GRAVITATIONAL WAVES

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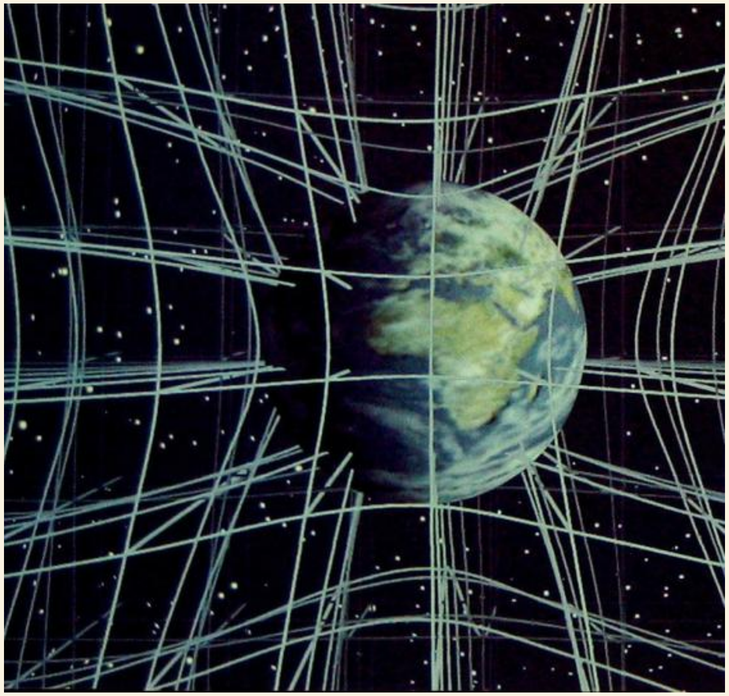
GRAVITATIONAL WAVES

- Gravitational waves and spacetime
- History: from concept to proof
- Recording gravitational waves
- Future use of gravitational waves

WHAT ARE GRAVITATIONAL WAVES?

- **Warping** of spacetime (general relativity)
- Ripples in spacetime caused by **moving mass**
  - **Massive** objects at **high speeds**
- Travel at the **speed of light** away from the source
- (curvature of ST)=$\mathbf{10^{-43}}$(matter and energy)

Demonstration



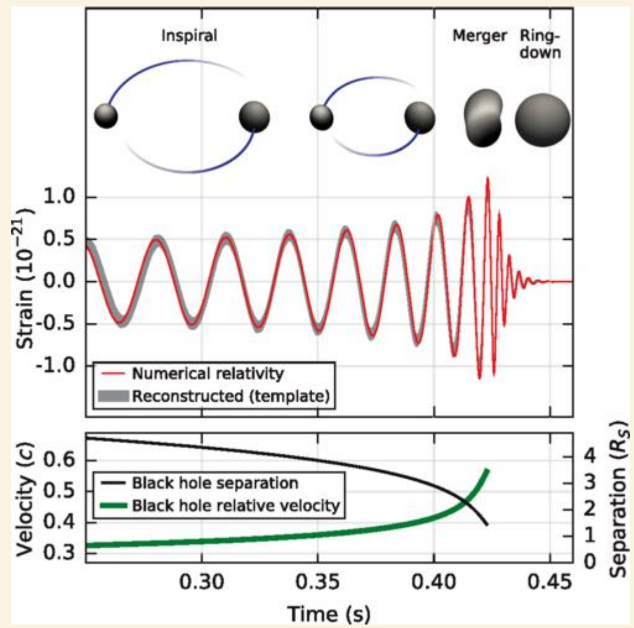
Source: Warped spacetime [Internet]. Forbes; 2019[updated Feb 16 2019, cited March 25th 2019]. Available from: https://www.forbes.com/sites/startswithabang/2019/02/16/ask-ethan-how-can-we-measure-the-curvature-of-gravity/#4306273b134f

HOW ARE GRAVITATIONAL WAVES PRODUCED?

- Rotating **binary systems**: e.g. Black holes, neutron stars, etc.
- Rotation of **asymmetrical** cores: e.g. Supernova collapse
- Frequency of gravity waves increase during merger
  - LIGO team converted GW signal to sound (**Chirps**).

