Key Points in Papers:

Pian E., 2021 - Mergers of Binary Neutron Star Systems: A Multi-Messenger Revolution

- Expected to open an effective window into the study of astrophysical sources that is not limited to exceptionally close (the Sun) or rare (Galactic supernova) events.
- GW170817: Accompanied by short gamma-ray burst (GrB) and afterglow, and its thermal aftermath ("kilonova")
- Kilonova is the characteristics optical and infrared source accompanying a binary neutron star merger, and due to the radioactive decay of many unstable isotopes of large atomic weight elements synthesised via rapid neutron capture in the promptly formed dynamical ejecta and in the delayed post-merger ejecta.
- S2: NS represent about 0.1% of the total stellar content of a galaxy. Since massive stars are mostly in binary systems (Sana et al., 2012), neutron star binaries should form readily, if the supernova explosion of either progenitor massive star does not disrupt the system (Renzo et al., 2019).
- BNS systems can form dynamically in dense environments like stellar clusters (Ye at al., 2020). NS & BH are also viable but rare (Pfahl et al., 2005)
- Shrinking binary system orbit: signalled by the secular decrease of the 7.75 hours orbital period, that could be entirely attributed to energy loss via gravitational radiation (Taylor & Weisberg, 1982; Weisberg & Huang, 2016)
- The local merger rate density is 250-2810 /Gyr^3 / yr (Abbott et al., 2020a)
- The merger of a binary neutron star system has four predicted outcomes:
    1. A gravitational wave signal that is mildly isotropic, with a stronger intensity in the polar direction than in the equatorial plane
    2. A relativistic outflow, which is highly anisotropic and can produce an observable high energy transient
    3. A thermal, radioactive source emitting most of its energy at ultraviolet, optical and near-infrared wavelengths
    4. A burst of MeV neutrinos (Eichler et al., 1989; Rosswog & liebendorfer, 2003) following the formation of the central remnant, and possible of high-energy (>GeV) neutrinos from hadronic interaction within the relativistic jet (Fang & Metzger, 2017; Kimura et al., 2018).
- The first three observables have been now all detected.
- The time behaviour of binary systems of compact stars consists of three phases:
    1. Inspiral phase: in a close orbit that shrinks as gravitational radiation of frequency proportional to the orbital frequency is emitted
        a. The amplitude of the sinusoidal gravitational signal rapidly increases as the distance between the two bodies decreases and the frequency increases (chirp)
    2. Merger phase: where a remnant compact body is produced as a result of the coalescence of the two stars,
    3. Post-merger, or ringdown phase where the remnant still emits gravitational radiation while settling to its new stable configuration
        a. The signal is an exponentially damped sinusoid.
        b. This final phase may encode critical information on the equation of state of the newly formed remnant (a black hole, or in the case of light neutron stars, a massive neutron star or metastable supermassive neutron star.
    4. The mathematical tool that is used to describe this evolution is the waveform model that aims at reproducing the dynamics of the system through the application of post-Newtonian corrections of increasing order and at a providing the essential parameters that can then be compared with the interferometric observations (Blanchet, 2014; Nakano et al., 2019)
    5. Since the amplitude of gravitational waves depends on the masses of the binary member stars, the signal will be louder and thus detectable from larger distances, for binary systems that involve black holes than those with neutron stars. The current horizon for binary neutron star merger detection with LIGO is about 200 Mpc, and 25-30% smaller with Virgo and KAGRA (Abbott et al., 2018).
        1. The dependence of the gravitational waves amplitude on the physical parameters of the system implies that gravitational wave sources are standard sirens (Schutz, 1986), provided account is taken of the correlation between the luminosity distance and the inclination of the orbital plane with respect to the line of sight (Nissanke et al., 2010; Abbott et al., 2016)

