SURFING GRAVITATIONAL WAVES

PRANAV SATHEESH
HSB 310
19.08.2019 , 7:30 PM

HORIZON
WHERE THE SKY MEETS THE EYE


I LOVE SEEING PEOPLE SMILE AT THEIR PHONES IN PUBLIC
HAVE THEY RECEIVED HAPPY NEWS?
IS IT A TEXT FROM A LOVED ONE PERHAPS?
WHAT COULD BE INSTILLING SUCH JOY IN THAT MOMENT?
Physicists Announce the Detection of Gravitational Waves
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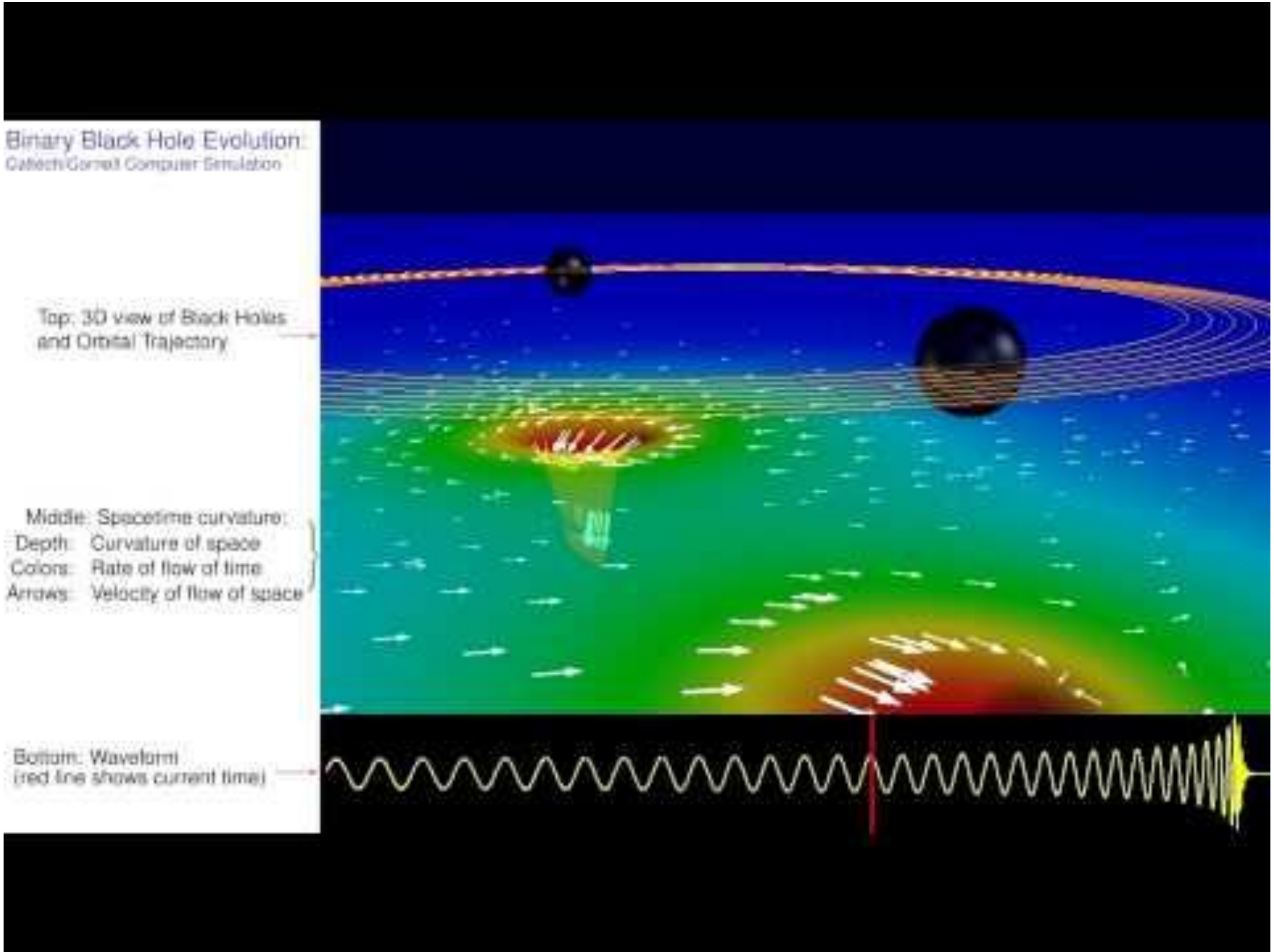
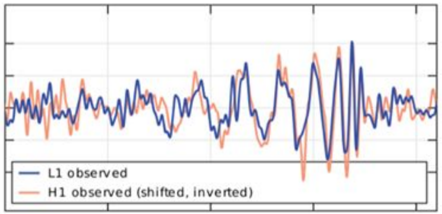


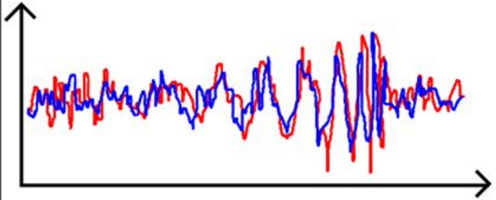
Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation
Top: 3D view of Black Holes and Orbital Trajectory
Middle: Spacetime curvature:
Depth: Curvature of space
Colors: Rate of flow of time
Arrows: Velocity of flow of space
Bottom: Waveform (red line shows current time)

GRAVITATIONAL WAVES HISTORY

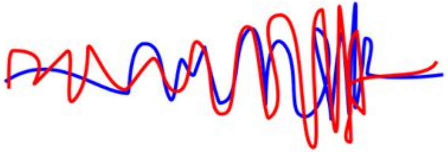
A Gravitational Wave Signal



A strain signal coincident at both LIGO detectors consistent with the gravitational waves produced from two colliding black holes



GW150914, a signal increasing in both frequency and amplitude over time, which was measured at both Laser Interferometer Gravitational-Wave Observatory detectors on September 14th 2015. The signal is consistent with the time evolution of differential strain expected from the merger of two black holes of 30 solar masses and 35 solar masses at a luminosity distance of 440 megaparsecs.



Consider the Einstein field equations of the form:

$$R_{ab} - \frac{1}{2} R\, g_{ab} = 8\pi G\, T_{ab}\,. \tag{53}$$

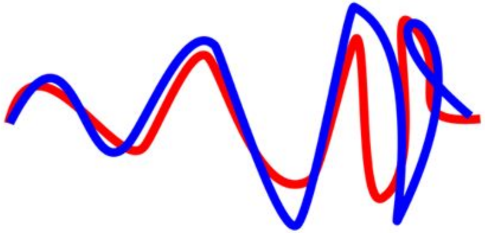
We may then proceed to linearize the Einstein equation (53) with respect to the metric perturbation h_{ab}. Substituting for Eqs. (56) and (58) into the expression (36) for the Riemann tensor, and using the explicit formula (29) for the Christoffel symbols, we find

$$R_{abcd} = -\partial_c \partial_{[a} h_{b]d} + \partial_d \partial_{[a} h_{b]c}\,, \tag{59}$$

where ∂_a is the ordinary derivative associated with the global inertial coordinates of η_{ab}, and square brackets are used to denote an antisymetrization over a pair of indices, e.g., $T_{[ab]} \equiv \frac{1}{2}(T_{ab} - T_{ba})$. Using the definitions (42)–(43) of the Ricci tensor and scalar curvature, the Einstein tensor G_{ab} can be linearized as well. Einstein's equation (53) then reduces to

$$\Box \bar{h}_{ab} - 2\partial_{(a} V_{b)} + \eta_{ab}\, \partial^c V_c = -16\pi G\, T_{ab}\,, \tag{60}$$

where $\Box \equiv \eta^{cd}\partial_c \partial_d$ is the usual flat-space wave operator, or d'Alembertian, and parenthesis are used to denote a symetrization over a pair of indices, e.g. $T_{(ab)} \equiv \frac{1}{2}(T_{ab} + T_{ba})$. Moreover, we introduced the notation $V_a \equiv \partial^c \bar{h}_{ac}$ for the divergence of the trace-reversed metric perturbation



Henri Poincare proposed gravitational waves as an analogue to EM waves in 1905

EM WAVES : Dipole Radiation

MAXWELL'S EQUATIONS

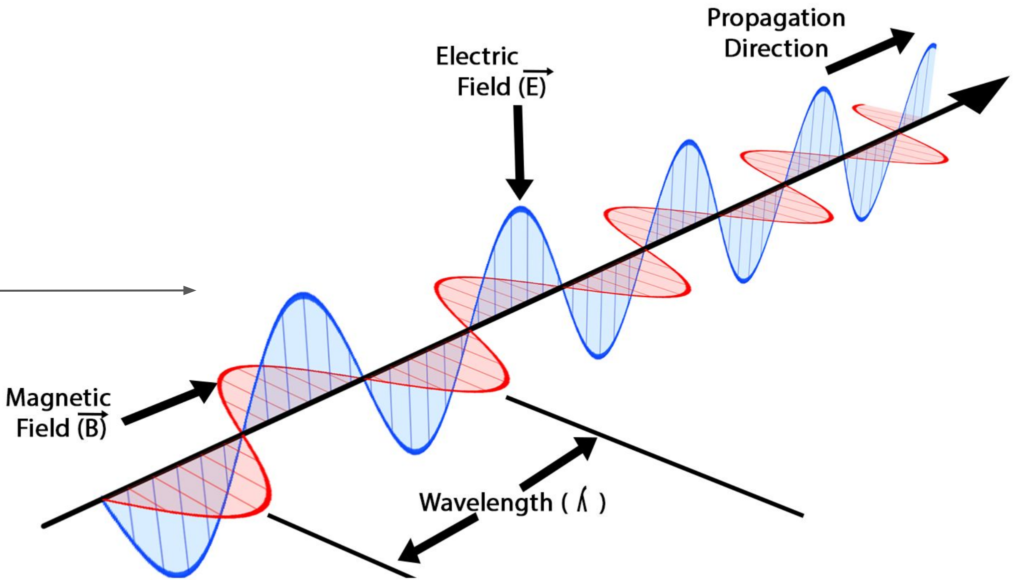
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

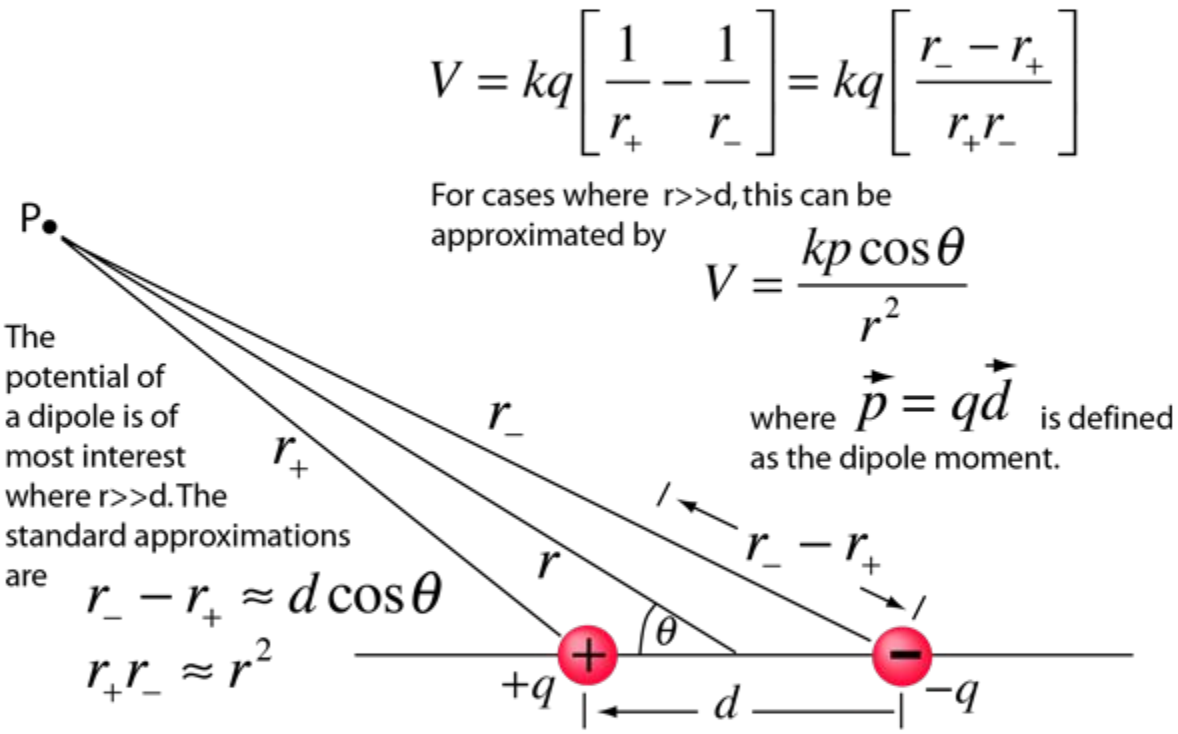
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

Electromagnetic Wave



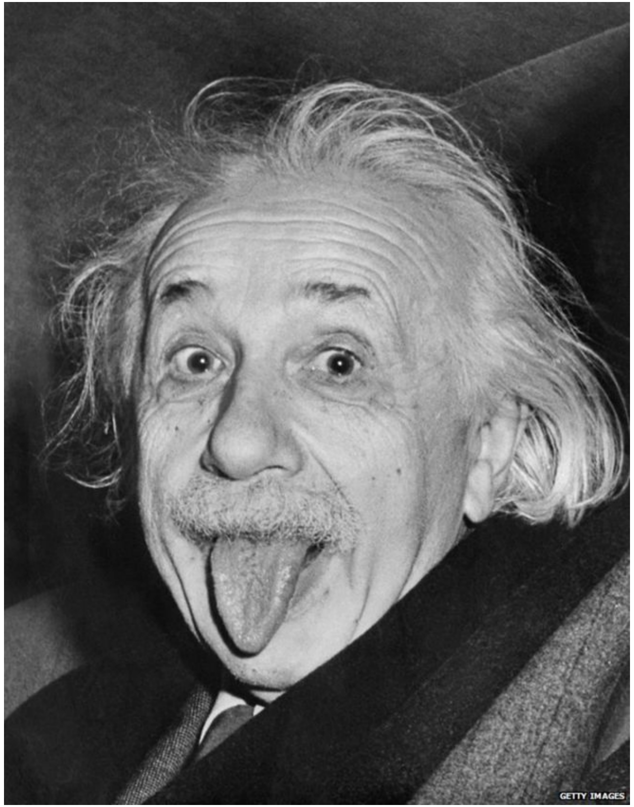
What about mass dipole? Is that even a thing?



Intuitively, there is no negative mass so there shouldn't be any mass dipole right?

If so can we think how higher moments for GWs?

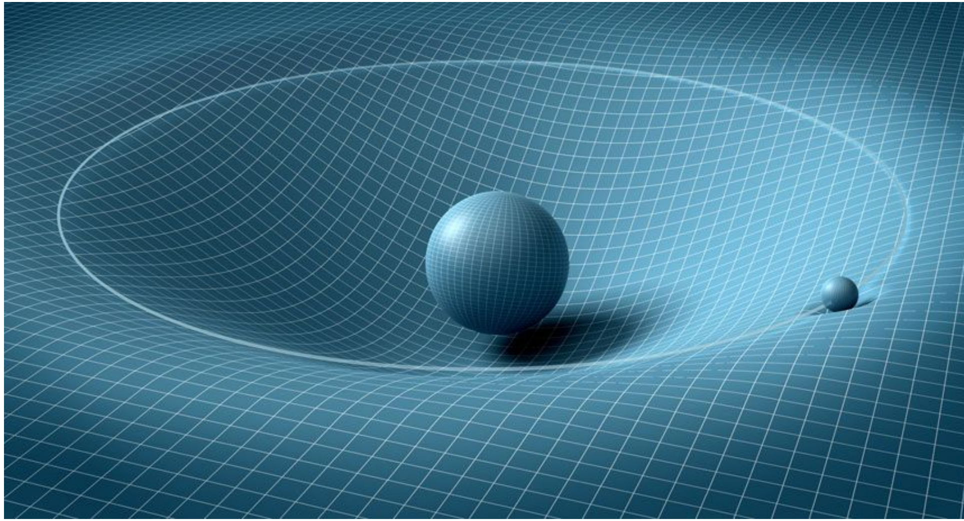
EINSTEIN AND RELATIVITY



- Special Theory of Relativity in 1905
- General Theory of Relativity in 1915

“Space tells matter how to move
Matter tells space how to curve”

- John Wheeler, *Gravitation (1973), Misner, Thorne and Wheeler*



EINSTEIN'S FIELD EQUATIONS (in the simplest way)

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

Einstein wasn't sure about gravitational waves

"Since then [November 14] I have handled Newton's case differently, of course, according to the final theory [the theory of General Relativity]. Thus there are no gravitational waves analogous to light waves. This probably is also related to the one-sidedness of the sign of the scalar T, incidentally [this implies the nonexistence of a "gravitational dipole]"

- *Einstein's letter to Schwarzschild*

Einstein and colleagues tried to manipulate the field equations and changed the coordinate system to find a wave equation but einstein had his doubts.

In 1920, Aurthur Eddington wrote an article entitled “The propagation of gravitational waves”. He prove that this last wave type propagates at the speed of light in all coordinate systems, so he did not rule out its existence.

