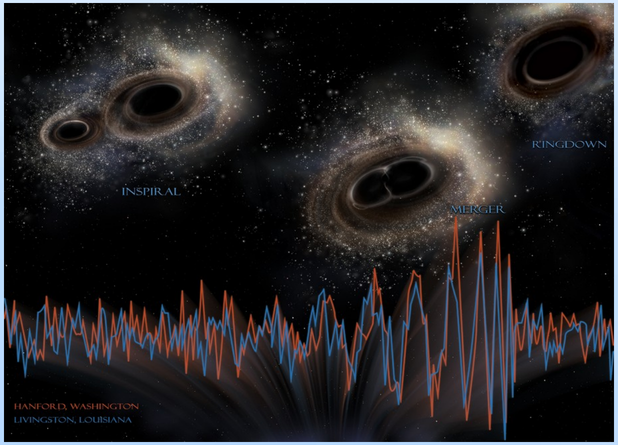
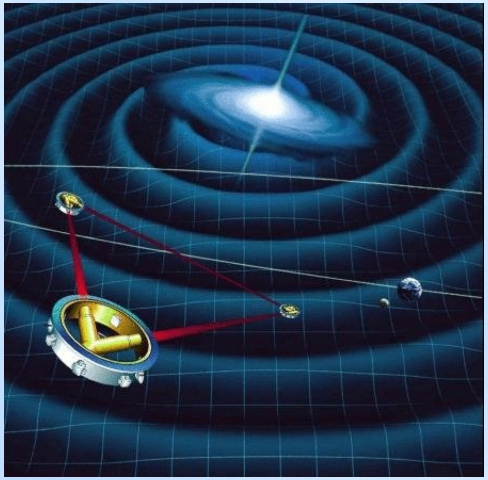




Gravitational Waves: Past, Present and Future

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

June 8, 2017. Karlsruhe Institute of Technology

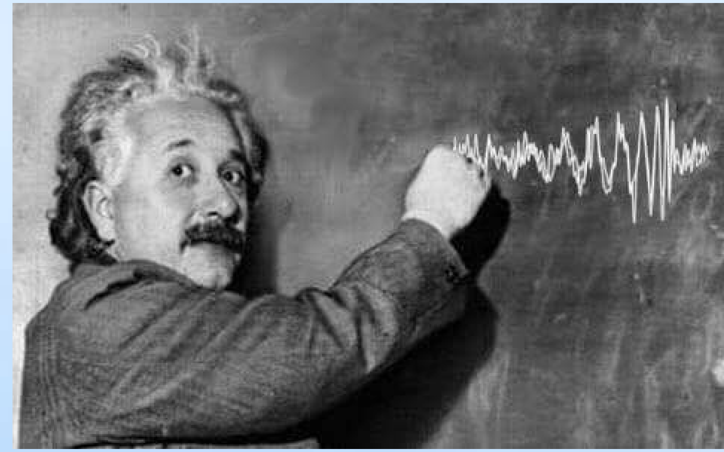
Talk Outline

- Past:
  - gravitational wave theory
  - detection attemps
  - confirmation
- Present:
  - LIGO-Virgo searches
  - gravitational wave detection
  - implications
- Future:
  - LISA
  - third generation detectors
  - atom interferometers
  - other methods

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.

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, …

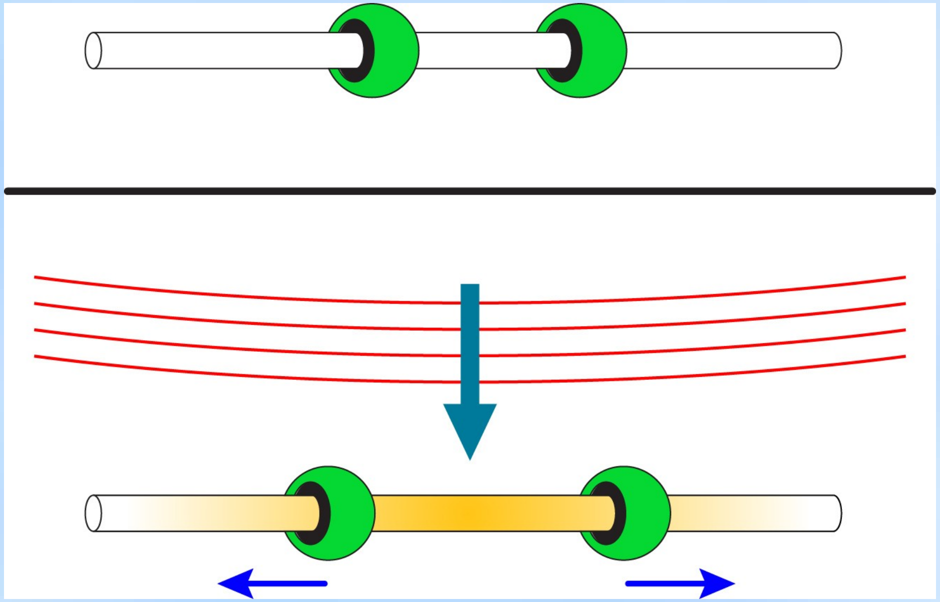
Are Gravitational Waves Real?

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)

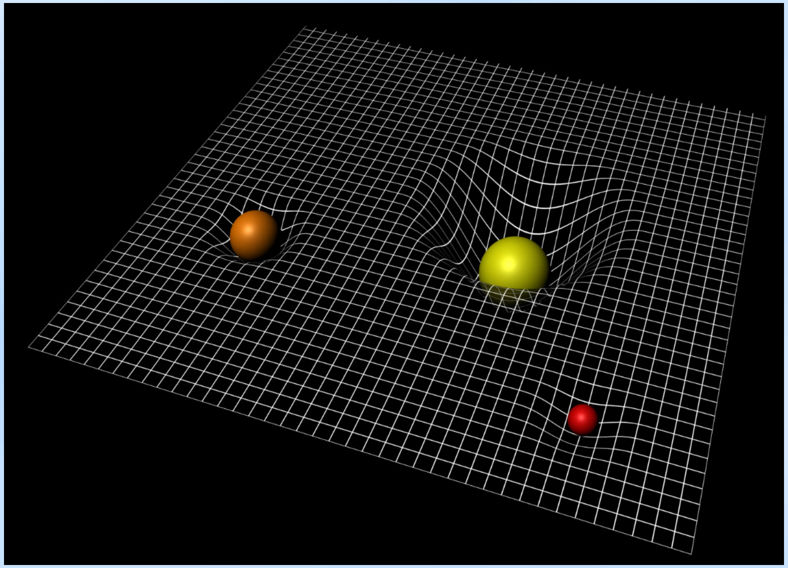
Joe Weber of the University of Maryland, and from this inspiration started to think about gravitational wave detection.



What Are Gravitational Waves?

- General relativity (1916) prediction.
- Gravity is not really a force in GR, but a space-time deformation.
- Masses locally deform space-time.
- Accelerated masses emit gravitational

waves, ripples in space time.



- Space-time is rigid:

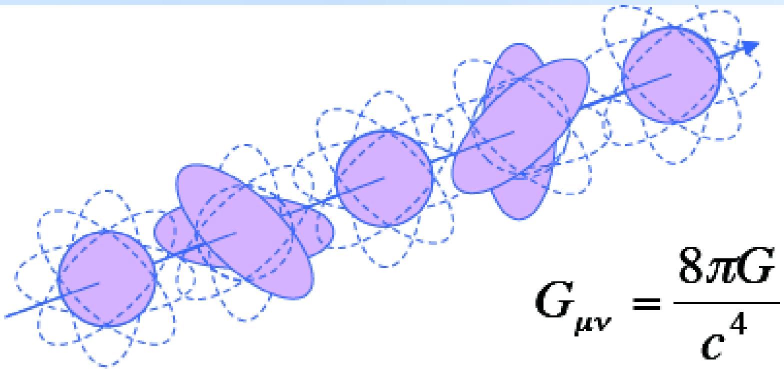
The amplitude of the deformation is tiny.

Need cataclysmic events in order to

expect to measure something on Earth … $h \sim 10^{-21}$

- Gravitational Wave sources: mainly astrophysical in the 10 Hz -10 kHz bandwidth

Gravitational Waves

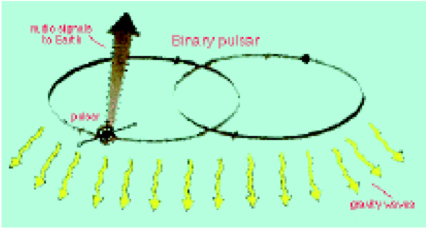


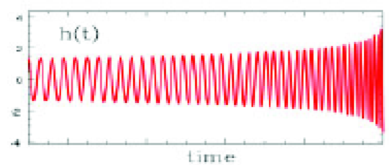
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

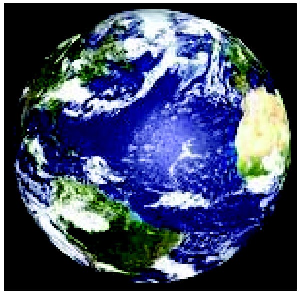
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \; (= 0 \text{ in vacuum})$$

$$h_{\mu\nu} \sim \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad h = 2\frac{\Delta L}{L}$$





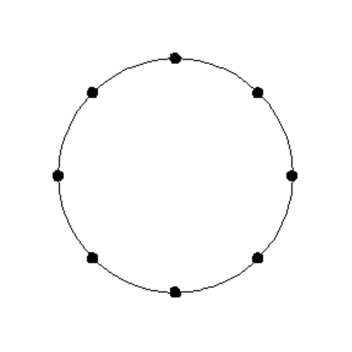


GWs from a NS-NS coalescence in the Virgo cluster has $h \sim 10^{-21}$ near Earth: change the distance between the Sun and the Earth by ~ one atomic diameter, and change 1km distance by ~10^{-18} m.

Effect Of A Gravitational Wave

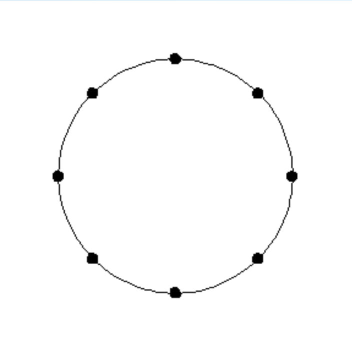
“+” polarization:

$$h_+(t-z) = h^{TT}_{xx} = -h^{TT}_{yy}$$



“x” polarization:

$$h_\times(t-z) = h^{TT}_{xy} = h^{TT}_{yx}$$



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

“strain”

Binary Pulsar PSR 1913+16

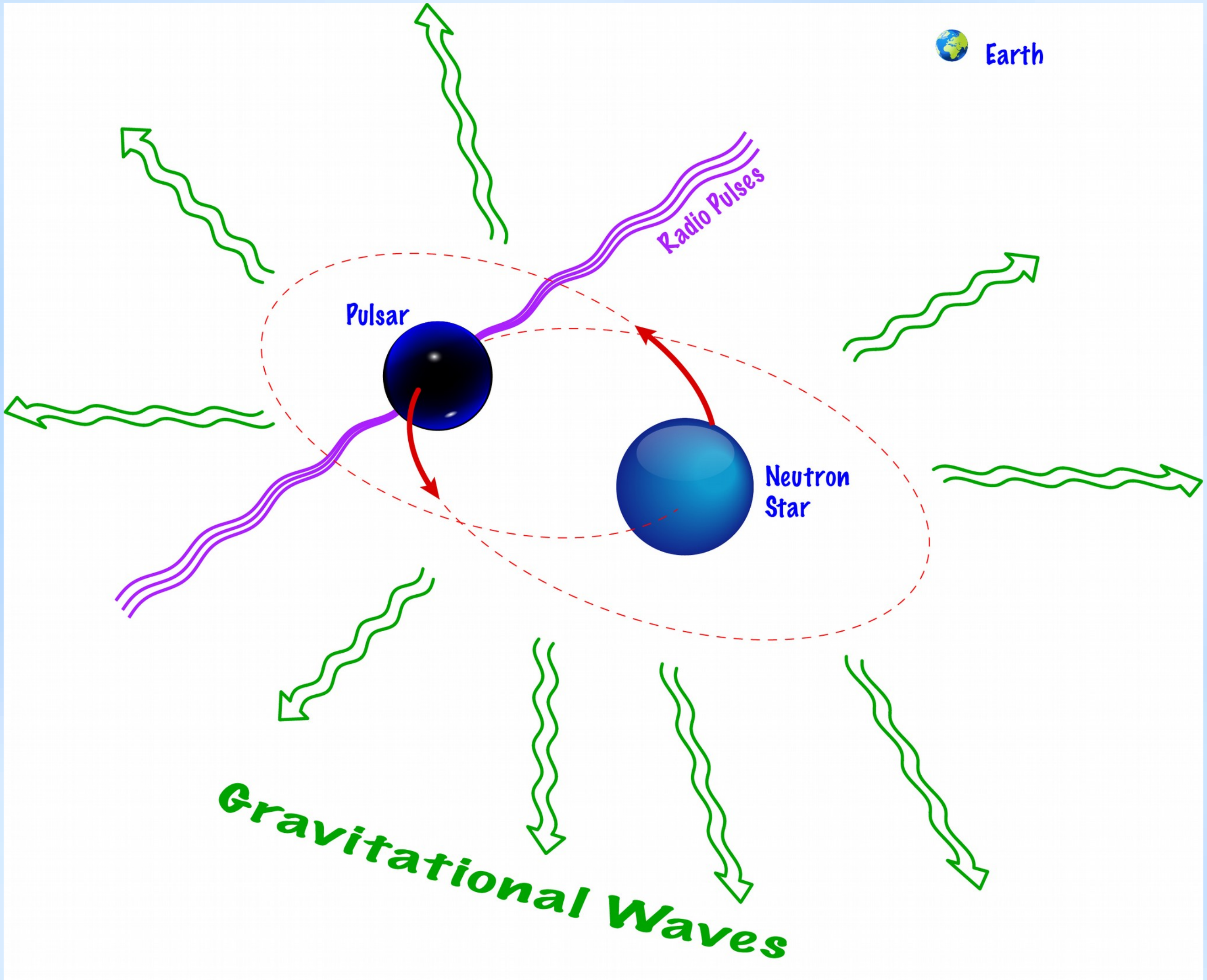
M1 = 1.438 M_o

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

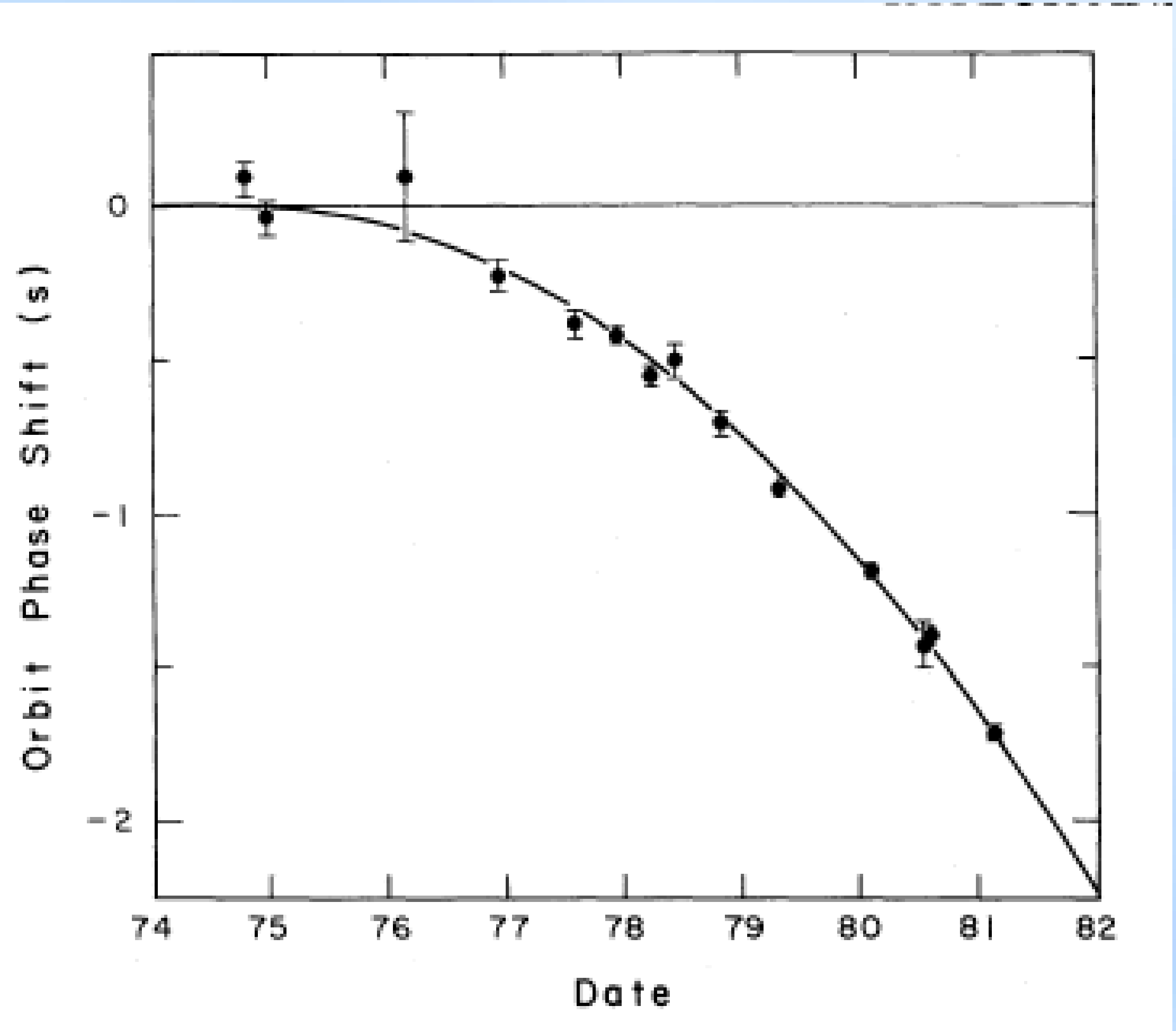
J. H. TAYLOR AND J. M. WEISBERG
Department of Physics and Astronomy, University of Massachusetts, Amherst; and Joseph Henry Laboratories, Physics Department, Princeton University
Received 1981 July 2; accepted 1981 August 28

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

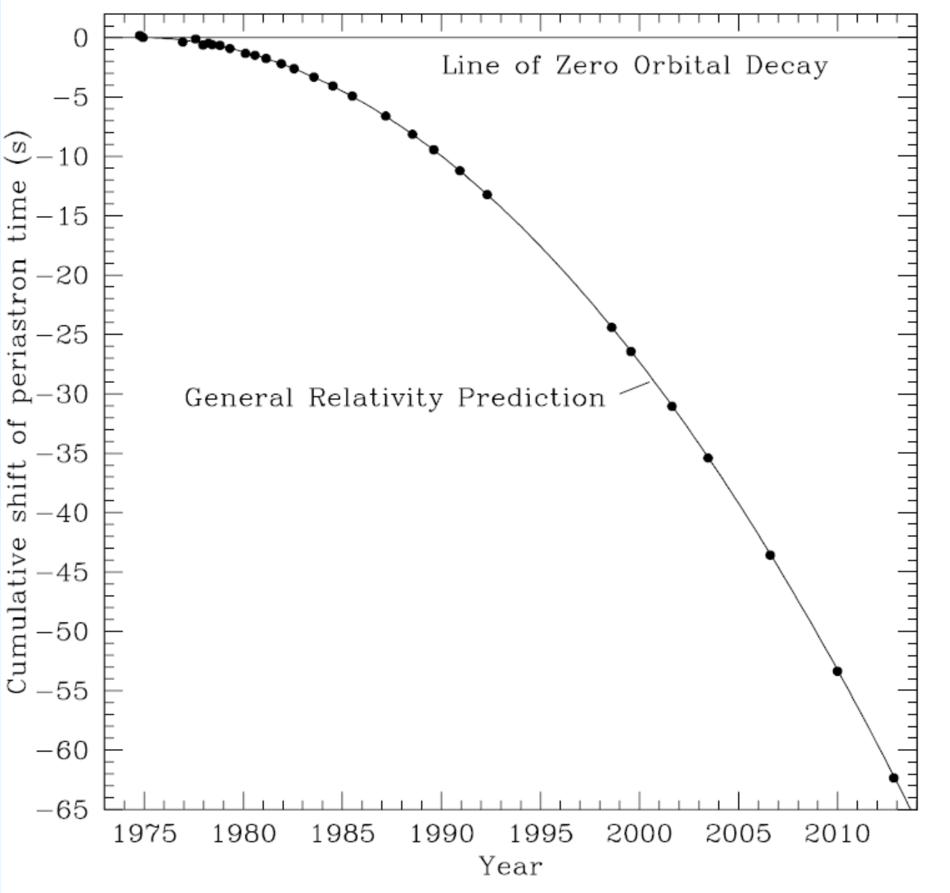
Binary Pulsar Studies Continue

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

CrossMark

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."

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

K. Thorne 1980

1960s & 70s: Detection claims and theoretical studies on sources

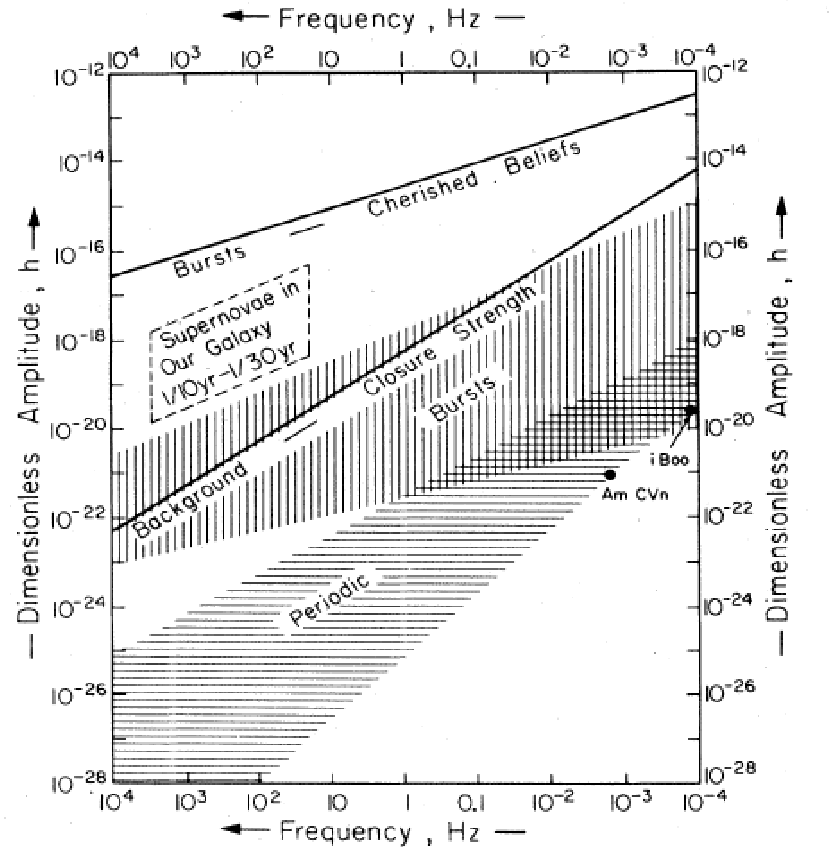


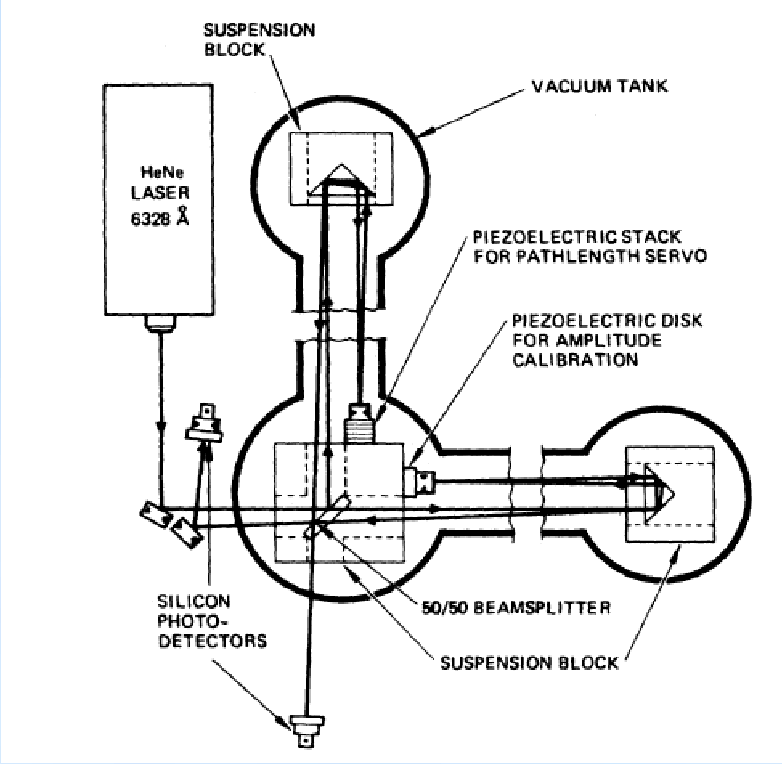
FIG. 3. Estimates of the strengths of the gravitational waves that bathe the Earth. See text for explanation of the lines and hatched regions.

The future looks promising—but by no means certain! The search for gravitational waves is a game requiring long, hard effort with a definite risk of total failure—but with very great payoff if it succeeds.

Interferometric GW Detectors

First suggestion: 1962 two Soviet physicists, V.I. Pustovoit and M.E. Gertsenshtein, noted that the use of a Michelson interferometer would be a possible means to detect gravitational waves over a frequency range that was broader than the Weber bars.

1970's, Robert Forward (student of Weber) at Hughes Aircraft builds a small Michelson interferometer to search for gravitational waves. Credits Rainer Weiss (MIT) and astronaut Philip Chapman (also at MIT) for inspiration.



The wideband interferometer data was analyzed by ear,

VII. CALIBRATION OF EAR

When the interferometer was working well, we were able to hear single-frequency 3- to 10-kHz tones of 10-fm rms amplitude introduced into the interferometer by the piezoelectric displacement transducer.

Since the noise level of the interferometer in that band is about 0.9 fm/$Hz^{1/2}$, this means that the audio system, including our ear-brain combination, had an effective detection bandwidth of about 120 Hz.

Rai Weiss Interferometer Study

1972: Weiss produces the first detailed study for a realistic interferometric gravitational wave detector.

