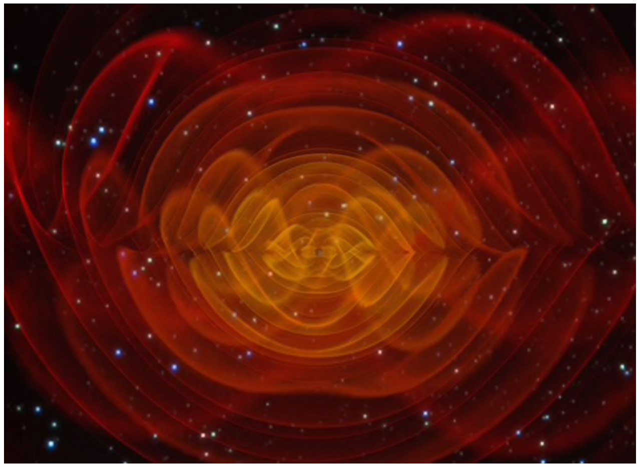
RECENT TRIUMPHS OF GR – GRAVITATIONAL WAVES

Lecture 15, Introduction to Black Hole Astrophysics

NTHU, 6/8/2021

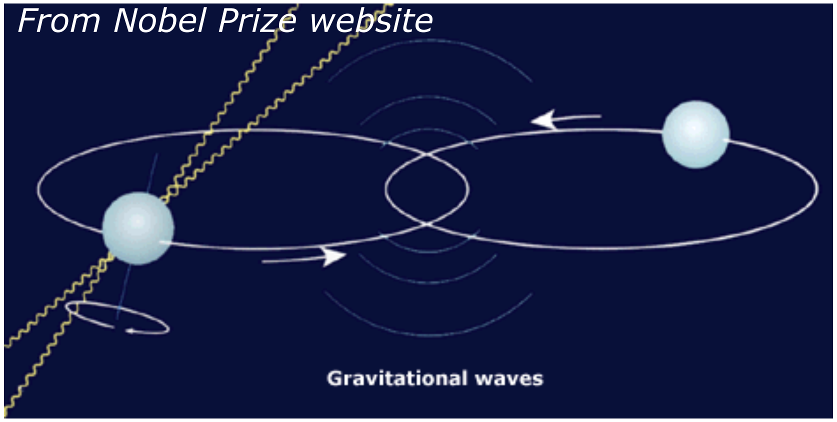
PROPERTIES OF GRAVITATIONAL WAVES IN GR

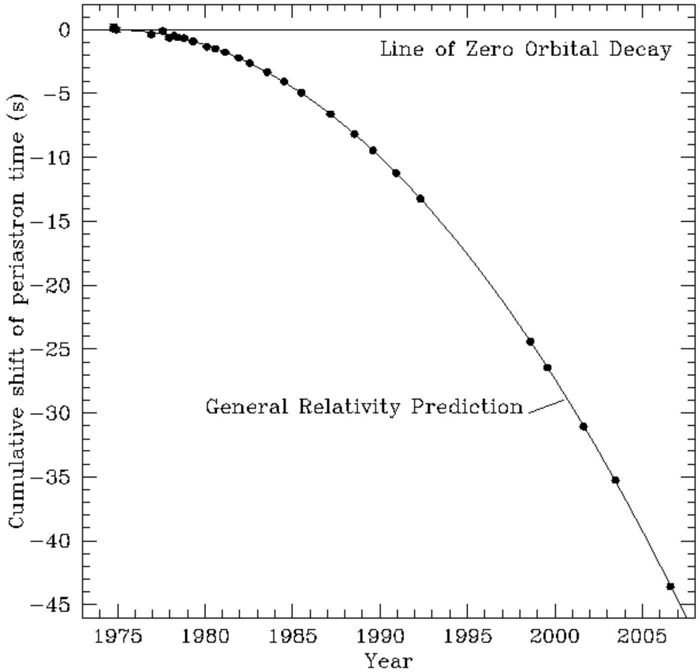
- GR predicts that ***gravitational waves*** (GWs), which are ripples of spacetime, should be produced when there is accelerating mass
- GWs propagate with the speed of light
- Usually extremely weak, stronger when massive objects orbit each other
- GWs carry away energy so the orbit would shrink and objects would merge
- Frequency of GWs ~ 4400 Hz (M_{sun}/M)
  - For smbhs of 10 M_{sun}, frequency ~ 440 Hz (hearable!)
  - For SMBHs of 10^6 M_{sun}, frequency ~ 4.4 mHz
- GWs are unique because
  - They are not scattered or impeded
  - They can probe quiescent BHs and IMBHs



