Universe Seen in Gravitational Waves

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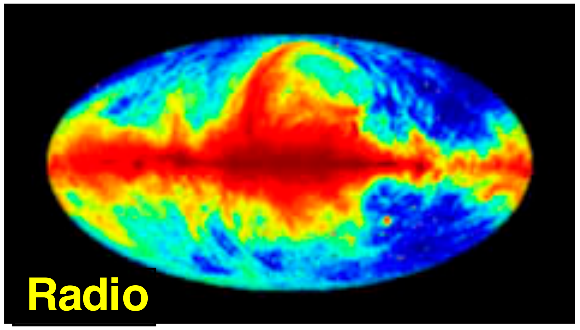
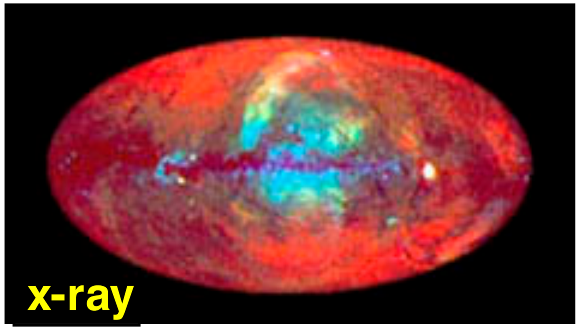
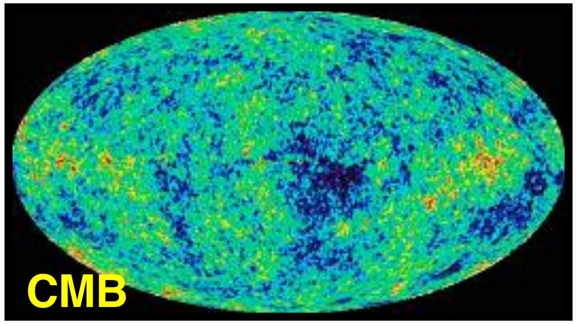
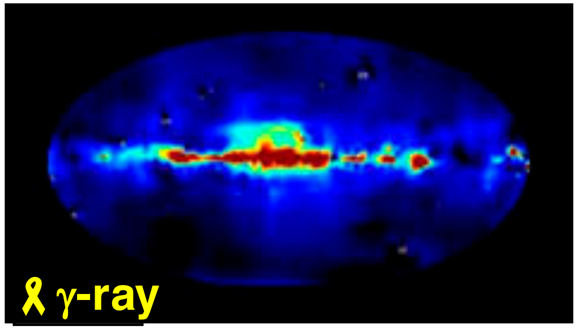
University of Trieste Lecture

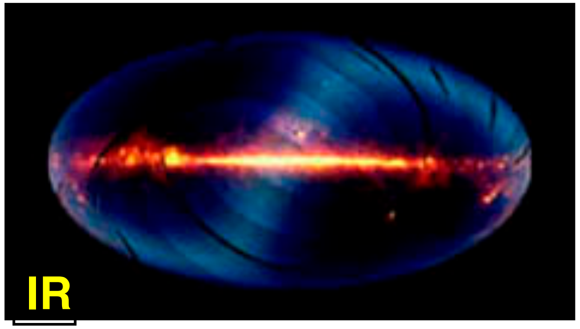
Cosmic Messengers

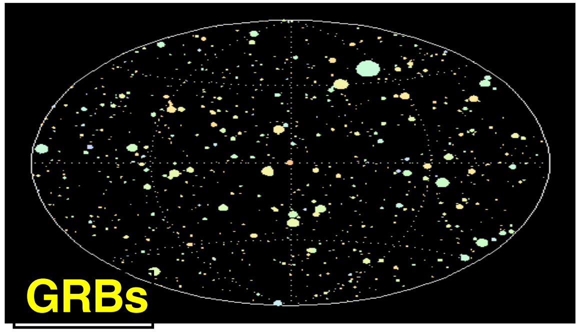










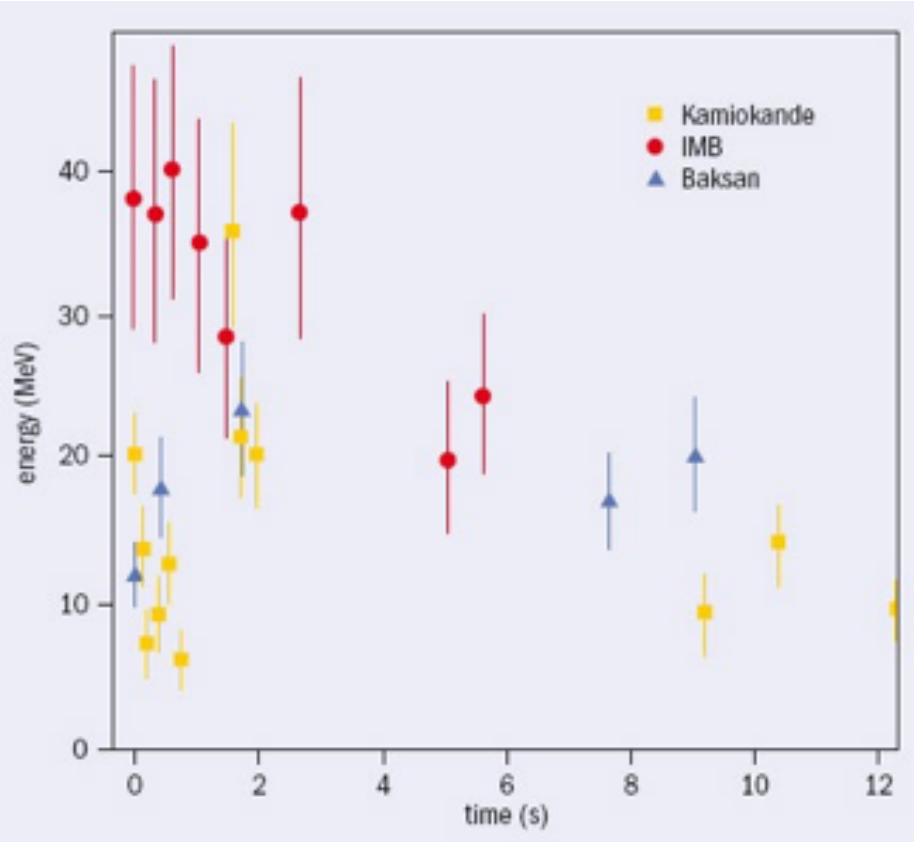


nasa.gov

- Most of what we know about the Universe is through photons
- Lot of ongoing efforts to obtain information about the universe using non-photon cosmic messengers.

Universe Seen in Neutrinos (2010)

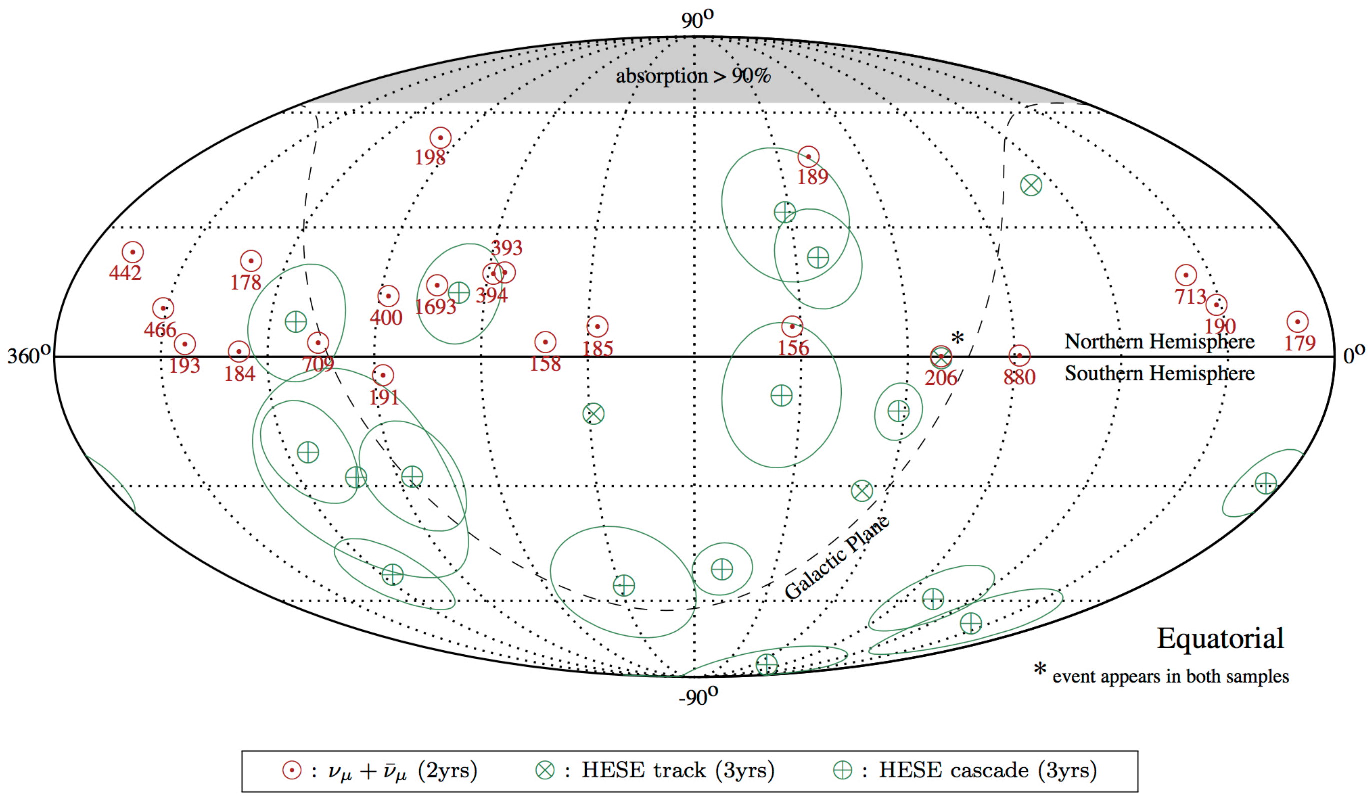
First detection from Supernova 1987 by IMB , Kamioka

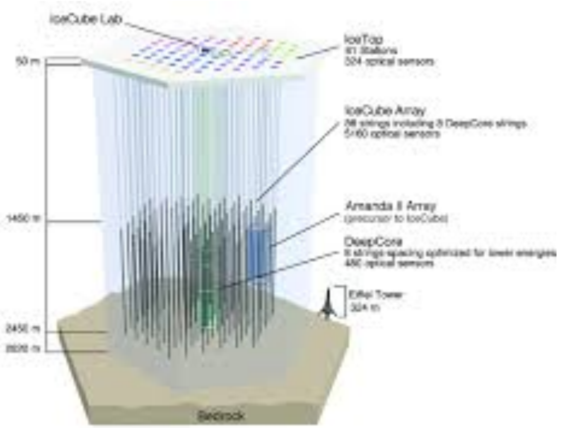


2002 Nobel Prize in Physics to M. Koshiba

IMB detector

Universe Seen in Neutrinos (2015)





Credit : IceCube Collaboration

Introduction

- Gravitational Waves: Ripples of space time curvature which propagate at speed of light and predicted by radiative solutions to General Relativity

Strain ← $$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2 I_{\mu\nu}}{dt^2}$$ → Quadrupole moment

$$I_{\mu\nu} = \int \rho(x_j x_k - \frac{1}{3}x^2\delta_{jk})d^3x$$

Intensity $$S_g = \frac{c^3}{16G\pi}\left\langle \dot{h}_+^{\,2} + \dot{h}_\times^{\,2} \right\rangle \qquad \frac{c^3}{16\pi G} = 7.8 \times 10^{36}\mathrm{erg}$$

$$h \sim \frac{4G}{c^4 r} K_{\mathrm{nonspherical}},$$

$$\sim 2\frac{GM}{Rc^2}\frac{GM}{rc^2}.$$

Plane Gravitational Waves

Transverse Plane Wave Solutions with "Electric" and "Magnetic" Terms

Geometric Interpretation

$$ds^2 = g_{ij} dx^i dx^j$$

$$g_{ij} = \eta_{ij} + h_{ij} \qquad \text{weak field}$$

$$\eta_{ij} = \begin{pmatrix} 1 & & & 0 \\ & -1 & & \\ 0 & & -1 & \\ & & & -1 \end{pmatrix} \qquad \text{Minkowski Metric of Special Relativity}$$

Gravity Wave Propagating in the x_1 Direction

$$h_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \qquad \text{all } h_{ij} \ll 1$$

Plane Wave

$\mathbf{h_{22}} = -\mathbf{h_{33}}$ $\qquad$ $\mathbf{h_{23}} = \mathbf{h_{32}}$