In 1936 Einstein wrote to his friend, renowned physicist Max Born, “Together with a young collaborator [Rosen], I arrive at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation”

But their calculations had errors and Einstein was convinced that he was wrong.

Furthermore, Einstein included this explanatory note at the end of his paper,

“Note—The second part of this article was considerably altered by me after the departure to Russia of Mr. Rosen as we had misinterpreted the results of our formula. I want to thank my colleague Professor Robertson for their friendly help in clarifying the original error. I also thank Mr. Hoffmann your kind assistance in translation.”

Me: I promise I won't find plane wave solutions to the linearised Einstein field equations in perturbed space-time tonight

3 DRINKS LATER

Linearized gravity is an adequate approximation to general relativity when the spacetime metric, g_{ab}, may be treated as deviating only slightly from a flat metric, η_{ab}:

$$g_{ab} = \eta_{ab} + h_{ab}, \qquad ||h_{ab}|| \ll 1 \,. \tag{2.1}$$

$$R_{ab} = R^{c}{}_{acb} = \frac{1}{2}\left(\partial_c \partial_b h^c{}_a + \partial^c \partial_a h_{bc} - \Box h_{ab} - \partial_a \partial_b h\right) , \tag{2.4}$$

where $h = h^a{}_a$ is the trace of the metric perturbation, and $\Box = \partial_c \partial^c = \nabla^2 - \partial_t^2$ is the wave operator. Contracting once more, we find the curvature scalar:

$$R = R^a{}_a = \left(\partial_c \partial^a h^c{}_a - \Box h\right) \tag{2.5}$$

and finally build the Einstein tensor:

$$\begin{aligned} G_{ab} &= R_{ab} - \frac{1}{2}\eta_{ab} R \\ &= \frac{1}{2}\left(\partial_c \partial_b h^c{}_a + \partial^c \partial_a h_{bc} - \Box h_{ab} - \partial_a \partial_b h \right. \\ &\qquad \left. - \eta_{ab} \partial_c \partial^d h^c{}_d + \eta_{ab} \Box h\right) \,. \end{aligned} \tag{2.6}$$

$$G_{ab} = \frac{1}{2}\left(\partial_c \partial_b \bar{h}^c{}_a + \partial^c \partial_a \bar{h}_{bc} - \Box \bar{h}_{ab} - \eta_{ab} \partial_c \partial^d \bar{h}^c{}_d\right) \,. \tag{2.7}$$

Applying the Lorentz gauge condition (2.10) to the expression (2.7) for the Einstein tensor, we find that all but one term vanishes:

$$G_{ab} = -\frac{1}{2} \Box \bar{h}_{ab} \,. \tag{2.14}$$

Thus, in Lorentz gauges, the Einstein tensor simply reduces to the wave operator acting on the trace reversed metric perturbation (up to a factor $-1/2$). The linearized Einstein equation is therefore

$$\Box \bar{h}_{ab} = -16\pi T_{ab} \,; \tag{2.15}$$

in vacuum, this reduces to

$$\Box \bar{h}_{ab} = 0 \,. \tag{2.16}$$

Just as in electromagnetism, the equation (2.15) admits a class of homogeneous solutions which are superpositions of plane waves:

$$\bar{h}_{ab}(\mathbf{x}, t) = \mathrm{Re} \int d^3k \; A_{ab}(\mathbf{k}) e^{i(\mathbf{k}\cdot\mathbf{x} - \omega t)} \,. \tag{2.17}$$

Gravity waves as solutions of linearized Einstein Field Equations

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1.$$

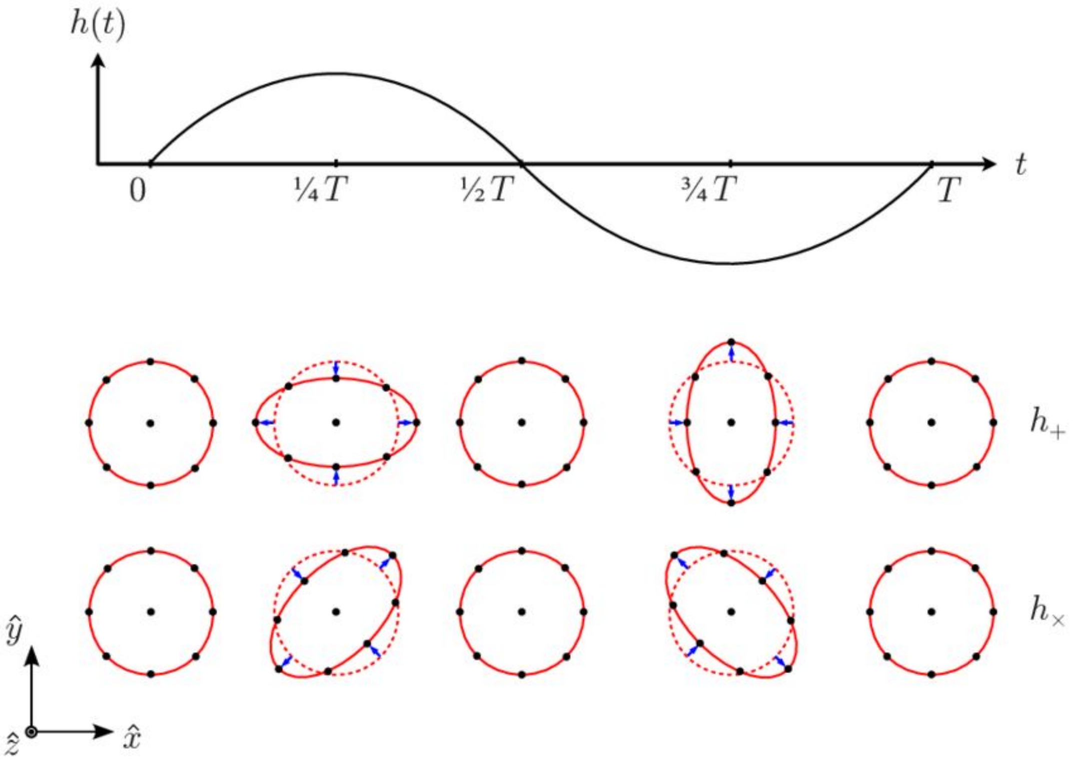
$$\Box \bar{h}^{(\epsilon)}_{\mu\nu} = -16\pi G T_{\mu\nu}.$$

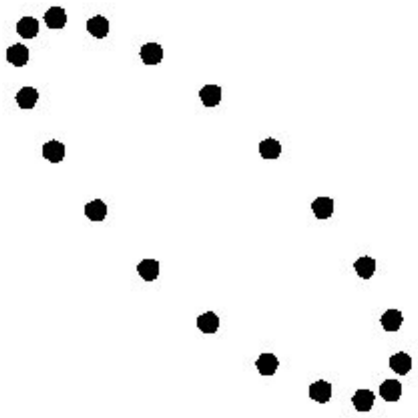
$$\Box = \nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}$$

$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = 0$$

$$\frac{1}{c_0^2}\frac{\partial^2 \mathbf{B}}{\partial t^2} - \nabla^2 \mathbf{B} = 0$$

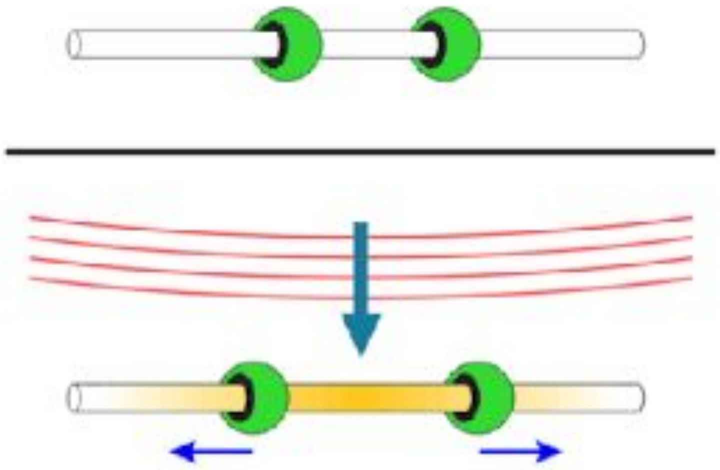
How does GWs affect a mass on it’s way?





Do GWs carry energy?

- The misperception stems from the way energy is defined in GR(We won't go into this rabbit hole for now)
- Chapel Hill Conference 1957
- Feynman's "sticky bead argument"



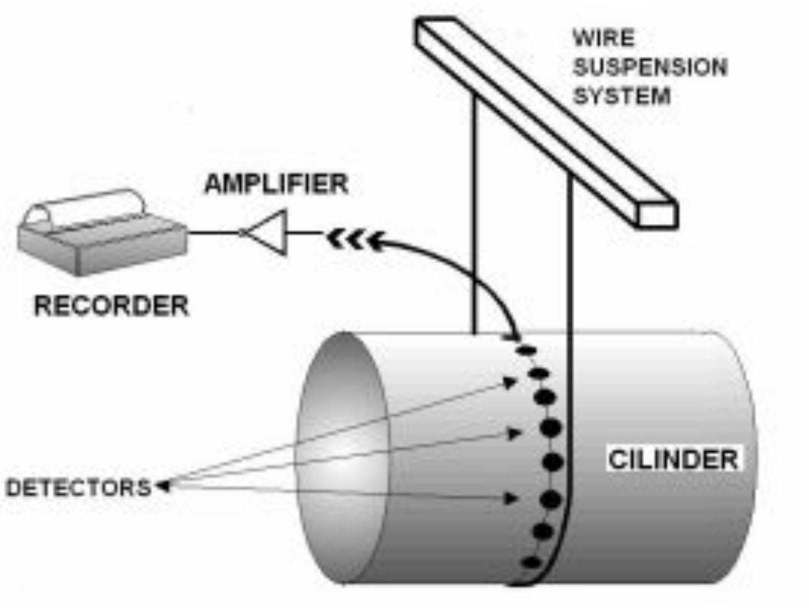
"I was surprised to find that a whole day of the conference was spent on this issue and that 'experts' were confused. That's what happens when one is considering energy conservation tensors, etc. instead of questioning, can waves do work?"

Early Gravitational Wave Detectors

- Joseph Weber proposed the detection of gravitational waves by measuring vibrations induced in a
mechanical system.

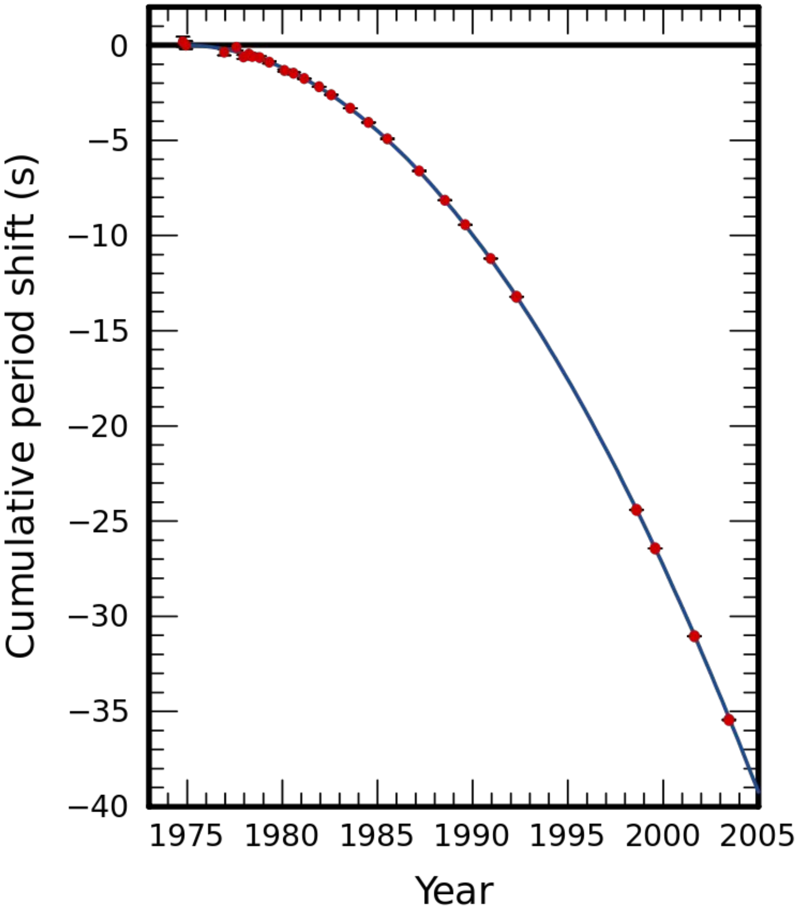
- Weber designed and built a large metal cylinder as a sort of “antenna” to observe resonant vibrations induced in this antenna that will eventually be produced by a transit of a gravitational wave pulse

- Weber’s frequent observations of gravitational waves related to very sporadic events and raised many suspicions among some scientists.


WIRE
SUSPENSION
SYSTEM
AMPLIFIER
RECORDER
CILINDER
DETECTORS

Taylor-Hulse Binary Pulsar Observation

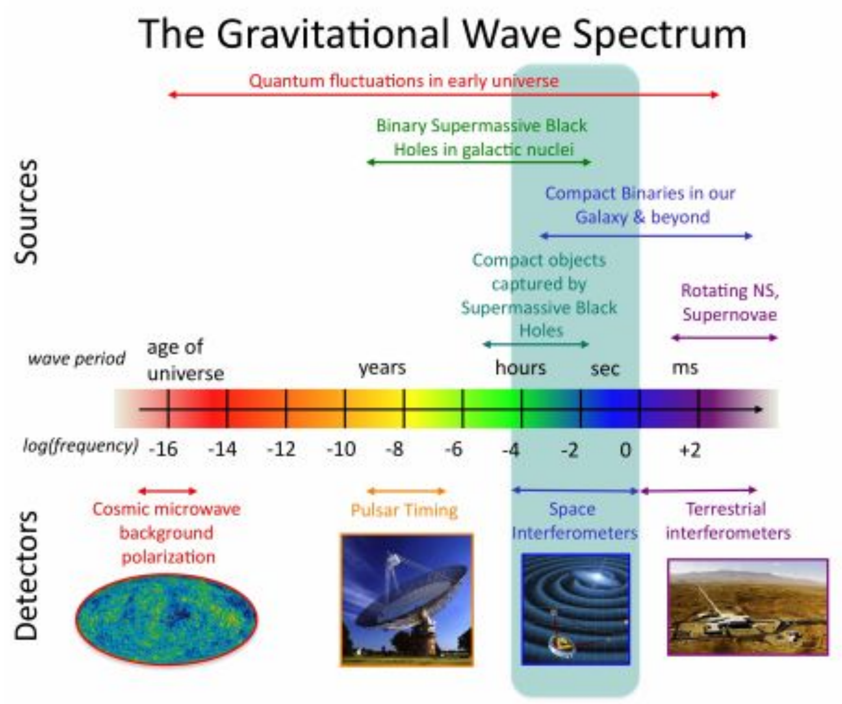
PSR 1913 + 16 leads to an increasing deviation in the time of periastron passage compared with a hypothetical system whose orbital period remains constant. Solid curve corresponds to the deviation predicted by general theory of relativity.



