LIGO-India – a unique adventure in Indian science

Tarun Souradeep[1,*], Sendhil Raja[2], Ziauddin Khan[3], C. S. Unnikrishnan[4] and Bala Iyer[5]

[1]Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India
[2]Raja Ramanna Centre for Advanced Technology, Indore 452 013, India
[3]Institute for Plasma Research, Bhat, Gandhinagar 382 428, India
[4]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[5]International Centre for Theoretical Sciences–TIFR, Hesaraghatta Hobli, Bengaluru 560 089, India

LIGO-India is an ambitious, large scale mega-science project that will establish a state-of-the-art advanced LIGO gravitational wave (GW) observatory on Indian soil in collaboration with the LIGO Laboratory in the USA. LIGO-India is expected to commence science operations in 2024 as a key element of a global array of gravitational wave observatories. Beyond the first direct detection of gravitational waves announced in February 2016 by LIGO Science Collaboration, LIGO-India brings forth a great opportunity for Indian scientists and technologists for leadership at the frontier, a new window of gravitational-wave astronomy to probe the universe.

Keywords: Astronomy and astrophysics, gravitational waves, layer interferometer, mega-science projects, observatories and detectors.

Introduction

THE historic detection of gravitational waves (GW) made by the advanced Laser Interferometer Gravitational-wave Observatory (LIGO) detectors located in USA has opened the possibility of observing our universe in gravitational waves[1]. The discovery announced on 11 February 2016 by the international LIGO Science Collaboration (LSC)[2] has launched India onto an exciting arena of frontier science. Not only did the discovery paper have 39 Indian co-author scientists from nine Indian institutions, but an opportunity for taking leadership in this field has opened up with the LIGO-India mega-science project[3].

LIGO-India is arguably one of the most ambitious, large-scale mega-science projects planned on Indian soil. The Union cabinet of India granted an ‘in principle’ approval to LIGO-India on 17 February 2016. The project will establish a state-of-the-art advanced observatory on Indian soil in collaboration with the LIGO Laboratory in the US, operated by Caltech and MIT. LIGO-India will allow considerably improved localization of the GW sources on the sky, opening the door to significantly enhanced prospects for GW astronomy as shown in Figure 1. The global science community is unanimous that the future of GW astronomy and astrophysics, beyond the first discovery, lies with the planned global array of GW detectors, including the LIGO-India observatory depicted in Figure 2.

Inclusion of LIGO-India greatly improves the angular resolution in the location of the GW source by the LIGO global network. As depicted in Figure 1, for the three events observed by the two advanced LIGO detectors in the US, with a hypothetical LIGO-India in operation, there would have been 20–60 times improvement in the angular resolution. This is a firm attestation to the promise of LIGO-India. Hence, LIGO-India brings forth a real possibility of Indian scientists and technologists stepping forward, with strong international cooperation, into the frontier of an emergent area of high visibility presented by the recent GW detections and the promise of a new window of GW astronomy to probe the universe.

Though the direct detection of GWs was the first mandate of the kilometre-scale advanced laser interferometer GW detectors, more than the discovery itself, the excitement following the first detection relates to the opening up of a new observational window into the dark universe. A few years into the millennium, during the first phase of operations with the initial LIGO detector in USA and its close cousin, VIRGO in Italy, concrete plans for the advanced detector configuration achievable by the middle of the next decade around 2015, were already being drawn up. They indicated that the next generation of GW detectors would allow a tenfold improvement in sensitivity and a thousand fold increase in the expected rate of cosmic events with detectable signals to more than one event per year, even in very pessimistic astrophysical scenarios. It was eminently clear that the detection of GW signals from astrophysical phenomena, in particular, from the merger of compact neutron star binaries and black hole binaries, was almost guaranteed with the observational runs of the advanced LIGO detectors. A few researchers in India recognized the great opportunity it presented to the Indian scientific community if it could

*For correspondence. (e-mail: tarun@iucaa.in)

