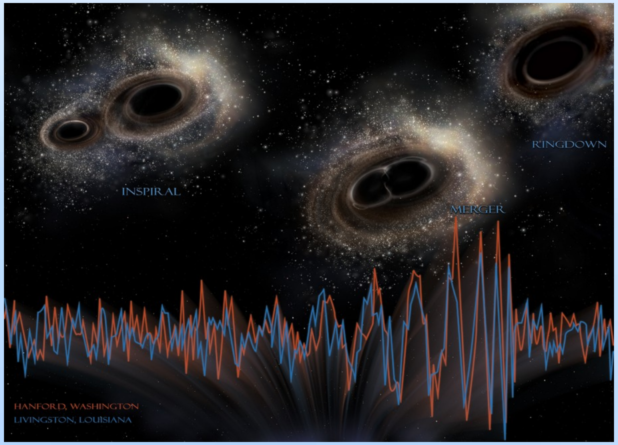
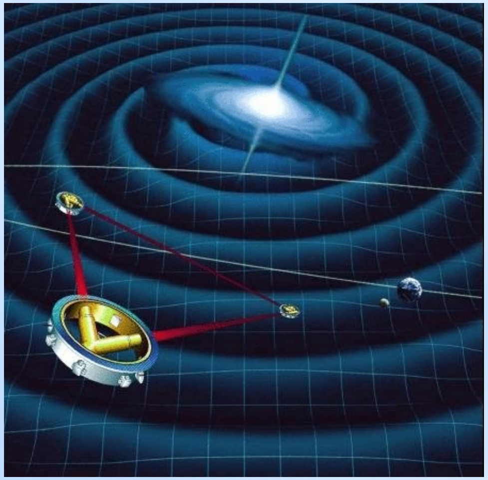




Current Experimental Limits on Gravitational Waves

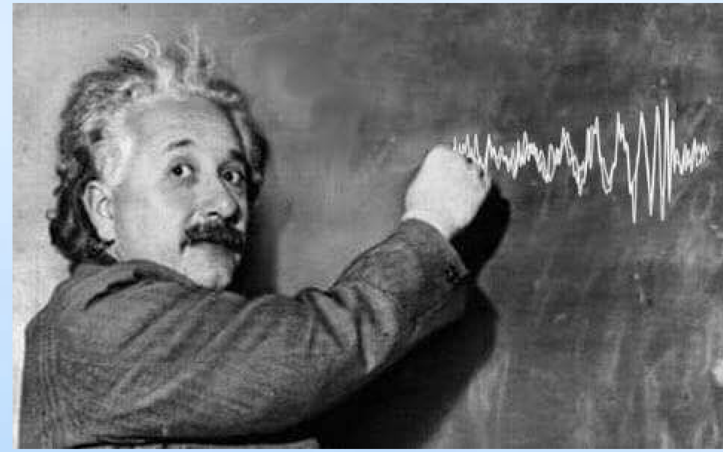
Nelson Christensen
Artemis, Observatoire de la Côte d’Azur, Nice

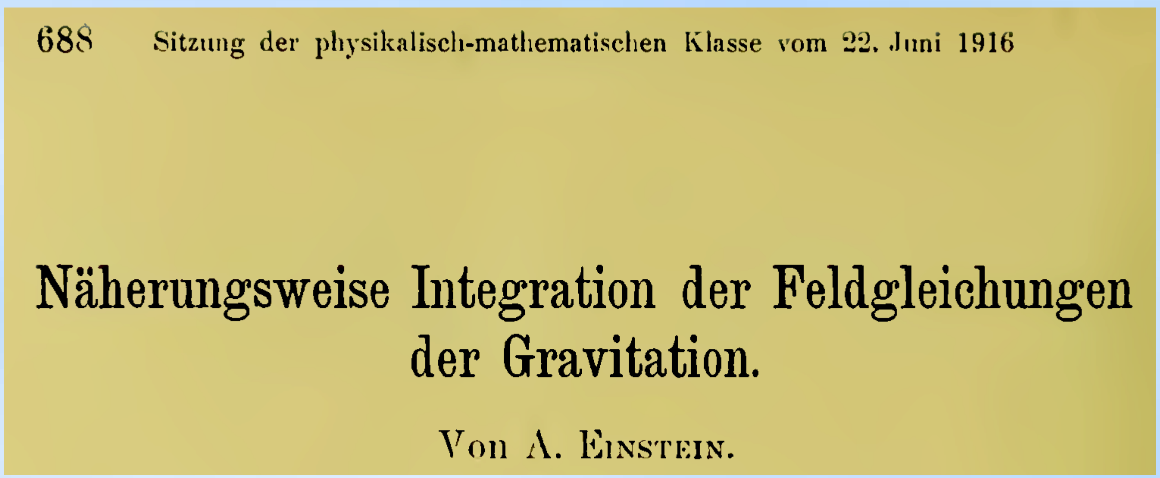
September 28, 2017. DESY Theory Workshop

General Relativity

1915: Einstein's Theory of General Relativity

1916: Einstein paper on linear approximation to general relativity with multiple applications, including gravitational waves.





688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Approximative Integration of the Field Equations of Gravitation

Gravitational Waves

$$A = \frac{\varkappa}{24\pi}\sum_{\alpha\beta}\left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"… in all conceivable cases, ***A*** must have a practically vanishing value."

Gravitational waves are predicted by Einstein, but he recognizes that they are too small.

Gravitational Waves

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

On Gravitational Waves – 1918

Einstein works out the remaining details on gravitational waves: emission (quadrupole), polarizations, they carry energy, etc

Dabei ist zur Abkürzung

$$\mathfrak{J}_{\mu\nu} = \int x_\mu x_\nu \rho \, dV_0 \qquad (23)$$

gesetzt; $\mathfrak{J}_{\mu\nu}$ sind die Komponenten des (zeitlich variabeln) Trägheitsmomentes des materiellen Systems.

$$\gamma'_{23} = -\frac{\varkappa}{4\pi R} \ddot{\mathfrak{J}}_{23} \, .$$

While we are at it … Black Holes!

Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie.

Von K. Schwarzschild.

(Vorgelegt am 13. Januar 1916 [s. oben S. 42].)

On the gravitational field of a mass point according to Einstein's theory

$$ds^2 = (1 - \alpha/R)\,dt^2 - \frac{dR^2}{1 - \alpha/R} - R^2(d\vartheta^2 + \sin^2\vartheta\, d\phi^2), \quad R = (r^3 + \alpha^3)^{1/3}. \quad (14)$$

Dasselbe enthält die eine Konstante α, welche von der Größe der im Nullpunkt befindlichen Masse abhängt.

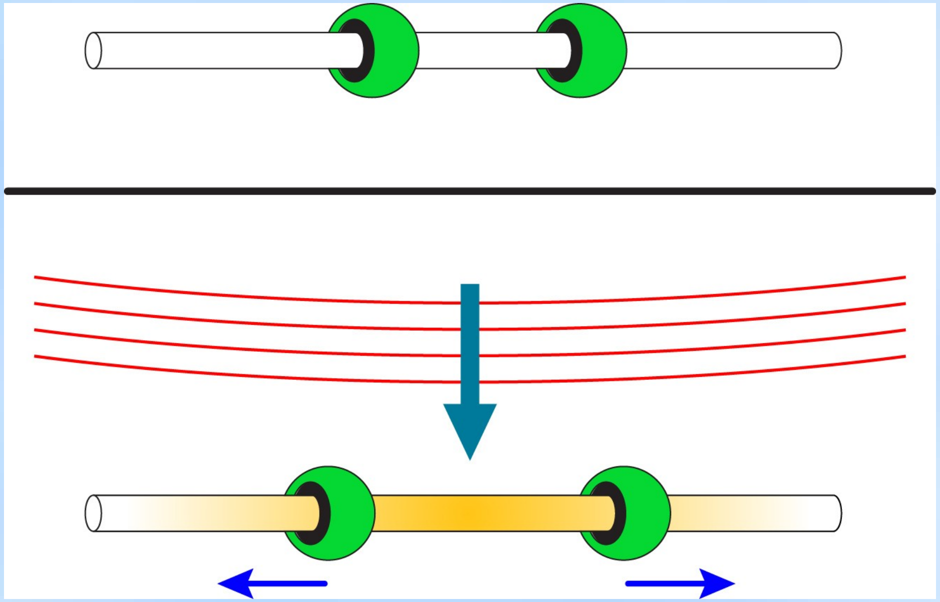
The concept of a “Black Hole” was not recognized by Schwarschild:
A. Eddington 1924, G. Lemaître 1933, R. Oppenheimer 1939, D. Finkelstein 1958, …

Are Gravitational Waves Real?

Continued debate on whether gravitational waves really exist up until 1957 Chapel Hill conference.

Felix Pirani paper and presentation: relative acceleration of particle pairs can be associated with the Riemann tensor. The interpretation of the attendees was that non-zero components of the Riemann tensor were due to gravitational waves.

Sticky bead (Felix Pirani, Richard Feynman, Hermann Bondi)



Joe Weber of the University of Maryland, and from this inspiration started to think about gravitational wave detection.

Binary Pulsar PSR 1913+16

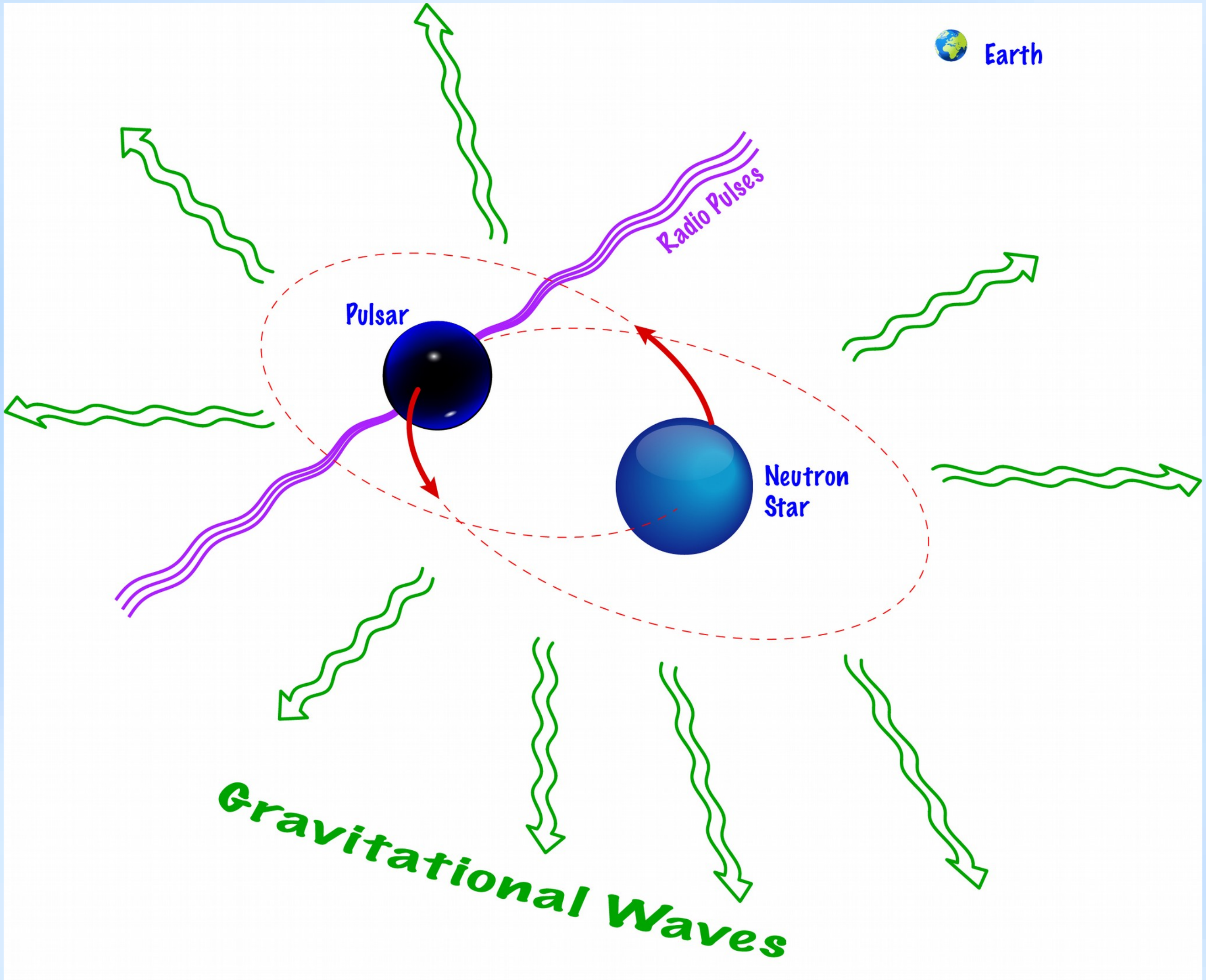
M1 = 1.438 M_o

M2 = 1.390 M_o

8 hour orbit

Orbit decays by 3mm per orbit.

Discovered in 1974 by Russell Hulse and Joseph Taylor, then at University Massachusetts.



A Nobel Prize for ...

"… for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."
1993

For more on this Nobel, see, "The Nobel pulsar", Nelson Christensen. Science, Vol. 348 no. 6236 p. 766 (2015).

First Proof That Gravitational Waves Exist - 1982

THE ASTROPHYSICAL JOURNAL, **253**:908–920, 1982 February 15

A NEW TEST OF GENERAL RELATIVITY: GRAVITATIONAL RADIATION AND THE BINARY PULSAR PSR 1913+16

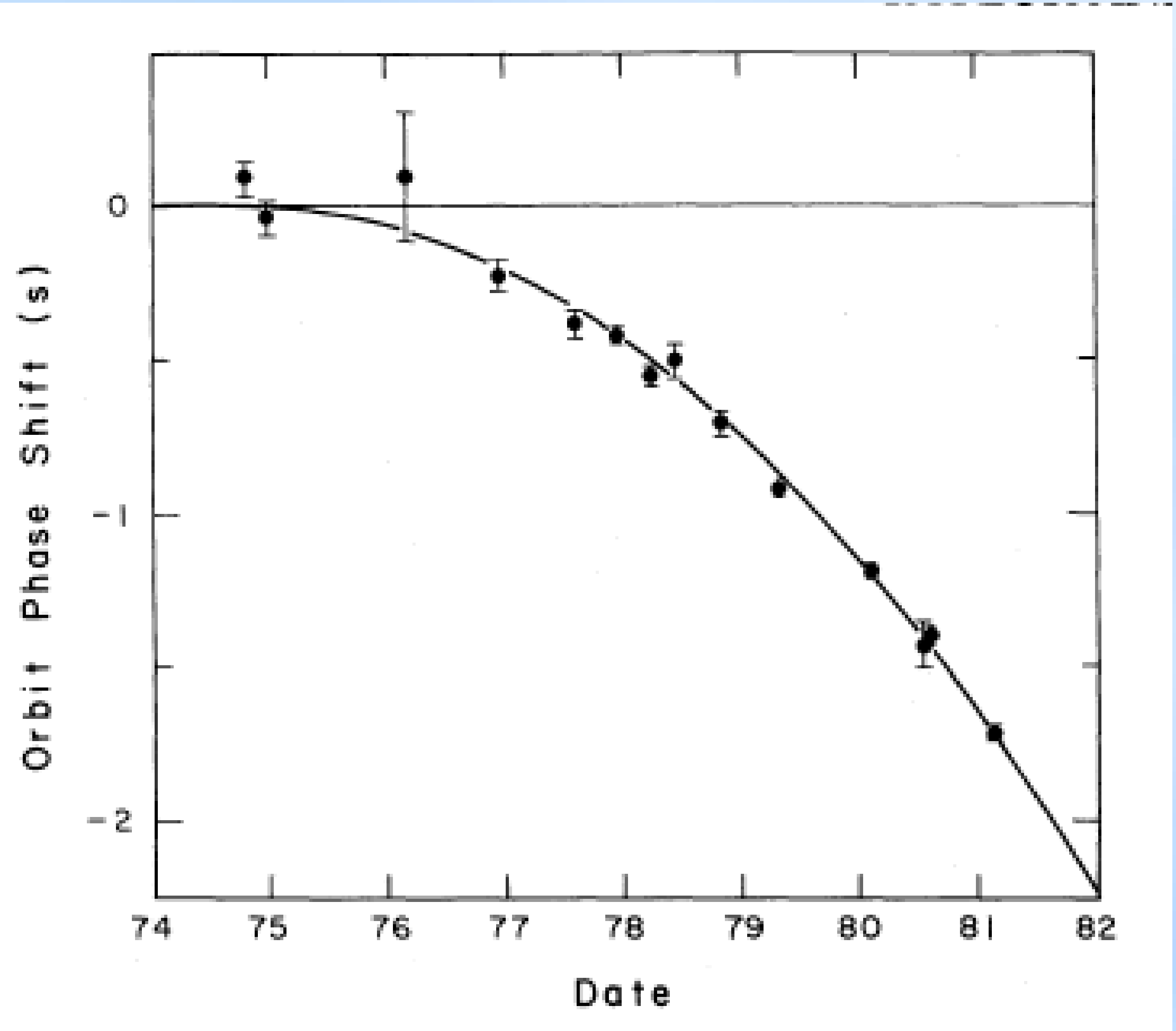
J. H. TAYLOR AND J. M. WEISBERG
Department of Physics and Astronomy, University of Massachusetts, Amherst; and Joseph Henry Laboratories, Physics Department, Princeton University
Received 1981 July 2; accepted 1981 August 28

ABSTRACT

Observations of pulse arrival times from the binary pulsar PSR 1913+16 between 1974 September and 1981 March are now sufficient to yield a solution for the component masses and the absolute size of the orbit. We find the total mass to be almost equally distributed between the pulsar and its unseen companion, with $m_p = 1.42 \pm 0.06\ M_\odot$ and $m_c = 1.41 \pm 0.06\ M_\odot$. These values are used, together with the well determined orbital period and eccentricity, to calculate the rate at which the orbital period should decay as energy is lost from the system via gravitational radiation. According to the general relativistic quadrupole formula, one should expect for the PSR 1913+16 system an orbital period derivative $\dot{P}_b = (-2.403 \pm 0.005) \times 10^{-12}$. Our observations yield the measured value $\dot{P}_b = (-2.30 \pm 0.22) \times 10^{-12}$. The excellent agreement provides compelling evidence for the existence of gravitational radiation, as well as a new and profound confirmation of the general theory of relativity.

