# Highlights of facilities and recent research at IUCAA

IUCAA

अंतर–विश्वविद्यालय केंद्र :
खगोलविज्ञान और खगोलभौतिकी

INTER-UNIVERSITY CENTRE FOR
ASTRONOMY AND ASTROPHYSICS
(An Autonomous Institution of the University Grants Commission)

# Preface

The main objectives of IUCAA are to provide a centre of excellence within the university sector for teaching, research and development in Astronomy & Astrophysics (A&A), as well as to promote nucleation and growth of active groups in this area in the universities. The aim is to provide researchers from university departments access to state-of-the-art astronomical instrumentation, theoretical know-how, well-equipped laboratories, data centre, and high-quality computing facilities. For more than three decades IUCAA has not only achieved these objectives, but has maintained the emphasis on fundamental research and innovative teaching in a wide range of areas of A&A. Over this period IUCAA's interactions with universities have also evolved as per the demands of the changing research and technology landscape in the country and abroad.

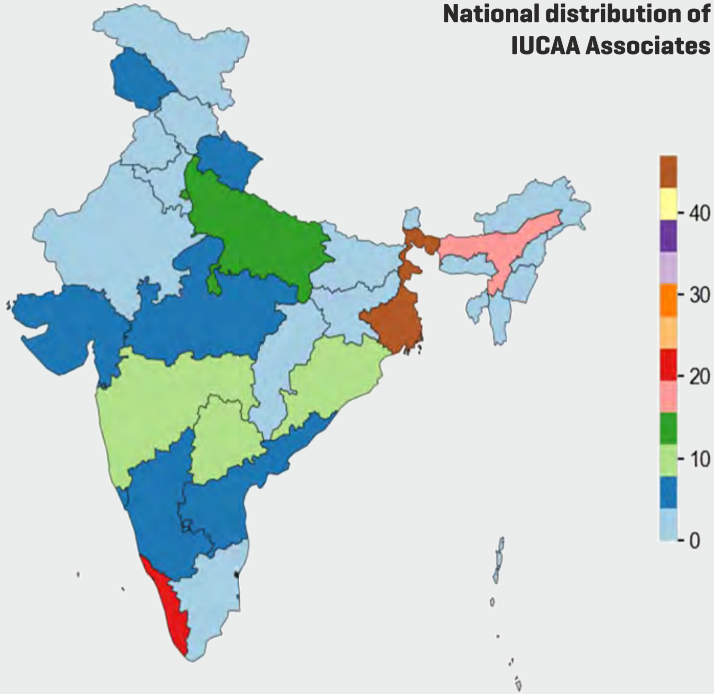
Indian Astronomy is expected to go through a major revolution in the coming decade through (i) our participation in Mega-Science projects such as TMT, SKA, and LIGO-India, (ii) ever-improving space programs (ADITYA-L1, Xposat, Daksha, INSIST, etc.) and (iii) rapidly growing computational resources (e.g  National Supercomputing Mission, NSM). Successful outcomes from all these developments will depend on how well we can develop the required human resources in the available time. Needless to say, the trained human resources have to come from universities, and here lies the major responsibility of inter-university centres like IUCAA to implement short and long-term strategic plans to move in this direction.

At present, IUCAA's academic staff consists of 27 faculty members (including Emeritus Professors), 4 Adjunct faculty members, 50 PhD students, 24 Postdoctoral fellows, 45 Scientific and Technical staff, and 06 project students. The high level of scientific productivity of IUCAA academic staff is reflected in the fact that during this academic year, they have published about 200 papers in peer-reviewed journals. Due to sustained efforts by IUCAA, there is a clear increasing trend in the number of active University Associates with the current associate number of 216 expected to rise to close to 300 soon. In particular, efforts are being made to include people with technical skills that are useful for Astronomy missions from the engineering departments. Due to this increase in the number of Associates, there is a concurrent strong increase in the number of publications originating from Associates and their students. This document contains some highlights of the recent developments in various fields of research covered by IUCAA.

# University Programmes

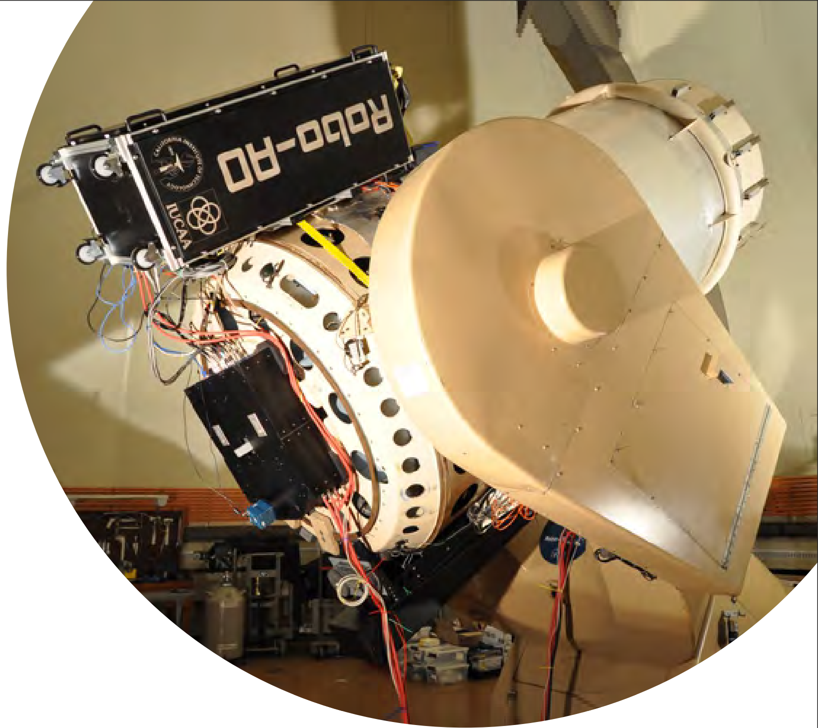
An important component of IUCAA's academic activities is the Associateship Programme, under which a faculty member of an Indian university or a postgraduate department in a college can visit IUCAA for periods of short and long durations over a span of three years, to develop his or her interest and expertise in astronomy and astrophysics. The Associateship Programme has been designed to promote mobility and, to this end, the travel and local living expenses of an associate for these visits is borne by IUCAA. Through its Teaching Learning Centre, IUCAA conducts a Refresher Course in Astronomy and Astrophysics for teachers at Indian universities during the summer break. The course is held in person at IUCAA every alternate year with topics including observational and theoretical aspects of astronomy and state-of-the-art methods of data analysis.

