**PUCV / AUT Project**

# **Introduction Layout**

1. What are gravitational waves, why are they important, and how are they detected?

* Meyer et al. 2016
* Einstein 1916 (Albert Einstein’s general theory of relativity)
* Abbott et al. 2016 (Properties of the binary black hole merger GW150914)
* Abbott et al. 2016 (Observation of gravitational waves from a binary black hole merger)

1. Methods implemented to detect GW from **coalescing binaries**

* Meyer et al. 2016
* Abbott et al. 2016 (Observation of gravitational waves from a binary black hole merger)

1. Pre-machine learning methods to differentiate CCSNe GW signals from detector noise

* *Summerscales et al. 2008*
* Christensen et al. 2022 (section IX.c Core-collapse supernovae)
* *Abbott et al. 2020e (*Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced ligo and advanced virgo)
* *Gossan et al. 2016* (Observing gravitational waves from core-collapse supernovae in the advanced detector era)
* *Lynch et al. 2017* (Information-theoretic approach to the gravitational-wave burst detection problem)

1. Machine learning methods of detection

* Antelis et al. 2021 (supervised ML using cWB pipeline, and SVMR classifier)
* Chan, Heng & Messenger 2019 (multi-class classification CNN)
* Astone et al. 2018 (CNN, takes advantage of g-mode)
* Abbott et al. 2020 (Optically detect CCSNe and search for GW signals with the on-source window, and employ cWB pipeline)

1. Approach we intend to propose

# **Literature Reviews**

**Using supervised learning algorithms as a follow-up method in the search of gravitational waves from core-collapse supernovae**

Antelis et al. 2021

Their method is based on supervised machine learning (ML) using the coherent WaveBurst (cWB) pipeline.

* *The ML model discriminates noise from signal events using as features a set of reconstruction parameters provided by cWB … such as duration and central frequency …*
* ***cWB will play a critical role in the detection of CCSNe GWs*** *in the upcoming fourth and fifth observing runs (O4 and O5) with the LIGO, VIRGO, and KAGRA (LVK) network.*
* *… this paper investigates the benefits of supervised ML as a follow-up method of cWB that discriminates between noise and signal events in searches of GWs from CCSNe.*
  + *… used the supervised classification models linear discriminant analysis (LDA) and support vector machines (SVM).*
  + *The classifier is a computational model that takes as input a vector of features extracted from a cWB event, and assigns to it one class label indication “noise” or “signal”.*

Existing method for detecting GW from coalescing binary systems.

* *In the case of GWs generated by binary black holes (BBH) and binary neutron stars (BNS), the existing algorithms benefits from having highly deterministic signal models, and thus, searches are based on match-filtering detector strain data with available template signals…*

Will we implement an algorithm that considers multiple detectors as part of a network?

* *With more than one detector, the data from one detector is shifted with respect to the other in a time length that has to be longer than the GW travel time between detectors …*
* *… results shows that classification performance … is higher for the two detector network.*

Different combinations for embedding signal into noise.

* *… waveforms are systematically added into detector noise data, rescaled to different amplitudes corresponding to diverse source distances, and at different time delays between detectors corresponding to diverse source sky locations.*
  + *All simulation analyses were done at different source distances from 0.1 up to 10kpc.*

The set of reconstruction parameters as features provided by cWB.

* *: cWB detection statistic.*
* *Volume: number of time-frequency pixels composing the event.*
* *Duration 1 and Duration 2: time length of the event computed from the energy-weighted and from the reconstructed waveform.*
* *Frequency 0 and Frequency 1: central frequency of the event computed from the energy-weighted and from the reconstructed waveform.*
* *Low and High: minimum and maximum frequency of the time-frequency map pixels.*
* *Bandwidth 1 and Bandwidth 2: bandwidth estimated from the energy–weighted and from the time-frequency map.*
* *Norm: effective number of time-frequency resolutions used for GW reconstruction.*

The Support Vector Machine - Radial Basis Function classifier had the lowest signal loss.

* *… results indicated a consistent superior performance with the support vector machine with radial basis function as kernel (SVMR). This model provides non-linear separation surfaces allowing to account for non-linearities in the feature space.*

Does this mean 50% of data points are noise/signal?

* *… it is important to indicate that the training data in all analyses was always balanced, hence, there is an equal probability for each class (noise and signal).*

**Gravitational Waves: A statistical autopsy of a black hole merger**

Meyer et al. 2016

Detection methods for coalescing binaries. They were able to produce template waveforms by match–filtering against all possible parameters combinations.

* *… frequentist chi-square test statistics were used to confirm the detection of a gravitational-wave signal and to calculate an (exceedingly small) false alarm probability of less than 2x10^-7.*
* *… ignore certain characteristics … effectively discretizing the parameter space into a grid of parameter combinations and trying all resulting 250,000 template waveforms in a* ***matched-filter search procedure*** *to check whether the observed waveform is close to any of the templates.*
* *The detection methods were tested through a “blind injection challenge” in which a synthetic coalescing binary signal was added…*

Einstein’s general theory of relativity predicts the shape of a waveform from two merging black holes, which serves as a good comparison for the observed signal. This theory does not predict the shape of a waveform from CCSNe. We then have to investigate and make some prior assumptions about the likely parameters of CCSNe.

