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indigo

LIGO Observation of Gravitational Waves from a Binary Black Hole Merger

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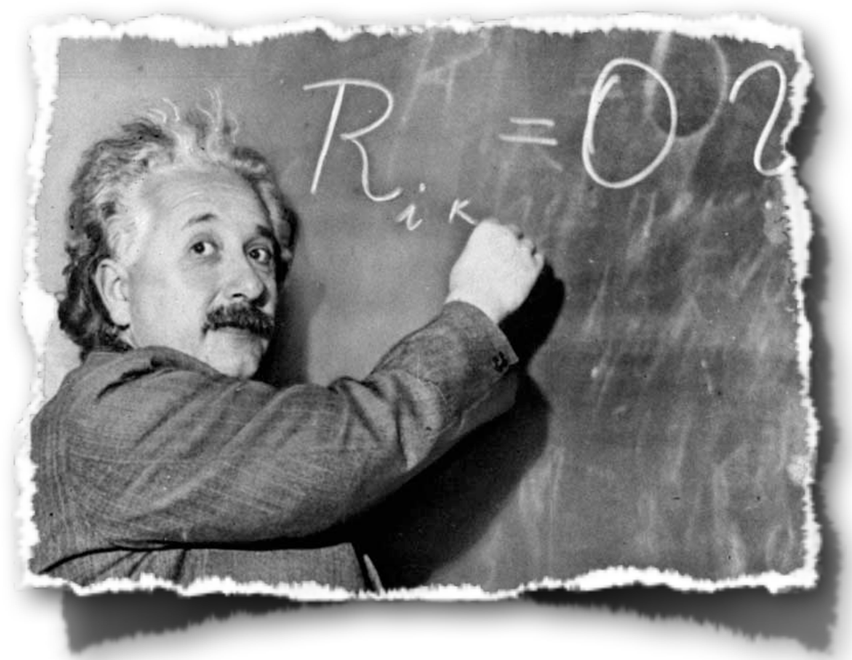
Gravitational waves

- The existence of gravitational waves (GWs) is one of the most intriguing predictions of the General Theory of Relativity.



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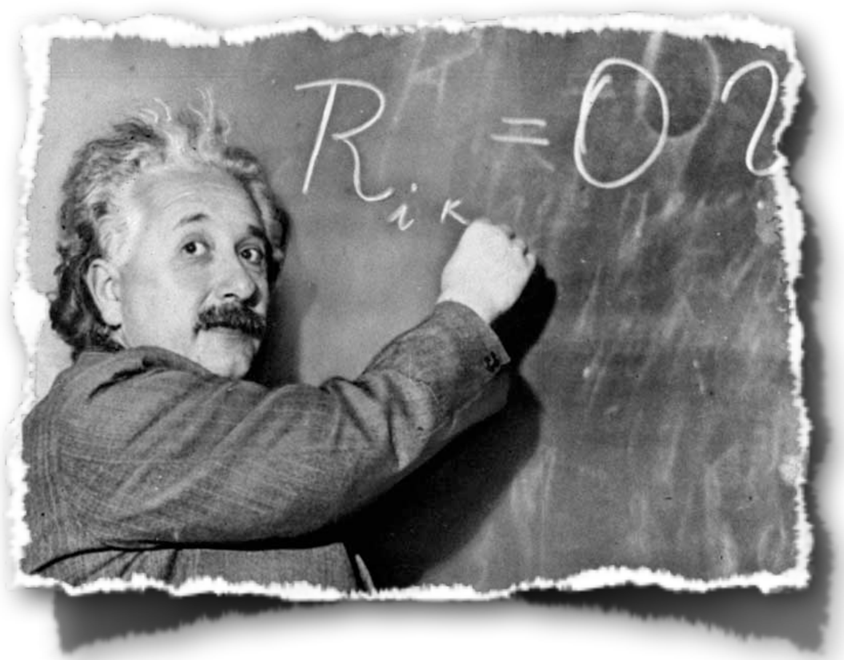
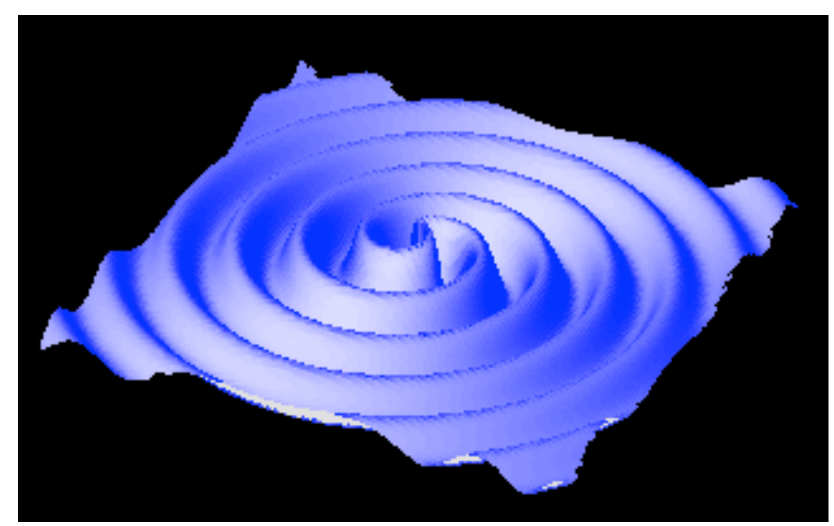
- GWs are freely propagating oscillations in the geometry of spacetime — ripples in the fabric of spacetime.





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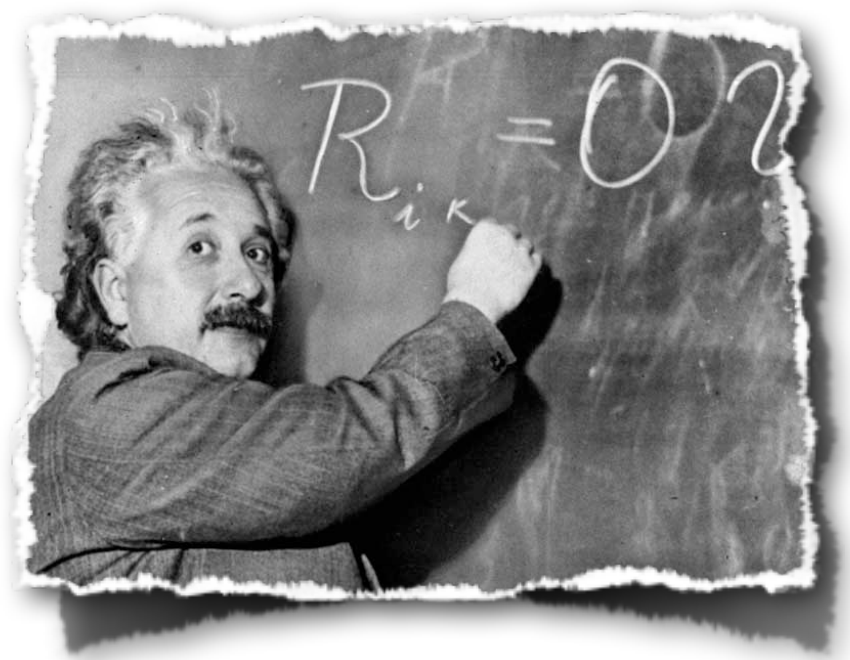
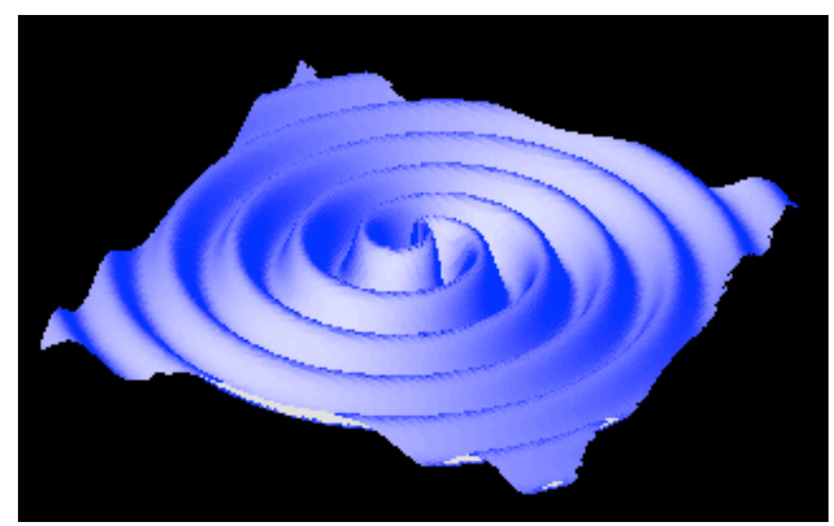


