High-energy phenomena in relativistic outflows IX

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Abstract book

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Invited Reviews

Radiation-driven outflows

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We introduce recent progress in the study of radiation-driven outflows around black holes, with a focus on insights gained from numerical simulations. Radiation hydrodynamic and radiation magnetohydrodynamic simulations have demonstrated that powerful outflows are launched from accretion disks via radiation pressure due to electron scattering. Black hole spin enhances the outflow power and, under certain conditions, induces precession of both the disk and the outflow. The simulations also reveal that the outflows can fragment into numerous gas clumps, in a manner consistent with recent XRISM observations. In addition, line-force-driven outflows—launched by radiation pressure through line absorption—have been actively investigated. We also highlight recent developments in understanding the dynamics and observational signatures of such line-driven outflows.

X-Ray Polarization in Blazars

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The Imaging X-Ray Polarimetry Explorer (IXPE), launched in December 2021, has opened a new window on relativistic jets. In this talk, I will review results of IXPE and co-ordinated multi-wavelength observations of blazars. Highlights are the strong evidence for a leptonic origin of the high-energy emission in low-synchrotron-peaked blazars as well as indications of energy stratification in the jets of high-synchrotron-peaked blazars. Unexpected results, such as polarization-angle swings in the optical without corresponding counterpart features in X-rays, and vice versa, continue to pose new puzzles.

LHAASO highlight results

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LHAASO is a hybrid detector experiment, its full array start operation in July 2021, becoming the leading Ultra-High-Energy (UHE) gamma-ray detection facilities with the highest detection sensitivity and all-sky monitoring capability in the world. The detector operates very stably and has collected a large amount of high-quality data sets. LHAASO has found more than 40 Ultra-High-Energy (UHE) cosmic accelerators within the Milky Way, with the highest energy photon reaching 2 quadrillion electron-volts, the highest energy photon ever observed. So many UHE gamma ray celestial body exit in our galaxy, prompting us to rethink the mechanism by which high-energy particles are generated and propagated in the Milky Way. It will also allow scientists to explore extreme astrophysical phenomena and their corresponding processes, thus enabling examination of the basic laws of physics under extreme conditions. Multi-parameter

observation of showers allows LHAASO to measurement the single elements energy spectrum, elemental composition and anisotropy with high resolution, which give us an excellent opportunity to understand the origin, acceleration and propagation of high energy cosmic rays. In this presentation, I will introduce the current status of LHAASO's discoveries in UHE gamma ray sources and cosmic ray measurements. I will also introduce the future plans and prospects of LHAASO experiment.

Jet Physics

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In this talk, I will review the recent advances in our understanding of jet physics that have been made possible by general relativistic magnetohydrodynamic simulations. In particular, I will review the formation, stability, and propagation of jets produced by thin, tilted, and self-consequently formed disks.

High-energy emission from GRBs The Fermi legacy

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Gamma-Ray Bursts (GRBs) are the most powerful explosions in the Universe. Their emission spans the entire electromagnetic spectrum, from radio waves to TeV energies, and has been studied since the 1970s by numerous space- and ground-based observatories. The Fermi Gamma-ray Space Telescope has been one of the leading instruments in GRB research over the past 17 years, providing unique insights into their nature. With thousands of GRBs detected by the Gamma-ray Burst Monitor (GBM) and hundreds by the Large Area Telescope (LAT), we have gained a comprehensive understanding of the high-energy properties of GRB populations, as well as valuable information on their emission mechanisms and physical characteristics. In this talk, I will highlight key aspects of GRB science across the energy range from low (keV) to high (GeV) energies, along with the most recent observations of very high-energy (TeV) emission, with a special focus on GRB 221009A, nicknamed "The BOAT´´ — short for Brightest Of All Time — a record-breaking event that is considered the brightest and most energetic GRB ever observed in over 50 years of gamma-ray astronomy."

PeVatrons in the Milky Way

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I will highlight the recent discovery of tens of Ultra High Energy (UHE: E ¿ 100 TeV) gamma-ray sources scattered across the Milky Way, and exhibiting a remarkable diversity in form and scale. They associate with at least four galactic source populations - Pulsar Wind Nebulae, Supernova Remnants, Stellar Clusters, and Microquasars, which gives optimism for solving the century-old mystery of the origin of Galactic Cosmic Rays. At the same time, these unexpected findings challenge conventional models of particle acceleration, particularly our understanding of the most extreme cosmic ray factories in the Galaxy — the Electron and Proton PeVatrons.

Invited Talks

Mapping Highly-Energetic Messengers throughout the Universe

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Cosmic rays prove that our Universe hosts elusive astrophysical "monsters" capable of continuously and efficiently accelerate particles at extreme energies. High-energy photons and neutrinos may provide the ultimate key to decipher the mystery of cosmic rays. Amongst the most promising neutrino candidate sources of high-energy neutrinos there are active galactic nuclei, and in particular blazars which host a relativistic jet pointed towards us. However, to date there is neither a consistent picture for the physical mechanism nor a theoretical framework capable of convincingly explain the full set of multi-messenger observations. This contribution presents initial encouraging steps in one of the foremost challenges in the astrophysics and multi-messenger fields, i.e. identifying the sources of extragalactic neutrinos, and discusses the latest status of the field.

Jets in microquasars

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The most spectacular jets are observed from active galactic nuclei, in particular, from quasars. However, highly interesting jets are also launched by accretion flows in stellar binaries containing a normal star accreting onto a stellar-mass black hole. Such systems are analogs of quasars on a much smaller scale and are called microquasars. There are two distinctly different types of jets in microquasars. Jets of the first type are steady and are launched during accretion states characterized by hard X-ray emission. They are launched over weeks to months but are observed only up to maximum distances of about 1/1000 of a parsec. Those of the other type are launched on time scales of only a day during transitions of the accretion flow from the hard to soft spectral states but are observed as moving blobs up to a parsec scale, i.e., up to 1000 times larger distances. I will discuss possible causes of this difference, the jet emission mechanisms, collimation, the presence of electron-positron pairs, magnetic fields, bulk Lorentz factors, and the jet power.

Pushing the limits of optical polarimetric monitoring of blazar jets

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Polarization variability can be the pathway to understanding the magnetic field evolution and particle acceleration processes in astrophysical jets. However, the systematic monitoring and the high-cadence observations required to make progress have been scarce. I will discuss results from past and current optical polarization monitoring of gamma-ray bright blazars using RoboPol at the Skinakas observatory on diverse timescales, as well as on-going synergies with radio and X-ray polarimeters to probe the physical processes in the largest particle accelerators in the Universe.

Jet-star interactions and their implications on the current paradigm of extragalactic jets

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Relativistic jets launched by active galactic nuclei decelerate as they propagate through their host galaxies, ultimately interacting with the interstellar or intergalactic medium at hotspots or forming plumes, depending mainly on their power. Although mass loading is the accepted scenario, identifying the dominant physical processes behind this deceleration — instabilities at the jet boundary or interactions with stars — has been a key theoretical challenge over the last few decades. While stellar winds alone are generally insufficient to slow down powerful jets, cumulative interactions with stars of various masses and evolutionary stages, including supernovae, may significantly alter jet dynamics.

In this talk, I will present results from relativistic hydrodynamic and magnetohydrodynamic simulations of jet-star and jet-supernova interactions, highlighting their role in driving shock formation, entrainment, and energy dissipation. From this, I will further discuss a scenario in which we studied multiple interactions between jets and red giants. These interactions may not only affect large-scale jet structure but also trigger localized acceleration of electrons and protons, producing non-thermal emission, and could also represent scenarios for the production of high-energy neutrinos via photo-hadronic processes. Using the radiative transfer code RIPTIDE, we model the resulting multi-wavelength and multimessenger signatures of these interactions. Finally, I will discuss how these mass-loading processes inform our understanding of FRI jet deceleration and place them within the broader context of AGN unification and jet theory.

Multi-messenger emission from choked jets in collapsars

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The death of massive stars is accompanied by the formation of central and accreting compact

objects and the subsequent launch of relativistic jets. However, not all jets successfully drill their way out of the stellar envelope, which would result in gamma-ray emission. Unsuccessful jets, also known as choked jets, might still produce radiation at lower frequencies by dissipating the jet energy into a pressurized cocoon, which expands within the stellar envelope and eventually breaks out as a mildly relativistic outflow. Differently from photons, the emitted neutrinos would not be absorbed, possibly contributing to the cosmic flux of very-high energy neutrinos detected by IceCube. In order to investigate the radiation output of choked jets, we perform relativistic non-resistive MHD simulations of jets launched into collapsars and derive in post-processing analysis the secondary emission by accelerated particles at shocks, including multi-wavelength and neutrino spectra. Results will be shown for different configurations of the system.