$+$ polarization $\qquad$ **$\times$polarization**

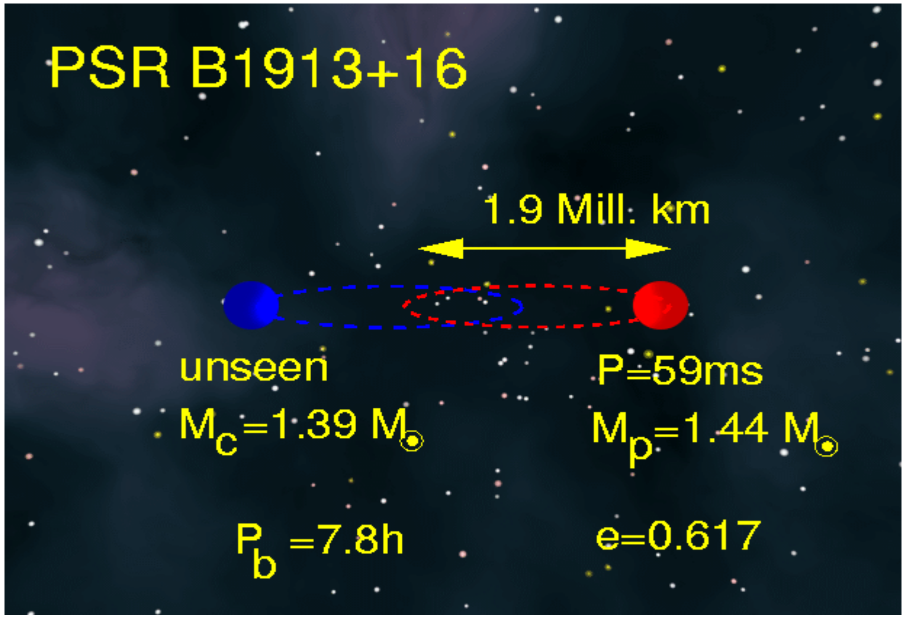
And All Only Function of $x_1 - ct$

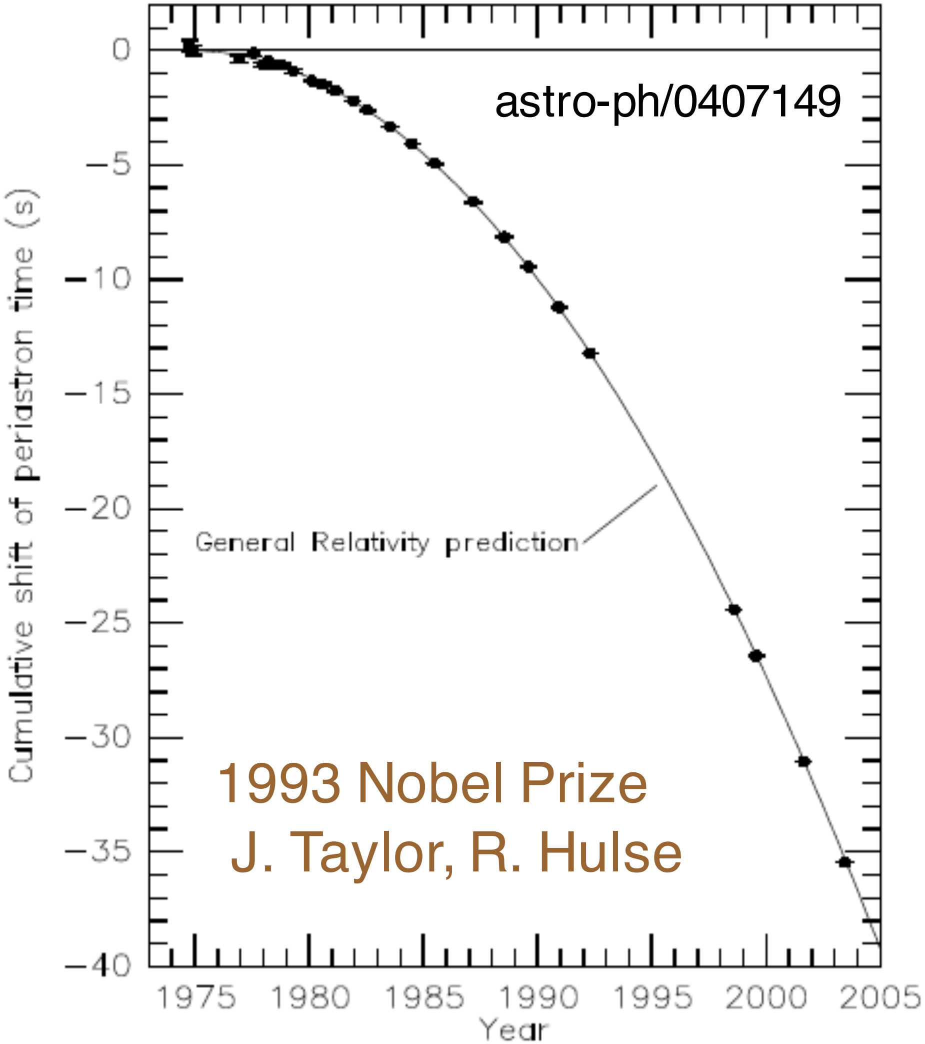
h+

hx

Indirect evidence for Gravitational Waves

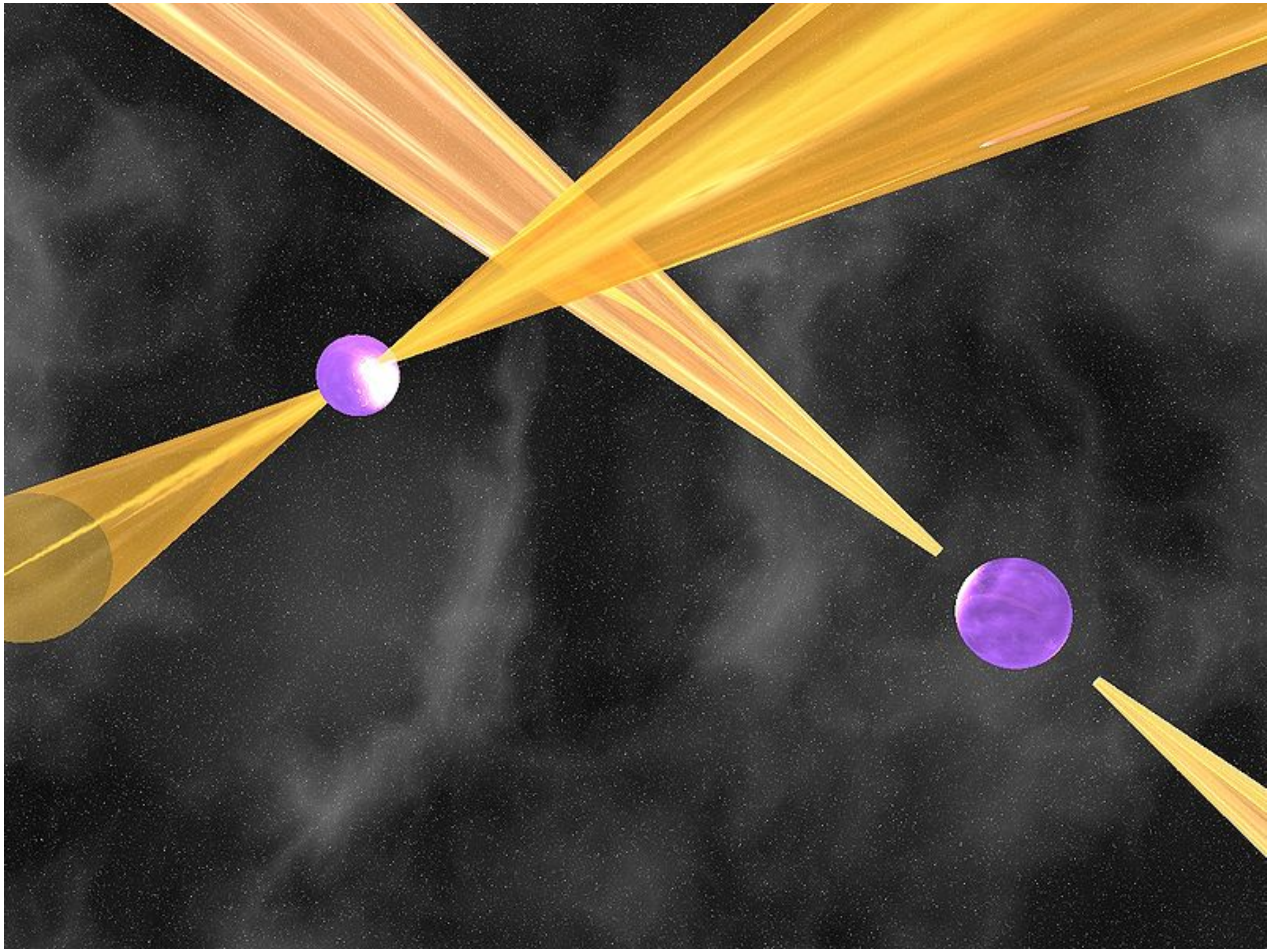
PSR 1913B+16 (binary pulsar)
discovered in 1974@Arecibo obs.





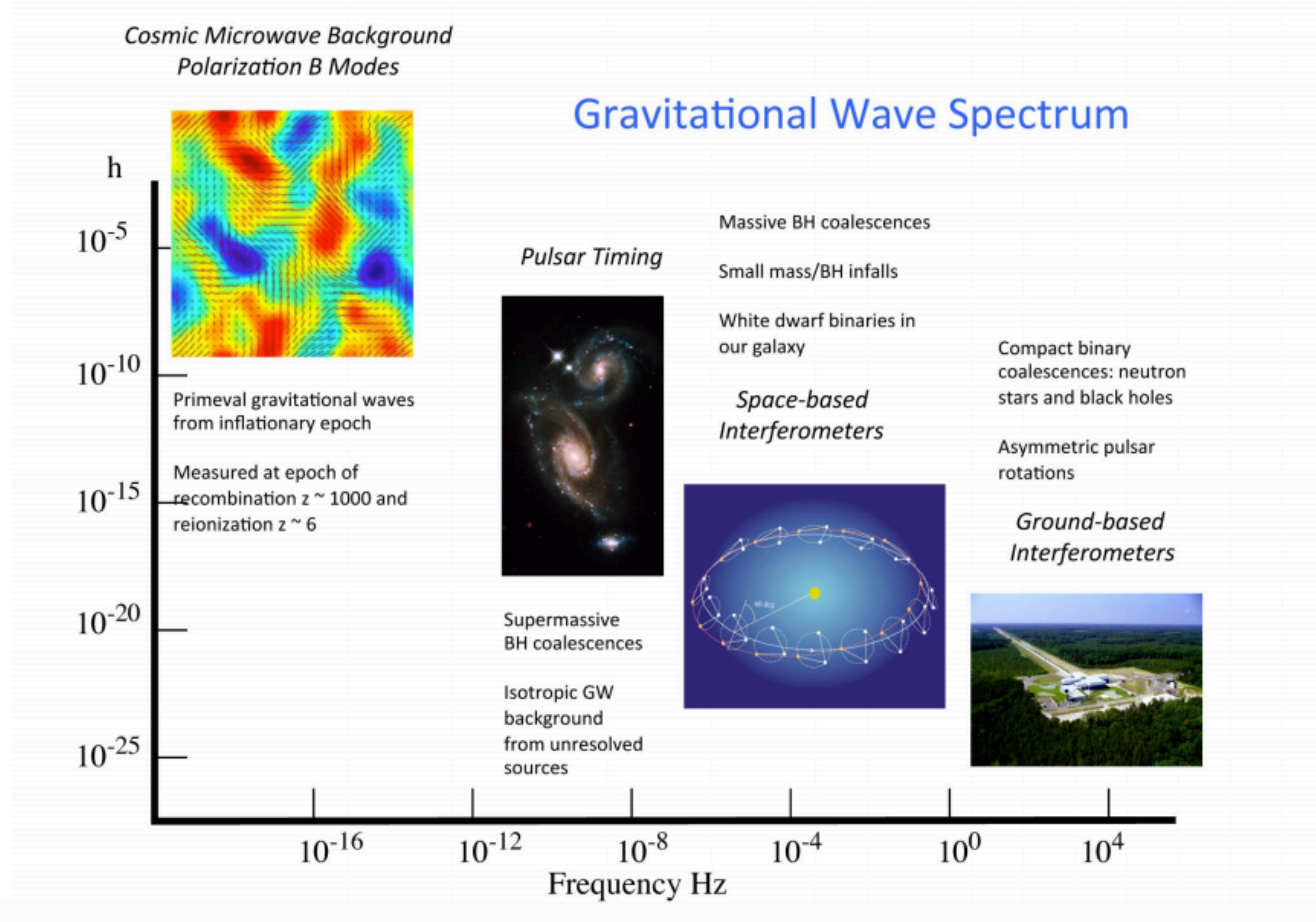
1993 Nobel Prize
J. Taylor, R. Hulse

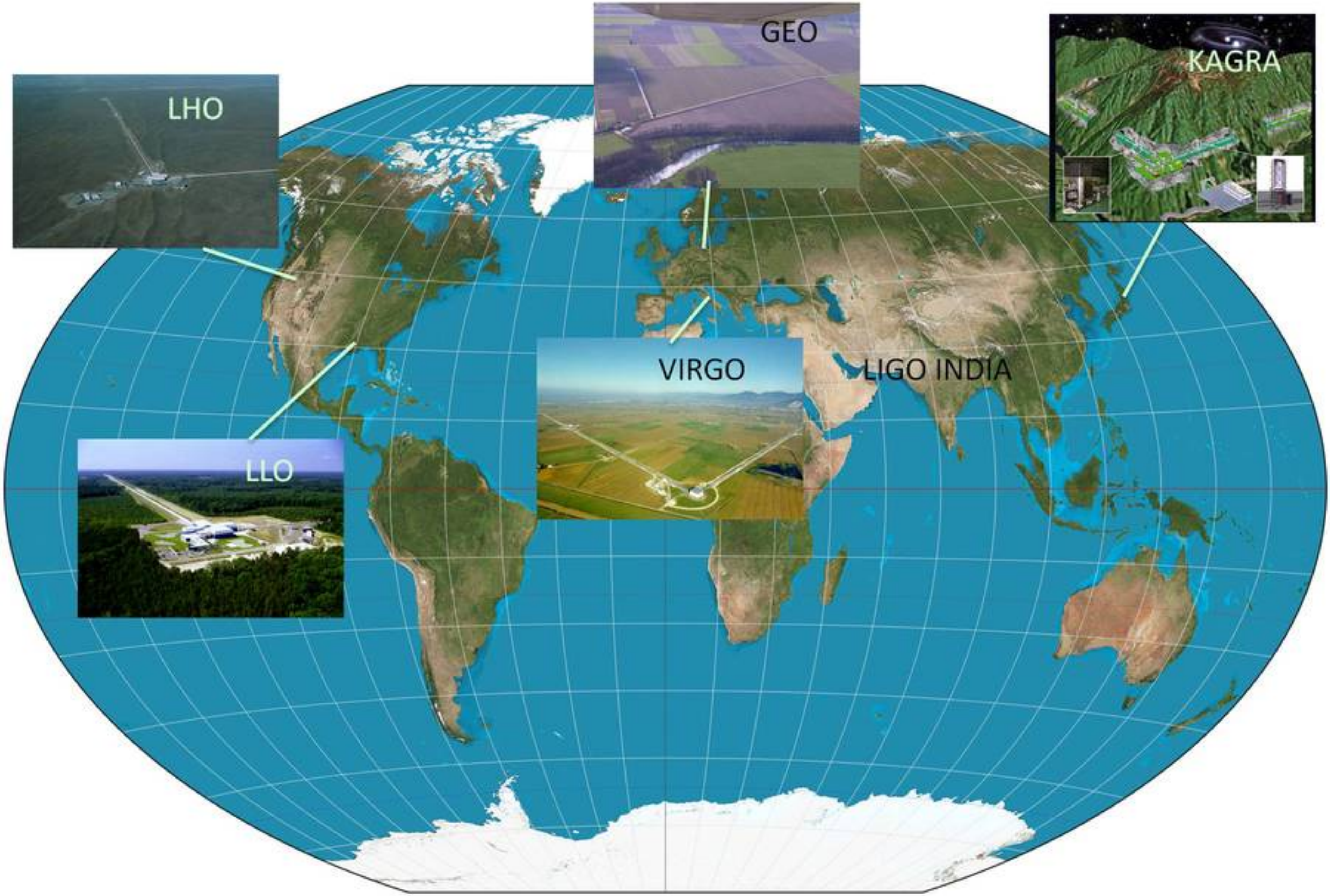
Double Binary Pulsar



Discovered by Marta Burgay, Calgiari

Excellent laboratory for tests of GR and evidence for slow down
Due to gravitational wave emission

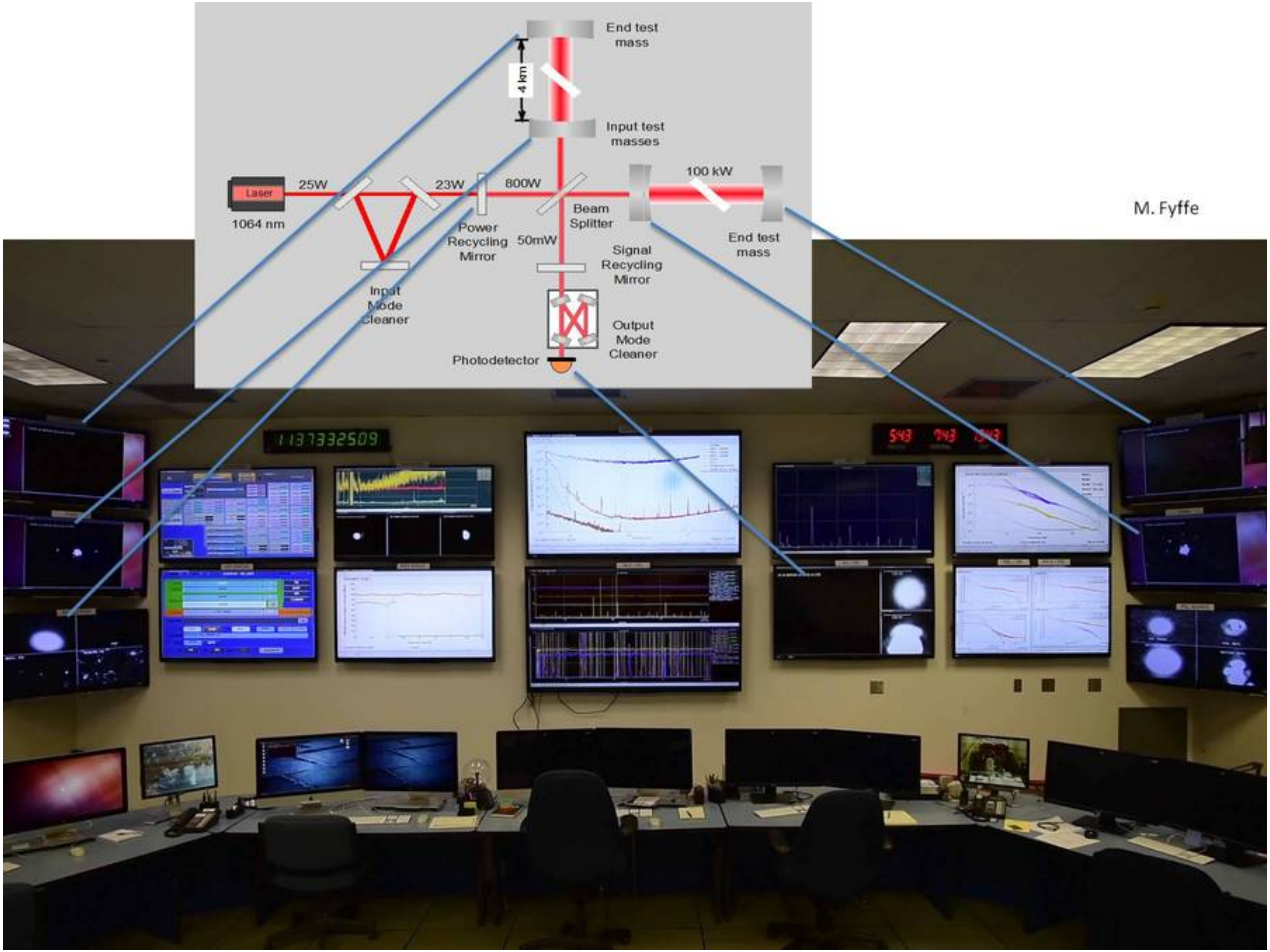

Gravitational Wave Spectrum
Cosmic Microwave Background
Polarization B Modes
h
10^-5
10^-10
10^-15
10^-20
10^-25
Primeval gravitational waves
from inflationary epoch
Measured at epoch of
recombination z ~ 1000 and
reionization z ~ 6
Pulsar Timing
Supermassive
BH coalescences
Isotropic GW
background
from unresolved
sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in
our galaxy
Space-based
Interferometers
Compact binary
coalescences: neutron
stars and black holes
Asymmetric pulsar
rotations
Ground-based
Interferometers
10^-16
10^-12
10^-8
10^-4
10^0
10^4
Frequency Hz


GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

LIGO & VIRGO Detectors

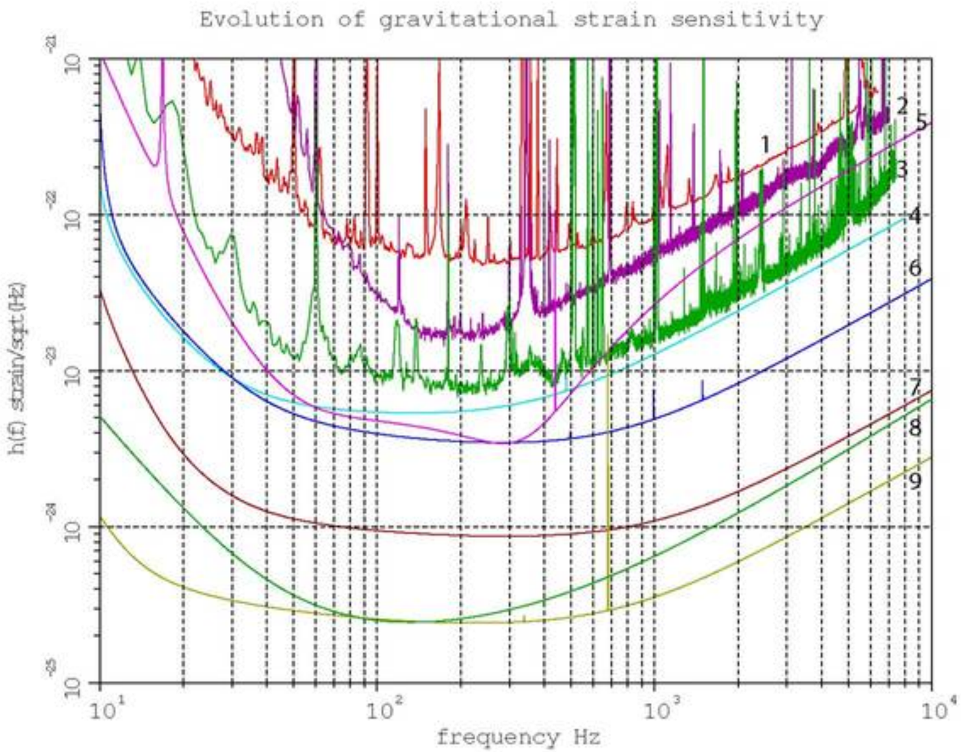
- LIGO observatory contains 2 (H2) km and 4 km (H1) interferometers at Hanford, WA and a 4 km interferometer at Livingston, LA (L1) separated by 3000 km (10ms)

Inside the LIGO control room



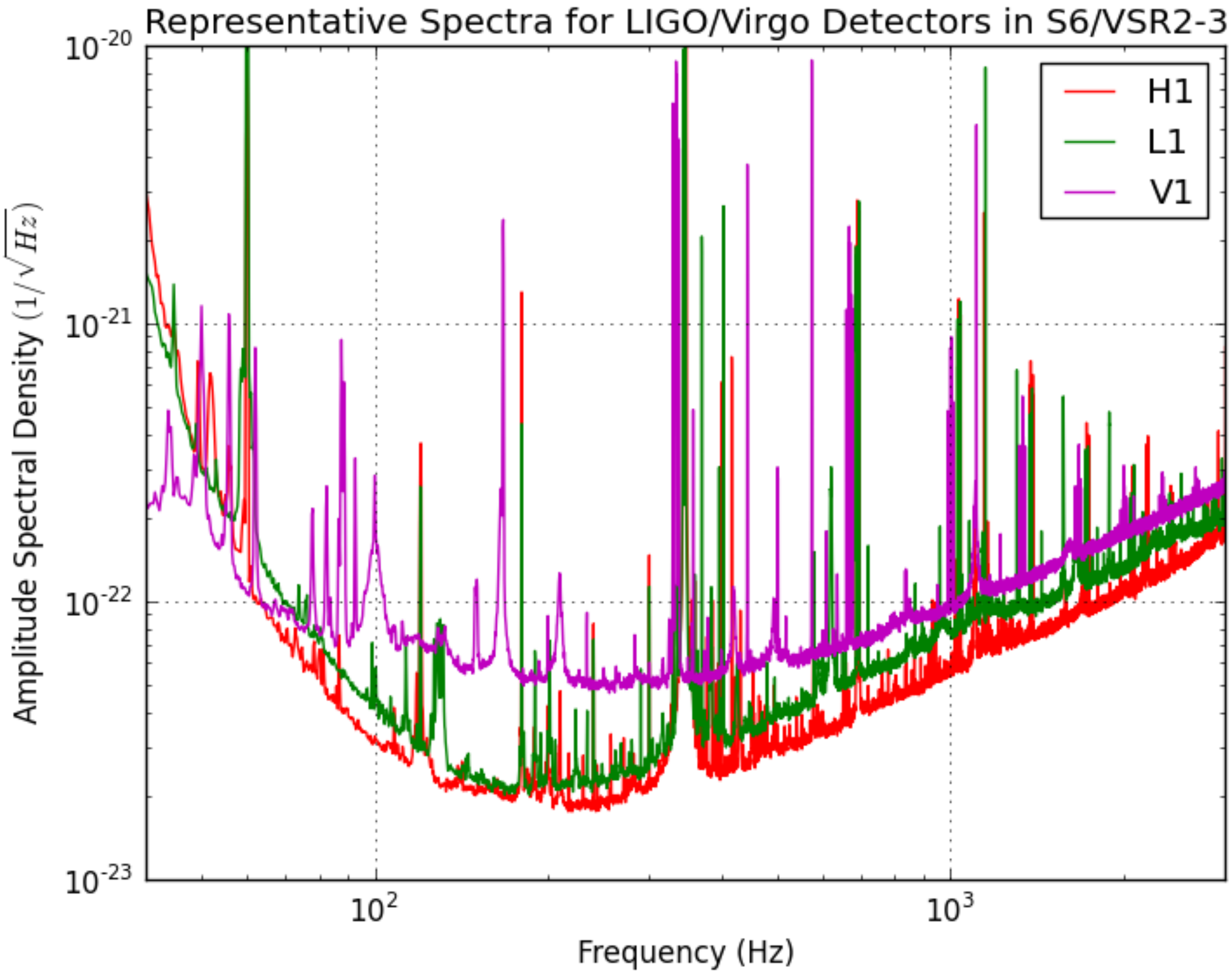
LIGO Sensitivity And Status

- Dimensionless strain (h = ΔL/L) is the main observable measured



1 VIRGO 2009
2 Enhanced LIGO 2009
3 Advanced LIGO 65Mpc NS/NS 2015
4 Advanced LIGO 150Mpc NS/NS Low Power
5 Advanced VIRGO
6 Advanced LIGO 190Mpc NS/NS High Power
7 4km "Voyager" example 600Mpc NS/NS
8 Einstein telescope B
9 40km "Cosmic Explorer" example

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		$5 deg^2$	$20 deg^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



Representative Spectra for LIGO/Virgo Detectors in S6/VSR2-3
Amplitude Spectral Density $(1/\sqrt{Hz})$
Frequency (Hz)
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}
H1
L1
V1

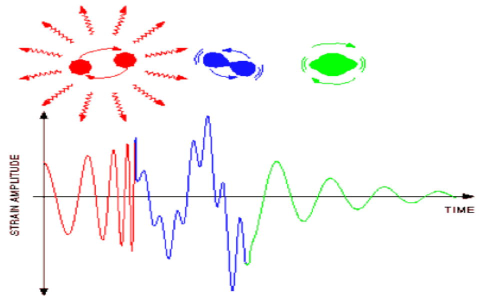
KAGRA GW detector

Located in Kamioka mine next to Super-K and Kamiokande expt

Joined LIGO VIRGO searches in Feb 2020

Science Analysis Efforts

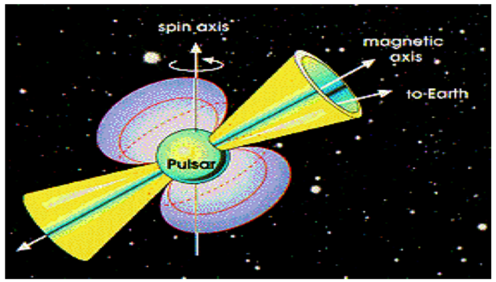
- Compact Binary Inspirals :
  - ➢Template based searches for merger of neutron star/black hole based binaries



- Unknown burst sources :
  - ➢Short duration transients(<1sec) without any knowledge of waveform (core-collapse SN, GRBs etc)

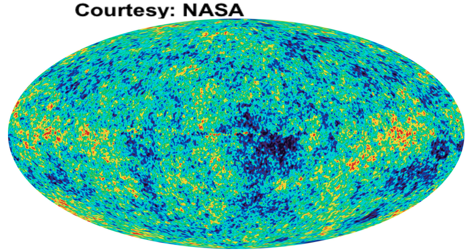
SN1987A

- Periodic sources :
  - ➢Known and unknown pulsars in our galaxy



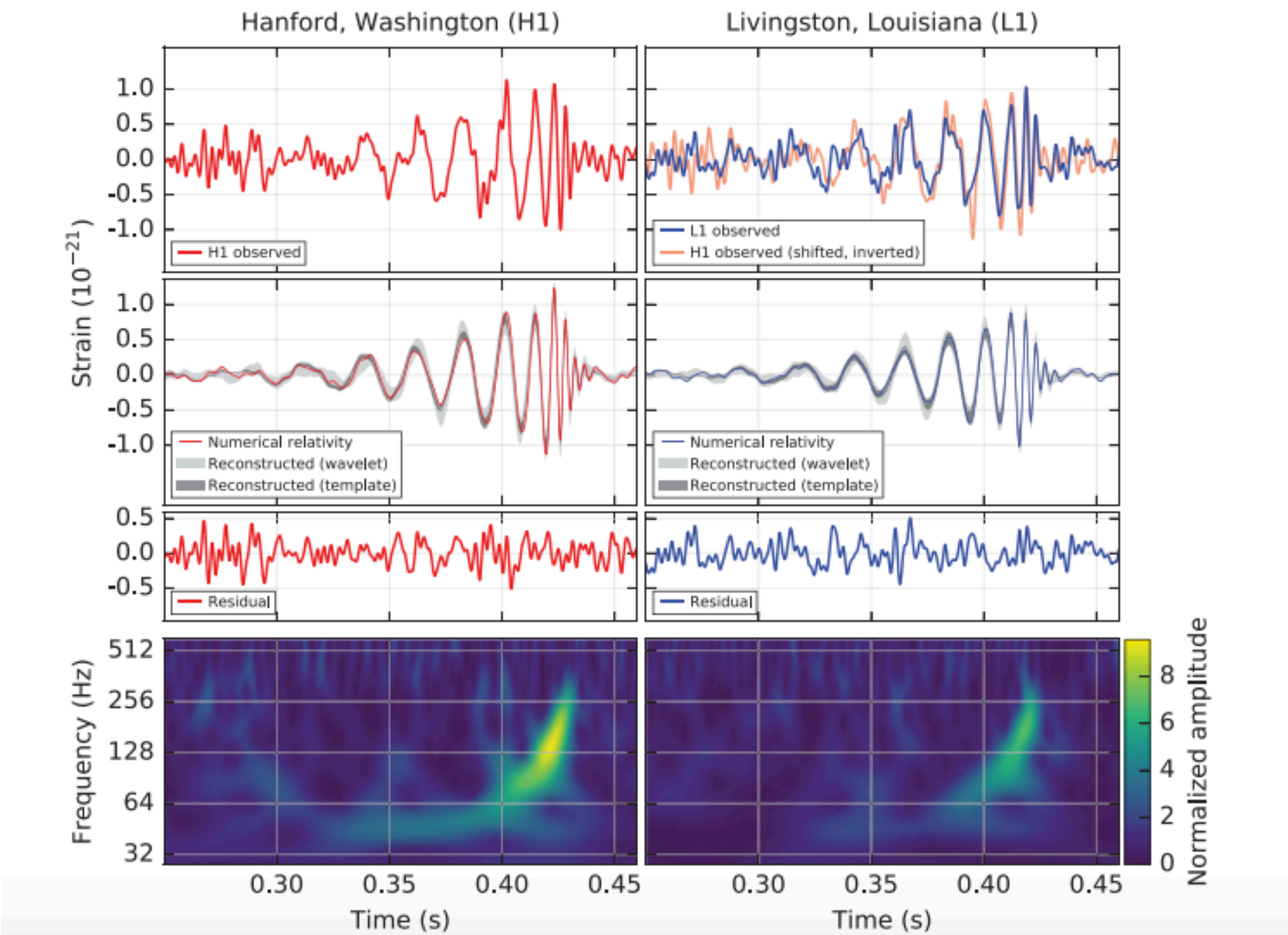
Courtesy: NASA

- Stochastic Background :
  - ➢Search for cosmological background from a variety of early universe processes.



NASA WMAP

First LIGO Detection



GW150914 Parameters

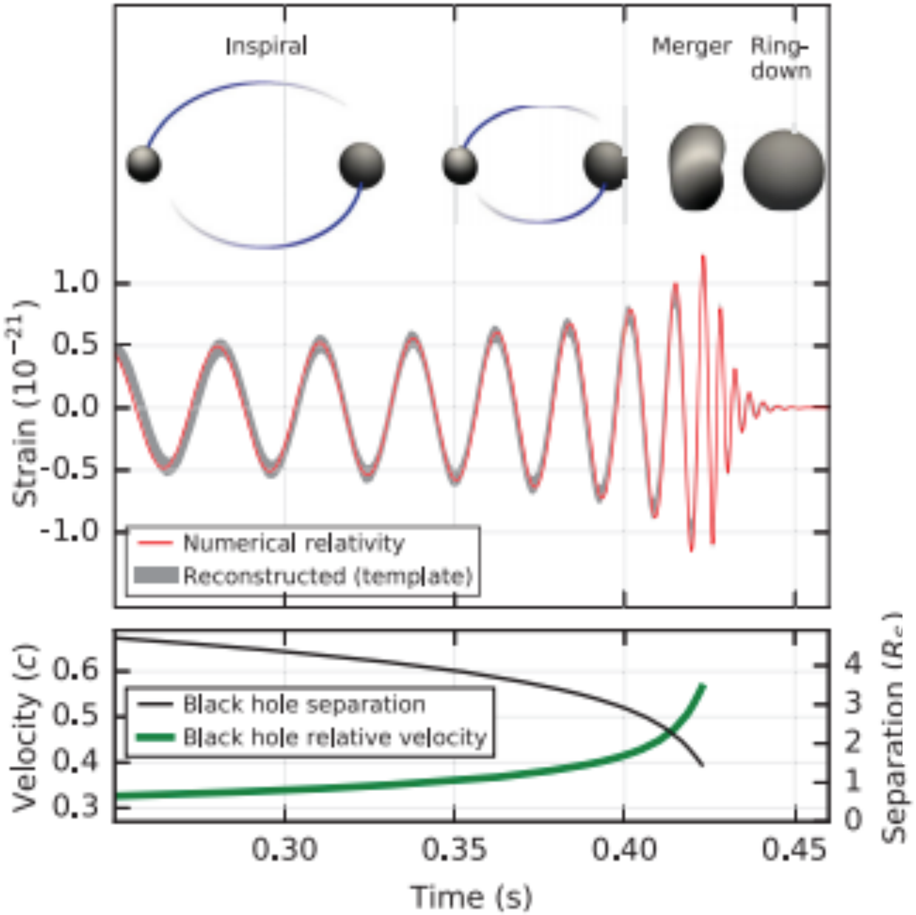
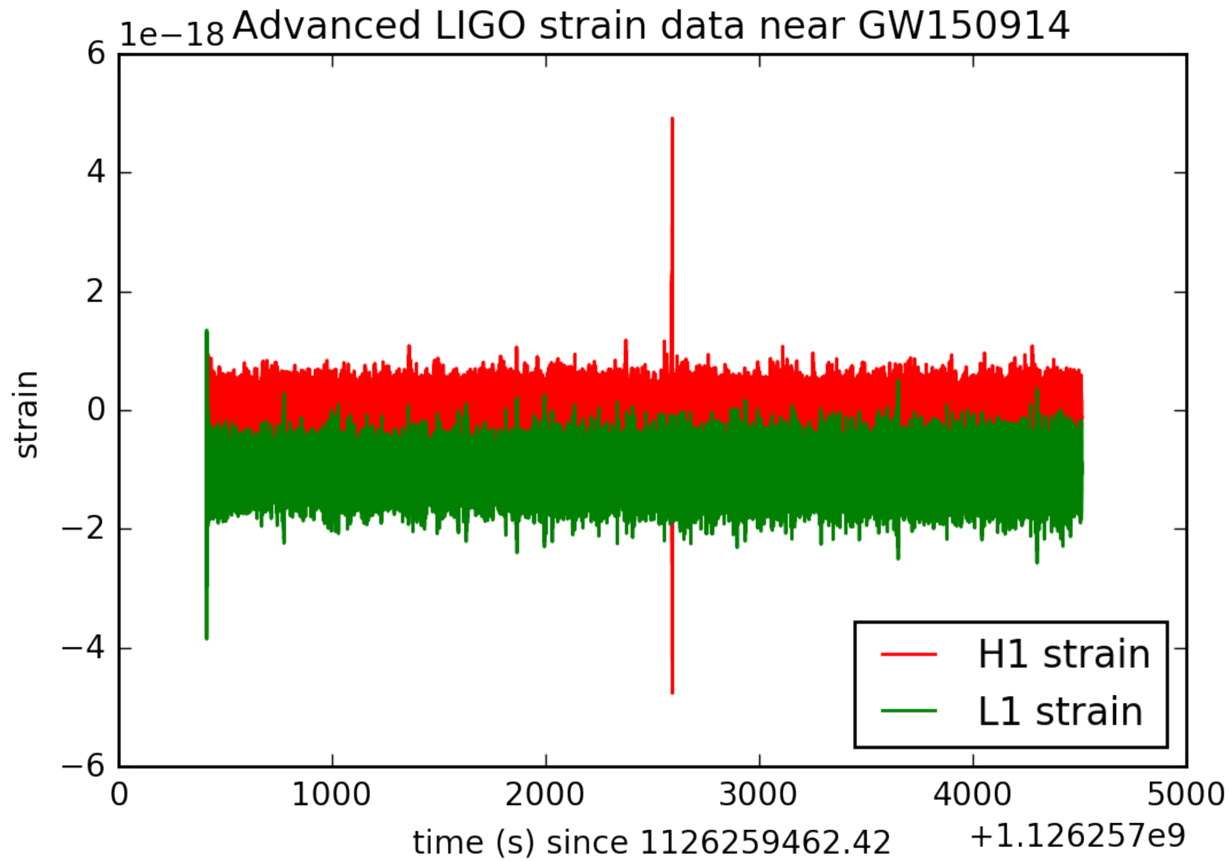


TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1 + z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

GW150914 from LIGO open data



Publicly released data from LIGO using open LIGO science data

A.Sukrutha, S.R. Dyuthi (IITH EE)

For more details check out gw-openscience.org

Looking for ancillary signals around GW150914

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[b]Department of Physics, IIT Hyderabad, Kandi, Telangana-502285, India

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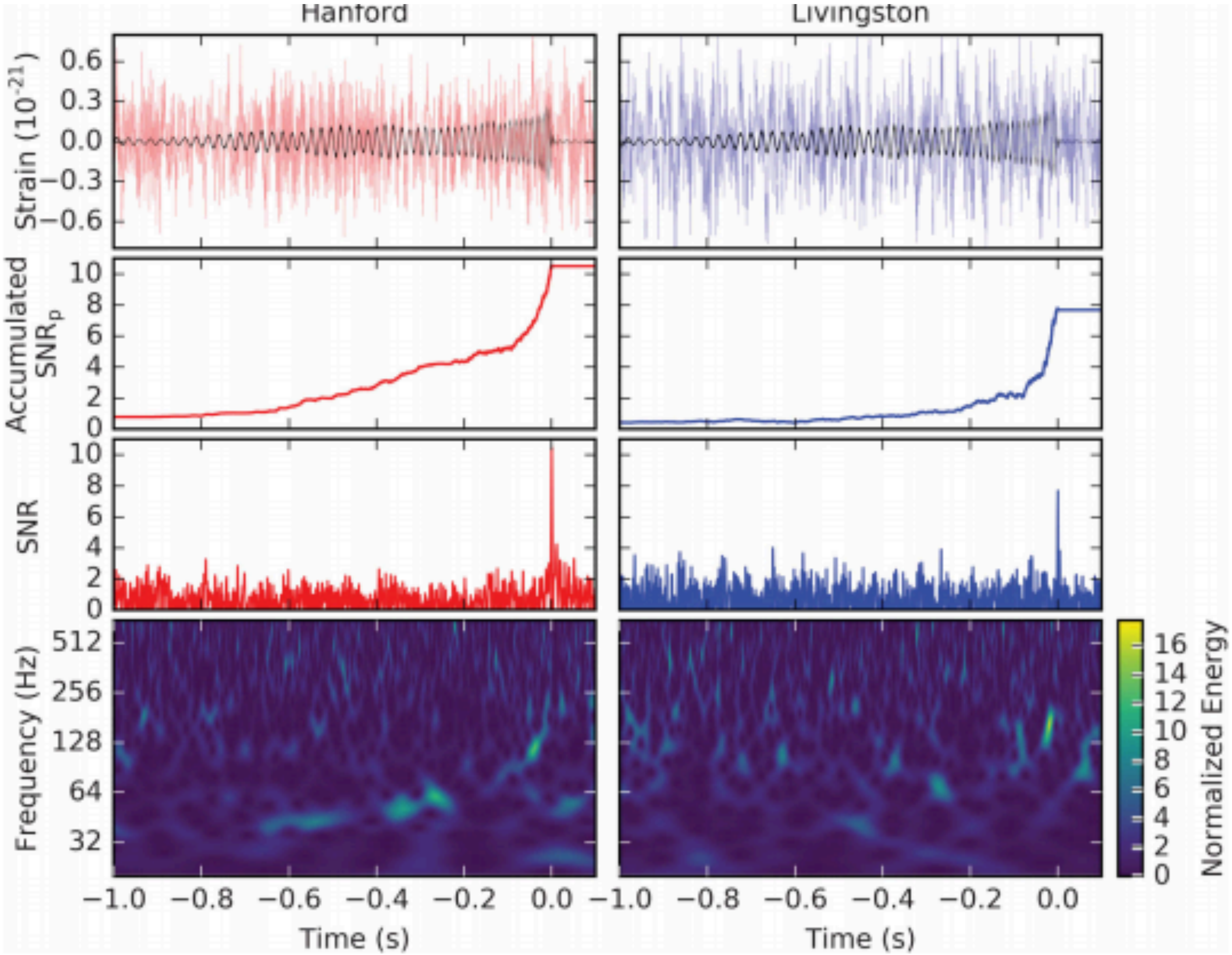
Abstract. We replicated the procedure in Liu and Jackson [1], who had found evidence for a low amplitude signal in the vicinity of GW150914. This was based upon the large correlation between the time integral of the Pearson cross-correlation coefficient in the off-source region of GW150914, and the Pearson cross-correlation in a narrow window around GW150914, for the same time lag between the two LIGO detectors as the gravitational wave signal. Our results mostly agree with those in Liu and Jackson [1]. We find the statistical significance of the observed cross-correlation to be about 2.5 σ. We also used the cross-correlation method to search for short duration signals at all other physical values of the time lag, within this 4096 second time interval, but do not find evidence for any statistically significant events in the off-source region.

JCAP 04, 007 (2019)

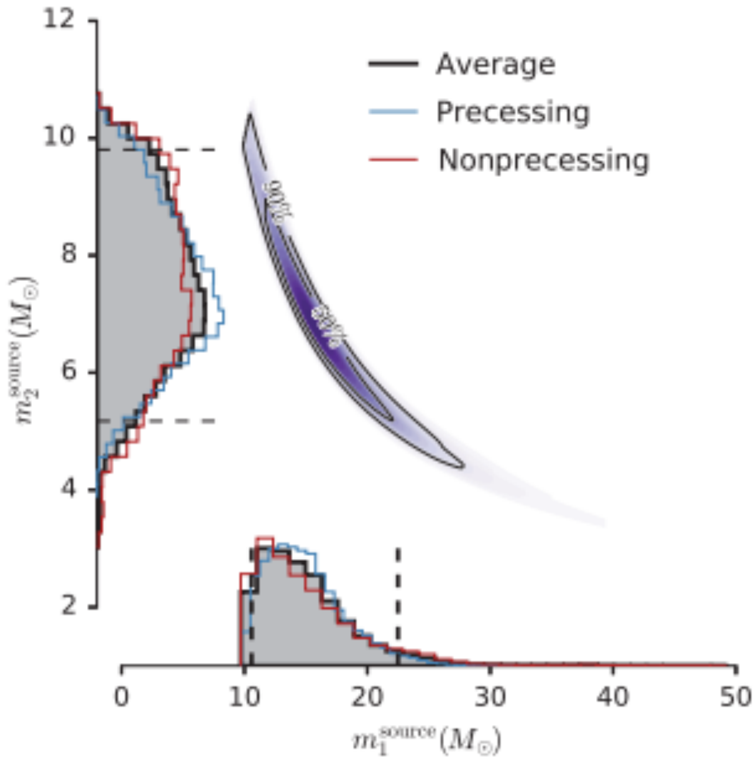
GW151226



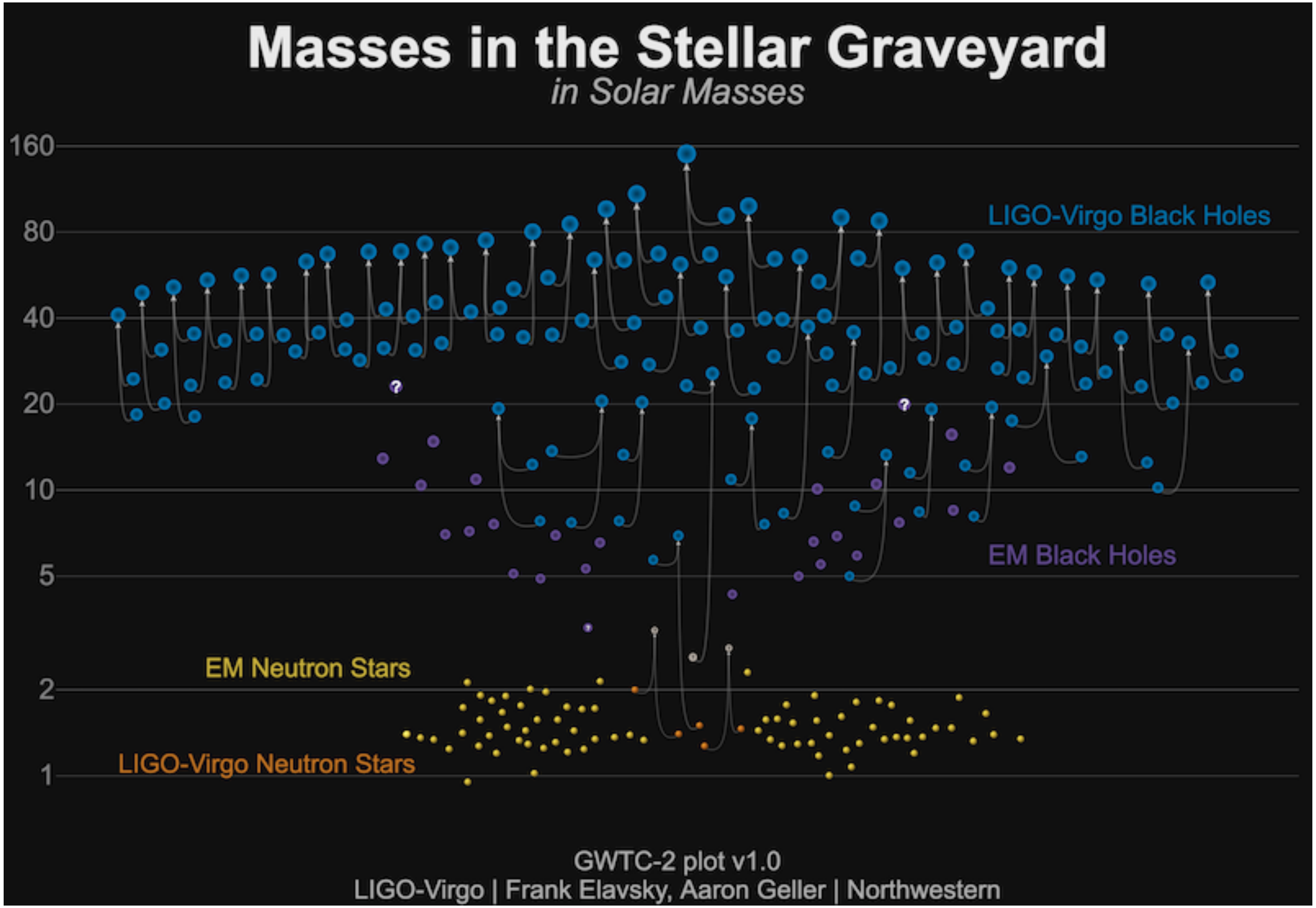
Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR$_p$
10
8
6
4
2
0
SNR
Frequency (Hz)
512
256
128
64
32
Normalized Energy
16
14
12
10
8
6
4
2
0
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)

GW151226 parameters

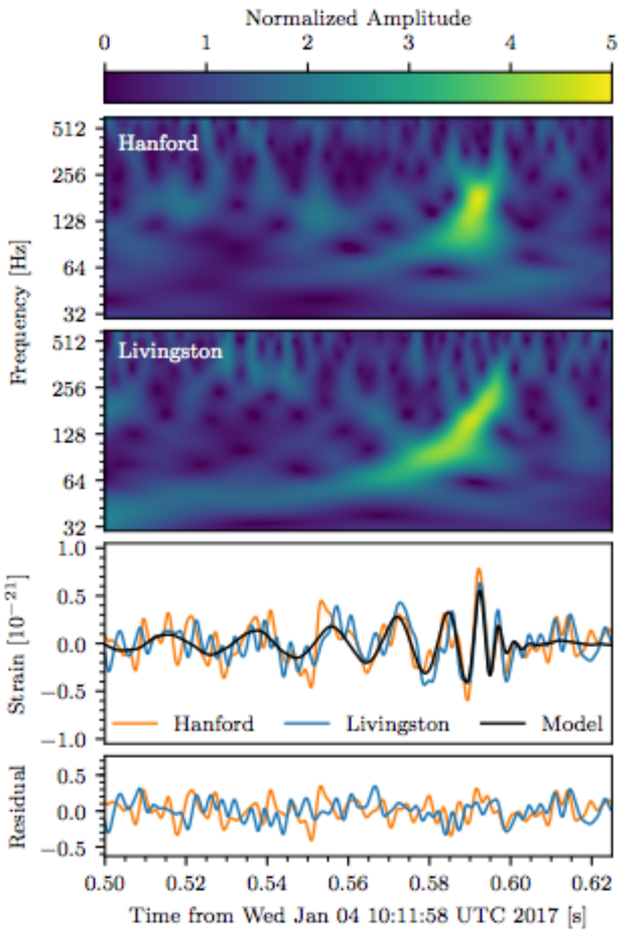
Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