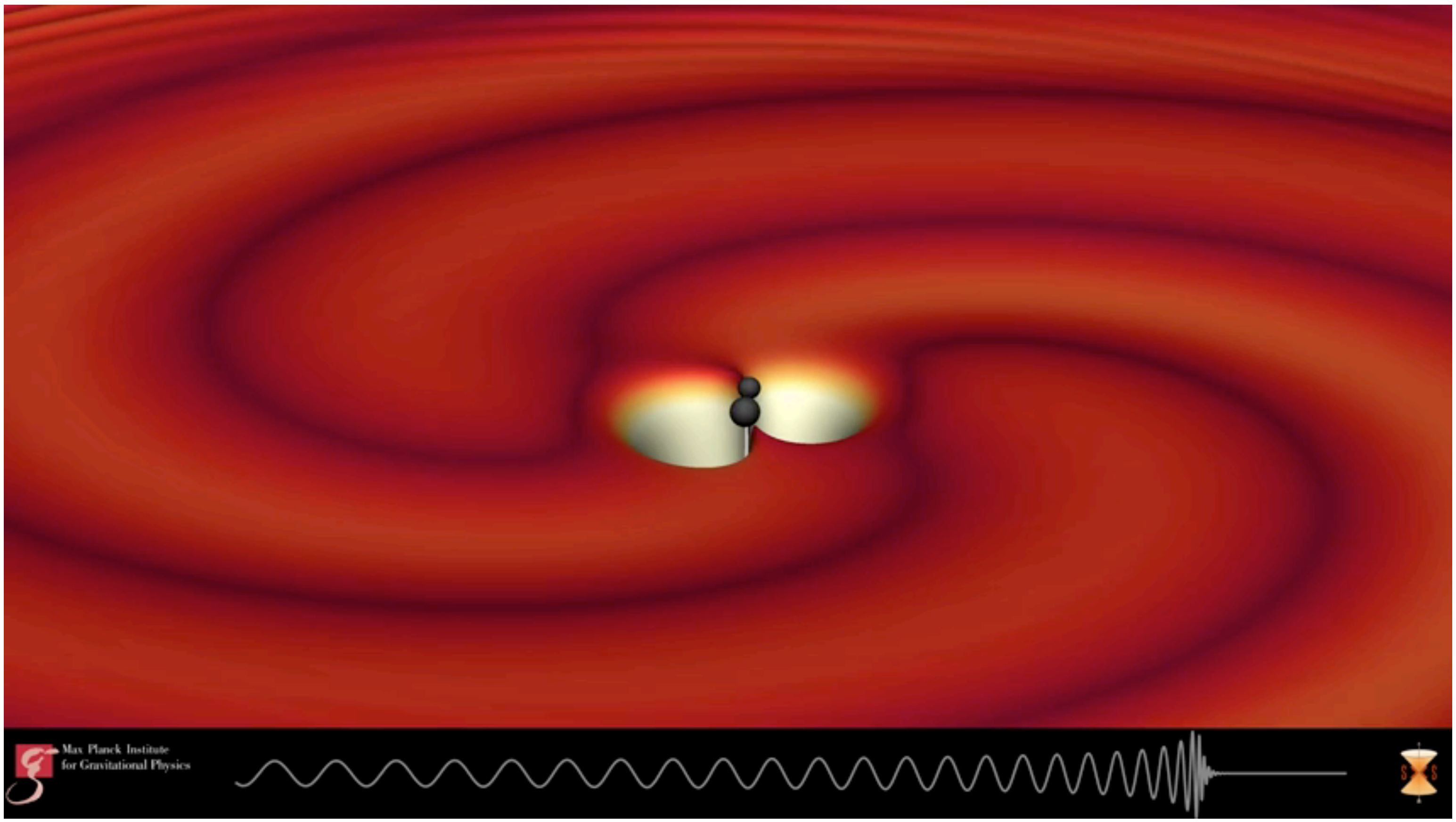
INDIRECT DETECTION OF GWS

- In 1974, Russell Hulse & Joseph Taylor discovered a ***NS-NS binary*** system PSR1913+16
- One of them is a pulsar (spinning NS) emitting radio pulses toward Earth with period of 59ms, which is a very accurate clock
- There are slight variations of pulse arrival times due to the orbital motions; orbital period ~7.75 hours
- ***The orbit shrinks due to GWs!***
- Nobel prize in 1993

