Measuring the core-collapse supernova (CCSN) engine dynamics with GWs

preliminary results

Sreeta Roy

Marek Szczepańczyk, Dorota Rosińska, Tomasz Bulik

Brainstorming workshop: Deciphering the equation of state
using gravitational waves from astrophysical sources

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FACULTY OF PHYSICS UNIVERSITY OF WARSAW

UNIVERSITY OF WARSAW

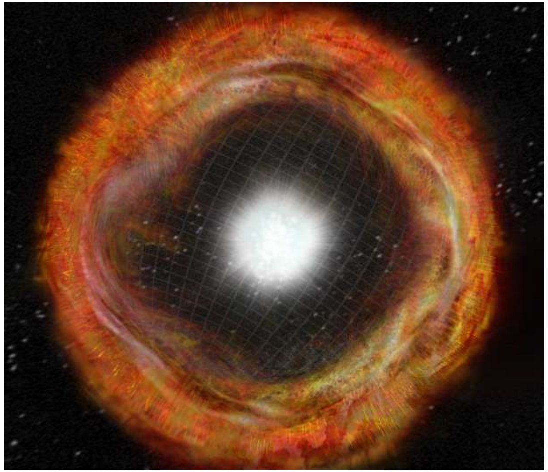
Astronomical Observatory of the University of Warsaw
Founded in 1825

Motivation

The next Galactic CCSN will be a landmark astronomical event, providing a unique opportunity to study these explosive phenomena in detail. GWs can reveal the dynamics of the explosion, such as core deformations and the violence of the event, helping answer the fundamental question of why stars explode. Our project aims at **developing a coherent WaveBurst (cWB) module to estimate GW energy and luminosity from the next CCSNe event**, providing crucial insights into the explosion dynamics and the central engine of these stellar phenomena.

E_{GW} ⟸

P_{GW} ⟸



⟹ $\frac{dE_{\mathrm{GW}}}{dt}$

⟹ $\frac{dE_{\mathrm{GW}}}{df}$

Credit : Bill Saxton, NRAO/AUI/NSF

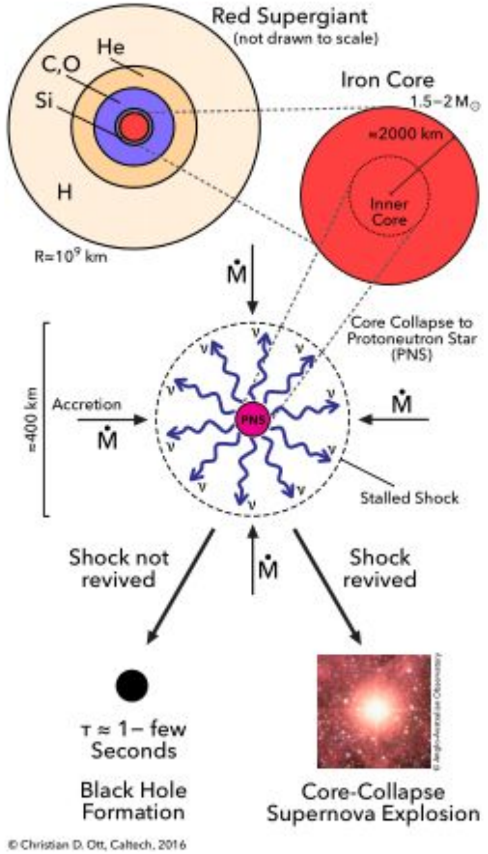
Content

Core Collapse Supernovae (CCSN): An overview

A **core-collapse supernova** is a powerful and luminous explosion occurring at the end of a massive star's life cycle, typically with masses **greater than 8 times the mass of the Sun**.

A supernova explosion can be summed up as :

- **Core Collapse**
- **Proto-Neutron Star (PNS) contraction**
- **Shock Wave formation**
- **Supernova explosion and remnants**



Gravitational Waves from CCSN

Origin of Gravitational Waves in CCSN :

- **Asymmetric Collapse:** The core of a massive star collapses asymmetrically, producing gravitational waves due to the uneven distribution of mass.
- **Neutrino-Driven Convection:** Instabilities and turbulence caused by neutrino emission can generate gravitational waves.
- **Rotational Dynamics:** Rapid rotation of the collapsing core can lead to significant gravitational wave emission, especially if the core forms a proto-neutron star or a rapidly spinning black hole.

