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Contents...

Research Highlights

GWAstro@IUCAA – A summary of research activities

Gravitational waves (GWs) are ripples in the fabric of space-time, produced when massive and dense objects, such as black holes or neutron stars, accelerate. More precisely, any system that exhibits a time-varying axial asymmetry, such as a compact binary consisting of black hole(s) and/or neutron star(s) orbiting their mutual centre of mass, will emanate GWs. Predicted by Albert Einstein over a century ago, GWs were discovered, for the first time, almost exactly ten years ago. Exploiting the fact that GWs manifest themselves as strains (change in length divided by length) on spatially separated test masses, sophisticated interferometric detectors with kilometre-long arms, called LIGO detectors, both constructed in the United States, unambiguously registered the passing of GWs from a merging binary black hole, each weighing about thirty times the mass of the sun, situated approximately a billion light years away. Since then, the LIGO detectors, in tandem with a Virgo detector in Italy, have detected over two hundred compact binary coalescence events (CBCs).

The production of GWs causes the orbit of compact binaries to lose energy and angular momentum. Consequently, the orbit shrinks while the components spiral in towards each other and ultimately merge. The shape of the motion of the in-spiralling and merging binary leaves its imprint on the GWs emitted, while the motion itself is determined by the space-time curvature produced by the individual components of the binary. Thus, the shape of the GWs provides access to the binary's intrinsic and extrinsic parameters, including the masses of the components, their spin angular momenta (or "spins" for short), the luminosity distance of the binary from the Earth, as well as the inclination of the orbit with respect to the line of sight. It is our ability to both detect these GWs and extract the parameters of the source that has truly opened a new window to the Universe and a new branch of astronomy – GW astronomy.

The GWAstro group at IUCAA, led by Shasvath Kapadia, works on various aspects of GW Astronomy, utilising cutting-edge theoretical, computational, data analysis, and Bayesian inference tools. The group consists of five graduate students and a postdoc. The thrust of this group is to find novel and creative ways to interface GW Astronomy with other branches of astrophysics, cosmology and fundamental physics, to help build a more complete picture of the Universe that we live in. We describe below some of the research directions and projects pursued by GWAstro@IUCAA.

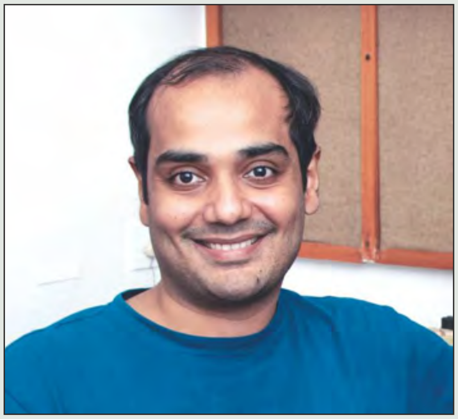
GWs provide perhaps the only way to directly observe stellar mass black holes and neutron stars situated at extragalactic distances. In principle, therefore, GWs could answer longstanding questions, such as: Where do binary black holes and neutron stars come from? How do they form? What are the environments that cradle and nurture their evolution? These are questions that are extremely difficult to answer, especially on a single-event basis, for two reasons. The first is that typically, electromagnetic counterparts from the mergers of CBCs are either too faint (as with binary neutron star and neutron star – black hole mergers) to be observed at distances exceeding a few hundred megaparsecs, or non-existent (as with stellar-mass binary black hole mergers). Pinpointing the location of these merger events in the sky with electromagnetic telescopes is, in general, extremely rare or impossible. The second is that localisation sky-areas for GW events are generally relatively poor, spanning tens to hundreds of square degrees. Determining the host galaxy within this sky area and the environment within the host galaxy where the CBC merged becomes virtually impossible using traditional localisation techniques. One of the key research directions pursued in the GWAstro group involves reconstructing the properties of the merger environment from the shape of the GW waveform. In a series of works led by graduate student Avinash Tiwari, we demonstrated that the accelerated motion of the CBC's centre of mass, due to the presence of an external potential, modulates the shape of the waveform through the time-varying Doppler effect. Since the motion of the centre of mass is itself determined by the structure of the gravitational potential of the merger environment, we showed that the profile of this potential can be inferred – in exquisite detail – with planned ground- and space-based GW detectors (e.g, XG detectors, DECIGO and LISA). These potentials include those of globular clusters, nuclear star clusters, the Keplerian potential in the vicinity of a supermassive black hole, and dark-matter cusps. Intriguingly, even the wobble of the CBC due to the presence of a heavy exoplanet can be identified, and the presence of the exoplanet inferred. This series of works was done in close collaboration with Aditya Vijaykumar at CITA, Canada, as well as other collaborators at TIFR, Mumbai and IISER Pune.

Gravitational lensing of GWs is a highly anticipated discovery, expected in LIGO-Virgo-KAGRA's (LVK) next observing run. It could occur when GWs encounter large agglomerations of matter, such as galaxies or clusters, to produce multiple temporally resolved copies of the source's GWs. These copies have identical GW phase evolution, but differing amplitudes. Sudhir Gholap, a graduate student in the GWAstro group, led the development of novel statistical techniques to assess the similarity (or lack thereof) in the frequency evolution of the phases of two signals, determining whether the two signals are lensed pairs or unrelated signals. This work is being performed in collaboration with Sanjeev Dhurandhar at IUCAA. Another GWAstro-group project involving lensing is being led by graduate student Sourabh Magare, with potentially critical applications in multi-messenger astronomy. Merging neutron stars produce GWs as well as electromagnetic radiation (light) in various frequency bands. Since these electromagnetic counterparts are transient, it is crucial to capture them at their onset, especially if the physics surrounding the merger of the neutron stars is to be extracted and understood. To that end, GW early warning is crucial, allowing telescopes to slew to the location of the event before it merges. In a series of works led by Sourabh and in collaboration with Anupreeta More at IUCAA, we demonstrated how GW lensing of binary neutron stars can be leveraged. The crux of the method relies on predicting the arrival times of forthcoming GW images based on the measurement of the first GW image, its electromagnetic counterpart, and pictures of the host galaxy. Since the difference in arrival times of images can span days to weeks, our method effectively provides ample early warning to capture electromagnetic radiation surrounding the merger of the binary neutron star.

Spinning neutron stars with a "mountain" on their surface could be sources of persistent, or continuous, GWs. Detecting such continuous GWs would be ground breaking, as it would provide unprecedented access to the structure of the neutron star, while also shedding light on ultra-dense matter that cannot be produced in human-made laboratories. To date, no detection of continuous GWs has been reported. Nevertheless, even the non-detection of continuous GWs provides clues to the abundance of neutron stars in the Galaxy. Using sophisticated Bayesian tools and realistic simulation-based predictions of the distribution of Galactic neutron stars, GWAstro's graduate student Gopal Prabhu was able to place unique constraints on their abundance in the Galaxy. Our work showed, for the first time, that, while allowed theoretically, at best, only a handful of highly deformed, highly spinning neutron stars exist within our Galaxy. This work is being conducted in collaboration with members at ICTS-TIFR.

Testing Einstein's General Relativity (GR) with GWs is a high-profile endeavour pursued by many research groups worldwide, including the LVK collaboration. Led by GWAstro's postdoc, Sajad A. Bhat, our group, in collaboration with Md. Arif Shaikh at VSM University developed a novel test of GR involving eccentric CBCs. As a consequence of GWs radiating away orbital energy and angular momentum, the eccentricity of the binary "evaporates" with time, effectively circularising itself. This decay of eccentricity with frequency has a specific functional form predicted by GR. The work led by Sajad proposes a unique test of the consistency of this frequency evolution of eccentricity with GR, using GWs from eccentric CBCs. The method essentially compares the eccentricity of the GW signal recovered at a reference frequency with that recovered at higher reference frequencies. Suppose those recovered at higher reference frequencies match up with what is predicted by evolving the eccentricity at the initial reference frequency. In that case, the eccentricity evolution is said to be consistent with GR. Otherwise, either other unaccounted-for physical effects are causing a violation, or GR itself is being violated. This method was found to be particularly effective at catching so-called "eccentricity mimickers" – GW signals recovered with eccentric waveform models that spuriously suggest the presence of eccentricity due to the unaccounted-for physics in the waveform model.

The era of GW astronomy has well and truly arrived, and with the advent of LIGO-India in the 2030s, India's role in GW astronomy will become crucial, potentially even guiding its direction and discoveries in the future. GWAstro@IUCAA works on a variety of interdisciplinary GW-projects that straddle other fields of scientific inquiry. The group strives to develop innovative projects that not only address important, fundamental astrophysics-driven questions, but also aims to cultivate and train astrophysics talent in India, which will one day leverage cutting-edge data provided by LIGO-India to make its own seminal discoveries.



Prof. Shasvath J. Kapadia is a gravitational-wave (GW) astronomer and an Associate Professor at IUCAA. He is a member of the LIGO Scientific Collaboration (LSC), the LIGO-India Scientific Collaboration (LISC), and LIGO-India (LI). His research focuses on various aspects of GW theory, data analysis, and astrophysical inference. He actively explores innovative ways to interface GW astronomy with other branches of astronomy, astrophysics, cosmology, and fundamental physics. Outside of his scientific work, Prof. Kapadia enjoys taking long walks and is often drawn to large bodies of water such as rivers, lakes, and oceans—a tendency that he humorously admits he is still trying to understand.

Solar Tsunamis: Propagating Extreme Ultraviolet (EUV) Waves Across the Sun

The Sun serves as our primary source of light and energy, and its influence on space weather makes it a unique and vital star to study. Activities on the Sun's surface produce solar wind, high-energy particle emissions, and radiation, all of which can disturb Earth's magnetic field and atmosphere, impacting our planet's environment. Solar activities are classified by their scale into large-scale events—such as solar extreme ultraviolet (EUV) waves, filament eruptions, solar flares, and coronal mass ejections (CMEs)—and small-scale phenomena like solar jets, micro/nano flares, and spicules. Despite the difference in size, both large and small eruptions share a common magnetic origin. Among the large-scale solar phenomena, EUV waves are particularly well-known. These are large, bright, wave-like fronts that propagate