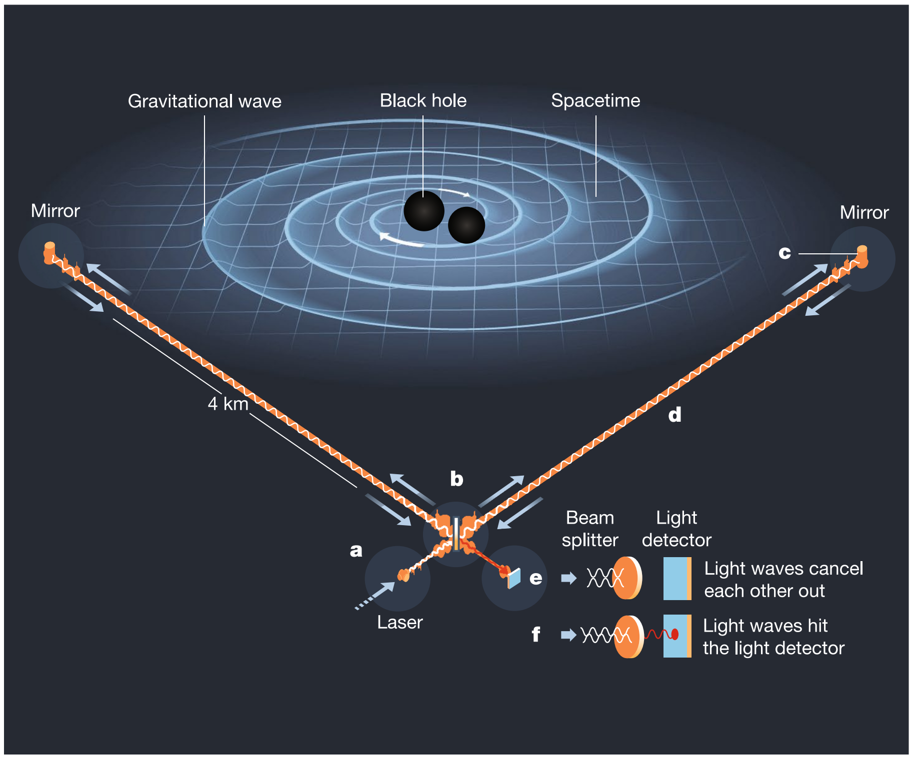




RIPPLES OF SPACETIME DUE TO BH MERGERS

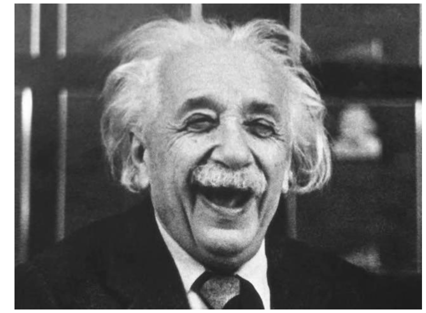


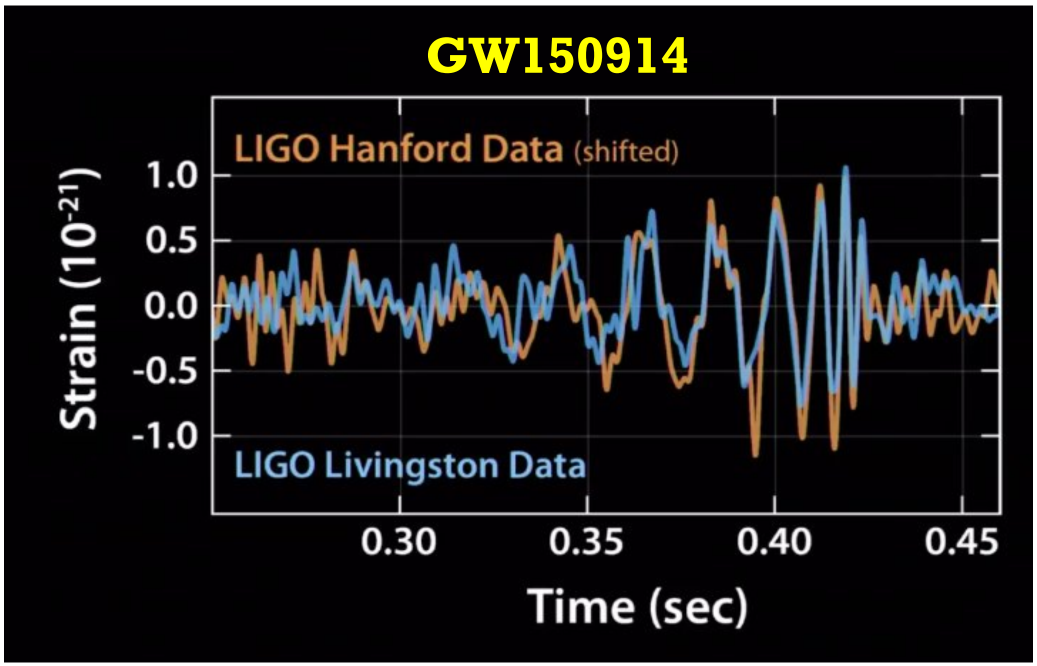
THE LIGO OBSERVATORY



- ***LIGO*** – Laser Interferometer Gravitational-wave Observatory
- Two L-shaped interferometers with 4km long arms
- Look for tiny changes in the length of arms when GWs pass by
- Extremely sensitive – ***1 part in 10^{21}***
  - For 4km, changes ~ 4×10^{-16} cm ~ 1/200 of size of proton!!
  - Need to remove noises from earthquakes, traffic, people, etc
- Can detect GWs with frequencies of ***~10-1000 Hz***

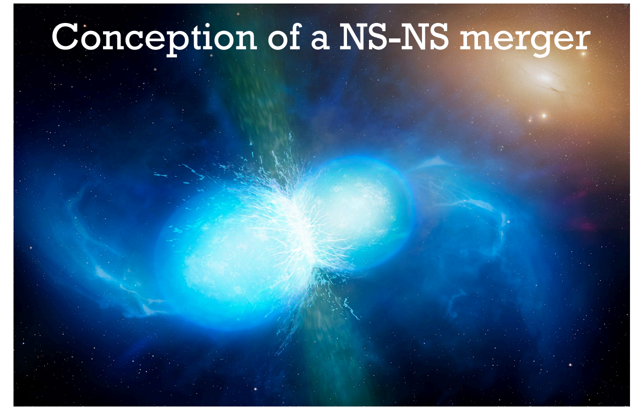
FIRST DIRECT DETECTION OF GWS!





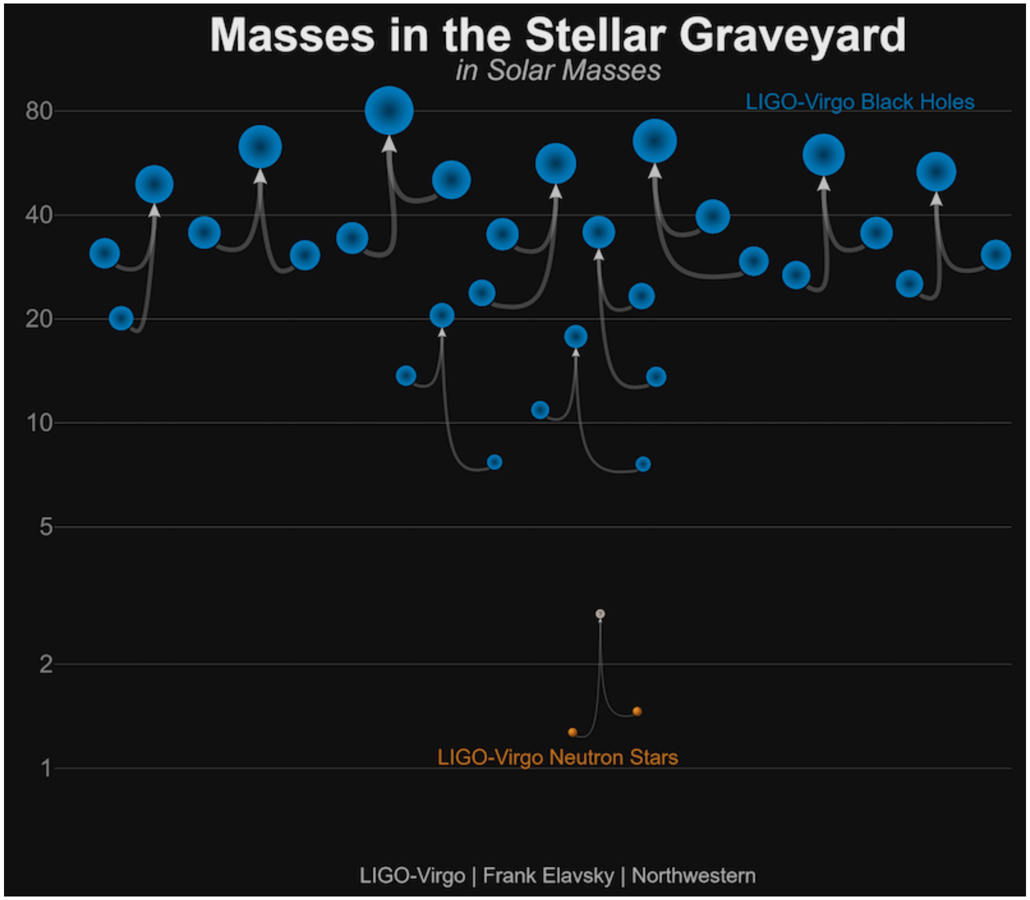
- On Sep. 14, 2015, LIGO detected the first GW signal from a BH-BH merger
- GR confirmed again!!
- 36 M_{sun} + 29 M_{sun} -> 62 M_{sun} (?)
- GW energy ~ 5×10^{47} W
- Distance ~ 440 Mpc
- Lasted for ~2 seconds
- Frequency starts from 35 Hz and increases to 250 Hz -> hear the "***chirp***"!
- Nobel prize in 2017 to Rainer Weiss, Kip Thorne, and Barry Barish