Characteristics of Gravitational Waves :

- **Frequency Range:** In the range of 100 Hz to 1 kHz, depending on the type of the collapse and the progenitor star's properties.
- **Waveform Types:** Include burst-like signals from the rapid core collapse, continuous waves from rotating neutron stars, and stochastic signals from turbulence and instabilities.
- **Signal Strength:** Generally weaker signals than those from compact binary mergers, making detection challenging with current technology.

Coherent Wave Burst: CWB(Klimenko+16)

Overview:

- Model-independent algorithm for detecting gravitational wave transients.
- Utilizes data from LIGO, Virgo, and KAGRA.

Working:

- **Coherent Analysis:** Combines data from multiple detectors.
- **Wavelet Transformation:** Identifies excess power in time-frequency space.
- **Reconstruction:** Estimates signal parameters and source location.

Key Features:

- **Versatile Detection:** Captures unmodeled signals, such as those from supernovae.
- **Real-Time Alerts:** Enables rapid follow-up observations.
- **Multidetector Synergy:** Enhances signal detection and localization.

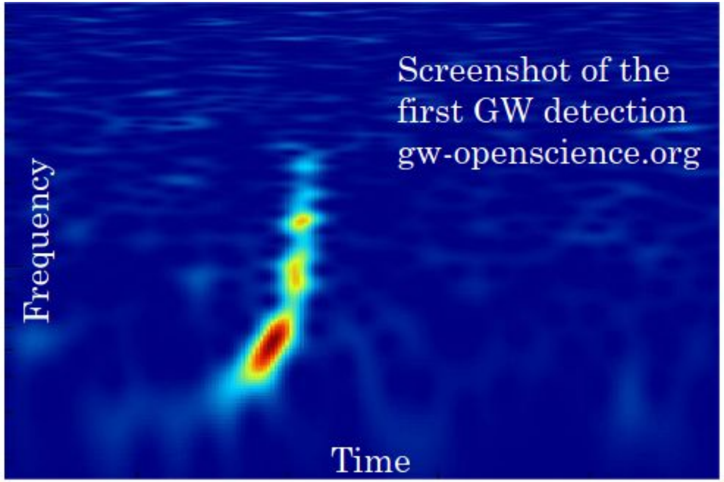
Applications and Future Prospects:

- **Core-Collapse Supernovae:** Critical for detecting signals from poorly modeled sources.
- **New Discoveries:** Potential to uncover new astrophysical phenomena.
- **Improving Sensitivity:** Ongoing upgrades and network expansion enhance detection efficiencies.

Coherent Wave Burst: CWB(Klimenko+16)

CWB Results :

- **GW150914** - the very first GW (PRL 116, 061102)
- **GW190521** - an intermediate mass binary black hole (PRL 125, 101102)
- Regularly detects GWs together with template based searches.



Waveform Analysis

We study different waveforms and their properties are summed up as follows :

- **Powell & Müller 2019 (Pow+19)**: Models with **low and regular CCSN explosion energies** covering all evolution phases. GW signals show **g-mode emissions peaking at high frequencies**.
- Radice et al. 2019 (Rad+19):GW properties dependence on **progenitor star mass (9 M⊙ to 60 M⊙).** Dominated by **f- and g-modes; some strong SASI or prompt-convection signatures**; 10 waveforms analyzed.
- Andresen et al. 2017 (And+17):**3D neutrino hydrodynamics simulations** of CCSNe. GW signals depend on **SASI and g-mode frequency components** in the pre-explosion phase.
- Kuroda et al. 2016 (Kur+16): **EOS impact** on GW signatures using a **15M⊙ progenitor star**. **SASI/convection and g-mode components** dominate pre-explosion phase; only one angle orientation analyzed.
- Mezzacappa et al. 2020 (Mez+20): GW emission origins, replacing Yakunin et al. [110]. **Low-frequency (< 200 Hz) from neutrino-driven convection and SASI**; **high-frequency (> 600 Hz) from PNS convection**.
- O'Connor & Couch 2018 (Oco+18): Impact of **progenitor asphericities, resolution, symmetry, dimensionality, and neutrino physics**. GW signals dominated by **g-mode; strong SASI activity**; 7 waveforms analyzed.

