KSPA 2017 Program: Astrophysics with Gravitational Wave Detections
Project Summaries

1: Novel tests of general relativity

The primary tests of general relativity (GR) conducted by the LIGO collaboration parametrize possible departures from GR as deviations at fixed post-Newtonian orders. While some theories of modified GR predict deviations at particular pN orders, others do not. The goal of this project will be to implement alternative models for deviations from GR, which will be able to constrain arbitrary deviations in the amplitude and phase of gravitational waves.

- Robust parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library (arXiv:1409.7215)
- Tests of general relativity with GW150914 (arXiv:1602.03841)
- Modeling Calibration Errors in CBC Waveforms (LIGO-T1400682)

2: Characterizing EM-bright gravitational wave sources in non-stationary interferometer noise

The merger of two neutron stars or a neutron star and a black hole is expected to produce a burst of electromagnetic emission in addition to gravitational waves detectable by LIGO, making these cosmic collisions a prime candidate for multi-messenger astronomy. Current parameter estimation algorithms for such events, including sky localization, assume the interferometer noise is well-behaved and stationary on the time scale of hundreds of seconds. However, terrestrial interferometer data often contains a high rate of non-stationary transient noise, or glitches. This project will characterize the impact of common forms of transient noise observed in the Advanced LIGO interferometers on the recovery of the sky position and physical parameters of compact binary systems, including those containing at least one neutron star, and explore methods of recovering signals from data containing transient noise.

3: Astrophysics with astrometric detection of gravitational waves

Gravitational waves (GWs) propagating in the spacetime between the Earth and distant stellar objects distort the trajectories of photons propagating between the source and the Earth. This is exploited in attempts to detect gravitational waves using pulsar timing arrays - an intervening gravitational wave leads to a periodic deviation between the observed and predicted arrival times of pulses from the pulsar. However, it also leads to periodic changes in the apparent locations of stars on the sky. Astrometric satellites such as GAIA can thus also detect gravitational waves. Recent work suggests GAIA will have a sensitivity comparable to current pulsar timing efforts, but with a more uniform dependence on frequency. This project will explore the astrophysics that might be possible with astrometric detections of GWs. Depending on the student's interests, there are various interesting aspects of the problem - 1) is there complementarity between pulsar timing observations and GAIA observations? 2) what are the prospects for detection of a signal using GAIA or a future third-generation astrometry mission? are there types of source that GAIA is better suited to the detection of than pulsar timing? 3) how does the gravitational wave background affect the ability of astrometry missions to determine stellar positions and can gravitational wave "noise" be removed from future astrometric data? 4) how can we map the gravitational wave background using astrometric observations?

References:

- Book & Flanagan (2011), "Astrometric Effects of a Stochastic Gravitational Wave Background", Phys Rev D83 024024, https://arxiv.org/abs/1009.4192
- Chen et al. (2017), "Probing the assembly history and dynamical evolution of massive black hole binaries with pulsar timing arrays", https://arxiv.org/abs/1612.02826
- Gair et al. (2014), "Mapping gravitational-wave backgrounds using methods from CMB analysis: Application to pulsar timing arrays", https://arxiv.org/abs/1406.4664

4: Mapping the weak lensing potential using decihertz gravitational wave sources

Gravitational waves (GWs) undergo gravitational lensing in a similar way to electromagnetic radiation. This leads to changes in the inferred luminosity distance of the GW source that are a nuisance in the sense that they limit the utility of individual GW sources as probes of the cosmological expansion history of the Universe, but have great scientific potential in that they provide information about the distribution of the lensing matter between the source and the observer. It was previously suggested that a GW detector such as DECIGO or BBO, operating in the decihertz range, could simultaneously provide exquisite cosmological measurements and map out the weak lensing potential through observations of GWs from neutron star binaries. The recent discovery by LIGO of a substantial population of binary black holes with comparatively high masses indicates that the decihertz band might be rich with such sources. These sources can potentially provide comparable or better measurements of the weak lensing potential and cosmological parameters. The aim of this project will be to explore what we could learn about cosmology and the distribution of matter in the nearby Universe through the observation of this population of stellar origin black hole binaries in the decihertz band.

