First detection of a gravitational wave signal

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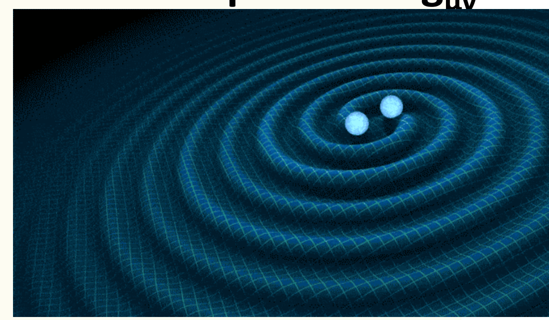
Gravitational waves
(solutions of Einstein's equations)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Linearized E. eqs. (Einstein 1916): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

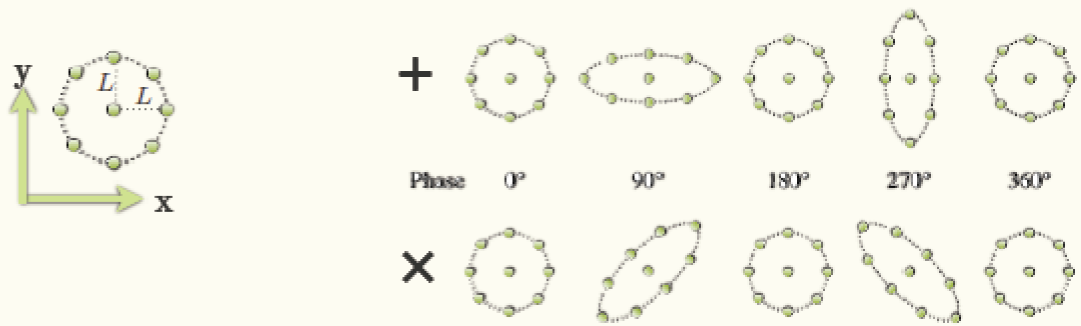
$$\Box \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

Einstein equations are a set of quasilinear partial equations of the second order for metric components $g_{\mu\nu}$



- **General relativity predicts gravitational waves as propagating oscillations of spacetime:**
  - » Propagate at the speed of light.
  - » Generated by quadrupolar mass movements: $h_{jk} = \frac{G}{c^4}\frac{2}{r}\frac{d^2}{dt^2}Q_{jk}$
  - » Two transverse polarizations: "+" and "x".

- **Ring of free particles**
  - » Responding to GW propagating along z-axis:



» Gravitational wave acts as a strain: $h \approx 2\Delta L/L$

BH merger and GWs

Hawking & Ellis, *The large scale structure of space-time*, CUP, 1972

$$\partial B = 8\pi m(m + (m^2 - a^2)^{1/2})^{1/2}$$

Area of the event horizon

TIME

322 GRAVITATIONAL COLLAPSE [9.2

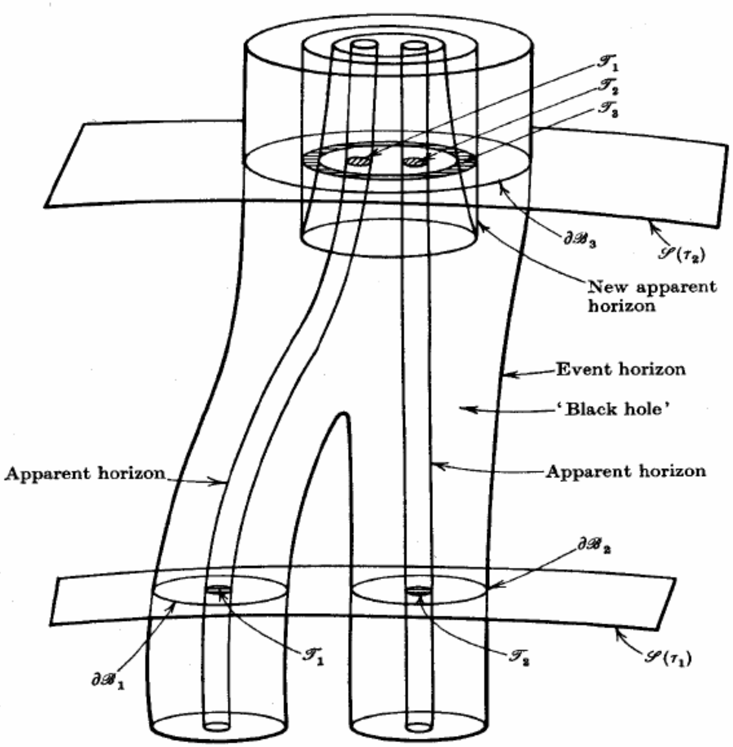


FIGURE 60. The collision and merging of two black holes. At time τ_1, there are apparent horizons $\partial\mathscr{T}_1$, $\partial\mathscr{T}_2$ inside the event horizons $\partial\mathscr{B}_1$, $\partial\mathscr{B}_2$ respectively. By time τ_2, the event horizons have merged to form a single event horizon; a third apparent horizon has now formed surrounding both the previous apparent horizons.

Efficiency for GW radiation using area theorem

$$\varepsilon_{GW} < 1/2$$

$$\varepsilon_{GW} < 1 - 1/\sqrt{2} \quad (\text{dla } a = 0)$$

Back of envelope calculation

$$E_{GW} \approx (m_1 + m_2)c^2 - Gm_1 m_2/(2r),$$

$$r \approx 5GM/c^2$$

$$\varepsilon_{GW} \approx 1/30$$

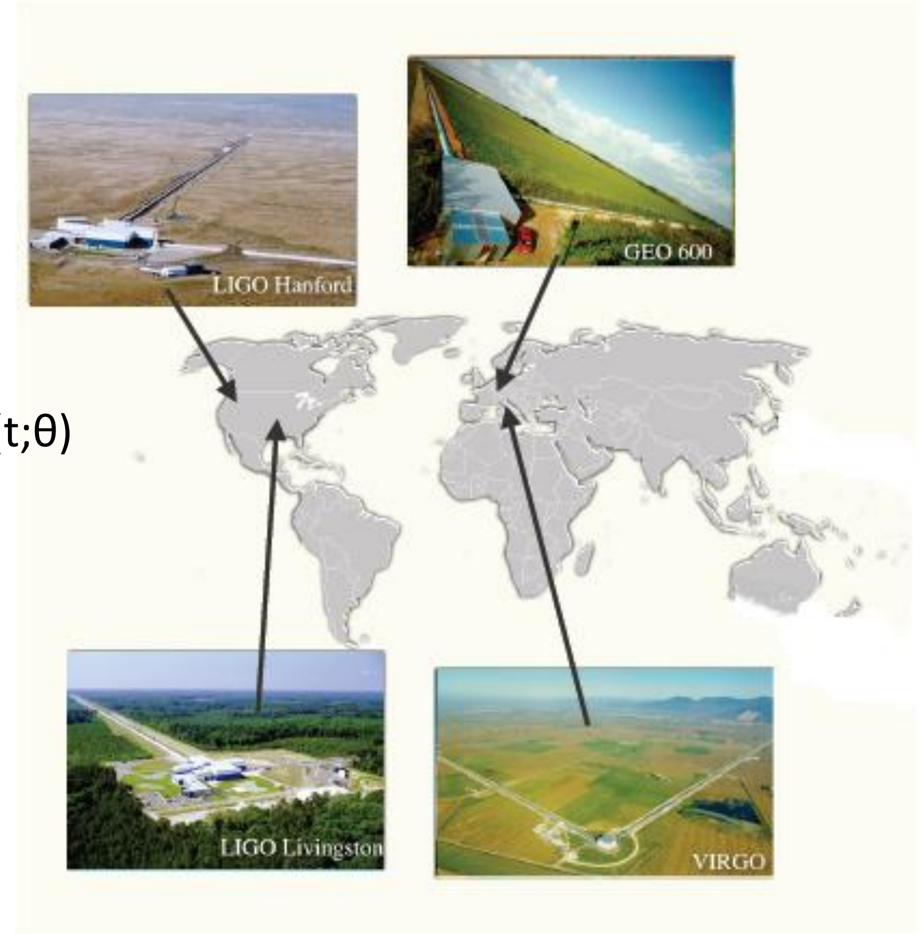
Numerical relativity (inspiral + merger)