Waveform Analysis: Equation of State

- **Powell & Müller 2019 (Pow+19)**:

  EOS : LS220(soft), Waveform Identifier : s3.5_pns, s18_3D
- **Radice et al. 2019 (Rad+19):**

  EOS : SFHo(soft), Waveform Identifier : s13, s25
- **Andresen et al. 2017 (And+17):**

  EOS : LS220(soft), Waveform Identifier : s11
- **Kuroda et al. 2016 (Kur+16):**

  EOS : SFHx(soft), DD2(stiff), TM1 (stiffer than DD2), Waveform Identifier : SFHx
- **Mezzacappa et al. 2020 (Mez+20):**

  EOS : LS220(soft), Waveform Identifier : c15-3D
- **O'Connor & Couch 2018 (Oco+18):**

  EOS : SFHo(soft), Waveform Identifier : SFHo

Energy of Gravitational Waves

The total energy of Gravitational Waves is given as :

$$E_{GW} = \int_{-\infty}^{\infty} \frac{dE_{\rm GW}}{dt} dt,$$

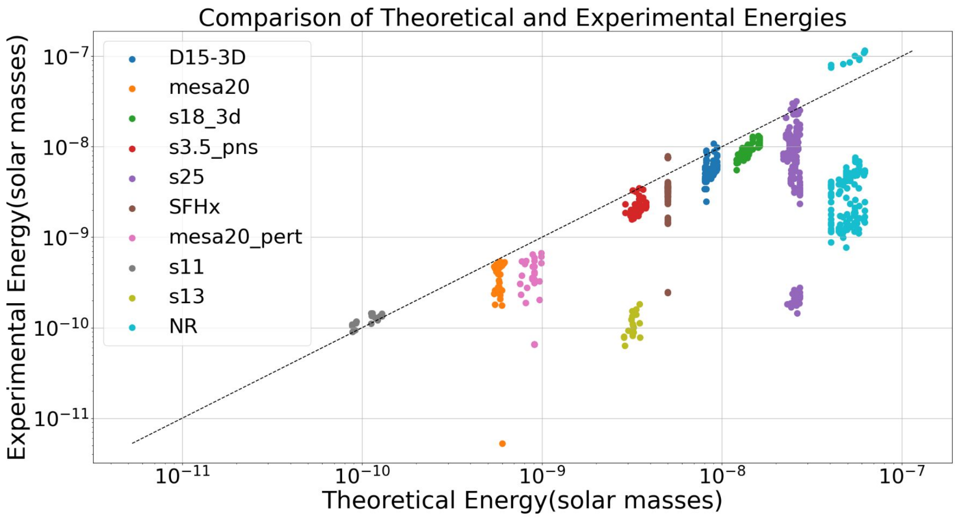
Where,

$$E_{\rm GW} = \frac{c^3}{4G} (D)^2 \sum_i \left(\left(\frac{dh_p}{dt}\right)_i^2 + \left(\frac{dh_c}{dt}\right)_i^2 \right) \Delta t$$