Subject headings: gravitation — pulsars — relativity

Gravitational Wave Proof



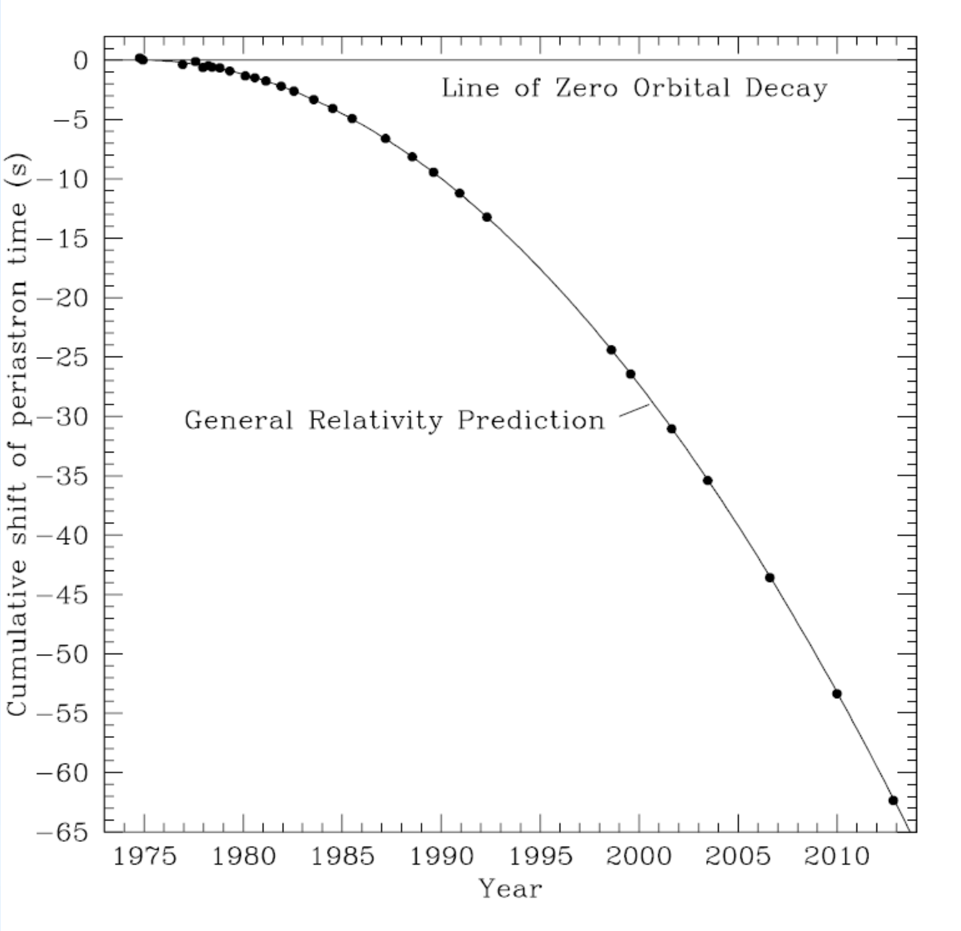
Taylor and Weisberg, 1982

Binary Pulsar Studies Continue

THE ASTROPHYSICAL JOURNAL, 829:55 (10pp), 2016 September 20
doi:10.3847/0004-637X/829/1/55

RELATIVISTIC MEASUREMENTS FROM TIMING THE BINARY PULSAR PSR B1913+16

J. M. WEISBERG AND Y. HUANG
Department of Physics and Astronomy, Carleton College, Northfield, MN 55057, USA; jweisber@carleton.edu
Received 2016 January 19; revised 2016 April 20; accepted 2016 June 1; published 2016 September 21



"The points, with error bars too small to show, represent our measurements"

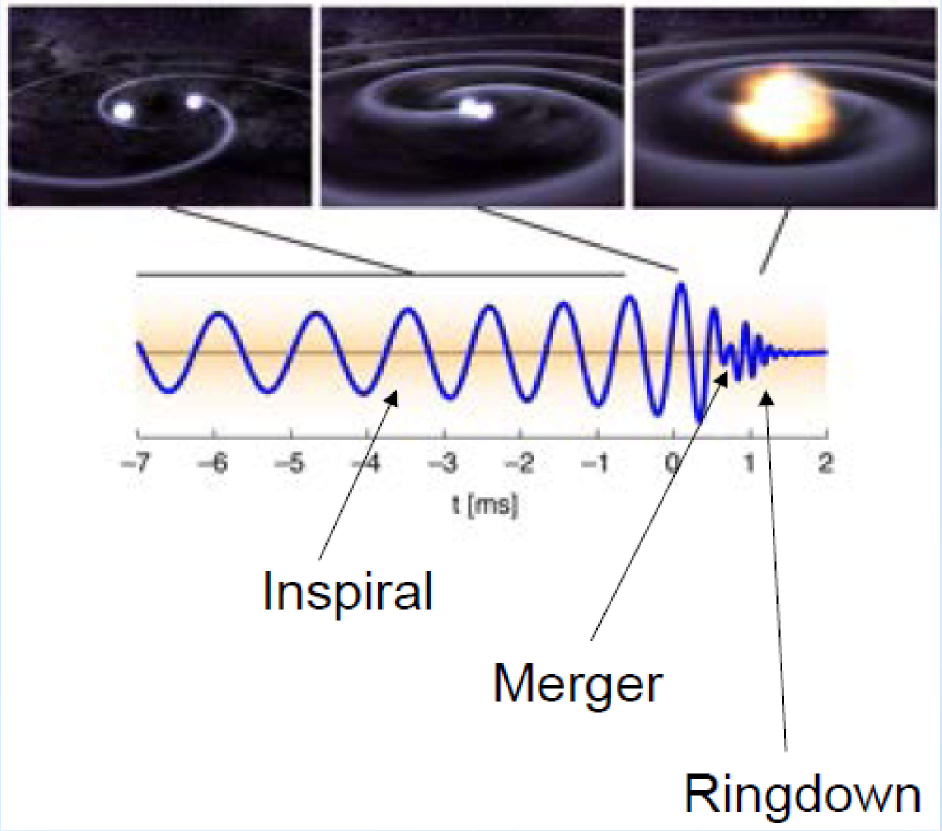
Gravitational Wave Detection

Inspired and motivated by the Chapel Hill Conference, Joe Weber of the University of Maryland constructs the first gravitational wave detectors.

"In 1958 I was able to prove, using Einstein's equations that a gravitational wave would change the dimensions of an extended body."

Sources: Compact Binary Coalescence

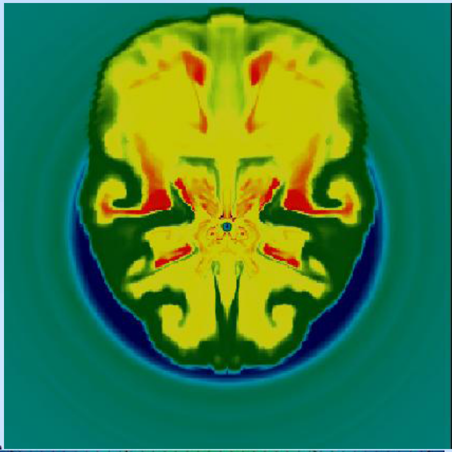
- Compact binary objects:
  - » Two neutron stars and/or black holes.
- Inspiral toward each other.
  - » Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform relatively well understood, matched template searches.

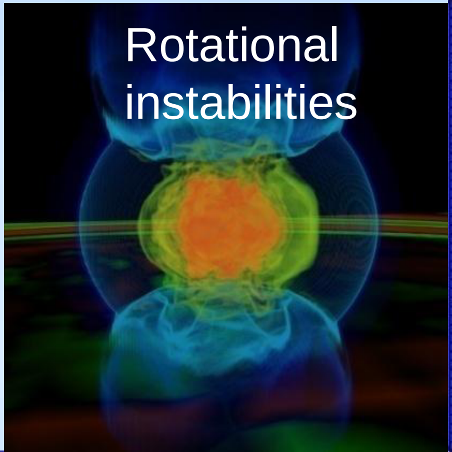


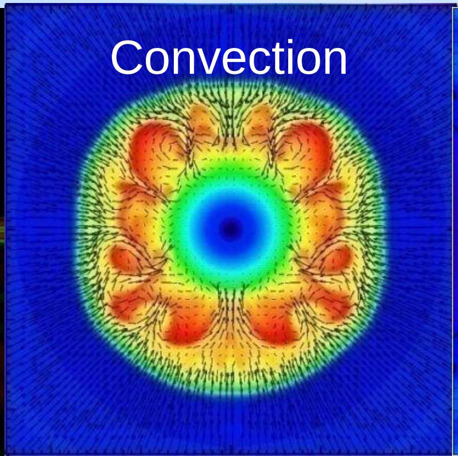
Sources: Bursts

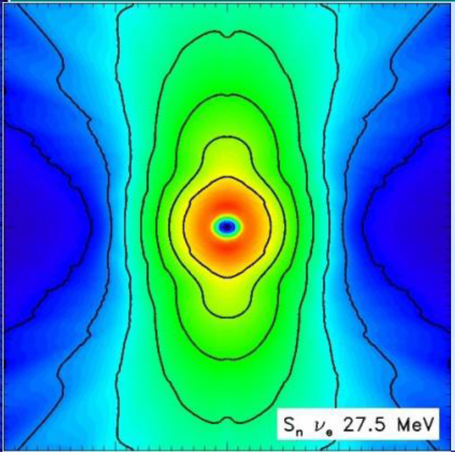
- Many potential transient sources:
  - » Supernovae: probe the explosion mechanisms.
  - » Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - » Pulsar glitches: accretion.
  - » Cosmic strings cusps and kinks.
- Models are ok, but not essential:
  - » Search for power excess in the data.
  - » Search for any short signal with measurable strain signal.

Aspherical outflows



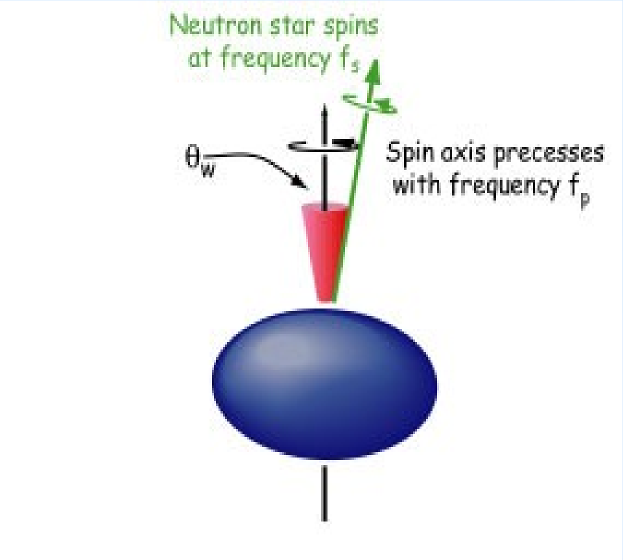






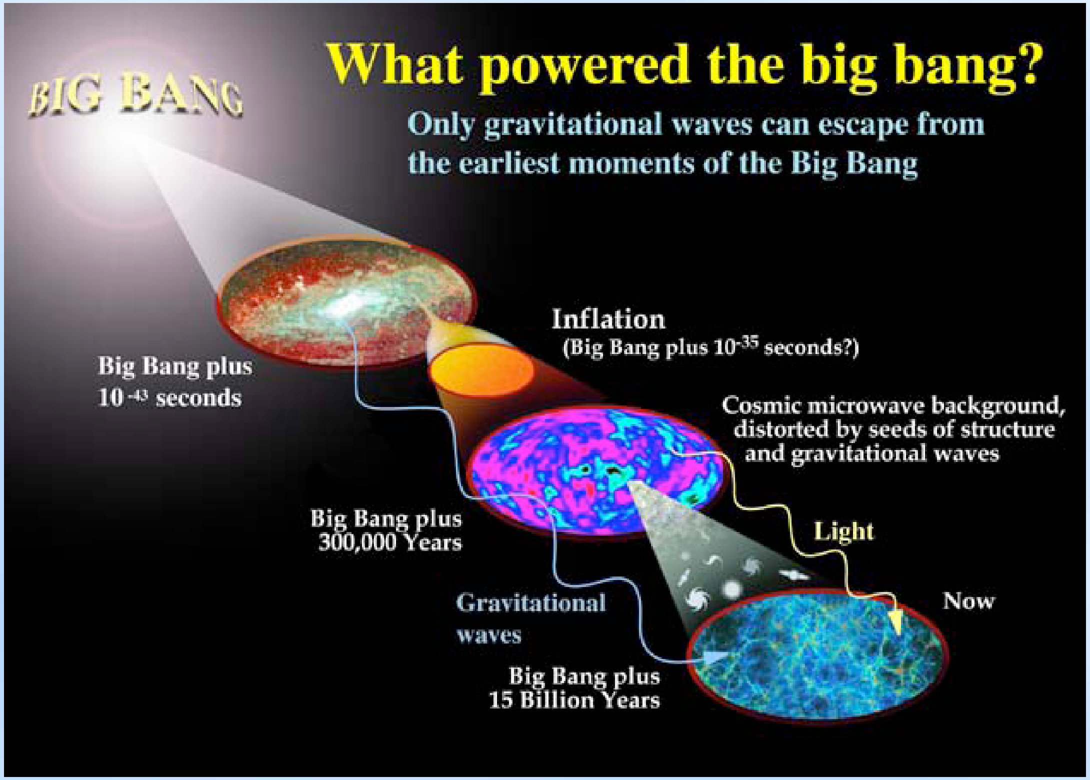
Sources: Periodic

- Pulsars with mass non-uniformity:
  - » Small “mountain”.
  - » Density non-uniformity.
  - » Dynamic processes inside neutron star, leading to various instabilities.
- Produce gravitational-waves, often at twice the rotational frequency.
- Waveform well understood:
  - » Sinusoidal, but Doppler-modulated.
- Continuous source!



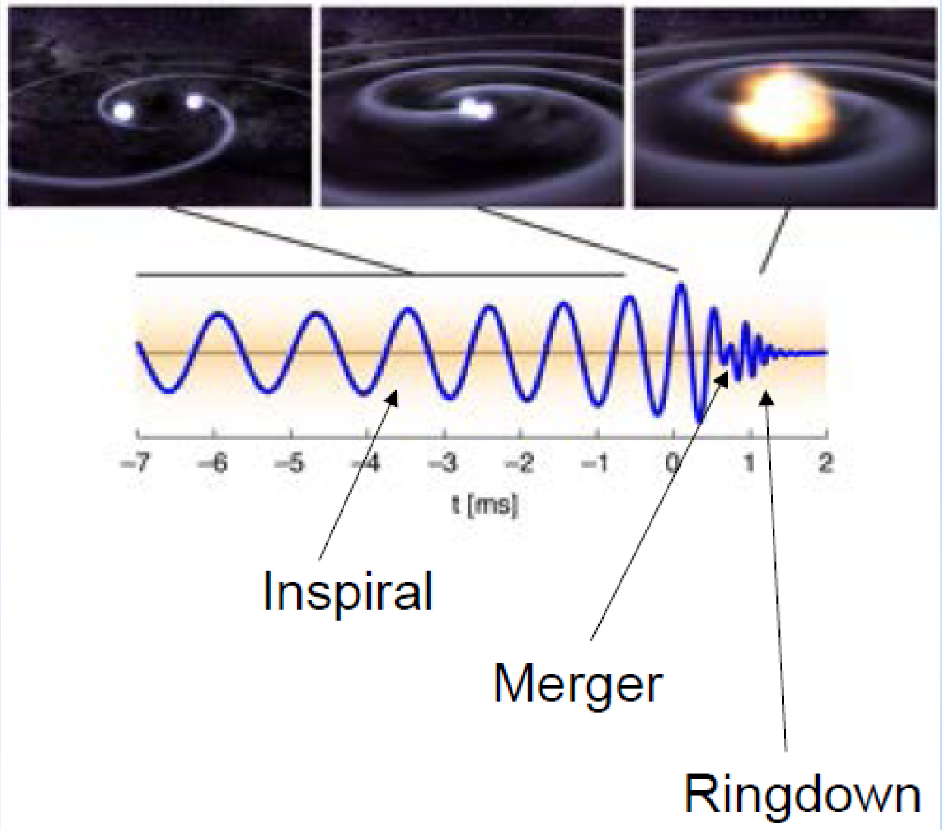
Sources: Stochastic

- Incoherent superposition of many unresolved sources.
- Cosmological:
  » Inflationary epoch, preheating, reheating
  » Phase transitions
  » Cosmic strings
  » Alternative cosmologies
- Astrophysical:
  » Supernovae
  » Magnetars
  » Binary black holes
- Potentially could probe physics of the very-early Universe.



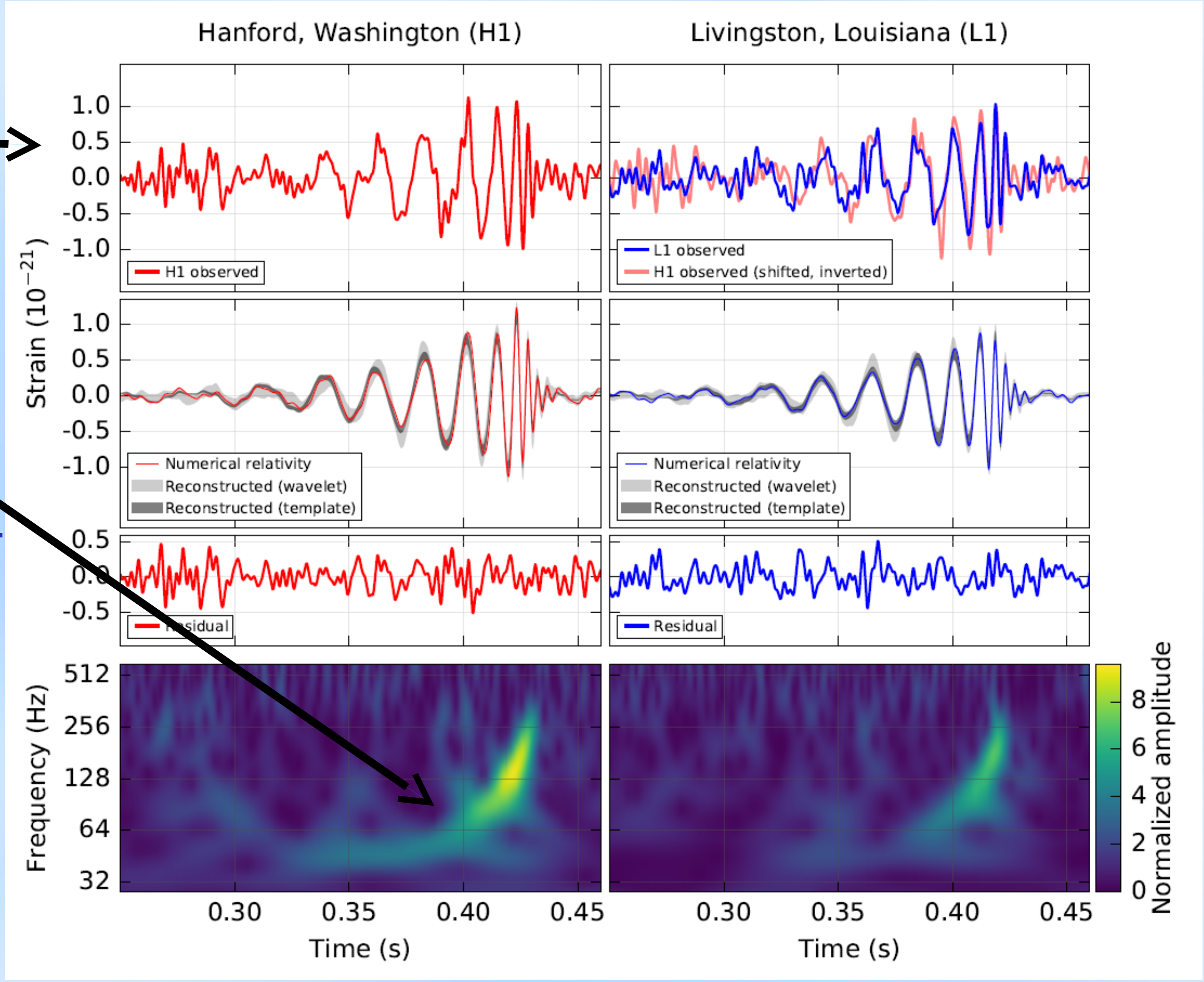
$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

A Century Of Theoretical Developments



GW150914

- Band-pass filter:
  35-350 Hz
- L1-H1 time delay of about 7ms.
- Chirp signal, typical of binary coalescences.
- Detected by online burst-search pipelines.
- Confirmed later matched template searches.
- Combined SNR: 24.



