Gravitational-Wave Astronomy

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Chennai Mathematical Institute

Mini School on Gravitation and Cosmology
IIT Madras

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CHENNAI MATHEMATICAL INSTITUTE

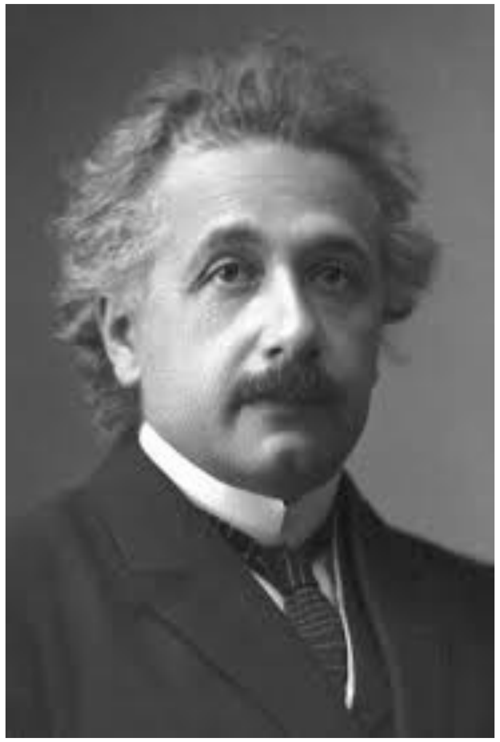
LIGO INDIA

LIGO–India Scientific Collaboration

This talk

- What are Gravitational Waves?
- Why should we be interested in this?
- What have we achieved so far?
- What are the future prospects?

Gravity is curvature of space time



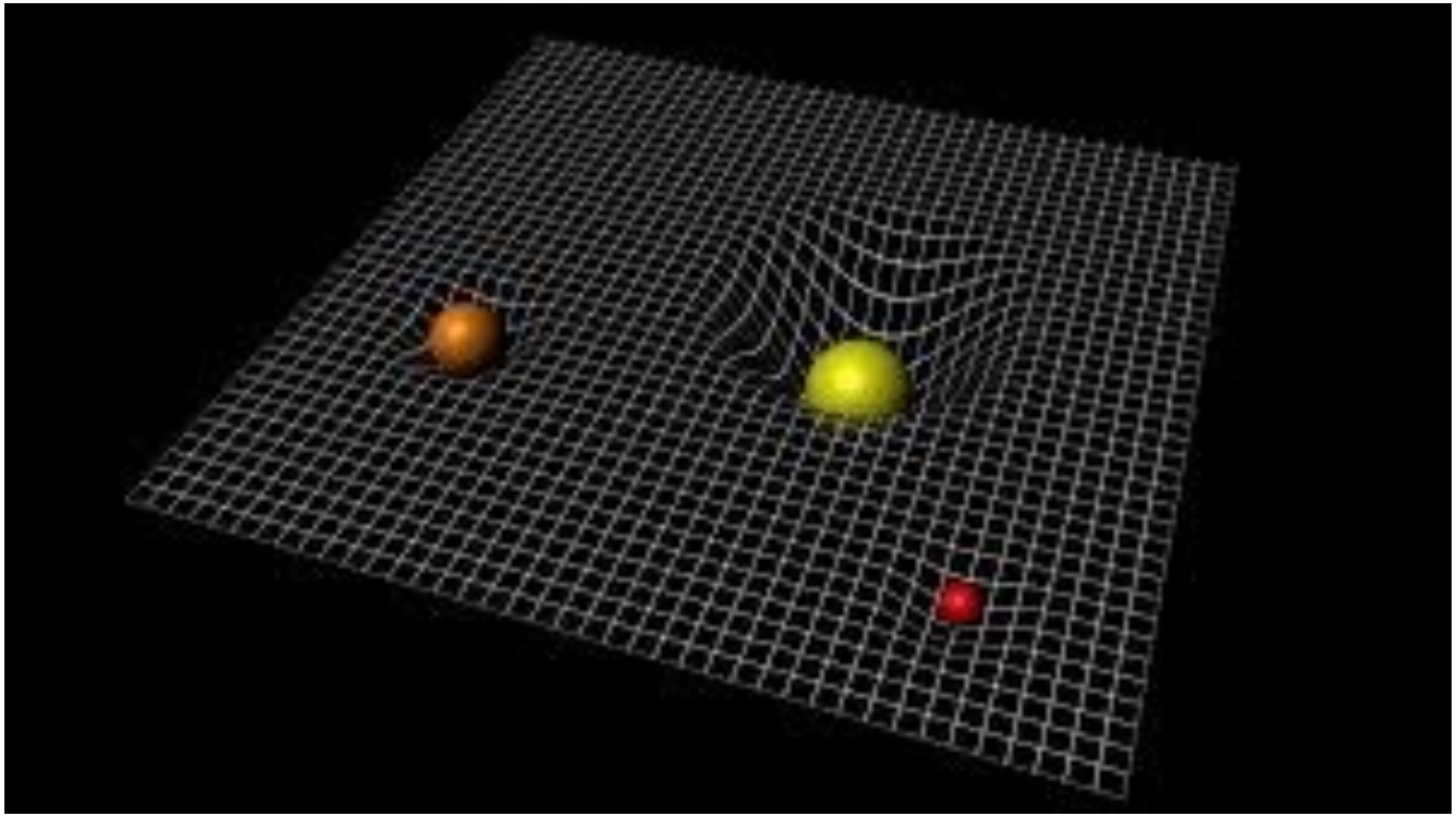
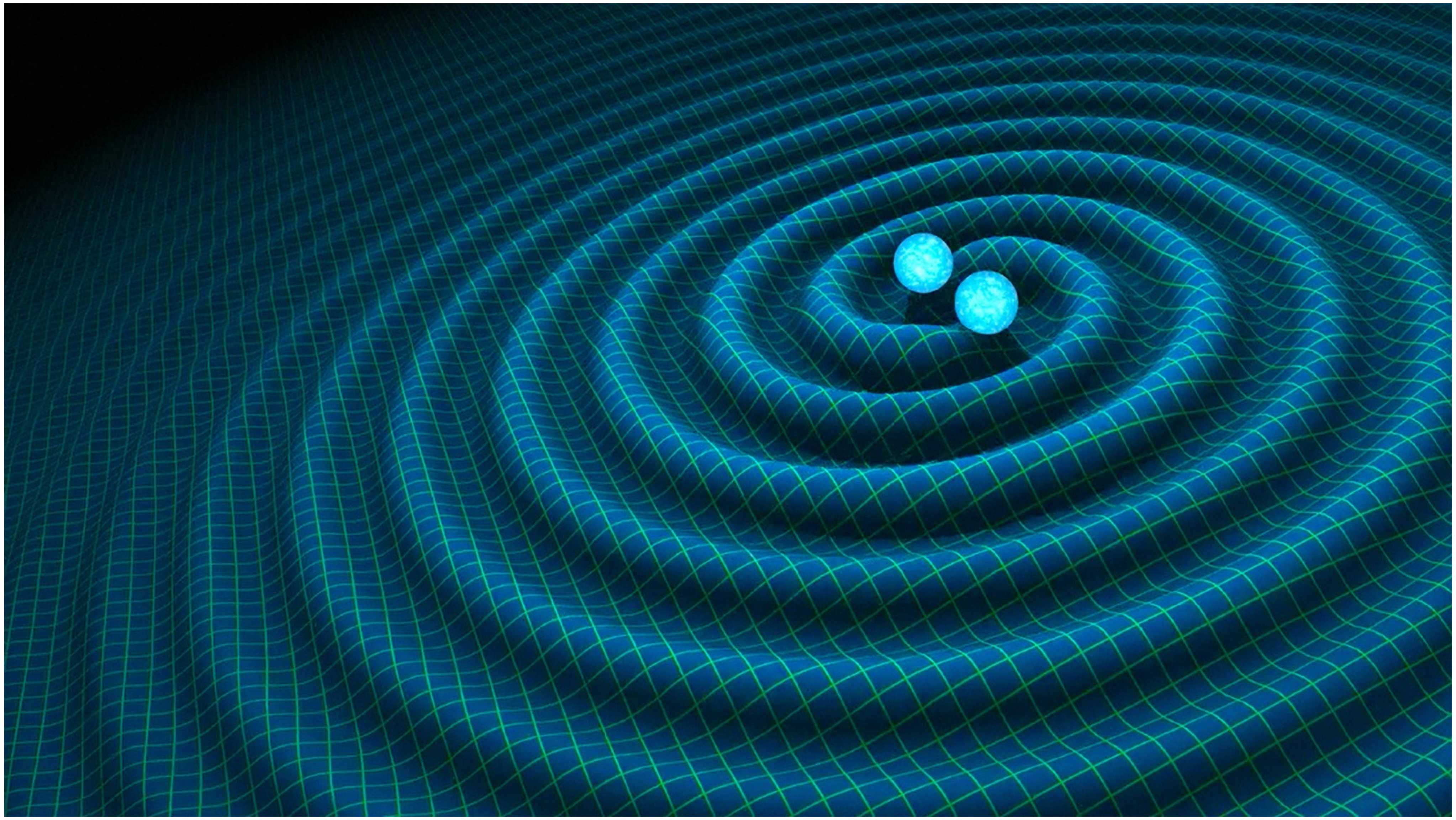


Image credit: ESA

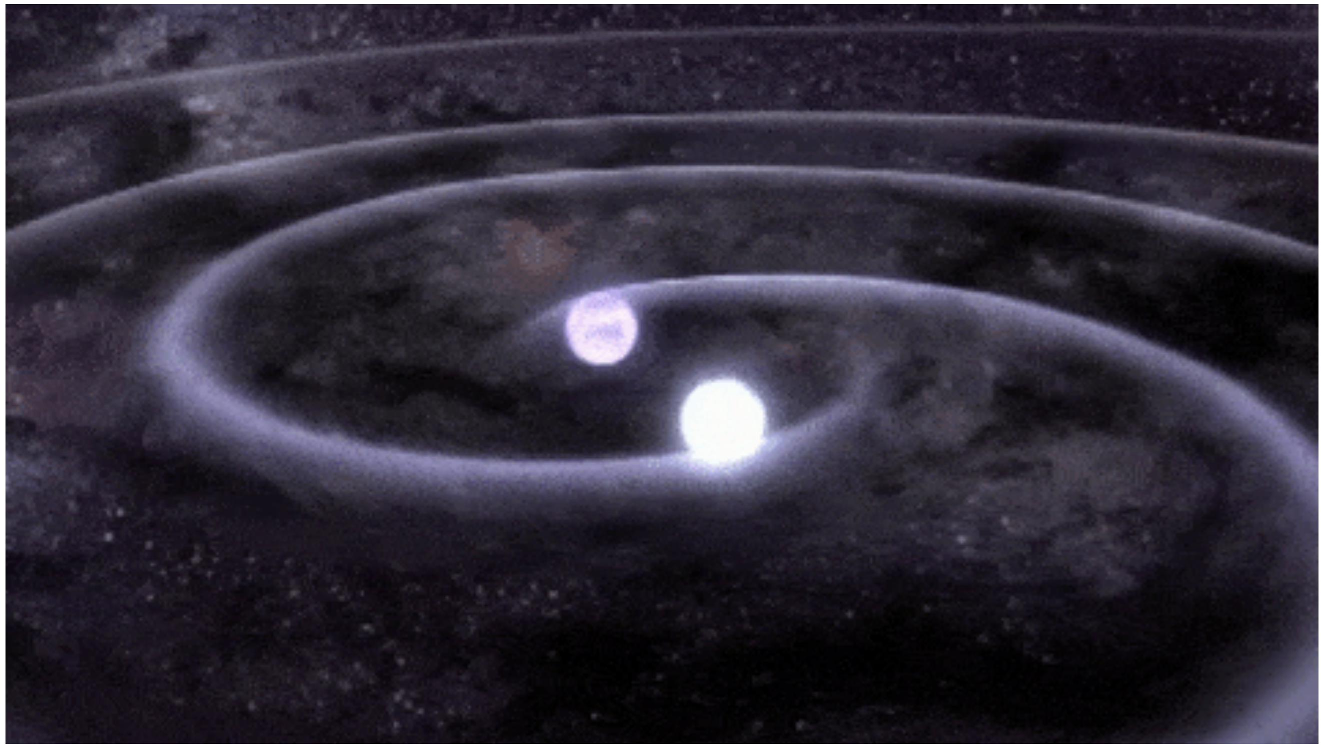
Gravitational Waves



….ripples in the curvature of space-time.

