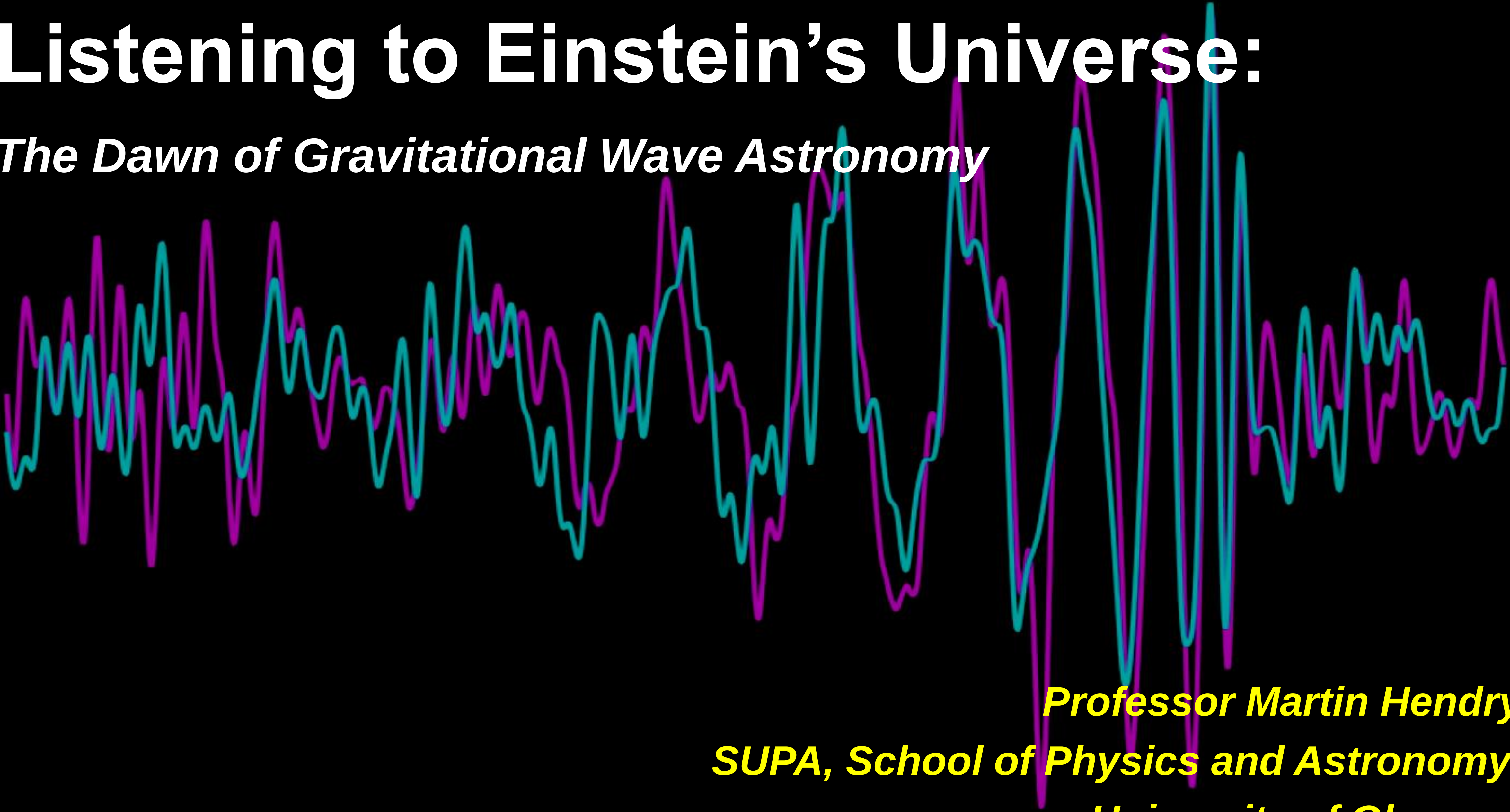
Listening to Einstein's Universe:

The Dawn of Gravitational Wave Astronomy



Professor Martin Hendry
SUPA, School of Physics and Astronomy
University of Glasgow

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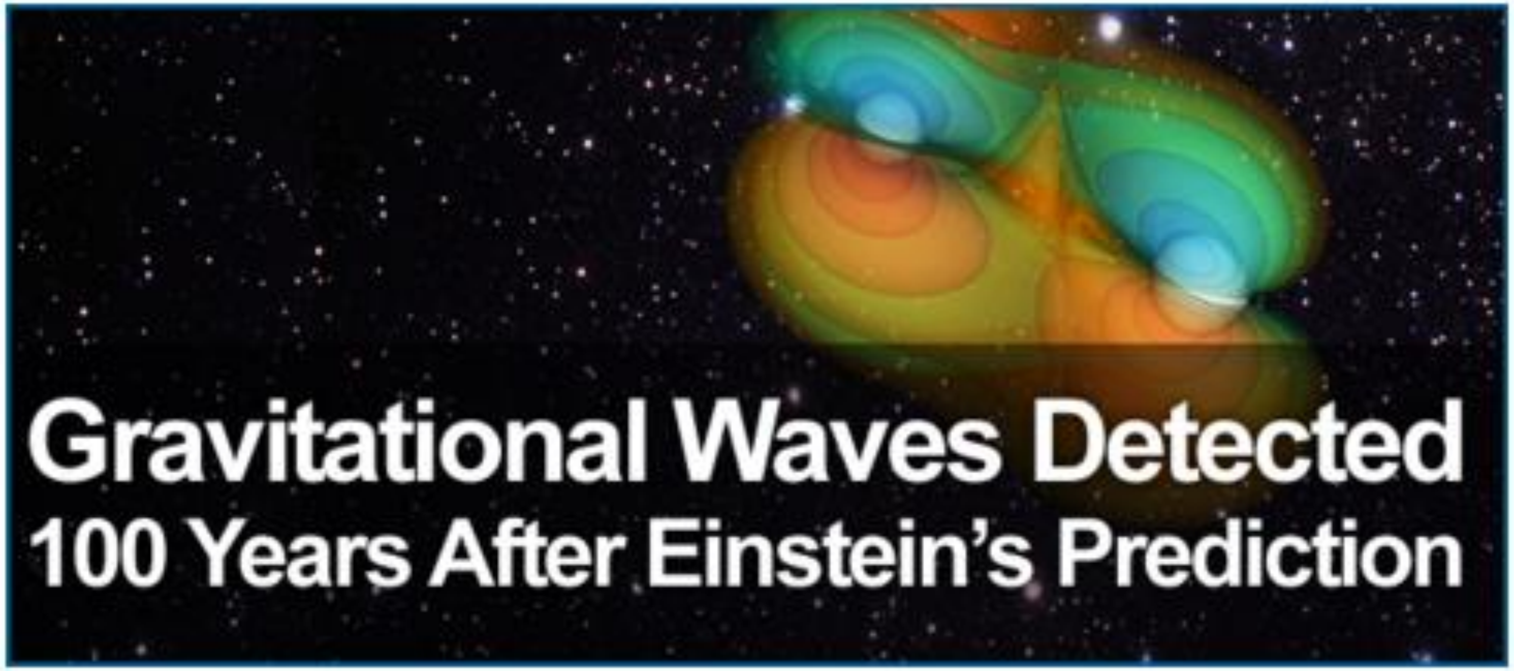

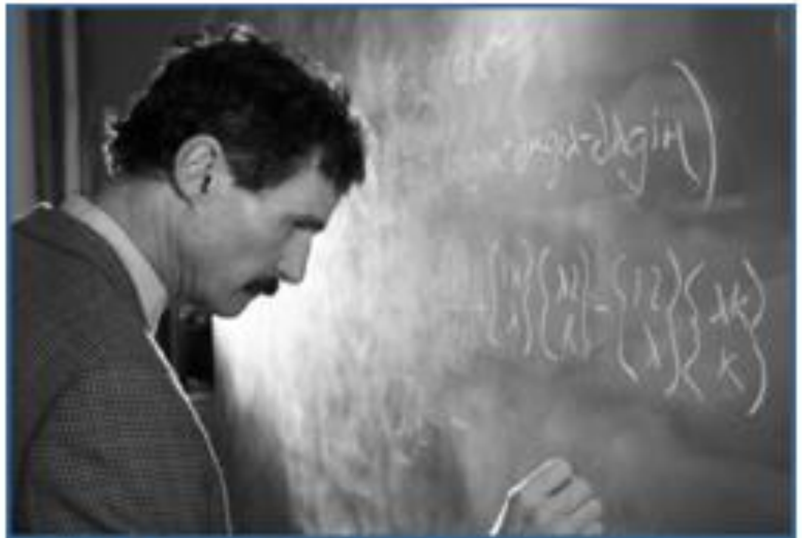

"LIGO, the Path to Detection": Watch the trailer for this new film.

NEWS

Feb 24, 2016 LIGO members to testify on the discovery at US Congress

Feb 17, 2016 LIGO-India approved

Feb 12, 2016 White House Congratulates the LIGO Team

PRESS RELEASE

Feb 11, 2016
Gravitational Waves Detected 100 Years After Einstein's Prediction

More at the LIGO Lab website

"LIGO Generations": Four generations of scientists working toward one goal. Watch

LIGO Scientific Collaboration

Abilene Christian University
Albert-Einstein-Institut
American University
Andrews University
Bellevue College
California Institute of Technology
California State Univ., Fullerton
California State Univ., Los Angeles
Canadian Inst. Th. Astrophysics
Carleton College
Chinese University of Hong Kong
College of William and Mary
Colorado State University
Columbia U. in the City of New York
Cornell University
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
GW-INPE, Sao Jose Brasil
Hillsdale College
Hobart & William Smith Colleges
IAP – Nizhny Novogorod
IIP-UFRN
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Marshall Space Flight Center
Montana State University
Montclair State University
Moscow State University
National Tsing Hua University
NCSARG – Univ. of Illinois, Urbana-Champaign

Northwestern University
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern University
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Syracuse University
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Trinity University
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University of Tokyo
University of Washington
University of Washington Bothell
University of Wisconsin – Milwaukee
USC – Information Sciences Institute
Villanova University
Washington State University – Pullman
West Virginia University
Whitman College

LIGO Laboratory: California Institute of Technology; Massachusetts Institute of Technology; LIGO Hanford Observatory; LIGO Livingston Observatory

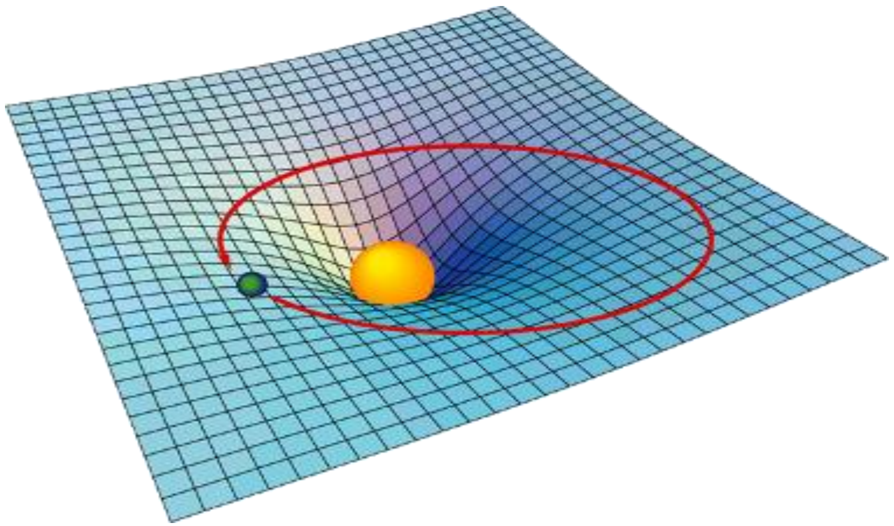
Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University; Charles Sturt University; Monash University; Swinburne University; University of Adelaide; University of Melbourne; University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Albert-Einstein-Institut, Hannover; Cardiff University; King's College, University of London; Leibniz Universität, Hannover; University of Birmingham; University of Cambridge; University of Glasgow; University of Hamburg; University of Sheffield; University of Southampton; University of Strathclyde; University of the West of Scotland; University of Zurich

Indian Initiative in Gravitational-Wave Observations (IndIGO):
Chennai Mathematical Institute; ICTS-TIFR Bangalore; IISER Pune; IISER Kolkata; IISER-TVM Thiruvananthapuram; IIT Madras, Chennai; IIT Kanpur; IIT Gandhinagar; IPR Bhatt; IUCAA Pune; RRCAT Indore; University of Delhi

Gravitational Waves: the Story So Far

In **General Relativity** gravity is described by the curvature of space-time



Matter tells spacetime how to curve.

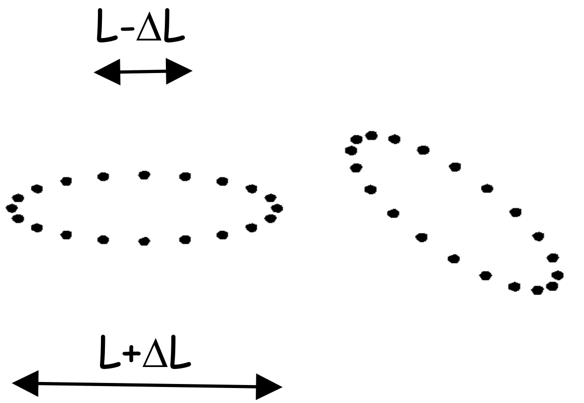
Spacetime tells matter how to move

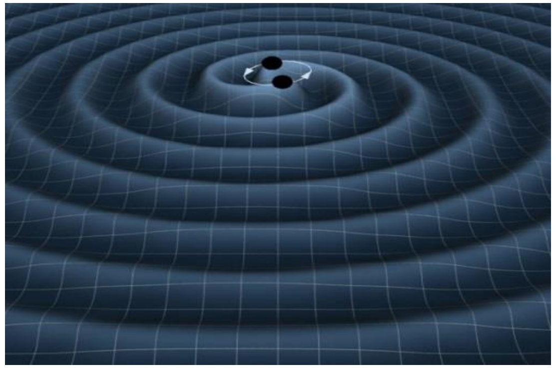
Gravitational waves are ripples in spacetime propagating at the speed of light (according to GR)

Created by acceleration of **massive compact objects**

Gravitational wave detectors measure changes in the **separation** between free test masses in this spacetime

$$\boxed{h = \frac{2\Delta L}{L}}$$

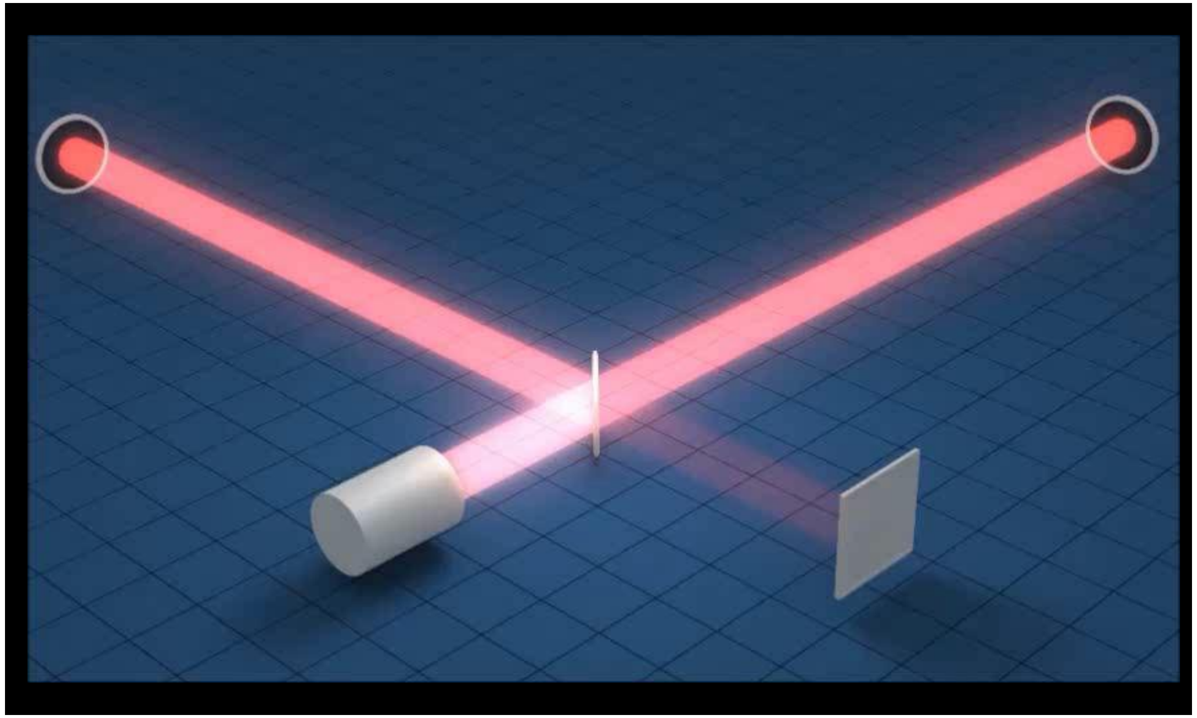


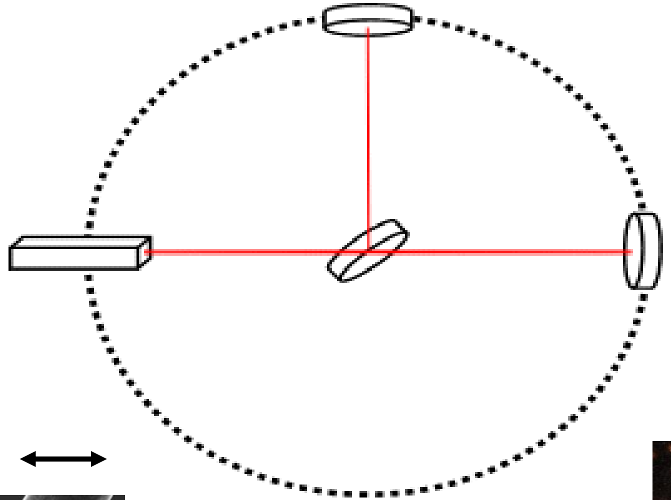


Interferometric Detectors

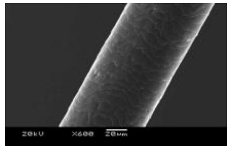
Interferometers monitor the position of suspended test masses separated by a few km

A passing gravitational wave will lengthen one arm and shrink the other arm; transducer of GW strain-intensity (10^{-18} m over 4 km)





10^{-5}m

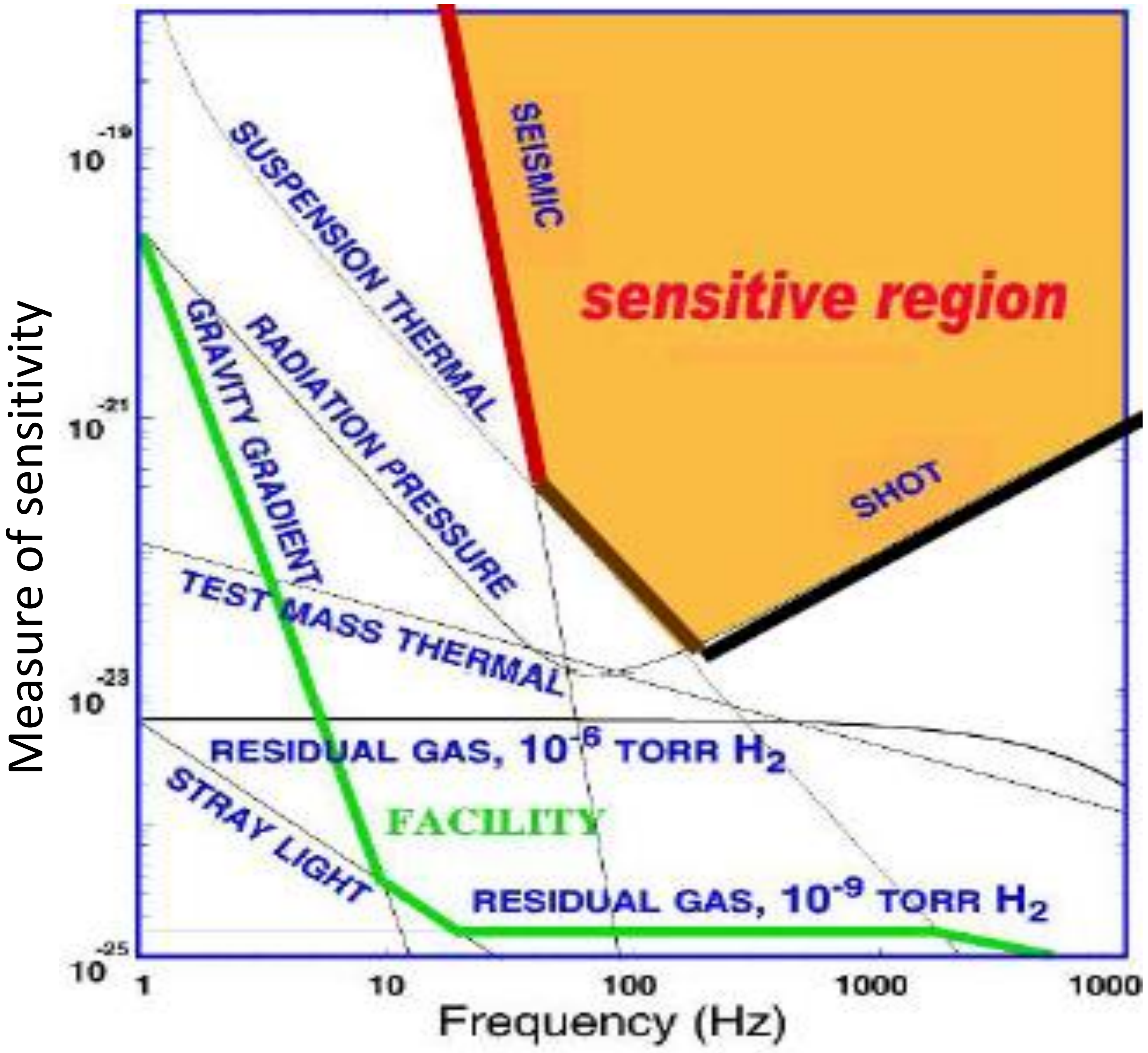


4×10^{16}m

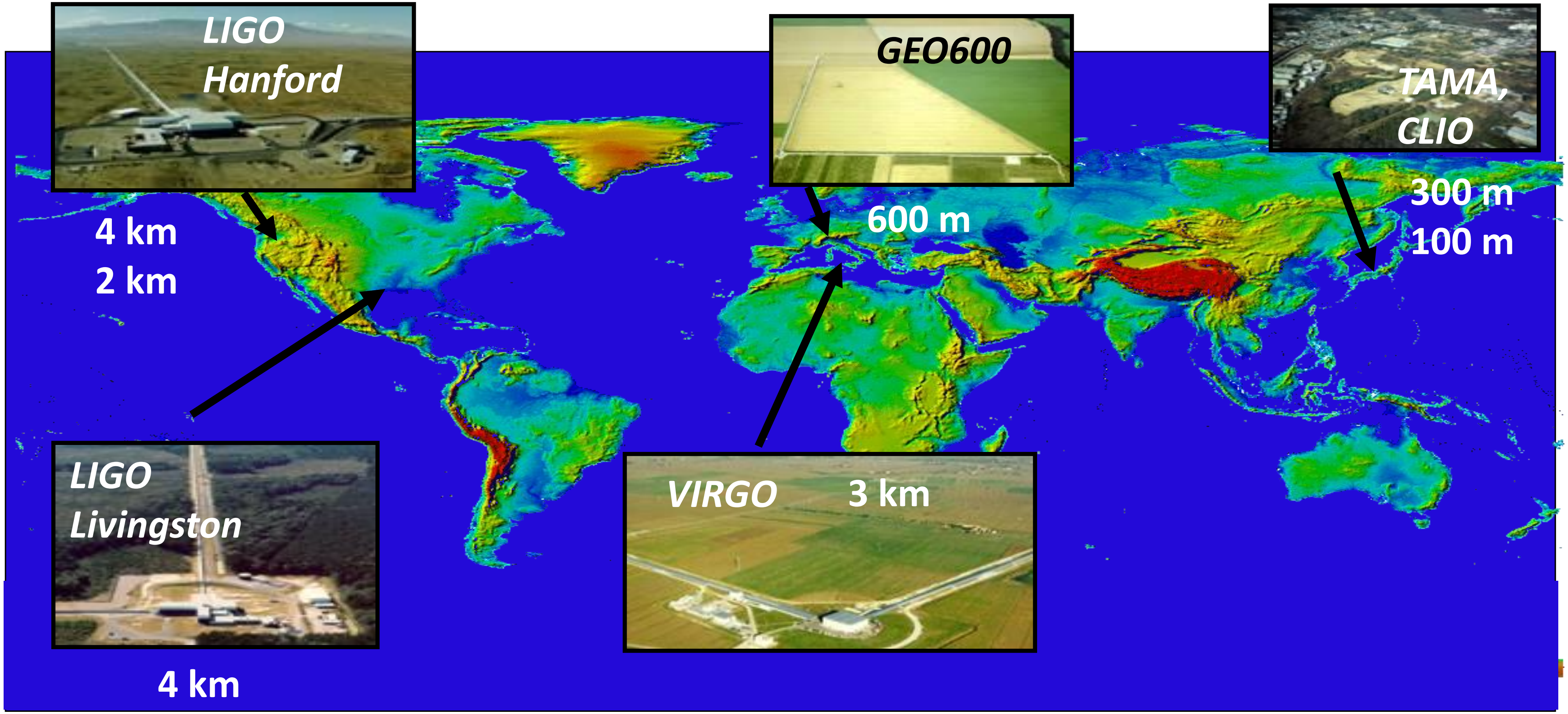
Limitations to sensitivity

Many sources of "noise"

- Seismic noise
- Gravitational gradient noise
- Radiation pressure
- Thermal noise
- Photon shot noise



Ground-based network of detectors: 2002-2010



LSC LIGO Scientific Collaboration

NEWS

09.20.10 LSC-Virgo Meeting in Cracow, Poland

04.27.10 LSC paper chosen by *Reports on Progress in Physics* as one of Highlights

PRESS RELEASES

05.24.10 'Astronomy's New Messengers' Arrive in Manhattan (2010 World Science Festival)

08.19.09 LIGO Listens for Gravitational Echoes of

The LIGO Scientific Collaboration (LSC) is a dynamic group of approximately 760 scientists worldwide who have joined together in the search for gravitational waves from the the most violent events in the universe. Learn more about gravitational waves and the LSC here!