Current LIGO detections

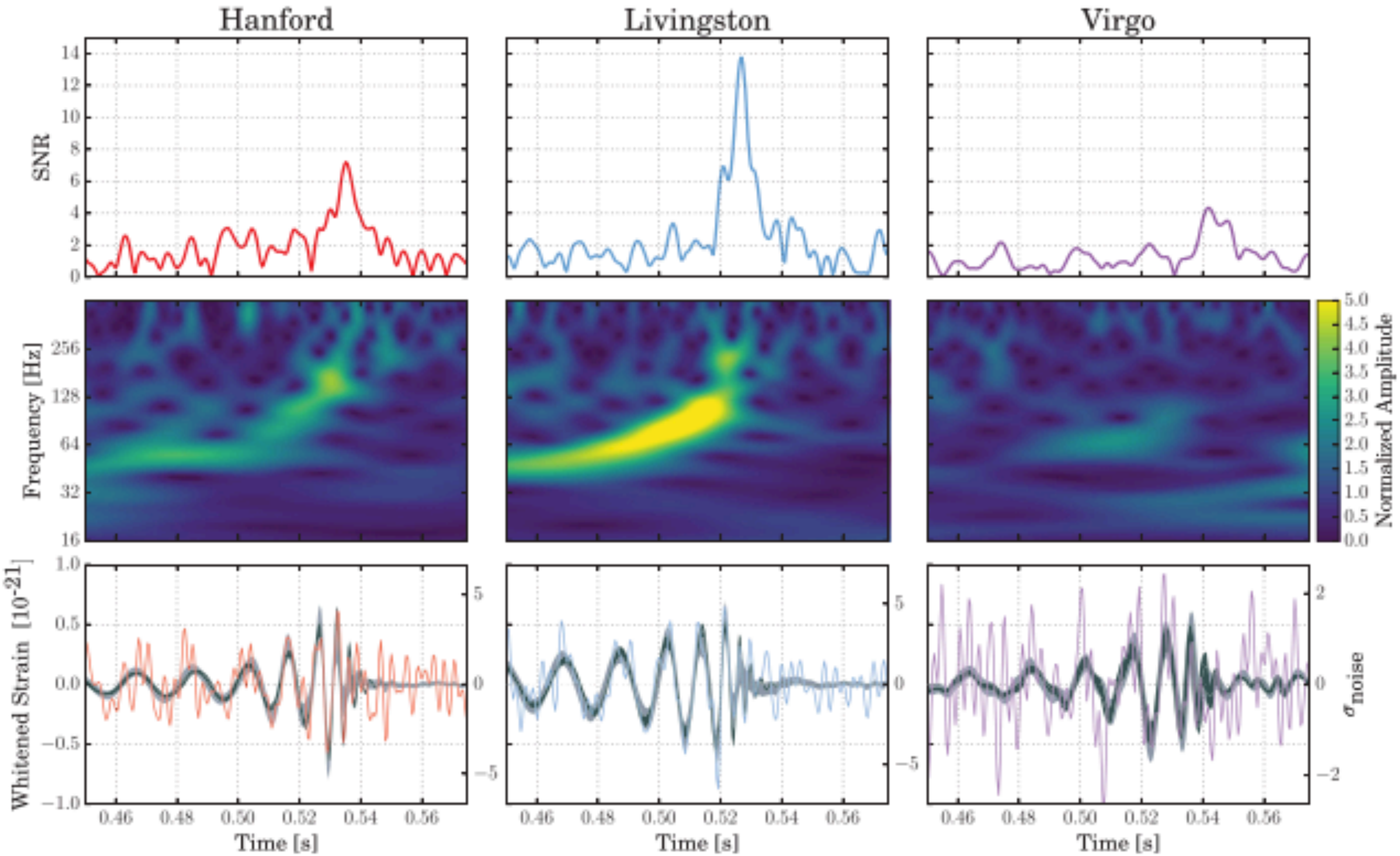


GW170104



Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\,M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\,M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7}\,M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\,M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6}\,M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7}\,M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56}\,\mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

GW170814



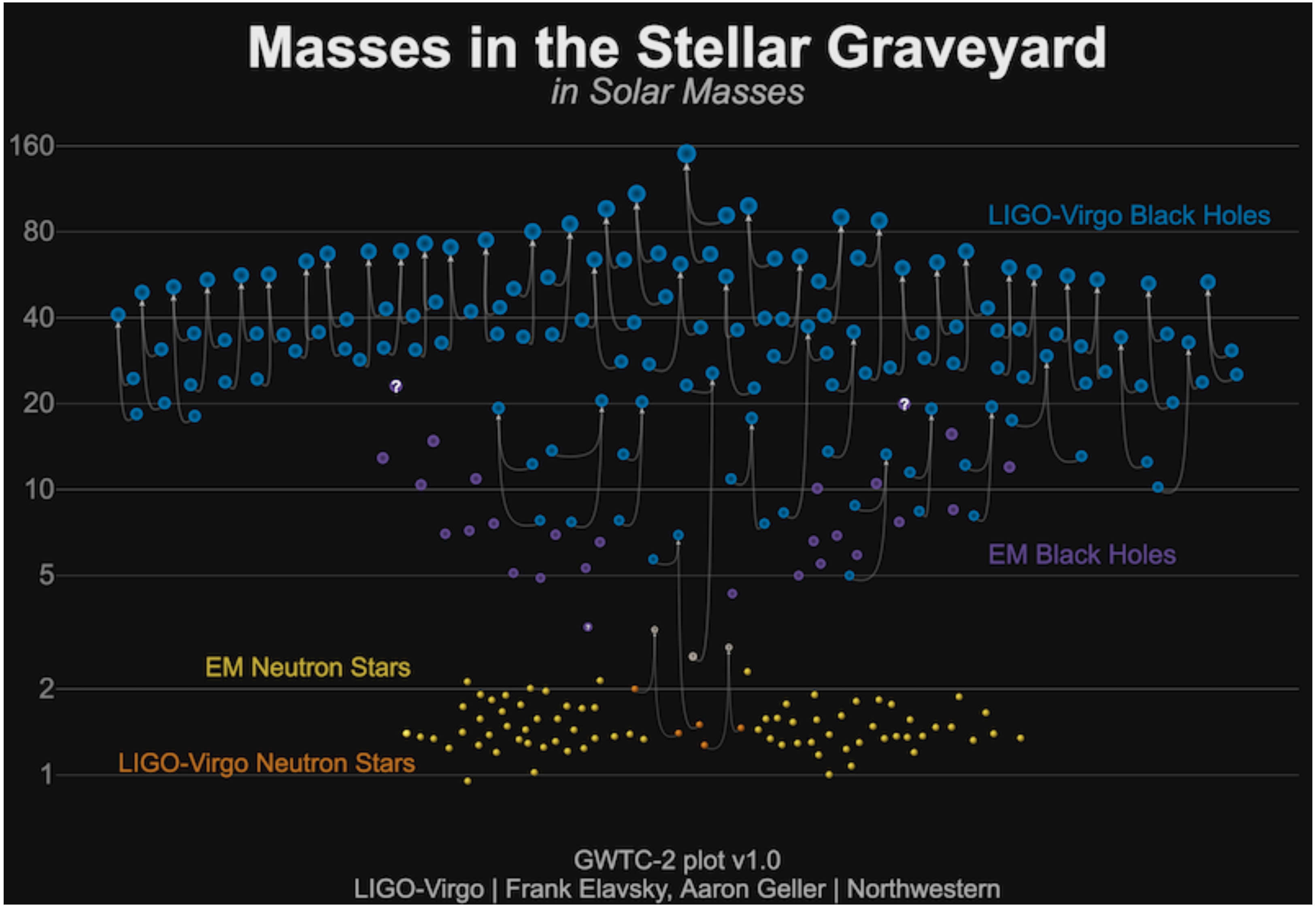
First three detector observation of a binary black hole merger

GW170814

Primary black hole mass m_1	$30.5^{+5.7}_{-3.0} M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2} M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1} M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7} M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5} M_\odot$
Radiated energy $E_{\rm rad}$	$2.7^{+0.4}_{-0.3} M_\odot\ c^2$
Peak luminosity $\ell_{\rm peak}$	$3.7^{+0.5}_{-0.5} \times 10^{56}$ erg s^{-1}
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

First three detector observation of a binary black hole merger

Summary of LIGO Black hole binaries



Credit: LIGO Scientific Collaboration

Science impact of first GW detection from BBH mergers

Did LIGO detect dark matter?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, Adam G. Riess

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

642 citations
LIGO discoveries of binary black hole mergers rekindled interest
In primordial black holes as dark matter

GW170817: First Binary Neutron Star

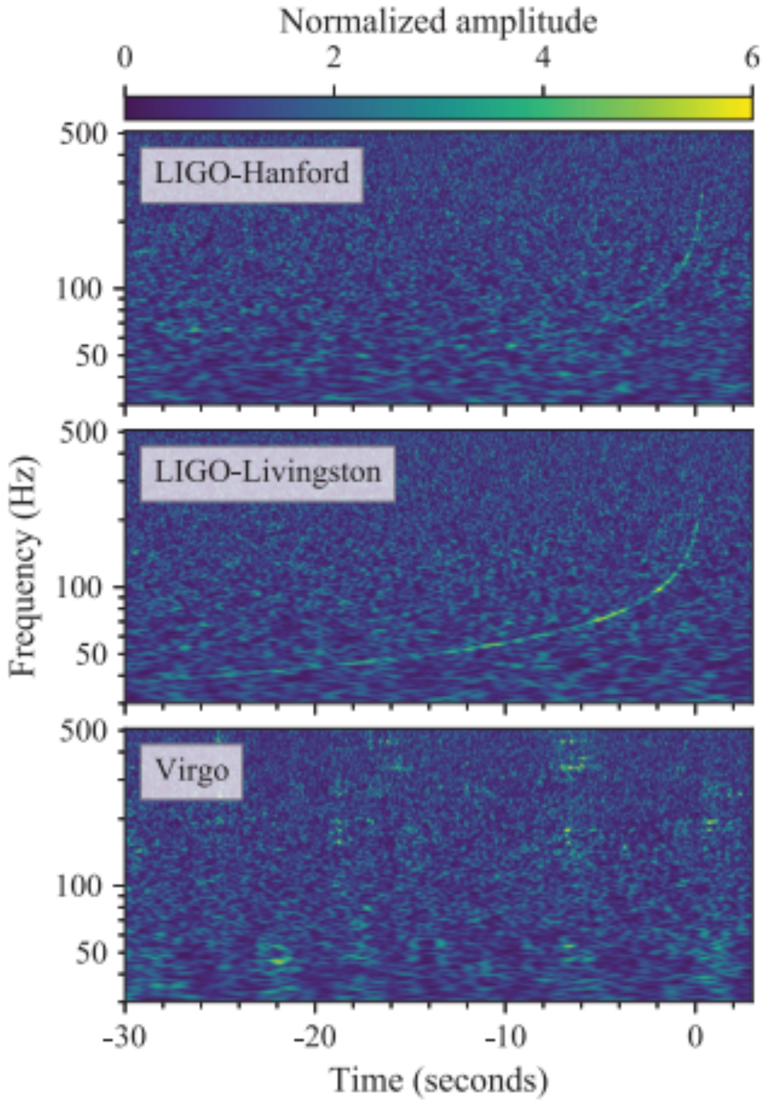
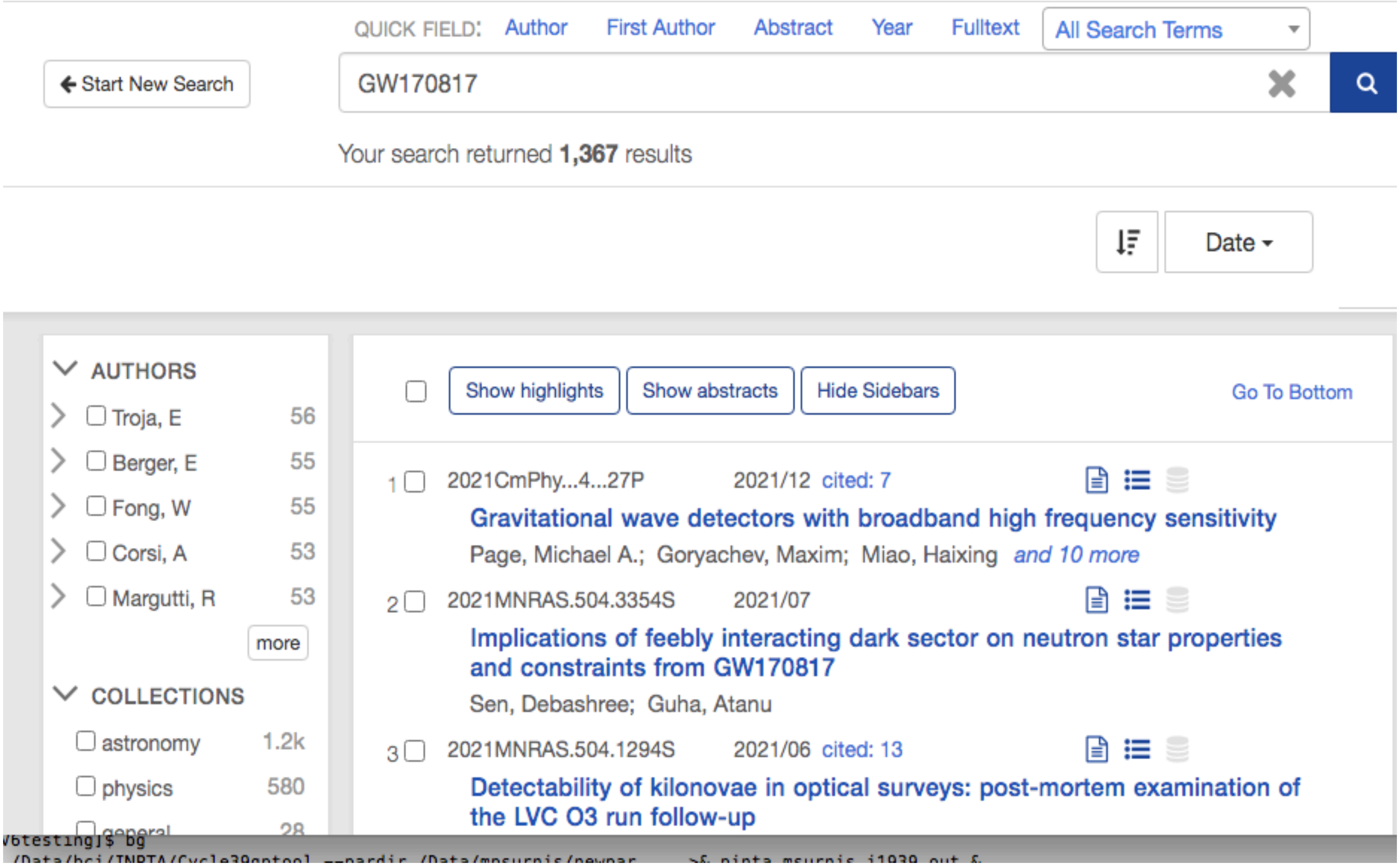


TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	$1.36–1.60\ M_\odot$	$1.36–2.26\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$	$0.86–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400


QUICK FIELD: Author First Author Abstract Year Fulltext
All Search Terms
Start New Search
GW170817
Your search returned 1,367 results
Date
AUTHORS
Troja, E 56
Berger, E 55
Fong, W 55
Corsi, A 53
Margutti, R 53
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1 2021CmPhy...4...27P 2021/12 cited: 7
Gravitational wave detectors with broadband high frequency sensitivity
Page, Michael A.; Goryachev, Maxim; Miao, Haixing and 10 more
2 2021MNRAS.504.3354S 2021/07
Implications of feebly interacting dark sector on neutron star properties and constraints from GW170817
Sen, Debashree; Guha, Atanu
3 2021MNRAS.504.1294S 2021/06 cited: 13
Detectability of kilonovae in optical surveys: post-mortem examination of the LVC O3 run follow-up