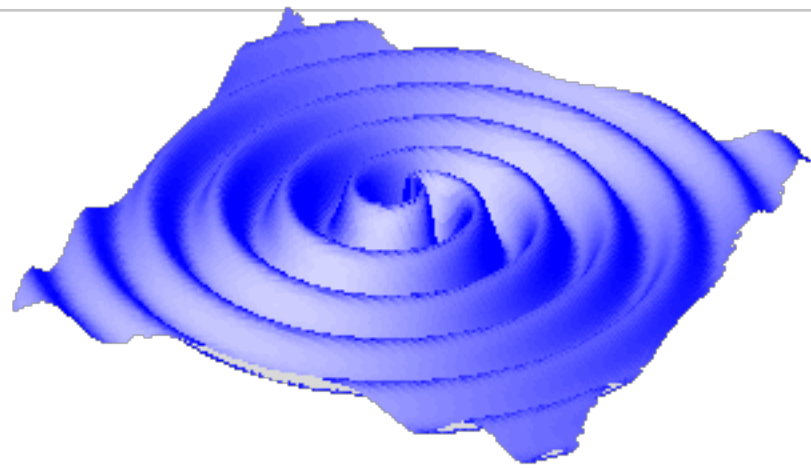
Gravitational Waves are simply …

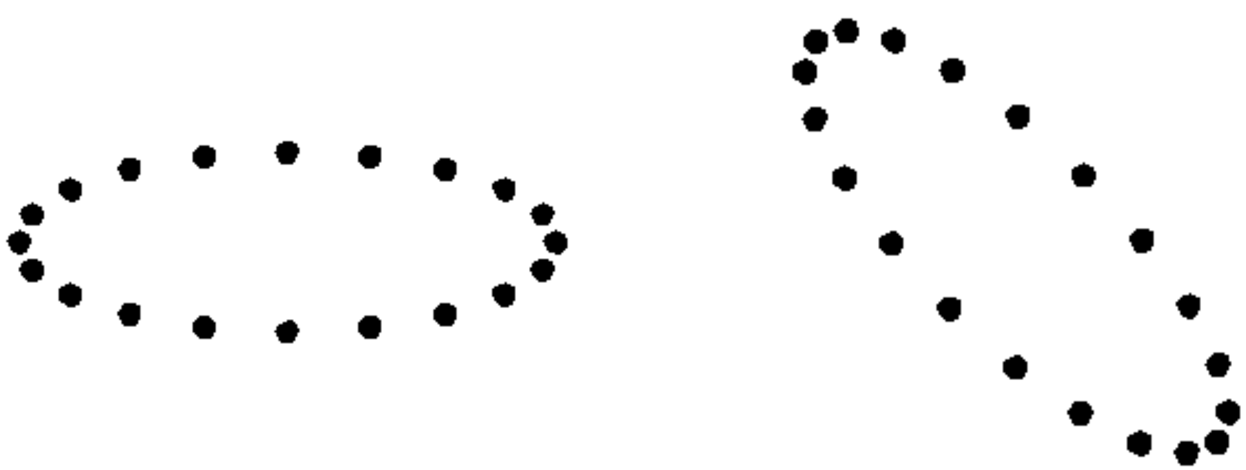
- Propagating gravitational fields.. (similar to EM waves which are propagating EM fields)
- Produced by acceleration of masses (EM waves produced due to accelerating charges)
- Transverse in nature (so are EM waves)
- Has two states of polarisations (similar to EM waves)
- Interacts very weakly with intervening matter (unlike EM waves)



GWs are quadrupolar, EM waves are dipolar

Properties of Gravitational Waves





$$h = \frac{\Delta L}{L}$$

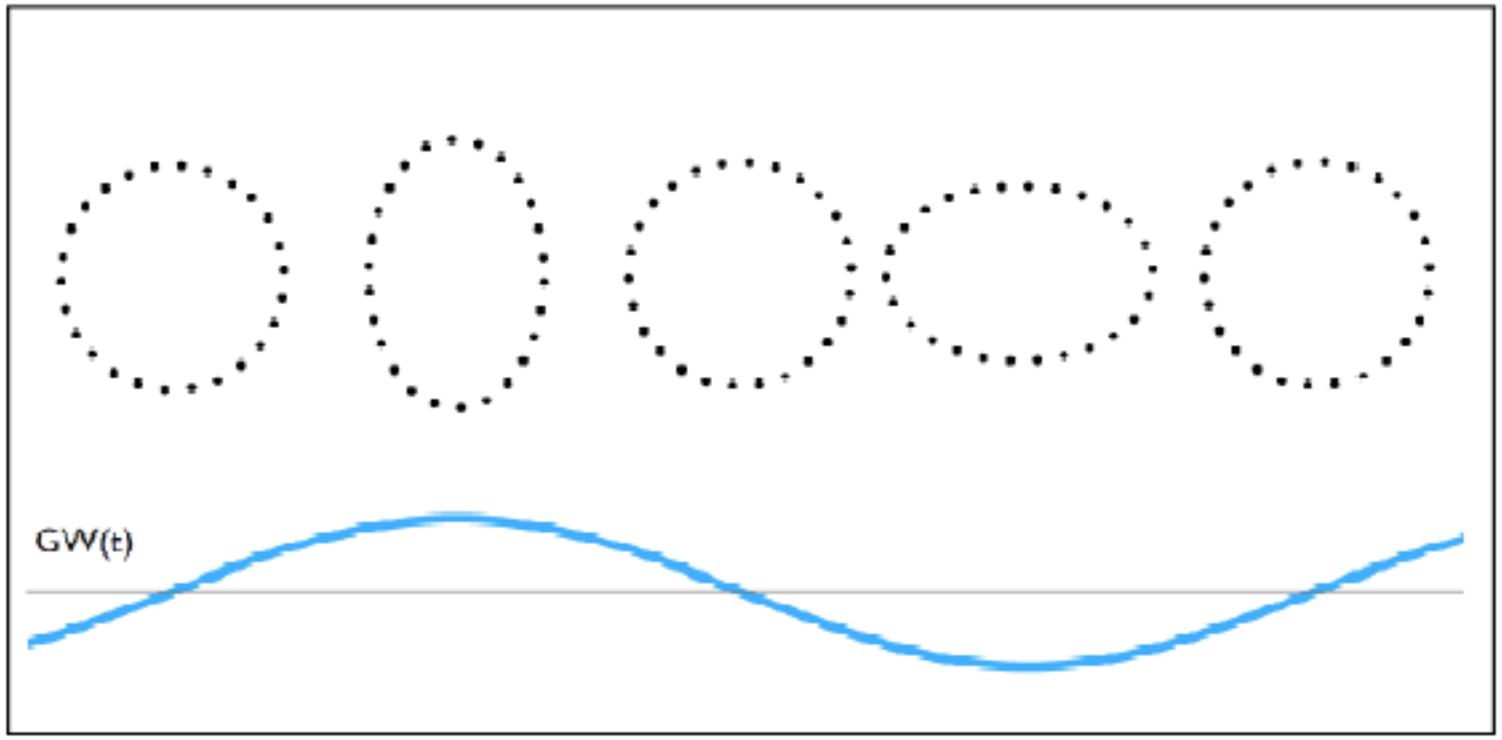
Plus

Measure of signal strength

Cross

- Any relativistic theory of gravity will predict Gravitational Waves (GWs).
- In General Relativity (GR), GWs travel at the speed of light and has two modes of polarisations called plus and cross polarisations.
- The physical effect of a passing GWs is to set them into motion transverse to the propagation direction.