accelerating charges (time-varying dipole moment) → electromagnetic waves

accelerating masses (time-varying quadrupole moment) → gravitational waves



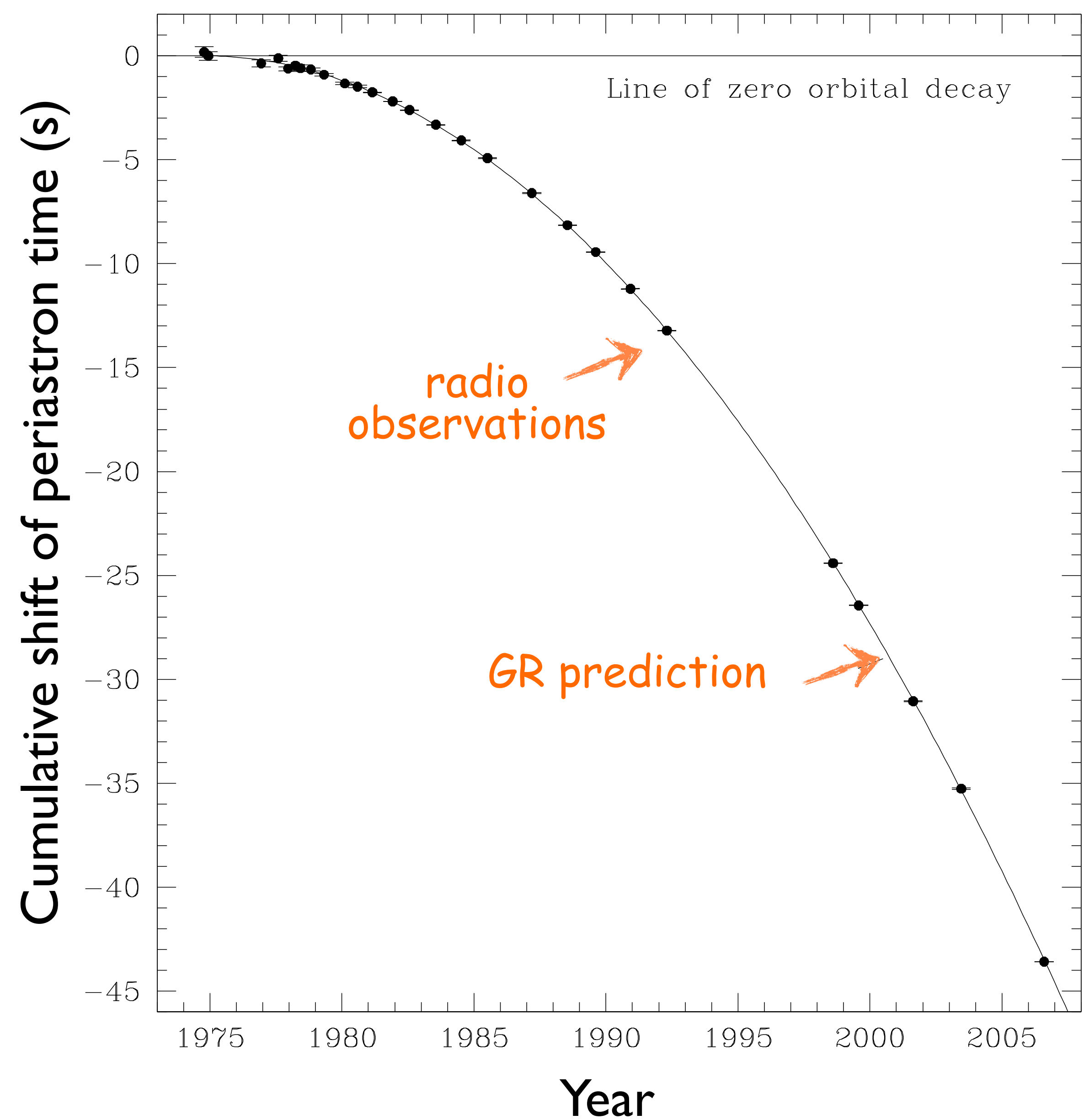
Pre-2016: Observational evidence of gravitational waves

- 36 years of radio observations of the binary pulsar PSR B1913+16 → Decay of the orbital period agrees precisely with GR prediction.

observed decay of the orbital period ↓ GR prediction ↓

$$\dot{P}_b = (0.997 \pm 0.002)\, \dot{P}_b^{\mathrm{GR}}$$

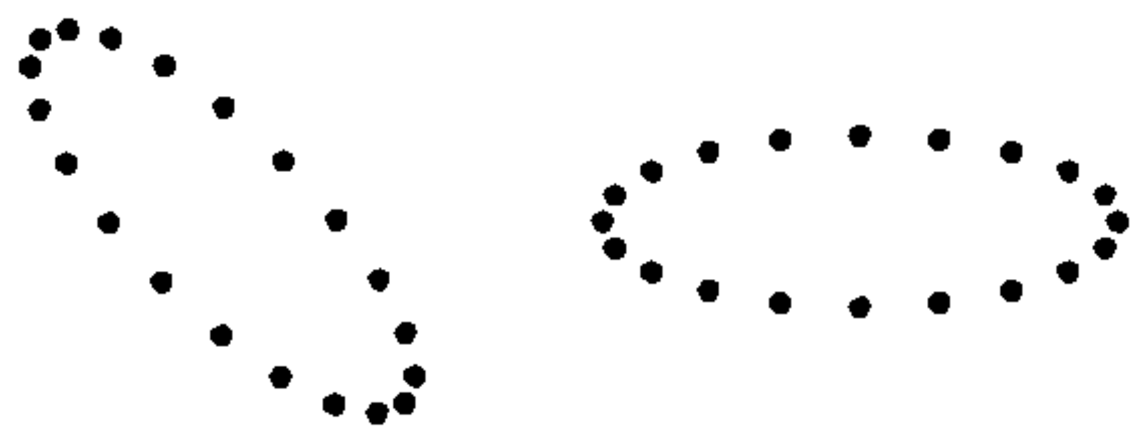
[Weisberg et al (2010)]



Direct detection of gravitational waves

- When GWs pass through earth, they produce a time-dependent change in the geometry of the space (spatial metric).
- These changes can be detected with the help of laser interferometers.