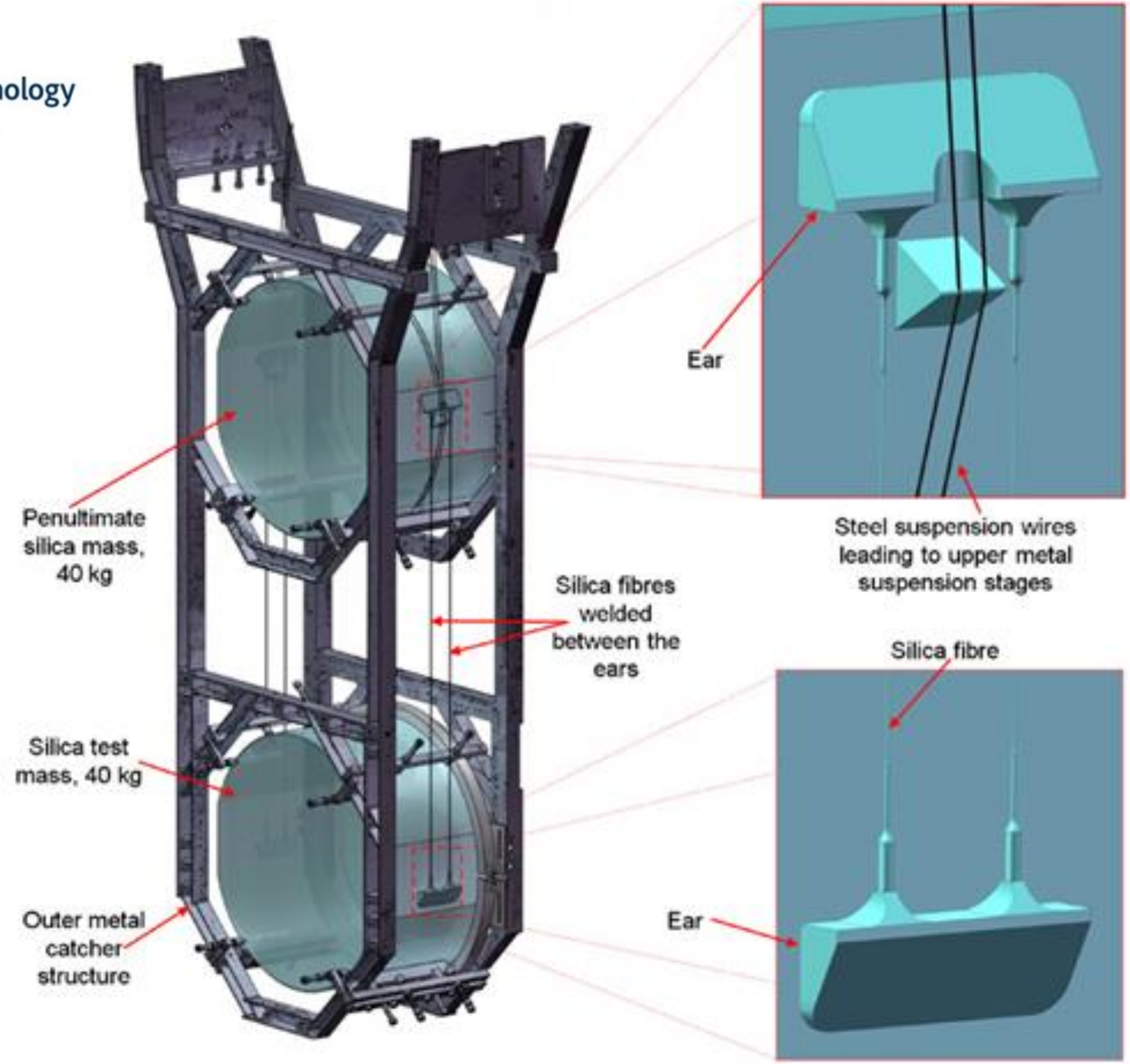
Science & Technology Facilities Council

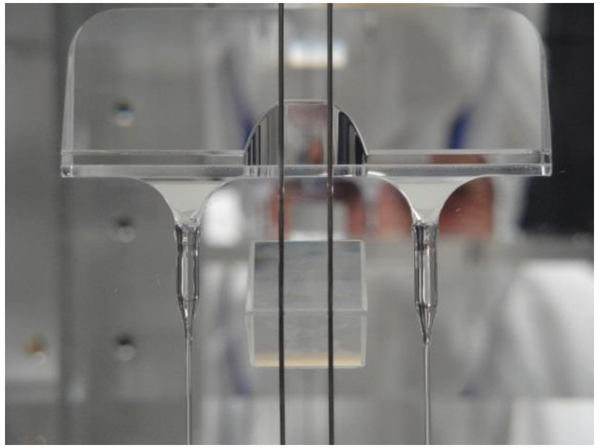
Developed in Glasgow, UK supplied:

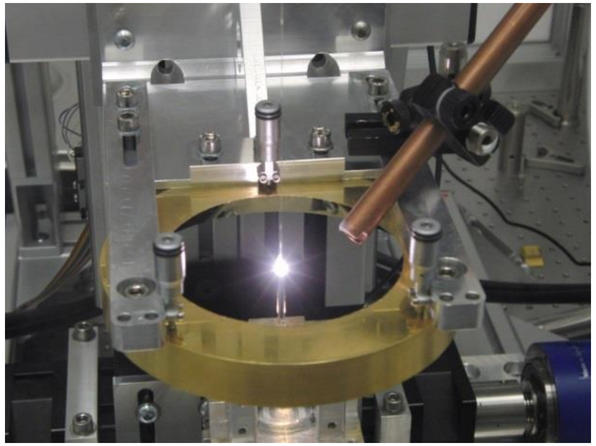
fused silica suspensions,

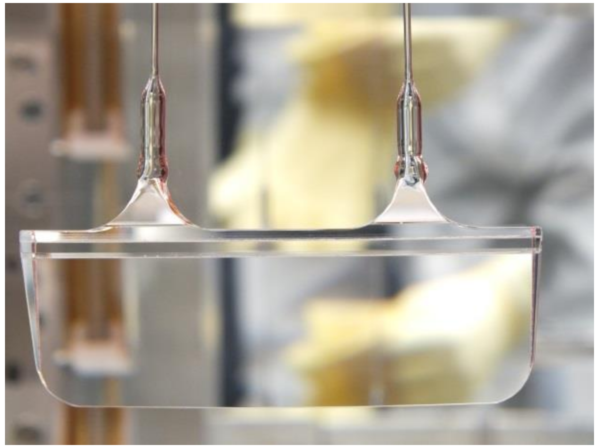
fibre-pulling,

bonding and welding









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"LIGO Generations": Bridging the gap between the language of astrophysics and bright young students. **Watch a new documentary about LIGO**

NEWS

Sep 22, 2015 LIGO featured in a BBC radio documentary

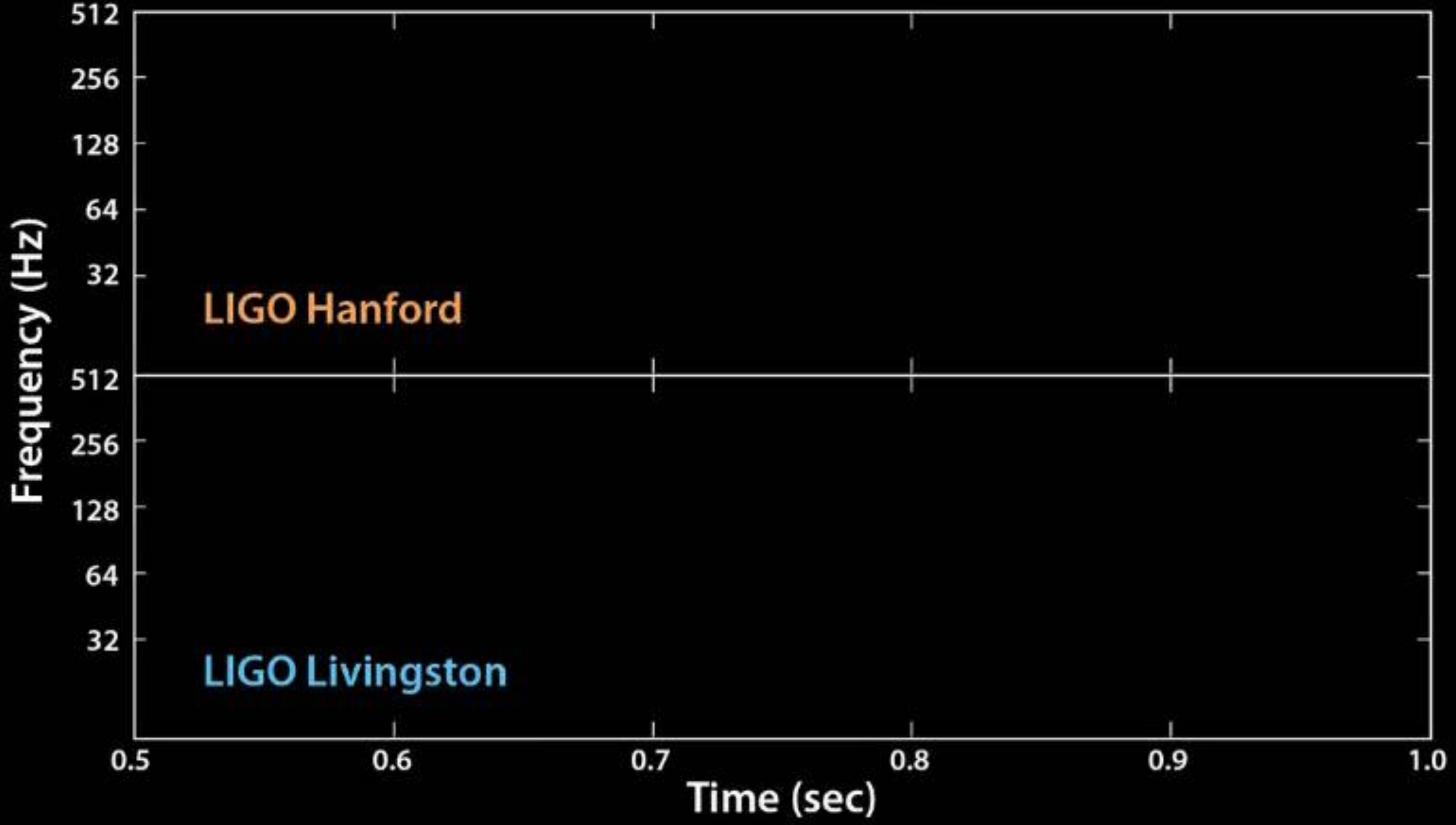
Sep 18, 2015 First Observing Run of LIGO's Advanced Detectors Begins

ABOUT

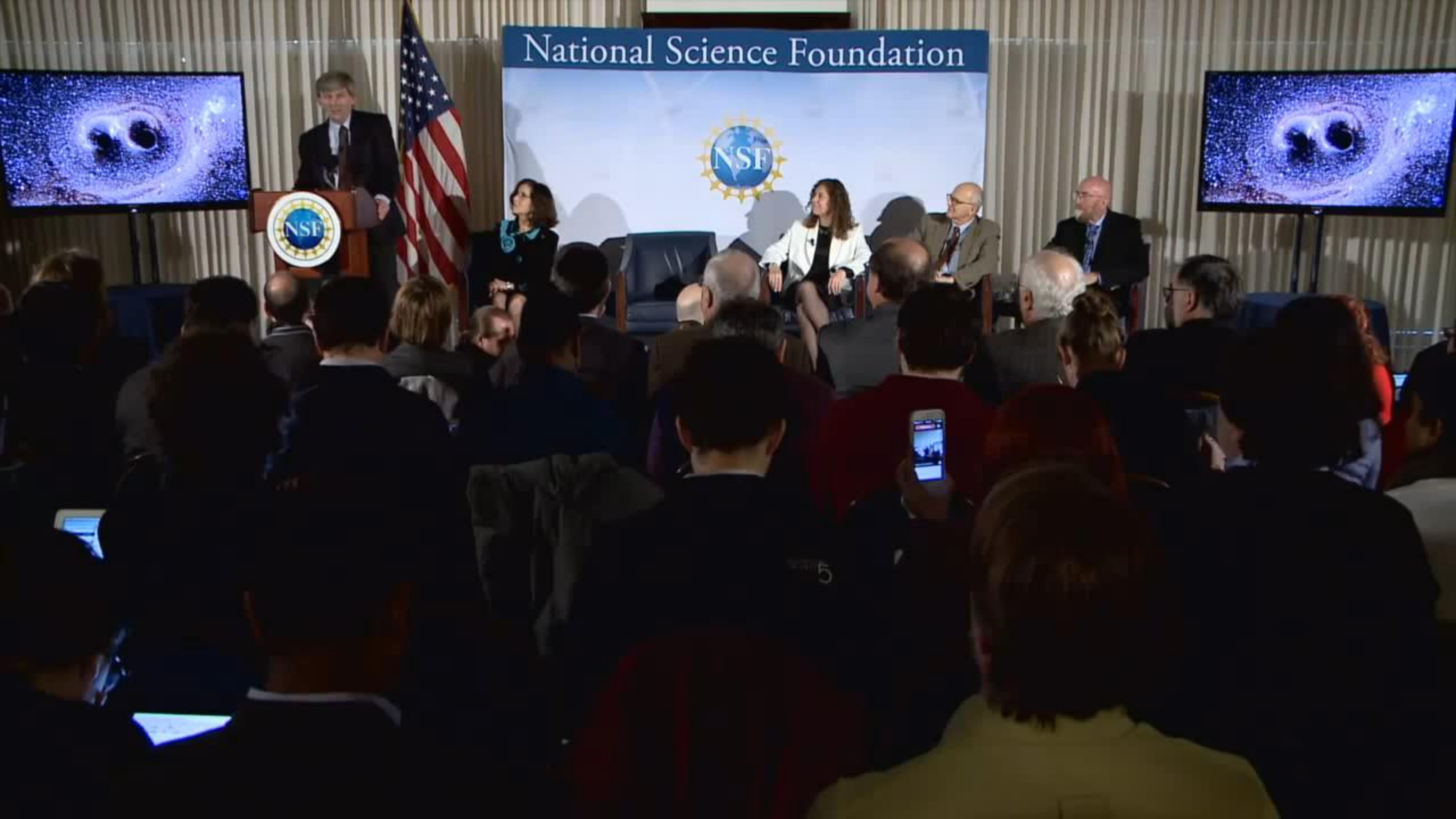
LIGO Scientific Collaboration is a group of **more than 900 scientists worldwide** who have joined together in the search for gravitational waves.

BBC WORLD SERVICE The Documentary

The Documentary Home Episodes Galleries Podcasts Join us on Facebook

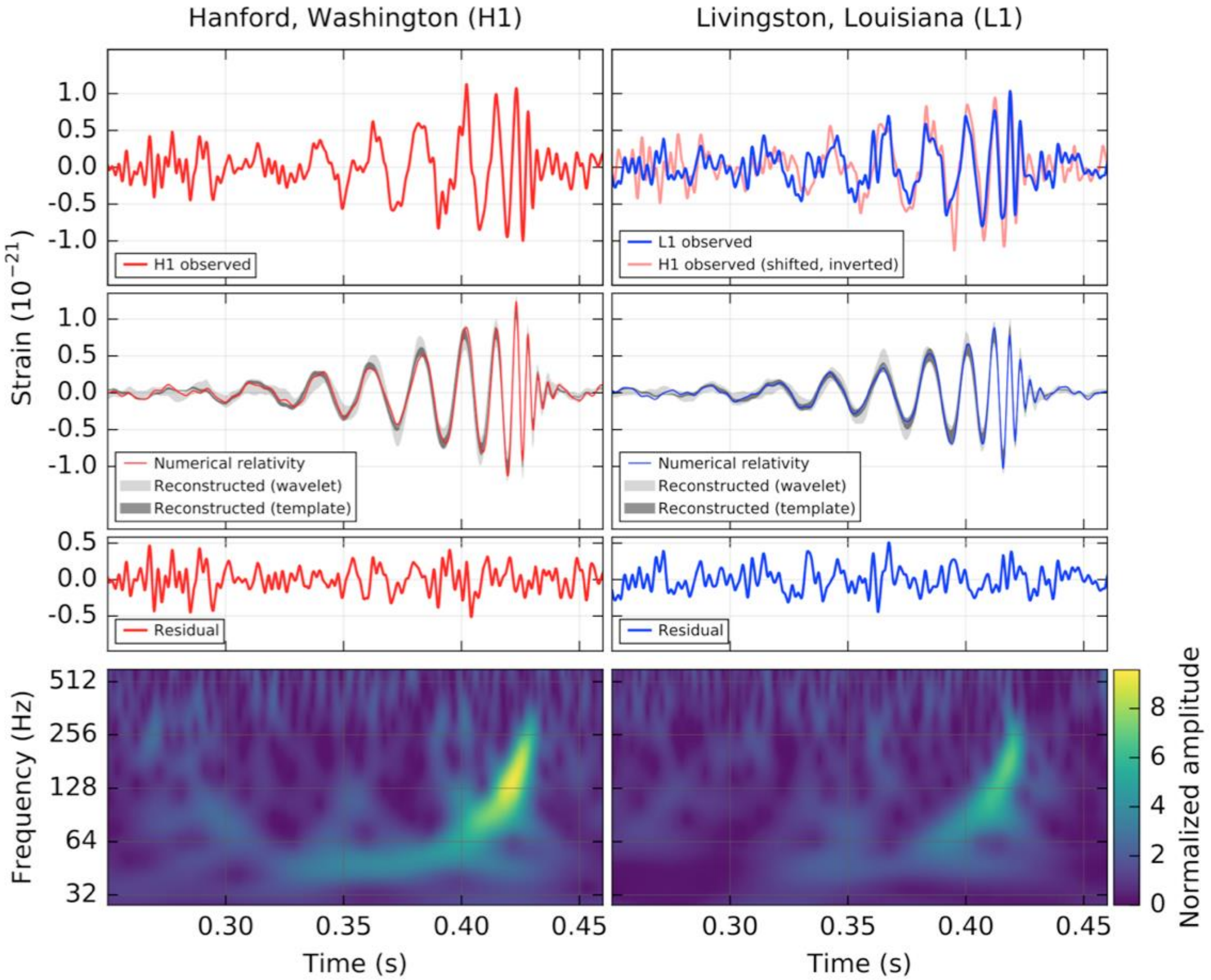


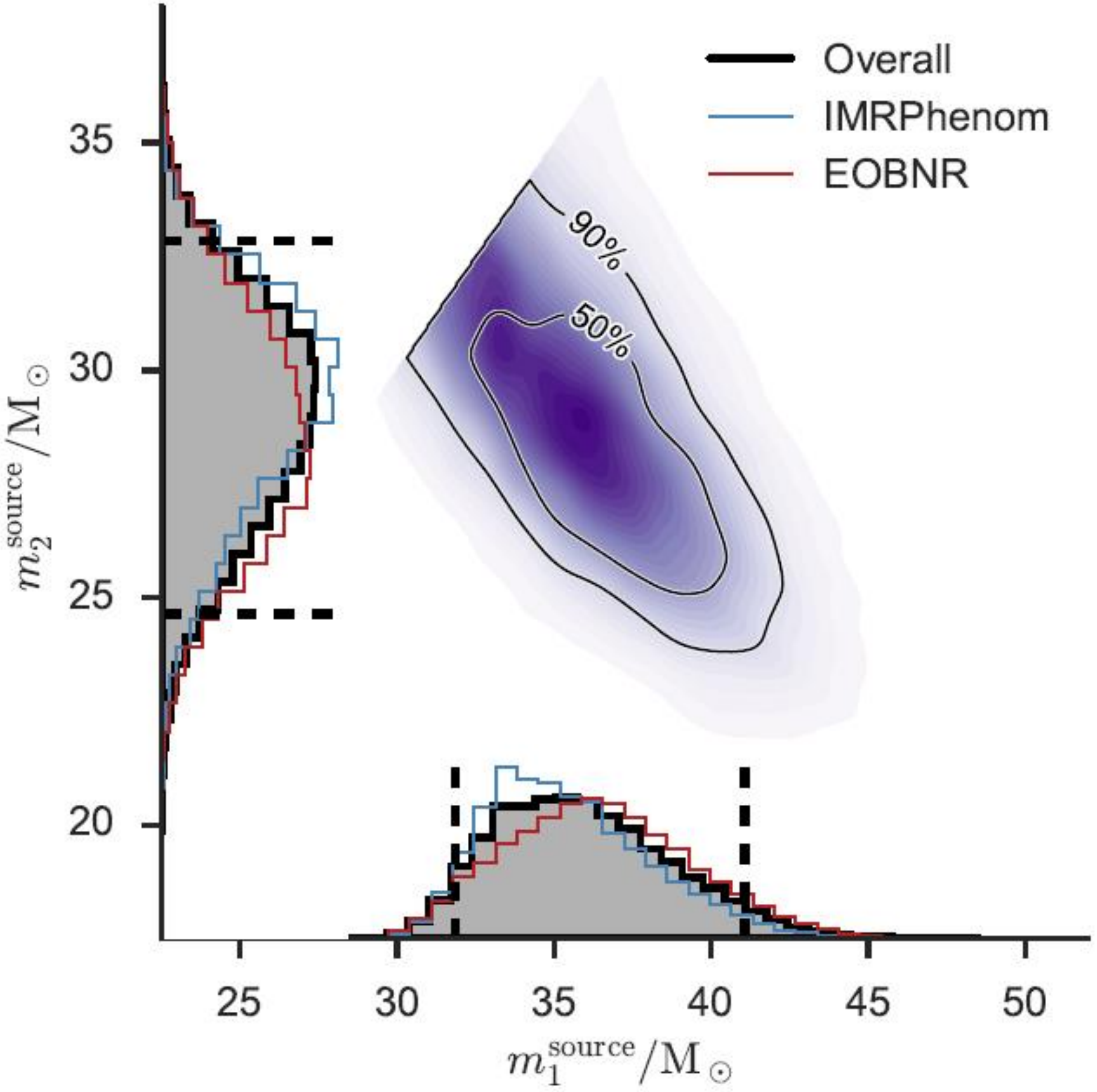
Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


National Science Foundation
NSF
NSF

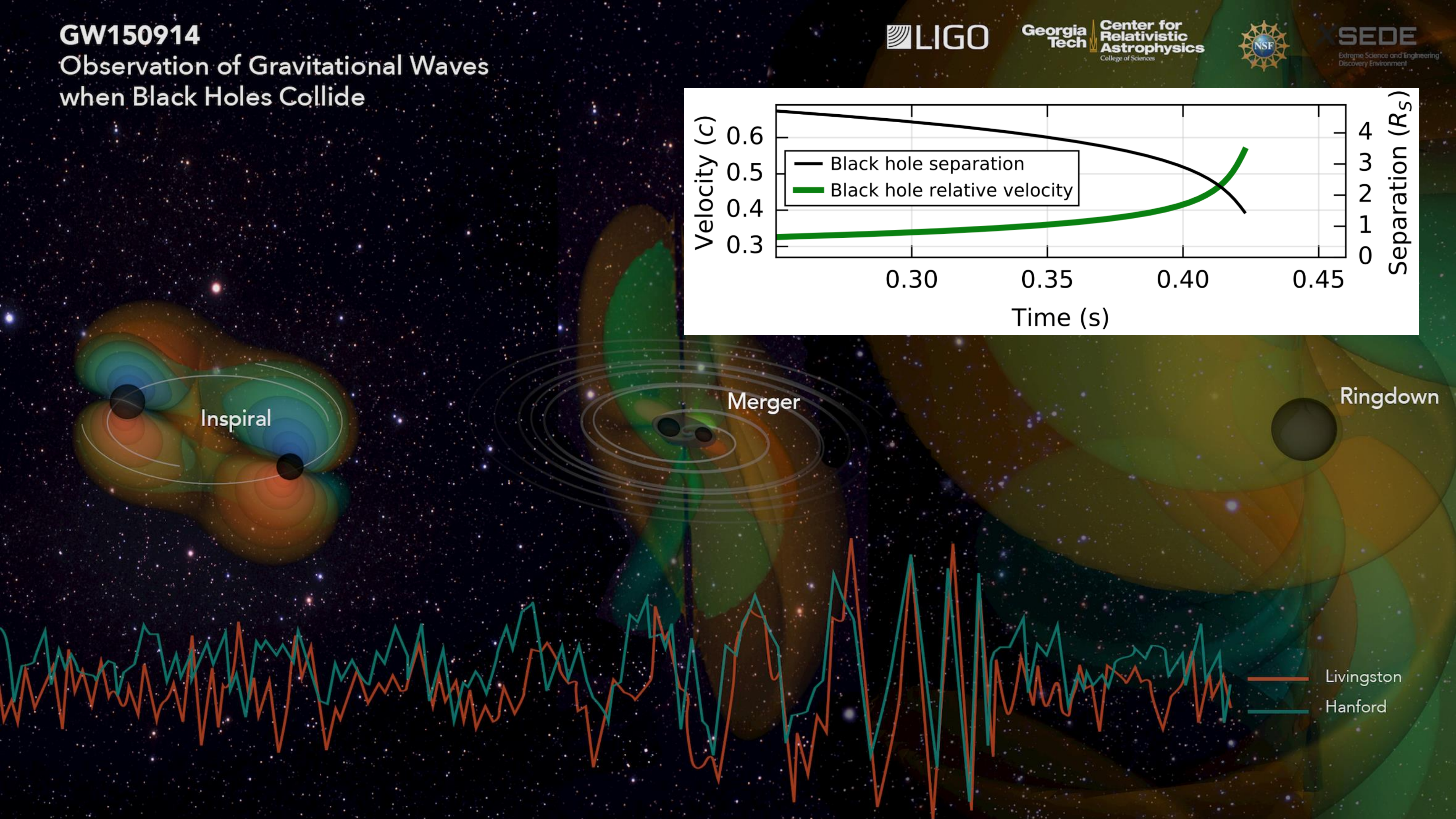
GW150914 – a burst of gravitational waves…

… matching a BBH inspiral and merger waveform from General Relativity

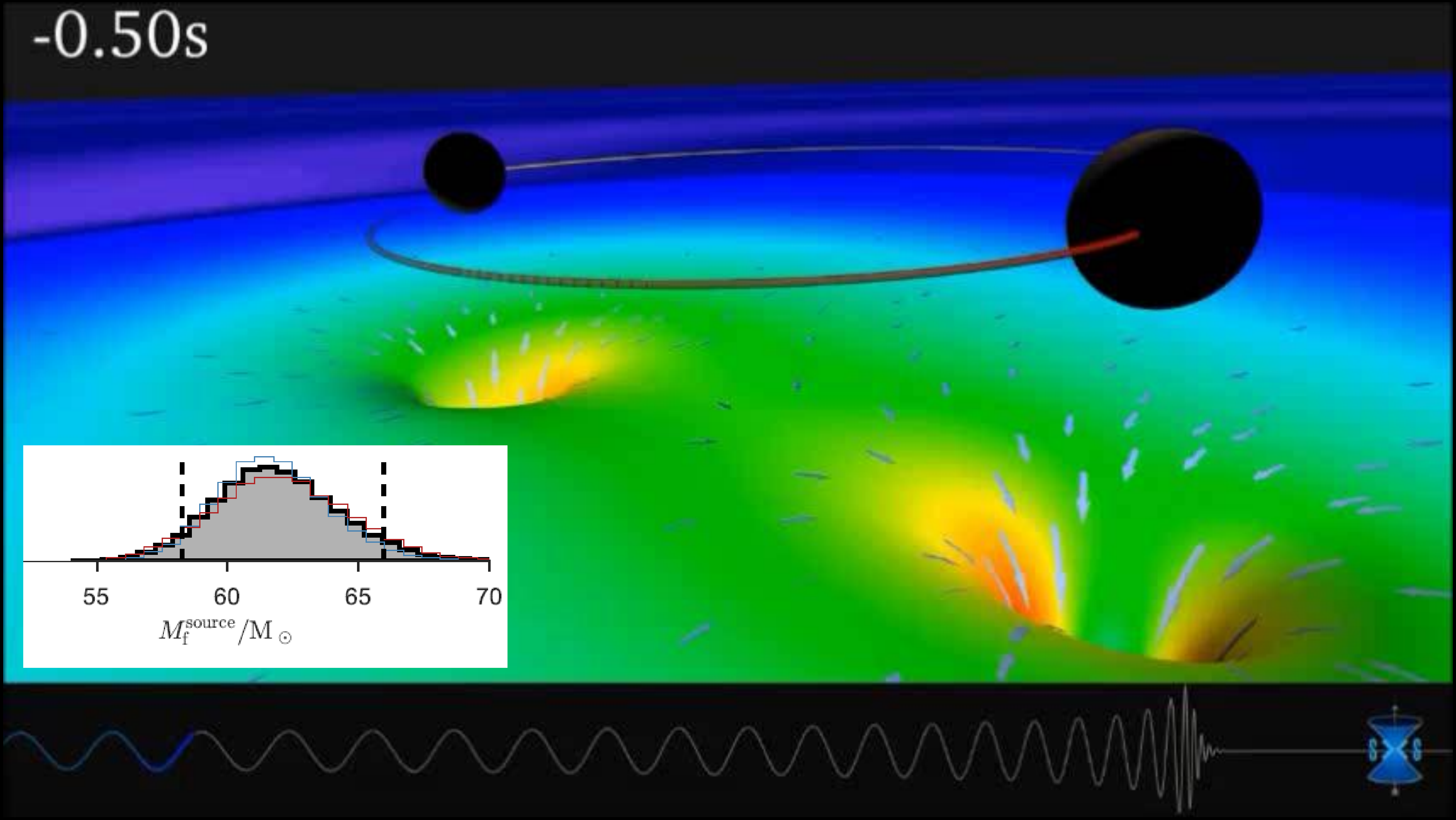




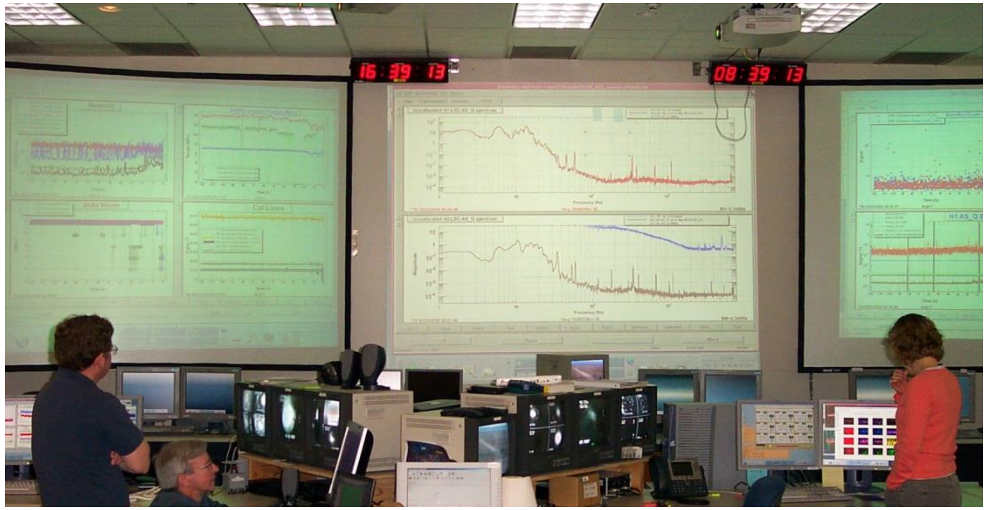
Abbott et al (2016): https://dcc.ligo.org/P1500218/

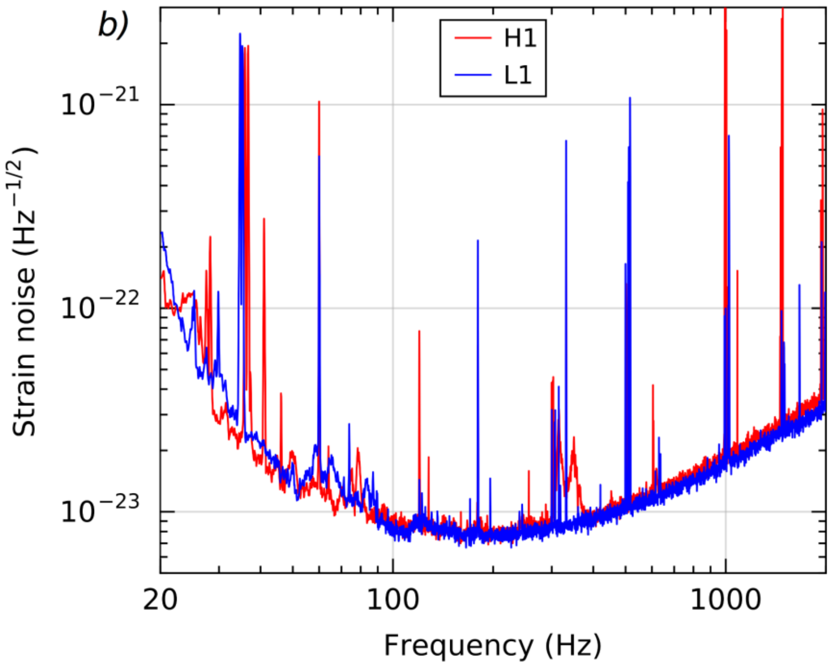

GW150914
Observation of Gravitational Waves
when Black Holes Collide
LIGO
Georgia Tech
Center for Relativistic Astrophysics
College of Sciences
NSF
XSEDE
Extreme Science and Engineering Discovery Environment
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
0.30
0.35
0.40
0.45
Time (s)
4
3
2
1
0
Separation (R_S)
Inspiral
Merger
Ringdown
Livingston
Hanford