$$\varepsilon_{GW} \approx 1/20$$

Worldwide detector network

- **Interferometric detector instruments**
  - » Tracking of km-scale separations between freely floating test masses
  - » Goal: **direct observation** of GWs
  - » Omnidirectional and broad-band (10Hz- 7kHz) detectors
- **Data Analysis for current Earth-based detectors:**

$$x(t) = n(t) + s(t;\theta)$$



>>Impulse signals - Supernovae (SN)

>>Chirp signals - NSNS, NSBH, BHBH binaries

>>Stochastic signals – early Universe

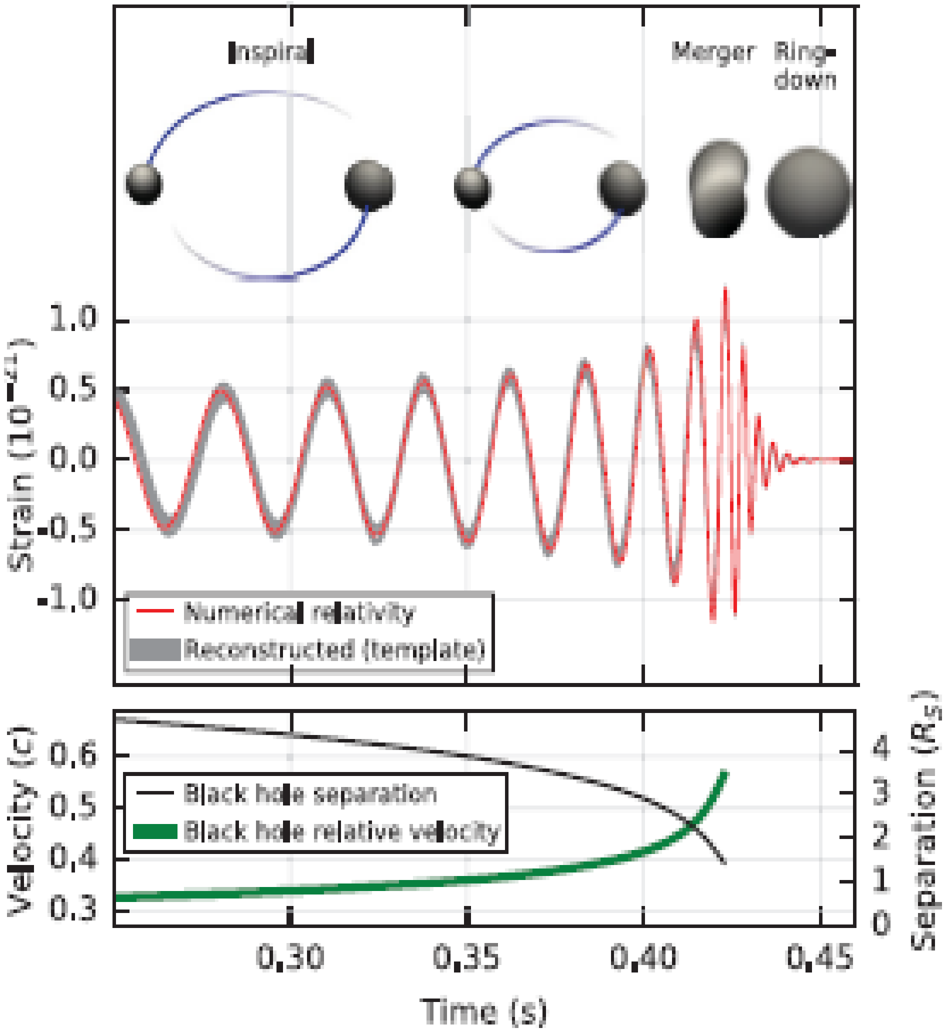
>>Periodic signals – Neutron stars (NS)

