SN2025gw: First IGWN Symposium on Core Collapse Supernova Gravitational Wave Theory and Detection

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University of Warsaw, Faculty of Physics

Book of Abstracts

Contents

Theory / 1

Neutrino Flavor Conversion in Supernovae: Quantum Kinetics and Astrophysical Implications

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High-energy astrophysical events, such as core-collapse supernovae and binary neutron-star mergers, are promising sources of detectable gravitational waves. In these extremely dense environments, neutrino transport plays a crucial role in shaping the dynamics and observables. However, most numerical models to date employ classical neutrino transport, neglecting quantum kinetic effects. In dense neutrino gases, neutrinos can change their flavors via nonlinear collective oscillations. Recent studies have revealed that quantum kinetics can induce dramatic flavor evolution over short spatial and temporal scales, fundamentally altering the neutrino radiation field in such astrophysical events. We have performed numerical simulations based on the quantum kinetic equations and found that the neutrino system evolves toward an asymptotic state through turbulent-like cascades and collisional processes with background matter. Moreover, by modeling the asymptotic states, we are able to incorporate the effects of quantum kinetics into classical transport frameworks without solving the full quantum kinetic equations directly. In this talk, we will present our latest results and discuss the astrophysical implications of nonlinear neutrino flavor conversion, particularly its potential impact on the dynamics of core-collapse supernovae.

Theory / 2

Low-Frequency Gravitational Waves from Core-Collapse Supernovae: Theory and Detection Prospects

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The low-frequency contribution to gravitational wave signals from core-collapse supernovae has often been overlooked due to the rapid increase in the LIGO noise floor at 10 Hz, but recent studies have illuminated the rich content of core-collapse supernova gravitational wave emission in this frequency range and the exciting prospects for its detection. Here, I will present a brief review of these past studies. I will also present our methodology for the detection of core-collapse supernova gravitational wave memory, utilizing matched filtering, as well as the low-frequency gravitational wave emission sourced from both the matter and the anisotropic neutrino emission in the three-dimensional models of the CHIMERA group, associated with the most recent release of gravitational wave data from that group.

Detection / 3

Simulations of core collapse supernova with QCD phase transition

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One of the major uncertainties in core-collapse supernova phenomenology lies in the equation of state at high densities. Of particular interest is the possibility of a first-order phase transition from hadronic matter to deconfined quark matter—a topic that has recently gained attention due to its potential observational signatures in neutrinos and gravitational waves [1–7]. In this talk, I will present recent results on QCD-driven supernova explosions, as well as cases of failed explosions leading to black hole formation, with an emphasis on their observable signatures.

[1] Fischer, T., Bastian, N.-U. F., Wu, M.-R., et al. 2018, NatAs, 2, 980
[2] S. Zha, E. P. O'Connor, M.-c. Chu et al. 2020, Phys. Rev. Lett. 125, 051102
[3] Fischer, T. 2021, EPJA, 57, 270
[4] T. Kuroda, T. Fischer, T. Takiwaki et al. 2022, Astrophys. J. 924, 38
[5] Jakobus, P., Müller, B., Heger, A., et al. 2022, MNRAS, 516, 2554
[6] Jakobus, P., Müller, B., Heger, A., et al. 2023, PhRvL, 131, 191201
[7] N. Khosravi Largani, T. Fischer, and N.-U. F. Bastian, 2024, Astrophys. J. 964, 143

Electromagnetic / **4**

Numerical simulations of jet launching and breakout from collapsars

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GRBs from collapsars have been studied by imposing jets at intermediate scales beyond the iron core region while exploring a wide range of parameters, such as luminosity and central engine duration. However, these conditions should be validated by studying jets launched directly from the central engine to show a global picture of the jet propagation inside and outside of the progenitor star. In this talk, I will present GRMHD simulations of GRB jets launched from a black hole and followed through to breakout from the collapsing star. From our simulations, I will discuss the implications of the inner progenitor structure, rotation, and magnetization on the properties of the jet emission (launching, duration, structure, and the variability). In addition, I will explain how future gravitational wave detections from highly relativistic jet's material could constrain central engine properties, such as energy and lifetime.

Poster Sparkler / **5**

GRMHD Simulations of Black Hole–Disk Systems: Heavy Element Nucleosynthesis and Implications for r-Process Sites

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The astrophysical origin of heavy elements in the universe synthesised through the rapid neutron capture process (r-process) remains an open question, with several compact object environments such as neutron star mergers, collapsars, and magnetorotational supernovae proposed as potential sites. Systems involving accreting black holes and surrounding disks are particularly promising, as they can give rise to neutron rich outflows capable of producing lanthanides and actinides, which power observable transients such as kilonova.
We investigate heavy element production in black hole–disk systems using general relativistic magnetohydrodynamic (GRMHD) simulations. Our tool is the HARM-EOS code, developed in the CTP PAS astrophysics group. The code incorporates a tabulated, composition-dependent, 3-parameter equation of state. Our simulations study how the accretion disk and black hole parameters influence the dynamics and composition of the outflows. Thermodynamic and kinematic conditions extracted from the disk winds are post-processed with the nuclear reaction network SkyNet to compute detailed r-process abundance yields. By characterising the heavy element production from disk-driven outflows in relativistic accretion environments, we offer insight into the range of astrophysical sites contributing to the origin of the universe's heaviest elements.