THE FIRST NS-NS MERGER



- On Aug. 17, 2017, the first ***NS-NS merger*** was detected by LIGO
- In addition to GWs, the NS-NS merger created a firework in the electromagnetic signal over different wavebands. 70 observatories were watching it!
- A ***gamma-ray burst (GRB)*** was detected 1.7 seconds after the GW signal
  - Because it is 40 Mpc away, this essentially means GWs travel with the speed of light
  - Confirms that NS-NS mergers are one of the sources of GRBs
- Longer-duration optical/IR transient was observed (jargon: kilonova)
  - This is powered by radioactive decay of nuclei heavier than iron
  - Confirms the hypothesis that these heavy elements are produced in NS-NS mergers rather than supernova explosions
- This event marks the birth of ***multi-messenger astronomy***!!!

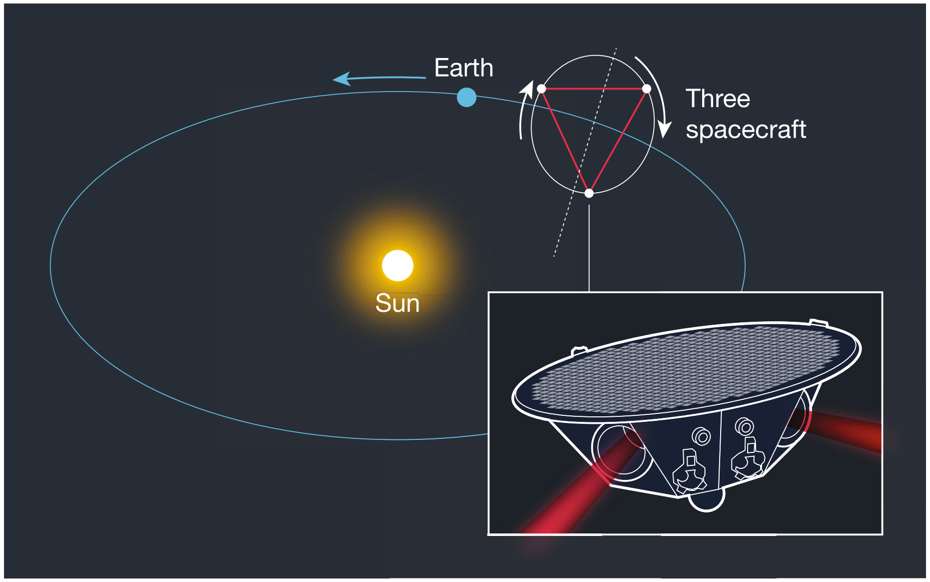
LIGO EVENTS TO DATE



FUTURE PROSPECTS

- The more the merrier! – more detectors would help with ***localization*** of the source
  - ***VIRGO*** (3km-arm detector in Italy) joined the observation in April, 2019
  - Future plans: ***KAGRA*** (japan), ***LIGO-India***
- ***LISA*** (Laser Interferometer Space Antenna)
  - Three test masses forming a triangle with 5 million km arms in space!
  - Frequency range ***~0.001-0.1 Hz***
  - Can detect mergers of SMBHs with $10^4 – 10^7$ M_{sun}!
- 3rd-generation detectors: Einstein Telescope (triangular underground facility), Cosmic Explorer (40km-arm detector)

Design of LISA gravitational wave detector



SUMMARY

- The theory of ***GR*** remains valid after the two recent observational breakthroughs
- ***The first BH image*** of the M87 SMBH by EHT
  - Requires extraordinary resolution ~ 25 microarcsec
  - The observed image is fully consistent with GR prediction
  - The bright ring comes from emission of gas within the thick accretion flows
  - The BH shadow is caused by ***gravitational lensing*** of light rays close to BH, shadow size ~ $2R_c \sim 5.2\ R_s$
- The detection of ***gravitational waves*** by LIGO
  - Requires extraordinary sensitivity to detect spacetime distortions with 1 part in 10^{21}
  - The first BH-BH merger -- the observed properties of GWs are consistent with GR
  - The first NS-NS merger explains the origin of GRB and heavy elements and leads to ***multi-messenger astronomy***!