Turbulent Magnetic Reconnection in Astrophysical Plasmas: 3D Dynamics, Relativistic Regimes, and Pathways to Particle Acceleration

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Magnetic reconnection is a cornerstone process for energy conversion in high-energy astrophysical environments, yet its dynamics are profoundly altered by the presence of turbulence. In this talk, I will present how three-dimensional turbulence fundamentally enables fast reconnection rates, independent of microscopic plasma parameters, both in the Newtonian and relativistic regimes. I will introduce the basics of reconnection physics, highlight the key role of driven and self-sustained stochastic turbulence, and demonstrate, through numerical results, the critical impact of realistic 3D turbulent structures compared to kinetic-scale instabilities. Emphasis will be placed on the transition to relativistic turbulent reconnection and the resulting implications for particle acceleration, particularly the emergence of first-order Fermi processes within the reconnection layer. These insights are essential for understanding energy release and non-thermal particle production in systems such as relativistic jets, pulsar winds, and gamma-ray bursts.

PeVatron Sources in the Galaxy

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In recent years, many gamma-ray sources with energies above 100 TeV have been reported. The search for Galactic cosmic-ray accelerators goes hand in hand with these discoveries. In many of the reported sources, the origin of the particles responsible for the gamma-ray emission remains

unclear. Often, multiple candidate sources exist within the observational confidence region. In this talk, I will briefly discuss the different classes of Galactic sources that could be responsible for the observed very high-energy radiation. Then, I will focus the discussion on the nature of three specific PeVatron candidates.

Recent progress in FRB theory

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Fast Radio Bursts (FRBs) are among the most intriguing astrophysical phenomena discovered in the past two decades. These millisecond-duration pulses of intense and coherent radio emission have motivated extensive theoretical and observational efforts aimed at uncovering their origin. Despite the progress, the physical mechanisms behind the coherent emission remain a matter of active debate. In this talk, I will briefly discuss the current state of theoretical models proposed to explain FRBs. I will then focus on a specific scenario in which the coherent radio emission is generated within the magnetosphere of a neutron star–motivated by the recent association of an FRB with a galactic magnetar. In this model, an expanding plasma interacts with an electron-positron pair wind, and the velocity differences between the plasmas lead to the formation of electrostatic cavities via plasma instabilities. Particle-In-Cell (PIC) simulations provide insights into the size of the cavities and the characteristics of the electrostatic fields. Under certain conditions, electrons from the pair wind can radiate coherently as they traverse these cavities, potentially accounting for the observed properties of FRBs.

Particle acceleration in relativistic jets

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Observations have shown that high-energy (HE) and very-high-energy (VHE ¿ 100 GeV) emissions are present in relativistic astrophysical jets, and that show the existence of particle acceleration, the study of these emissions can help us understand the acceleration mechanisms that these particles may be suffering. It is believed that in these jets within active galactic nuclei the particles get accelerated to extreme speeds via Fermi-type acceleration, mainly along the magnetic field lines. In this talk, I will present the results of simulations of test particle acceleration in relativistic jets, especially by magnetic reconnection. Also I will show an analysis of the emission energy of different VHE sources focuses in radio galaxys.

Accretion and Jets with the EHT

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Over the past few years, we have obtained an unprecedented view of black hole accretion and jets with high-resolution mm-wavelength observations from the Event Horizon Telescope (EHT). Not only has the EHT imaged Sagittarius A* and the black hole in M87, we also produced images of the jets launched by more distant active galactic nuclei. I will review some of the Event Horizon Telescope results and discuss how they may inform our understanding of jet and accretion physics. Time permitting I will also discuss some recent and upcoming theoretical studies of jet dynamics.

Particle transport in outflows and jets

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Outflows and jets are ubiquitous at several scales throughout the Cosmos. They often develop extended structures characterized by strong shocks and turbulence where high-energy particles can be efficiently produced. I will discuss the particle transport in these objects and I will especially focus on diffusive shock acceleration as a key acceleration mechanism. I will finally show some model applications with particular emphasis on the maximum energy of accelerated particles and the associated multi-messenger implications in terms of high-energy photons, neutrinos and escaping cosmic rays.

Gamma-ray binaries: recent observational results

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In the last 20 years, very-high energy gamma rays have been detected in different types of binary systems, including gamma-ray binaries, X-ray binaries, colliding-wind binaries and novae. Owing to the nature of the two components in these binaries, different scenarios have been considered for particle acceleration, gamma-ray emission and aborption processes. In this talk I will review our current knowledge and understanding of gamma-ray emitting binaries, with a special focus on recent results and on gamma-ray binaries.

Magnetized Turbulence Powering the Universe's Most Energetic Particles

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In this talk, we will explore how turbulence efficiently accelerates particles in highly magnetized plasmas and examine its relevance to the origin of high-energy cosmic rays. Using first-principles kinetic simulations, we show that reconnecting current sheets embedded within the turbulent

cascade act as injection sites, enabling particles from the thermal pool to enter a stochastic acceleration process driven by large-scale turbulent fluctuations. Scattering off these fluctuations energizes particles on a fast timescale. Beyond the particle energy spectrum, we will highlight how the particle distribution develops a pronounced pitch-angle anisotropy, particularly among the accelerated electrons. We will discuss how magnetized turbulence provides a physically grounded mechanism for understanding the production of ultra-high-energy cosmic rays and other nonthermal particle populations in astrophysical plasmas.

Contributed Talks

Unusual Changes in the Orientation of the Radio Jets of GRS 1915+105

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The hard X-ray transient GRS 1915+105 is the prototype of galactic microquasars. Its radio outbursts produce double-sided relativistic ejections of plasma clouds that show superluminal transverse motions. Since 1994 the position angle of these ejecta was consistent with $148^\circ \pm 8^\circ$, suggestive of modest or no precession effects. Unexpectedly, new Very Large Array observations taken in 2023 show a position angle of $174\overset{\circ}{.}3 \pm 0\overset{\circ}{.}5$, discrepant with the historic values. Our analysis indicates that during 2023 the plane of the disk was aligned with the line of sight, accounting for the X-ray obscure state present in that epoch. More recent VLA observations obtained in 2024 show a return of the position angle to the historic values. Future radio observations are needed to establish the nature of this phenomenon. We speculate that these abrupt changes could be due to the presence of an undetected eccentric tertiary component in the system, that may be revealed in high quality infrared observations.

Probing radio-quiet AGN feedback: Insights from ASKAP and GAMA

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Observational studies confirm that radio-loud AGN strongly influence and quench the host galaxy star formation. However, we have only scratched the surface in understanding the feedback mechanism of radio-quiet AGN. Are the quieter counterpart powerful enough to impact the host galaxies production of stars? With the last generation of interferometers, we are now able to investigate fainter radio sources and make statistical analysis on the interaction between radio- quiet AGN and their host environment. We conduct a multi-wavelength analysis of selected radio-quiet AGN using deep ASKAP radio surveys across multiple GAMA fields. This allows us to exploit one of the SKA Pathfinder instruments to investigate the connection between radio emission and the [OIII] optical line. We examined whether radio emission correlates with outflow signatures, offering insight into the role of low- power jets in AGN feedback. Additionally, we assess the potential influence on the SMBH on these constraints. I will present our data selection process and preliminary statistical analysis on the link between [OIII] outflows and radio emission, discussing the implica- tion of SKA on future studies. In fact, thanks to the deepest data ever achieved over large areas, SKA will enable the detection of larger samples of AGN at much lower luminosities, significantly advancing the statistical studies on radio-quiet AGN feedback.

Radiation Propagation in Astrophysical Relativistic Jets

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Astrophysical relativistic jets, such as those emitted by active galactic nuclei and gamma-ray bursts, present extreme environments where radiation propagates through magnetized, relativistically moving plasmas. In this presentation, we explore the dispersion relations governing electromagnetic wave propagation within such jets, emphasizing the role of plasma frequency, refractive index, and relativistic velocity effects. Starting from a general dispersion equation that accounts for the jet's high-speed motion and internal plasma structure, we analyze the solutions under relativistic approximations. Special attention is given to how these solutions deviate from classical results, the emergence of anisotropies due to bulk motion, and the influence of Lorentz transformations on wave behavior. The resulting refractive indices provide insight into wave-particle interactions, signal propagation, and observational signatures such as polarization and spectral shifts. This study contributes to a deeper understanding of how radiation travels through jets and supports efforts to interpret high-energy astrophysical observations.

Microquasar remnants as PeVatrons

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The Large High Altitude Air Shower Observatory (LHAASO) has recently detected several ultrahigh-energy gamma-ray sources whose nature remains unclear. We propose that some of these sources may be remnants of microquasars (MQs) capable of producing cosmic rays (CRs) up to several PeV. These microquasar remnants (MQRs) are systems where mass transfer from the companion star to the black hole has permanently stopped, effectively shutting down the central engine. However, if an MQR lies in a star-forming region, CRs injected during the MQ's active phase can still interact with dense clouds inside the giant cocoon that envelops the system. These interactions can produce gamma-ray emission through proton-proton collisions and the decay of neutral pions. In this talk, we present results on the feasibility of detecting these "afterlife" signatures of MQs, with a focus on electromagnetic radiation and CR production by MQRs, relics of extinct microquasars.

