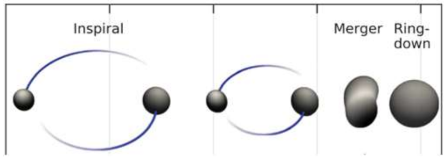






- **BH no-hair theorem or QNM test:**

QNMs of the Kerr BH are completely determined by its mass and angular momentum.



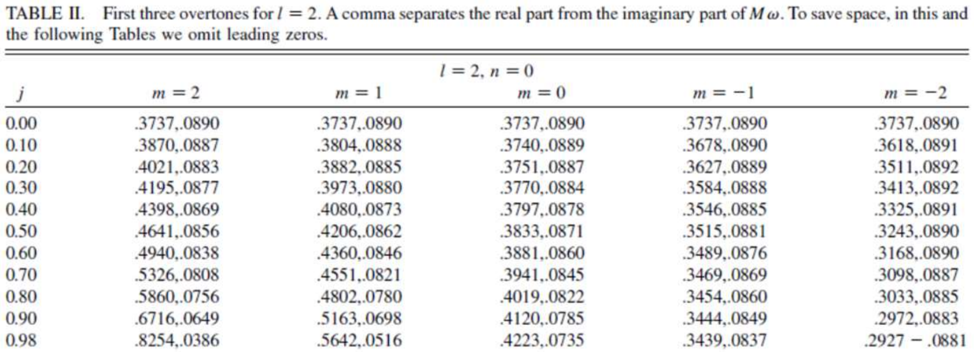
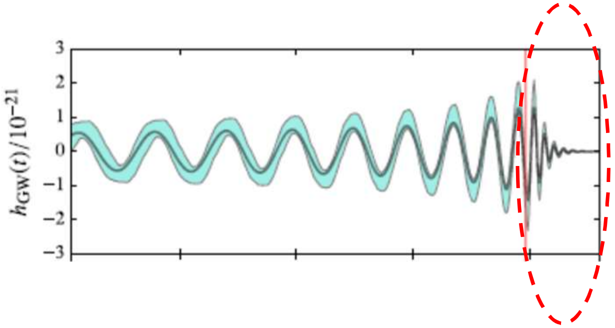


TABLE II. First three overtones for $l = 2$. A comma separates the real part from the imaginary part of $M\omega$. To save space, in this and the following Tables we omit leading zeros.

			$l = 2, n = 0$		
j	$m = 2$	$m = 1$	$m = 0$	$m = -1$	$m = -2$
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

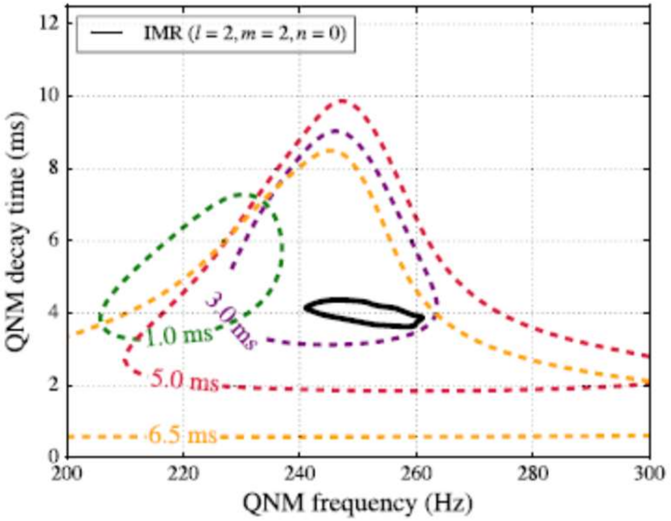
Berti, Cardoso, Will (2006)



$$e^{i\omega t} = e^{i(\omega_R + i\omega_I)t} \sim e^{-\omega_I t} \cos \omega_R t$$

$$h(t \geq t_0) \\ = Ae^{-(t-t_0)/\tau} \cos[2\pi f_0 (t - t_0) + \phi_0]$$

Abbott+ (2016)



