61st Karpacz Winter School of Theoretical Physics and ChETEC-INFRA Training School – "Multi-messenger nuclear astrophysics in the 21st century"

Saturday 01 March 2025 - Friday 07 March 2025

Artus Hotel

Lecturers and topics

Nuclear reaction measurements with unstable nuclei

Lecturer: Daniel Bemmerer (Helmholtz Centre Dresden-Rossendorf & University of Dresden, Germany)

Lecture 1: Big-bang nucleosynthesis

Lecture 2: Nuclear physics of the sun

Explosive nucleosynthesis - Formation of heavy elements in core-collapse supernova explosions

Lecturer: Carla Fröhlich (North Carolina State University, USA)

Metal poor star observations

Lecturer: Camilla Hansen (University of Frankfurt, Germany)

Recommended software for the stellar spectroscopy:

Stellar Analysis Pipeline webSME http://websme.chetec-infra.eu/

IRAF: https://iraf-community.github.io/install.html

SUPPNET for normalisation: https://github.com/RozanskiT/suppnet https://rozanskit.com/suppnet

Simulations of compact binary star mergers

Lecturer: Kenta Hotokezaka (Tokyo University, Japan)

Lecture 1, Birth to merger of binary neutron stars

Neutron star mergers produce strong gravitational-wave signals, r-process elements,
gamma-ray bursts, and other electromagnetic emission across multi-wavelengths. The first lecture will cover the nature of binary neutron stars known in the Galaxy, the mergers detected by the LIGO/Virgo detectors and other related astrophysical phenomena. We will also discuss the basics concepts of gravitational-wave emission of compact binaries and electromagnetic counterparts of the first neutron star merger, GW170817.

Lecture 2, Dynamics of mergers and post merger phenomena

Numerical relativity simulations predict rich phenomena in mergers including mass ejection, formation of hyper/supermassive neutron star, jet formation. We will review the methods of numerical simulations and the results. We will discuss the jet propagation inside merger ejecta and gamma-ray bursts.

Lecture 3, Kilonova

R-process elements produced in merger ejecta power UV-optical-IR transients, kilonovae. We will learn the key ingredients of the kilonova radiation modelings such as the radioactive heating and opacity, and how to calculate light curves.
We will discuss the elemental identifications from kilonova spectra.

Observing cosmic gamma rays

Lecturer: Roland Diehl (Max-Planck Institute for Extragalactic Physics, Garching, Germany)

Lecture 1: Cosmic nucleosynthesis and astronomical tools

Nucleosynthesis in cosmic sites occurs under extreme environmental conditions. These often prevent observational access, from overlying matter that absorbs any direct signals, or from the extreme conditions where different messengers appear.
We discuss the direct and (mostly) indirect ways one may be able to record signals about cosmic nucleosynthesis. Herein, we will discuss how one may address the inherent experimental difficulties and observational biases.

Lecture 2: Gamma-ray astronomy: Profile of a difficult experimental-physics field

Gamma-ray telescopes have been established in the recent decades. With the prospect
of rather direct observations of cosmic nucleosynthesis signals, hopes were great
50 years ago. But we will discuss the experimental difficulties that are faced by the different telescope designs, and present the two legacy space missions together
with future prospects of this field of astronomy

Lecture 3: Lessons from gamma-ray spectroscopy

As one example of the astronomy of cosmic nucleosynthesis, we present the measurements made in gamma rays from radioactive decays of short-lived isotopes that are a by-product of nucleosynthesis processes in cosmic sites. We discuss what has been learned about stars and stellar explosions, and how their ejecta are distributed towards next-generation star formation.

Galactic chemical evolution

Lecturer: Chiaki Kobayashi (University of Hertfordshire, UK)

Lecture 1: Galactic chemical evolution

Stars are fossils that retain the history of their host galaxies. Carbon and heavier elements are created inside stars and are ejected when they die. Iron-peak elements are further produced by Type Ia supernovae. Elements heavier than iron (such as gold) can also be produced by neutron star mergers, but they alone cannot explain the observed "r-process" elements in the Milky Way. Thanks to Gaia satellite and multi-object spectrographs on ground-based telescopes, kinematics and detailed elemental abundances are available for stars in the Milky Way.

Theoretically, the evolution of elements in a galaxy can be calculated with Galactic chemical evolution (GCE) models. After explaining the basic equations of so-called ‘one-zone’ model, I will show how to constrain the models for the Milky Way, and summarise the origin of elements. Then expanding the model to include hydrodynamics and cosmological growth, I will show how chemical enrichment takes place inhomogeneously in a galaxy, and discuss the spacial distribution of elements within the Milky Way.

lecture 2: Cosmic chemical enrichment

The James Webb Space Telescope allowed us to study elemental abundances across cosmic time. I will first show some latest observational results comparing to one-zone GCE models. I will start from the Andromeda Galaxy M31, where it is possible to measure some elements of planetary nebular, HII regions, and some red giant stars, then to distant galaxies beyond redshift 10 - only 400 Myrs after Big Bang.

Finally using cosmological chemodynamical simulations, I will show how chemical enrichment takes place inhomogeneously in the Universe depending on galaxy mass (the mass-metallicity relation) and location within galaxies (metallicity radial gradients). I will end the lectures with future prospects including missing nuclear astrophysics that might be important in the early Universe.

Nuclear astrophysics challanges in core collapse supernova simulations

Lecturer: Takami Kuroda (Max Planck Institute for Gravitational Physics Potsdam, Germany)

Lecture 1: Core-collapse supernovae and their diversity

Core-collapse supernovae (CCSNe) are one of the most explosive events in the universe, which leave behind various relativistic compact stars: neutron stars, black holes, and possibly other more exotic stars such as hybrid stars. The variety of these remnant types relies on yet-to-be-understood various supernova explosion mechanisms governed by the four fundamental forces of nature: the strong, weak, electromagnetic, and gravitational forces. At the same time, CCSNe emit copious amounts of neutrinos and sizable gravitational waves, and may also eject huge amounts of radioactive elements, which illuminate the universe. These facts make CCSNe fascinating observational targets particularly in the era of multi-messenger astronomy. I will first review the basics of CCSN mechanisms and then introduce the recent progress in various CCSN explosion scenarios.

Lecture 2: Multi-messenger signals from CCSNe as probes to nuclear physics

In the latter part, I will discuss how each explosion scenario imprints its distinct features into the emergent multi-messenger signals, with a particular focus on the impacts of nuclear physics inputs.

Observational night and hands-on stellar spectroscopy

Lecturer: Tiina Liimets (Tartu Observatory, Tartu University, Estonia)
Brankica Kubatova (Ondřejov Observatory, Czech Republic)

"Observing in a nutshell – NOT”

We will be giving an overview of the Nordic Optical Telescope (NOT) as well as the spectrograph FIES we are going to use in our observing night. In addition, the lecture will contain information how to prepare for the observing night.

Learning outcome: How to prepare and perform modern spectroscopic observations, in order to deduce stellar properties such as surface temperature and abundances.

Spectroscopy software: ANACONDA and/or IRAF/pyraf