Short Gamma-Ray Bursts

1. Subsecond GRBs are produced by the merger of two neutron stars or a NSBH
2. The duration distribution is bimodal, with a peak around 0.2 s for short or sub second GRBs
3. About 140 short GRBs were localised so far to a precision that is better than 10 arc-minutes, of these, there was a detected afterglow in:
    1. ~100 X-rays
    2. ~40 optical
    3. ~10 radio wavelengths
4. Short GRBs are located at projected distances of a fraction of, to several kilo parsecs from, the centres of their host galaxies, which are of both early and late type, reflecting the long time delay between the formation of the short GRB progenitor binary systems and their mergers (Berger, 2014)
5. According to the classical fireball model, both prompt event and multi wavelength afterglow of short GRBs are produced in a highly relativistic jet directed at a small angle with respect to the line of sight, whose aperture can be derived form the achromatic steepening (or "jet break") of the observed afterglow light curve (Nakar, 2007). In principle, this could be used to reconstruct the collimation-corrected rate of short GRBs, to be compared with predictions of BNSM rates. However, these estimates provide to be very uncertain, owing to the difficulty of measuring accurately the jet breaks in short GRB afterglows

R-Process Nucleosynthesis

1. Elements heavier than iron cannot form via stellar nucleosynthesis, as not enough neutrons are available for the formation of nuclei and temperatures are not sufficiently high to overcome the repulsive Coulomb barrier that prevents acquisition of further baryons into nuclei (Burbidge et al., 2957).
2. Supernovae (especially the thermonuclear ones) produce large amounts of iron via decay (through 56Co) of radioactive 56Ni synthesised in the explosion. Heavier nuclei form via four neutron capture process (Thielemann et al., 2011), the dominant ones being slow and rapid neutron capture, in brief s- and r-process, where "slow" and "rapid" refer to the timescale of neutron accretion into the nucleus with respect to that of the competing process of beta-decay. In the s-process, neutron captures occur with timescales of hundreds to thousands of years, making beta- decay highly probable, while r-process neutron capture occurs on a timescale of ~0.01 s, leading to acquisition of many neutrons before beta- decay can set on.
3. As a consequence, the s-process producers less unstable, longer-lived isotopes, close to the so-called valley of beta-stability (the decay time of a radioactive nucleus correlates inversely with its number of neutrons), while the r-process produces the heaviest, neutron-richest, and most unstable isotopes of heavy nuclei, up to uranium.
4. The r-process requires much higher energy and neutron densities, which are only realised in most physically extreme environments. While it can be excluded that big-band nucleosynthesis can accommodate heavy elements formation in any significant amount, there is currently no consensus on the relative amounts of nucleosynthetic yields in the prime r-process candidate sites: core-collapse supernovae and mergers of binary systems composed by neutron stars or a NSBH.
5. The tidal disruption of neutron stars by black holes in close binaries and coalescences of binary neutron star systems could be at the origin of r-process nucleosynthesis. This should manifest as a thermal optical-infrared source of radioactive nature of much lower luminosity (a factor of 1000) and shorter duration (rise time of a few days) than supernova.
6. August 17, 2017 event has now provided incontrovertible evidence that binary neutron stars host r-process nucleosynthesis
7. Neutrons are tightly packed together in neutron stars, but during coalescence of a binary neutron star system the tidal forces disrupt them and the released materials forms promptly a disk-like rotating structure (dynamical ejecta, Rosswog et al., 1999; Shibata and Hotokezaka, 2019) where the neutron density rapidly drops to optimal values for r-process occurrence ($\sim 10^{24-32}$ neutrons cm^{-3}, Freiburghaus et al., 1999) and for copies formation of neutron-rich stable and unstable isotopes of large atomic number elements.