- **Test of waveform modelings:**

$$h(f) = A(f)e^{i\Phi(f)}.$$

$$p_i = \{\varphi_i, \varphi_i^{(l)}, \beta_i, \alpha_i\} \quad p_i^{\rm GR} \rightarrow \left(1 + \delta\hat{p}_i\right)p_i^{\rm GR}$$

$$\Phi(f) = \begin{cases} \Phi_{\rm I}(f) \sim \cdots + \sum_{i=0}^{7}\left[\varphi_i + \varphi_i^{(l)}\ln f\right]f^{(i-5)/3}, \\ \Phi_{\rm IM}(f) \sim \beta_0 + \beta_1 f + \beta_2 \ln f - \frac{1}{3}\beta_3 f^{-3}, \\ \Phi_{\rm MR}(f) \sim \alpha_0 + \alpha_1 f - \alpha_2 f^{-1} + \frac{4}{3}\alpha_3 f^{3/4} + \alpha_4 \tan^{-1}\left(\frac{f - \alpha_5 f_{\rm RD}}{f_{\rm damp}}\right) \end{cases}$$

$$\delta\hat{p}_i = \{\delta\hat{\varphi}_{-2}, \delta\hat{\varphi}_0, \delta\hat{\varphi}_1, \delta\hat{\varphi}_2, \delta\hat{\varphi}_3, \delta\hat{\varphi}_4, \delta\hat{\varphi}_{5l}, \delta\hat{\varphi}_6, \delta\hat{\varphi}_{6l}, \delta\hat{\varphi}_7, \delta\hat{\beta}_2, \delta\hat{\beta}_3, \delta\hat{\alpha}_2, \delta\hat{\alpha}_3, \delta\hat{\alpha}_4\},$$

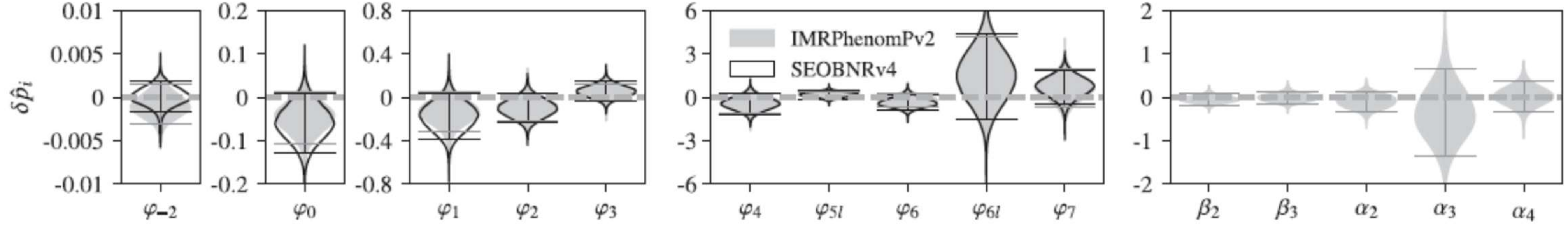


FIG. 3. Combined posteriors for parametrized violations of GR, obtained from all events in Table I with a significance of FAR < $(1000\ \mathrm{yr})^{-1}$ in both modeled searches. The horizontal lines indicate the 90% credible intervals, and the dashed horizontal line at 0 corresponds to the expected GR values. The combined posteriors on φ_i in the inspiral regime are obtained from the events which in addition exceed the SNR threshold in the inspiral regime (GW150914, GW151226, GW170104, GW170608, and GW170814), analyzed with IMRPHENOMPv2 (grey shaded region) and SEOBNRv4 (black outline). The combined posteriors on the intermediate and merger-ringdown parameters β_i and α_i are obtained from events which exceed the SNR threshold in the postinspiral regime (GW150914, GW170104, GW170608, GW170809, GW170814, and GW170823), analyzed with IMRPHENOMPv2.

8. 국내의 중력파 연구 현황은?