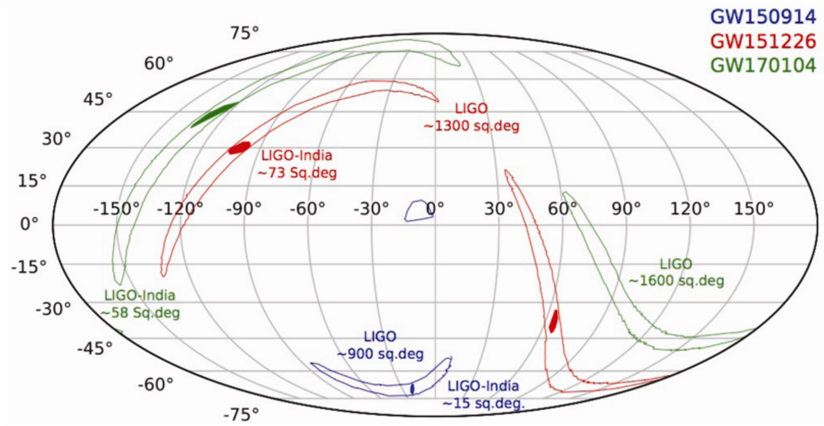

Figure 1. The sky localization, i.e. angular uncertainty in pointing back to the source on the sky, of the three gravitational wave (GW) events detected by the two Laser Interferometer Gravitational-wave Observatory (LIGO) detectors in USA shown as coloured closed empty contour (90% CL) lines. The filled colour contours are the corresponding expected pointing uncertainties, if hypothetically, LIGO-India had been operating at the same sensitivity during these detections. The sky area in square degrees in each case is mentioned. Note the remarkable potential of LIGO-India to dramatically improve the pointing accuracy to observed GW sources.

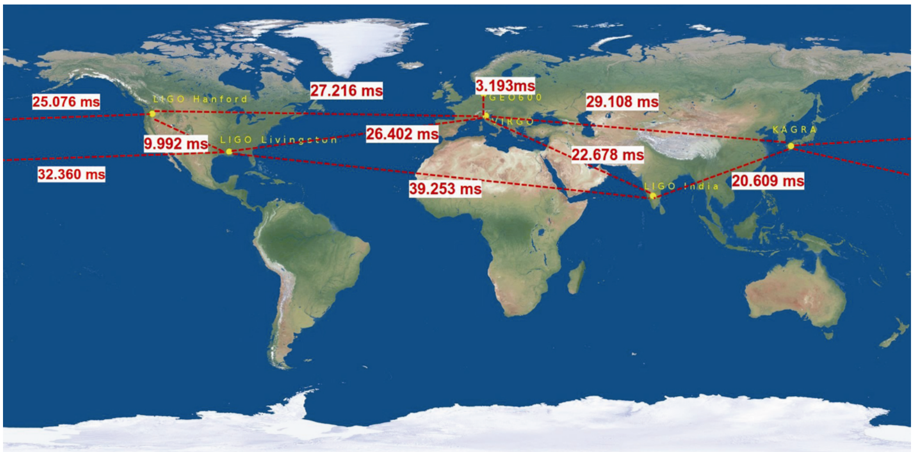

Figure 2. The global array of GW observatories expected to be operational at the time LIGO-India commences scientific observations by the middle of the next decade.

gear up, plan and prepare a decade in advance for carrying out a large-scale research endeavour in this emergent field.

As early as 2007, at the International Conference in Gravitation and Cosmology (ICGC) meeting at the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, first discussions about a GW detector in India were aired among a group of interested researchers in the country with some international experts. In August 2009, at a meeting in IUCAA, a consortium of interested groups of Indian researchers called IndIGO[4], which collectively had expertise in theoretical and experimental gravity, cosmology and optical metrology was formed. The consortium sought to promote GW research in the country with a summit goal of realizing an advanced detector in India in the same time-frame as the global advanced generation of detectors.