Along with this IUCAA also sponsors about 8-10 workshops and conferences hosted by IUCAA Associates in their respective Universities / Institutes. In particular, the series of North East Meeting of Astronomers (NEMA) and Regional Astronomy Meeting (RAM) in South India have been consistently successful in generating great interest among University faculty and students who did not have this exposure before.

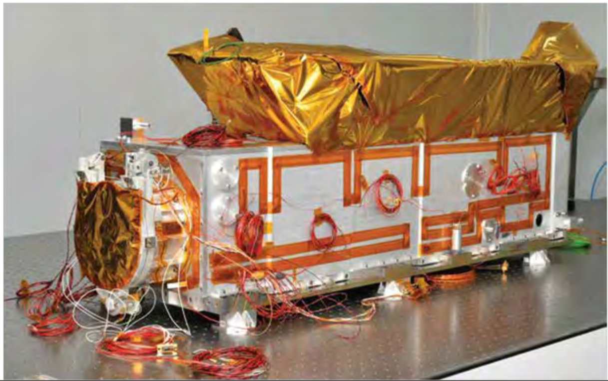



**National distribution of IUCAA Associates**

# Astronomical Instrumentation




The instrumentation lab at IUCAA has built the Solar Ultraviolet Imaging Telescope (SUIT) that is part of the ADITYA-L1 solar mission. It has already given great results post the placement of the telescope in its planned location in space. The software for pipeline data reduction was also developed in IUCAA laboratories. Another important instrument developed at IUCAA's instrumentation lab is Wide-Area Linear Optical Polarimeter (WALOP). Two WALOPs (South and North) have been designed and are being built at IUCAA as part of an international collaboration between Caltech, University of Crete, Greece and South African Astronomical Observatory. The data from this instrument will help create a 3D tomographic map of the galactic magnetic fields and dust cloud structure. This is mainly funded from external sources through multi-institutional collaboration. IUCAA is also developing labs and a skilled instrumentation team to carry out the commissioning and post commissioning operations of LIGO-INDIA.



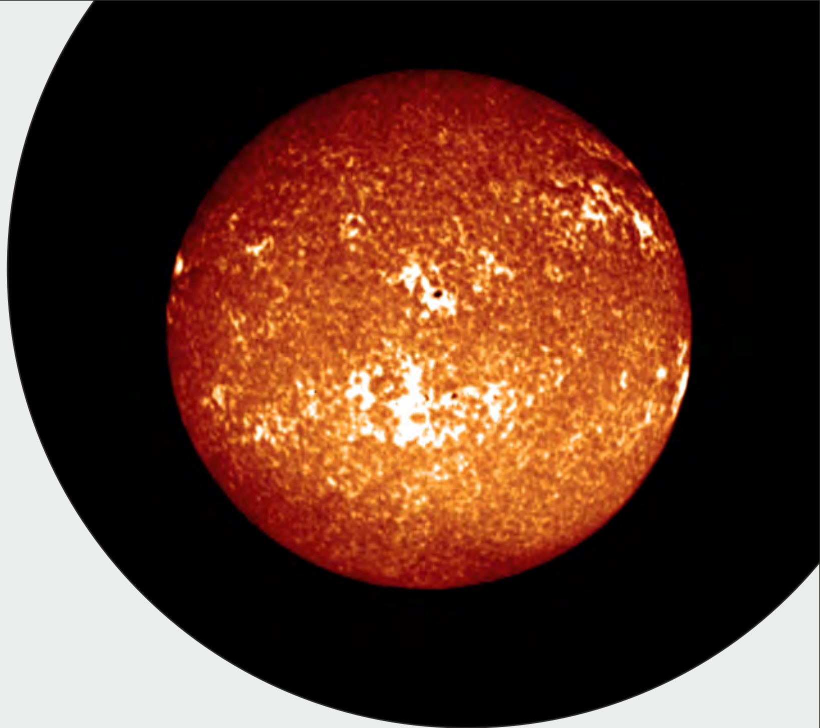
## IUCAA Girawali Observatory (IGO)

IGO has a 2-meter optical telescope with a workhorse imaging spectrometer, the IUCAA Faint Object Spectrometer and Camera (IFOSC). This instrument has the capability for imaging in various bands (U, B, V, R, I etc with band-pass filters) and also performs spectroscopy in these bands. It has a CCD with 2048X2048 pixels with 13.5μ size each. Further it can also do polarimetric and spectro-polarimetric measurements in these optical bands. This instrument is placed at the Cassegrain focus and renders a field-of-view of about 11 square arc-min in the sky.