Two-component jet model for afterglow emission of very-high-energy gamma-ray bursts and implications for jet structure

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In recent years, afterglow emission in the very-high-energy (VHE) band above 100 GeV has been clearly detected for at least five gamma-ray bursts (GRBs 180720B, 190114C, 190829A, 201216C and 221009A). For some of these VHE GRBs, we previously proposed a two-component jet model, consisting of two uniform jets with narrow and wide opening angles to explain their multiwavelength afterglows including VHE gamma rays. In this talk, we show that the VHE gamma-ray emission of GRBs 201216C and 221009A can also be explained by our two-component jet model. We find that for the five VHE GRBs, the collimation-corrected kinetic energies of the narrow and wide jets have typical values. We discuss the similarities and differences among the VHE GRBs, and the implications for the structure of their jets. In agreement with previous studies, the narrow jet of GRB 221009A has an atypically small opening angle, so that its intrinsic energy remains within a plausible range despite the unusually large isotropic-equivalent energy. Furthermore, the properties of the observed afterglow emission can be explained by two top-hat jets propagating into a constant-density circumburst medium.

How do recollimation-induced instabilities shape the propagation of hydrodynamic relativistic jets?

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Recollimation is a phenomenon of particular importance in the dynamic evolution of relativistic jets and in the emission of high-energy radiation. Additionally, the full comprehension of this phenomenon provides insights into fundamental properties of jets in the vicinity of the Active Galactic Nucleus (AGN). Three-dimensional (magneto-)hydrodynamic simulations revealed that the jet conditions at recollimation favor the growth of strong instabilities, challenging the traditional view-supported from two-dimensional simulations-of confined jets undergoing a series of recollimation and reflection shocks. To investigate the stability of relativistic jets in AGNs at recollimation sites, we performed a set of long duration three-dimensional relativistic hydrodynamic simulations with the state-of-the-art PLUTO code, to focus on the development of hydrodynamic instabilities. We explored the non-linear growth of the instabilities and their effects on the physical jet properties as a function of the initial jet parameters: jet Lorentz factor, temperature, opening angle and jet-environment density-contrast. The parameter space is designed to describe low-power, weakly magnetized jets at small distances from the core (around

the parsec scale), but the results are broadly applicable due to the scale-invariant nature of the simulations. All collimating jets we simulated develop instabilities. Recollimation instabilities decelerate the jet, heat it, entrain external material, and move the recollimation point to shorter distances from the core. This is true for both conical and cylindrical jets. The instabilities, that are first triggered by the centrifugal instability, appear to be less disruptive in the case of narrower, denser, more relativistic, and warmer jets. These results provide valuable insights into the complex processes governing relativistic jets and could be used to model the properties of low-power, weakly magnetized relativistic recollimated jets.

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Repeated patterns of gamma-ray flares in blazars and their possible connection to neutrinos

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It has been demonstrated that at least 10% of the brightest blazars in the Fourth Fermi-LAT Catalog exhibit repeating patterns of gamma-ray flares — intervals in the light curve with non-trivial structures consisting of multiple flares that appear more than once. These events may be manifestations of a non-uniform sheath surrounding a fast jet spine in these blazars. Theoretical models suggest that such a sheath could facilitate neutrino production in these structured jets. In this talk, we report on newly discovered patterns in several additional blazars and briefly discuss the properties of the subclass of blazars exhibiting these events. Using high-energy neutrino detections from IceCube and Baikal-GVD, we demonstrate that these events often coincide spatially with a blazar undergoing a pattern of gamma-ray flares at that moment. We also present results from a Monte Carlo simulation evaluating the likelihood of accidental coincidences between the repeating flare patterns and neutrino events.

Particle acceleration in Ultra fast Outflows

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Ultra Fast Outflows (UFOs), wide-angle winds from Active Galactic Nuclei (AGN), have recently been identified through X-ray spectroscopy. These powerful outflows may play a significant role in the origin of high-energy cosmic rays. In particular, strong sub-relativistic shocks associated with UFOs can accelerate particles via Diffusive Shock Acceleration (DSA), producing Very High Energy Cosmic Rays (VHECRs) and Ultra High Energy Cosmic Rays (UHECRs). Interactions between these cosmic rays and dense circum-nuclear medium are expected to produce high-energy gamma rays and neutrinos. In this work, we model particle acceleration in UFO-driven shocks using DSA and estimate the resulting gamma-ray and neutrino fluxes. A semi-analytical framework was developed to predict these emissions and evaluate their de-

tectability with current and next generation observatories. Preliminary results, presented in a paper, indicate that certain UFOs—particularly nearby sources with high wind velocities (up to 0.4c)—could be observable in the very high-energy regime. If the accelerated particle spectrum is sufficiently hard and acceleration efficiency is high, these sources may produce detectable gamma-ray emission in the TeV range, even in the absence of GeV detections by Fermi-LAT. We aim to make predictions for best UFOs candidates, particularly in the TeV range, using CTAO and LHAASO for gamma rays and IceCube for neutrinos.

Dynamical and radiative impacts of jet-star interactions

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To fully understand the multi-messenger emissions from AGN jets, it is essential to connect their dynamics with the underlying physical processes. Recent numerical studies indicate that jet-star interactions significantly contribute to mass-loading the jet with protons. These interactions, coupled with local shock acceleration, can propel electrons and protons to high energies, facilitating the production of non-thermal emission and cosmic rays, including neutrinos. If perturbations are injected into the jet, this can temporarily increase the non-thermal emission during shock-shock interactions and allow the production of neutrino flares during shock-star interactions.

Using RMHD numerical simulations of jets and the post-processing radiative transfer code RIPTIDE, we show the role of protons on the dynamics of jets, non-thermal emission, and cosmic ray production. Specifically, protons affect jet dynamics through mass-load: at large scales, they dissipate kinetic energy, while at small scales, they are accelerated by shocks. Additionally, mass-load could play a significant role in structuring the multi-wavelength non-thermal emission from accelerated electrons along the jet and induce local, temporal production of very energetic neutrinos through the photo-pion process with stellar fields at small scales.

Our results are compared to multimessenger observations. At large scales, the structuring possibly induced by mass-load is observed by VLBI-Gaia observations, which show the presence of positive radio-optical shifts that depend on the AGN type and characteristics. At small scales, we compare our results with simultaneous multi-wavelength activities in blazar jets. The neutrino flux implied by jet dynamics in our simulations is to be compared with the sensitivities of neutrino detection facilities, particularly in light of the recent neutrino detection by KM3NeT.

From collapsars to gamma-ray bursts: exploring the variety of disc wind-driven explosions and gamma-ray burst afterglows

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Massive stars play a central role in high-energy astrophysics, yet they are not totally understood, especially their fate. They, in fact, distinguish themselves from lower mass stars by the events that can take place at their death. While the majority of stars will fade away as white dwarfs, massive stars with an initial mass $> 8M_\odot$ at the end of their evolution form a degenerate iron core which collapses into a proto-neutron star (PNS). This is the starting point for a complex sequence of events with many possible outcomes. Less to moderately massive stars (with $8 < M < 16M_\odot$) are expected to undergo an explosion during the PNS phase as core-collapse supernova (CCSN), whereas more massive stars ($M > 16M_\odot$) may fail to launch a successful shock, hence leading to a final collapse forming a black hole (BH). This event is known as "failed supernovae". The failed collapse could represent the end of the phenomena, unless another ingredient is added: the rotation. In case the progenitor is a massive rotating star, an accretion disk can be formed around the BH, in turn generating a disk wind. This wind can be the source of a super energetic explosion with an energy $E_{\rm expl} > 10^{52}$ erg and has been found to be rich in 56Ni. In this collapsar scenario the properties of the ejecta and the 56Ni production are strongly related to the wind injection from the accretion disk and these properties had not yet been studied in a systematic manner until our latest work. Moreover these collapsar-driven explosions are associated with broad-lined Type Ic supernovae (Ic-BL SNe) and, in some cases, long gamma-ray bursts (GRBs).

Understanding the nature of these explosions requires detailed numerical modeling, capturing the formation and evolution of the central engine, the propagation of relativistic outflows, and the resulting observational signatures. In this talk, I will present our last study of the ejecta generated by the collapse of rotating massive stars, with a focus on the late-phase mass ejection after BH formation. I will do that by systematically exploring the effects of progenitor mass, rotation, and the properties of the injected wind on the dynamics of the ejecta and the production of 56Ni . This study is based on several two-dimensional hydrodynamics simulations of axisymmetric models of the ejecta generated by the collapse of rotating massive stars performed using the code Athena++. Based on the collapsar scenario, we assume an explosion powered through a BH-accretion disk system and investigate the impact of the disk mass and energy injected from the system on the final ejecta.

We find a tight correlation between Eexpl and Mej and a bimodality of the explosions energy that I will explain in my talk. I will support our results with comparison to the observational data.

I will also discuss about the Python code I developed to model the afterglow emission in long GRBs that synchrotron radiation, inverse Compton scattering, adiabatic cooling, and pair production and has been included in the published C++ code PyBlastAfterglow.

By mapping the parameter space of collapsar-driven explosions, our study sheds light on the conditions required to produce highly energetic supernovae and GRBs. We find that the diversity in explosion properties observed in broad-lined Ic SNe can be naturally explained by variations in the accretion disk characteristics and progenitor structure. Our models also suggest a possible link between long GRBs and failed SN. By extending our models to different initial conditions and varying key parameters, we aim to establish a more comprehensive understanding of the pathways leading to extreme stellar explosions. Our work provides a theoretical framework to interpret current and future observations, offering predictions that can be tested with upcoming surveys and multi-messenger facilities.