Detection / 6

Title: Classification of the nuclear equation of state using the reconstructed core-collapse supernova gravitational wave high-frequency feature in real interferometric data

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Galactic (or near Galactic) core-collapse supernova (CCSN) is currently one of the most anticipated astrophysical events of the century. CCSN are multimessenger astronomy events that work as exceptional laboratories enclosing different carriers of physical information, neutrinos, photons, and gravitational waves (GWs) all coexisting in a single event. The CCSN GW signals are characterized by a non-deterministic nature in their GW emission, as is revealed by the CCSN numerical simulations available to date. LIGO, Virgo and KAGRA (LVK) interferometric data has opened a window for exploration of mechanisms to estimate physical parameters from the GW source, decoding the information incorporated in the CCSN GW burst signals. We present a methodology, following Casallas-Lagos et al. 2023 (PRD.108.084027), Murphy et al. 2024 (PRD.110.083006) and Casallas-Lagos et al. 2024 (MDPI.15010065), based on a convolutional neural network (CNN) to distinguish and classify the nuclear equation of state (EOS) in isolation, for E series, CCSN GW signals from Mezzacappa et al. 2023 (PRD.107.043008) using the estimated slopes of the temporal evolution of the high-frequency feature GW emission for a CCSN at three Galactic distances of 1 kpc, 5 kpc and 10 kpc using LIGO interferometric noise of the third observing run of LVK. The accuracy of this classification algorithm is evaluated by the implementation of the Receiver Operating Characteristic curve, classification accuracy, and the confusion matrix. Our CNN model demonstrates robust discriminative ability in classifying the EOS, achieving 98% accuracy classifying correctly the EOS classes within 1 kpc, with sustained performance at 92% (5 kpc) and 87% (10 kpc). The high micro-average area under the curve AUC (0.93) confirms strong overall classification reliability, while the macro-average AUC (0.87) indicates consistent performance across all EOS categories, even for subtle or rare features. These findings highlight the significant potential of our methodology for effectively discerning EOS within GW detector noise.

Detection / 7

Towards core-collapse supernovae asteroseismology including the standing accretion shock instability

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The yet-to-be-detected gravitational wave signal from core-collapse supernovae is expected to be dominated by oscillation modes of the newly born proto-neutron star (PNS). I am going to present a new general relativistic framework for computing the oscillation modes of a PNS, including, for the first time, an accretion flow and a surrounding stalled accretion shock. The oscillations can be described by a system of partial differential equations, which can be solved as an eigenvalue problem. In that frame, the eigenvalues are the characteristic frequencies of the oscillation modes. In this work, I have considered two different schemes, spectral methods and a machine learning method based on physics-informed-neural-networks, as the eigenvalue solver. By doing so, we can explore the PNS oscillation modes and especially those related to the standing-accretion-shock instability (SASI). In that way, we include some of the missing ingredients towards a more realistic PNS asteroseismology.

Detection / 8

Dedicated-frequency analysis of gravitational-wave bursts from core-collapse supernovae with minimal assumptions

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Gravitational-wave (GW) emissions from core-collapse supernovae (CCSNe) provide insights into the internal processes leading up to their explosions. Theory predicts that CCSN explosions are driven by hydrodynamical instabilities like the standing accretion shock instability or neutrino-driven convection, and simulations show that these mechanisms emit GWs at low frequencies ($lesssim 250$ Hz). Thus the detection of low-frequency GWs, or lack thereof, is useful for constraining explosion mechanisms in CCSNe. In this talk, we introduce the dedicated-frequency framework, designed to follow-up GW burst detections using bandpass analyses. We discuss how low-frequency follow-up analyses, limited to ≤ 256 Hz, can be used to detect low-frequency GW signatures, and therefore constrain CCSN explosion mechanisms in practical observing scenarios. The dedicated-frequency framework also has other applications, such as enhancing signal detectability. As a demonstration, we present a high-frequency follow-up analysis, limited to ≥ 256 Hz, of the loudest trigger from the SN 2019fcn supernova.

Theory / 9

Gravitational Wave Emissions From Magnetized Core-Collapse Supernova Simulations

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Detection of gravitational wave emissions from a nearby core-collapse supernova explosion would mark the next milestone in gravitational wave astrophysics and multi-messenger astronomy, although the nature of the supernova explosion engine remains elusive. One possible engine is through the magneto-rotational mechanism, which may power extreme phenomena such as hypernovae and long gamma-ray bursts, and produce unique gravitational wave signatures. In this talk, I will present our recent multi-dimensional magnetized core-collapse supernova simulations with self-consistent neutrino transport. We find that the simulation outcomes fall into four categories: bipolar jets, monopolar jets, neutron-driven winds, and failed supernovae, depending on the initial magnetic field strength and rotational speed. Each category exhibits a unique gravitational signature.

Detection / 10

Constraining core-collapse supernova engine with Einstein Telescope

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Till date ~200 compact binaries have been detected with the current gravitational wave (GW) detectors. This number is expected to increase by orders of magnitude in the 3G detector era.
In Singh et al 2020 and 2024, we have shown that with just ET as a single instrument, the mass distributions and the merger rate densities of compact binaries will have much better constraints.
The constraints will be strong enough to allow us to distinguish between different populations such as Population I+II, Population III, and globular cluster compact binaries.
One of the key elements which affect the binary merger rates is dynamics of the engine behind core-collapse supernovae and the fate of the stellar collapse of a massive star.
It has been shown recently by Olejak et al 2022 that timescale of convection growth may have a large effect on the strength of SN explosion and therefore also on the mass distribution of stellar remnants.
In this talk I will discuss the prospect of constraining the uncertainties in the convection growth time with Einstein telescope by inferring the constraints on the merger rate density evolution of the compact binaries.