Effect of Gravitational Waves

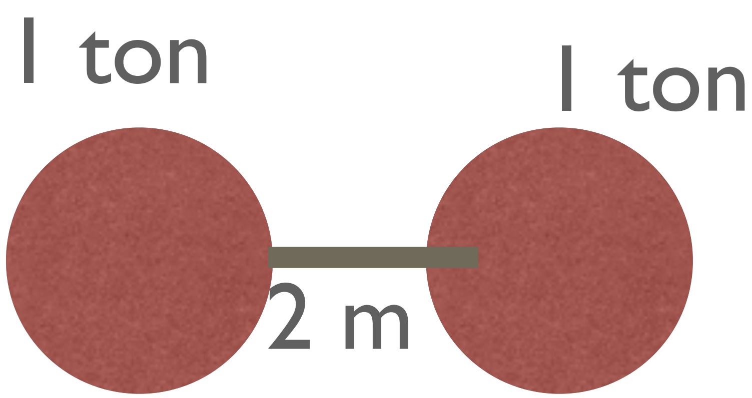


Measure of signal strength

$$h = \frac{\Delta L}{L}$$

The challenge with direct detection

Terrestrial Source

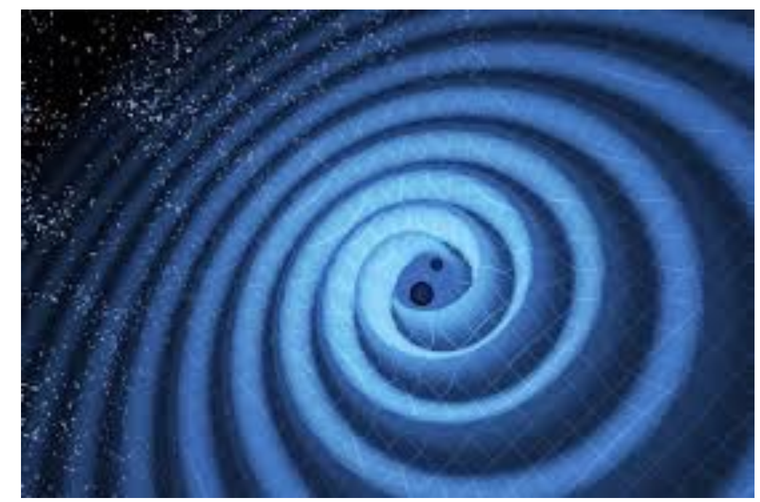


$$f = 1\ kHz$$

$$h = \frac{\Delta L}{L} \sim 10^{-39}$$

$$\Delta L(km\ arm) \sim 10^{-36} m$$

Astrophysical



Binary black hole @ 100 Mpc

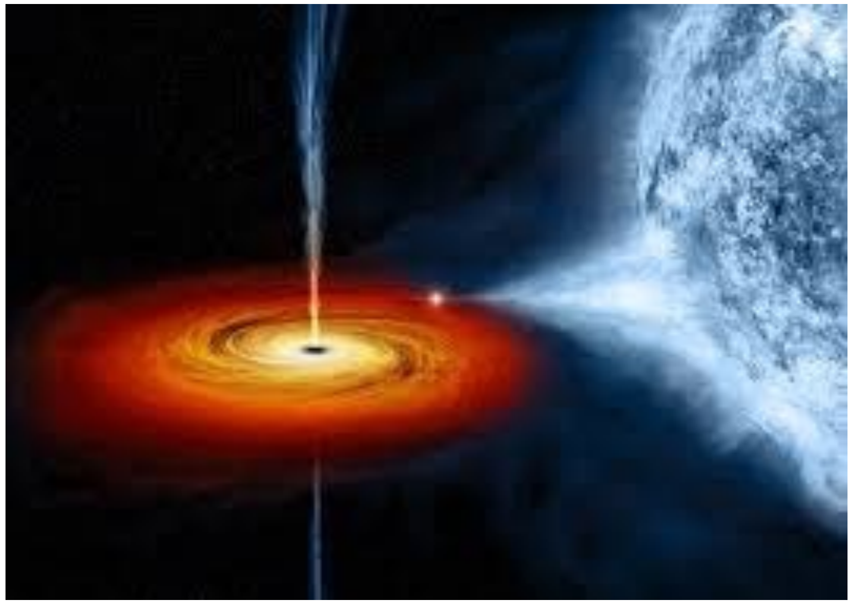
$$\frac{\Delta L}{L} \sim 10^{-21}$$

$$\Delta L(km\ arm) \sim 10^{-18} m$$

Smaller than the size of an atomic nucleus

Neutron Stars and Black Holes

A Neutron Star

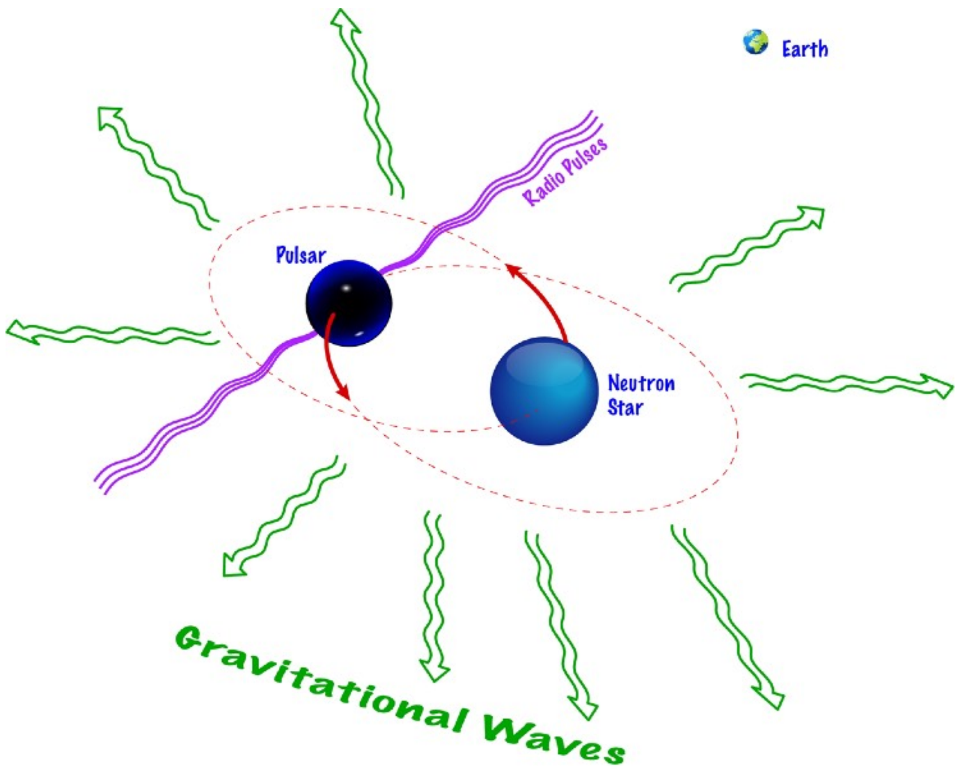


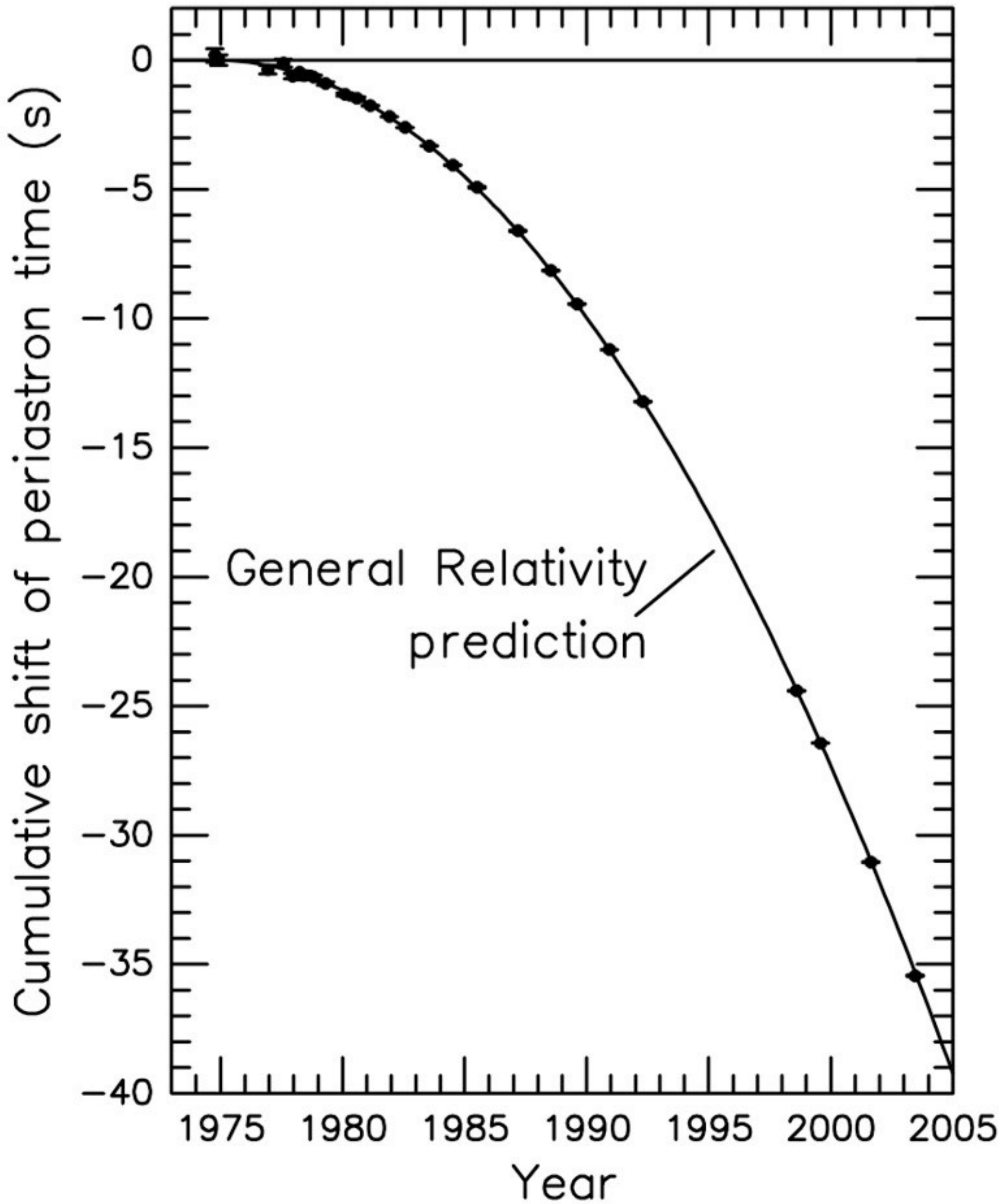
A black hole

Image credits: NASA

Hulse-Taylor Binary pulsar (1974)

Indirect evidence





Nobel Prize in 1993

Why Gravitational Waves?

Our understanding of the Universe

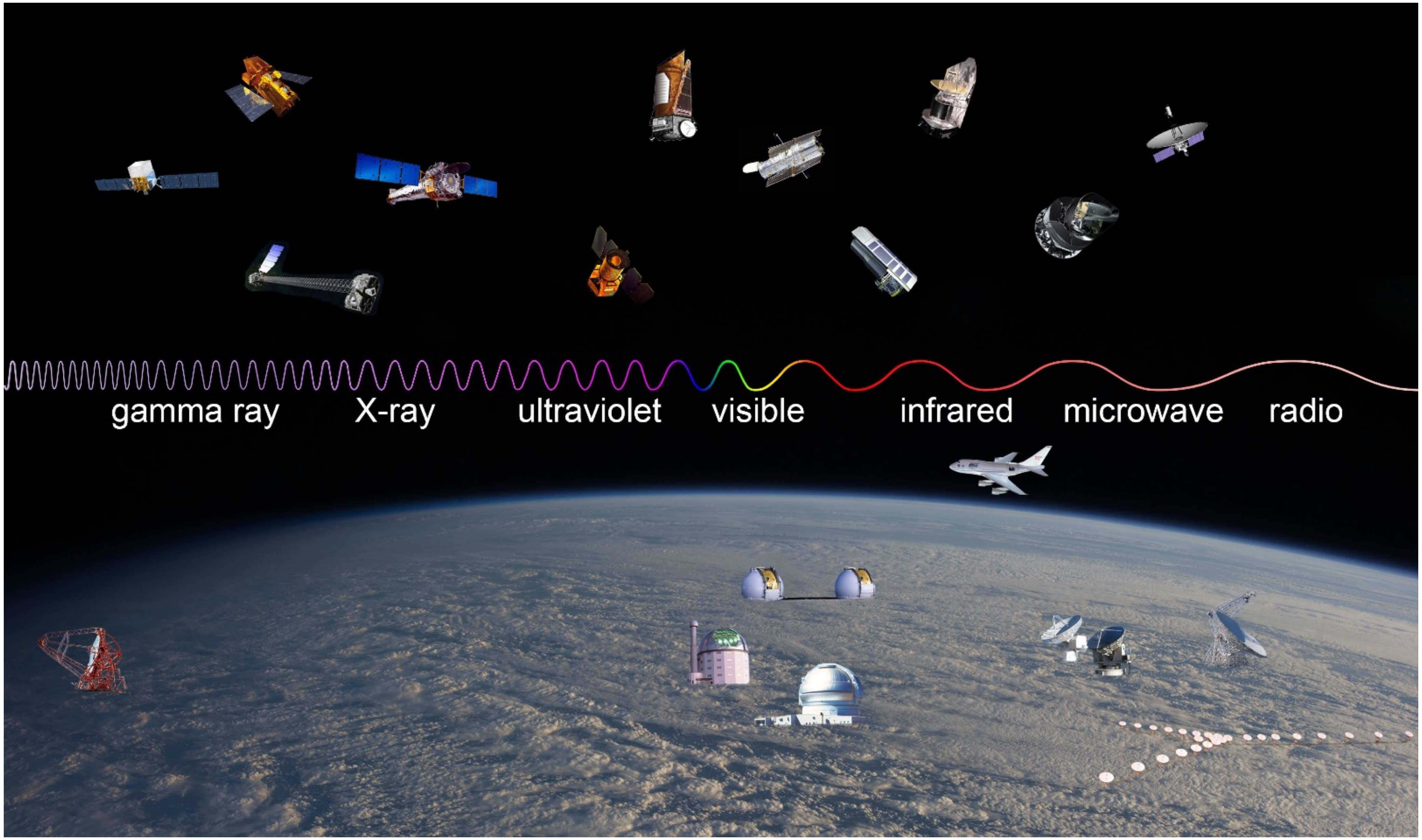


Image credits: NASA

Gravitational Waves provide…

Whole new way of looking at the dark side of the Universe.

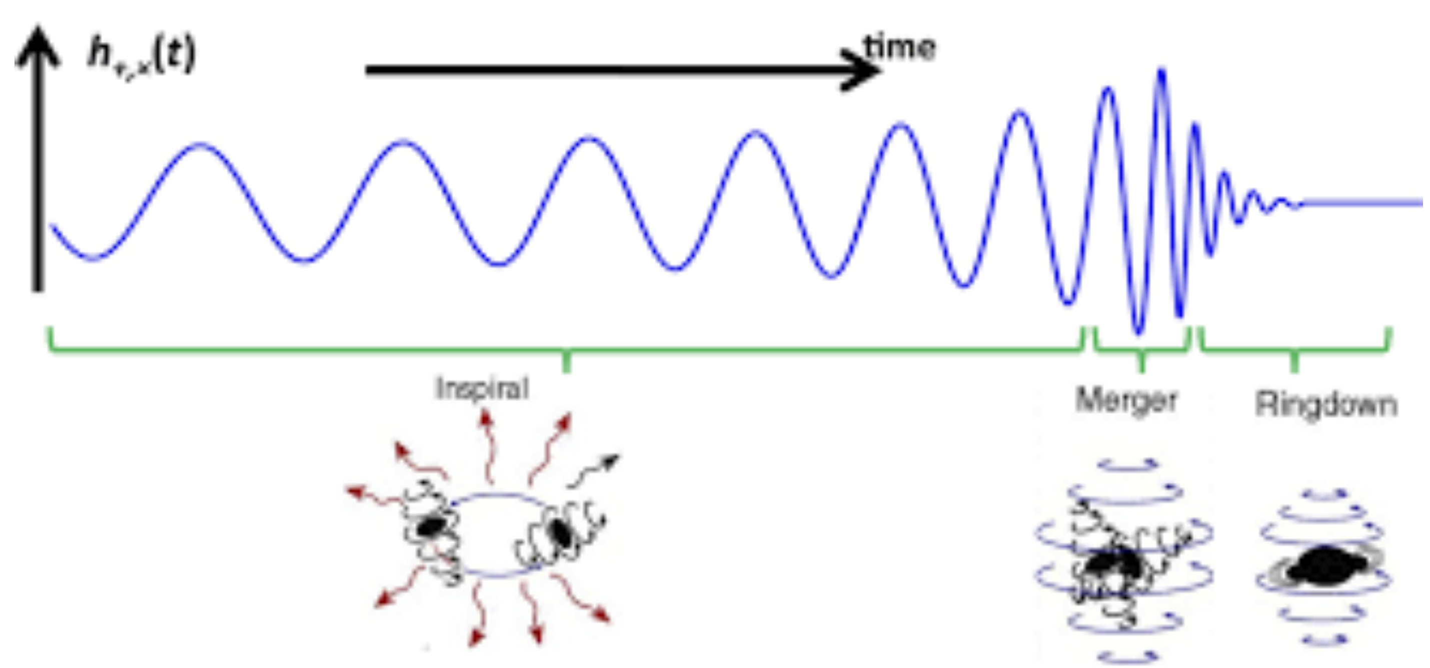
A new branch of Astronomy capable of revolutionising our understanding of the cosmos.

A new tool to probe fundamental Physics (Testing General Relativity.)