References:

- Sesana (2016), Phys Rev Lett 116 231102, "The promise of multi-band gravitational wave astronomy",https://arxiv.org/abs/1602.06951
- Abbott et al. (2016), "Supplement: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914",
ApJS, 227, 14, https://arxiv.org/abs/1606.03939
- Cutler & Holz (2009), "Ultra-high precision cosmology from gravitational waves", Phys Rev D80 104009,https://arxiv.org/abs/0906.3752

5: Resolving failed supernovae fractions with the Hyper-Kamiokande neutrino detector

Project Description: Hyper-Kamiokande is a proposed water Cherenkov neutrino detector that will be an excellent probe of the diffuse supernova neutrino background (DSNB)?. Measuring the DSNB signal provides a complementary measurement of failed supernova rates from that inferred by the rate of black hole - black hole mergers measured by gravitational wave experiments. For this project, you will simulate a DSNB model with different fractions of failed supernovae using the Hyper-Kamiokande Monte Carlo code, WCSim, in order to determine the sensitivity of the experiment to the rate of failed supernovae.

Suggested reading:

- Davis and Faibairn 2017 (arXiv:1704.05073)
- Hyper-Kamiokande design report (https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf)
- WCSim Github page (https://github.com/WCSim/WCSim)
- Nakazato et al 2017 (https://arxiv.org/abs/1503.01236)

6: Gravitational Wave Probes of Supernovae

Gravitational waves have the potential to probe the convection and rotation in the engine of a core-collapse supernova. Although the gravitational wave signal from core-collapse has been simulated for over 3 decades, most studies of this signal have focused on specific models or simulations. This project will produce a comprehensive study of the gravitational wave signals from supernovae, developing simplified models that describe the features expected in different supernova engines and comparing these models to our current understanding of detection efficiencies. With this study, we can determine what we can learn from a gravitational wave signal for supernovae at different distances. This effort will be coupled with a statistical study of the rate of local group supernovae from historical records to determine the rate for different constraints on the supernova engine.

7: Non-Thermal Optical Transients from Neutron Star Mergers

What are the possible (particularly non-"kilonova") optical transients from neutron star mergers There are several components to consider: the on axis afterglow from the jet forward shock, off axis afterglow from the jet forward shock, the reverse shock emission, and emission from dynamical ejecta. In contrast to extensive efforts studying kilonova, calculations quantifying the impact of non-thermal emission from the ejecta have been lacking. To better understand these signatures, we propose to perform a suite of relativistic hydrodynamic simulations of neutron star merger ejecta expanding in environments with conditions derived from cosmological simulations.

Papers: Berger 2014, ARA&A, vol. 51 ; Lee & Ramirez-Ruiz, 2007, NJPh, 9, 17; Mesler et al. 2012, ApJ, 757, 117; Metzger & Berger 2012, ApJ, 746, 48, Wollaeger et al. 2017 (preprint)

8: Neutrinos and gravitational waves from core-collapse supernovae: Constraints on the supernova progenitor properties

Gravitational waves and neutrinos are the only direct messengers of the dynamics, thermodynamics, and structure of the core-collapse supernova central engine. According to the delayed neutrino explosion mechanism, the neutrino signal as well as the gravitational wave one of a core-collapse supernova carry peculiar signatures of the bouncing of the stalled shock-wave as it acquires energy to trigger the explosion (SASI sloshing motions). We plan to use the SASI imprints in the neutrino and gravitational wave signals to learn about the neutron-star properties. Detectable correlations between the neutrino and the gravitational wave signals may also give us hints about the rotation of the stellar core.

By combining the neutrino and gravitational wave signals observable in next generation detectors such as Hyper-Kamiokande and Advanced-LIGO, one could learn about the neutron star radius, the supernova bounce time and the core rotation. We will forecast the determinability of such parameters and the implications on our knowledge of the physics of the supernova progenitor.

References:

- https://arxiv.org/abs/1307.7936
- https://arxiv.org/abs/1607.05199
- https://arxiv.org/abs/0908.2317
- https://arxiv.org/abs/1402.3415
- https://arxiv.org/abs/1204.0512

Details of work: Simulation codes in various languages will be used, but mainly the student will be performing analysis. This can be done in Python.

9: Predicting Black Hole Remnant masses from Failed Supernovae

Description: A key link in the chain for population synthesis models of black hole-black hole and black hole-neutron star binaries is the remnant compact-object masses of the core collapse event. Recent work (Lovegrove & Woosley 2013) has shown that for failed core-collapse events, where the supernova shock is never revived and instead a black hole forms soon after collapse, a hydrodynamic response to the mass loss from neutrino emission can cause some of the outer envelope to be ejected from the star. In cases where this occurs, it will alter the remnant mass.