Effect of GWs on a ring of test particles



“x” polarisation

“+” polarisation

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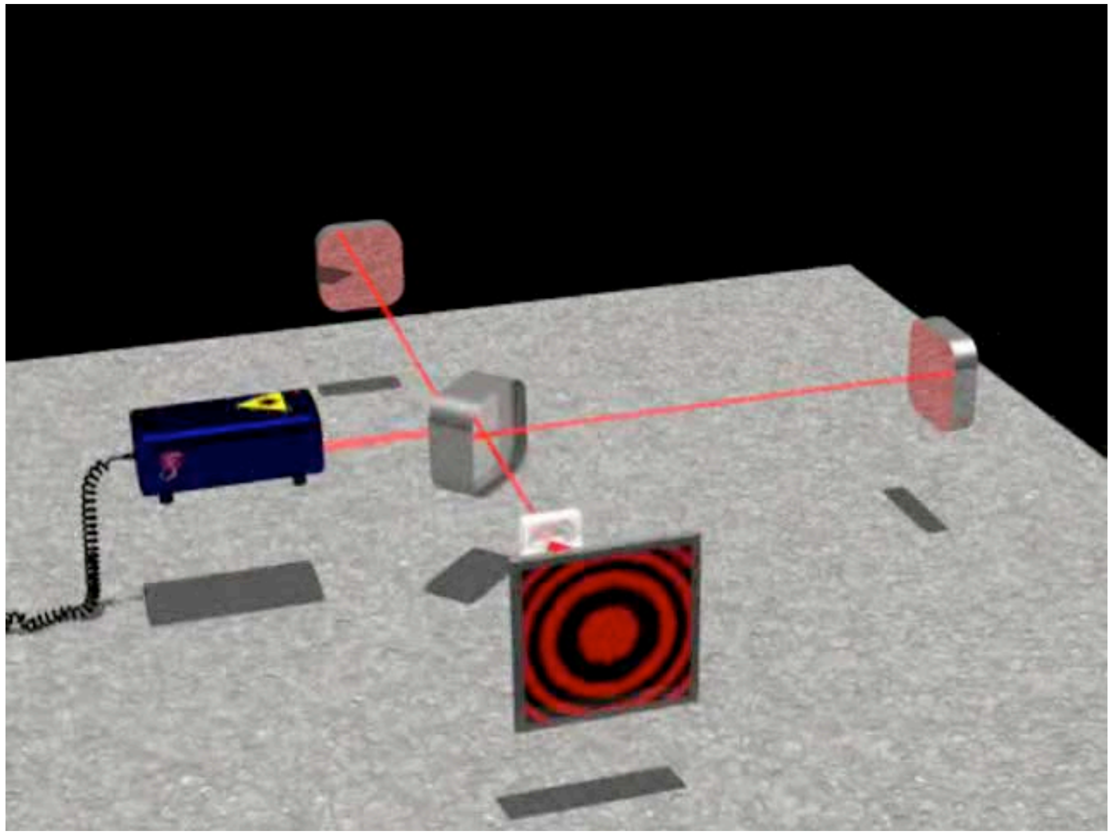
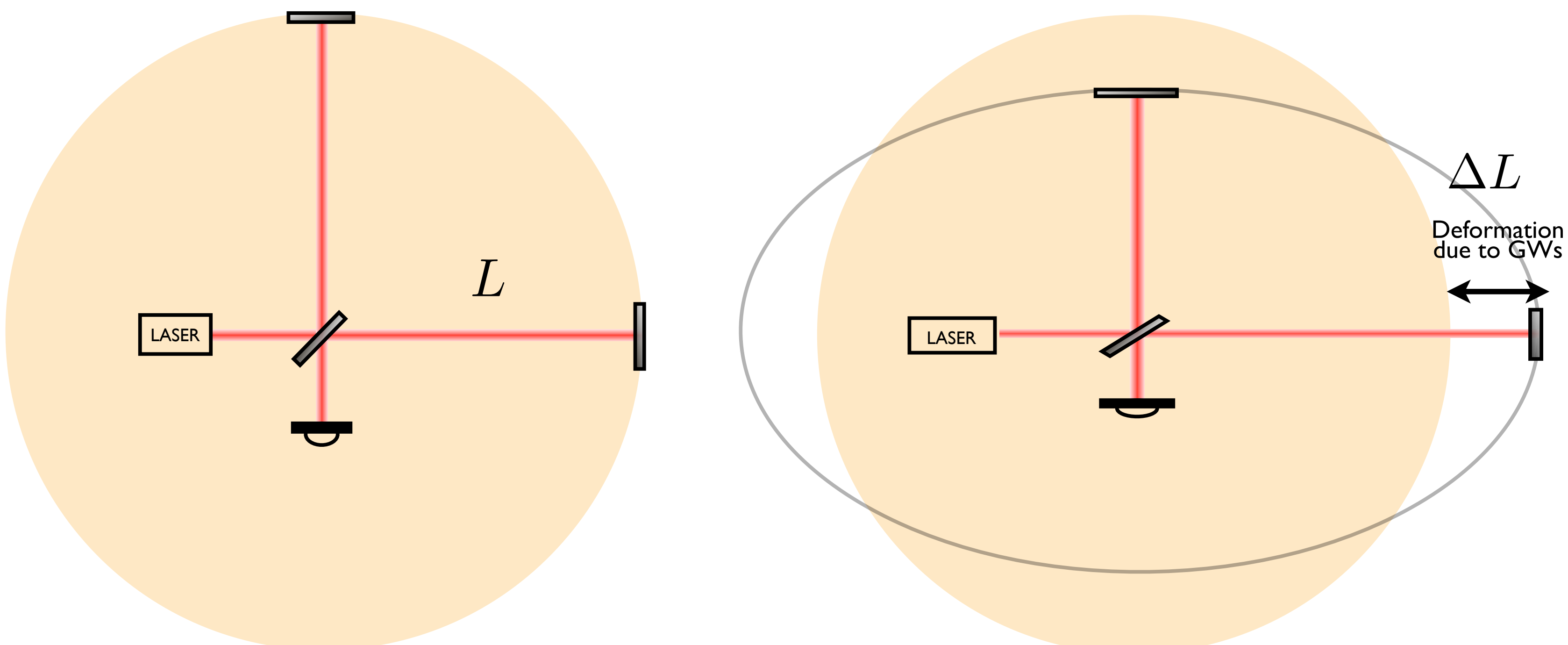


Animation *Albert Einstein Institute*

Direct detection of gravitational waves

- **Experimental challenge** Expected distortions are tiny!



GW strain

Expected distortions: $h = \frac{\Delta L}{L} \sim 10^{-21}$ (BNS inspiral at 20 Mpc)

Required displacement sensitivity of interferometers (L ~ 1 km) 10^{-18} m (1/1000 size of nucleus)

The quest for the direct detection of gravitational waves

- An international network of ground-based detectors. Several science runs using the first-generation instruments. No detection! Consistent with astrophysical expectations.