The future is unwritten.
Joe Strummer
quotefancy

RECENT TRIUMPHS OF GR – GRAVITATIONAL WAVES (UPDATES)

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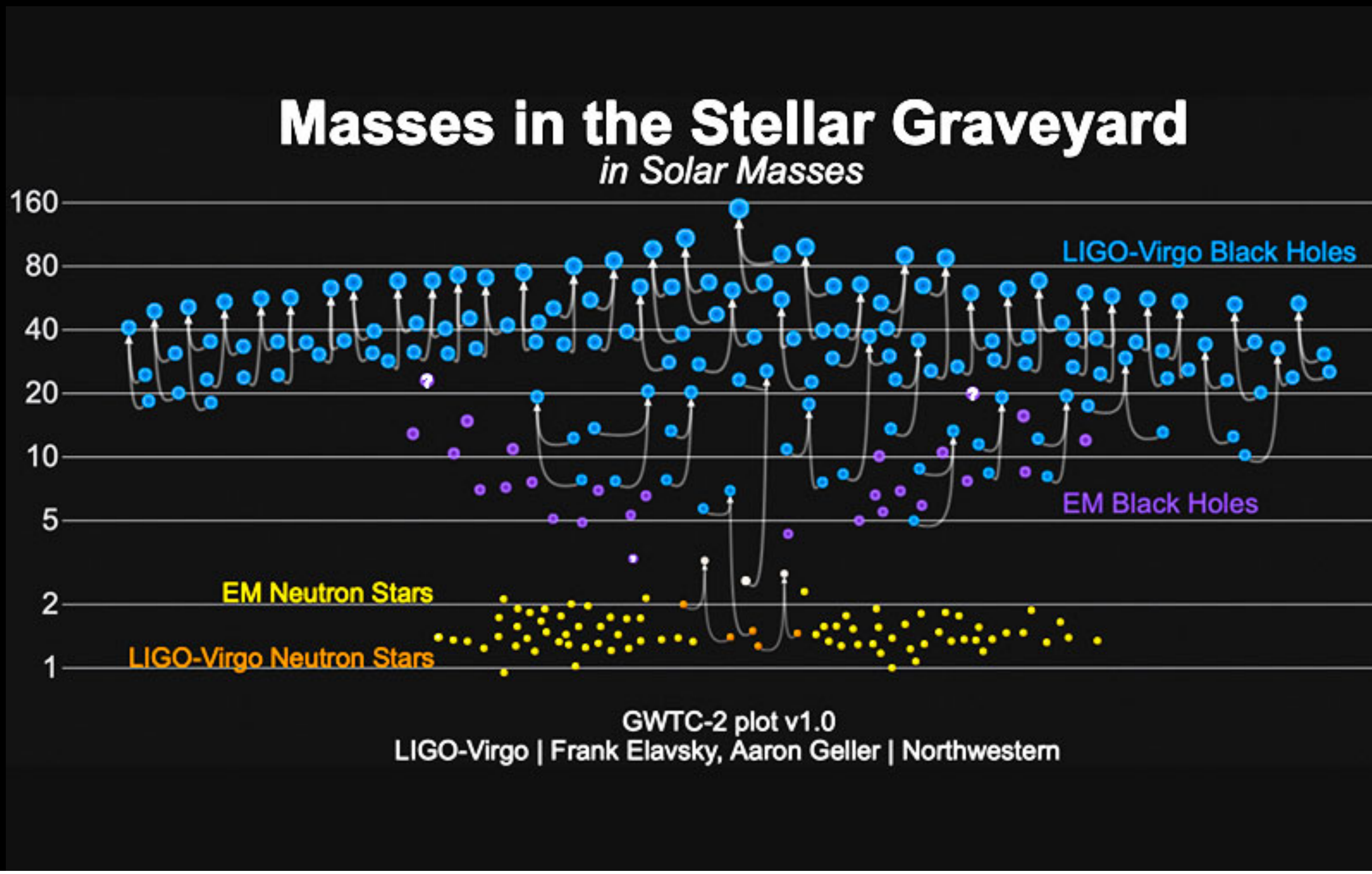
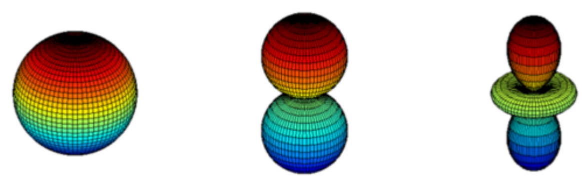
LIGO DETECTIONS TO DATE: 50 EVENTS



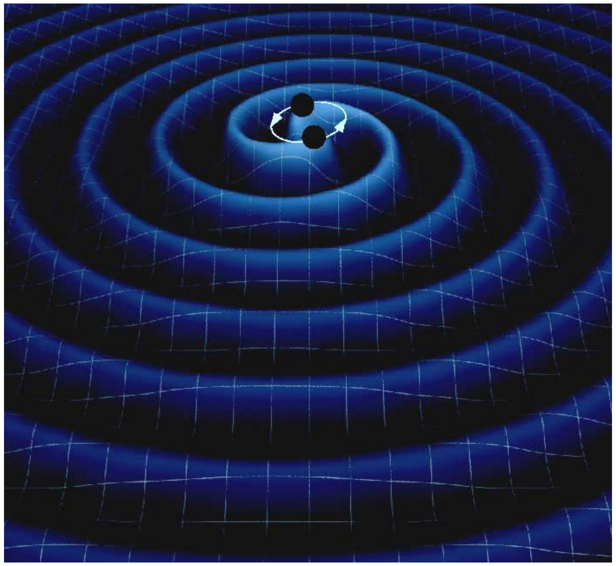
GRAVITATIONAL WAVES

- In 1918, Einstein solved the Einstein's field equations for small perturbations and found the solutions of gravitational waves (GWs)
- GWs propagate with the speed of light as predicted by GR
- GWs are generated whenever there is ***acceleration in the quadrupole moment*** of the matter distribution



- "***Strain***" defines how much spacetime is distorted: $h = \frac{\Delta L}{L}$