- 2008년 『한국중력파연구협력단(KGWG)』 결성
- 2009년 라이고 멤버 가입
- KAGRA 멤버: 36명
- LIGO 멤버: 13명

한국중력파연구협력단: Korean Gravitational Wave Group

한국중력파연구협력단, Korean Gravitational Wave Group(KGWG)

LIGO/Virgo/KAGRA 국제 연구협력단의 한국 측 회원기관으로서 중력파검출을 위한 학연 컨소시엄 형태의 공동연구협력단 - 대표 웹페이지: http://www.kgwg.org/

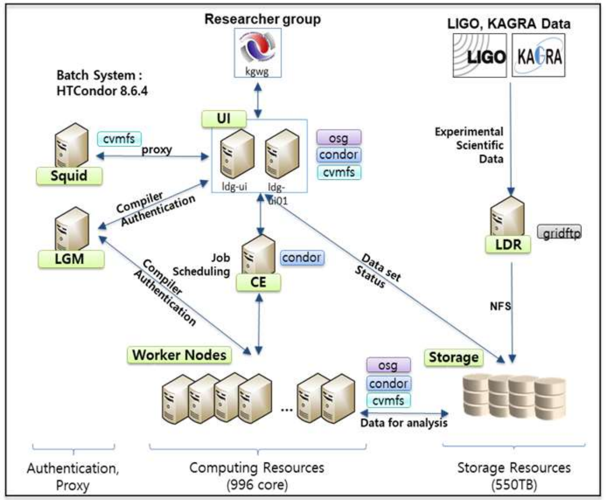
한국중력파연구협력단 Korean Gravitational-wave Group
단 장 Principal Investigator
운영위원회 Steering Committee
언론홍보대변인 Press Coordinator
간 사 Executive Assistant
LIGO Scientific Collaboration Group
KAGRA Scientific Collaboration Group

- LIGO-Virgo협력
  - 서울대학교
  - 한양대학교
  - 부산대학교
  - 국가수리과학연구소 (NIMS)
  - 한국과학기술정보연구원(KISTI)
- KAGRA협력
  - 고려대학교
  - 서울대학교
  - 한양대학교
  - 부산대학교
  - 전북대학교
  - 명지대학교
  - 광주과학기술원 (GIST)
  - 국가수리과학연구소(NIMS)
  - 한국과학기술정보연구원(KISTI)
  - 한국원자력연구원(KAERI)

한국 중력파 연구 협력단

28

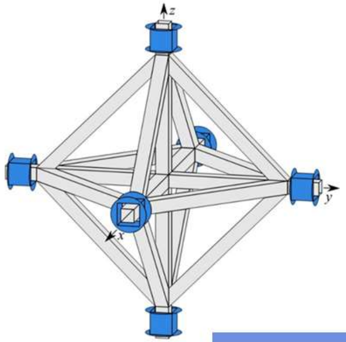
(2016)