Electromagnetic / 11

Collapsing massive stars and their possible electromagnetic transients

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I will present recent results of the CFT astrophysics group on the theoretical modeling of long Gamma Ray Bursts resulting from collapsars. We focus on the massive star collapse mechanisms as well as the jet breakout and its interactions with dynamically ejected envelope.
We also probe the crucial role of self-gravity and magnetic field play

in determining the newly formed black hole properties. Finally, the recently discovered long GRBs motivate us to study collapsars as the r-process production sites and ejecting radioactive materials from accretion disks to power collapsar kilnovae.

Detection / 12

The impact of calibration uncertainty on supernova searches and parameter estimation

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Calibration of gravitational wave detectors is an intricate and critical process, with amplitude and phase uncertainties typically at the percent level. These calibration uncertainties, which vary with frequency, are routinely incorporated into compact binary coalescence parameter estimation. However, their influence on burst searches and supernova parameter estimation is less explored. In this presentation, we introduce a method designed to apply physically motivated calibration errors on injected signals in the Coherent WaveBurst pipeline. This tool enables systematic studies of how calibration errors affect both detection efficiency and the detection statistics. Using the calibration envelopes for SN 2023ixf, we show that the impact on the detection efficiency is less than 2%. For parameter estimation, we present a preliminary investigation of the impact on core-bounce signals from rapidly rotating progenitors. Using the fitting factor as a proxy for waveform distinguishability, we quantify the extent to which calibration uncertainties may become a limiting factor in identifying source properties.

Electromagnetic / 13

Electromagnetic observations of supernovae for gravitational wave searches

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Electromagnetic observations of core collapse supernovae (CCSNe) provide a wealth of information about the explosion mechanisms and trigger the searches for the possible associated gravitational wave emission.
CCSNe with distances that are less than approximatively 30 Mpc are candidate targets for the LIGO/Virgo/KAGRA searches during the ongoing observing run. Supernovae are routinely monitored by the astronomical community, including all sky surveys. Photometric light curves in different bands allow to narrow the time interval where to search for possible gravitational wave transients.
The light curves for some case studies will be presented, together with the estimates of the progenitor mass.
The issues related to the distance of the host galaxies will also be discussed.

Detection / 14

Detectability of Standing Accretion Shock Instability: New results with cWB XP

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Core-collapse supernovae are the most promising astrophysical sources of burst gravitational waves for current and next-generation interferometric detectors. In the post-bounce phase of CCSNe, the Standing Accretion Shock Instability (SASI) plays a crucial role in the explosion mechanism, generating distinctive, quasi-periodic gravitational wave signatures. Accurate detection and characterization of the SASI signal, especially its central frequency and duration, provide valuable insights into the dynamics of the stalled shock and the proto-neutron star. In this work, we advanced the methodology for identifying SASI signatures by leveraging a new configuration of the coherent WaveBurst pipeline, labeled XP, which employs the novel wavescan time-frequency transformation. We analyze likelihood maps from XP reconstructions of simulated CCSN gravitational wave signals embedded in LIGO O3 data using the SASImeter, a Python-based pipeline that isolates and characterizes SASI components. These results underscore the potential of upgraded analysis pipelines for extracting physical information from stochastic, transient gravitational wave signals of astrophysical origin.

Theory / 15

Core-collapse Supernova Simulation with Subgrid Modeling of Fast Neutrino Flavor Conversion with Boltzmann Radiation Hydrodynamics Code

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Collective neutrino oscillation induced by neutrino self-interaction has been brought great attention in theoretical CCSN modeling.
Especially fast flavor conversion (FFC), which is caused by angular crossings in momentum space, is expected to affect CCSN dynamics.
However, including FFC effects into CCSN simulation is challenging because (1) FFC depends on momentum space angle distribution, and (2) the length scale of FFC is orders of magnitude shorter than that of classical simulations.
In this talk, I present results of CCSN simulations based on Boltzmann radiation hydrodynamics code with Bhatnagar-Gross-Krook (BGK) subgrid modeling of FFC.
I compare several mixing methods and numerical strategies and discuss effects onto CCSN dynamics and neutrino signals.

Electromagnetic / 16

The Correlation Between Supernova Fallback and Progenitor's Hydrogen Envelope

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During a core-collapse supernova, a strong reverse shock forms at the interface between the hydrogen envelope and the helium core, slowing the ejecta and driving some material back onto the newborn compact object. Conventional Eulerian simulations usually place an inner radial boundary, yet when the reverse shock reaches this boundary, it can generate a reflecting wave that hides the true accretion history. To avoid this drawback, we treat the stellar core as a point mass that supplies gravity and surrounds it with a very light buffer zone, so inflow passes smoothly to the center, and spurious reflections disappear. Using the hydrodynamics code Athena++, we follow the shock inward for various explosion energies and discover a steep change in remnant compact object mass around the binding energy of the hydrogen envelope (10^{47} up to 10^{50} erg). If the explosion energy exceeds the binding energy of the hydrogen envelope, the reverse shock doesn't reach the core. In contrast, when the explosion energy is similar to or lower than the binding energy of the hydrogen envelope, the reverse shock infalls to the center. More than two solar masses settle on the remnant, making it heavier. This boundary-free method, therefore, gives the first reliable connection between explosion energy, envelope binding energy, and fallback accretion.

Poster Sparkler / 18

Numerical GRMHD Simulations of Self-Gravitating Collapsing Stars

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Gamma-ray bursts are one of the most energetic phenomena in the Universe. The collapsar model is the most widely accepted model for explaining long gamma-ray bursts. This model proposes that cores of massive stars with sufficient angular momentum collapse to black holes, while the stellar envelope starts to fall onto the newly born object. We performed three-dimensional GRMHD simulations of this phenomenon with various initial conditions, including the physical fact that the gravitational field comes not only from the central black hole, but also from the stellar envelope. We compared models with and without self-gravity to investigate the exact effects of self-gravity in these models. We discuss black hole mass, spin, and accretion rate evolution in time, as well as conditions necessary for jet emission and, as a result, an observable electromagnetic transient. At the end, we discuss the effect of self-gravity on the disc fragmentations, which, under specific conditions, can be a source of gravitational waves.