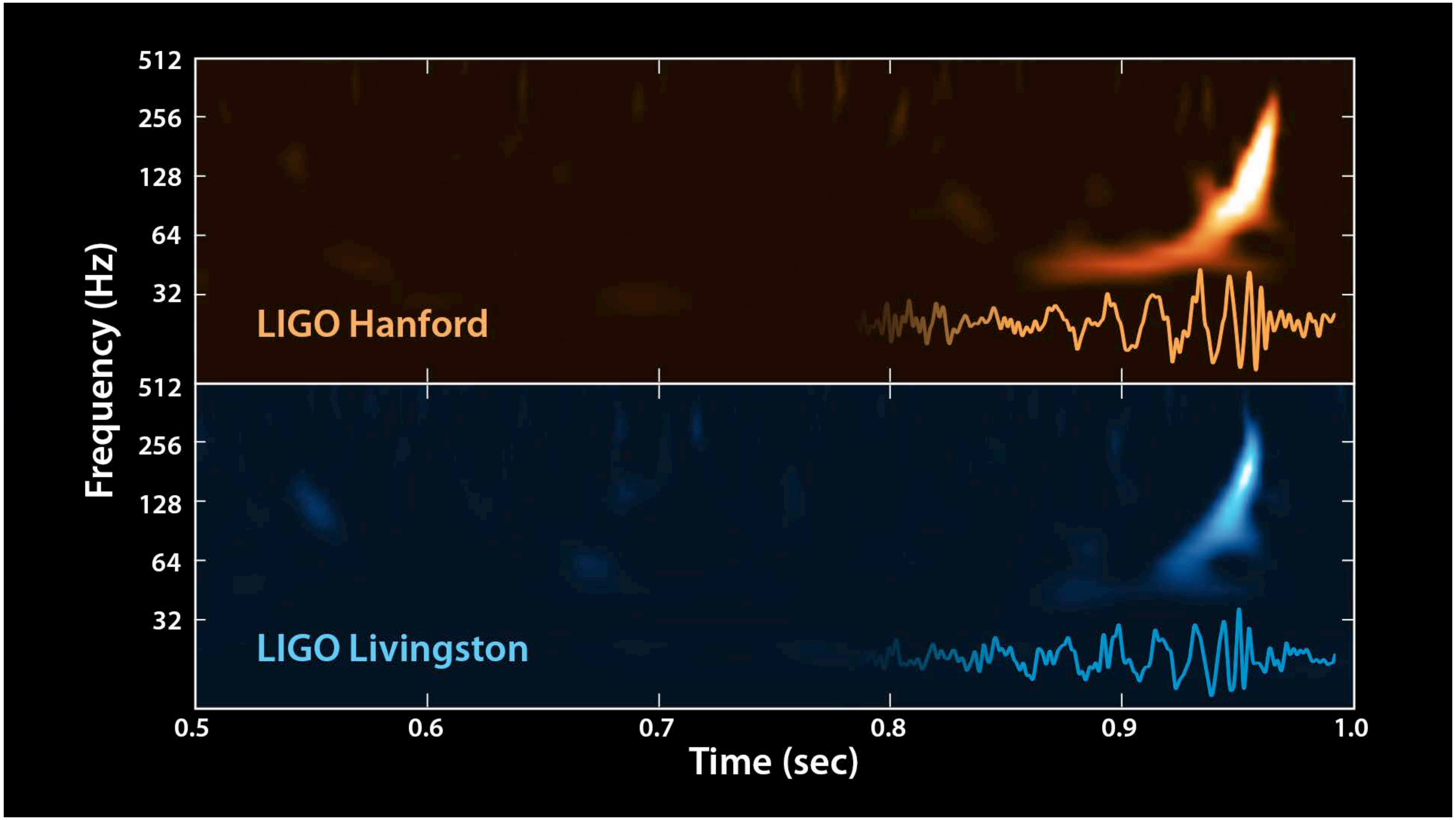

LIGO Observatories in Hanford and Livingston, USA

The first direct detection of gravitational waves

On September 14, 2015 at 09:50:45 UTC (15:20:45 IST)
two LIGO observatories in Hanford and Livingston (USA)
detected a coincident gravitational-wave signal.

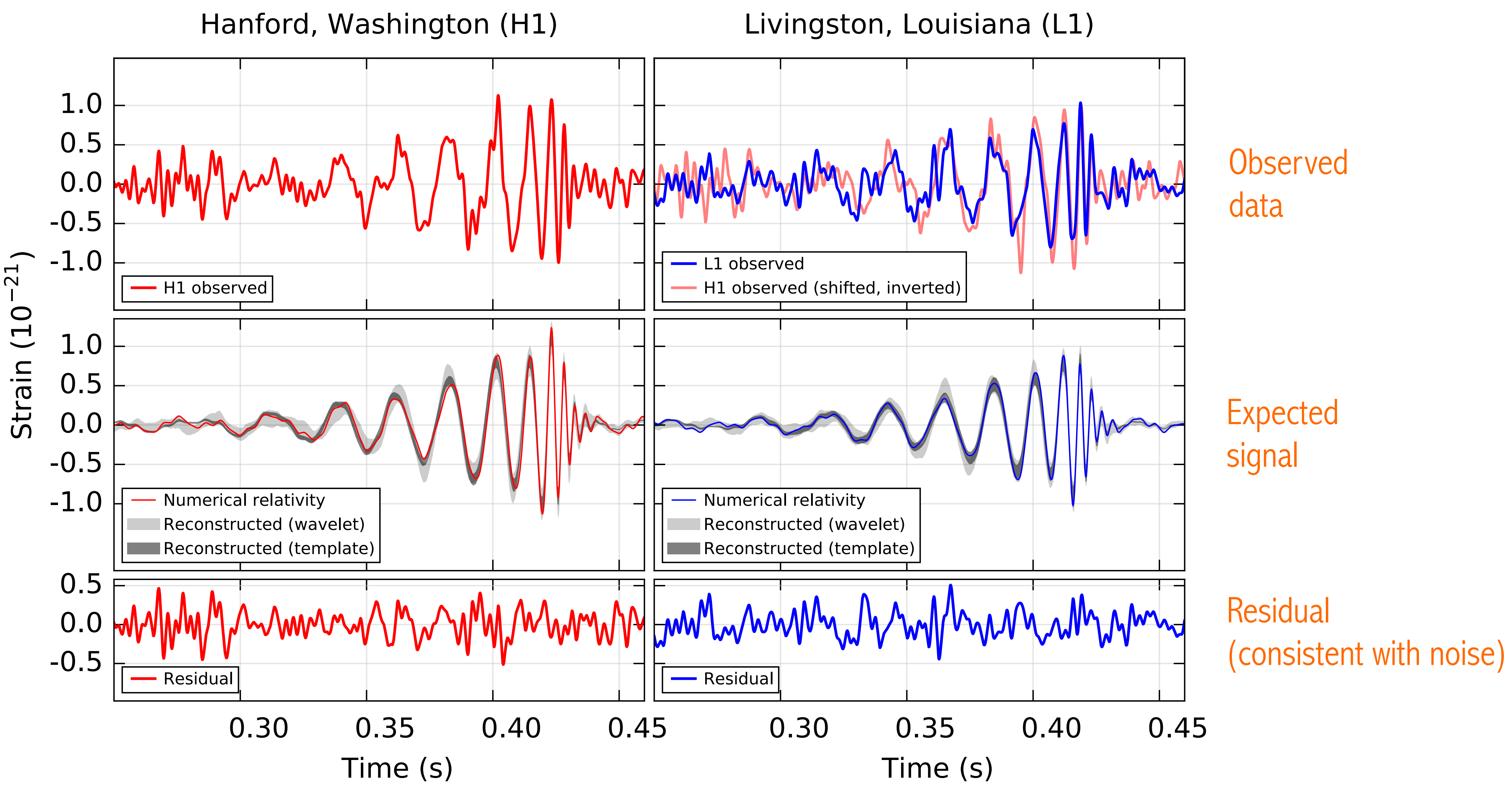
Signals arrived in the two detectors within ~7 milliseconds.
Combined signal-to-noise ratio 24.