Physical Review Letters, Vol. 116, p. 061102 (2016)

The Results

Observation of Gravitational Waves from a Binary Black Hole Merger

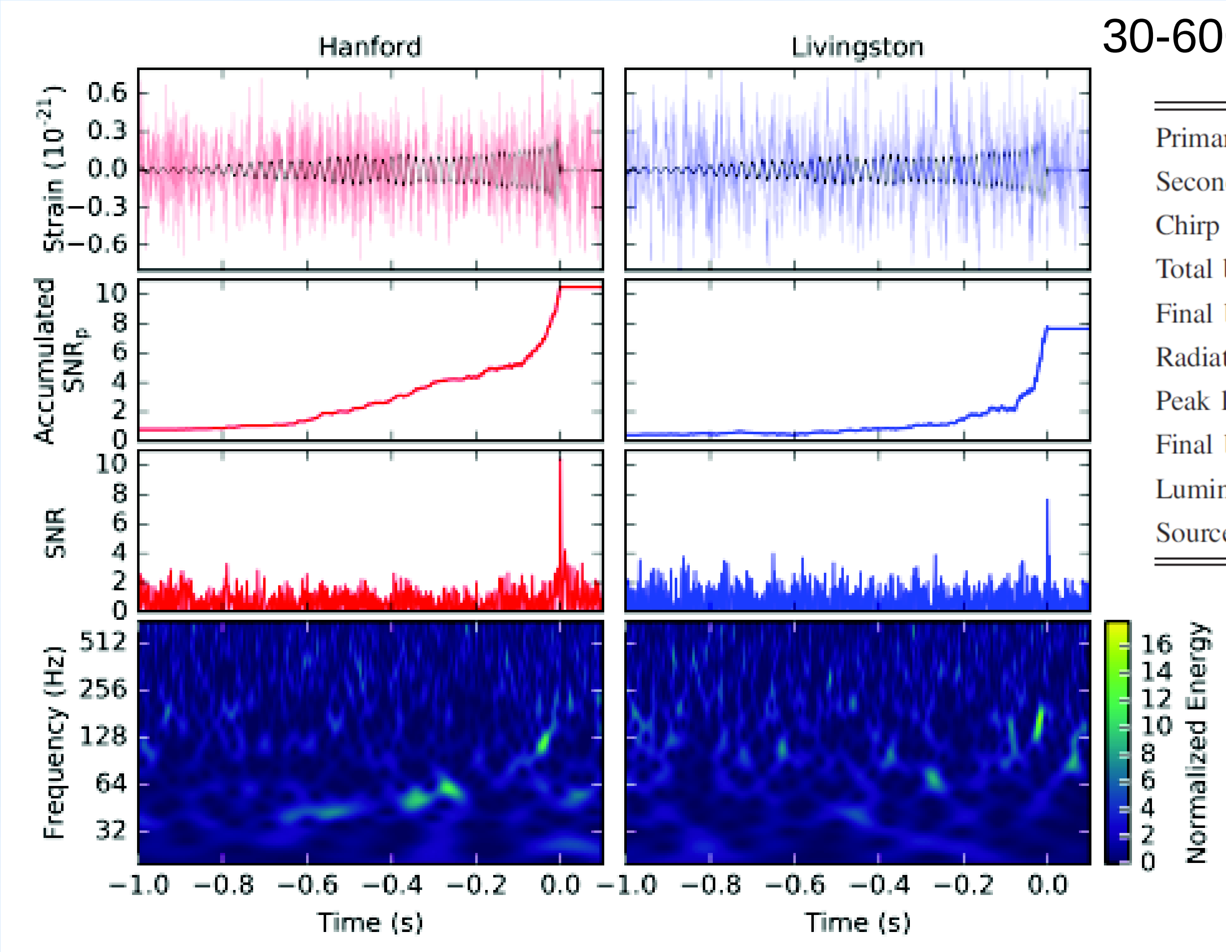
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

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	$0.09^{+0.03}_{-0.04}$

GW151226 – A Success For Matched Filtering



30-600 Hz bandpass

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	$0.09^{+0.03}_{-0.04}$

Physical Review Letters, Vol. 116, p. 241103 (2016)

O1 Events

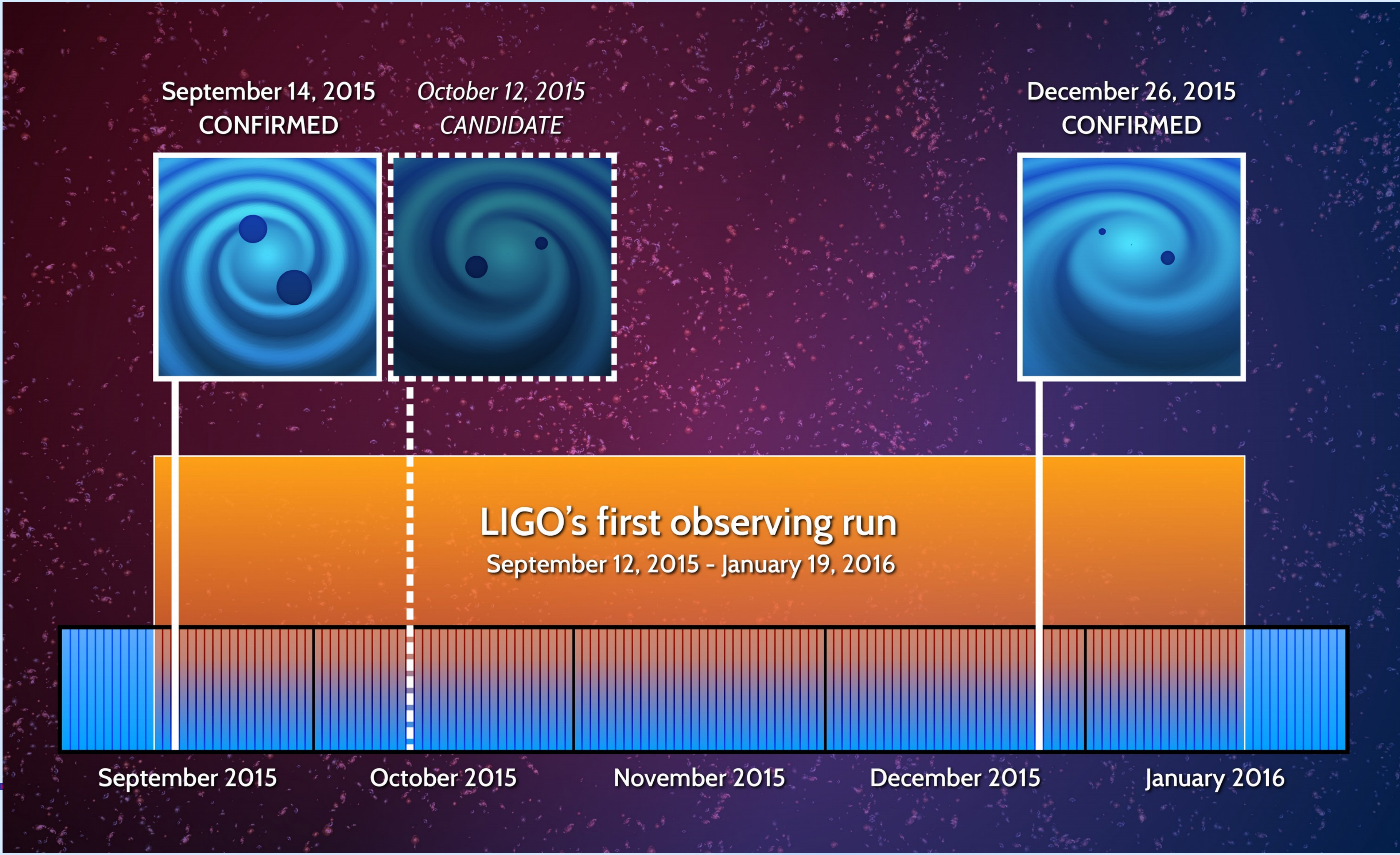


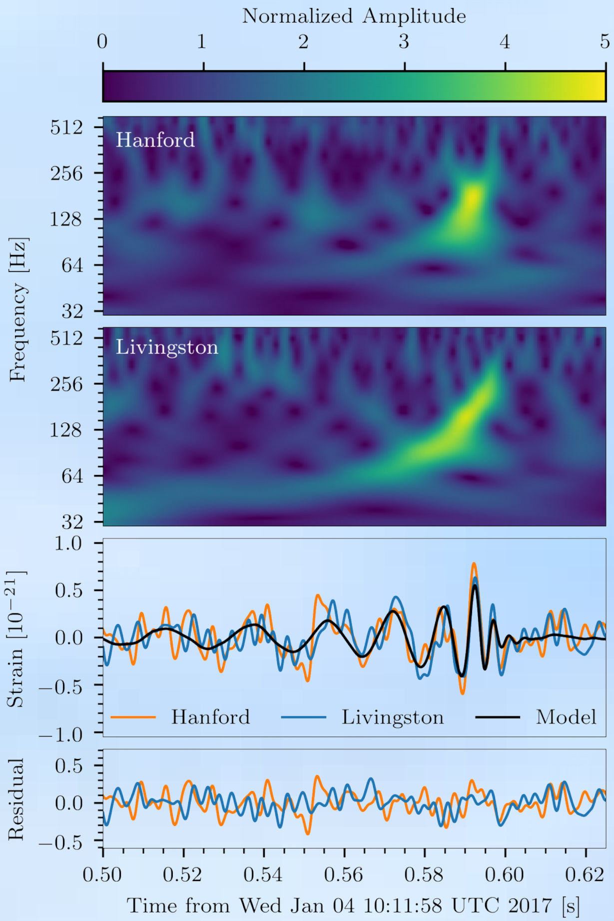
Image Credit - LIGO

Observing Run O2

30 November 2016 to 25 August 2017

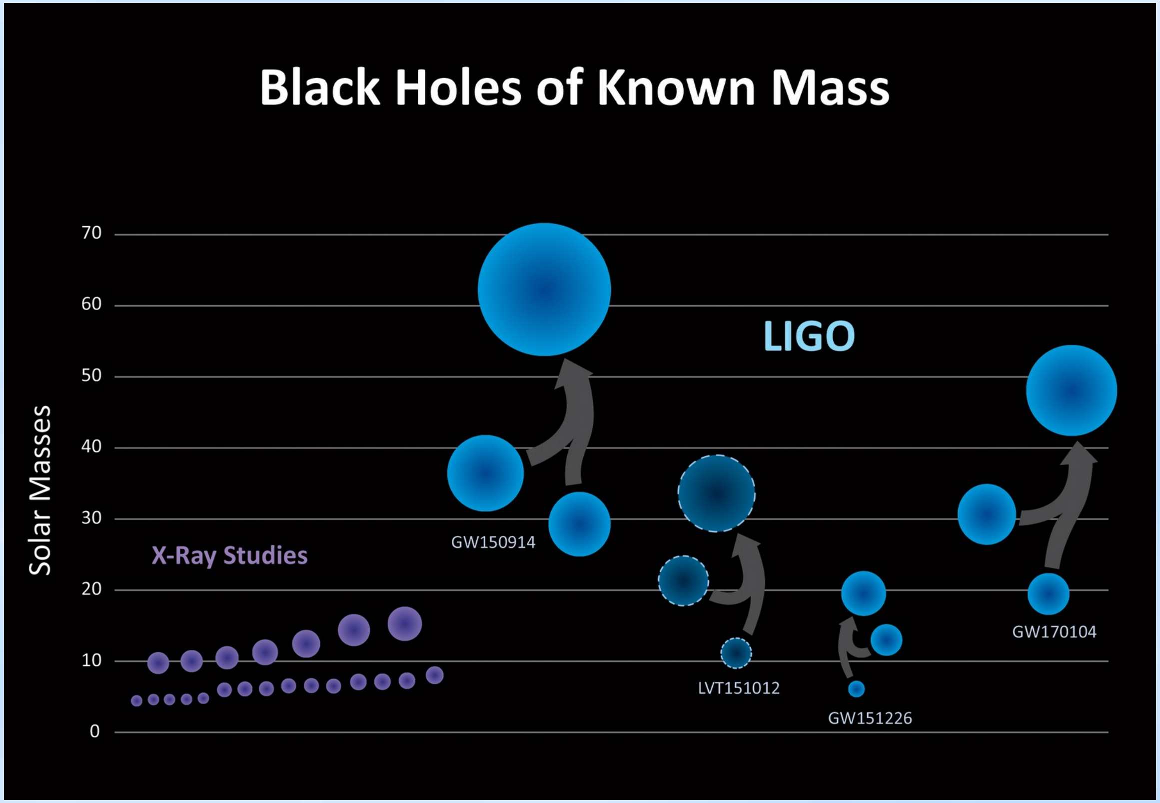
Advanced Virgo 1 August – 25 August 2017

GW170104 – O2 Observing Run BBH Detection



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	$0.18^{+0.08}_{-0.07}$

Black Hole Population



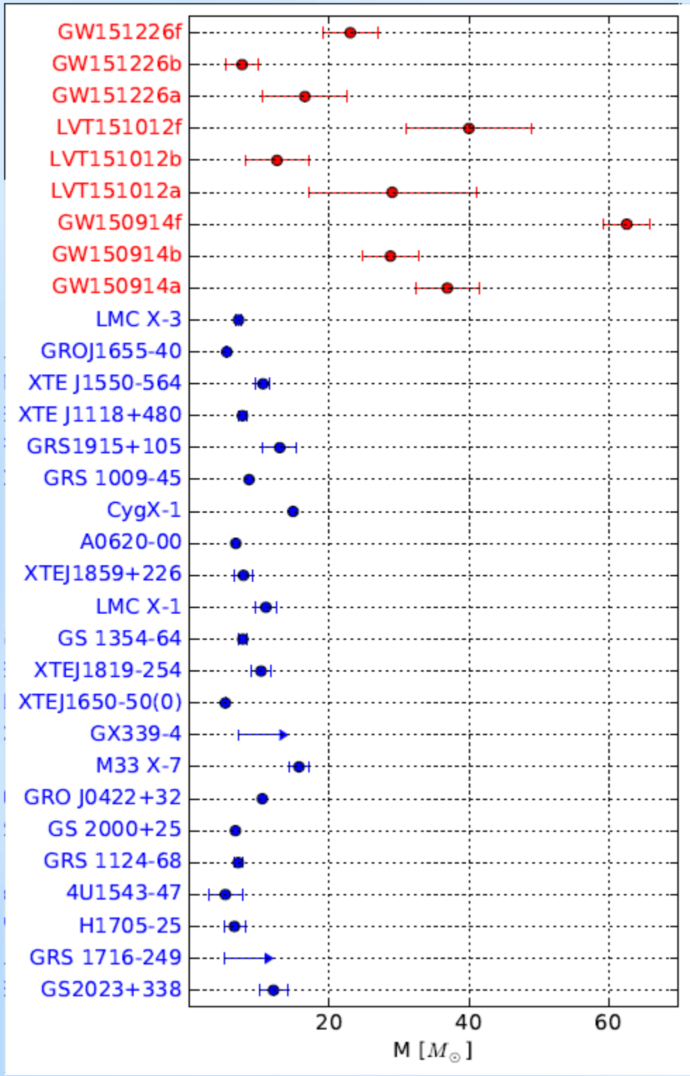


Image Credit LIGO

GW170814 – 3 Detector Observation

GW170814 : A three-detector observation of gravitational waves from a binary black hole coalescence

The LIGO Scientific Collaboration and The Virgo Collaboration

On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of $\lesssim 1$ in 27000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are $30.5^{+5.7}_{-3.0}\,M_\odot$ and $25.3^{+2.8}_{-4.2}\,M_\odot$ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$. A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg^2 using only the two LIGO detectors to 60 deg^2 using all three detectors. For the first time, we can test the nature of gravitational wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

Virgo has arrived!

A real world-wide network of gravitational wave detectors.

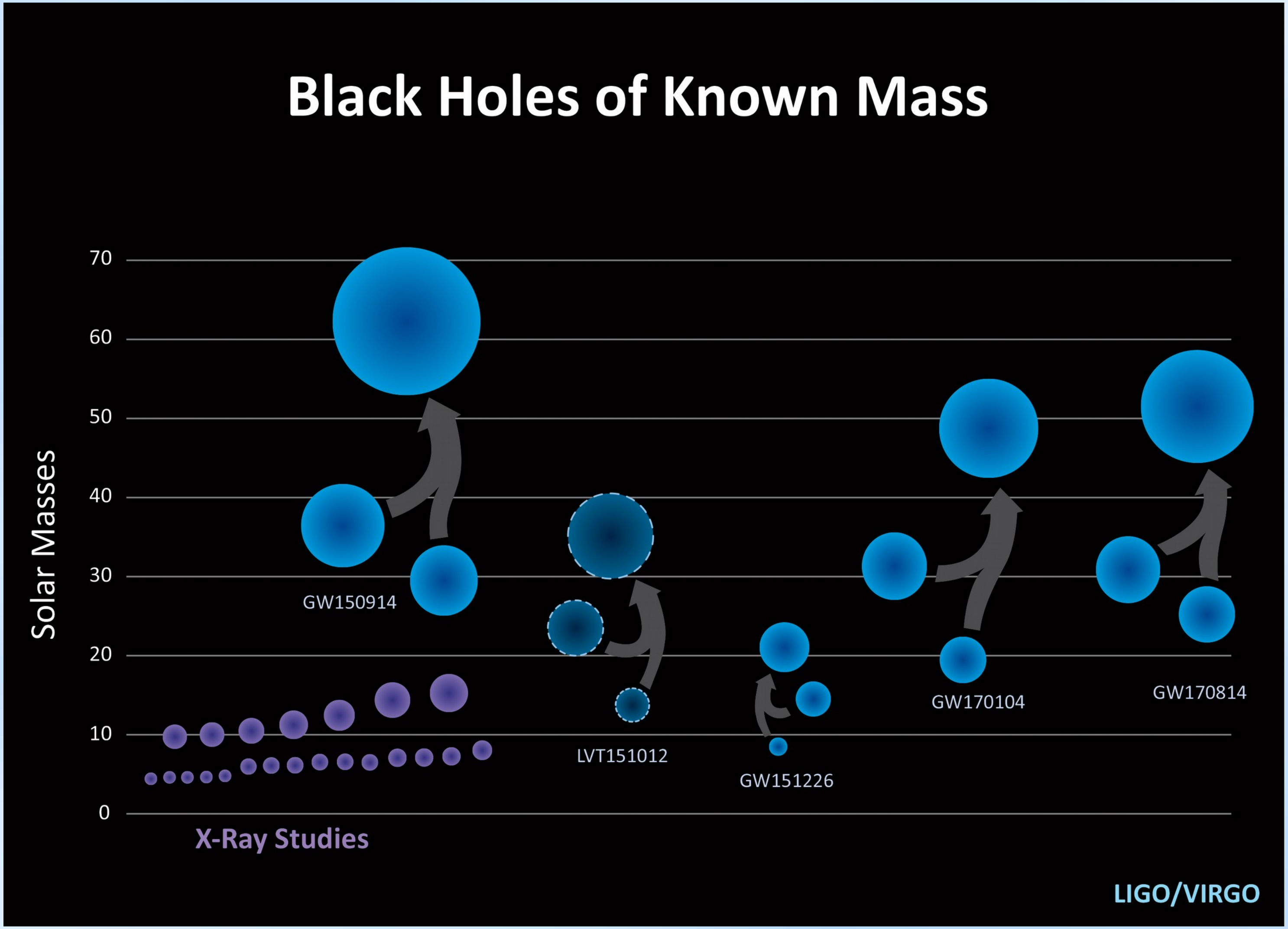
arXiv:1709.09660 and accepted PRL

GW170814 – 3 Detector Observation

TABLE I: Source parameters for GW170814: median values with 90% credible intervals. We quote source-frame masses; to convert to the detector frame, multiply by $(1+z)$ [120, 121]. The redshift assumes a flat cosmology with Hubble parameter $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and matter density parameter $\Omega_\mathrm{m} = 0.3065$ [122].

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

GW170814 – 3 Detector Observation



Population of Black Holes

LIGO/Caltech/Sonoma State (Aurore Simonnet)]