Neutron star kicks in magnetorotational supernovae

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Rapidly moving neutron stars are believed to gain high linear velocities – kicks – in aspherical supernova explosions. The mechanism of the kick formation is probably connected with anisotropic neutrino flash, and/or anisotropic matter ejection during the explosion. In this work, we numerically investigate a neutron star kick origin due to a recoil effect in a magnetorotational (MR) supernova explosion model. The simulations have been done for a series of core collapse supernova models of a massive star with rotation and initial equatorially asymmetric magnetic fields. We have conducted 2D MHD simulations, considering the kick of a protoneutron star and explosion properties in three different asymmetric magnetic field configurations, namely in presence of multipoles composition in the core, an offset dipole field, as well as a superposition of dipolar and toroidal fields. The simulations show that in the MR supernova model protoneutron star kicks are formed with velocities up to 500 km/s during 1 second after the core bounce, due to asymmetric matter ejection in jet-like outflows, which may explain the observed kick velocities.

An Observational Test of the ULX Nature of SS 433

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The X-ray binary SS 433, a Galactic microquasar, has been hypothesized to be an ultraluminous X-ray source (ULX) like those observed in nearby galaxies. It is well known that the compact object emits oppositely directed semi-relativistic jets that carry a much larger kinetic power than observed radiatively in the X-ray band. Much of the radiative power may be obscured from our view, which would link SS 433 to ULXs. SS 433 has extended X-ray emission, like Sy 2s where the extended gas is photo-excited by the obscured nuclear X-ray emission. We carried out regular Chandra imaging of the arc-second scale extended emission over a period of several months for comparison to the continuum flux monitored with Swift. The extended emission appears to show structure that has not been previously observed.

1FLAC: a Firmamento-based catalog of AGN in Fermi-LAT high Galactic latitude γ-ray sources

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We present the results of a study on high-Galactic latitude γ-ray sources from the Fermi-LAT 4FGL-DR4 catalog, focusing on the search for blazar and other AGN counterparts. The work, carried out independently of the Fermi-LAT team, was performed using Firmamento, a web-based platform designed for the discovery and detailed analysis of multi-frequency sources. The main goal is to provide a new evaluation of the AGN counterparts of 4FGL-DR4 γ-ray sources, utilizing novel methods and taking advantage of recently released multi-frequency data. Our results agree with those of the Fermi-LAT catalogs, 4FGL-DR4 or 4LAC-DR3, in over 85% of cases. However, though limited in percentage, the discrepancies are of considerable importance. In particular, we have been able to find robust blazar identifications, based on unambiguous SEDs, for 415 previously unassociated γ-ray sources, reducing the fraction of still unidentified extragalactic Fermi-LAT sources by approximately one third, to 17.2%. Additionally, for 62 sources we found a more reliable association than in 4FGL-DR4, and in 51 cases we were unable to confirm the 4FGL-DR4 identification. Using machine learning and infrared-based-methods, we estimated the synchrotron peak energy and peak flux of the Spectral Energy Distribution of the blazar counterparts in a consistent and automated manner, minimizing human intervention. Most of our peak energy estimates agree within a factor of a few with those in the 4LAC-DR3 catalog, but they deviate by two to four orders of magnitude for a few dozen sources. We named the catalog including all our results 1FLAC (First Firmamento LAT AGN Catalog), which will be available online via the Firmamento platform. The simplicity of use and the commitment to educational engagement of Firmamento enabled active participation from both graduate and undergraduate students in this project.

Relativistic Jet Propagation into Vacuum Simulated with the Godunov-Type SPH Method

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In this presentation, we analyze the acceleration of a stationary high-temperature gas into relativistic velocity using numerical simulations. The Special Relativistic Godunov Smoothed Particle Hydrodynamics (SRGSPH) method [Kitajima et al. 2025, revised] is employed to model the fluid as a collection of discrete particles (SPH particles), allowing the fluid motion to be tracked through the interactions between particles and their environment.

By leveraging the advantages of the SPH method—such as its ability to handle vacuum boundaries and large deformations—we investigate the dynamics of fluids expanding into vacuum, a

challenge for conventional grid-based methods. This study demonstrates the utility of SRGSPH in simulating jet formation from a high-temperature source and elucidates its acceleration mechanism into a vacuum.

Our findings offer valuable insights into the driving processes of relativistic jets, with implications for phenomena such as those observed in active galactic nuclei and gamma-ray bursts.

Analysis of the historical observations of Cygnus X-3 with the MAGIC telescopes.

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Cygnus X-3 is a microquasar consisting of a compact object of unknown nature and a Wolf-Rayet star, which orbit each other with a very short period of 4.8 hours. The compact object launches powerful jets that are an excellent site for particle acceleration up to relativistic energies. The presence of these relativistic particles, combined with the proximity to the star and its high luminosity, makes the conditions in the source very favorable for inverse Compton scattering of stellar photons by the jet electrons, resulting in gamma-ray emission. Cygnus X-3 has been detected in a broad frequency range, from radio to gamma rays above 100 MeV, although it has never been confirmed as a very-high-energy (VHE; above 100 GeV) gamma-ray emitter. Studies of microquasars in gamma rays have recently become a hot topic in the community after the LHAASO detection of four microquasars above 100 TeV, establishing these sources as potential contributors to the Galactic cosmic-ray spectrum at energies above the PeV. Due to the scientific interest of the source, the MAGIC telescopes have observed Cygnus X-3 in the VHE band since they became operational. In this contribution, we present a long-term analysis of 130 h collected by MAGIC between 2013 and 2024. This represents the largest available dataset (in both exposure and time coverage) at VHE to date, resulting in the strongest VHE upper limits of the source between 100 GeV and a few TeV. Both the temporal and spectral constraints of Cygnus X-3 during this 11-year period will be interpreted within the multi-wavelength context, providing meaningful constraints on the source properties based on its (lack of) emission in gamma rays at different energies.

On the Detectability of Electromagnetic Signatures from Galactic Isolated Black Holes

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A vast population of isolated stellar-mass black holes (IBHs) is expected to reside in the Galaxy, yet only one candidate has been confirmed through a microlensing event, and no electromagnetic detection has been reported so far. We investigate the detectability of their putative multi-wavelength emission, assuming accretion from the interstellar medium and the formation of an outflow. Using semi-analytical modelling, we simulate the accretion process, the impact of outflows on the surrounding medium, and the resulting emission from three key regions: the immediate accretion zone, the outflow-medium interaction structure (thermal and non-thermal), and the non-thermal radiation from relativistic particles diffusing in the environment. Our results indicate that IBHs traveling through dense media, such as molecular cloud cores, can produce detectable emission across the spectrum. In particular, accretion related emission could be observed in the mid-infrared and hard X-rays, while the outflow-medium interaction structure may be detectable in the radio and millimetre bands. Gamma-ray detection of diffusing particles is also plausible in dense environments. Applying our model to the IBH candidate from microlensing event MOA-2011-BLG-191/OGLE-2011-BLG-0462, we find that detection in the radio and infrared is feasible.

Plasmoid-Powered Relativistic Magnetic Reconnection in HBL Jets

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Relativistic Magnetic reconnection (RMR) is a rapid and very efficient and rapid mechanism to converting a magnetic field energy into particles' kinetic energy in relativistice jets of high-energy peaked BL Lacertae objects (HBLs), which form a majority among the extragalactic TeV-detected objects and represent bright X-ray sources. A fast RMR is capable of producing a self-similar chain of plasmoids, which can accumulate particles from the adjacent current sheets and grow in time. Meanwhile, the plasmoid interiors compress and amplify the internal magnetic field linearly with time, leading to particle energization and addition of a high-energy nonthermal tail to the existing electron energy distribution (EED). The cutoff energy of this tail increases linearly with time, sometimes to extremely large values depending on the process duration and produces an electron population capable of emitting synchrotron photons in the energy range beyond 10 keV. A plasmoid-dominated RMR can produce contemporaneous rapid variability/flare in the X-ray and TeV energy ranges, as observed in different nearby TeV-detected HBLs (Mrk 421, Mrk 501, 1ES 1959+650). According to time-dependent modeling, the plasmoid-powered gamma-ray flares can be observed as symmetric in the case the plasmoid is not changing in size rapidly.

A Novel Relationship Between Gamma Ray Burst Duration And Photospheric Radius

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Association of Long Gamma Ray Bursts (lGRBs) with jets in Type Ic broadline supernovae provides a theoretical framework for the jet formation from the core collapse of a massive star. It is traditionally assumed that GRBs are produced only if the jet successfully breaks out from the star, and the GRB duration ($t90$) is set by the jet engine activity duration ($t_{\rm eng}$) after the jet breaks out ($t_{\rm bo}$), that is, $t_{90} = t_{\rm eng} - t_{\rm bo}$. This disallows for $t_{90} > t_{\rm eng}$ and puts a lower bound on successful lGRB jet central engine duration ($t_{\rm eng} > t_{\rm bo}$), however, various numerical simulations have shown otherwise. In this talk, I will discuss aspects of the jet-stellar envelope interactions that may lead to lGRB durations deviating from the aforementioned relation. This study considers a photospheric GRB emission from a relativistic jet punching out of a Wolf-Rayet-like star. We generate bolometric lightcurves to calculate the lGRB duration (t_{90}) for varying engine duration, and compare them to the light crossing time for structures within the jet. I will present our results where we find significant photospheric radius (Rph) dependence on t_{90} for shorter jet engine durations ($t_{\rm eng} \sim t_{bo}$). However, for longer engine durations ($t_{\rm eng} \gg t_{\rm bo}$), the lGRB lightcurve reflects the jet profile and $t_{90} \approx t_{\rm eng}$. These can be modeled by a relation, $t_{90} = t_{\rm eng} + 0.03(Rph/c)$, where c is the speed of light, with a lower bound on t_{90} for a successful lGRB. I will conclude by discussing how this relation could be most relevant for possible low-luminous lGRBs originating from a collapsar with a central engine duration comparable to the jet breakout time.