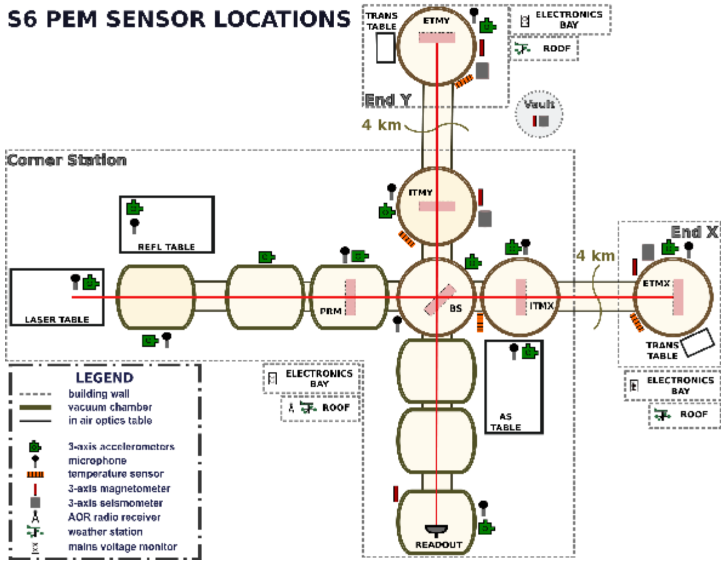
https://www.ligo.caltech.edu/video/ligo20160211v10

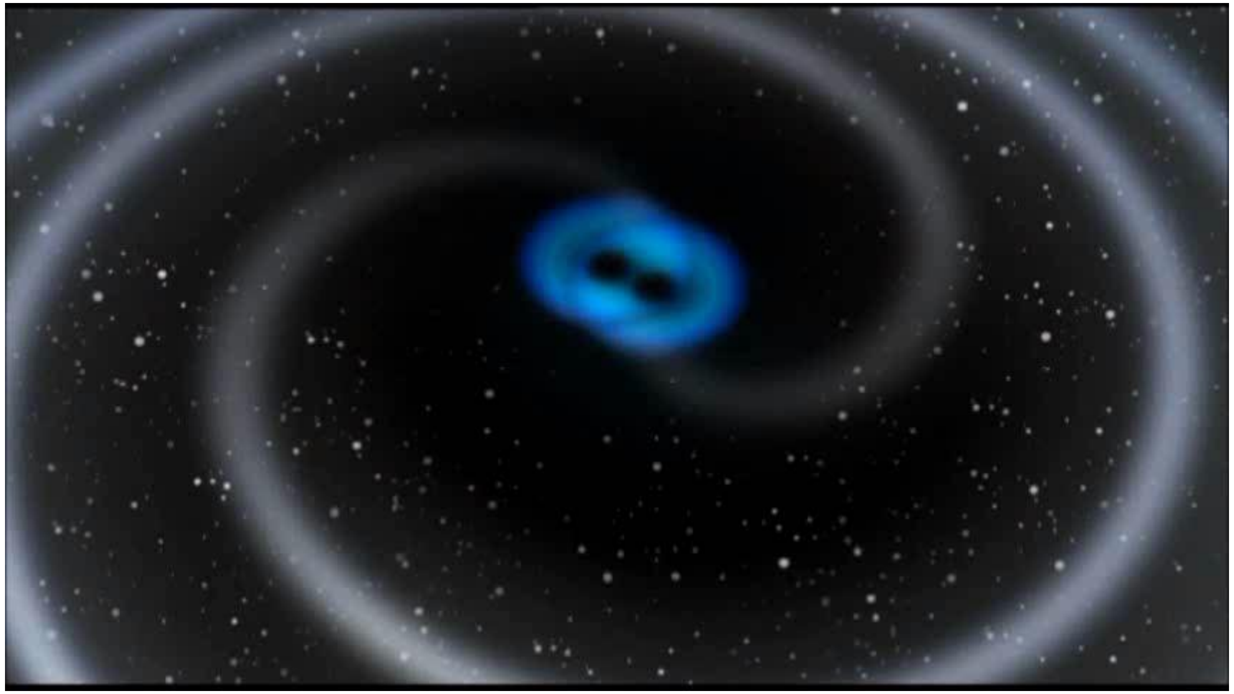


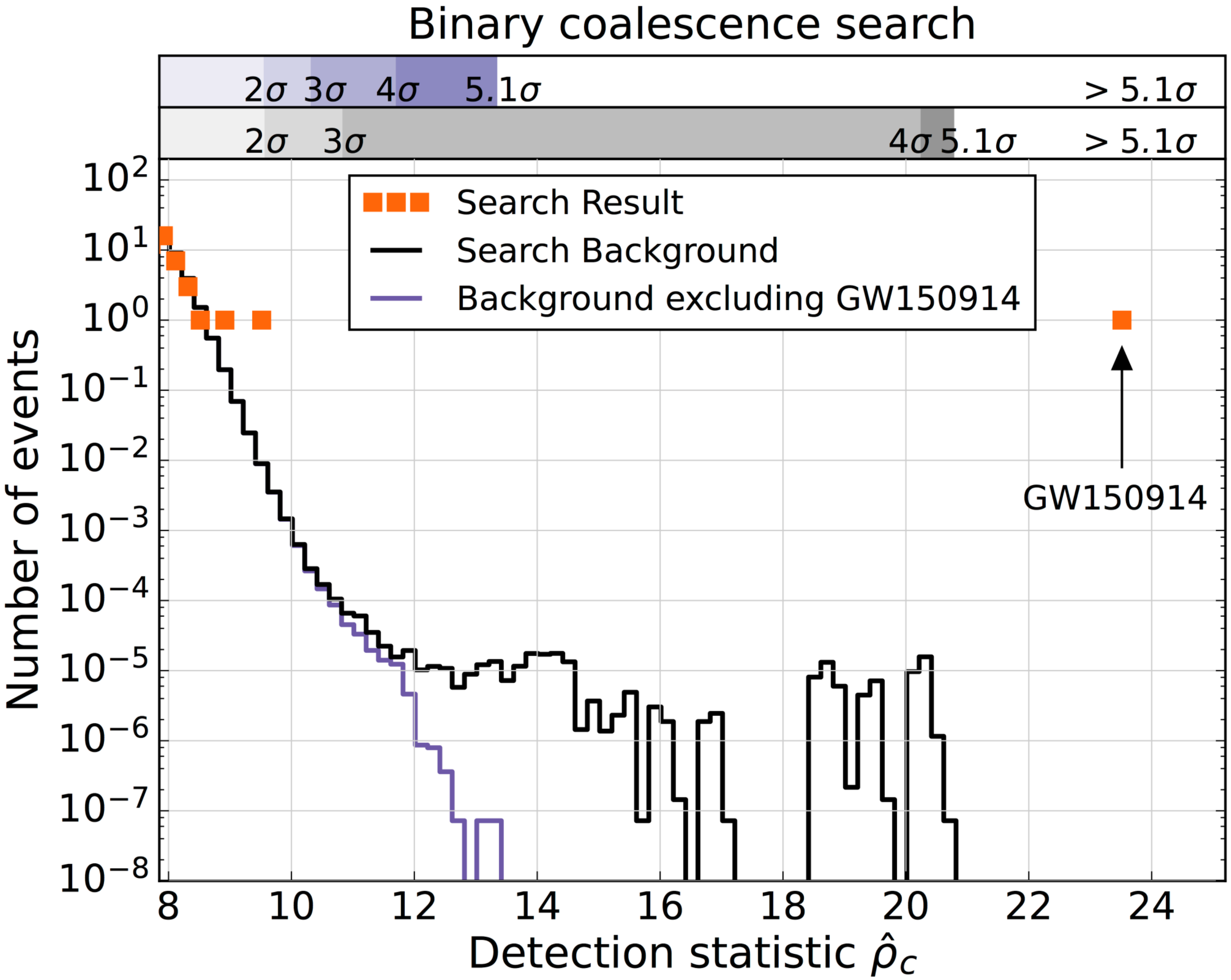
Are we sure that GW150914 was real?...



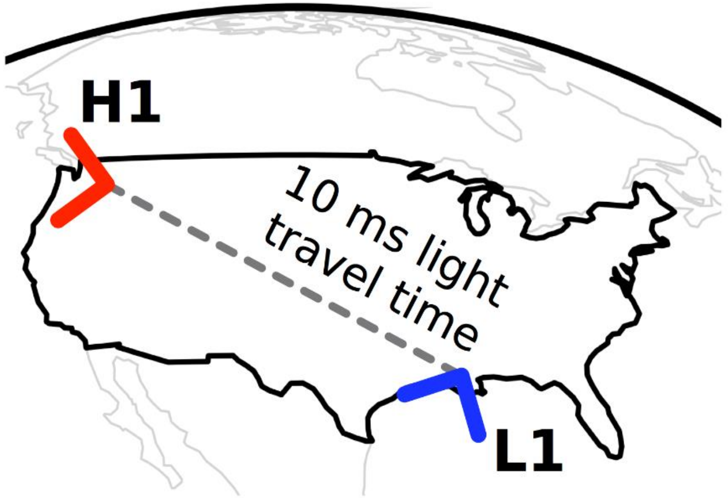






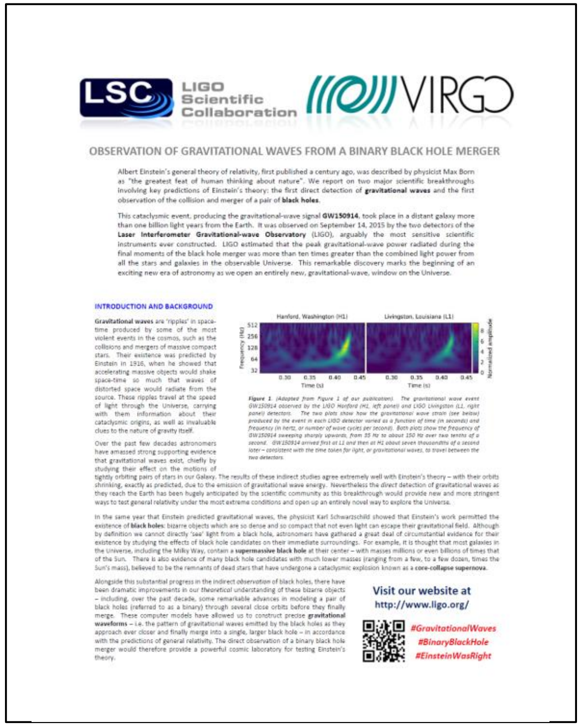


Binary coalescence search
2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Number of events
Detection statistic $\hat{\rho}_c$

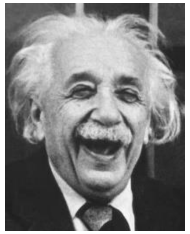


H1
10 ms light travel time
L1

www.ligo.org



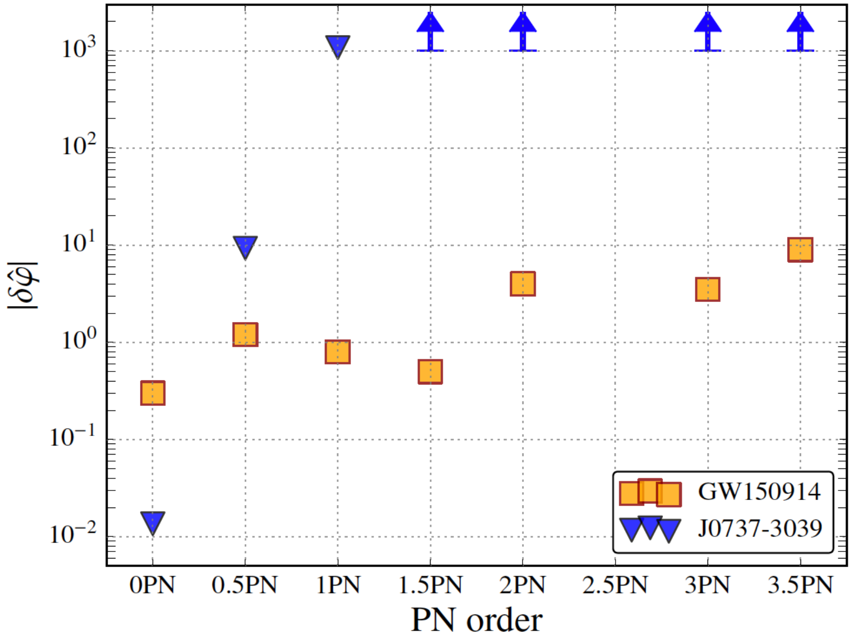
LSC LIGO Scientific Collaboration
VIRGO
OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER
INTRODUCTION AND BACKGROUND
Visit our website at
http://www.ligo.org/
#GravitationalWaves
#BinaryBlackHole
#EinsteinWasRight



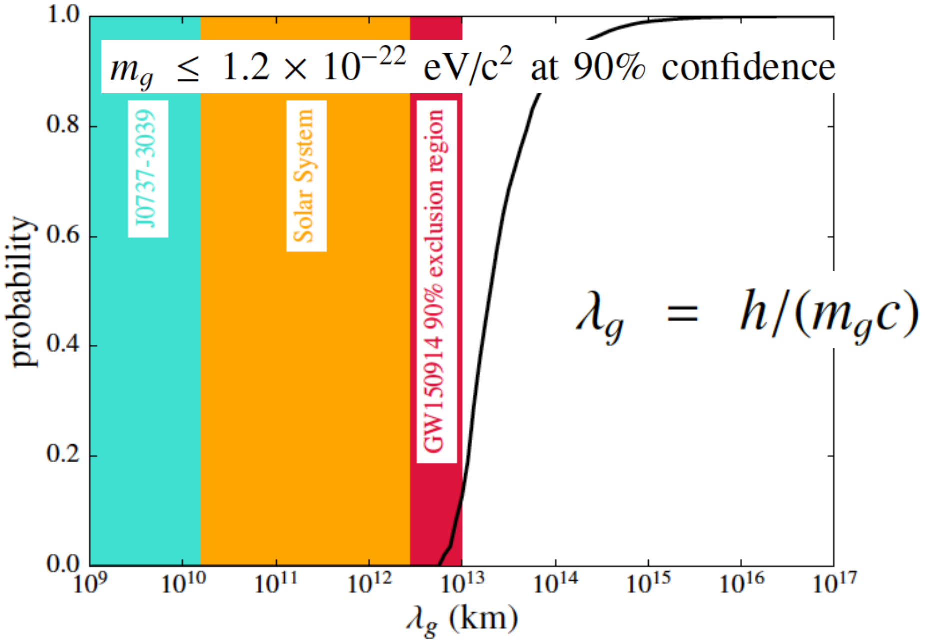
Does General Relativity really fit?

- GW150914 was the first observation of a binary black hole merger
- Our best test of GR in *the strong field, dynamical, nonlinear regime*
- Event better than the binary pulsar system PSR J0737-3039

Post-Newtonian Approximation to GR

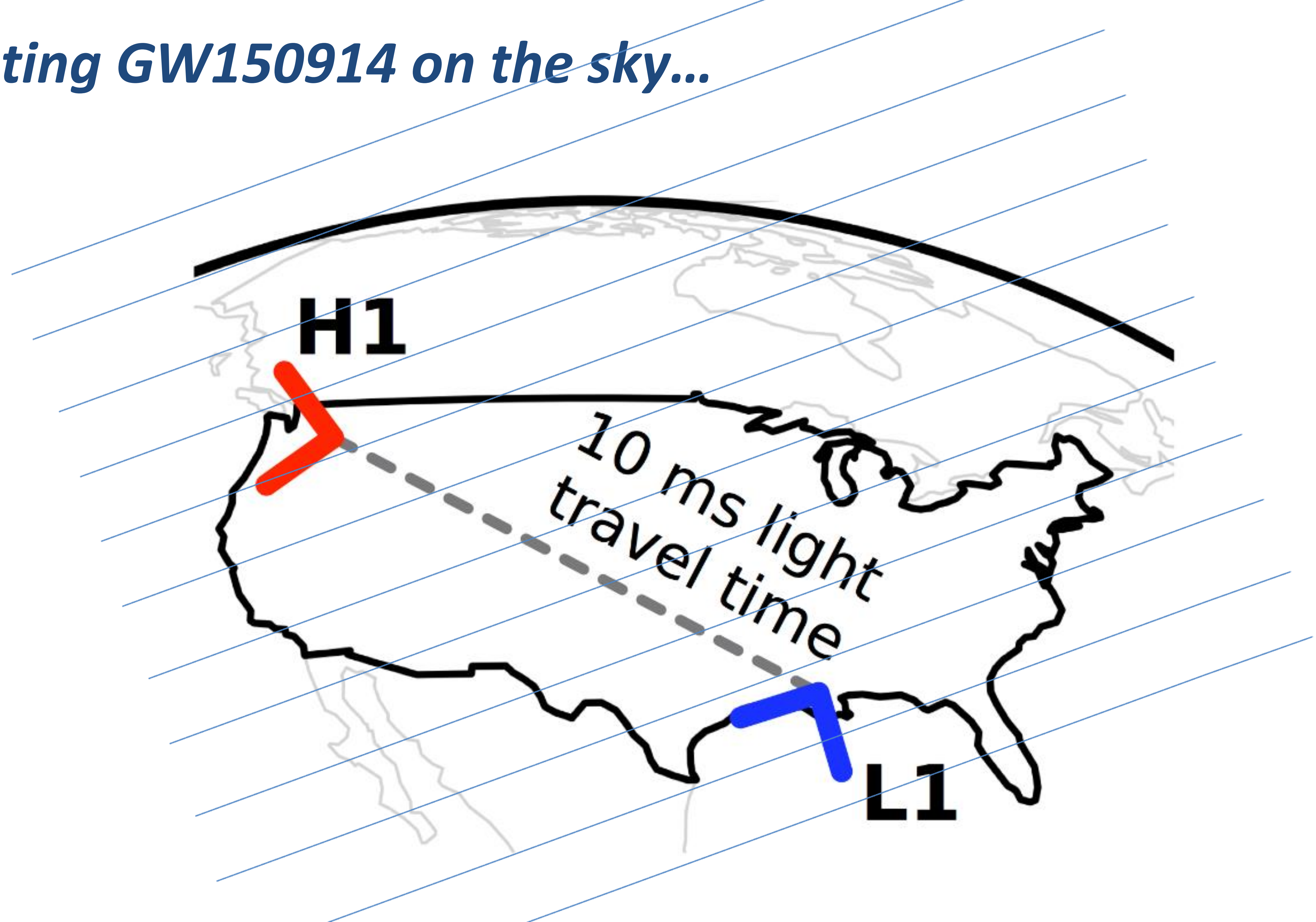


Compton Wavelength of the Graviton

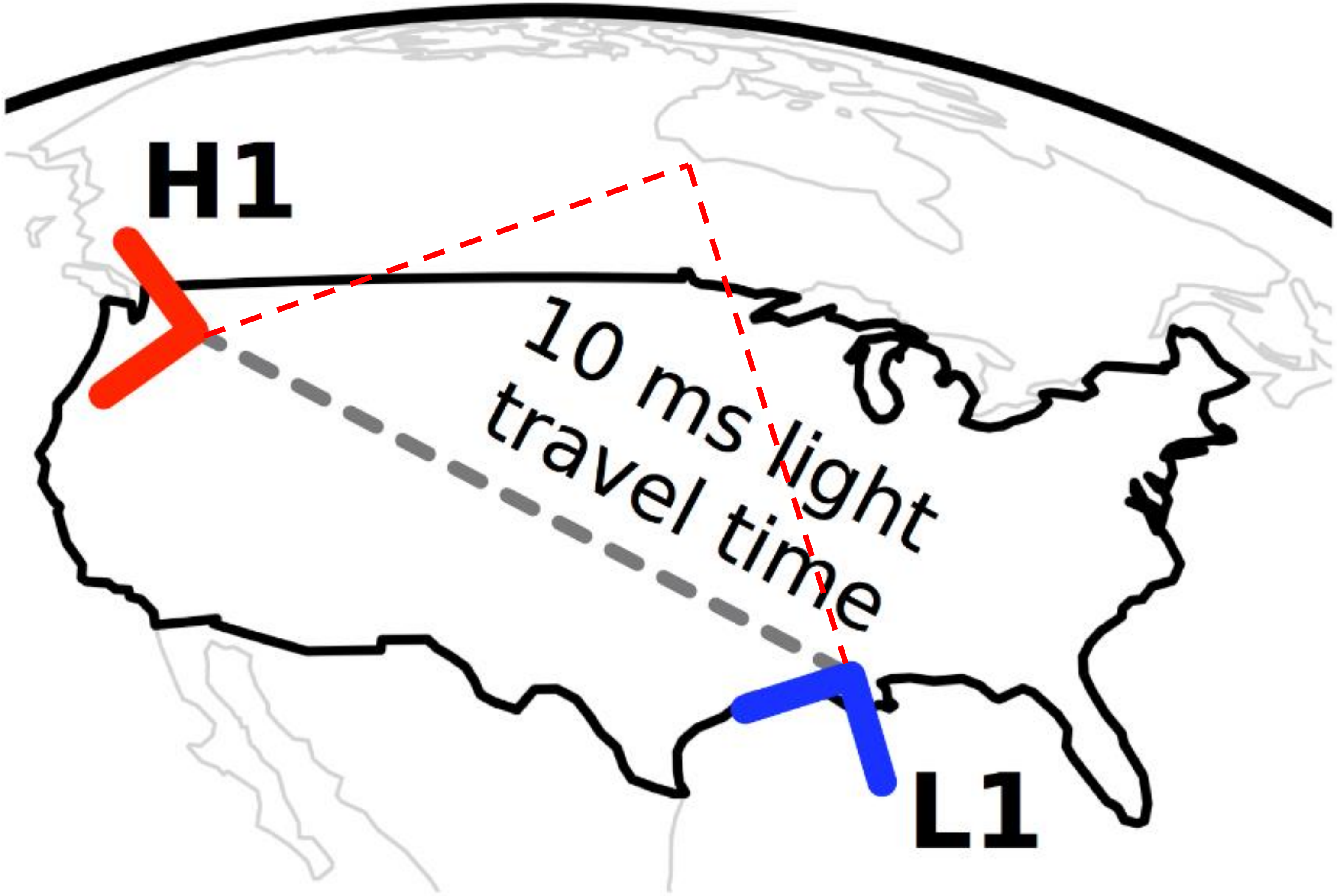


Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Tests of general relativity with GW150914”, http://arxiv.org/abs/1602.03841

Locating GW150914 on the sky…

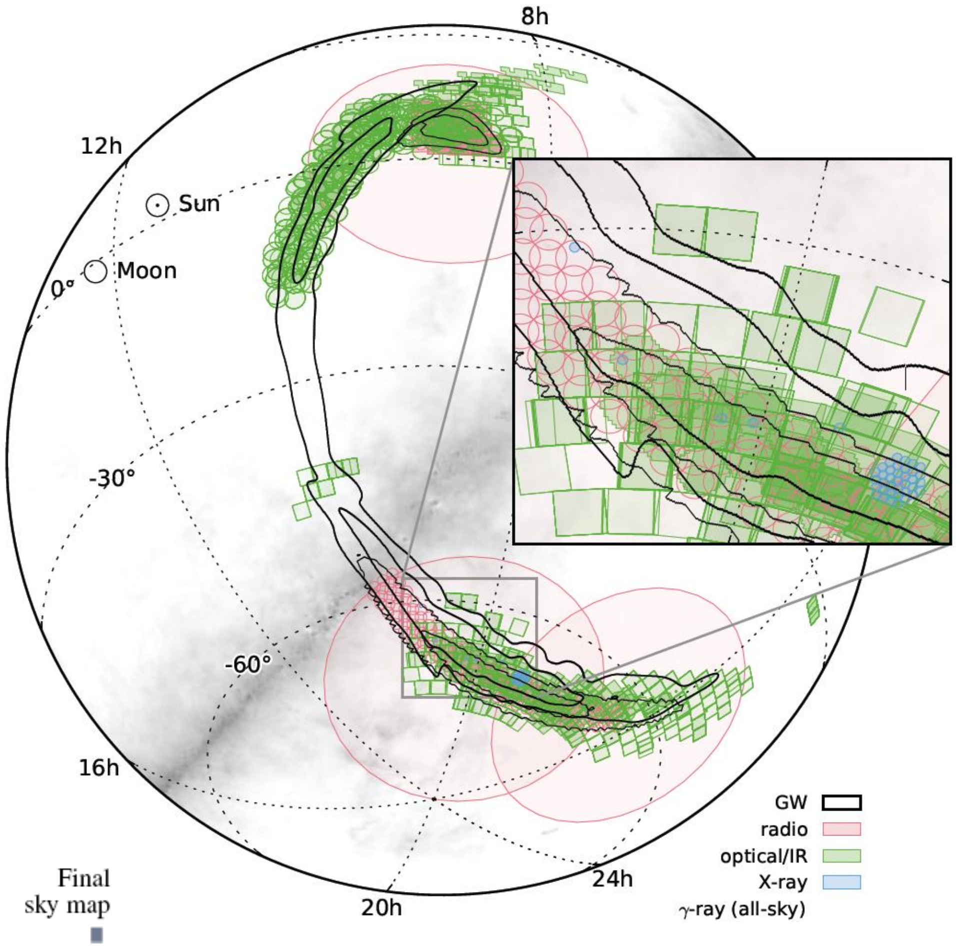


Locating GW150914 on the sky...

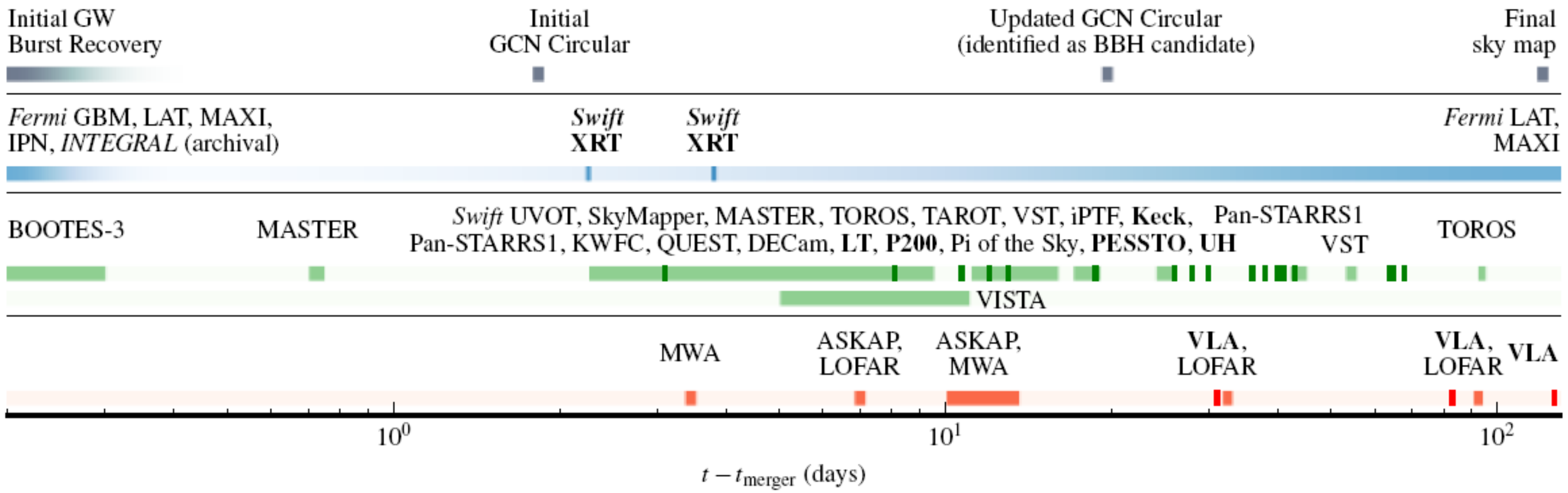


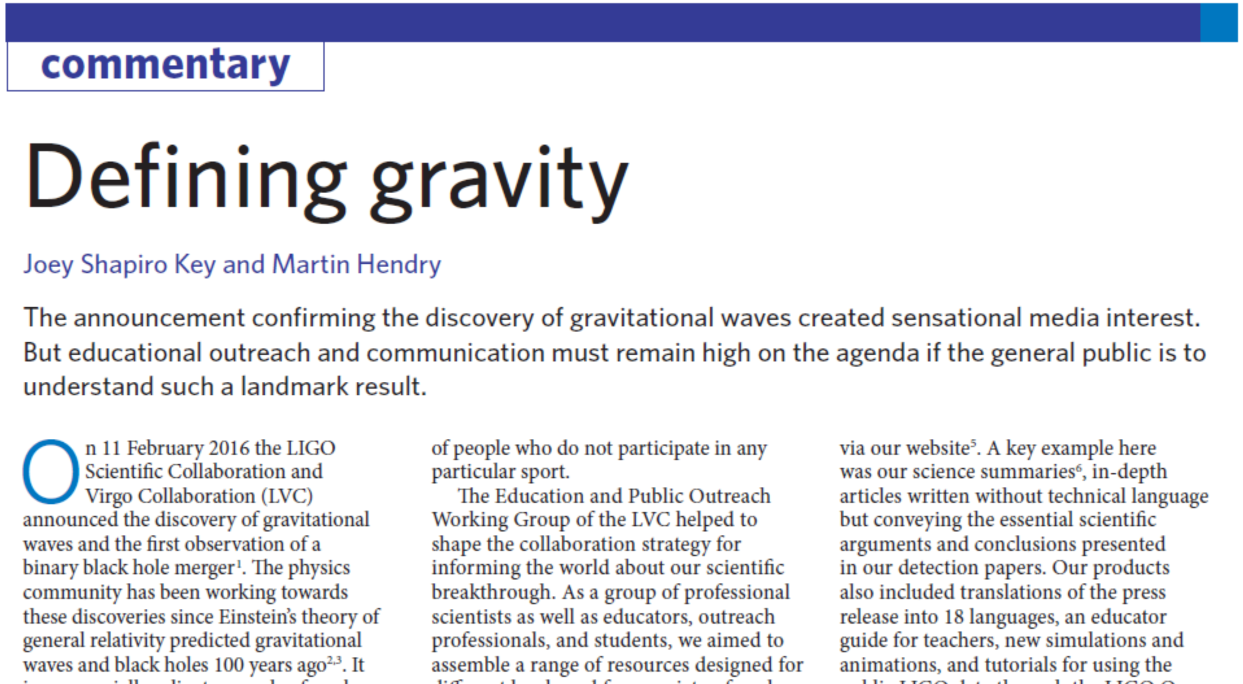
Electromagnetic Follow-up

- Consortium agreement between LIGO and 63 teams using ground- and space-based telescopes (gamma-ray, X-ray, optical, IR and radio) to follow-up the alert.



http://arxiv.org/abs/1602.08492





commentary

Defining gravity

Joey Shapiro Key and Martin Hendry

The announcement confirming the discovery of gravitational waves created sensational media interest. But educational outreach and communication must remain high on the agenda if the general public is to understand such a landmark result.