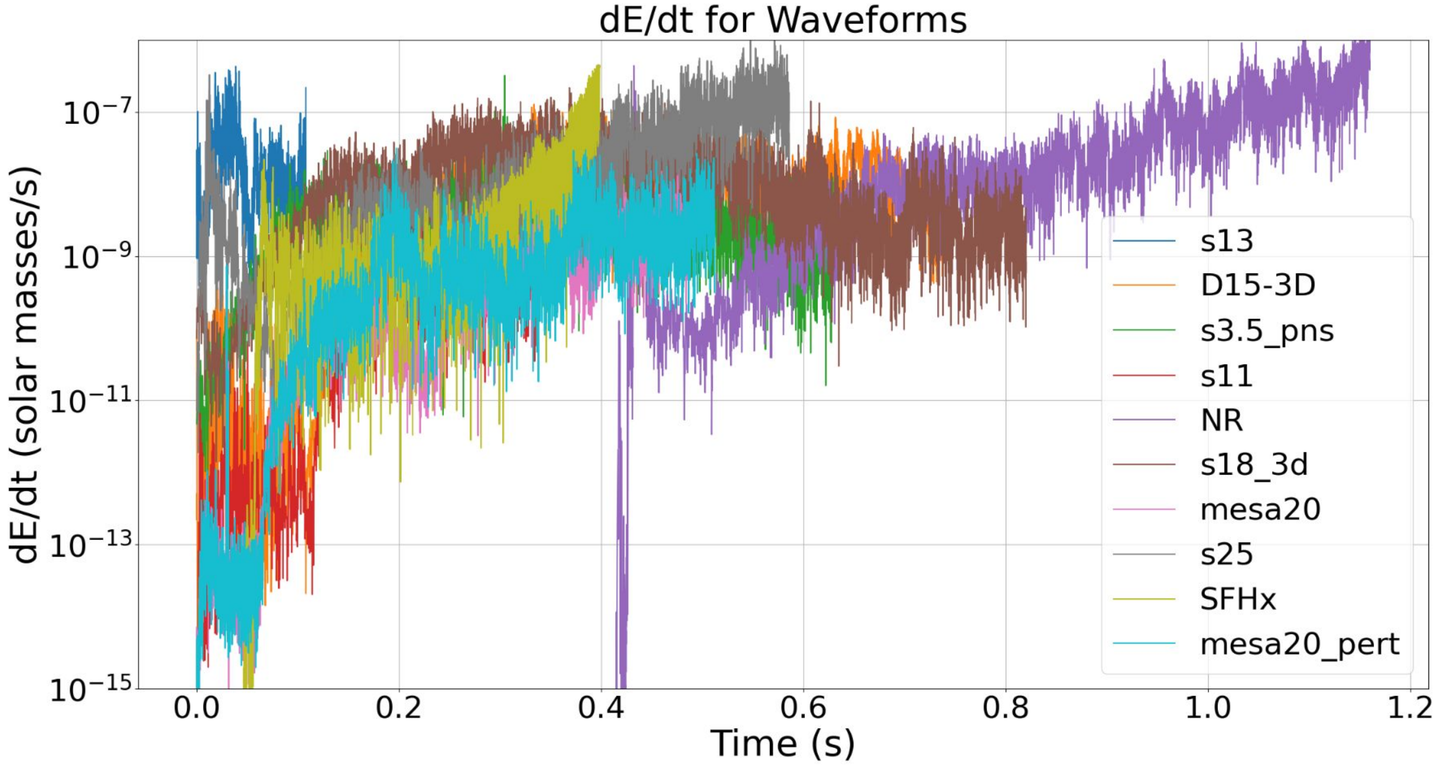
For the theoretical calculation, we consider the source distance 'D' to be 10 kpc and the Gravitational wave polarization values are taken from cWB.

For the experimental calculation, we assume to know the distance to the supernova and consider isotropic emission and narrow band and energy is given by :