Localization of GW170817

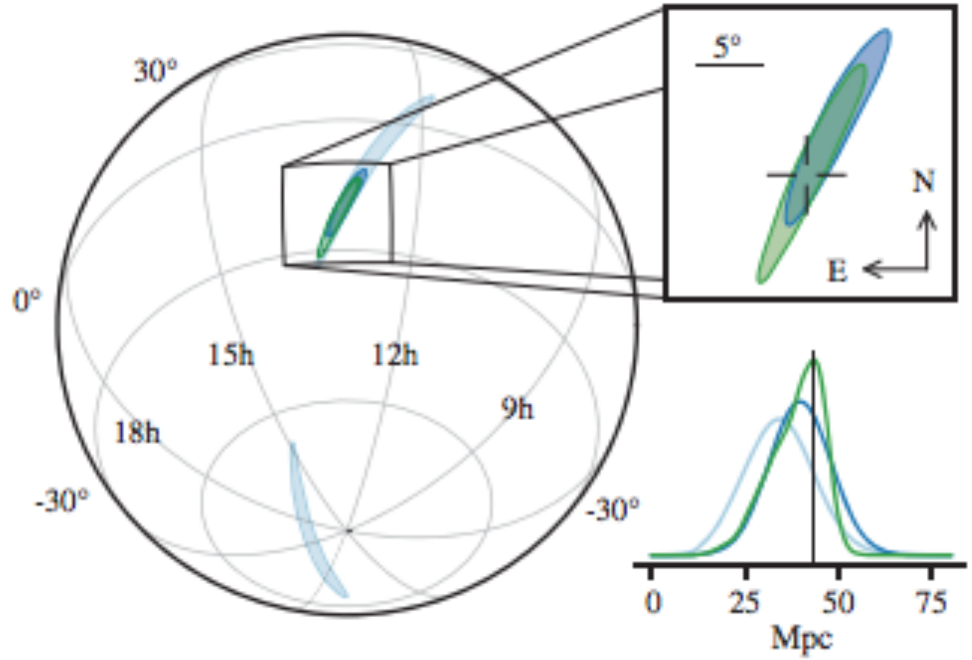
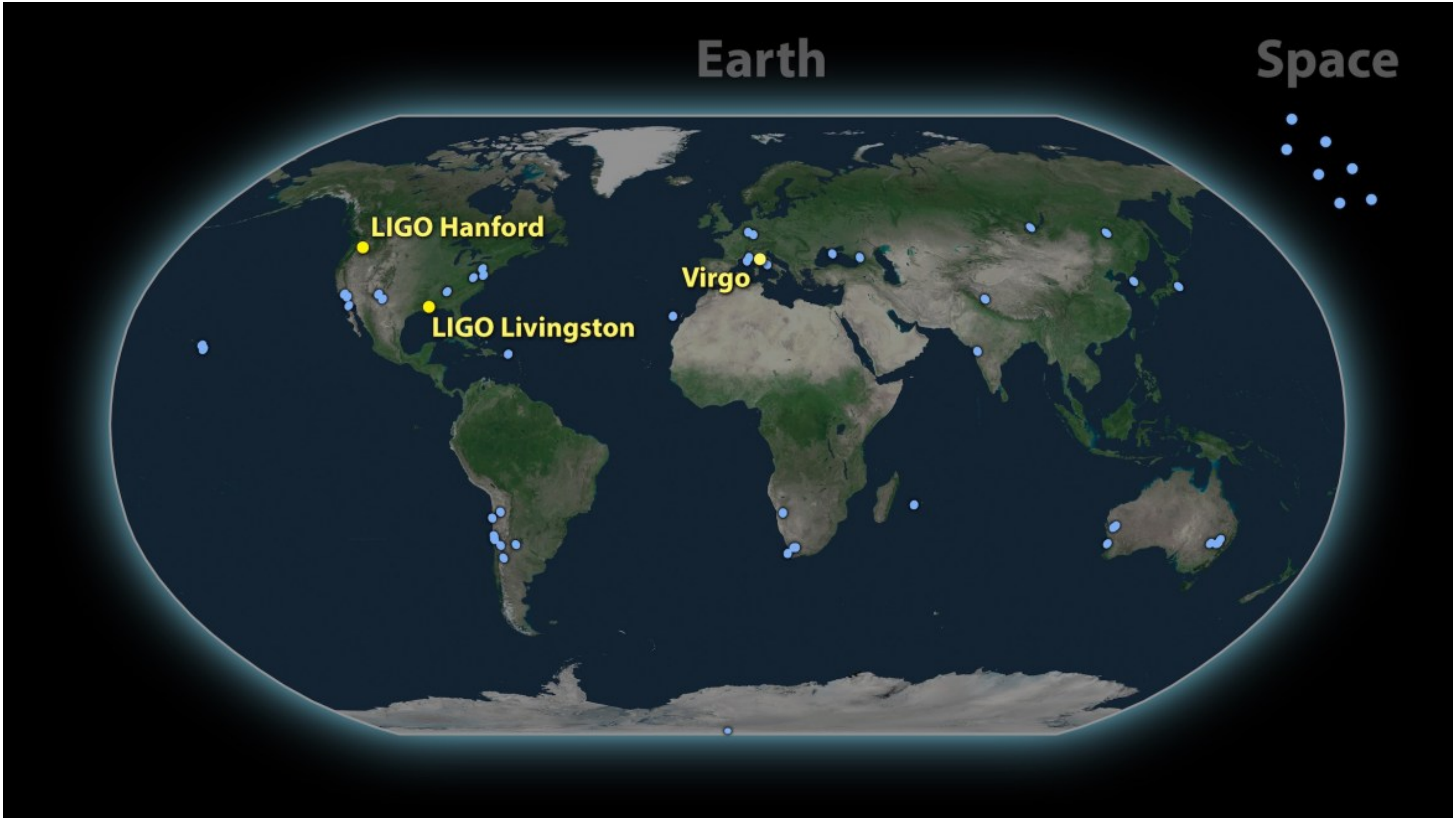
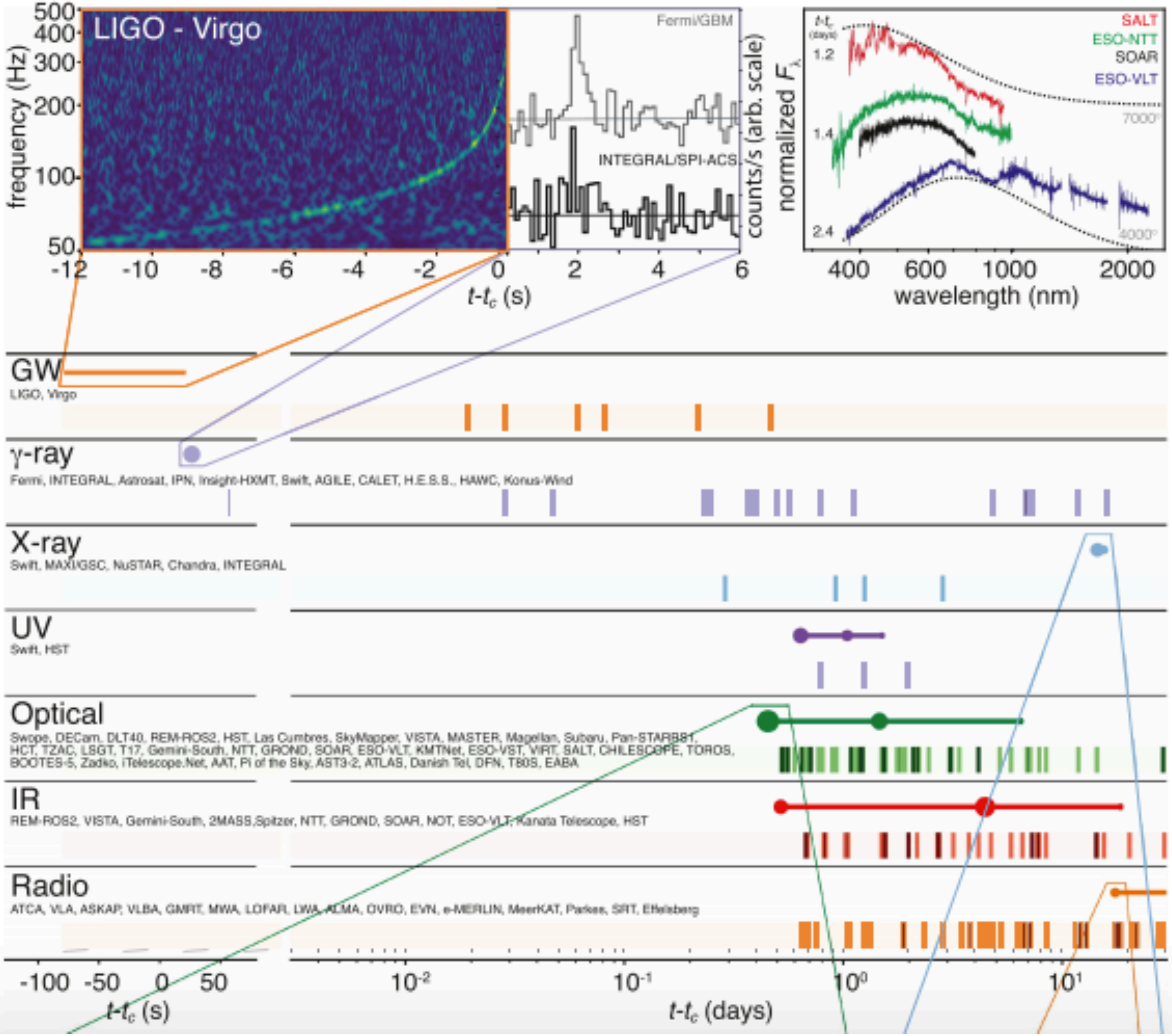


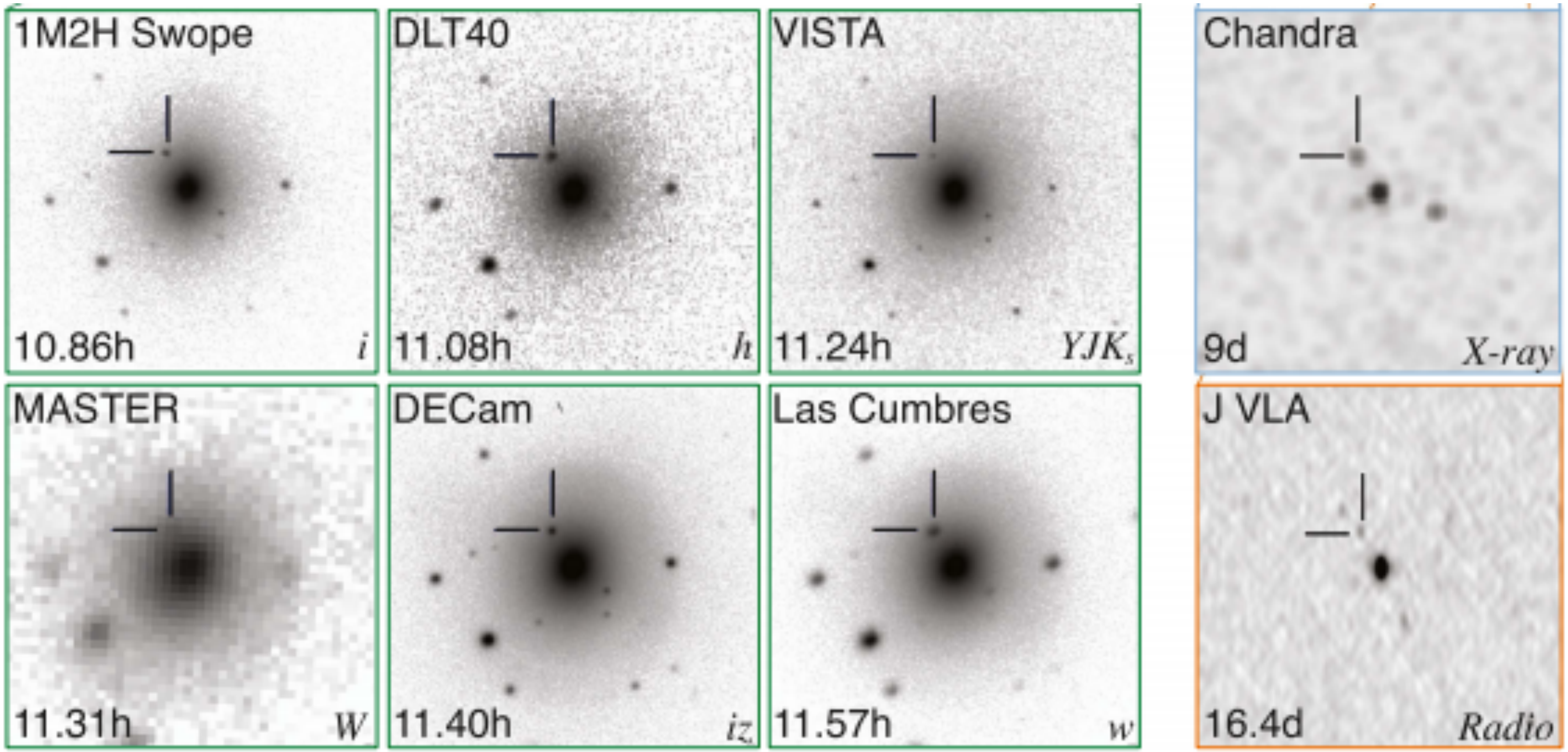
FIG. 3. Sky location reconstructed for GW170817 by a rapid localization algorithm from a Hanford-Livingston (190 deg^2, light blue contours) and Hanford-Livingston-Virgo (31 deg^2, dark blue contours) analysis. A higher latency Hanford-Livingston-Virgo analysis improved the localization (28 deg^2, green contours). In the top-right inset panel, the reticle marks the position of the apparent host galaxy NGC 4993. The bottom-right panel shows the *a posteriori* luminosity distance distribution from the three gravitational-wave localization analyses. The distance of NGC 4993, assuming the redshift from the NASA/IPAC Extragalactic Database [89] and standard cosmological parameters [90], is shown with a vertical line.

EM follow-up of GW170817



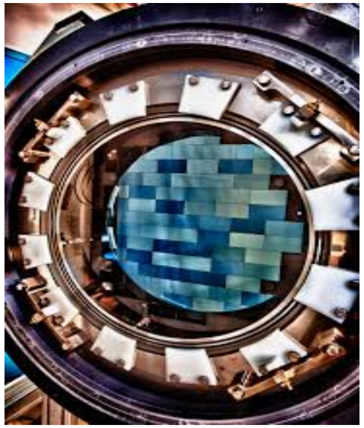

LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized Fλ
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-tc (s)
t-tc (days)

EM counterparts of GW170817



For more details of EM follow-ups of LIGO-VIRGO GW triggers,
Contact Marisa Branchesi (Gran Sasso Science Institute)

DECam discovery of counterpart



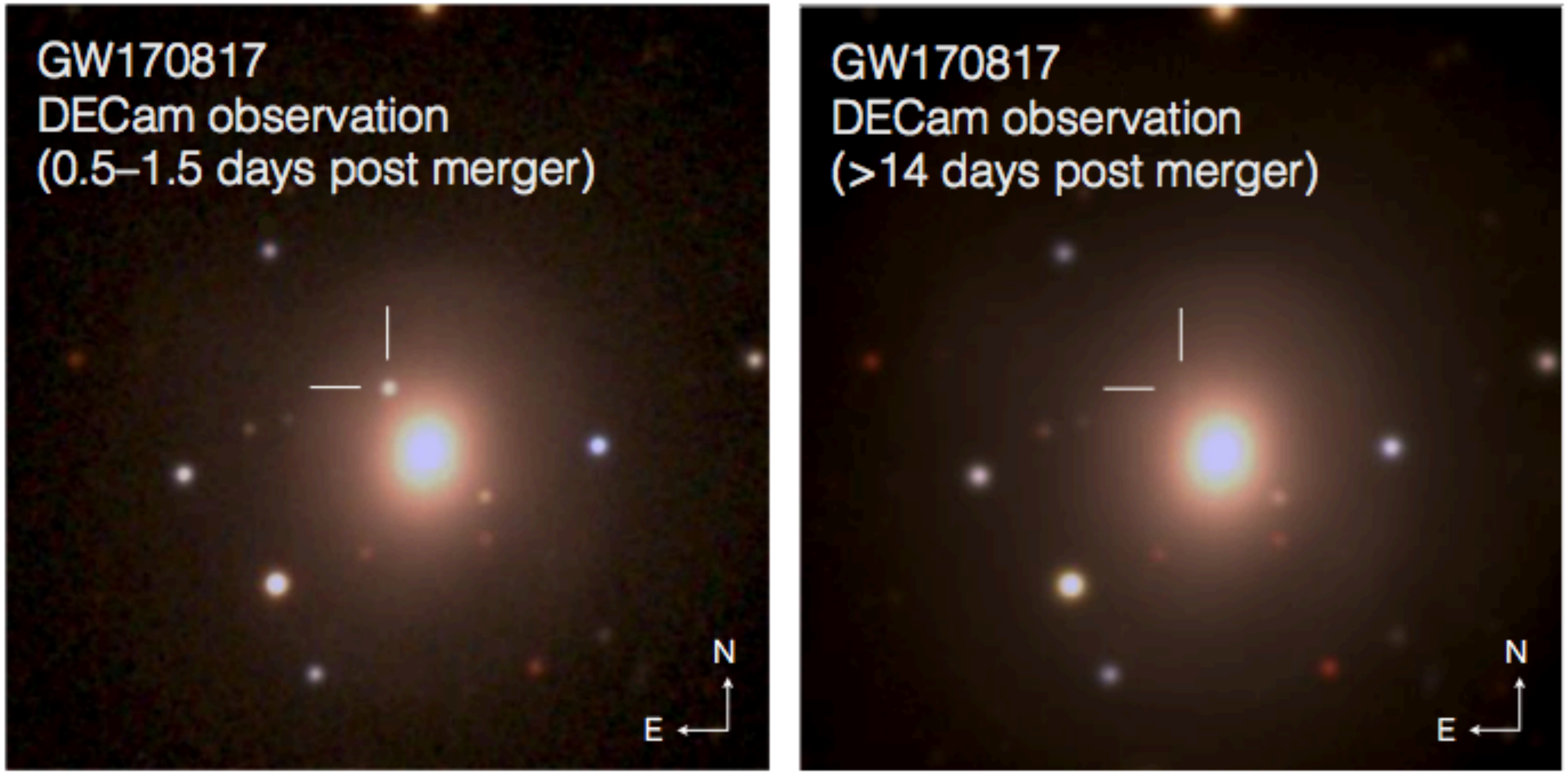
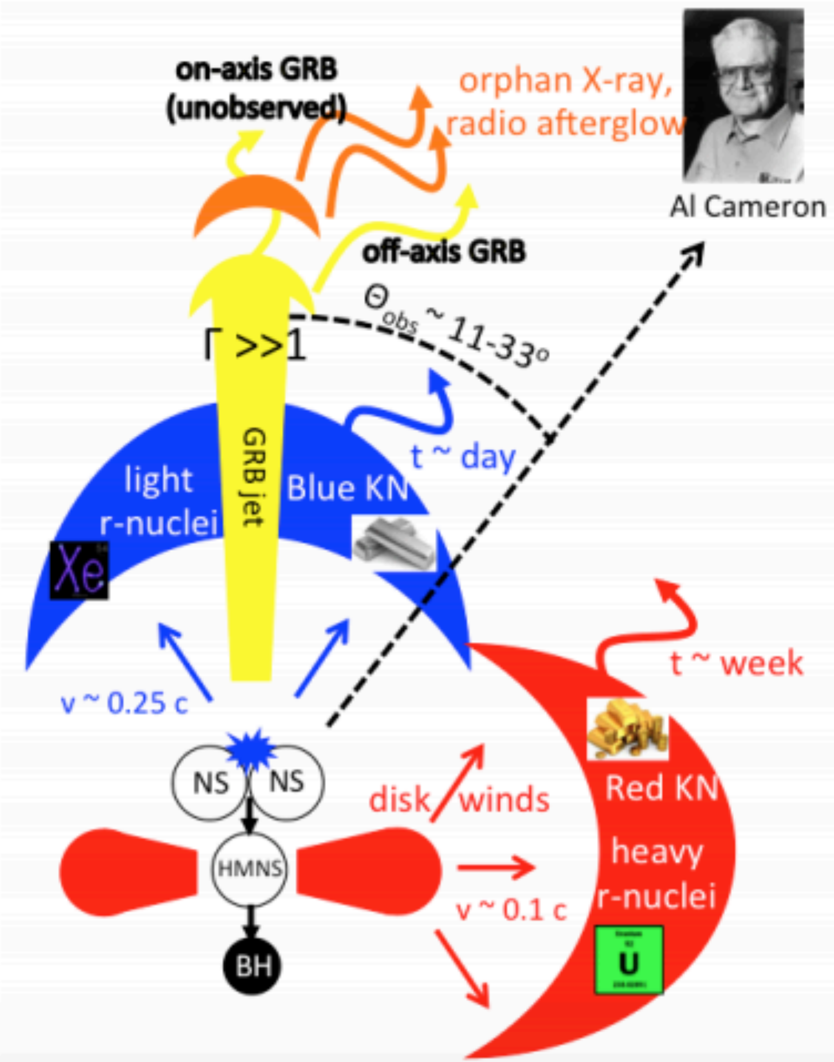