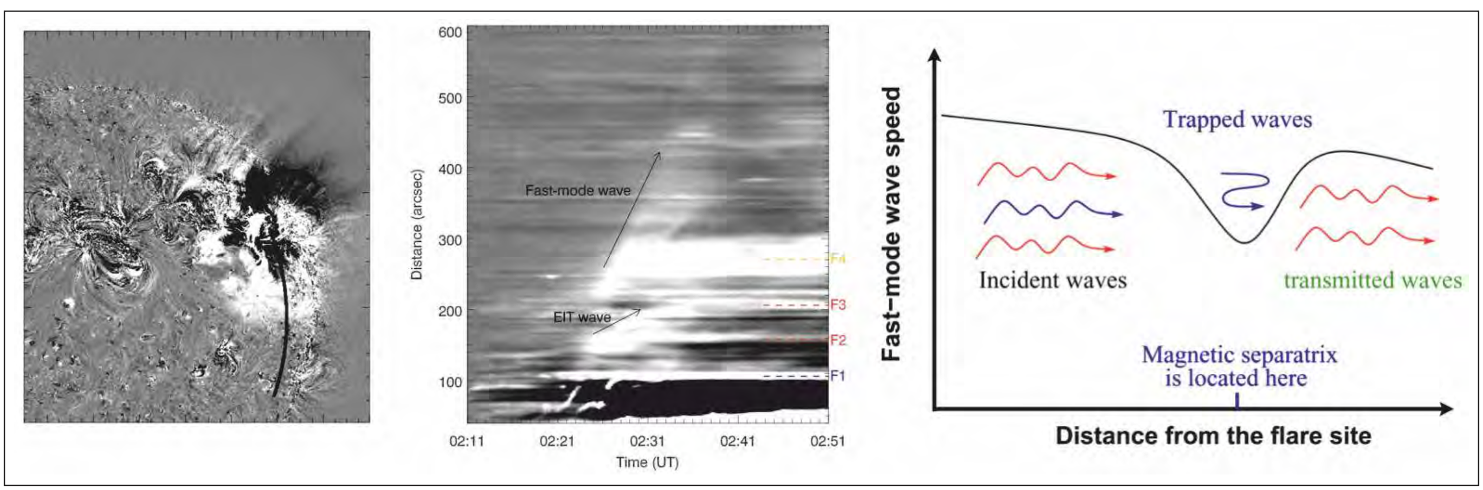


*Fig 1: **Left:** SDO/AIA 193 Å difference image (02:11 UT, 11 May 2011) with a black line indicating the path for the time–distance diagram. **Middle:** Time–distance diagram showing two EUV wave components and stationary fronts (F1–F4). Arrows highlight the fast MHD wave and the slower EIT wave (non-wave component). **Right:** Schematic illustrating the physical process behind stationary front F4 (adapted from Chandra et al. 2016 [9]).*

from solar eruption sites—similar to a tsunami in the Earth ocean—and can be observed in multiple wavelengths, including Hα, EUV, UV, and X-rays. They were first detected using the Hα ± 0.5 Å filter by Monton and Ramsey (1960) [1] and known as Moreton waves. Their propagation speed ranges from a few tens to over thousand km s^{-1} [2, 3, 4]. EUV waves are closely associated with CMEs and travel ahead of them. They are thought to be shocks driven by CMEs in the low corona. Fig 1 depicts an example of the EUV wave with its kinematics.

The Moreton waves observed in Hα are interpreted as coronal fast-mode magnetohydrodynamic (MHD) shock sweeping the chromosphere [5]. After the launch of the Solar and Heliospheric Observatory (SOHO) [6], Thompson et al. (1998) [7] observed Moreton wave-like features in the solar corona using images from SOHO's Extreme-ultraviolet Imaging Telescope (EIT) [8] in 195 Å waveband. Initially, it was proposed that EUV waves are the coronal counterparts of the chromospheric Moreton wave and they are signatures of the same physical phenomena [12, 13]. However, due to the large difference between their velocity ranges, EUV and Moreton waves seemed to be different phenomena.

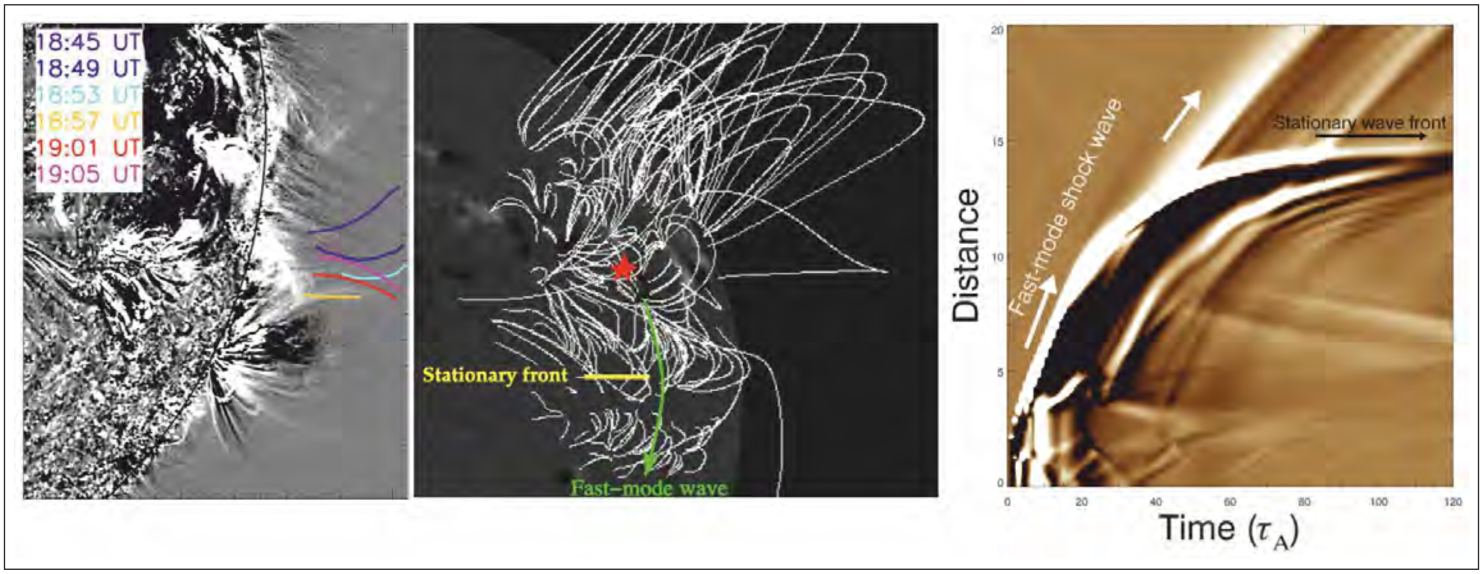


*Fig 2: **Left:** EUV wave reflection through an active region observed in AIA 171 Å on 31 March 2022. Incident and reflected wavefronts are shown in purple, blue, cyan (incident) and yellow, red, pink (reflected). **Middle:** EUV wave direction and stationary front formed after interaction with a magnetic QSL on 11 May 2011. **Right:** Distance-time diagram from MHD simulation showing fast-mode EUV waves converting into stationary fronts upon interacting with QSLs (adapted from Chandra et al. 2024 [10], Chen et al. 2016 [11]*

To correlate the velocity discrepancy, Warmuth et al. (2004) [13] proposed that Moreton waves are observed near the flare site, but EUV waves are observed further away. Therefore, the velocity difference might be due to the deceleration of the same fast-mode MHD wave. However, very low speed (~20 km s-1) and stationary fronts shown by the EUV waves cannot be explained by the MHD wave model. To explain these features, Delannée and co-workers proposed that the slow speed wave is a pseudo wave and could be observed due to the opening of magnetic field lines and the stationary fronts represent the compression near the magnetic separatrix or Quasi-Separatrix Layers (QSLs, magnetic field where the field line connectivity changes dramatically over a very short distance) [14, 15]. However, reflection, refraction, and mode conversion of EUV waves when encountering a coronal magnetic structure indicate that these are true waves [16]. To explain all the observed features of EUV waves, Chen et al. [17] proposed a hybrid model. According to their model, after the eruption of a flux rope, two wavelike phenomena with different speeds (fast and slow) are observed in the solar corona. The fast component is a piston-driven shock which travels ahead of the erupting flux rope or CME, and the slow component is a non-wave component, generated due to successive stretching of the closed field lines overlying an erupting flux rope.

There are observations of EUV waves, which can demonstrate the wave and non-wave nature of the EUV waves [9, 10, 19]. The wave features are reflection [10, 16], oscillations [18] in nearby coronal loops and the mode conversion [20, 21] of the EUV waves. The non-wave features show the stationary fronts and the slow non-wave components [9, 10, 11]. The observational evidence of the EUV wave two components was first observed by Chen et al, 2009 [19] using the high temporal and spatial Solar Dynamics Observatory data. Further the clear evidence of these two components and the stationary fronts are reported in the study of Chandra et al. 2016 [9] (see Fig.1). Conclusive proof of the reflection of EUV waves through the coronal holes and the active regions are presented [10, 16, 13]. An example of the reflection of the EUV wave through the coronal structure is shown in Fig 2 (left). The oscillations in the nearby loops hit by the EUV wave are demonstrated in the study of Devi et al 2022 [18] (c.f. Fig 2, right). An important phenomenon is the fast-to-slow mode conversion of the EUV wave. The converted wave can be observed at stationary fronts. This phenomenon was first reported by Chandra et al 2016 [9] (see Fig 1, right) and later confirmed in more observations [20, 21]. Inspiring these observations Chen et al 2016 [11] perform the three dimensional MHD simulations of the EUV wave and confirm the mode conversion at the magnetic separatrix regions. The observations and the simulation of the mode conversion are presented in Fig 3. The use of the coronal loop oscillations triggered by the EUV waves and the coronal parameters calculation is presented in Devi et al. 2022 [18]. Several coronal loop oscillations created by this wave are shown in Fig 3.

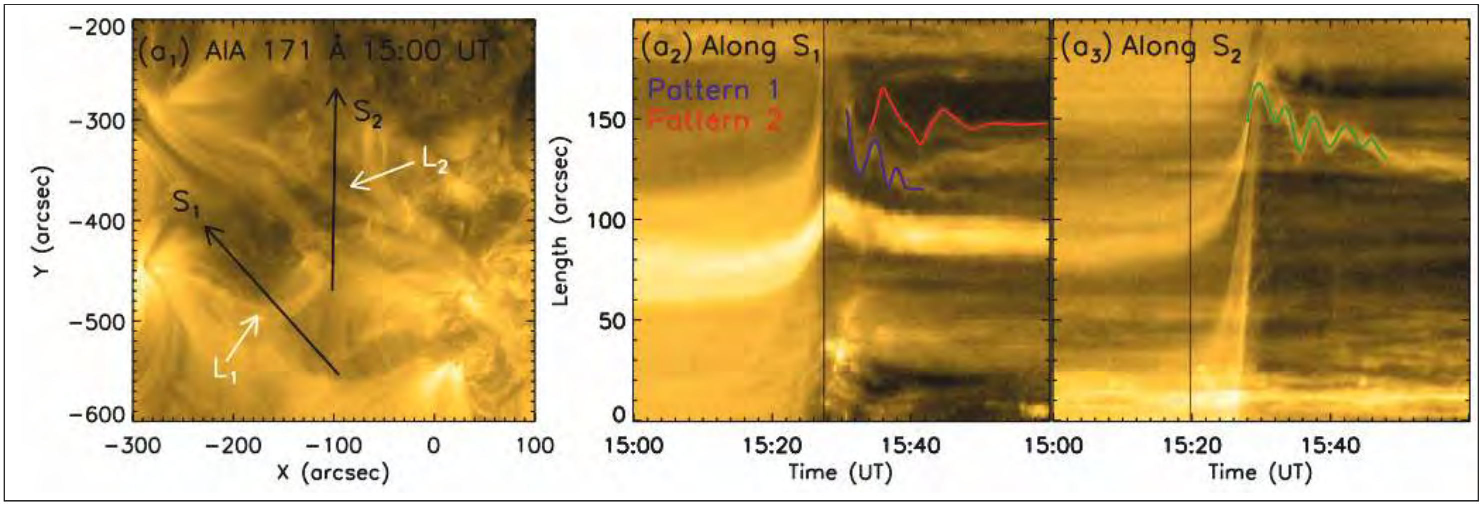


Fig 3: Coronal loops (L1 and L2) oscillating due to an EUV wave on October 28, 2021. Slits S1 and S2 (panel a1) used for time–distance analysis; results shown in panels a2 and a3 (adapted from Devi et al. 2022 [18]

As mentioned above, the EUV wave exhibits wave and non-wave components in observations and also in simulations. Moreover, the separation between the wave and non-wave components of the EUV wave is very crucial [4, 22]. This separation helps to clarify the associations among EUV waves, CMEs, solar energetic particles, and type II radio bursts. The association between EUV waves and CMEs can be determined more precisely if we have observations of the inner corona. The recently launched ADITYA-L1 Indian spacecraft, provides important observations to understand these phenomena in greater detail. It is observed that the EUV wave creates oscillations in nearby loops and prominences. These oscillating loops and prominences serve as a tool for investigating coronal seismology to measure the coronal magnetic field and the density, which cannot be measured directly.