STRAIN OF GWS



- For two orbiting mass, the strain can be expressed as

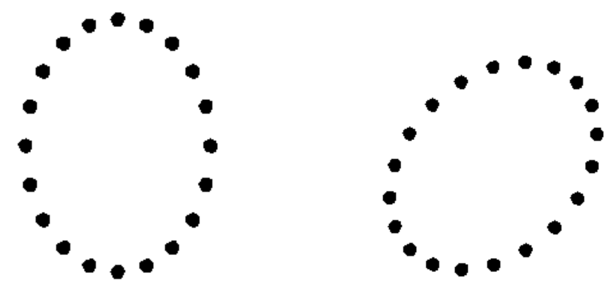
$$h = \frac{4G}{c^2} \times \frac{\mu}{r} \times \left(\frac{GM}{c^3} \times 2\pi f\right) \qquad \mu = \frac{m_1 m_2}{M}$$

- Compared to EM waves which decays with $1/r^2$, GWs decay as ***1/r***
- But it requires extraordinary sensitivity to detect GWs!

$$h \sim 10^{-19} \left(\frac{M}{10M_{sun}}\right) \left(\frac{r}{20Mpc}\right)^{-1}$$

OTHER PROPERTIES OF GRAVITATIONAL WAVES

- Perpendicular to its propagating direction, GWs can be decomposed into two ***polarizations***: '+' and 'x' modes



- GWs carry momentum and energy with energy flux:

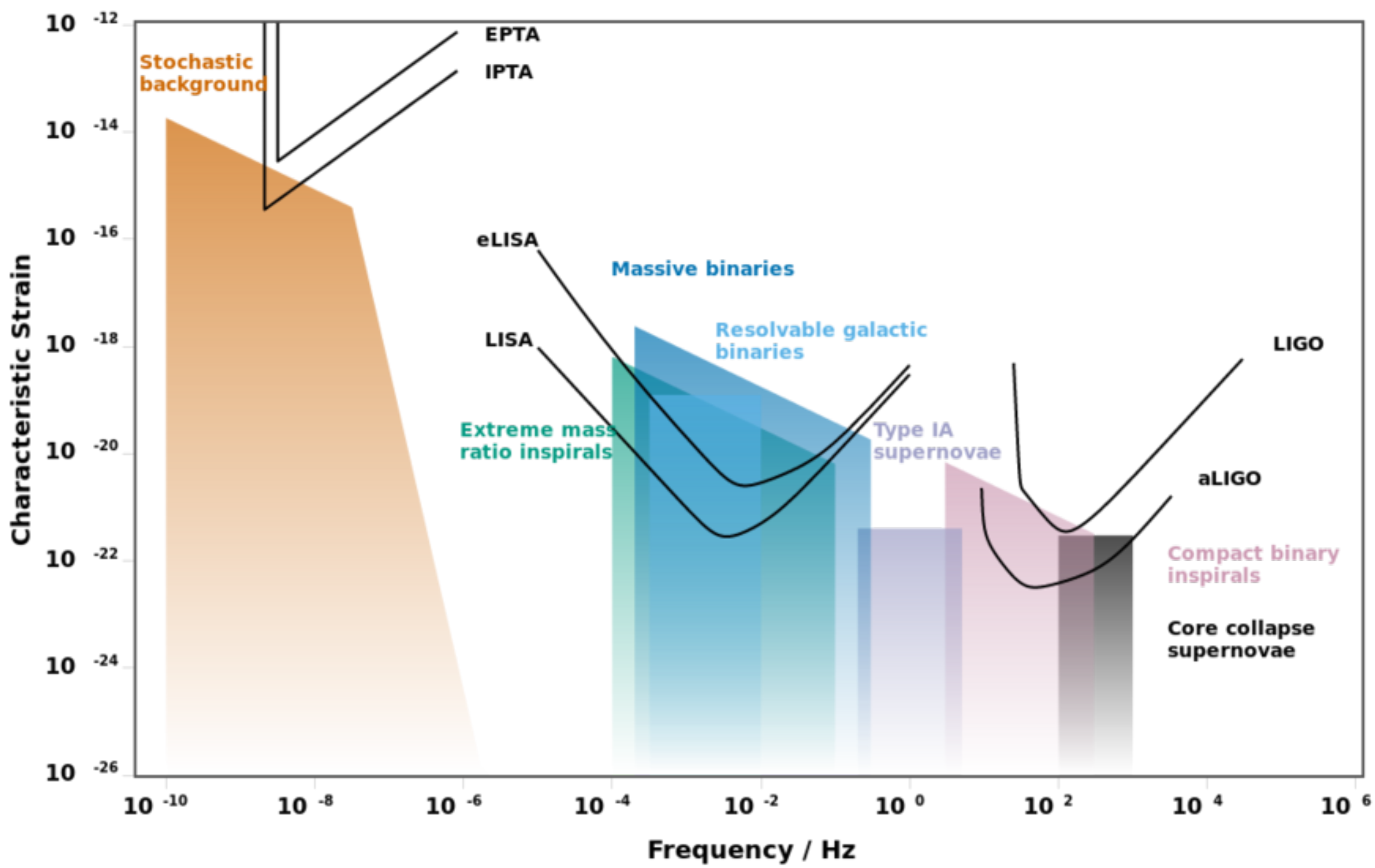
$$\frac{dE}{dAdt} = \frac{c^3}{16\pi G}\left(\dot{h}_+^2 + \dot{h}_X^2\right)$$

- GWs would carry away the rotational energy of binary systems, resulting in shrinking of the orbits (e.g., Hulse-Taylor NS binary)