The Binary Neutron Star Merger of 17 August, 2017

1. First detection of a gravitational signal that corresponds to the final inspiral and coalescence of a binary neutron star system (Abbott et al., 2017a).
2. The sky uncertainty area associated with the event was 28 square degrees, in principle too large for a uniform search for an electromagnetic counterpart with ground-based and orbiting telescopes. However, its small distance (40^{+8}_{-14} Mpc), estimated via the "standard siren" property of gravitational wave signals associated with binary neutron star mergers, suggested that the aftermath could be rather bright and motivated a large-scale campaign at all wavelengths from radio to very high energy gamma-rays, which was promptly and largely rewarded by success and then timely followed by a long and intensive monitoring.
3. No MeV-to-EeV neutrinos detected
4. Based on the detection of electromagnetic radiation (Bauswein et al., 2017) have argued that the merger remnant may not be a black hole or at least the postmerger collapse to a black hole may be delayed.
5. The gravitational data made it possible to set an upper limit on the tidal-deformability parameter of the binary neutron stars ($\tilde{\Lambda} \lesssim 800$, Abbott et al., 2017a), the optical observation of kilonova ejected limited the same parameter from below ($\tilde{\Lambda} \gtrsim 400$, Radice et al., 2018), based on the consideration that for smaller values of \tilde{\Lambda} a long-lived remnant would not be favoured.
6. The limits constrain the neutron star radius to the range 11.8 km $\lesssim R_{1.5} \lesssim 13.1$ km, where $R_{1.5}$ refers to a $1.5 M_{\odot}$ neutron star (Burgio et al., 2018), and in turn confine the possible ensemble of viable equations of state (Annala et al., 2018; Lim and Holt, 2018), a fundamental, yet poorly known, descriptor of neutron star physics (Ozel and Freire, 2016).
7. Furthermore, by circumscribing the number of equations of state of the compact stars, their exploration can be brought beyond nucleonic matter and extended to scenarios of matter presenting a phase transition.
8. The results on the tidal deformability of the neutron star progenitors of GW170817 and on the behaviour of the remnant thus provide a brilliant confirmation of the added value of a multi messenger approach over separate observations of individual carriers of information.
9. The gamma-ray transient GRB170817A, whose large error box was compatible with that determined by LIGO-Virgo, lags the gravitational merger by 1.7 s, a delay that may be dominated by the propagation time of the jet to the gamma-ray production site.
10. About 70 ground-based optical telescopes participated in the hunt and each of them adopted a different pointing sequence.
11. The optical sources lies at 10 arc-second angular separation, corresponding to a projected distance of ~ 2 kph, from the centre of the spheroidal Galaxy NGC 4993 at 40 Mpc (lots of refs)
12. The afterglows from misaligned GRB jets have longer rise times than those of jets observed at small viewing angles. X-rays detected ~ 10 days after merger, whose intensity continued to rise up to ~100 days. Cm and mm wavelengths failed to detect the source before ~16 days after the GW signal. Thus, evidence that a jetted source accompanying the binary neutron star merger must be directed at a significant angle ($\geq$20º) with respect to the line of sight (lots of refs)
13. While the radio and X-ray detections are attributed to the afterglow of the short GRB, the ultraviolet, optical, and near-infrared data are dominated by the kilonova at early epochs (with a possible contribution at $\lesssim$ 4 days at blue wavelengths from cooling of shock-heated material around the neutron star merger, and later on by the afterglow.
14. Hypothesis that the GRB was produced by a relativistic jet viewed at a comparable angle. However, the early light curve of the radio afterglow is not consistent with the behaviour predicted for an off-axis collimated jet and rather suggests a quasispwerical geometry, possible with two components, a more collimated one and a nearly isotropic and mildly relativistic one, which is responsible for producing the gamma-rays (Mooley et al., 2018a).
15. The shocked cloud surrounding a binary neutron star merger forms a middle relativistic cocoon that carries an energy comparable to that of the jet and is responsible for the prompt emission and the early multi wavelength afterglow.
16. Superluminal motion detected with $\beta = 3 - 5$.

17. At 207 days, the source is still angularly smaller than two milliarcseconds at the 90% confidence, which excludes that a nearly isotropic, mildly relativistic outflow is responsible for the radio emission.
18. These observations point to a structured jet as the source of GBR170817A. The late-epoch flux is not consistent with kilonova emission and is rather due to the afterglow produced within an off-axis structured jet (Fong et al., 2019).
19. The decay is not fully compatible with a structured jet, indicating that the physical conditions have changed or that an extra component is possibly emerging (e.g. a non thermal aftermath of the kilonova ejecta)

The Kilonova

1. The spectrum at day 1.5 shows an absorption feature extending from ~7,000 to 8,100 $\mathring{A}$ is detected. Preliminary identification of atomic transitions occurring in neutral Cs and Te, broadened and blue shifted by ~0.2c, consistent with the expansion velocity of the photosphere. May have been disproven.
2. The absorption features can be identified with Sr II. Develops a P Cygni profile.
3. Strontium is very abundant element and is produced close to the first r-process peak. Its possible detection makes it important to consider lighter r-process elements in addition to the lanthanides in shaping the kilonova emission spectrum (Watson et al., 2019)