GW150914 (white noise)

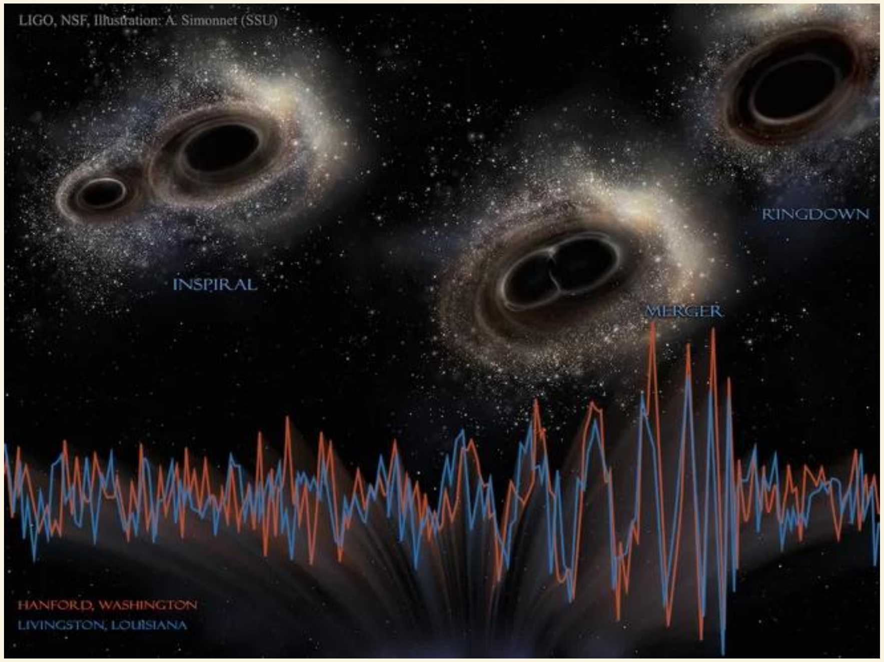
GW151226 (Filtered)



Source: Gravitational strain from merger [Journal article]. Abbott et al. 2016. Doi: 10.1103/PhysRevLett.116.061102

INFORMATION FROM GRAVITATIONAL WAVES

- Information about source from GW signal and General relativity models
- First recorded event:
  - Black holes 36M and 29M
  - Final mass 62M (**missing** mass?)
  - **3M's** worth of energy **as** gravitational waves



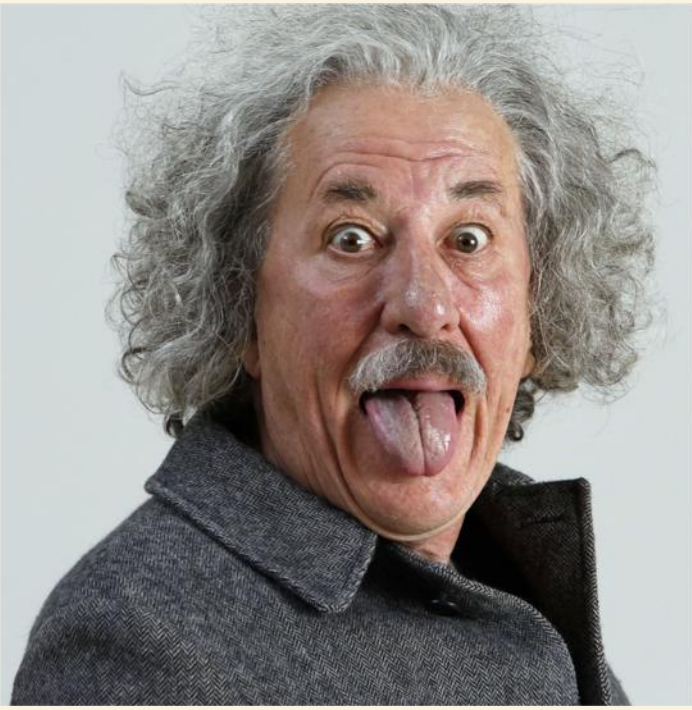
Source: Black hole mergers [Internet]. LiveScience 2016 [updated Feb 11 2016, cited March 25 2019]. Available from: https://www.livescience.com/53693-image-gravitational-wave-black-hole-merger.html

PROPERTIES OF GRAVITATIONAL WAVES

- Waves **weakly** interact with matter; allows us to see **hidden** features
- Some objects may **not** radiate **light**, but do radiate **gravitational waves** (e.g. black holes, dark matter?)
- During Neutron mergers, gravitational waves are released **before** visible gamma-ray burst