GW170814 – 3 Detector Observation

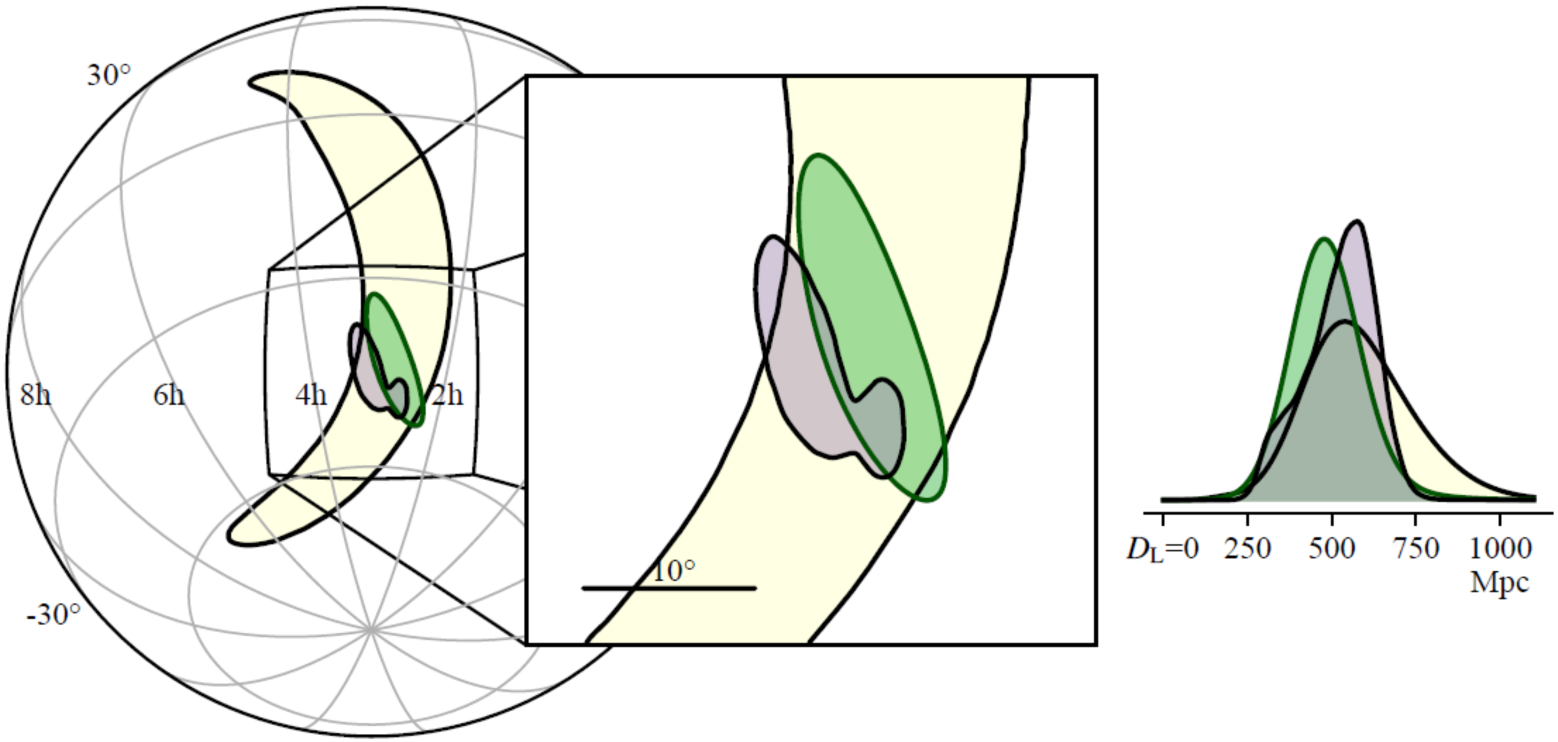
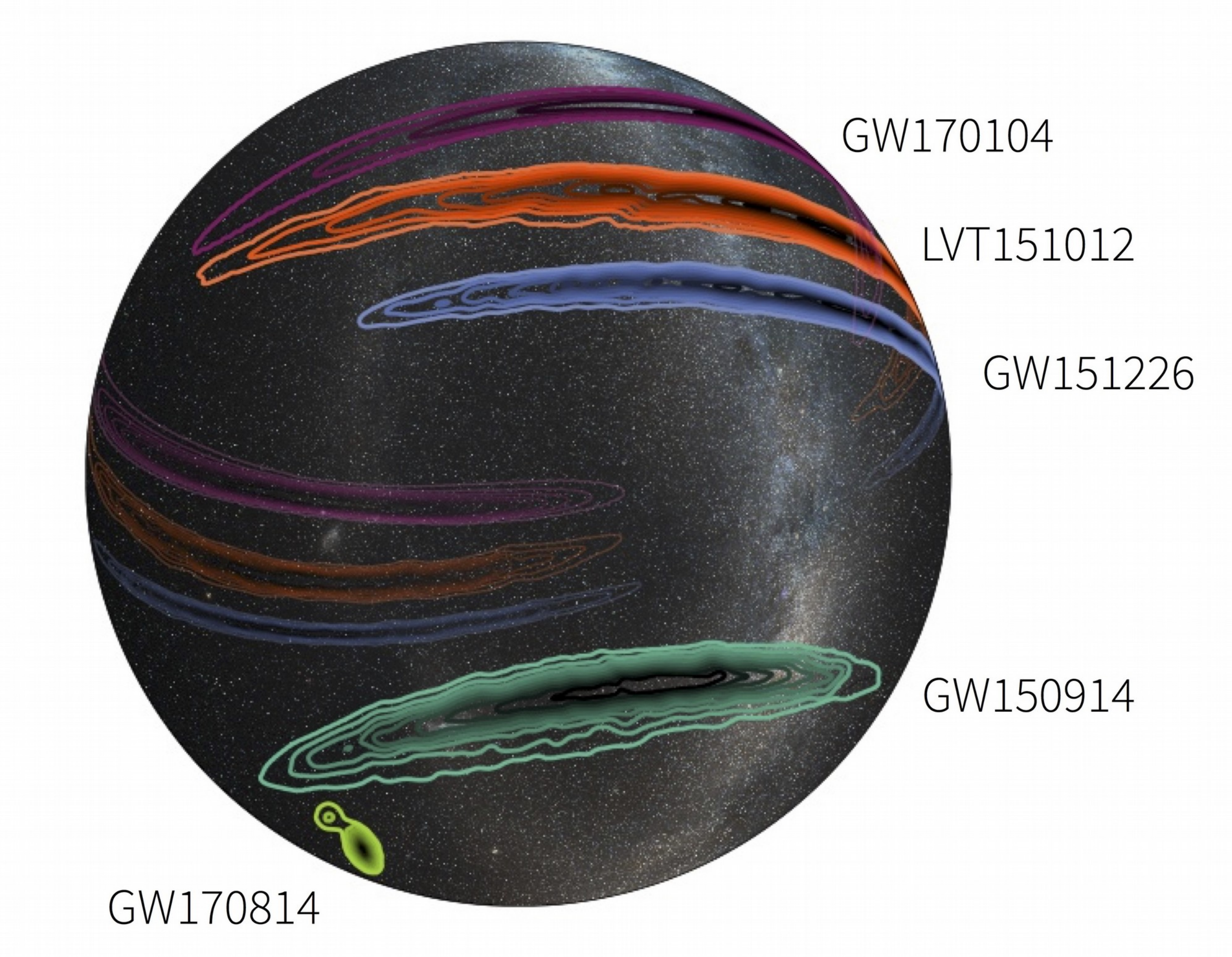


FIG. 3: Localization of GW170814. The rapid localization using data from the two LIGO sites is shown in yellow, with the inclusion of data from Virgo shown in green. The full Bayesian localization is shown in purple. The contours represent the 90% credible regions. The left panel is an orthographic projection and the inset in the center is a gnomonic projection; both are in equatorial coordinates. The inset on the right shows the posterior probability distribution for the luminosity distance, marginalized over the whole sky.

1160 sq. deg 2 LIGOs only → 60 sq. deg for 2 LIGOs + Virgo

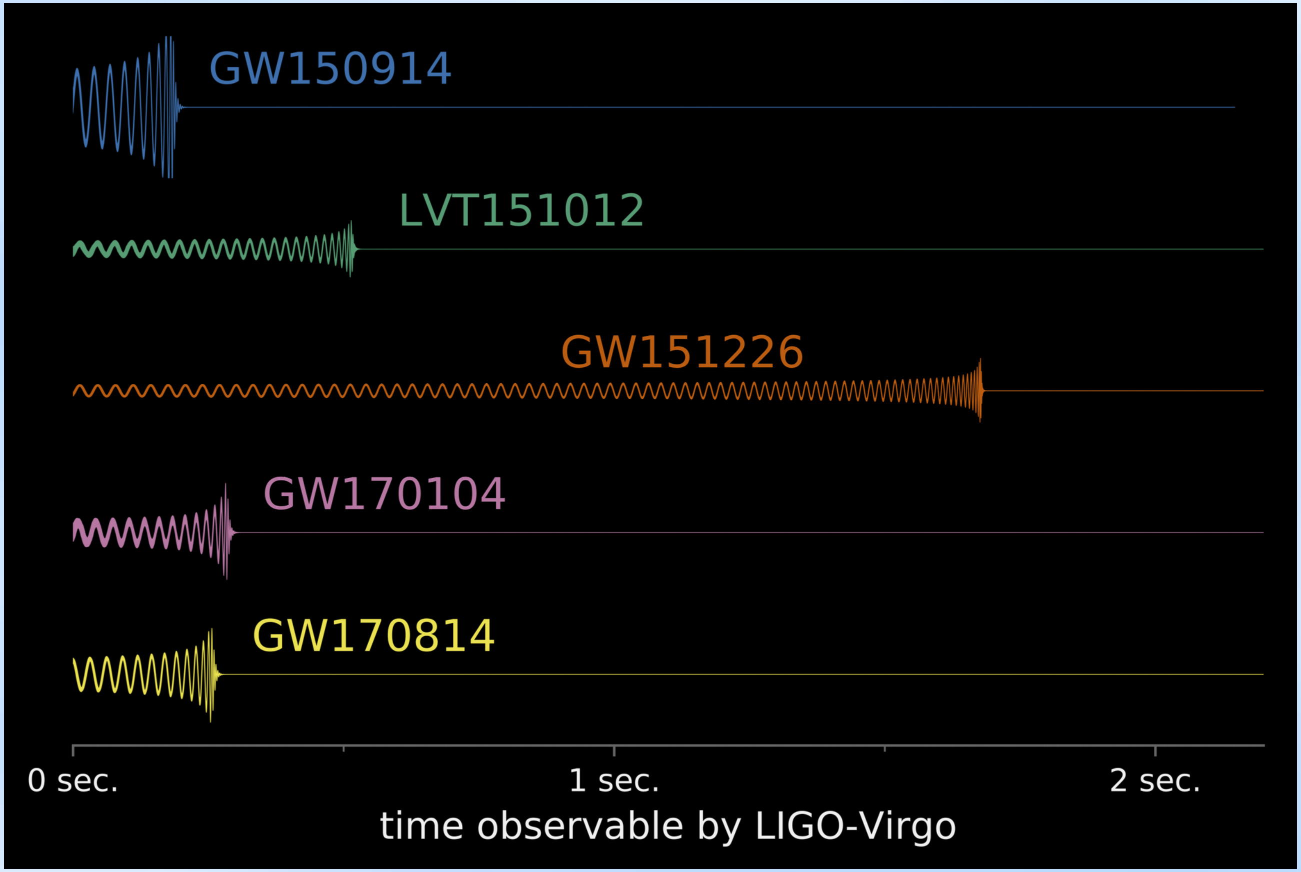
Sky Position Estimation Comparison



LIGO/Virgo/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger

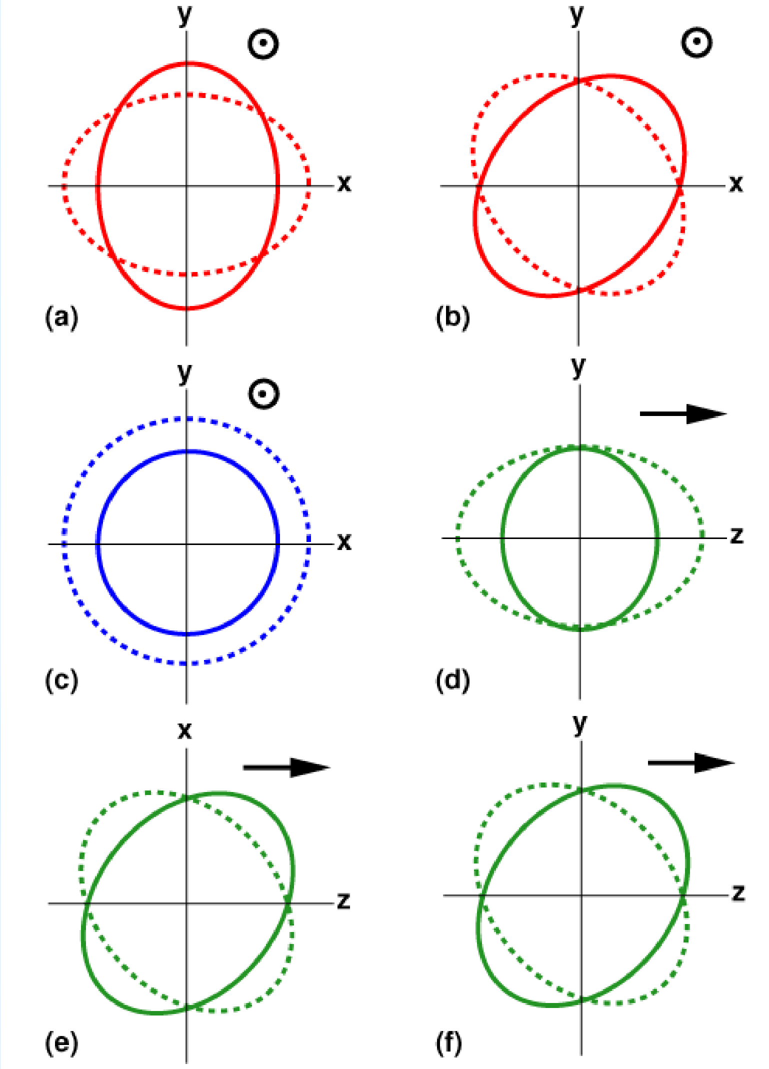
Skymap of the LIGO/Virgo black hole mergers. This three-dimensional projection of the Milky Way galaxy onto a transparent globe shows the probable locations of the black hole mergers.

Observed Gravitational Wave Signals



LIGO/Virgo/B. Farr (University of Oregon)]

Testing General Relativity With GW170814



We now have a network of detectors with different orientations (2 LIGO are almost co-aligned, Virgo is not).

Allows the study of polarization of the gravitational waves.

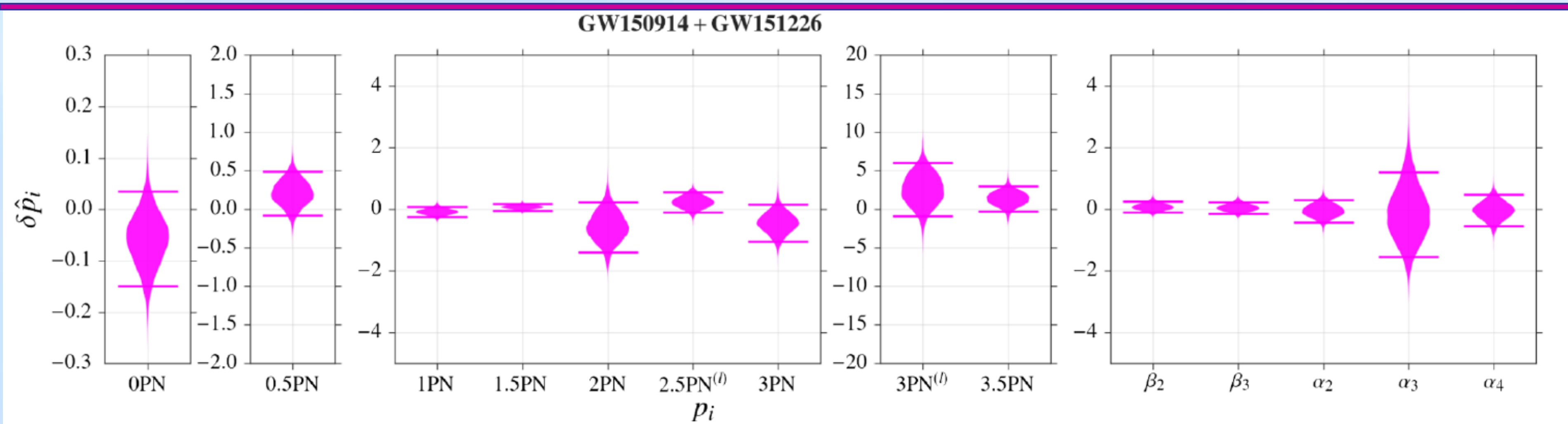
Results favor purely tensor polarization against purely vector and purely scalar.

Tests of GR performed similar to those carried out for the previous confirmed detections — similar results, consistent with the predictions of Einstein's theory.

Post-Newtonian tests, signal consistency, ...

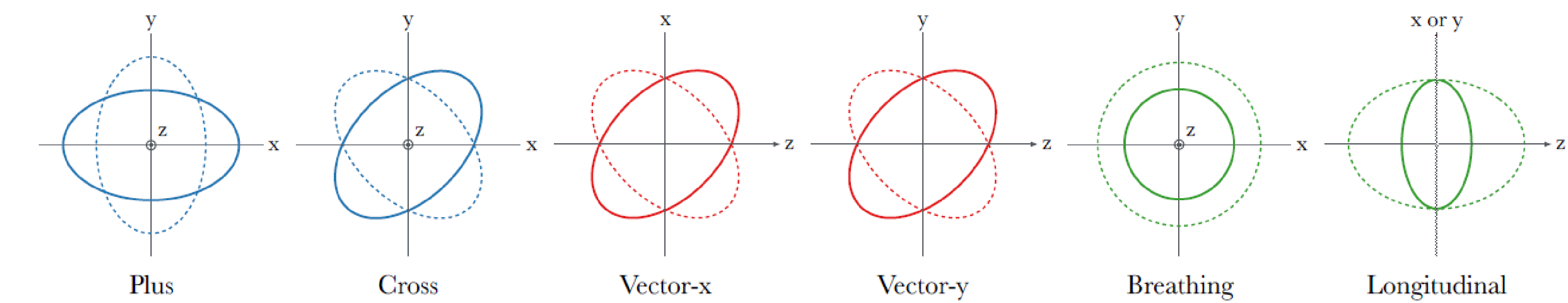
Clifford Will, Living Reviews in Relativity)

Testing General Relativity



PHYS. REV. X 6, 041015 (2016)

Posterior density distributions for relative deviations in the PN, intermediate, and merger-ringdown parameters.



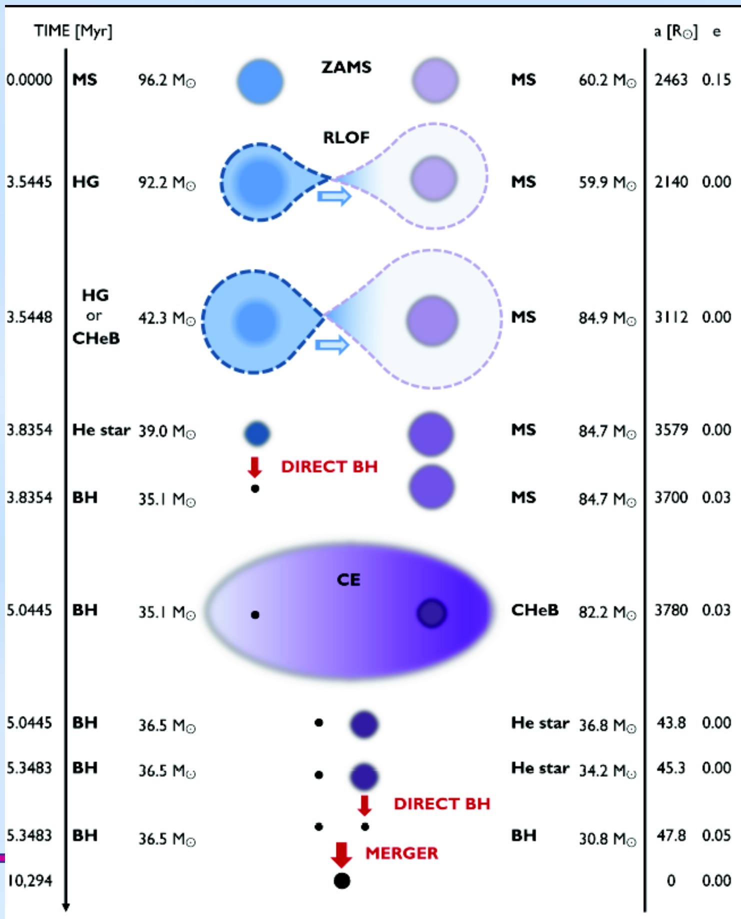
arXiv:1704.08373

arXiv:1709.09203

Modified Gravity Theories : Searches including extra polarizations (Stochastic and CW)

Astrophysics: Binary Black Hole Formation

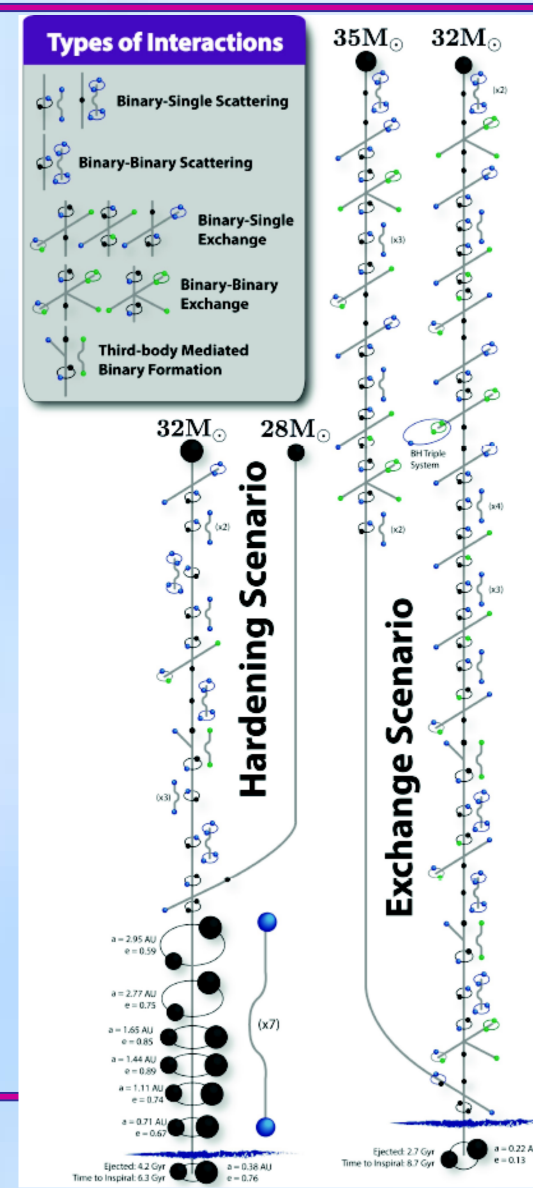
- Isolated Binaries
  - Solar to Population III
  - Rapid rotation



