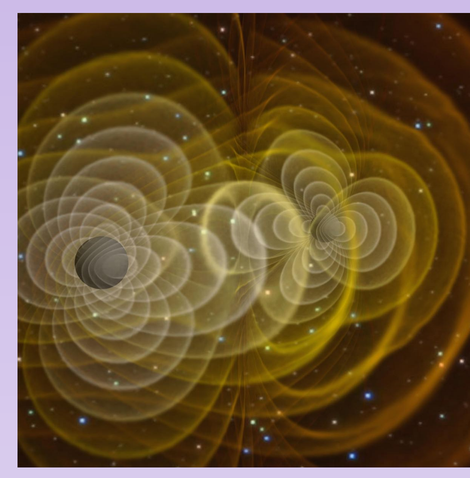
IndIGO-LSC Contributions in GW150914 and Related Science

Pic coutesy: NASA

The Indian participation in the LSC, under the umbrella of the Indian Initiative in Gravitational-Wave Observations (IndIGO), involves sixty-one scientists from nine institutions - CMI Chennai, ICTS-TIFR Bengaluru, IISER-Kolkata, IISER-Trivandrum, IIT Gandhinagar, IPR Gandhinagar, IUCAA Pune, RRCAT Indore and TIFR Mumbai. The discovery paper has 35 authors from these institutions. IndIGO was formed in 2009 by a group of researchers with expertise in theoretical and experimental gravity, cosmology and optical metrology, who were keen to promote gravitational wave research in the country with a dream of realizing an advanced detector in India. Indian groups contributed significantly to understanding the response of the detector to the signals and terrestrial influences, to the method used for detecting the signal, bounding the orbital eccentricity, estimating the mass and spin of the final black hole and the energy and power radiated during merger, confirming that the observed signal agrees with Einstein's General Theory of Relativity, and to the search for a possible electromagnetic counterpart using optical telescopes. Some of these works were carried out on high performance computing facilities at IUCAA, Pune, and ICTS, Bengaluru.

The discovery paves the road to the possibility of observing our universe in gravitational waves if one can locate their source with additional detectors placed far from the LIGO detectors, in a large triangle. The proposed LIGO-India project, in which a third detector will be built and operated in India, in collaboration with LIGO-USA and its international partners, Australia, Germany and UK, will be the most critical element in enabling the new scientific



Pic coutesy: NASA

Chennai Mathematical Institute
Chennai

The Gravitational Wave group at the Chennai Mathematical Institute (CMI) works on topics related to astrophysical source modelling, data analysis, astrophysics and fundamental physics using GWs. It is also a founder member of the Indigo consortium and Indigo-LSC collaboration.

Over the past few years, the Indigo-LSC group at the Chennai Mathematical Institute has been involved in the following activities:

1. Developing ready to use gravitational waveforms from compact binary coalescences for various of binary configurations, which are one of the crucial theoretical input required for detection and parameter estimation of GW signals,
2. Developing data analysis tools for the searches of binary black holes especially related to the placement of templates in searches for binary black holes,
3. Developing methods aimed at testing General Relativity and alternative theories of gravity using GW observations.The group was closely involved in the analysis and interpretation of GW150914 in connection with the tests of Einstein's General Theory of Relativity. The study found the consistency of the observed GW signal with General Relativity in the genuinely strong-field regime of gravity.

International Centre for Theoretical Sciences
Bengaluru

The Astrophysical Relativity group at ICTS-TIFR has broad interests in gravitational-wave data analysis, source modelling and the astrophysics of compact objects. Recent work from the group includes a test of general relativity using binary black hole coalescences, based on the consistency of the estimates for the mass and spin of the final black hole obtained from different parts of the waveform. This is among the suite of tests used to show that GW150914 is consistent with a binary black hole coalescence in general relativity. The group has also contributed to obtaining estimates of the mass and spin of the final black hole, and the energy and peak luminosity radiated by the binary in gravitational waves. These are obtained by applying fits to numerical simulations of binary black holes to the estimates of the binary's initial masses and spins. The group has also contributed to the astrophysical interpretation of the event using the estimated spins.

ICTS members also create accurate models of gravitational waveforms that are used to detect and interpret signals from coalescing compact binaries, and work on designing and testing the algorithms employed in detecting such systems. In addition, the group is interested in the astrophysics of compact binaries including neutron stars and black holes, and in the search for continuous gravitational waves from neutron stars that are deformed due to accretion from a companion.