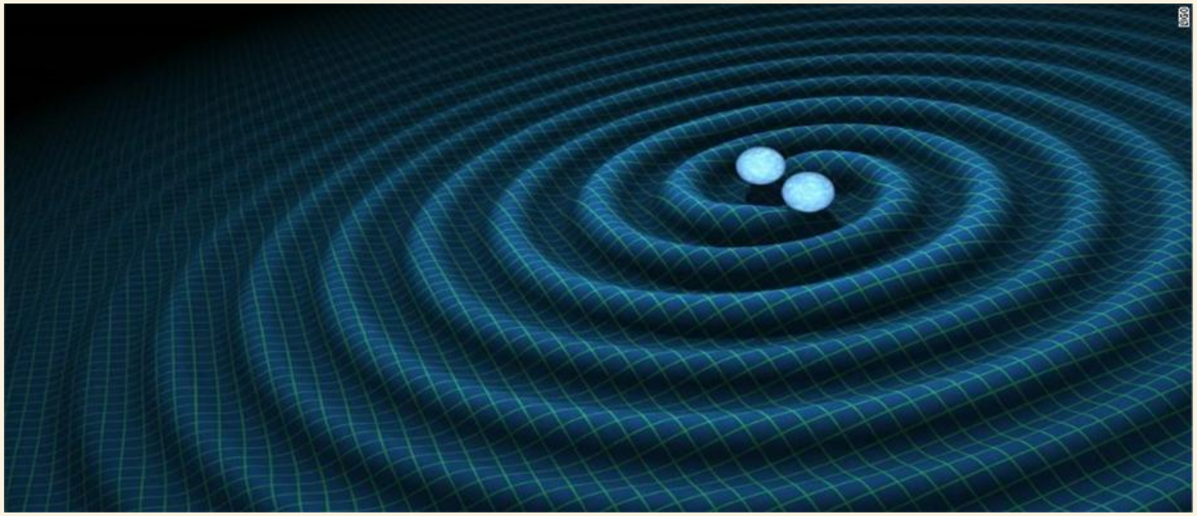
A Brief History Of Gravitational Waves

- 1915 - Einstein publishes his theory on General Relativity.
- 1916 - Using relativity, Einstein predicts "ripples" in spacetime, the "ripples" are known as Gravitational Waves.
- 1962-1972 - Many tests are thought of and tried to prove the existence of gravitational waves, none are successful.



Source: Mallenbaum, C. 2017. Albert Einstein [Photo] [Accessed on March 17, 2019] Retrieved from https://www.usatoday.com/story/life/tv/2017/04/24/albert-einstein-genius-national-geographic/100824198/

- 1972 - Rainer Weiss from the Massachusetts Institute of Technology (MIT) proposes the optical method for detecting gravitational waves.
- 1978 - Scientists are able to prove that gravitational waves do exist (not detection, just existence) by spending 4 years measuring the change in the orbit of 2 objects in the constellation of Aquila. The change that they measured matched up with Einstein's calculations of how the interaction between the 2 would be affected by giving off gravitational waves.

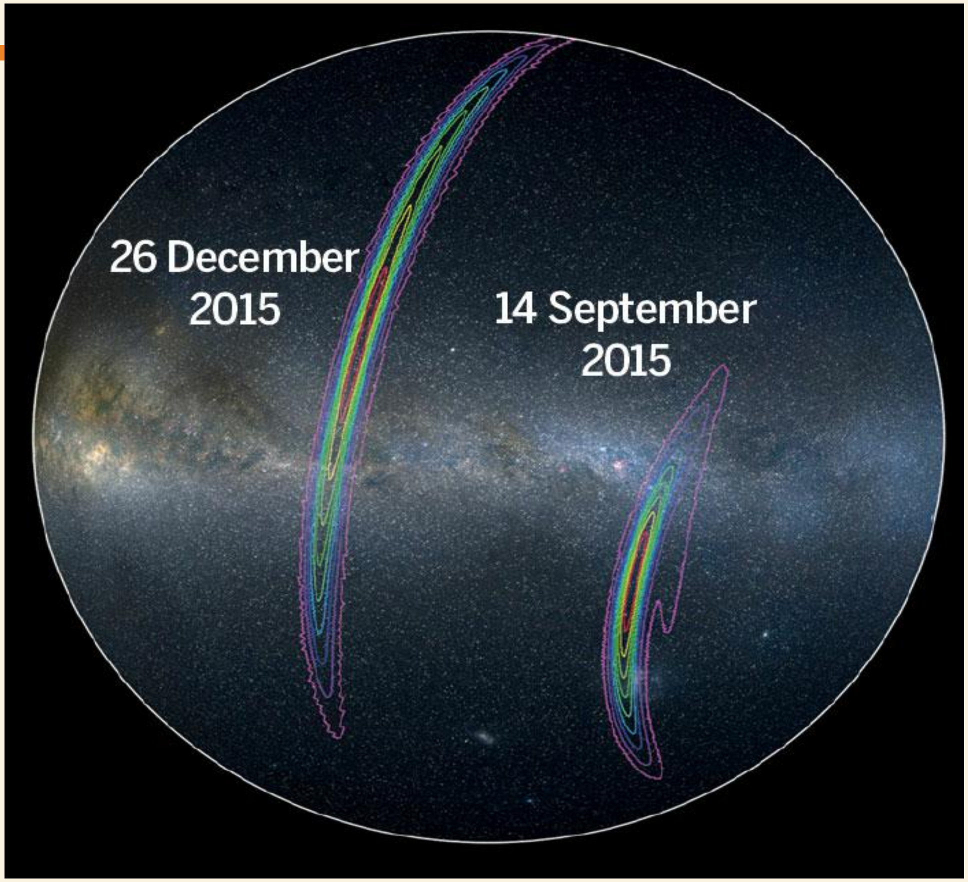


Source: Worland, J. 2016. A Brief History of the Search for Gravitational Waves. [Photo] [Accessed on March 10, 2019]. Retrieved from http://time.com/4217820/gravitational-waves-history/