The Host Galaxy of GW170817

1. The host Galaxy, NGC 4993, is a lenticular (S0) Galaxy at z=0.009783 that has undergone a recent (~1 Gyr) galactic merger (Levan et al., 2017; Palmese et al., 2017).
2. This merger may be responsible for igniting weak nuclear activity.
3. No globular or young stellar clusters are detected at the location of GW170817.
4. The distance of NGC 4993 was determined to be 41.0 ± 3.1 Mpc (Hjorth et al., 2017).
5. Combining this with the recession velocity measured from optical spectroscopy of the Galaxy, corrected for peculiar motions, returns a Hubble constant of $H_0 = 71.9 \pm 7.1$ km s^{-1} Mpc^{-1}.
6. Based only on the gravitational data and the standard siren argument and assuming that the optical counterpart represents the true sky location of the gravitational-wave source instead of marginalising over a range of potential sky locations, Abbott et al., 2017d determined a "gravitational" distance of $43.8^{+2.9}_{-6.9}$ Mpc. Together with the corrected recession velocity of NHC4993, this yields a Hubble constant $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}, comparable to, but less precise than, that obtained from the superluminal motion of the radio counterpart core, $H_0 = 70.3^{+5.3}_{-5.0}$ km s^{-1} Mpc^{-1} (Hotokezaka et al., 2019)

Kilonova Light Curve and Spectrum

1. The unstable isotopes formed during coalescence of a binary neutron star system decay radioactively and the emitted gamma-ray photons are downscatteeed to the ultraviolet, optical, and infrared thermal radiation that constitutes the kilonova source.
2. If the neutron stars coalescence does not produce instantaneously a black hole and a hyper massive neutron star is formed as a transitory remnant, a neutrino wind is emitted that may inhibit the formation of neutrons and reduce the amount of neutron-rich elements (lost of refs).

Summary & Future Prospects

1. The gravitational and electromagnetic event of August 17, 2017, provided the long-awaited confirmation that binary neutron star mergers are responsible for well identifiable gravitational signals at kHz frequencies, for short GRBs, and for thermal sources, aka kilonovae or macro novae, produced by the radioactive decay of unstable heavy elements synthesised via r-process during the coalescence.
2. The many findings and exceptional new physical insight afforded by GW170817/GRB170817A make it a *rosetta stone* for future similar events. When a sizeable group of sources with good gravitational and electromagnetic detections will be available, the properties of binary systems containing at least one neutron star, of their mergers and their aftermaths, can be mapped.
3. It will then become possible to clarify
    1. how the dynamical ejected mass depends on the binary system parameters,
    2. mass asymmetry,
    3. and neutron stars equation of state (Ruffert and Janka 2001; Hotokezaka et al., 2013),