Probing the disk-jet coupling in M87

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Due to its size and proximity, M87 represents a unique laboratory for testing theories about the origin of relativistic jets. Observations at 1.3 mm and 3.5 mm resolving the scales of the innermost accretion flow and jet formation in M87 have shown a disparity in the size of the ring, suggesting that non-thermal particles may play a crucial role at these scales, challenging our current understanding of jet-disk structures. To further investigate the effects of the non-thermal particles, we perform 3D general relativistic magnetohydrodynamic simulations including a population of accelerated non-thermal electrons parametrized by a kappa-distribution. We study the radiative signatures of the injected non-thermal electrons by solving the radiative transfer equations for synchrotron emission and by producing synthetic observations at multiple sub-mm VLBI frequencies tailored to current and future VLBI arrays. Our Bayesian analysis in Fourier space of the coupled jet-disk simulations is able to retrieve ring-like structures in the jet launching region consistent with those of the actual VLBI observations, 42 μas at 230 GHz and 64 μas at 86 GHz. We find that the variability of the accretion flow greatly impacts the perceived ring size at 86 GHz, pointing towards the importance of non-thermal particle

populations in testing theory against observations.

The polarization of the synchrotron radiation from a recollimated jet: application to high-energy BL Lacs

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Multifrequency polarimetry, recently extended to the X-ray band thanks to the Imaging X-ray Polarimetry Explorer (IXPE) satellite, is an essential tool for understanding blazar jets. High-frequency-peaked BL Lacs (HBLs) and extreme high-frequency-peaked BL Lacs (EHBLs) are especially interesting because the polarimetric properties of their synchrotron emission, extending up to the X-ray band, can be fully tracked by sensitive polarimetric measurements. We investigated the polarization properties of the synchrotron emission of these sources, starting directly from relativistic magnetohydrodynamic simulations of recollimated relativistic jets. To bridge the gap between fluid and kinetic scales, we elaborated a post-processing code based on the Lagrangian macroparticle approach, which models the spectral evolution and emission of non-thermal particles within the jet given the local fluid conditions. When comparing our results with early particle-in-cell (PIC) simulations, we find that shocks formed through jet recollimation are primarily superluminal, limiting particle acceleration in a laminar flow. However, recent PIC simulations suggest that acceleration can occur in the presence of small-scale turbulence or inhomogeneities even in superluminal configuration. In this case, we reproduce the observed polarization chromaticity (i.e. the polarization degree increases with frequency), along with a stable polarization angle between the X-ray and optical bands. This study sheds light on the role of recollimation shocks in blazar jets and supports the energy-stratified shock model as a plausible explanation for IXPE observations.

The Extreme Multi-Messenger Astrophysics of Collapsar Jets

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Collapsars are known to be the origin of GRB jets, black hole populations, and even potentially important r-process production sites in the early universe. I will present the first end-to-end 3D general-relativistic magnetohydrodynamic simulations of collapsar jets. I will demonstrate how such simulations open a new window to study profound astrophysical questions such as the origin and emission of GRBs, the natal properties of their black holes, the origin of black holes' strong magnetic field, collapsar r-process nucleosynthesis, and even new promising non-inspiral gravitational wave sources.

Constraints on Cosmic Rays Acceleration in Bright Gamma-ray Bursts with Observations of Fermi

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Gamma-ray bursts (GRBs) are widely suggested as potential sources of ultrahigh-energy cosmic rays (UHECRs). The kinetic energy of the jets dissipates, leading to the production of an enormous amount of γ-ray photons and possibly also the acceleration of protons. The accelerated protons will interact with the radiation of the GRB via the photomeson and Bethe-Heitler processes, which can initiate electromagnetic cascades. This process can give rise to broadband radiation up to the GeV-TeV γ-ray regime. The expected γ-ray flux from cascades depends on properties of the GRB jet, such as the dissipation radius $R_{\rm diss}$, the bulk Lorentz factor Γ, and the baryon loading factor η_p. Therefore, observations of Fermi-LAT can impose constraints on these important parameters. In this study, we select 12 GRBs of high keV-MeV fluence and constrain the baryon loading factor, under different combinations of the bulk Lorentz factor and the dissipation radius based on Fermi-LAT's measurements. Our findings indicate a strong constraint of $\eta_p < 10$ for most selected GRBs over a large parameter space except for large dissipation radii ($\gtrsim 10^{15}$ cm) and high bulk Lorentz factors ($\gtrsim 600$). The constraint is comparable to, and in some GRBs even stronger than, that from high-energy neutrinos for stacked GRBs. Our results suggest that for typical bulk Lorentz factor of several hundreds, the dissipation radii of GRBs need be large to avoid overshooting the GeV gamma-ray flux during the prompt emission phase of GRBs, which can be used to constrain GRBs.

Oblique Black Hole Magnetospheres: Implications for Accretion Flow Structure and Variability

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We present results from three-dimensional general relativistic magnetohydrodynamic (GRMHD) simulations that investigate the impact of magnetic field obliquity on accretion dynamics around a spinning black hole. Our simulations model a Fishbone–Moncrief torus accreting onto a Kerr black hole with spin parameter a = 0.9375, threaded by large-scale magnetic fields inclined at 30°, 45°, and 60° relative to the spin axis. We explore a range of plasma beta values ($\beta =$ 0.01–0.001) to assess how magnetic inclination affects disk morphology, magnetic field evolution, and angular momentum transport.

We find that increased magnetic obliquity induces significant tilt and warping in the inner disk, leads to asymmetric outflows, and drives time-variable accretion rates. These effects are amplified at lower beta values where magnetic pressure dominates. The simulations reveal dynamically evolving magnetic topologies, including current sheet formation and enhanced reconnection activity near the event horizon. Power spectral density (PSD) analysis of turbulent

fluctuations shows an alpha-profile consistent with magnetorotational instability (MRI)–driven turbulence, in agreement with observational trends.

Our results underscore the critical role of magnetic misalignment in shaping relativistic accretion flows and jet launching asymmetries. These findings have direct implications for interpreting variability, polarization, and jet orientation in black hole systems observed by facilities such as the Event Horizon Telescope.

Stellar Bubbles as Particle Accelerators: A Case Study of G2.4+1.4

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Strong stellar winds from massive, early-type stars have been suggested as capable of accelerating particles to very high energies. Intense shock waves are formed as the wind propagates and interacts with the interstellar medium, shaping the surrounding region into a stellar bubble. In some cases, part of the kinetic power of the shock contributes to the creation of relativistic particles. In 2019, Prajapati et al. reported the first detection of nonthermal radio emission from the stellar bubble G2.4+1.4, associated with an oxygen-rich Wolf-Rayet star. The observed emission is consistent with synchrotron radiation from relativistic electrons. Assuming the particles are locally accelerated at the termination shock, we have developed a detailed spatially extended model to estimate the nonthermal emission produced by both electrons and protons. Under very general assumptions, we obtained maximum energies for electrons of the order of TeVs and protons can reach hundreds of TeVs. In order to account for the observations, a high magnetic field (ca. 250 μG) is required. We obtained emissivity maps at radio, both thermal and nonthermal, and gamma energies. Our results support the idea that the winds of massive stars are efficient particle accelerators.

Particle Acceleration and Very High Energy Emission via Turbulence-Induced Magnetic Reconnection: from Micro to Macro Scales in Relativistic Jets and Accretion Flows

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Turbulence-driven magnetic reconnection is increasingly recognized as a key mechanism for accelerating cosmic rays (CRs) to very high energies (VHEs) in magnetized astrophysical environments, from compact objects to extended regions. In this talk, I will present an overview of this acceleration process and provide a comparative analysis of particle acceleration in 3D magnetohydrodynamic (MHD) and particle-in-cell (PIC) simulations. I will examine how cosmic ray acceleration operates across both microscopic and macroscopic scales, drawing on insights from 3D PIC kinetic simulations, hybrid 3D MHD-PIC models, and large-scale MHD simulations. While micro-scale (PIC) models are crucial for addressing the injection problem—the initial stage of particle acceleration—macro-scale MHD simulations help establish the maximum energies particles can achieve. I will highlight key similarities and differences between these regimes, their influence on acceleration rates and spectral properties, and how the transition from micro to macro scales shapes the overall acceleration process. Furthermore, I will demonstrate that particle acceleration in 3D turbulent reconnection is dominated by the Fermi process, rather than by drift acceleration. This mechanism efficiently propels particles to extreme energies and has significant implications for astrophysical systems such as AGN accretion disks and relativistic jets. I will conclude by discussing applications to the AGN sources TXS 0506+056, Mrk 501, and NGC 1068, which have been associated with very high energy gamma-ray flares and/or neutrino detections.