Systematically addresses a number of realistic noise sources:

- Amplitude Noise in the Laser Output Power
- Laser Phase Noise or Frequency Instability
- Mechanical Thermal Noise in the Antenna
- Radiation-Pressure Noise from the Laser Light
- Seismic Noise
- Thermal-Gradient Noise
- Cosmic-Ray Noise
- Gravitational-Gradient Noise
- Electric Field and Magnetic Field Noise

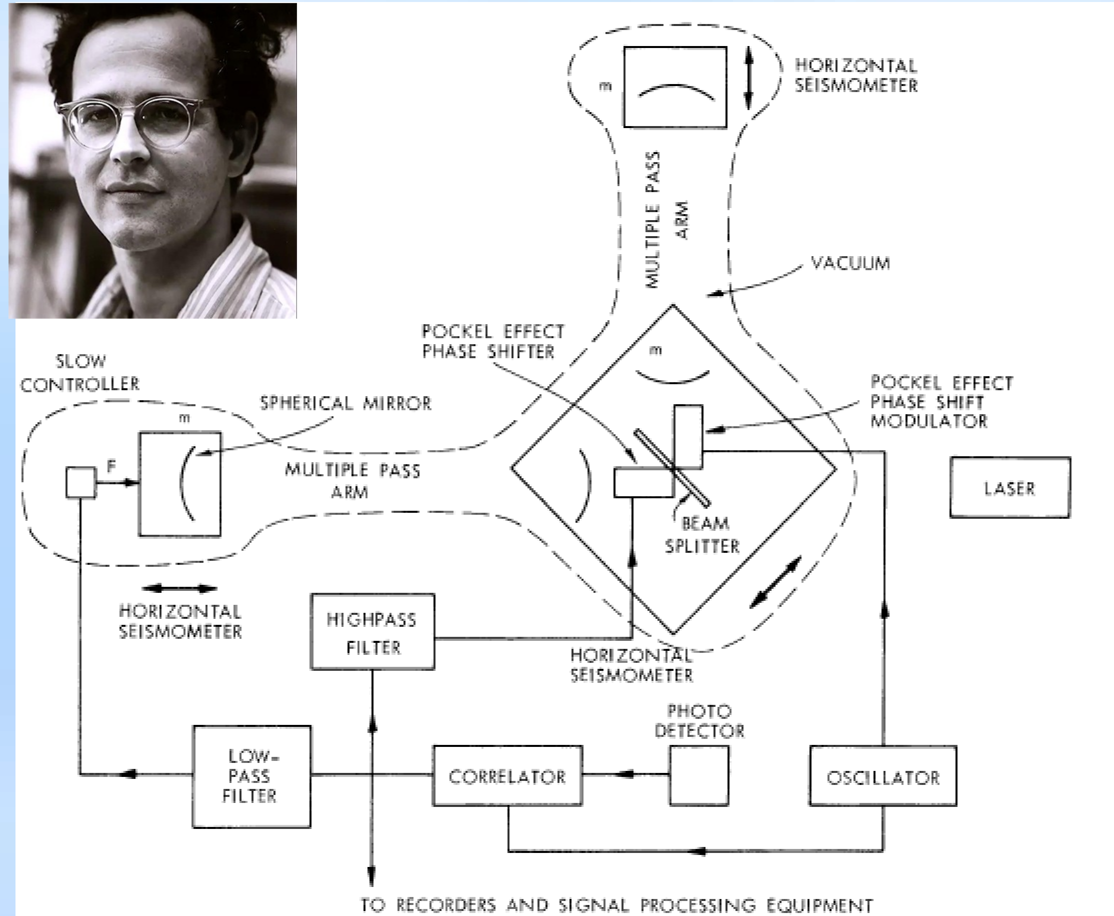
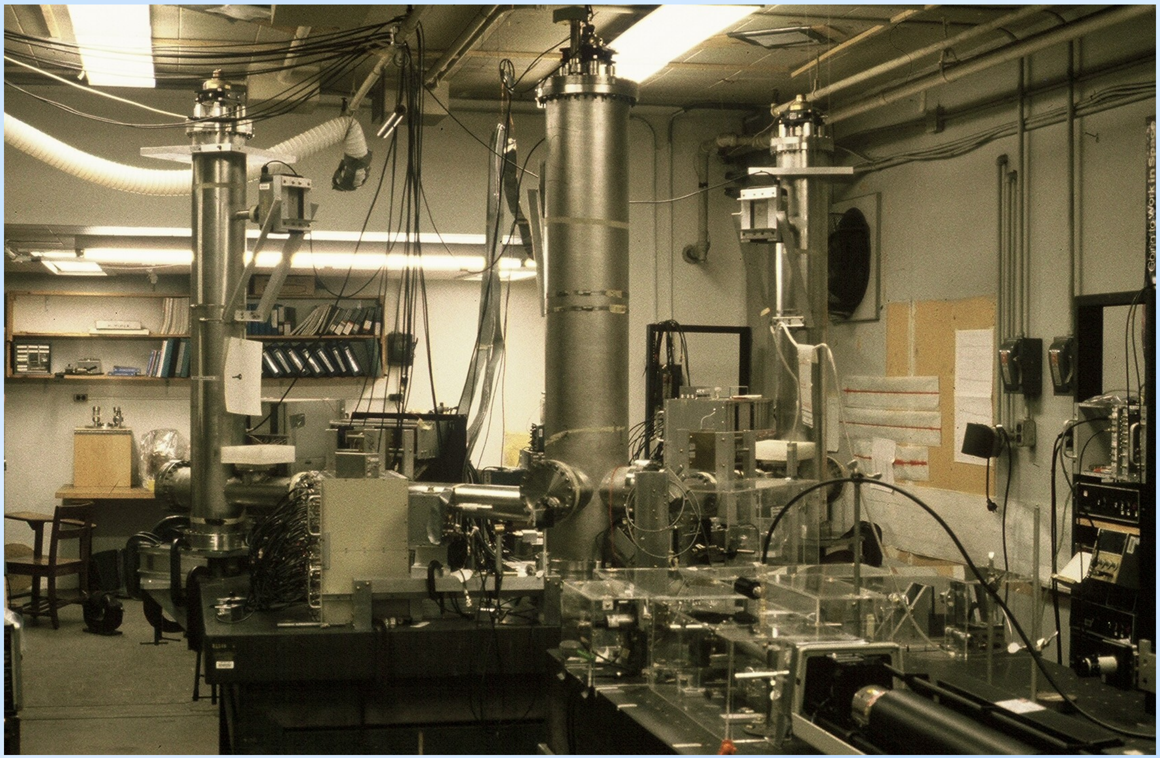


Fig. V-20. Proposed antenna.

Prototype Interferometric Detectors



MIT 1.5 m delay line Michelson Interferometer

1970s and 80s:
Interferometers constructed at
Garching
Glasgow
MIT
Caltech

The interferometer technology started progressing rapidly.

1980s LIGO is Born

Thorne, Drever (Caltech)

Weiss (MIT)

National Science Foundation

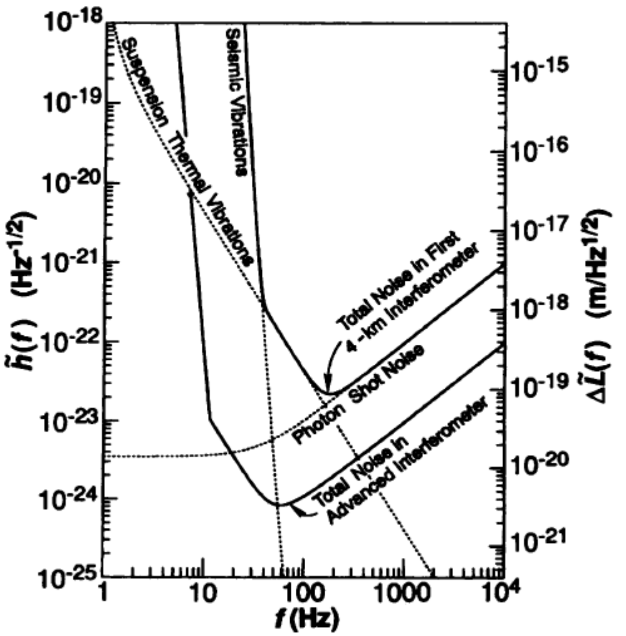


Fig. 7. The expected total noise in each of LIGO's first 4-km interferometers (upper solid curve) and in a more advanced interferometer (lower solid curve). The dashed curves show various contributions to the first interferometer's noise.

SCIENCE • VOL. 256 • 17 APRIL 1992

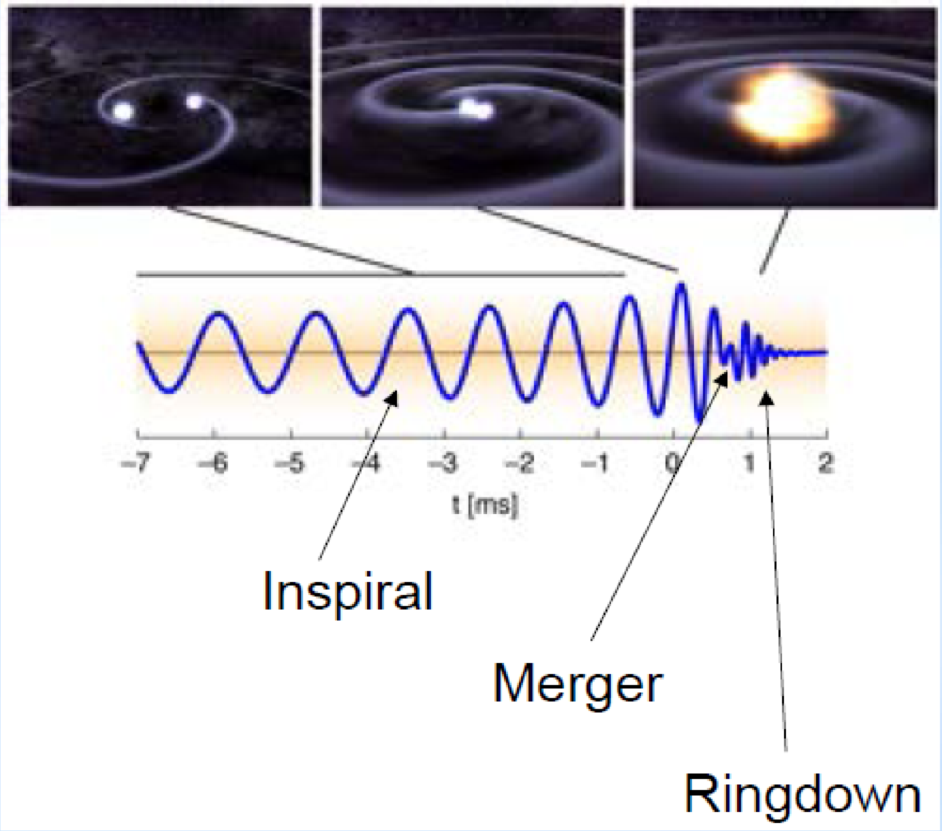
While in Europe … Virgo

A. Brillet (Orsay, Nice)
Lasers, Optics

A. Giazotto (Pisa)
Vibration Isolation

Sources: Compact Binary Coalescence

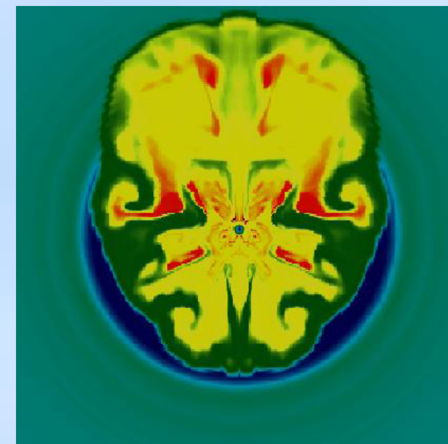
- Compact binary objects:
  » Two neutron stars and/or black holes.
- Inspiral toward each other.
  » Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform relatively well understood, matched template searches.

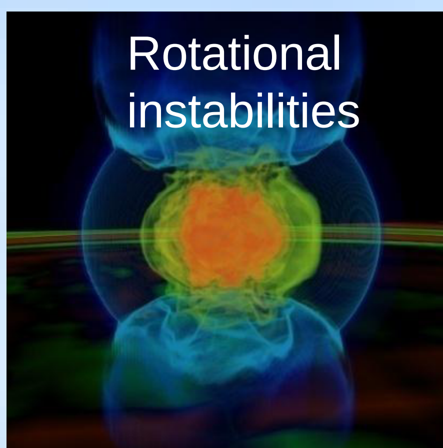


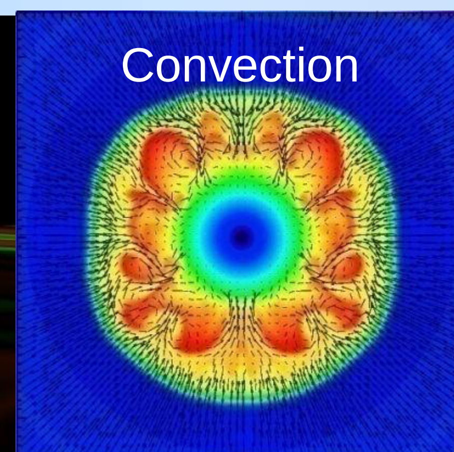
Sources: Bursts

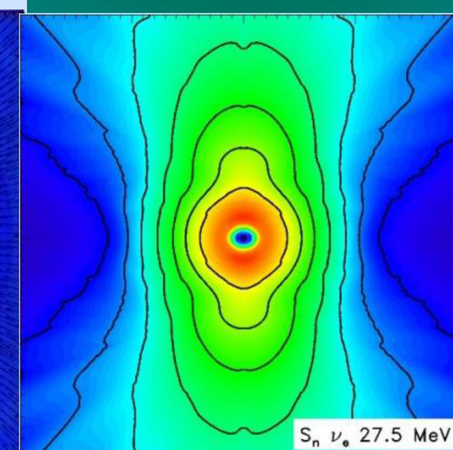
- Many potential transient sources:
  - » Supernovae: probe the explosion mechanisms.
  - » Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - » Pulsar glitches: accretion.
  - » Cosmic strings cusps and kinks.
- Models are ok, but not essential:
  - » Search for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

Aspherical outflows



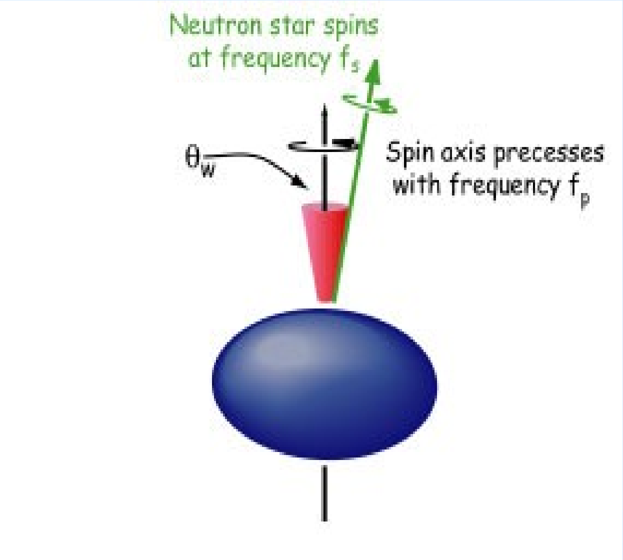






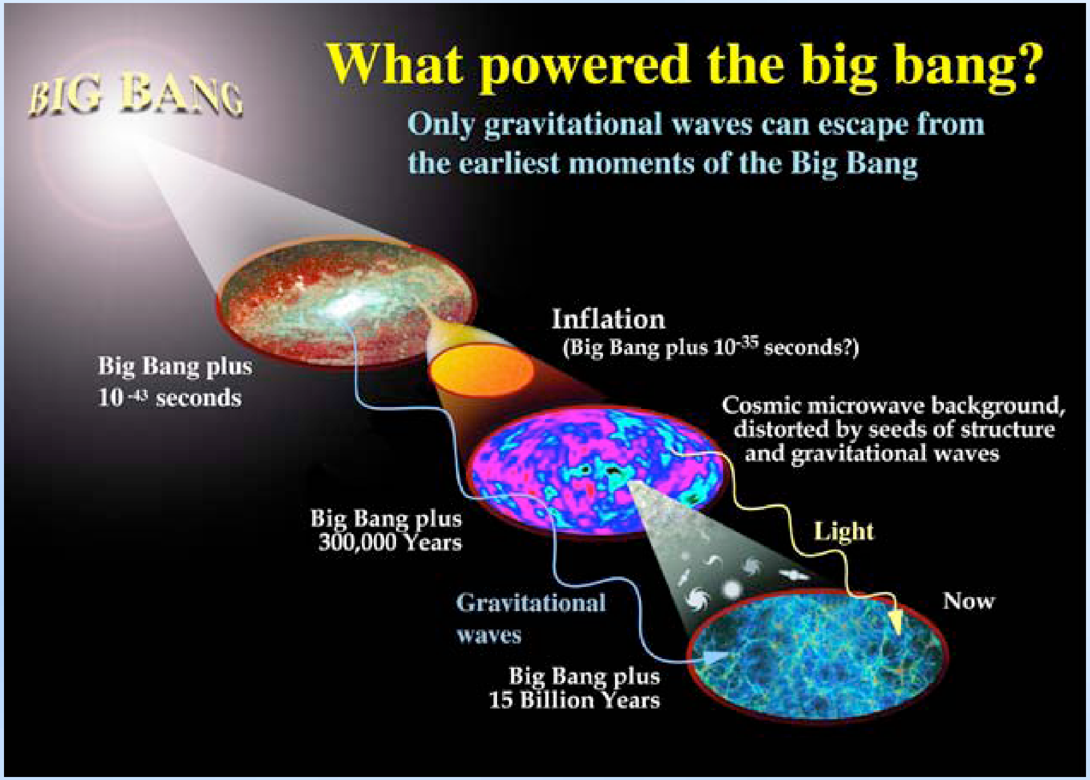
Sources: Periodic

- 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!



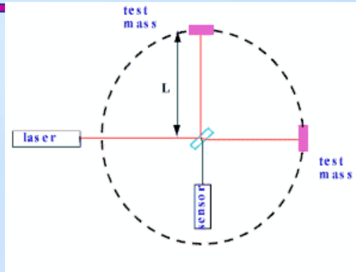
Sources: Stochastic

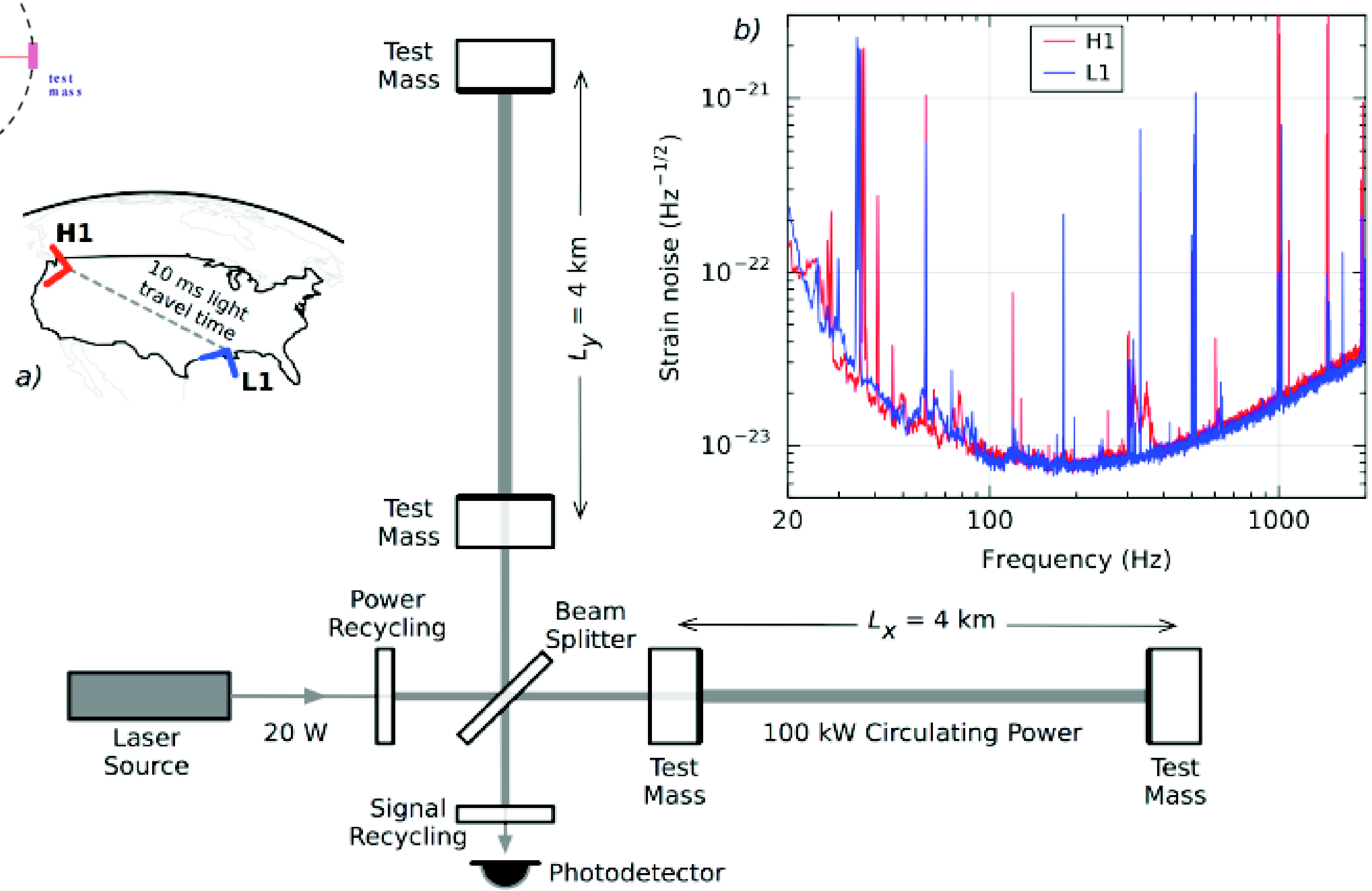
- Incoherent superposition of many unresolved sources.
- Cosmological:
  - » Inflationary epoch, preheating, reheating
  - » Phase transitions
  - » Cosmic strings
  - » Alternative cosmologies
- Astrophysical:
  - » Supernovae
  - » Magnetars
  - » Binary black holes
- Potentially could probe physics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



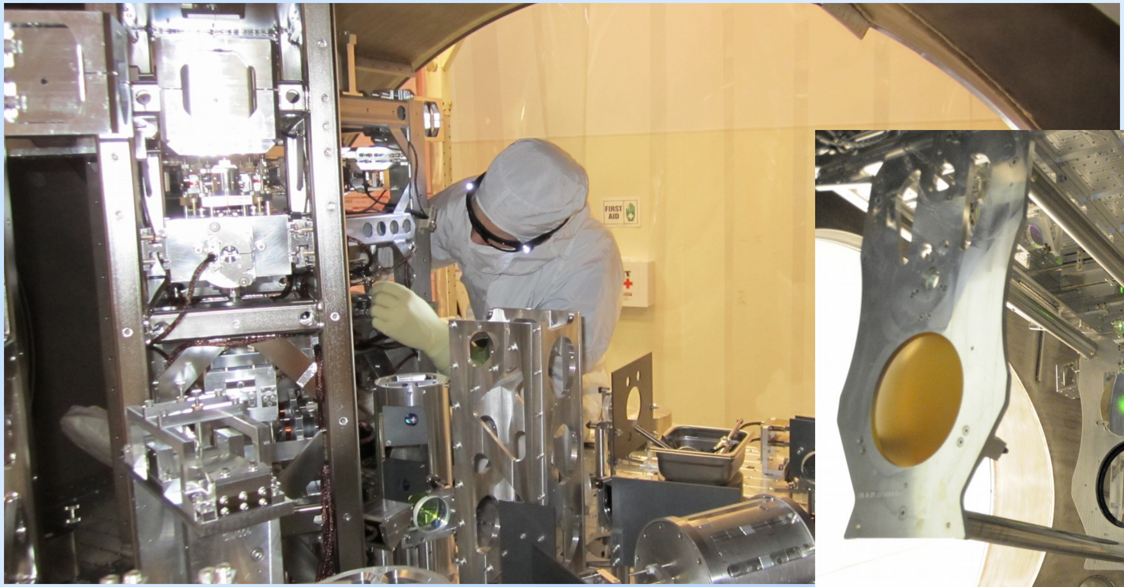
$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

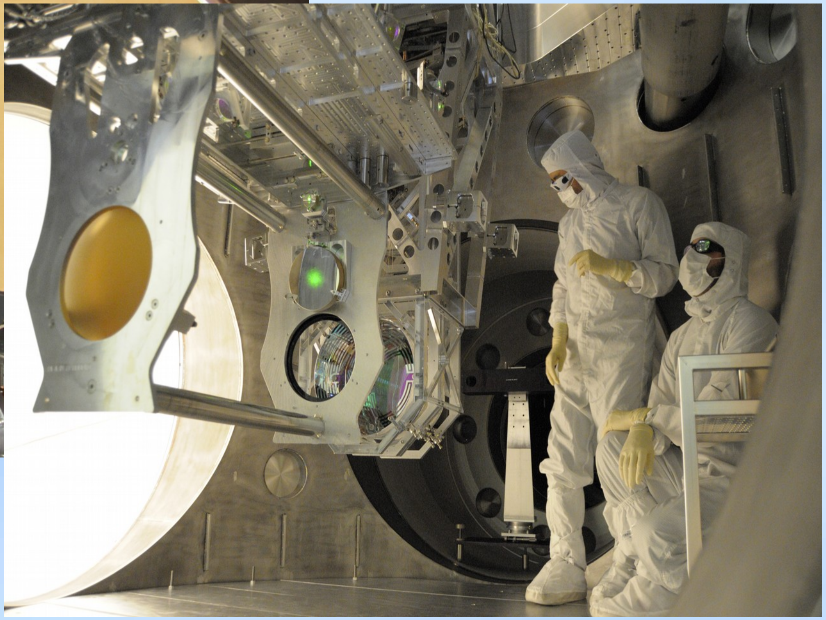
The Detectors





Advanced LIGO – Advanced Virgo

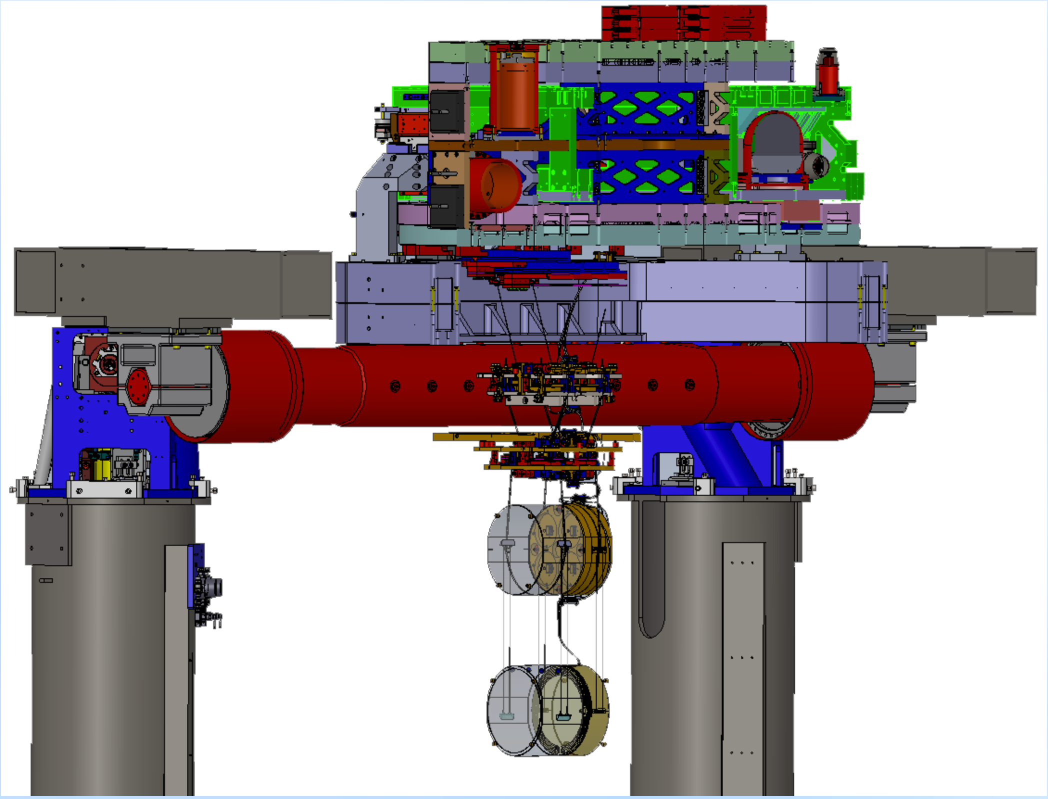




Built on the experience gained from the first generation detectors

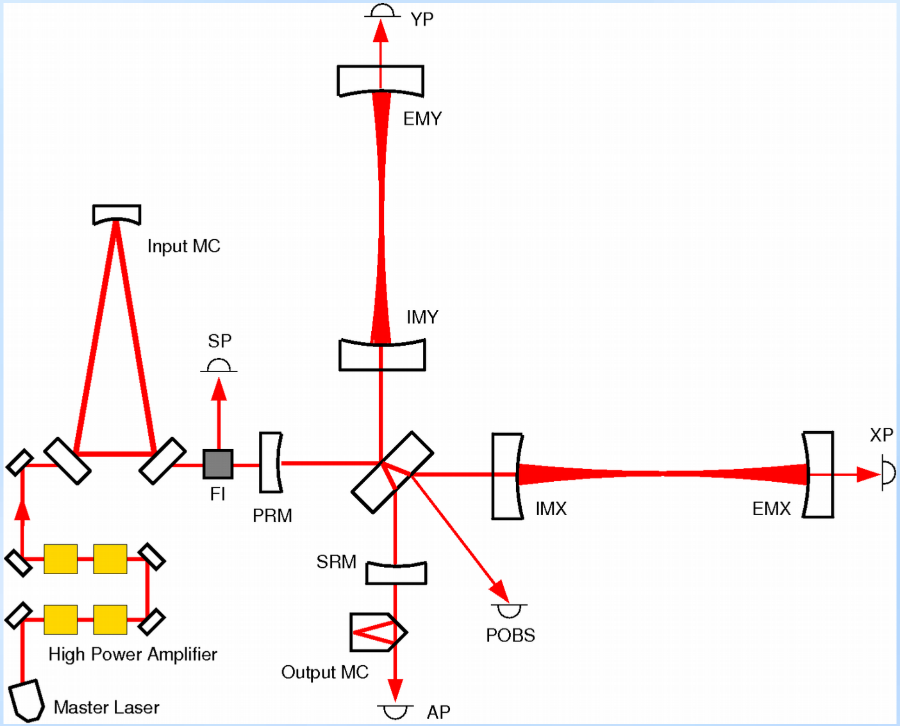
Advanced LIGO

- Initial LIGO: 2005-2010.
- Advanced LIGO commissioned 2010-2015.
  - Increased laser power
  - Sophisticated seismic/vibration suppression
  - Quadruple pendula suspensions
  - Larger mirrors, better suspension material
  - More complex and versatile interferometer configuration.