    4. how the jet forms and evolves, which kinematic regimes and geometry it takes up in time, and
    5. how the GRB and afterglow observed phenomenologies can help distinguish the intrinsic properties from viewing angle effects (lost of refs),
    6. what the detailed chemical content of the kilonova ejecta is and
    7. how the r-process abundance pattern inferred from kilonova spectra compares with the history of heavy elements cosmic enrichment (Rosswog et al., 2018),
    8. how kilonovae can help constrain the binary neutron star rates and
    9. how the parent population of short GRBs evolves (lots of refs), and
    10. how gravitational and electromagnetic data can be used jointly to determine the cosmological parameters (lots of refs).
4. Regrettably, short GRBs viewed at random angles, and not pole on, are relativistically beamed away from the observer direction and kilonovae are intrinsically weak. These circumstances make electromagnetic detections very difficult if the sources lie at more than ~100 Mpc, as proven during the third and latest observing run (Apr 2019 - Mar 2020) of the gravitational interferometers network.
    1. In this observing period, two merger events possibly involving neutron stars were reported by the LIGO-Virgo consortium: GW190425, caused by the coalescence of two compact objects of masses each in the 1.12 - 2.52 $M_\odot$ at ~160 Mpc (Abbott et al., 2020a), and HW190814, caused by a 23 $M_\odot$ black hole merging with a compact object of 2.6 $M_\odot$ at ~ 240 Mpc (Abbott et al., 2020b).
    2. In neither case did the search for an optical or infrared counterpart return a positive result owing presumably to the large distance and sky error areas
5. Note: All coalescing stars may have been black holes, as the neutron star nature of the binary members lighter than 3 $M_\odot$ could not be confirmed
6. The search for electromagnetic counterparts of gravitational radiation signals is currently thwarted primarily by the large uncertainty of their localisation in the sky, which is usually no more accurate than several dozens of square degrees.
7. Much smaller error boxes are expected to be available when the KAGRA and the INDIGO interferometers will operate at full regime (more interferometers = better localisation)
8. Gravitational waves from binary neutron star inspires and mergers; gamma-ray photons —downscatteeed to UV/optical/infrared light— from radioactive decay for unstable nuclides of heavy elements, freshly formed after the merger; multi wavelength photons from non thermal mechanisms in the relativistic jet powered by the merger remnant; and thermal and high-energy neutrinos accompanying the remnant cooling and hadronic processes in the jet, respectively, all collectively underpin the role of the four physical interactions.
9. This fundamental role of compact star merger phenomenology thus points to the formidable opportunity offered by a multi messenger approach: bringing the communities of astrophysicists and nuclear physicists closer will foster corse-fertilisation and interdisciplinary coordination that is not only beneficial but also essential for progress in this field.

Summary:

The article discusses the significant findings from the detection of the binary neutron star merger event GW170817. This event, detected on August 17, 2017, marked a milestone in multi messenger astronomy by providing comprehensive data across various wavelengths and signals, including gravitational waves, gamma-ray bursts, and electromagnetic counterparts.

Enhancement of Interferometers and Detection of Binary Neutron Star Mergers:
* **Gravitational Wave Detection:** The article emphasises the importance of gravitational wave observations in detecting binary neutron star mergers. The detection of GW170817 by LIGO and Virgo provided critical insights into the gravitational wave signal emitted during such mergers. Enhancing current interferometers to improve sensitivity, especially in the 2-4 kHz band, could significantly increase the detection rate of these events.

Refinement of Neutron Star Equations of State:
* **Neutron Star Equations of State:** The ringdown phase of the gravitational wave signal from a neutron star merger contains information about the equation of state of the neutron star material. The detection and analysis of the 2-4 kHz band signals can refine these models by providing data on the behaviour of matter at extreme densities and pressures.

Probing Non-Light-Emitting Celestial Objects:
* **Non-light-emitting Objects:** The article highlights the value of gravitational waves as a probe for non-light-emitting celestial objects, such as neutron stars and black holes. Unlike electromagnetic observations that rely on light emission, gravitational waves offer a direct way to study these objects' dynamics and properties.

Importance of the 2-4 kHz Band:
* **Signal Frequency and Mass Relationship:** The frequency of the gravitational wave signal is related to the mass and dynamics of the merging objects. The 2-4 kHz band is crucial because it corresponds to the frequencies emitted during the merger and ringdown phases. Enhancing detectors to better capture these frequencies could provide more detailed information about the mass and internal structure of the merging neutron stars.

Methodological Advances:
* **Interferometer Design:** The article discusses the use of advanced interferometer designs like LIGO and Virgo, which have successfully detected gravitational waves from binary neutron star mergers. Future improvements and new detectors such as the proposed Cosmic Explorer (CE), aim to enhance sensitivity and broaden the observable frequency range.

Broader Implications:
* **Cosmic Nucleosynthesis:** The detection of the kilonova associated with GW170817 provided insights into the nucleosynthesis of heavy elements through the r-process. This process, occurring during neutron star mergers, contributes to the formation of elements heavier than iron, highlighting the broader astrophysical implications of these events.

Expansion Directions:
To expand my thesis further in an astrophysical context, consider delving into the following areas:
* Detailed analysis of current and proposed neutron star equation of state models.
* Mathematical modelling of gravitational wave signals in the 2-4 kHz band
* Advanced interferometer technologies and their potential improvements
* Multi-messenger observations and their role in understanding cosmic events.
* Theoretical implications of high-frequency gravitational wave signals for dark matter detection.