Belczynski et al. 2016

- Dense Clusters
  - Globular clusters
  - Young clusters
  - Galactic centers

Low metallicity environment needed for large stellar mass black hole formation

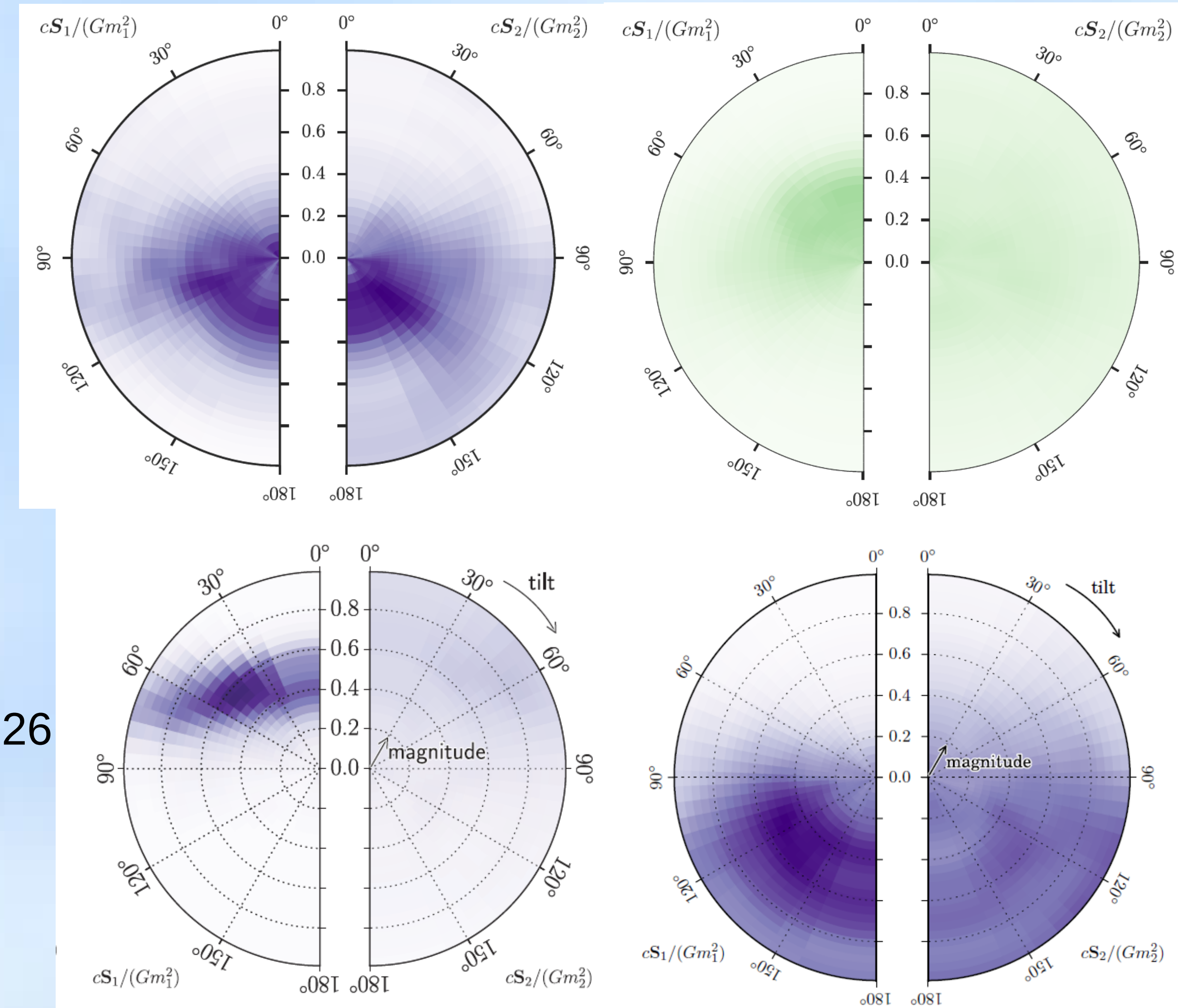


Arxiv 1602:02444, 1604:04254

Spin Observations Are Becoming Interesting

GW150914

LVT151012



GW151226

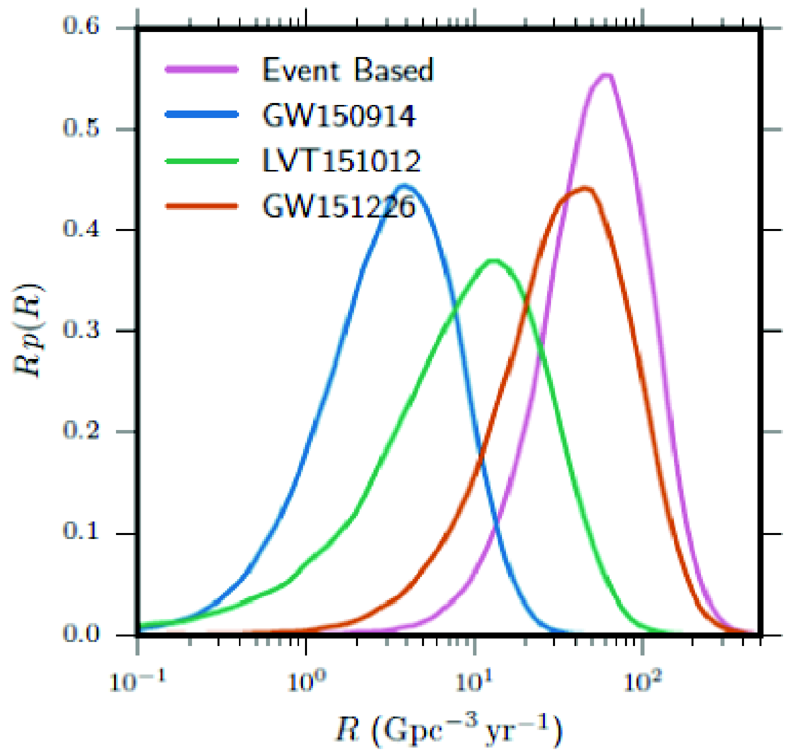
GW170114

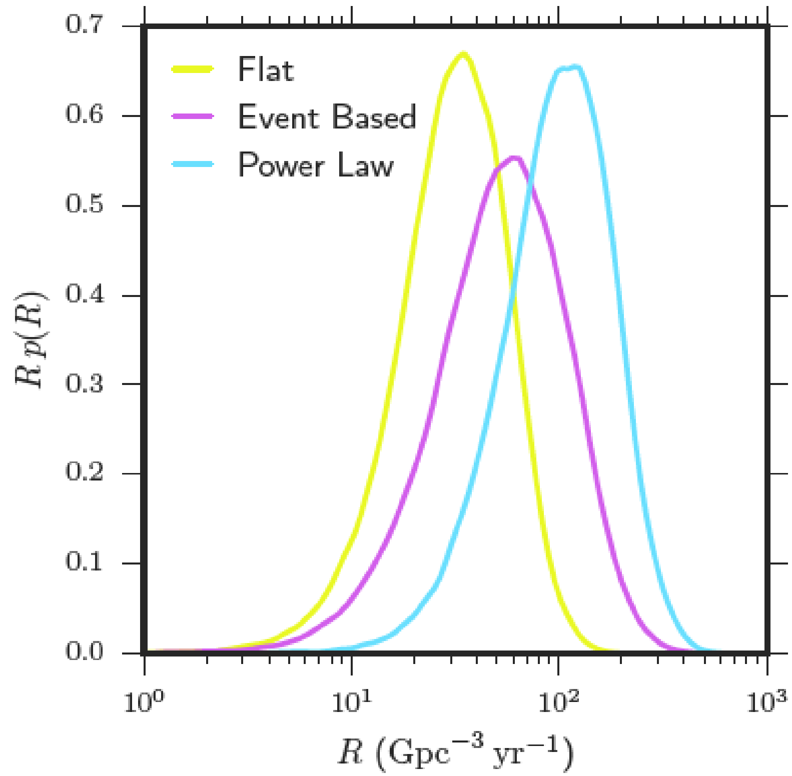
No significant spin for GW170814

Isolated Binary Formation?

Cluster Formation?

Binary Black Hole Merger Rate – O1 results

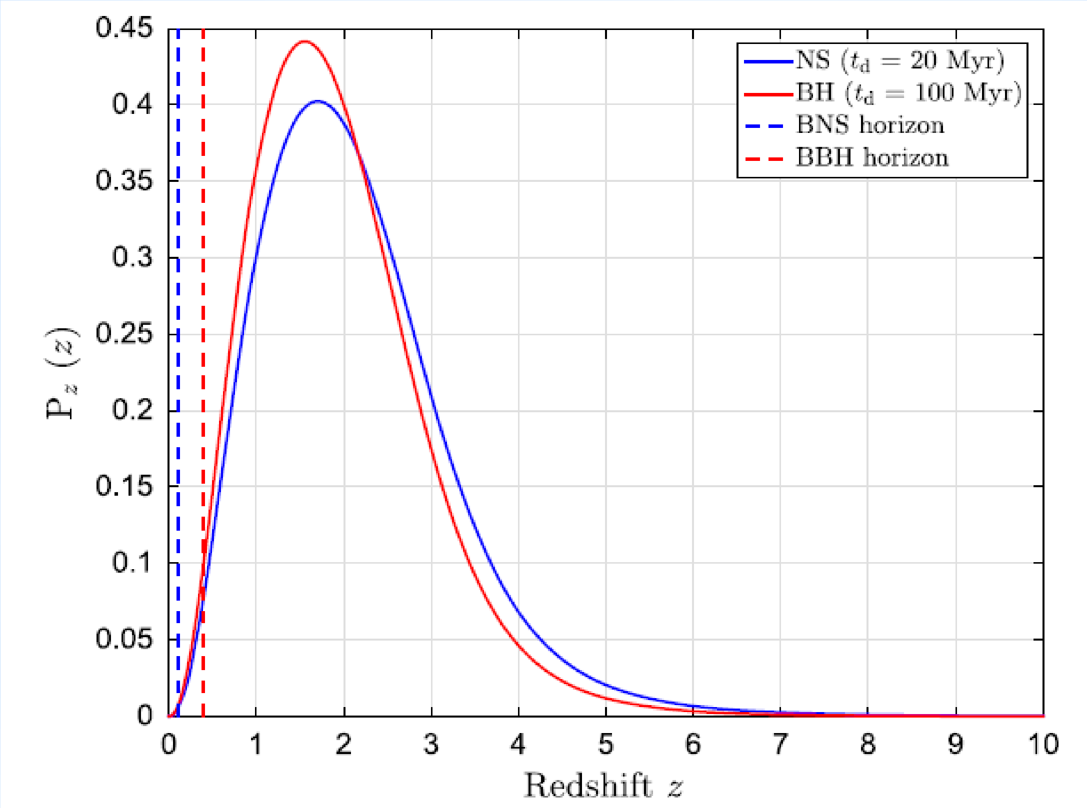




90% allowed range: [9-240] /Gpc^3/yr

Implications for a Stochastic Background of GWs

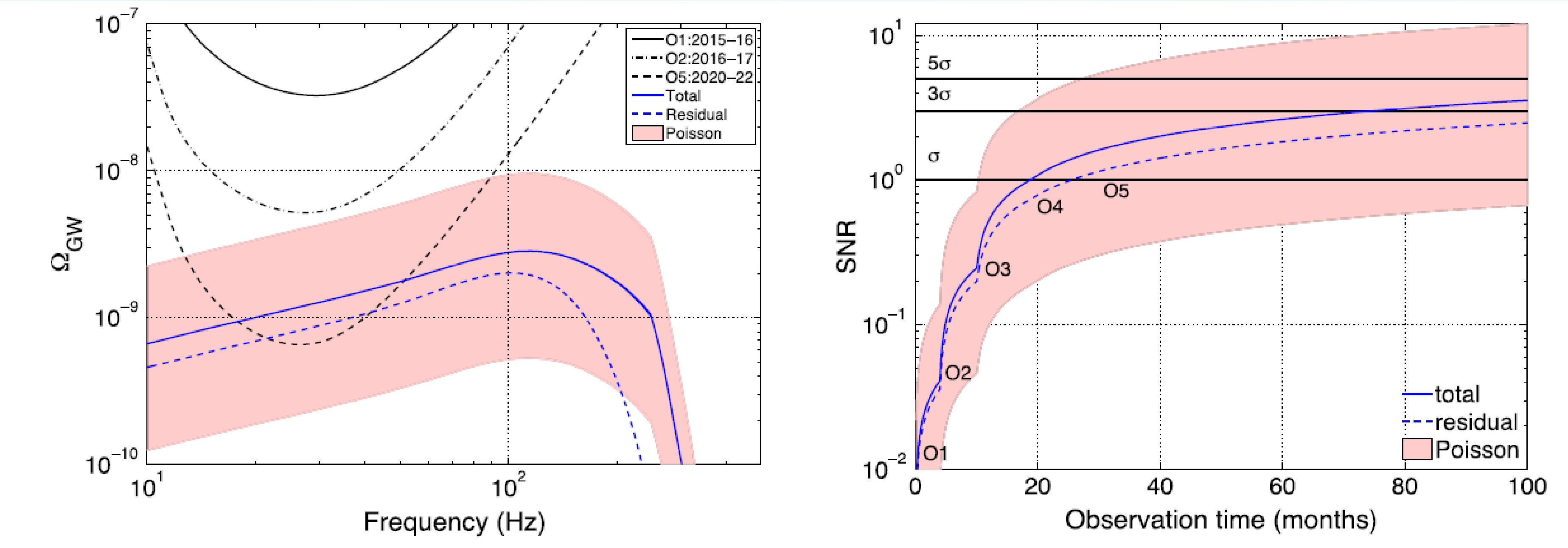
Probing compact binary decays predominantly between z ~ 1 – 3.



Source redshift probability distribution for binary neutron stars and (blue) and binary black holes (red).

Physical Review D, Vol. 92, p. 063002 (2015)

Implications for a Stochastic Background of GWs

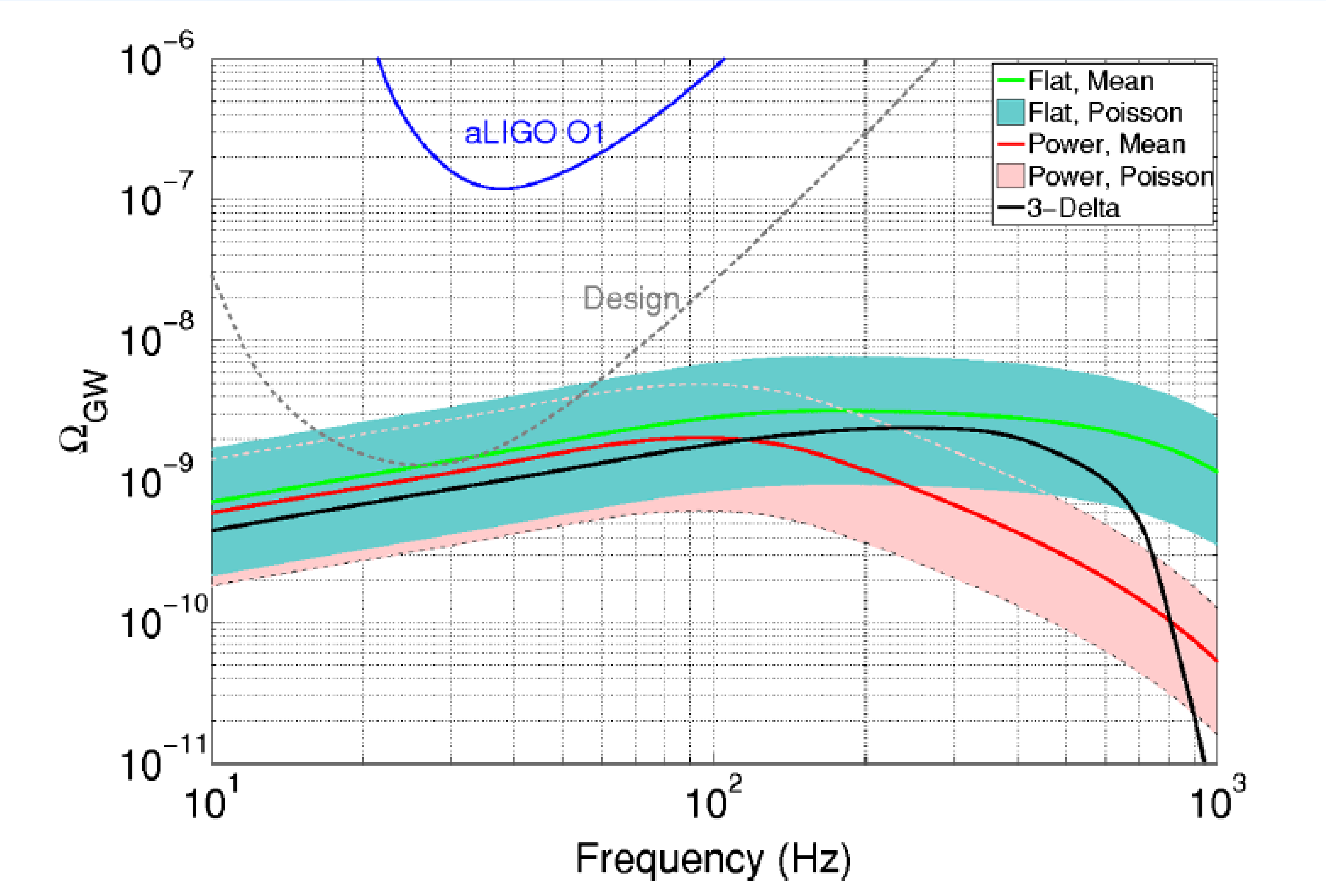


Based on the Field formation mechanism, assuming GW150914 parameters.

Assumptions are necessary; best information available in literature.

Abbott et all (LIGO-Virgo) Physical Review Letters **116**, 131102 (2016)

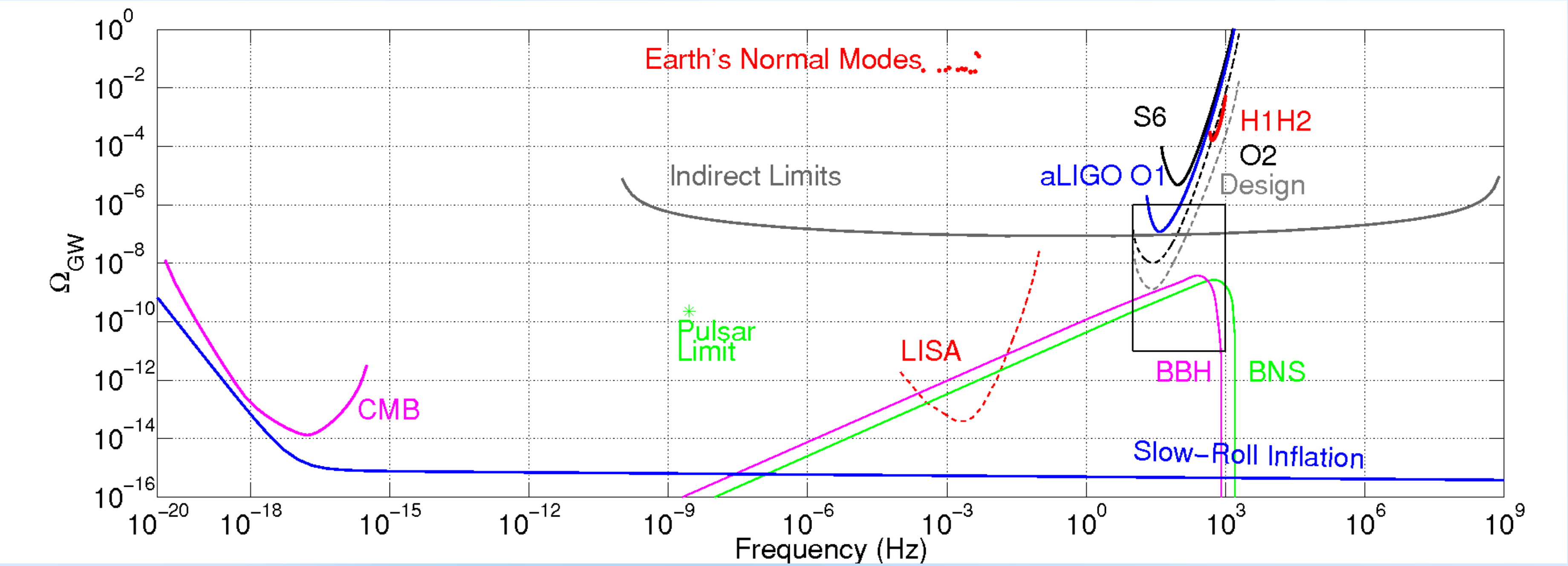
Implications for a Stochastic Background of GWs



Predictions after O1.

PRL **118,** 121101 (2017)

O1 isotropic stochastic search



Phys. Rev. Lett. 118, 121101 (2017)

Indirect limits: PhysRevX.6.011035
"CMB temperature and polarization power spectra, lensing, BAOs and BBN"

$$\Omega_{gw}(25\text{Hz}) < 1.7 \times 10^{-7}$$

Continuous Wave (pulsar) Searches

- All-sky search for periodic gravitational waves in the O1 LIGO data (PRD **96**, 062002 (2017)). $h_0 \sim 2.5 \times 10^{-25}$
- Gravitational waves from low mass X-ray binary Scorpius X-1 (PRD **95**, 122003 (2017)). $h_0 \sim 3 – 8 \times 10^{-25}$
- Gravitational Waves from Known Pulsars (ApJ **839**, 12 (2017)). 200 pulsars.
- First search for nontensorial gravitational waves from known pulsars (arXiv:1709.09203). Upper limits for scalar and vector strains and constraints on specific alternative theories of gravity.