Classical and Quantum Gravity 32, 074001 (2015)

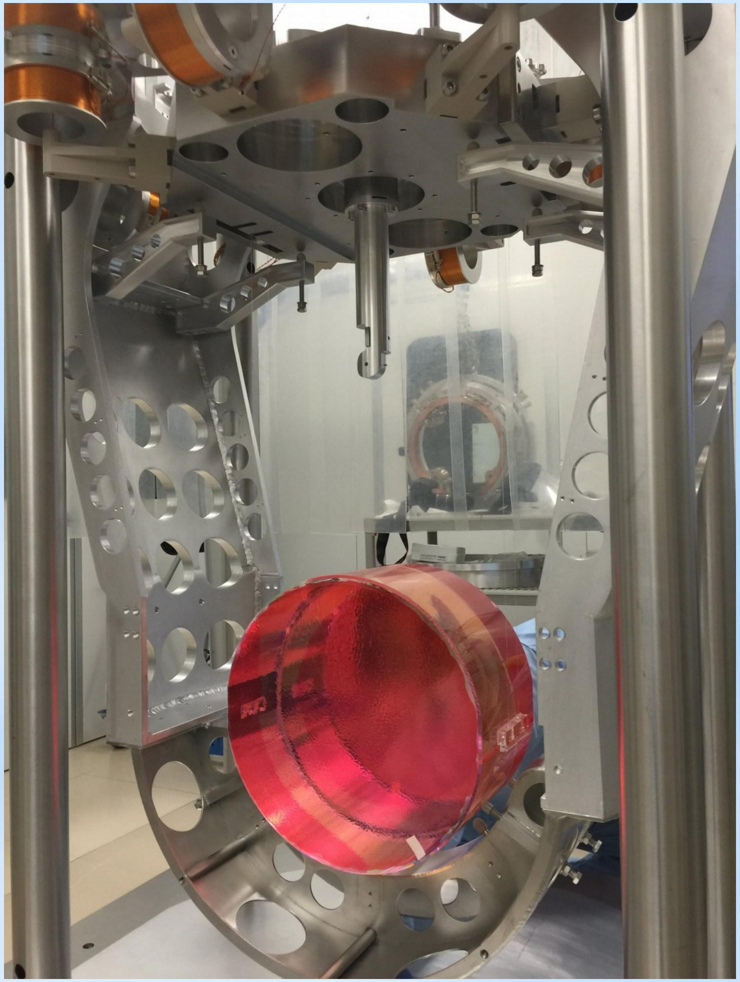
Advanced Virgo



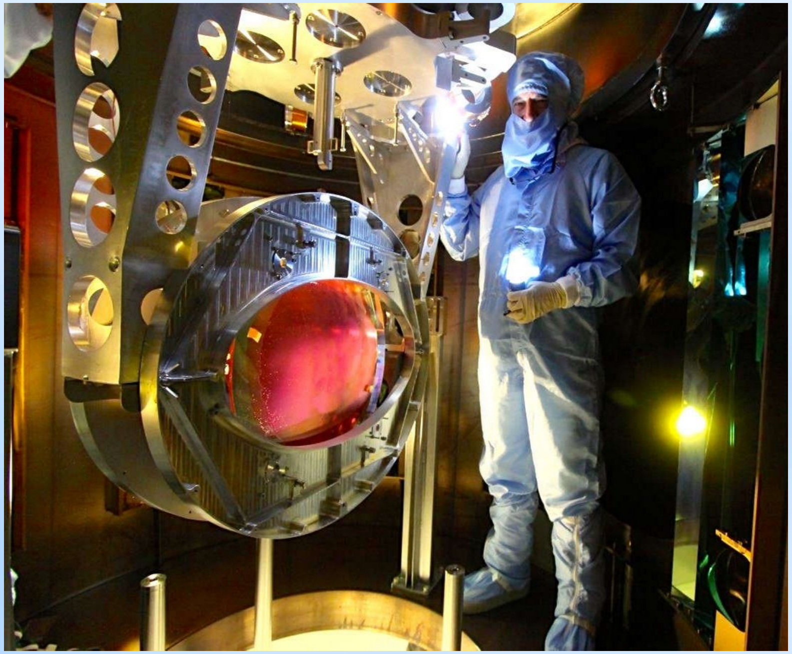
- Larger mirrors; better optical quality.
- Higher finesse of the arm cavities
- Increased laser power.
- Coming on-line in Summer 2017.

AdV TDR: VIR-0128A-12 https://tds.ego-gw.it/?content=3&r=9317

Advanced Virgo



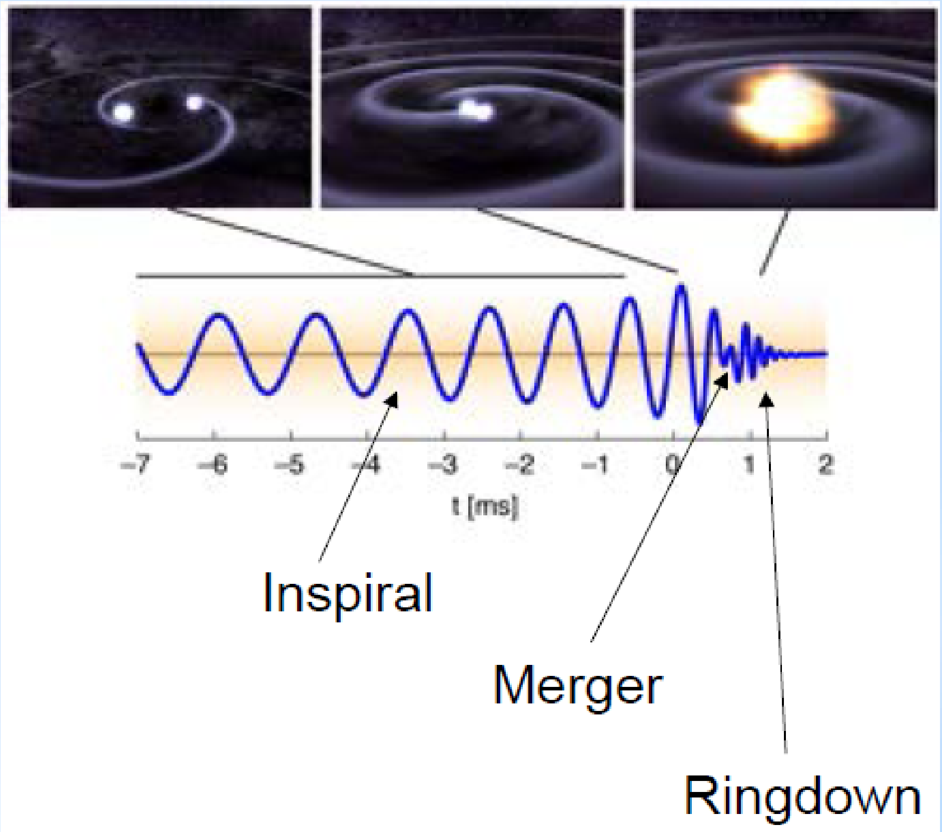
Mirror



Beamsplitter

The optical components are very large, but their quality is exquisite.

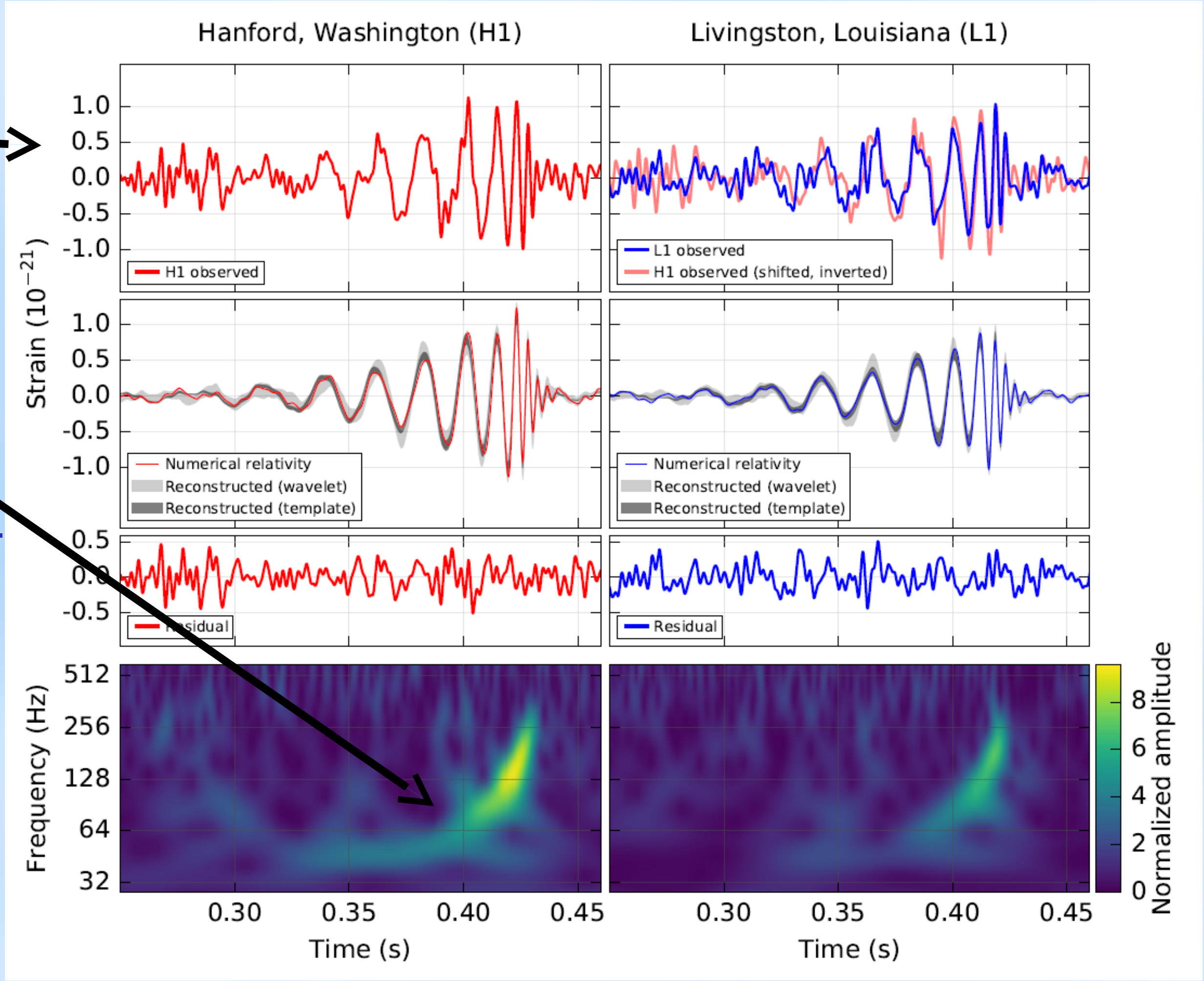
A Century Of Theoretical Developments



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)

September 14, 2015

Subject: [CBC] Very interesting event on ER8
From: Marco Drago <marco.drago@aei.mpg.de>
Date: 09/14/2015 05:55 AM
To: burst@sympa.ligo.org
CC: "cbc@ligo.org Binaries Group" <cbc@ligo.org>, The LIGO Data Analysis Software Working Group <daswg@ligo.org>, Calibration <calibration@ligo.org>, dac@sympa.ligo.org, "<burst@ligo.org>" <burst@ligo.org>, "<detchar@sympa.ligo.org>" <detchar@sympa.ligo.org>, losc-devel@ligo.org, "lsc-all@ligo.org" <lsc-all@ligo.org>

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625
/1126259540-1126259600/OUTPUT_CED
/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1
/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

The Word From Above

September 14, 2015, 11:58 am Central. “The BI team has indicated that they have not carried out a blind injection nor an untagged hardware injection.” Dave Reitze, Executive Director of the LIGO Laboratory.

The Results

Observation of Gravitational Waves from a Binary Black Hole Merger

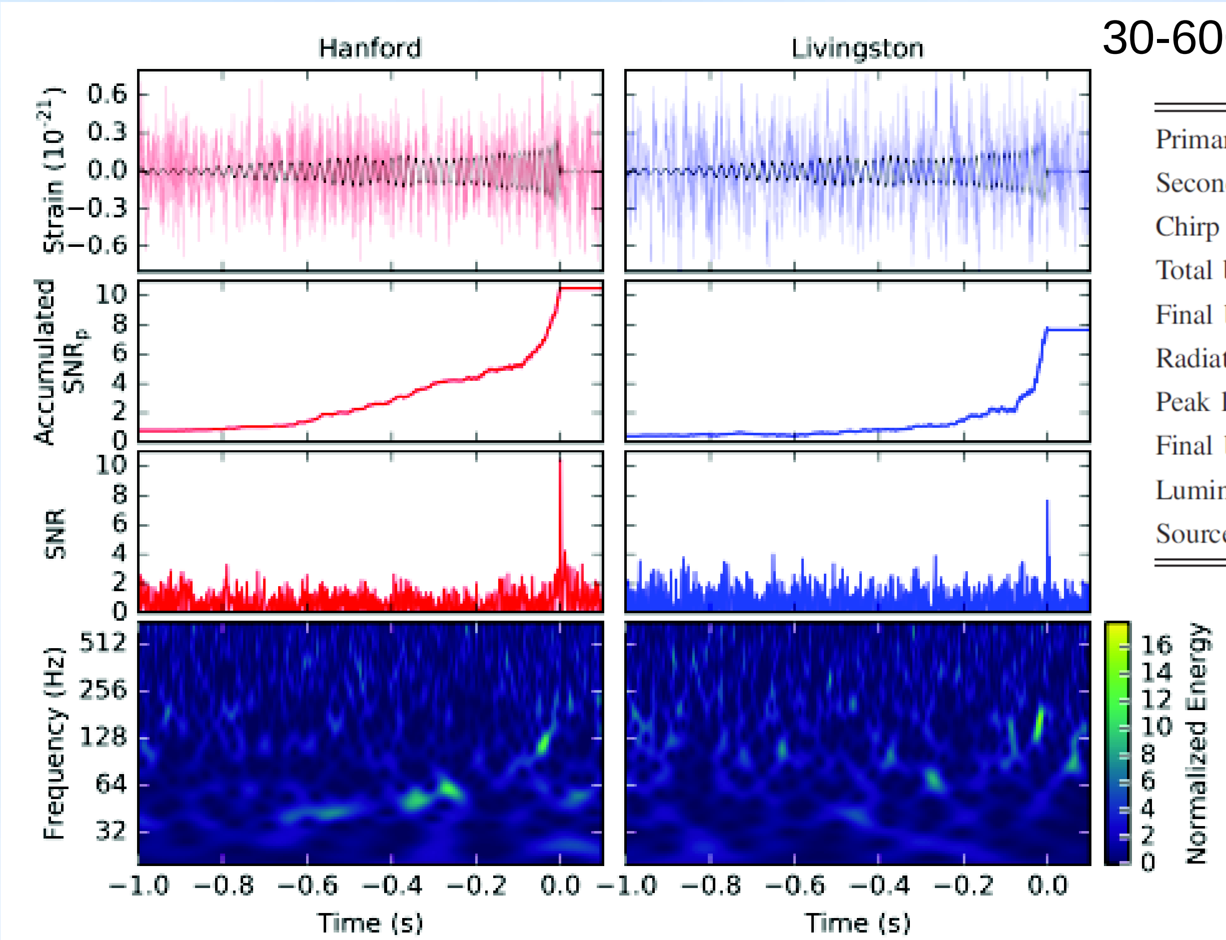
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

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

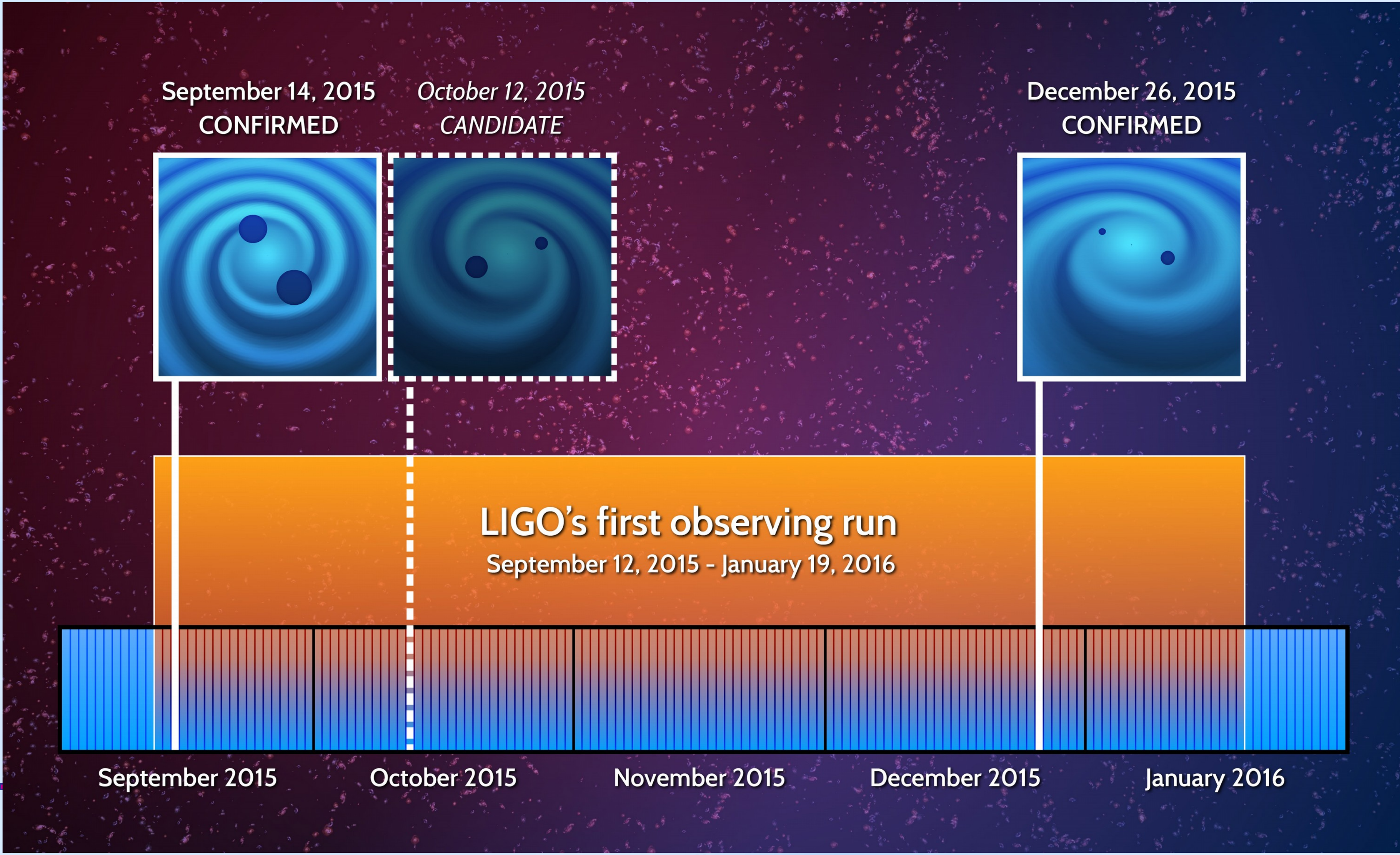
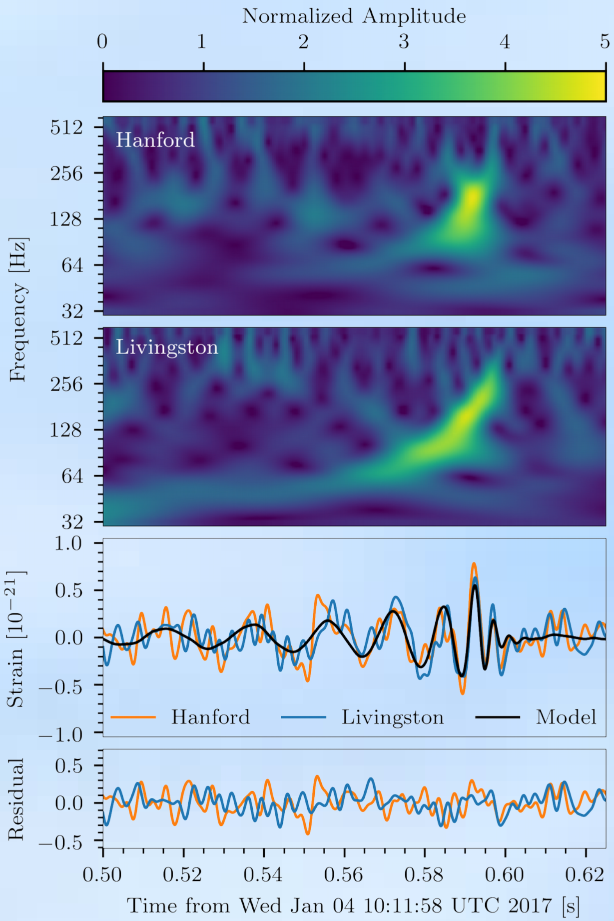


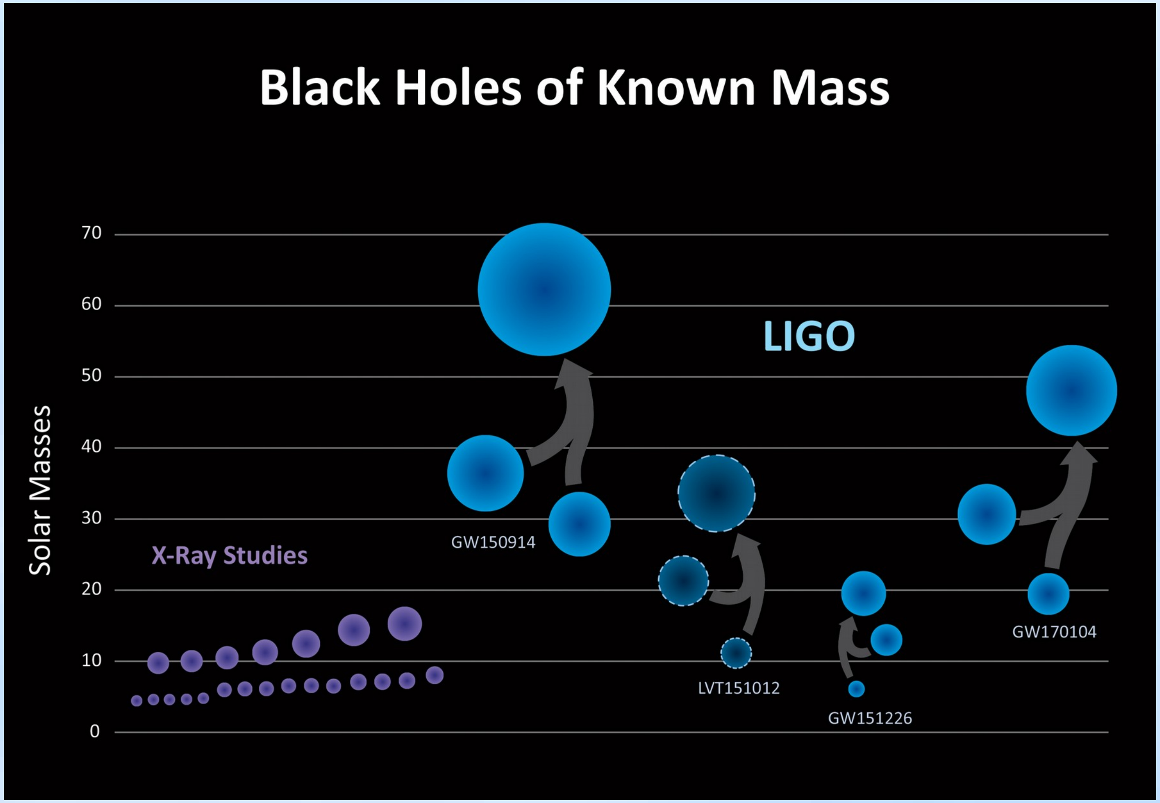
Image Credit - LIGO

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



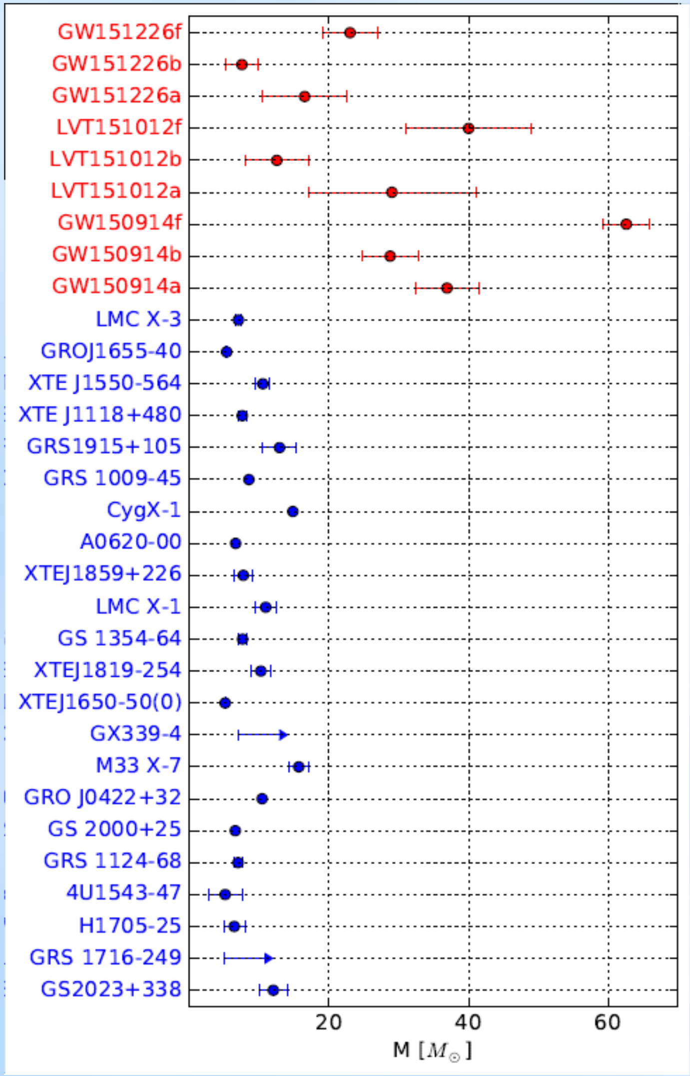
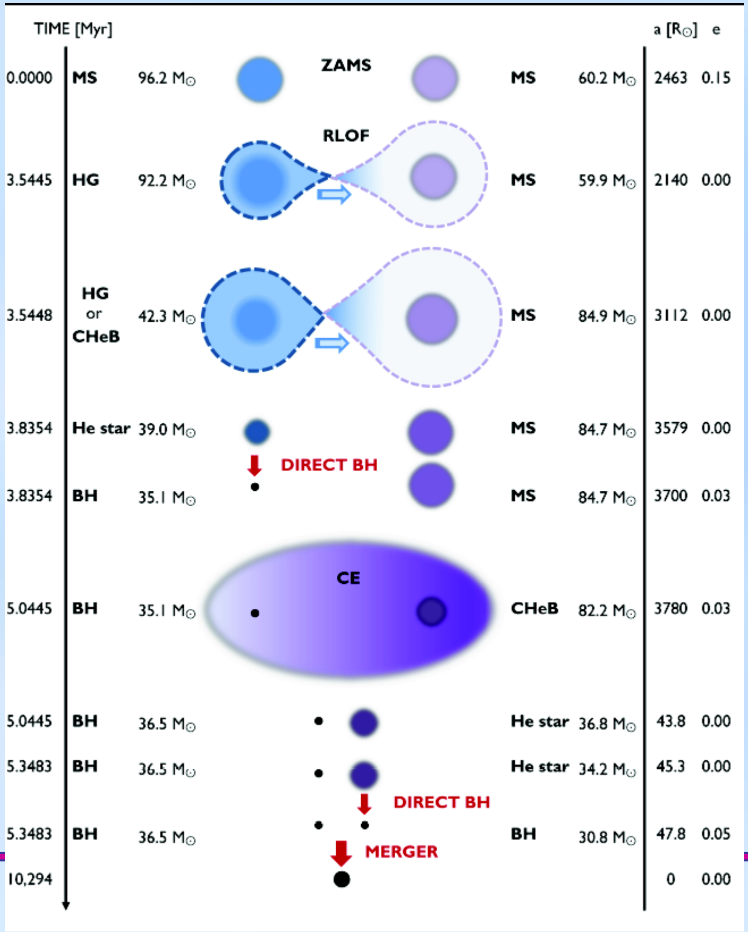