Detection / 19

Distributional methods for detecting Gravitational Waves from Core-Collapse Supernova

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The goal of the project is to investigate the potential of different distributional methods in the detection of Core-Collapse supernova gravitational waves (GW) for quiet signals that would have been previously missed. To date, no supernova GW detections have been made. We use coherent WaveBurst to look at the loudest events in a span of time and form a metric for each event, which we collect to form 'shaped'distributions containing the signal and all the loud noise. Our method focuses on applying non-parametric distributional tests to separate noise-only distributions with those containing our GW signal. With an understanding of the behavior of these tests and tuning parameters, we have a method to search for supernova GW at signals much quieter (and therefore farther away) than ever before possible.

Poster Sparkler / 20

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

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Core-collapse supernovae (CCSNe) are among the most energetic astrophysical phenomena. The next Galactic CCSN will be a landmark event and Gravitational Waves (GWs) from this CCSN will offer an unique opportunity to study the explosion dynamics in detail. In this poster, we will present the development of a method for the model-independent Coherent WaveBurst (cWB) algorithm to estimate GW energy and luminosity from CCSNe. Estimating the GW energy evolution may provide insight into the explosion dynamics, constrains progenitor properties such as rotation, asymmetries, stiffness of core and also offers a way to test theoretical models against observational data. This method may help in interpreting future CCSNe GW signals and advance our understanding of the core-collapse supernova mechanism.

Theory / 21

The MHD-CCSN code comparison project

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The gravitational collapse of massive stars can lead to extreme stellar explosions when both fast rotation and strong magnetic fields are present during the onset of the supernova. A detailed understanding of how magnetic fields extract angular momentum from the central proto-neutron star is paramount to produce quantitative predictions with respect to not only the explosion dynamics, but also the associated multi-messenger emission of gravitational waves and neutrinos. Numerical simulations are one of the most important tools at disposal to characterize the properties of magneto-rotational supernovae. Their ever-increasing accuracy and complexity allows one to tackle the non-linear dynamics at work during the onset of such explosive events, but there are still many uncertainties related to the specific numerical algorithms and physical approximations adopted.

I will present recent results obtained by an on-going comparison project that involves 5 state-of-the-art codes for the modeling of extreme core-collapse supernovae. Starting from the same initial conditions (i.e. a massive star with a fast rotating and highly magnetized inner core) all codes produce prompt magneto-rotational explosions. All models lead to proto-neutron stars with similar masses and rotation, but we observe some variations in quantities such as the shock expansion and the explosion energy which are connected to the technical properties of the individual codes. I will discuss the impact that aspects such as neutrino transport, grid geometry, and gravity treatment can have on both the explosion and the associated multi-messenger emission.

Detection / 22

Omicron-X: a new pipeline to search for gravitational waves from core-collapse supernovae

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Core-collapse supernovae stand out as key multi-messenger candidates to probe the internal dynamics of stellar supernova explosions with gravitational waves, light, and neutrinos. These complex processes have motivated multiple efforts to simulate core-collapse supernovae and predict the observational signatures with different simulation and progenitor parameters. In order to develop a relevant gravitational-wave search, we have characterized waveform morphologies derived from simulations to outline effective patterns. Our gravitational-wave search for core-collapse supernovae, Omicron-x, is based on the cross-correlation of Q-transform spectrograms and is essentially un-modelled, allowing us to scan a large parameter space. Building on our waveform studies, we measure the search sensitivity to various components in supernova gravitational-wave signals.

Detection / 23

PNS parameters estimation with neutrino emission from supernovae

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A novel functional form for fitting neutrino luminosities from core-collapse supernovae was recently proposed by Lucente et al. (2024), capturing the effects of convection inside the proto-neutron star (PNS) through a power-law temporal decay. While this model accurately describes the cooling phase, it does not account for the neutrino flux during, approximately, the first second, which is primarily driven by accretion. To address this, we introduce an additional term that models the early post-bounce phase in a simple yet effective way. After validating this extended model against multiple simulation datasets, we explore its applicability to SN1987A data. This approach allows us to extract meaningful estimates of the PNS temperature and radius. The radius is of particular interest, as it is closely linked to gravitational wave (GW) emission. Improved radius estimates may therefore enable joint neutrino-GW detection strategies and enhanced multi-messenger parameter inference.

Detection / **24**

Model-agnostic inference of gravitational waves from core collapse-supernovae

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Gravitational waves from core-collapse supernovae remain one of the most promising, but as yet undetected, sources for LIGO, Virgo, and KAGRA. Confidently reconstructing a supernova waveform, or inferring key signal properties, could provide critical insight into the explosion mechanism. This task remains challenging however due to the wide range of possible signal morphologies. In this talk, I will present a Bayesian approach for reconstructing transient gravitational-wave signals with minimal assumptions about their waveform structure. I will show results demonstrating how well this method recovers simulated signals based on current supernova models at various distances. I will also discuss how to refine the reconstruction methods specifically for supernovae, while remaining flexible enough to capture a broad range of potential signal features.