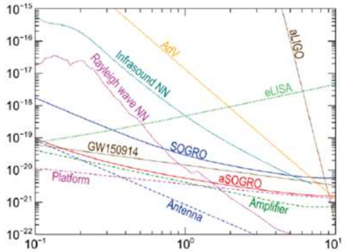


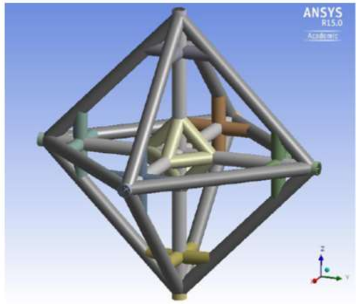
KISTI-LDG Tier-2 센터

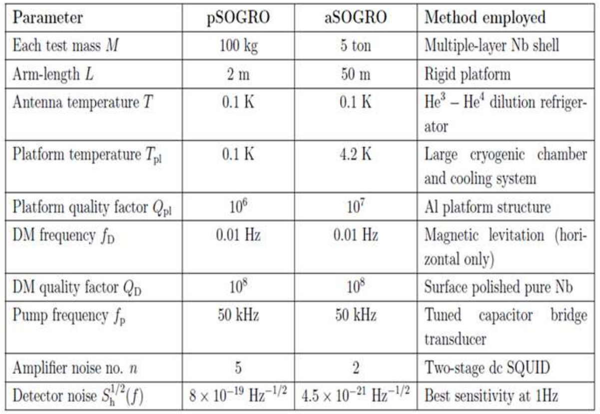
- 연구 분야/주제:
  - 검출기 특성분석
  - 파형 개발, 수치상대론, PN development
  - 파원 모수 추정
  - 중성자별 상태방정식
  - 추적 관측, 중력 렌징
  - 실험: 미러코팅, 카그라 실험 참여
  - 차세대 검출기: SOGRO, SIGN (?)
  - 컴퓨팅 팜 구축
- 다양한 분야에서 활발히 연구

소그로 연구

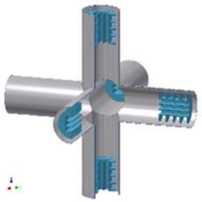






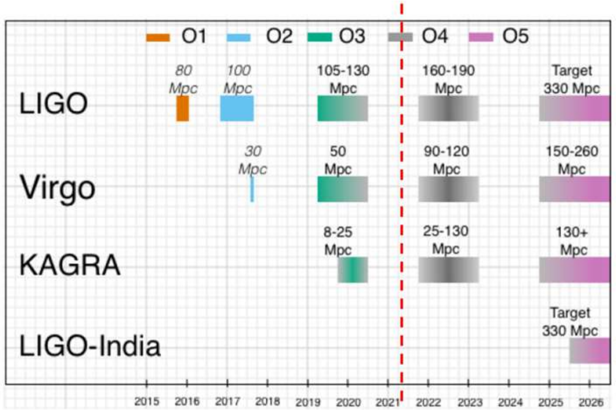


Parameter	pSOGRO	aSOGRO	Method employed
Each test mass M	100 kg	5 ton	Multiple-layer Nb shell
Arm-length L	2 m	50 m	Rigid platform
Antenna temperature T	0.1 K	0.1 K	$He^3 - He^4$ dilution refrigerator
Platform temperature $T_{\rm pl}$	0.1 K	4.2 K	Large cryogenic chamber and cooling system
Platform quality factor $Q_{\rm pl}$	10^6	10^7	Al platform structure
DM frequency $f_{\rm D}$	0.01 Hz	0.01 Hz	Magnetic levitation (horizontal only)
DM quality factor $Q_{\rm D}$	10^8	10^8	Surface polished pure Nb
Pump frequency $f_{\rm p}$	50 kHz	50 kHz	Tuned capacitor bridge transducer
Amplifier noise no. n	5	2	Two-stage dc SQUID
Detector noise $S_{\rm h}^{1/2}(f)$	8×10^{-19} Hz$^{-1/2}$	4.5×10^{-21} Hz$^{-1/2}$	Best sensitivity at 1Hz



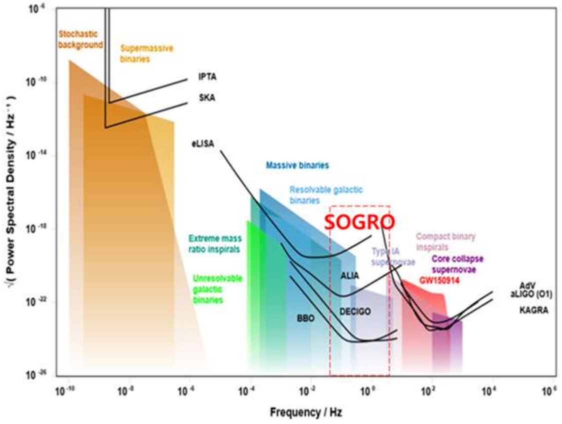
9. 중력파 검출 실험의 전망은?