Beyond Fermi-II: Intermittent Particle Acceleration by Relativistic Turbulence in Astrophysical Plasmas

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Stochastic particle acceleration in turbulent plasmas plays a key role in shaping high-energy emission from relativistic outflows, such as those in Active Galactic Nuclei (AGN) and microquasars. While traditional Fermi-II models provide a foundational framework, they often oversimplify the complex nature of realistic magnetohydrodynamic (MHD) turbulence. Recent plasma simulations have revealed highly non-linear energization effects, such as sudden, large momentum jumps, that remain largely unexplored in astrophysical applications. We present a novel Monte Carlo framework that models particle acceleration as a continuous-time random walk (CTRW), capturing both intermittent energy gains and radiative losses. The stochastic evolution of particle momenta is driven by jumps with a random magnitude induced by interactions with multifractal MHD turbulence, with synchrotron and inverse Compton cooling incorporated in a self-consistent manner. Using our code, we explore a wide range of magnetic field strengths and turbulence parameters, simulating acceleration to the highest energies in AGN and microquasar jets. Our findings suggest particle spectra that exhibit sharp peaks, spectral curvature, as well as distinct low- and high-energy tails – features that differ significantly from those predicted by the standard Fermi theory. We compute the corresponding multi-wavelength spectral energy distributions (MWL SEDs), identifying distinct features that could serve as observational diagnostics for probing the nature of particle acceleration in relativistic jets.

Exceptional 2017 and 2018 flaring episodes of 3C 279

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The very bright Flat Spectrum Radio Quasar 3C 279 (z = 0.536) is the first source of this class to be detected at very high energy (VHE, ¿ 100 GeV) gamma-rays by MAGIC in 2006

and is known for its intense and rapid variability across all wavelengths, especially at highest energy gamma-rays, where the amplitude and variability timescales are most extreme. The High Energy Stereoscopic System (H.E.S.S.) telescopes observed 3C 279 as part of a Target of Opportunity program, triggered by the record optical and exceptional high energy (HE) gamma-ray flaring episodes of the source in 2017 and 2018, a few years after the first (re-)detection of the source at VHE with the H.E.S.S. array in 2015, where no VHE gamma-ray variability was found and standard one-zone lepto-hadronic radiative models failed to reproduce the complex MWL behaviour of 3C 279. During the strong VHE gamma-ray flare of 3C 279 in January 2018 a peak of 50% of Crab flux above 70 GeV was reached, that only lasted one day and was surprisingly delayed by more than one week with respect to the peak of the prominent Fermi-LAT flare. On the other hand, H.E.S.S. observations of June 2018 covered the Fermi-LAT peak and followed its decreasing part. We will present the temporal and spectral characterisation results of exceptional VHE - HE gamma-ray and MWL flares of 3C 279 in 2017 and 2018. They allow us to put significant constraints on the source that is known for orphan flares, dramatic changes in the optical polarization and complex MWL variability patterns that challenge our understanding of radiation processes in blazars in general.

A look into MAGIC Collaboration's 20-year history: an overview of the VHE blazar catalog and its related discoveries

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The Florian Goebel Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) is a stereoscopic telescope system in La Palma, Canary Islands. It is dedicated to observing Very High-Energy (VHE) gamma rays in the range of 50 GeV to a few TeV. Over more than 20 years of operations, MAGIC has contributed significantly to the study of extragalactic sources. Among them, we can mention distant Flat Spectrum Radio Quasars (FSRQs) such as 3C 279 ($z = 0.536$), and highly variable BL Lac objects like Markarian 501, which exhibited intranight flux variability in the order of minutes in 2005. MAGIC has also contributed to detecting new TeV-emitting extremely high-peaked BL Lacs (EHBLs, or extreme blazars), characterized by hard spectra and synchrotron peaks exceeding 10^{17} Hz. These observations at VHE gamma rays have increased our understanding of the astroparticle processes at the origin of blazars' extreme physics. A notable example is the blazar TXS 0506+056, for which MAGIC played a key role in the detection of Very High-Energy emission that was found in spatial and temporal coincidence with a high-energy neutrino event. This multi-messenger association was crucial to support the presence of complex lepto-hadronic interactions within the jets of blazars. This presentation offers a broad overview of the most impactful MAGIC campaigns on blazars, also providing highlights from ongoing projects and future perspectives in the field.

The low-luminosity radio galaxy NGC 4278 Fermi-LAT detection and SED modeling

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Gamma-ray observations have firmly established active galactic nuclei (AGN) as the dominant extragalactic sources in the high-energy sky, with blazars comprising the vast majority due to their jet alignment with the observer's line of sight. Conversely, radio galaxies—AGN with misaligned jets—remain rare, accounting for only 2% of AGN in the Fermi-LAT 4LAC-DR3 catalog and an even smaller fraction of TeV detections. The recent identification of TeV emission from the low-luminosity radio galaxy NGC 4278 by the Large High Altitude Air Shower Observatory (LHAASO) has shifted the focus of once again to this underexplored class of sources. In this contribution, we present a dedicated analysis of Fermi-LAT data in the region of 1LHAASO J1219+2915, coincident with the time of the TeV detection. Our results reveal a point-like gamma-ray source, detected with a test statistic $TS \approx 29$, spatially consistent with both the LHAASO source and the radio coordinates of NGC 4278. This association is further supported by evidence of enhanced X-ray activity contemporaneous with the gamma-ray signal. This discovery highlights the potential of even low-power, compact jets to accelerate particles to very high energies, broadening the population of known TeV emitters and offering new insights into the conditions under which extreme acceleration occurs. These findings raise important questions about the jet structure, composition, and radiative mechanisms in such sources. In particular, the unusual nature of NGC 4278 provides a test case for examining particle acceleration and high-energy emission in non-blazar AGN. We will discuss possible interpretations of the TeV flare in both leptonic and hadronic frameworks, and consider its implications for multimessenger studies and AGN feedback in low-luminosity environments.

When Relativistic Jets Shape Galaxies: A Physically-Motivated Framework for AGN Feedback Across Scales

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AGN feedback spans an enormous range of scales—from the event horizon of supermassive black holes (SMBHs) to galactic halos and beyond—posing a major challenge for theoretical models. Capturing both the launching and large-scale impact of AGN outflows remains a challenge. We address this by combining GRMHD simulations of hot accretion flows with low accretion rates ($\dot{M} < 0.01\dot{M}_{\rm Edd}$), performed with H-AMR (Liska et al. 2019), with galaxy-scale simulations in AREPO (Springel 2010, Weinberger et al. 2020), where the mass, momentum, and energy fluxes from the GRMHD jets are injected into the galaxy centre (Costa et al. 2020, Ward et al. 2024). This enables a more realistic treatment of AGN relativistic jets as they interact with the host galaxy's multiphase ISM. Our ongoing simulations allow us to quantify the outflow rate and kinetic energy coupling to the galactic gas, offering insights into the state of the ISM and highlighting scale relations. We also discuss the observational implications of our results, providing a bridge between high-resolution SMBH-scale physics and galaxy evolution.

Magnetic field tomography at horizon-scales (MATHS) with black hole accretion flows

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Magnetic fields are believed to play a pivotal role in the dynamics of black hole accretion flows and the formation of relativistic jets. Recent horizon-scale observations by the Event Horizon Telescope (EHT) and GRAVITY have provided unprecedented insights into the magnetic field structures near supermassive black holes. However, interpreting these observations requires theoretical frameworks capable of linking polarized emission to underlying accretion flow properties and magnetic field geometries. In the talk, I will talk about the impact of magnetic field topologies on the polarized emission observed near black holes. By employing a semi-analytic radiatively inefficient accretion flow (RIAF) model, we explore how magnetic field configurations influence the EVPA (Electric-Vector Position Angle) and the polarization quantities, and compare these predictions with existing GRMHD simulations and the EHT observations of M87*.

The role of internal shocks in prompt gamma-ray burst emission: implications for synchrotron emission and spectral breaks

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The observed spectra of the prompt emission of gamma-ray bursts (GRBs) are commonly attributed to synchrotron radiation. Although GRB detectors such as those in the Fermi and Swift telescopes are sensitive to energies starting from 10 keV, the emission in soft X-rays and optical wavelengths is also crucial to understand and model the bursts' spectral shapes. In particular, the observed presence of an additional break in the low-energy part of prompt GRB spectra warrants attention. Internal shocks, formed upon the collision of shells within the relativistic jet of a burst, are one of the mechanisms considered for energy dissipation. We study the aforementioned spectral breaks by employing a synchrotron model that considers the contribution of both reverse and forward shocks, extending the emission to X-rays and optical wavelengths. We discuss the implications of our model for the current state of observations, the changes brought upon by varying our parameter space, and the inclusion of additional physics, such as inverse Compton scattering.