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Dr. Ramesh Chandra is a Professor in the Department of Physics at Kumaun University, Nainital. His research focuses on multi-wavelength observations of solar eruptions and their impact on space weather. He has published extensively on solar flares, EUV waves, and sunspot dynamics, contributing significantly to the understanding of solar – terrestrial interactions. Dr. Chandra is also a Visiting Associate at IUCAA, Pune, and a member of the International Astronomical Union.

A Tiny Galaxy Blows Big Bubbles

A key ingredient in contemporary galaxy evolution models are feedback processes. By this terminology we encapsulate astrophysical phenomena that inject significant amounts of energy and momentum into a galaxy's interstellar medium. In some cases, feedback may have relatively modest effects, but in others it may be dramatic and transformative. The latter is thought to occur frequently in small and lightweight actively star-forming "dwarf" galaxies (star-burst galaxies). Active star-formation connotes that the galaxy gives birth to very massive (i.e., up to 100 times the solar mass, or more) and short-lived stars. After three to five million years, the cores of these stars collapse and giant nuclear explosions, dubbed supernovae, blast vast amounts of material into the surrounding space. The energy and momentum injected by supernovae into the interstellar gas may accelerate matter to such high velocities that it may potentially escape from the low-mass dwarfs, as their gravitational attraction is not very strong. Therefore, little to no gas might be available to fuel the formation of the next generation of stars. This quenching of star formation in low-mass galaxies due to feedback is, in fact, a crucial requirement for successful models of galaxy evolution in the Universe. Models without quenching predict an excessive number of star-forming dwarf galaxies — in disagreement with observed galaxy counts. Moreover, feedback from small galaxies also impacts the intergalactic medium, i.e., the space between galaxies. The latter is particularly relevant for the phase transition from a neutral to an ionised Universe during the so-called "Epoch of Reionisation" that lasted from about 500 million to 1 billion years after the Big Bang. To truly understand quenching and the "Epoch of Reionisation", we require an accurate quantitative understanding of feedback.

Developing ab initio physical models that quantitatively describe feedback is a complex task. For this, we must deal with involved physical processes (e.g., radiation-hydrodynamics). We also have to account for many (known) unknowns regarding the galactic environments in which these physical processes occur (e.g., the density and temperature distribution of the interstellar and circumgalactic gas). Such models are needed to better understand what feedback can and cannot do to a galaxy. For example, we aim to quantify the strength of feedback-driven galactic winds and the amount of matter that may actually escape from the galaxy's gravitational potential well harbouring the galaxy. Empirical insights from observations may nourish our quantitative understanding in this respect. In turn, this will help to constrain astrophysical and cosmological models.

Making direct images of the very faint and diffuse gas expelled from galaxies is, however, very challenging. Feedback-driven ejecta may emit, under certain conditions, emission lines of ionised and recombining hydrogen and collisionally excited doubly-ionised oxygen (especially Balmer-α and [OIII]λ5007 in the optical). However, this emission is several orders of magnitude fainter than the line emission seen from the interstellar gas. Nevertheless, within the last decades, astronomers obtained spectacular emission-line images of galactic winds around star-forming galaxies in the not-so-distant Universe. These images revealed a variety of structures. Some of the feedback-driven winds appear bi-conical- or hourglass-shaped, while frothy networks of filaments and shell-like structures surround other galaxies.

We gained many insights regarding feedback mechanisms from such images. However, the observed sample of not-so-distant galaxies does not represent galaxies at earlier cosmological epochs, where transformative feedback processes are imagined to be most prevalent. Fortuitously, potential young universe analogues, where such transformative effects could be studied in detail, do exist in the present-day Universe, but at distances where it was, until recently, impossible to image the diffuse wind material. This situation only changed with the deployment of the Multi-Unit Spectroscopic Explorer (MUSE) instrument at one of the European Southern Observatory's Very Large Telescopes (mirror diameter: 8m) on Cerro Paranal in Chile. This instrument, an integral-field spectrograph, provides an unprecedented sensitivity for imaging faint emission-line structures in the Universe. Capitalising on this opportunity, we embarked on a programme to analyse early universe analogues observed with MUSE to map potential feedback effects.

Our latest analysis in this programme concerns the very extreme star-forming dwarf J1044+0353, and the results were astounding. J1044+0353 is a very tiny galaxy (diameter 7.100 light-years) at a distance of 170 million light-years. This extreme dwarf was initially discovered in the Sloan Digital Sky Survey in 2003. Due to its peculiarity, it has since been observed with many of the world's state-of-the-art telescopes (e.g., Keck, Subaru, or Hubble Space Telescope). These measurements already suggested extreme feedback effects, but our analysis now revealed the unexpected dimension of the expelled material (see Figure). The data clearly show that J1044+0353 is surrounded by seven giant elliptical arcs that exceeds the galaxy's extent by large. These arcs trace relatively thin and dense shells surrounding bubbles filled with hot and extremely diffuse gas. While a few of these bubbles appear to have popped, others remain remarkably intact. Morphologically, similar configurations were already known around star-forming galaxies in the not-so-distant Universe, but the newly discovered bubble structure is five times larger. In fact, classical analytical models of large-scale bubble formation due to the combined effect of supernovae fail to reproduce the properties of the shells surrounding J1044+0353.

Our analysis reveals that our current understanding of feedback processes remains limited. To comprehend how galaxy-scale winds driven by supernovae really work, we need to collect more images of diffuse gas around extreme star-burst

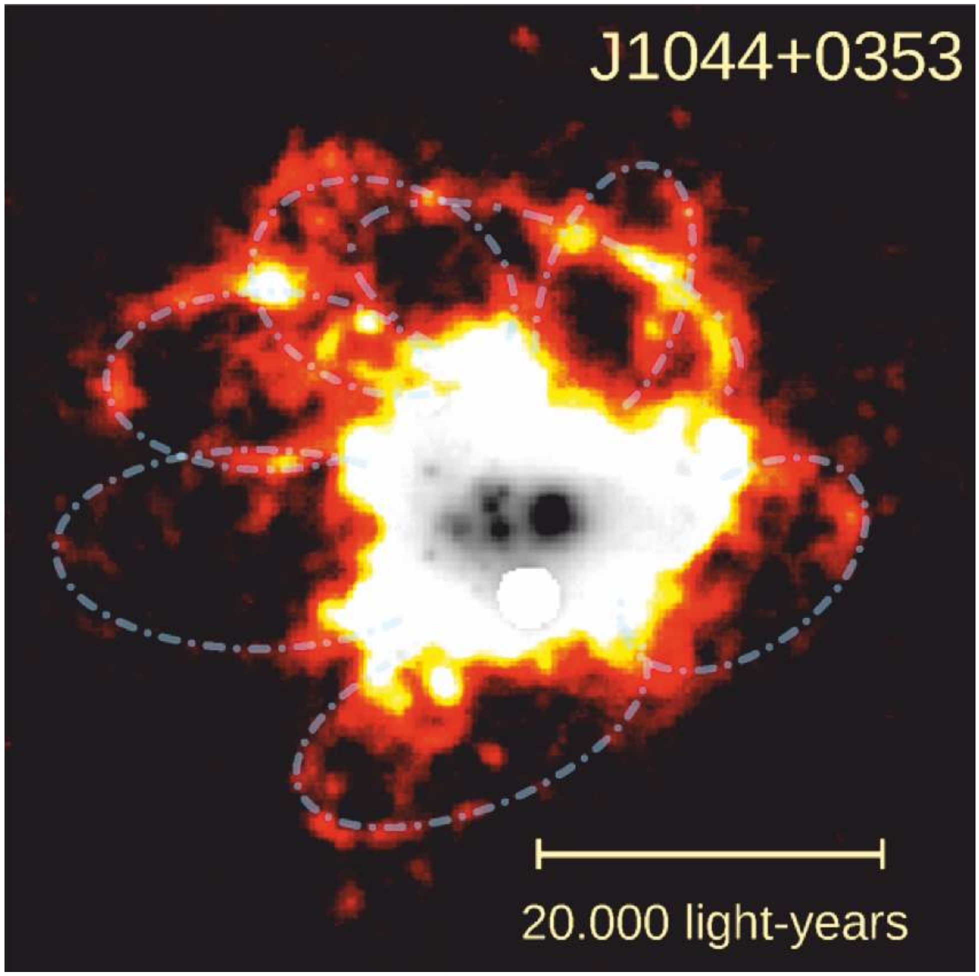

Figure 1: In the centre of the image, the stellar light of the galaxy J1044+0355 is shown in black. The galaxy is tiny (diameter 7100 light-years) and consists of several star clusters, each of which contains about 1 million stars. We have now discovered that the galaxy is surrounded by a more than 20,000 light year extended filamentary structure of diffuse ionised gas. This gas is detected in hydrogen Balmer-α optical line emission (wavelength = 656.3 nm) in a 1.5-hour exposure with the Multi Unit Spectroscopic Explorer on the 8 8-meter diameter telescope "Yepun" at the European Southern Observatory on Cerro Paranal in Chile. The detection is visualised in hues of bright yellow to red. These filaments connect along several elliptical loops, which are indicated with dot-dashed lines. These loops are the dense surfaces of bubbles that are likely blown by more than 50000 supernovae explosions in the last 20 million years.

(Image based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 0103.B-0531)

galaxies. We do not yet know whether the structure around J1044+0353 is truly special or whether many more tiny galaxies may blow similar super-sized bubbles. We will therefore have to move away from single-object studies and aim at sample-based studies with MUSE. This will allow us to census extended line emission around star-bursting dwarfs. Moreover, we will soon complement the MUSE observations with deep 21cm observations, allowing us to map the circumgalactic neutral hydrogen around star-forming dwarfs. To this end, we are currently conducting observations with the MeerKAT radio telescope in South Africa and the GMRT in India. Ultimately, these endeavours shall deliver a more holistic picture of feedback from star-burst galaxies.