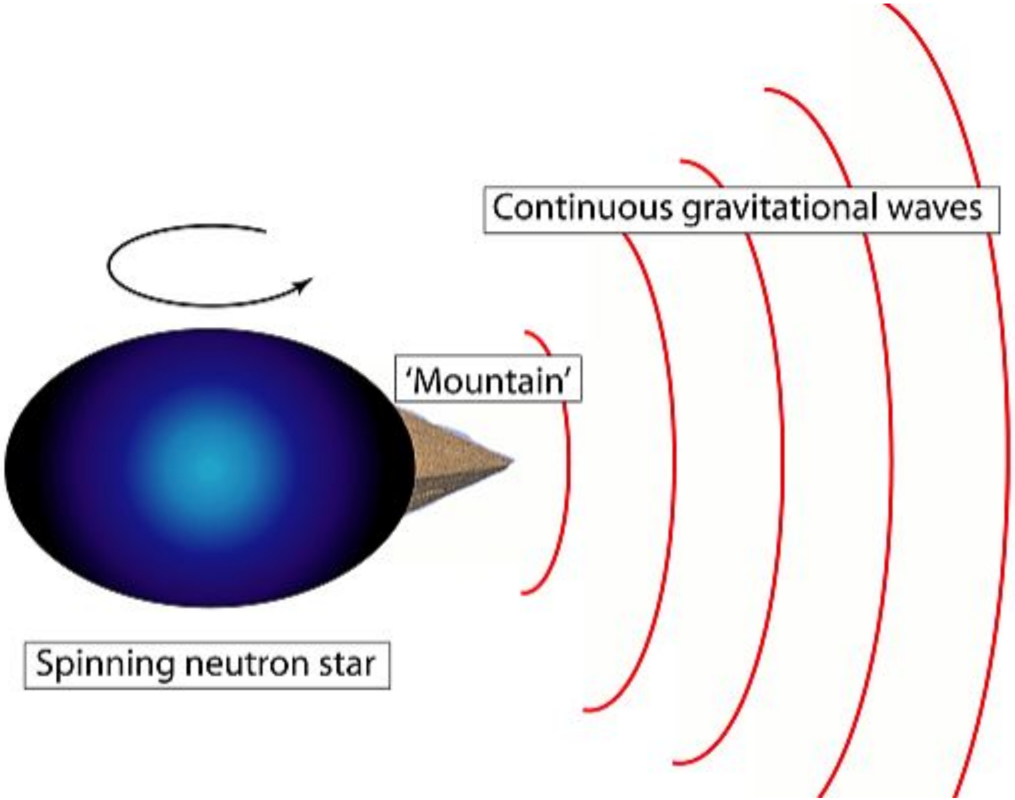
GRAVITATIONAL WAVE SOURCES

There are four main sources of gravitational waves caused by different kinds of motion and changing distributions of mass:

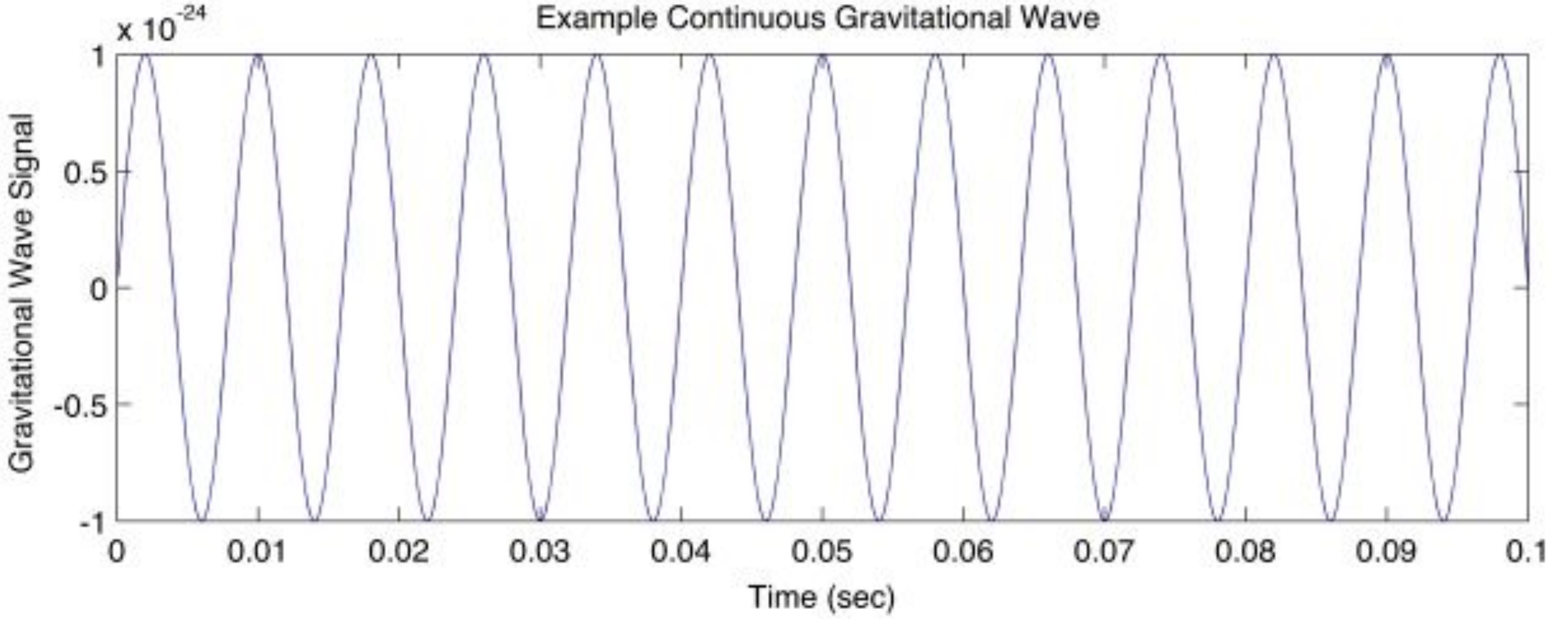
- Continuous
- Inspiral
- Bursts
- Stochastic



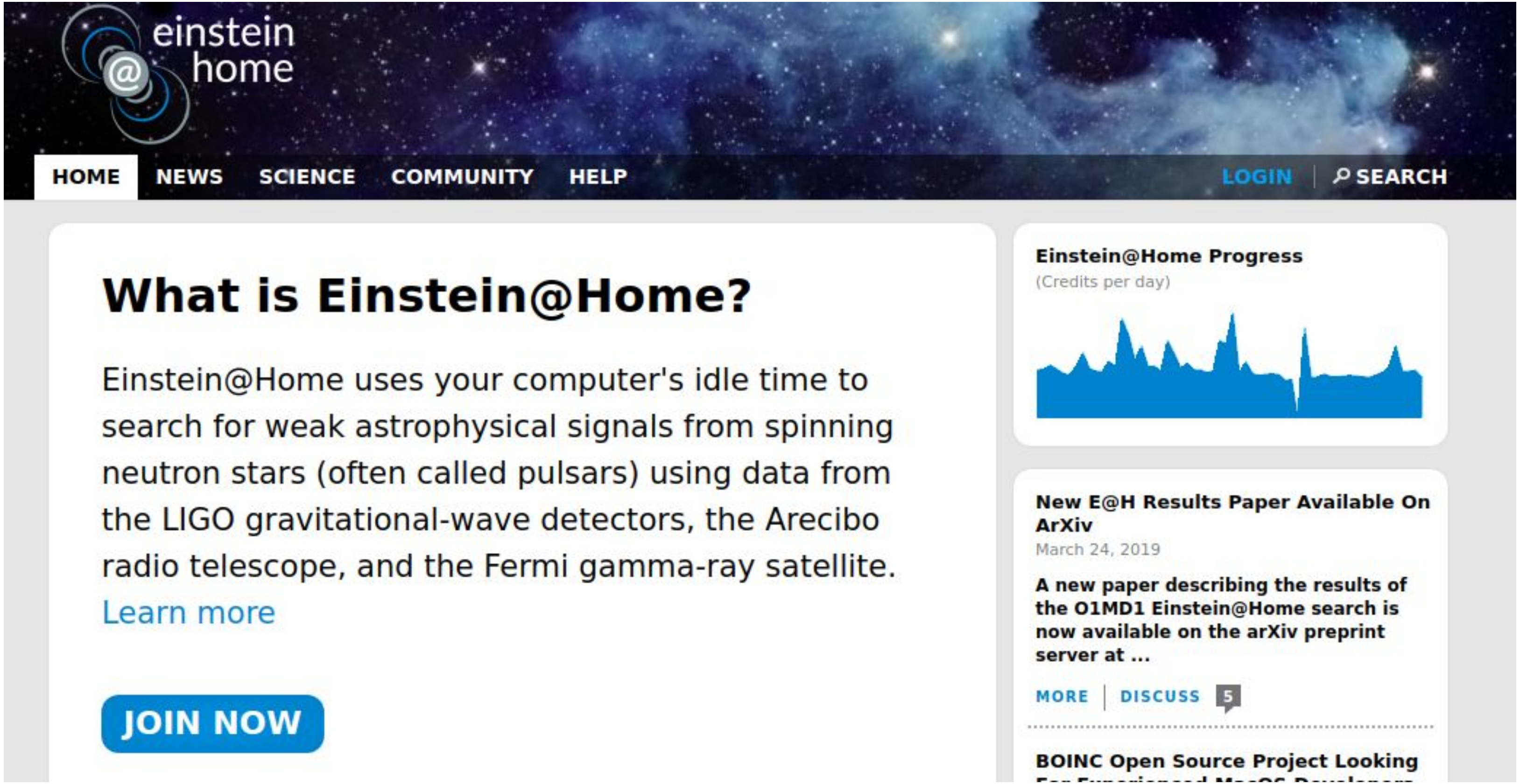
Continuous gravitational waves



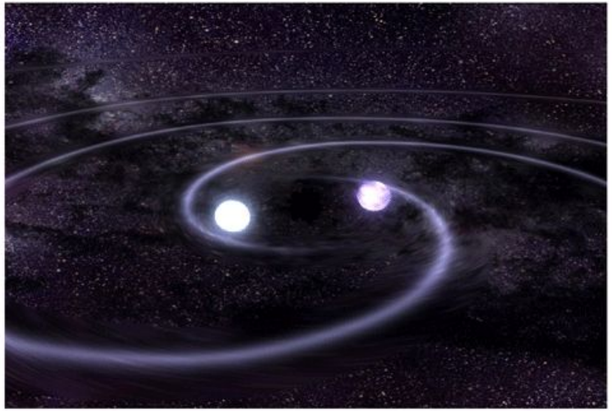
Any bumps on or imperfections in the spherical shape of this star will generate gravitational waves as it spins. If the spin rate of the star stays constant, so too do the gravitational waves it emits. That is, the gravitational wave is continuously the same frequency and amplitude


Example Continuous Gravitational Wave
x 10^-24
Gravitational Wave Signal
1
0.5
0
-0.5
-1
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (sec)

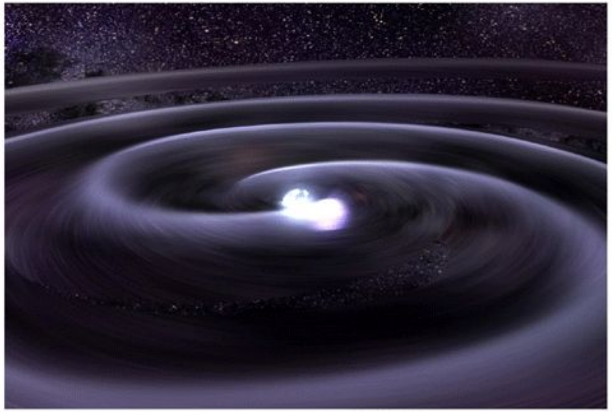
Einstein@Home



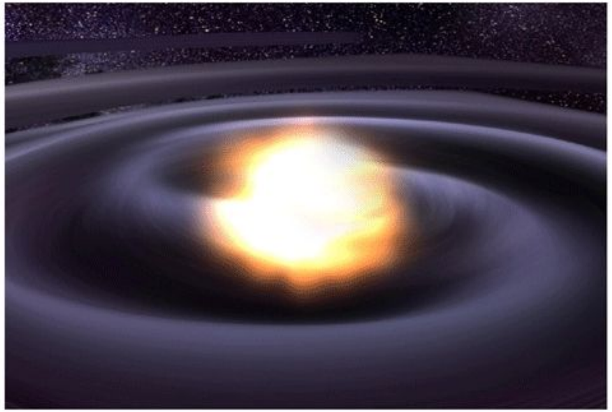
INSPIRAL GRAVITATIONAL WAVES



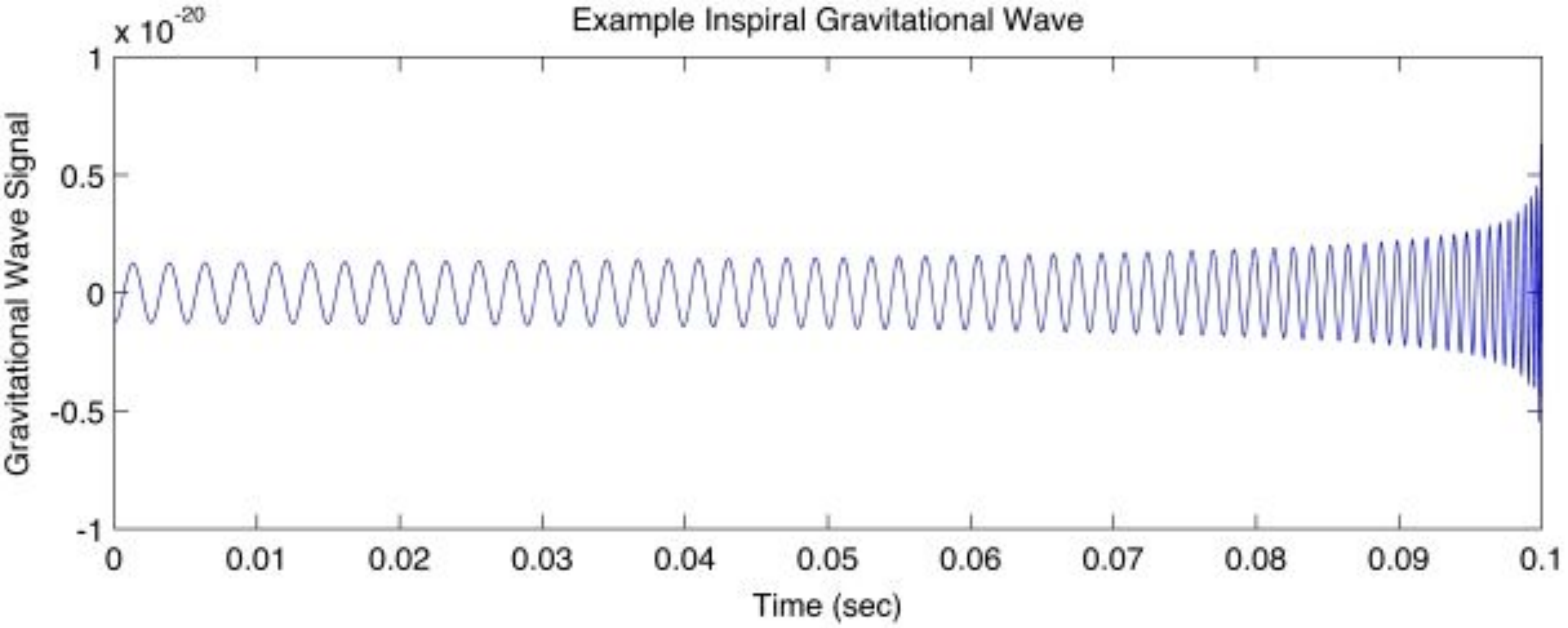
Binary Neutron Star (neutron star - neutron star) or **NSNS**

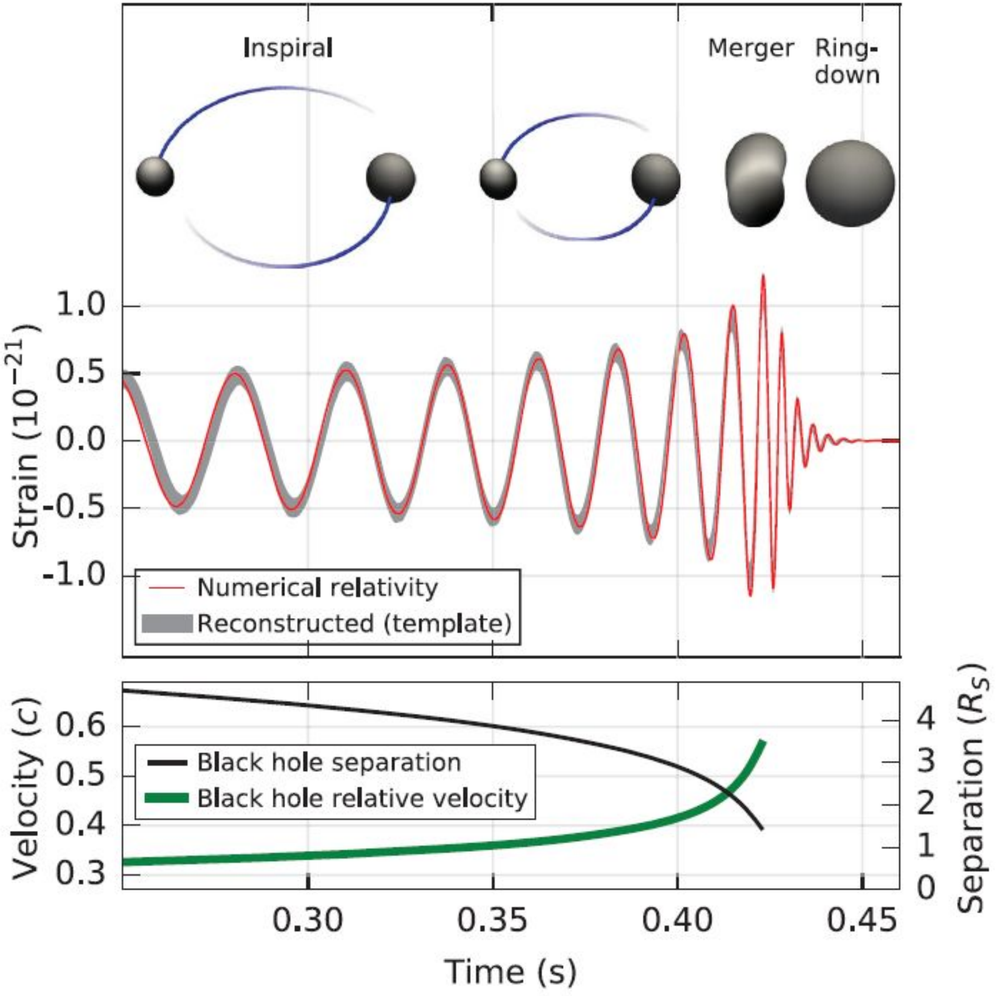


Binary Black Hole (black hole - black hole) or **BHBH**



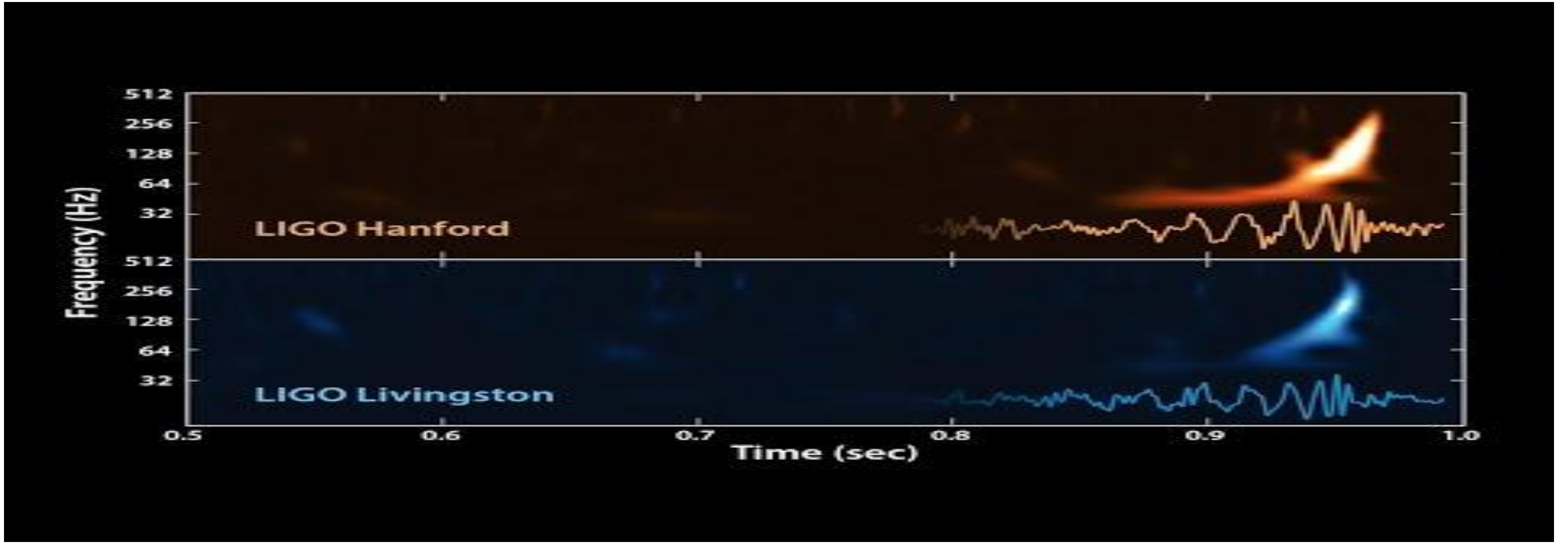
Neutron Star - Black Hole Binary or **NSBH**