In this project the student will extend the breadth of the previous work by exploring a larger set of progenitor models, realistic neutrino luminosity histories, and several equations of state in order to find empirical relations for the amount of mass ejected, and hence, predictions of the final remnant masses.

References to familiarize with topic:

- Lovegrove & Woosley (2013); http://iopscience.iop.org/article/10.1088/0004-637X/769/2/109
- Kochanek (2015); https://doi.org/10.1093/mnras/stu2056

Details of work:

- Simulation codes in modern Fortran will be used, but only minor modification will be needed
- Most analysis can/will be done in Python

10: Short GRBs as EM counterparts of GW: formation channel studies

Short GRBs are thought to result from either binary neutron star or neutron star-black hole mergers, giving rise to some of the most luminous astrophysical events seen with either force carrier. A joint observation, in both ?-rays and gravitational waves, would give unprecedented insights about the formation environment (star formation rates, age of the stellar population, metallicity, density) and possible formation mechanisms (isolated/field, dynamical/cluster or something more exotic). We want to explore the capabilities of future observational constraints, and use these together with rate estimates from both population synthesis and current observations to put limits on the formation of sGRB progenitors.

11: Local simulations of common envelope: The bridge to binary population modeling

We believe common envelope binary interactions are a critical link in the assembly of many compact binaries ? especially those that can merge in less than a Hubble time. In this project the student will build on 'local' models of gas flow around objects that are embedded inside the common envelope gas. These models can be used to derive generalized coefficients that relate rates of orbital decay, mass accretion, and energy injection to the properties of the material that an embedded star or black hole will experience. A goal of this work is to facilitate accurate but simplified population modeling that will allow us to map binary conditions to their outcomes (including, for example, the mass and spin of a black hole) through the common envelope phase.

We will use an already well-tested application built in the FLASH, grid-based, adaptive mesh refinement hydrodynamic code. The student will run a range of models with varying binary mass ratio (and possibly envelope properties) and can study the unexplored physics of flows inside common envelope with varying mass ratio and simultaneously derive a grid of the critical inputs for simplified population modeling.

This project is suitable who are interested in learning more about grid-based hydrodynamics (with no prior experience needed for success). General Unix/Linux and basic (modern) fortran familiarity will be useful. Previous experience with cluster-scale computing will be helpful but is certainly not essential.

To learn more about this topic (and the methods that will be used) start here:
http://adsabs.harvard.edu/abs/2017ApJ...838...56M

For a sense of how the results of these simulations can be applied to modeling the common envelope phase of compact objects, see: http://adsabs.harvard.edu/abs/2015ApJ...798L..19M

12: Modeling wind capture in HMXBs: Toward understanding electromagnetic emission from precursors of the LIGO sources

An evolutionary precursor to a merging double black hole binary is a phase of separated binary where a black hole captures the stellar wind of its companion. The associated accretion luminosity makes a bright x-ray source. In fact, there are observed systems that are thought to be direct analogs of the present LIGO detections. In this project we will create detailed hydrodynamic models of the wind capture flows specialized to these particular systems. Detailed modeling of mass and angular momentum transfer during this phase is a first step toward connecting the observed systems to the gravitational wave mergers they will later produce.

We will use the Athena++ grid-based hydrodynamic code in this modeling. Experience with cluster-scale computing, general unix/linux, and c++ programming will all be helpful but any of these pieces can be learned in process.

To learn about the context for x-ray analogs to GW mergers see:
http://iopscience.iop.org/article/10.1088/0004-637X/730/2/140/meta

And to learn about simulations of wind capture in binary systems (just one example):
https://arxiv.org/pdf/1211.1672.pdf

1 13: Efficient sampling of the initial binary parameter space for population synthesis

Binary Population Synthesis (BPS) codes often sample the parameter space of binaries at formation by randomly drawing from the initial distributions. An obvious weaknesses of that choice includes potentially heavily oversampling more likely but eventually less interesting regions of the initial parameter space. One alternative that has been regularly used is evolving systems on a [quasi-]regular grid in the initial conditions, and only later applying the statistical weights appropriate for the initial distribution functions (i.e., more heavily weighting systems in the synthesised population which arose from common initial conditions). As BPS aims towards greater statistical rigour, it is desirable to:

- quantify the uncertainties in BPS which are introduced by choices of sampling methods, such that, e.g., claims based on model predictions can avoid being misled by sampling noise and optimally find rare parts of the initial parameter space with interesting outcomes
- understand which methods are more efficient in use of computer time for given problems (including for different dimensions of initial conditions)
- explore whether more modern sampling methods have clear advantages for use in BPS.