- 이미 세기적인 과학적 성과 창출하고 있고 활발한 연구 및 발전 예상: “Rich data rich science”
- 상시적 중력파 관측
- 다양한 차세대 중력파 검출기 개발: Ex) $m_g \le 1.2 \times 10^{-23}\ \mathrm{eV}/c^2$ ➔ $\sim 10^{-25}\ \mathrm{eV}/c^2$
- 천체물리학, 우주론, 천문학 등의 분야에서 근원적 물리 문제 해결에 기여



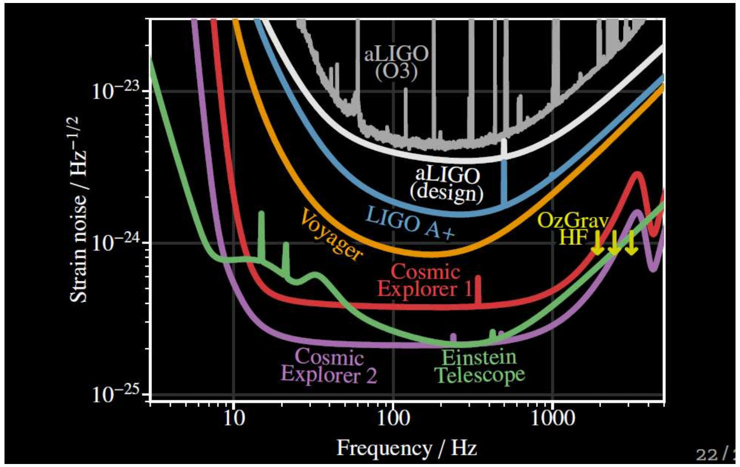
Living Rev Relativity (2018)

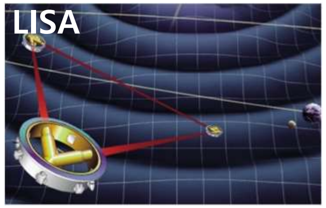
중력파 스펙트럼: 파원과 검출기

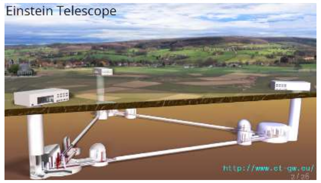


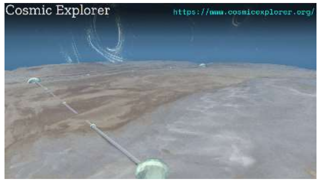
Based on http://rhcole.com/apps/GWplotter/
by Moore, Cole & Berry