## Southern African Large Telescope (SALT)

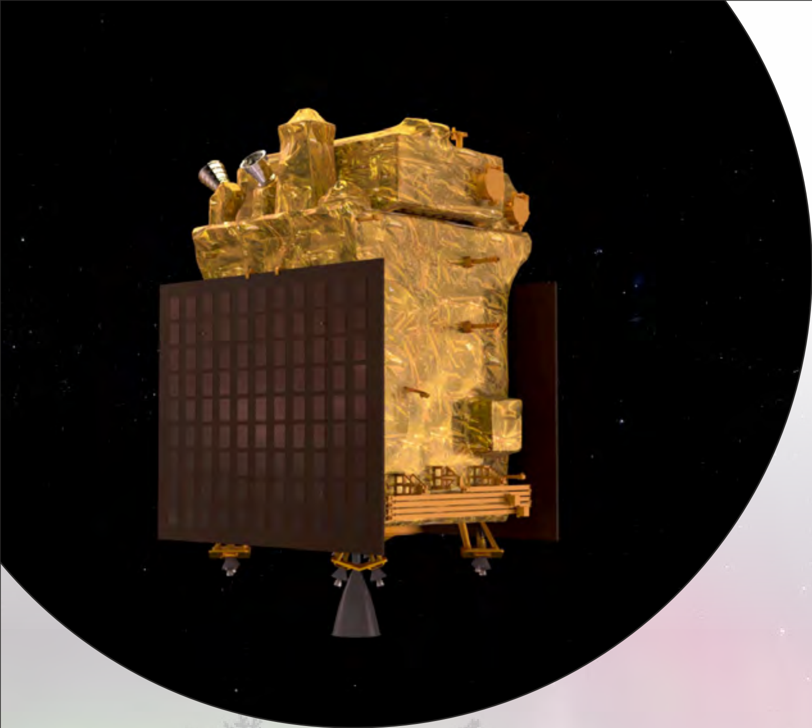
SALT is the largest multi-mirror telescope operating in the southern hemisphere with an effective primary mirror size of ~12 meters, located in Sutherland, South Africa. It is currently funded by a consortium of international partners including IUCAA and other partners from South Africa, the United States, Poland and the United Kingdom and has been in full science operation since 2011. IUCAA's share in SALT partnership corresponds to an observing time of about 180 hrs per year. The observing time is open to astronomers from IUCAA and Indian Universities. There are two main workhorse instruments in SALT that support the astronomical observations: (i) The Robert Stobie Spectrograph and (ii) the High Resolution Spectrograph. Observations using these are carried out in service mode (i.e astronomers from IUCAA can obtain data without going to the observatory by submitting observing blocks well in advance) with a typical completion rate of about 70%. Over the past couple of years they have completed 4 main surveys using SALT. These are (i) identification of distant radio bright quasars as targets for MeerKAT Absorption Line Survey, (ii) Lyman-α Diffuse emission around a complete sample of distant radio-bright quasars, (iii) Time variability of very fast outflows from bright distant quasars and (iv) Largest sample of host galaxies that are responsible for strong absorption lines seen in the spectra of distant quasars. SALT has also been used to study transient sources like Gamma Ray Bursts, Supernovae and Gravitational Wave sources.

# Solar Astrophysics



The Sun, our star, is the source of all life-giving energy and also of the ever varying space-weather. However, it can also provide knowledge about very fundamental Physics in conditions not possible on the Earth. Humankind stands to gain a lot by the study of these.

The Solar Physics group at IUCAA works on the overall understanding of the dynamic coupling of the magnetized solar atmosphere. During the high solar activity phase, there could be as many as 20 highly energetic eruptions which release plasma, highly energetic charged particles into interplanetary space. These phenomena are powered by magnetic fields which are generated within the Sun. They directly influence terrestrial life, space weather, space-reliant technologies and may cause electric power blackouts in countries at higher latitudes on Earth. Although these sudden bursts have proven to be highly difficult to predict, the group tries to understand the Sun's dynamo mechanism, to be able to make an early prediction of coronal mass ejections and solar flares. Moreover, the atmosphere of the Sun presents several intriguing, mysterious phenomena eg. the strange existence of a million-degree temperature layer called the Corona, that lies above cooler, lower atmospheric layers, such as the photosphere and chromosphere. In the last few years, among others, the IUCAA group has proposed a unified scenario to explain the solar atmospheric heating and the origin of the solar wind; presented an alternative explanation for Doppler shifts Observations in the



solar transition region and discovered evidences for further strengthening the support for nano-flare heated solar corona.

Important studies of the Sun also need to be made through the radiation it emits at high energies, such as ultraviolet, extreme ultraviolet, and X-rays. These cannot be seen from the Earth due to their absorption in the atmosphere. For this the IUCAA solar and instrumentation group together have created the Solar Ultraviolet Imaging Telescope (SUIT) that is now working onboard the successful Aditya-L1 mission to study the Sun from Space. As the observational data from SUIT starts coming in, the group will investigate the nature of various types of waves in solar atmospheres in order to understand the heating mechanisms of solar corona.

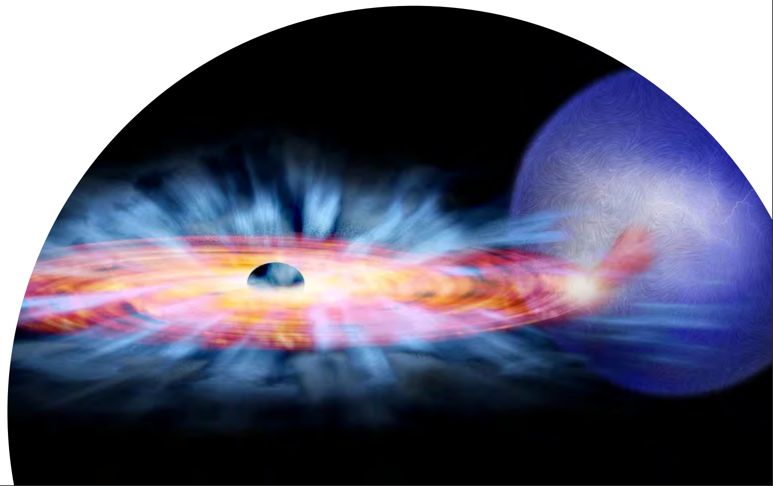
# High Energy Astronomy of Black Holes

The enigmas of Black Holes are not easy to study due to the lack of any light information coming directly from them. However, black holes in X-ray binary systems and at the centres of active galaxies accrete material that results in copious amounts of radiation primarily in the X-ray and Ultraviolet bands. India's first multi-wavelength space observatory AstroSat has been vital and has allowed Indian astronomers to study the immediate environments near stellar mass black holes in X-ray binaries and super-massive black holes in active galaxies.

IUCAA plays a major role in AstroSat, India's first dedicated multi-wavelength space observatory which has special instruments particularly sensitive to UV and different energies of X-rays. IUCAA researchers are members of instrument teams, run the Astrosat science support cell (ASSC), and host the payload operation centre for the CZTI instrument aboard the satellite. Some of the software for AstroSat was written by members of ASSC. The ASSC also runs training workshops, schools, and instrument calibration meetings which are extremely useful, enabling researchers all over India to use AstroSat, in writing proposals for scientific observations and analyzing its data.