ASTROPHYSICAL SOURCES OF GWS

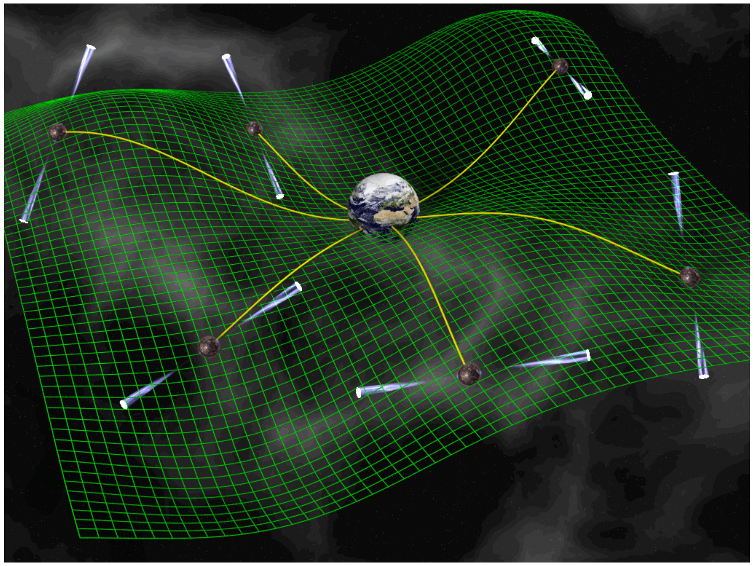
- Mergers of compact binaries: BH-BH, BH-NS, NS-NS, SMBH-SMBH, SMBH-BH (Extreme Mass Ratio Inspirals = EMRI)
- Periodic sources: binary WDs, binary pulsars, spinning NSs
- Burst events: supernova explosions
- Stochastic background: unresolved sources, primordial Big Bang

Gravitational Wave Spectrum

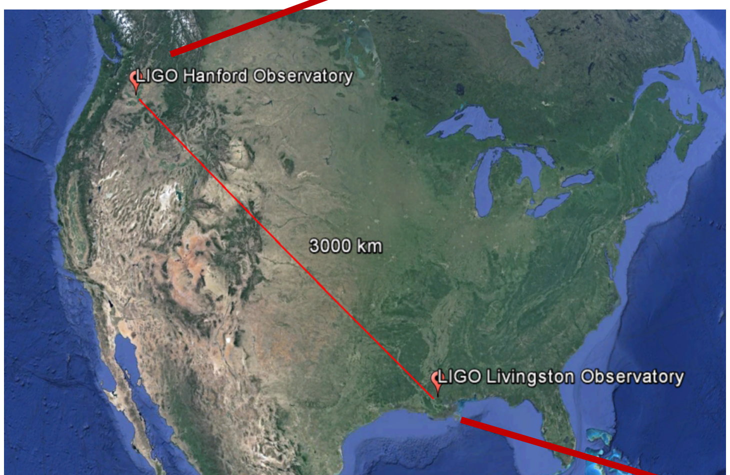


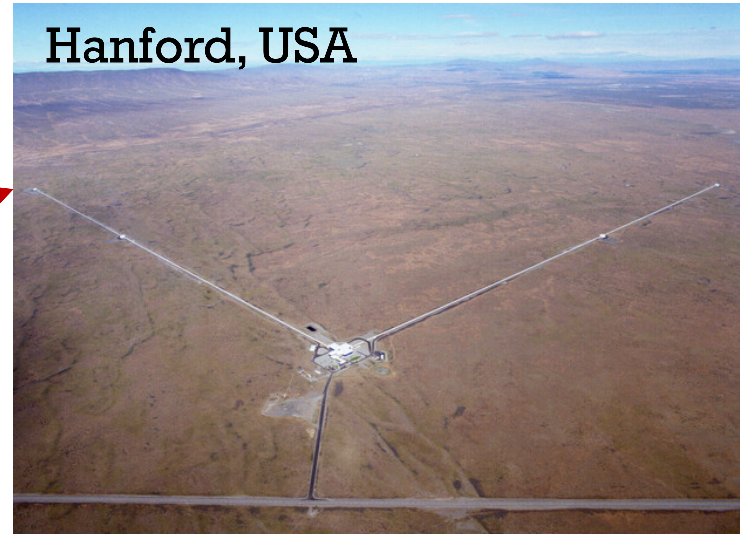
PULSAR TIMING ARRAYS

- ***Pulsar timing arrays (PTAs)*** could detect stochastic GW background, primarily generated by SMBH binaries and mergers around ***nanoHz*** frequencies
- Pulses of milli-second pulsars (fast rotating NSs) are extremely precise clocks
- When GWs pass by, the arrival times of pulses would be modified
- By long-time monitoring dozens of pulsars in the Galaxy, it is possible to detect the stochastic GWs