The observed signal



The observed signal

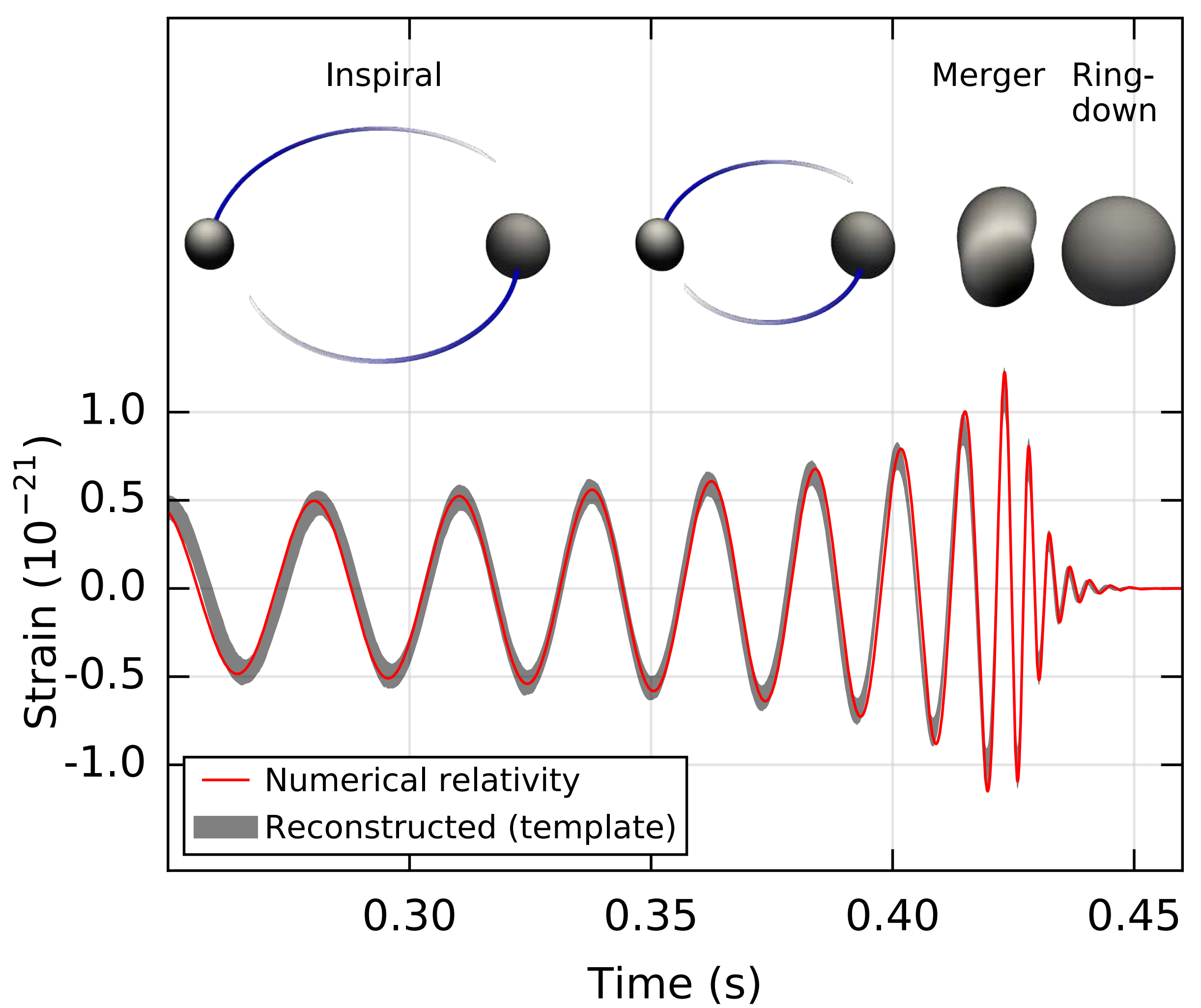
Consistent with a signal expected from the coalescence of two black holes



The observed signal: A binary black-hole coalescence

Consistent with a signal expected from the coalescence of two black holes

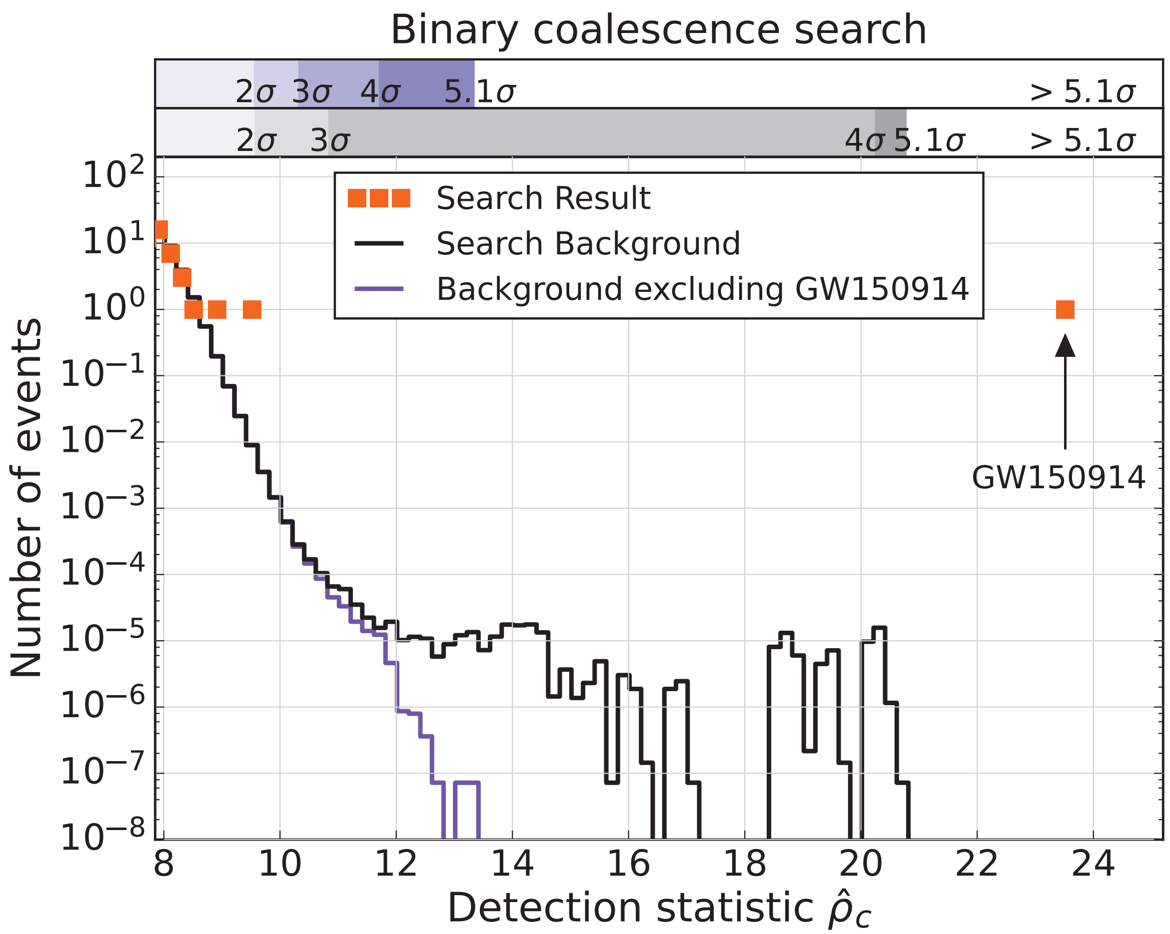
that is., their orbital inspiral and merger, and subsequent ringdown of the final black hole



A “five-sigma” detection!

Detected by two independent searches

First, by low-latency searches for generic gravitational wave transients. Subsequently, by matched-filter analyses that use relativistic models of binary black hole waveforms.