G.F. Burgio - Neutron Stars and the Nuclear Equation of State

- Review the current status and recent progress of microscopic many-body approaches and phenomenological models, which are employed to construct the equation of state of neutron stars.
- The equation of state is relevant for the description of their structure and dynamical properties, and it rules also the dynamics of core-collapse supernovae and binary neutron star mergers.
- Compare the theoretical predictions of the different equation-of-state models with the currently available data coming from other terrestrial laboratory experiments and recent astrophysical observations.
- Also analyses the importance of the nuclear strong interaction and equation of state for the cooling properties of neutron stars

- Beneath a thin stellar atmosphere, a NS interior consists of three main layers, i.e. an outer crust, an inner crust, and a core, each one characterised by different physical conditions
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K. Ackley - Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network

- The late inspired is influenced by the presence of tides, which depend on the neutron star equation of state
- The signature of nuclear matter in gravitational waves contains most information in the 2-4 kHz frequency band, which is outside the most sensitive of current detectors.
- Such sensitivity changes expected event rates for detection of post-merger remnants from approximately one per few decades to a few per year and potentially allow for the first gravitational-wave observations of supernovae, isolated neutron stars, and other exotica
- Detection of many gravitational wave signals from binary black hole collisions (Abbot et al., 2019a) leading to an enhanced understanding of their population properties (Abbott et al., 2019d), measurement of the Hubble parameter (Abbott et al., 2017d; Hotokezaka et al., 2019), unprecedented tests of Einstein's theory of General Relativity, including constraints on the speed of gravity (Abbott et al., 2017e) and hence the mass of the graviton (Abbot et al., 2017b; 2019b).
- Advanced LIGO (aLIGO, A+), will increase the sensitivity of the current detectors by a factor of 203 dependent on the specific frequency of interest (Miller at al., 2015).
- Research and development is ongoing for third-generation observatories, the Einstein Telescope (Punter et al., 2010a) and Cosmic Explorer (Abbot et al., 2017a): broad-band instruments with capabilities of hearing black hole mergers out to the dawn of the Universe.
- Third-generation observatories require substantial, global financial investments and significant technological development over many years. To bridge the gap between A+ and full-scale third-generation instruments, it is necessary to explore smaller-scale facilities that will not only produce significant astrophysical and fundamental physics outcomes but will simultaneously drive technology development.
- Neutron stars are an end of state of stellar evolution. They consist of the densest observable matter in the Universe and are believed to consist of a superfluid, superconducting core of matter at supranuclear densities
- Such conditions are impossible to produce in the laboratory, and theoretical modelling of the matter requires extrapolation by many orders of magnitude beyond the point where nuclear physics is well understood.
- As two neutron stars coalesce, their composition leaves an imprint on the gravitational waveform, which becomes increasingly important at higher frequencies ~0.4-4 kHz
- Mergers produce remnants, some of which collapse to black holes, and some of which survive as long-lived, massive neutron stars.
- Up to approximately 79% of all binary neutron strands mergers may produce massive neutron star remnants that emit strong gravitational wave signatures (Margalit & Metzger, 2019).
- The precise nature of the remnant is strongly dependent on the details of nuclear physics which is encoded in the neutron star equation of state (e.g. see Bernuzzi 2020, and references therein)
- Measuring gravitational waves at these high frequencies therefore offers a window into the composition of neutron stars, not accessible with other astronomical observations or terrestrial experiments.
- Figure 1 shows the predicted characteristic gravitational wave strain, h_c, for a typical binary neutron star inspiral, merger, and post-merger at 40 Mpc, the same distance as the first binary neutron star merger detection GW170817.
- Tidal effects during the inspiral become prominent around 500 Hz and above, while the post-merger signal is above 1 kHz.
- Simultaneously achieving high sensitivity at low (below 50 Hz) and high (above 1 kHz) frequencies in a single detector is extremely challenging. First, the optical bandwidth of high-sensitivity kilometre-scale detectors is limited. Thus, to achieve sensitivity peaked at ~2 kHz requires a loss of optical sensitivity of below 500 Hz. Secondly, the high-circulating power required to improve high-frequency sensitivity introduces optic-mechanical instabilities whose control strategies can easily increase the noise in the low-frequency band.
- This detector will only concentrate on the frequency regime above around 1 kHz, sacrificing low-frequency sensitivity and thereby decreasing engineering challenges and cost. The low-frequency sensitivity required for sky localisation will be achieved by the other detectors in the network.
- Martynov et al 2019 have shown that the optimal length of a detector with optimum sensitivity at 2 kHz is 16 km.