LIGO in USA consists of two observatories at Hanford, Washington and Livingston, Louisiana. The original advanced LIGO project, however, envisaged three detectors with two of them being housed in the same beam tube at Hanford. Beyond discovery, an improved source location is critical for GW observations to become part of the new wave of multi-messenger astronomy, which means doing astronomy employing multiple windows of observation in parallel. Realizing the strategic importance for astronomy of an enhanced ability to localize GW sources in the sky, LIGO chose to pursue the geographical relocation of the second Hanford detector at a distant site on the globe, that was preferably also away from the plane formed by the two US LIGO sites and Virgo. A global array of LIGO and LIGO-like GW observatories is coming up across the globe (Figure 2). Table 1 provides the baselines in terms of light travel time of the global

Table 1. LIGO-India will operate as part of a global array of gravitational wave observatories, including three identical advanced LIGO 4 km detectors in USA and India, the European (3 km) Virgo detector and the Japanese 3 km cryogenic Kagra detector. The baselines between pairs of detectors in terms of light travel time in milliseconds is tabulated

Observatory	H	L	V	K	I
LIGO–Hanford (H)	–	9.993	27.216	25.076	36.530
LIGO–Livingston (L)	9.993	–	26.402	32.360	39.254
Virgo (V)	27.216	26.402	–	29.109	22.678
Kagra (K)	25.076	32.360	29.109	–	20.609
LIGO–India (I)	36.530	39.254	22.678	20.609	–

Note that LIGO-India would provide the largest two baselines in the global array at 92% and 86% of the maximum distance possible on Earth.

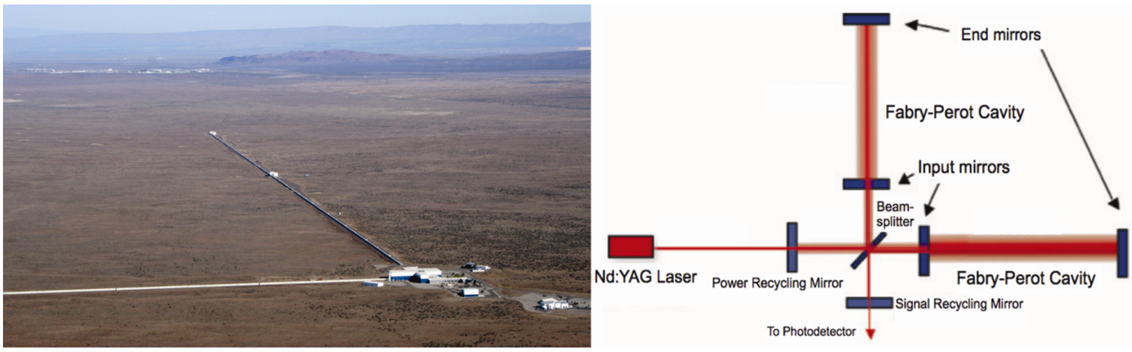

Figure 3. (Left) LIGO at Hanford, Washington, USA (credit: Caltech/LIGO Laboratory). (Right) A broad-level schematic of the optical layout of the advanced LIGO interferometer.

array of observatories. Additional observatories also lead to increased event rates, improved duty cycle, improved detection confidence, improved sky coverage, and improved determination of the polarization of GWs. Since GWs provide complementary information to that provided by other means, by combining observations of a single event using different probes, it is possible to gain a more complete understanding of the properties of astrophysical sources and physical phenomena occurring in them.

The LIGO-India proposal is for the construction and operation of an advanced LIGO (with displacement sensitivity: 4×10^{-20} m/$\sqrt{\text{Hz}}$) in the country in collaboration with the LIGO laboratories, USA. The left panel of Figure 3 shows a picture of the LIGO facility at Hanford, USA. The objective is to set up the Indian node of the three-node global Advanced LIGO network by 2024 and operate it for a baseline period of 10 years. The LIGO laboratory made the formal offer for the LIGO-India joint collaboration in October 2011. A detailed LIGO-India proposal[5] was submitted to the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST), Government of India immediately in November 2011 and presented at a meeting of the Planning Commission committee on mega projects in Delhi. The project was recommended by the mega-science committee and the Atomic Energy Commission in the following year.