Using AstroSat, IUCAA researchers are also involved in studying complex processes in the innermost regions close to supermassive black holes (SMBH) in active galaxies (AGN) and stellar-mass black holes in X-ray binaries. They have found accretion disks that do not extend to the innermost stable orbit as predicted by Einstein's general theory of relativity. They have also found the first evidence for a state transition in a changing-look active galaxy where the standard disk changes its structure and forms a warm medium producing soft X-ray excess emission. As part of an international collaboration, IUCAA researchers observed with AstroSat's Soft X-ray Telescope, and helped unravel a mysterious super bright flash with fast variability, to be a tidal disruption event in which an SMBH in a distant galaxy captured a star and produced a relativistic jet which pointed towards the earth, which produced more light than a 1000 trillion Suns.

In a study of a transient black hole X-ray binary MAXI J1820+070, IUCAA scientists find changes in the inner radius of the accretion disk associated with changes in the structure of and emission from the hot Corona. This study further revealed a captivating connection between the X-ray emission from the inner regions near the black hole and optical/UV emission from the outer region of the accretion disk. In another research data from AstroSat's Cadmium Zinc Telluride Imager (CZTI), reported around 24% polarised high energy X-rays from the black hole X-ray binary Cygnus X-1. This is much higher than the expected less than 10%, thus hinting that the mechanism of X-ray emission (more energetic than 200 keV) is from the jet, possibly synchrotron radiation in an ordered magnetic field. Moreover, the CZTI detected high X-ray polarisation only in the state that exhibits strong radio emission from the jet. For the first time, therefore, one can confirm the direct connection of the hard X-ray emission to the relativistic jet.



# Active Galactic Nuclei and Jets

The Universe is filled with billions of galaxies. These collections of hundreds of billions of stars form some of the most complex gravitationally bound systems with so much unknown about their various parts like the nuclei, disks, surrounding halo etc. These, their various types and their interactions with other galaxies are studied by IUCAA researchers. The larger picture that we arrive at by these studies addresses some fundamental questions, such as how galaxies evolve and exist during their lifetime, interact with their neighbours, and how it impacts their fate.

Many Galaxies host supermassive black holes (SMBH) at their centers which become active when gas infalling towards the black hole results in release of large amounts of energy. The energy output from these Active Galactic Nuclei (AGN), often outshines the light from the entire galaxy. Additionally, one in about one thousand galaxies eject "jets": collimated streams of highly-energetic ionized gas particles, shooting out from their centers and piercing through the interstellar medium (ISM) amid the stars.

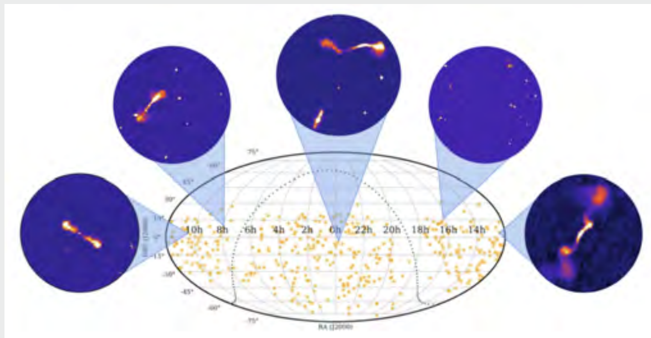
IUCAA researchers are studying the jets in Galaxies using the observations from both space- and ground-based telescopes. Using radio and near-infrared observations (for morphology of jets, their hosts and possible interactions with the surroundings) as well as high-energy X-ray and gamma-ray data they explore the mechanisms powering these jets and other observational features, e.g., erratic brightness changes from jets on timescales from minutes to years. The observational findings are also supplemented with theoretical modeling to interpret the results.

Consistent efforts are ongoing at IUCAA to understand the impact of the relativistic jets on their host galaxy's environment. Recently, high resolution simulations have been performed to study how such galactic scale jets affect the dense multi-phase gas in galaxies and several observable signatures of such interactions have been predicted. This effort has spawned a few campaigns by international researchers to search for such signatures in observed results. In one such case, strong signatures of the central jet driving shocks into a galactic scale molecular disc was actually found using the ALMA telescope. Using newly developed tools to model observable motions of shocked gas from simulations, IUCAA researchers found the observed results to provide a very good qualitative match with the predictions from the simulations. A key highlight of this predictive work indicates that the jets, though appearing narrow and collimated in radio observations, can have a wide-spread galactic scale effect, inducing shocks and turbulence in the dense gas structures both along and perpendicular to their direction. Such interactions may distort the standard gas flow patterns found in such rotating discs and are also expected to impact the star formation rate in the long term.

# Radio Galaxies

The MeerKAT radio telescope in South Africa is currently the most sensitive radio telescope and IUCAA researchers are using it to detect millions of normal and active galaxies. The MeerKAT Absorption Line Survey (MALS) is a large survey that observes the sky and the team led by IUCAA has collected radio continuum images to make a catalog of 495325 radio sources detected over an area of 2289 square degrees from 391 telescope pointings at 1 - 1.4 GHz. The interplay between energetic output from AGN and cold gas in host galaxies is central to understanding the fueling of massive black holes and the evolution of galaxies hosting these. A majority of these radio sources were detected for the first time by MALS in 2023, and will be used to investigate the evolution of cold gas in active and normal galaxies via absorption lines. These may be used for a diverse range of scientific objectives by the astronomy community, and is among the first of several data releases to come from MALS.

The team also used the MeerKAT to study a galaxy towards PKS 1830-211, and discovered unexpected gas clouds made up of the largest hydrogen atoms in the universe - Rydberg atoms. It is the first time scientists have observed these atoms in a distant galaxy. This tells us that interstellar gas in this galaxy is much denser than what is found in the Milky Way. Moreover, they believe the large atoms are spread throughout the galaxy in ionized interstellar gas clouds. The discovery gives a new way to observe our Universe and possibly study the evolution of interstellar gas in galaxies over cosmic time. The research could also help us to understand how interstellar gas drives and inhibits the activity of SMBH.