- The high-frequency sensitivity of interferometric gravitational-wave detectors is predominantly limited by quantum phase noise, which is due to the quantum nature of light, and not displacement noise sources such as seismic and thermal. Increasing the circulating power within the detector reduces the impact of this quantum noise proportional to the inverse of the square root of the power (Martynov et al., 2019). Therefore, to maximise sensitivity, the circulating power in the arms must be as large as possible.
- This quantum phase noise source can also be reduced by injecting squeezed vacuum into the dark port (Aasi et al., 2013).
- The quantum phase noise limited nature of high frequency interferometers means that there are unlikely to be significant advantages in using exotic interferometer types such as speed metres (Chen 2003) or other Sagnac style interferometers (Mizuno et al., 1997). For this reason, we choose a dual-recycled Michelson interferometer design with Fabry-Perot arm cavities, similar to current interferometric gravitational-wave detectors (Aasi et al, 2015; Acernese et al., 2015; Also et al., 2013). However, there are some key differences targeted to maximise the sensitivity in the 1-4 kHz signal band of interest.
- The signal-recycling cavity and the arm cavity of the interferometer form a coupled cavity system which determines the overall bandwidth of the interferometer.
- This 'long' signal-recycling cavity displays the characteristic splitting of a coupled cavity system (McClelland 1995; Martynov et al., 2019) around the interferometer carrier frequency where the gravitational-wave signal sidebands are resonantly enhanced.
- Experience with current gravitational-wave detectors has shown that otto-mechanical instabilities arise when operating with high-circulating powers, such as parametric instabilities (Evans et al., 2015b) and angular misalignment (Sidles & Sign 2006; Hirose et al., 2010). The high-circulating power inside the arm cavities could make the detector quite sensitive to otto-mechanical instabilities. However, this is where the dedicated high-frequency nature of the detector really comes onto its own. In the case of angular instabilities, the bandwidth of the angular control loops can be significantly increased beyond what can be used for broadband detectors.
- To motivate the science case, we discuss physics encoded in the kilohertz gravitational-wave emission during both the inspiral and post-merger phases of a binary neutron star merger. These two phases probe different temperature regimes of the neutron star equation of state.
- During inspiral, neutron stars are relatively cold with temperatures less than 10^9K, having had sufficient time to cool since birth. Under such conditions, the temperature does not significantly affect internal physical structure that determines bulk stellar quantities such as the stellar radius. Temperatures during merger can reach as high as $T \sim 10^{11}$ K (e.g. Baiotti, Giacomazzo, & Rezzolla 2008; Foucart et al., 2016) and can therefore affect the equation of state.
- For cold neutron neutron stars in the pre-merger phase, the tidal deformation of the individual components is imprinted in the gravitational wave emission. The tidal deformation is dependent on the equation of state and is parametrised by the 'combined dimensionless tidal deformability' $\tilde{\Lambda}$, given by: $\tilde{\Lambda} \equiv \frac{16}{13} \frac{\left(m_1 + 12m_2\right) m_1^4 \Lambda_1 + \left(m_2 + 12m_1\right) m_2^4 \Lambda_2}{\left(m_1 + m_2\right)^5}$
  - Here m_1 and m_2 are the masses of the component neutron stars and Λ_1 and Λ_2 are the tidal deformability's of each neutron star defined as: $\Lambda_i \equiv \frac{2k_{2,i}}{3} \left(\frac{c^2 R_i}{G m_i}\right)^5$
    - Where R is the radius and k_2 is the second Love number, which measures the rigidity of the neutron star.
- Gravitational-wave astronomers measure $\tilde{\Lambda}$ because it is the leading-order correction to gravitational waveforms due to tides.
  - For a fixed mass, both R and k_2 are determined by the neutron star equation of state. Small values of Λ imply soft equations of state, corresponding to small, compact neutron stars. Large values of Λ imply stiff equations of state, where neutron stars are large and comparatively fluffy. Black holes have $k_2 = 0$, implying the tidal deformability also vanishes.
- A key goal in nuclear astrophysics is to measure the tidal deformability as a function of neutron star mass. These tidal effects become increasingly important when the two neutron stars are

close to one another, which occurs late in coalescence and therefore at kilohertz gravitational-wave frequencies.