The advanced LIGO detectors are Michelson interferometers of arm-length 4 km each, with light path folding by about 300 multiple reflections on two mirrors implemented by Fabry–Perot cavities inside the Michelson arms[6]. The right side panel of Figure 3 shows a broad schematic overview of the optical layout of LIGO. Thus the effective length exceeds 1000 km (about a fourth of the wavelength of GWs targeted) and the minimum detectable strain is determined by the random noise of the number of photons in the input laser beam in the 150–1000 Hz frequency range and also by thermally generated noise on the suspended optical elements at lower frequencies below 150 Hz.

The laser source is a frequency and intensity stabilized 200 W Nd : YAG laser at 1064 nm. The mirrors of the interferometer (also referred to as test masses) are made of fused silica, each of 40 kg mass, and 320 mm diameter with exquisite surface finish at the level of 1/3000th of the wavelength of laser light. The test masses are suspended via a quadruple pendulum to provide mechanical isolation from ground-induced motions to well below the displacement sensitivity of 10^{-20} m. A combination of high-gain servos and passive isolators, along with the quadruple pendulum provide an attenuation of 10^{-14} from the ground-induced motion. All the optical components within the two 4 km long arms of the interferometer are maintained under ultrahigh vacuum (10^{-9} mbar) to minimize noise due to gas density fluctuations and scattering. Large gate-valves are provided between the chambers and beam tubes for isolation during installation of components in the chambers and during bake-out of the beam tubes. The beam tubes over their 4 km length, should be straight to within a centimetre and are installed on a level concrete base that is geometrically straight as opposed to the normal practice of being 'plumb-level' to the earth's curvature. In essence, the 4 km arm length interferometer should rest on a flat and stable base capable of maintaining alignment and the level of ground displacement noise has to be limited below a nanometre in the frequency band (0.01–10 Hz) to avoid disturbing the laser interferometer out of alignment.

The task for LIGO-India includes the challenge of constructing the very large vaccum infrastructure that would hold a space of volume 10 million litres that can accomodate the entire 4 km scale laser interferometer in ultra high vacuum. The Indian team is also responsible for the installation and commissioning of the complex instrument and eventually attaining the design sensitivity. The process of commissioning towards full sensitivity is a laborious and technically complicated process because already the optical power held by the two mirrors of the Fabry–Perot cavity is 100 kW, and much larger power can distort the best of mirrors technically possible to fabricate, leading to unstable operation. Isolation from seismic and environmental noise is achieved by a combination of passive isolation consisting of low-frequency springs and pendulums, and active feedback isolation consisting of a large number of sensors and actuators with a very large complex control system with tens of thousands of control channels. Equally critical in ensuring the success of LIGO-India has been the selection of an appropriate site that limits the natural and anthropogenic ground vibration noise and other ambient disturbances that need to be shielded by the advanced isolation system.

The LIGO-India project is being jointly executed by lead institutions: the IUCAA, Pune of the University Grants Commission (UGC), and DAE organizations; Institute for Plasma Research (IPR), Gandhinagar; the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, and the Directorate of Construction and Estate Management (DCSEM) of DAE. LIGO-India is being jointly funded by DAE and DST. A LIGO-India Apex Committee, together with the LIGO-India Project Management Board (LI-PMB) and LIGO-India Scientific Management Board (LI-SMB), were constituted in August 2016 to oversee the project execution, and there has been a rapid pace of progress since then.

The key hardware components of the advanced LIGO detector, along with designs and software, are to be provided by LIGO-USA and its UK, German and Australian partners. The entire civil design and construction, and the complex and large vacuum beam tubes with associated chambers, corner and end stations, related laboratories and clean rooms, as well as creation of a team to build and operate the observatory will be the Indian responsibility. The LIGO Laboratory, USA is committed to share and provide detailed designs and documentation of all aspects of the Advanced LIGO observatory. It would also jointly participate in the installation, commissioning and noise-limited operation at the LIGO-India site.