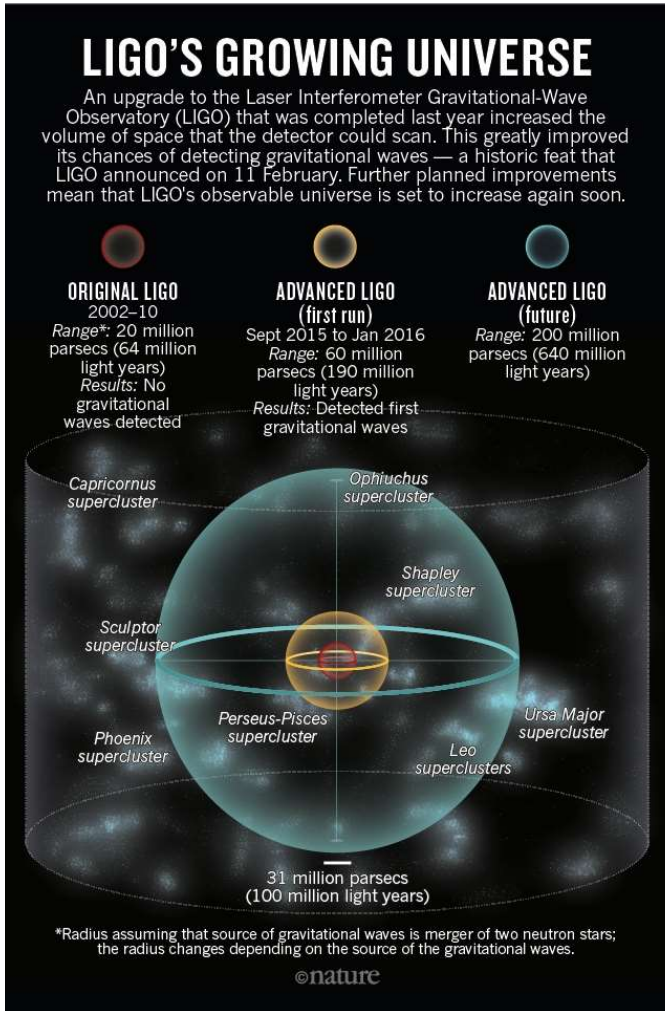
중력파 검출기 감도











LIGO'S GROWING UNIVERSE

An upgrade to the Laser Interferometer Gravitational-Wave Observatory (LIGO) that was completed last year increased the volume of space that the detector could scan. This greatly improved its chances of detecting gravitational waves — a historic feat that LIGO announced on 11 February. Further planned improvements mean that LIGO's observable universe is set to increase again soon.

ORIGINAL LIGO
2002–10
*Range**: 20 million parsecs (64 million light years)
Results: No gravitational waves detected

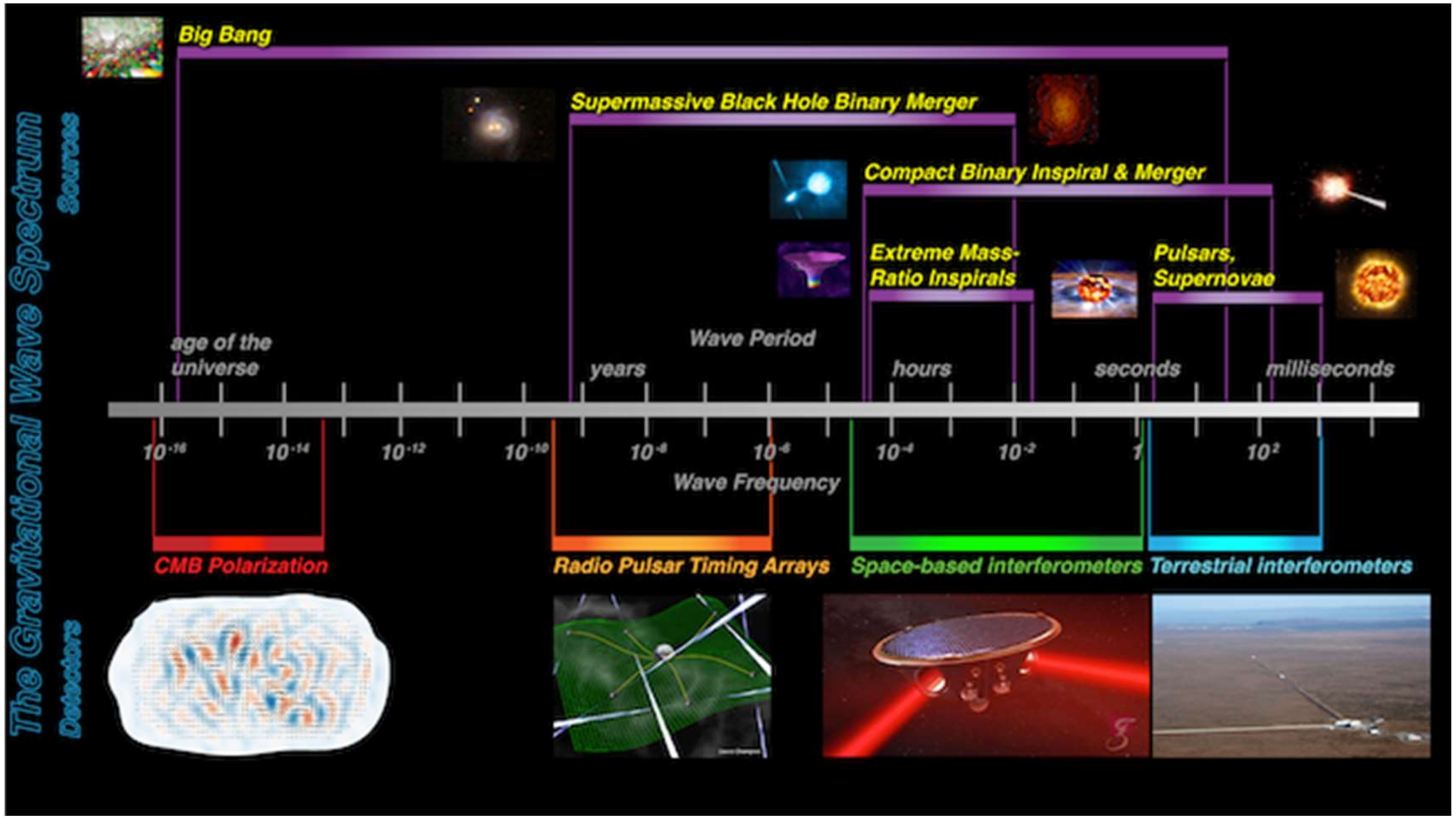
ADVANCED LIGO (first run)
Sept 2015 to Jan 2016
Range: 60 million parsecs (190 million light years)
Results: Detected first gravitational waves