Image Credit LIGO

Astrophysics: Binary Black Hole Formation

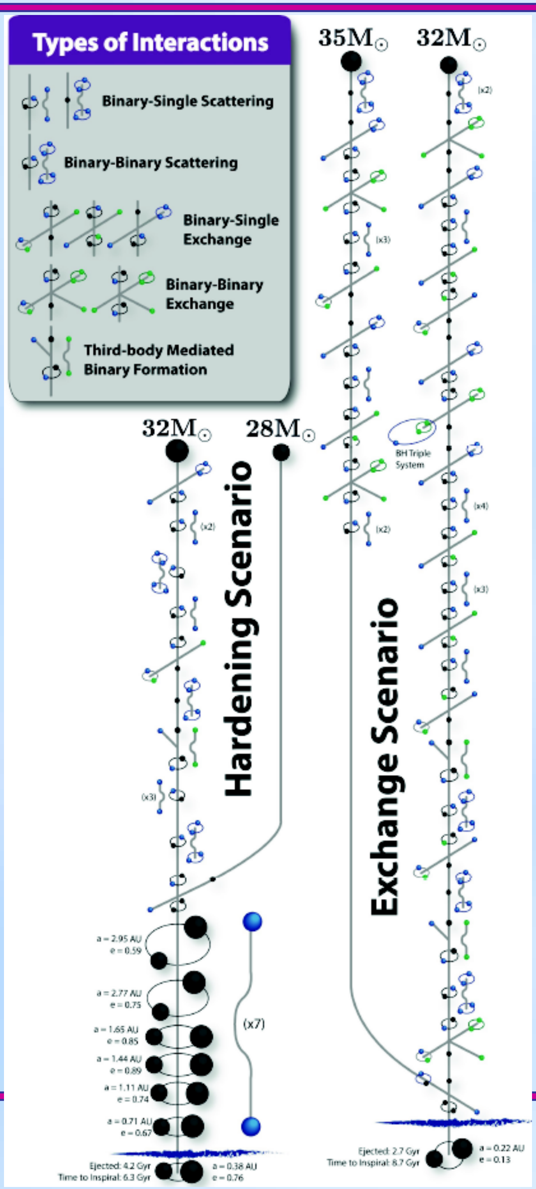
- Isolated Binaries
  - Solar to Population III
  - Rapid rotation



Belczynski et al. 2016

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

Low metallicity environment needed for large stellar mass black hole formation

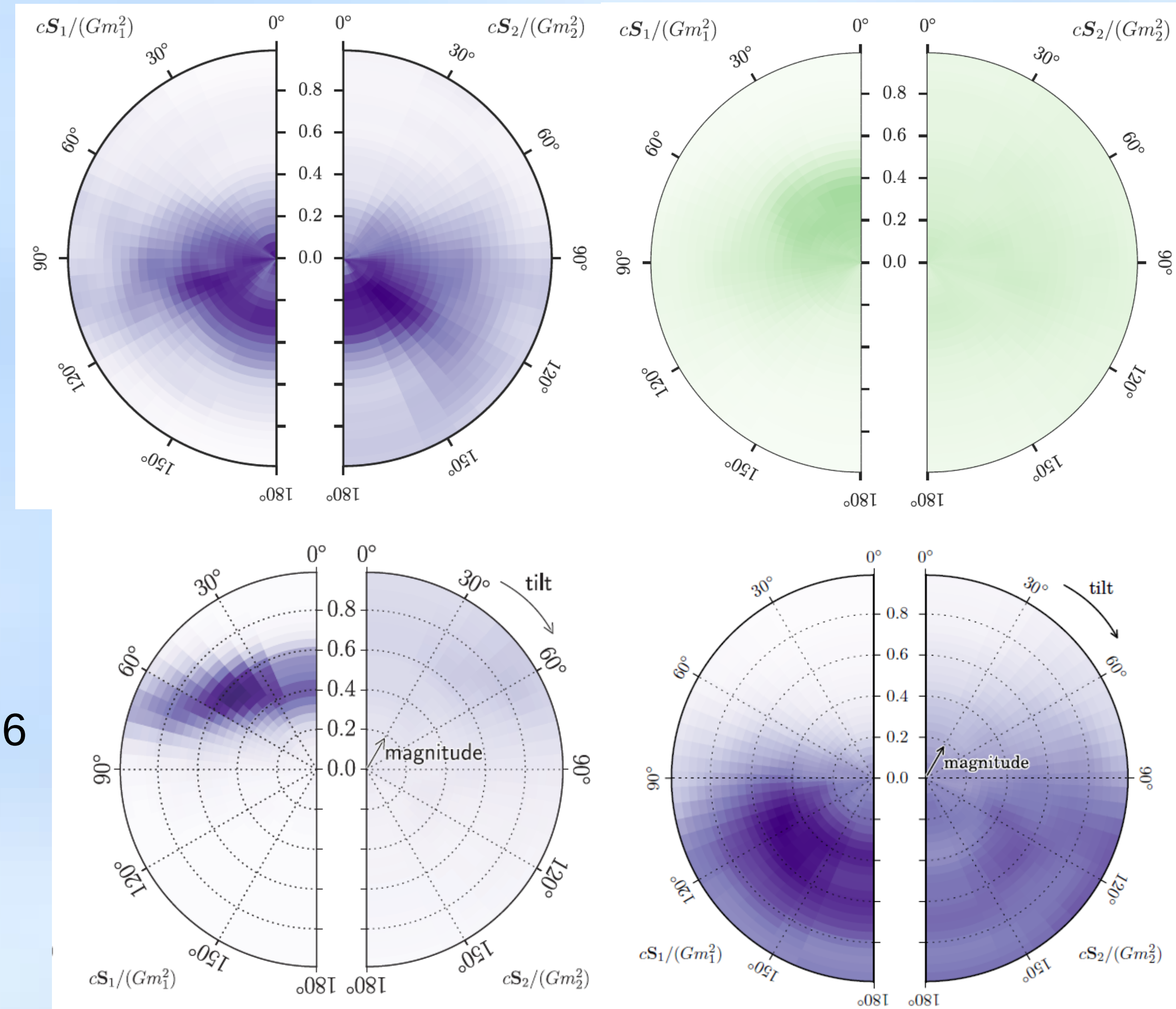


Arxiv 1602:02444, 1604:04254

Spin Observations Are Becoming Interesting

GW150914

LVT151012



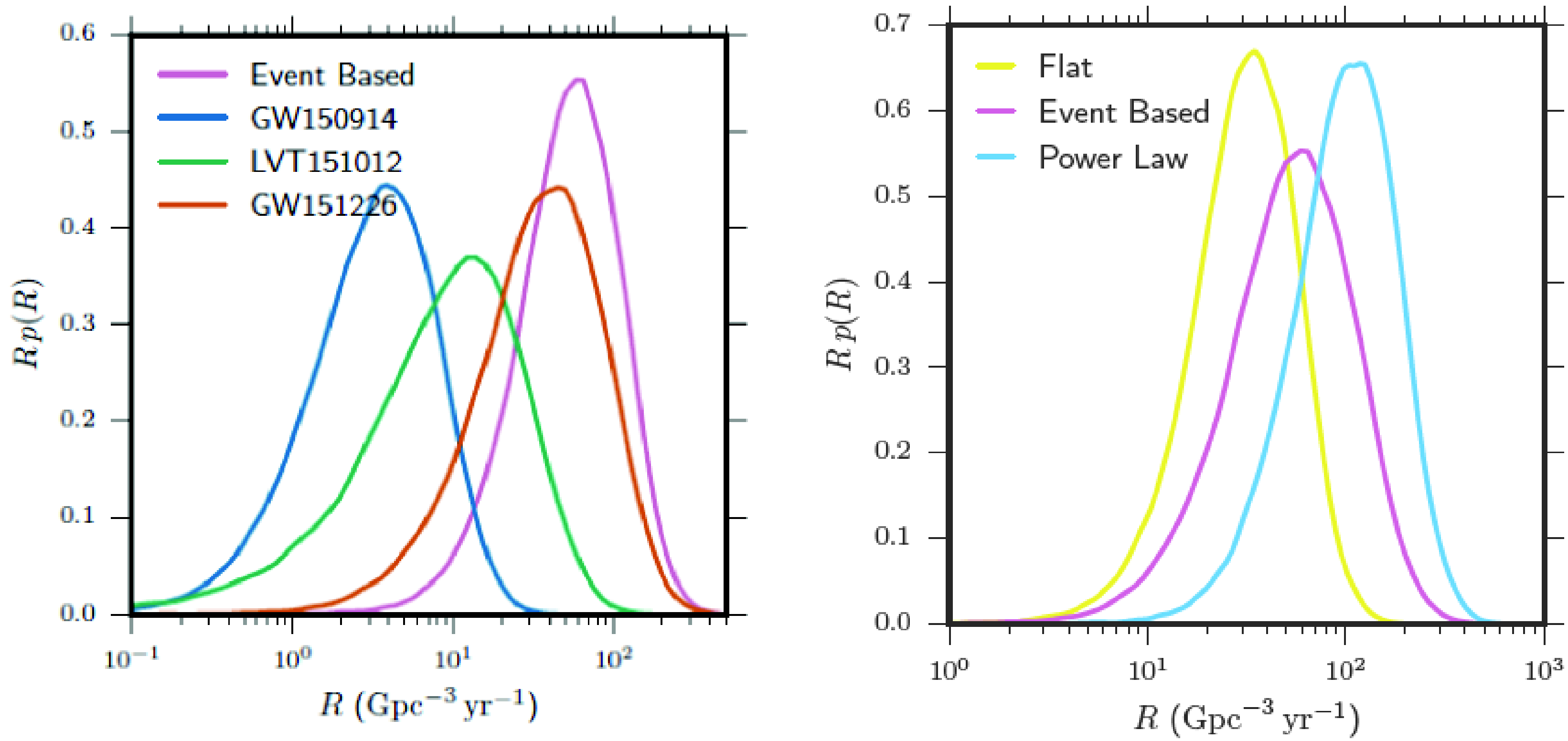
GW151226

GW170114

Isolated Binary Formation?

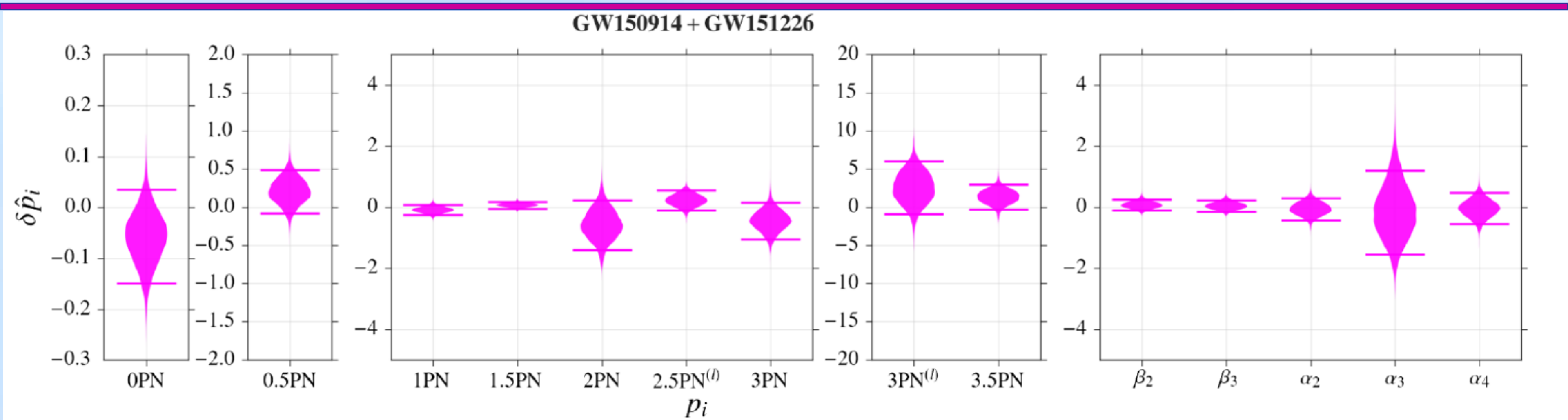
Cluster Formation?

Binary Black Hole Merger Rate



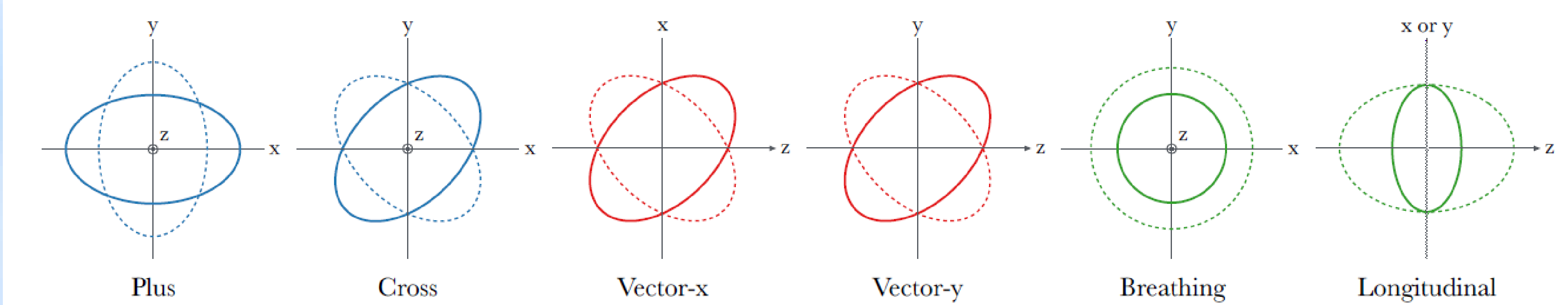
90% allowed range: [9-240] /Gpc^3/yr

Testing General Relativity



PHYS. REV. X 6, 041015 (2016)

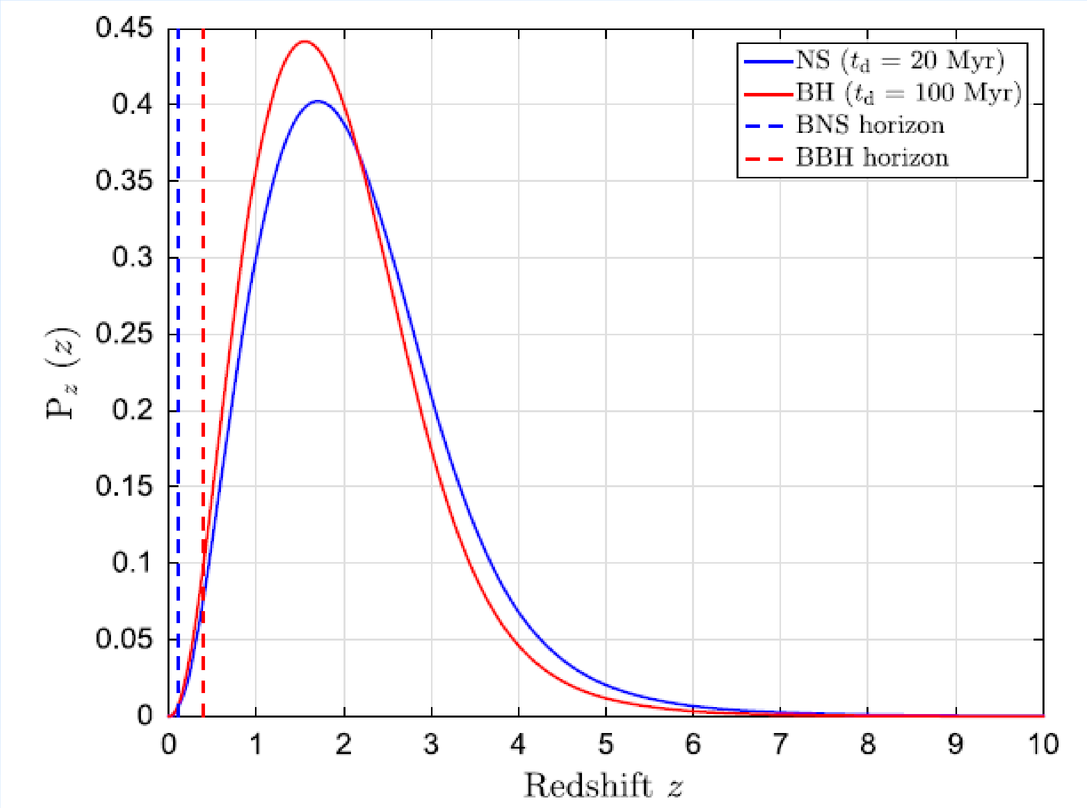
Posterior density distributions for relative deviations in the PN, intermediate, and merger-ringdown parameters.



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

Implications for a Stochastic Background of GWs

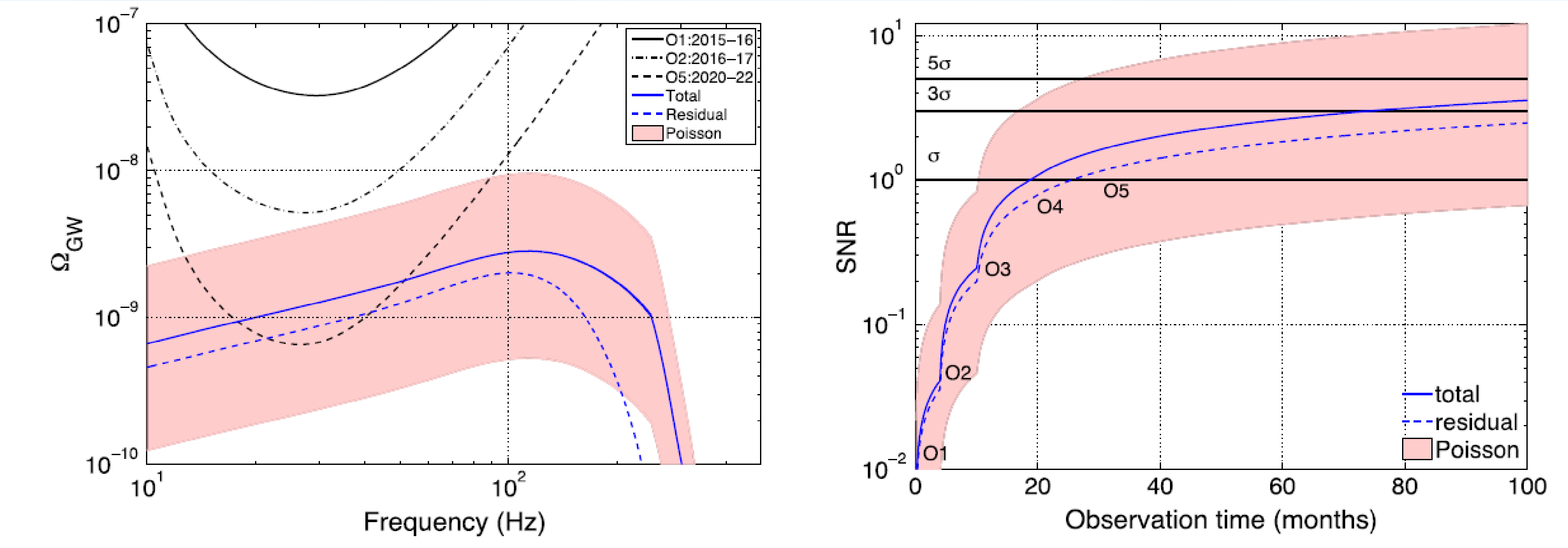
Probing compact binary decays predominantly between z ~ 1 – 3.



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

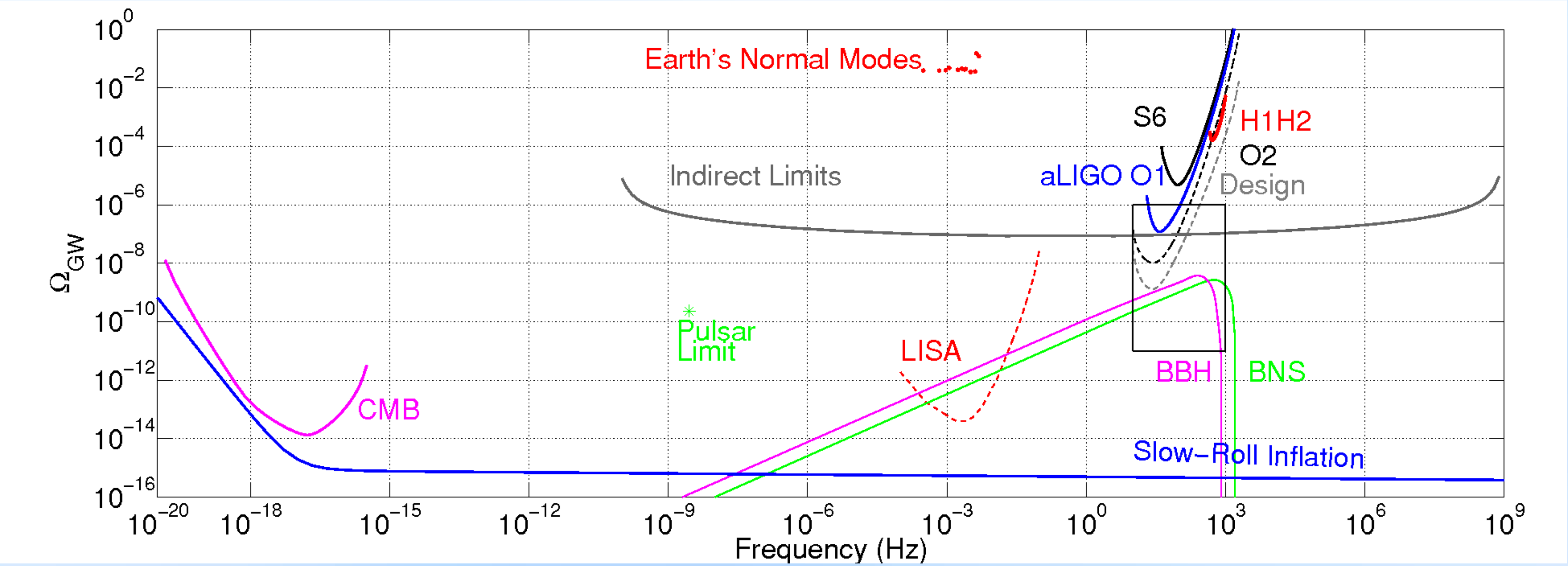


Based on the Field formation mechanism, assuming GW150914 parameters.

Assumptions are necessary; best information available in literature.

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

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"

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

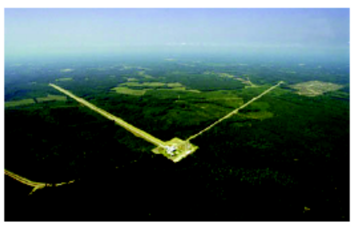
Future Observing Runs

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



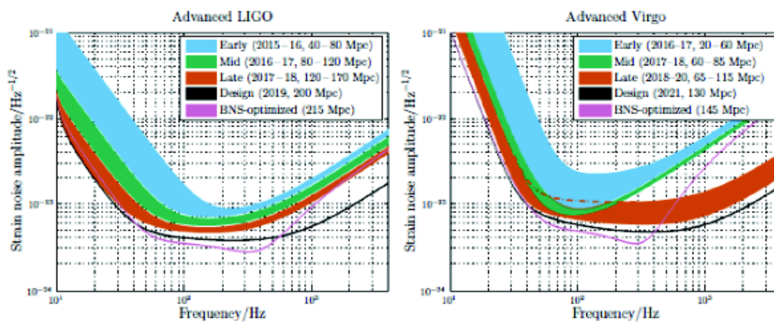


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late 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).