- 1979 - National Science Foundation (NSF) funds the California Institute of Technology (Caltech) and MIT to begin designing the Laser Interferometer Gravitational-wave Observatory (LIGO).
- 1992 - 2 sites are selected for 2 LIGO facilities.
- 1994 - Construction begins on the 2 LIGO facility sites.
- 1999 - The LIGO facilities hold their inauguration ceremonies.

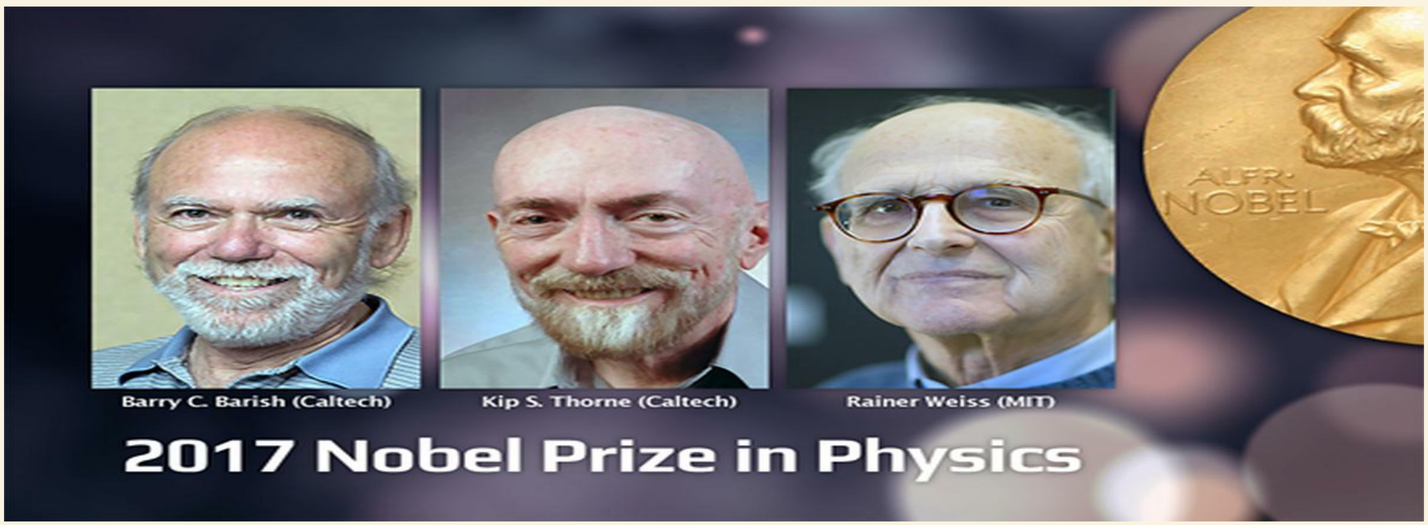
Source: LIGO. n.d. LIGO Faclities. [Photo] [Accessed March 17, 2019]. Retrieved from https://www.ligo.caltech.edu/

- 2002 – First operation of LIGO facilities. No gravitational waves are detected.
- 2008-2014 – Upgrades to go from LIGO to Advanced LIGO (aLIGO).
- Sept 2015 – aLIGO begins operations.
- Sept 14, 2015 – aLIGO detects gravitational waves from the collision of 2 black holes.
- Dec 26, 2015 – aLIGO observes a second binary black hole coalescence. Both facilities detect evidence of gravitational waves, **finally confirming Einstein's theory from 100 years earlier.**



Source: Cho, A. 2016. LIGO detects another black hole crash. [Photo]. [Accessed on March 14, 2019]. Retrieved from https://www.sciencemag.org/news/2016/06/ligo-detects-another-black-hole-crash

- Aug 14, 2017 – Gravitational waves from a third binary black hole coalescence are detected.
- Aug 17, 2017 – aLIGO and Virgo, LIGO's sister facility in Europe, make first detection of gravitational waves from the collision of 2 neutron stars.
- Aug 25, 2017 – Observing ends so that aLIGO can under upgrades for better detection.
- Oct 3, 2017 – LIGO co-founders Rainer Weiss, Barry Barish, and Kip Thorne are awarded the 2017 Nobel Prize in Physics.