On 11 February 2016 the LIGO Scientific Collaboration and Virgo Collaboration (LVC) announced the discovery of gravitational waves and the first observation of a binary black hole merger[1]. The physics community has been working towards these discoveries since Einstein's theory of general relativity predicted gravitational waves and black holes 100 years ago[2,3]. It

of people who do not participate in any particular sport.

The Education and Public Outreach Working Group of the LVC helped to shape the collaboration strategy for informing the world about our scientific breakthrough. As a group of professional scientists as well as educators, outreach professionals, and students, we aimed to assemble a range of resources designed for

via our website[5]. A key example here was our science summaries[6], in-depth articles written without technical language but conveying the essential scientific arguments and conclusions presented in our detection papers. Our products also included translations of the press release into 18 languages, an educator guide for teachers, new simulations and animations, and tutorials for using the

961 front-page stories worldwide on February 12th

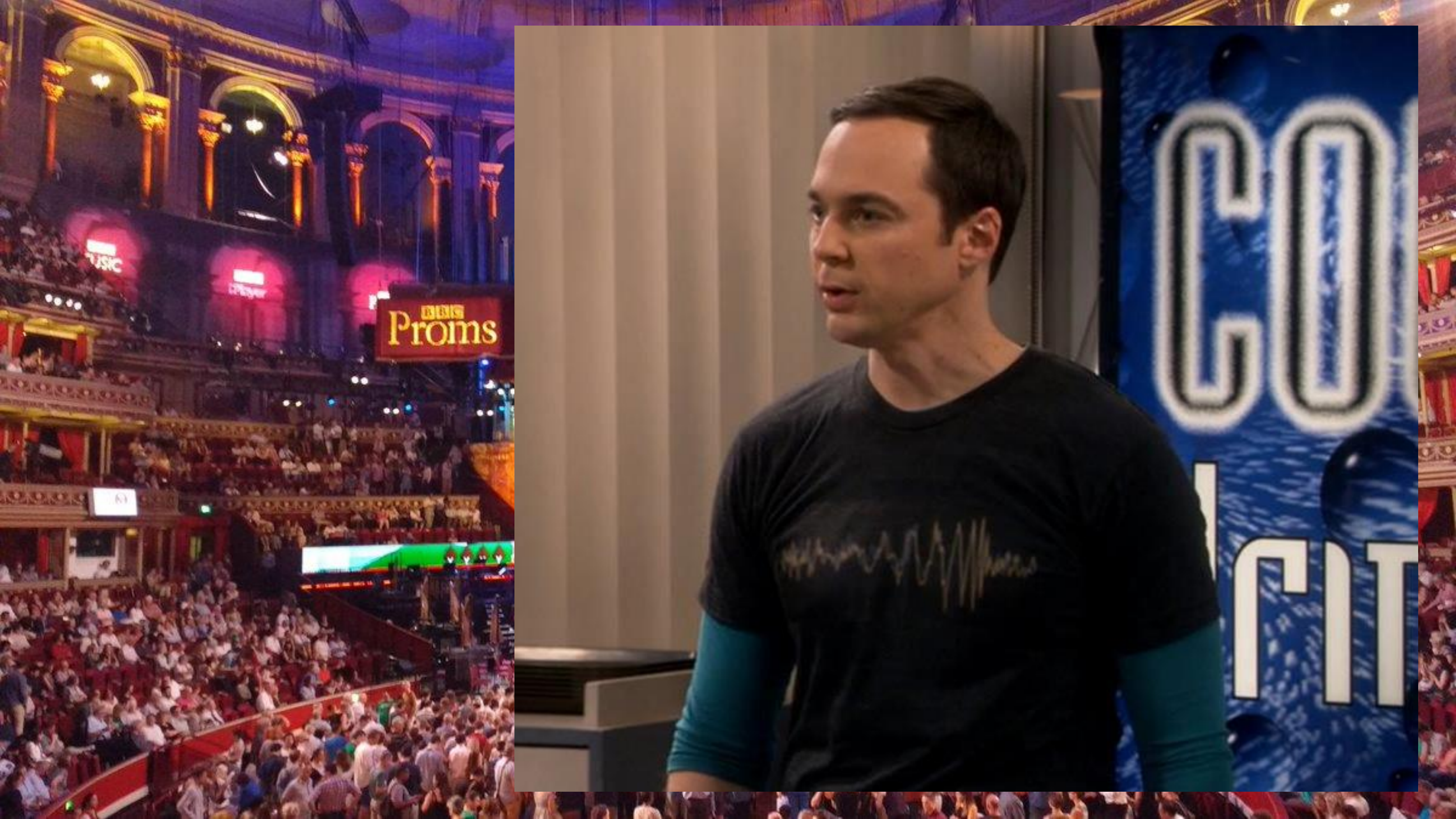
@ligo

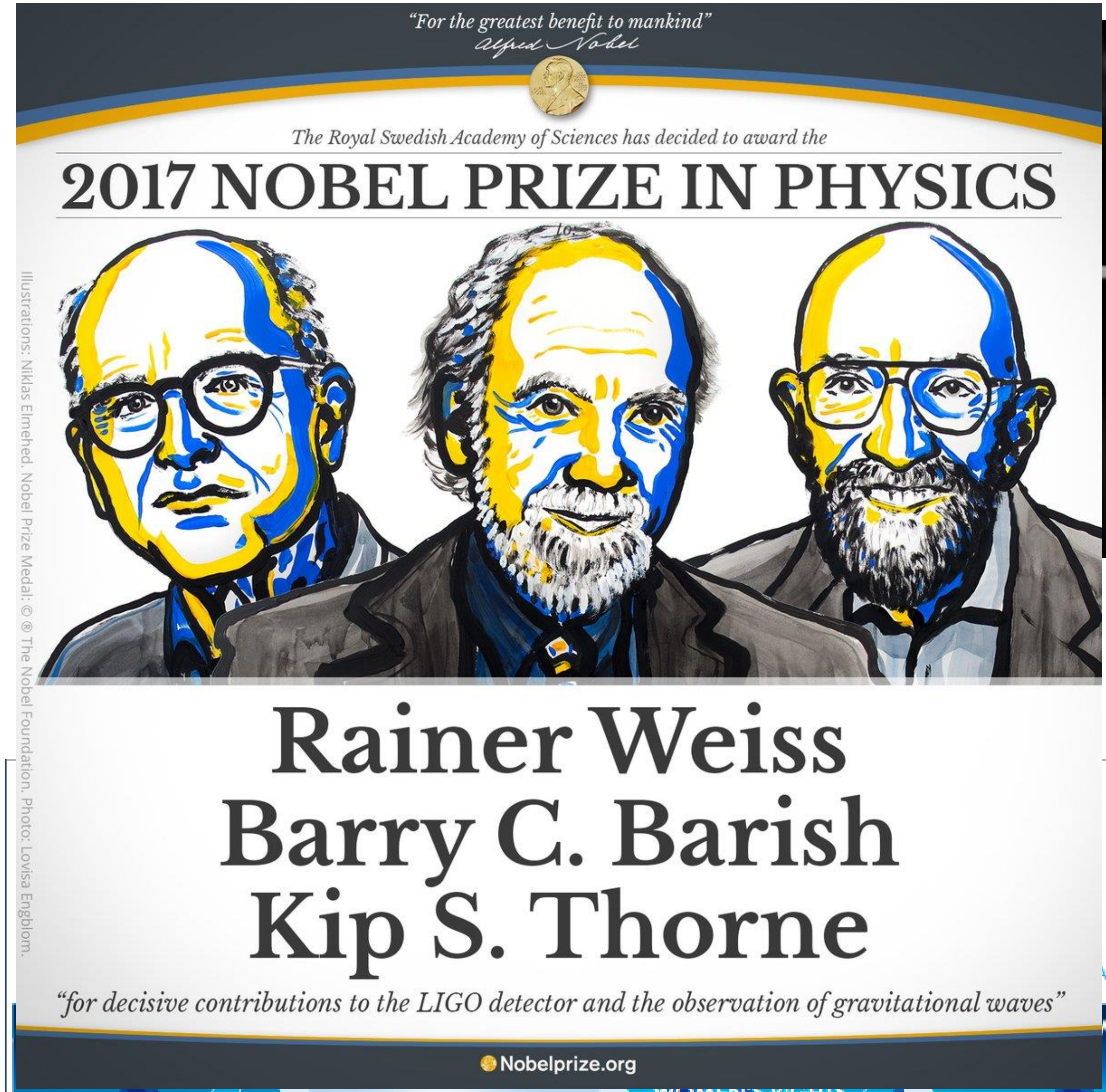
#Gravitationalwaves

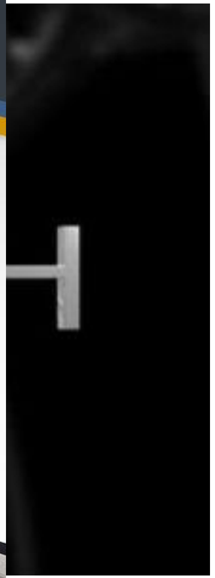
#GW150914

#Einsteinwasright

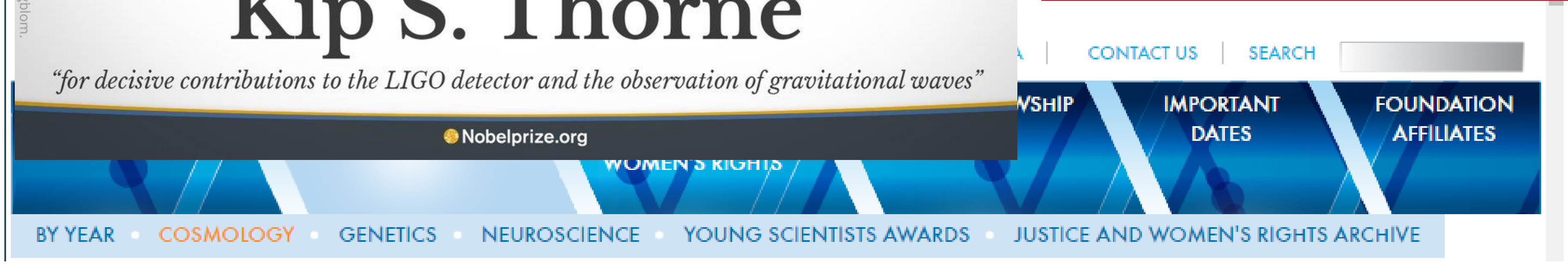
70 million+ impressions


BBC
Proms



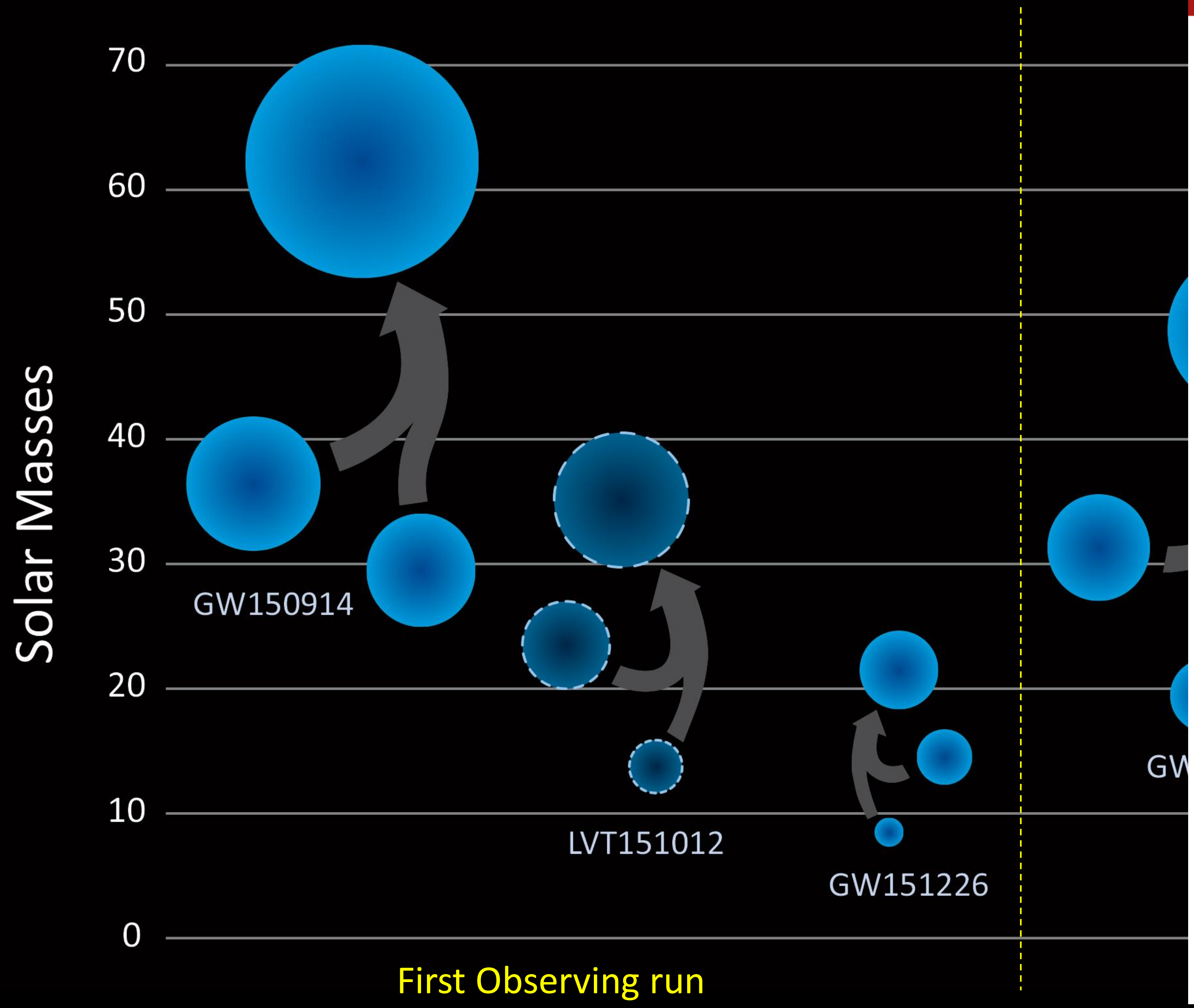


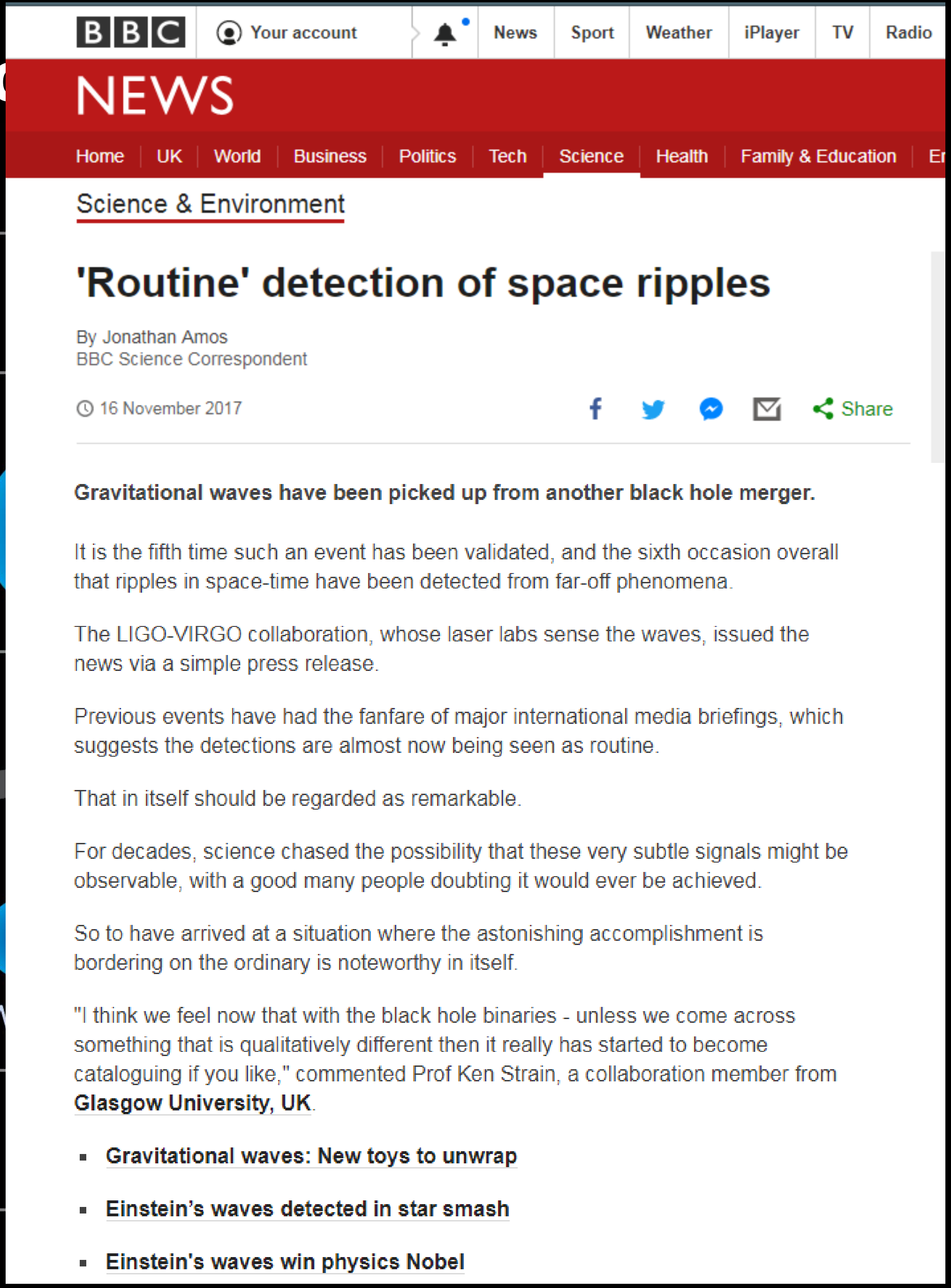
Science
AAAS



ROYAL ASTRONOMICAL SOCIETY
QUICQUID NITET NOTANDUM
1820

BBH detections announc





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Science & Environment

'Routine' detection of space ripples

By Jonathan Amos
BBC Science Correspondent

16 November 2017

Share

Gravitational waves have been picked up from another black hole merger.

It is the fifth time such an event has been validated, and the sixth occasion overall that ripples in space-time have been detected from far-off phenomena.

The LIGO-VIRGO collaboration, whose laser labs sense the waves, issued the news via a simple press release.

Previous events have had the fanfare of major international media briefings, which suggests the detections are almost now being seen as routine.

That in itself should be regarded as remarkable.

For decades, science chased the possibility that these very subtle signals might be observable, with a good many people doubting it would ever be achieved.

So to have arrived at a situation where the astonishing accomplishment is bordering on the ordinary is noteworthy in itself.

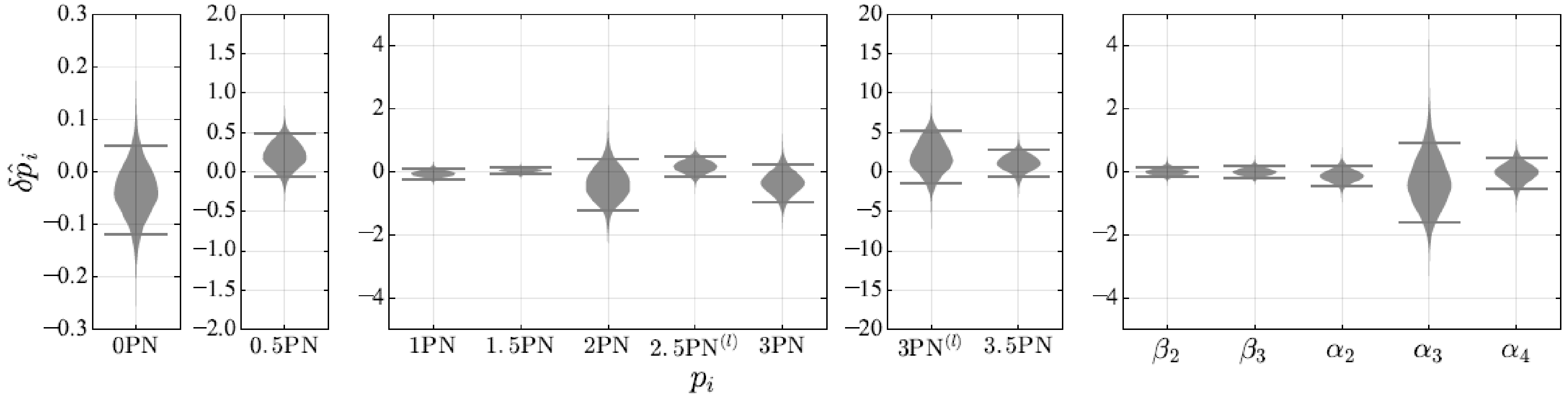
"I think we feel now that with the black hole binaries - unless we come across something that is qualitatively different then it really has started to become cataloguing if you like," commented Prof Ken Strain, a collaboration member from **Glasgow University, UK**.

- **Gravitational waves: New toys to unwrap**
- **Einstein's waves detected in star smash**
- **Einstein's waves win physics Nobel**

Further tests of General Relativity

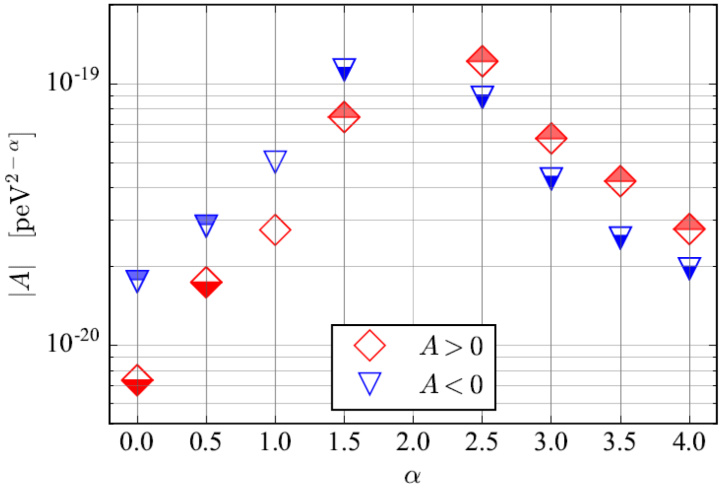
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "GW170104: Observation of a 50-solar binary black hole coalescence at redshift 0.2"
Phys. Rev. Lett. 118, 221101 (2017)

Parameterised test of PN expansion



Modified dispersion relation

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \ \alpha \geq 0$$

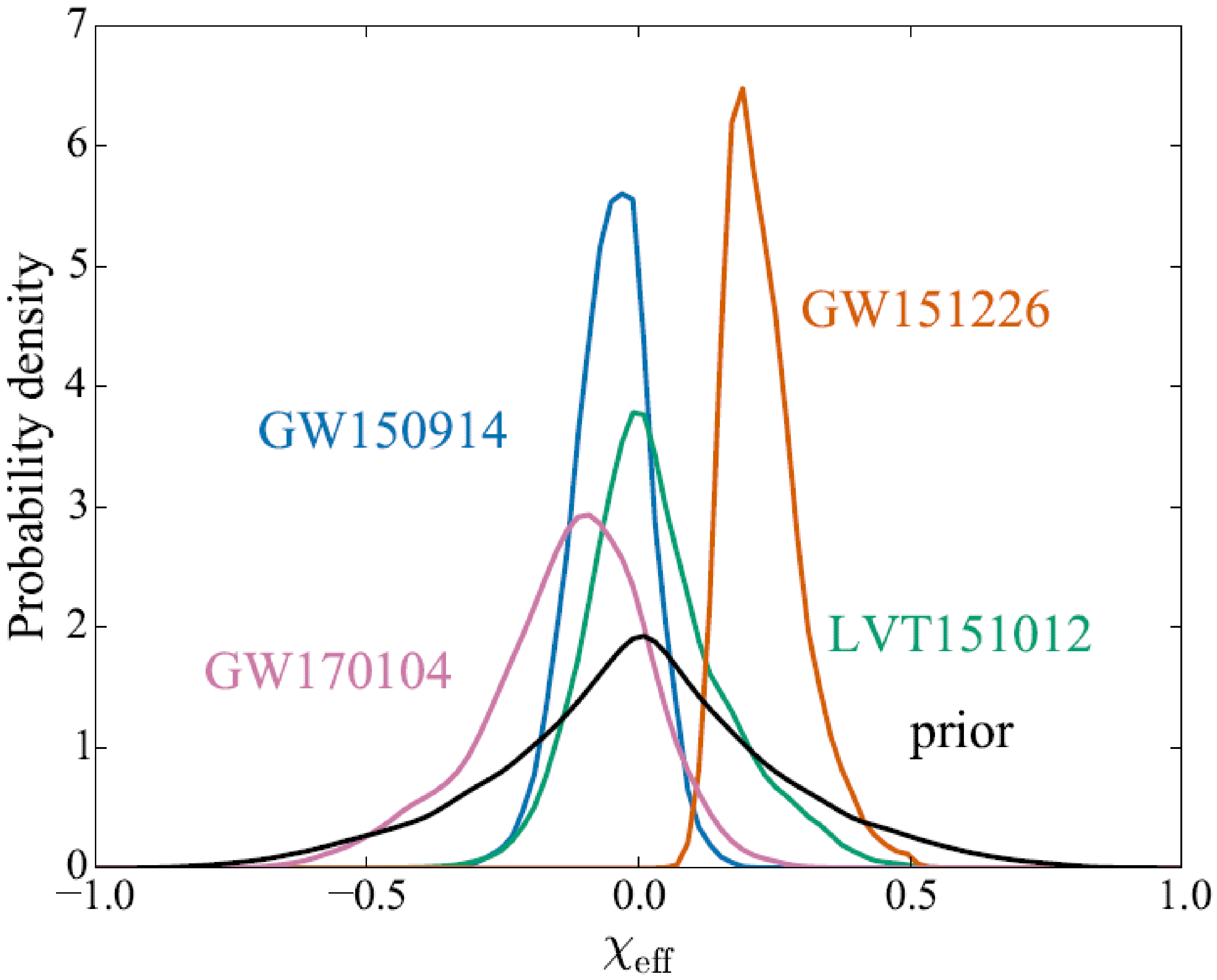


Lower limit on QG energy scale

		$\alpha = 3$	$\alpha = 4$
Sub	GW170104	1.1×10^7 eV	3.6×10^{-3} eV
	Gamma rays [195]	5×10^{24} eV	1.4×10^{16} eV
	Neutrino [196]	1.2×10^{26} eV	7.3×10^{20} eV
	Cherenkov [192, 194]	4.6×10^{35} eV	5.2×10^{27} eV
Super	GW170104	6.0×10^6 eV	3.2×10^{-3} eV
	Neutrino [193]	1.2×10^{33} eV	1.2×10^{24} eV

Population-level inferences

Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, "GW170104: Observation of a 50-solar binary black hole coalescence at redshift 0.2"
Phys. Rev. Lett. 118, 221101 (2017)



- Only GW151226 has $\chi_{\rm eff}$ inconsistent with zero
- Future measurements may constrain *isotropy* of spin distribution
- This may constrain BH formation mechanisms

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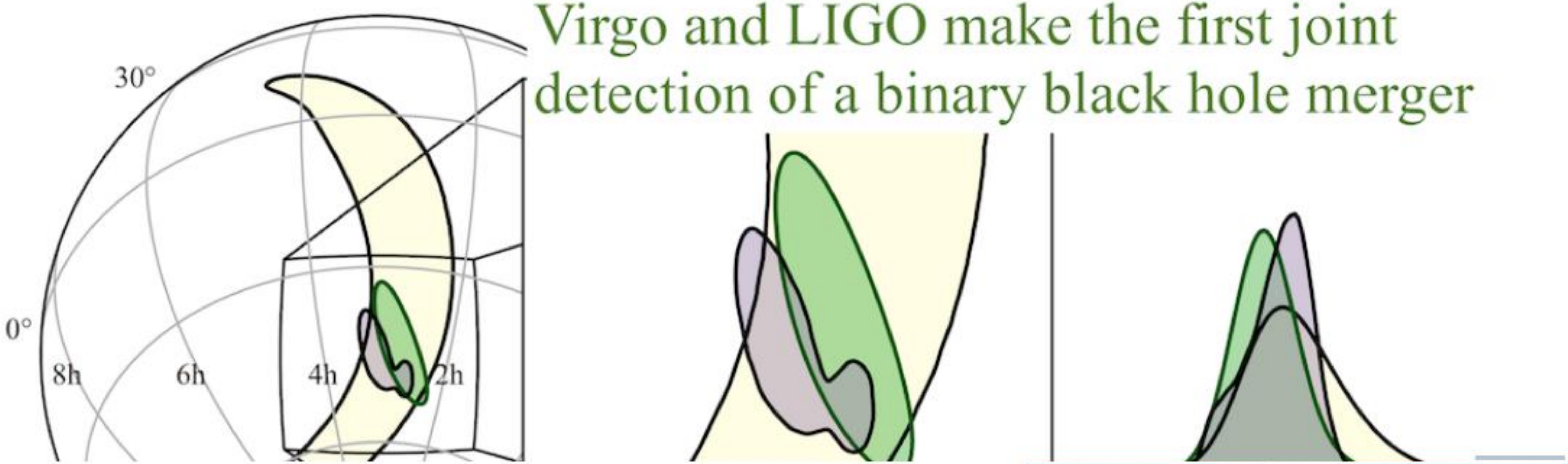
Virgo and LIGO make the first joint detection of a binary black hole merger



NEWS

Sep 27, 2017 LIGO and Virgo make the first joint detection of merging black holes