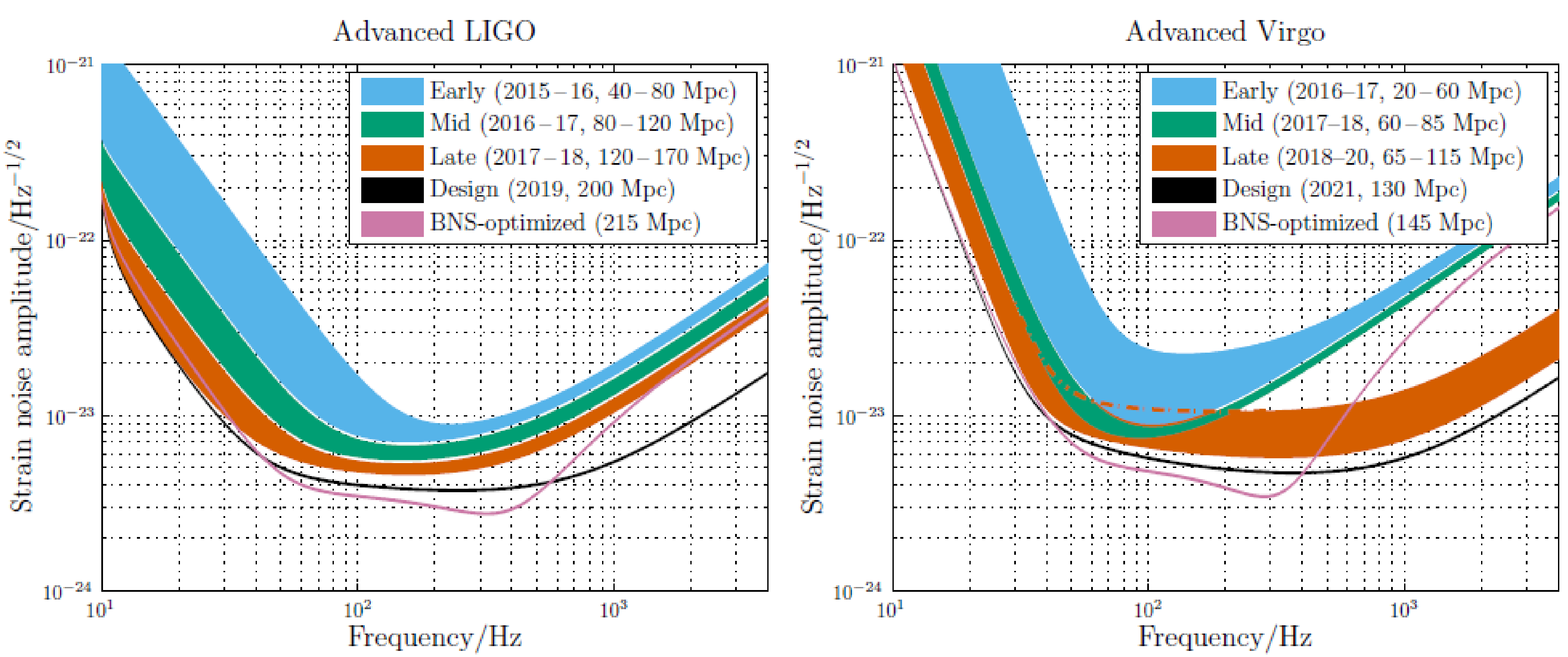
2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

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.

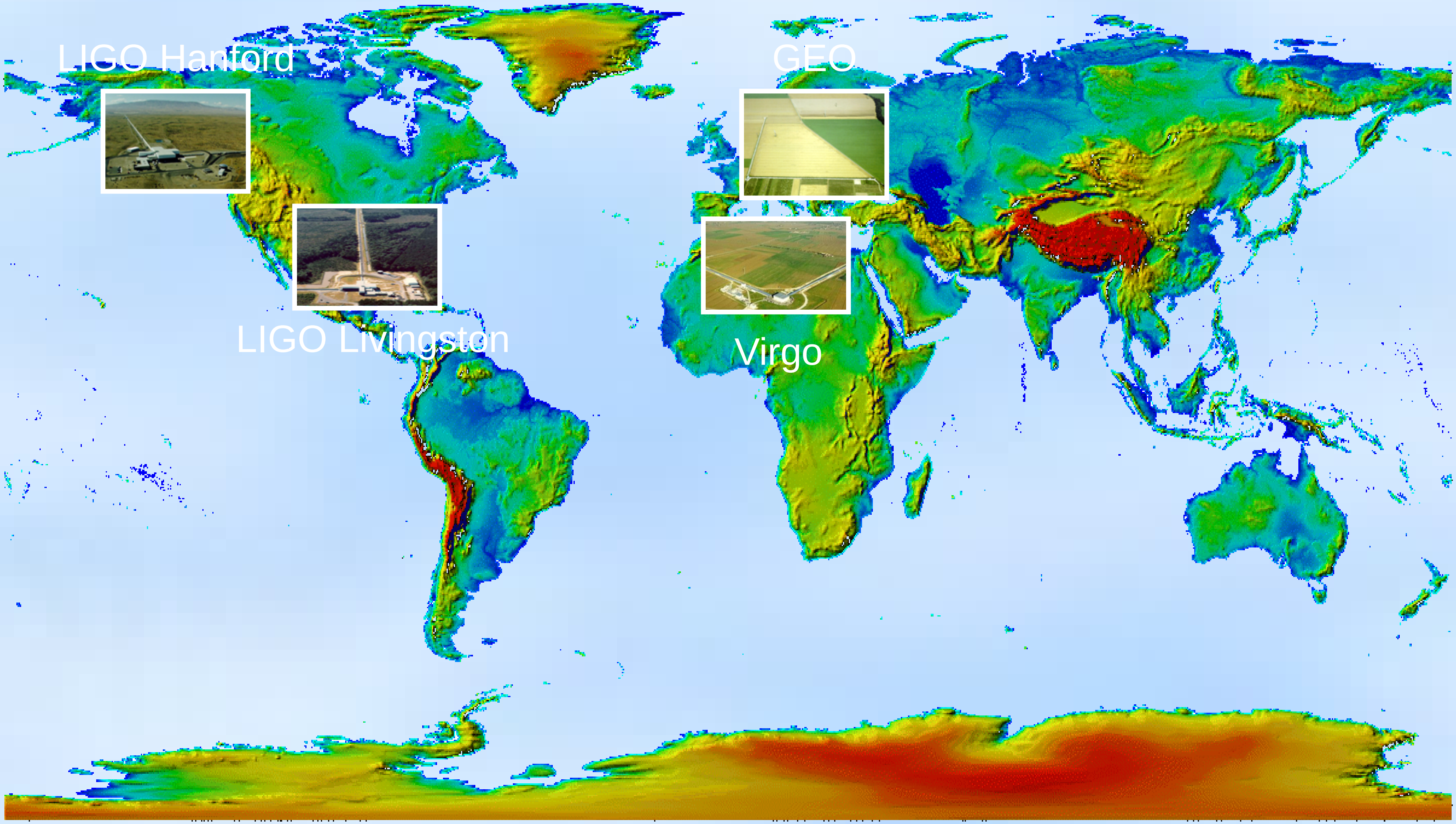
Observing Run O2 started November 30, 2016. Should last until end of August.

Expected Advanced LIGO-Virgo Sensitivities

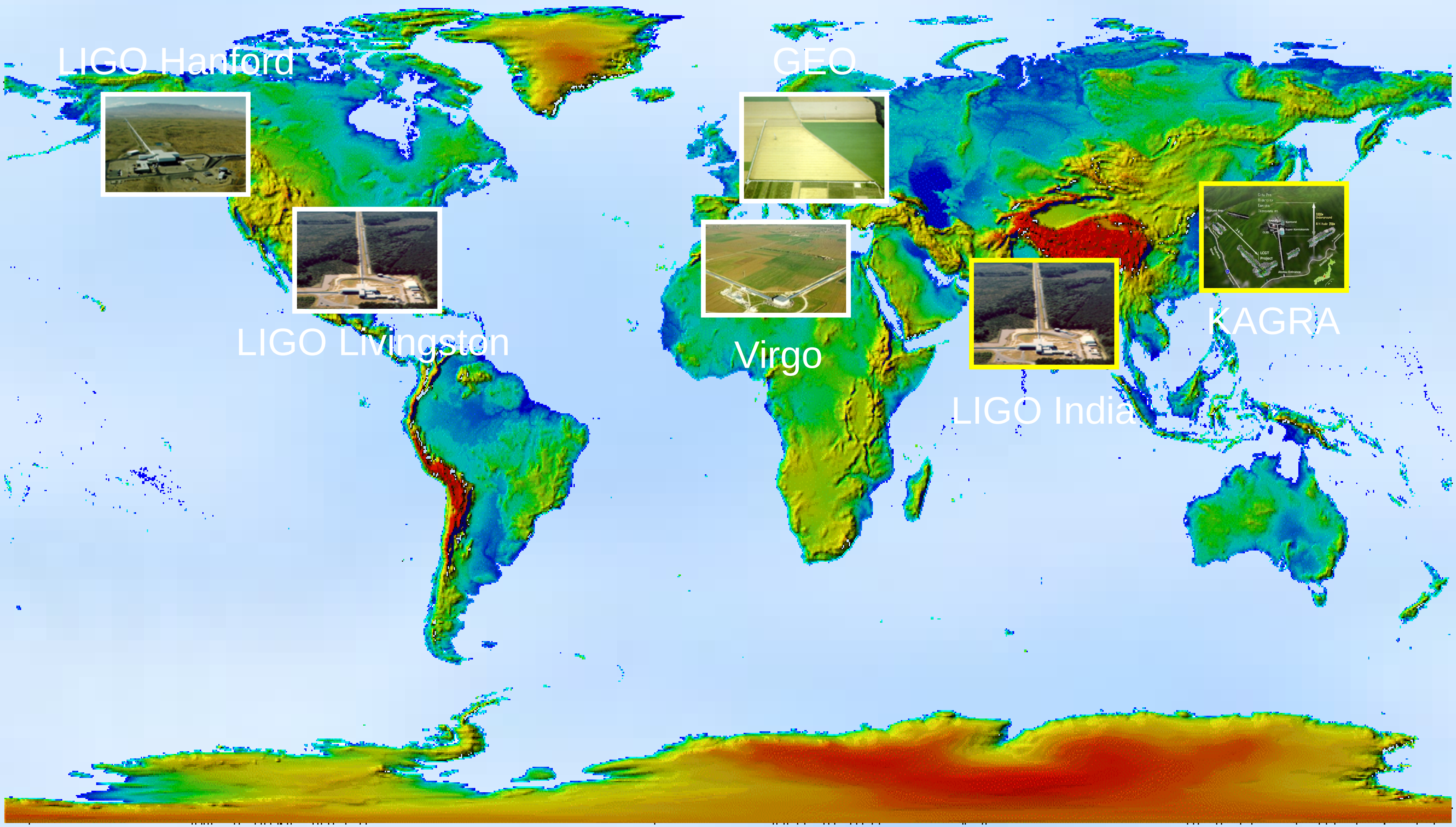


Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

A detector network



An even better detector network

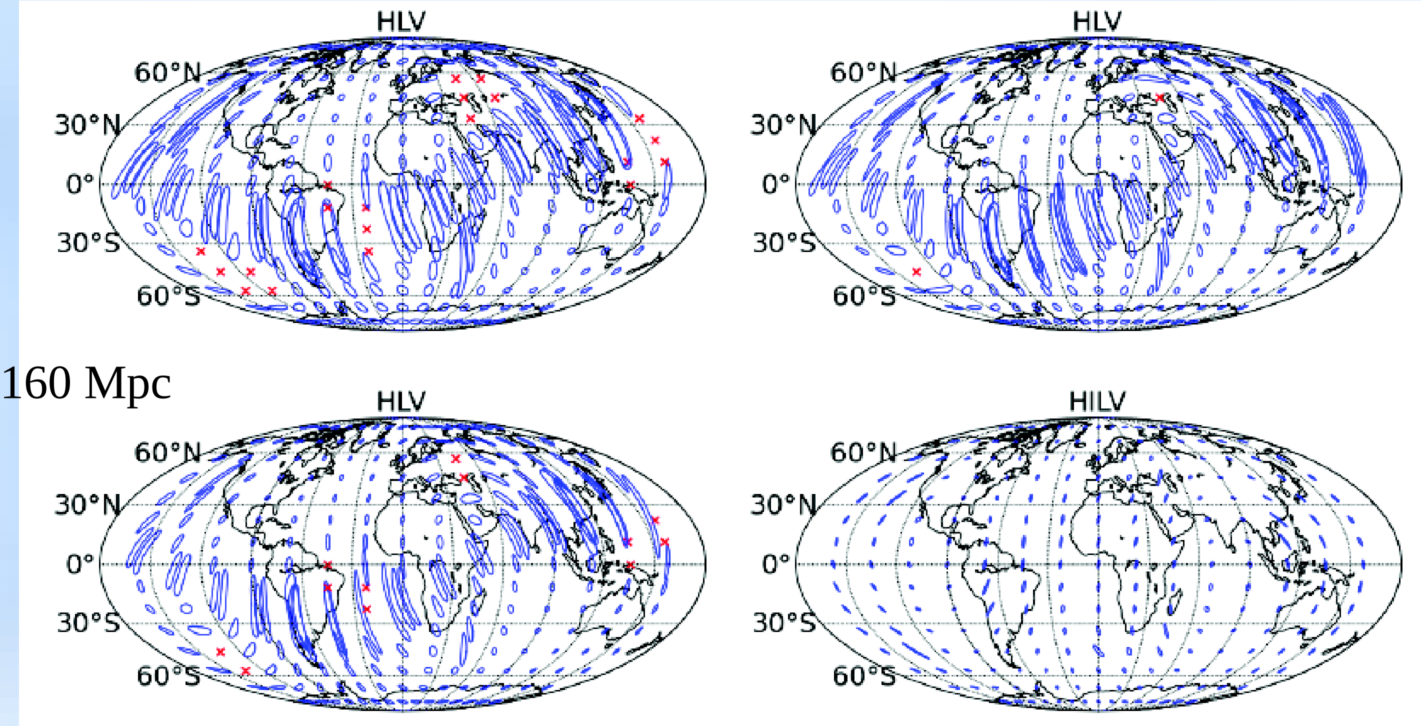


Advanced LIGO/Virgo sky localization

BNS source @ 80 Mpc

2016-2017 runs

2018-2019 runs



BNS source @ 160 Mpc

2019+ runs

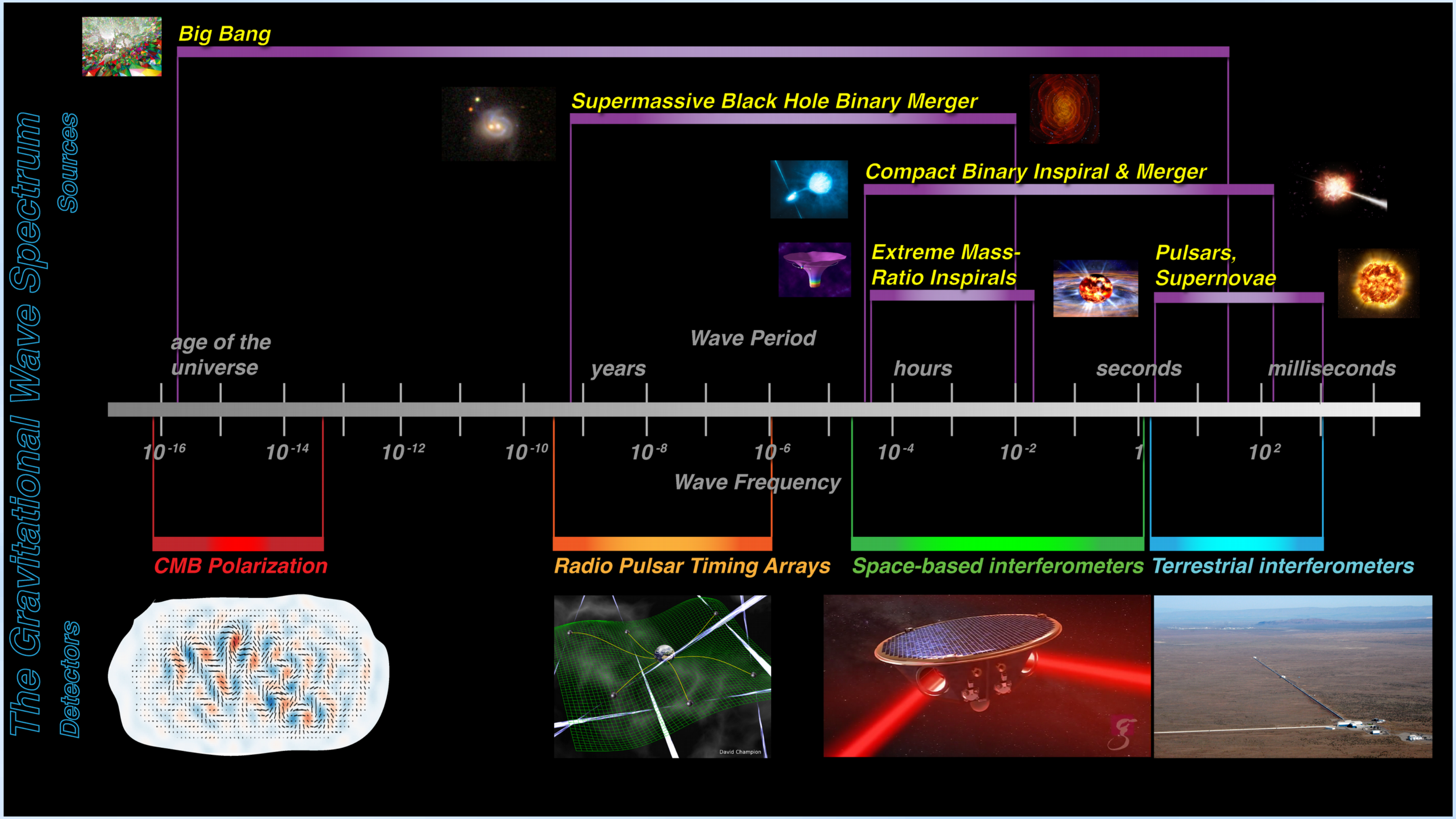
HLV + LIGO India 2022+

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

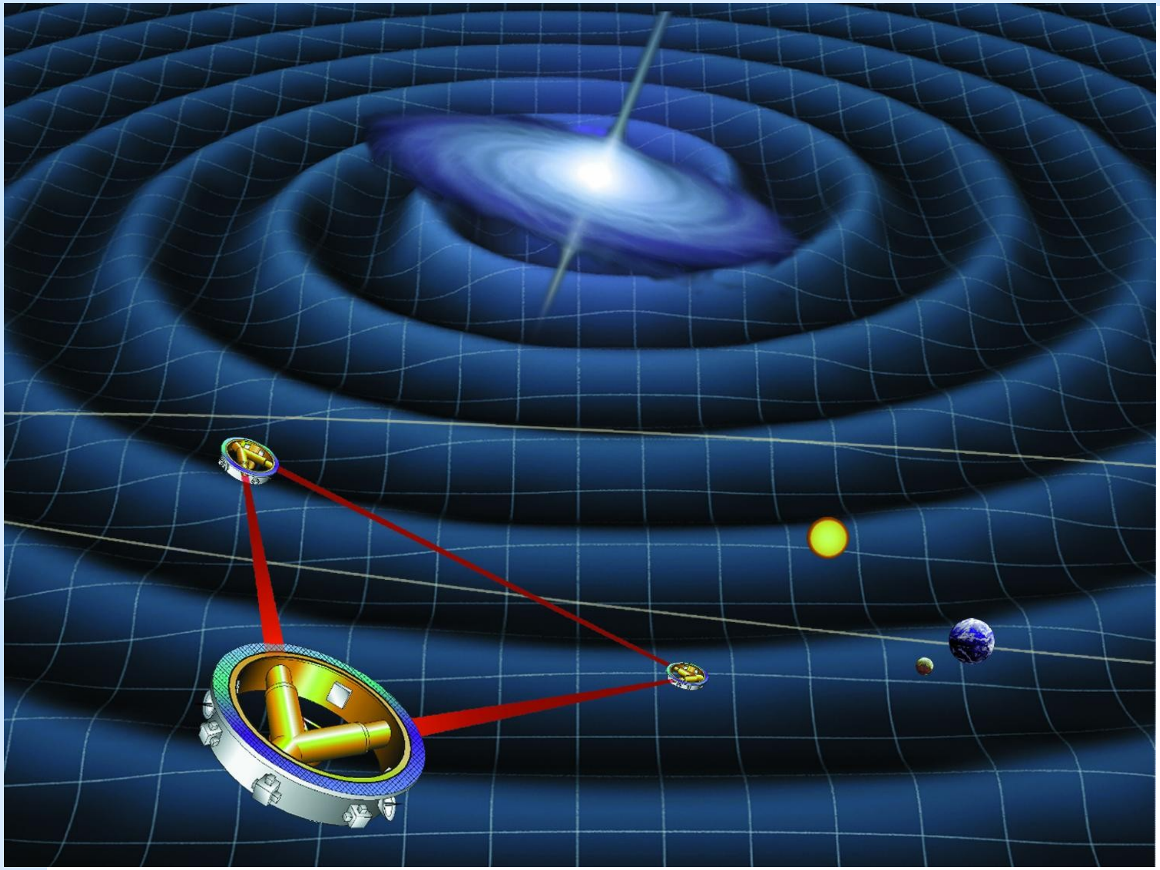
LIGO – Virgo Summary

- 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 ongoing, with Virgo joining in a couple of months
- 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



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

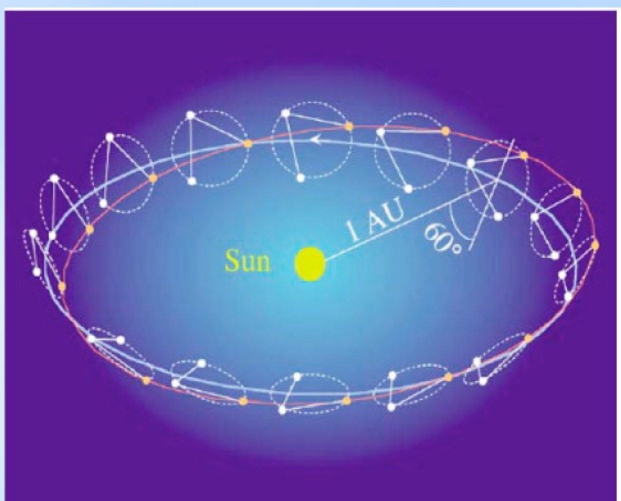
Tremendous activity at present

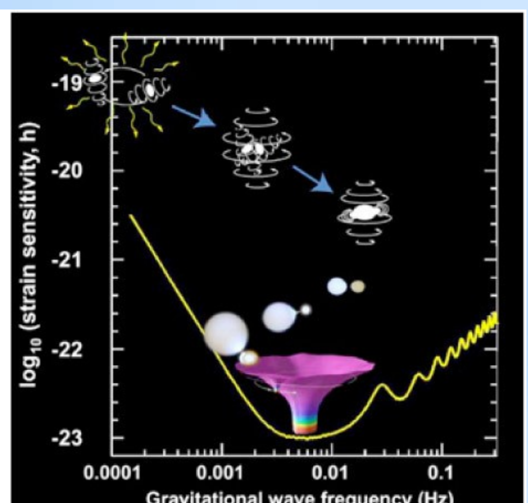
Present plan: 3 Interferometers
2.5 x 10^6 km arm lengths

LISA physics

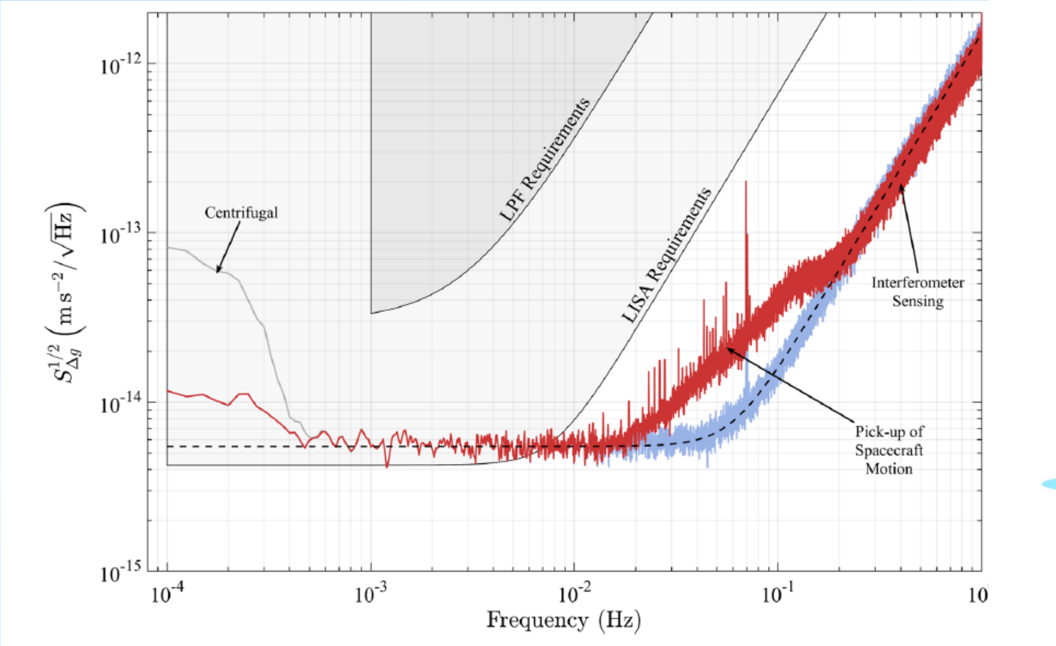
- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

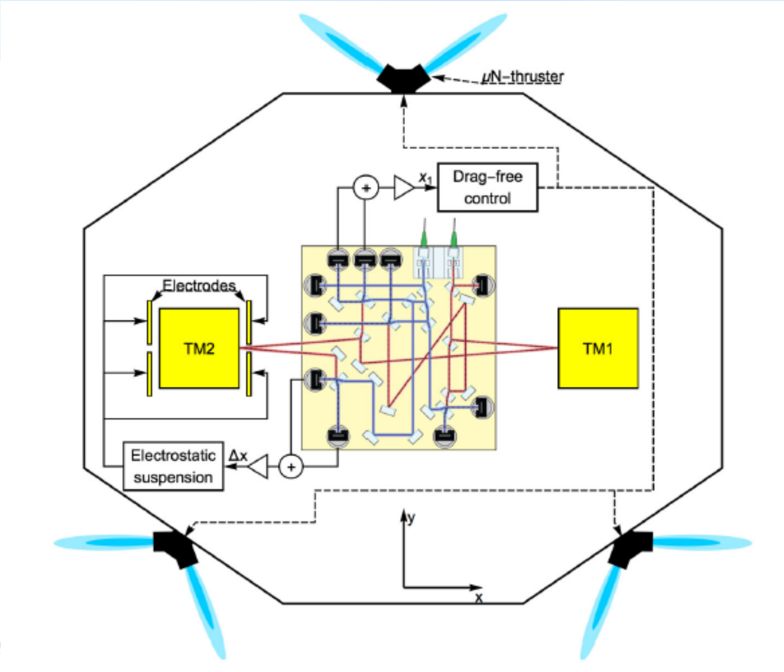
Gravitational Observatory Advisory Team – GOAT (ESA web site)





LISA Pathfinder – Demonstrating LISA Technology



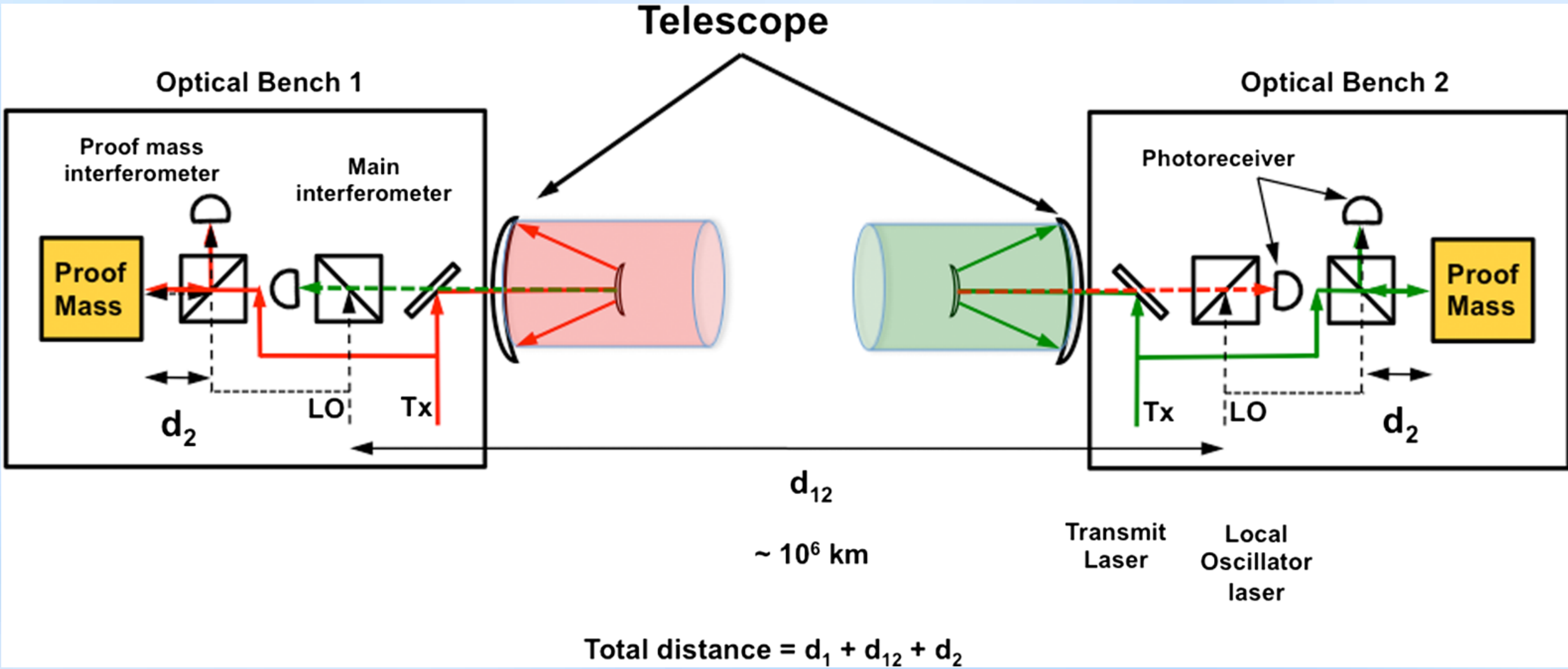


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

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.