Source: N.a. 2017. 2017 Nobel Prize in Physics. [Photo]. [Accessed on March 17, 2019]. Retrieved from https://www.elisascience.org/multimedia/image/nobel-prize-physics-2017

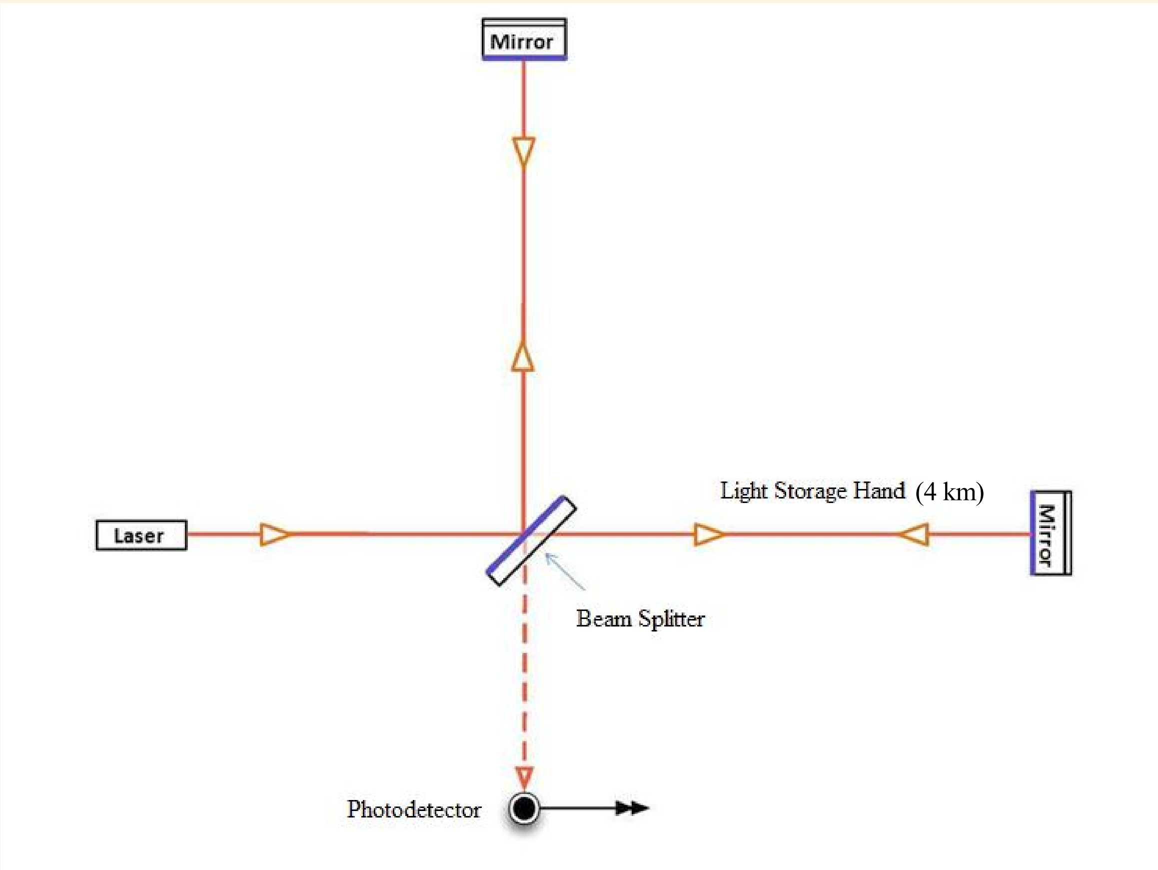
Measurement Of Gravitational Waves

Interferometer – tool to merge two of more sources of light in order to create an interference pattern.

Used to measure almost everything from small events to big ones.

The basic configuration was presented in 1880s by Albert Michelson.

Measurement Of Gravitational Waves



1) Laser passes beam splitter.

2) Each beam travels forward until it encounters a mirror.

3) Two beams recombine into one, interfering with each other and creating an interference pattern.

If arms don't change in length, light waves of beams cancel each other. "Totally destructively interfered".

Source: *What Is Interferometer?* (n.d.). Retrieved March 28, 2019, from LIGO Caltech: https://www.ligo.caltech.edu/page/what-is-interferometer

Measurement Of Gravitational Waves

Laser Interferometer Gravitational-Wave Observatory's (LIGO) success inspired Europeans to create LISA.