LIGO-India teams at IUCAA, IPR and RRCAT have continued to work steadily through the pre-approval period from 2012 to 2016. The site-selection effort led by IUCAA explored 39 site leads and systematically shortlisted a few of them based on site selection criteria like low seismicity (ground noise), low human-generated noise, socio-environmental considerations of land acquisition, air connectivity, road connectivity and data connectivity. IUCAA also initiated the science team building activity, including setting up a state-of-the-art computing and data infrastructure and associated manpower in anticipation of LIGO-India. The team at IPR prepared system requirement documents, conceptual drawings and engineering drawings for the sophisticated civil infrastructure and ultra high vacuum systems in consultation with LIGO-USA. The team at RRCAT developed plans for setting up an offsite laboratory to receive the laser systems for LIGO-India. Preparatory activities on silica suspension fibre drawing and bonding and laser system development have also been undertaken at RRCAT. Pre-approval preparation has also involved many schools and workshops at different levels, and exchange visits to attract and train young researchers.

After the approval from the Government, LIGO-India has progressed at a rapid pace. The main highlights of the progress over the past year are summarized below:

- At the first post-approval review by DAE of readiness for the LIGO-India project in July 2016, it was decided that the immediate focus would be on the obvious critical step of site acquisition. Plans were also made for fast-tracked funds to be made available for land acquisition. Recently, the entire pre-project funds that cover all aspects of work in the next three years have been sanctioned.
- In August 2016, DAE initiated the primary project structure by setting up the LIGO-India Apex Committee, LI-PMB and LI-SMB.
- In September 2016, the LIGO-India site selection committee set up in April 2013 formally recommended the primary and back-up sites for LIGO-India in a detailed study report. The study and final recommendation were based on five years of intense effort, starting September 2011, led by IUCAA and involving many members from multiple institutions, to shortlist three sites among about 39 leads followed up. The effort was greatly assisted when SAC, ISRO shared with IUCAA full-resolution CartoSat terrain