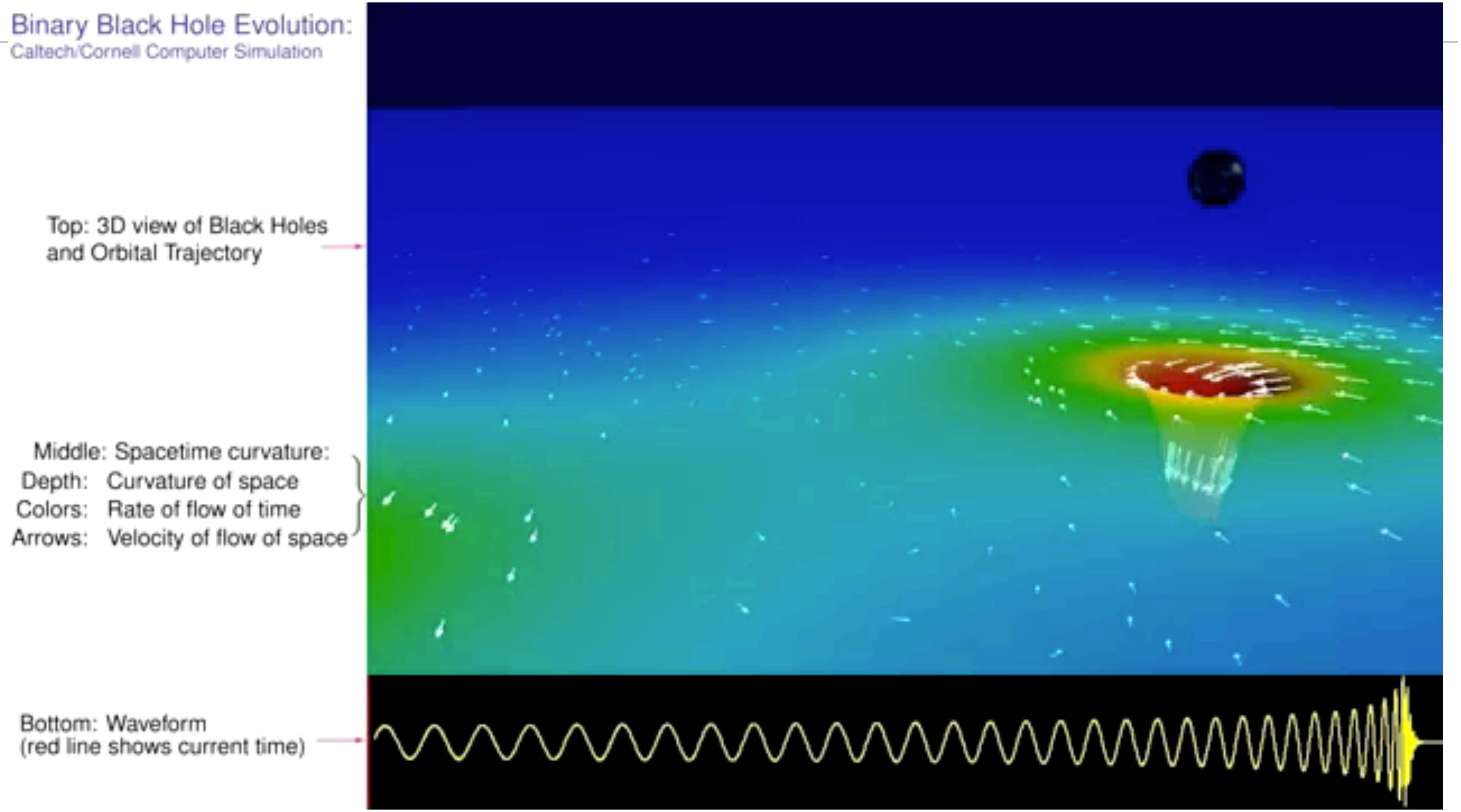
Compact binary mergers

Most promising GW source

Binaries consisting of Neutron Stars or Black holes loose energy to GWs and they merge.

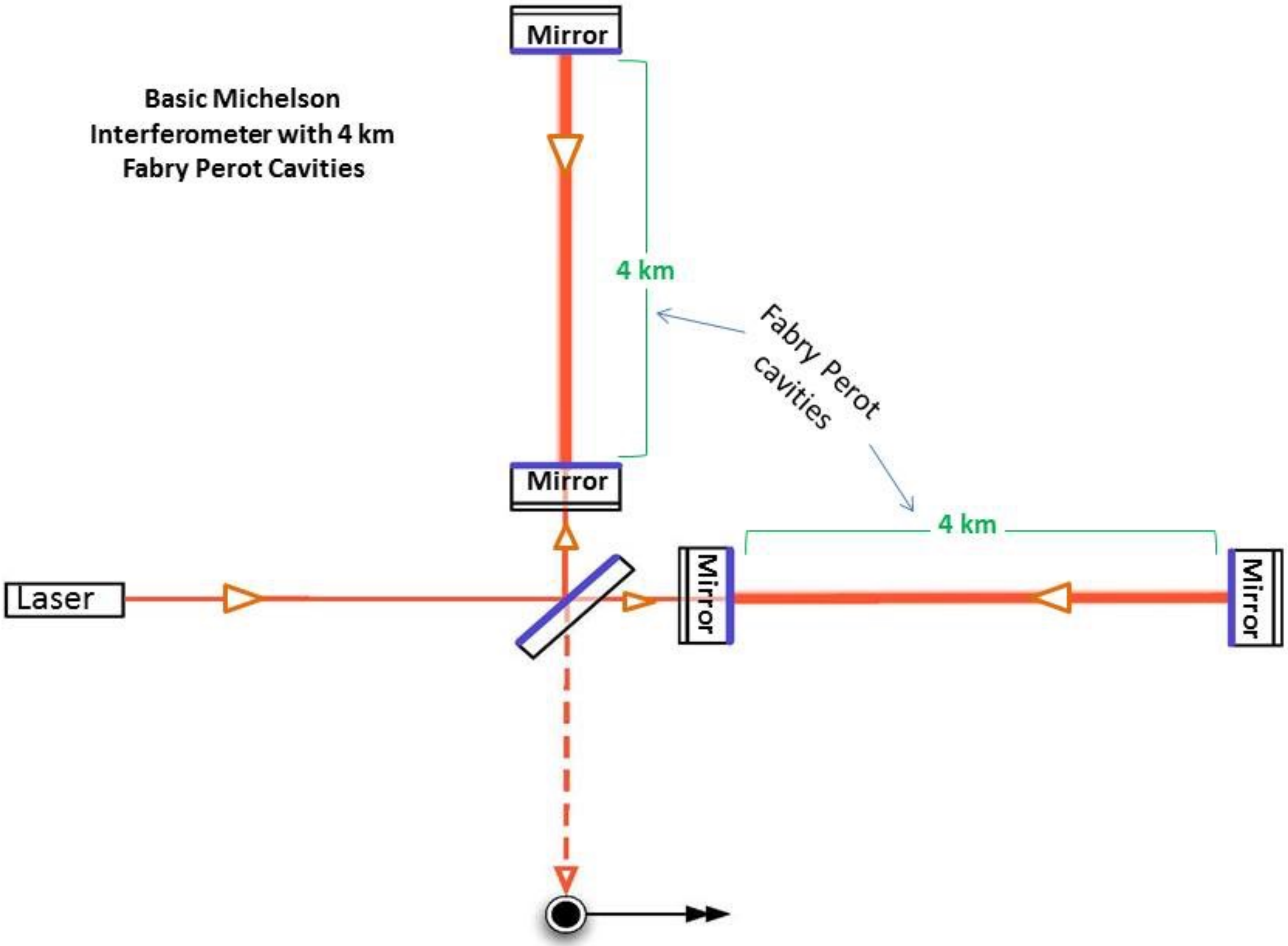


Binary black hole mergers



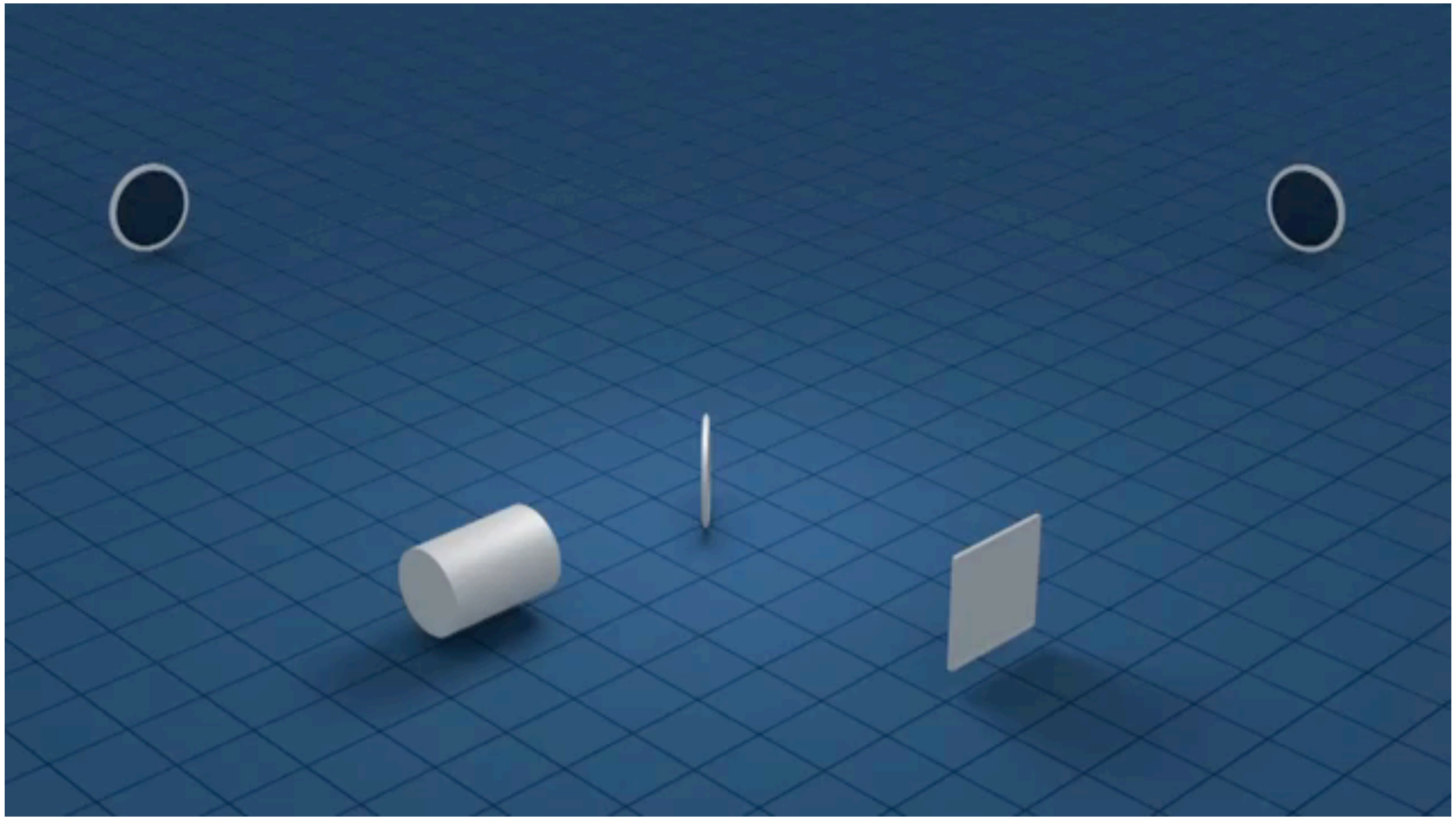
Courtesy: SXS Collaboration

Detecting Gravitational Waves



Basic Michelson
Interferometer with 4 km
Fabry Perot Cavities
Mirror
4 km
Fabry Perot
cavities
Mirror
4 km
Laser
Mirror
Mirror