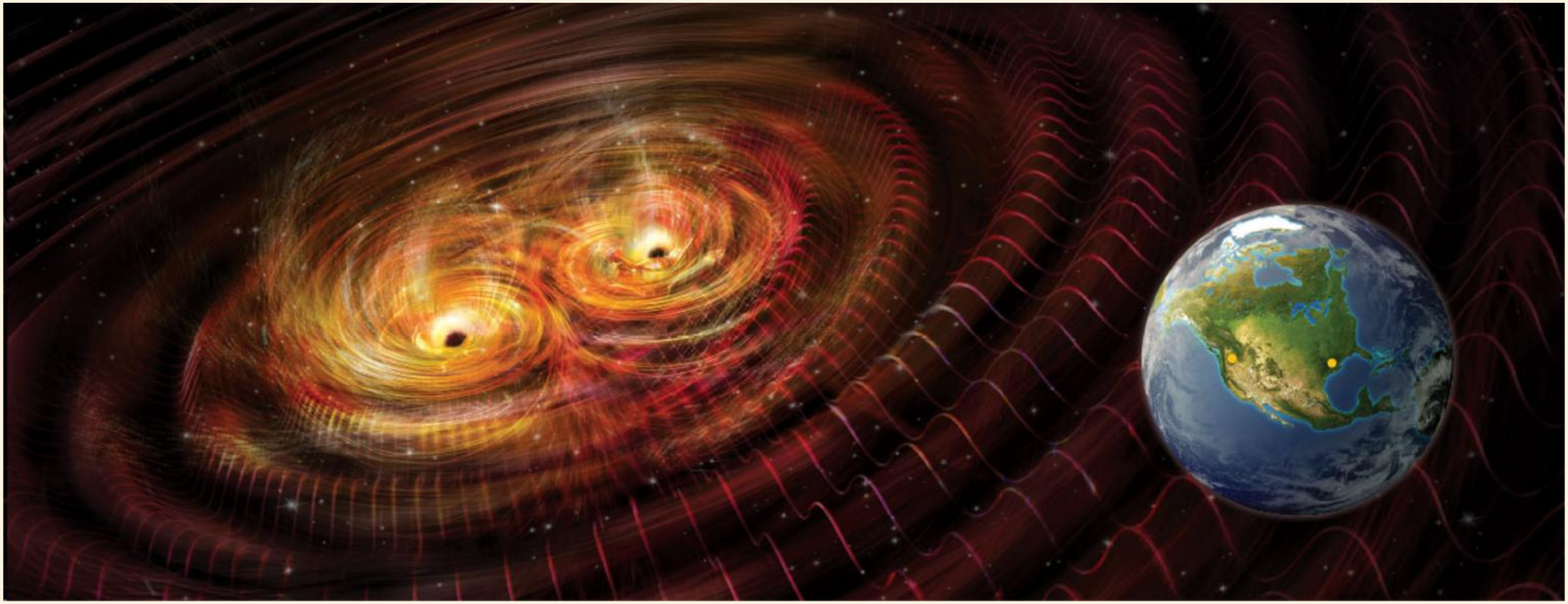
Laser Interferometry Space Antenna (LISA) - three satellites at a distance 2.5 million kilometers apart.

Much more precise. Aim: measure relative shifts in position that are less than the diameter of a helium nucleus over a distance of a million miles

Planned launch date is 2034.

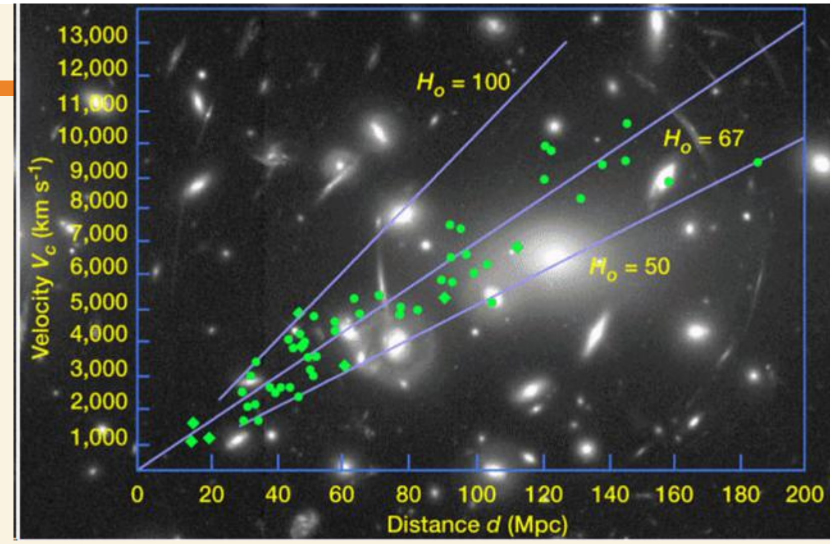
WHAT GRAVITATIONAL WAVES CAN TELLS US

Source: Crockett, C. Gravitation waves explained. *Science News.* [Internet]. **2016**. https://www.sciencenews.org/article/gravitational-waves-explained (accessed March 28, 2019).