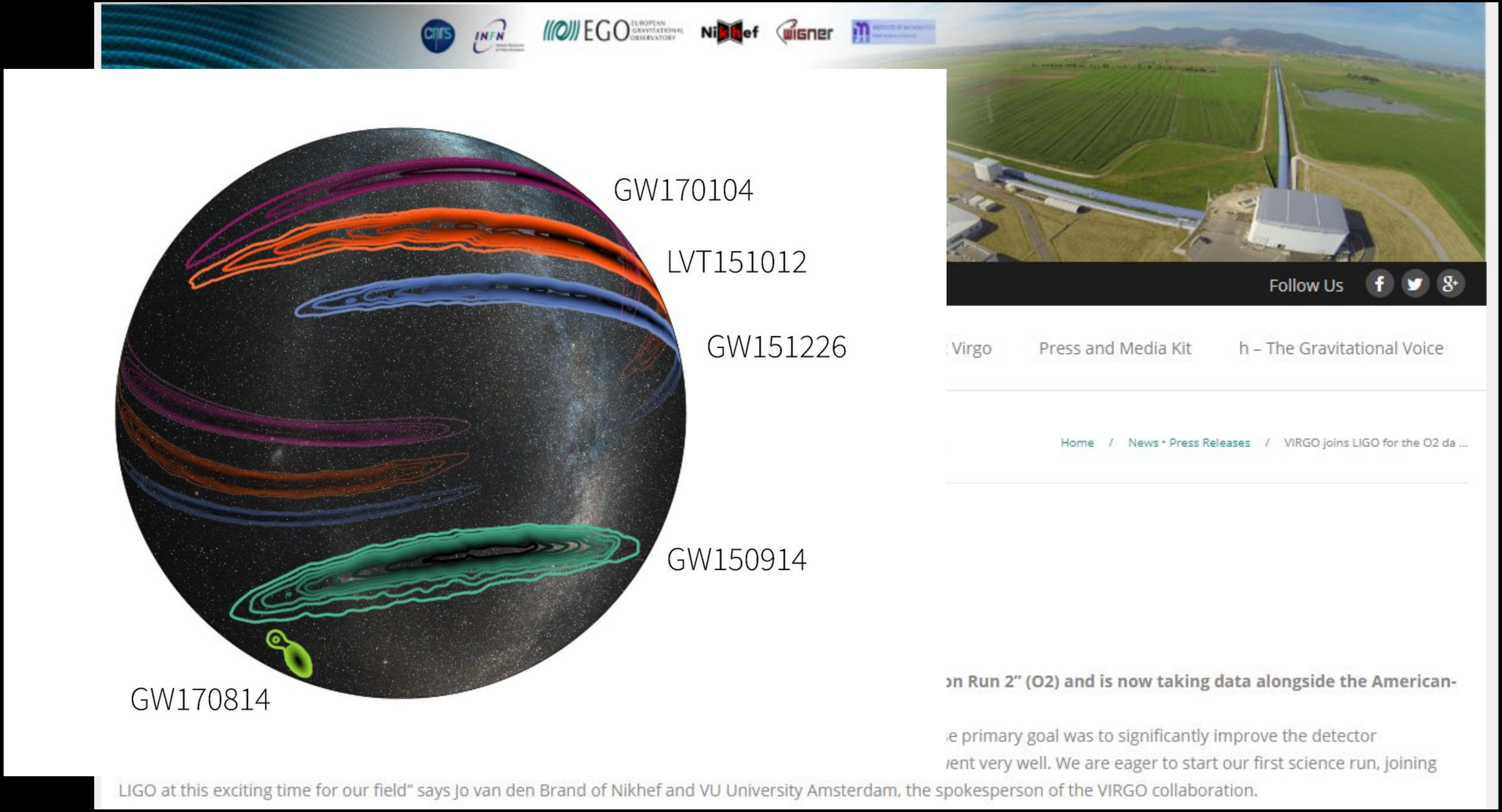
Aug 30, 2017 Read the August 2017 Issue of LIGO Magazine

PRESS RELEASES

Sep 27, 2017
Gravitational waves from a binary black hole merger observed by LIGO and Virgo

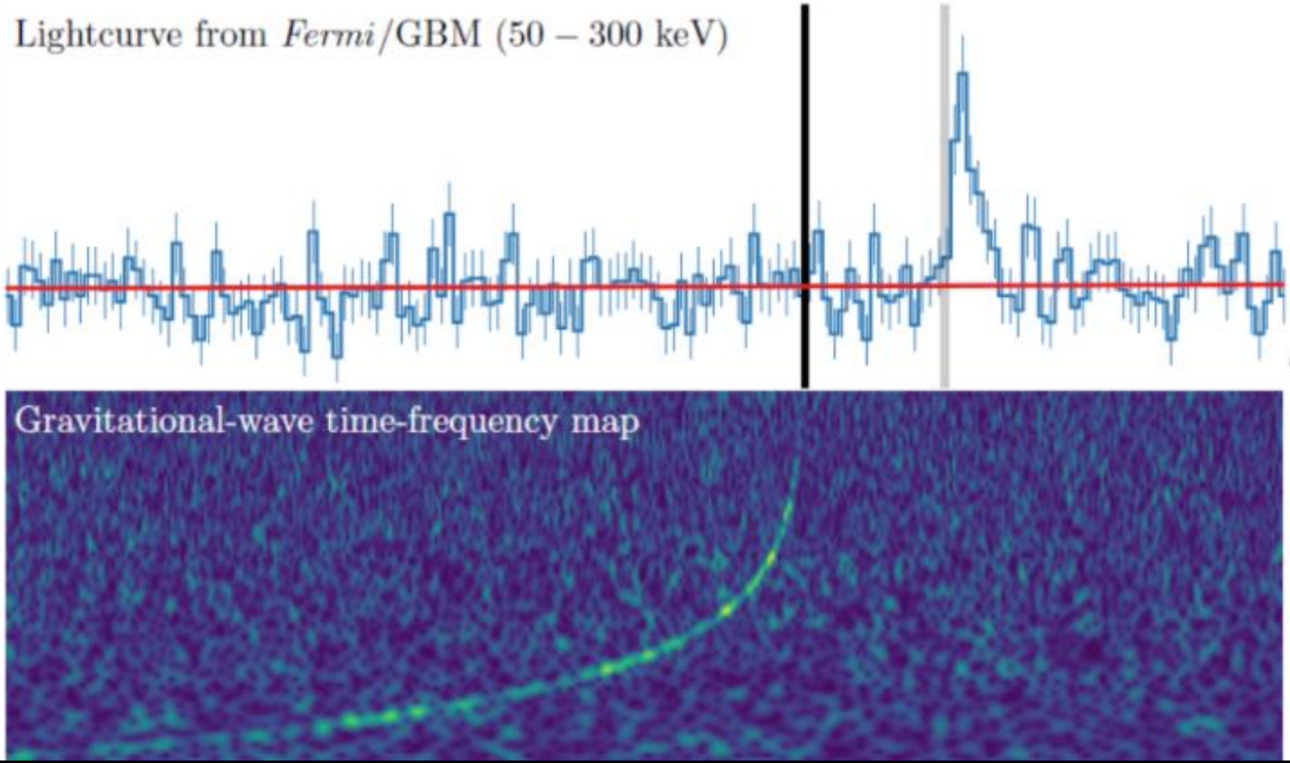
Jun 1, 2017
LIGO Detects Gravitational Waves for Third Time

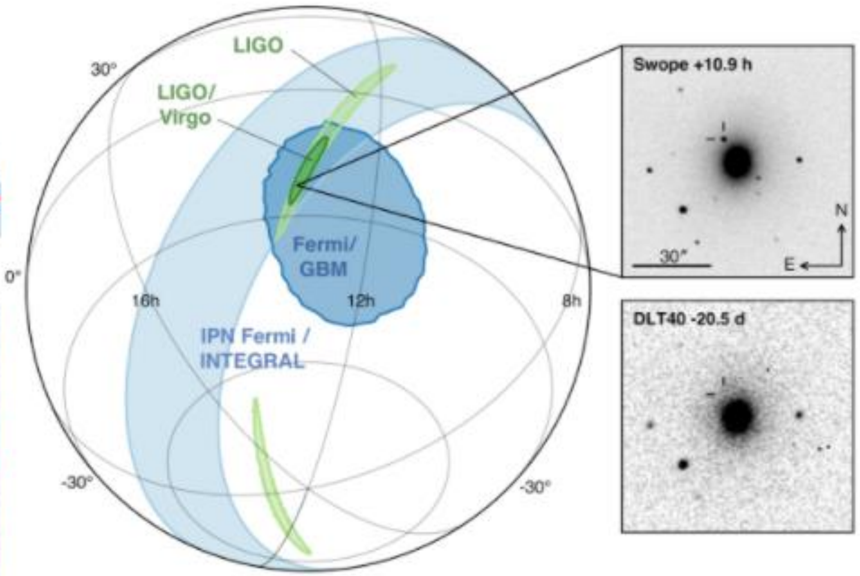
August 2017: a 3-detector global network

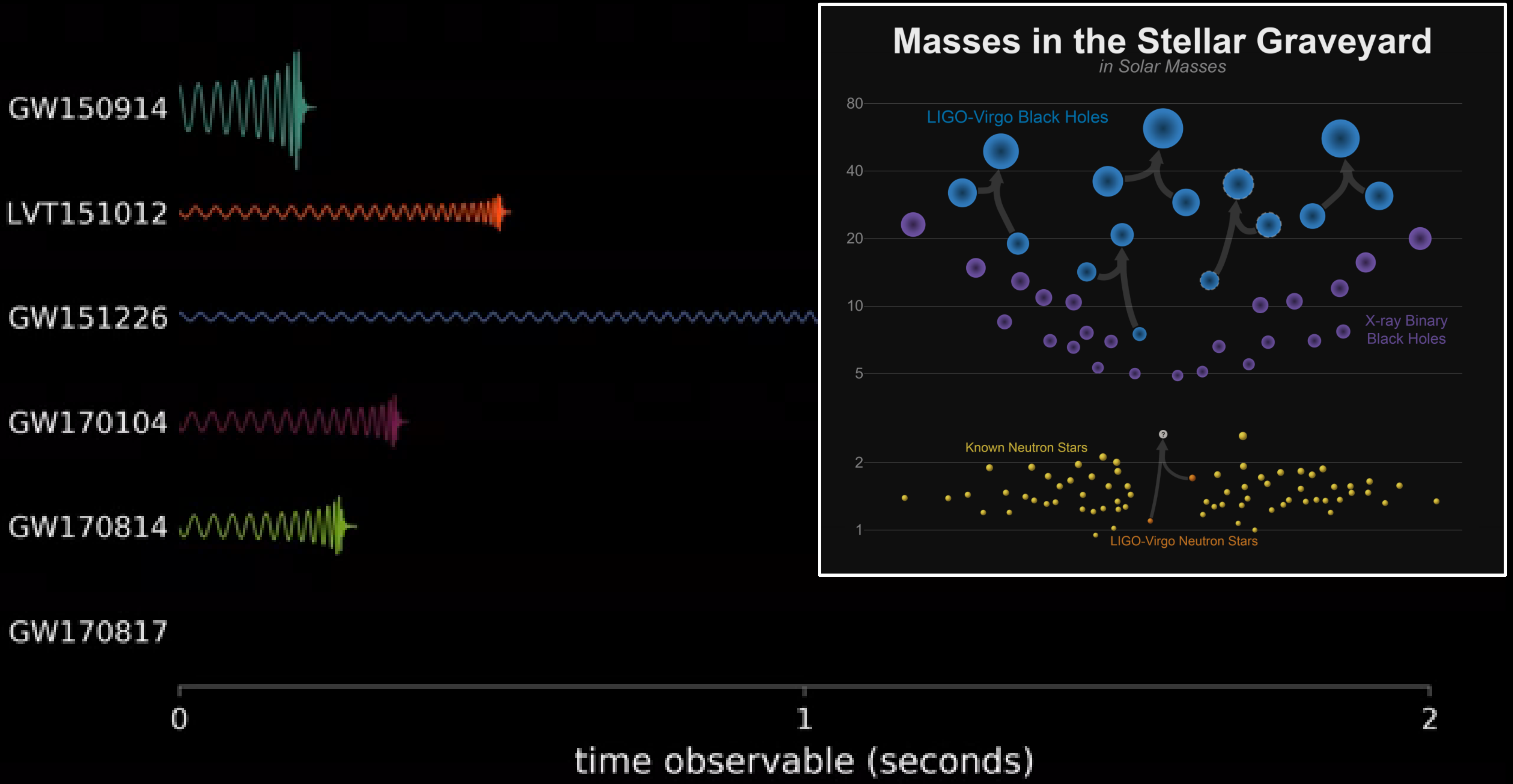


LSC LIGO Scientific Collaboration

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

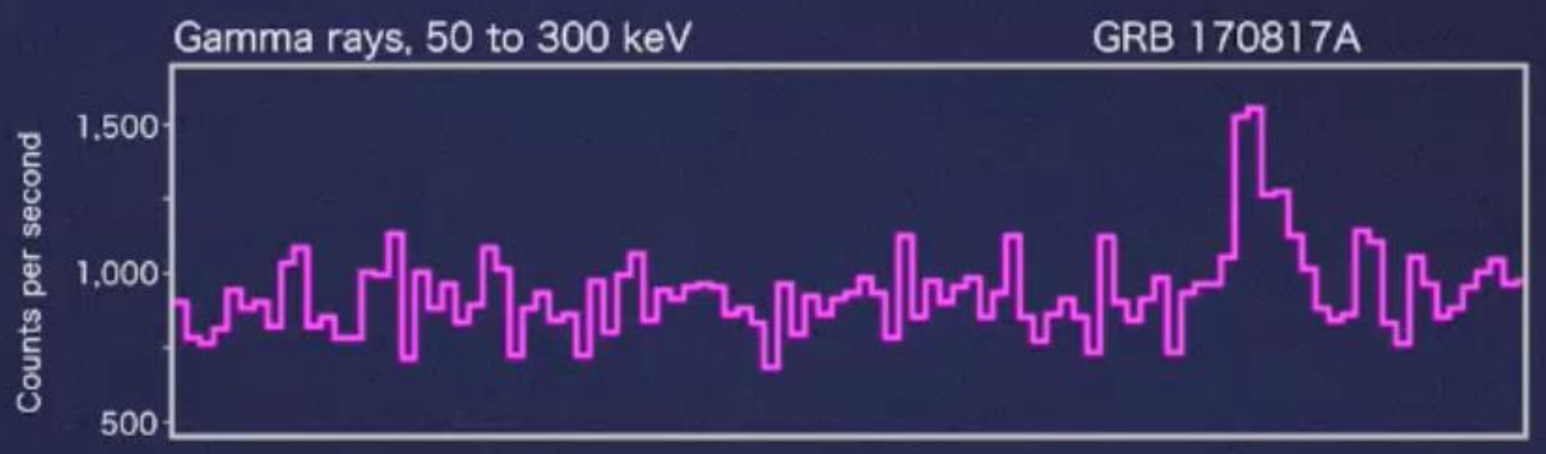




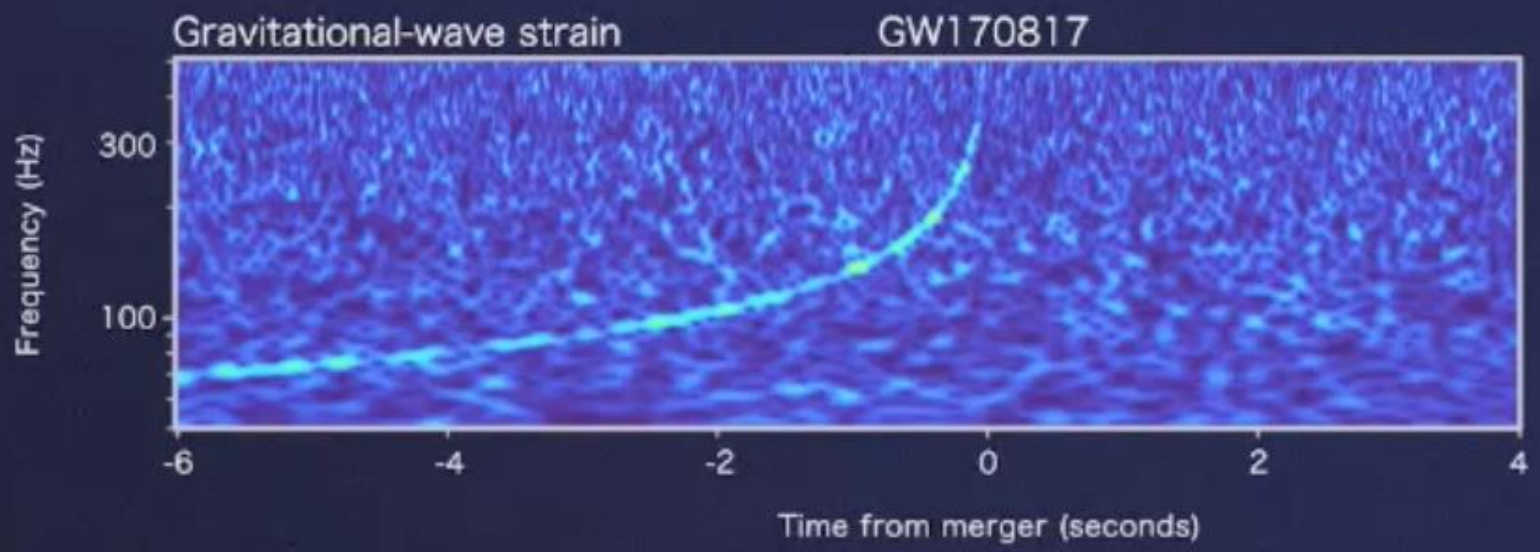


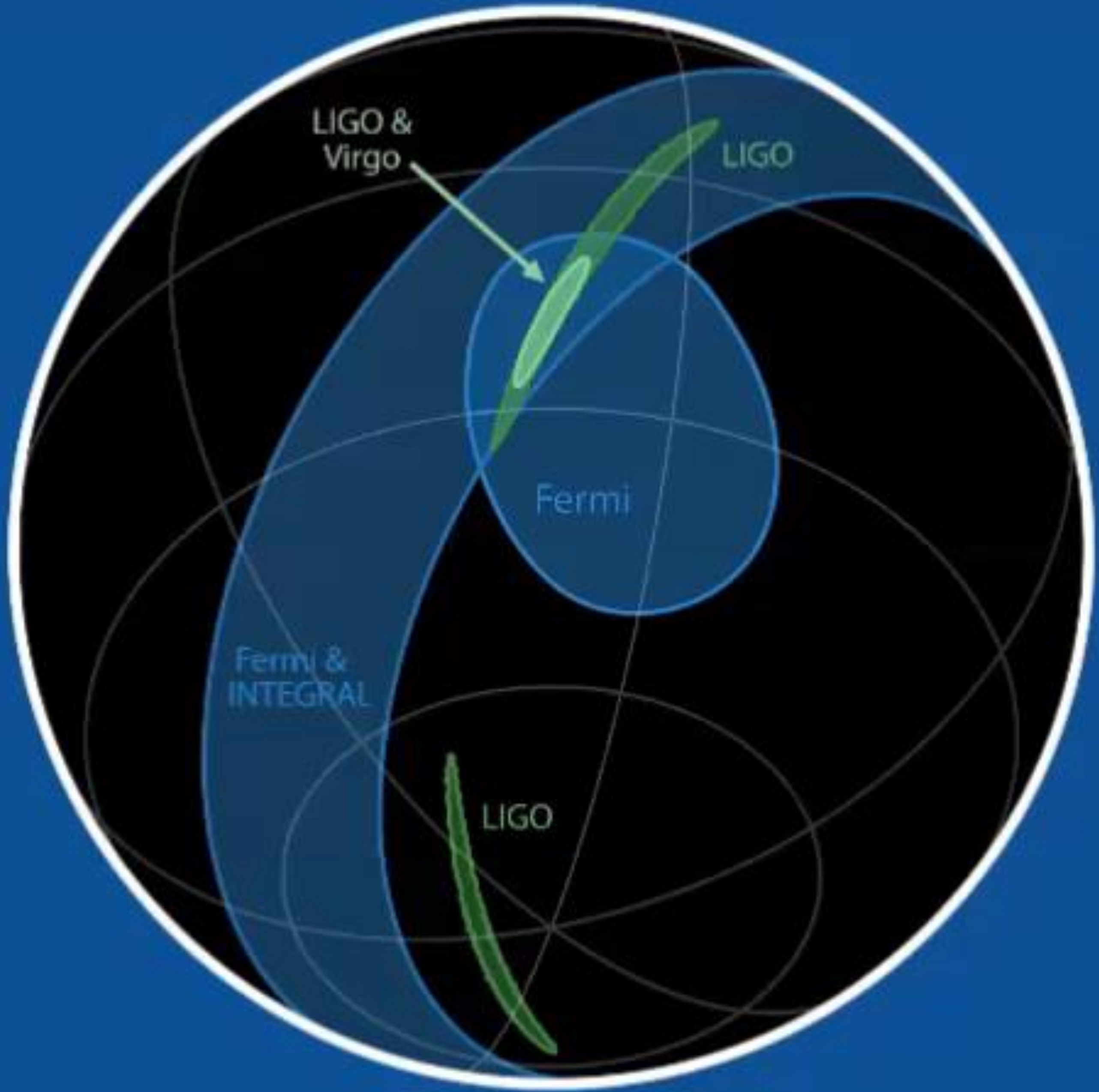
LIGO/University of Oregon/Ben Farr

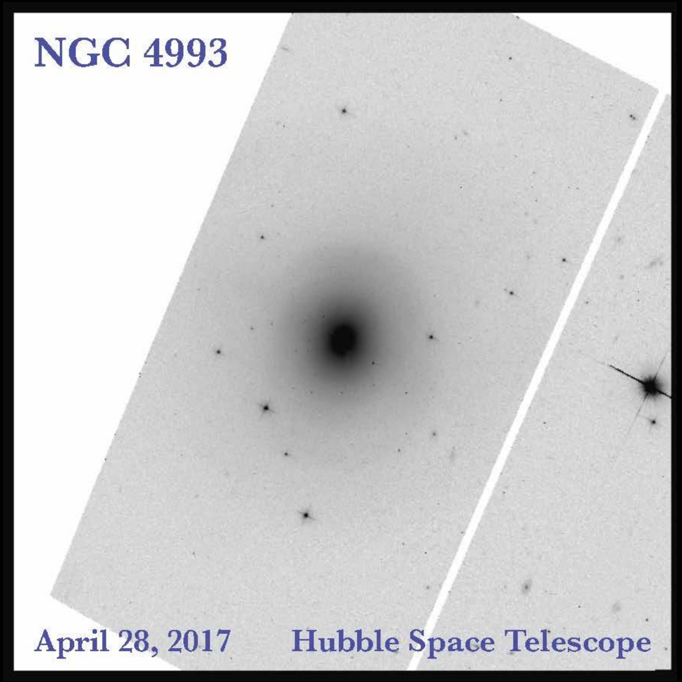
Fermi

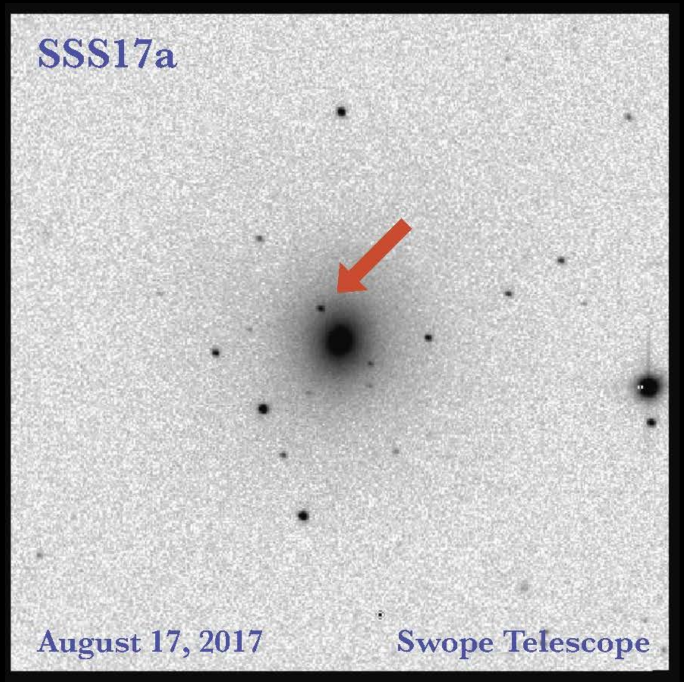

Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500

LIGO


Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

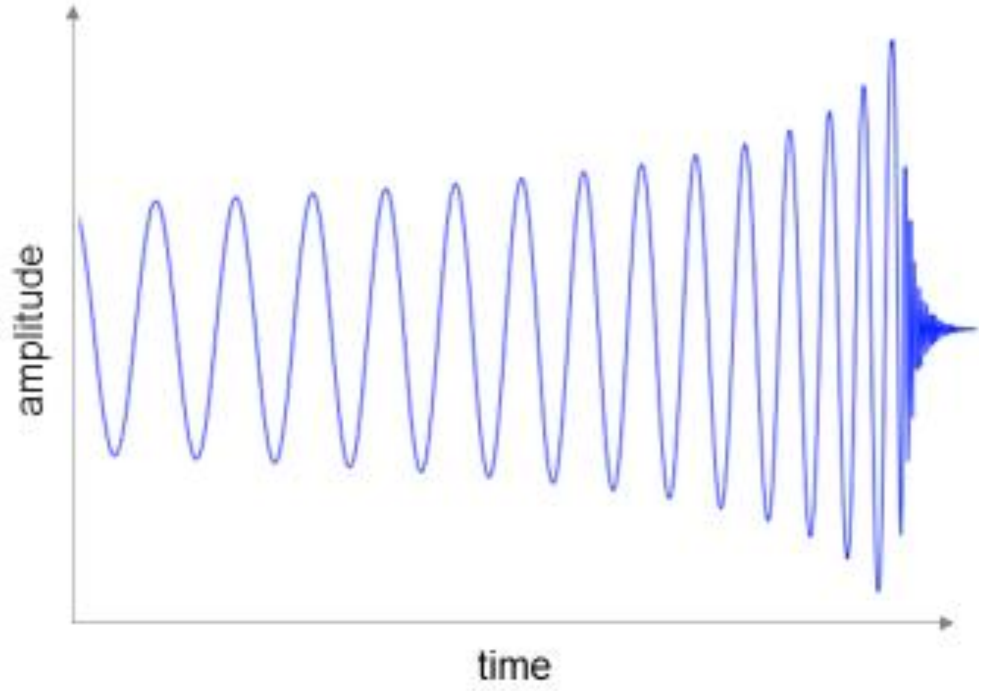

LIGO &
Virgo
LIGO
Fermi
Fermi &
INTEGRAL
LIGO


NGC 4993
April 28, 2017
Hubble Space Telescope


SSS17a
August 17, 2017
Swope Telescope


Earth
Space
LIGO Hanford
LIGO Livingston
Virgo

Cosmology with Standard Sirens



'Chirping' waveform

Chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$h \propto \mathcal{M}^{5/3} f^{2/3} D_L^{-1}$$

$$\dot{f} \propto \mathcal{M}^{5/3} f^{11/3}$$

Measure

$$h, f, \dot{f} \Rightarrow \mathcal{M}, D_L$$

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

The signal from a system of two $1 M_\odot$ stars (where $M_\odot$ is the mass of the Sun) will sweep from 100 Hz to 1 kHz in ~3 s. There might be three events per year out to 100 Mpc, and if the detectors achieve their current design sensitivity, such events will be detectable with a signal-to-noise ratio of 30. To determine the distance, the signal has to be observed by a worldwide network of three, and preferably four, detectors. By measuring both the response of the detectors and the delays between the arrival times of the signal at different detectors, the network should be able to locate the source in an error box of ~36 square degrees. There is some chance that the coalescence event will be optically identifiable (I.D. Novikov, personal communication); otherwise, clustering of galaxies provides a statistical method that will still yield H_0 after remarkably few events. Here I give only a brief discussion; full details will be published elsewhere.

Several detectors being developed in the United States and Europe[2–4] will take the form of interferometers with arm lengths 1-4 km, observing bandwidths 10^2–10^4 Hz and r.m.s. noise levels at 100 Hz of $<10^{-24}$ strain $\mathrm{Hz}^{-1/2}$. Within 10 years we may expect that there will be four or five such detectors in operation in America and Europe, with typical separations of 6,500 km. [It is possible that bar detectors could contribute to these observations. However, because of their narrow bandwidth, their detection of coalescing binaries requires quite different methods, which have not been studied. I shall therefore concentrate on interferometric detectors.]

Although there are many possible sources of gravitational waves, the most promising for detection by these instruments seems to be the coalescence of binary neutron stars, as will happen to the binary pulsar PSR1913+16 in $\sim 10^8$ yr. The gravitational waves from these sources before coalescence can be predicted very reliably (K. S. Thorne, personal communication). As an orbit decays through the emission of gravitational radiation, its eccentricity is reduced, so we need only consider systems with circular orbits[5]. Consider a binary at a distance $100 r_{100}$ Mpc, with total mass $m_T M_\odot$ and reduced mass $\mu M_\odot$, emitting waves at frequency $100 f_{100}$ Hz (twice its orbital frequency). The standard 'quadrupole formula' of general relativity[6,7] shows that the waves will have amplitude (r.m.s.-averaged over detector and source orientations)

$$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1} \qquad (1)$$

and that their frequency will change on a timescale

$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3}\ \mathrm{s} \qquad (2)$$

Two $1.4 M_\odot$ neutron stars will coalesce[1] when $f \approx 10^3$ Hz. By using matched filters to analyse the data[5], the noise can effectively be limited to a bandwidth of $\sim \tau^{-1}$. This will enable the detectors to see binary neutron star sources at 100 Hz at a distance of 100 Mpc, with a mean signal-to-noise ratio (SNR) of >30. An observation will therefore determine τ and h to perhaps 3%. The key to our method is that the stars' masses enter equations (1) and (2) in exactly the same way, so that

$$r_{100} = 7.8 f_{100}^{-2} (\langle h_{23} \rangle \tau)^{-1} \qquad (3)$$

where $\langle h_{23} \rangle = \langle h \rangle \times 10^{23}$, independently of the masses of the stars.

This result is not quite so strong as it seems, as equation (1) gives the r.m.s. value of h averaged over orientations, whereas the value of h inferred from the network's observations will depend on the binary system's orientation and position relative to the detectors as well as its distance. However, these can be determined from the observations: as I show below, provided that three or more detectors register the same event, they can determine the location on the sky and the degree of elliptical polarization of the wave. (In general relativity, gravitational waves are transverse and have only two independent polarizations[6–7].) Now, the radiation emitted by the binary along its angular momentum axis is circularly polarized, whereas that in the equatorial plane is linearly polarized. The degree of eliptical polarization therefore determines the inclination of the orbit to the line of sight, which enables us to solve for r_{100} in terms of the observed h. Equation (3) also depends on being able to model the system as two newtonian point masses. As we shall see below, tidal and relativistic corrections are negligible in the range of orbital parameters we require.