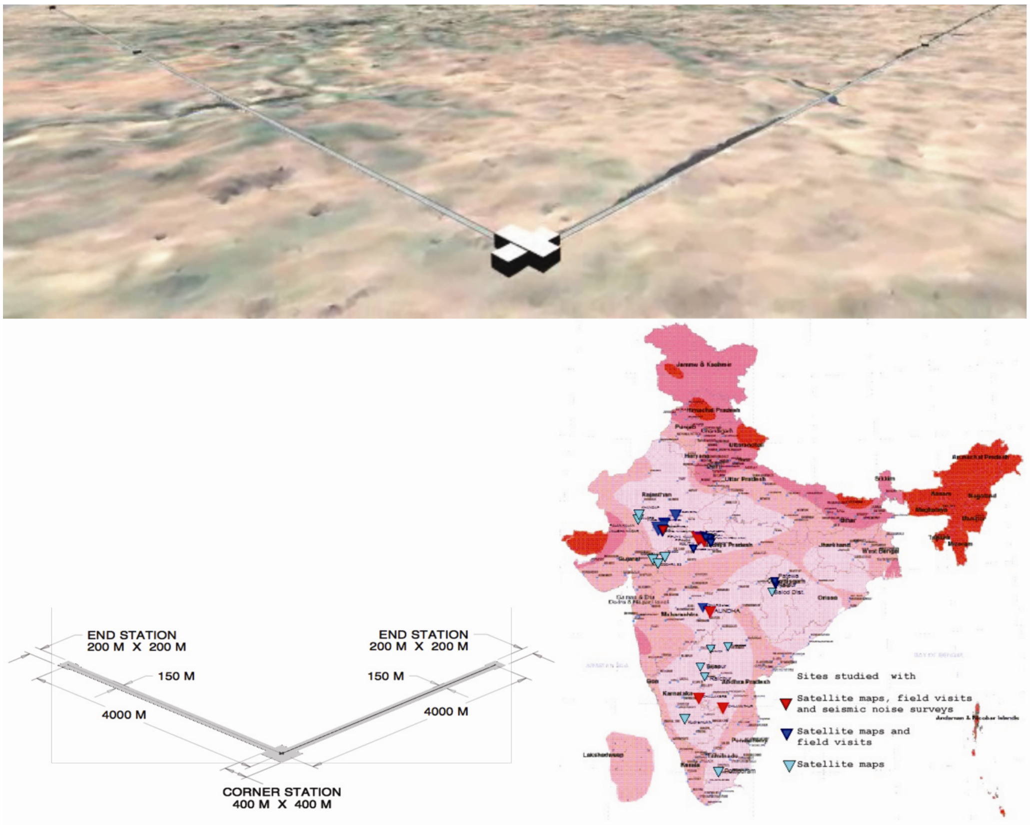

Figure 4. (Top) Engineering concept design of LIGO-India at one of the shortlisted sites in the country showing the actual terrain data obtained from SAC, ISRO (courtesy: TCE, India). (Bottom, left) The broad layout and footprint of land requested for the LIGO-India project. (Bottom, right) Seismic zonation map of India showing the numerous potential candidate site locations studied for selection spread all over the country.

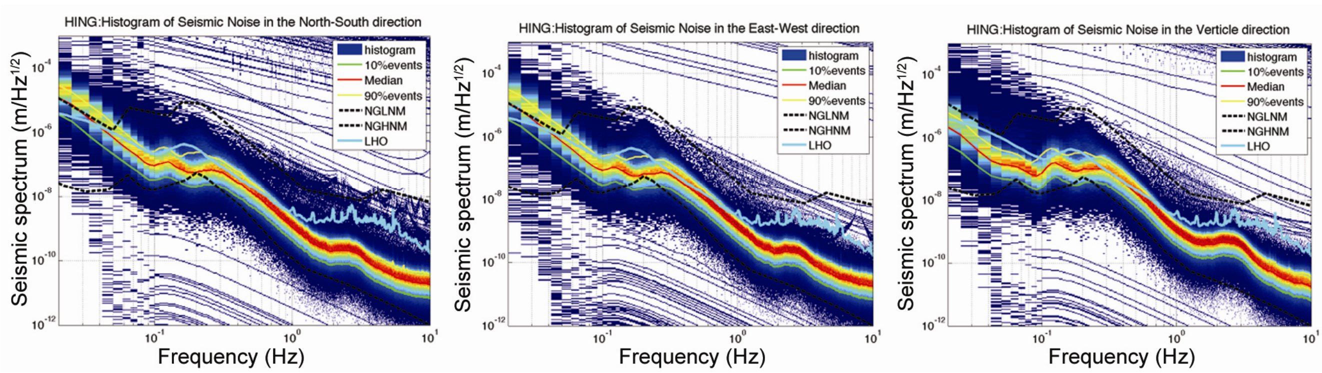

Figure 5. Seismic study data for the preferred site for LIGO-India showing promising geophysical environment at the Indian site. The displacement power spectral density along three components (vertical, east–west and north–south) are shown in the three panels. The median behaviour in red shade compares advantageously to the cyan curve that gives the corresponding average at the US LIGO-Hanford observatory. Dashed lines show minimum (NLNM) and maximum (NHNM) noise levels of the standard global noise model.

data for all the shortlisted sites. IUCAA commissioned Tata Consulting Engineers (TCE) to carry out a detailed engineering feasibility study at the shor-listed sites. The conceptual engineering design of LIGO-India created by TCE is shown in Figure 4 (top). The bottom panels of Figure 4 show the footprint of LIGO-India and the extensive site selection exercise. The seismic characteristics at the recommended primary site is shown in Figure 5.

- A LIGO-India site acquisition team was constituted in August 2016. Assessment and initiation visit to the primary site, district office and divisional office took place soon after. Multiple visits to the site since then have led to good progress on the land acquisition front. State Cabinet approval was granted promptly to the request for land from the DAE Secretary on 4 October 2016. Joint measurement survey was completed in February 2017. Detailed discussions with town planning office led to the establishment of restricted development zones in 5, 10 and 15 km distances around LIGO-India in the district development plans. The grant of special project status to LIGO-India is also expected soon.