Theory / **25**

Post-explosion Hydrodynamics in 3D Neutrino-driven Supernova Models

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After decades of intense research, the "neutrino-driven explosion mechanism" has meanwhile been established as the most promising and widely accepted paradigm for the majority of core-collapse supernovae (CCSNe). Nevertheless, the question remained whether the neutrino-driven mechanism can explain the characteristic properties of observed supernovae, such as explosion energies, nucleosynthesis yields, and neutron star (NS) and black hole (BH) kicks and spins. In my talk, I will address this question by presenting most recent results from a growing set of three-dimensional (3D) neutrino-hydrodynamics simulations of the Garching group that extend over timescales of many seconds, i.e., significantly beyond the times when the explosions are launched. I will show that the highly non-linear post-explosion dynamics of 3D CCSN models with coexisting in- and outflows enable the long-lasting growth of the explosion energy, the efficient production of radioactive isotopes such as ^{44}Ti and ^{56}Ni, and the development of large-scale ejecta asymmetries, with important implications for NS and BH natal kicks and spins. Our results demonstrate that state-of-the-art 3D models of neutrino-driven CCSNe —if evolved over sufficiently long timescales —can reproduce the typical explosion properties as deduced from astronomical observations. One of the major remaining uncertainties in CCSN theory concerns the nuclear equation of state (EoS). Based on our set of recent 3D simulations, I will also discuss the impact of the EoS on the explosion dynamics and the properties of the new-born NSs, such as the development of proto-NS convection and the growth of neutrino emission anisotropies.

Theory / **26**

Gravitational wave signal of protoneutron star convection

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Gravitational waves offer a direct way to probe the explosion mechanism of core-collapse supernovae and proto-neutron star turbulence. By combining state-of-the-art 3D-MHD convection simulations with physics-informed scaling laws, we generate synthetic GW spectrograms up to 7 seconds post-bounce—much longer than what is typically achieved with global core-collapse models. We examine how the GW signal from proto-neutron star convection is affected by both rotation and dynamo-generated magnetic fields and estimate its detection horizon with current and future ground-based detectors, such as the Einstein Telescope.

Theory / **27**

Core-Collapse Supernova Simulations with a Multidimensional Full Boltzmann Solver in Gmunu

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Simulations of astrophysical systems where neutrinos play a significant role, like core-collapse supernovae, would ideally solve the neutrino transport equation fully, i.e. solve the full Boltzmann

equation. Because of its very high computational cost (6+1D), simulations generally rely on approximations of the equation that are more affordable. It is however difficult to estimate what is lost through these approximations if we do not have access to a full solution. Therefore, we developed a multidimensional full Boltzmann solver based on the Finite Volume method within the GRMHD simulation code Gmunu in order to perform those more accurate simulations. We present our solver, its performance on some first test cases and show the results of 1D core-collapse supernova simulations.

Poster Sparkler / 28

Deep Conditional Generative Adversarial Networks for Rapidly Rotating Core-Collapse Supernovae Gravitational Waves

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The generation of synthetic gravitational wave signals from core-collapse supernovae can provide a valuable tool for data augmentation in machine learning pipelines, especially for the training of detection and classification algorithms. These waveforms encode critical astrophysical information, such as the ratio of rotational kinetic to gravitational potential energy at bounce, pre-collapse differential rotation, nuclear equation of state, and explosion mechanism. Recent efforts have explored the use of generative models to synthesize waveform-like data, most existing models lack the ability to condition outputs on specific astrophysical parameters. In this work, we present two conditional generative adversarial network architectures for synthesizing gravitational wave signals from rotating core-collapse supernovae, conditioned on three discrete categories of the ratio of rotational kinetic to gravitational potential energy at bounce parameter. The training data is derived from the Richers et al. catalog, which includes time-series gravitational waveforms and associated physical parameters from numerical simulations. The first model operates directly on raw time-series data. The second model utilizes image-based inputs obtained by converting time series into Gramian Angular Summation Fields. Our results demonstrate that both conditional generative adversarial network architectures successfully learn the underlying structure of gravitational wave signals from rotating core-collapse events, producing synthetic waveforms that are statistically consistent with the original simulation data

Theory / 29

Multi-Messenger Signals from Magnetorotational Stellar Core Collapse

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Multi-messenger signals of gravitational waves and neutrinos from supernovae carry information about properties of supernova cores, which cannot be directly observed with electromagnetic waves. To maximize impacts of future detection of these multi-messenger signals, it is important to understand the relationship between the characteristics of the multi-messenger signals and the properties of the supernova cores.

We performed fully general relativistic three-dimensional neutrino-radiation magneto-hydrodynamic simulations of stellar core collapse with spectral neutrino transport to explore the impacts of characteristic fluid motions on the gravitational wave and neutrino signals from progenitors with various rotation speeds and magnetic field strengths. In this talk, I show the results of the time-frequency analysis of the gravitational wave and neutrino signals obtained from our simulations. In the non-magnetized rapidly rotating models, non-axisymmetric instabilities develop and generate the characteristic gravitational wave and neutrino signals that are correlated in the time-frequency plane. The highly magnetized rapidly rotating model shows that, for an observer on the equatorial plane perpendicular to the rotation axis, the low-frequency gravitational wave amplitude from anisotropic neutrino emission from deformed proto-neutron star becomes more than one order-of-magnitude bigger than that from the bipolar magnetohydrodynamic jets. I also discuss the detectability of their characteristic features.

Detection / 30

Robustness of Markov Chain –Monte Carlo in parameter estimation of gravitational waves emitted during Core-Bounce phase of Core Collapse Supernovae.