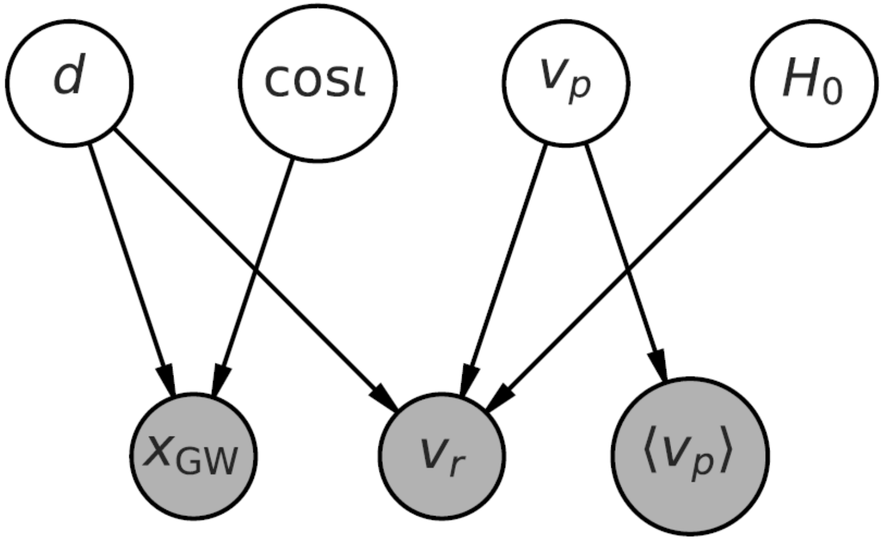
Being able to determine r directly from the observations is remarkable in itself, but it is only really useful if the source of the event can be identified. For this an accurate position is required. Because this accuracy is crucial for the determination of the Hubble constant, I will discuss it in some detail.

Each detector has quadrupolar linear polarization, so it is not highly directional; however, the differences in arrival time of a wave at different detectors can be used to triangulate the position. Between any two detectors with separation d, a wave travelling at an angle θ to the line joining the detectors will arrive at the second detector with a delay $\Delta t = d \cos\theta / c$ relative to the first, where c is the speed of light. For $d = 6.5 \times 10^3$ km, we have $|\Delta t| \leq 22$ ms. As the two detectors will generally not have the same polarization, there will be a further effective time delay due to the wave's elliptical polarization. Such a polarization can be regarded as a superposition of the two independent linear polarizations defined by the detectors, with a phase shift between them. This sphase shift means that differently polarized detectors record the wave train with extra time delays of up to one period (+10 ms for a 100-Hz signal). The two independent time delays measured among three detectors and the three measured amplitudes are sufficient to determine the waves' five unknowns: arrival directions (two), amplitudes of the different polarizations (two), and phase lag of the polarizations (one).

The precision with which the source's position and polarization can be measured depends on the two sorts of errors: the accuracy with which the arrival time of the wave at a detector (and hence the time delays) can be determined, and the accuracy with which the amplitude of the detector's response can be measured. In what follows, I will assume that $m_T^{2/3} \mu = 1$ (for example, two stars of $\sim 1.1 M_\odot$) to illustrate the situation. We shall see that the timing accuracy is typically 1% of the maximum timing range (from −22 to +22 ms), and the amplitude error is ~3%. When only three detectors see an event, there are actually two error boxes of size ~$10° \times 10°$, which may be too large for our purposes. I will therefore consider events detected in four instruments. The seven data overdetermine the five unknowns, and this redundancy offers us the opportunity to reduce the effective amplitude noise (it also allows a test of Einstein's polarization predictions). In this way, three timing measurements at ±1% and one amplitude measurement with effective error ±3% can be used to locate the source. This suggests that a positional error of ±3° is not unreasonable, giving an error

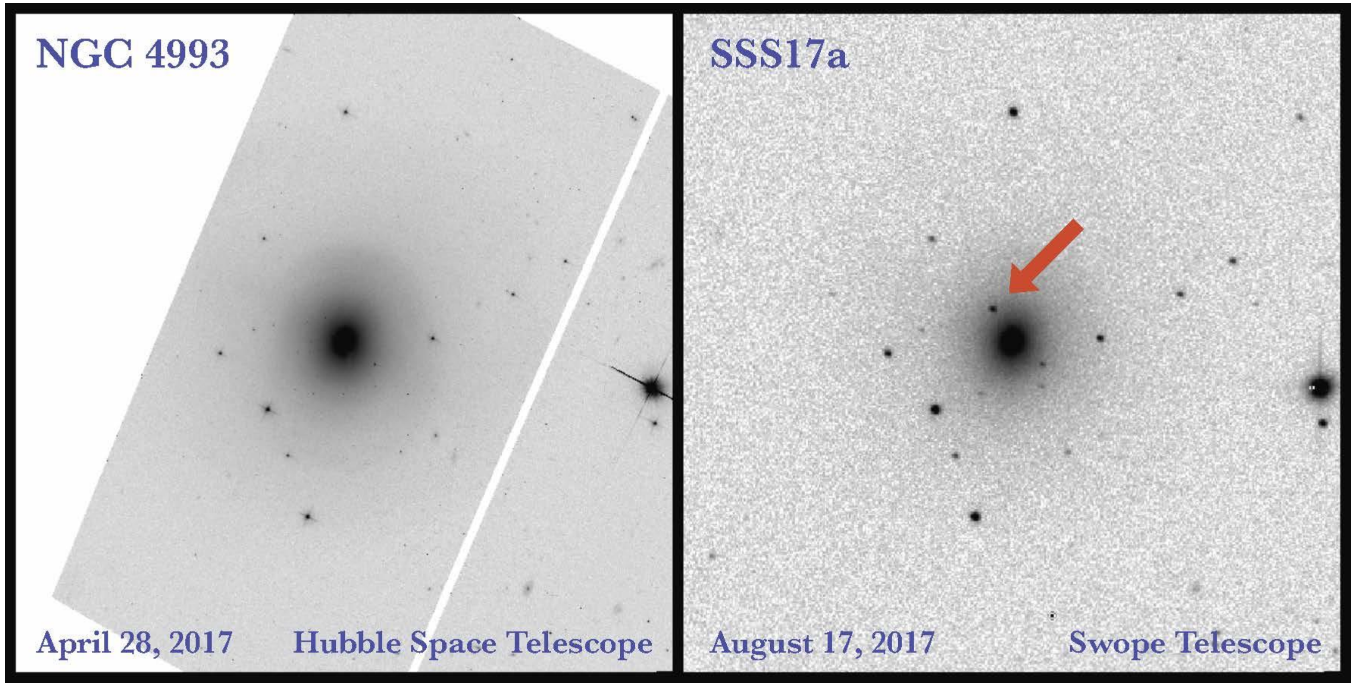
Schutz, Nature, **323**, 310 (1986)

$$h_{\rm meas} = \frac{G\boxed{(1+z)\mathcal{M}}/c^2}{D_L(z)} [\pi \boxed{(1+z)\mathcal{M}} f(t)]^{2/3} \mathcal{F}\,(\text{angles}) \cos\Phi\left(m_1, m_2, \vec{S}_1, \vec{S}_2; t\right)$$



Observables:

- x_{GW} = **GW170817 distance**
- v_r = **recession velocity**
- $\langle v_p \rangle$ = **mean pec. velocity**



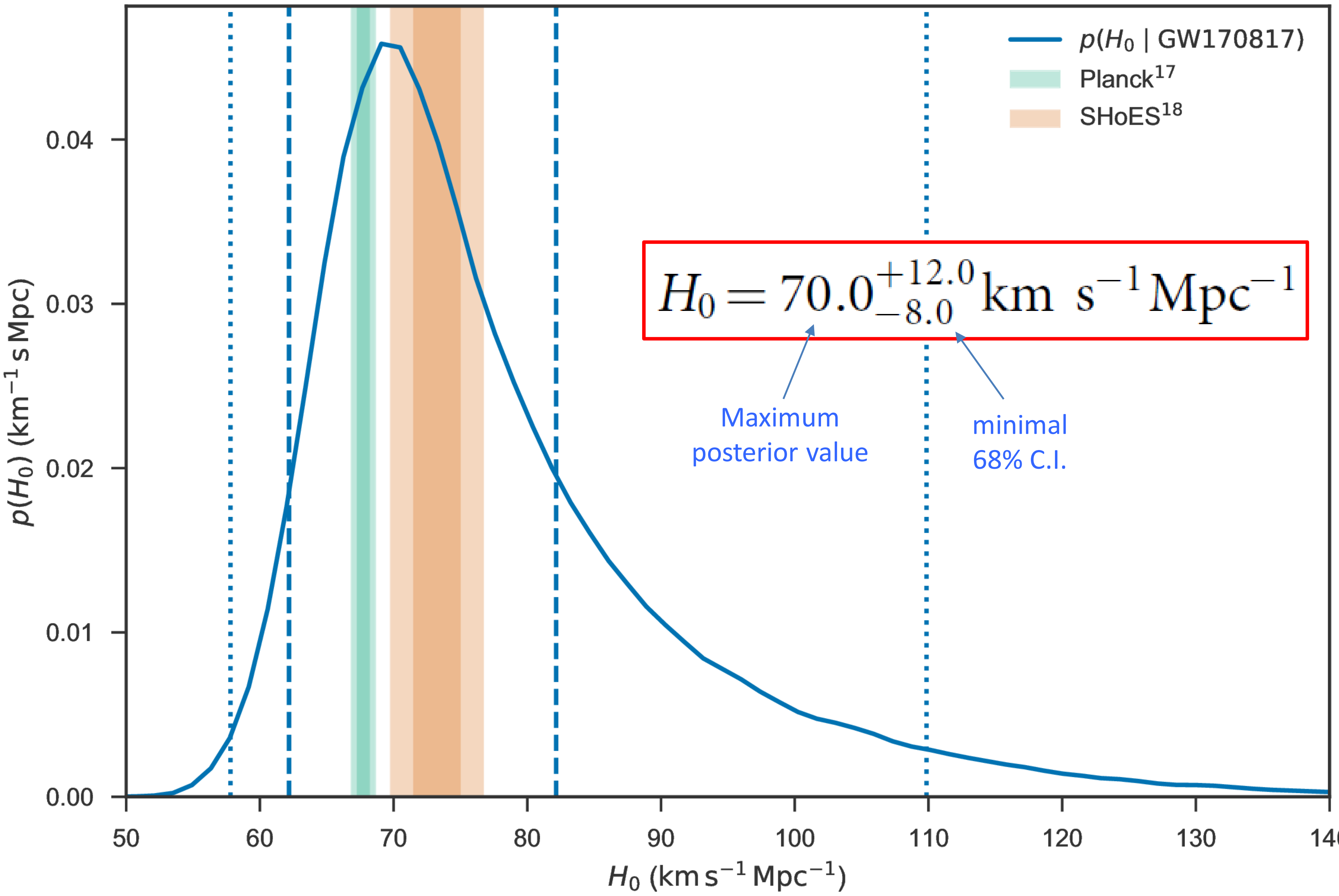
Assuming optical counterpart in NGC 4993, and at true sky location of BNS…

$$d = 43.8^{+2.9}_{-6.9}\ \mathrm{Mpc}$$

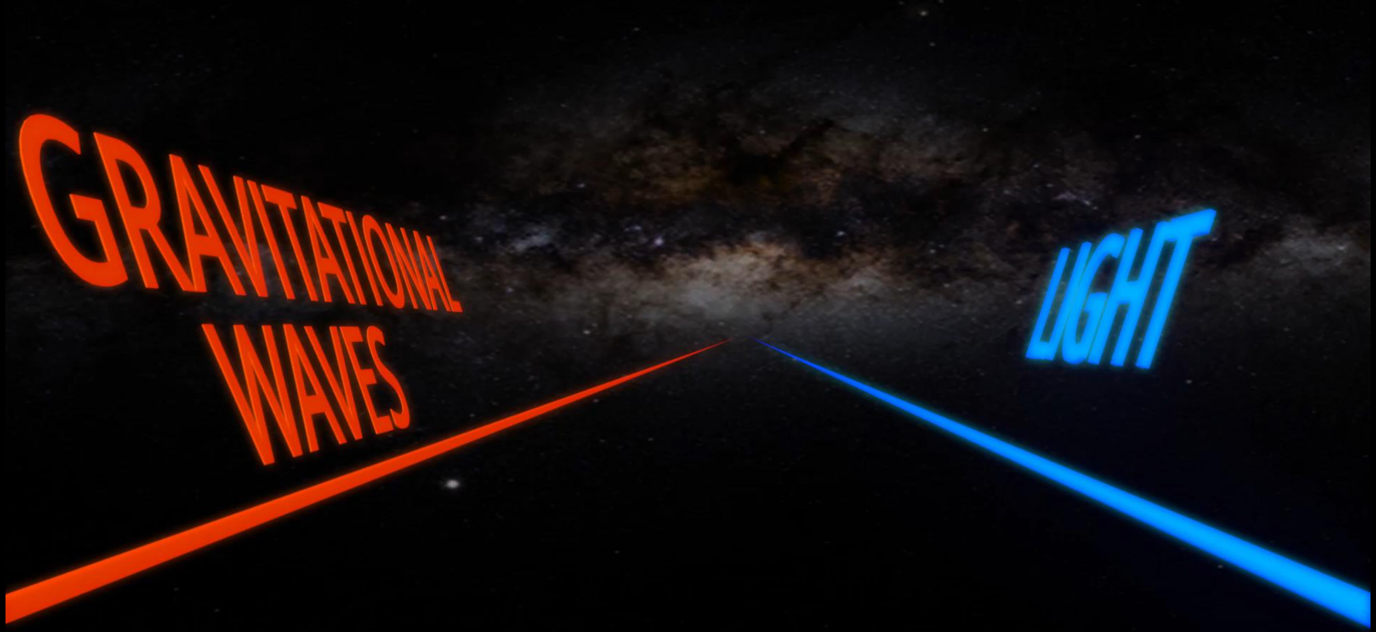
$$v_r = 3{,}327 \pm 72\ \mathrm{km\ s^{-1}}$$

Recessional velocity of CoM of galaxy group

Abbott et al. Nature, **551**, 85 (2017)



Abbott et al. Nature, **551**, 85 (2017)



$$-3 \times 10^{-15} \le \frac{\Delta v}{v_{\mathrm{EM}}} \le +7 \times 10^{-16}$$

LSC LIGO Scientific Collaboration VIRGO

GRAVITATIONAL WAVES AND GAMMA-RAYS FROM A BINARY NEUTRON STAR MERGER: GW170817 AND GRB 170817A

The gravitational-wave signal GW170817 was detected on August 17, 2017 by the Advanced LIGO and Virgo observatories. This is the first signal thought to be due to the merger of two neutron stars. Only 1.7 seconds after the gravitational-wave signal was detected, the Fermi Gamma-ray Burst Monitor (GBM) and the Anticoincidence Shield for the SPectrometer for the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL SPI-ACS) detected a short gamma-ray burst GRB 170817A. For decades astronomers suspected that short gamma-ray bursts were produced by the merger of two neutron stars or a neutron star and a black hole. The combination of GW170817 and GRB 170817A provides the first direct evidence that colliding neutron stars can indeed produce short gamma-ray bursts.

INTRODUCTION

Gamma-Ray Bursts (GRBs) are some of the most energetic events observed in Nature. They typically release as much energy in just a few seconds as our Sun will throughout its 10 billion-year life. They occur approximately once a day and come from random points on the sky. These GRBs can last anywhere from fractions of seconds to thousands of seconds. However, we usually divide them in two groups based roughly on their duration, with the division being at the 2 second mark (although more sophisticated features are also taken into account in the classification). Long GRBs (>2 seconds) are caused by the core-collapse of rapidly rotating massive stars. Now we have evidence that short GRBs (<2 seconds) are due to the merger of two neutron stars, and also perhaps (although not directly observed yet) a neutron star and black hole.

FIGURES FROM THE PUBLICATION

For more information on the meaning of these figures, see the full publication here.

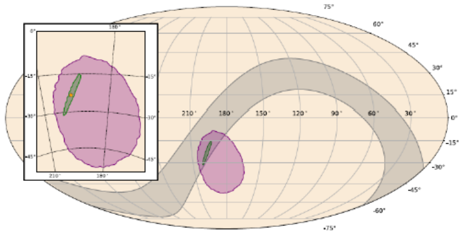


Figure 1: The final localization of the source which produced GW170817 and GW170817A. All contours are at 90% confidence. The contour for the skymap produced from LIGO-Virgo is shown in green. The Fermi-GBM targeted search localization is overlaid in purple. The annulus determined with Fermi and INTEGRAL timing information is shaded in gray. The zoomed inset also shows the position of the optical transient marked as a yellow star. The axes are Right Ascension and Declination in the Equatorial coordinate system.

THE GRAVITATIONAL-WAVE AND GAMMA-RAY BURST SIGNALS

The gravitational-wave observation: The two Advanced LIGO and the Virgo detectors observed the gravitational-wave signal GW170817 with a combined signal-to-noise ratio of 32.4, making it the loudest gravitational-wave signal recorded to date. Analysis of the gravitational-wave data revealed the signal to be consistent with the merger of two neutron stars, with masses between 0.86 and 2.26 times the mass of the Sun, over a hundred million light years away. This makes GW170817 the closest gravitational-wave event ever observed. The triangulation between the three detectors allowed the signal to be localized to within a 28 square degree patch of sky with 90% confidence; this is the smallest localization region LIGO-Virgo have ever reported and is shown in Figure 1. The time-frequency trace of GW170817 can be seen in the bottom panel of Figure 2.

The gamma-ray burst observation: The gamma-ray emission was detected independently by Fermi-GBM and INTEGRAL, two gamma-ray observatories orbiting the Earth. GRB 170817A was autonomously detected by Fermi-GBM in 3 out of 12 sodium iodide (NaI) detectors; the signal shows two apparently distinct components. The triggering observation, which lasts about half a second, shows characteristics typical of a short GRB and is shown in the second panel of Figure 2. This is then followed by a weaker emission at lower energy which lasts a few seconds, shown in the first panel of Figure 2. GRB 170817A is 3 times more likely to be a short GRB than a long GRB based solely on the GRB characteristics. Fermi-GBM localized GRB 170817A (at 90% confidence) to 1100 square degrees. The routine untargeted search for short transients by INTEGRAL SPI-ACS identified GRB 170817A, as shown in the third panel of Figure 2. Fermi-GBM and INTEGRAL SPI-ACS often jointly detect short GRBs; it has been confirmed to high confidence that the short GRB observed by Fermi-GBM is the same. Using the difference in the arrival time of GRB 170817A in INTEGRAL SPI-ACS and Fermi-GBM a joint localization can be made. This localization, as well as the Fermi-GBM search and LIGO-Virgo localizations, are presented in Figure 1.

Despite the overlapping sky localizations determined from the gravitational-wave detectors and the gamma-ray burst satellites, and the close time relation of the two signals, the question remains whether GW170817 and GRB 170817A originate from the same source. The probability that two unrelated signals would overlap this closely in space and time can be shown to be only 1 in 20 million. Therefore, it is extremely likely that the two signals are due to the same neutron-star merger.

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Selected for a Viewpoint in *Physics*
PRL **119**, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

I. INTRODUCTION

On August 17, 2017, the LIGO-Virgo detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger. This discovery comes four decades after Hulse and Taylor discovered the first neutron star binary, PSR B1913+16 [1]. Observations of PSR B1913+16 found that its orbit was losing energy due to the emission of gravitational waves, providing the first indirect evidence of their existence [2]. As the orbit of a BNS system shrinks, the gravitational-wave luminosity increases, accelerating the inspiral. This process has long been predicted to produce a gravitational-wave signal observable by ground-based detectors [3–6] in the final minutes before the stars collide [7].

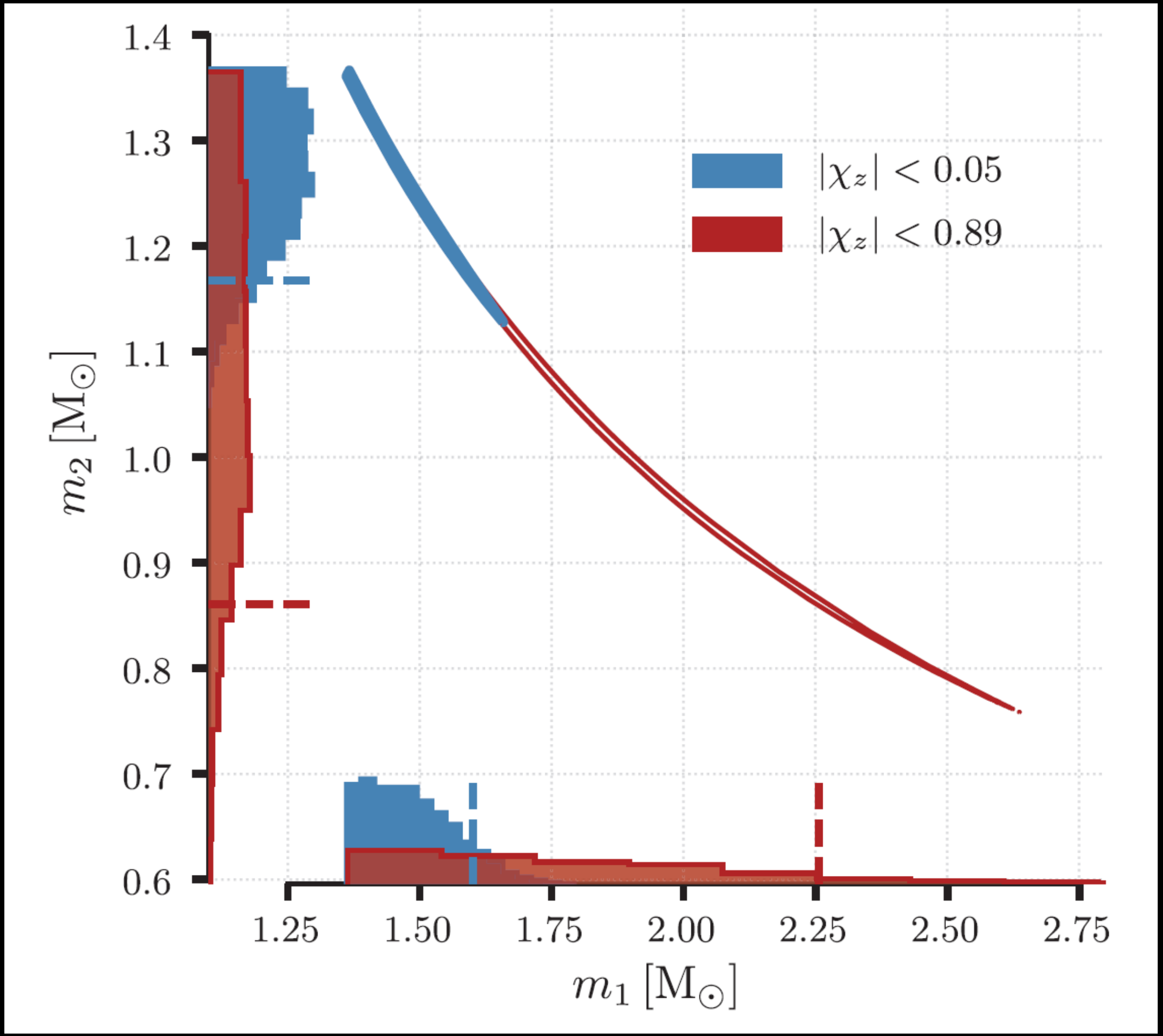
Since the Hulse-Taylor discovery, radio pulsar surveys have found several more BNS systems in our galaxy [8]. Understanding the orbital dynamics of these systems inspired detailed theoretical predictions for gravitational-wave signals from compact binaries [9–13]. Models of the population of compact binaries, informed by the known binary pulsars, predicted that the network of advanced gravitational-wave detectors operating at design sensitivity will observe between one BNS merger every few years to hundreds per year [14–21]. This detector network currently includes three Fabry-Perot-Michelson interferometers that measure spacetime strain induced by passing gravitational waves as a varying phase difference between laser light propagating in perpendicular arms: the two Advanced LIGO detectors (Hanford, WA and Livingston, LA) [22] and the Advanced Virgo detector (Cascina, Italy) [23].

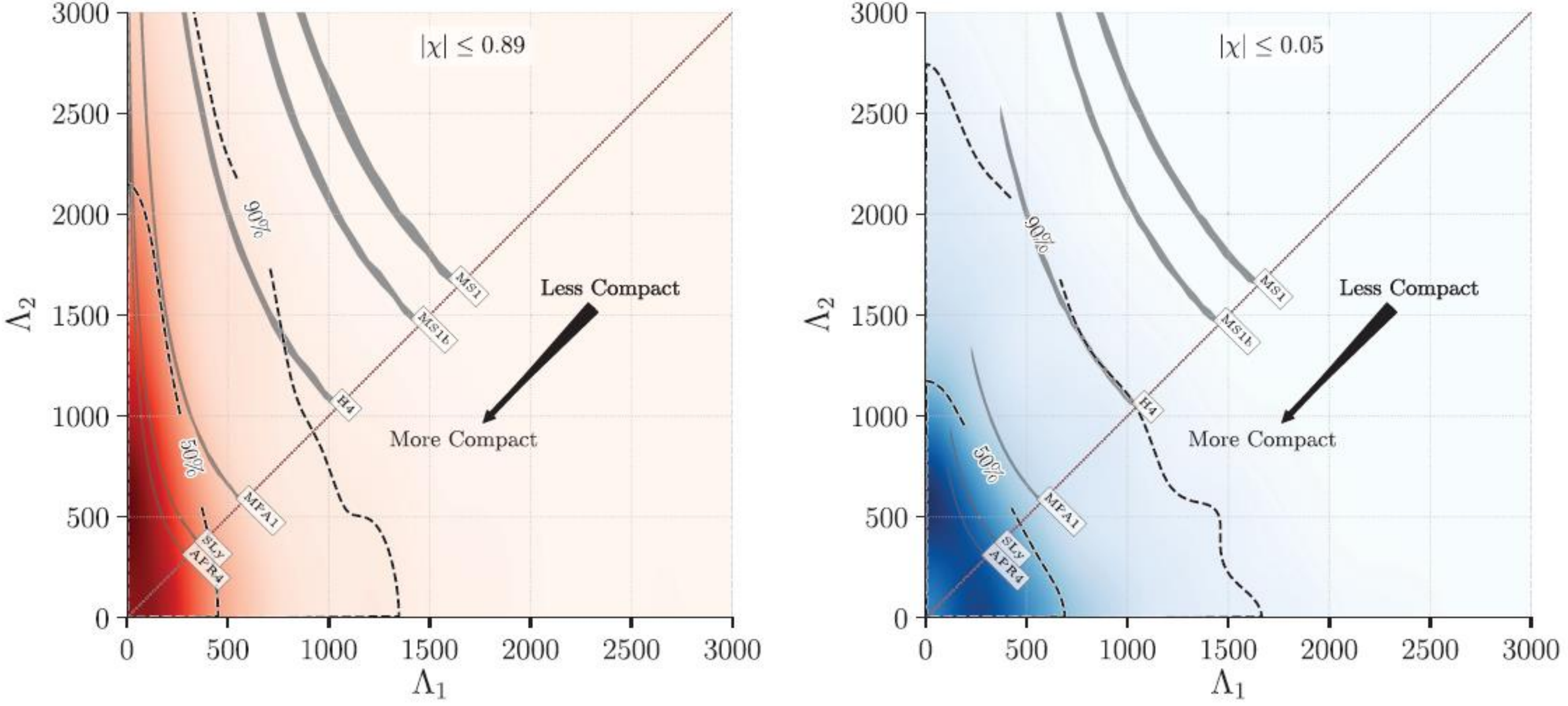
Advanced LIGO's first observing run (O1), from September 12, 2015, to January 19, 2016, obtained 49 days of simultaneous observation time in two detectors. While two confirmed binary black hole (BBH) mergers were discovered [24–26], no detections or significant candidates had component masses lower than $5 M_\odot$, placing a 90% credible upper limit of 12 600 Gpc^{-3} yr^{-1} on the rate of BNS mergers [27] (credible intervals throughout this Letter contain 90% of the posterior probability unless noted otherwise). This measurement did not impinge on the range of astrophysical predictions, which allow rates as high as ~10 000 Gpc^{-3} yr^{-1} [19].

The second observing run (O2) of Advanced LIGO, from November 30, 2016 to August 25, 2017, collected 117 days of simultaneous LIGO-detector observing time. Advanced Virgo joined the O2 run on August 1, 2017. At the time of this publication, two BBH detections have been announced [28,29] from the O2 run, and analysis is still in progress.

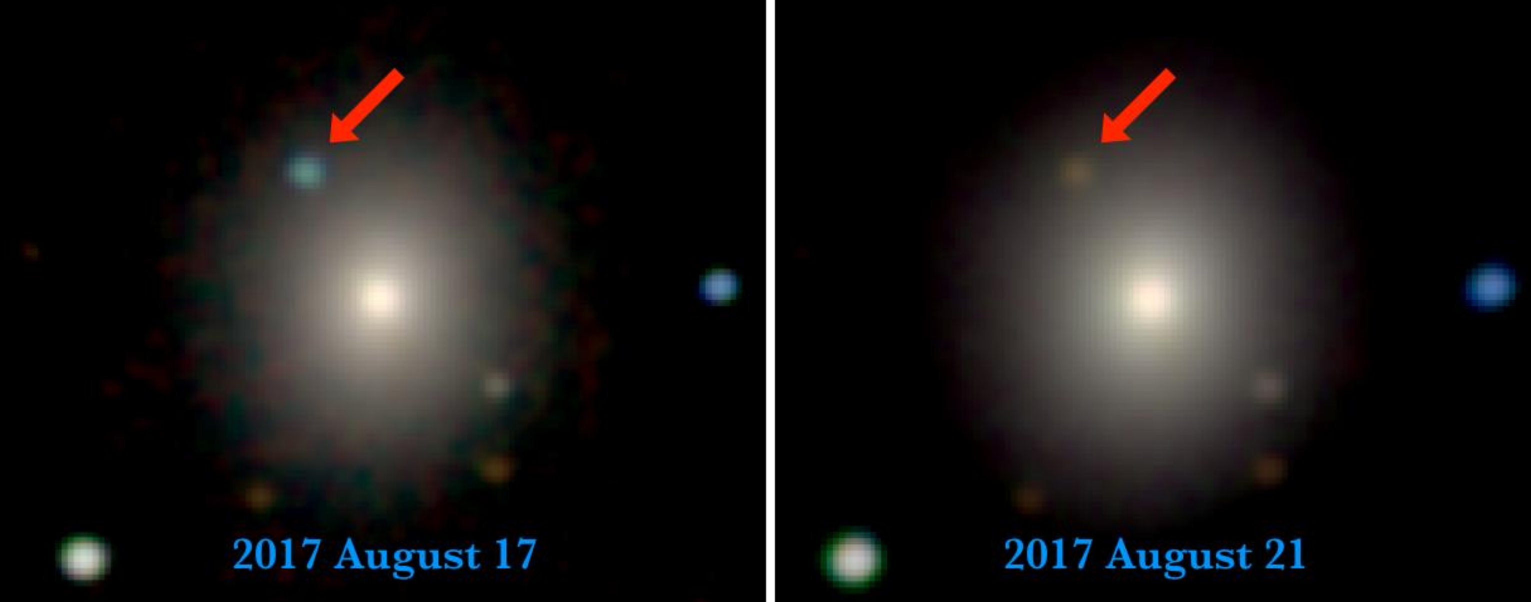
Toward the end of the O2 run a BNS signal, GW170817, was identified by matched filtering [7,30–33] the data against post-Newtonian waveform models [34–37]. This gravitational-wave signal is the loudest yet observed, with a combined signal-to-noise ratio (SNR) of 32.4 [38]. After

[*]Full author list given at the end of the Letter.