Turbulent Reconnection Acceleration as the Origin of the Multimessenger Flare from the Blazar TXS 0506+056

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Recent observations indicate blazars as sources of high energy neutrinos, with TXS 0506+056 providing the most significant multimessenger association in blazars to date. However, the location and acceleration mechanism responsible for neutrino production in blazars remain uncertain. In this talk, we explore turbulent magnetic reconnection as a viable particle acceleration mechanism within the blazar jet. We find that this process can account for both the neutrino and electromagnetic emission observed during the 2017 flare of TXS 0506+056 in regions where the jet transitions from magnetically to kinetically dominated flow. In this scenario, PeV neutrinos are observed in the absence of very-high-energy gamma rays, which emerge days later as the particle acceleration region propagates downstream along the jet.

Natural Order in Gamma-ray Pulsar Physics: How Observations Define, and Models Deliver

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The release of the Fermi Third Pulsar Catalog and the detection of pulsed TeV emission from the Vela pulsar mark a pivotal moment in the study of high-energy pulsars. These data impose stringent constraints that demand theoretical models capable of capturing the essential physics with predictive power and precision. Our global, kinetic Particle-in-Cell (PIC) simulations naturally reproduce, and in some cases anticipate, these key observational signatures.

Our models self-consistently recover the gamma-ray Fundamental Plane (FP) and its associated death lines and death valleys, revealing the physical boundaries of gamma-ray activity across the pulsar population. We show that the observed confinement of Fermi pulsars on the FP arises from transitions between radiation reaction-limited and potential-limited regimes, and we predict the presence of a hidden population of MeV-bright pulsars lying just below the Fermi-LAT detection threshold. These predictions offer a compelling target for upcoming missions such as AMEGO-X.

Extending the applicability of our framework, we demonstrate that the same models can account for the TeV emission from Vela via inverse Compton scattering, using particle distributions extracted from our simulations. Furthermore, our analysis suggests that magnetars may also exhibit high-energy emission, likely peaking in the MeV band, placing them within reach of future gamma-ray observatories. Together, these results establish a unified framework for interpreting gamma-ray emission across neutron star classes, grounded in first-principles modeling and anchored by observational constraints.

A Synchrotron-Self-Compton Model with Klein-Nishina Effects in TeV Afterglows of Gamma-Ray Bursts

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In recent years, very high-energy (VHE) emission has been detected in a few gamma-ray bursts (GRBs) suggesting that Inverse Compton (IC) scattering contributes to the afterglow emission. The degree of IC dominance is determined by the Compton γ-parameter, when $\gamma \gtrsim 1$, IC cooling dominates over synchrotron cooling. Modeling VHE emission using IC processes requires the inclusion of Klein-Nishina (KN) corrections, because it alters the shape of spectra and lightcurves, impacting the accurate derivation of physical parameters. Therefore, due to the importance of the γ-parameter, adopting a more accurate treatment beyond standard analytical approaches is essential. In this work, we present a semi-analytic Synchrotron-Self-Compton (SSC) model that incorporates KN effects to describe the broadband spectra of TeV GBRs in the afterglow phase. Our model focuses on numerically determining the Compton γ-parameter which governs both the electron distribution and the spectral shape. Furthermore, we calculate the spectra performing the integration over the Equal-Arrival-Time-Surface (EATS). We find good agreement when comparing our results with a kinetic approach. On the other hand, our results deviate significantly from those obtained using analytical models. Finally, as a case of study, we apply our model to the GRB 19011C and compare our results and inferred physical parameters with those reported by other works.

Non-Equilibrium Thermodynamics of Black-Hole Coronae: QPOs, Turbulence, and Jets.

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The black hole corona is a natural laboratory for probing extreme plasma physics and its close link to relativistic jets. The rich X-ray variability observed in accreting black hole systems, including quasi-periodic oscillations (QPOs), strongly suggests the presence of complex, nonlinear dynamics within the corona. In this talk, we will discuss how such variability, particularly QPOs, can be linked to turbulence generation and jet powering. We develop a new theoretical framework that advances coronal physics by incorporating principles of non-equilibrium thermodynamics and nonlinear dynamics. In this model, coronal variability arises from self-oscillations, a mechanism where the system generates and sustains periodic behavior without requiring the source of power to have a periodicity. The system can autoregulate its oscillations. By recognizing that black hole coronae are inherently out of thermal equilibrium, we show how self-oscillatory dynamics can drive variability, turbulence, or provide energy to power jets. This non-equilibrium thermodynamic perspective offers key insights into the physical properties of the corona and enhances our understanding of the complex interplay between X-ray variability, turbulence, and relativistic outflows in black hole systems.

Is plasmoid-mediated reconnection really important in accretion flows to drive flares in AGNs?

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Based on very high-resolution resistive 2D and 3D magnetohydrodynamical (MHD) simulations of current sheets, our findings suggest that the answer to this question is likely no. In contrast, turbulence-mediated reconnection yields significantly faster reconnection rates - about an order of magnitude higher than the so-called universal rate for plasmoid-mediated reconnection in MHD flows ($v_{\rm rec}/v_A = 0.01$). We conclude that turbulence-driven reconnection is the dominant mechanism responsible for fast reconnection and flares in systems such as accretion flows and relativistic jets in Active Galactic Nuclei (AGNs). In these environments, turbulence is driven by instabilities such as the magneto-rotational instability (MRI), Parker-Rayleigh-Taylor instability (PRTI), and current-driven kink instability (CDKI). Finally, we will present 3D General Relativistic MHD simulations of accretion flows that confirm the crucial role of turbulence-mediated reconnection in AGN systems. These findings have important implications for understanding the origin of flares and the production of polarized radiation in these extreme environments.

Ultra Fast Outflows in AGNs: from X-rays to TeV energies, to (maybe) high-energy neutrinos and cosmic rays

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I will briefly review the current status of high energy observations of Ultra Fast Outflows (UFOs) in AGNs. I will give particular emphasis on recent results obtained with the XRISM/Resolve X-ray microcalorimeter, and future prospects with the X-IFU microcalorimeter on-board NewAthena, but will also briefly present some recent observations which indicate UFOs as potential sources of photons at hundreds of GeV, of high-energy neutrinos, and how they could serve as source of ultra-high-energy cosmic rays (UHERCs).

Tidal disruption of a magnetized star

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Tidal disruptions of stars by supermassive black holes in galactic centres are now being actively studied both theoretically and observationally. Such tidal disruption events (TDEs) are observed

throughout the electromagnetic spectrum, from radio to gamma-rays. It is still unclear how the emission is produced and, in particular, what is the role of the magnetic field of the disrupted star. There are many ways how magnetic fields might affect the dynamics of a TDE. They are likely responsible for angular momentum transfer in the accretion disc formed at later stages and thus affect the X-ray and UV radiation associated with the disc. Magnetic fields are also an important requirement for the formation of relativistic jets, that are seen in a small minority of TDEs. The goal of our study is to connect the initial, seed magnetic field of the star to the actual fields that develop during the fallback and disc accretion. Using the multi-purpose fluid-dynamic code `Athena++`, we perform large-scale three-dimensional magnetohydrodynamic simulations of tidal disruptions of magnetized stars. The fallback stream returning to the black-hole vicinity after the disruption contains smooth magnetic fields aligned with the stream. Formation of a nozzle shock near the pericentre point leads to a turbulent eccentric disc-like structure where the field is amplified and entangled on the local dynamic time scales. In the disc, the field is in approximate equipartition state, its energy reaching about 10 per cent of the internal energy density in the disc. The field is mildly anisotropic (toroidal component stronger by about a factor of 2) and has a typical length several times smaller than the pericentre distance. The properties of the field are consistent with the early stages of turbulent dynamo. The magnetic flux retained in the disc formed by the end of the circularization stage is large enough to power a relativistic jet for a smaller-mass supermassive black hole.

Magnetic amplification via turbulent dynamos driven by cosmic-rays at non-relativistic shocks

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Galactic cosmic rays (CRs) are believed to be accelerated via Diffusive Shock Acceleration (DSA) mainly at shocks in supernova remnants. However, theoretical and observational constraints require a magnetic field amplification in the pre-shock region during the DSA process. A mechanism capable of amplifying the large-scale magnetic field via turbulent dynamos has been suggested to solve or at least alleviate the problem. In this work, we revisit this mechanism, using a computationally efficient approach for representing the already accelerated CRs and considering an acceleration efficiency rate based on previous kinetic studies. We use 2D simulations with scales of 0.1 pc around a non-relativistic shock, employing a modified technique of Particle-In-Cell-Magnetohydrodynamics, in which we use the relativistic guiding-center equations to solve the particles' dynamics. In both the parallel and perpendicular directions of the shock velocity with respect to the magnetic field, we obtain an amplification factor of at least 10. The amplification efficiency obtained here is below the values obtained with non-resonant CR instability. Still, the dynamo can provide a considerable pre-amplification, which can reduce the acceleration time and maximize the maximum energy achieved in the acceleration process.