Example Inspiral Gravitational Wave
x 10^-20
1
0.5
0
-0.5
-1
Gravitational Wave Signal
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (sec)

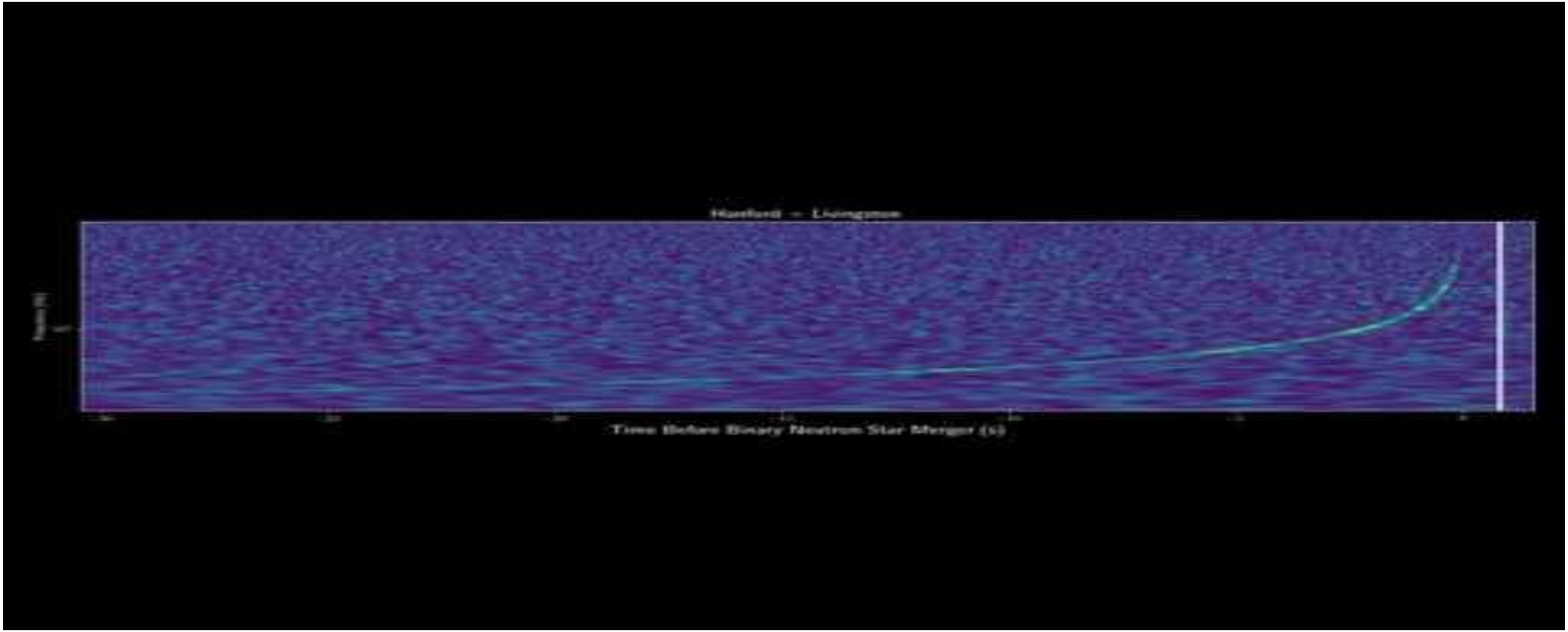


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

- Compact Binary Inspiral gravitational waves vary in duration depending on the masses of the objects involved.
- Colliding black holes produce characteristically short gravitational waves on the order of fractions of a second, whereas neutron stars (being less massive than black holes) generate signals several tens of seconds long.
- In both cases, the signal frequency increases rapidly as the objects spiral into each other, orbiting ever-faster.



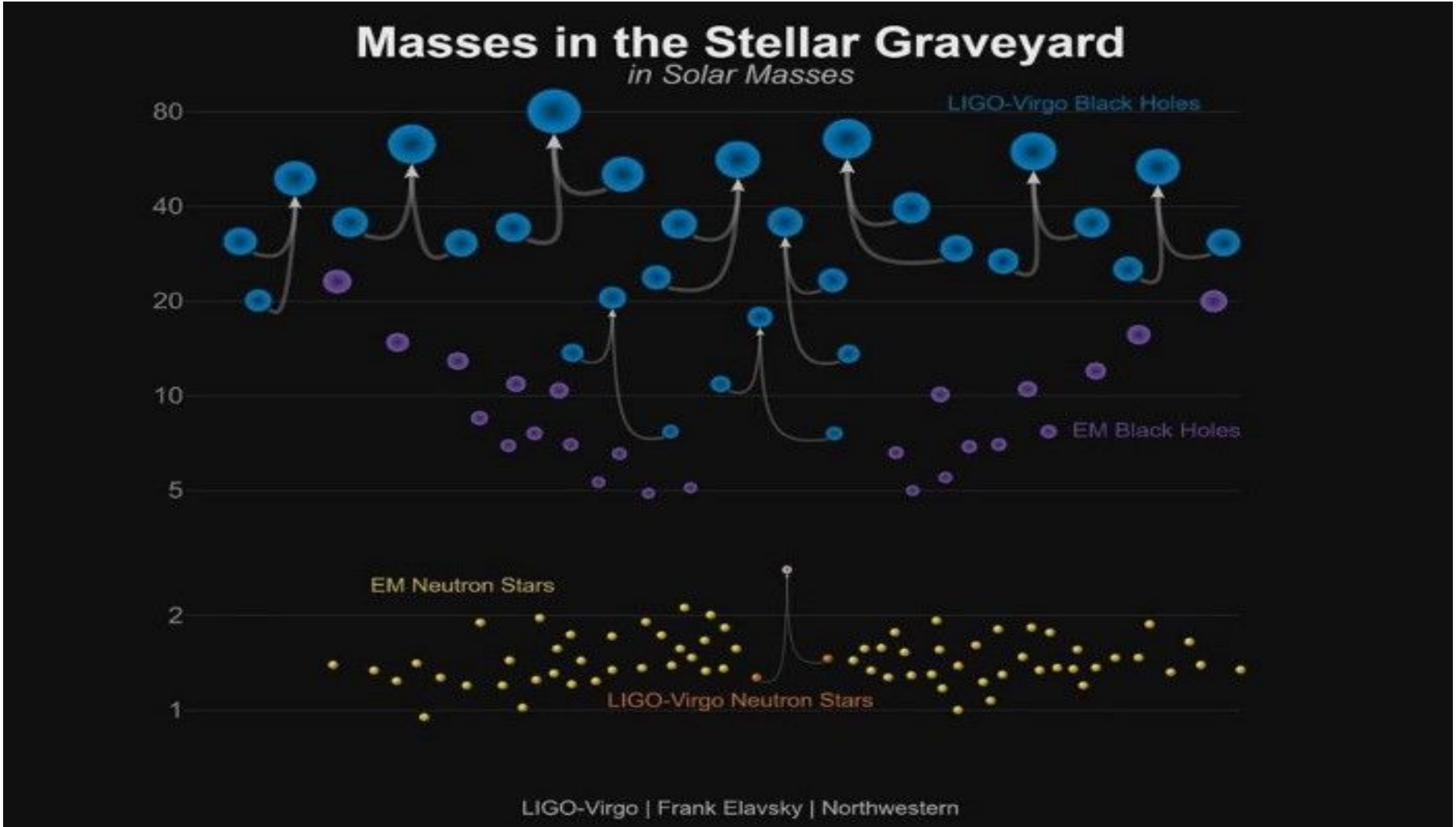
NS-NS Inspiral GW



To date, **LIGO** has verified the detection of gravitational waves generated by **10 pairs of merging black holes** (as of December 2018 catalogue(O3 run not counted), and **one pair of colliding neutron stars**.

This success relies the fact that LIGO's instruments must strain to sense anything over the constant din generated by everything on Earth, from internal fluctuations of the laser beam itself, to traffic on nearby roads, to weather, and earthquakes happening all over the world.

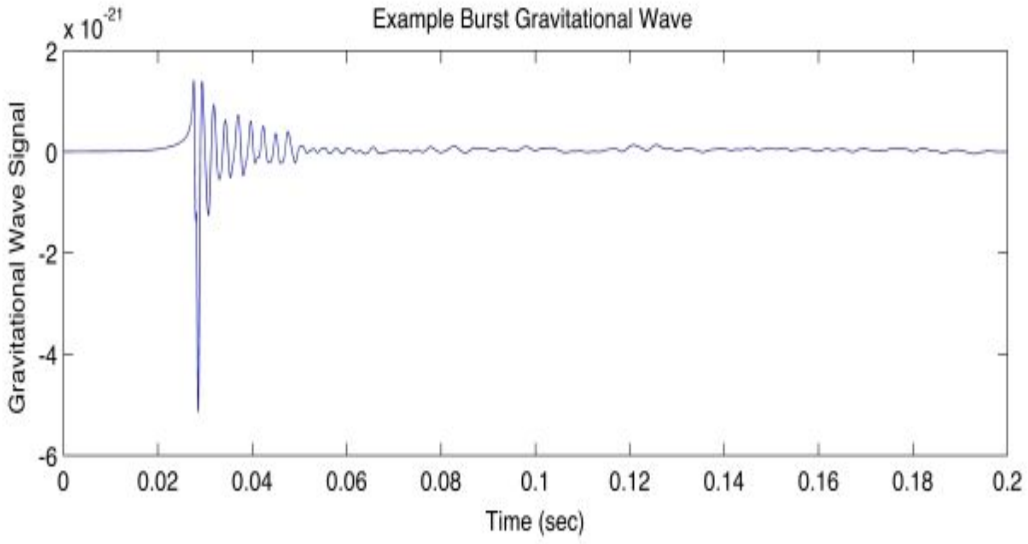

WINTER 2018-19
CATALOG SEASON
SHOP NOW
Masses in the Stellar Graveyard
LIGO-VIRGO O2 GRAVITATIONAL
WAVE CATALOG RELEASE
imgflip.com


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Burst GWs

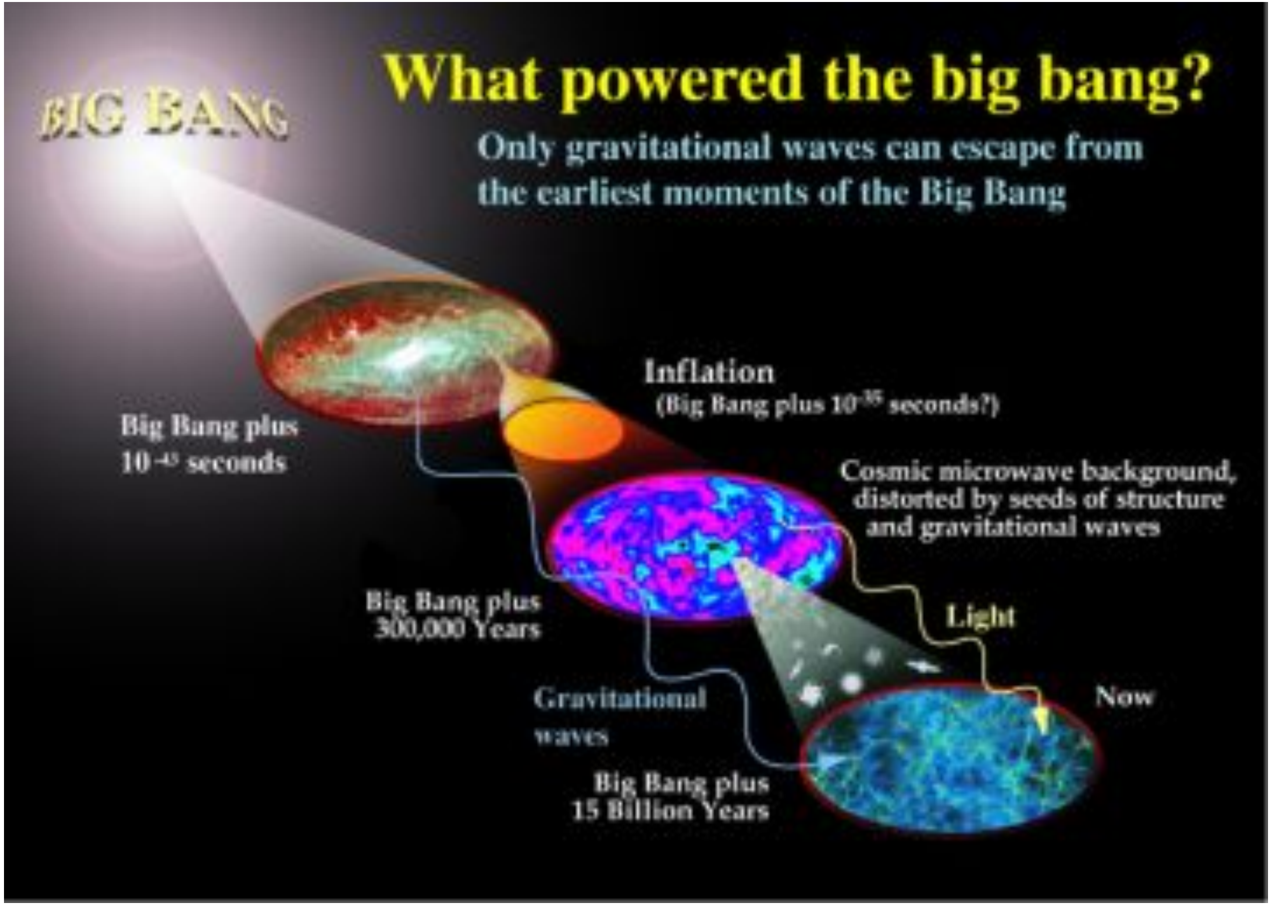
Burst gravitational waves come from short-duration unknown or unanticipated sources.