$$E_{\rm GW} = \frac{\pi^2 c^3}{G} D^2 f_{\rm peak}^2 h_{\rm rss}^2$$

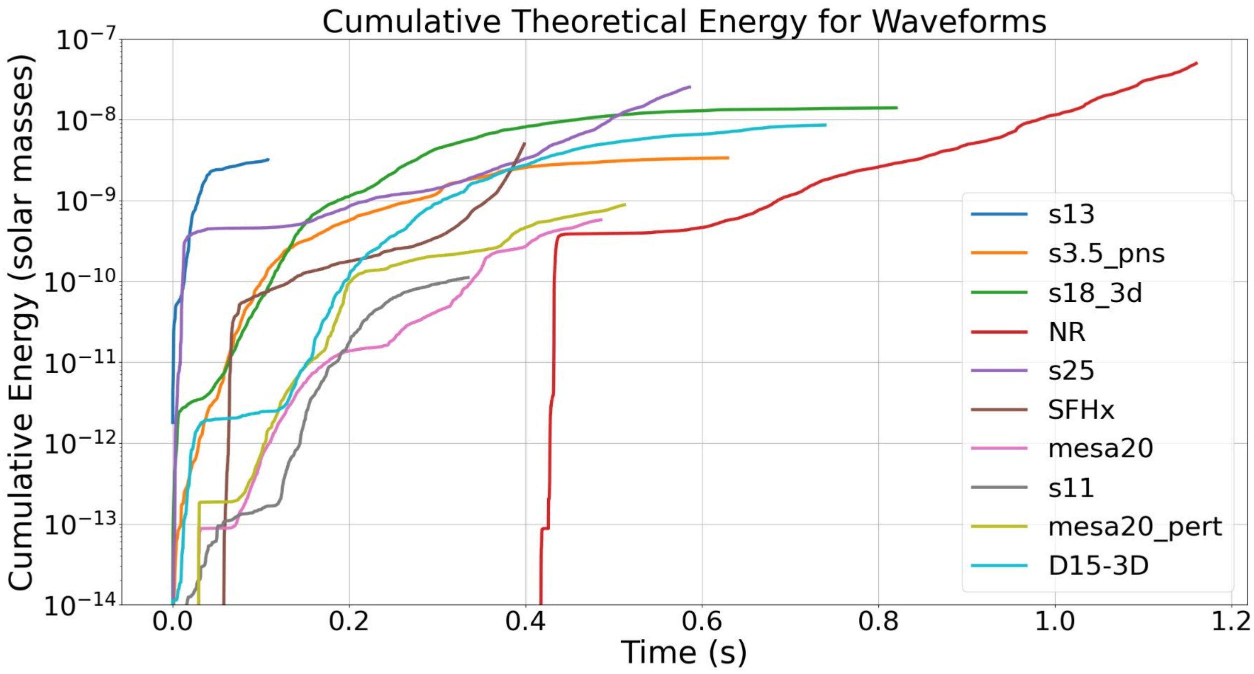


Energy evolution of Gravitational Waves



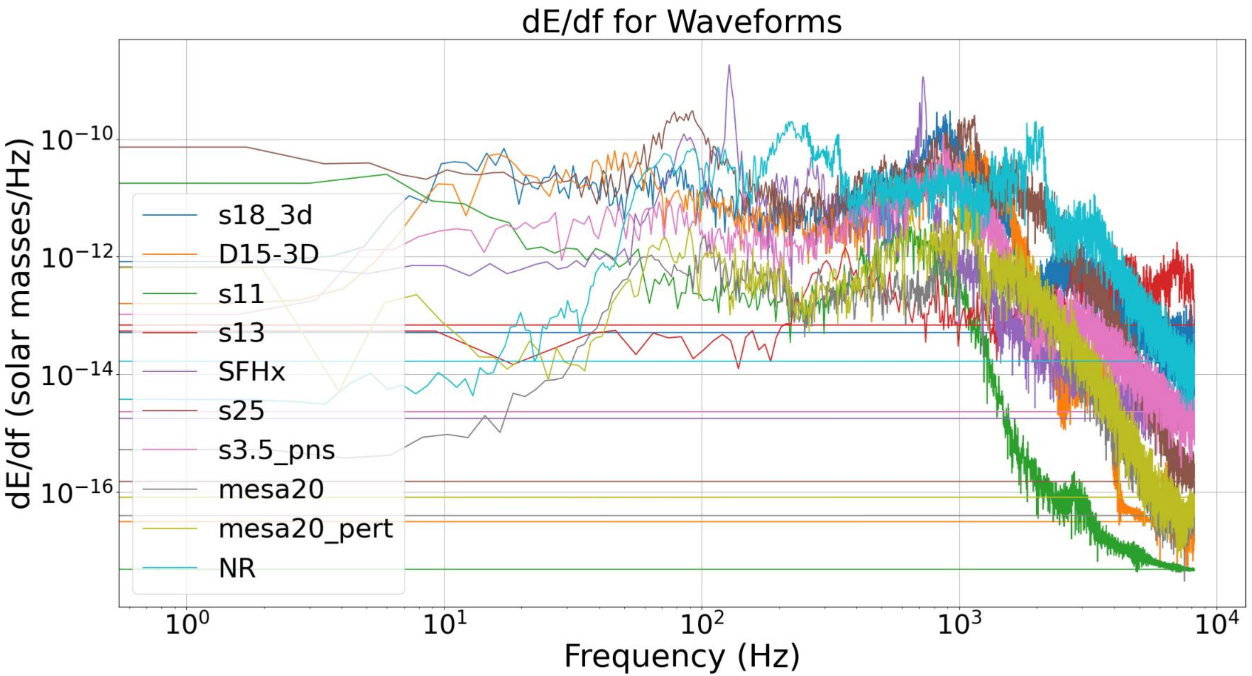
Cumulative energy of Gravitational Waves

Example curves of the cumulative energy emitted in GW as a function of time after core bounce. The timescales and strengths differ with the waveforms.



Energy Spectrum of Gravitational Waves

GW energy spectra are plotted for the waveforms. GW signals from CCSN are generally broadband with majority of energy at the higher frequencies. The dominant GW emission is from PNS oscillations. For some waveforms, the peak frequency cannot be determined accurately.