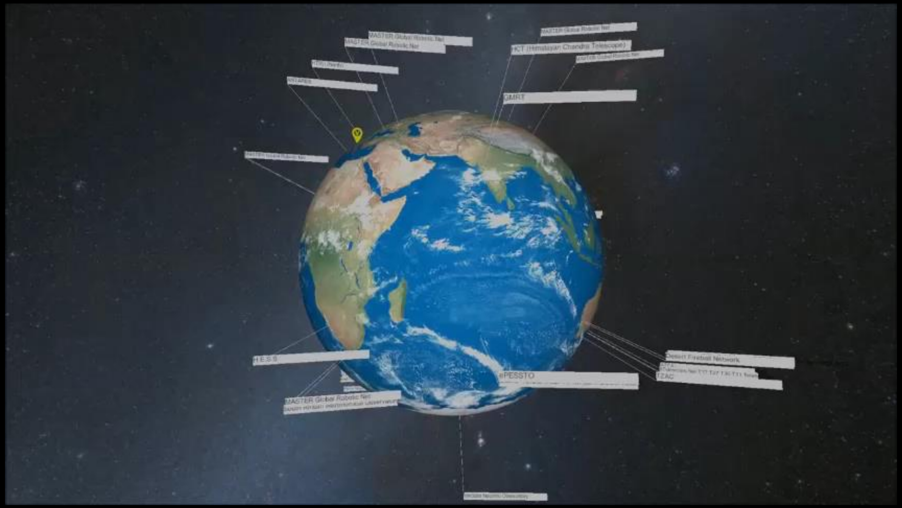


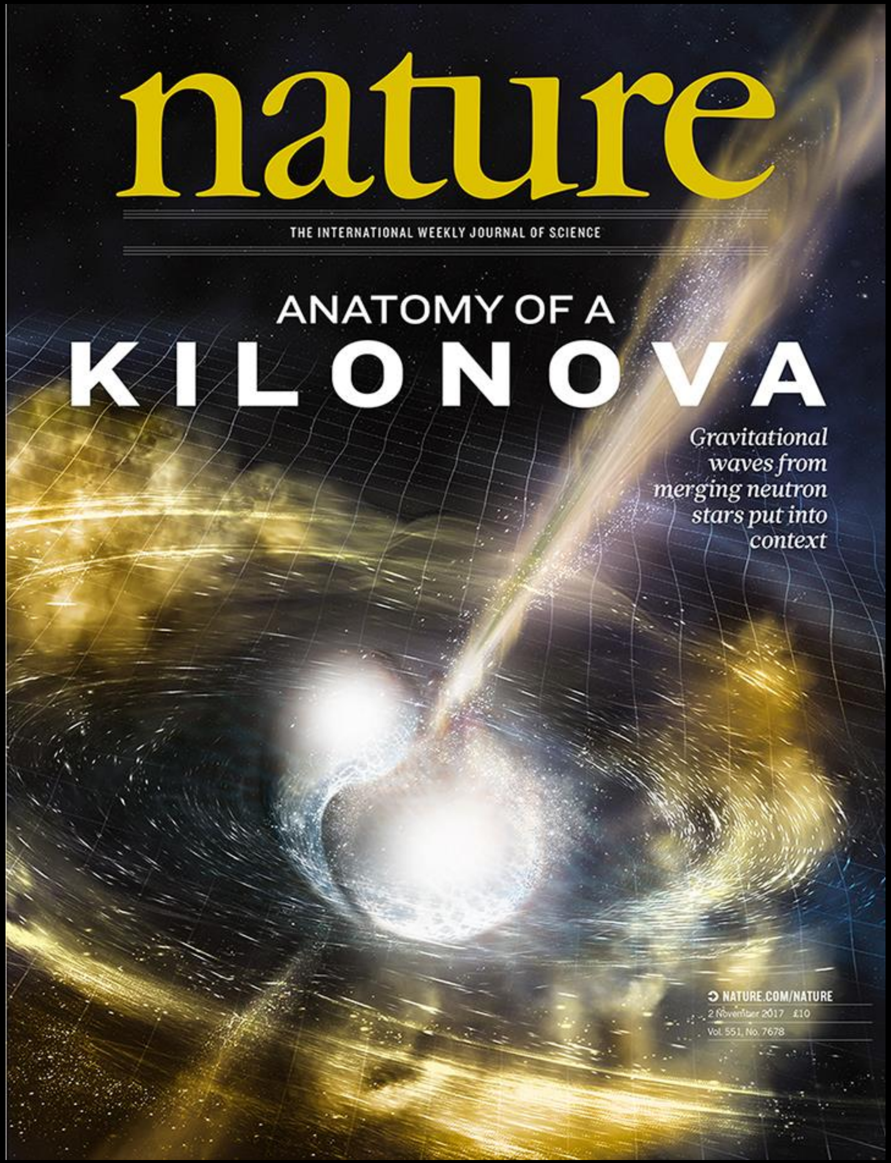

$|\chi| \leq 0.89$
$|\chi| \leq 0.05$
Less Compact
More Compact
MS1
MS1b
H4
MPA1
SLy
APR4
90%
50%
Λ_1
Λ_2
0
500
1000
1500
2000
2500
3000

SSS17a

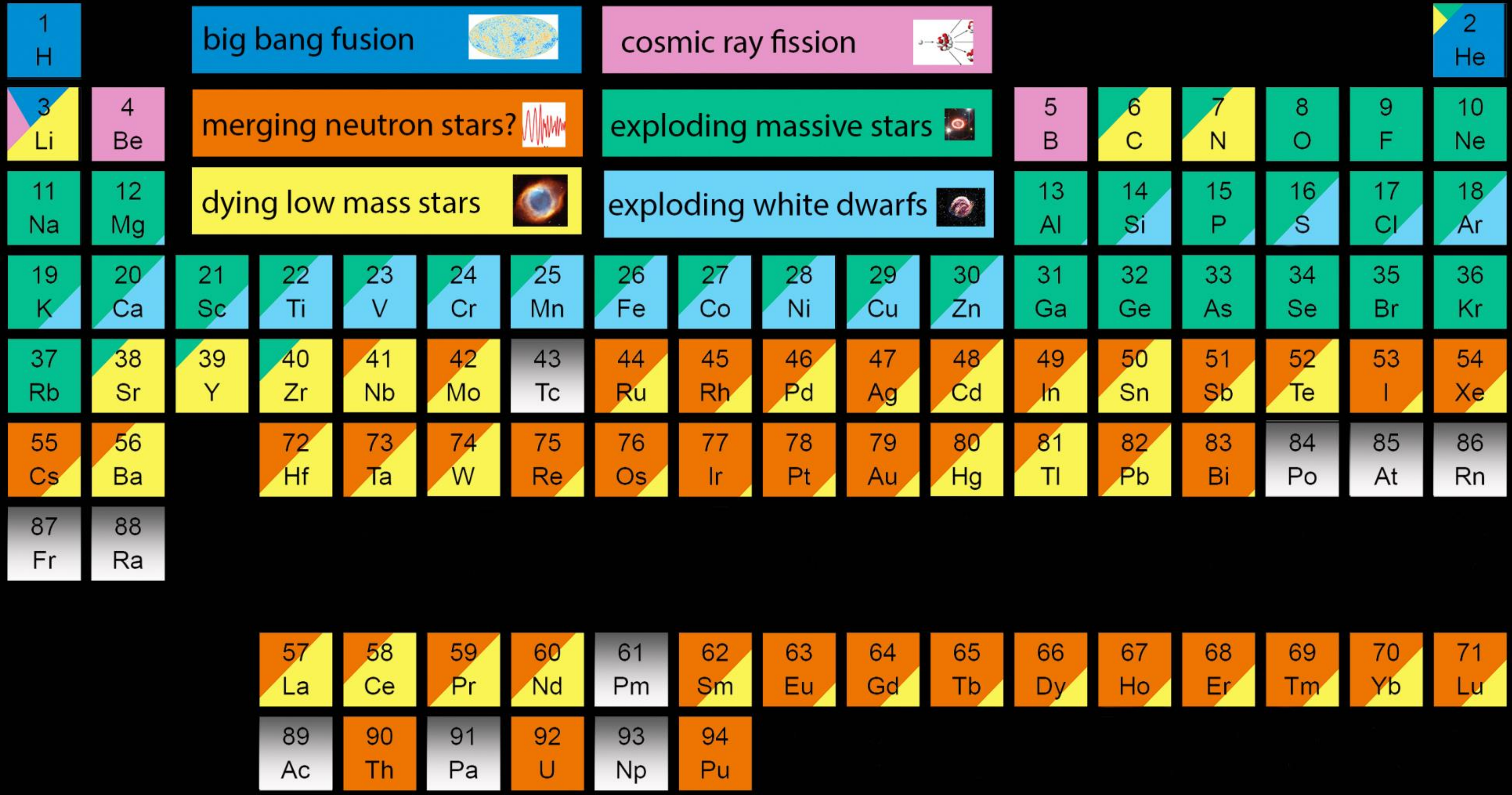


Swope & Magellan Telescopes





The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
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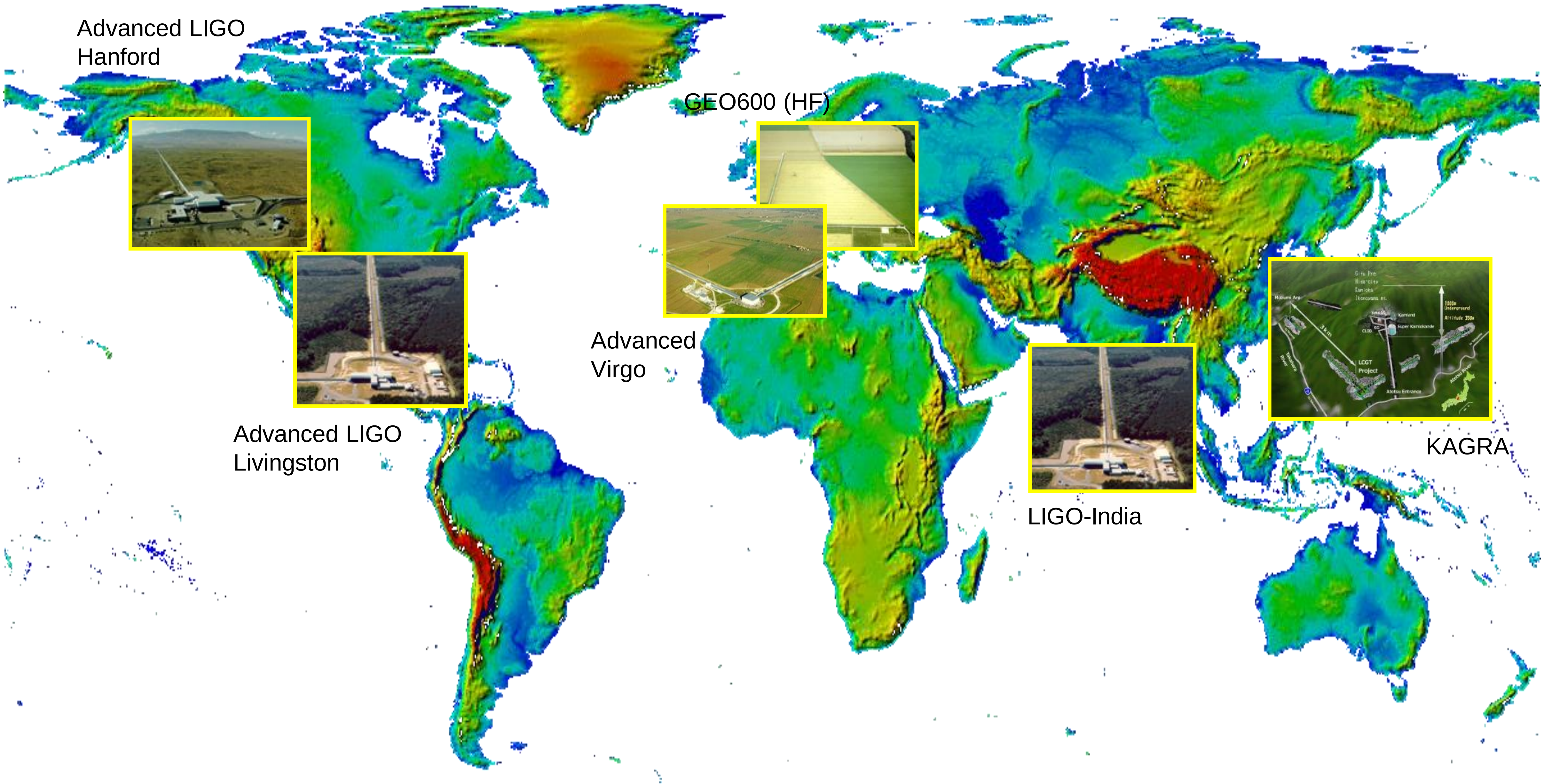
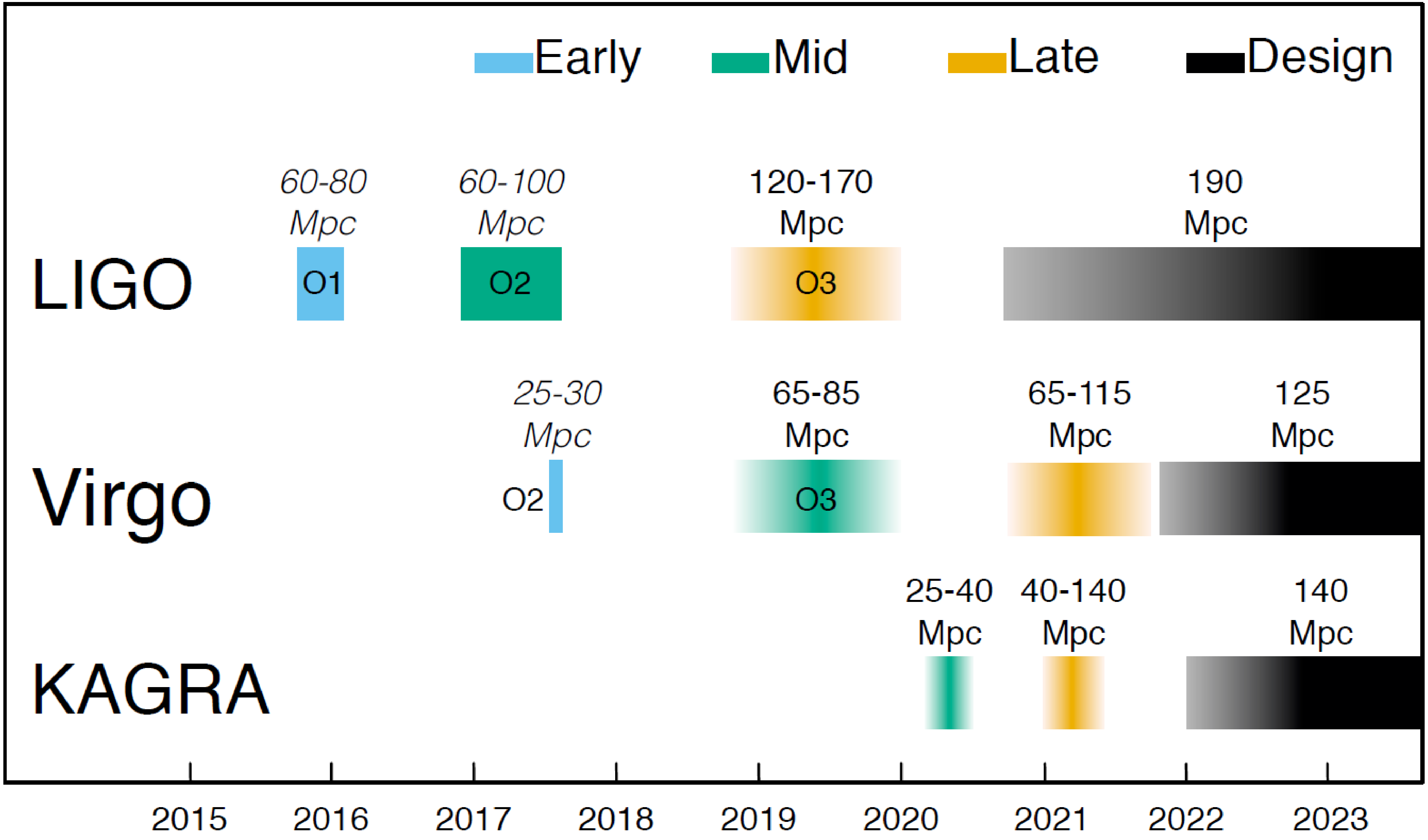
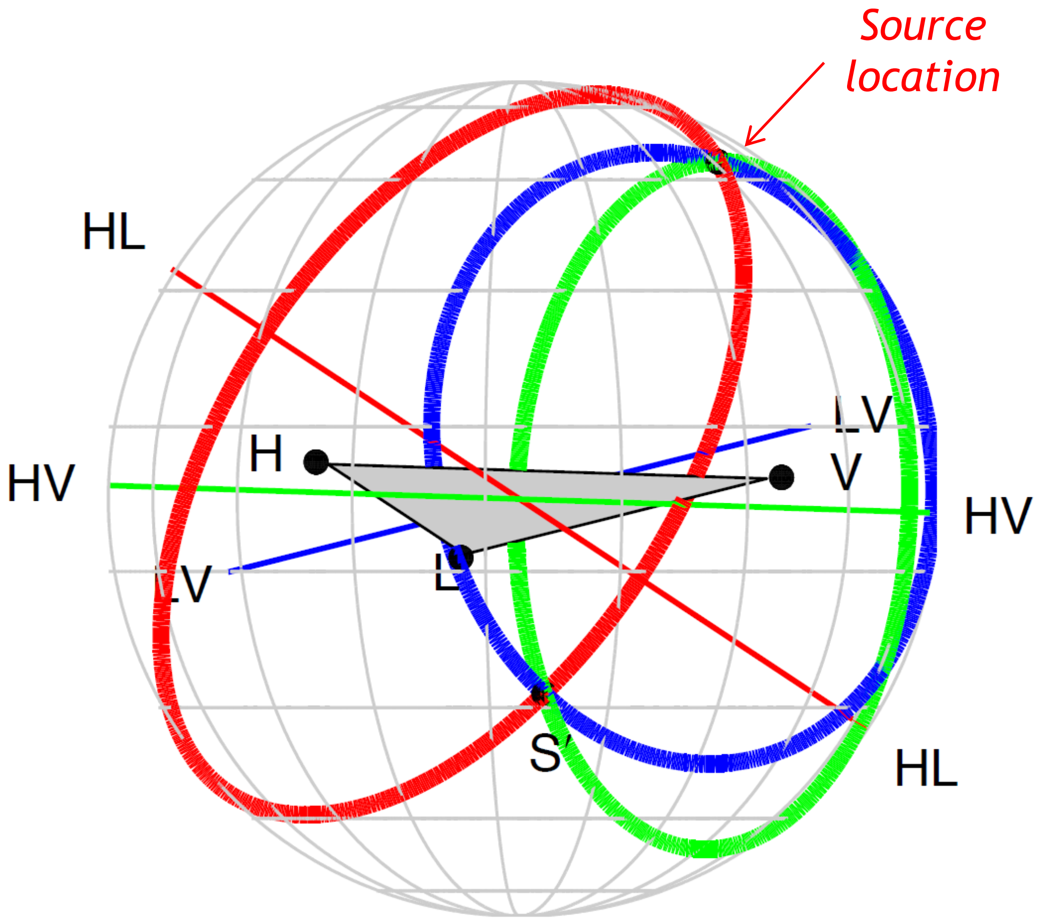
Network of advanced detectors





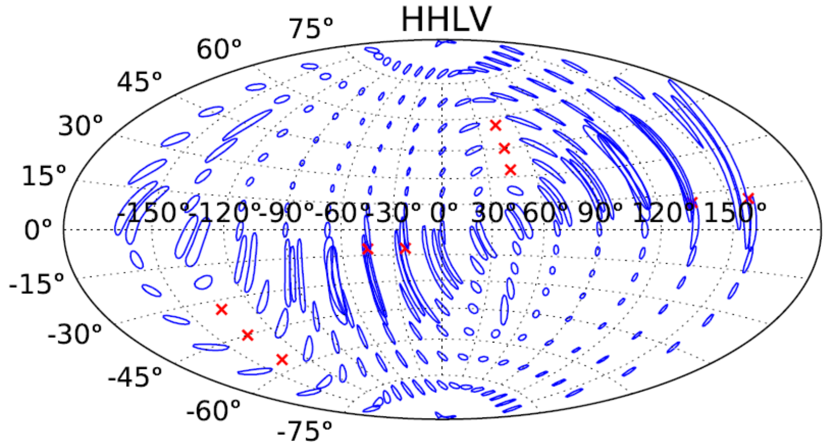
Early
Mid
Late
Design
LIGO
60-80 Mpc
O1
60-100 Mpc
O2
120-170 Mpc
O3
190 Mpc
Virgo
25-30 Mpc
O2
65-85 Mpc
O3
65-115 Mpc
125 Mpc
KAGRA
25-40 Mpc
40-140 Mpc
140 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023

With a global **network** of interferometers we can triangulate the sky position of a gravitational wave source even better.

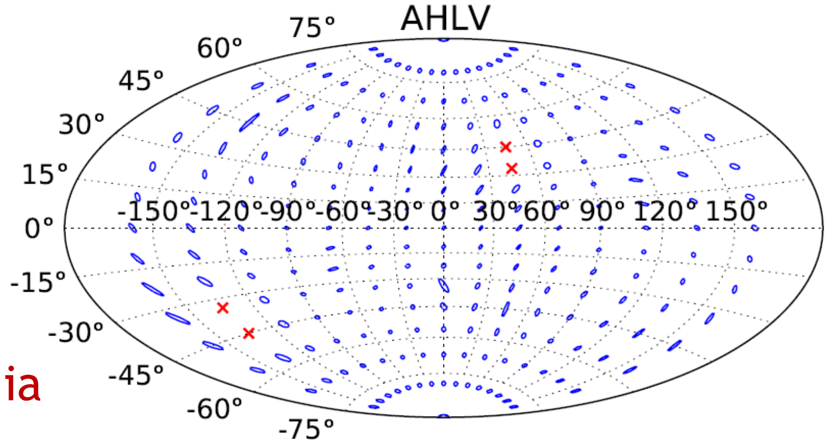


From Aasi et al.
arXiv:1304.0670

- The sky localisation depends on
  - the individual detector beam patterns
  - time delay between well separated sites
- *vastly* improved with more detectors:

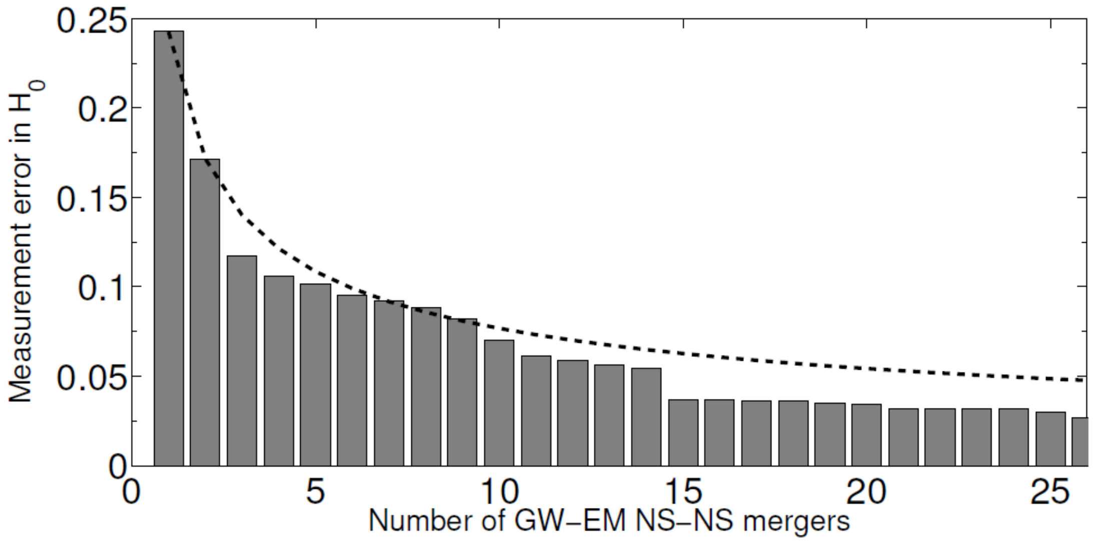


LIGO and Virgo only



Adding LIGO India

Coming attractions…



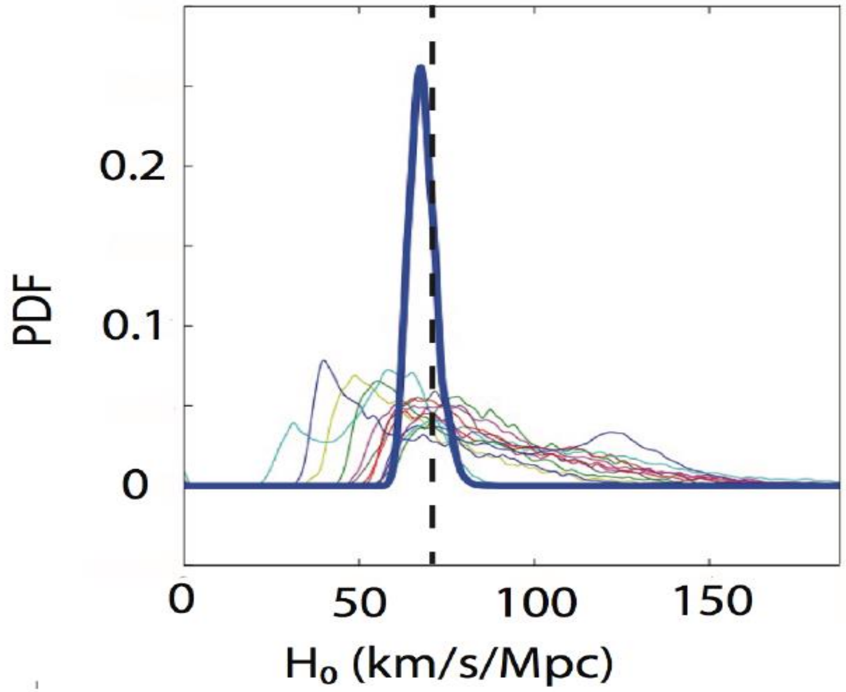
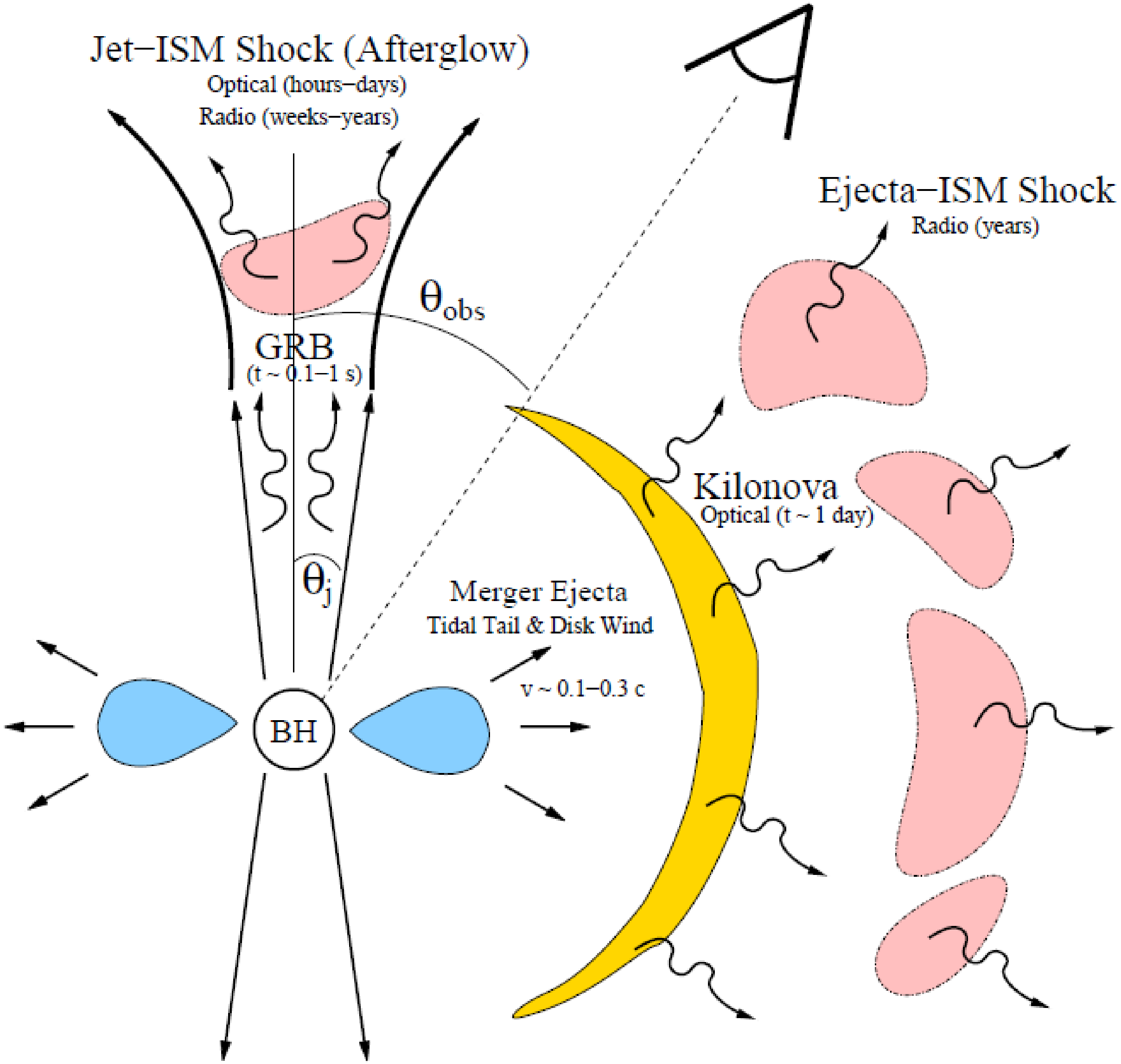


TABLE 1
MEASUREMENT ERRORS IN H_0 FOR A SAMPLE OF GW-EM EVENTS. RESULTS ARE PRESENTED FOR UNBEAMED AND BEAMED SOURCES, FOR BOTH NS-NS AND NS-BH MERGERS, AND FOR A RANGE OF DETECTOR NETWORKS. THE % VALUES ARE THE 68% C.L. FRACTIONAL ERRORS, AND THE NUMBER OF BINARIES DETECTED BY EACH NETWORK IS GIVEN IN PARENTHESES.