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Scientific Article

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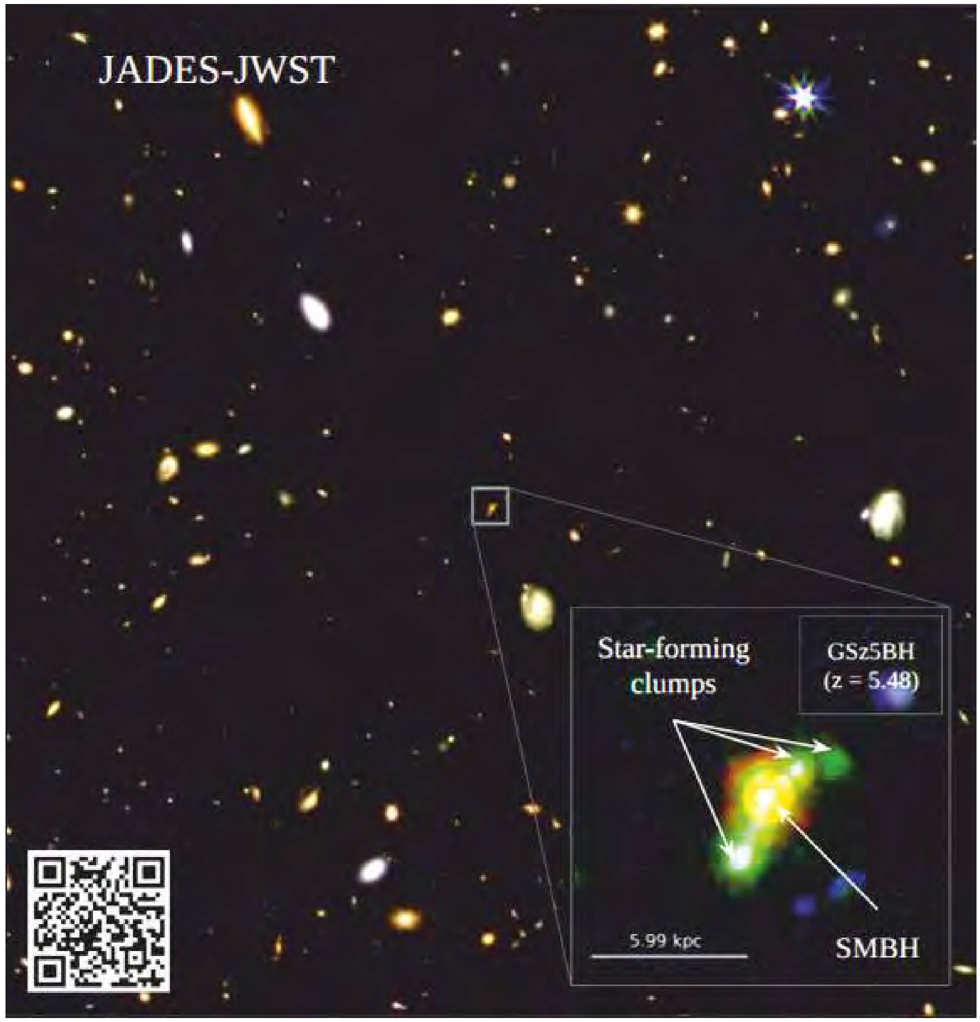
Dr Edmund Christian Herenz is a Vaidya-Raychaudhuri postdoctoral fellow with IUCAA. He is interested in observational extragalactic astrophysics, and his favourite observing technique is integral-field spectroscopy. He obtained his PhD in 2016 from the University of Potsdam, with thesis supervisors Prof. Lutz Wisotzki and Prof. Martin Roth from the Leibniz-Institute for Astrophysics, Potsdam (AIP). Following graduation, he worked as a Postdoctoral fellow under the supervision of Prof. Matthew Hayes at Stockholm University. He was then awarded a Fellowship from the European Southern Observatory in Chile, where he supported operations of the instruments HAWK-I and MUSE for three years at the Very Large Telescope "Yepun" on Cerro Paranal. Before joining IUCAA in 2023, he spent one year as a visiting researcher at the Leiden Observatory (Leiden University) in the Netherlands.

Clump-fed Black Hole Growth in the First Billion Years of the Universe

The efforts of past decades of observational astronomy have established the fact that every galaxy hosts a Supermassive Black Hole (SMBH) at their center. Although in the nearby Universe, these SMBHs make up a fraction of a percent of the total stellar mass of the galaxy, the strong correlations among the central stellar mass/kinematics and SMBH mass hint towards a co-evolution. This makes studying the evolution of SMBHs crucial for understanding galaxy evolution. The masses of SMBHs in the nearby universe can be explained well through gradual growth, considering their ample time. The problem arises when we find SMBHs very early in the Universe (i.e, at high redshifts (high-z)), as it becomes increasingly complex to explain these masses with the most popular models of SMBH growth. These high-z SMBHs usually do not follow the galaxy-SMBH correlations found at low-z, which suggests a rapid growth scenario compared to the host galaxy. With JWST finding these previously undiscovered SMBHs, thanks to its sensitivity, it is necessary to test these models of SMBH evolution using the real data.

As we see in the nearby Universe, galaxies appear to have very well-defined shapes and large-scale near-smooth morphology. This picture breaks down as we start to observe deep in space and time, when most galaxies were still in their infancy, their shapes are clumpy and irregular, far from being a regular spiral or elliptical. Although these star-forming clumps are present in the nearby galaxies, their size compared to the whole galaxy is much smaller than in the high-z galaxies, where they contribute significantly to the total stellar mass of the galaxy. Due to the heavier masses of these clumps, there is a larger force on them caused by the dark matter halo of the host galaxy. Some models took this line of thought and showed in simulations that these clumps could play a crucial role in feeding the central SMBH as they inspiral quickly to the center, and hence can explain the rapid growth at high-z. Here in this study, we tested this model on one such galaxy

(GSz5BH), shown in zoom-in, which met all the criteria and has all the data available fit for testing such an interpretation. This galaxy hosts an SMBH of 30 million solar masses (~2% of the stellar mass of the host galaxy) at a time when the Universe was only one billion years old. In addition to the black hole, this galaxy has detected three massive star-forming clumps, a few kpc away from the AGN. We measure these clump masses using HST and JWST imaging data, and the motion of these clumps, assuming the same motion as gas motion, is found using MUSE instrument data on this galaxy. Assuming a simplistic dark matter model, we calculate the time it takes for these clumps to inspiral into the center, which turns out to be less than ⅓rd of a billion years. Hence, even if 1% of these masses fall into the central black hole, it can grow the black hole to the observed mass within the galaxy's lifetime, assuming a continuous infall of material. This study shows the feasibility of such a growth mechanism. However, many questions remain regarding fully understanding the SMBH growth in the early universe, and we are still far from fully understanding the early universe and its evolution. New and upcoming observatories have just started limiting our current understanding.



Manish Kataria's research focuses on the kinematics and evolution of galaxies in the Universe. He frequently utilises integral field spectroscopy and multi-wavelength data to investigate how gas flows, star formation, and black holes influence the evolution of galaxies over cosmic time. He is particularly interested in connecting observations of high-redshift systems to the physical processes driving their growth and assembly.

Events outside IUCAA

Seminar on Advances in Cosmology at CHRIST (Deemed to be University) at Bengaluru

The Centre of Excellence in Astronomy and Astrophysics, Department of Physics and Electronics at CHRIST (Deemed to be University), *Bengaluru*, in collaboration with and funded by the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, organized a two-day *Seminar on Advances in Cosmology during July 15–16, 2025.*

The seminar was designed to engage postgraduate, doctoral, and motivated undergraduate students with the latest research developments in cosmology. It featured invited talks by eminent researchers, along with contributed oral and poster presentations by students. In total, 31 participants from institutions across India took part, including 11 contributed talks and 2 poster presentations, all selected through a competitive abstract review process.

The inaugural session opened with a welcome address by Kenath Arun, followed by Manoj B, Head of the Department, who highlighted the department's achievements and vision. The inaugural address was delivered by Fr. Viju P.D., Pro-Vice Chancellor, who reflected on cosmology from a philosophical perspective. Blesson Mathew introduced the activities of the Centre of Excellence in Astronomy and Astrophysics, while Gudennavar spoke about the IUCAA Centre for Astronomy Research and Development. The session concluded with a vote of thanks by Jithesh V.

The academic program began with an invited talk by Surhud S. More (IUCAA, Pune), who discussed the cosmic interplay between gravity and dark energy, emphasizing contributions from the Subaru Telescope and future prospects with the Vera Rubin Observatory's LSST. The second invited lecture, delivered by V. Sreenath (NITK Surathkal), titled Primordial Relics Beyond Slow-roll, examined early-universe physics beyond the standard slow-roll inflationary paradigm and its observational signatures.

The student talks on Day 1 covered diverse topics such as modified gravity and torsion-based models (Suraj Kumar Behera, Mukta Dash), SKA-era observational cosmology (Suvedha Naik),

gravitational redshift effects near Kerr bodies (N. Bevan Arena Kharbithai), modifications to Newtonian gravity in galaxy clusters (Louise Rebecca), gravitational waves as cosmological distance indicators or "dark sirens" (Trisha V.), and the role of compact dark matter objects in galactic dynamics (Vinit D. Tyagi).

Day 2 featured invited lectures that focused on gravitational theory and quantum field approaches to cosmology. Bivudutta Mishra (BITS Pilani, Hyderabad) spoke on alternative gravitational formulations and their cosmological implications, while Kazuyuki Furuuchi (MCNS, Manipal) presented quantum field theory in curved spacetime and its relevance to evolving dark energy models. The final invited lecture was delivered by Debika Chowdhury (IIA, Bengaluru), who highlighted observational challenges in studying cosmic structures, particularly those arising from uncertainties in dark sector interactions.

The contributed sessions of Day 2 explored photon rings around compact objects (Ayush Hazarika), inhomogeneous dark energy models (Sadia Kaniz Fatima), interacting dark components in scalar field cosmology (Sneha Pradhan), and gravitational wave templates for hierarchical triple systems (Mukhil C.). Poster presentations were also displayed and discussed during the breaks.

The seminar provided an excellent platform for young researchers to present their work, receive constructive feedback, and explore frontier topics in cosmology. The invited speakers succeeded in explaining complex subjects such as dark energy, dark matter, inflationary models, and large-scale structure formation in an accessible and engaging manner. Interactive Q&A sessions stimulated critical discussion on open questions in cosmology, including the nature of dark energy and the ultimate fate of the universe.

Overall, the seminar was intellectually stimulating and highly successful, fostering academic exchange and collaboration between theorists and observationalists. It not only inspired curiosity among students but also strengthened the spirit of research in cosmology.

Gravitational Waves & LIGO India Workshop at SRM University, AP

As the scientific community celebrates a decade since the first direct observation of gravitational waves from the binary black hole merger event GW150914 by the LIGO detectors, SRM University, AP recently hosted a comprehensive *workshop on Gravitational Waves and LIGO India* from *September 10–14, 2025*. The event was jointly organized by the Center for Astrophysics, Gravitation and Cosmology (CAGC), SRM University Sikkim, and the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, with sponsorship from IUCAA and the Department of Physics & Research Office, SRM University, AP.

The workshop aimed to advance knowledge and foster collaboration in gravitational-wave research. The main coordinators were *Shubhrangshu Ghosh*

(Chairperson, CAGC, SRM University Sikkim), *Apratim Ganguly* (IUCAA), and *Soumyajyoti Biswas* (SRM University, AP). The program was inaugurated by the Ch. Satish Kumar (Vice Chancellor of SRM University, AP) who graced the occasion as Chief Guest.