Other Searches In Progress

- Un-modeled burst searches
  - Merging intermediate mass black hole binaries, 50 to 600 Mo total mass (PRD **96**, 022001 (2017))
  - Supernovae
  - Short duration transients, ms to 10 s (PRD **95**, 042003 (2017))
  - Long duration (10s, 100s, 1000s, …) transients
- Cosmic string signals: burst and stochastic background
- Signals in association with gamma ray bursts (ApJ **841**, 89 (2017)) and high energy neutrinos (PRD **96**, 022005 (2017))
- Anisotropic stochastic background (PRL **118**, 121102 (2017))
- Stochastic background search with non-GR polarizations (arXiv:1704.08373)
- Numerous CW (pulsar) searches: all-sky, targeted (Sco X-1), binaries

Future Observing Runs

Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1
LIVING REVIEWS in relativity

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
email: lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it

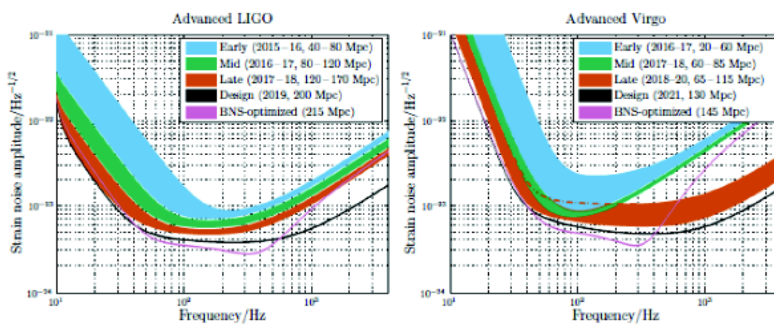


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

2015 – 2016 (O1) A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

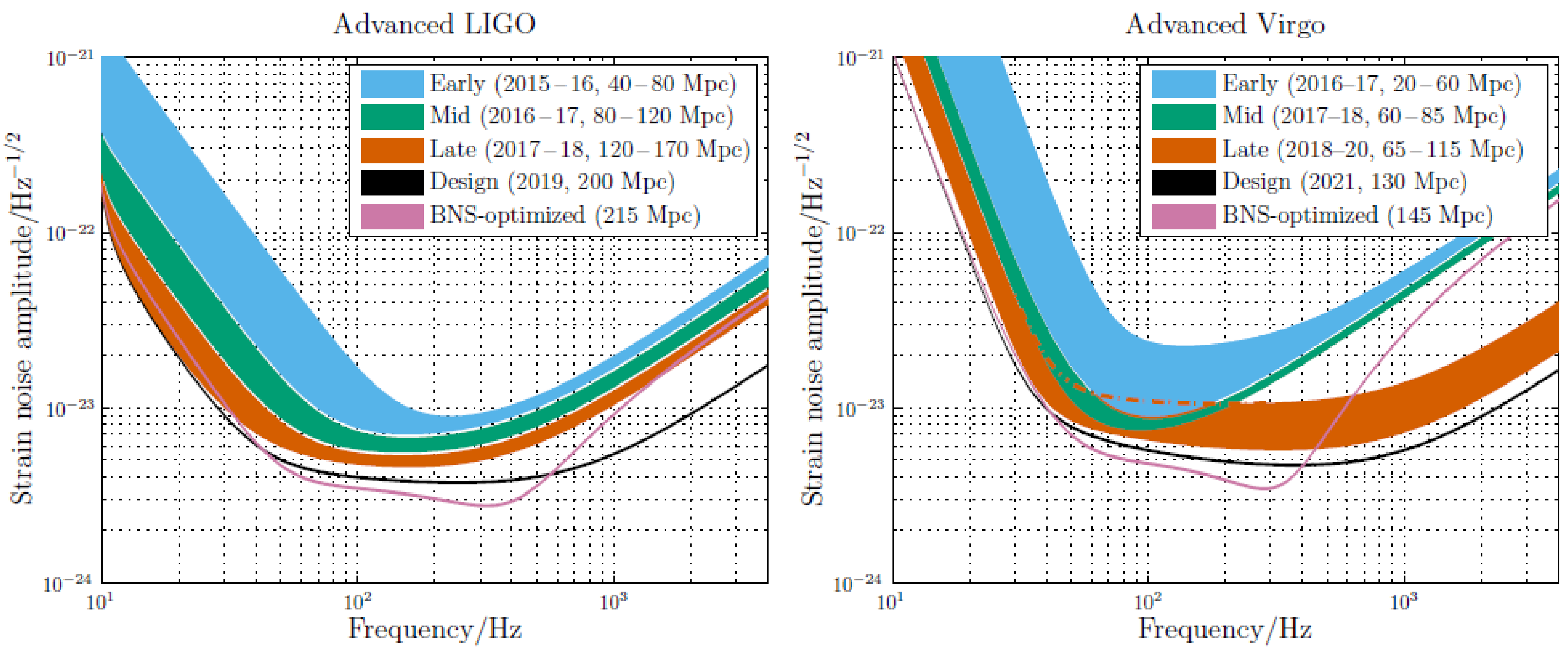
2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

2017 – 2018 (O3) A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

2019+ Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.

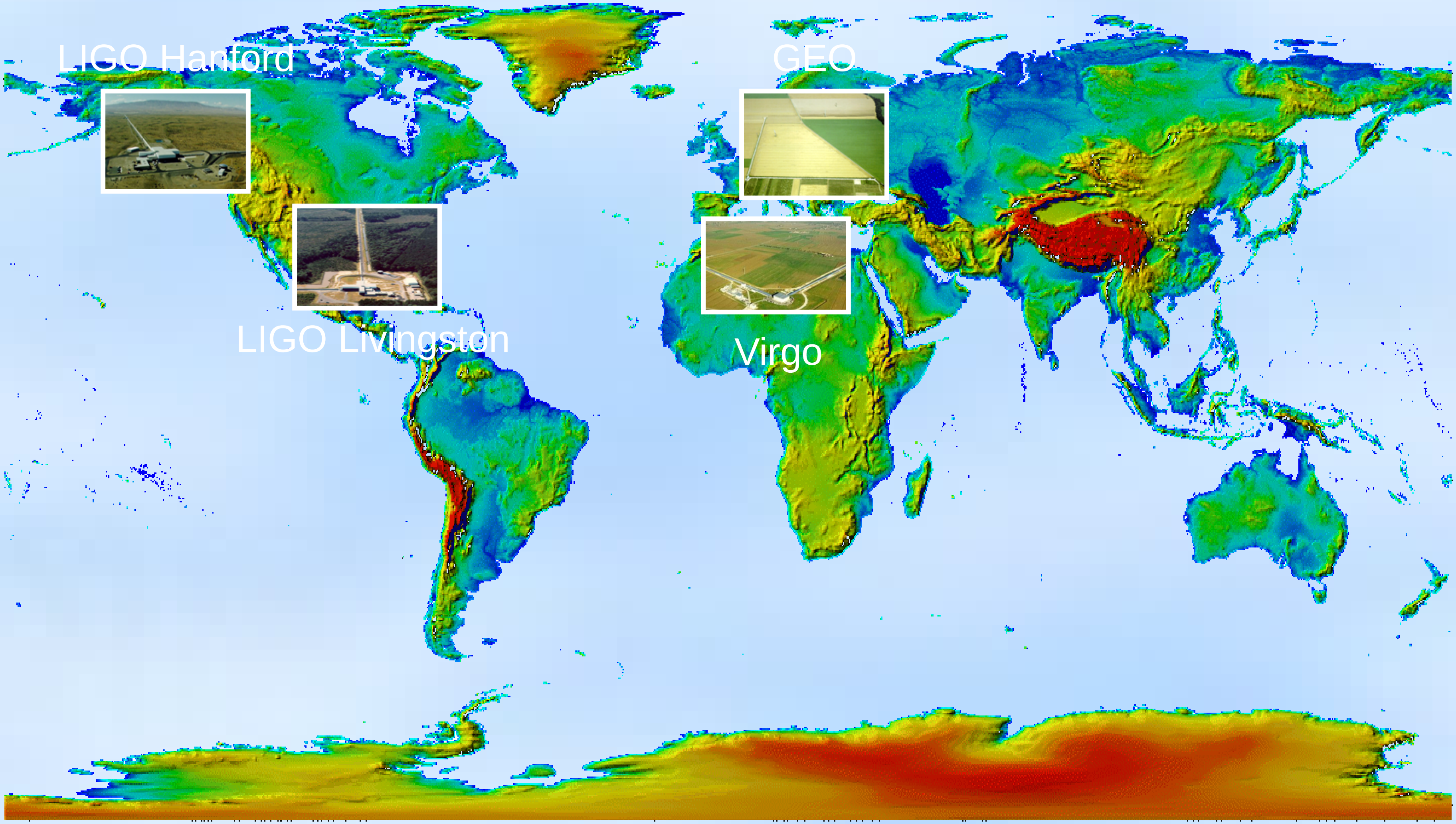
O2 30-11-2016. to 25-8-2017. O3 in fall of 2018, if all goes well.

Expected Advanced LIGO-Virgo Sensitivities

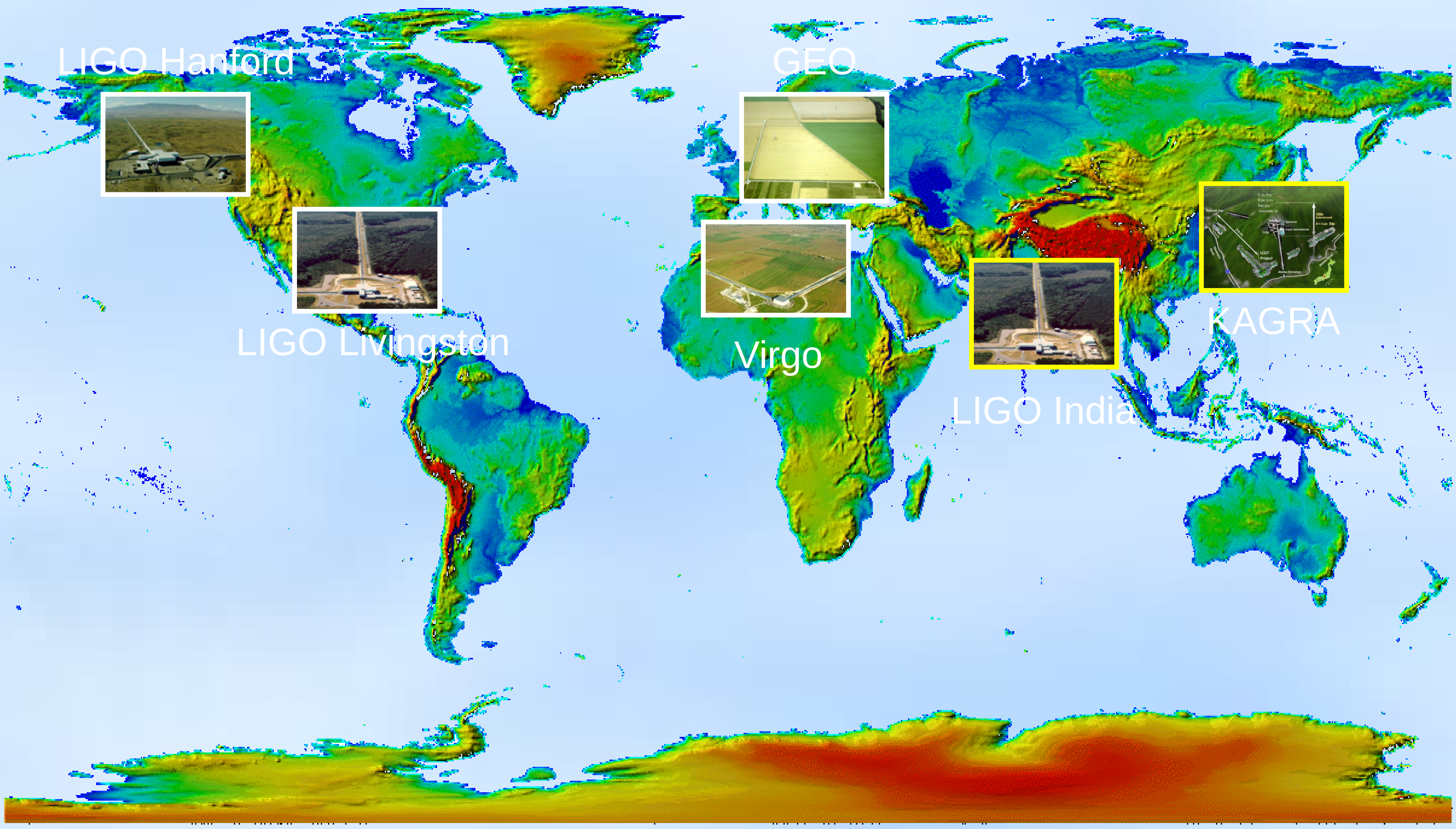


Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

A detector network



An even better detector network



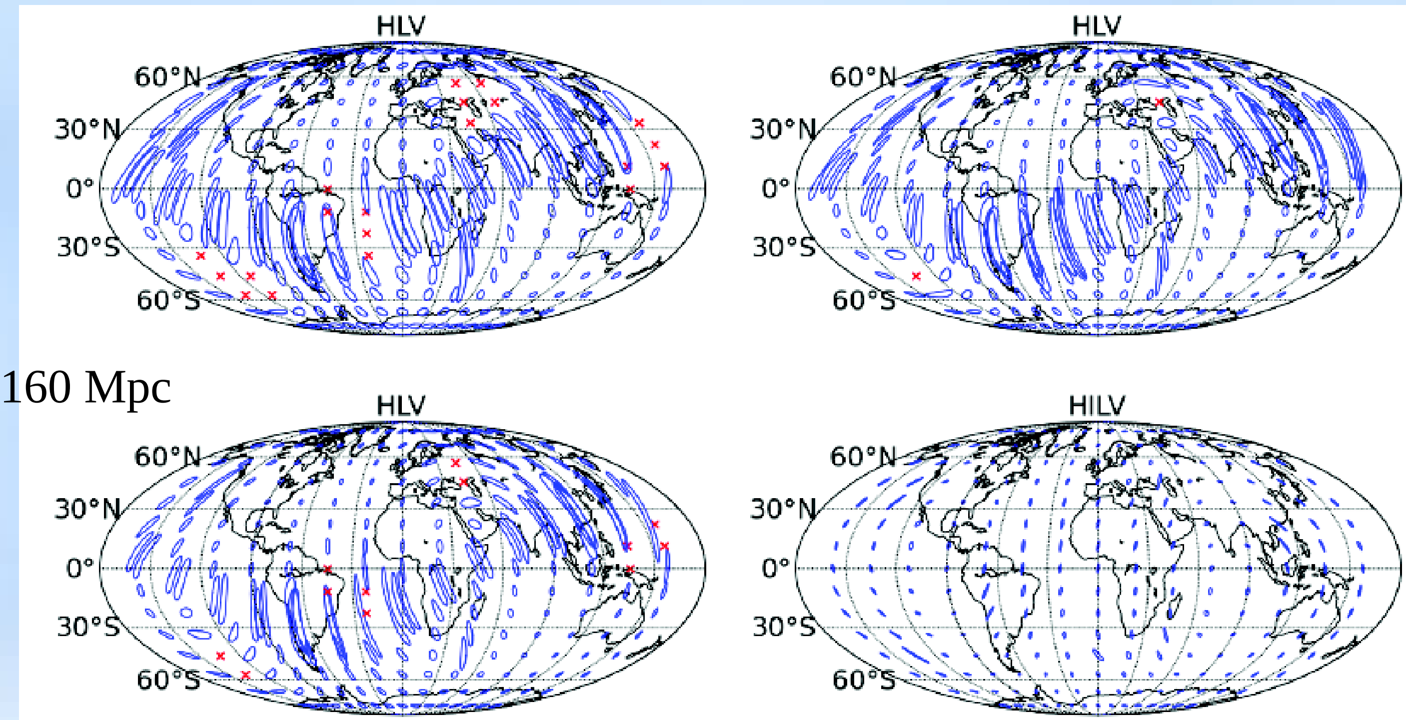
Advanced LIGO/Virgo sky localization

BNS source @ 80 Mpc

2016-2017 runs

2018-2019 runs

BNS source @ 160 Mpc



2019+ runs

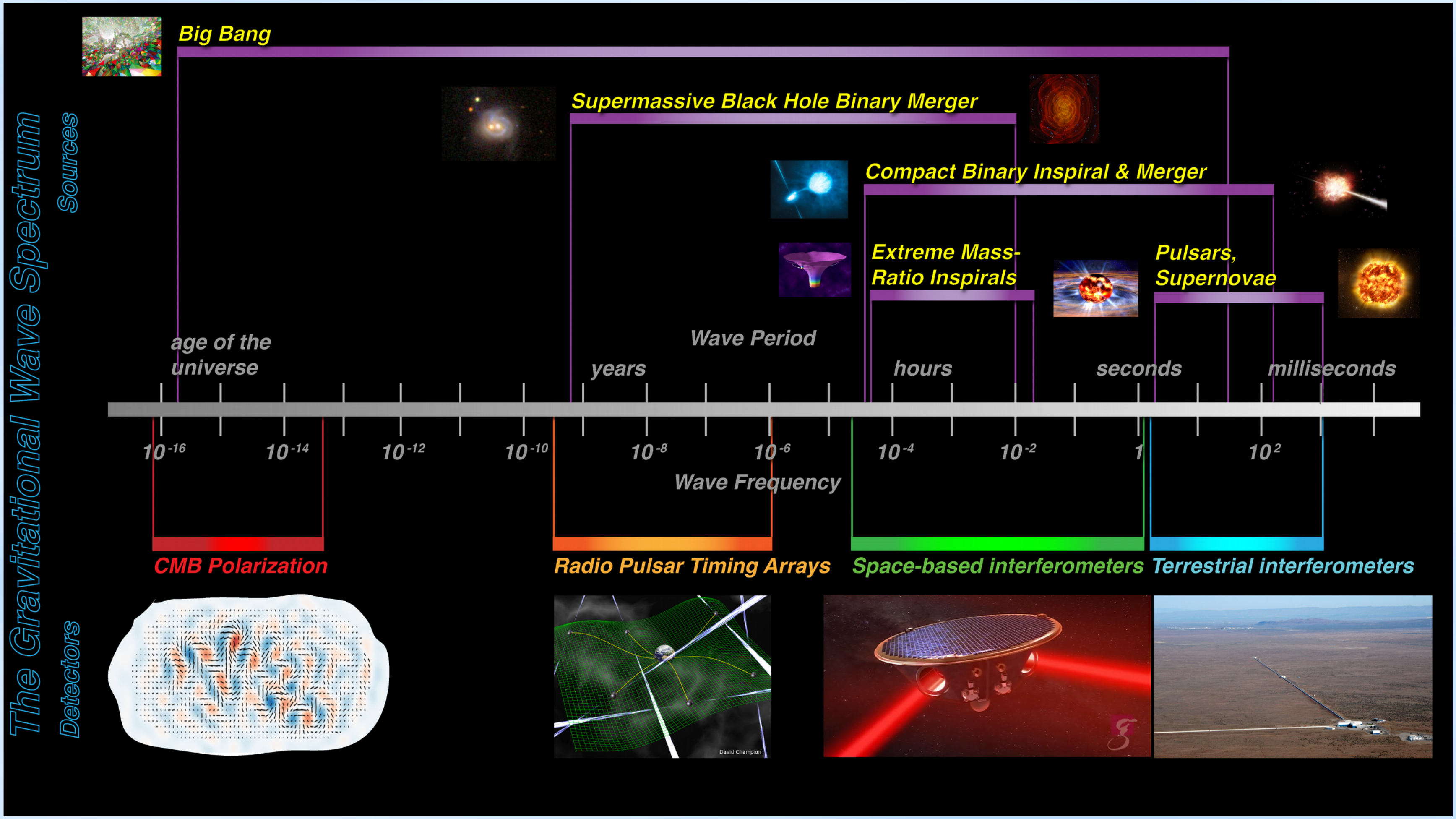
HLV + LIGO India 2024+

Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

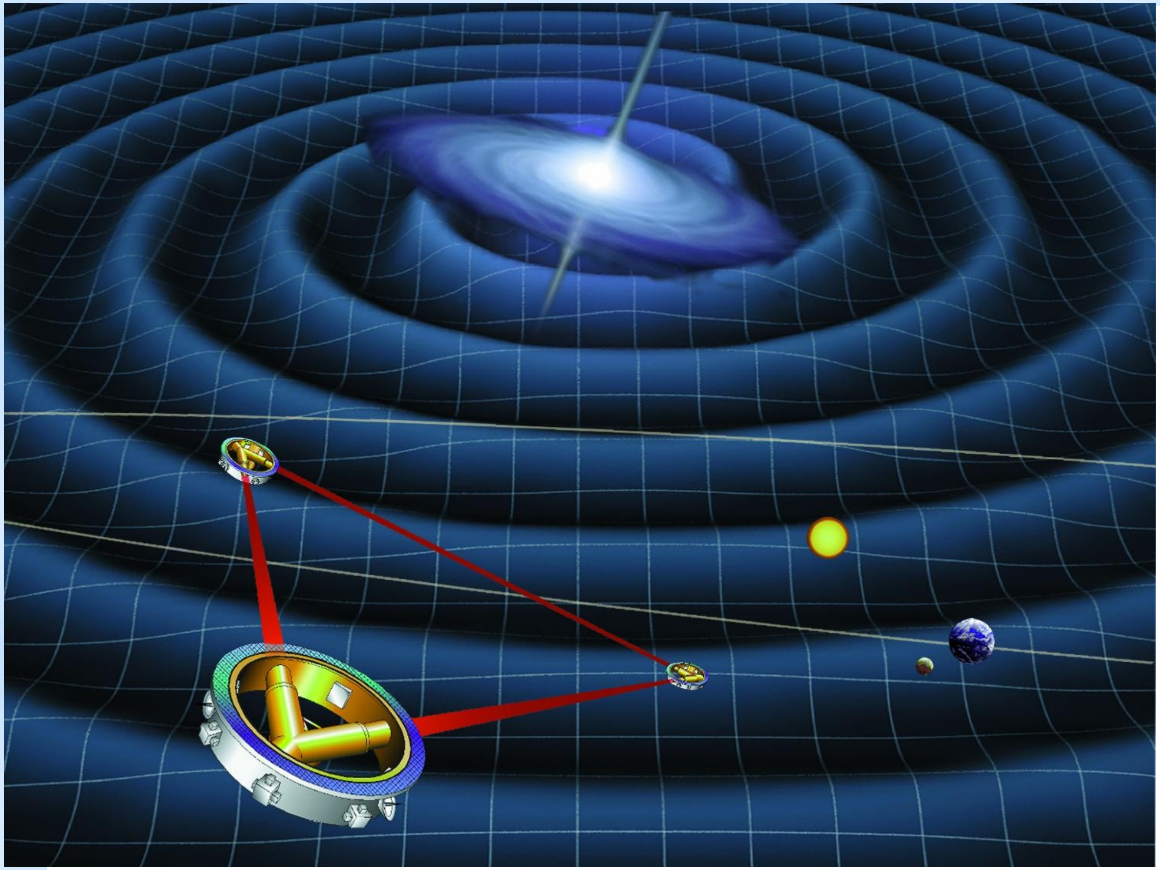
LIGO – Virgo Summary

- Gravitational waves have been observed
- The universe has more stellar mass black holes than expected
- A stochastic background of gravitational waves from throughout the history of the universe could be observed in a few years
- Intensive effort to find burst, compact binary coalescence, continuous wave, and stochastic signals.
- Looking for signals in coincidence with electromagnetic and neutrino signals.
- Observing run O2 is just completed. Virgo joined and made a detection!
- KAGRA and LIGO-India will join in the coming years
- The future looks bright for ground based detectors

Gravitational Wave Spectrum



Laser Interferometer Space Antenna - LISA



Present plan: 3 Interferometers
2.5 x 10^6 km arm lengths

ESA – All Systems GO!