* *… two orbiting objects slowly spiral together because they lose energy from the emission of gravitational waves. As the two objects approach one another, the frequency and amplitude of the emitted gravitational waves increases. If the objects are black holes, they form a single perturbed black hole when they finally merge, which then emits gravitational waves at a constant frequency and exponentially damped amplitude.*

**Inference of protoneutron star properties from gravitational-wave data in core-collapse supernovae**

Bizouard et al. 2021

Are we modelling fast or slow (more common) rotating CCSNe?

* *A neutrino-driven explosion is the most likely outcome in the case of slowly rotating cores, which are present in the bulk of CCSN progenitors.*
* *For the case of rapidly rotating progenitor cores the result is likely a magnetorotational explosion, yielding a more powerful GW signal that could be detected within 50 kpc and, for some extreme models, up to 5-30 Mpc.*

This paper focuses on inferring the properties of PNS from detected GW with a view to understanding the explosion mechanism of massive stars.

* *… present a parameter estimation approach which is based on the gravitational waves associated with oscillations of protoneutron stars (PNS).*
* *Use a set of 1D CCSN simulations to build a model that relates the evolution of the PNS properties with the frequency of the dominant* g *mode* (continuously excited gravity mode)*, which is extracted from the gravitational-wave data…*
  + *The model is used to infer the time evolution of a combination of the mass and the radius of the PNS.*
* *Considering signals embedded in Gaussian gravitational wave detector noise, we show that it is possible to infer PNS properties for a galactic source using Advanced LIGO and Advanced Virgo data at design sensitivities.*

A key feature of interest is the continuously excited gravity mode (*g* mode) that appears in all multidimensional numerical simulations of CCSN that we may perhaps use as a characteristic for a classification model.

* *… systematic appearance in time-frequency diagrams of a distinct and relatively narrow feature during the postbounce evolution of the system, with frequency rising from about 100 Hz up to a few kHz (at most) and a typical duration of 0.5-1 s.*

**Detection and Classification of Supernova Gravitational Waves Signals: A Deep Learning Approach**

Chan, Heng & Messenger 2019

Apply a convolutional neural network to the gravitational wave signals from core-collapse supernovae.

* *… can be used to detect and classify the gravitational wave signals buried in noise.*
* *… likely to detect a magnetorotational* (rapidly rotating progenitor cores) *core collapse supernovae within the Large* (48.5 kpc) *and Small* (61 kpc) *Magellanic Clouds, or a Galactic event if the explosion mechanism is the neutrino-driven mechanism* (slow rotating cores).

Multi-class classification convolutional neural network

* *A convolutional neural network (CNN) is a computational processing system that takes in data and is able to classify the input data as one of the N types it has learnt through training.*
* *The problem we are trying to solve is a problem of multi-class classification, and hence the loss function employed for this work is the categorical cross-entropy, defined as (equation 1)...*

What class are our 8 signals?

* *We establish a CNN for the purpose of distinguishing detector time series among three classes, i.e., magnetorotational signals + background noise, neutrino-driven signals + background noise, and pure background noise.*

Have our 8 signals been normalised

* *Since the waveforms are generated at various distances, sampling rates and durations, it is necessary to normalise the waveforms before they can be used for the generation of the time-series.*

**New method to observe gravitational waves emitted by core collapse supernovae**

Astone et al. 2018

Aim to detect CCSNe GW by implementing a convolutional neural network and taking advantage of “a peculiarity of the gravitational wave signal emitted in the core collapse supernovae…”

* *… take advantage of the* (CCSNe) *signal peculiarity, in particular that associated to monotonically raise of the frequency related to the g-mode excitation* (mentioned in Bizouard et al. 2021)*.*
* *… search strategy of events … characterised by a raising monotonic behaviour in the time-frequency plane …*

Focus work on nonrotating stars/progenitors and produce waveforms with a number of features/characteristics.