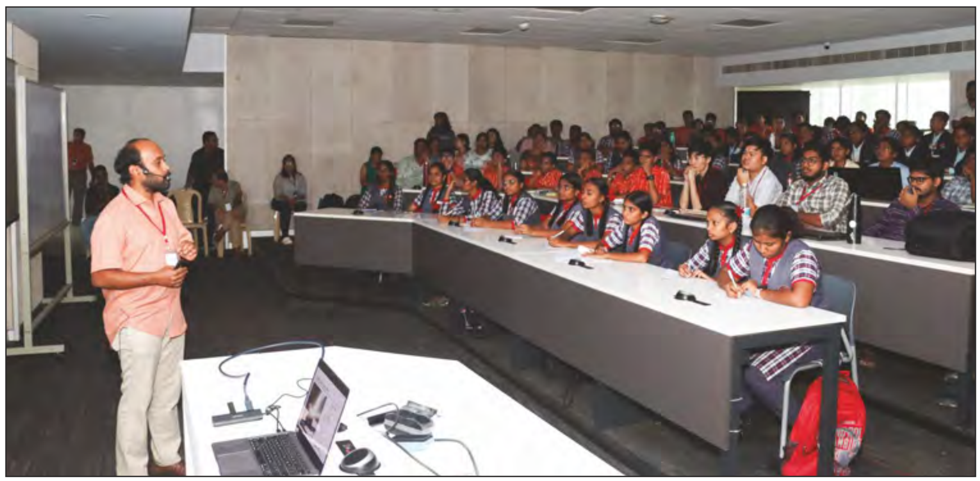
Around 50 participants attended the workshop, including 20 faculty members and students from SRM University, AP and approximately 30 external participants from prestigious institutions such as the Central University of Andhra Pradesh, IIT Hyderabad, Osmania University, IISc Bangalore, Indian Institute of Astrophysics, Manipal Academy of Higher Education, University of Madras, The Institute of Mathematical Sciences, VIT Vellore, NIT Calicut, and CUSAT. In addition, a large number of students from regional colleges and universities, spanning both physics/astrophysics and engineering backgrounds, took part enthusiastically.

The week-long program featured detailed lectures on general relativity, interferometry, computing infrastructure, gravitational-wave sources, and detection methods. Practical hands-on sessions on detector calibration, instrumentation, and feedback control systems added immense value. These were conducted by IUCAA resource persons, including Apratim Ganguly, Sandeep K. Joshi, Shivaraj Kandhasamy, Shasvath J. Kapadia, and Manasadevi P. T. Special colloquia were also delivered by distinguished scientists such as T. R. Govindarajan (The Institute of Mathematical Sciences) and Banibrata Mukhopadhyay (IISc Bangalore).

To mark the 10th anniversary of the first gravitational-wave detection, a special outreach program was organized on September 13, titled "Phy-Spark 3.0: Stars, Scopes, and Spacetime", by the Department of Physics, SRM University, AP. The highlight was a popular lecture by Shivaraj Kandhasamy (IUCAA, Pune), "Accomplishing the Impossible: Detection of Gravitational Waves by LIGO." The talk was attended by over 120 school students, as well as participants from nearby towns and distant locations.

The event received wide media coverage, particularly during the outreach program. Several IUCAA experts and organizers gave interviews to news outlets and the SRM, AP Communications Directorate. These were later broadcast across local, state, and national platforms in both print and electronic media. Interviews and highlights were also uploaded to the University's website.

Overall, the workshop was highly successful, meeting most of its objectives and providing an enriching learning and collaborative experience for all participants



Welcome to...

IUCAA welcomes **Chandreyee Maitra, Deepak Pandey** and **Bhooshan Uday Gadre**, who have joined IUCAA as Scientist-F (Associate Professor) and Scientist-E (Assistant Professor), respectively.

We also extend a warm welcome to **Payel Nandi, Lalit Pathak, Ritish Kumar, Suchismito Chattopadhyay,** and **Tathagata Saha**, who have joined IUCAA as Post-Doctoral Fellows, and to **Kuldeep Nishad, Ramesh Bagdi, Shubh Mittal, Nitish Kumar Meher,** and **Jishnu Patra,** who have joined as Research Scholars.

Visiting Associates selected with effect from 01 August 2025

1. **Dr. Abhijit Bhausaheb Bendre,**
   Dr. Vishwanath Karad MIT-Peace World University,
   Kothrud, Pune
2. **Dr. Prasanta Bera,**
   Banaras Hindu University Varanasi,
   Uttar Pradesh.

3. **Prof. Eswaraiah Chakali,**
Department of Physical Sciences,
IISER, Mohali, Punjab.

4. **Dr. Arka Chatterjee,**
The University of Petroleum and Energy Studies (UPES),
Dehradun, Uttarakhand.

5. **Dr. Santabrata Das,**
Department of Physics,
Indian Institute of Technology Guwahati,
Guwahati, Assam.

6. **Dr. Suratna Das,**
Department of Physics,
Ashoka University,
Sonepat, Haryana.

7. **Prof. Jincy Devasia,**
Department of Physics,
Henry Baker College, Kerala.

8. **Dr. Savithri H. Ezhikode,**
Department of Physical Sciences and Mathematics,
St. Francis de Sales College (Autonomous),
Bengaluru.

9. **Dr. Kazuyuki Furuuchi,**
Manipal Centre for Natural Sciences,
Manipal Academy of Higher Education,
Manipal, Karnataka.

10. **Dr. Prakash Suryakant Gaikwad,**
Indian Institute of Technology,
Indore, Madhya Pradesh.

11. **Dr. Sharvari Nadkarni Ghosh,**
Department of SPASE,
Indian Institute of Technology Kanpur,
Uttar Pradesh.

12. **Dr. Soumavo Ghosh,**
Department of Astronomy,
Astrophysics and Space Engineering (DAASE),
Indian Institute of Technology Indore,
Madhya Pradesh.

13. **Dr. Soumya Jana,**
Department of Physics,
Sitananda College,
Nandigram (affiliated to Vidyasagar University)
Purba Medinipur, West Bengal.

14. **Prof. Lata Venkata Phani K.**,
Department of Physics,
Pondicherry University,
Kalapet, Puducherry.

15. **Dr. Vikram Kisan Khaire,**
Department of Physics,
Indian Institute of Technology Tirupati,
Andhra Pradesh.

16. **Dr. Hema Kharayat,**
Department of Physics,
M. L. K. P. G. College,
Balrampur, Uttar Pradesh.

17. **Prof. Raj Kuma**r,
Department of Physics,
Himachal Pradesh University,
Shimla, Himachal Pradesh.

18. **Dr. Nitesh Kumar,**
The University of Petroleum and Energy Studies (UPES),
Dehradun, Uttarakhand.

19. **Dr. Kavita Kumari,**
Kamla Rai College,
Jai Prakash University, Patna Bihar.

20. **Dr. Pankaj Kushwaha,**
Department of Physical Sciences,
IISER Mohali, Punjab.

21. **Dr. Pankaj Kumar Maharaja,**
Agrasen University,
Himachal Pradesh.

22. **Dr. Goutam Manna,**
Department of Physics,
Prabhat Kumar College, Contai,
West Bengal.

23. **Dr. Banibrata Mukhopadhyay,**
Department of Physics, Indian Institute of Science,
Bangalore, Karnataka.

24. **Dr. Alekha Chandra Nayak,**
Department of Physics,
National Institute of Technology,
Meghalaya.

25. **Dr. Prasia P,**
Government Victoria College Palakkad,
Kerala.

26. **Dr. Sahil Saini,**
Guru Jambheshwar University of
Science and Technology,
Hisar, Haryana.

27. **Dr. Varun Saxena,**
Jawaharlal Nehru University,
Delhi.

28. **Dr. Rohit Sharma,**
Indian Institute of Technology Kanpur,
Uttar Pradesh.

29. **Dr. Apara Tripathi,**
Department of Physics,
Deen Dayal Upadhyaya Gorakhpur, University,
Uttar Pradesh.

Visiting Associates Term Extended Beyond August 01, 2025

1. **Dr. Sheelu Abraham,**
Department of Physics,
Marthoma College,
Malappuram, Kerala.

2. **Dr. G. Ambika,**
IISER,
Thiruvananthapuram, Kerala.

3. **Dr. Debbijoy Bhattacharya,**
Manipal Centre for Natural Sciences,
Manipal Academy of Higher Education,
Manipal, Karnataka.

4. **Dr. Susanta Kumar Bisoi,**
Department of Physics & Astronomy,
National Institute of Technology Rourkela,
Odisha.

5. **Dr. Chandrachur Chakraborty,**
Manipal Centre for Natural Sciences,
Manipal Academy of Higher Education,
Karnataka.

6. **Dr. Sumanta Chakraborty,**
Indian Association for The Cultivation of Science,
Kolkata.

7. **Professor Subenoy Chakraborty,**
Dean of Science, Brainware University, Kolkata, West Bengal.

8. **Dr. Raghavendra Chaubey,**
Centre for Interdisciplinary Mathematical Sciences,
Institute of Science,
Banaras Hindu University,
Varanasi.

9. **Dr. Bhag Chand Chauhan,**
Department of Physics & Astronomical Sciences,
Central University of Himachal Pradesh,
Dharamshala, Himachal Pradesh.

10. **Dr. Himadri Sekhar Das,**
Department of Physics,
Assam University,
Silchar, Assam.

11. **Dr. Prasanta Kumar Das,**
BITS Pilani,
K K Birla Goa Campus,
Zuarinagar, Goa.

12. **Dr. Kanan Kumar Datta,**
Jadavpur University,
Kolkata.

13. **Prof. Sukanta Deb,**
Department of Physics,
Cotton University,
Guwahati, Assam.

14. **Dr. Moon Moon Devi,**
Department of Physics,
Tezpur University, Assam.

15. **Dr. Archana Dixit,**
Department of Mathematics,
Gurugram University,
Gurugram, Haryana.

16. **Dr. Mayukh Raj Gangopadhyay,**
Thanu Padmanabhan Centre for
Cosmology and Science Popularization,
SGT University,
Kolkata West Bengal.

17. **Dr. Gurudatt Gaur,**
St. Xavier's College (Autonomous),
Ahmedabad, Gujarat.

18. **Dr. Prabir Gharami,**
Department of Mathematics,
Belda College,
West Bengal.

19. **Professor Sushant Ghosh,**
Centre for Theoretical Physics,
Jamia Millia Islamia,
New Delhi.

20. **Dr. Ankur Gogoi,**
Department of Physics,
Jagannath Barooah University,
Jorhat, Assam.

21. **Dr. Rupjyoti Gogoi,**
Department of Physics,
Tezpur University,
Assam.

22. **Dr. Umananda Dev Goswami,**
Department of Physics,
Dibrugarh University,
Assam.

23. **Dr. Aruna Govada,**
Department of Computer Engineering
Government Polytechnic
Varkund, Daman and Diu.

24. **Dr. Shivappa Bharamappa Gudennavar,**
Department of Physics and Electronics,
Christ University, Bangalore.

25. **Dr. Mamta Gulati,**
School of Mathematics,
Thapar Institute of Engineering and Technology,
Patiala, Punjab.

26. **Dr. Rinku Jacob,**
Department of Basic Sciences & Humanites,
Rajagiri School of Engineering & Technology,
Kochi, Kerala.

27. **Dr. Chetana Jain,**
Department of Physics,
Hansraj College,
Delhi.