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In this work we use an analytical model that fits the Core-Bounce phase of Core Collapse Supernovae and it depends upon one physical parameter (the rotational rate) and two more phenomenological ones, which adjust the waveform to a Richers catalog of 2D axisymmetric simulations. Three different scenarios were considered in this work. The first one aims to test Markov Chain –Monte Carlo robustness in terms of prior sensitivity, using uniform, triangular, and LogUniform probability density functions in 37 injections at 11 kpc, showing that there is a difference in the uncertainties among the posteriors associated with each prior. The second scenario analyzes how different reparametrizations (parameter transformations) affect the estimated values and posterior probability densities. We found out that there is actually worse performance when there is a transformation of the parameters. The last situation tests the relative probability of different models (varying the number of parameters) calculating the bayesian evidence and comparing them to show which model suits better the 2D simulated waveforms, and it turns out that the model which includes only one parameter is preferred. In a more general way, a set of 126 injections showed that the reconstructed waveforms using Markov Chain –Monte Carlo yielded better Fitting Factors compared to the ones calculated recurring to frequentist methods.

Detection / 31

Core-Collapse Supernova Waveform Generation Using Machine Learning

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Gravitational waveforms arising from core-collapse supernova are yet to be observed by the existing detectors. Simulating GW waveforms for CCSN consumes a considerable number of resources. In this work we have employed the advantage of a machine learning technique, specifically conditional variational autoencoder to generate the waveforms of the CCSN. For training, publicly available simulated waveforms are used while conditioning those on the required physical parameters. Certain equations of states were used as one of the conditioning parameters. To generate new waveforms based on the required parameters, data is sampled from the latent space distribution. This generated data corresponds to the generated waveforms. Certain metrics are employed to calculate the accuracy of the generated waveforms. Currently the generated waveforms are in agreement with the true waveforms with a mean squared value of ~0.05. This technique enables us to generate waveforms withing milliseconds using lesser resources. In future, more tests will be using more physical parameters of CCSN.

Detection / **32**

Parameter estimation from the core-bounce phase of rotating core collapse supernovae in real interferometer noise

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In this study, we formulate and describe a method for estimating parameters for rotating core-collapse supernovae, using the gravitational wave core bounce phase as a basis.

We introduce an analytical framework for the core bounce component that is determined by the ratio β, which characterizes the relationship between rotational kinetic energy and potential energy, alongside a phenomenological parameter α that pertains to rotational dynamics and the equation of state. We assess the accuracy of our phenomenological model by utilizing 126 numerical waveforms sourced from the Richers catalog.

The fitting factor used in searches for compact coalescing binaries serves as a metric to measure the effectiveness of the analytical model. The error in the frequentist parameter estimation of β using a matched filter is assessed. Results are analyzed based on actual interferometric noise and a waveform situated 10 kpc away with an ideal orientation. These findings are also contrasted with the situation where Gaussian recolored data is utilized.

Moreover, our study indicates that third-generation interferometers such as the Einstein Telescope and Cosmic Explorer could detect rotation at a distance of 0.5 Mpc. In the analysis, we evaluated an optimal alignment and accounted for the actual noise from the interferometers, particularly focusing on the O3L1 data.

Detection / **33**

Detection of gravitational waves from core collapse supernovae with an AI enabled pipeline using a network of detectors.

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The use of Artificial Intelligence (AI), Machine Learning (ML), and High-Performance Computing (HPC) is playing an increasingly important role in advancing how we detect gravitational waves (GW).GW signals from core-collapse supernovae (CCSN) are still undetected. These signals are inherently weak, unmodeled and often masked by environmental and instrumental noise, presenting significant challenges for detection. CCSN waveforms are derived from complex simulations in the HPC. The simulations yield signals of stochastic nature that mimic noise. This study explores how convolutional neural networks (CNN) can effectively distinguish diverse CCSN GW signals from background noise.
This study addresses a fundamental query: how can a CNN be comprehensively trained to capture all potential CCSN signatures, optimizing accuracy? The investigation presents a multivariate classification of the entire supernova waveform landscape to strategically select training waveforms that maximize the feature space. Rigorously tested on both known and unknown waveforms, the method achieves a classification accuracy of ≥90%. This approach has been seamlessly incorporated into the multilayer signal enhancement with coherent wave burst and CNN (MuLaSEcC) analysis pipeline, showcasing promising outcomes using LIGO O3b data. Noteworthy improvements include a reduction in background by ≥99%, along with the calculation of detection efficiencies for ten contemporary explosion models. The study evaluates the search pipeline's performance by illustrating detection probability as a function of false alarm rate and false alarm probability. The results highlight a ≥50% detection efficiency within an SNR range of 20–35 for the ten analyzed models, whether trained or untrained. Time-frequency images of CCSN signals detected by the pipeline show broadband features of the CCSN waveforms that are predicted in the simulations.
This study underscores the potential of artificial intelligence in gravitational wave data analysis, paving the way for more accurate and scalable detection frameworks.

Detection / 34

The impact of rotation and the nuclear equation of state on core-collapse supernova explosion dynamics

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Explosive massive stars are powerful emitters of gravitational waves. In the last 10 years, significant progress has been made in understanding the characteristics of their gravitational-wave emission. However, better coverage of the core-collapse supernova progenitor parameter space is still needed to fully understand the gravitational-wave detection prospects, the explosion dynamics, and the birth properties of neutron stars and black holes. Here we show results from 150 supernova simulations with progenitor star masses between 9 and 36 solar masses, 3 nuclear equations of state, and a variety of different rotation rates. We describe the impact of the rotation and equation of state on the explosion dynamics and remnant birth properties. We describe the differences in the gravitational-wave emission, and discuss the detection prospects for next generation ground and space observatories.

Poster Sparkler / 35

Accessing explosion properties in a core-collapse supernova through the star's emission regions.