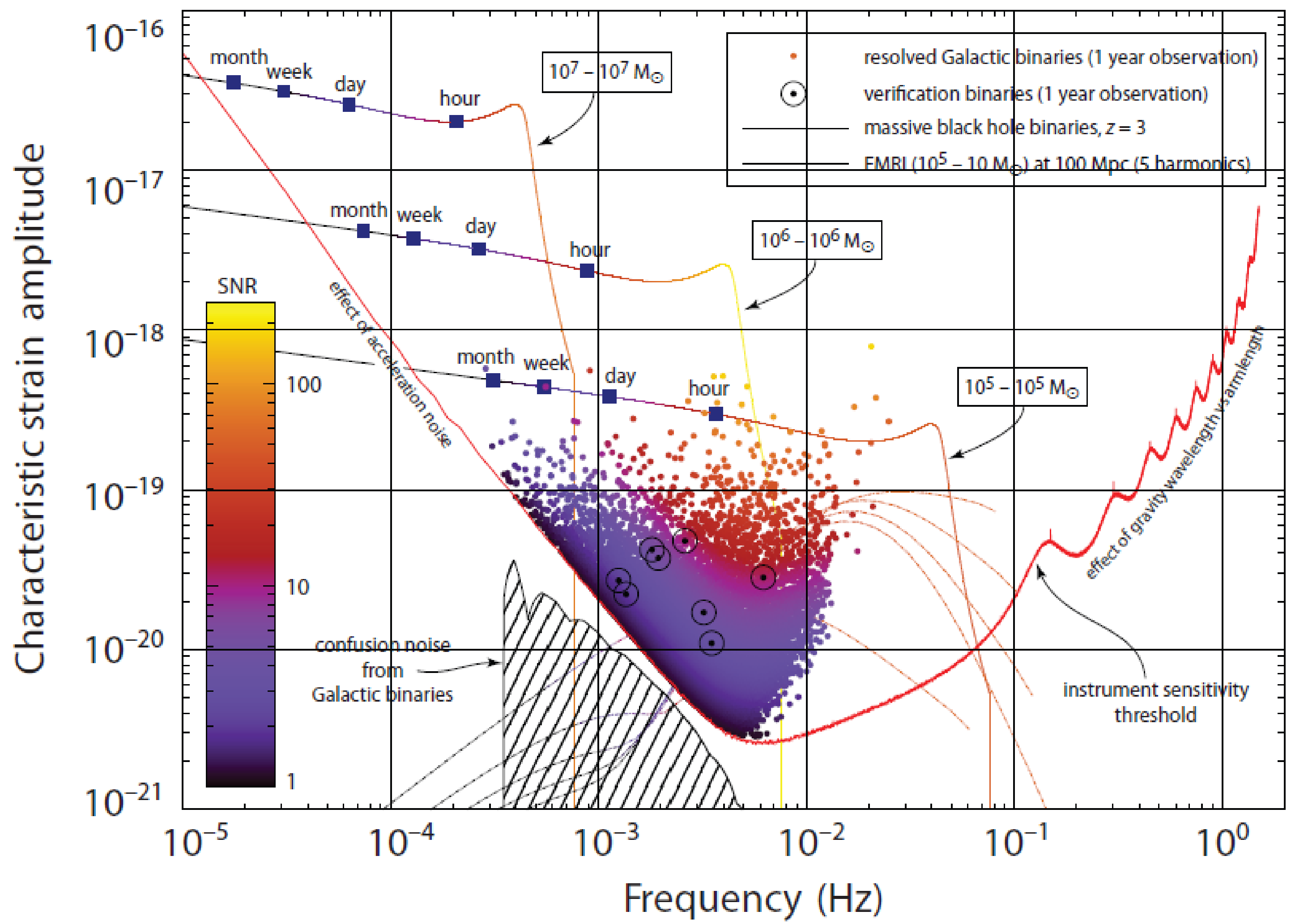
PRL **116**, 231101 (2016)

LISA Proof Masses, Optical Bench, Interferometry and Telescopes



Livas et al, Opt. Eng. 52(9), 091811 (2013)

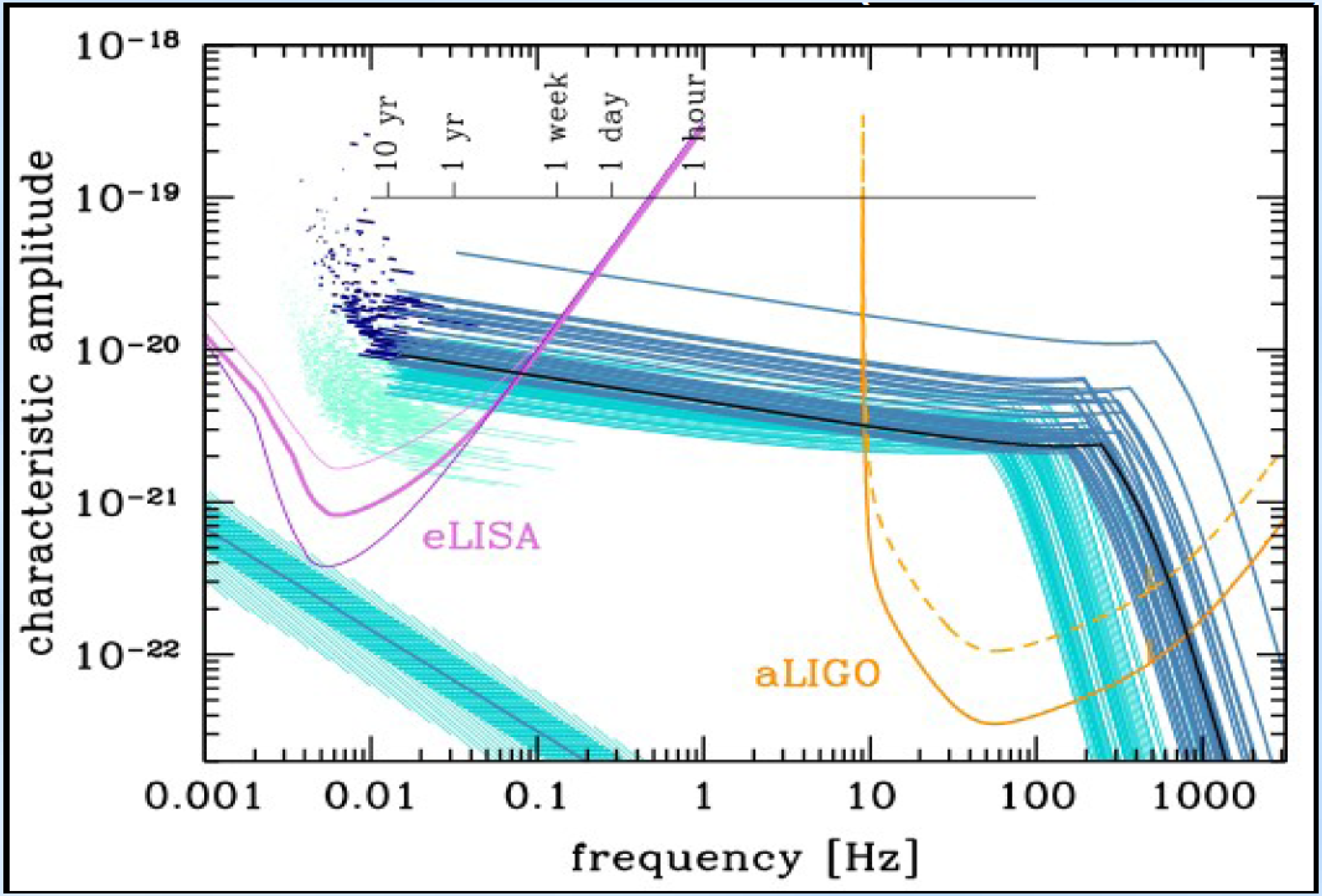
LISA Physics



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.

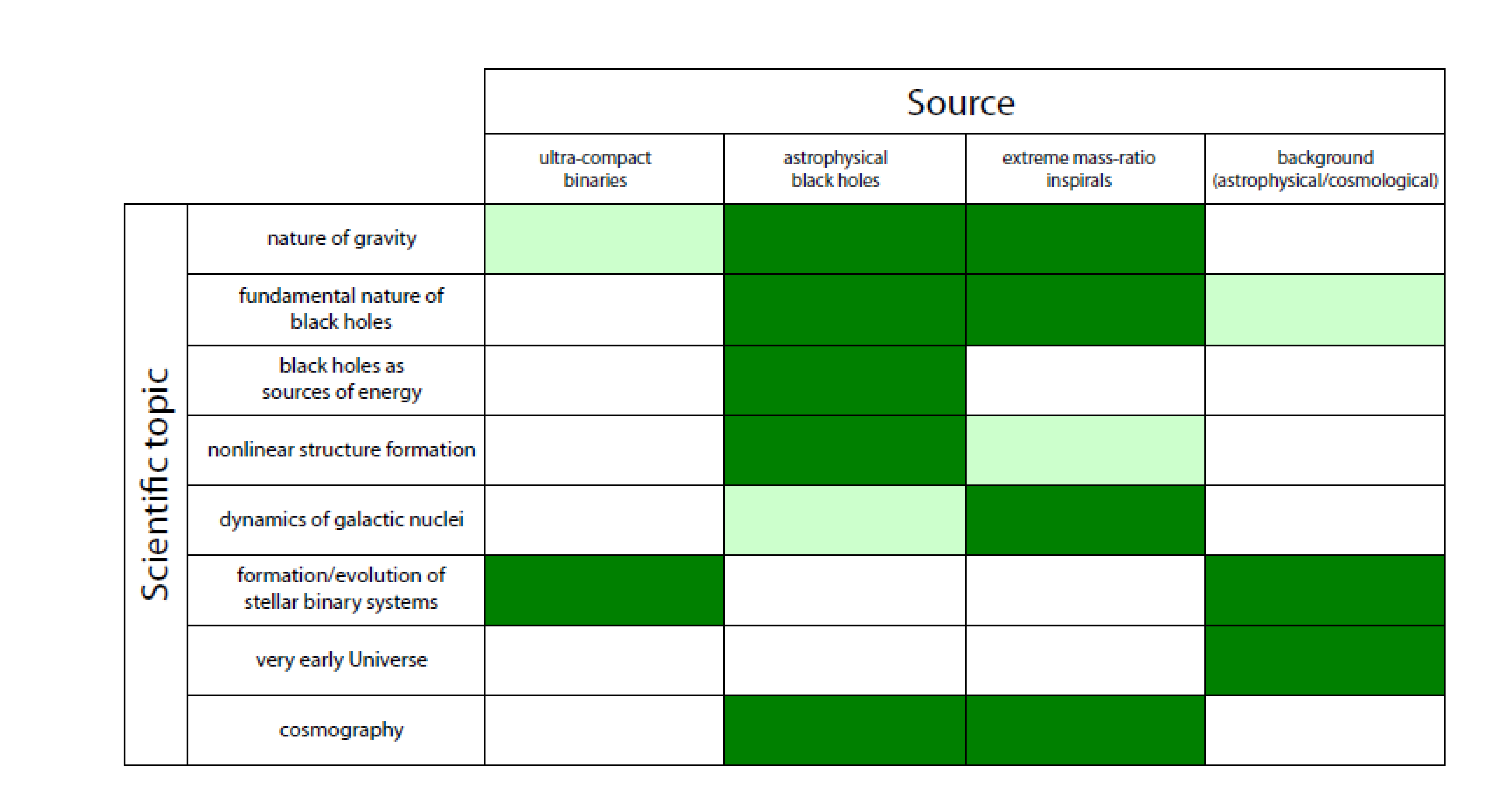
LISA Physics



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

Testing the Early Universe

- Inflation
- Electro-weak phase transition, or phase transitions related to new physics
- Cosmic strings (phase transitions, topological defects, cosmic superstrings)



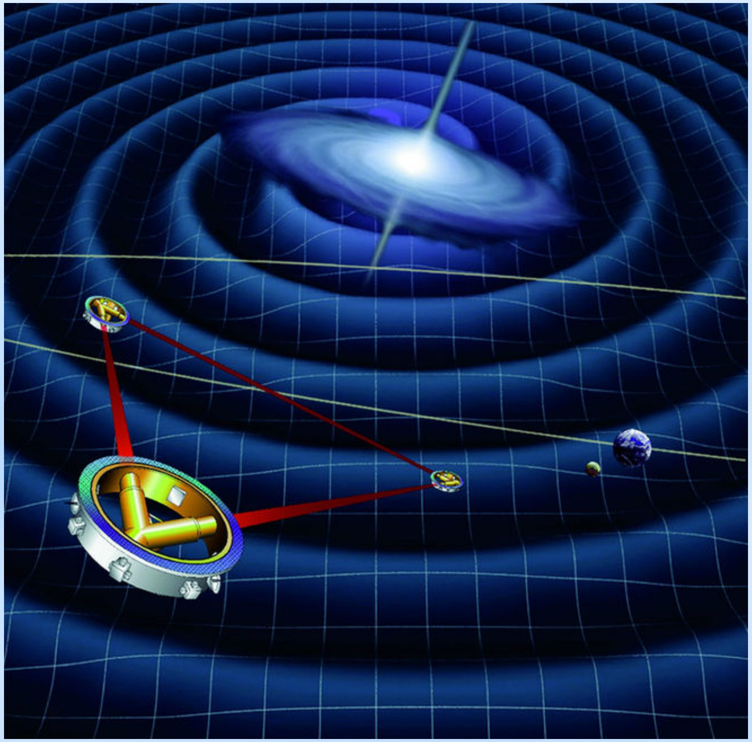
LISA Summary

The LISA project is presently moving forward rapidly.

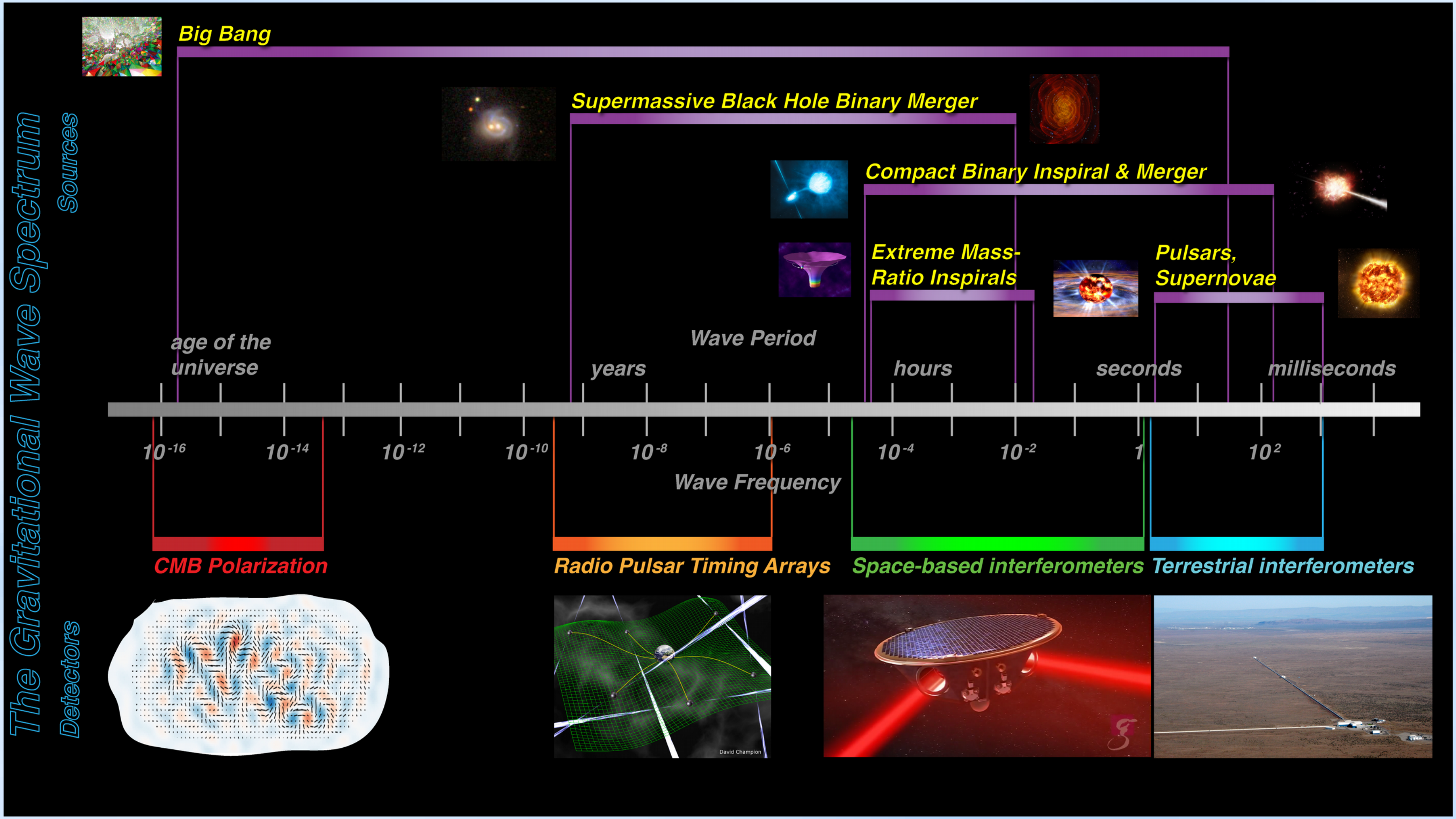
ESA and NASA see this as a high priority.

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

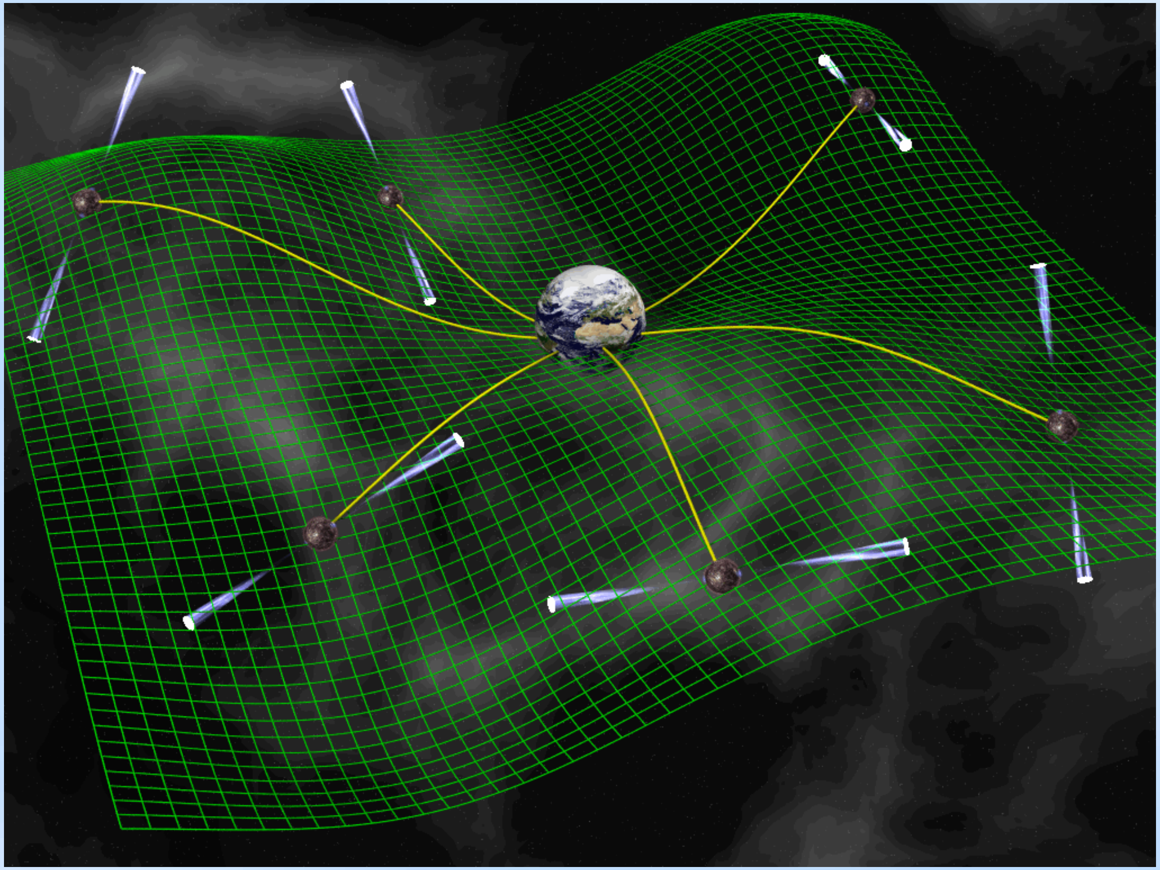
After the LHC, LISA may offer the best opportunity to observe the high energy physics that describes the universe.