GW150914

GW from a binary black hole merger

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

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



- **General relativity has been tested in extreme gravity regime where the gravitational field is strong and dynamical**

- **A new field – gravitational wave astronomy has been opened.**

Astrophysical origin of GW150914

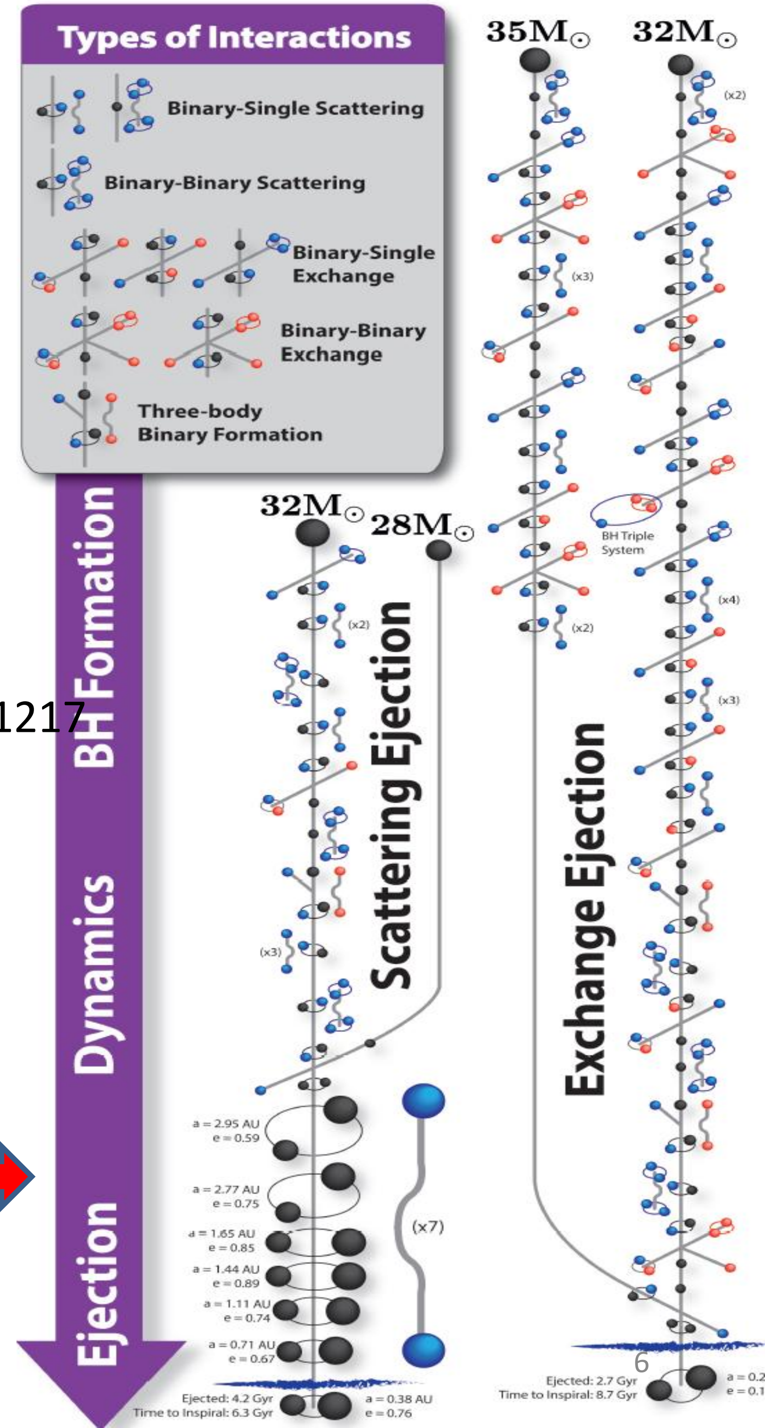
LSC-Virgo, [ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914, ApJL, 818, L22, 2016 (http://arxiv.org/abs/1602.03846)](http://arxiv.org/abs/1602.03846)