A video of How LIGO works



Courtesy: Caustic Soda, youtube channel

Advanced LIGO and Virgo Interferometers

Kilometre scale interferometers

LIGO website

Virgo Website

Sensitivity of LIGO

Projected Noise Power Spectral Densities

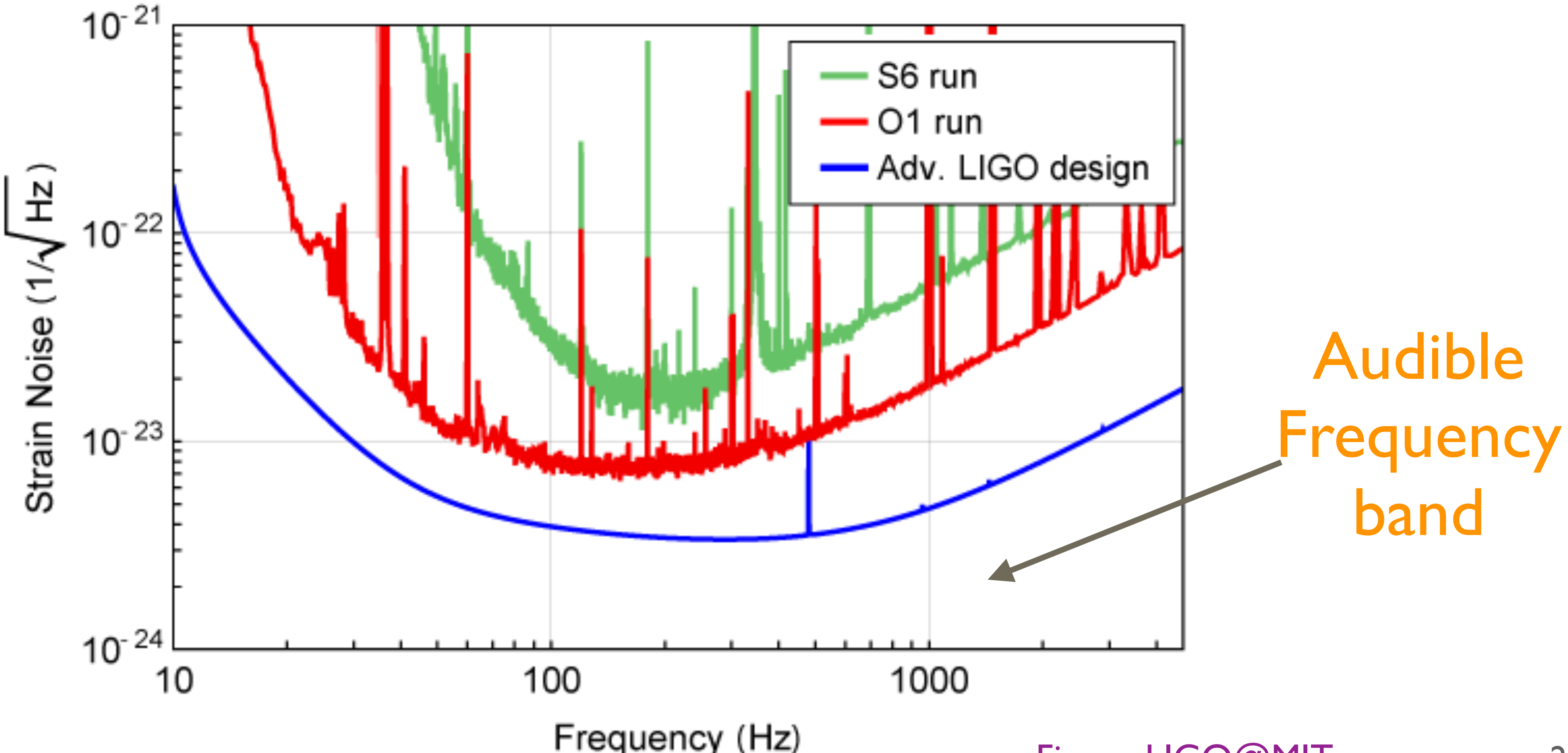
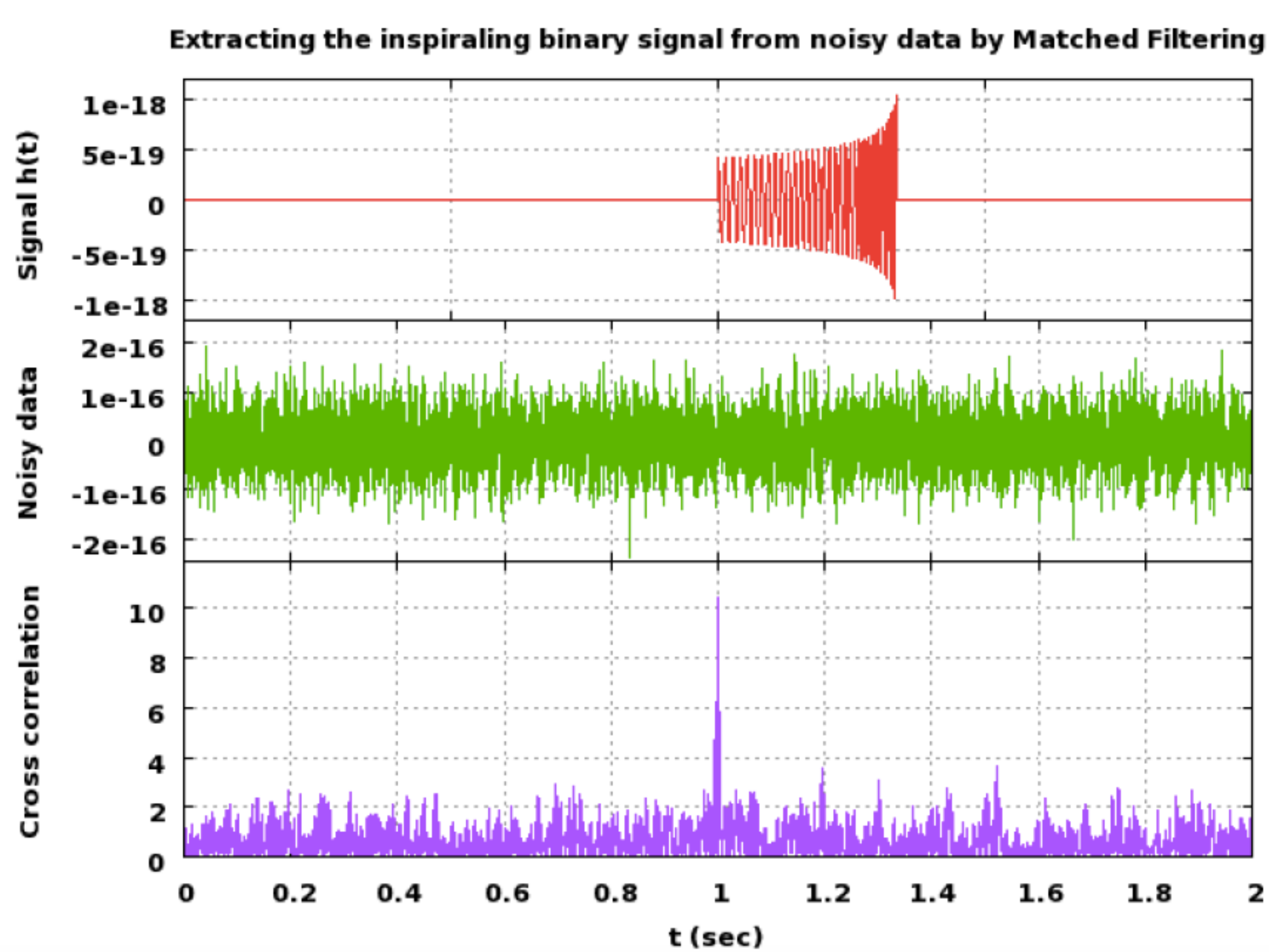


Figure: LIGO@MIT

Matched Filtering

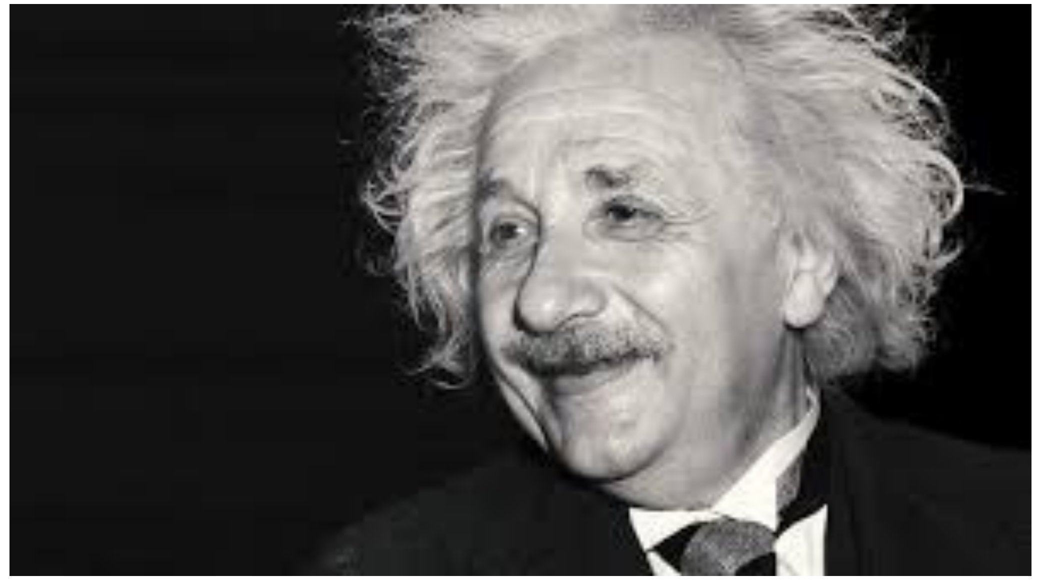
Searching weak signals in noisy data



Very accurate theoretical modelling is crucial.

Requires..

Very close interplay
between Experiments, Theory, Algorithms



Gravitational waves finally captured

On 14 September 2015, the universe's gravitational waves were observed for the very first time. The waves, which were predicted by Albert Einstein a hundred years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA.

The signal was extremely weak when it reached Earth, but is already promising a revolution in astrophysics. Gravitational waves are an entirely new way of observing the most violent events in space and testing the limits of our knowledge.

Nobel prize press release

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Rainer Weiss
Prize share: 1/2

© Nobel Media. Ill. N. Elmehed
Barry C. Barish
Prize share: 1/4

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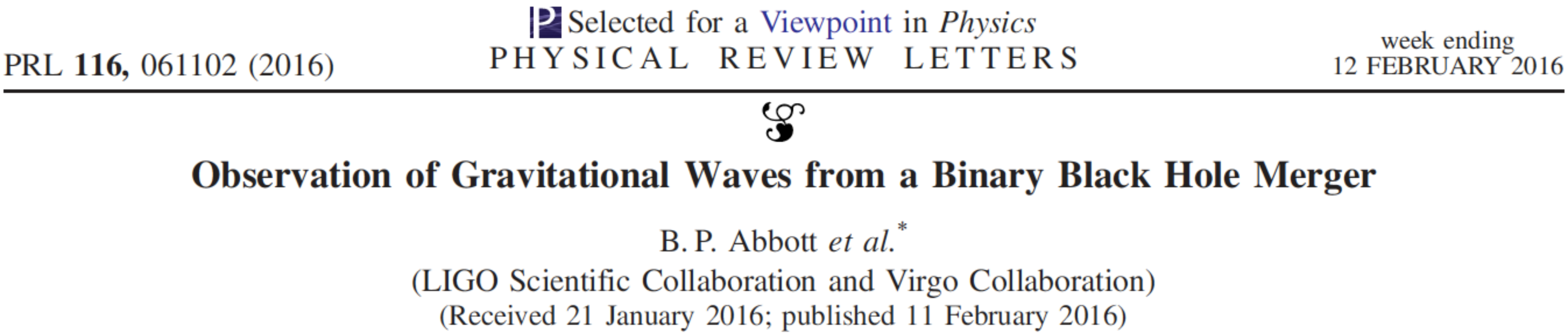
Kip S. Thorne
Prize share: 1/4

Nobel Prize, 2017

GW150914


PRL **116,** 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

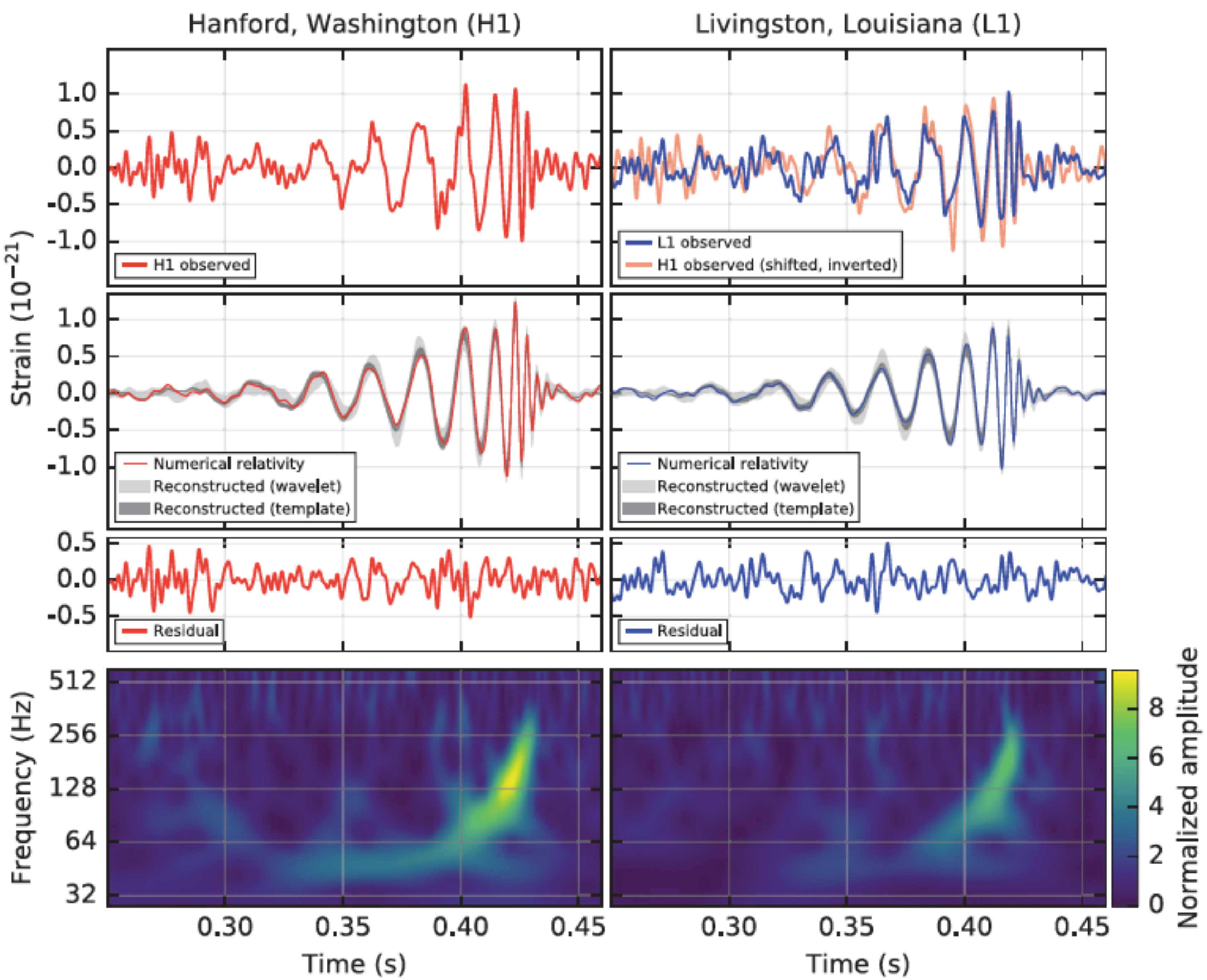
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