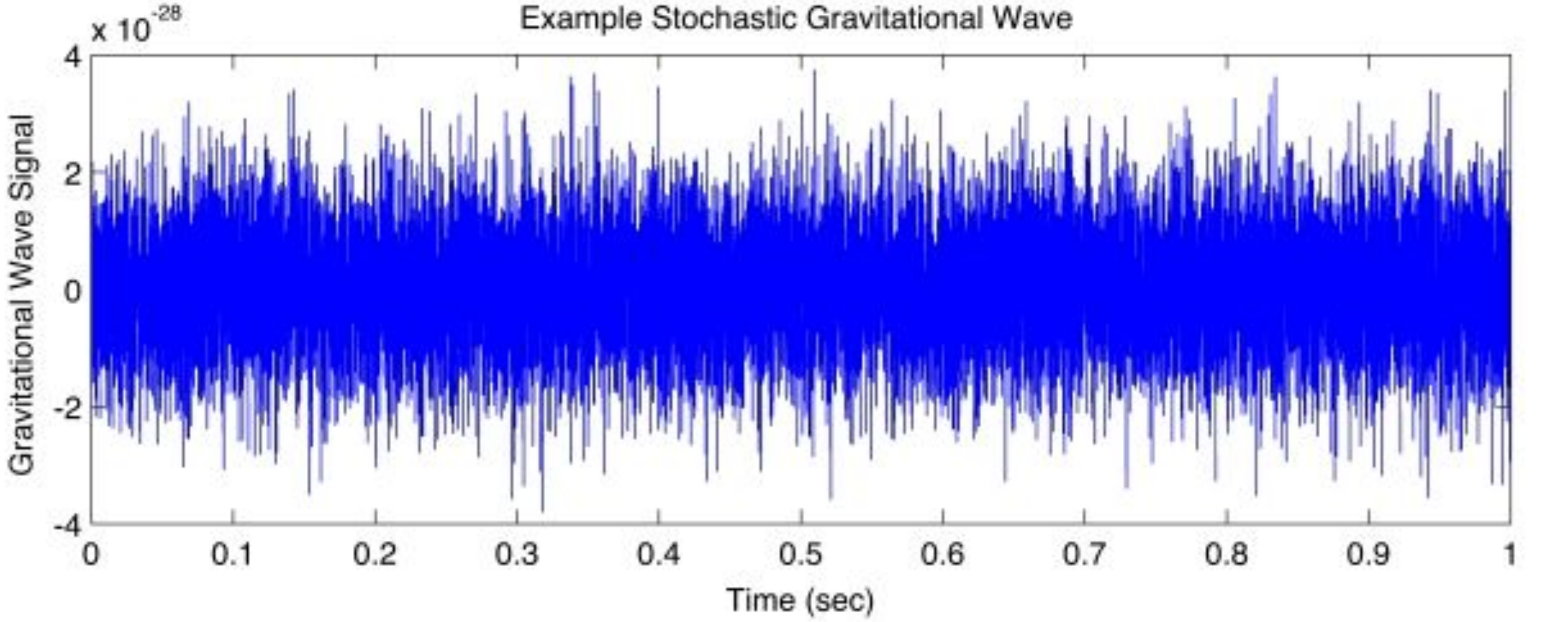
In burst gravitational waves we are expecting the unexpected. There are hypotheses that some systems such as supernovae or gamma ray bursts may produce burst gravitational waves, but too little is known about the details of these systems to anticipate the form these waves will have.



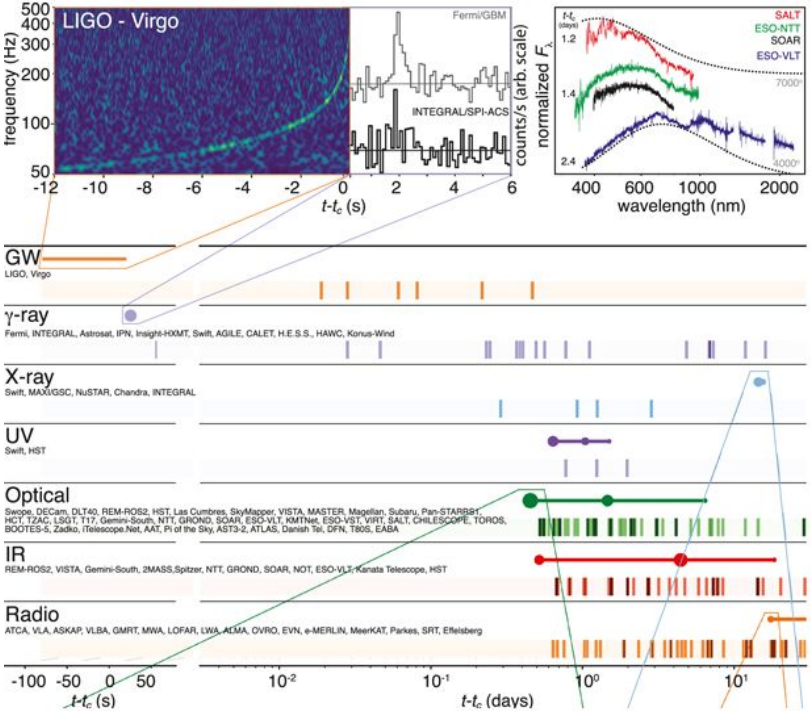
Stochastic GWs

Stochastic gravitational waves are the relic gravitational waves from the early evolution of the universe.




Example Stochastic Gravitational Wave
x 10^-28
4
2
0
-2
-4
Gravitational Wave Signal
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (sec)

Marvel: "Infinity war is the most ambitious crossover event in history"
Me:



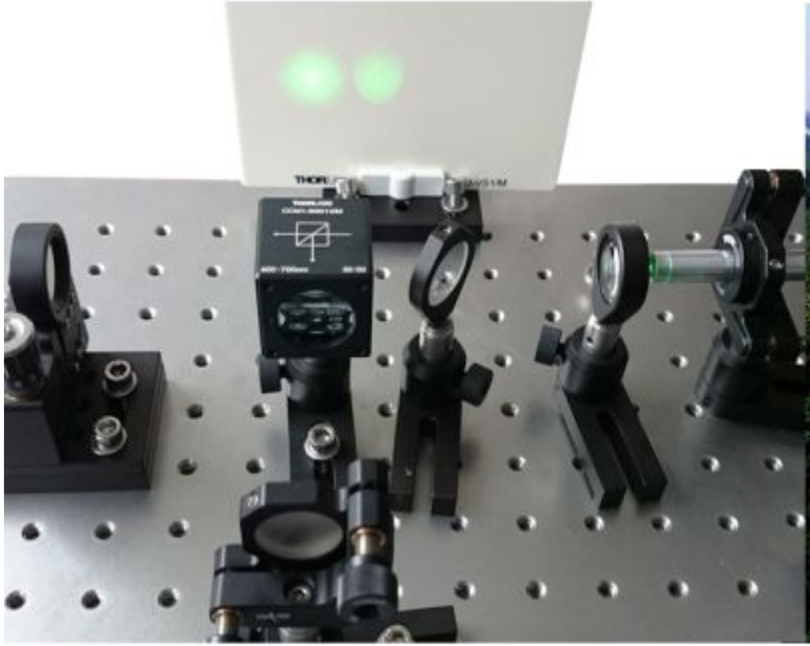
LIGO Scientific Collaboration

DETECTING GRAVITATIONAL WAVES

LIGO and Interferometry

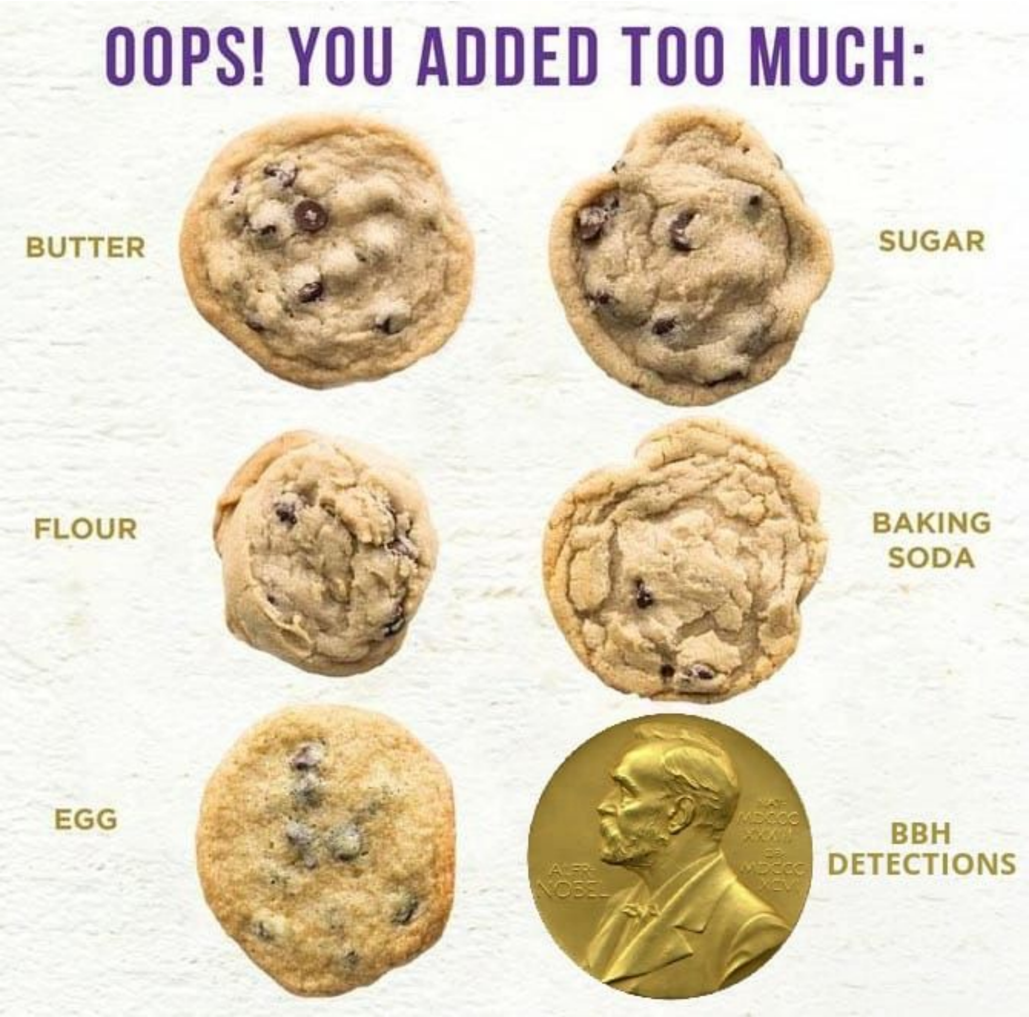
LIGO is the largest of the gravitational wave detectors with arms 4 km (a little less than 2.5 miles) in length interferometers (the international detectors include VIRGO in Italy, GEO in Germany and TAMA in Japan).

You vs. the interferometer she tells you not to worry about

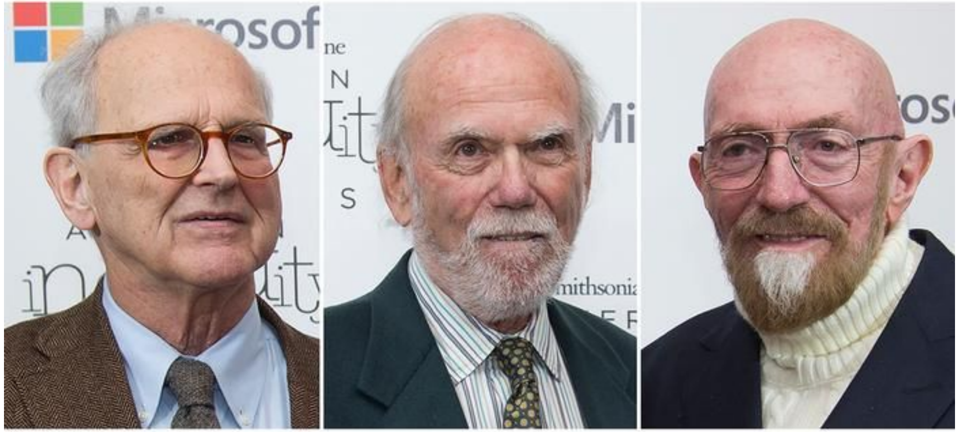


In the late 1960s, Weiss began laying conceptual foundations for these interferometers. In parallel, Thorne, along with his students and postdocs at Caltech, worked to improve the theory of gravitational waves, and estimated the details, strengths, and frequencies of the waves that would be produced by objects in our universe such as black holes, neutron stars, and supernovas.

In 1972, Thorne, with his student Bill Press (MS '71, PhD '73), published the first of many articles that would appear over the next three decades, summarizing what was known about the gravitational-wave sources and formulating a vision for gravitational-wave astronomy.


OOPS! YOU ADDED TOO MUCH:
BUTTER
SUGAR
FLOUR
BAKING SODA
EGG
BBH DETECTIONS

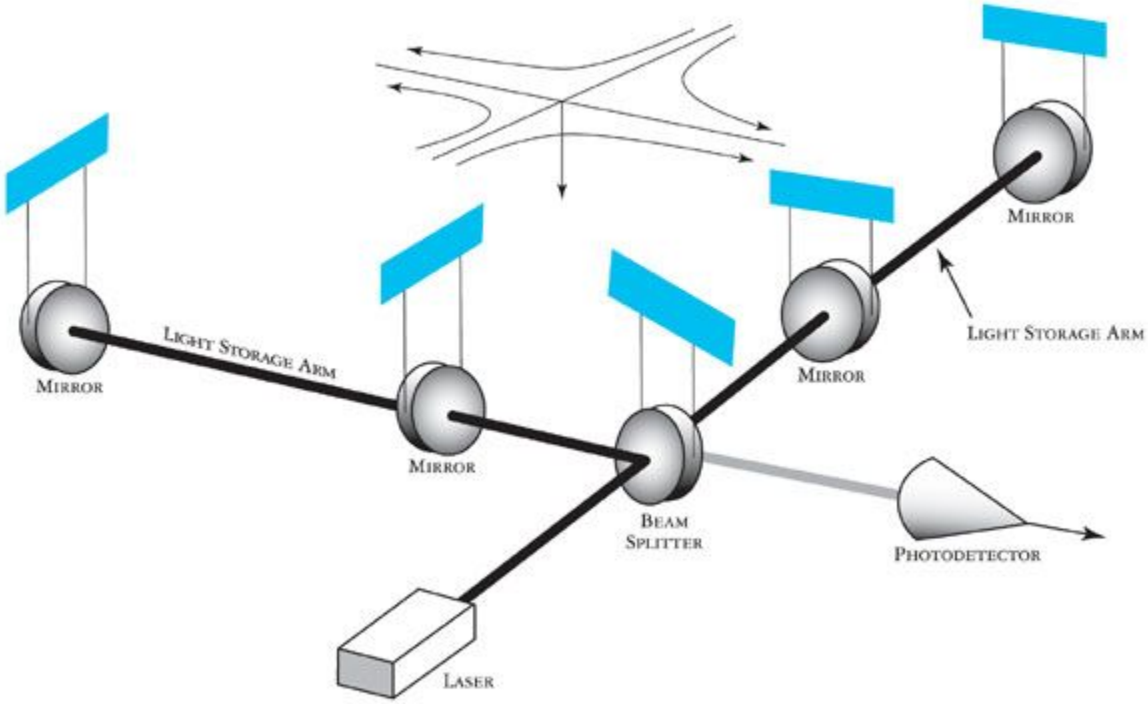
Building LIGO was a tremendous challenge—logistically and technically. To meet this challenge, Caltech and MIT later recruited, as LIGO's second director, Barry Barish, who at that time had been the leader of several very large high-energy physics projects. Barish developed the first high-energy neutrino beam experiment at Fermilab near Chicago and was one of the leaders of a large international collaboration that performed a search for magnetic monopoles