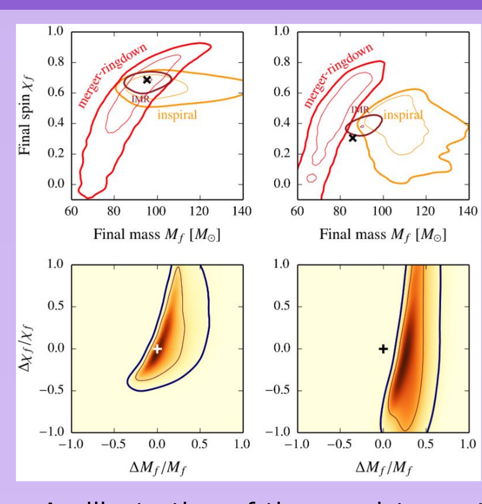


Figure: An illustration of the consistency test on a general relativity waveform (left) and on a waveform with a departure from general relativity (right). The consistency test is able to exclude general relativity in this latter case with very high confidence. The crosses in the upper panels mark the final mass and spin corresponding to the waveform used, and the plusses in the lower panels mark the result for no departure from general relativity

Indian Institute of Science Education and Research
Kolkata

Gravitational wave group in IISER Kolkata mainly works on the data analysis. Some of the ongoing research are listed here:

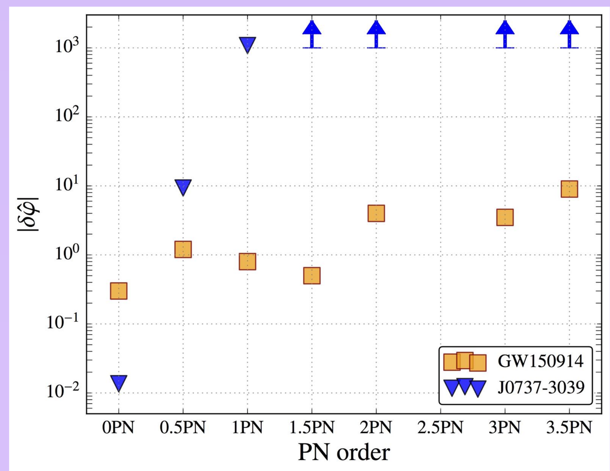
The team is developing a numerically efficient parameters estimation scheme using "Particle swarm optimisation" for compact coalescing binaries.

Test the Einstein's theory of gravity using the gravitational waves signal from the coalescing neutron star or black hole binaries.

In connection with LIGO India, IISER team is collaborating with IUCAA, Pune for seismic and terrane analysis of possible sites of LIGO-India.

Indian Institute of Science Education and Research
Thiruvananthapuram

The gravitational wave group at School of Physics, IISER Thiruvananthapuram, is a member of LIGO Science Collaboration since March 2012 under the umbrella of IndIGO consortium. The research interests of the Group span from novel gravitational wave detection algorithms, extracting astrophysical parameters with possible joint observation with electromagnetic counterparts, Testing General Theory of Relativity using the global network of interferometers such as two LIGO interferometers, French Italian Virgo located in Pisa, Italy, Japanese detector KAGRA and the proposed LIGO-India, and probing gravitational waves with Pulsar Timing Arrays. The research using interferometers is centered around the astrophysical binary systems with compact objects such as neutron stars, black holes.



Merger of black holes is a regime of strong gravity where Einstein's theory was never tested.Gravitational wave group at IISER Trivandrum contributed in Testing General Relativity with GW150914 along with the colleagues of LIGO-Virgo Science Collaboration. With extensive computational analysis, the study found that the emitted signal is consistent with the predictions of general relativity within the domain of available models.

Indian Institute of Technology Gandhinagar
Ahmedabad

IIT Gandhinagar has been a member of the LIGO Scientific Collaboration since 2012 under the aegis of the IndIGO consortium (of which it is a founder member) and has been a partner to the global efforts in gravitational wave detection.

The group's main interest is towards the development of sensitive search algorithms for detecting faint gravitational waves signals using data from a network of terrestrial detectors and their deployment over automated data analysis workflows using high-throughput computing technology. In particular, Gurudatt Gaur at IIT Gandhinagar is collaborating with IndIGO partner institution in developing techniques for combining triggers from multiple interferometers using geometrical properties of the signal manifold that includes spin as a search parameter.

The group is also developing an alternate scheme of data analysis where data is analyzed using a hierarchical search pipeline in collaboration with IndIGO-LSC members at IUCAA, Pune. Undergraduate student Samarth Vaijanapurkar is developing an efficient template placement scheme that is expected to significantly speed up the analysis time, thereby freeing up precious computational cycles for a deeper analysis. Graduate students at IIT Gandhinagar are working on identifying noisy glitches using state of the art developments in the areas of machine learning and computer vision. IIT Gandhinagar group is also working on automated follow up of gravitational wave events in the electromagnetic spectrum using robotic telescopes.

