Research Statement

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Gravitational waves were predicted by Einstein's General theory of Relativity in 1916. A common source of these waves are inspiralling binary compact objects, losing energy as gravitational waves until they merge. Detectors needed to observe them comprise giant interferometers called Laser Interferometer Gravitational Wave Observatory (LIGO). About a hundred years after Einstein's theory, gravitational waves were observed for the first time by LIGO on September 14, 2015. I was a part of the team that conducted searches which helped detect the very first gravitational wave event named "GW150914", which came from two coalescing black holes Abbott et al. (2016). This officially ushered in an era of doing science with gravitational waves. This discovery, hailed to be one of paramount importance in this century, gave us a new window to look through at the universe, besides regular astronomy with telescopes using electromagnetic waves. It is no wonder that it led to the 2017 Nobel Prize in physics, awarded to the three key founding members of LIGO. Ever since the first observation, I have majorly been involved in analyzing data collected by the LIGO and Virgo detectors, to look for signatures of gravitational waves. I have also been involved in developing an early alert system to rapidly follow up such gravitational wave candidates which are also observable electromagnetically. Also, I have been helping with using results of such searches to glean significant astrophysical conclusions, by setting upper limits on astrophysical models in ways that was not possible before the era of gravitational waves. I have been working with the Compact Binary Coalescence (CBC) working group within the LIGO-Virgo Kagra Collaboration (LVK). I have also recently joined the LISA (Laser Interferometer Space Antenna) Consortium where I am developing a low-latency search algorithm to detect and send out pre-merger alerts for massive black hole binaries. As we now know, several detections of gravitational wave events have been made by LVK so far. Research in the field will require present and future students to be trained in drawing astrophysical conclusions from such observations and developing novel methods of analyzing data from present and future generation of gravitational wave detectors. I would like to contribute to this effort.

Analysis of data and search development:

Modeled search:

I have been working with a group that uses the Gstreamer and LIGO Algorithm Library based, GstLAL-inspiral search algorithm to analyze gravitational wave data Messick et al. (2017); Sachdev et al. (2019). I have contributed to the search in the 1st (O1 lasting between 2015-2016), the 2nd (O2 in 2017) and the 3rd (O3 in 2019-2020) observation phases of LVK. Detections of gravitational wave events made by LVK up to O3 The LIGO Scientific Collaboration et al. (2021) includes compact objects including black hole binaries, binary neutron stars and neutron star-black hole binary mergers. I helped compute the astrophysical rate of coalescence of such binary neutron stars, which was incorporated in the first detection paper Abbott et al. (2017b). Such analysis and followup requires development of software and optimization of existing searches, which will re main a necessity in the near future, which I plan to directly contribute to personally, as well as through research activities in my group.

Development and optimization of the search and template banks and better noise mitigation:

The GstLAL search uses gravitational wave templates constructed using general relativity. These templates, spanning the searched parameter space, constitute a bank and the data is cross-correlated against it to look for signals. The challenges faced and tackled by my working group during O1, O2 and O3, include effective designing of template banks and search algorithms for well optimized searches. For O1, the search bank for stellar-mass objects included binary black holes (BBH), binary neutron stars (BNS) and neutron star-black hole binaries (NSBH), spanning a region of 2 to 100 solar masses in total mass of the binaries. The dedicated search for the heavier black hole binaries called the Intermediate Mass Black Hole (IMBH) binaries, used a separate bank spanning a region of 50 to 600 solar masses in total mass. With increase in sensitivity of the detectors in O2, heavier stellar mass binaries could be detected and hence we needed an expanded search for various astrophysical populations. I made major contributions in developing a combined search bank which was used in O2 spanning 2 to 400 solar masses in total mass. I helped optimize this bank, especially in the IMBH region, by ensuring proper placement of templates for an accurate binning and estimation of the noise background Mukherjee et al. (2021). I have also helped with investigations for the implementation of using statistical data quality information in the likelihood ratio calculation of the GstLAL algorithm Godwin et al. (2020). Such inclusion of data quality information, informs the ranking statistic computation about the presence of noise transients in the data, without the need for human intervention in vetting of noisy data. This incorporation benefits the IMBH search, which is otherwise sensitive to short duration transients as the signals of these systems are short lived within the LIGO-Virgo band.

I am currently involved in the development of the low-latency and archival GstLAL searches for the ongoing 4th observing run (O4). Optimization of the search methods is required going from one observing run to the next, to keep up with the expanding detector network, its sensitivity and the larger volume of detections. It is important to develop and test searches, which my students can contribute to and learn from. Development of newer techniques, incorporation of newer technology like artificial intelligence (A.I) and carrying out tests for the same can become fruitful student projects.