HUBBLE'S CONSTANT

- Binary Neutron star merger GW170817 provided a unique opportunity to measure H_0
- Instead of using standard candles, used standard sirens to determine H_0
  - is a gravitational source of known "loudness"
- This method was independent of the comic distance ladder, which is important in confirming H_0
  - Help determine bias
  - 70.0 +/- 12.0 KMS-1/MPC

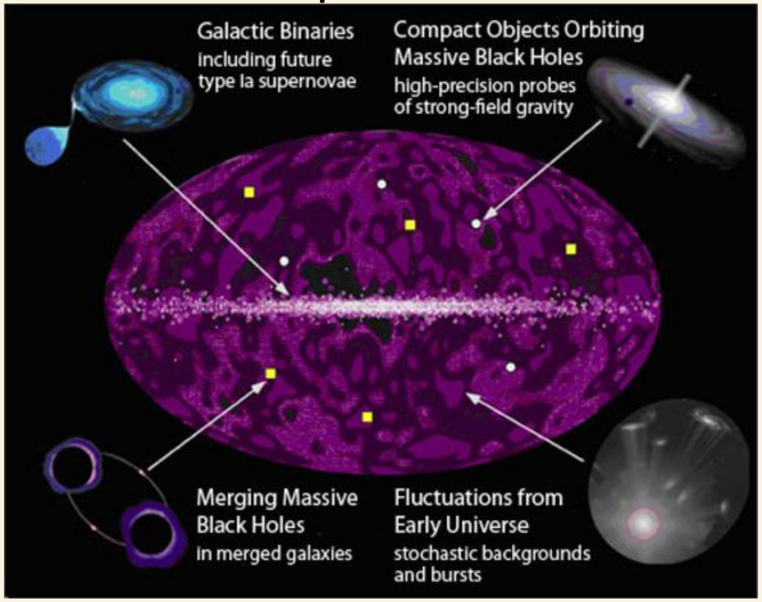


Source: Resonance Publications: http://www.resonancepub.com/hubble.htm (accessed March 28, 2019)

Source: Daniel Palacios: https://danielpalacios.info/waves (accessed March 28, 2019)

STOCHASTIC BACKGROUND (SB)

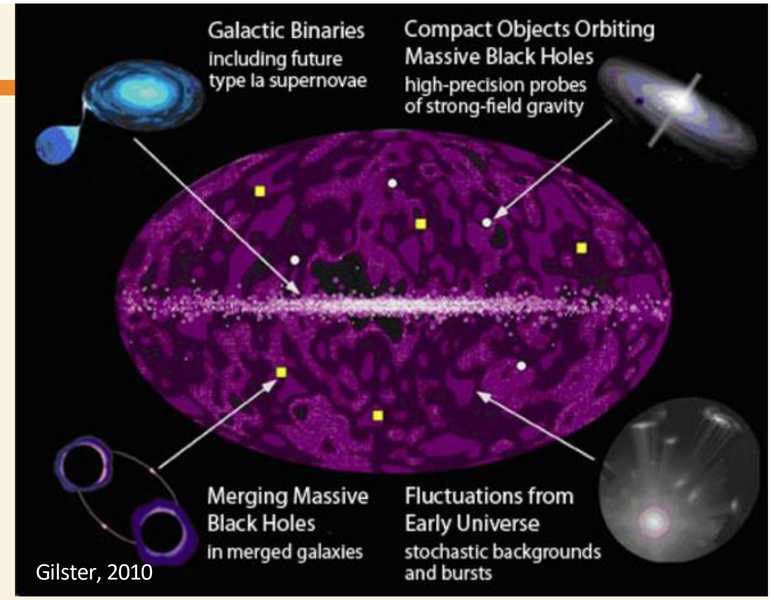
- Stochastic Gravitational Background is the coalition of random gravity waves from independent sources throughout the history of the Universe



Source: Gilster, P. A Cosmic Gravitational Wave Background. *Centauri Dreams.* [Internet]. **2010**. https://www.centauri-dreams.org/2010/11/24/a-cosmic-gravitational-wave-background/ (accessed March 28, 2019)

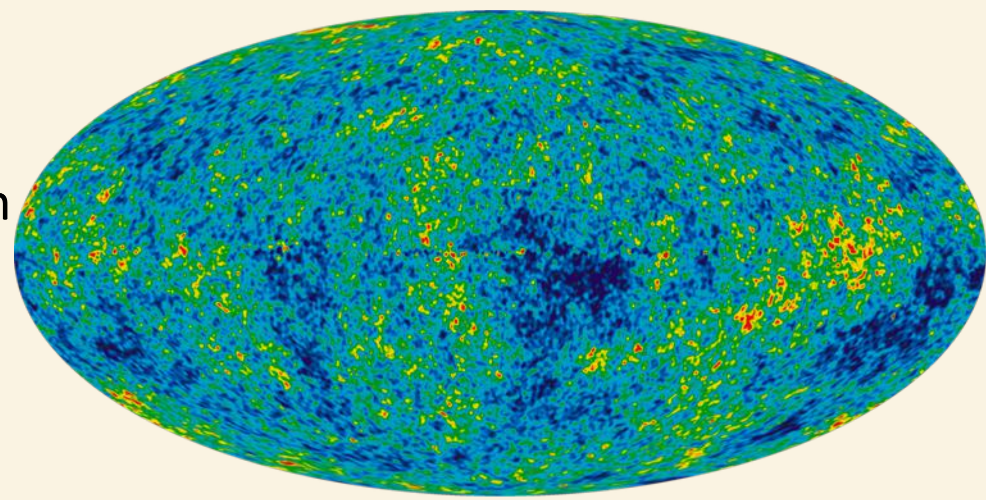
- assumed to be uniform, static, stationary & constantly oscillating
- Some sources:
  - 1st order phase transitions
    - Inflation & electroweak
  - Binary BH & Neutron stars, & their mergers
  - close compact binary stars like white dwarfs
  - supernovae, pulsars
- Think of them as GW version of CMB