30 Msun + 35 Msun —> 62 Msun + 3 Msun GWs

1.3 billion light years away

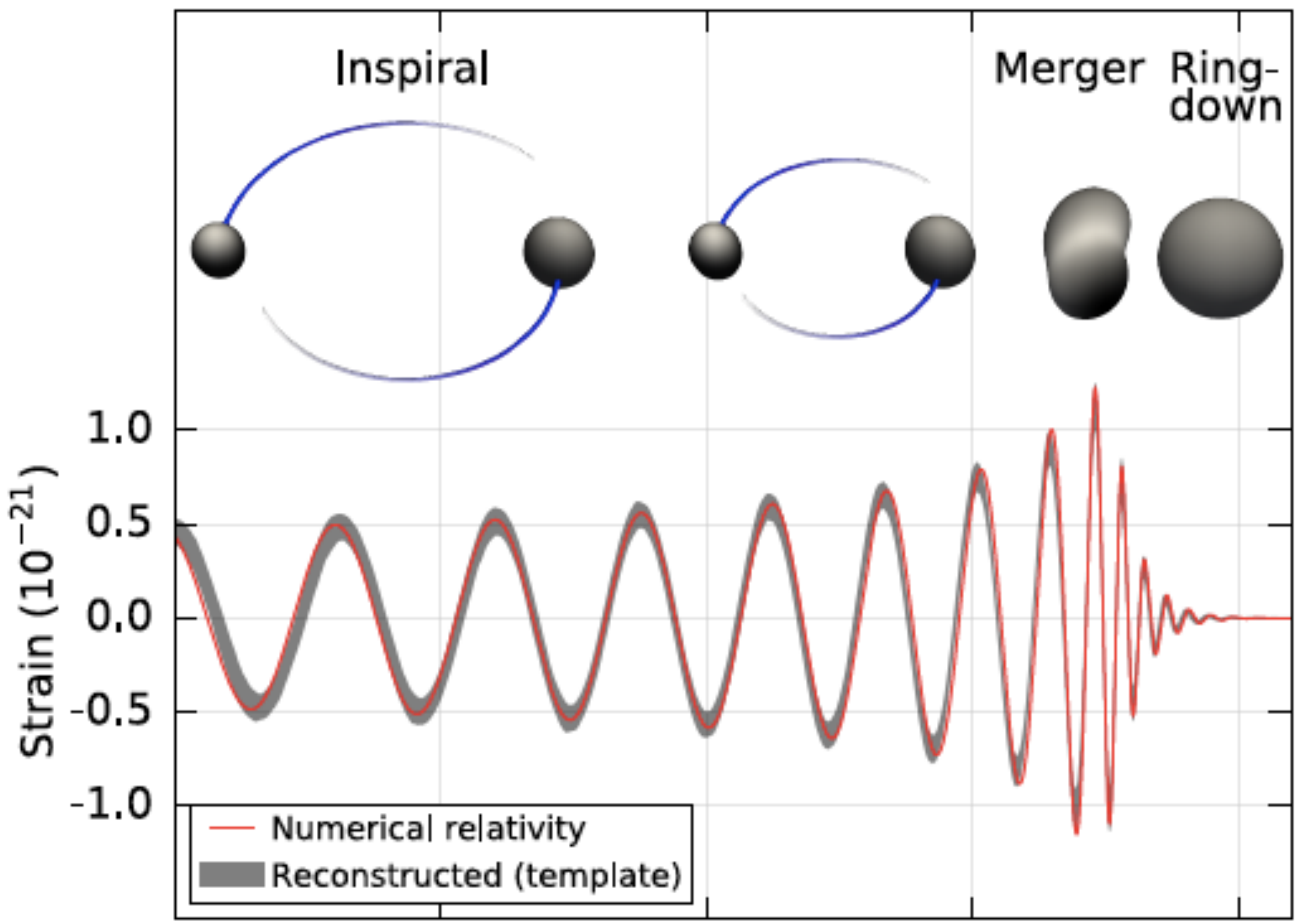
Several Indian Scientists played a crucial role in the Discovery.

Detected signal



LVC, PRL 116, 061102 (2016)

GW150914: Reconstructed Waveform

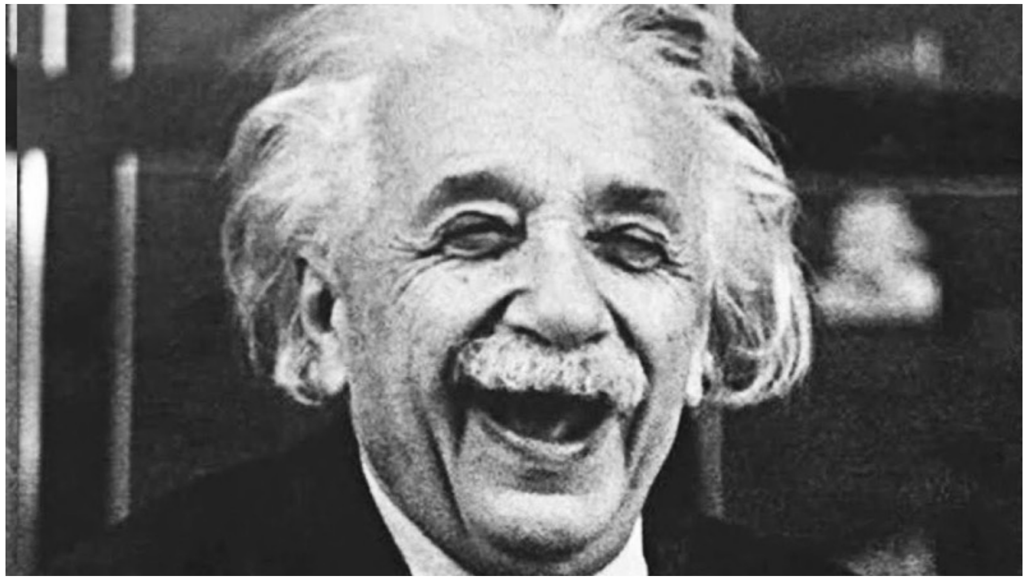


LVC, Phys. Rev. Lett. 116, 061102 (2016)

Template Based reconstruction and agreement with Numerical Relativity

Tests of General Relativity using GW150914

- Possible deviation of the observed signal from General Relativity was investigated by various means.
- The observed signal is consistent with the predicted GR waveform, within statistical uncertainties.
- These are the bounds from genuinely strong-field, radiative dynamics.
- **GR rocks!**



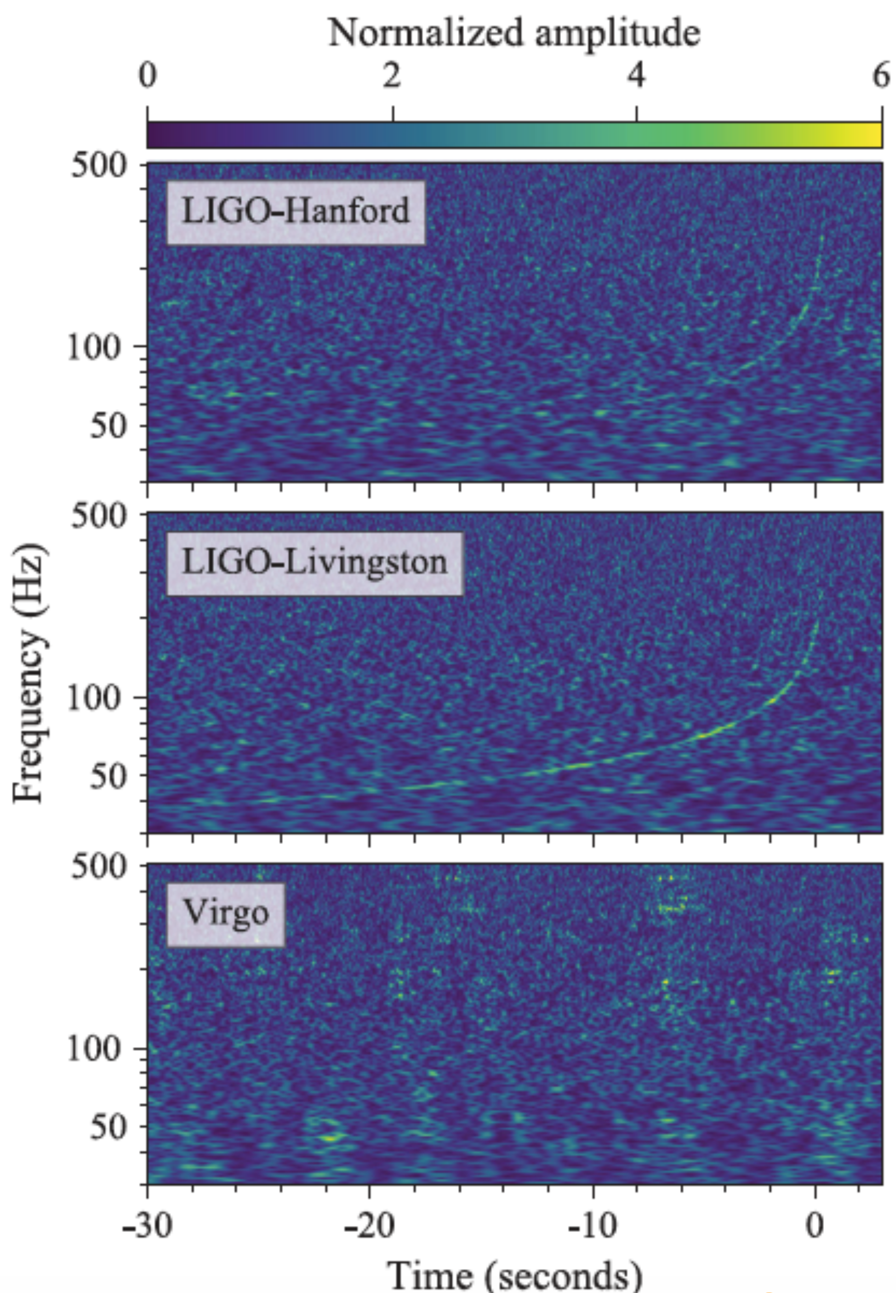
The firsts…

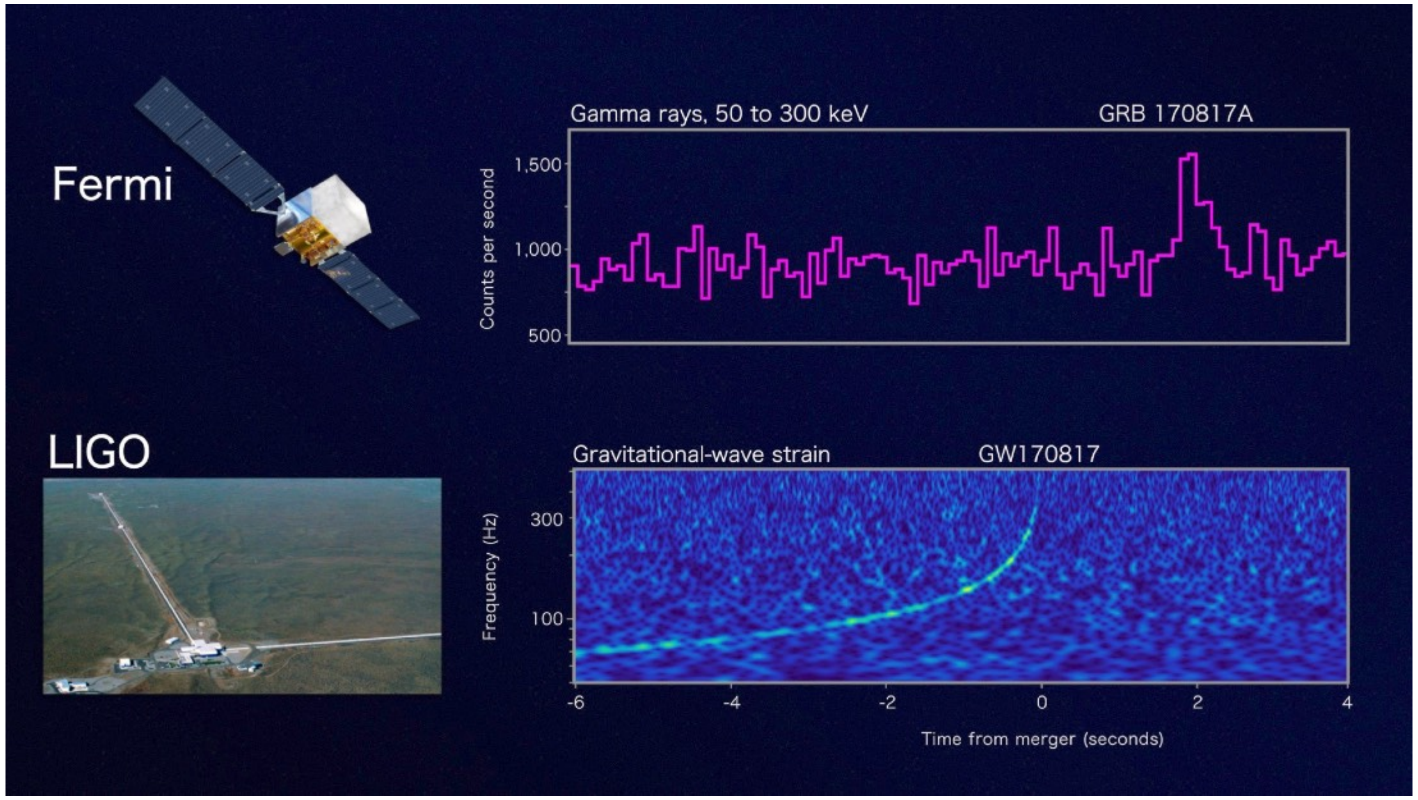
A milestone in astronomy

- First direct detection of a GW signal inaugurated Gravitational Wave Astronomy.
- First direct detection of black holes.
- First observation of a binary black hole merger.
- First tests of GR from highly relativistic, radiative regime.