28. **Prof. Md. Mehedi Kalam,**
Aliah University,
Kolkata.

29. **Dr. Sanjeev Kalita,**
Department of Physics,
Gauhati University,
Guwahati, Assam.

30. **Dr. Arun Kenath,**
Department of Physics & Electronics,
Christ University,
Bengaluru, Karnataka.

31. **Dr. Ram Kishor,**
Department of Mathematics,
Central University of Rajasthan,
Ajmer, Rajasthan.

32. **Dr. Newton Singh Kshetrimayum,**
Department of Physics,
National Defence Academy,
Khadakwasla, Pune, Maharashtra.

33. **Dr. Jaswant Kumar,**
Department of Physics and Astrophysics,
Central University of Haryana,
Mahendergarh, Haryana.

34. **Dr. Nagendra Kumar,**
M.M.H. College,
Ghaziabad, Uttar Pradesh.

35. **Prof. Vinjanampaty Madhurima,**
Department of Physics,
Central University of Tamil Nadu,
Thiruvarur, Tamil Nadu.

36. **Prof. Shiva Kumar Malapaka,**
International Institute of Information Technology,
Bangalore.

37. **Dr. Manesh Michael,**
Department of Physics,
Bharata Mata College,
Kochi.

38. **Dr. Mubashir Hamid Mir,**
Govt. Degree College Baramulla,
Jammu & Kashmir.

39. **Dr. Bivudutta Mishra,**
Department of Mathematics,
BITS- Pilani,
Hyderabad Campus,
Telangana.

40. **Dr. Aditya Sow Mondal,**
Department of Physics,
Visva-Bharati, Santiniketan,
West-Bengal.

41. **Dr. Mahadevappa Naganathappa,**
Gitam (Deemed to Be University)
Hyderabad Campus,
Telangana.

42. **Dr. Chandrachani Devi Ningombam,**
Physics Department,
Manipur University,
Imphal.

43. **Dr. Prince P R,**
Department of Physics,
University College,
Trivandrum, Kerala.

44. **Prof. Sreejith Padinhatteeri,**
Manipal Centre for Natural Sciences,
Manipal Academy of Higher Education,
Karnataka.

45. **Dr. Barun Kumar Pal,**
Netaji Nagar College for Women,
Kolkata, West Bengal.

46. **Dr. Rutu Mahendrabhai Parekh,**
Dhirubhai Ambani Institute of Information
& Communication Technology,
Gandhinagar, Gujarat.

47. **Professor M. K. Patil,**
School of Physical Sciences,
S.R.T.M. University,
Nanded.

48. **Dr. Devraj Damaji Pawar,**
Department of Physics,
R.J. College,
Ghatkopar (West) Mumbai.

49. **Prof. Anirudh Pradhan,**
Centre for Cosmology,
Astrophysics and Space Science,
G.L.A. University,
Mathura, Uttar Pradesh.

50. **Dr. Ramprasad Prajapati,**
School of Physical Sciences,
Jawaharlal Nehru University,
Delhi.

51. **Dr. Rajesh S. R.,**
Department of Physics,
Sanatana Dharma College,
Kerala.

52. **Dr. Anisur Rahaman,**
Department of Physics,
Durgapur Government College,
West Bengal.

53. **Dr. Biplab Raychaudhuri,**
Department of Physics,
Visva-Bharati,
Santiniketan West Bengal.

54. **Dr. Anirban Saha,**
Department of Physics and Astrophysics,
West Bengal State University,
Kolkata.

55. **Prof. Pradyumn Kumar Sahoo,**
BITS-Pilani,
Hyderabad Campus,
Telangana.

56. **Prof. Eeshankur Saikia,**
Department of Applied Sciences,
Gauhati University,
Assam.

57. **Dr. Biplob Sarkar,**
Department of Applied Sciences,
School of Engineering,
Tezpur University,
Assam.

58. **Dr. Tamal Sarkar,**
High Energy & Cosmic Ray Research Centre,
University of North Bengal,
Siliguri, West Bengal.

59. **Prof. Anjan Ananda Sen,**
Centre for Theoretical Physics,
Jamia Millia Islamia,
New Delhi.

60. **Dr. Geetanjali Sethi,**
Department of Physics,
St. Stephens College,
Delhi.

61. **Dr. Dharm Veer Singh,**
Department of Physics,
GLA University,
Mathura, Uttar Pradesh.

62. **Prof. Suprit Singh,**
Department of Physics,
Indian Institute of Technology,
New Delhi.

63. **Dr. Sourav Sur,**
Department of Physics &Astrophysics,
University of Delhi,
New Delhi.

64. **Dr. Nilkanth Dattatray Vagshette,**
Department of Physics & Electronics,
Maharashtra Udaygiri Mahavidyalaya,
Udgir, Maharashtra.

65. **Prof. Murli Manohar Verma,**
Department of Physics,
University of Lucknow, Lucknow.
llege (Affiliated To Vidyasagar University)
Medinipur, West Bengal.

Farewell to...

IUCAA bids farewell to **Mayur Bhaskar Shende, Moupiya Maji, Suchira Sarkar, Akash Garg, Swadeeh Chand,** and **Anisha Ramsurat Kashyap,** who have completed their tenure at IUCAA as Post-Doctoral Fellows.

We also bid farewell to **Hareh Mathur** and **Souradeep Bhattacharya,** who have resigned from IUCAA as Post-Doctoral Fellows.

Additionally, we bid farewell to **Premvijay V., Soumya Roy,** and **Priyanka Parehuran Gawade,** who have completed their tenure as Research Scholars at IUCAA, as well as to **Jamnejoy Sarkar, Kishore Gopalakrishnan,** and **Shehil Pandey,** who have resigned as Research Scholars at IUCAA.

Seminars

01.07.2025	Dr. Sabyasachi Chattopadhyay on ***Application of photonics in astronomy and other verticals***
03.07.2025	Dr. Raj Kishor Joshi On ***Evolution of Magnetic Fields in Isolated Neutron Stars***
08.07.2025	Prof. T. P. Singh on ***Flat galaxy rotation curves: dark matter or modified Newtonian dynamics (MOND)? - Part II***

24.07.2025	Dr. Sameer on ***Project AMIGA: Physicochemical Properties of the Circumgalactic Gas of the Andromeda Galaxy***
29.07.2025	Dr. Vipin Kumar on ***Optical/IR Instrumentation for Astronomy: Design and Development of Spectrographs, Spectro-polarimeters, Calibration Unit***
05.08.2025	Dr. Annu Jacob on ***Pushing the Frontiers of Astronomical Instrumentation: From Segmented Mirrors to Space-Based Systems***
14.08.2025	Dr. Ramya M Anche on ***High-contrast imaging and polarimetry with the next-generation space and ground-based telescopes***
19.08.2025	Dr. Supriyo Ghosh on ***Astronomical instrumentation: from cost-effective innovative technology development to on-sky performance testing and data-reduction pipeline***
21.08.2025	Dr. Shabbir Shaikh on ***Probing the Growth of Structure with CMB Lensing–Cosmic Shear Cross-Correlation***
26.08.2025	Dr. Tushar Mondal on ***Magnetorotational Turbulence and Dynamo in Accretion Disks: a Unified Mean-Field Theory***
28.08.2025	Dr. Soumak Maitra on ***Charting the Cosmic History***
02.09.2025	Soumya Shreeram on ***The hot CGM in X-rays: projection effects, forward model for eROSITA and the cosmic web - halo connection***
09.09.2025	Dr. Namita Uppal on ***Reconstructing magnetic interstellar structure using interstellar polarization***

Colloquium

10.07.2025	Prof. Naresh Dadhich on ***End state of gravitational collapse: Black hole or Buchdahl star?***
17.07.2025	Dr. Vaibhav Gupta on ***Solar EUV Spectrophotometers on SOHO/SDO and ARMAS Dosimeters for Aerospace Safety***
31.07.2025	Dr. M. R. Ramesh Kumar on ***Vagaries in Monsoon: Role of Oceans***
07.08.2025	Dr. Rahul Kannan on ***Modelling high redshift structure formation and reionization in the JWST era***
17.09.2025	Mr. Ted Blank on ***Art in Space and Space in Art***

Public Outreach Activities

IUCAA–Zilla Parishad, Pune Rural Education Programme

IUCAA is conducting a rural educational programme in collaboration with the Zilla Parishad, Pune (ZPP), for under-served rural schools in the district. The two organisations signed an MoU in April 2025 to establish a collaborative framework for conducting awareness and training sessions, as well as organising exposure visits for students and teachers from ZPP schools.

As a first step, IUCAA is supporting the organisation of exposure visits to ISRO and NASA facilities for selected bright students of ZPP schools studying in Classes 6 and 7. The programme includes scientific guidance, student screening, development of visit content, and associated educational and inspirational activities.

To identify participants, IUCAA conducted a three-level selection process consisting of two multiple-choice tests and one set of in-person interviews. Approximately 13,500 students appeared for the first round, from which a final shortlist of 100 students was prepared and shared with the ZPP (25 for the NASA visit, 50 for the ISRO visit, and 25 on the waiting list). IUCAA faculty, outreach personnel, and external experts participated at every stage to ensure a scientifically sound and fair process.

As part of this programme, the 235 students who reached the third round of interviews also had the opportunity to visit the IUCAA campus and learn more about its research and outreach activities. These students, from various rural schools across the Pune district, demonstrated remarkable motivation toward pursuing careers in STEM fields despite socio-economic challenges.

Following the selection process, IUCAA, in collaboration with the ZPP Education Department, has conducted six teacher workshops for science teachers from nine talukas. Four more workshops are planned to cover all talukas in the district, after which follow-up activities will be carried out with the most motivated participants.

2nd Saturday Lectures

1. July 12, 2025 – Prof. R. Srianand, Director, IUCAA, Pune – *"Galaxies"*

2. August 02, 2025 –
Dr. Parisee Shirke – *"Astronomy of the X-Ray Sky"*

3. September 13, 2025 –
Mr. Ted Blank – *"Pizza in Space"*

Regular Workshops, Visits, and Other Outreach Events

1. **World Peace School, Alandi** – Science & Astronomy Session (July 03, 2025) 50 students and 2 teachers attended.

2. **Saraswati Vishwa Vidyalaya School, Chinchwad** – Science & Astronomy Session (July 08, 2025) 73 students and 2 teachers participated.

3. **S.M. Choksey High School** – Science & Astronomy Session (July 15, 2025) 90 students and 5 teachers participated.

4. **Aljamea-tus-Saifiyah School**
– Science & Astronomy Session (July 31, 2025) 60 students and 6 teachers participated

5. **Mahatma Gandhi Vidyalaya, Manchar**
– Astronomy & Science Toys Session (August 04, 2025)
. 350 students and 7 teachers participated.

6. **Aditya English Medium School, Baner** – Science & Astronomy Workshop (August 12, 2025) 60 students and 2 teachers participated.

7. **Delhi Public School, Mohammadwadi** – Science Toys Session (August 13, 2025) 300 students and 4 teachers participated.

8. **Saraswati Vishwa Vidyalaya, Talawade**
– Science & Astronomy Workshop (August 14, 2025) 50 students and 2 teachers participated.

9. **Radhabai Kale College, Ahilyanagar** – Science & Astronomy Workshop (August 20, 2025) 180 girl students and 7 teachers participated.