Reading:

- Numerical Recipes, 3 edition, Press, Teukolsky, Vetterling, Flannery – chapter 7.9
- Rubinstein, R. Y., & Kroese, D. P. (2011). Simulation and the Monte Carlo method (Vol. 707). John Wiley & Sons.
- Stevenson et al., Forming GW151226 and LVT151012 through isolated binary evolution. Nature Communications, 8, 14906. arXiv:1704.01352

14: Binary mergers and the nature and fate of LBVs and massive stars

Understanding the unperturbed evolution of the massive stars responsible for stellar BH formation is clearly vital for making reliable predictions of BH-BH mergers. In recent years it has been strongly suggested that the observed LBV population doesn't represent the single-star evolutionary phase which had previously been assumed (see, e.g., Smith & Tombleson 2015, 2015MNRAS.447..598S ; Smith 2016, 2016MNRAS.461.3353S). In that case the observational properties of the class appear more consistent with members produced following binary mergers or stable mass accretion. Binary mergers had already predicted that at least some merger products naturally contribute to the LBV population (see, e.g., Justham et al. 2014 2014ApJ...796..121J). However, the new observational indications that observed LBVs are dominated by binary products is far more surprising, and invites investigation. There are at least two independent but related projects which could be pursued in Copenhagen:

(a) How do near-equal-mass mergers affect predictions for populations of pair-instability supernovae? (See section 6.3 of Justham et al. 2014 for a mostly qualitative discussion.) This is a well-defined and self-contained project, and should be publishable given sufficient stellar calculations and analysis.

(b) Is there a structural or evolutionary reason why binary mass gainers or mergers might be more likely to exhibit LBV outbursts than single stars of the same mass? A full answer to this is unlikely during the Summer Program. However, one of the possible avenues to investigate is that single stars do exhibit LBV phases, just spend such little time in that phase that their presence is suppressed in our current samples; that possibility might reasonably be explored and published.

15: The effects of formation environment on the properties of massive binaries

In crowded birth environments of stars, close encounters may be relatively common. Such encounters will sculpt the properties of the binary population. For example, more massive stars will exchange into binaries, with the stars being left on more bound, and possibly more eccentric, orbits. Collisions between one of the binary components and an incoming star may even occur.

In this project the student will investigate quantitatively how such encounters change the population of binaries containing stars that subsequently evolve into neutron stars and black holes. It may well be that these encounters have a significant effect on the merger rate of binary black holes.

As a first step, the student will populate a region of open cluster density with a reasonable initial stellar and binary population and investigate the rates of encounters between stars and binaries. Along with some prescriptions as to outcome that will allow us to identify which processes are most important, e.g. exchanges vs triple formation, and how the expected rates compare to stellar evolution and cluster dissolution timescales.

An extension to this would be to use N-body calculations to investigate the behaviour of the few-star objects that we form in more realistic simulations: either using N-body6 to model clusters of a few hundred stars or Monte-Carlo models of larger stellar clusters.

Some key papers:

- Malmberg et al., 2007, Close encounters in young stellar clusters: implications for planetary systems in the solar neighborhood, MNRAS, 378, 1207
- Miller, 2016, Implications of the gravitational wave event GW150914, General Relativity & Gravitation, 48, id. 95
- Parker, Church, Davies, Meyer 2014, Supernova enrichment and dynamical histories of solar-type stars in clusters MNRAS, 437, 946,
- Rodriguez et al., 2016, Dynamical Formation of the GW150914 Binary Black Hole, ApJ, 824, L8

16: Binary-Binary interactions with General Relativistic (GR) effects included in the N-body equation-of-motion

Recent studies suggest that binary-binary black hole (BH) interactions occur frequently in globular cluster (GC) systems. Common for such four-body interactions is that they are highly chaotic, which occasionally lead to very close encounters between two of the four interacting BHs. Studies of chaotic binary-binary scatterings have so far only been performed using standard Newtonian equations, however, recent work on the related three-body problem have shown that General Relativistic (GR) force terms actually play an important role for the formation of BH mergers. The most important effect from GR relates to the formation of two-body GW captures forming as a result of gravitational wave (GW) emission. In the three-body case it has been shown that such GW capture mergers appear in the LIGO band with a particular high eccentricity, however, no study has been performed on the eccentricity distribution of BH mergers forming during four-body interactions. A key question here is if the resultant eccentricity distribution looks different from BH mergers forming through competing channels. The first part of the project will be to understand how GR corrections affect the distribution of BH mergers forming during binary-binary interactions, where the second part will focus on deriving an actual observable LIGO rate using merger trees from state-of-the-art GC simulations.