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Core-collapse supernovae are exploding massive stars and the next Galactic event will be one of the most interesting astronomical events of the century. After the collapse of a star's core, a so-called proto-neutron star (PNS) is formed, heating the star from the inside and creating a shock wave. It is believed that the majority of the gravitational-wave (GW) emission comes from PNS. The GW signals from the recent three-dimensional numerical core-collapse supernova simulations (Murphy et al 2025, arXiv:2503.06406) can be divided into a few signals corresponding to the star's regions. In this project, we analyze the GW signatures and study whether it's possible to distinguish these regions based on a GW. We will utilize real LIGO-Virgo-KAGRA noise and model-independent coherent WaveBurst to study the detectability in case of a discovery of GWs.

Poster Sparkler / 37

Accessing explosion properties in a core-collapse supernova through the gravitational-wave source angular dependence

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Core-collapse supernovae (CCSN) are one of the most violent and energetic astronomical processes in the Universe. The next Galactic supernova can offer us an exceptional opportunity to delve deep into the explosion mechanism through gravitational waves (GWs) emission. Theoretical developments in CCSN modeling hint at the variation of GW signature with respect to the source angle orientation. For example, a GW signal from a core bounce has only one polarization that is emitted perpendicularly to the axis of rotation. In this project, we study the angle dependence of GW signals derived from multidimensional CCSN simulations. Then, we analyze their detectability with model-independent coherent WaveBurst algorithm using LIGO-Virgo-KAGRA data.

Poster Sparkler / 38

Distinguishing Signatures of Prompt Convection in Core-Collapse Supernovae Using Coherent WaveBurst Gravitational Wave Searches

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Core collapse supernovae (CCSNe) are the explosive deaths of massive stars, followed by the formation of a proto-neutron star. Gravitational wave signals from these extremely compact objects can simultaneously inform macroscopic and microscopic physics, ranging from modeling what powers supernovae to constraining the nuclear equation of state. As the inner core of the collapsing star becomes denser, degeneracy pressure causes the core to stiffen, which halts collapse and triggers a rebound of the inner core. A dynamical shock wave propagates outward, causing prompt convection. This convection emits a high-frequency gravitational wave. In this project, we develop a method to distinguish the prompt convection region from other CCSN explosion stages. We use the model-independent coherent WaveBurst search algorithm and perform the analysis in the time-frequency space.

Poster Sparkler / 39

Single detector search for Core Collapse Supernova using Maching Learning

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The traditional CCSN search method relies on coherence information between multiple gravitational wave detectors to identify candidate events. This requirement reduces the effective lifetime of the search, as it excludes periods when only a single detector is operational. To address this limitation, we present a machine learning (ML)-based framework designed to enable single-detector detection of CCSN GWs by learning to discriminate between glitches and physically motivated CCSN signals. Our ML model is trained on 31 CCSN simulatioa waveforms obtained from three-dimensional hydrodynamic simulations spanning a broad range of progenitor masses, rotation rates, and explosion mechanisms. We evaluate classifier performance in both stationary and glitch-contaminated noise data from O3b using signal injections across the LIGO detector network. We compare our result with the two detector settings of our ML model, which retains 80.1% of dual detector sensitivity. At a fixed false positive rate of 5%, the model recovers CCSN signals with signal-to-noise ratios above 15.69, corresponding to a detection horizon of 3.06 kpc for standard explosions and up to 63.09 kpc for extreme progenitor models with one detector.

Poster Sparkler / 40

Core-collapse supernova gravitational-wave sounds

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Core-collapse supernovae (CCSNe) are exploding massive stars and the next Galactic event will be one of the most interesting astronomical events of the century. If the nearby CCSN will be strong enough and the light won't be obscured by the Galactic dust then it may be visible in the sky. If gravitational waves are detected, we will be able to even listen to this explosion. The sounds of merging compact binaries like black holes and neutron stars are fairly well known, but the sounds of CCSNe are not available publicly. We will fill this gap by converting CCSN gravitational-wave signatures to sounds. They will be easily accessible on a website.

41

Core-collapse supernova gravitational-wave physical inference in low-latency

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Core-collapse supernovae (CCSNe) are exploding massive stars and the next Galactic event will be one of the most interesting astronomical events of the century. With the advent of the three-dimensional CCSN simulations, the number of methods to infer physical information from a gravitational wave (GW) discovery grew significantly. For example, the proto-neutron star evolution and deciphering equation of state through High-Frequency Feature, or understanding the shock oscillations by the presence of the Standing Accretion Shock Instability. We present a comprehensive effort at the University of Warsaw to develop and optimize physical inference methods for low-latency operation. We use a model-independent coherent WaveBurst and the latest multidimensional CCSN waveforms.

Poster Sparkler / 42

Core-collapse supernova gravitational-wave physical inference - estimating the time of the Ledoux convection

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Core-collapse supernova in the Milky Way will be one of the most interesting astronomical events of the century. As the massive core suddenly collapses a huge number of neutrinos is produced. Around a hundred milliseconds after the collapse the asymmetry of a supernova evolves through a Ledoux convection. It is believed that it marks the beginning of an efficient emission of gravitational waves. In our work, we develop a method to determine the beginning of the Ledoux convection from simulated gravitational-wave strains. We use the model-independent coherent WaveBurst (cWB) search pipeline and the most recent core-collapse supernova multidimensional simulations for testing the method. We apply the timing information from the neutrino observations. Finally, the code is then optimised to a low-latency cWB operation.