© Getty Images/Molly Riley

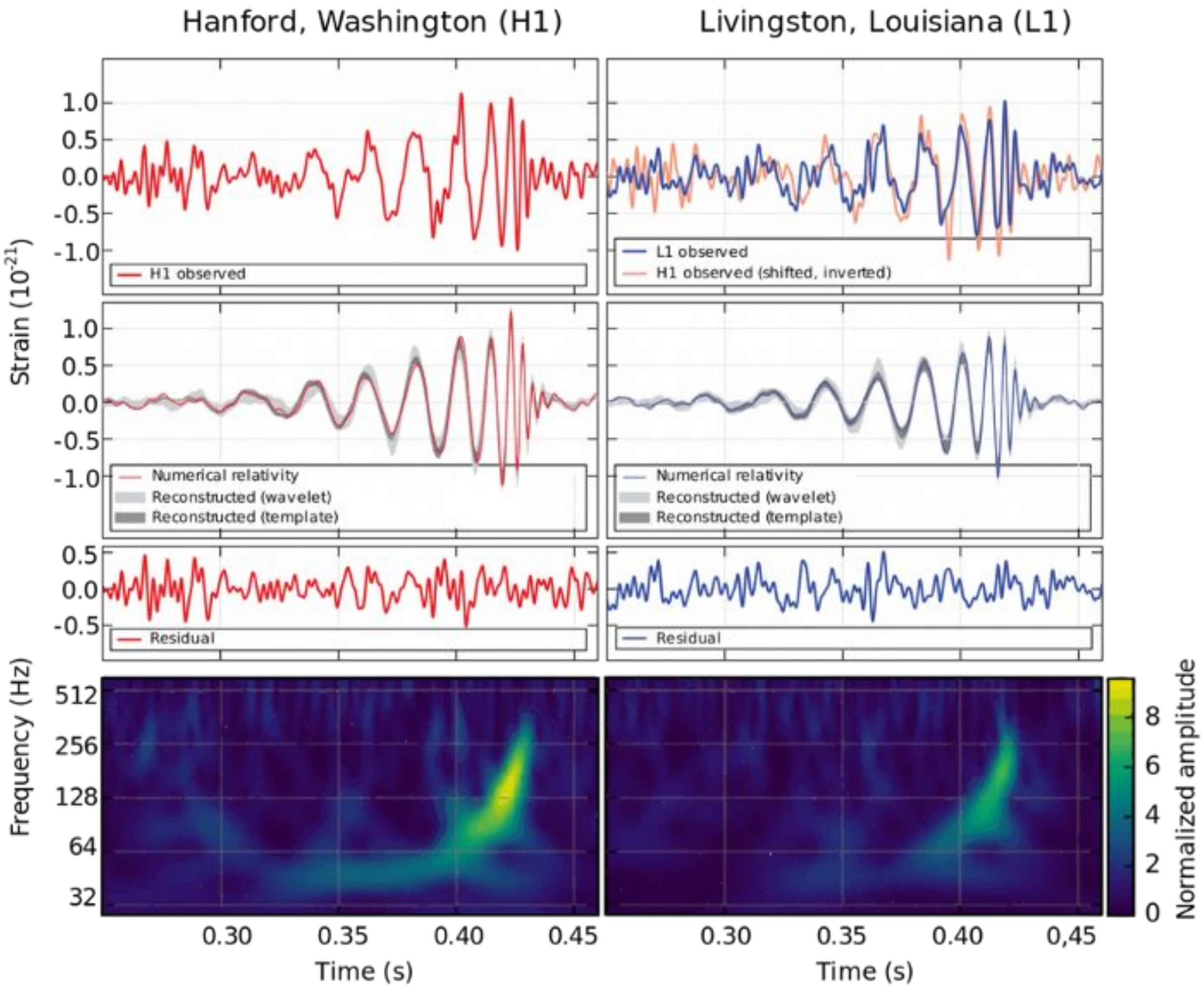
AN INTERFEROMETER

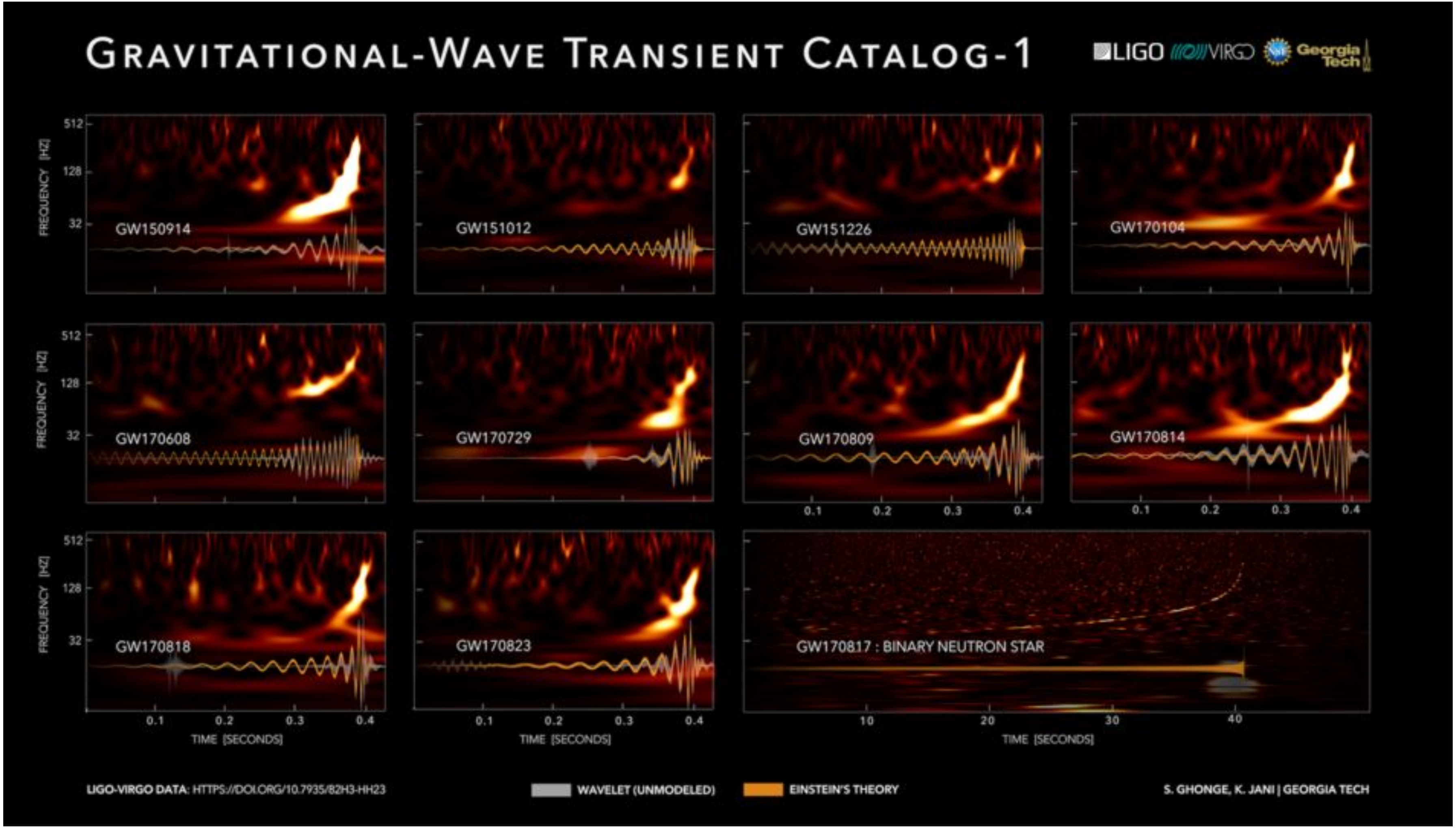
Many things on Earth are constantly causing very small relative length changes in the arms of LIGO. These ever-present terrestrial signals are regarded as noise



When you try to localize a GW event without a global detector network

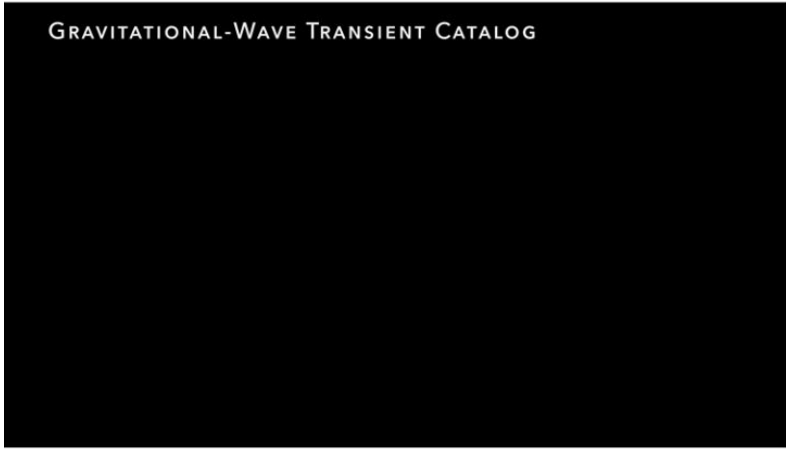
Multiple interferometers are needed to confidently detect and locate the sources of gravitational waves. If a candidate gravitational wave is observed at one detector but not the other within the light travel time between detectors, the candidate event is discarded.