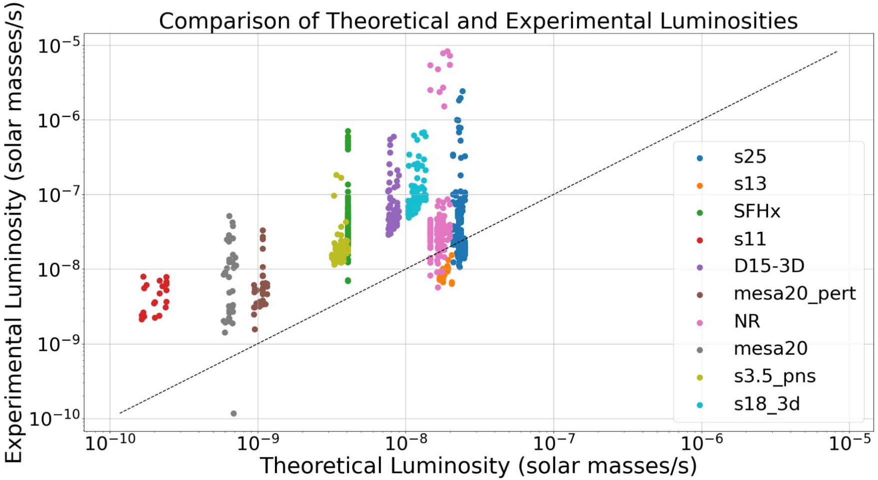


Luminosity of Gravitational Waves

The luminosity of gravitational waves is given as

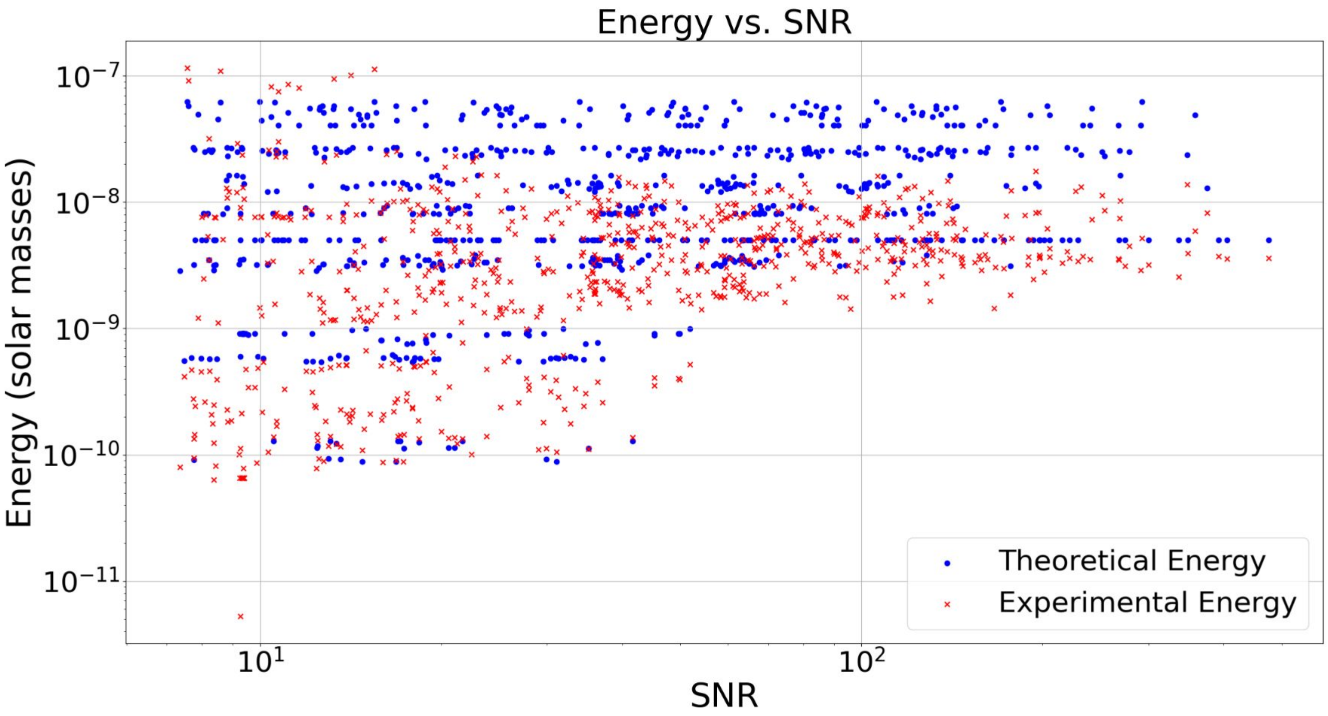
$$P_{\mathrm{GW}} = \frac{0.9\, E_{\mathrm{GW}}}{\Delta t}$$

The detector Gaussian noise and glitches affect the event's reconstructed parameters, such as duration. To minimize this bias, we use signal duration containing 90% of the signal's energy.