Inter-University Centre for Astronomy and Astrophysics
Pune

Physicists at the Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune, made significant contributions to this discovery. They are Professors Sukanta Bose, Sanjeev Dhurandhar (Emeritus), Sanjit Mitra, Tarun Souradeep, postdoctoral fellow Anuradha Gupta, PhD students Anirban Ain, Bhooshan Gadre, Nikhil Mukund, and visiting scientists Jayanti Prasad and Sharad Gaonkar. They are all active members of the LIGO Scientific Collaboration.

IUCAA's involvement spanned across a wide range of areas of this multi-disciplinary search, beginning with the basic idea used in finding the weak and short-lived gravitational wave signal in the very noisy data of the LIGO detectors. That idea, due to Dhurandhar and his collaborator B. Sathyaprakash (now in Cardiff) from 1991, was of matching thousands of wave patterns expected from black hole binaries, as derived from Einstein's theory, with the data from the detectors. For further confirmation of the common astrophysical origin of the signals, a multi-detector consistency test was applied. The theoretical foundation for it was laid by Bose and Dhurandhar, alongwith Archana Pai (now at IISER Thiruvananthapuram). More recently, the duo, along with Mitra, Gupta and Mukund, carried out extensive studies towards understanding the LIGO detectors' data and found ways of discriminating between transient terrestrial noise in the detectors and astrophysical signals. IUCAA scientists also contributed towards developing a set of the analysis tools that were used in this discovery. The High Performance Computing facility at the IUCAA Data Center provided valuable support.

Raman Research Institute
Bengaluru

The Gravitational Wave group at the Raman Research Institute (RRI) lead by Prof Bala Iyer has contributed significantly to mathematical calculations of gravitational waves from binary systems made of black holes and neutron stars and to methods to test Einstein's gravity by gravitational wave observations. Binaries consisting of neutron stars and black holes are among the most important targets of gravitational wave detectors like LIGO. GW signals from even such strong sources are weak relative to other effects acting on the detector and need sophisticated data-analysis techniques to detect the GW and unravel the source parameters. An important ingredient for the success of such a technique is the gravitational waveform that is expected to result from Einstein's General Theory of Relativity (GTR). Starting 1990, over two decades, in India, the RRI group spearheaded this theoretical endeavor, in collaboration with its international partners. This work produced waveforms for binaries consisting of neutron stars and/or black holes accounting for various physical effects. These results, being the starting points for the complex data analysis involved in GW detection, have a crucial role in this discovery. The RRI group also played a pivotal role in theoretical studies at the interface of theory and data-analysis introducing concepts and ideas that have become standard tools involved in this discovery. Finally, the RRI group also put forward a generic method to test the correctness of Einstein's GTR, once a signal is detected. This was one of the methods used in the context of the present discovery, to quantify the consistency of the observed signal with the predictions of GTR. Three of the former students of this group (A. Gopakumar, TIFR, Mumbai, K G Arun, CMI, Chennai and Chandra Kant Mishra, ICTS-TIFR, Bangalore) and undergraduate project students (which includes P. Ajith, [who currently leads the Astrophysical Relativity group] at ICTS-TIFR, Bangalore) are currently members of the IndIGO consortium and the LIGO Scientific Collaboration and actively contributed to the analysis and interpretation of this discovery.

Executive summary of the contributions.
1. Development of accurate GTR based gravitational wave signals from black hole and neutron stars pairs in circular and elliptical orbits, which were very useful for the discovery.
2. Fundamental studies at the interface of theory and data analysis which paved way for many future studies.
3. Proposal of a generic method to test Einstein's general theory of relativity, one of the methods carried out in the context of the discovery.

Tata Institute of Fundamental Research
Mumbai

TIFR, Mumbai has two groups in the IndIGO consortium and LSC.

A small group of researchers at the Department of Astronomy and Astrophysics has been contributing to the LSC for the last two years. They are developing accurate numerical codes that model the expected GW signals from black hole pairs merging along elliptical orbits. These waveform models allowed the group to constrain the orbital ellipticity of the GW150914 black hole binary. This analysis validated the assumption of binary evolution along circular orbits,presumed in the LSC data analysis of GW150914.Additionally, the group is also contributing to the accurate modeling of GWsignals from spinning black hole pairs.The group members include A. Gopakumar, M. Haney and A. Gupta (now at IUCAA).

The gravitational experiments group of TIFR pioneered precision experiments totest gravity theories in India in the mid-eighties with special purpose laboratories and novel instruments. TIFR funded a prototype interferometer GW detector, proposed by IndIGO-LSC members C. S. Unnikrishnan and G. Rajalakshmi in 2011.This new laboratory and prototype instrument are expected to play a significantrole in training and research that support the LIGO-India project. The group has contributed actively to the LIGO-India project proposal and GW outreach and teaching programs.