Figure 1. NGC4993 *grz* color composites (1.5’×1.5’). Left: Composite of detection images, including the discovery *z* image taken on 2017 August 18 00:05:23 UT and the g and r images taken 1 day later; the optical counterpart of GW170817 is at RA,Dec = 197.450374, −23.381495. Right: The same area two weeks later.



of GW170817, as viewed by the observer (Al Cameron) from the inferred binary inclination angle $\theta_{\rm obs} \approx 0.2 - 0.5$ (LIGO Scientific Collaboration et al., 2017d), as motivated by interpretations presented in several papers (e.g. Cowperthwaite et al. 2017; Kasen et al. 2017; Nicholl et al. 2017; Chornock et al. 2017; Fong et al. 2017; Kasen et al. 2017; Margutti et al. 2017; LIGO Scientific Collaboration et al. 2017b). **Timeline:** (1) Two NSs with small radii $\lesssim 11$ km and comparable masses ($q \approx 1$) coalesce. The dynamical stage of the merger ejects only a small mass $\lesssim 10^{-2}M_{\odot}$ in equatorial tidal ejecta, but a larger quantity $\approx 10^{-2}M_{\odot}$ of $Y_e > 0.25$ matter into the polar region at $v \approx 0.2 - 0.3$ c, which synthesizes exclusively light r-process nuclei (e.g. xenon and silver); (2) The merger product is a meta-stable hypermassive NS, which generates a large accretion torus $\sim 0.1M_{\odot}$ as it sheds its angular momentum and collapses into a BH on a timescale of $\lesssim 100$ ms; (3) The torus-BH powers a collimated GRB jet, which burrows through the polar dynamical ejecta on a timescale of $\lesssim 2$ s; (4) Gamma-rays from the core of the GRB jet are relativistically beamed away from our sight line, but a weaker GRB is nevertheless observed from the off-axis jet or the hot cocoon created as the jet breaks through the polar ejecta; (5) On a similar timescale, the accretion disk produces a powerful wind ejecting $\approx 0.04M_{\odot}$ of $Y_e \lesssim 0.25$ matter which expands quasi-spherically at $v \approx 0.1$ c and synthesizes also heavy r-process nuclei such as gold and uranium; (6) After several hours of expansion, the polar ejecta becomes diffusive, powering $\sim$ visual wavelength ("blue") kilonova emission lasting for a few days; (7) over a longer timescale $\approx$ 1 week, the deeper disk wind ejecta becomes diffusive, powering red kilonova emission; (8) the initially on-axis GRB jet decelerates by shocking the ISM, such that after ≈ 2 weeks its X-ray and radio synchrotron afterglow emission rises after entering the observer's causal cone.

Metzger : arXiv:1710.05931

Measurement of H_0 from GW170817

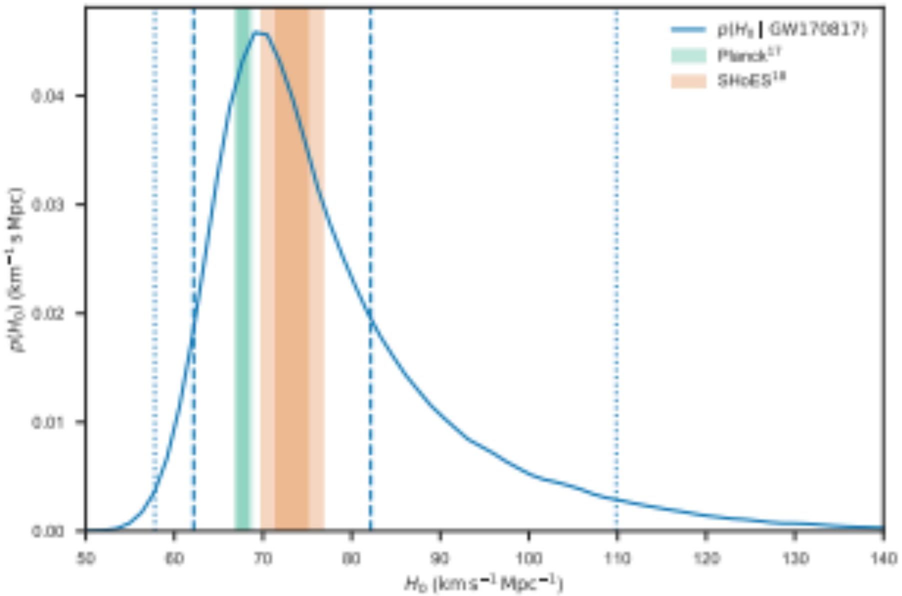
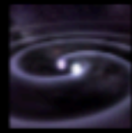
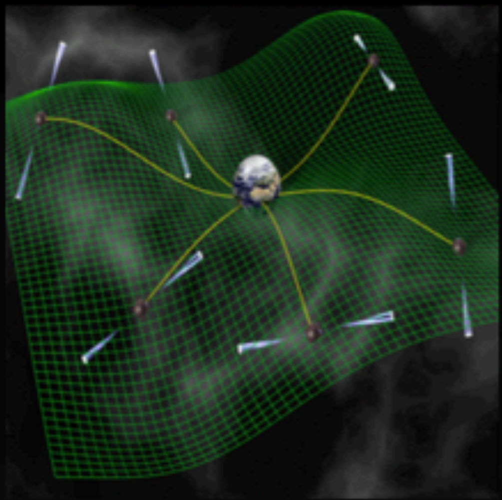


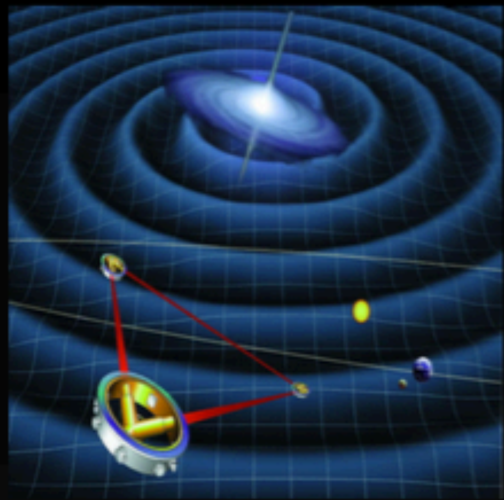
Figure 1. GW170817 measurement of H_0. Marginalized posterior density for H_0 (blue curve). Constraints at 1- and 2σ from Planck (Planck Collaboration et al. 2016) and SHoES (Riess et al. 2016) are shown in green and orange. The maximum a posteriori value and minimal 68.3% credible interval from this PDF is $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The 68.3% ($1\sigma$) and

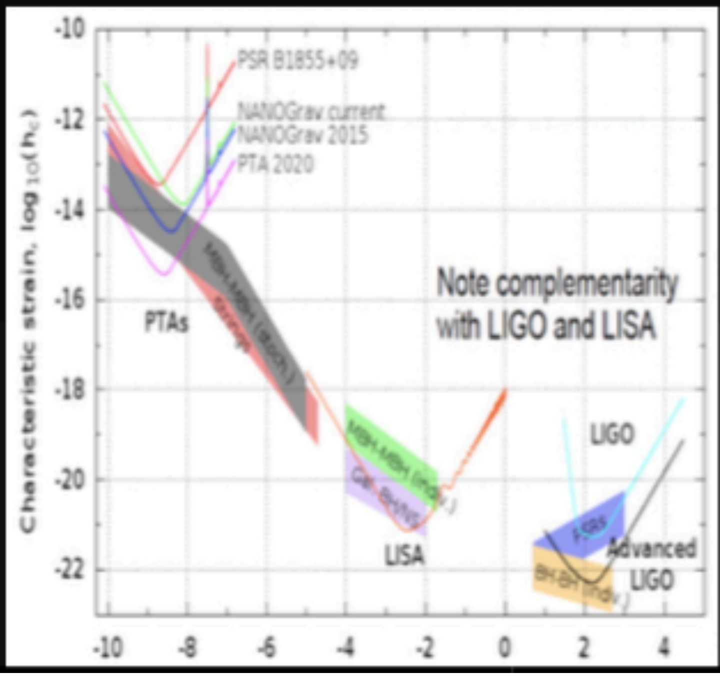
1710.05835
Nature (2017)