GW170817: Binary Neutron Star merger

Gravitational Waves and Light





Source: NASA

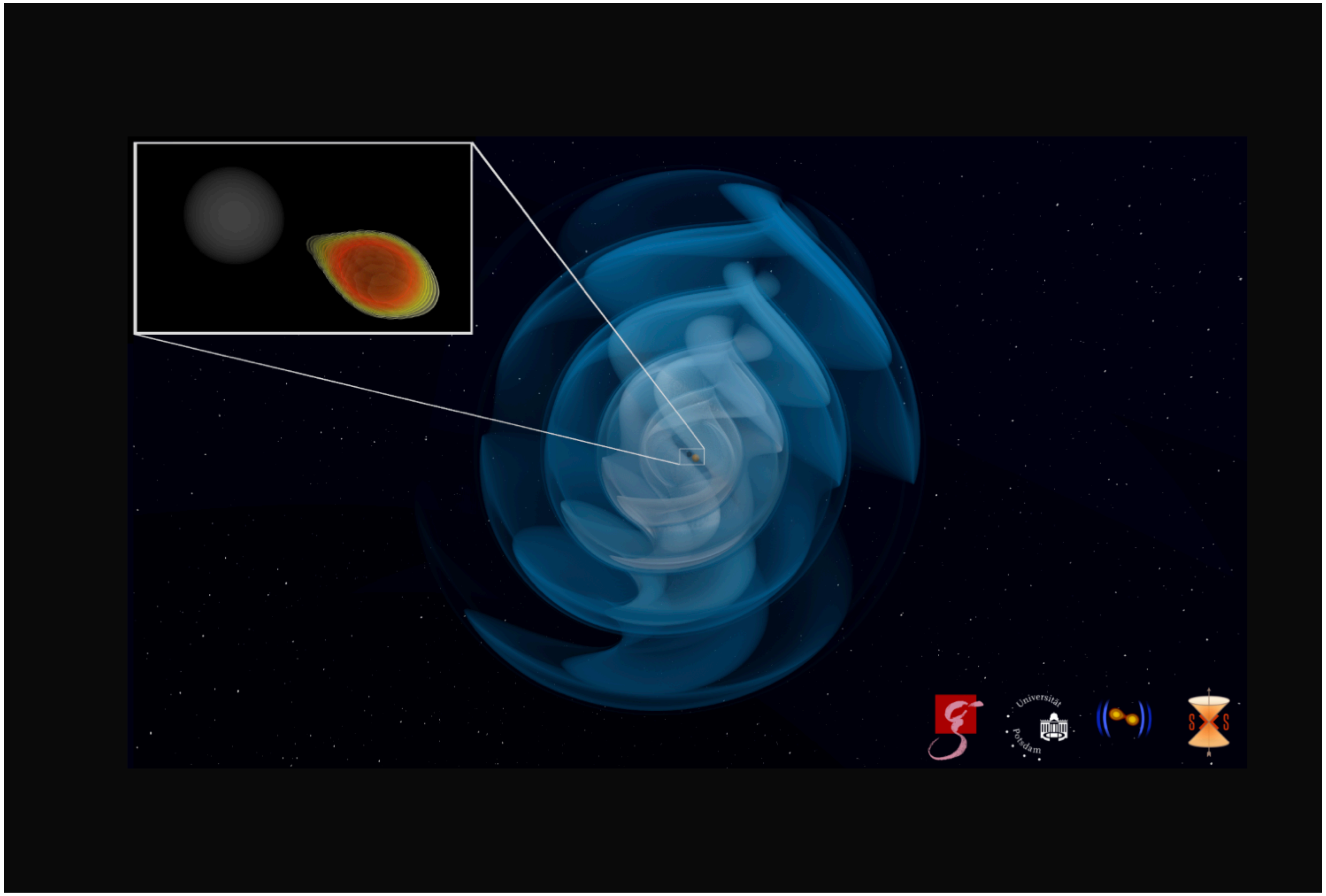
LVC, PRL 119, 161101 (2017)

Another Milestone in Astronomy

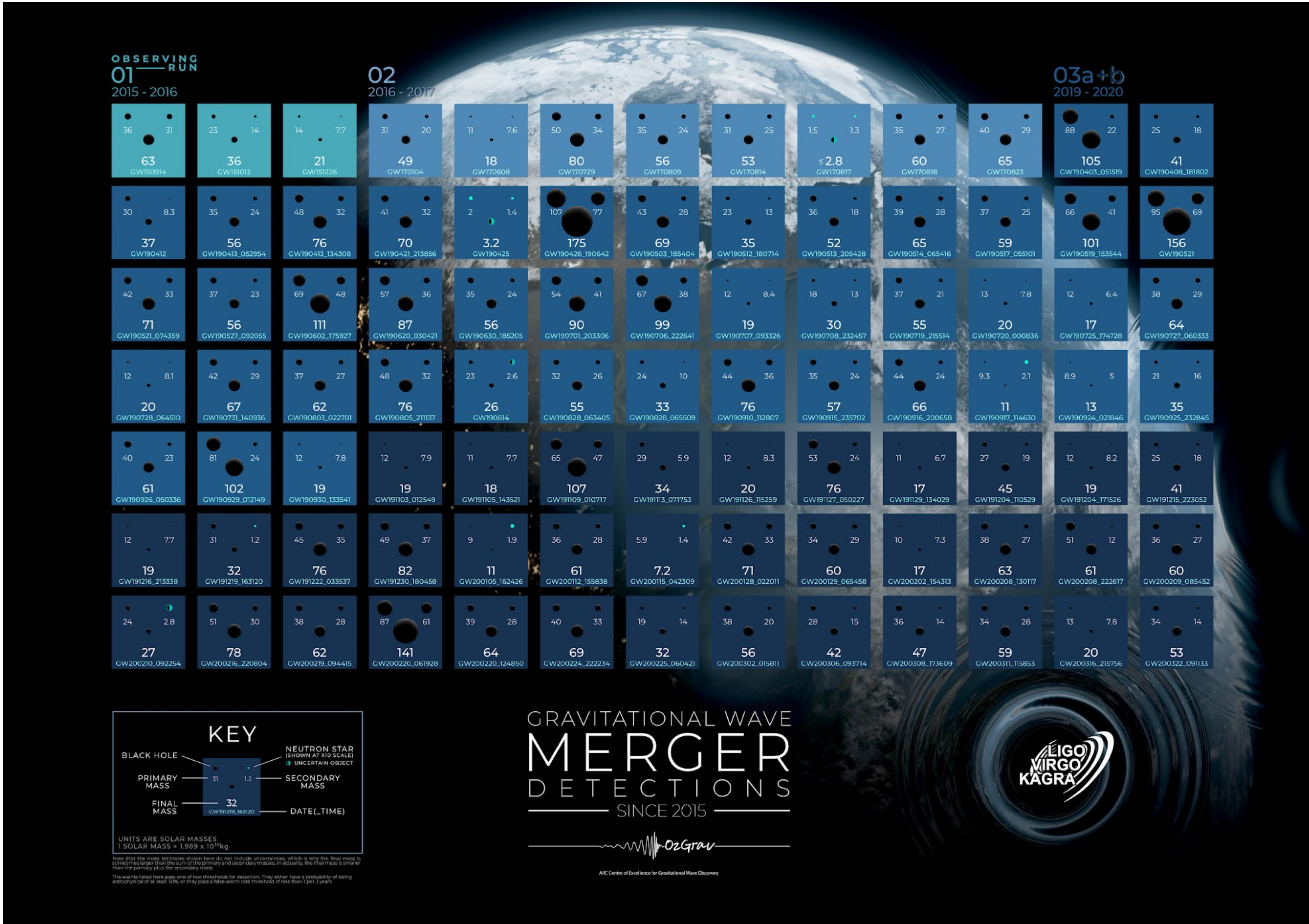
- First detection of the merger of two neutron stars (predicted to exist by Hulse-Taylor 1972)
- Light and GWs from the same source! [Multi-messenger Astronomy]
- Verification of the hypothesis that binary neutron star mergers produce short gamma ray bursts.
- A direct way to measure the equation of state of the neutron star.
- Several other impacts on fundamental physics and cosmology.

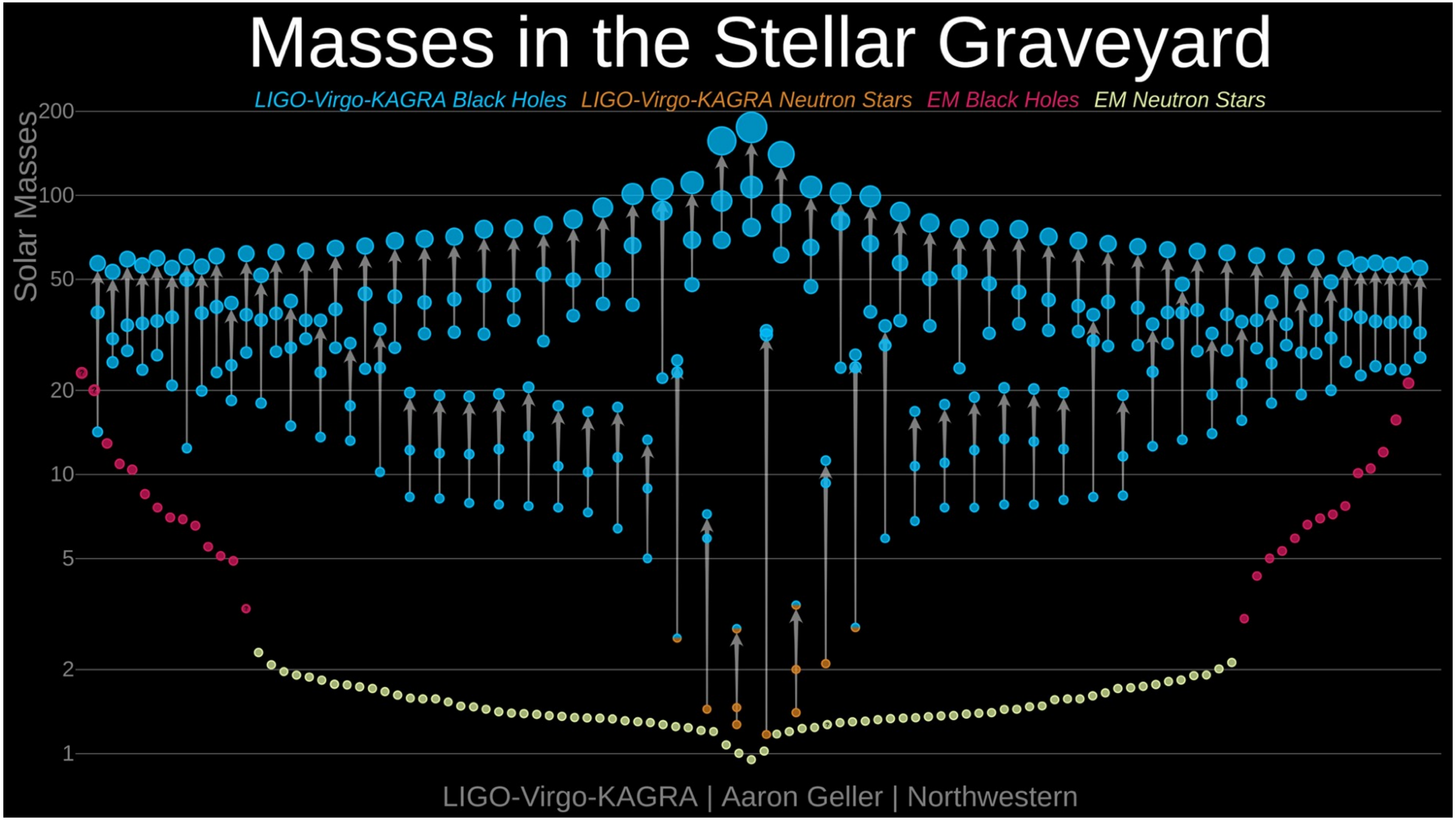
This path-breaking discovery has given us
unique insights about astrophysics and fundamental physics