The surprisingly large masses of the individual BH components (36M and 29M) strongly suggest that the binary BH (BBH) progenitor of GW150914 was formed in a low-metallicity environment

Belczynski, K., Bulik, T., Fryer, C. L., et al. 2010a, ApJ, 714, 1217

1. In the galactic field with Z_s < ½ , < ¼

2. After ejection from the globular cluster with low Z_s



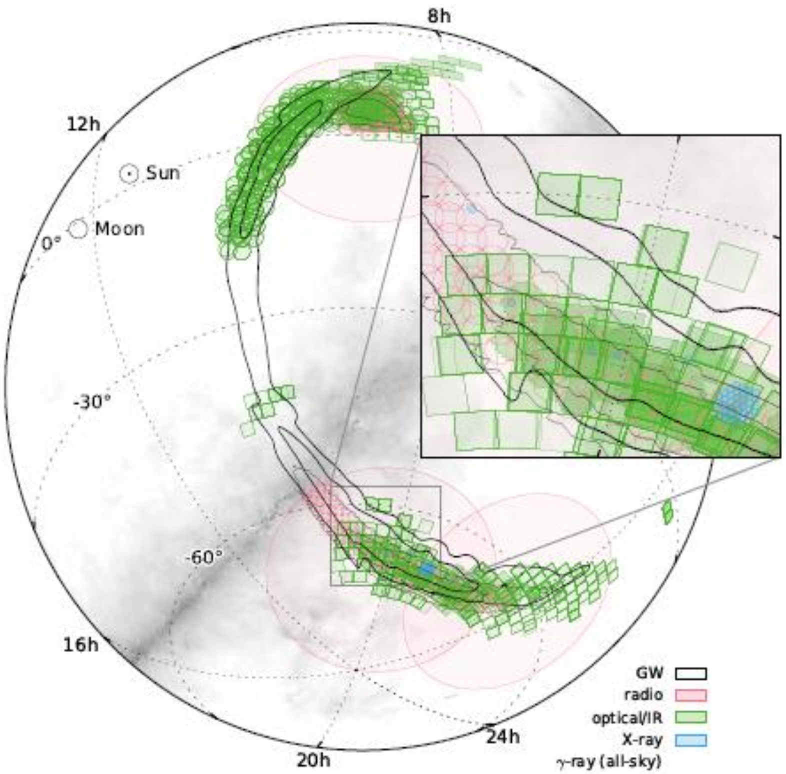
[arXiv:1604.04254](https://arxiv.org/abs/1604.04254)

Coincidences with EM observations

- There are > 70 EM observational projects with MoA with LVC to do joint observations .
- G184098 -> GW150914 followed by 25 teams including Pi-of-the-Sky.
- Alerts sent 2 days after detection (goal - 10 minutes)
- In a standard scenario we do not expect EM radiation from stellar BH merger

arXiv:1602.08492
Localization and broadband follow-up of the gravitational-wave transient GW150914
LIGO Scientific Collaboration, Virgo Collaboration and EM partners

Jaranowski & Krolak , Optimal solution to the inverse problem for the gravitational wave signal of a coalescing compact binary, *Phys. Rev. D*, ***49, 1723–1739, (1994)***