10. **Bishop's School, Camp** – Science & Astronomy Workshop (August 21, 2025) 100 students and 5 teachers participated.

11. **G.S. Moze School, Yerwada** – Science & Astronomy Workshop (August 26, 2025) 125 students and 2 teachers participated

12. **VNIT, Nagpur**
– Telescope-Making Workshop (September 27, 2025) 70 teachers participated.

(All the above sessions were organised by members of the IUCAA SciPOP Team, who served as organisers or resource persons.)

Special Outreach Programmes

1. **IUCAA–Pune Zilla Parishad Teachers' Training Programme**
   (September, 10-30, 2025)

   A total of nine teacher-training sessions were organised across the talukas of Shirur, Haveli, Khed, Junnar, Ambegaon, Indapur, Daund, Bhor, Velhe, Maval, and Mulshi. About 450 teachers from Pune ZP schools participated in these workshops.

2. **IUCAA Rural Teachers' Training (Asteroid Search Campaign – Special Batch)**

   A two-day astronomy workshop was conducted for teachers from Ambegaon, Junnar, and Khed talukas, focusing on training them to conduct the Asteroid Hunt Campaign in their respective schools. Thirty teachers from rural Pune participated.

3. **K–12 Astronomy Education Conference – Thailand**
   (September 1–4, 2025).

   Prasad Adekar conducted a hands-on workshop for sixty educators from across Asia who participated in this international conference. He also presented a poster on an astronomy game developed by him.

Astronomy Centre for Educators

National Education Policy – 2020: Orientation and Sensitization

The Malaviya Mission Teacher Training Centre (MMTTC) of the Astronomy Centre for Educators (ACE) conducted a two-week online capacity-building programme on National Education Policy – 2020: Orientation and Sensitization from July 21-29, 2025.

The programme was open to faculty members, research scholars, research associates, postdoctoral fellows, demonstrators, and tutors from higher education institutions across India. Participants were required to submit two essays on selected topics covered during the sessions to qualify for a certificate. Approximately 55–60 participants attended daily, of which 40 participants successfully completed the programme and received certificates.

The course consisted of two sessions each on eight NEP–2020 themes, delivered by distinguished speakers with expertise in their respective fields.

Themes and Speakers:

- **Academic Leadership, Governance, and Management**

  Eisha Kannadi
  (IGNOU)
  and **Sushanta Dattagupta**
  (Founder Director, IISER Kolkata)

- **Skill Development**

  Vineeta Sirohi
  (NIEPA)
  and **Maithreyi Ravikumar**
  (Karnataka Health Promotion Trust)

- **Indian Knowledge Systems**

  Mayank Vahia
  (Former Professor, TIFR)

- **Research and Development**

  Sourav Pal
  (Ashoka University, Sonepat)
  and **Farhat Naz**
  (IIT Jodhpur)

- **Holistic and Multidisciplinary Education**

  Shubhangi Vaidya
  (IGNOU)

and **Saikat Majumdar**
(Ashoka University)

- **Higher Education and Society**

Dhruba J. Saikia
(Former Head, ACE, IUCAA)

- **Student Diversity and Inclusive Education**

Gurujegan Murugesan
(IIT Jodhpur)
and **Deepa Chari**
(HBCSE, TIFR)

- **Information and Communication Technology**

Sahana Murthy
(IIT Bombay)
and **Prakash Arumugasamy**
(IUCAA)

General Relativity – A Refresher Course

A Refresher Course on General Relativity was organized by the Astronomy Centre for Educators (ACE) as part of the Malaviya Mission Teacher Training Programme (MMTTP) from June 23 to July 5, 2025. The programme was designed for research scholars, postdoctoral fellows, and college or university faculty members who apply general relativity in their research or teaching. It was conducted in hybrid mode, with 20 participants attending in person on the IUCAA campus and more than 50 joining online.

Beginning with the fundamentals of special relativity and the mathematics of differential geometry, the course covered the core principles of general relativity and their applications to astrophysical systems. The intensive two-week programme comprised lectures, tutorial sessions, and participant presentations on the concluding day.

Lectures were delivered by a distinguished group of general relativists:

1. Patrick Das Gupta (University of Delhi),
2. Tejinder Pal Singh (Tata Institute of Fundamental Research, Mumbai),
3. Apratim Ganguly (IUCAA),
4. Ashmita Das (SRM University, Andhra Pradesh),
5. Anuj Misha (International Centre for Theoretical Sciences, Bengaluru), and
6. Bhaswati Mandal (Indian Statistical Institute, Kolkata).

The programme also featured a special lecture on the Laser Interferometer Gravitational-Wave Observatory (LIGO) by Sanjit Mitra (IUCAA). The Refresher Course received highly positive feedback from participants. Those attending in person commended its comprehensive content, engaging lectures, and practical tutorials, noting that it deepened their conceptual understanding and inspired further research. Online participants appreciated the well-structured content and expert delivery, while suggesting that additional preparatory material could be useful for future hybrid courses.

All course materials, including assignments, resources, and recorded lectures, were made available to participants through ACE's Moodle platform.

LIGO-India Education & Public Outreach (LIEPO) Activities

Virtual Tour Series of LIGO Livingston in Marathi (July, 8th, 12th & 29th, 2025)

To demystify the functioning of the interferometric detectors at LIGO for the Marathi-speaking public of Hingoli, the LIGO-India Education and Public Outreach (LIEPO) team arranged recordings of virtual guided tours in Marathi. These were conducted by Indian students interning at the LIGO Livingston Observatory (LLO), USA.

A series of LLO tour videos featuring Shreejit Jadav (Postdoctoral Researcher, Swinburne University of Technology, Australia) and Gaurav Waratkar (PhD student, IIT Bombay) was announced on April 12, 2025 on LIGO-India's social media platforms, with the first video released on May 31, 2025.

In the opening video, Waratkar takes the audience on a virtual tour of the Science Education Centre at LLO, explaining in Marathi the science behind the four-stage suspension system used for gravitational wave detection. The videos were released on the LIGO-India EPO YouTube channel, which currently has around 6,500 subscribers.

Subsequent videos in the series covered topics such as the Gravity Well experiment and Multi-Messenger Astronomy. This initiative was conceptualized by Debarati Chatterjee, with video editing by Anurag Bhaisare (LIEPO intern) and coordination by Saurabh Salunkhe.

Press Release: Exceptional Gravitational Wave Discovery (Event GW231123)

On November 23, 2023, the LIGO–Virgo–KAGRA (LVK) collaboration detected the most massive black hole merger to date. The LIGO-India EPO team shared this landmark discovery with Indian media, releasing infographics, a science summary, and a press note translated into several Indian languages including Hindi, Marathi, Malayalam, Tamil, and Bengali.

The Indian contribution to the discovery was prominently highlighted in the press release issued in India. The translations were made possible through the efforts of several members of the LIGO-India Scientific Collaboration (LISC). The announcement received widespread national coverage in leading newspapers such as The Times of India, The Indian Express, and Deccan Herald.

Event: "Quantum Physics and Gravitational Waves" (Commemorating the International Year of Quantum) – August 05, 2025

To celebrate 2025 as the International Year of Quantum, LIEPO organised a special event at IUCAA on August 05, 2025. The event brought together experts in Quantum Science and Technology from across India to discuss the intersections of quantum measurement, communication, and gravitational wave detection.

The session began with an introduction by Manasadevi P. T. (IUCAA), followed by invited talks from Anil Shaji (IISER Thiruvananthapuram), Kanaka Raju Pandiri (Defence Institute of Advanced Technology, Pune), and Anirban Pathak (Jaypee Institute of Information Technology).

A panel discussion on "Quantum Advantage for the Most Sensitive Instrument in the World" was moderated by Subhadeep De (Principal Investigator, Precision and Quantum Measurement Lab, IUCAA). The panel included Anil Shaji, Sendhil Raja (RRCAT, Indore), Anindita Banerjee (Centre for Development of Advanced Computing), and Deepak Pandey (IUCAA).

Delegates also visited the LIGO-India instrumentation laboratories, and discussions highlighted the potential synergy between LIGO-India and the National Quantum Mission (NQM). The event attracted over 300 registrations and received coverage from The Times of India and The Indian Express.

10th Anniversary of the First Direct Detection of Gravitational Waves – September 14, 2025

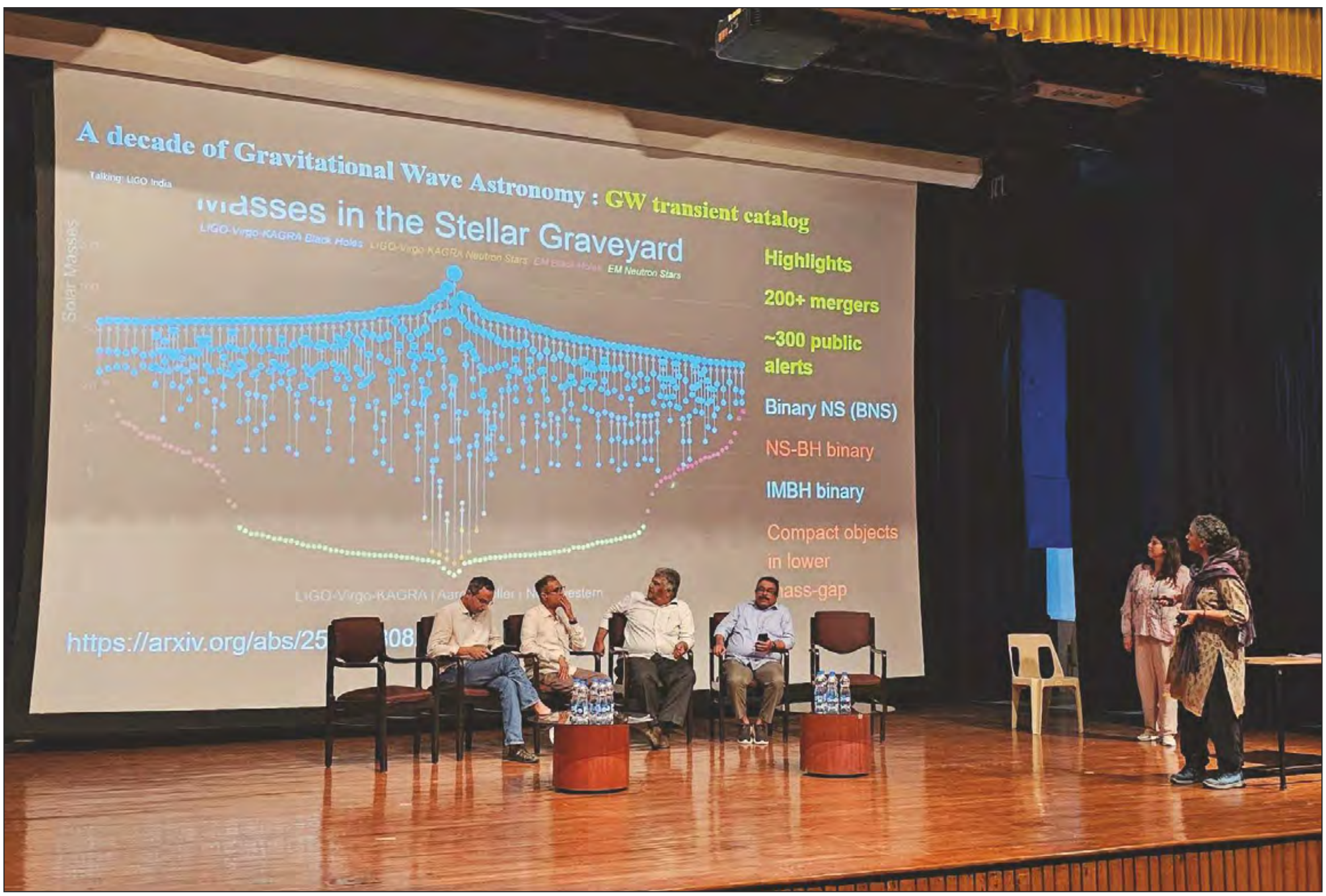
To commemorate the 10th anniversary of the first gravitational wave detection, LIEPO organised a special programme at IUCAA on September 14, 2025.

