Project Proposal

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In recent years binary neutron star (NS) merger events have been detected, presenting an opportunity to learn about NSs and the properties of matter with super-nuclear densities that cannot easily be replicated in experiments. As outlined in [1] these NS merger events are measured by the aLigo and Virgo, enhanced Michelson interferometers that measure the strain in space-time as gravitational radiation passes through the earth. Known as gravitational wave detectors. Decades of engineering were required to develop detectors capable of measuring these fantastically small perturbations, that were believed to exist as a consequence of Einstein's work.

The primary challenge in detecting gravitational wave signals is detector noise. The detectors must be highly sensitive, and are a result are also impacted by many sources of noise ranging from weather and seismic activity to quantum sensing noise. Sections from [1] explain the properties of this noise from which the targeted signals are identified, separated, and reconstructed.

When a candidate event is identified by the detectors, the signals are checked for consistency between sites to confirm that the event was observed by all detectors within the appropriate light travel times between them, 26-27 milliseconds between the Ligo and Virgo detectors and [the better defined] 4 ms travel time. If multiple detectors did register an event, each signal is then match-filtered and compared for agreement. The signal characteristics are all consequences of generation, merger, and post-merger object. Signal characteristics include the mass distribution of the binary pair, spins, orientation (angles relative to us, and each other), and the distance traveled. The cardinality of characteristic traits requires an immense template bank of generic signals to match in search for a detection against a constant noise background. For high confidence in event detection, signals must be independently verified by matching parameters between at least two detectors. The first binary Neutron merger was measured on August 17th, 2017 [2], highlighting a new opportunity to better understand these bizarre ultra-dense bodies.

However, there are some challenges with binary neutron star mergers. The signals are typically separated into two parts: a *pre* and *post-merger* signal, the pre-merger signal is detectable with well-researched information on the responsible bodies, while the post-merger signal carries the rest of the information necessary to learn about the coalesced object. In the example of GW170817, the first such event to be detected, the pre-merger was used to measure the radii

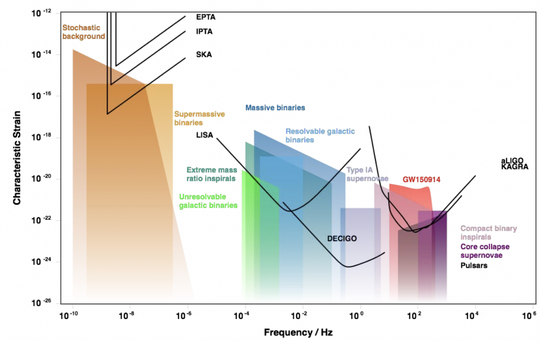

Figure 1: The frequency ranges of existing and future gravitational wave detectors. Core collapse Supernovae, and Neutron stars are depicted but are clearly on the fringes of detector sensitivity.

of the coalescing neutron stars, their tidal parameters, and to place meaningful constraints on their equations of state (EoS). But, in this case, no post-merger signal was detected, presumably hidden within detector noise at frequencies beyond the optimized band of the detectors.

Resolving the postmerger signal would allow a unique insight into the remnant compact object formed by the merger; whether the objects collapsed into a black hole instantaneously, survived for a short time as a NS-like object before further collapsing, or formed a stable NS. This information and further constraints on the equations of state governing NSs would be results of post-merger analysis, and the answer to long-standing questions on the structure of neutron stars and the state of matter at hyper-nuclear densities.

Research has identified needed improvements to access post-merger data. For example, [3] proposes this can be achieved through improving detector sensitivity in the kHz range by 2 to 3 times current capabilities. Observing run four, (abbreviated O4) will begin soon including some improved sensitivities as well as planned project upgrade parameters. New signals from O4 could contain post-merger frequencies, providing the ability to improve models and understanding of BNS merger events

This sensitivity issue is shown in the figure below 2; where we can see the frequency of the signal growing beyond the range of the detectors as the bodies merge.

The main focus of my research will be to explore the (still mysterious) equations of state that structurally govern neutron stars, offered by the evolution of binary neutron star coalescence. This could lead to a better understanding of the expected post-merger signals by developing analysis algorithms to determine the distinguishability of direct collapse mergers from those leaving behind stable, long-lived, remnants.

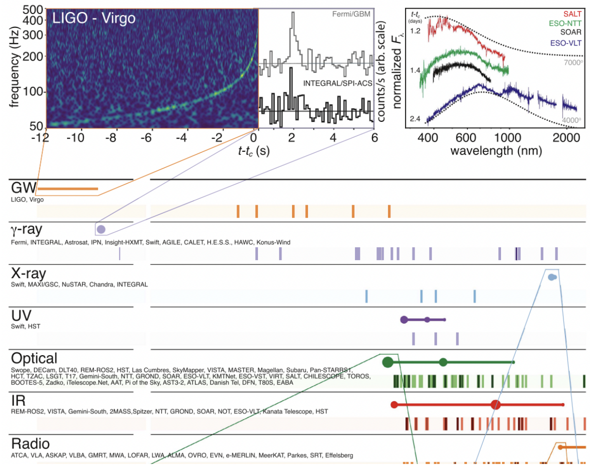

Figure 2: The multi-messenger signal from a BNS merger. Adapted from [2]

Neutron stars range in mass between 1 and 2 solar masses[1] Limits on maximum masses for NS, because we don't fully understand them yet, are known to exist in the range of 2 to 3 solar masses. The relevance of this is the merger event and ring down during coalescence, the remnants when merged could instantaneously collapse into a black hole or exist momentarily as a deformed quasi-neutron star where rotational energy combats the gravitational in-fall, before eventually collapsing. Better understanding of the coalescence process will help narrow the possible equations of state that currently describe neutron stars and help inform us about what to look for in incoming BNS system signals.

Understanding BNS merger ring-down and whether a NS forms or if a black hole is instantly formed, is analogous to current research in 3-D modeling core-collapse supernova. Supernovae are gravitational radiation-producing events, and the recent research in [4], have provided a calculation of gravitational-wave signatures for 3D core-collapse supernova in simulations of massive stars. This research is analogous in that collapse of supermassive stars can also fall immediately to a black hole, or first to a NS. Supernovae happen to be cosmological for more common events so if their signals could be measured, data will consequently be more available, this is shown in Table II of [5] which characterizes the merger rate of BNS over a range of $10 - 1700$ mergers per cubic Gpc per year. Therefore our research into the evolution of merging NS could be both informed by or informative to core-collapse supernova modeling.

[1] In theory, lower mass neutron stars could exist, but due to the nature of neutron star formation seem unlikely to be observed in nature

References

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