17: Few-body interaction near super-massive black-holes

Theoretical studies suggest that stellar mass black holes might exist and interact in active galactic nuclei (AGN) discs near super massive black holes (SMBHs). Such interactions will either take place throughout the disc during BH migration, or in so-called migration traps where BHs can pile up as a result of gas toques cancelling out. If more than two BHs are interacting, the dynamics is likely to be highly chaotic, which generally leads to the formation of a BH merger that could be detected by LIGO. This channel for producing BH mergers has recently been proposed, but no actual dynamical interactions have been performed yet. In this project the student will perform few-body scatterings between BHs in AGN discs with the main goal of exploring if such mergers have different observable characteristics than BH mergers forming in other dynamical environments such as globular clusters. The first step of the project will be to understand what force terms that are relevant for the problem; do we need tidal forces from the SMBH and dynamical drag from the gas disc? The second step will be to perform a range of BH scatterings and derive orbital elements of the merging BHs to see if the resultant distribution is different from the one formed in e.g. clusters. A range of other exotic outcomes can also be studied, including double-GW-mergers and scattering of BHs into the SMBH. This study has major implications for distinguishing the proposed GW merger channels.

18: Low angular momentum leading to black hole assembly in LIGO progenitors

LIGO BHs are probably produced by direct collapse, when the entire star at the end of its life collapses to form the BH. This is appealing because you can form large BHs without invoking very rare, significantly more massive stars. This collapse should lead to a quasi-spherical accretion in order for feedback to not be too damaging. The binding energy of the star is much lower than that of the resulting BH by a factor of $(v_{esc}/c)^2 \sim 1/10^6$), which implies that a small amount of feedback could help unbind the star and prevent the formation of a massive BH. This outs severe constraints on the angular momentum content of the star as well as on the resultant spin of the BH.

The tasks within this project will be to compute the slowly-rotating quasi spherical collapse with changing black hole spin and mass. The numerics will be based on the HARM-2D computational code, for GR hydrodynamical simulations. This will also be supplied with the initial conditions with a more realistic density profile, as results from the stellar evolutionary model. Discussion will focus on the effects of varying the angular momentum content in the collapsing progenitor, derived using stellar evolution models.

Literature:

- Gammie, McKinney & Toth, 2003, ApJ, 589, 444
- Gammie, Shapiro & McKinney 2004, ApJ, 602, 312
- Lee & Ramirez-Ruiz 2006, ApJ, 641, 961
- Janiuk, Moderski & Proga, 2008, ApJ, 687, 433
- Janiuk, Mioduszewski & Moscibrodzka, 2013, ApJ, 776, 105

19: The luminosity function of macronovae

The detection of an electromagnetic counterpart to a gravitational wave source will be a watershed moment for this new field. Our current follow-up strategies are based on basic theoretical models and scant observational data. Here, we will use observations of short GRBs to constrain the properties of the population of possible isotropic emission associated with binary neutron star/neutron star black hole mergers. The population demographics will then constrain the possible physical parameters (e.g., ejecta masses and velocities), potentially the involved nuclear physics (mass formula, nuclear heating rates) and inform observational strategies (e.g., filter choices, cadence).

20: Testing Compact Binary Formation Models with Supernova Observations

Predicting the characteristics and formation rate of the compact binaries detected by advanced LIGO relies on population synthesis models incorporating uncertainties in stellar evolution, supernova explosions and binary evolution. Without constraining the errors, the uncertainties on the merging systems detected by aLIGO can be large. We can place limits on many of the errors by comparing these population studies to other products of binary star evolution including binary pulsars, X-ray binaries, and a broad range of supernova types. In this project, we will test binary models against supernova observations to both better constrain the uncertainties in population synthesis and better understand the progenitors of supernovae.