Recent “Call” for mission

Acceptance - soon?

Planned launch 2034

NASA coming back

Earlier launch? 2028?

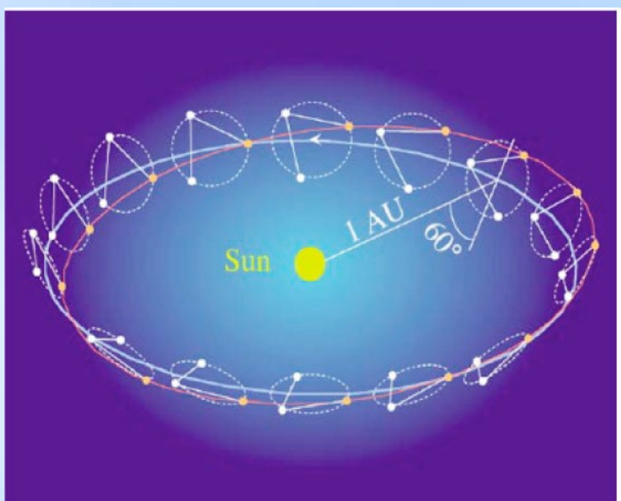
LIGO GW events and Lisa Pathfinder success have helped significantly

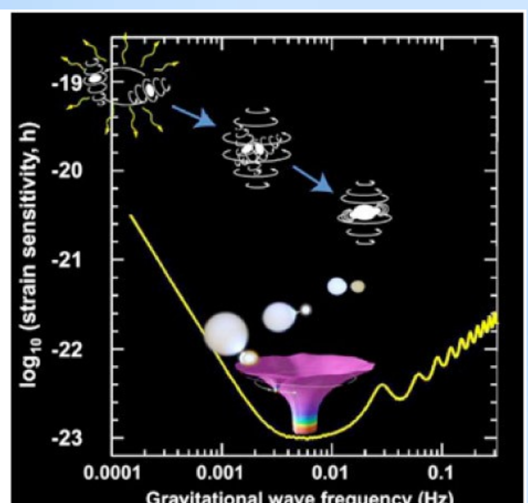
Tremendous activity at present

LISA physics

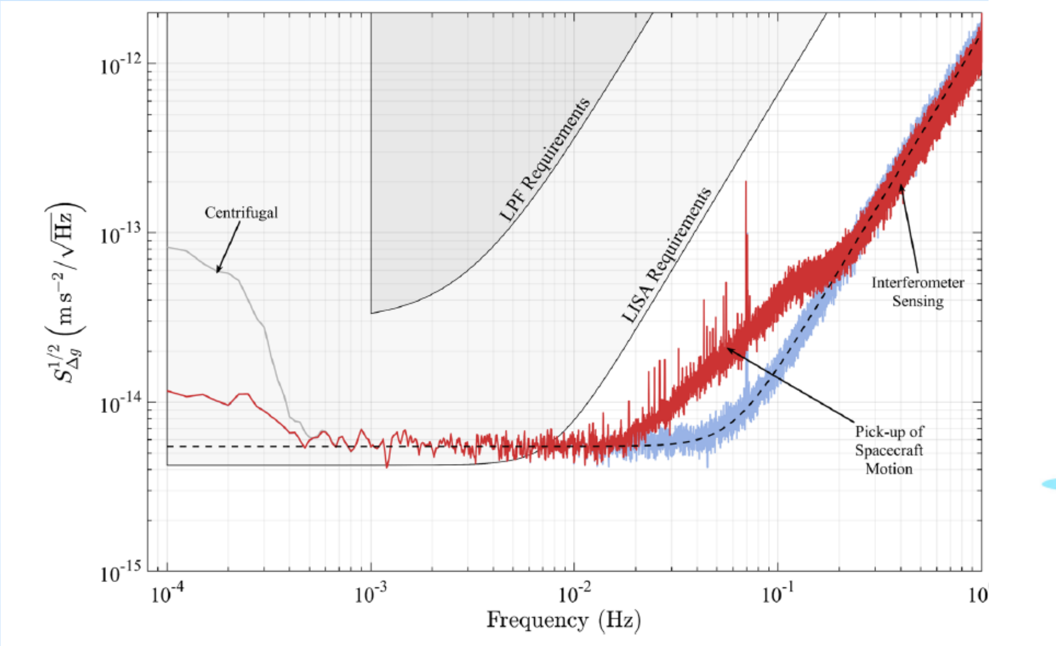
- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

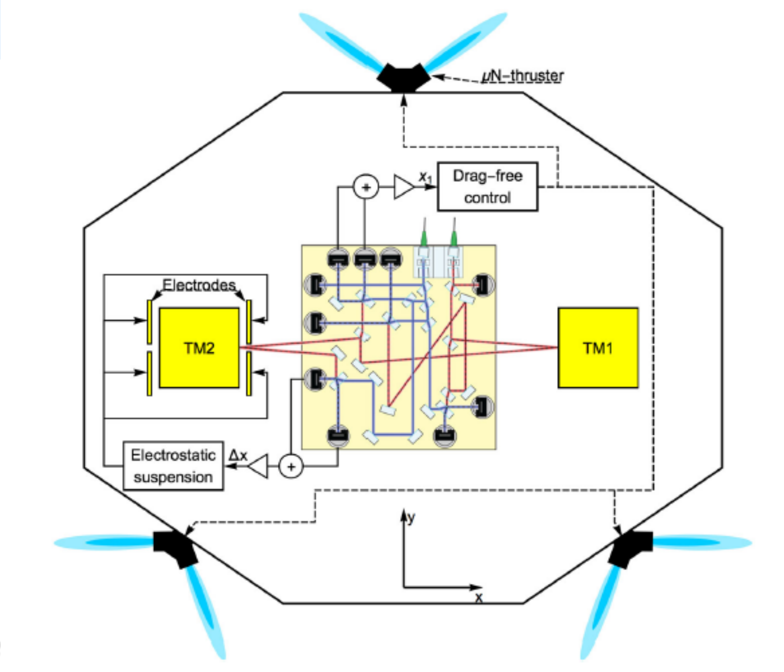
Gravitational Observatory Advisory Team – GOAT (ESA web site)





LISA Pathfinder – Demonstrating LISA Technology



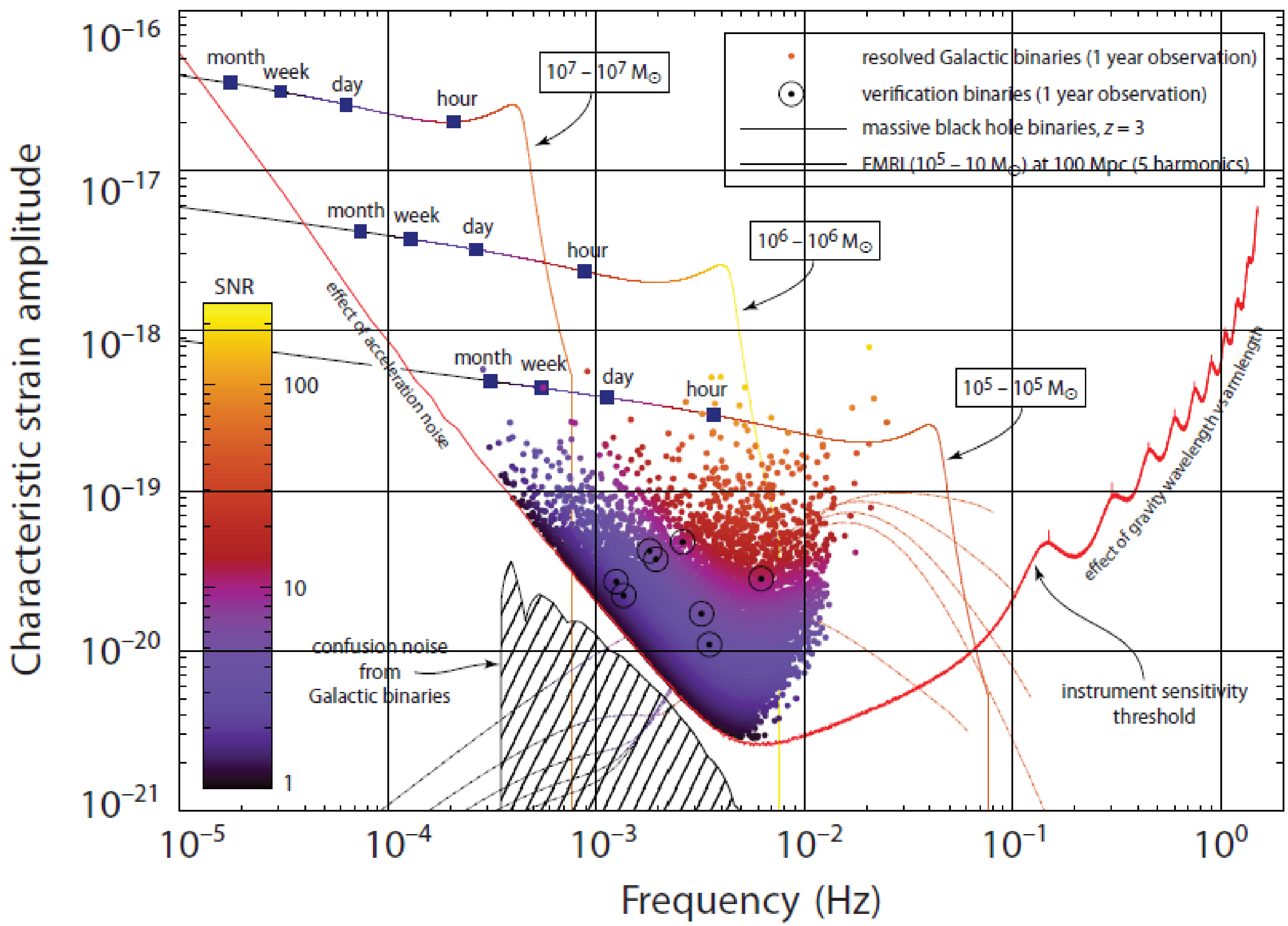


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

A set of cold gas micro-newton thrusters to ensure the spacecraft follows TM1. A second control loop forces TM2 to stay at a fixed distance from TM1 and thus centered in its own electrode housing.

PRL **116**, 231101 (2016)

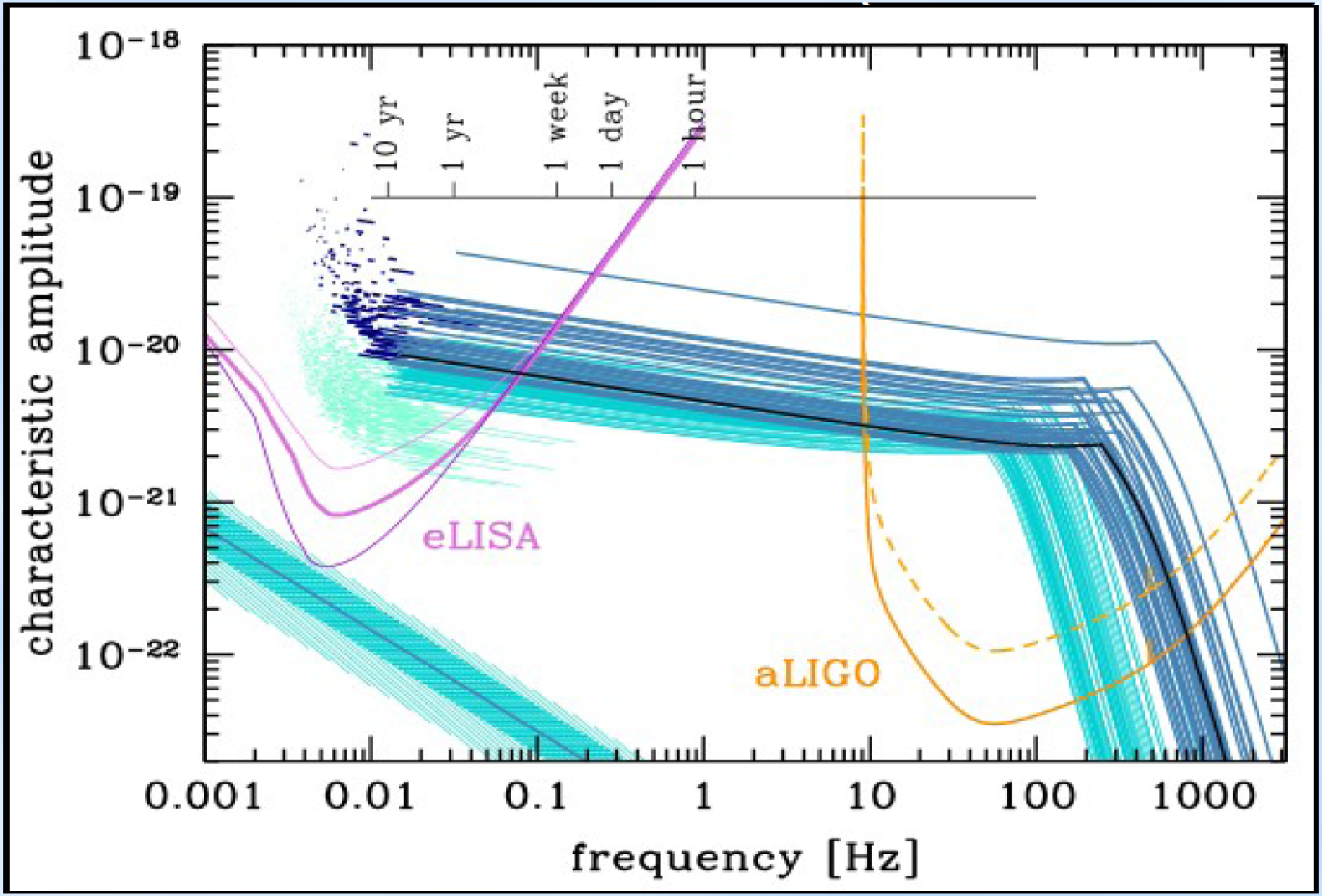
LISA Physics



LISA GOAT

Characteristic strain amplitude versus frequency for a space-based laser interferometry mission (armlength 10^6 km, 1-yr observations). Objects expected to be strong gravitational wave sources over this frequency range.

LISA Physics



Gravitational wave signals from a heavy stellar black hole binaries. BBH systems can be observed by both LISA and Advanced LIGO – Advanced Virgo.

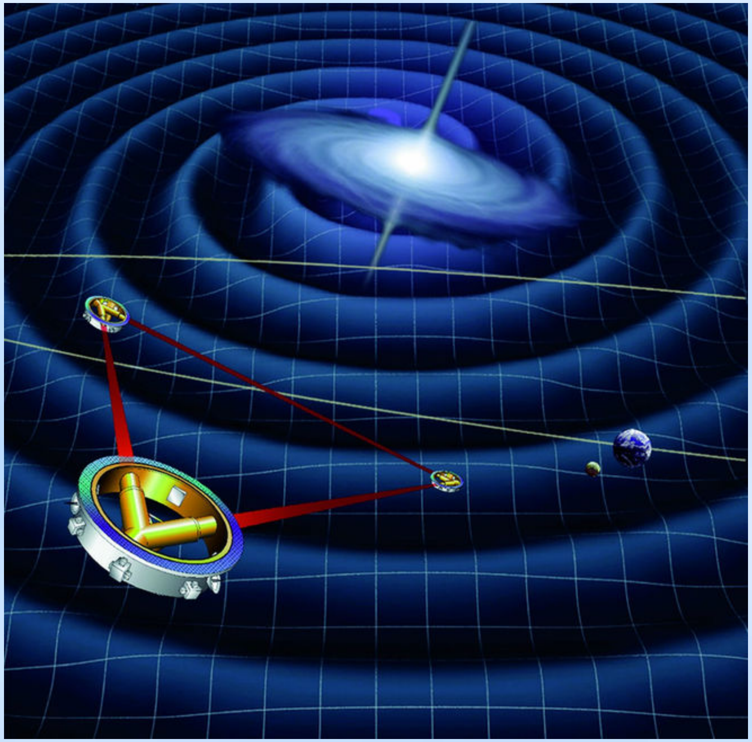
LISA Summary

The LISA project is presently moving forward rapidly.