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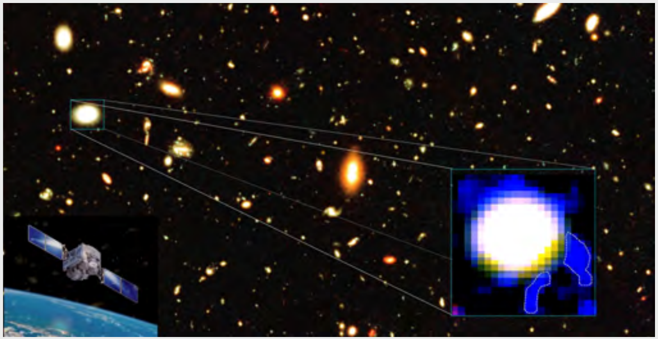
# Dwarf galaxies

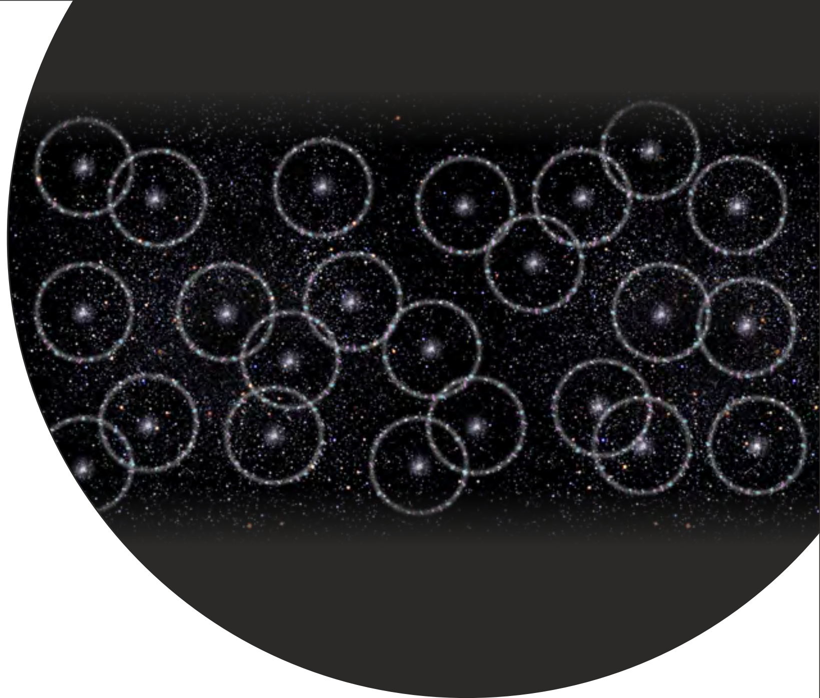
Giant galaxies, like our Milky Way and its neighbor Andromeda, are surrounded by tens of dwarf galaxies - irregular in shape and often forming stars. Looking back in time, we see that galaxies were smaller and more irregular. How these dwarf galaxies assemble their stars and evolve is still one of the outstanding questions of galaxy formation.

A recent study using AstroSat shows how the star-forming clumps in the outskirts of a dwarf galaxy migrate towards the central region due to dynamical friction and contribute to its growth in mass and luminosity. The discovery of this process in several dwarf galaxies has been made for the first time by a group of IUCAA researchers in collaboration with Indian university students and international scientists.

The resolving power of Astrosat's UltraViolet Imaging Telescope and AstroSat UV Deep Field (AUDF) imaging has been the key to spotting such extremely blue, young star-forming clumps that in-spiral inside the optical boundary within a billion years (much shorter than a galaxy's lifetime) timescale to grow these galaxies. One of the key challenging tasks has been to establish the detection of these. Another key research activity of the Galaxy group at IUCAA is to search for extended UV emission in the outskirts of dwarf galaxies, some of which are seen now at a stage when our universe was less than half its current age. In parallel, the group is actively hunting for such distant dwarf galaxies (at redshift z>1) that might have contributed to the reionization history of the universe.

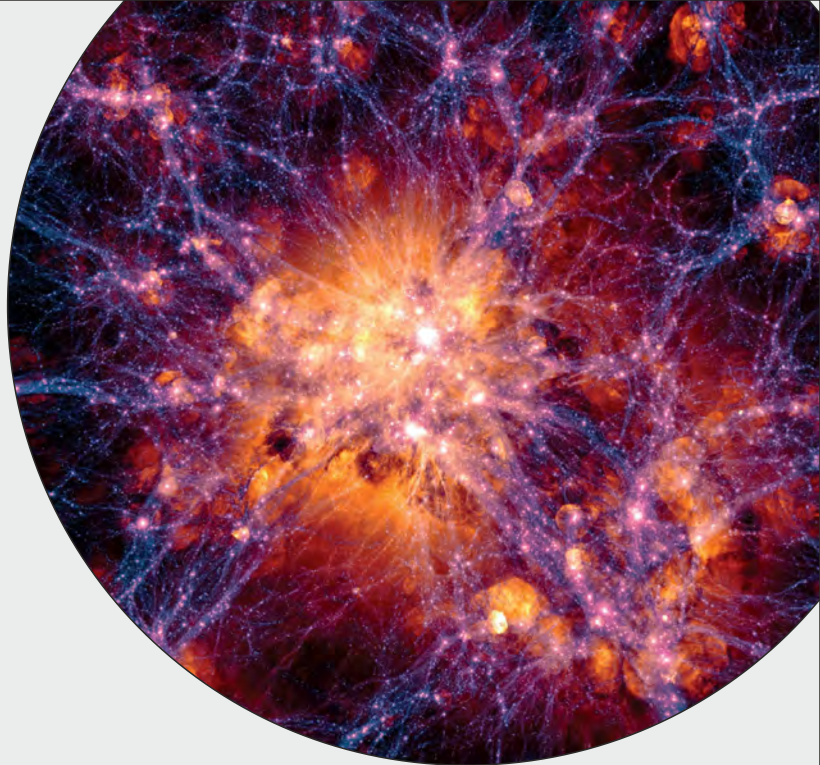


# Cosmology from Large-Scale Structure



The physics of the early Universe predicts a distinct set of spatial correlations called baryon acoustic oscillations (BAO) that imprint on the large-scale distribution of galaxies in the Universe. The BAO feature shows up as a bump when measuring the pairwise number density of galaxies as a function of pair separation. The length scale at which the BAO feature occurs (typically of order 150 Megaparsec at the present epoch) can act as a standard rod that can be used to constrain cosmological parameters. Measuring the precise value of this scale at different epochs of the Universe is one of the key science drivers of current and upcoming galaxy surveys. Typical analyses in this `BAO cosmology' programme assume that the underlying model of the Universe is well-approximated by the Lambda-cold dark matter (LCDM) framework. IUCAA researchers have developed an analysis technique that allows the BAO feature to be used in a model-independent manner, i.e., the same analysis is simultaneously applicable in constraining not only LCDM but also other classes of `modified gravity' or `dark energy' models. The new technique relies on basic physical aspects of cosmological structure formation shared by a wide class of models including and beyond LCDM, combined with a simple data-driven description of the BAO feature using polynomials which is embedded in a fully Bayesian analysis framework. The new technique thus opens the door to using the BAO feature to its full capacity as a probe of primordial Cosmology.