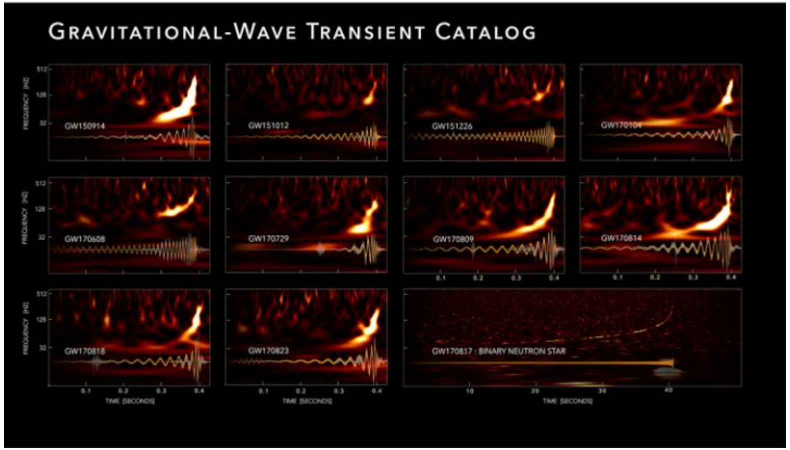

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

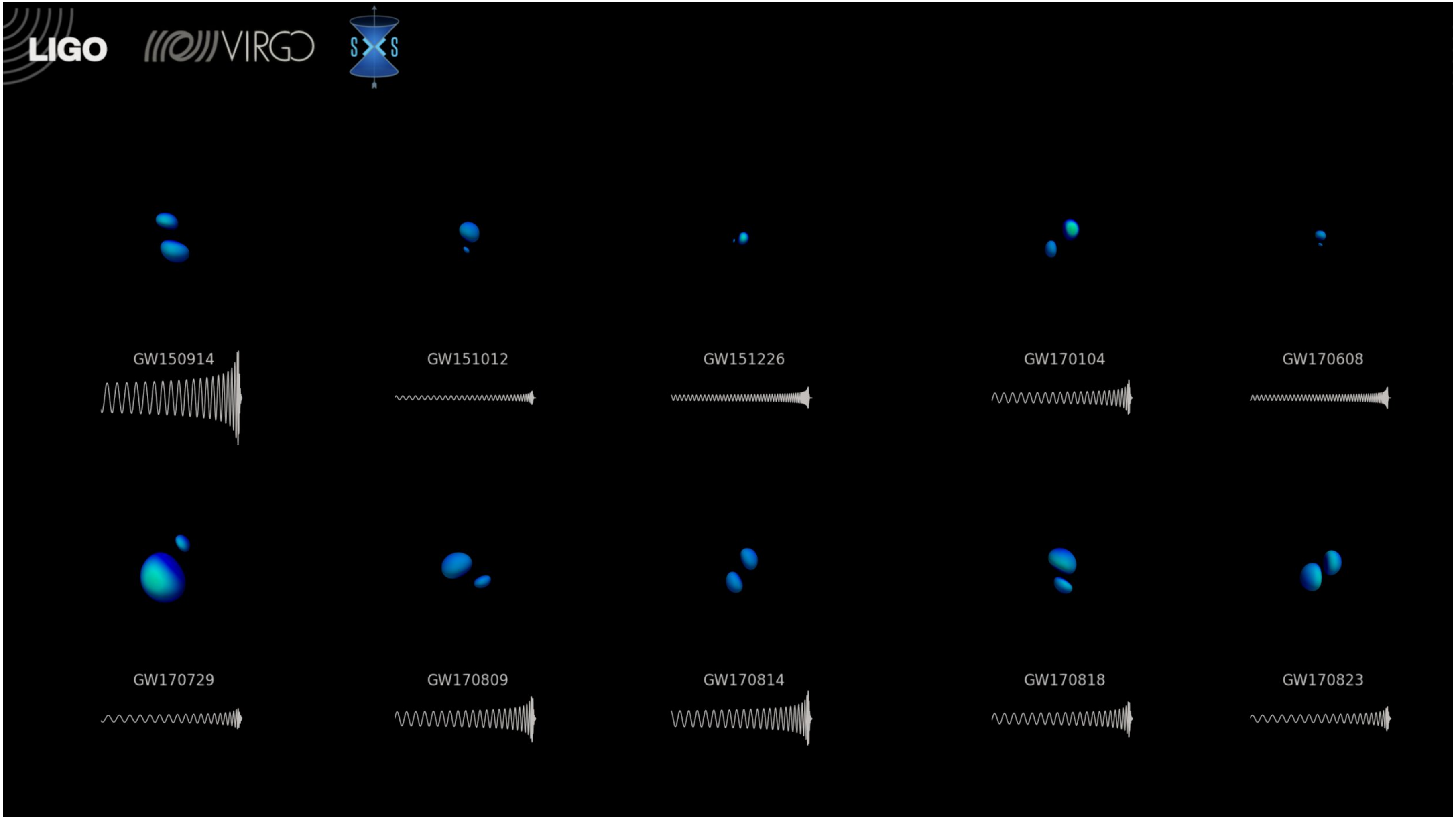
#10yearchallenge

2009



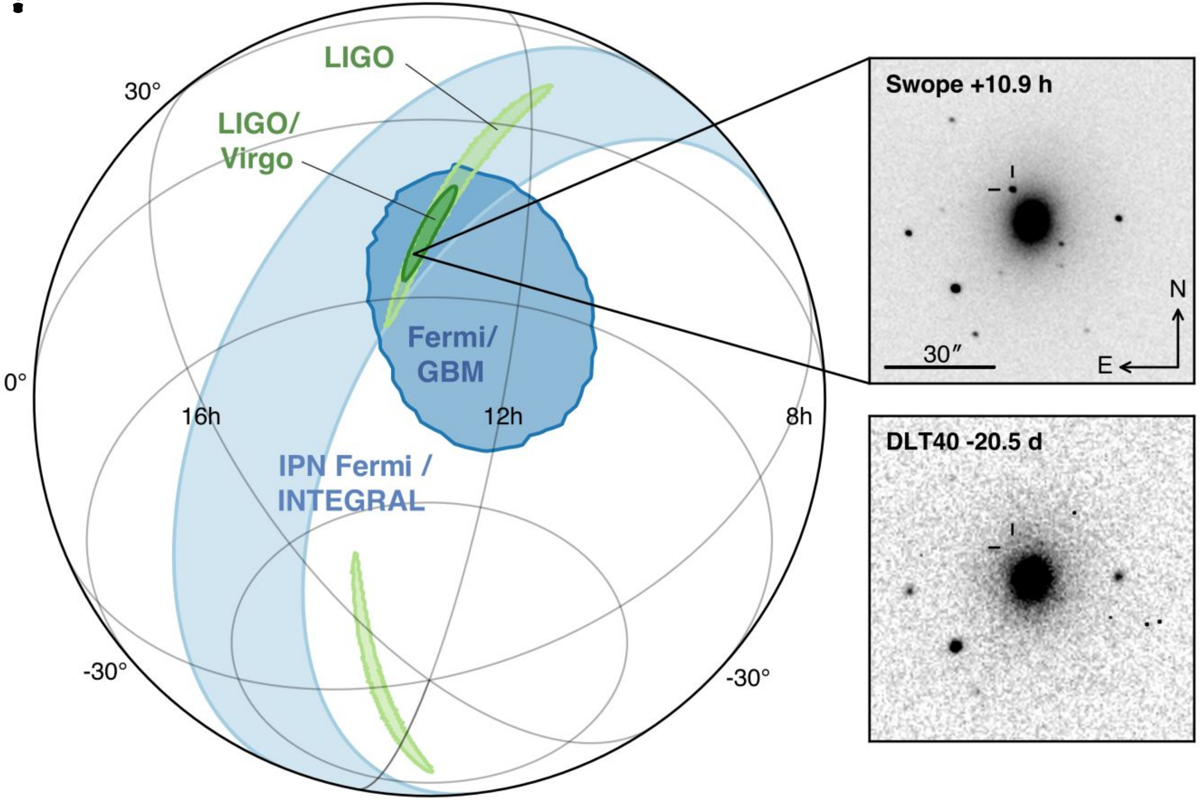
2019

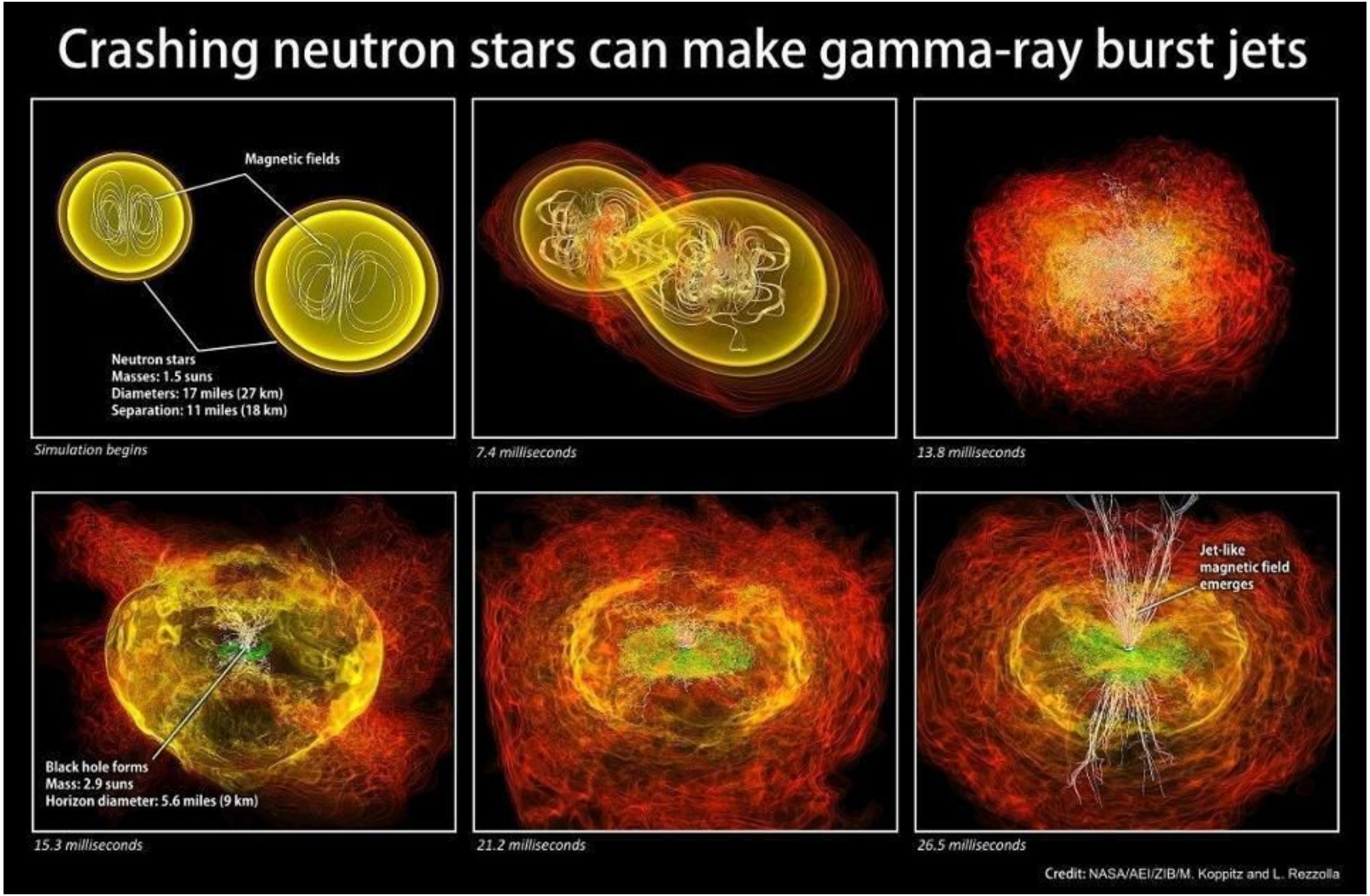



LIGO
VIRGO
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823

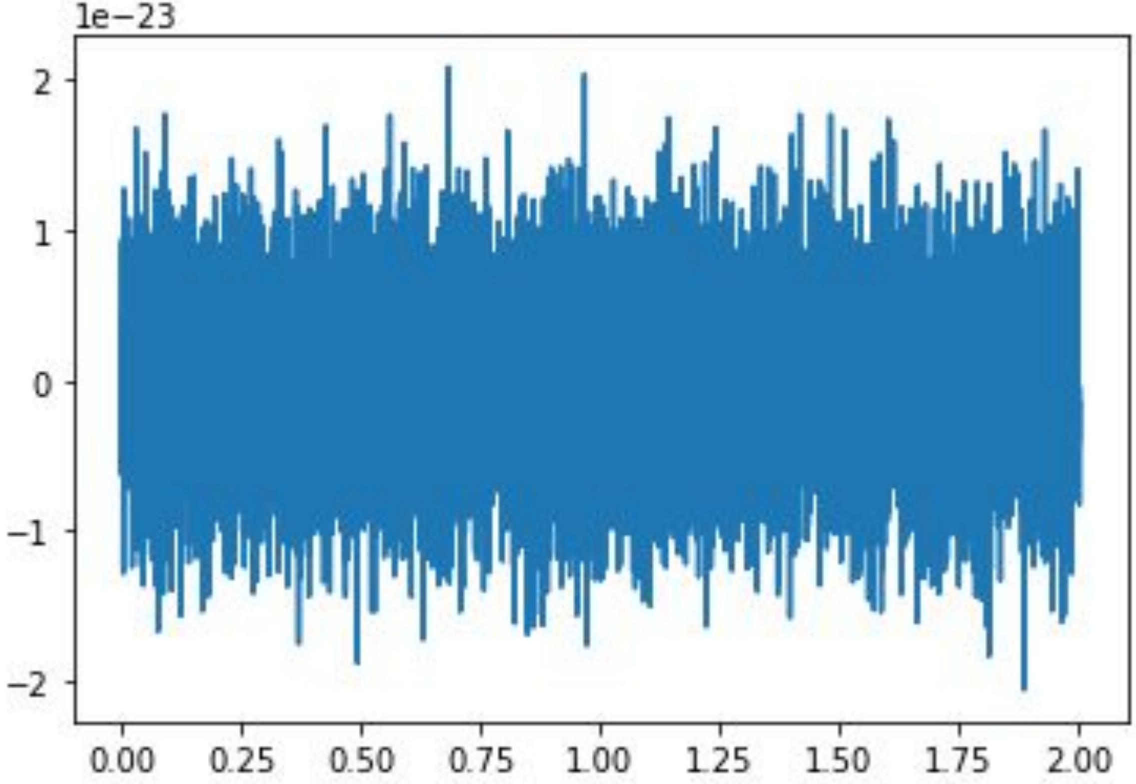
GW170817

2ND YEAR ANNIVERSARY!

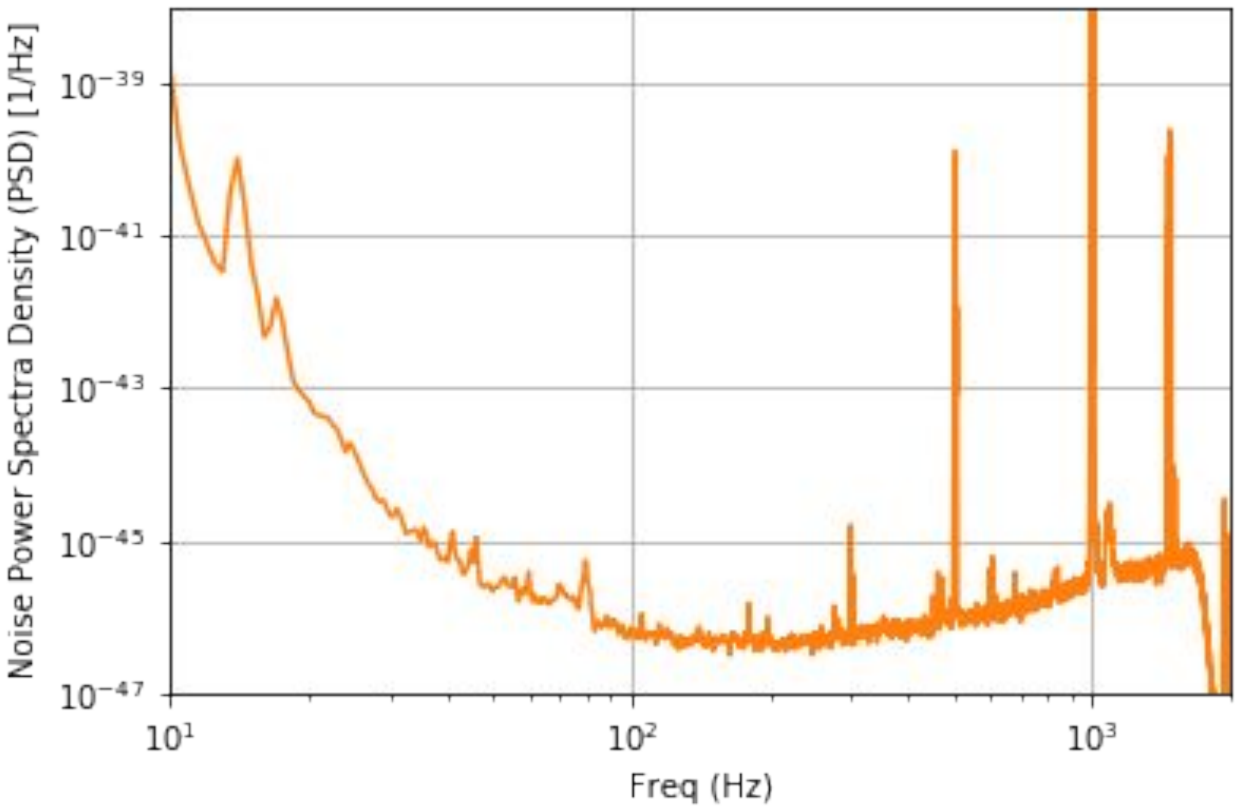



Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like
magnetic field
emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

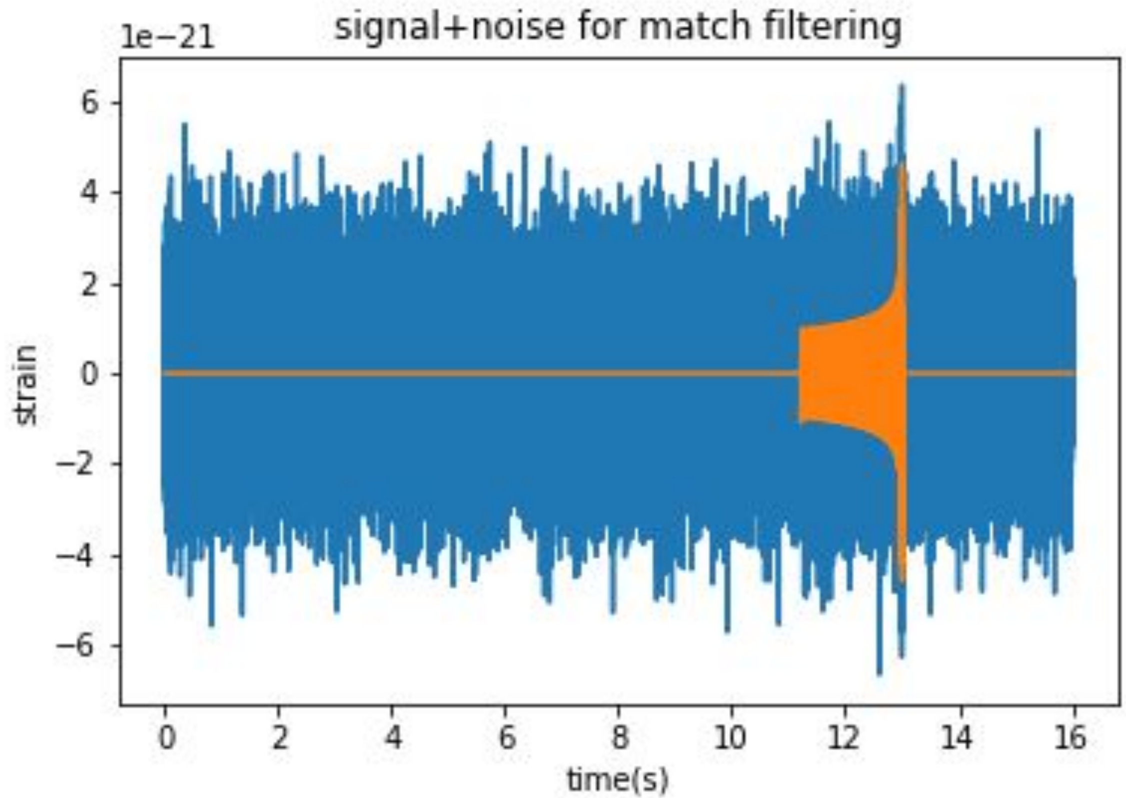
Detection Techniques



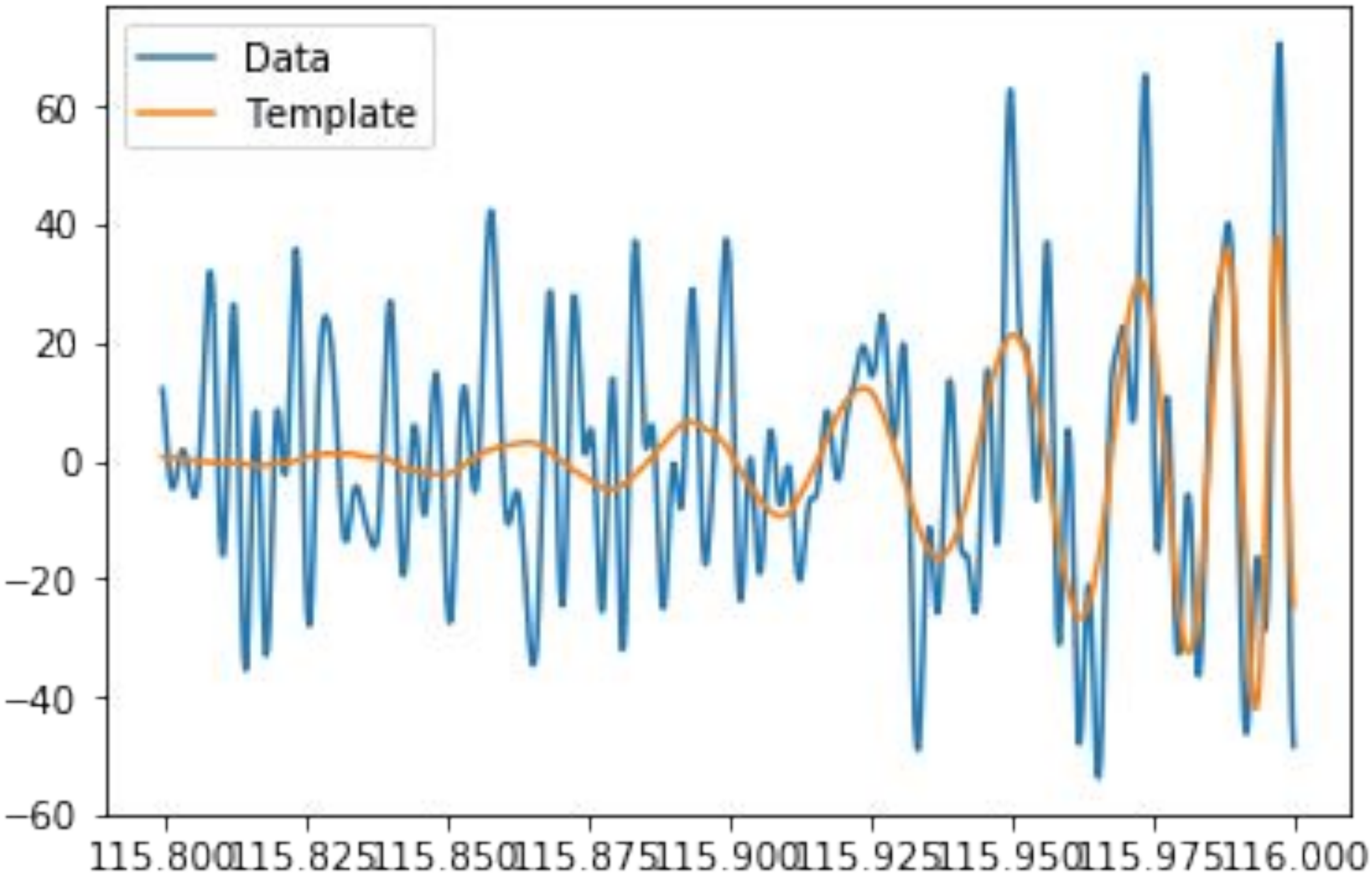
Power Spectral Density

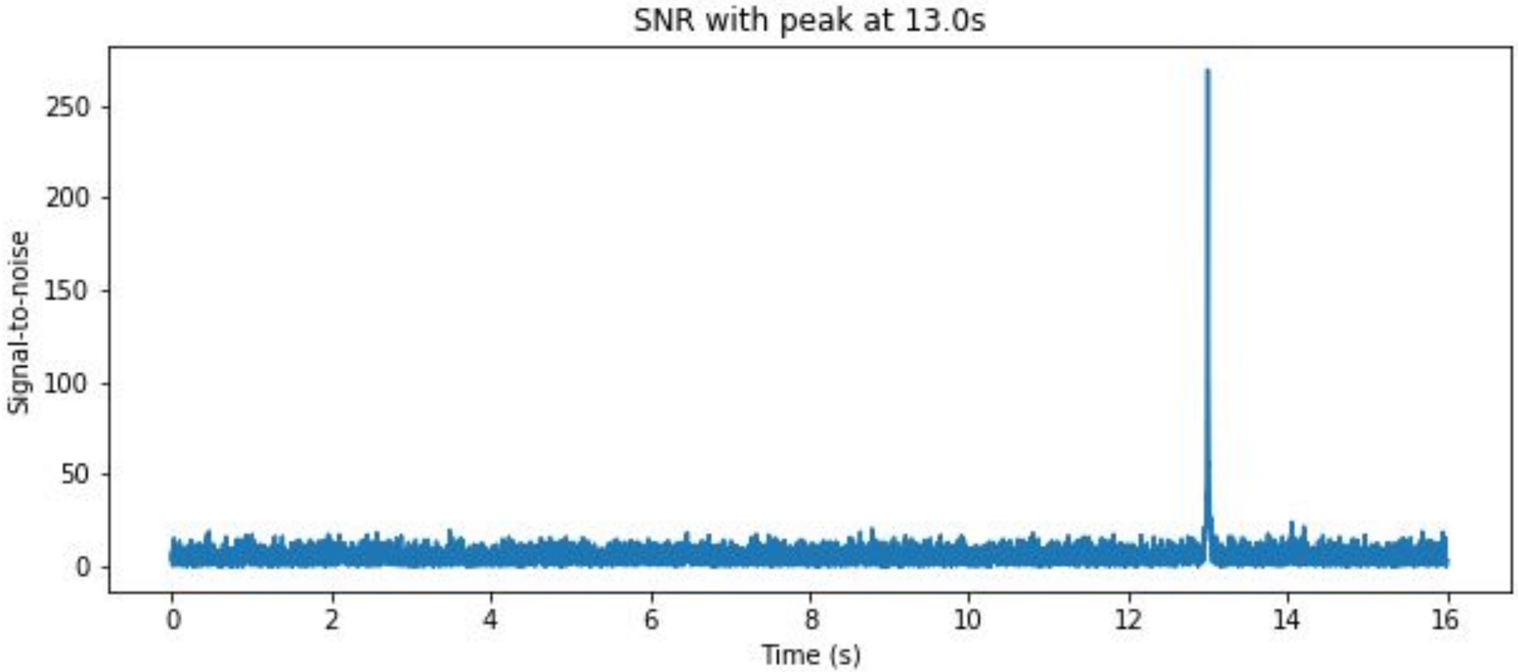


PIKA-BOO!



signal+noise for match filtering
1e−21
6
4
2
0
−2
−4
−6
strain
0
2
4
6
8
10
12
14
16
time(s)