Network	LIGO+Virgo (LLV)	LLV+LIGO India	LLV+KAGRA	LLV+LIGO India+KAGRA
NS-NS Isotropic	5.0% (15)	3.3% (20)	3.2% (20)	2.1% (30)
NS-NS Beamed	1.1% (19)	1.0% (26)	1.0% (25)	0.9% (30)
NS-BH Isotropic	4.9% (16)	3.5% (21)	3.6% (19)	2.0% (30)
NS-BH Beamed	1.2% (18)	1.0% (25)	1.1% (24)	0.9% (30)

Nissanke et al, arxiv:1307.2638

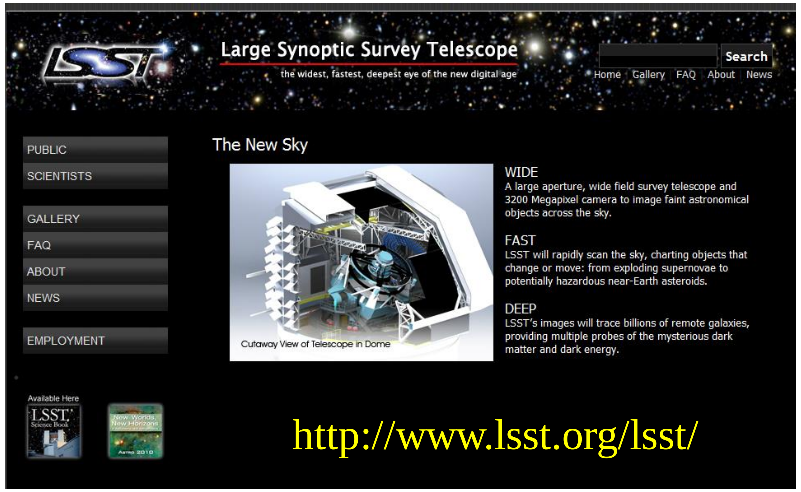
Finding the E-M counterpart…

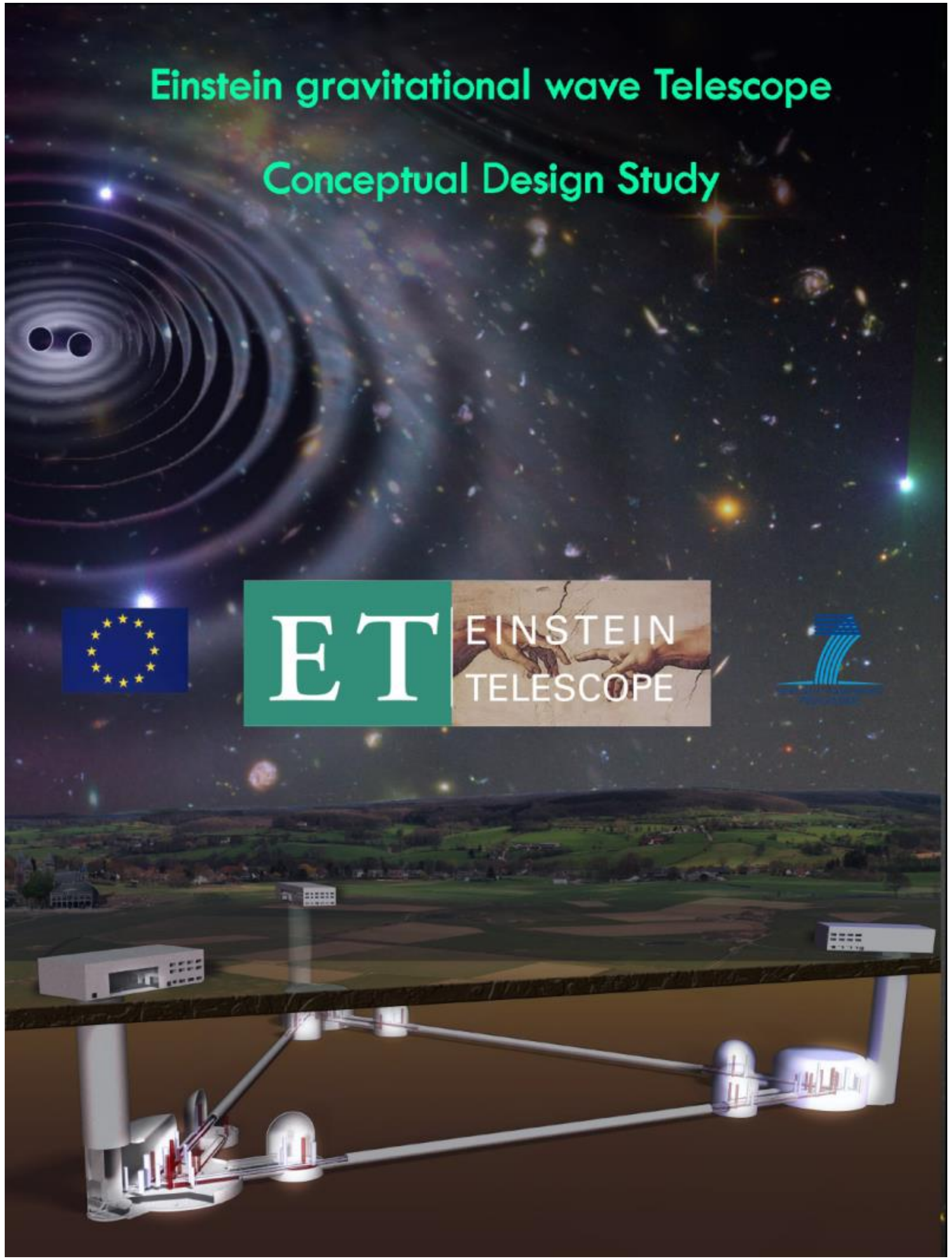


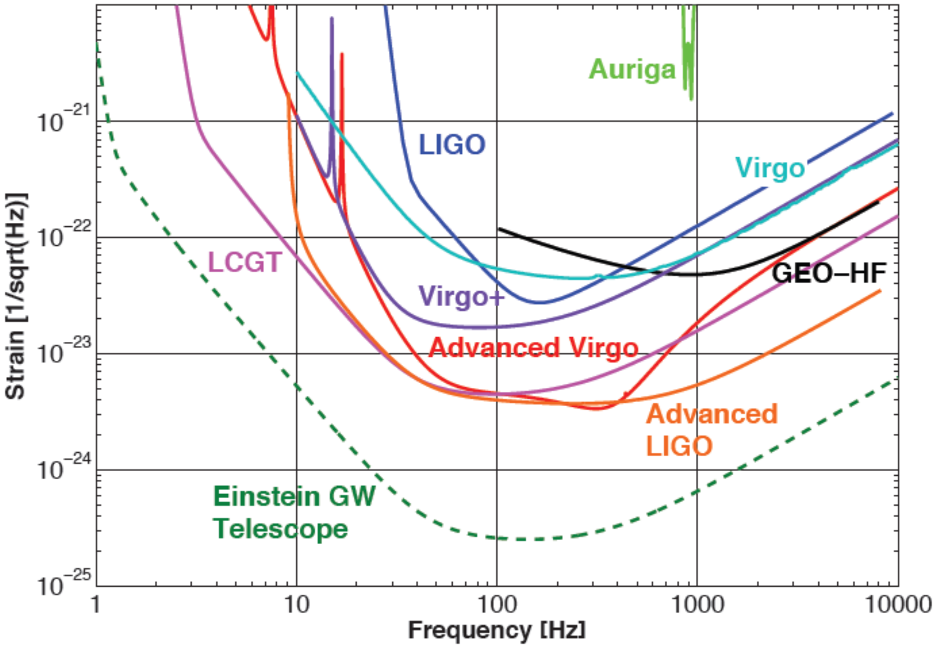
Metzger & Berger 2012

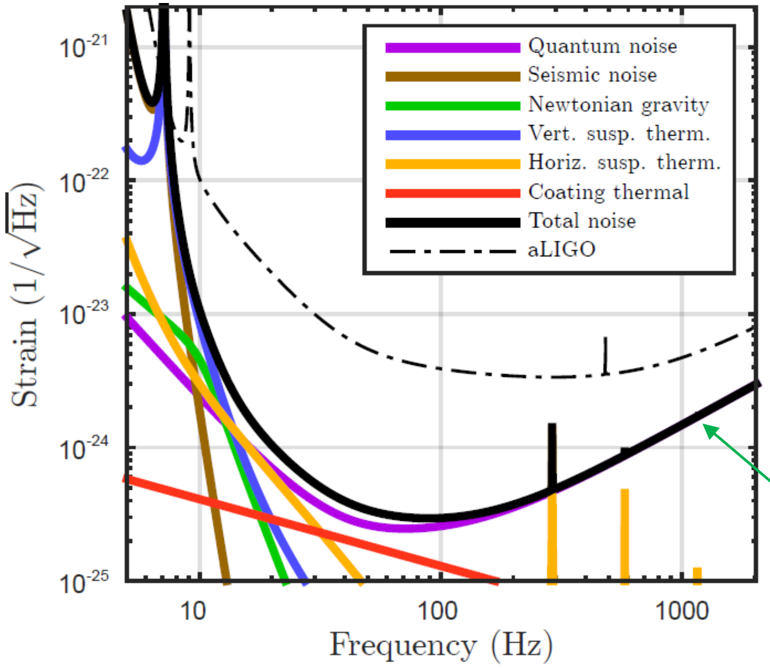
The Gravitational-Wave Optical Transient Observer

http://goto-observatory.org/









Cosmic
Explorer

Cosmological constraints from 3G detectors

Zhao et al. **(2011)**
[See also Zhao & Wen in prep.]

~10^6 NS-NS mergers observed by ET.

Different models for spatial distribution, source evolution; more general DE models

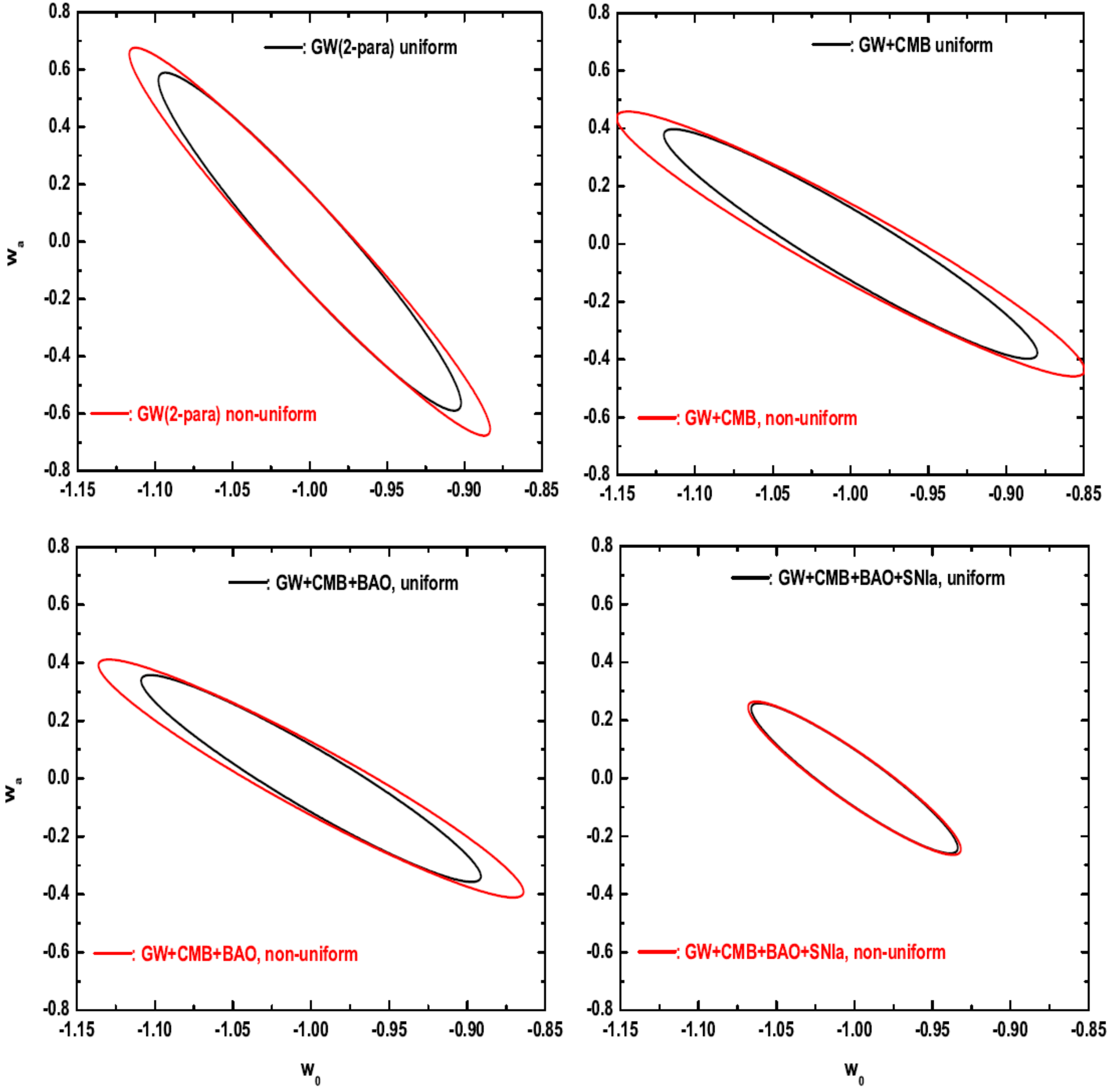
$$\boxed{w(z) = w_0 + w_a \frac{z}{1+z}}$$

GW constraints similar to those from BAO, SNIe.

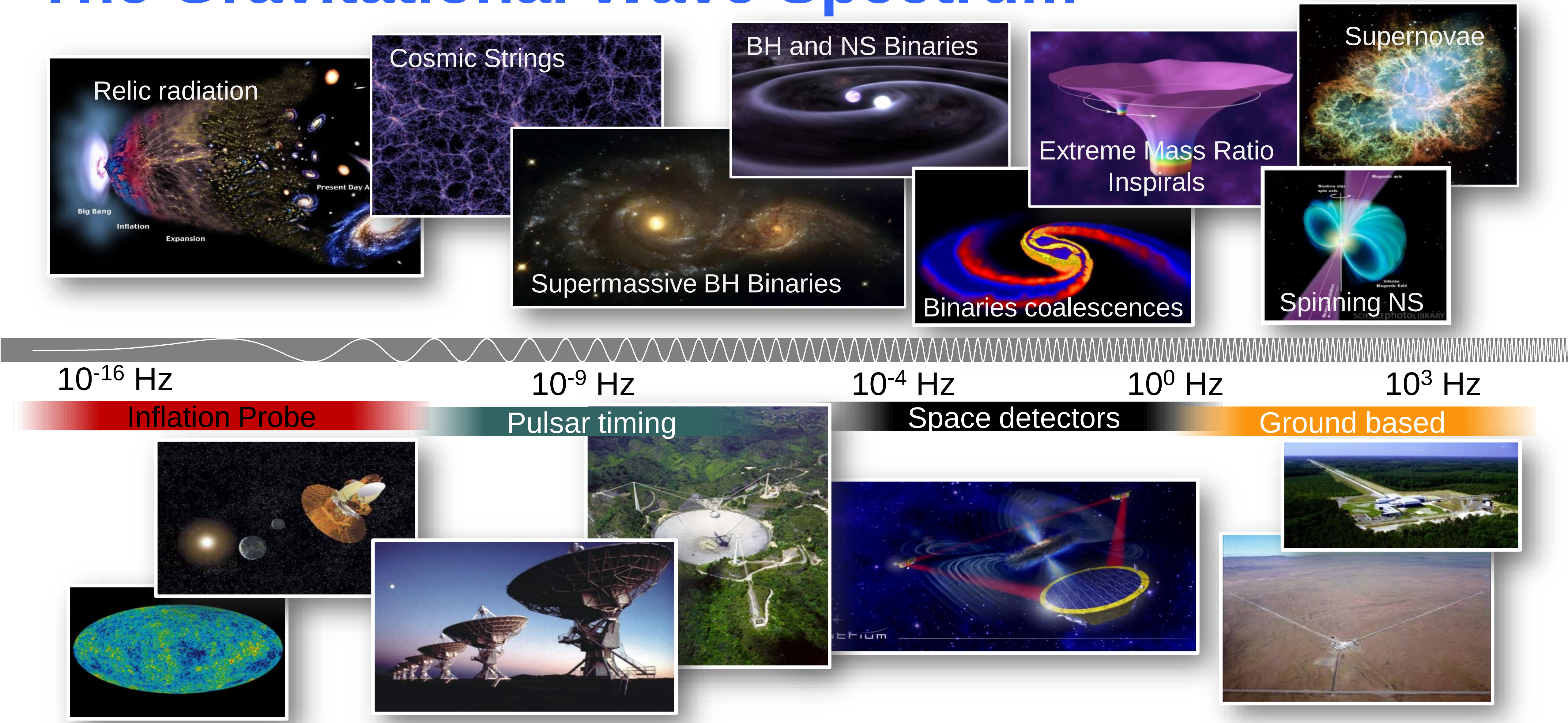
Results only weakly affected by source evolution.

BUT assumes z known for ~1000 sources

Significant 'multi-messenger' challenge



The Gravitational Wave Spectrum



Adapted from M. Evans (LIGO G1300662-v4)

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We will observe gravitational waves in space | New Astronomy | LISA Pathfinder

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Gravitational Wave mission selected for ESA's L3 mission

The LISA trio of satellites to detect gravitational waves from space has been selected as the third large-class mission in ESA's Science programme

1 2 3 4 5 6 7 8 9 10

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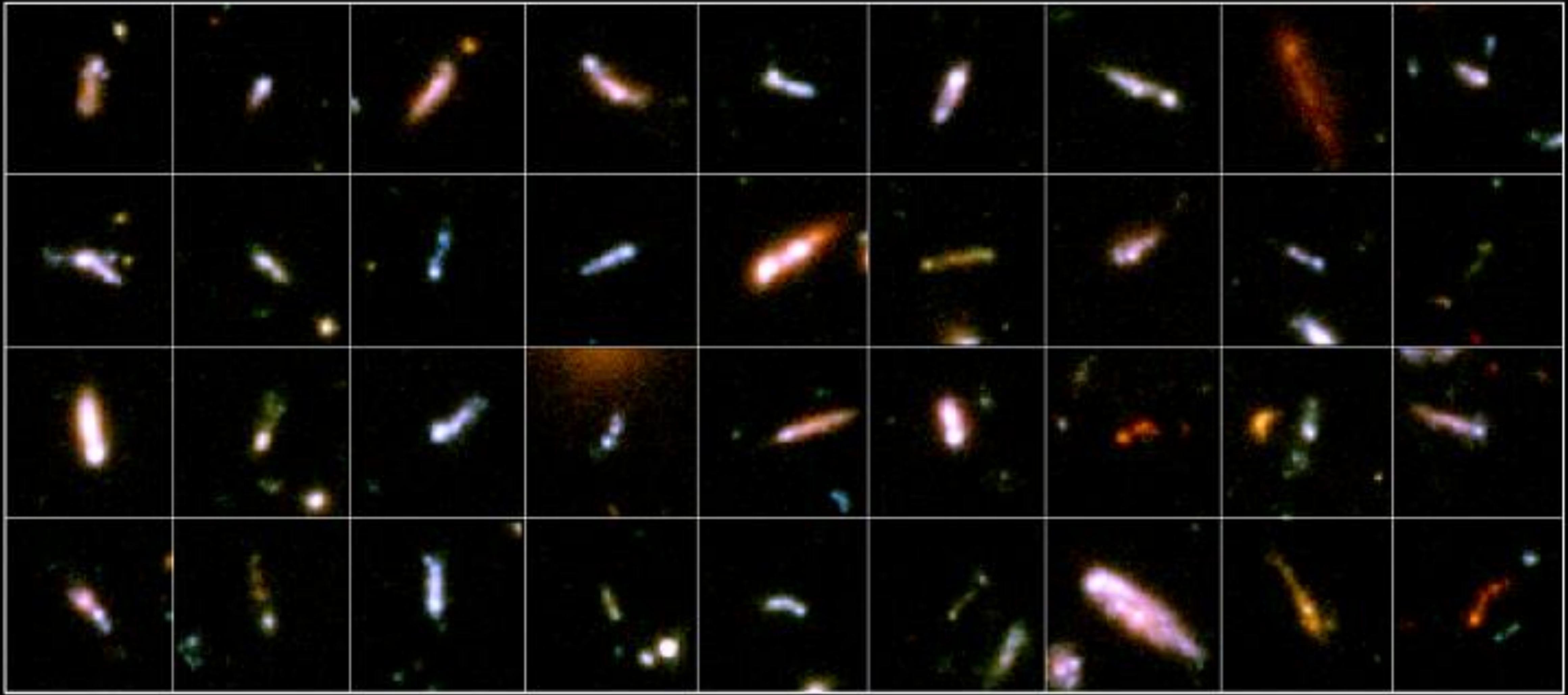
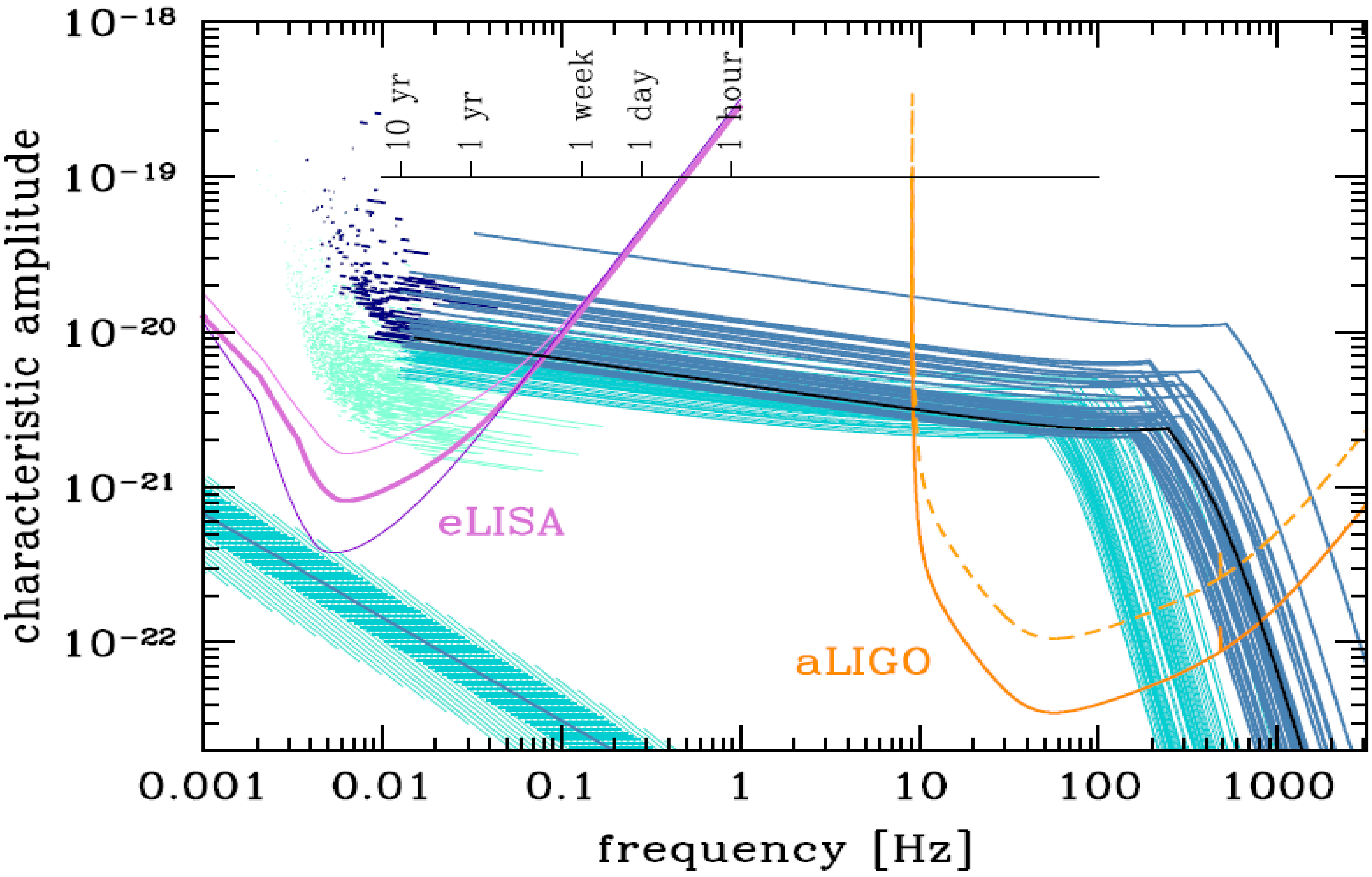


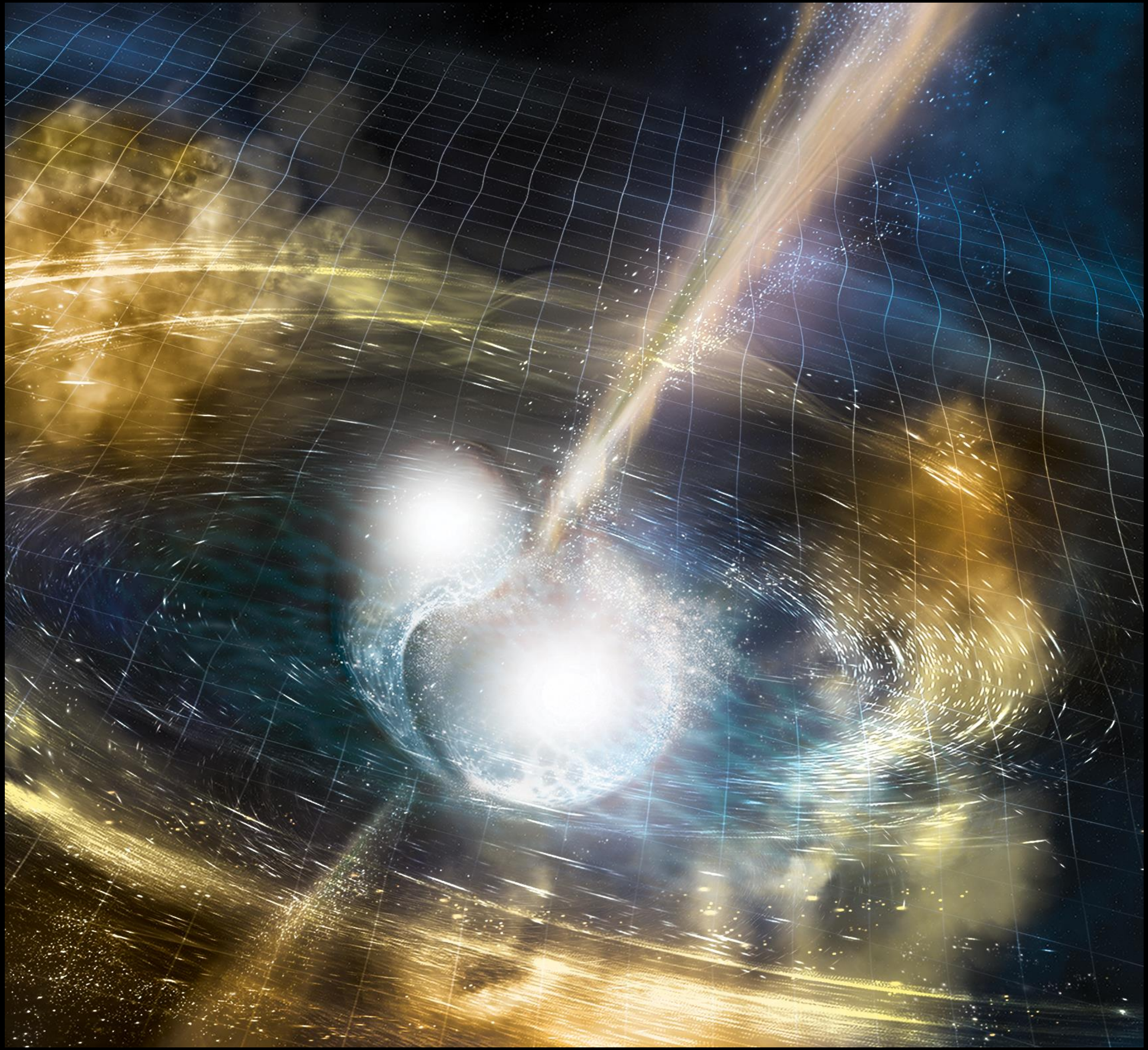
“Tadpole” Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)

STScI-PRC06-04

See e.g. Colpi & Sesana – arxiv: 1610.05309; Sesana, PRL , 116, 231102 (2016)






BRIGHT
FUTURE
AHEAD