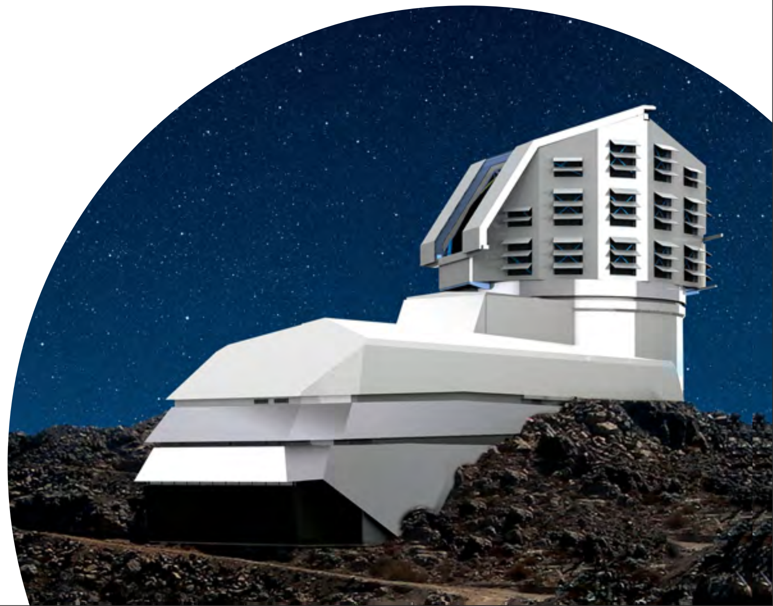
# Cosmology & Matter distribution in the Universe



Research at IUCAA in Cosmology and Large-Scale Structure explores a number of areas using both observational and theoretical techniques, ranging from fundamental questions such as the nature of dark matter and dark energy — including standard and alternate cosmological models — to the phenomenology and physics of the Cosmic Web.

An international team of scientists led by IUCAA, measured the shapes of more than 25 million galaxies to map out the matter distribution in the Universe. Their headline result published in a series of 5 papers states that the measured clumpiness of the matter distribution today is lower than that expected from the standard cosmological model. This difference in the expected and observed clumpiness may indicate a deficit in our understanding of the Universe. The scientists used the Subaru telescope in Hawaii to image a part of the sky as large as that would fit with an outstretched hand in unprecedented detail. The light coming from the galaxies, some as far as 9 billion years away, gets bent due to gravitational lensing caused by the matter distribution between them and us, distorting the shapes of these galaxies. By carefully studying how the shapes of neighbouring galaxies are distorted in a coherent manner, they inferred the matter distribution in the Universe and its clumpiness. This clumpiness can be predicted in the standard cosmological model based on observations of the earliest light in the Universe coming from the cosmic microwave background. The new result seems lower than this prediction at more than 99 percent confidence and could indicate a breakdown of the standard cosmological model.

These results pave the way for new observations from the upcoming Vera C. Rubin observatory, where IUCAA is an international partner. With an 8.4-meter mirror and the largest camera ever built for astronomy and astrophysics, the observatory will conduct a ten-year survey of the Southern Hemisphere sky from its site in Chile. It will help us discover about 20 billion galaxies and a similar number of stars, to further our understanding of the structure and evolution of the Universe



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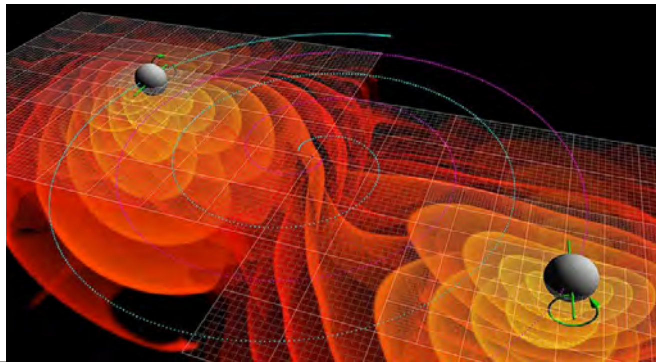
# Gravitational Waves

Predicted by Einstein a hundred years ago, Gravitational waves were the biggest discovery of 2015, which was awarded the Nobel Prize in Physics in 2017. More than a thousand researchers, including many from India, participated in this effort.

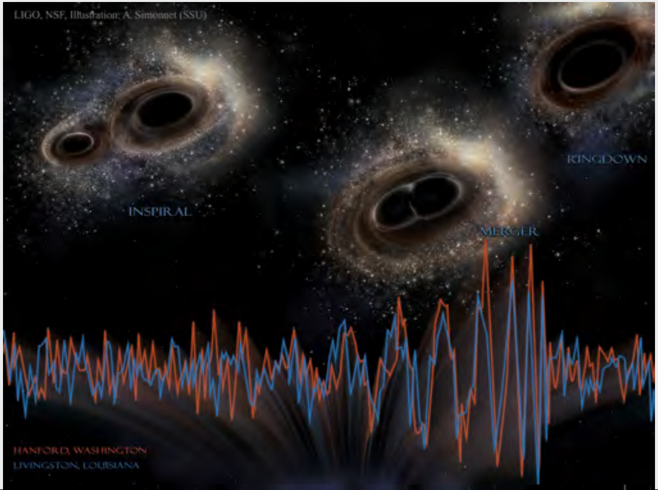
## LIGO-India

The first detection of Gravitational waves (GW) was made by the two most sensitive detectors, the Laser Interferometer Gravitational-wave Observatory (LIGO), which are located in the USA. The third LIGO detector, LIGO-India, will be built near Aundha, in the Hingoli district of Maharashtra. With its geographical advantage, it will enable precise localisation of the sources of gravitational waves, enabling them to be followed up by conventional (electromagnetic) telescopes for extracting exciting scientific details. The project will be built by the Department of Atomic Energy (DAE) and the Department of Science and Technology (DST), Government of India, with a Memorandum of Understanding (MoU) with the National Science Foundation (NSF), USA, along with several national and international research and academic institutions. The project received cabinet approval in April 2023 and is expected to start operating in 2030. The project is being led by four institutions, Directorate of Construction Services and Estate Management (DCSEM), Mumbai, Institute of Plasma Research (IPR), Gandhinagar, Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune and Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. IUCAA is the key science stakeholder in the project and leading the computing and data management, human resource development and education and public outreach activities.