False alarm probability $< 2 \times 10^{-7}$

Significance > 5.1σ

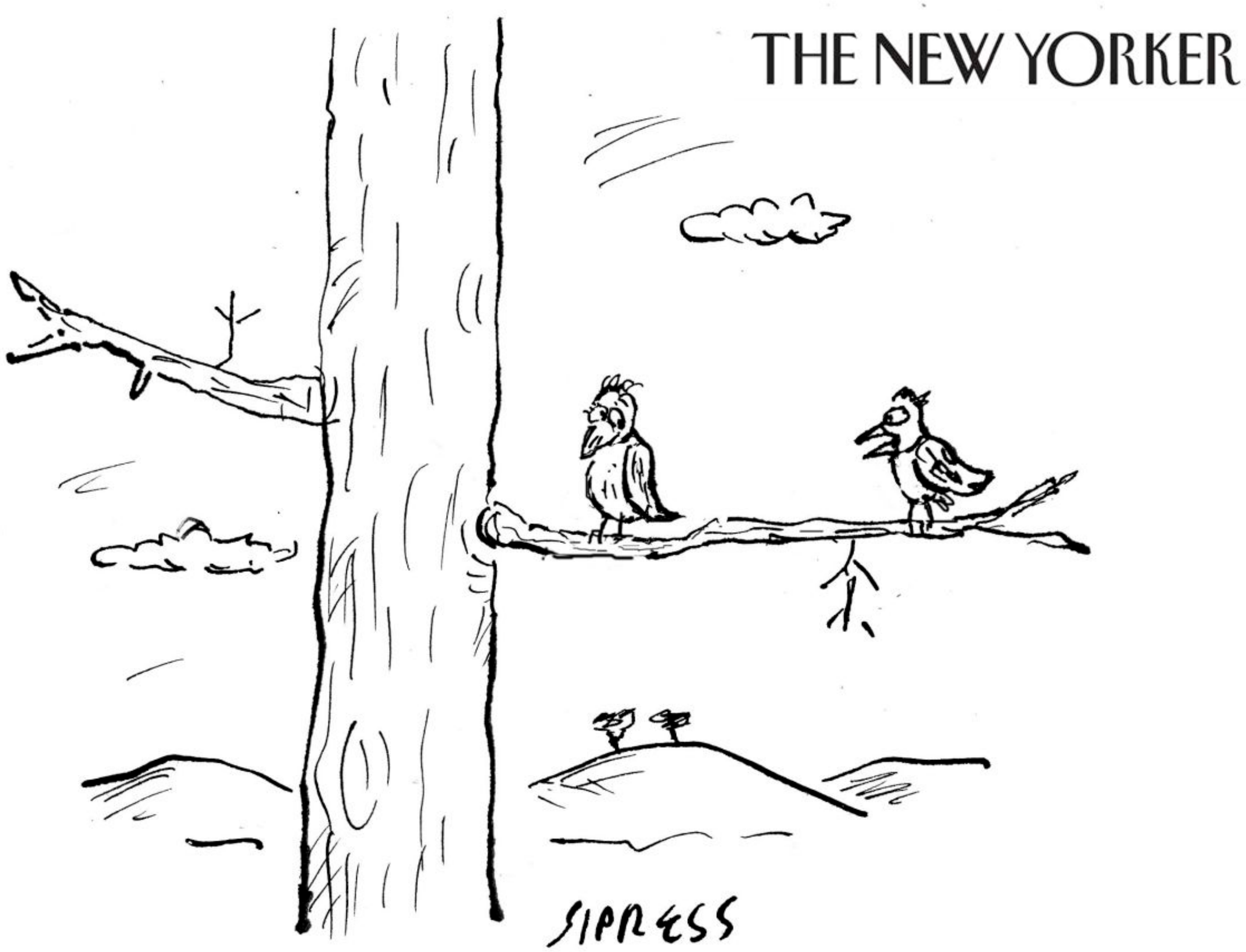
False alarm rate < 1/203,000 years

[Fundamental Indian contribution in GW modeling and development of search methods]

Verification of the detector and data quality

- Both the detectors were in a steady state of operation for several hours around the event -- **no evidence that this could be an instrumental artifact.**
- None of the environmental sensors recorded disturbances that could potentially couple with the detectors.
- Ruled out the possibility of “signal injections”.

[Direct contribution from Indian groups]

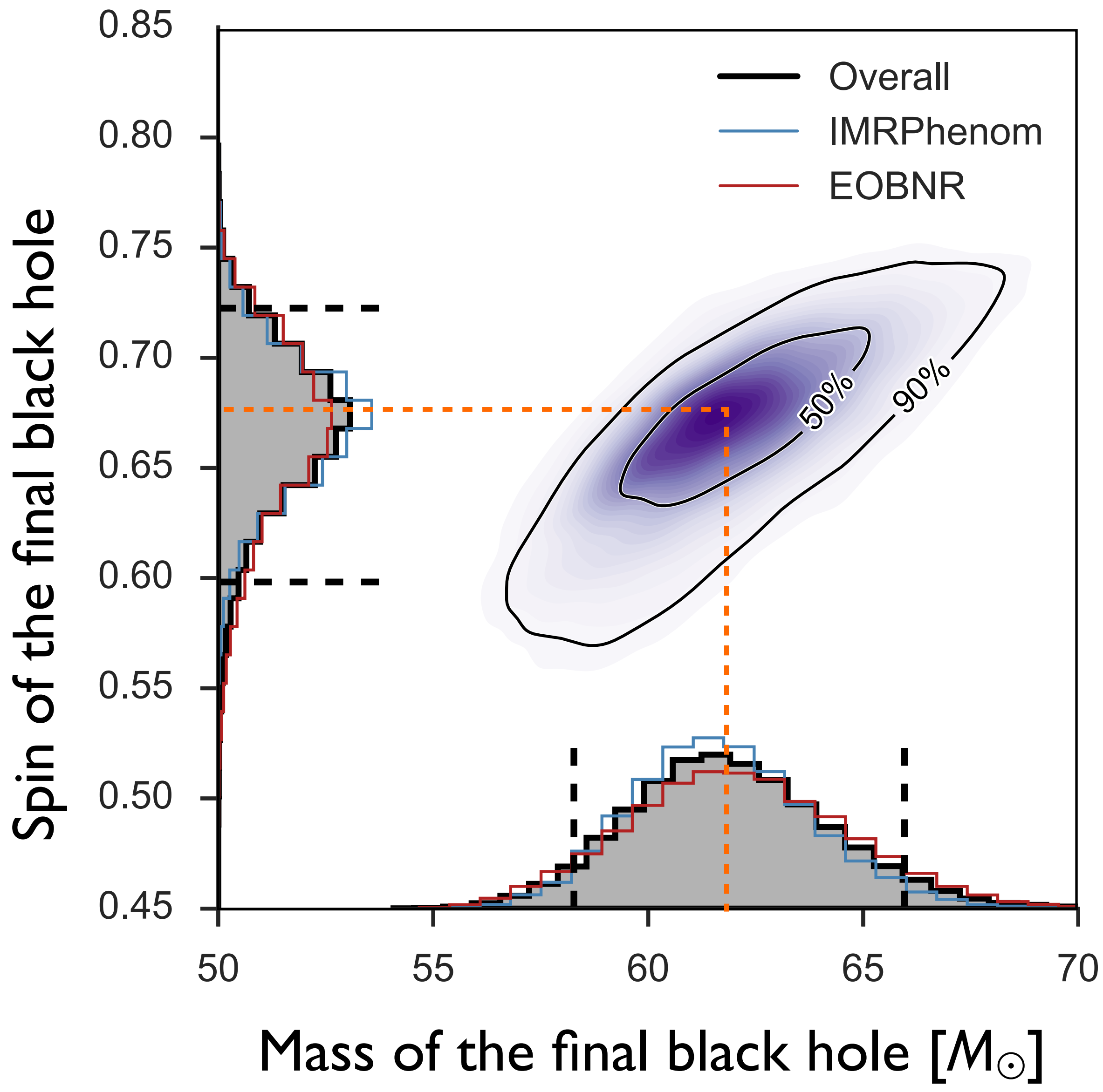


“Was that you I heard just now, or was it two black holes colliding?”

Estimating the parameters of the astrophysical source

- Two black holes of masses 36 $M_\odot$ and 29 $M_\odot$ in nearly circular orbit merged to form a rapidly spinning black hole of mass 62 $M_\odot$ and spin 0.67.
  - One of the best inference of the mass and spin of a stellar-mass black hole. Poor estimation of the individual spins.

Properties of the binary black hole merger GW150914
arXiv:1602.03840



[Direct contribution from ICTS]

Estimating the parameters of the astrophysical source

The very first detection of a binary black hole!
First observation of stellar-mass black holes with mass ≳ 25 M⊙

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

90% credible intervals including statistical and systematic errors

The most powerful astronomical source, ever!