ADVANCED LIGO (future)
Range: 200 million parsecs (640 million light years)

*Radius assuming that source of gravitational waves is merger of two neutron stars; the radius changes depending on the source of the gravitational waves.

©nature

(출처: Nature 2016)



(Credit: NASA/J. I.Thorpe)

10. Science Fiction with GWs?

Imaginations!

尖端科学시대

金貞欽칼럼

〈51〉

重力波통신

地球중심통과 반대쪽 사람과 직접교신

「네안데르탈人(3만~20만년전 생존) 또는 어쩌면 直立猿人인 「호모하빌리스」(약 2백만년전 생존)이래 인류는 오랫동안 音波를 통신수단으로 써왔다. 그러나 音波로는 통신이 가능한 거리라고 해보았댔자 몇백m도 되지 않는다. 그 통신의 거리가 비약적으로 커진 것은 「마르코니」에 의한 무선전신발명 이후의 이야기이다. 90여년전인 1895년의 일이다.

인류가 손에 쥔 제2의 통신, 즉 전파는 지구상을 오갈 뿐아니라 지금은 멀리 달세계에 자리잡은 「아폴로」우주선으로부터도 멀리 27억여㎞저쪽의 天王星으로부터도 [illegible]을 교신할 수 있게 되었다. 그러나 그 전파에도 한계는 있다. 지구상 어디와도 통신이 가능한 것은 아니기 때문이다. 예컨대 전파를 써서 태평양 한복판에 잠수한 잠수함과 교신한다는 것은 달표면의 우주비행사와 통신하는 것보다 훨씬 힘들다. 왜냐하면 전파는 공중이나 진공속은 잘 지나가지만 바닷속으로는 잘 지나갈 수가 없기 때문이다.

또 지구의 중심을 지나 지구의 반대쪽에 있는 사람과 통신하기도 힘들다. 또 지형관계로 전파의 골짜기라 해서 전파가 잘 도달되기 힘든 장소, 예컨대 TV의 경우라면 難視聽지역이란 곳도 있다.

그래서 과학자들은 이 난관을 돌파하기 위해 새로운 통신수단을 연구중에 있다. 그 하나가 重力波이다.

일단 重力波는 1916년 「아인시타인」의 「一般相對論」에 의해 그 존재가 예언되었고 그 遠方波는 아직 정식으로 검지 또는 발견조차 안되어 있다. 그러나 近傍場이라면 겨우 검출이 가능할 정도로까지 되어있다.

근방장이란 파동을 발출하는 波源의 극히 近傍에 발생하는 파동으로서 거리가 멀어지면 극히 약화되는 것으로 멀리까지 전달되는 遠方波와 그 성질이 다르다.

예컨대 라디오방송 안테나근처에서는 라디오가 아니라 그냥 이어폰만 귀에 꽂아도 라디오방송이 들릴때가 있다. 이것은 근방파를 수신한 것으로 근방파를 이용한 무선통신은 이미 1887년 英國에서는 실용화까지 되어 있었다. 예컨대 광산내서의 통신이라든지 잠수부와의 통신에서 말이다. 1888년 「헤르쯔」에 의해 電磁氣波의 遠方波(맥스웰에 의해 그 존재는 이미 1864년에 예언)가 발견되기 전의 이야기이다.