Energy and SNR

The GW energy values are underestimated for the experimental values.



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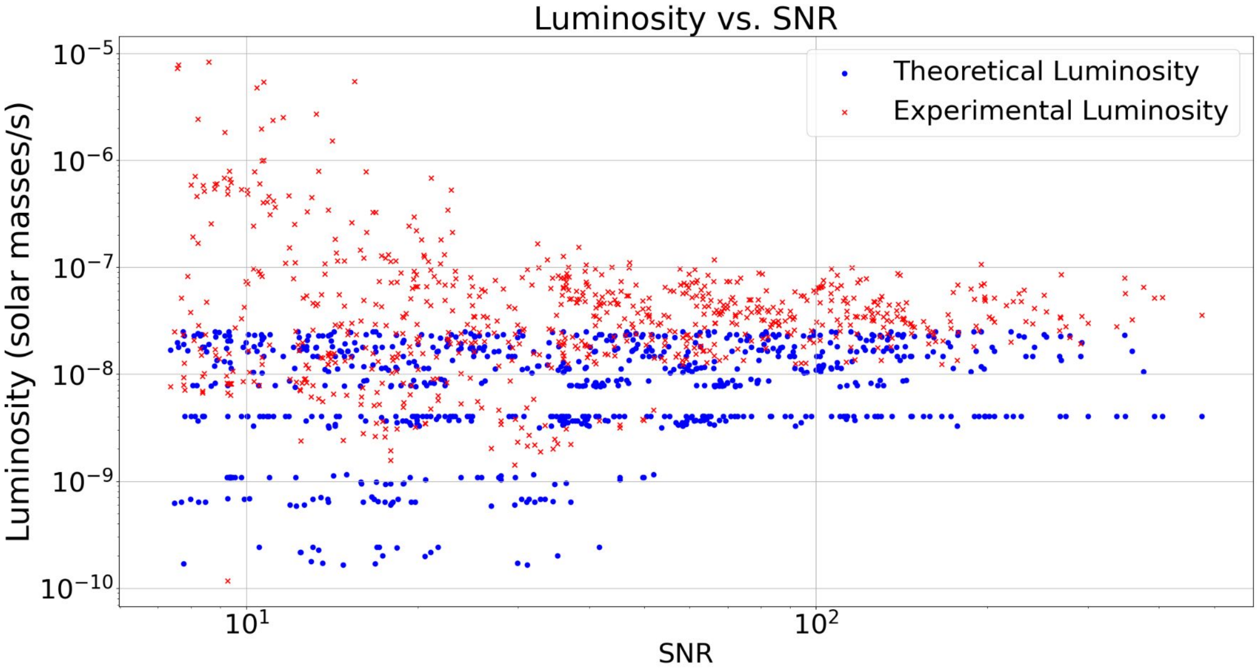

Future Work

- Understanding the discrepancy between the theoretical and experimental values of GW energy and luminosity.
- Improving our approach in order to correct the discrepancy.
- Developing a CWB module to estimate GW energy and luminosity from the next CCSN event and interpreting GW candidates in LVK searches.

What would be the most interesting information for CCSN modelers ?

Summary

- **GWs from six different waveform families** are studied and their **energy and luminosity are calculated both theoretically and experimentally**.
- Calculation of **GW energies** from different waveforms show that the **experimental values are underestimated**.
- Energy values from waveform families of **Radice et al. 2019 (Rad+19), Andresen et al. 2017 (And+17), Mezzacappa et al. 2020 (Mez+20) and O'Connor & Couch 2018 (Oco+18)** shows **good agreement with theoretical values**.
- In case of **GW luminosities**, results show that most of the **experimental values are higher than the theoretical values**.
- Luminosity values for waveform family of **Radice et al. 2019 (Rad+19)** only is **in accordance with the theoretical value**.
- The **energy and luminosity values** from both **theoretical and experimental calculations** from all waveforms are collectively **plotted with the SNR**. **Higher SNR values indicate stronger GW emission**.
- Understanding the **relation of GW energy and luminosity with SNR** helps to i**mprove the sensitivity and effectiveness of GW detectors and enables better detection of CCSN events**.

Energy vs Distance Plots