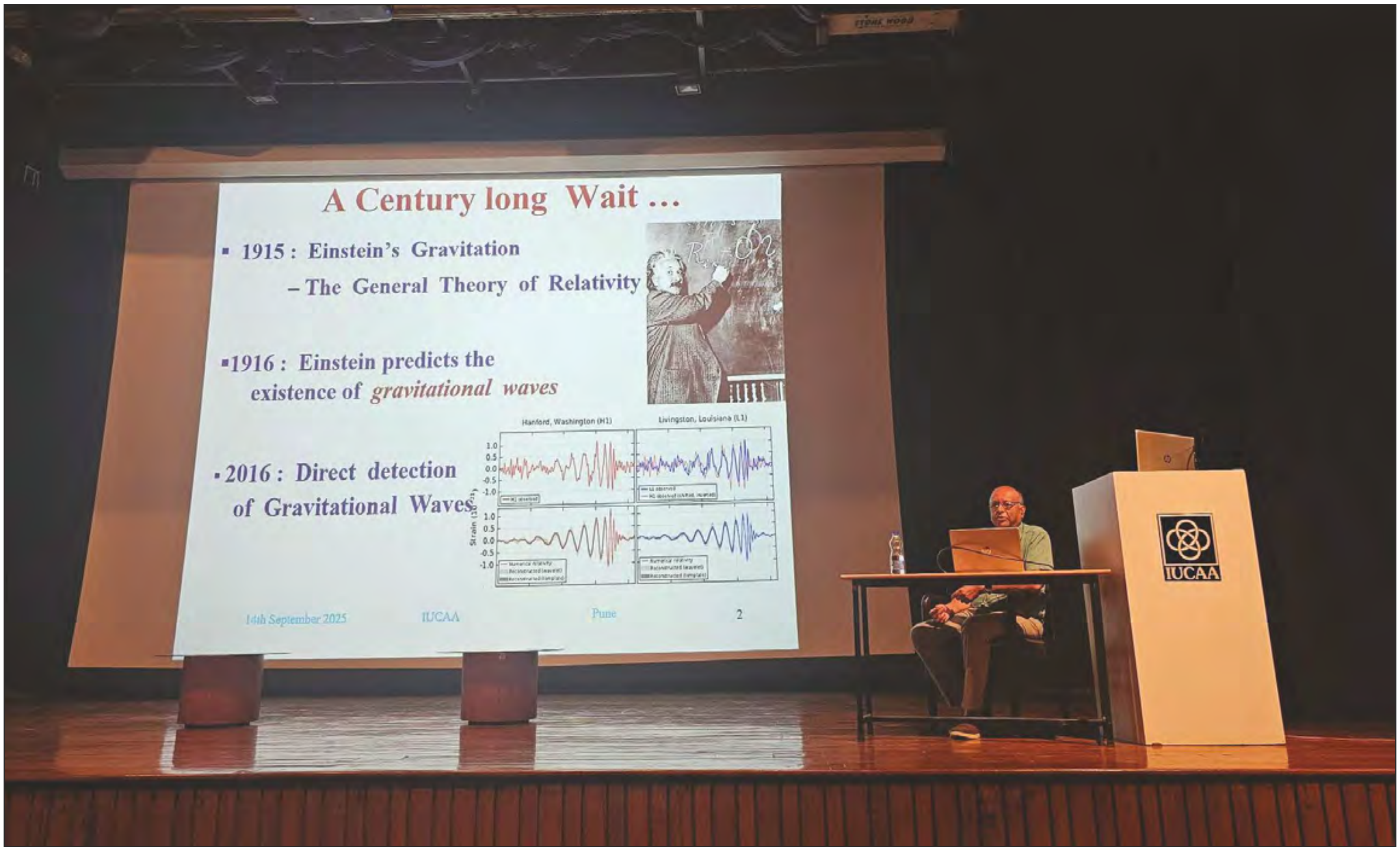
The event was inaugurated by R. Srianand (Director, IUCAA) and introduced by Debarati Chatterjee and Saurabh Salunkhe. A panel discussion, moderated Debarati Chatterjee, featured distinguished scientists from the LIGO-India Scientific Collaboration (LISC), P. Ajith (ICTS-TIFR, Bengaluru), Archana Pai (IIT Bombay), Anand Sengupta (IIT Gandhinagar), Subroto Mukherjee (IPR Gandhinagar), Sanjit Mitra (IUCAA, Pune), and Rajesh Kumble Nayak (IISER Kolkata).

The discussion revisited the historic first detection, explored the evolution of gravitational wave astronomy in India, and discussed future prospects including the LIGO-India project and the planned Deci-Hz space-based detector.

The programme also featured a talk on the recent GW250114 discovery by Rahul Kashyap, followed by engaging science activities such as the "Guess What" Quiz and "Astro Charades", hosted by Saurabh Salunkhe and actively participated in by LISC PhD students.

The event concluded with a public lecture by Sanjeev Dhurandhar, who shared his personal journey in gravitational wave science and reflected on a decade of progress since GW150914.




A Century long Wait ...
1915 : Einstein's Gravitation
– The General Theory of Relativity
1916 : Einstein predicts the existence of gravitational waves
2016 : Direct detection of Gravitational Waves
Hanford, Washington (H1)
Livingston, Louisiana (L1)
14th September 2025
IUCAA
Pune
2
IUCAA


anel Discussion:
"Quantum Advantage for the most sensitive instrument in the World"
Moderator: Prof. Subhadeep De
RRCAT Indore (I-Block)
Dr. Sendhil Raja
Prof. Anil Shaji
Prof. Dee ak Pandey
Dr. Anind Banerjee
IUCAA

Visitors

[July – September 2025]

Kewal Anand, Chandranathan Anandavijayan, Anuraag Arya, Birger Felix Aufschlaeger, Trishit Banerjee, Devansh Bangar, S.S. Bellale, Manthan Bhagat, Gaurav Bhandari, Agnidipto Bhattacharya, Soumya Bhattacharya, Sree Bhattacherjee, Soumadip Rabindranath Bhowmick, K.G. Biju, Atreyee Biswas, Ritabrata Biswas, Sanchari Biswas, Ted Blank, Hritwik Bora, Fairoos C., Sulagna Chakrabarti, Nabajit Chakravarty, Hum Chand, Sabyasachi Chattopadhyay, Shivani Chaudhary, Suvas Chandra Chaudhary, Simbarashe Bryne Chipembe, Tanmoy Chowdhury, Ahmed Rizwan CL, Pravat Dangal, Ashmita Das, Santanu Das, Patrick Dasgupta, Samadrita De, Sushmita Deb, Ujjal Debnath, Uddeepta Deka, Ashwin Devaraj, Ruchika Dhaka, Amit Dhakulkar, Broja Gopal Dutta, Samridhi Dwivedi, Eslam Elhosseiny, Johann Fernandes, Mukesh Gaikwad, Romanshu Garg, Sayantan Ghosh, Rupjyoti Gogoi, G.K. Goswami, Abhinav Goyal, Labanya Kumar Guha, Vaibhav Gupta, Muhammed Irshad, Kazi Rajibul Islam, Md Monirul Islam, Annu Jacob, Joe Jacob, Shreejit Jadhav, Dhairyashil Jagadale, Deepak Jain, Priyansh Jaswal, Arpan Aryam John, Raj Kishor Joshi, Malavika K., Anil Kakodkar, Shravani Kale, Sammi Kamal, Shashi Kanbur, Rahul Kannan, Subhajit Kar, Rahul Kashyap, Ankit Khunt, Harshit Krishna, Aaditya Himanshu Kshatriya, Akshay Kumar, Himanshu Kumar, M.R. Ramesh Kumar, Rajesh Kumar, Vipin Kumar, Kavita Kumari, Baisali Kundu, D. Lakshamanan, H. Lalthantluanga, Jeremie Lasue, Jonathan Jacobeum Love, Devabrat Mahanta, Nilanjana Mahata, Soumak Maitra, Prajjwal Majumder, Priyanka Mandal, Dinesh Chandra Maurya, Sunil Kumar Maurya, Thokchom Yaiphaba Meitei, Anuj Mishra, Asish Mitra, Debasmita Mohanty, Subhra Mondal, Tushar Mondal, Sneha Prakash Mudambi, Subroto Mukherjee, Mayur Mune, Ganga R. Nair, Vishnu Namboothiri, Haraprasad Nandi, Rajesh Nayak, Vibhore Negi, Anirudh Nemmani, Gayatri P., Prasia P., Sreebala P.S., Archana Pai, Vishnu A Pai, Main Pal, Moumita Pal, Subhajit Pal, Rakesh Kumar Panda, Sanjay Pandey, Shivam Pandey, Mahadev Pandge, Ashish Pandita, Yash Parakh, Arvind Paranjpye, Rekha Patel, Anirban Pathak, K.D. Patil, Sarika Patil, B.C. Paul, Surajit Paul, Devraj Pawar, Anirudh Pradhan, Arbind Pradhan, Durakshan Ashraf Qadri, Hridya R., Farook Rahaman, A.R. Rao, Divya Rawat, Saibal Ray, K.V. Reghuthaman, Zairemmawia Renthlei, Rupayan Roy, Athira S., Sonali Sachdeva, Subhajit Saha, Tathagata Saha, Bidisha Samanta, Jayesh Manoj Saraswat, Biplob Sarkar, Chitrak Sarkar, Anand Sengupta, Dhrubojyoti Sengupta, Shabbir Shaikh, Anil Shaji, Abhishek Sharma, Anshul Kumar Sharma, Isha Sharma, Kaushal Sharma, Paryag Sharma, Priya Sharma, Shubham Sharma, Vaibhav Sharma, Soumya Sheeram, Mayur Shende, Parisee Sunil Shirke, Gyan Prakash Singh, Ramanshu P. Singh, T.P. Singh, Sreedevi, S. Sridhar, Madhu Sudan, Shree Suman, Divya Tahelyani, Pratik Takale, Mohit Thakre, Vivek Baruah Thapa, Ajay Tripathi, Garima Tyagi, Rashmi Uniyal, Vivek Upadhaya, Namita Uppal, Esther Vanlalramchhani, Aditya Vijaykumar, Vinu Vikraman, Rauf Zargar, Andrzej Antoni Zdziarski, Priya, Sameer, Sunaina, Vandana.

Khagol (the Celestial Sphere) is the quarterly bulletin of IUCAA

We welcome your feedback at the following address:

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