EM observations results

- High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with **ANTARES** and **IceCube** (http://arxiv.org/abs/1602.05411)
- **Swift** follow-up of the Gravitational Wave source GW150914 (http://arxiv.org/abs/1602.03868)
- **Pan-STARRS** and **PESSTO** search for the optical counterpart to the LIGO gravitational wave source GW150914 (http://arxiv.org/abs/1602.04156)
- **INTEGRAL** upper limits on gamma-ray emission associated with the gravitational wave event GW150914 (http://arxiv.org/abs/1602.04180)
- Fermi-LAT Observations of the LIGO event GW150914 (http://arxiv.org/abs/1602.04488)
- A **Dark Energy Camera** Search for Missing Supergiants in the LMC After the Advanced LIGO Gravitational Wave Event GW150914 (arXiv:1602.04199)
- **iPTF** Search for an Optical Counterpart to Gravitational Wave Trigger GW150914 **(arXiv:1602.08764)**
- **XMM-Newton** Slew Survey observations of the gravitational wave event GW150914 **(arXiv:1603.06585)**
- **AGILE** Observations of the Gravitational Wave Event GW150914 **(arXiv:1604.00955)**
- **J-GEM** Follow-Up Observations to Search for an Optical Counterpart of The First Gravitational Wave Source GW150914 **(arXiv:1605.03216)**

ALL negative, except…

Fermi GBM „observation”

•**Fermi GBM Observations of LIGO Gravitational Wave event GW150914** http://arxiv.org/abs/1602.03920

„weak transient source above 50 keV, 0.4 s after the GW event detected” !?

- Many experts doubt significance of this event
- Other GRB observations (Swift, INTEGRAL, Agile) did not see this event

Fundamental Physics

LSC-Virgo, [Tests of general relativity with GW150914 (http://arxiv.org/abs/1602.03841)](http://arxiv.org/abs/1602.03841)

S. Bird et al. **Did LIGO detect dark matter? (arXiv:1603.00464)**

- Dark matter may be primordial black holes (PBH).
- Window for masses $10M_\odot \lesssim M_{bh} \lesssim 100M_\odot$ where primordial black holes (PBHs) may constitute the dark matter.
- BH binary detected by LIGO may be PBH binary.

Nunes et al. **Theoretical Physics Implications of the Binary Black-Hole Merger GW150914 arXiv:1603.08955**

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$	Example Theory Constraints		
			GW150914	Repr. Parameters	**GW150914**	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6\times10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [39], 2 [40–42]
	SEP, No BH Hair	-1	$\mathbf{1.6\times10^{-4}}$	$\lvert\dot\phi\rvert$ [1/sec]	—	10^{-6} [43]
	SEP, Parity Invariance	$+2$	$\mathbf{1.3\times10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2\times10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	(0.03, 0.003) [46, 47]
Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1\times10^{-9}}$	ℓ [μm]	$\mathbf{5.4\times10^{10}}$	10–10^3 [48–52]
Time-Varying G	SEP	-4	$\mathbf{9.1\times10^{-9}}$	$\lvert\dot G\rvert$ [10^{-12}/yr]	$\mathbf{5.4\times10^{18}}$	0.1–1 [53–57]
Massive graviton	massless graviton	$+1$	$\mathbf{1.3\times10^{-1}}$	m_g [eV]	$\mathbf{1.2\times10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
Modified Dispersion Relation	$v_g = c$	$+5.5$	$\mathbf{2.3\times10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6\times10^{-7}}$	—
(*Modified Special Relativity*)		$+5.5$	$\mathbf{2.3\times10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6\times10^{-7}}$	2.7×10^{-36} [63]
Modified Dispersion Relation	$v_g = c$	$+7$	$\mathbf{8.7\times10^{2}}$	$\mathbb{A} > 0$ [1/eV^2]	$\mathbf{9.3\times10^{4}}$	—
(*Extra Dimensions*)		$+7$	$\mathbf{8.7\times10^{2}}$	$\mathbb{A} < 0$ [1/eV^2]	$\mathbf{9.3\times10^{4}}$	4.6×10^{-56} [63]
Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	$\mathbf{0.7}$ [64]	(0.03, 0.003) [46, 47]

TABLE I. Theoretical mechanisms (first column) that arise in modified theories of gravity

Meaning of the discovery

1. For the first time gravitational wave signal was registered by a detector on Earth
2. For the first time merger of two black holes into a single black hole was observed.

The end product of a black hole binary coalescence is perfectly consistent with Kerr black hole as described by Einstein's general relativity