Search for intermediate mass black hole (IMBH) binaries:

Search for IMBHs so far:

I worked on the IMBH specific searches of GstLAL in O1 and O2 Abbott et al. (2017a, 2019b). This had the motivation of estimation of rates of observation and understanding the astrophysical distribution of these binary populations. Such rate estimates are used for making astrophysical statements about population distributions, and hence origins of compact objects, making their accuracy necessary. I have also majorly continued to work on the GstLAL search for IMBHs in O3. The first gravitational wave from an IMBH system was observed on May 21, 2019 (GW190521) Abbott et al. (2020a). I have led the observation and follow up efforts for this very short and difficult to detect signal using the GstLAL algorithm. The remnant produced by this merger is about 150 solar masses which places it in the mass range associated with IMBHs, an elusive type of heavy black holes with masses between 100 to 100,000 solar masses. The formation channels of IMBHs are not well understood by astrophysicists. Being heavier than the stellar-mass black holes observed thus far, but less heavy than the supermassive black holes that are known to occupy the centers of galaxies, these intermediate-mass black holes are suspected to be the ”missing link” between the two. More discoveries like GW190521 are likely to shed light upon such formation channels. This inspires dedicated effort in future searches for IMBHs. This discovery is also unusual because the heavier of its 66 and 85 solar mass components, belongs in a theorized gap in the mass distribution, where black holes are not expected to exist by conventional models. Hence this discovery indicates possible channels of black hole formation other than stellar collapse and stands to open new doors in our understanding of these objects. The various other scientific implications of this discovery can be found in Abbott et al. (2020b). I have led the designing of a dedicated IMBH search and the analysis of O3 data with it to look for IMBH event candidates that the general GstLAL compact object search may have missed. The results of this all sky IMBH search have been published in Abbott et al. (2022).

Development of the search for IMBHs in O4 and future, including precession:

I am currently working on developing the IMBH search for O4. The currently implemented version of the GstLAL search algorithm does not include precessing systems in the template banks, although it is capable of detecting such systems. The present banks comprise systems with their spins either aligned or anti-aligned with the total angular momentum. Incorporation of precession in our search will make us sensitive to generically spinning binaries, leading to better understanding of formation scenarios. I am currently involved in helping with developing a template bank that can be used to search for such systems, thus expanding the parameter space we have coverage for. Incorporation of such non vanilla effects in our searches is an active area of research that I would like my students to contribute to and learn from.

Early warning alert system for multi-messenger follow up:

Development of early alert system for LVK so far:

I have been involved in helping develop a pre-merger alert system to enable early observation of the electromagnetic counterparts of compact object coalescences. A new era of multi-messenger astronomy started with the joint observation of gravitational and electromagnetic waves from the BNS merger named GW170817 (Abbott et al. (2019a), Abbott et al. (2017c)). As detailed in our article Sachdev et al. (2020) and in the references therein, the gamma-ray burst could be observed within the first 2s but the the first manual follow up did not take place until about 8 hours after the merger and by the time the telescopes started observing, the source was below the horizon. The discovery and its multi-messenger follow up led to several important scientific results. However, reduction of this latency and hence observation of prompt emissions would lead to better understanding of the outflow, the r-process nucleosynthesis and the state of the remnant. This necessitates the presence of an alert system for electromagnetic (EM) observing partners that can enable prompt observations in the future. Since BNSs can spend up to 10-15 minutes in the LIGO-Virgo frequency band at design sensitivity, enough signal to noise ratio (SNR) can accumulate within 60s-10s before merger, especially for systems at low redshifts. Using simulated events following the distribution arrived at from observations, and simulated data over a month, we found that we can detect 7% to 49% of total detectable BNSs, 60s-10s respectively before their mergers and we can localize at least 1 such event per year to within 100 deg^2. Despite an additional data transfer latency, this would enable us to send out pre-merger alerts for multi messenger follow ups. I have helped implement the search at low-latency for O4.

Low-latency and Early warning search for LISA massive black holes:

The space based laser interferometer LISA, is expected to be operational in the next decades and will be able to probe the millihertz frequency band. This will make it sensitive to a vast array of compact object mergers, including the massive black holes or MBHs. These black holes, straddling the intermediate and supermassive types of black holes, have masses extending above a minimum of 1000 solar mass. They are expected to be observable within the LISA band for several weeks to months before they merge. This makes them excellent candidates for low latency, pre-merger observations. Also, some mergers of MBHs are expected to have electromagnetic counterparts due to the presence of gas or disks. Pre-merger alerts with sky location information from LISA data analysis sent out to the astronomy community, would enable early detections of such mergers in multiple electromagnetic bands. Such multi-messenger observations stand to further our knowledge of astrophysics, including that of black hole formation and evolution. I am working on developing a low-latency search algorithm based on stochastic sampling, for potential LISA massive black hole binary sources. Such a search will enable sending out estimates of binary parameters and sky locations as pre-merger alerts to astronomers.

I would like my group to lead the development of production level search pipelines needed to analyze data from future generations of gravitational detectors like LISA. It would be important and educational for new students to get involved in mock data challenges, learn using existing data analysis software and also help develop new techniques. These are good early research and publication opportunities for both undergraduate and graduate students.