Poster Sparkler / 43

Rapid Accessing Explosion Properties in a Core-Collapse Supernova - Oscillations of the Newly Formed Proto-Neutron Star

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Core-collapse supernova (CCSN) marks the final stage of massive stars ($M > 8M_{\odot}$) entering in a violent and energetic explosion process that might be considered as one of the most anticipated astrophysical events of the century. Following the collapse of the star's core, a dense proto-neutron star (PNS) forms. Within this PNS, complex dynamics involving convection instabilities, accretion, and accretion funnels are believed to excite the high-frequency gravitational wave (GW) emissions, particularly the distinctive high frequency feature (HFF) known as the "g-mode". This HFF can be recognized in a time-frequency spectrogram as a continuous, approximately linear feature, typically starting around 100 Hz and rising to 1–2 kHz over time after the stellar core bounce.This project expands upon the recent advancements detailed in (Phys.Rev.D108.8(2023)), which introduced an algorithm for estimating parameters of CCSN GW HFF using model-independent coherent WaveBurst (cWB) and machine learning. Our primary objective is to study these HFF from CCSN GW signals to provide insight into the complex physical processes occurring deep within CCSN during stellar collapse. Furthermore, we seek to identify potential correlations between these features and key astrophysical parameters of the source, including the nuclear equation of state. To accomplish this, we will integrate and comprehensively test these improved techniques with state-of-the-art waveforms derived from three-dimensional numerical CCSN simulations, with a particular focus on optimizing performance for low-latency cWB operations.

Poster Sparkler / 44

Online infrastructure for detecting the presence of the Standing Accretion Shock Instability in CCSNe GW candidates

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Core-collapse supernovae are exploding massive stars and the next Galactic event will be one of the most interesting astronomical events of the century. In recent paper (Phys.Rev.D 107 (2023) 8, 083017), the authors developed an algorithm for assessing the presence of standing accretion shock instability (SASI) in simulated gravitational waves in a core-collapse supernova, the so-called SASI-meter. In this poster we discuss the implementation of an online module to coherent WaveBurst high significance events with the purpose of assessing the presence of SASI. We discuss the computational times, receiver operating characteristic curves and results on noise only events.

Poster Sparkler / 45

Core-collapse supernova gravitational-wave data representation

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Core-collapse supernovae (CCSNe) are exploding massive stars and the next Galactic event will be one of the most interesting astronomical events of the century. While these events are violent, the gravitational field is still relatively weak. Unlike the compact binaries with strong field regime where gravitational waveforms are given as spherical-harmonic modes in the Newman-Person formalism. It's natural to use quadrupole approximation to represent gravitational waves from CCSNe. However, the way of extracting and representing the gravitational wave data vary between CCSN simulation groups. We compare some of these approaches, primatily the the quadrupole approximation with the that is used for extracting gravitational waves from compact binaries. We study what data format would be suitable to store the gravitational wave data.

Theory / 46

Theory Lecture 1

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Theory / 47

Theory Lecture 2

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Detection / 48

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Detection / 49

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Neutrino / 50

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10 years / 54

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56

Predicting Gravitational Waves: from before collapse to after explosion

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58

Roles of self-induced neutrino flavor conversions in core-collapse supernova theory

59

Core collapse with rotation and magnetic fields: explosion, compact remnants, observables

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60

From Bounce to Beyond Breakout: A Theoretical Study for the Transient Sky

61

Understanding proto-neutron star oscillations in core-collapse supernova

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62

Search for Gravitational Waves emitted from Core Collapse Supernovae

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63

Data analysis for Supernova search: A focus on multimessenger approaches

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64

Supernova gravitational waves and protoneutron star asteroseismology

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65

The joint analysis of core-collapse supernovae physics using neutrino and gravitational wave signals

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66

Presupernova Evolution of Massive Stars: Current Status and Future Directions

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67

Neutrino signal from (long-term simulations of) core-collapse supernovae

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68

Core Collapse Supernova Modelling and Gravitational Wave Prediction: Perspectives from the UT-ORNL Group

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69

Signals from White Dwarfs Collapsing to Neutron Star

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Poster Sparkler / 70

3D numerical study of gravitational-wave signatures from magnetorotational effects in extreme core-collapse supernovae.

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Core-collapse supernovae are among the most energetic explosions in the universe. Their evolution is shaped by hydrodynamics, neutrino transport, and magnetic fields at work in the first seconds after collapse. We investigate these processes through 3D simulations of an extremely compact 39 Msun progenitor using the FLASH M1 magnetohydrodynamics code. Our study explores three models –a non-magnetized non-rotating baseline model, a non-magnetized rotating model, and a

magnetized rotating model –to highlight the roles of rotation and magnetic fields in shaping the explosion mechanisms and associated gravitational-wave (GW) and neutrino signatures.

We evolve each model from core collapse through bounce into the early post-bounce phase. We employ a three-species, energy-dependent M1 moment scheme for neutrino transport, incorporating a state-of-the-art nuclear equation of state and advanced treatments of deleptonization and neutrino heating/cooling. All models undergo similar gravitational collapse and bounce. However, during post-bounce, rotation and magnetic fields significantly impact the shock dynamics, explosion morphology, protoneutron star evolution, and variations in neutrino emission.

We specifically analyze GW signals derived from quadrupole moment calculations and neutrino emission asymmetries, emphasizing how rotation and magnetization distinctly shape these signals. We highlight key features in the GW emission patterns, such as frequencies, amplitudes, and time evolution, that could aid observational identification of magnetorotational effects. Our results underscore the potential of GW astronomy to differentiate magnetorotationally influenced explosions from more spherical scenarios. Future work will extend our gravitational wave analysis by refining neutrino microphysics, incorporating full general-relativistic treatments, and exploring a broader range of progenitor conditions.