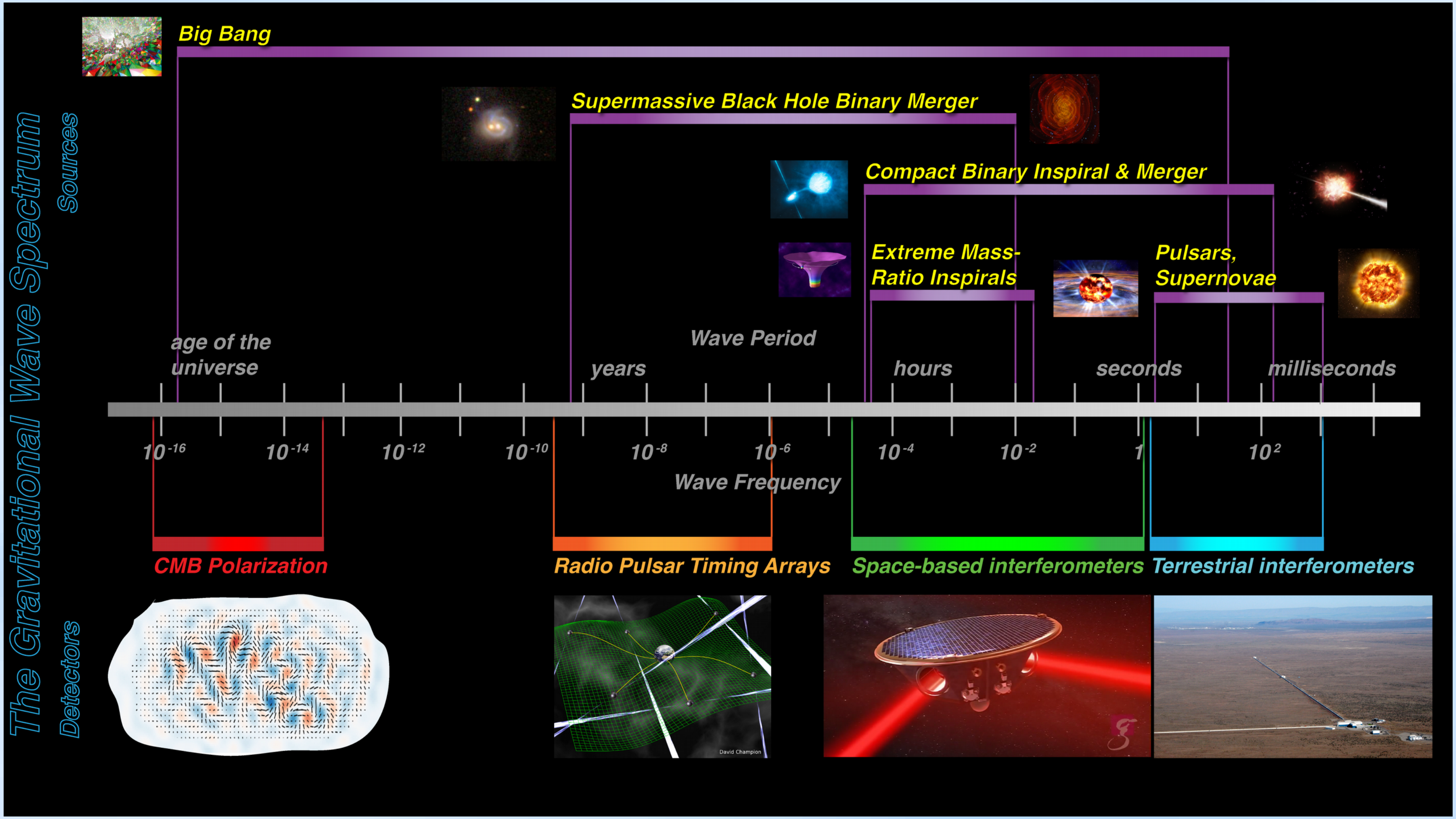
ESA and NASA see this as a high priority.

A tremendous amount of R&D still needs to be done for LISA, and there is much experimental activity.

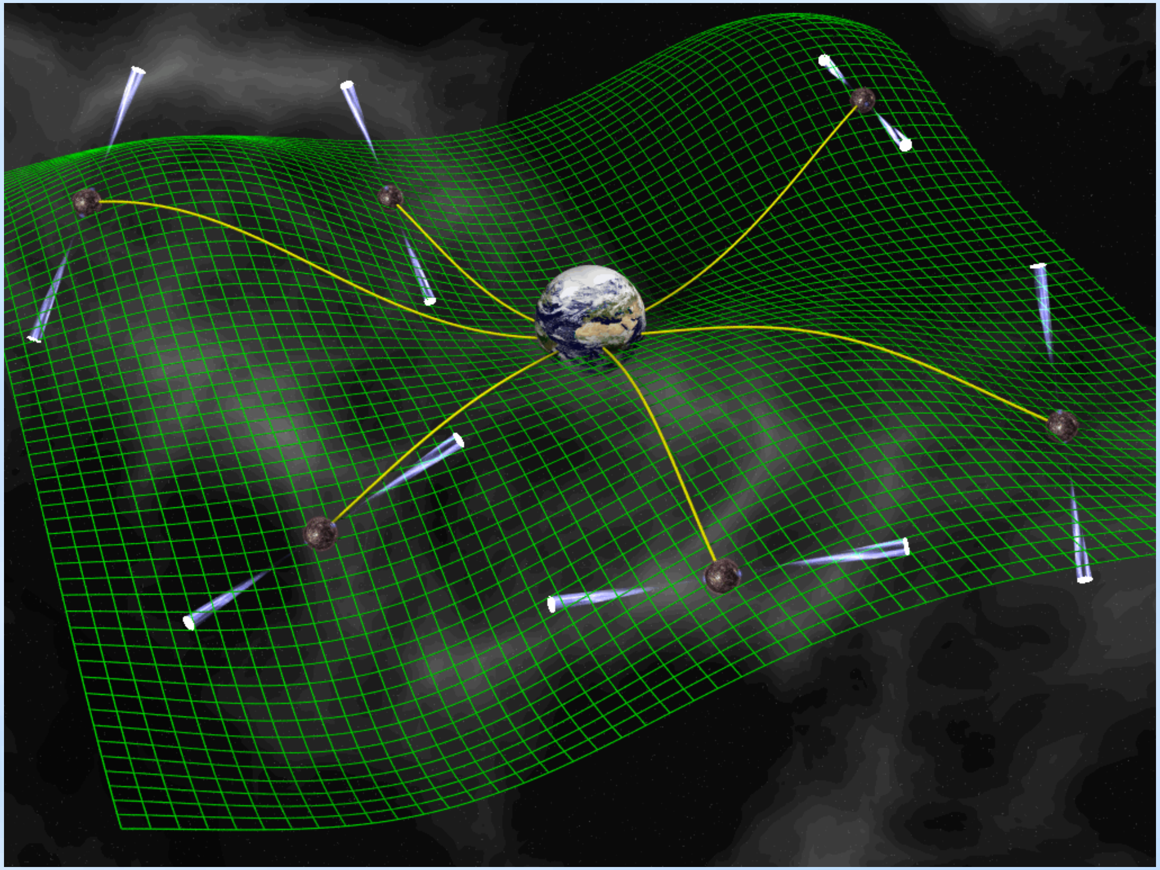
After the LHC, LISA may offer the best opportunity to observe the high energy physics that describes the universe.



Gravitational Wave Spectrum



Pulsar Timing



Parkes Pulsar Timing Array

$\Omega_{GW}(f) < 2.3\times10^{-10}$

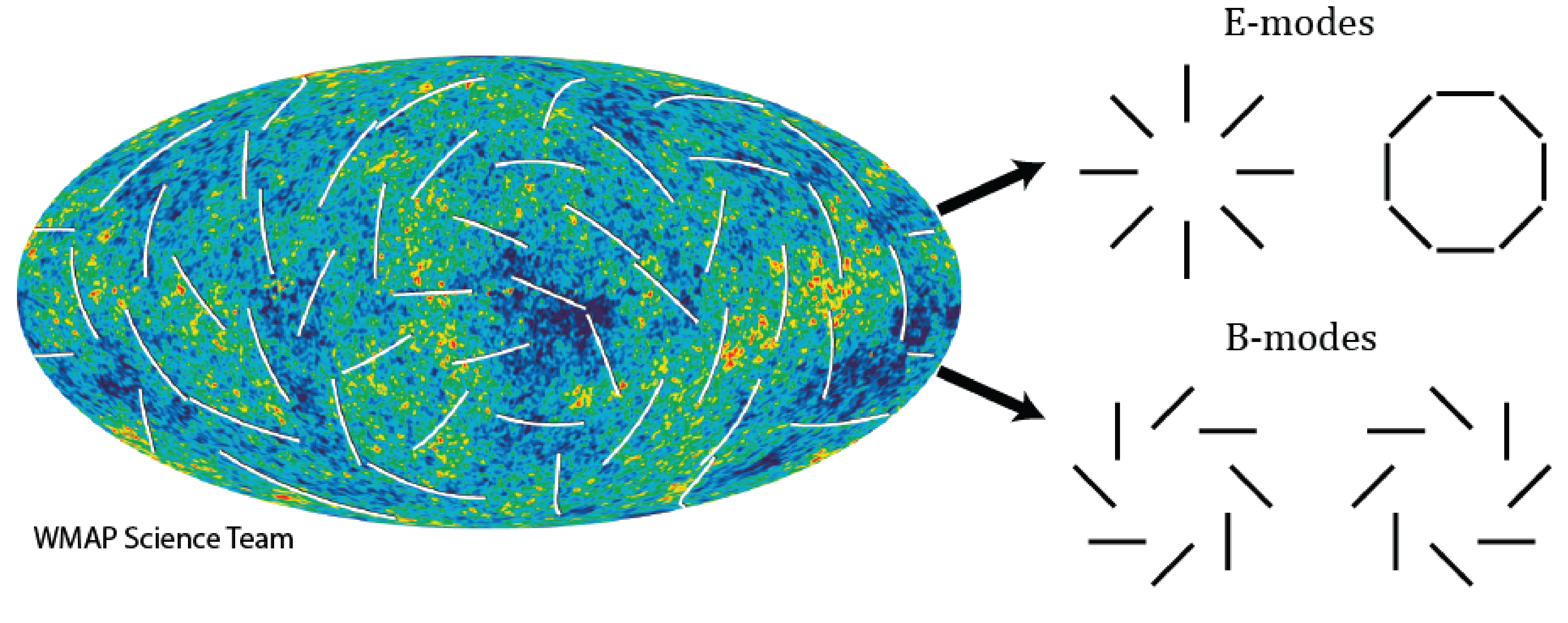
PRX 6, 011035 (2016)

Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

arXiv:1211.4590

Polarization Map of the Cosmic Microwave Background



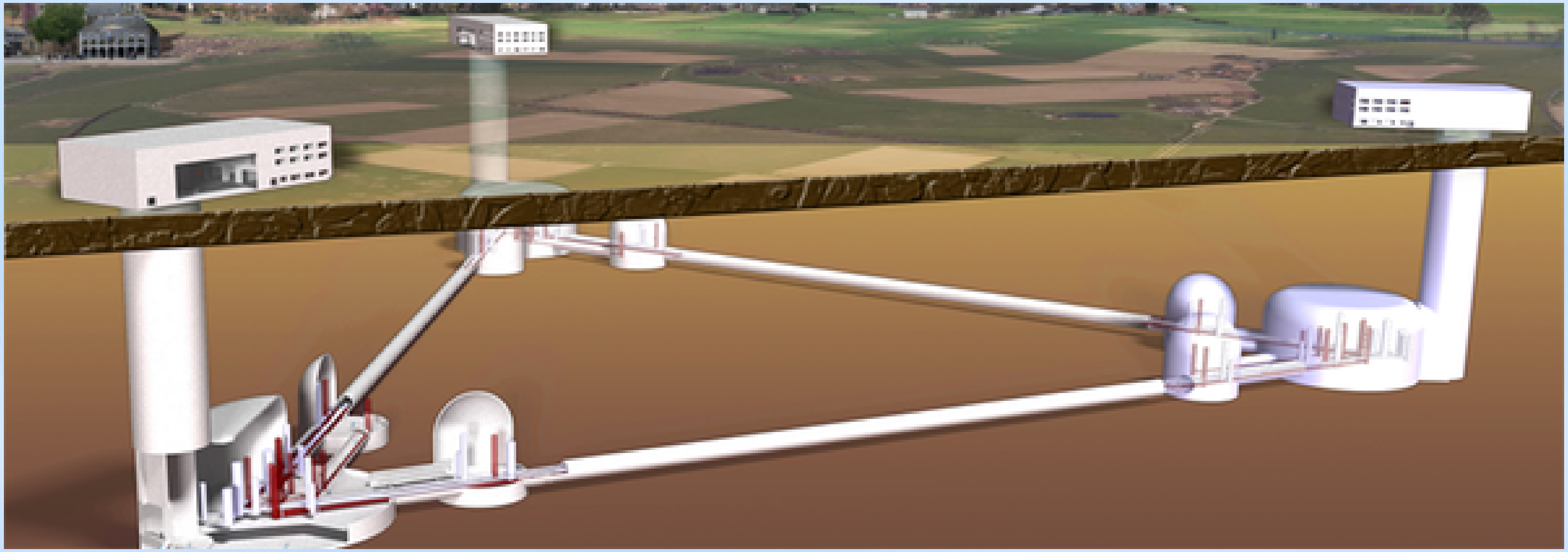
The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

Gravitational waves in the early universe imparts a “curl” on CMB polarization.
arXiv:1407.2584

BICEP2/Keck Array and Planck, $r < 0.12$ (PRL **114**, 101301 (2015))

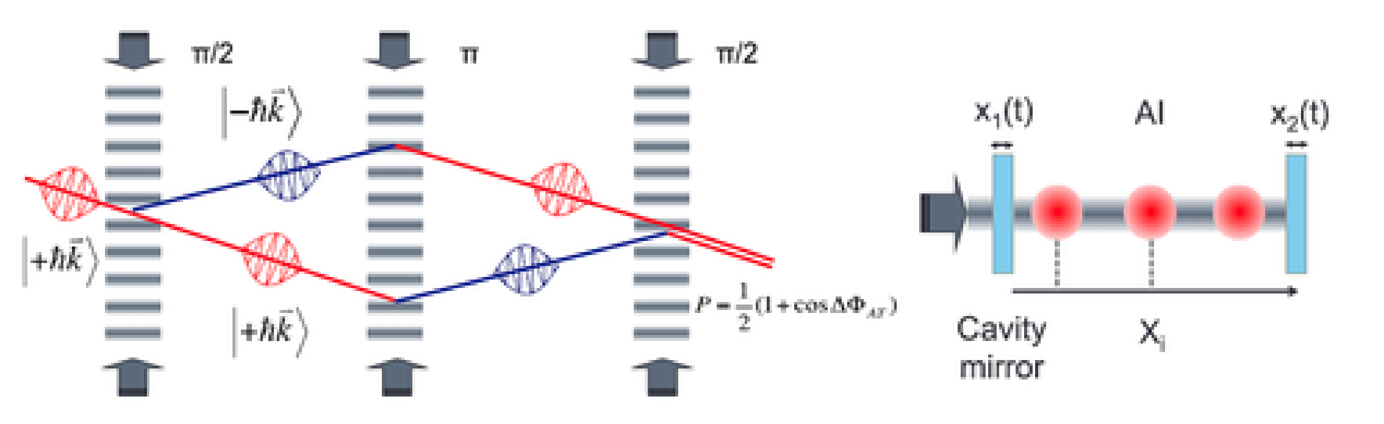
Third Generation Gravitational Wave Detectors

Einstein Telescope



Underground to reduced seismic noise.
10 km arms
Cryogenic mirrors
Lower frequency limit – 1 Hz
10 x better sensitivity than 2nd generation detectors
Farther back in the universe

Atom Interferometers

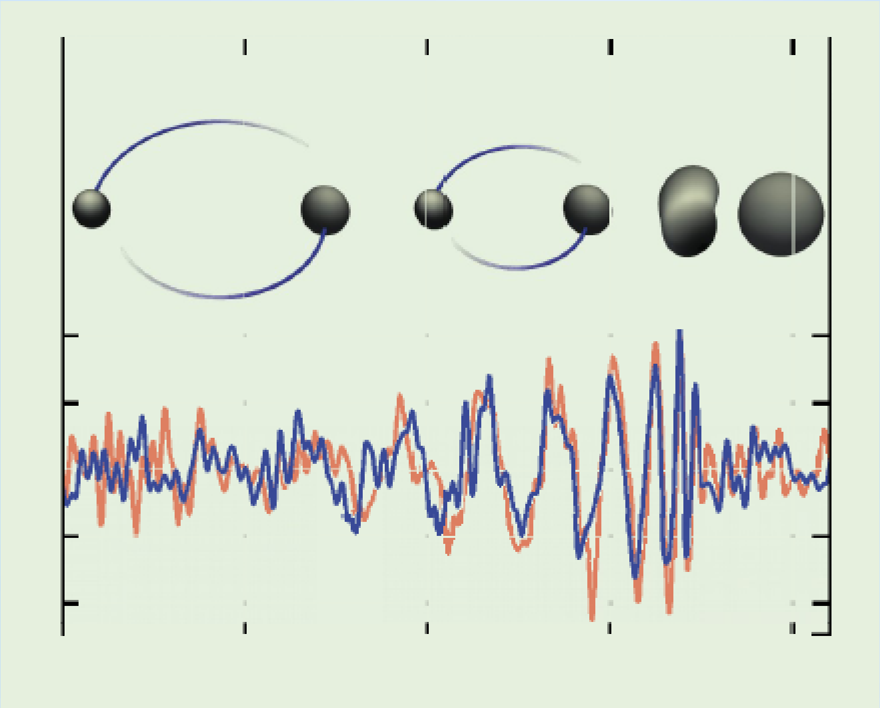


Use a long optical cavity to interrogate atom interferometers.

It may be possible to use this method to build a gravitational wave detector in the 0.1 Hz – 10 Hz band, between LISA and LIGO-Virgo.

Arxiv 1505:07137

Conclusion on Gravitational Waves



A new window on the universe has opened.

We are just beginning!

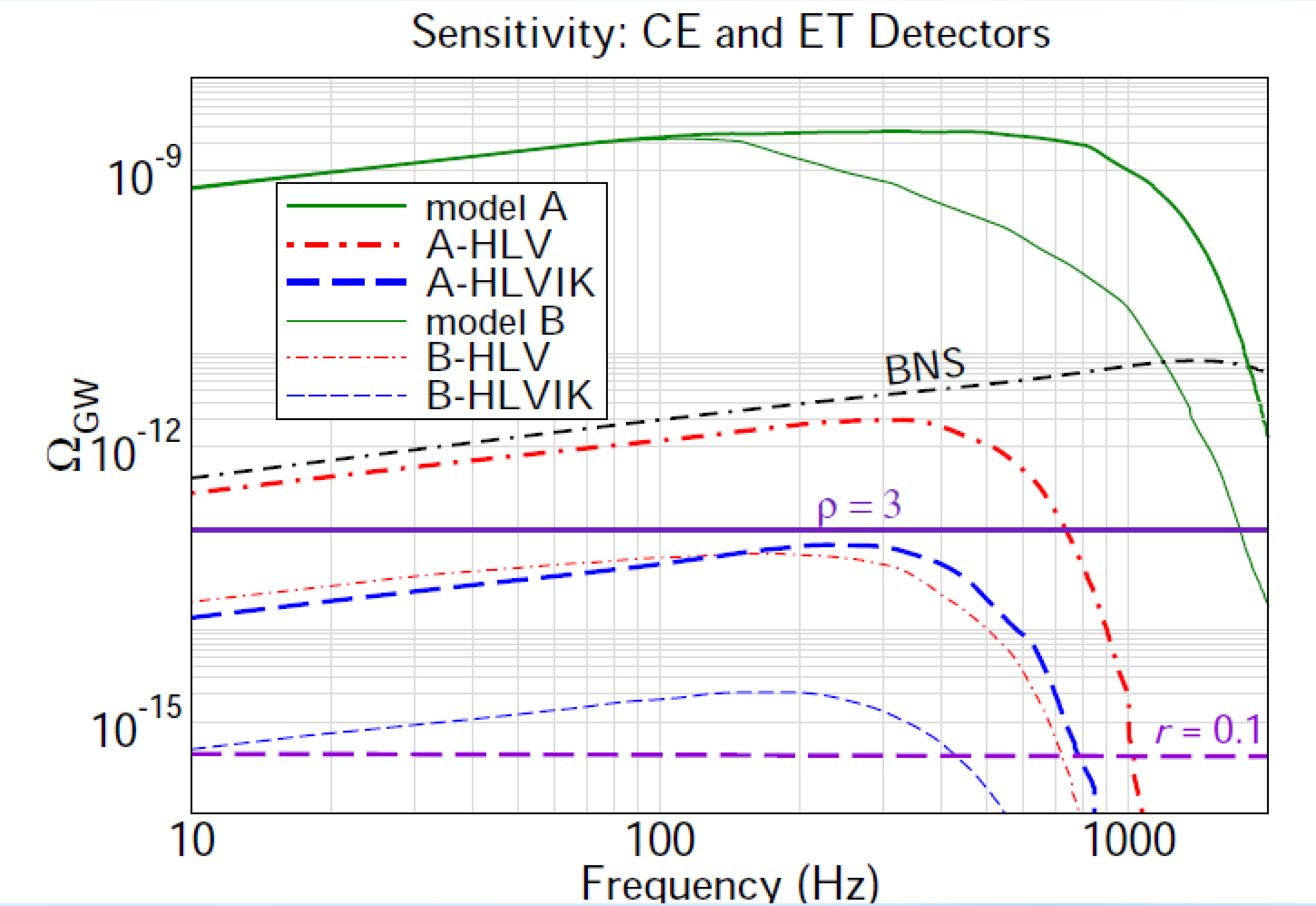
Extra Slides

Talking Points

LSC and Virgo are hard at work on other promising gravitational-wave candidates that were identified during the preliminary analysis, but out of respect for the scientific process we will continue to do the work necessary to establish the level of confidence needed to bring any other results to the scientific community and the greater public. We will let you know as soon as we have information ready to share on any other discoveries.

Third Generation Gravitational Wave Detectors

With Einstein Telescope (European) or Cosmic Explorer (US) almost every stellar mass binary black hole merger in the observable universe will be detectable.



BBH confusion background can potentially be subtracted to observe the primordial background at the level of $\Omega_{GW} \sim 10^{-13}$ after five years of observation.

Arxiv:1611.08943