WHAT THE SB CAN TELL US



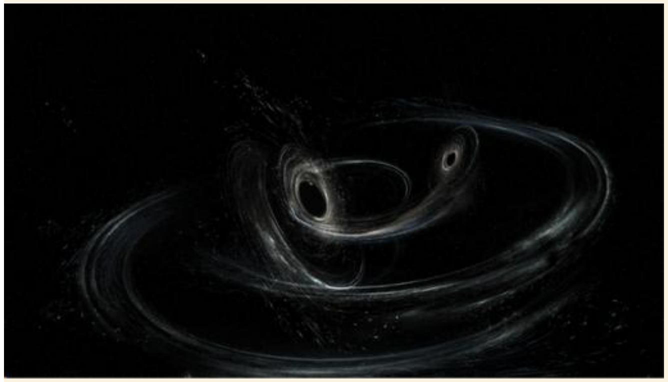
Gilster, 2010

- Studying SB will allow us to "hear" further in to the history of the Universe
  - Before Recombination maybe as far as Planck
- Don't know what GWs to look at in SB, clues in CMB
  - GWs created from quantum fluctuations during Inflation thought to have created temp. fluctuations in CMB
  - Might help with electroweak & Planck era SB



Source: Wikipedia: https://en.wikipedia.org/wiki/Cosmic_microwave_background#/media/File:Ilc_9yr_moll4096.png (accessed March 28, 2019).

BLACK HOLES (BH)

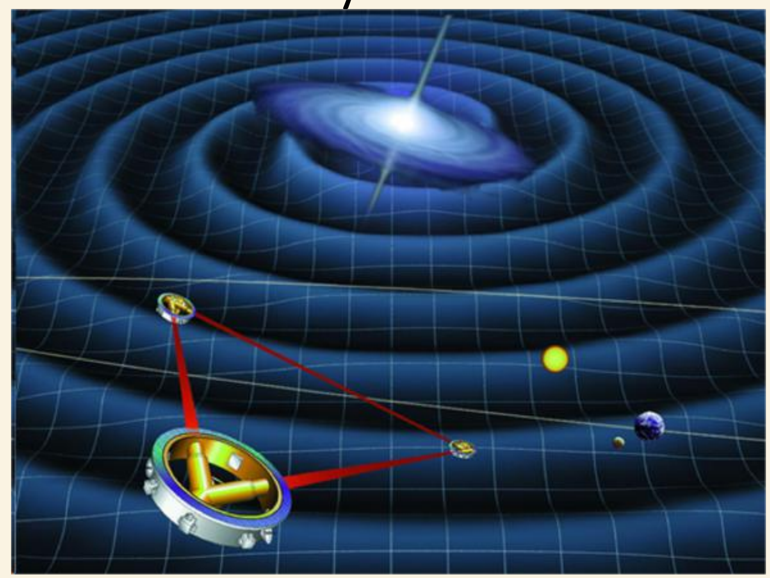


Source: LIGO Caltech. LIGO Catches its third Gravitational Wave!. *LIGO Caltech*. [Internet]. **2017**. https://www.ligo.caltech.edu/news/ligo20170601 (accessed March 28, 2019)

- GWs help better understand how BH are created from supernovae
- Extreme mass-ratio inspirals i.e. stellar-mass BH spiral into a supermassive BH (LISA needed)
    - Provides high precision test for GR & provide insight on the geometry of primary mass BH

WHAT ABOUT DARK MATTER & DARK ENERGY?

- Not a lot info on these
- Believed that the more instruments in coalition, the more likely to find them
  - LISA will be a major help



Source: Wikipedia: https://upload.wikimedia.org/wikipedia/commons/f/f5/LISA-waves.jpg (accessed March 28, 2019)

- Potential limited to understanding
  - We're like Galileo & his 1st telescope

Source: Wootton, D. Galileo's telescopes: Facing the facts. *History Today*. [Internet] **2010**. 60. https://www.historytoday.com/archive/galileos-telescopes-facing-facts (access March 28, 2019)