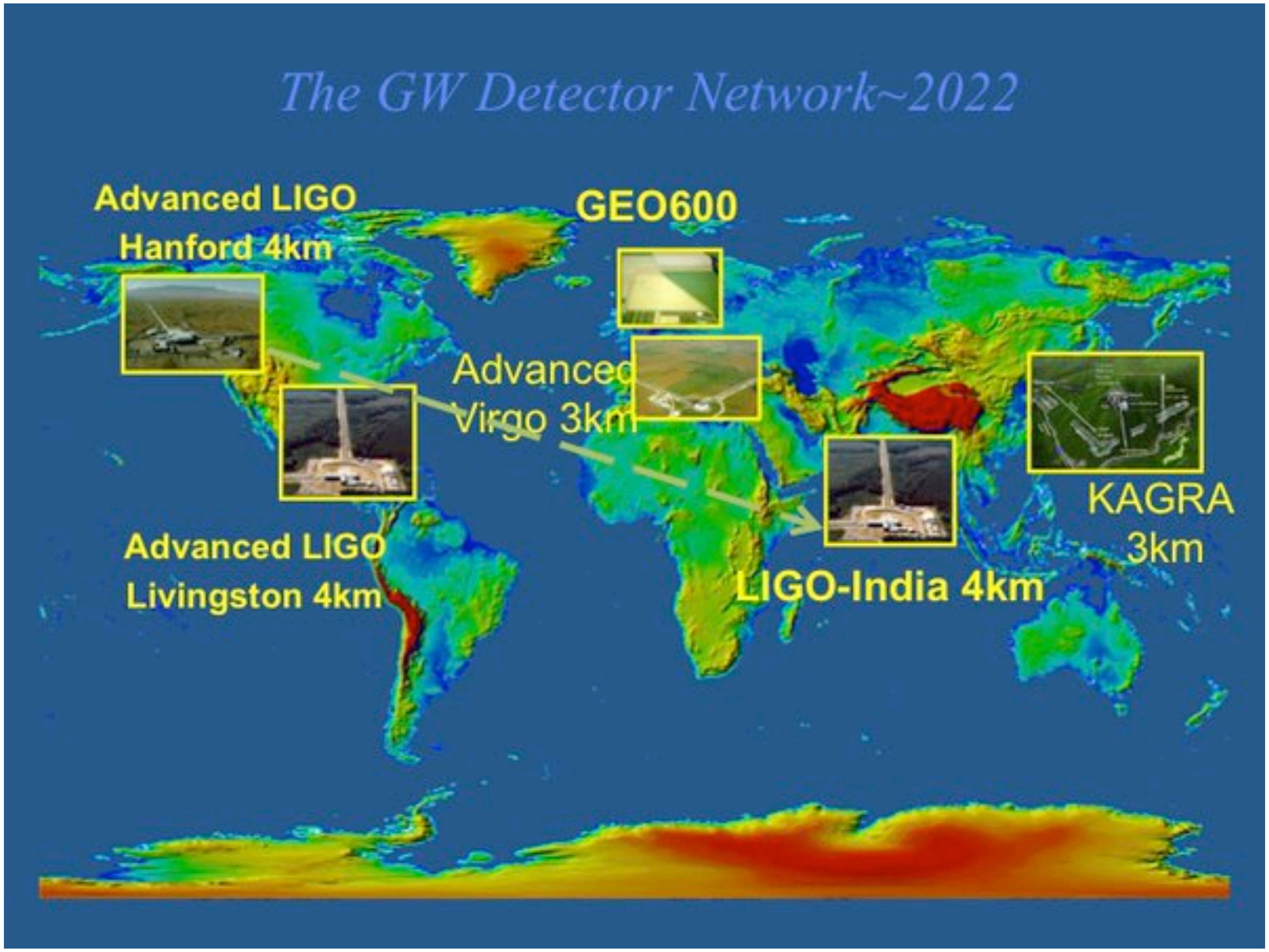
LIGO


LIGO Hanford Observatory
3000 km
LIGO Livingston Observatory


Hanford, USA


Livingston, USA

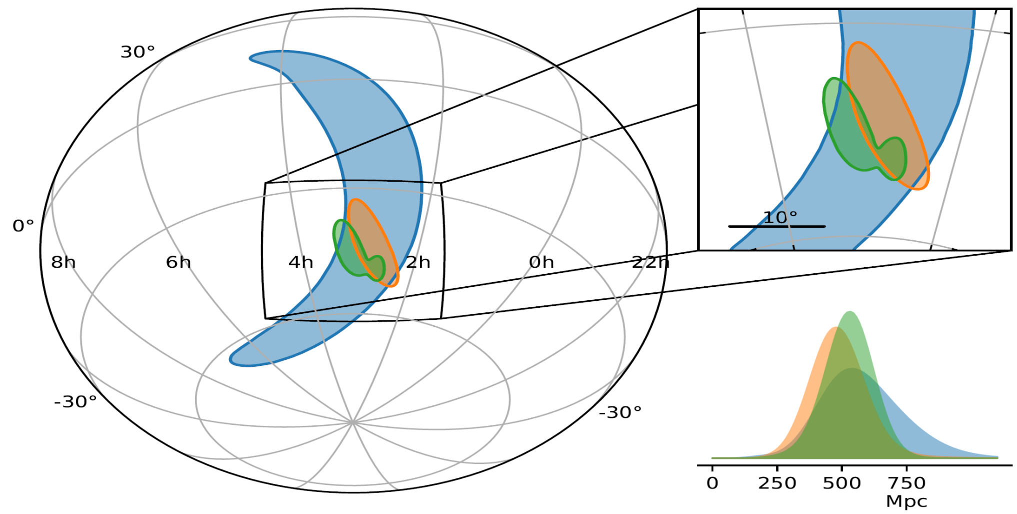
GRAVITATIONAL WAVE NETWORK



LOCALIZATION OF GW SOURCES

- Adding different sites of GW detectors could significantly improve the ***localization*** of possible sources
- GW170814: adding the VIRGO detector shrinks the region from 1160 square degrees to <100 square degrees
- This is very important for follow-up EM observations!

Localization of GW 170814's source on the sky



LOCALIZATION OF GW SOURCES

- Using differences in arrival times between two GW detectors, location of sources could be constrained into a circle on the sky
  - Adding a 3rd detector would narrow down the region into cross sections of 3 circles
- Additional information can be gained because GW detectors are most sensitive to directions perpendicular to the two arms
  - There are "blind spots" along the directions of the arms
  - Could further constrain the source location if the signal is not detected by one of the detectors

QUESTIONS TO ADDRESS USING GWS

- Is the nature of gravity fully consistent with GR?
- Mass distributions of smbhs -> binary star evolution
- What can we learn about properties of gamma-ray bursts (GRBs) using GWs from NS-NS mergers and EM signals?
- What is the structure of NSs and other compact objects?
- Independent measurement of masses and spins of quiescent BHs
- How did SMBHs form and grow with cosmic time?

SUMMARY

- LIGO's detection of GWs have opened up a brand new window for understanding the universe
- It allows us to gain additional info about the astrophysical objects (e.g., independent measurements of BH masses and spins)
- It has revolutionized our understanding of stellar-mass BHs, and revealed the nature of short gamma-ray bursts
- Future GW detectors across the GW spectrum will bring us more and more excitements about our universe!

PRESENTATIONS 6/8

- Not all theories can explain the black hole M87* by Geng-Wei Wu 吳耕緯

https://qrgo.page.link/Wc2qk

- Enormous X-ray bubble of the Milky Way by Yun-Xin Zhong 鍾昀欣

https://qrgo.page.link/eETXw

- Astronomers discover two very distant double quasars by Yu-Wei Lin 林于瑋

https://qrgo.page.link/7uP5h