마찬가지로 重力波의 경우도 근방파라면 이미 그 신호가 인지되기 시작하고 있다. 안테나 사이의 거리가 현재로서는 1.72m의 극도로 짧은 거리이긴 하지만 말이다. 장치의 크기는 지름58㎝ 길이 1백52㎝의 알루미늄제 원통이고 그 표면에 壓電變換器가 붙여있다.

과학자들은 21세기까지는 이런 重力波를 쓴 통신장치가 실현되어 바닷속 깊이 있는 잠수함과의 교신 또는 지구중심을 통과하여 지구반대쪽 사람과의 직접통신도 가능하게 되리라 믿고 있다.

〈고려대교수·물리학〉

1986년 3월 8일
동아일보 칼럼
故 김정흠 교수 (고려대)

EM Waves

- Theory: Maxwell (1864)
- Detection: H. Hertz (1886)

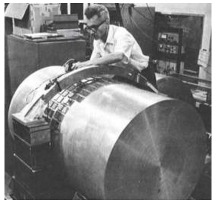
20년

100년

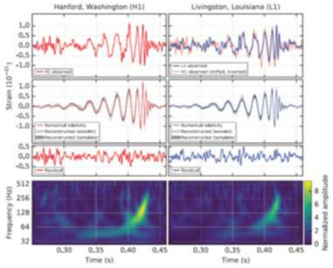
Gravitational Waves

- Theory: Einstein (1916)
- Detection: LIGO (2015)

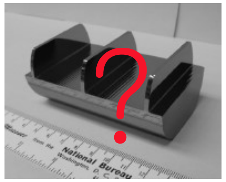
100년



Weber (1960)



GW150914



500년(?)

Weak because of

$\sim G/\hbar$

$\sim\vartheta(1)$

GWs+QS

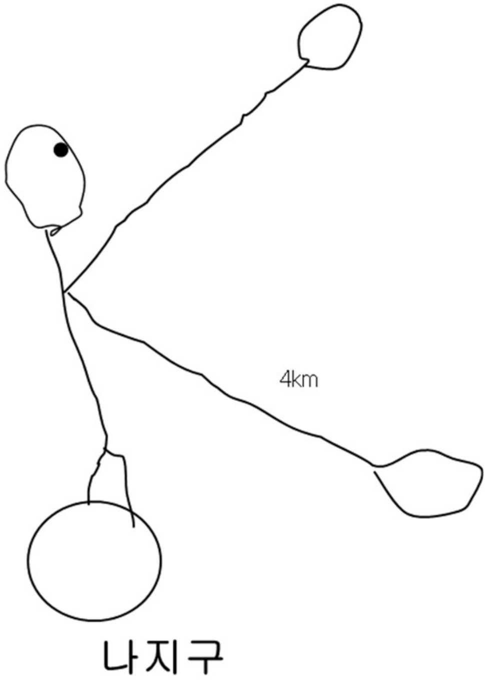
결 론

- Based on the observed GW data, GR is so far valid as a theory of gravitation for the real world.
- 중력파는 우주를 탐색하는 매우 독특하고 강력한 도구
- 장기적인 과학사적 관점에서 보면 여전히 태동기
- 과학적 성취의 잠재력이 매우 높고 도전할 미개척지 많음
- 다중신호 천문학 등 기존 관측방법과의 협력으로 상호보완 및 종합적 규명과 이해 가능

GW150914 & KGWG KOREAN GRAVITATIONAL WAVE GROUP

on behalf of Korean Gravitational Wave Group

국제협력연구 컨퍼런스에 참가한『한국중력파연구협력단』멤버들
(2016년 3월 미국 파사데나)



(좌로부터) 손재주, 김환선,
강궁원, 오정근, 이형목,
이창환, 김정리, 조희석,
이현규, 오상훈