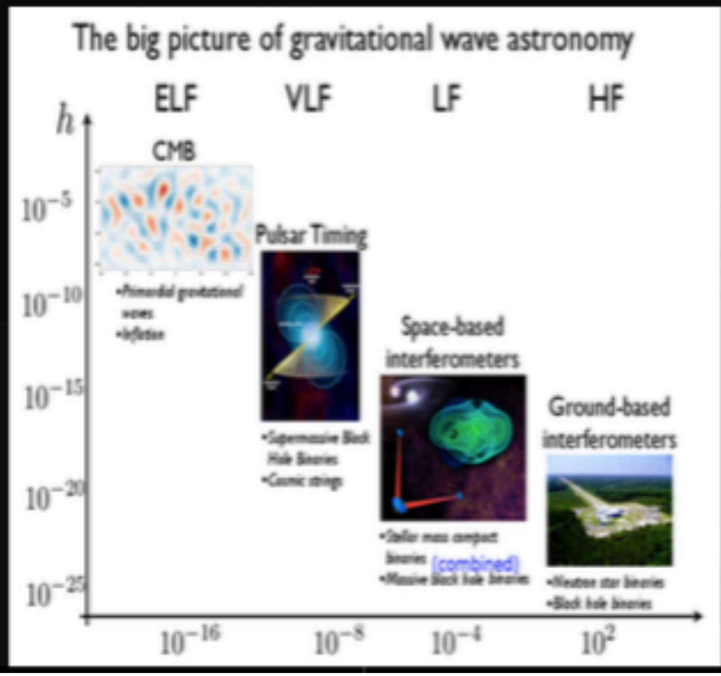
Pulsars and Gravitational Waves



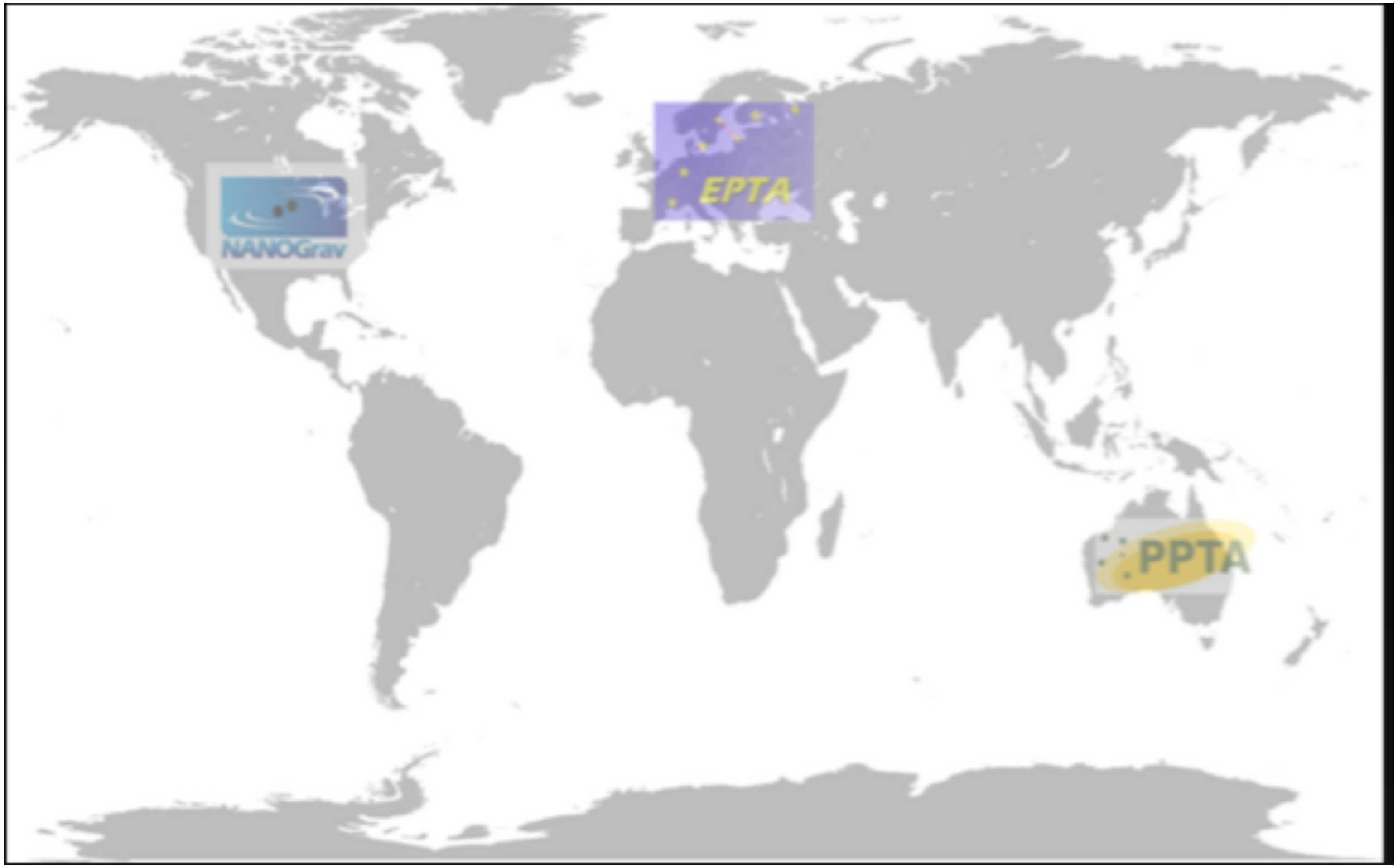






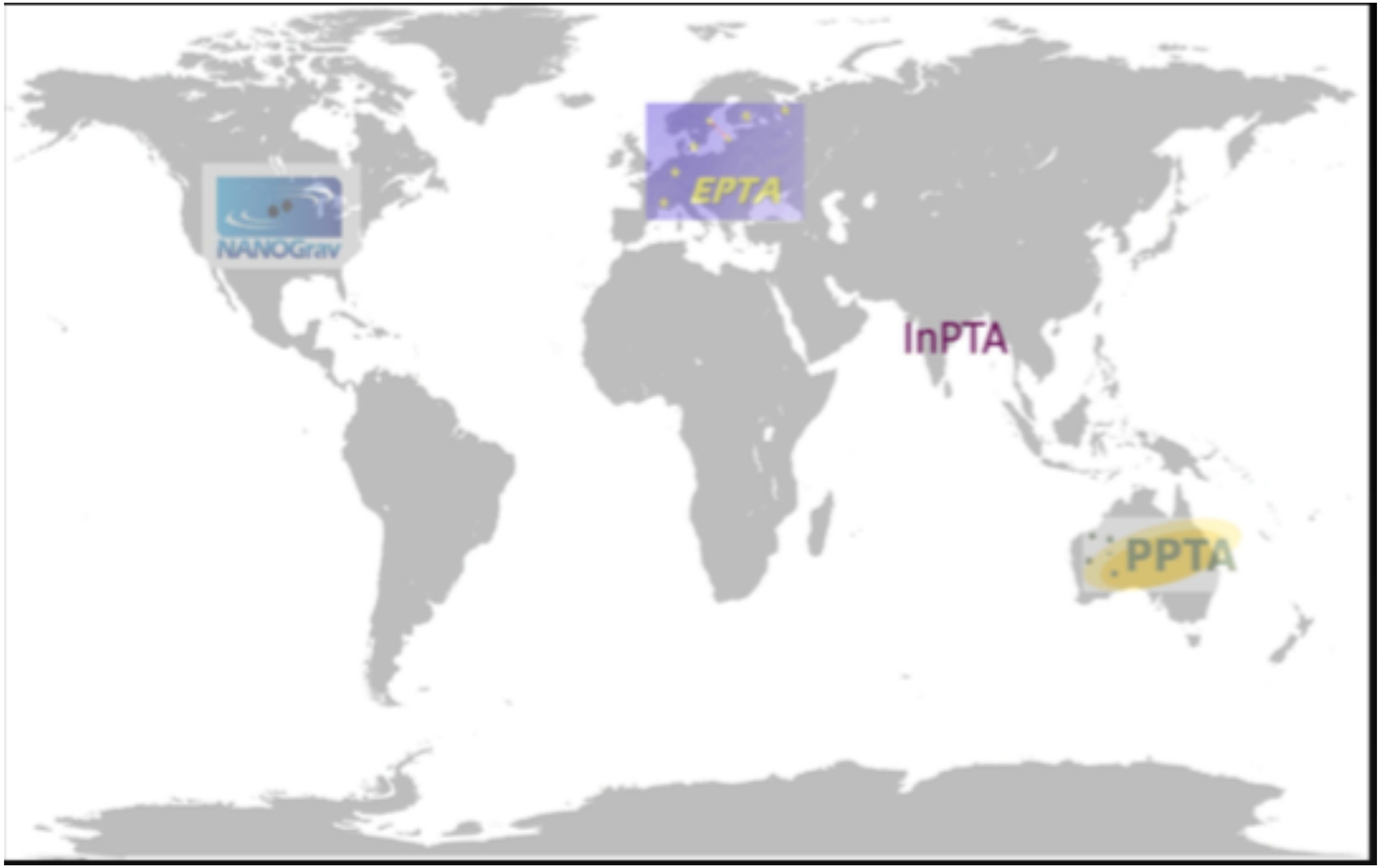


International Pulsar Timing Array



International Pulsar Timing Array

M. Bagchi



ORT+ Legacy GMRT (coherent de-dispersion 9 pulsars)
uGMRT (incoherent dedispersion, 18 pulsars band3+band 5)

European Pulsar timing array

- Includes Sardinia Radio telescope in Italy

INAF, Cagliari and University of Milan
Contact Alberto Sesana (Univ of Milan) for more details

Indian Pulsar timing array consortium

- Uses the upgraded GMRT radio telescope (sensitive at low frequencies). Joined the global consortium

Intriguing Results from Nanograv

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. The Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%--95% quantiles of 1.37--2.67×10^{-15} at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$. The Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

arXiv:2009.04496

Shapiro Delay

Irwin Shapiro (1964)

FOURTH TEST OF GENERAL RELATIVITY

Irwin I. Shapiro
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts
(Received 13 November 1964)

Recent advances in radar astronomy have made possible a fourth test of Einstein's theory of general relativity. The test involves measuring the time delays between transmission of radar pulses towards either of the inner planets (Venus or Mercury) and detection of the echoes. Because, according to the general theory, the speed of a light wave depends on the strength of the gravitational potential along its path, these time delays should thereby be increased by almost 2×10^{-4} sec when the radar pulses pass near the sun.[1] Such a change, equivalent to 60 km in distance, could now be measured over the required path length to within about 5 to 10% with presently obtainable equipment.[2]

Measurements over
last 5 decades
at all scales from
solar system to
binary pulsars

Used as tests of GR
and also as an
astrophysics probe
to measure masses of
neutron stars in binary
systems

Shapiro Delay Measurements

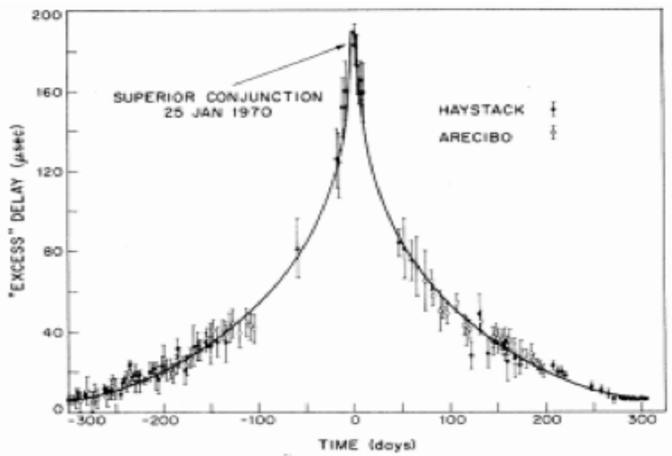
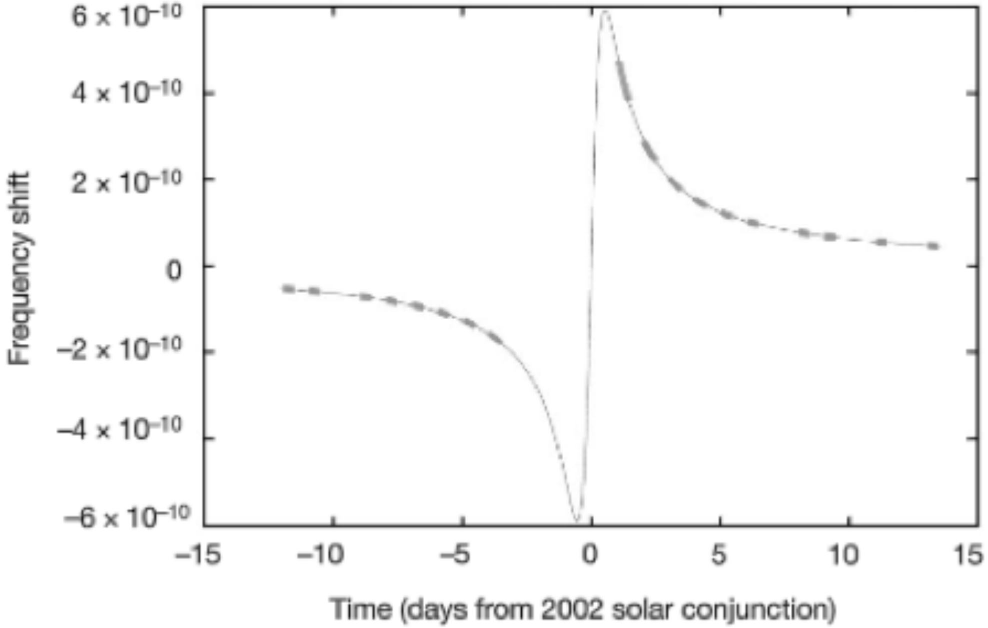


FIG. 1. Typical sample of post-fit residuals for Earth-Venus time-delay measurements, displayed relative to the "excess" delays predicted by general relativity. Corrections were made for known topographic trends on Venus. The bars represent the original estimates of the measurement standard errors. Note the dramatic increase in accuracy that was obtained with the radar-system improvements incorporated at Haystack just prior to the inferior conjunction of November 1970.



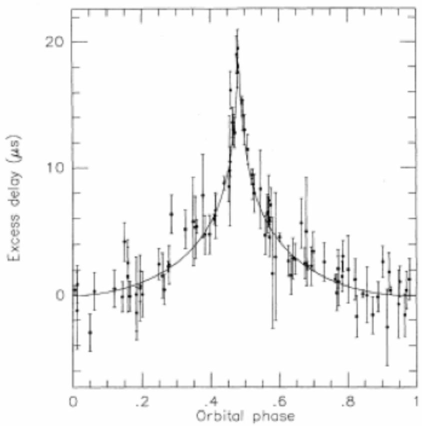
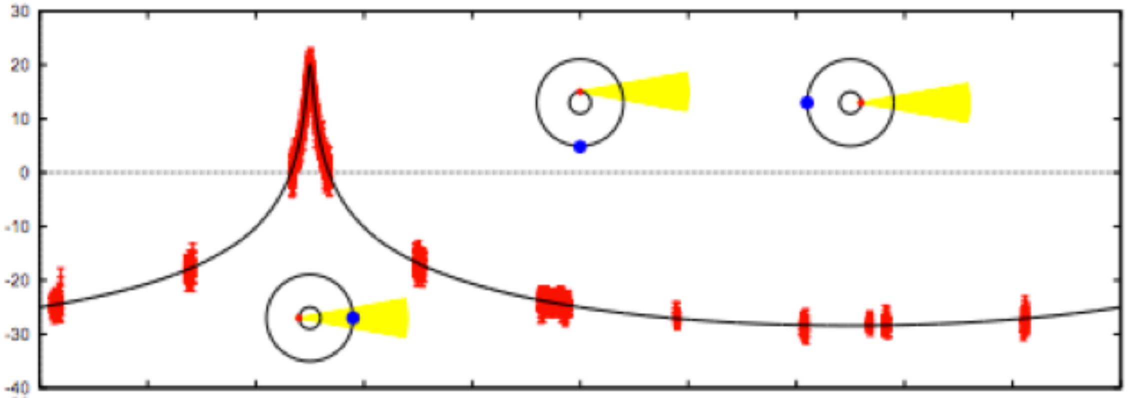
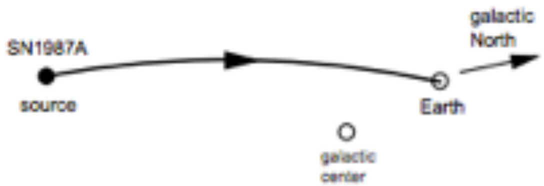


FIG. 8. Measurements of the Shapiro time delay in the PSR 1855+09 system. The theoretical curve corresponds to Eq. (10), and the fitted values of r and s can be used to determine the masses of the pulsar and companion star.



Shapiro delay for neutrinos



New Precision Tests of the Einstein Equivalence Principle from SN1987A

Michael J. Longo
University of Michigan, Ann Arbor, Michigan 48109

(Received 14 September 1987)

As is shown below, the gravitational field of our galaxy causes a significant time delay, ≃5 months, in the transit time of photons from SN1987A. (This is the delay relative to the transit time expected if the gravitation of the galaxy could be "turned off.") The fact that the arrival time of the neutrinos from SN1987A was the same as that for the first optical photons from the supernova to within several hours allows an accurate comparison of the general-relativistic time delay of the photons and neutrinos. The arrival time of the neutrinos is known to

PRL 60, 173 (1988)
Also, Krauss & Tremaine (1988)
same issue of PRL next paper

Only direct proof that neutrinos are affected by gravity and obey equivalence principle (to within 0.2%)

Shapiro delay For GWs

As

$$\frac{\delta t_\gamma (\gamma_{ray}) - \delta t_{opt}}{\delta t_\gamma} = ½ (\gamma_\gamma - \gamma_{opt}) < 20/9 \times 10^7$$

(from the observed delay of 20 seconds)

This gives

$$\gamma_\gamma - \gamma_{opt} \leq 4 \times 10^{-7} \quad (7)$$

Thus γ_{ray} and optical photons 'see' the same gravitationally induced time delay to about 4 parts in 10^7 and the difference between gamma and radio photons is about one part in 10^3 (as here $\delta t \sim$ 1day). If future detectors are able to register simultaneously neutrino and gravitational waves during gamma rays bursts, all the above formulae would give similar constraints on their properties and limits on violation of EEP for them also.

First proposed test by C. Sivaram (1999)

Bulletin of Astronomical Society of India 27,627

Gravitational waves gravitate due to a static potential at infinity.

Shapiro delay From GW150914

Constraints on frequency-dependent violations of Shapiro delay from GW150914

Emre O. Kahya, Shantanu Desai

(Submitted on 15 Feb 2016 (v1), last revised 16 Mar 2016 (this version, v3))

On 14th September 2015, a transient gravitational wave (GW150914) was detected by the two LIGO detectors at Hanford and Livingston from the coalescence of a binary black hole system located at a distance of about 400 Mpc. We point out that GW150914 experienced a Shapiro delay due to the gravitational potential of the mass distribution along the line of sight of about 1800 days. Also, the near-simultaneous arrival of gravitons over a frequency range of about 100 Hz within a 0.2 second window allows us to constrain any violations of Shapiro delay and Einstein's equivalence principle between the gravitons at different frequencies. From the calculated Shapiro delay and the observed duration of the signal, frequency-dependent violations of the equivalence principle for gravitons are constrained to an accuracy of $\mathcal{O}(10^{-9})$

Comments:	3 pages, accepted for publication in Phys. Lett. B. This paper is dedicated to the memory of Prof. Steven Detweiler
Subjects:	**General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE)
Journal reference:	Phys. Lett. B 756, 265 (2016)

Similar paper by Wu et al, 2016 PRD 1602.01566
with same conclusions

Shapiro Delay From GW170817

GW170817 Falsifies Dark Matter Emulators

Sibel Boran, Shantanu Desai, Emre Kahya, Richard Woodard

(Submitted on 17 Oct 2017)

On August 17, 2017 the LIGO interferometers detected the gravitational wave (GW) signal (GW170817) from the coalescence of binary neutron stars. This signal was also simultaneously seen throughout the electromagnetic (EM) spectrum from radio waves to gamma-rays. We point out that this simultaneous detection of GW and EM signals rules out a class of modified gravity theories, which dispense with the need for dark matter. This simultaneous observation also provides the first ever test of Einstein's Weak Equivalence Principle (WEP) between gravitons and photons. We calculate the Shapiro time delay due to the gravitational potential of the total dark matter distribution along the line of sight (complementary to the calculation in arXiv:1710.05834) to be about 1000 days. Using this estimate for the Shapiro delay and from the time difference of 1.7 seconds between the GW signal and gamma-rays, we can constrain violations of WEP using the parameterized post-Newtonian (PPN) parameter γ, and is given by $|\gamma_{\rm GW} - \gamma_{\rm EM}| < 3.9$

arXiv:1710.06168

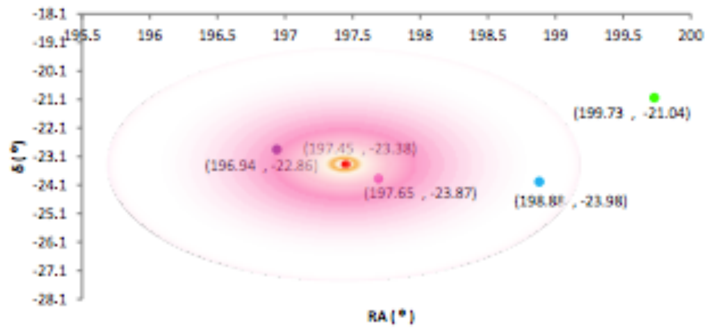


FIG. 1: The angular locations of galaxies which affect the Shapiro delay of any cosmic messenger coming from NGC 4993

Conclusions

- We have made a direct detection of gravitational waves from large no of binary black hole systems and one neutron star binary and a few NS-BH binary

- E-M counterpart detected from first NS-NS merger at all wavelengths

- Direct probes of strong field gravity, smoking gun evidence for existence of black hole binaries, evidence for r-process nucleosynthesis

- Ongoing efforts to detect gravitational waves at other wavelengths. Detection of nanoHz gravitational waves frm pulsar timing imminent

- For further information
  - http://www.ligo.org

Acknowledgments :
S. Mitra, V. Bhalerao, M. Bagchi, E. Kahya, R. Woodard,

Thank you for your attention!!!!

Books on GR/GWs

- Gravity : An introduction to Einstein's General Relativity – Jim Hartle
- Introduction to Relativity- Jayant Narlikar
- Introduction to General Relativity – A course for undergraduate students of Physics – Cosimo Bambi

For specialized books on GR

- Gravitational Waves Michele Maggiore
- Gravitational Wave Physics and Astronomy : An Introduction to Theory, Experiment and Data Analysis