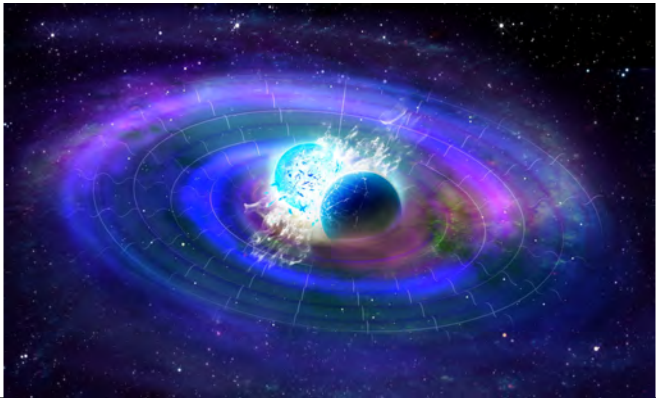
# Gravitational Wave Data Analysis

Extracting science out of data from gravitational wave detectors is non-trivial. Smart algorithms are necessary to detect signals in noisy data and to constrain astrophysical models and parameters. Detection of signals from the merger of compact stars relies on the method of matched filtering - a method mastered at IUCAA for application to gravitational wave data analysis. This method relies on prior knowledge of the waveform which one is searching for in the data. However, since the waveforms depend on the masses and spins of the component stars, millions of such waveforms need to be searched in the data, which is computationally expensive. The challenge becomes even more when one is looking for interesting sources, like precessesing, eccentric or sub-solar mass binaries, which increases the computation cost by many folds. A hierarchical search algorithm was proposed for this purpose. IUCAA Scientists recently implemented the algorithm on real data and showed that the search could be performed more than 10 times faster along with a fairly accurate estimation of the noise background, which is necessary to assign significance to the detections. On another front, an algorithm, along with necessary statistical quantifiers, was developed to probe anisotropies of a stochastic gravitational wave background (SGWB) in pixel and spherical harmonic bases. An SGWB can be created due to phenomena in the very early universe and by distant unresolved or unmodelled sources in the nearby universe. SGWB may be detected by LIGO in the next few years, where the above techniques will play a crucial role in characterising the detected signal and for placing precise constraints on the astrophysical parameters.



# Neutron Stars and GW

A research group at IUCAA is involved in studying Neutron Stars (NS) using Gravitational Waves (GW). Being ultra-dense, NS show a myriad of extreme properties and serve as cosmic laboratories to investigate Fundamental Physics. Their strong gravity can bend space-time a lot, and their collisions or perturbations can result in strong GW emission. Since 2017, the groundbreaking detection of GW signals from NS by the LIGO-Virgo detectors allow us to look into their interior and constrain dense matter properties. IUCAA research studies are going on to improve limits for continuous GW searches.



Over the past year, several studies looked for signatures of the Neutron Stars internal composition in unstable oscillation modes. The results showed that Nuclear Physics can be better constrained using signals from such oscillations, in both isolated or binary NS, via planned future generation GW detectors. They also investigated how such detections may allow us to distinguish between NS and other stable families of compact stars or probe the nature of possible phase transitions in their interior.

Other works imposed constraints on compact star properties using multi-disciplinary Physics (nuclear theory, heavy-ion, multi-messenger astronomy) at different densities. Tidal heating in Neutron Stars mergers was also proposed as a novel probe of strangeness in NS. Their oscillation modes were also suggested as a new probe of the presence of dark matter in NS.

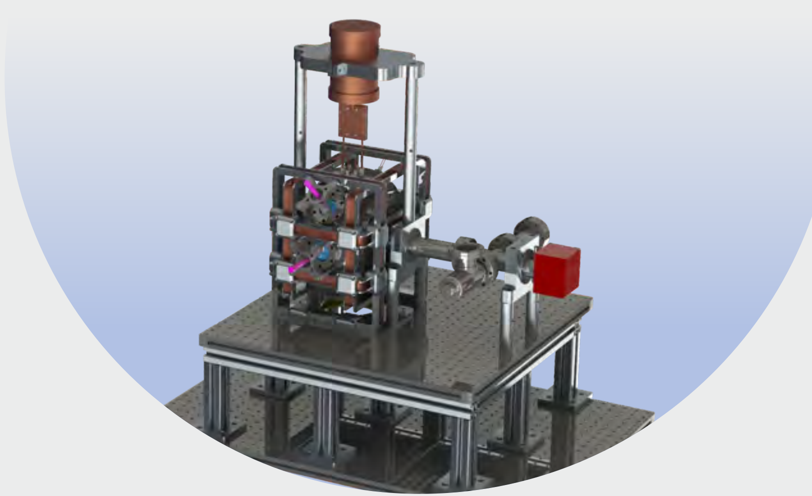
# Intergalactic medium

Galaxies are the building blocks of the universe. However, more than 90% of all the ordinary matter in the universe resides outside galaxies in a tenuous medium called the intergalactic medium (IGM). Galaxies attract and accumulate gas from the IGM to grow in mass and size. On the other hand, large-scale winds from galaxies also eject gas, including the heavy elements (e.g., Carbon, Oxygen and Nitrogen) produced inside galaxies, into the IGM. IUCAA researchers are involved in understanding how such interactions between galaxies and the IGM shape galactic evolution.