- With the noise amplitude curves and gravitational-wave characteristic strain from the inspiral and post-merger phase of an equal-mass binary neutron star coalescence at 40 Mpc, the expected signal-to-noise ratio ρ is simply as (e.g., Moore, Cole & Berry 2015):
$$\rho^2 = \int_{-\infty}^{\infty} d \ln f \left(\frac{h_c(f)}{h_n(f)} \right)^2$$
- Tidal effects become important at frequencies $\gtrsim 400$ Hz (Harry & Hinderer 2018); at that point, the gravitational waveforms describing a binary black hole system and a binary neutron star system begin to dephase.
- For Monte Carlo simulations, we chose $\rho_{mf} > 20$, as signals weaker than this do not contribute appreciably to the cumulative inference of the equation of state (Hernandez Vivanco et al., 2019)
  - Our injections are performed using an SLy equation of state (Douchin & Haensel, 2001). We reconstruct the equation of state following the procedure outlined in Lackey & Wade 2015 and Hernandez Vivanco et al 2019.
- in general, equation of state constraints such as those presented in this section are complementary to those using other methods such as X-rays and radio observations of isolated and accreting neutron stars (see Lattimer & Prakash 2007, for a review) and observations of post-merger remnants.
- Following the merger of two neutron stars, a new compact object is created. Depending on the remnant mass, this compact object can be a black hole or a massive neutron star. In the former case, gravitational-wave emission is difficult to observe because of the relatively short damping time and high frequency $\gtrsim$ 6 kHz (Echeverria 1989). However, if a neutron star survives the merger, gravitational waves can be emitted at frequencies of ~ 1-4 kHz for up to hundreds of milliseconds (Baiotti et al 2008; Shibata & Taniguchi 2006).
- The spectral content of the post-merger gravitational waves contains information about the neutron star equation of state (Takami, Rezzolla & Baiotti 2015).
- Following the merger, the temperature becomes an important equation of state parameter. For example, temperature-dependent phase transitions may occur in the core of post-merger neutron stars. Measuring gravitational waves from the inspiral and post-merger phase could provide a unique opportunity to identify phase transitions from hadronic matter to deconfined quark matter (Bauswein et al., 2019).
- Furthermore, as the remnant is supported by differential rotation, the resulting neutron star in the post-merger phase has a higher density than the component neutron stars from the pre-merger phase. Thus gravitational wave emission from the post merger phase affords the opportunity to probe the equation of state in a different density regime.
- The precise signal morphology of neutron star post-merger gravitational waves remains unknown. However, numerical simulations have shown that the spectra of the emission from the nascent neutron star contain a characteristic peak frequency, approximately related to the fundamental quadrupolar mode of that neutron star and lower-frequency peaks (e.g. Bausein & Stergioulas 2015, and references therein)
- Since the natural timescales for neutron star physics is $\mathcal{O}$(1 ms), the frequency of gravitational waves from binary neutron star mergers is well matched to our detector.
- The direct measurement of the effects of matter in binary neutron stars will facilitate additional science, for example, breaking degeneracies in measurements of the Hubble flow (Messenger & Read 2012; Calderon Bustillo, Dietrich & Lasky 2020), helping to distinguish between neutron stars and black holes (e.g. Fasano et al., 2020) and any potential cosmological effects on the equation of state (e.g. Haster et al., 2020).
- The operation of a new detector in a heterogeneous gravitational wave network with two A+ interferometers will allow an unprecedented view into the hearts of short gamma ray bursts.
- Additional sources *may* be within reach of a NEMO, for example, supernovae (e.g. Powell & Muller 2019), quasi-monochromatic signals from rotating neutron stars (e.g. Lasky 2015; Riles 2017), or more speculatively, superradiance from axion clouds (Yoshino & Kodama 2014)