Data
Template
60
40
20
0
−20
−40
−60
115.800
115.825
115.850
115.875
115.900
115.925
115.950
115.975
116.000

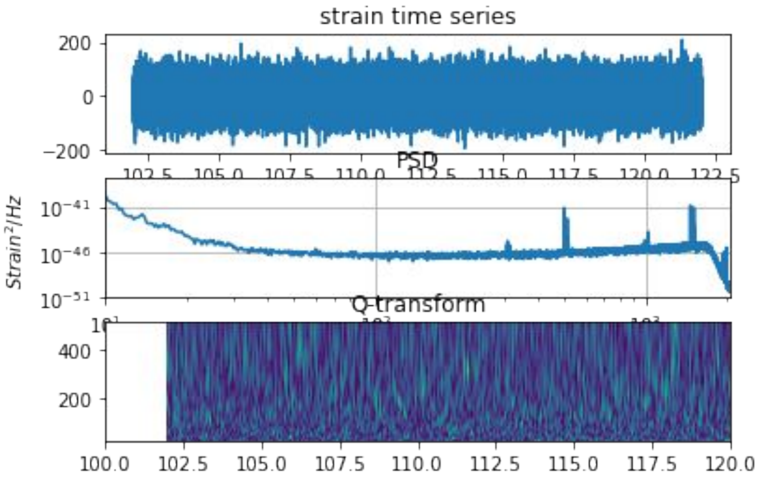


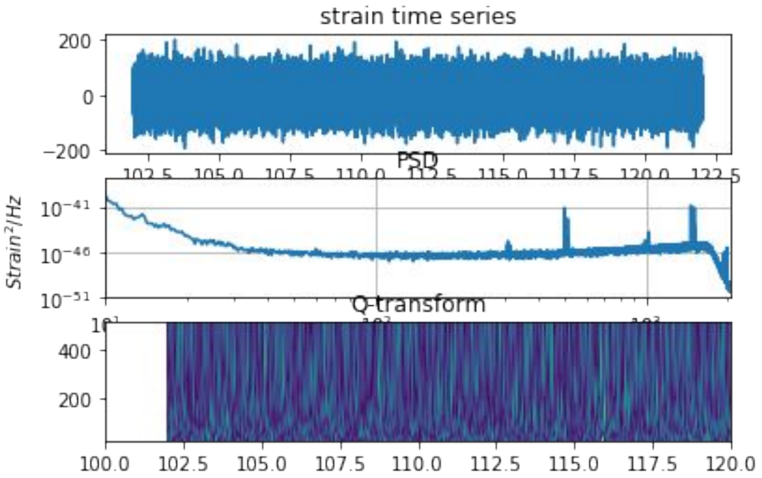
SNR with peak at 13.0s
Signal-to-noise
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
Time (s)

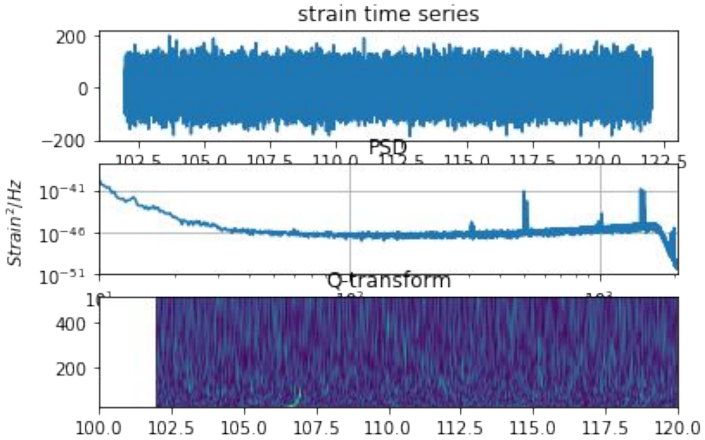
LHO data is shown in red,
LLO data is shown in blue,
If you were a CBC template,
Then I'd match with you

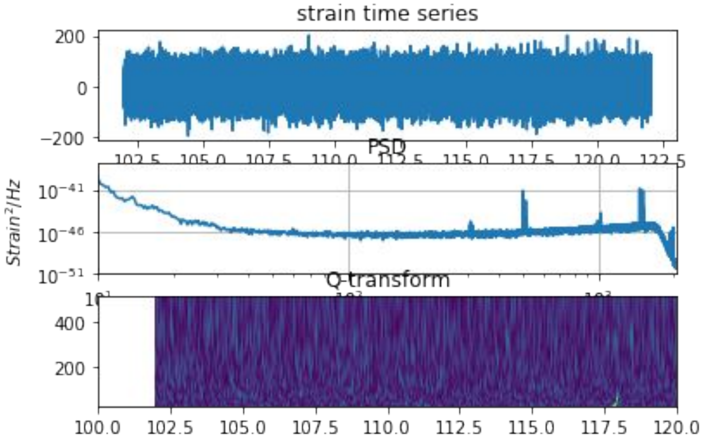
To:

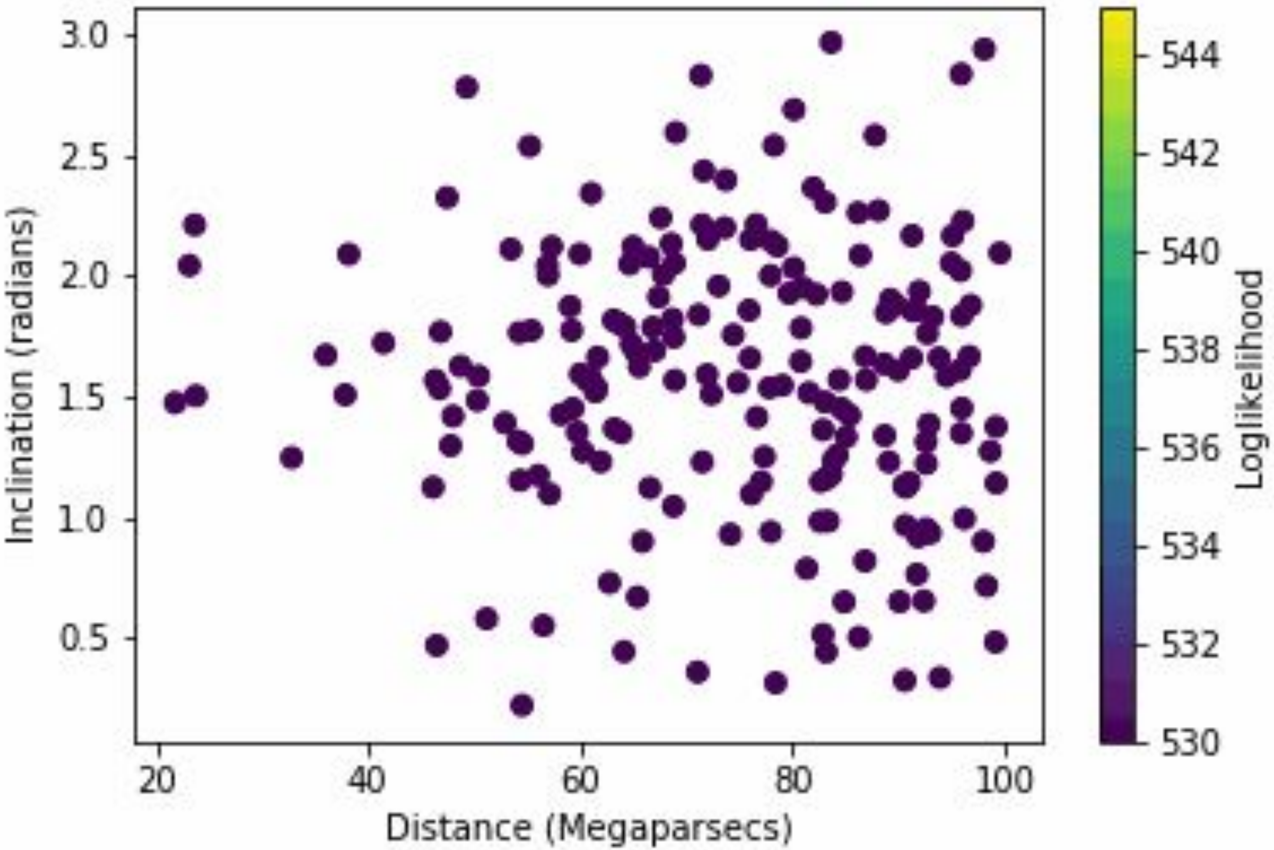
From:


strain time series
200
0
−200
102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0 122.5
PSD
Strain²/Hz
10⁻⁴¹
10⁻⁴⁶
10⁻⁵¹
Q-transform
400
200
100.0 102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0


strain time series
200
0
−200
102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0 122.5
PSD
Strain²/Hz
10⁻⁴¹
10⁻⁴⁶
10⁻⁵¹
Q-transform
400
200
100.0 102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0

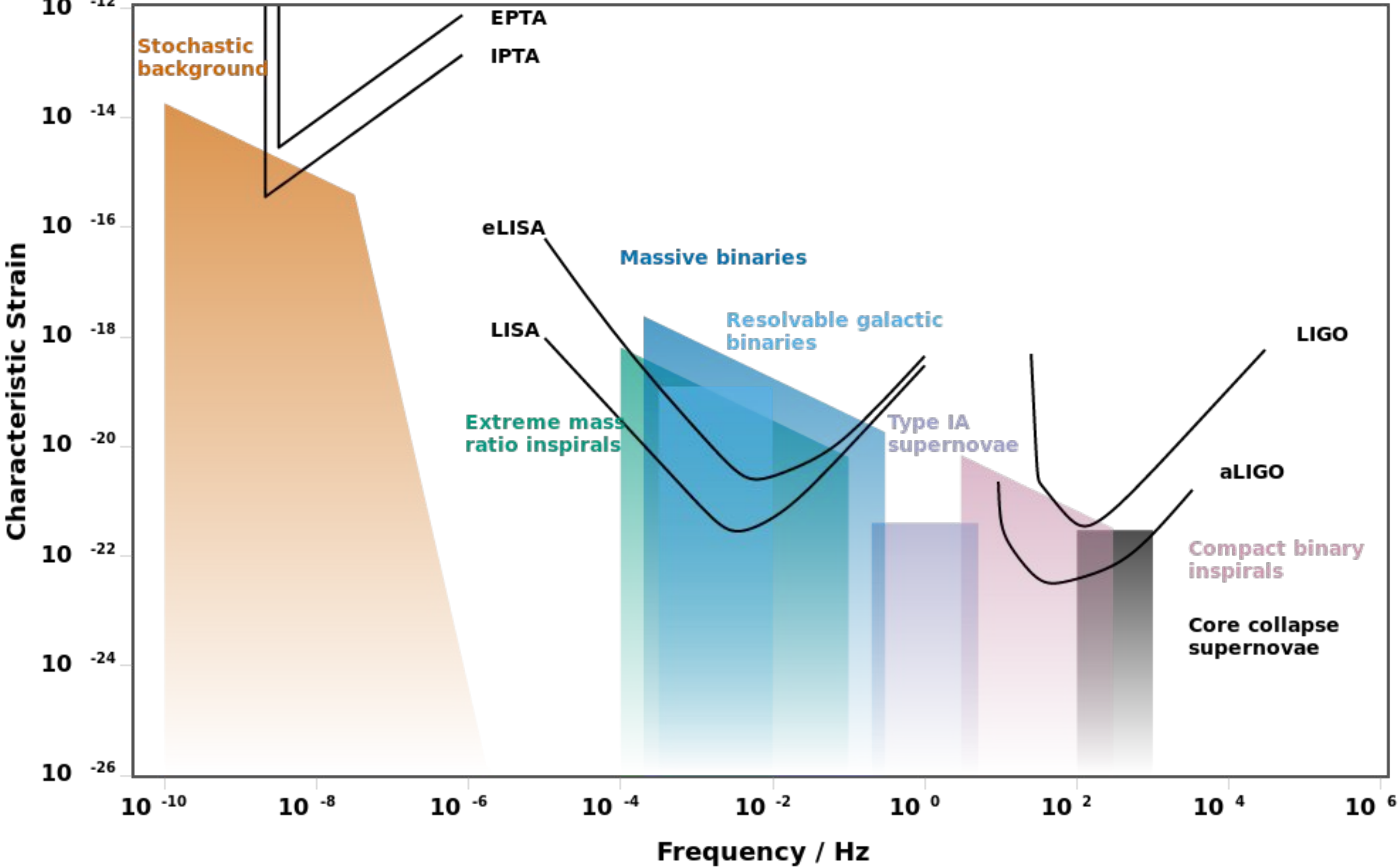

strain time series
200
0
−200
102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0 122.5
PSD
Strain²/Hz
10⁻⁴¹
10⁻⁴⁶
10⁻⁵¹
Q-transform
400
200
100.0 102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0


strain time series
200
0
−200
102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0 122.5
PSD
Strain²/Hz
10⁻⁴¹
10⁻⁴⁶
10⁻⁵¹
Q-transform
400
200
100.0 102.5 105.0 107.5 110.0 112.5 115.0 117.5 120.0



Inclination (radians)
3.0
2.5
2.0
1.5
1.0
0.5
20
40
60
80
100
Distance (Megaparsecs)
544
542
540
538
536
534
532
530
Loglikelihood

Next Generation Detectors

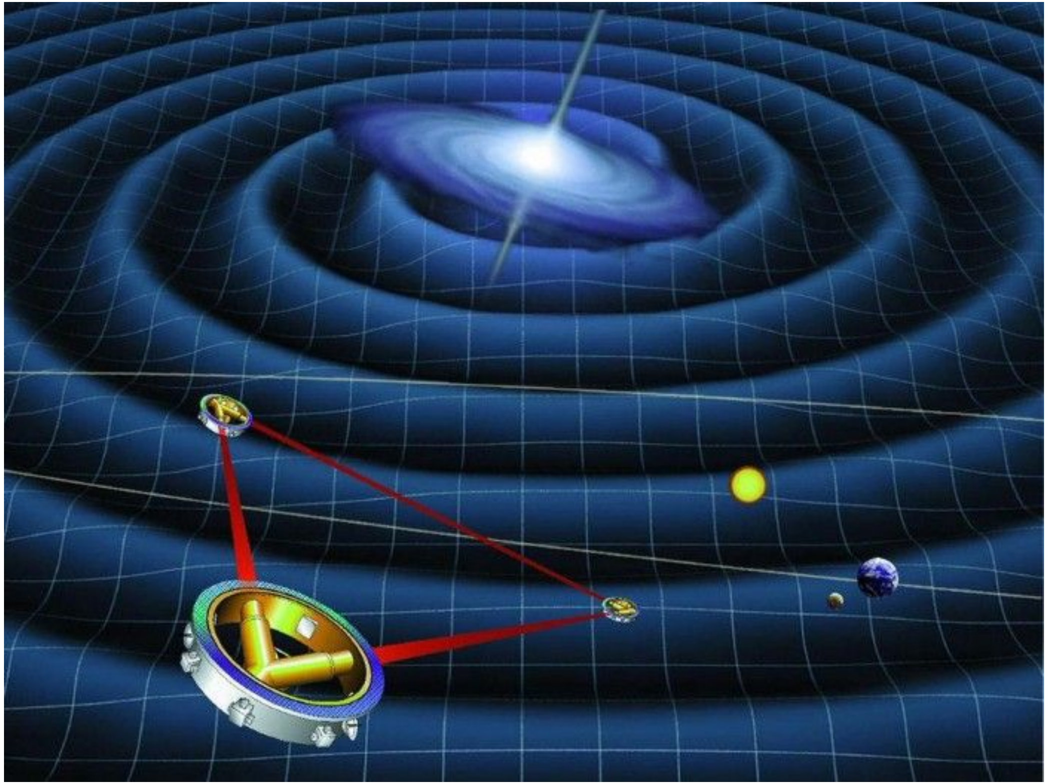


EPTA
IPTA
Stochastic background
eLISA
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Type IA supernovae
LIGO
aLIGO
Compact binary inspirals
Core collapse supernovae
Characteristic Strain
Frequency / Hz
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

Operational and planned gravitational-wave detectors [edit]

- (1995) TAMA 300
- (1995) GEO 600
- (2002) LIGO
- (2003) Mario Schenberg (Gravitational Wave Detector)
- (2003) MiniGrail
- (2005) Pulsar timing array (for Parkes radio-telescope)
- (2006) CLIO
- (2007) Virgo interferometer
- (2015) Advanced LIGO
- (2016) Advanced Virgo
- (2018) KAGRA (LCGT)
- (2023) IndIGO (LIGO-India)[36]
- (2025) TianQin
- (2027) Deci-hertz Interferometer Gravitational wave Observatory (DECIGO)
- (2034) Laser Interferometer Space Antenna (Lisa Pathfinder, a development mission was launched December 2015)
- (2030s) Einstein Telescope

LISA




The LSC during O3
Compact binary events
The astrophysics community

Gravitational Wave Astronomy has a long way to go and be ready for surprises!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GRAVITY | RESEARCH UPDATE

Were gravitational waves from a black-hole–neutron-star merger detected on 14 August?

16 Aug 2019 Hamish Johnston

THANK YOU!

May the Force be with you!

Meme Credits :
Gravitational Waves Meme

Simulations credits :
Simulating eXtreme
Spacetime

Video credits : LIGO
Caltech