IUCAA is leading major observational campaigns, in collaboration with international scientists, to map the distribution of very diffuse, invisible gas surrounding galaxies and clusters of galaxies and characterize their physical properties. Using large quantities of spectroscopic data, the team has recently reported the detection of neutral gas and heavy elements surrounding clusters of galaxies and mapped their spatial distributions out to several million light years for the first time. The team has also produced statistical maps on the distribution of neutral hydrogen surrounding low-redshift galaxies with the largest-ever sample size. Using state-of-the-art integral-field spectroscopy, they are also studying the connection(s) between very distant galaxies and the gas around them when the universe was only 15% of its current age.

A unique method has also been used to probe coherence in metal absorption towards multiple images of strong gravitationally lensed quasars. Two of the few currently known quasars with multiple images due to strong gravitational lensing by galaxy clusters at redshift z~0.5-0.6 were studied. The integral field spectroscopic observations of these quasar fields using Multi Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT) facilitated the study of the galaxies associated with the absorbing gas. The results indicate that the metal-enriched gaseous structures around galaxies become less coherent with distance, with a likely coherence length scale of ~10 kpc. A recent work also involves a tomographic analysis of the structure of metal-enriched cool gas in the halos around galaxies at, z<2. Diffuse gas is detected in absorption in the spectra of two background quasars at z~2-3 with angular separations between different pairs of quasar multiple images, enabling us to probe the absorption over transverse physical separations of ~0.4-150 kpc. Further cutting-edge research in this and several other observational challenges will be possible with advanced instruments on the upcoming Thirty Meter Telescope (TMT). From India, IUCAA is playing an important role in this international partnership as part of the India-TMT collaboration. It is leading the development of the Telescope Control System for TMT consisting of several independent software subsystems for running the observatory.

# Quantum Technologies



Since the conceptualization of Quantum Mechanics, we are now in an era of a second quantum revolution, when several countries in the world, including India, are advancing cutting-edge quantum-enhanced technologies in computation, communication, sensing, and metrology.

The Precision & Quantum Measurement Laboratory (PQM lab) at IUCAA is developing a state-of-the-art facility dedicated to explore the fundamental aspects of science using optical atomic clocks as a quantum sensor. The lab's research interests involve developing quantum phenomena-based technologies for metrology-grade measurements and accurate sensing. The heart of the experimental setup is a trapped ytterbium-ion-based quantum clock. For this, we shall probe the highly forbidden electric octupole (E3) transition at 467 nm wavelength of a single trapped and laser-cooled ytterbium-ion. To excite that clock transition, an ultra-stable sub-Hz line-width laser will be produced by referencing the laser to an indigenously developed ultra-stable Fabry-Pérot cavity. Upon development, the change in the tick rates of such clocks is altered by unimaginably tiny perturbations of the energy states associated with the clock transition. The resulting shift in tick rates of the clock could be caused by variations of the fundamental constants, breaking of fundamental symmetries, gravitational red-shifts at the submillimeter scale, gravitational waves, cosmic microwave background, and so on. For such scientific explorations, the lab-based clocks must be part of a geographically distributed "quantum clock network." To pursue this, the reference clock photons must be disseminated from one node to another within the clock network using "phase stabilized optical fibers"; the PQM lab has already developed the required technology.

# High Performance Computing


To get scientific knowledge out of Astronomical observations we need large computing resources to analyse the raw data and realistically simulate the observations to extract the physical insights. The most common High Performance Computing (HPC) usage in Astronomy and Astrophysics is in i) Simulations of astrophysical phenomenon requiring large scale distributed computing with fast interconnect speeds between nodes and ii) Analysis of Terabyte / Petabyte scale data which are massively parallel and often require fast I/O without the need of fast exchange between nodes. There is also a progressive increase in the application of Machine Learning, suitable for GPU based hardware. For all these domains, the academic members and Associates of IUCAA are already actively involved in cutting edge research which uses state of the art computing codes and are leading major projects and collaborations of international stature.

For simulations, researchers in IUCAA are currently actively pursuing several topics of cutting edge research involving HPC in fields such as Galaxy evolution and structure formation, Astrophysical Turbulence, Accretion discs, Numerical relativity, Solar convection, Radiation transport etc. IUCAA also hosts data from various prominent Astronomical observatories, namely, LIGO, Virgo and KAGRA, the MeerKAT Absorption Line Survey (MALS), etc. It also hosts the science support cell for AstroSat. There are dedicated computing clusters for in-house analysis of these datasets. The Sarathi cluster, primarily dedicated to gravitational wave data analysis, offers more than 500 TeraFlops of peak theoretical performance. IUCAA also offers prototype GPU clusters primarily for applications of Machine Learning that can be used by university researchers too.

# Public Outreach and Education


With an Inherent vision of informing and inspiring the next generation of astronomy enthusiasts IUCAA has been doing proactive outreach to the public since its beginning. It has been a pioneer in this field with the earliest steps by the great science communicators like Prof. Yash Pal and Prof. J. V. Narlikar. For more than three decades it has grown and now reaches thousands of students, teachers and members of the public every year. Through our well designed educational and outreach programs the IUCAA Scientific Public Outreach Programme (SciPOP) facilitates fun stem learning and practical astronomy. Our regular events like the Second Saturday lectures, science toys and astronomy sessions, telescope making workshops, planetarium and sky watching events allow people to be in touch with IUCAA. The open day on National Science Day is looked forward to, with visitors coming from far off places. The enthusiastic teams from various projects regularly enhance the outreach with their contributions to public and media events. There is also special emphasis on reaching rural audiences who do not usually get access to a research Institute or information about cutting edge science.IUCAA was recently invited to showcase its educational efforts and resources at the G20 Education meeting and at the celebration of the adoption of National Education Policy, where they were also appreciated by the Honourable Prime Minister of India.

As part of more formal education efforts, IUCAA has also set up a Teaching Learning Centre and National Resource Centre at its Astronomy Centre for Educators and it also hosts the India Centre of the International Astronomical Union's Office of Astronomy for Education. The former runs the IUCAA Summer School on Astronomy and Astrophysics, the Radio Astronomy Winter School along with several seminars on Education, Science and Society. The latter is helping to advance the professionalization of astronomy education by conducting various teacher training programs and developing materials for facilitating teaching of Astronomy at school level.

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