NS-BH merger: GW200115



No light detected in association with this event


OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
31 1.2
FINAL MASS
32
GW191219_163120
DATE(_TIME)
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^30 kg
Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
LIGO
VIRGO
KAGRA



86 BBHs, 2 BNSs and 1 NS-BH with $p_{\mathrm{astro}} \geq 0.5$

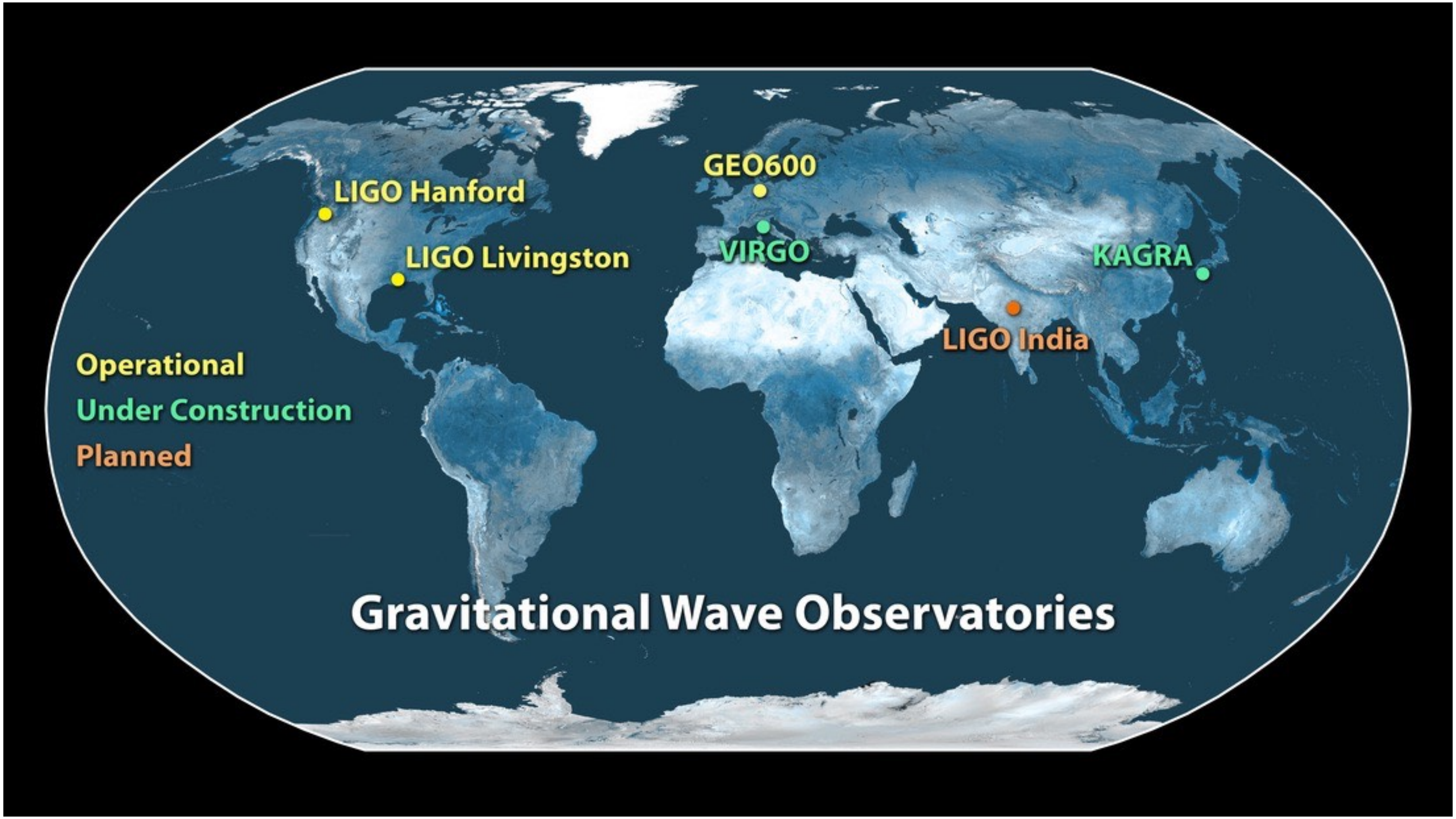
It is raining Black holes!

Story so far

- Discoveries of binary BHs, binary NSs and NS-BH.
- Light from the BNS merger (Multi-messenger astronomy)
- A BBH with a total mass of ~150 Msun.
- Mass spectrum of BHs.
- Tests of GR, Measurement of Hubble constant, NS equation of state,…

Looking forward

World-wide network of detectors



Courtesy: LSC

LIGO-India

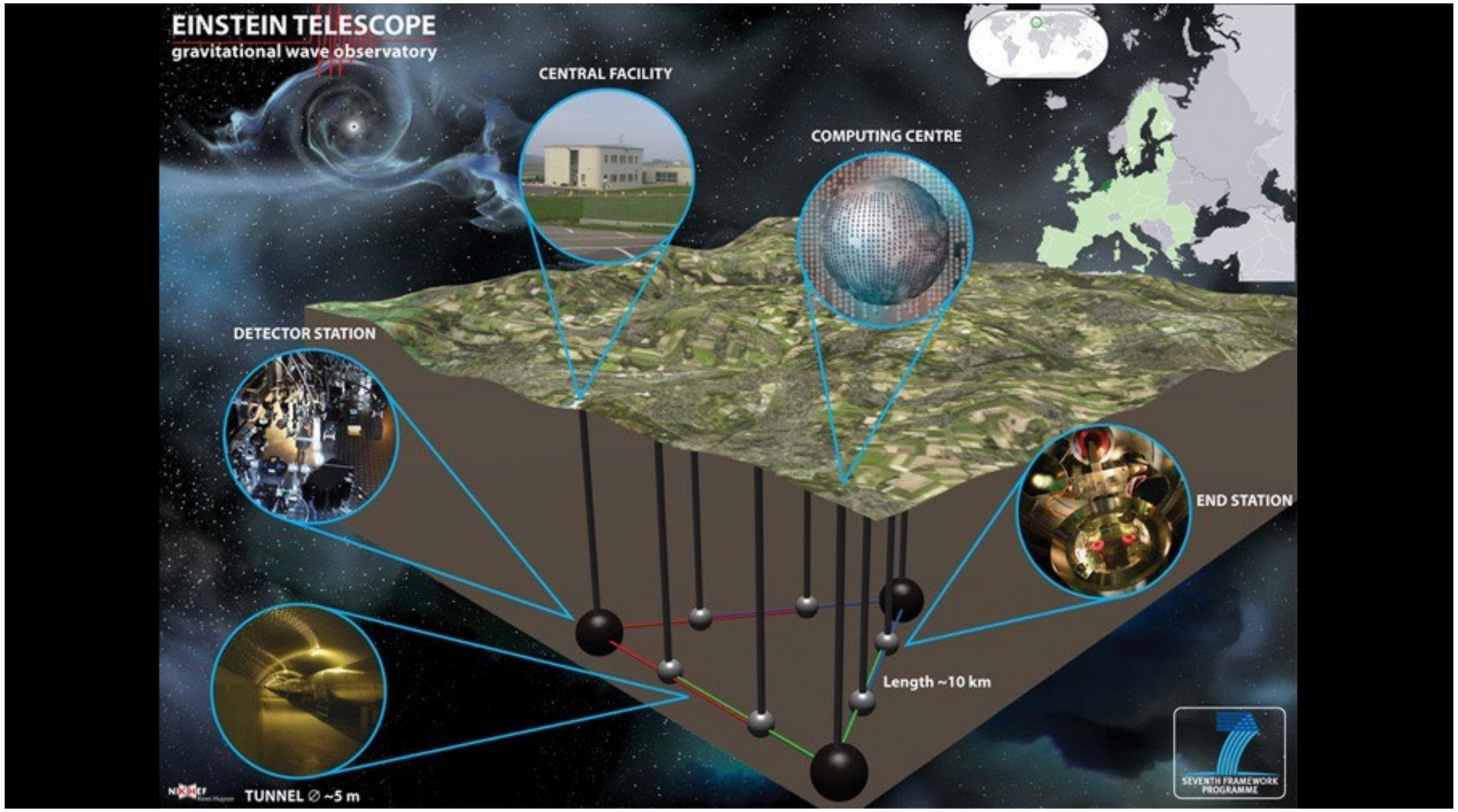
A planned GW detector in India

Design of the proposed site,
Credits: T. Souradeep

- Adding LIGO-India to the planned world wide network of advanced GW detectors would significantly enhance the sky coverage, duty cycle as well as the source localisation which are crucial for multi-messenger astronomy.

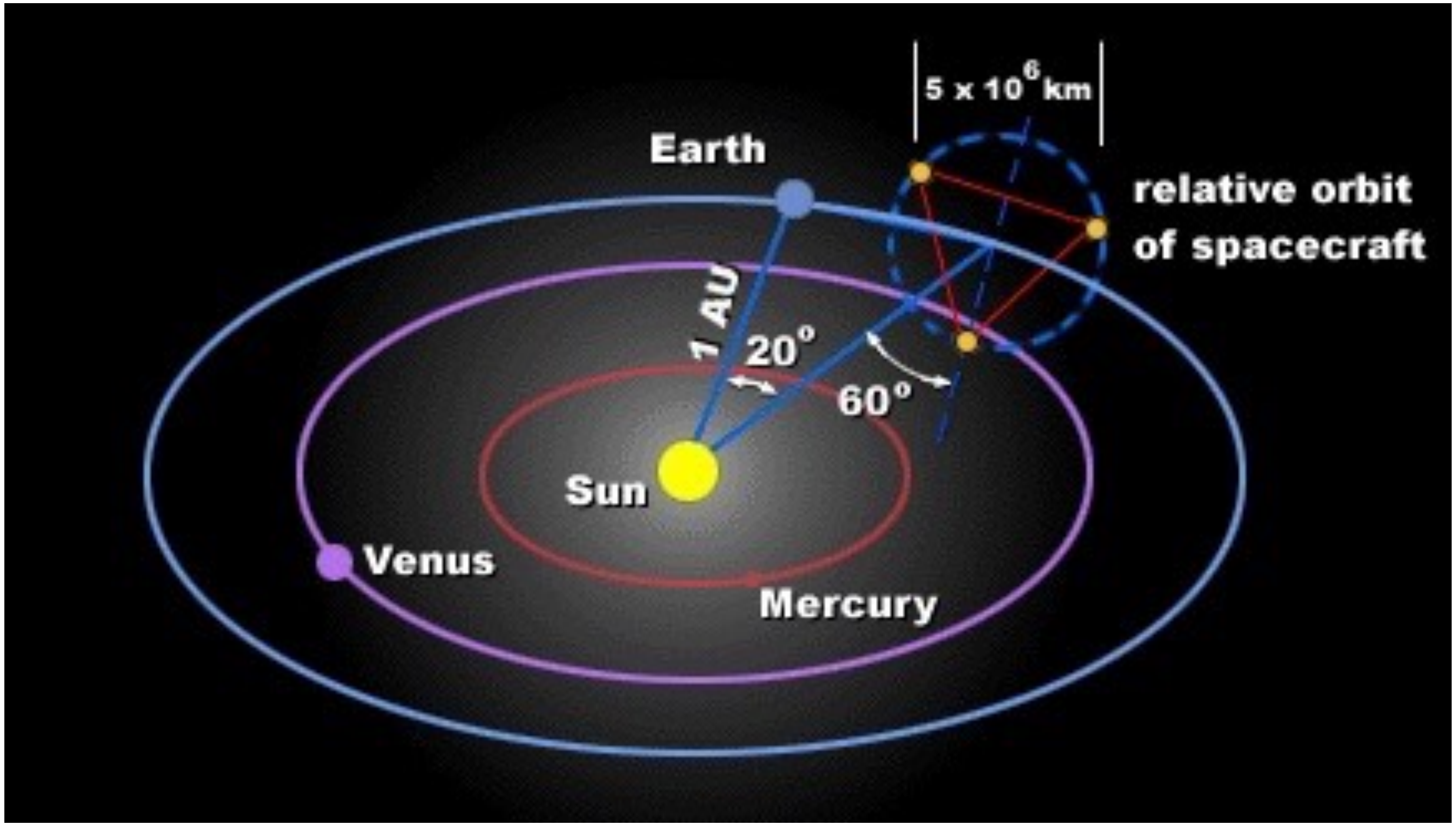
3G detectors beyond Adv LIGO

Einstein Telescope



2034+

LISA mission



Pic: ESA

A milli Hertz detector to listen to supermassive BH mergers

Conclusions

- Gravitational Waves are unique messengers of the cosmos, which can complement the information we get from Light.
- First detection of gravitational waves has made a significant impact on our understanding of the Nature.
- With LIGO-India, India is slated to play a big role in the field of gravitational wave astronomy in the years to come.