- Preparation of the Detailed Project Report for LIGO-India by the project coordinators has been progressing well under LI-PMB. Conceptual drawings of the civil infrastructure have been reviewed. The final architectural and structural designs of civil infrastructure facilities are under preparation. The entire set of vacuum infrastructure drawings has been prepared.
- Development of extensive R&D programmes and HRD under LI-SMB has been undertaken. Four meetings in the series of LITRA (LIGO-India: The Road Ahead) have been held at IUCAA, aimed at bringing together Indian researchers in allied areas with leading international experts to draw them into the GW R&D programmes. Researchers from the Indian Institute of Technology (IITs) at Madras, Delhi, Kanpur and IIT Hyderabad; IISERs, Pune and Kolkata; TIFR Mumbai and Hyderabad; Universities at Pune and Nanded; Saha Institute for Nuclear Physics; BITS Hyderabad; National Physical Laboratory, Physical Research Laboratory, with coordination from the lead institutions RRCAT, IPR and IUCAA are currently organizing themeselves into active working groups. The working groups within optics – laser development, squeezed light, mirror coating, isolation control systems, wind-loading studies, seismic and Newtonian noise have been set up in addition to the existing data analysis and source modelling activities. Regular telecons have been initiated in some of the working groups. The initiative continues to steadily add more institutions and universities in its fold.
- Scientific analysis and inference on data from the LIGO observatories are carried out by LSC at a few dedicated computing facilities (Tier-2) in the world. A Tier-2 LSC Data Centre has been set up at IUCAA and has been operational since the start of O2 runs of LIGO-USA detectors in November 2016. ICTS-TIFR has set up a Tier-3 Data Centre.
- The pan-Indian group that participates in the LSC, has currently 71 members from 13 institutional groups at CMI, ICTS-TIFR, IISERs at Thiruvanantapuram and Kolkata, IITs at Gandhinagar, Hyderabad and Mumbai; IPR; IUCAA; RRCAT, TIFR and UIAR. This group has contributed to the LSC for all the three GW events detected by LIGO so far.

The Indian GW science community, mainly consisting of researchers trained at the research groups in IUCAA and RRI, has spread to take up faculty positions at a number of educational and research institutions in the country. As members of the LSC, they have made major contributions to the development of novel techniques to identify the weak GW signals, enabling GW astrophysics. The quest to build LIGO-India has brought Indian researchers with expertise in precision metrology, laser and optics development, ultra-high vacuum techniques and control systems to the fold of the Indian initiative in GWs observations.

The milestone direct detection of GWs and the approval of LIGO-India pave the road to highly visible Indian contribution in the emergent science from observing our universe in GWs. There has also been an increasing participation from the Indian astronomy community in anticipation of this new emerging frontier of 'Electromagnetic follow-up' of GW events. As the global GW network expands to include LIGO-India, its successful operation will help transform the field to an active frontier area of astronomy, astrophysics and gravitational physics.

1. Abbott, B. P. *et al.*, Observation of gravitational waves from a binary black hole merger. (LIGO Scientific Collaboration and Virgo Collaboration). *Phys. Rev. Lett.*, 2016, **116**, 061102.
2. http://www.ligo.org
3. http://www.gw.iucaa.in/ligo-india/
4. http://www.gw-indigo.org
5. https://dcc.ligo.org/public/0075/M1100296/002/LIGO-India_lw-v2.pdf
6. https://www.advancedligo.mit.edu

ACKNOWLEDGEMENTS. LIGO-India has been a dream nurtured and sustained by many colleagues in India and abroad over the last eight years. From heads and colleagues in the funding agencies to directors and colleagues in the lead institutes, from distinguished scientific leaders around the world to young faculty aspiring to make a mark, we gratefully acknowledge their contribution to this mega-science effort. We specifically thank young students, Javed Rana (IUCAA) and Karthik Prabhu (IISER-Pune and IUCAA) for providing some of the figures and the table for the article.

doi: 10.18520/cs/v113/i04/672-677