* *The progenitors used are nonrotating stars with solar metallicity and correspond to zero-age main-sequence masses in the range 8-40 Msun.*
* ***Prompt convection:*** *Some models show prompt convection right after bounce, which lasts for 50-100 ms at about 100 Hz (see, e.g., [18,32]).*
  + *[18] J. W. Murphy, C. D. Ott, and A. Burrows, Astrophys. J.* ***707****, 1173 (2009).*
  + *[32] A. Marek, H.-T. Janka, and E. Müller, Astron. Astrophys.* ***496****, 475 (2009).*
* ***Excitation of g-modes of the PNS: basically all simulations in the literature show this feature.*** *Its frequency starts around 100 Hz and grows in time as the mass of the PNS grows creating a characteristic raising arch in the spectrogram. It may start right after the bounce or with some delay (up to ~200 ms). The signal lasts until the onset of the explosion or the formation of the black hole.*
  + *… g-modes, the most common feature of all modes, which also are responsible for the bulk of the GW signal in the postbounce evolution of the PNS.*
* ***SASI (spherical accretion shock instability) modes:*** *SASI modes are observed in models in which the SASI is active [16,19,20]. It starts at ~100 Hz, usually with some delay after bounce, and its frequency grows in time, albeit at a lower pace than g-modes. Its frequency growth is close to linear rather than an arch.*
  + *[16] P. Cerdá-Durán, N. DeBrye, M. A. Aloy, J. A. Font, and M. Obergaulinger, Astrophys. J. Lett.* ***779****, L18 (2013).*
  + *[19] T. Kuroda, K. Kotake, and T. Takiwaki, Astrophys. J.* ***829****, L14 (2016).*
  + *[20] H. Andresen, B. Müller, E. Müller, and H.-Th. Janka, Mon. Not. R. Astron. Soc.* ***468****, 2032 (2017).*
* ***Memory:*** *The explosion and the anisotropic neutrino emission, leave a low frequency signal in the range ~1-10 Hz (e.g., [18,32], usually described as a memory effect.*

**Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced LIGO and advanced VIRGO**

Abbott et al. 2020

As a method of detection, they first optically detect the CCSNe, then look for GW signals within an on-source window (OSW).

* *… When it reaches the surface, i.e., shock breakout,* ***a CCSN emits observable light.***
* *The OSW is defined as the time interval [t1, t2], where t1 and t2 are the beginning and end times, respectively.*

Employ cWB as the search algorithm.

* *… based on the constrained maximum likelihood ratio method.*
  + *S. Klimenko et al., Phys. Rev. D* ***93****, 042004 (2016).*
* *For each event, the pipeline calculates correlation coefficients cc = Ec / (Ec+En) which measures the degree of similarity of the waveforms between the detectors.*
  + *Ec is the normalised coherent energy obtained by cross-correlating the reconstructed waveforms in each detector.*
  + *En is the normalised per detector residual noise energy after the reconstructed waveform is subtracted from the data.*
  + *For a real GW, cc ~ 1, and we accept events that have cc > 0.8.*
* *… we use the* ***selection criteria*** *described in [89].*
  + *B. P. Abbott et al. (LIGO Scientific and Virgo Collaborations), Phys. Rev. D* ***93****, 122004 (2016).*

Testing the search sensitivity of the pipeline to different waveform families (varying amplitudes, etc.) against background data/events (false alarm rate, FAR).

* *cWB adds (injects) supernovae waveforms to the detector data inside the OSW with the right time delay in each detector such that the GW signal comes from the accurately known CCSN sky location.*
  + *The fraction of the injected signals that can be detected and pass the* ***selection criteria*** *is the* detection efficiency.
  + *The injection procedure is repeated with waveform amplitudes corresponding to different source distances. We select any event that passes the* ***selection criteria*** *of the search …*

Two sets of multidimensional CCSN simulations according to explosion mechanism.

* *… neutrino-driven explosion mechanism for nonrotating or slowly rotating progenitor stars.*
  + *GWs are emitted in the frequency range from 100-300 Hz, while at later times, GWs up to around 2 kHz can be expected.*
  + *A typical duration for a GW transient is 0.5-1 s.*
* *… rapid and differential rotation progenitor stars (magneto-hydrodynamically (MHD) driven).*

**Parameter Estimation with Gravitational Waves**

Christensen & Meyer 2022

**Section IX Other Signal Searches for LIGO and VIRGO**

* *These types of signals have yet to be observed, but sophisticated methods are in place for attempts at detection and then associated parameter estimation.*

**Section IX.c Core-Collapse Supernovae**

* *The work of Summerscales et al. (2008) use a maximum-a-posteriori approach to attempt to separate the gravitational wave signal produced by a CCSN from the detector noise.*
* *Summerscales, T Z, Adam Burrows, Lee Samuel Finn, and Christian D. Ott (2008), “Maximum entropy for gravitational wave data analysis: Inferring the physical parameters of core-collapse supernovae,” The Astrophysical Journal* ***678*** *(2), 1142-1157.*
* *The physics behind CCSN is complicated and complex. The way in which the explosion happens is not yet totally explained. Different models exist, and lead to different parameter estimation results. For example, one mechanism that has been proposed is a neutrino driven explosion; this would apply to slowly rotating progenitors. Another possibility is a magnetorotational driven explosion, which applies for progenitors that are rapidly rotating.*
* *An information-theoretic approach to the detection of unmodeled short-duration transient gravitational wave signals is presented in Lynch et al. (2017).*
* *Lynch, Ryan, Salvatore Vitale, Reed Essick, Erik Katsavounidis, and Florent Robinet (2017), “Information-theoretic approach to the gravitational-wave burst detection problem,” Phys. Rev.* ***D95*** *(10), 104046, arXiv:1511.05955 [grqc].*