3 $M_\odot c^2$ energy is radiated as gravitational waves in ~0.1 seconds

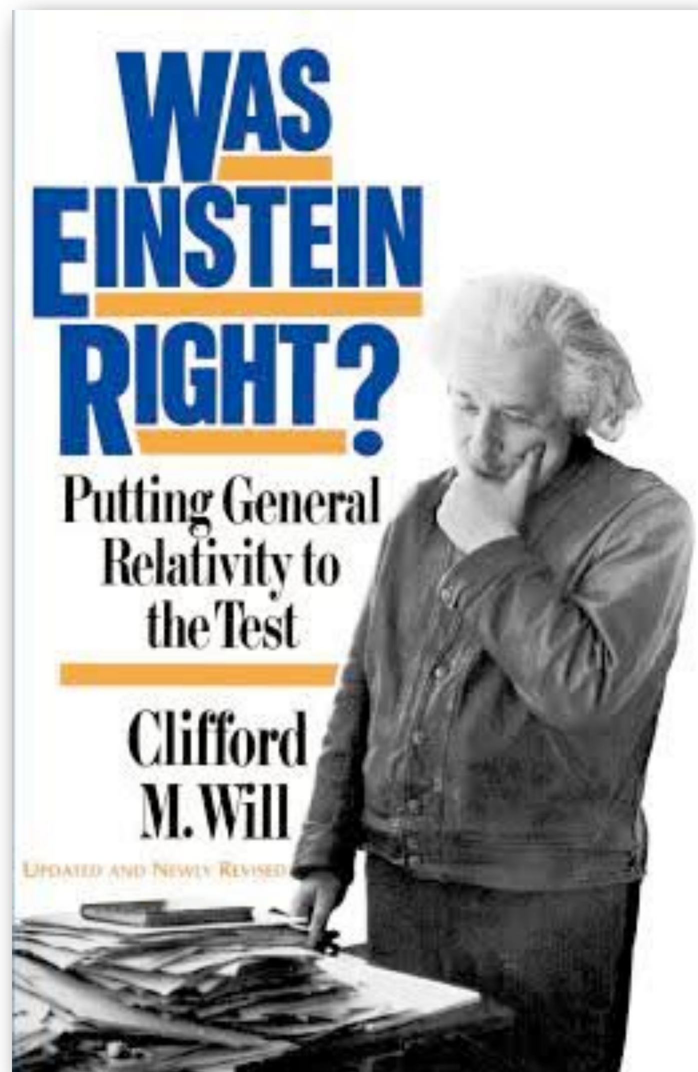
Peak power emission 10^{49} W!

(more than the luminosity of all the stars in the universe)

[Direct contribution from ICTS]

Einstein, right again!

Observed signal consistent with the prediction of General Relativity

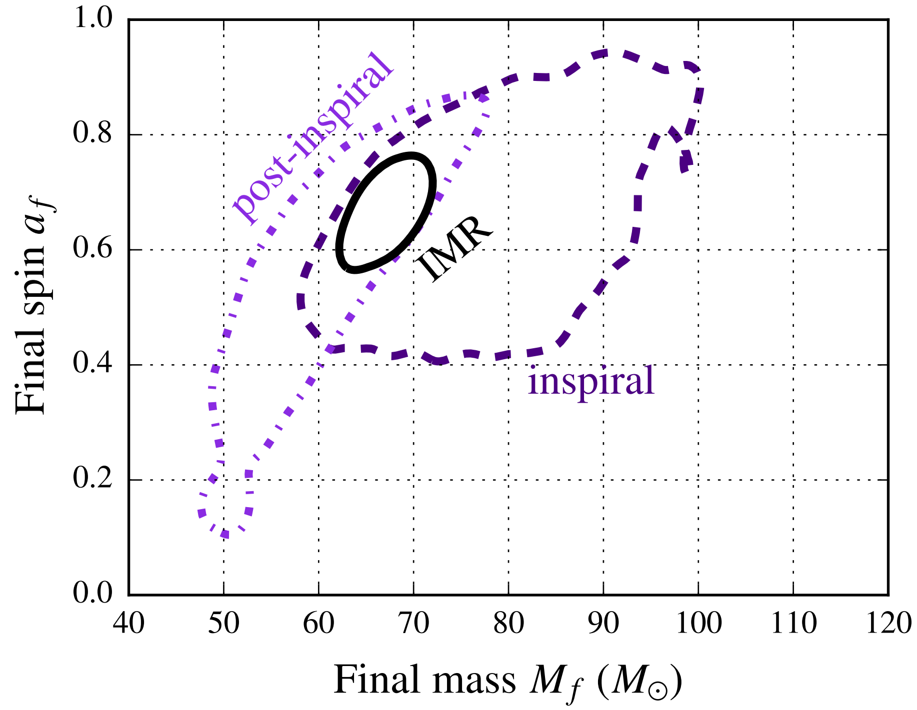


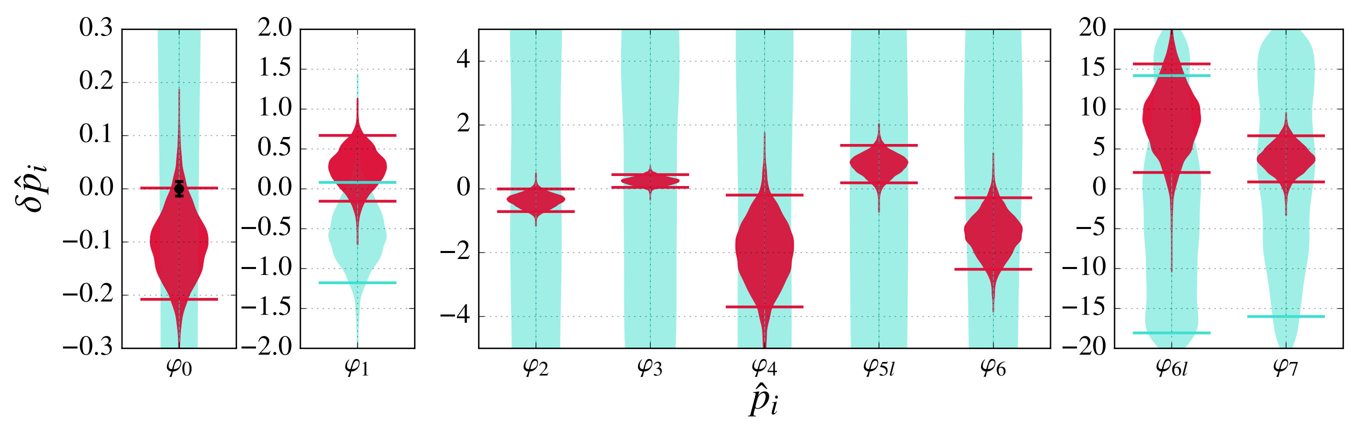
Einstein, right again!

- Residual of the data after subtracting the best-fit template is consistent with noise.
- Final mass/spin estimated from the inspiral and post-inspiral parts of the signal are in agreement.
- Final part of the signal is consistent with quasi-normal-mode ringing.
- Post-Newtonian coefficients estimated from the data agree with the theory prediction.
- Propagation effects consistent with a massless graviton.

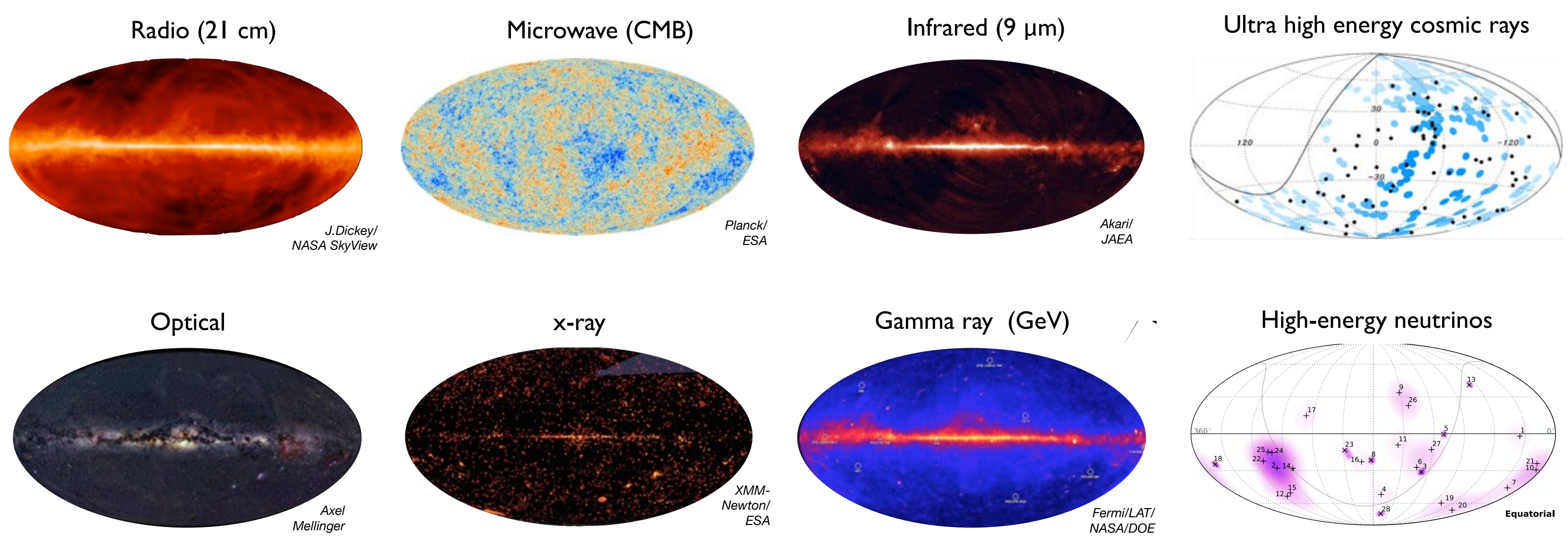
[Direct contribution from Indian groups]