Gravitational Wave Spectrum



Pulsar Timing

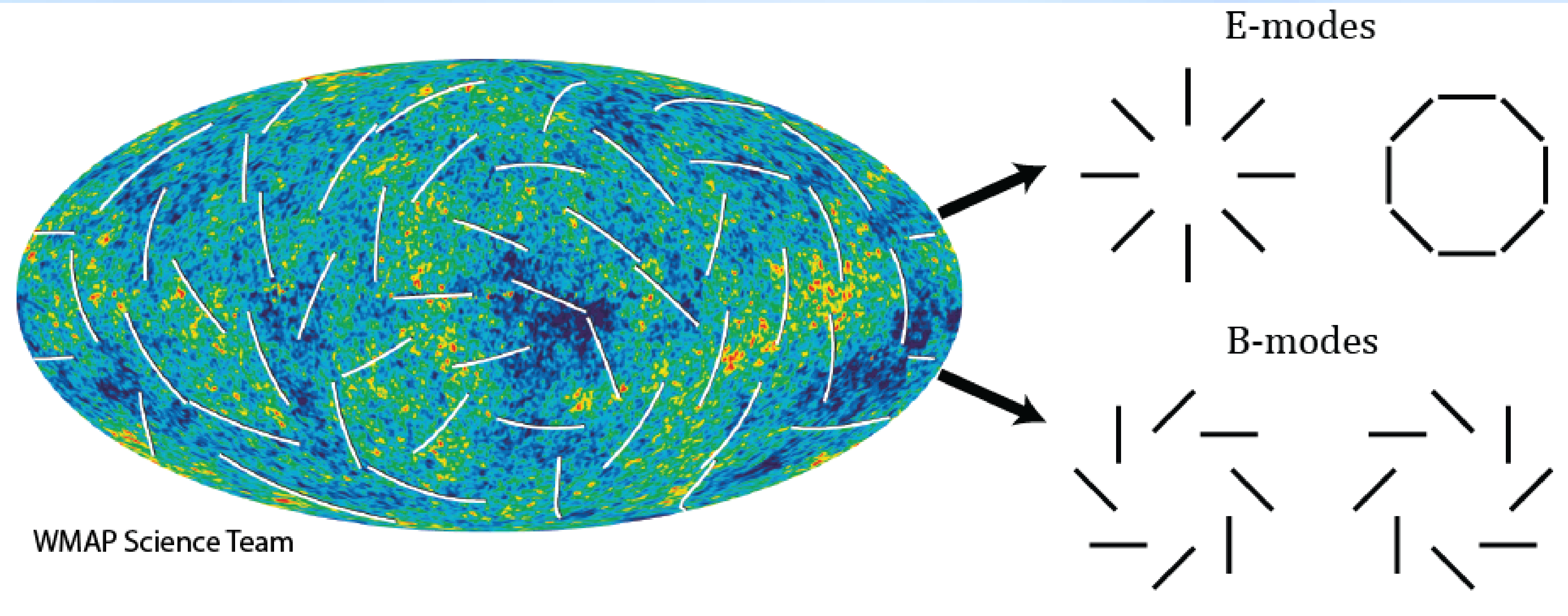


Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

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

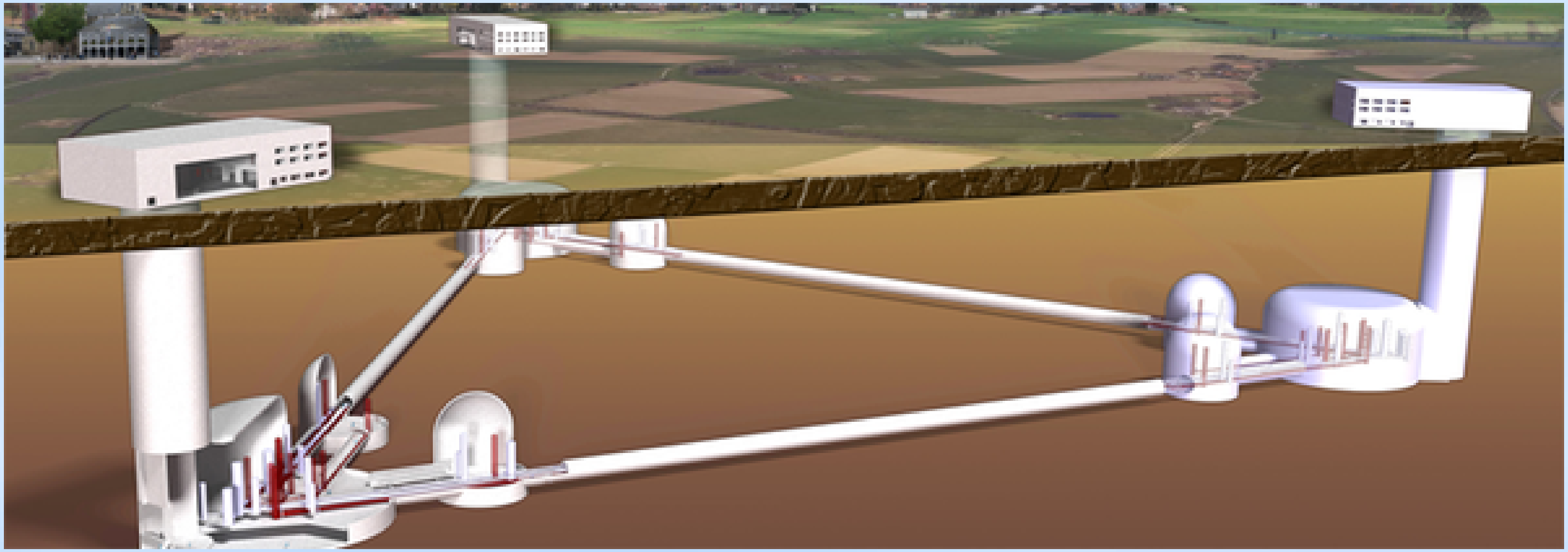


The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

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

Third Generation Gravitational Wave Detectors

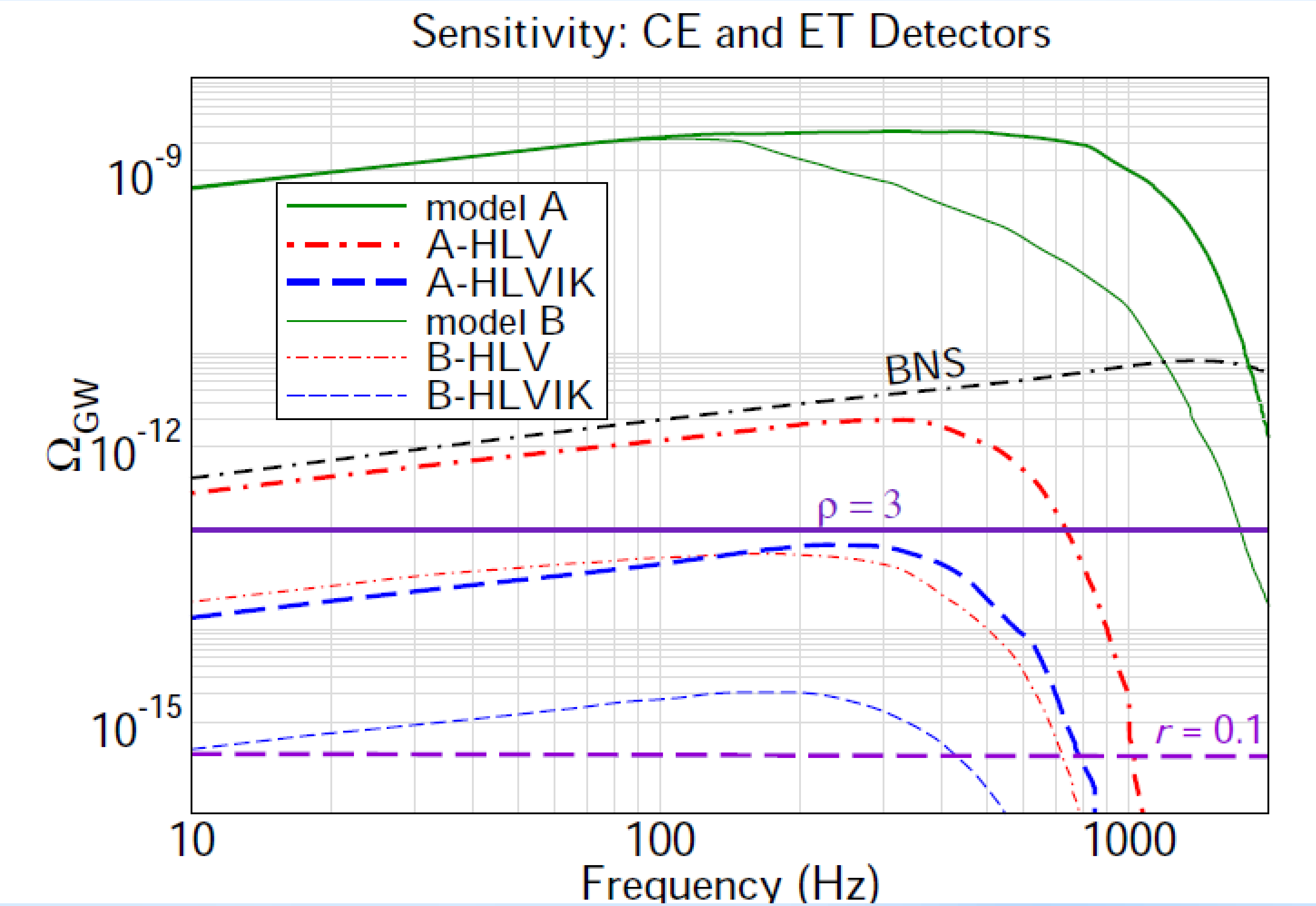
Einstein Telescope



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

Third Generation Gravitational Wave Detectors

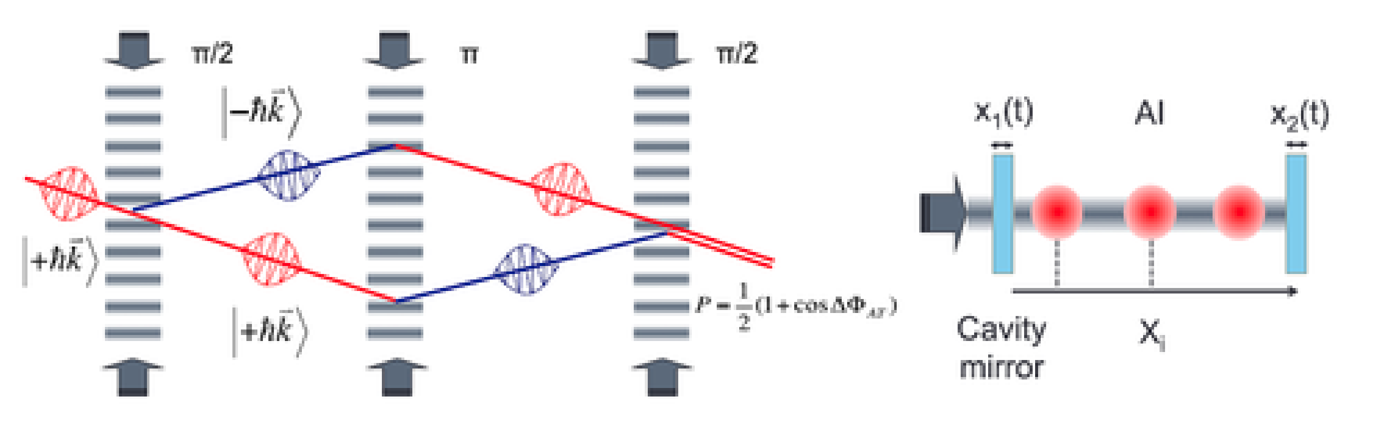
With Einstein Telescope (European) or Cosmic Explorer (US) almost every stellar mass binary black hole merger in the observable universe will be detectable.



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

Atom Interferometers

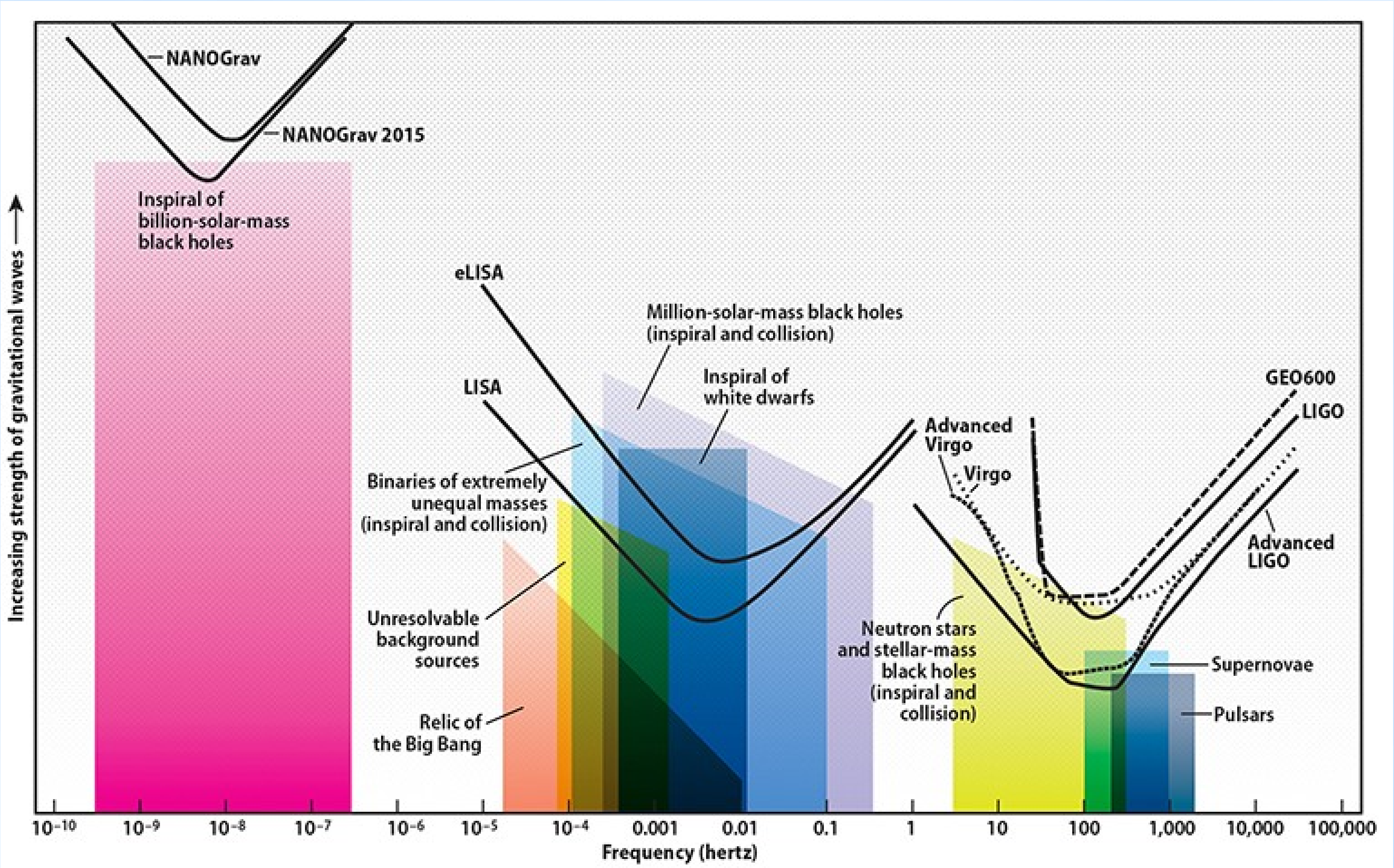


Use a long optical cavity to interrogate atom interferometers.

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.

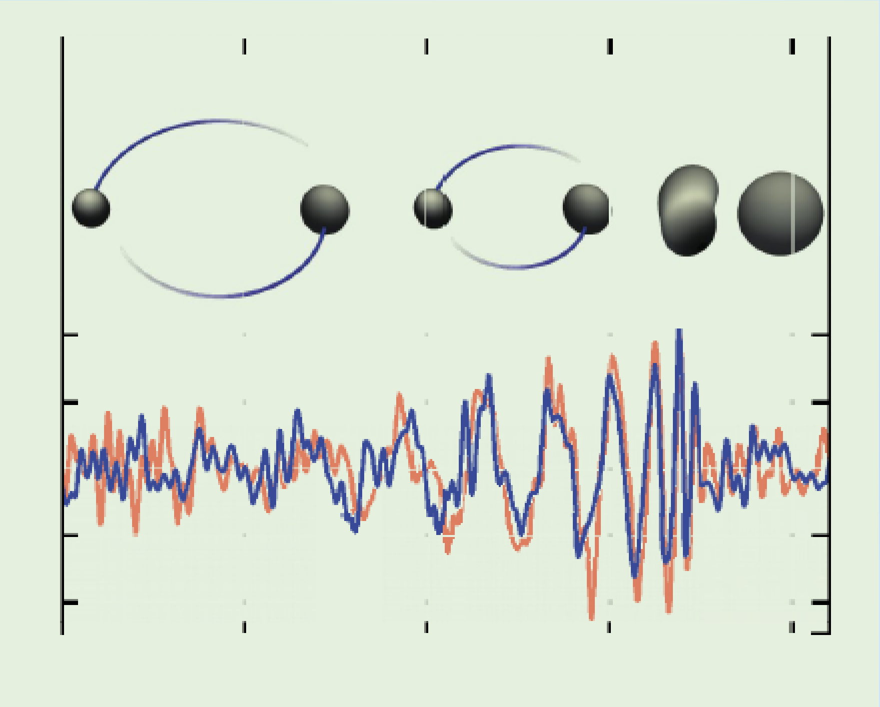
Arxiv 1505:07137

Gravitational Wave Spectrum



Atom interferometric detectors would fill a critically important region of the GW spectrum. Between LISA and LIGO-Virgo

Conclusion on Gravitational Waves

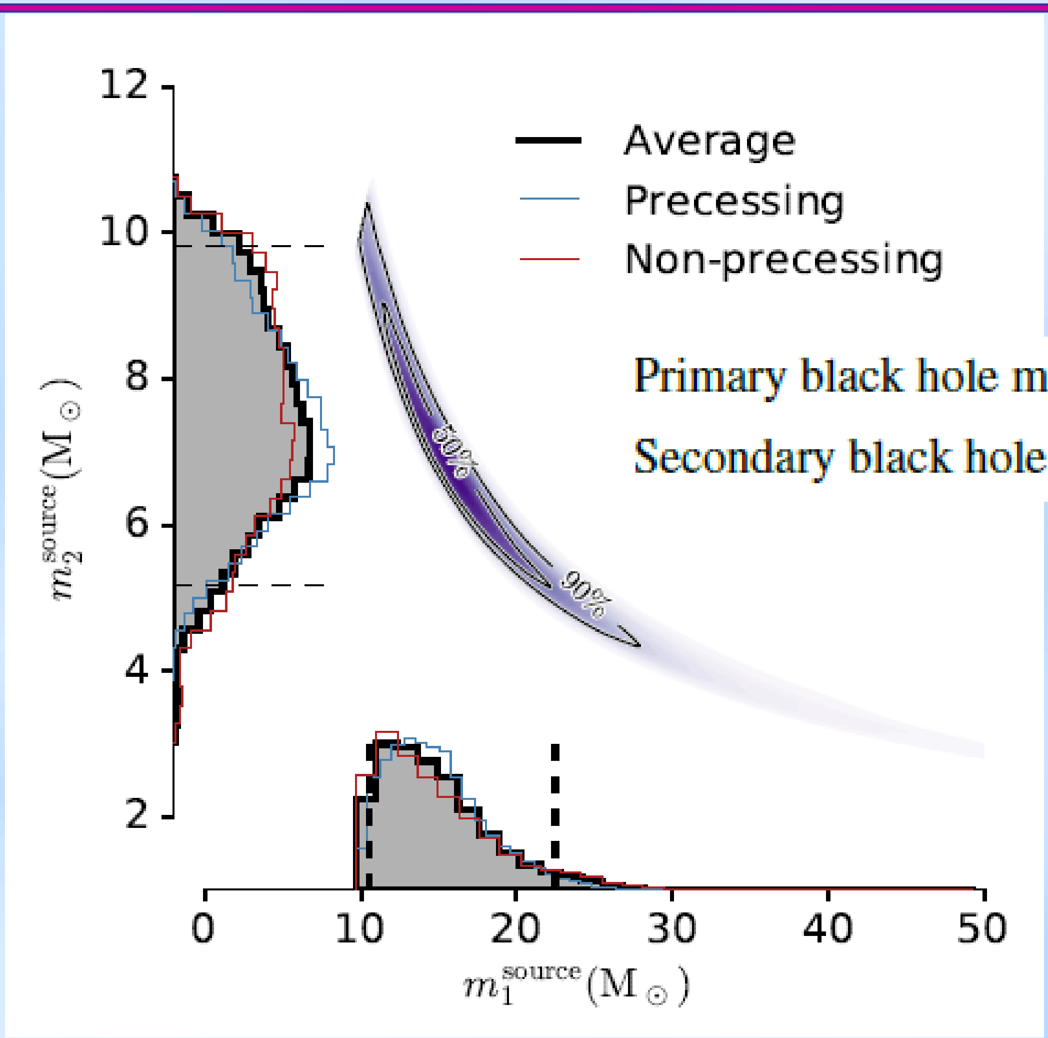


A new window on the universe has opened.

We are just beginning!

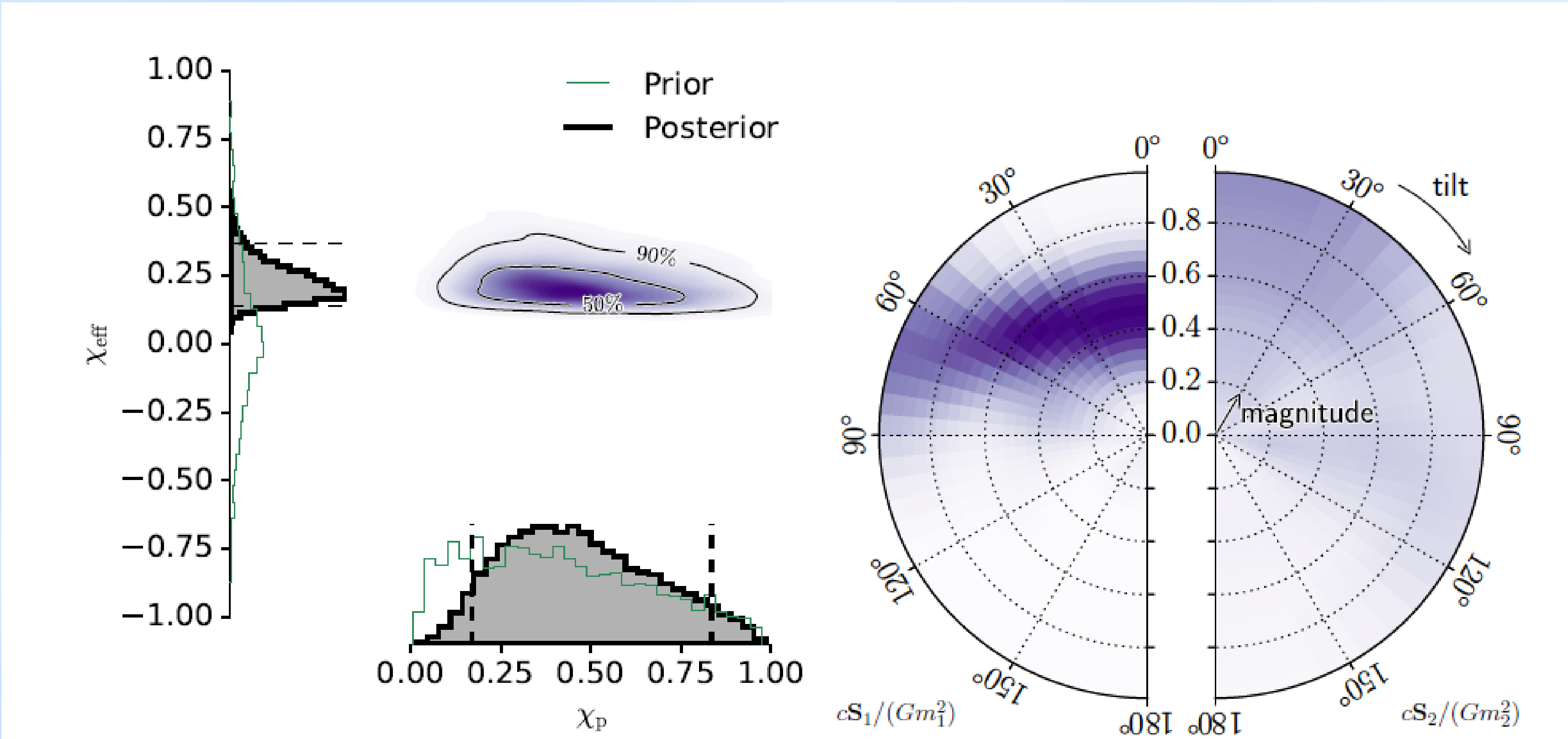
Extra Slides

GW151226 – Mass Estimates (source frame)



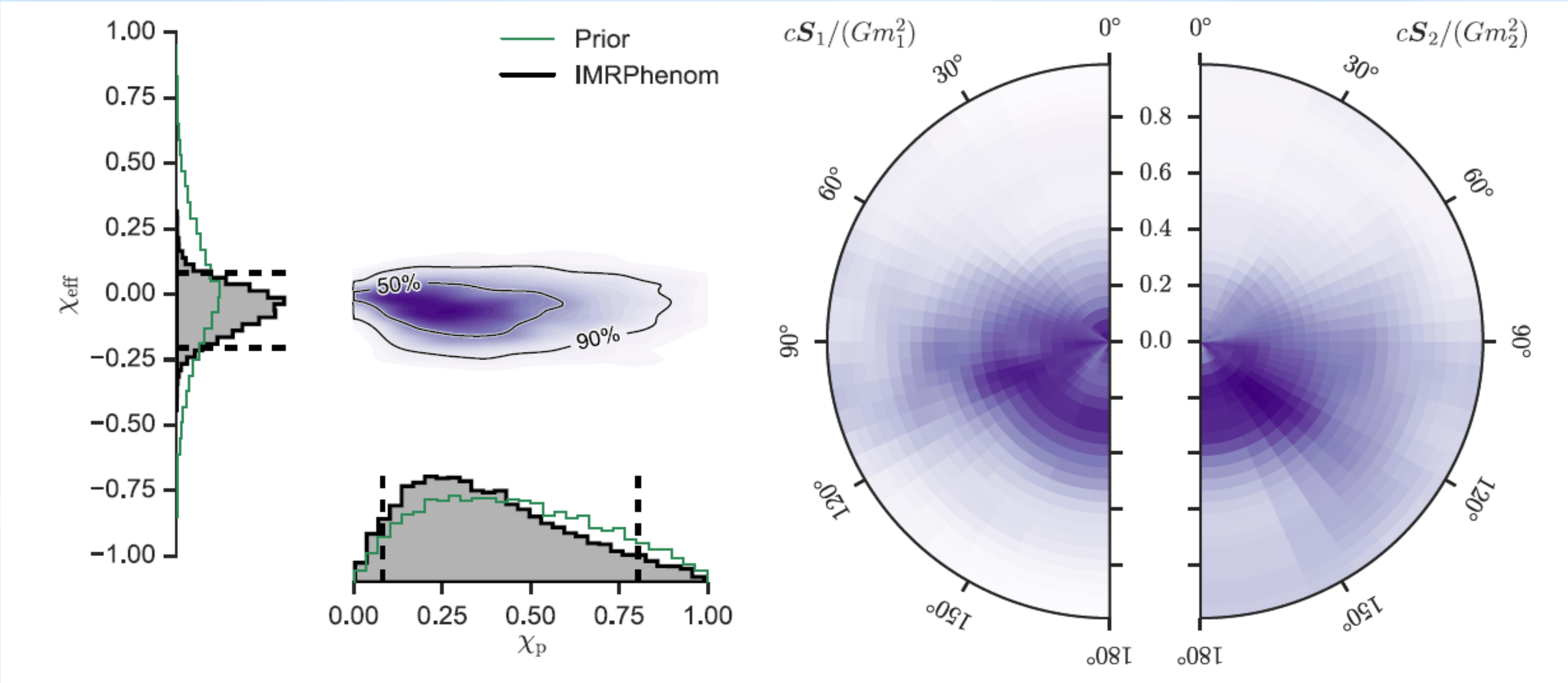
Primary black hole mass	$14.2^{+8.3}_{-3.7}\ \mathrm{M}_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3}\ \mathrm{M}_\odot$

GW151226 – At Least One BH Had Spin



At least one black hole has spin greater than 0.2. Spins of the primary and secondary black holes are constrained to be positive. Mass-weighted combinations of orbit-aligned spins χ_{eff} and in-plane spins χ_p (weak constraints only, non-informative).

GW150914 – No Detected Spin



Prefer no spin in the direction of orbital angular momentum.
Cannot constrain precession, i.e. spin components in the orbital plane.

Binary Black Hole Merger Rate

- Assuming that all binaries are like these 3 events is not realistic.
- Try two alternative models:
  - Flat distribution in log m1 – log m2
  - (m1) $\propto m_1^{-2.35}$ with a uniform distribution for the second mass.
- Significantly different rate estimates.
- Altogether: 9 – 240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.
- Lower limit comes from the flat in log mass population and the upper limit from the power law population distribution.

- Rules out <9 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, which were previously allowed.

Implications for a Stochastic Background of GWs

• For every detected binary merger, there are many more that are too distant and too faint.

• They generate a stochastic background of gravitational waves.