Future research:

I plan to continue working on observing and interpreting gravitational wave data and doing astrophysics with it. I have also been working on developing tools and software that would help search for gravitational wave signals from compact binary mergers and help with the follow up of gravitational wave candidates to send out early multi-messenger alerts. I plan to continue such work for present and future gravitational wave detectors. I am interested to work with your group and help with their contributions to mentoring and research in the field of astronomy and astrophysics, through gravitational waves. The group's interests in multi-messenger observations or theory and gravity, astronomy and astrophysics in general, is compatible with my areas of research in gravitational wave data analysis and astrophysical interpretation of gravitational wave detections and multi-messenger astrophysics. Being directly involved with the development of data analysis and search pipelines and with the astrophysical interpretation of gravitational wave detections and multi-messenger astrophysics, will help me also provide students with opportunities of research involvement in these very active areas. I would like to work on observations and also searches and interpretation of data from gravitational wave detectors on the ground (LVK) and in space (LISA). I would be interested to collaborate with and complement the work on multi-messenger observations of compact object sources with gravitational waves. I am currently working on a machine learning-based approach of creating search template banks for compact object searches, with a focus on searches for IMBHs. I would also like to lead the effort towards massive black hole searches and expand the group's contributions to development of searches for compact objects. I would also like to collaborate with the astronomers to develop tools for multi-messenger observations. I would like to in general work with the research faculty members with interest in astronomy or astrophysics and help strengthen the research, outreach and teaching efforts of the group.

As we know now, neutron star-neutron star coalescences can lead to electromagnetic counterparts, besides being observable in gravitational waves, leading to multi-messenger observations. Also, it has been postulated that black hole coalescence in disks of active galactic nuclei (AGNs) could be electromagnetically observable. As the future generation of gravitational wave detectors acquire the ability to observe more heavy mass black holes, developing abilities of such potential multi-messenger observations will become important. I am currently working on developing a prototype for a low-latency search algorithm based on stochastic sampling, for potential LISA massive black hole binary sources, that can send out early warning alerts to astronomers. Such a pipeline would need to be tested in real time through mock data challenges and optimized to handle realistic noise and data complications. I would also like to involve students in related projects to develop a full scale, production ready low-latency early warning pipeline for NASA's LISA mission.

Being associated with the LIGO-Virgo-KAGRA collaboration will enable me to not only continue my own research, but also advise students interested in exploring new ideas to develop new searches and techniques in data analysis. Such techniques could be used to detect novel sources and understand astrophysical implications of our detections at present and in the long-term future. My work in the LISA consortium on the development of low latency early warning searches for massive black holes and hence novel contributions to the long-term detection efforts, enables me to prepare prospective students to become active researchers in the future generation of detectors. It gives students an early opportunity to experience developing search algorithms from scratch. In general, Some of my present work interests with prospective students in the future includes:

- I am interested in continuing to work on improving template bank based searches. This would include incorporation in the search of non fundamental effects like the contributions from higher order modes, highly asymmetric or precessing systems or ones with eccentricity. For heavy binaries, especially IMBHs with mass ratios less than 1, the higher order modes start to have contributions. These modes have higher power content, thus increasing the search sensitivity towards such high mass systems and including them in the templates help in the correct estimation of the parameters of the binary Calderón Bustillo et al. (2018). Such detections can help us constrain the formation channels of non vanilla binaries.
- I would also like to continue the development of low-latency searches and early warning alert systems for multi messenger observations. This will enable us to glean more astrophysical information and better understand the formation and evolution of such compact objects.
- With detections like IMBH GW190521 becoming more common as our detector's sensitivity increases in future runs, it will be useful to use LIGO-Virgo data to inform our understanding of their formation channels. But to achieve such science we need to develop robust mechanisms to identify short duration non-astrophysical transients in the data and diagnose noise better to improve our search sensitivity, an effort I wish to contribute to.
- I am interested in continuing studying astrophysical rates of mergers of compact objects and using them to understand their population distributions. Such studies can throw light upon formation mechanisms of such objects or other less understood astrophysical mechanisms. I would also be interested in developing novel methods for detection, using machine learning. With the increase in sensitivity of the detectors and hence the number of detections, it would become important to develop machine learning based follow up tools for estimation of detection rates or binary parameters, which I would like to contribute to.
- Developing sub-threshold searches that can probe deeper into the data. Combining sub-threshold catalogs from different multi-messenger channels and combining their sky maps can help in discovering new astrophysics and better localization.

I have been thoroughly involved in public outreach and activities during my PhD and postdoc years, as outlined in my CV. Diversity and inclusion within academia has been a great priority to me. During my PhD, I was a part of the women's advocacy group in my department. During my postdoc at Penn State, I have been part of PAW+ (Physics and Astronomy for Women and other minorities). I have been a part of discussion panels at conferences and radio programs aimed at empowering under represented minorities in STEM. I would like to bring these skills and mindsets to my teaching and mentoring.

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