Tests of general relativity with GW150914 [arXiv:1602.03841]





A new window to the Universe!



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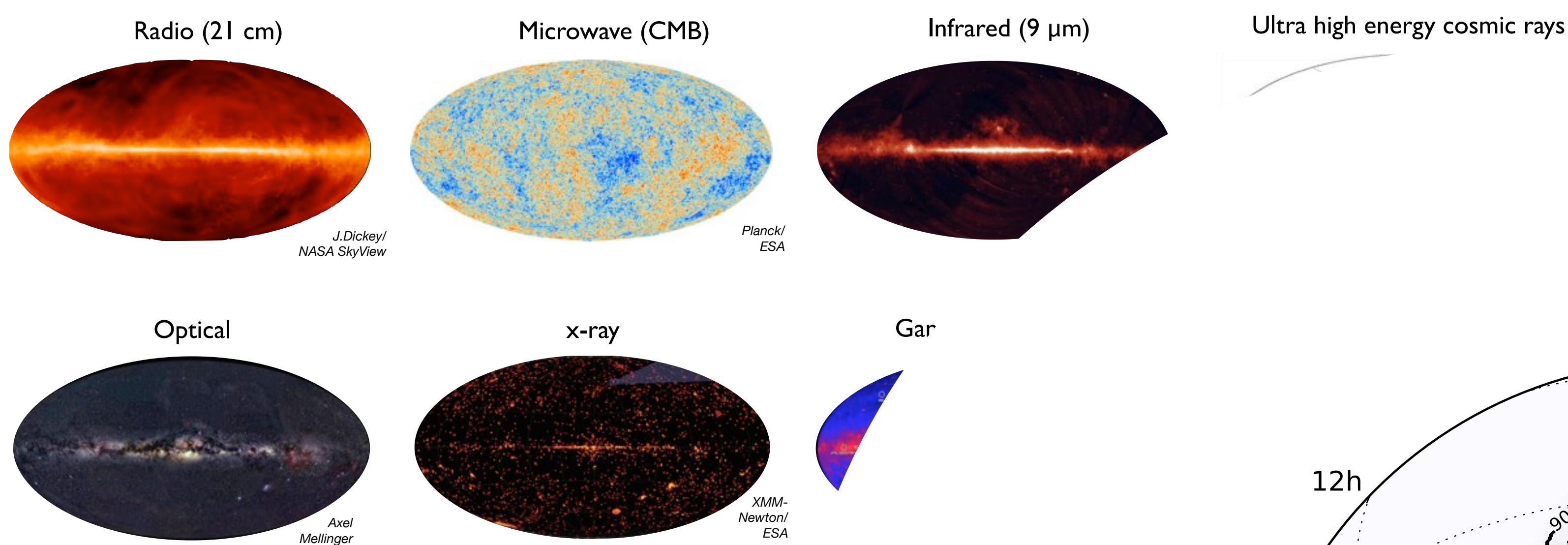

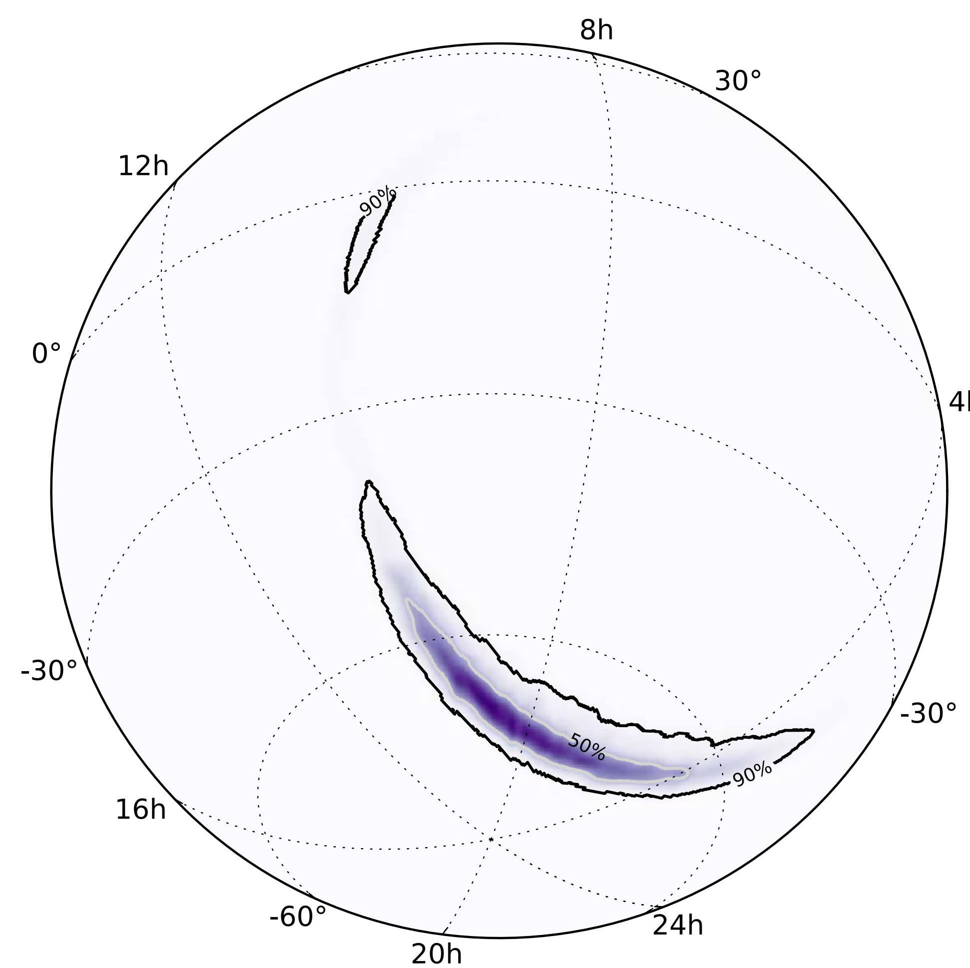

Poor localization of the source. Need more detectors in the network. Perhaps one in India?!

Acknowledgments

- LIGO research is carried out by the LIGO Scientific Collaboration (LSC), a group of more than 1000 scientists from universities around the United States and in 14 other countries.

- The discovery was made possible by the enhanced capabilities of Advanced LIGO, a major upgrade that increases the sensitivity of the instruments compared to the first generation LIGO detectors, enabling a large increase in the volume of the universe probed — and the discovery of gravitational waves during its first observation run. The US National Science Foundation leads in financial support for Advanced LIGO. Funding organizations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council) also have made significant commitments to the project.