Merger Rate

Source Energy Spectrum

$$\Omega_{\rm GW}(f;\theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\rm max}} dz \frac{R_m(z,\theta_k)\frac{dE_{\rm GW}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_{\rm M},\Omega_\Lambda,z)}$$

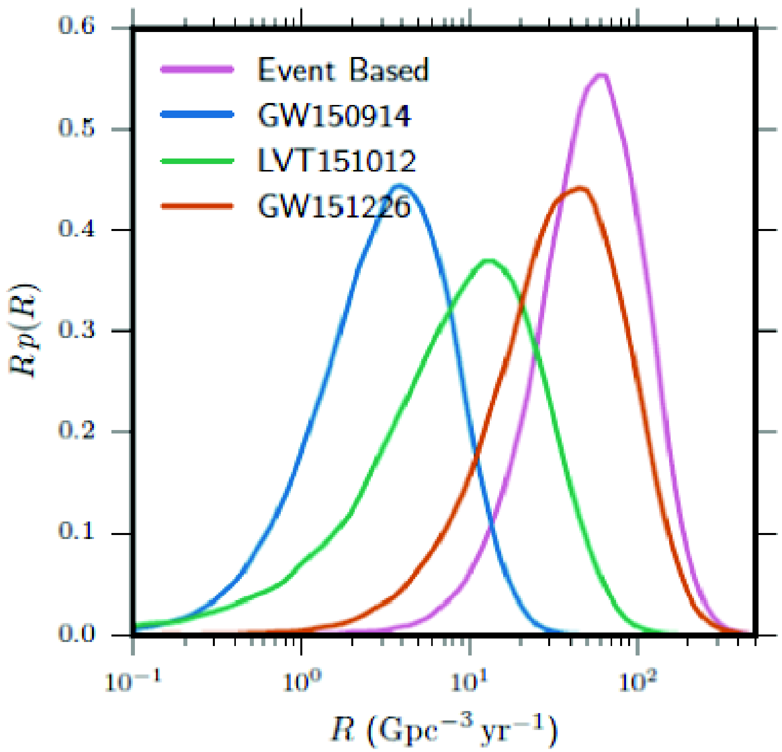
Cosmology

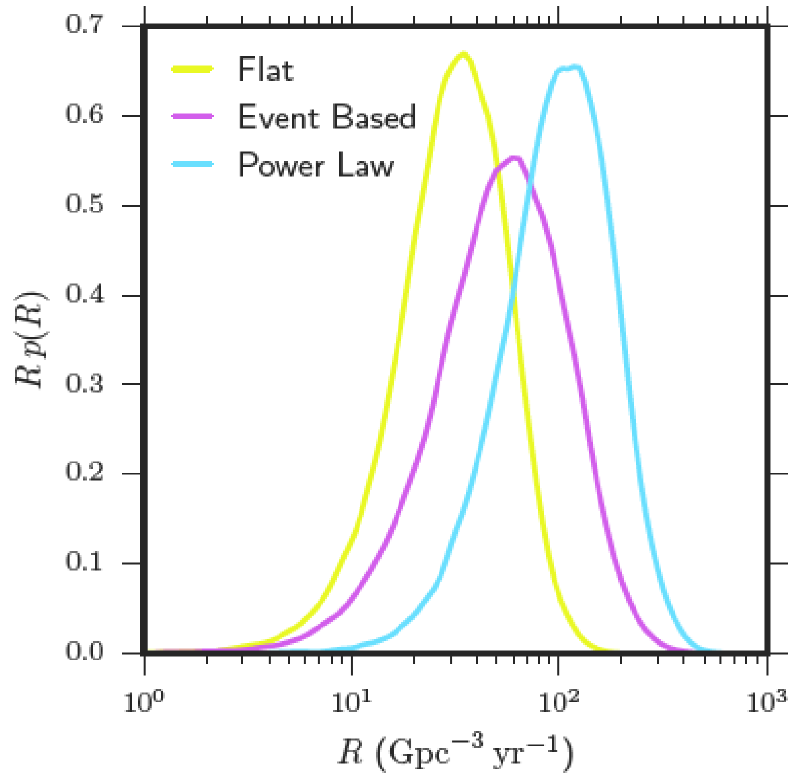
• Relatively high rate and large masses of observed systems implies a relatively strong stochastic background.

Astrophysics: Binary Formation

- Two binary formation mechanisms have been proposed.
- Field:
  - » Starting from a binary star system, with each star going through the core-collapse to a black hole.
- Dynamic:
  - » Individually formed black holes in dense environments (globular clusters) fall toward the center of the potential well, where they dynamically form binaries (and are often ejected).
- GW150914 and GW151226 spin parameter estimates are consistent with either formation mechanism.

Binary Black Hole Merger Rate





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

Did LIGO Detect Dark Matter?

- “There remains a window for masses $20\ M_\odot \lesssim M_{bh} \lesssim 100\ M_\odot$ where primordial black holes (PBHs) may constitute the dark matter.”
- Reasonable rate estimates overlap LIGO rate limits.
- No neutrino or optical 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.” PRL 116, 201301 (2016)
- “We show that if PBHs make up the dark matter, then roughly one event should have a detectable eccentricity given LIGO’s expected sensitivity and observing time of six years.” PRD 94, 084013 (2016)

Stochastic Background Primordial Black Hole

"We have shown that the amplitude of this spectrum is significantly lower than that arising from the stellar BBH mergers, although there is currently a large uncertainty in the local merger rate for stellar BBH systems.

…

Consequently, the stochastic GW background measurement with Advanced LIGO detectors is unlikely to detect this background."

Other studies are more optimistic:

https://arxiv.org/abs/1610.08725
https://arxiv.org/abs/1610.08479

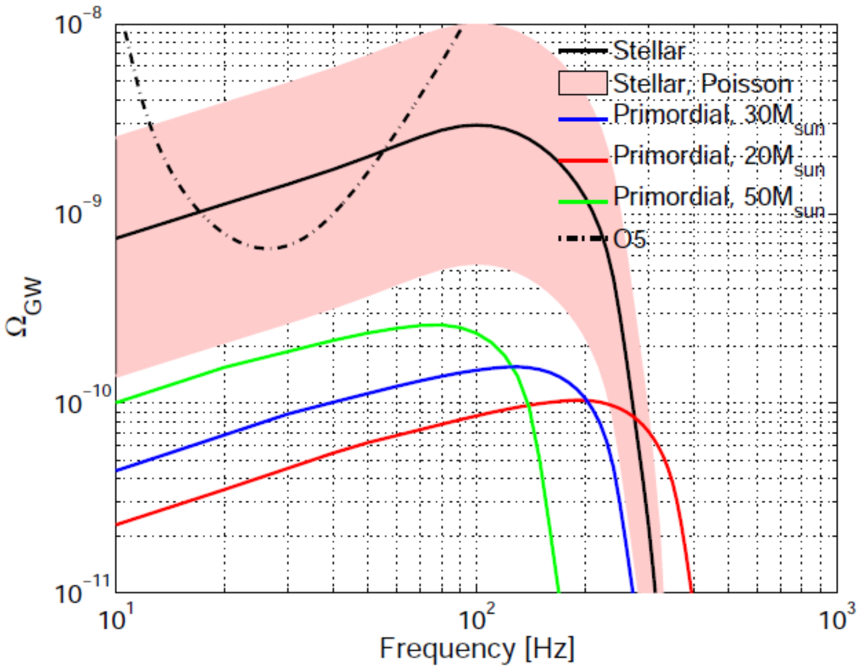


FIG. 4: Gravitational-wave energy density for the primordial BBH model is shown as a function of frequency for several values of the black hole mass, assuming the Ludlow et al. concentration model [28] and the Watson et al. model of the halo mass function [31]. Also shown is the projected final sensitivity of advanced detectors, denoted O5, as well as the fiducial stellar model and its Poisson error band [34].

Mandic et al., Phys. Rev. Lett. **117**, 201102 (2016)

Gravitational wave background from Population III binary black holes consistent with cosmic reionization

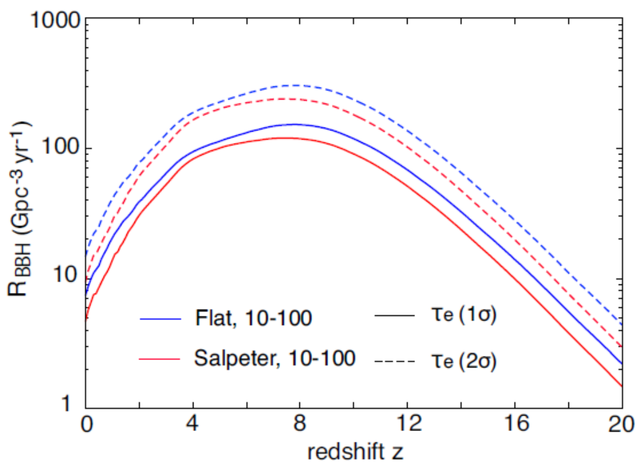


Figure 3. Merger rate of PopIII BBHs for different assumed IMFs, as in Fig. 2. The data is taken from K14, but renormalized to be consistent with the electrons scattering optical depth τ_e measured by *Planck* within the 1σ (solid) and 2σ (dashed) error (Eq. 1 with $f_{\mathrm{esc,m}} = 0.1$ and $\eta_{\mathrm{ion}} = 5 \times 10^4$).

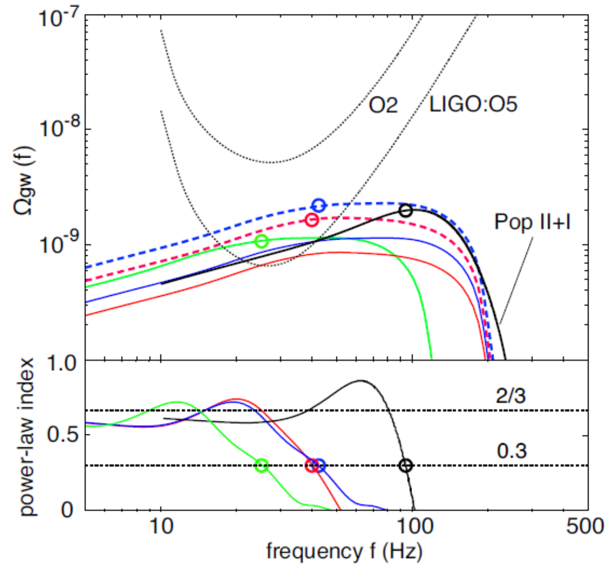


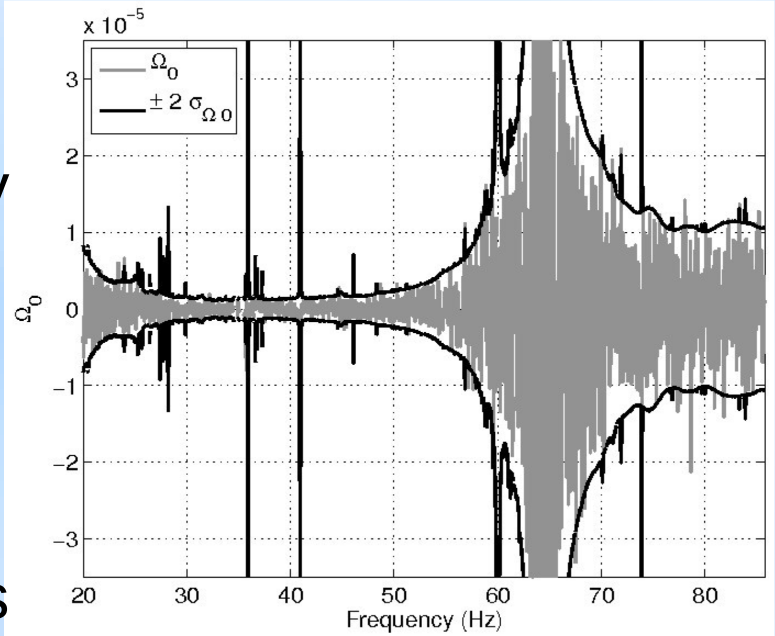
Figure 4. *Top*: spectra of GWB produced by PopIII BBHs for the same IMFs, $f_{\mathrm{esc,m}}$ and τ_e as in Fig. 3 (blue and red curves). We assume binaries with the average chirp mass of $\langle M_{\mathrm{chirp}} \rangle = 30\ \mathrm{M}_\odot$ on circular orbits. The background expected from all unresolved PopII+PopI BBHs is shown for reference (solid black curve, Abbott et al. 2016b, their fiducial model). Black dotted curves show the expected sensitivity of AdLIGO/Virgo in the observing runs O2 and O5. The green solid curve is the same as the blue solid curve, but with a higher chirp mass of $\langle M_{\mathrm{chirp}} \rangle = 50\ \mathrm{M}_\odot$ and with a lower merging rate by a factor of 3/5. *Bottom*: the spectral index; open circles mark the frequencies above which $\alpha < 0.3$.

Potentially a stronger stochastic background than what we would expect from direct BBH observations.

MNRAS 461(3) · March 2016 Thanks to Zoltan Haiman for pointing this out.

O1 Stochastic Search Results

- No evidence for a stochastic background for both the isotropic and direction searches
- Put upper limits on the energy density for different power indices
- Took a long time to clean the data.
- For α=0, the isotropic bound is 33x better than with initial LIGO/Virgo



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

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

Constraints on Cosmic String Parameters Coming

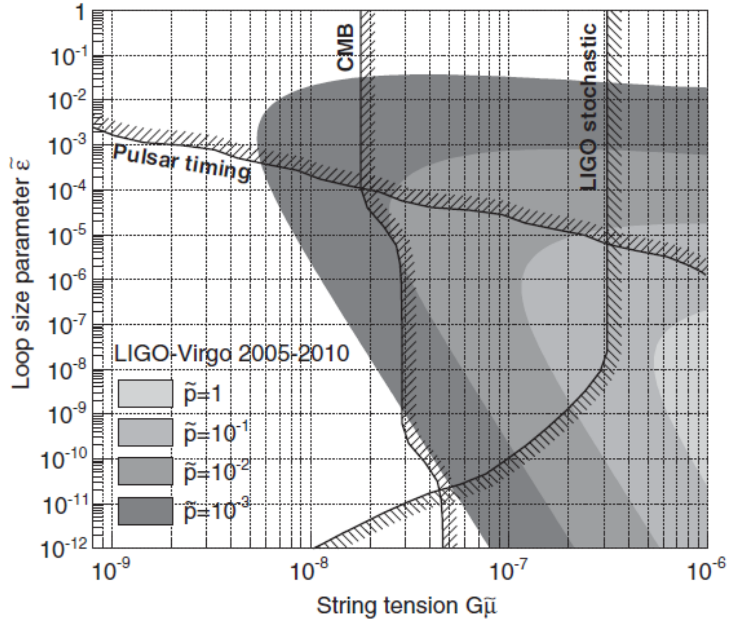


FIG. 2. Constraints on the modified cosmic string parameters $G\tilde{\mu} = g_1 g_2^{-2/3} G\mu$, $\tilde{\varepsilon} = g_1^{-1} g_2^{5/3} \varepsilon$, and $\tilde{p} = (n_c g_1)^{-1} g_2^{-1/3} p$, where g_1, g_2 and n_c are numerical factors of $\mathcal{O}(1)$. The gray regions, in different shades for four reconnection probability values, are rejected by our analysis at a 90% level. The black lines show the bounds derived from the GW stochastic background spectrum for $\tilde{p} = 10^{-3}$ and for a small loop scenario (CMB, pulsar, and LIGO data). The rejected region is always on the right-hand side of these lines.

Initial LIGO-Virgo results, PRL **112**, 131101 (2014)

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

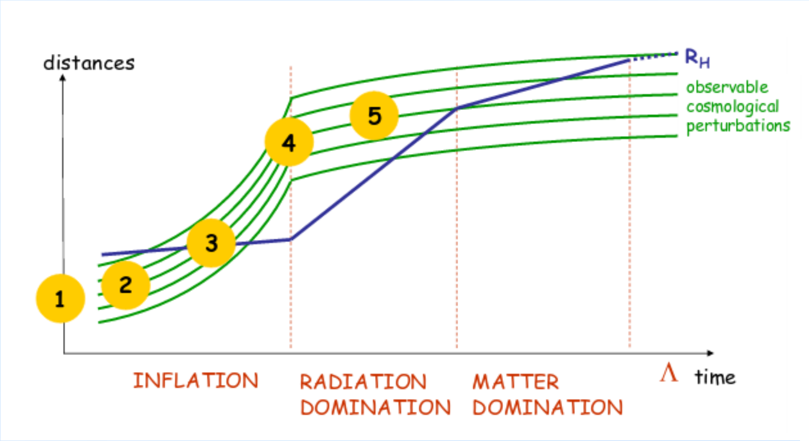
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2×10^{-22} eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

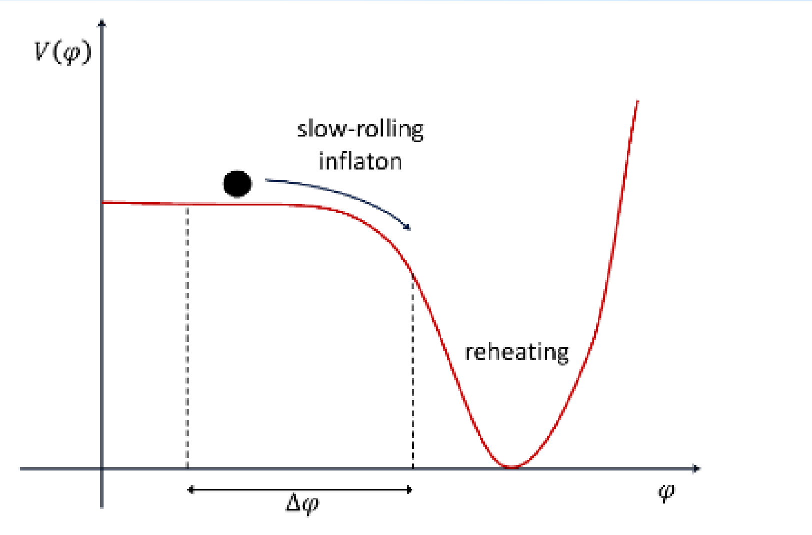
Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

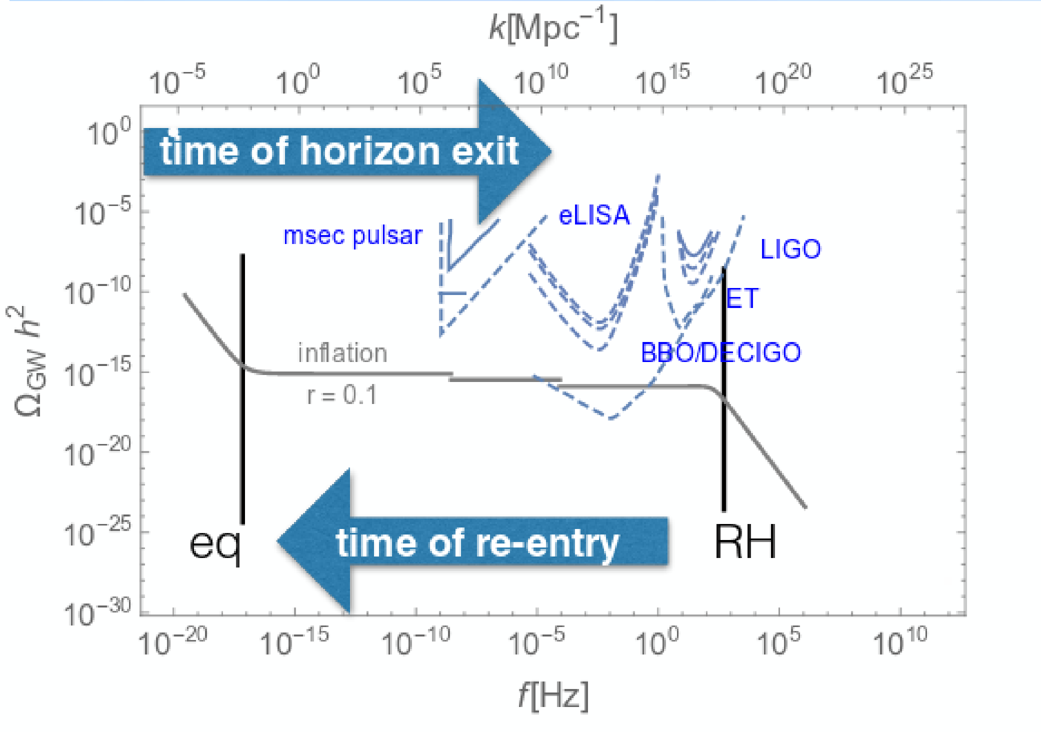
1.3 billion light years away.

Inflation



Standard inflationary models will not be observable by LISA.





Numerous Non-Standard Inflation Theories

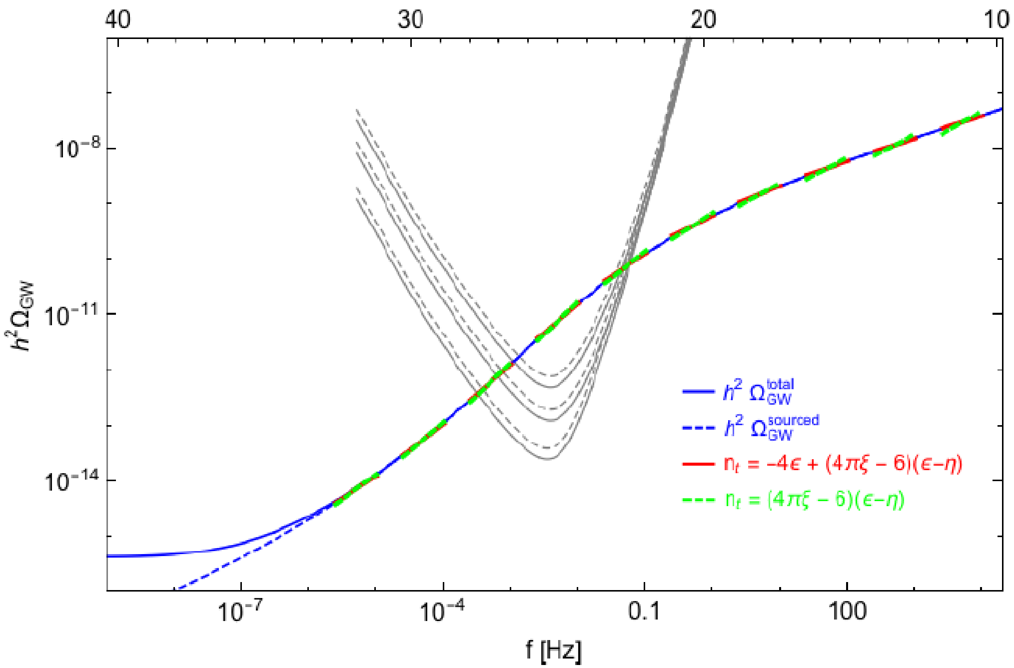
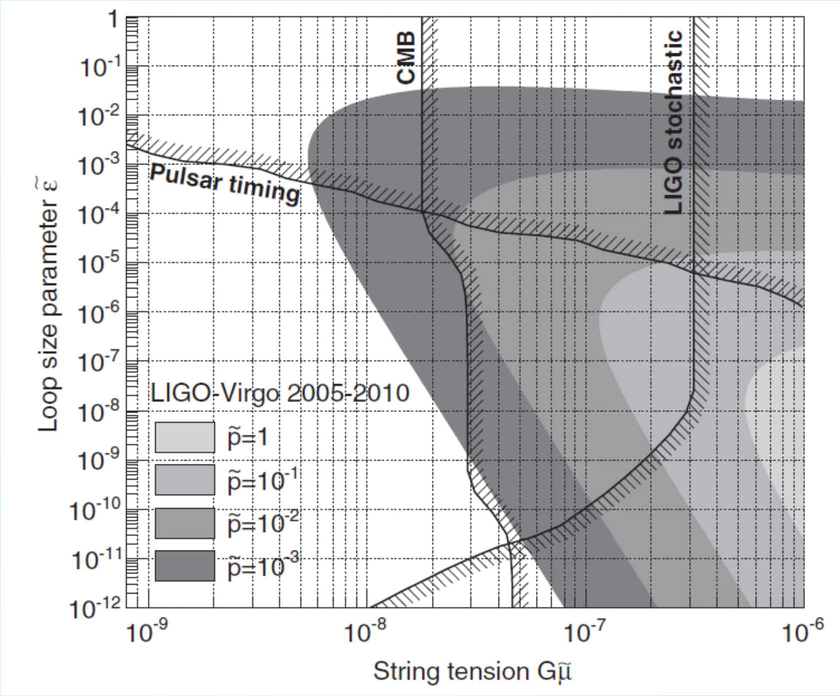


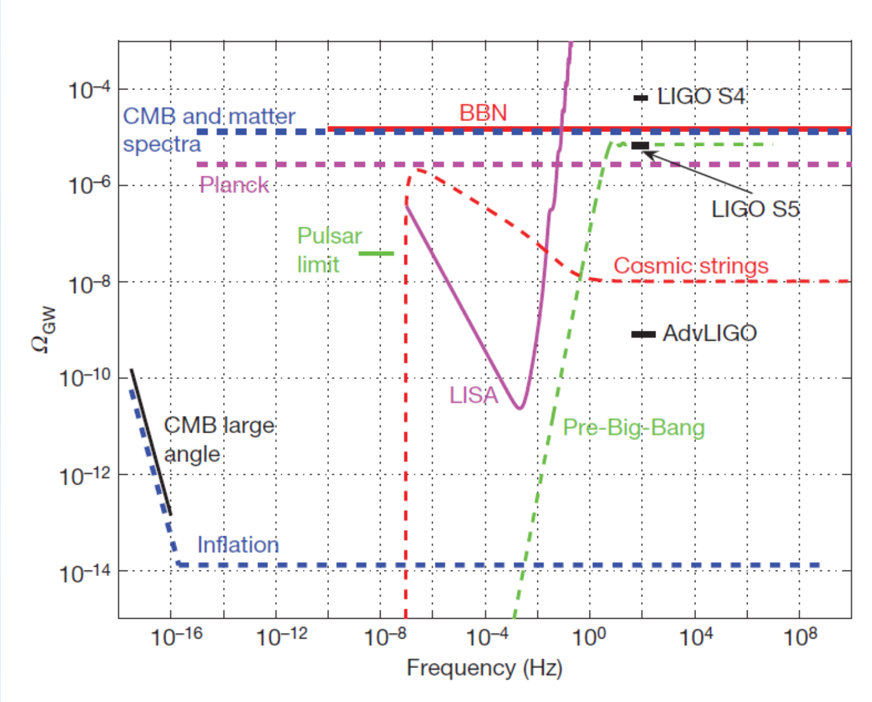
Figure 4: Spectrum of GWs today $h^2\Omega_{\rm GW}$ obtained from a numerical integration of the dynamical equations of motion (for a model of quadratic inflaton potential, with inflaton - gauge field coupling $f = M_{Pl}/35$), versus the local parametrization $h^2\Omega_{\rm GW} \propto (f/f_*)^{n_T}$, evaluated at various pivot frequencies f_* and with the spectral tilt n_T obtained from successive approximations to the analytic expression (3.13).

https://arxiv.org/abs/1610.06481

Cosmic strings

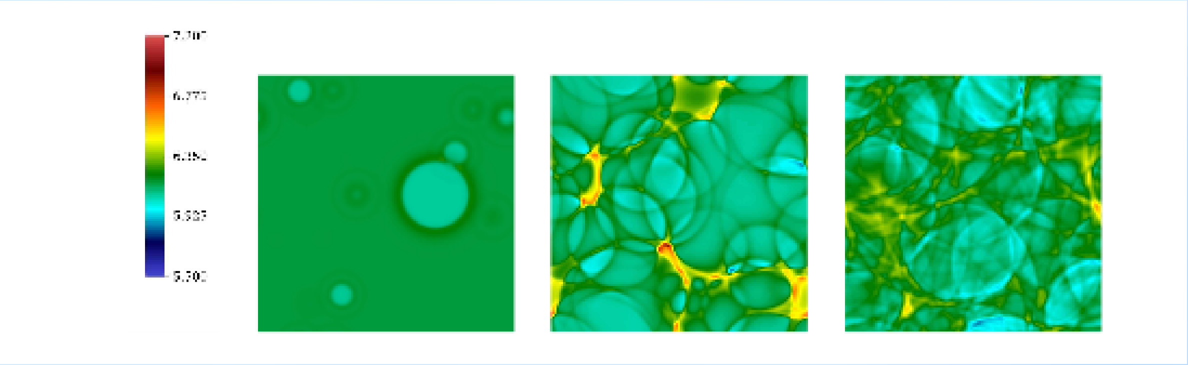
- LISA observation band can provide important information on a stochastic GW background from cosmic strings.
- LISA vs LIGO-Virgo comparison





Phase Transitions

- Phase transitions happened in the early Universe (EW symmetry breaking)
- A first order PT leads to GW emission
- EWPT might be first order in standard model (SM) extension
- 1st order PT GW emission:
  - nucleation of vacuum bubbles at the end of a PT and convert the entire universe to the broken phase. The collisions break the spherical symmetry of the bubble walls and generates a non zero anisotropic stress → GW emission
  - Bubbles collision inject energy in the primordial plasma → MHD turbulence that generates GW through the chaotic generated stress.



[Binetruy 12, Hindmarsh 14, Caprini 15]

O1 BBH: Two Golds and a Silver

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

PHYS. REV. X 6, 041015 (2016)