Interpretation for a GeV afterglow in the shallow decay phase

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While some studies report the absence of the X-ray shallow decay for hyper-energetic GRBs, recently discovered GRB 240529A shows a clear shallow decay phase with an isotropic gamma-ray energy larger than 2×10^{54} erg, making it a highly unusual case compared to typical GRBs. Our LAT data analysis reveals evidence of GeV emission during the shallow decay phase, which can be interpreted as the first case for hyper-energetic GRBs with a typical shallow decay phase. We carry out multiwavelength modeling based on time-dependent simulations with two promising models, the energy injection and wind models. Both models can explain the X-ray and gamma-ray data, while our modeling demonstrates that gamma-ray observations, along with future GeV–TeV observations by CTAO, will distinguish between them.

The effects of variability on morphology of kpc-scale jets using radio emission maps from high resolution simulations

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We present high resolution simulated radio emission maps of AGN jets propagating to 50kpc and focus on the effects of variable jet power on observable signatures at kpc scales. We use a novel treatment of mixing of shocked and unshocked material within the existing Lagrangian particle (Vaidya, B. et al. 2018) module of the PLUTO code. This approach, together with the high resolution of the underlying fluid simulations, results in radio emission maps capturing features such as hotspots, shocks along the jet, and diffuse emission from the lobes in a spectrally resolved manner. Simulations provide a critical means to connect observations from large-scale surveys of AGN jets to the evolution of these systems. This evolution is closely connected to the accretion process and fuelling physics, which is often variable on a range of timescales. We study the effects of jet power variability on morphology and the efficiency with which jet power is converted to radiation. We find significant variability in the morphology of variable jets, leading to clear differences from that of steady jets. To link observational signatures to physical processes, we investigate the effects of variability on the formation and speed of backflows near the jet head, on the strength of shocks along the jet, at the jet head and in the backflows. Overall, our physically motivated radio emission maps link the propagation of kpc scale jets to consequences of various formation mechanisms, capturing the evolution of key features in FRII radio galaxies. Our results highlight the importance of jet variability for understanding both individual radio sources and the AGN jet population as a whole.

High-Energy Neutrino Emission in NGC1068 driven by turbulent magnetic reconnection

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The Seyfert Type II galaxy NGC 1068 has been identified as a potential neutrino source by Ice-Cube, with a 4.2σ significance detection of a 79^{+22}_{-20} neutrino excess from 2011 to 2020 (IceCube Collaboration 2020, 2024). The observed high-energy neutrino flux indicates efficient particle acceleration of hadronic nature along with strong gamma-ray absorption in the source.

In this work, we investigate turbulence-driven magnetic reconnection as a mechanism for particle acceleration in the coronal accretion flow surrounding the central black hole. We develop a one-zone model following the framework of de Gouveia Dal Pino & Lazarian (2005) and Kadowaki et al. (2015) to explore how fast magnetic reconnection in the inner coronal disk region accelerates protons and electrons, shaping the spectral energy distribution (SED). Under this scenario, the acceleration sites that inject relativistic protons are significantly smaller than the entire corona.

In contrast to recent studies, we find that the acceleration of hadrons is primarily driven by Fermi acceleration within the turbulent reconnection layers, rather than drift acceleration. Our results also indicate that the dominant cooling mechanism for accelerated protons is Bethe-Heitler pair production, driven by interactions with both the disk's thermal OUV photon field and the coronal X-ray photons.

Sub-photospheric dissipations in variable collapsar jets and the GeV-TeV neutrino counterparts

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Observational data and theoretical considerations both indicate that the central engine of a gamma-ray burst (GRB) is intrinsically time-variable. A jet whose Lorentz factor is uneven inevitably develops internal shocks, and such shocks are expected to arise both below and above the photosphere. Below the photosphere, neutrons—whose mean free paths are much longer than those of charged particles—play an essential role in the dissipation process. Neutrons dissipate their energy through inelastic neutron-proton scattering, producing neutrinos that carry information from regions inaccessible to electromagnetic observations. Using the neutron-inclusive shell toy model with initial conditions based on the collapsar scenario, we link the statistical inhomogeneity of the jet at stellar breakout to the dissipation that occurs inside and outside the photosphere. We show that, for fluctuation wavelengths of order $c\delta t \simeq 3 \times 10^7$ cm and sufficiently large fluctuation amplitudes, the significant fraction of the dissipated energy can be carried away by neutrinos rather than photons. These classes, in which a large fraction of the energy is dissipated below the photosphere, could be viable candidates for relatively weak GRBs.

Testing a Stochastic Acceleration Model of Pulsar Wind Nebulae: High-Energy Neutrino Emission

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Pulsar wind nebulae are clouds of magnetised relativistic electron-positron plasma supplied from a central pulsar, and non-thermal emissions ranging from radio to PeV gamma-rays are observed. However, the origin of the radio-emitting particles remains under debate. A stochastic acceleration model has been proposed to account for the flat radio spectrum. In this model, the radio-emitting particles are supplied from the ejecta of the parent supernova. Here we discuss the possibility of ion acceleration, along with the radio-emitting electrons, under the same stochastic acceleration process. We estimate the resulting flux of high-energy neutrinos produced by the accelerated ions.

Relativistic MHD simulations of merging and collapsing stars and effects on GRB transients

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Compact binary mergers and the collapse of massive stars can produce intense transients observable across high-energy wavelengths. Events such as gamma-ray bursts and kilonova emissions are often accompanied by gravitational wave detections, making them crucial sources for multi-messenger astrophysics. To explore these phenomena theoretically, state-of-the-art approaches of GR magnetohydrodynamic simulations are used. In this talk, I will present recent findings from my team, and dicuss observational consequences of the stellar/post-merger environment on the GRB prompt emission properties.

DIPLODOCUS: going beyond isotropic, single zone blazar emission models

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The DIPLODOCUS (Distribution In PLateaux methODOlogy for the Computation of transport eqUationS) code, written from scratch in the Julia coding language, is being developed to enhance emission modelling of AGN jets and other high-energy astrophysical environments. It is a generic code which evaluates the transport of particle distribution functions through 7D of phase space, including non-conservative forces, particle interactions, and directed electromagnetic fields. The code is built on the "distribution-in-plateaux" formalism, allowing conservative transport through phase space and pre-computation of anisotropic collision inte-

grals via a Monte-Carlo sampling. We will present an overview of the framework and a series of test cases, tailored towards blazar emissions, to demonstrate the capabilities and performance of the code.

Activating Black Holes: Plasma Injection and the Role of Spark Gaps

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The Blandford-Znajek (BZ) mechanism, considered to be the standard process for powering relativistic jets, requires a sustained supply of plasma to the magnetosphere to maintain force-free conditions. Injection of electron-positron pairs via the annihilation of MeV photons emitted from the accretion disk is a viable possibility; however, it requires sufficiently high accretion rates. At low accretion rates, the magnetosphere may become charge-starved, leading to the formation of intermittent "spark gaps", regions with intense pair cascades that enable the outflow formation. It is often speculated that plasma from the accretion flow can penetrate the inner magnetosphere through magnetic field line rearrangement, potentially preventing the formation of spark gaps. In this talk, I will review the various mechanisms for supplying plasma to the magnetosphere, focusing on the possibility of direct feeding by an external source. I will present results from a series of 2D axisymmetric general-relativistic particle-in-cell simulations, demonstrating that in the absence of spark-gaps, the formation of large charge-starved regions, significantly reducing the efficiency of the BZ mechanism, is unavoidable.

Joint AGILE-Fermi Analysis of Bright Gamma-Ray Flares in Low-Synchrotron Peaked Blazars

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Using a new code, we are carrying out a systematic joint AGILE-FERMI re-analysis of the brightest GeV gamma-ray flares observed in low-synchrotron peaked blazars. The goal is to reach down to sub-day timescales and robustly probe and characterize the rapid variability (extending down to sub-hour timescales in some cases) that seems to be a common feature of these flares. Where possible, we will also compare the observed gamma-ray behavior to that seen in simultaneous NIR/optical observations. Our preliminary results indicate that the correlations often seen between GeV and the NIR/optical emission, used as evidence that the same electrons are responsible for this emission, actually break down on timescales shorter than a day. If true, this poses a challenge for current emission models.

Poster Presentations

High Energy Extraction from a Naked Singularity

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Energy extraction mechanisms such as the Penrose process and the magnetic Penrose process are traditionally associated with the presence of an ergoregion, where negative energy states enable particles to extract rotational energy and escape to infinity. In this talk, we discuss the possibility of energy extraction in the absence of a conventional ergoregion by considering the electromagnetic field in the rotating Janis-Newman-Winicour (JNW) naked singularity spacetime. This scenario is physically motivated by the presence of accretion disks, which naturally generate electromagnetic fields around horizonless compact objects. We analyze the existence of negative energy orbits and explore their critical role in enabling energy extraction. Although the rotating JNW spacetime lacks a standard ergoregion, we demonstrate the presence of an effective ergoregion, which allows efficient energy extraction. The influence of the magnetic field strength B, spin parameter a, and electric charge Q on the properties of negative energy orbits is systematically examined. Our findings reveal that the efficiency of energy extraction can reach 60% in this framework, highlighting the potential of rotating naked singularities as viable energy sources in high-energy astrophysical environments.

Effects of Bethe-Heitler pair production in ultraluminous X-ray sources

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Ultraluminous X-ray sources (ULXs) are binary systems where the observed X-ray luminosity exceeds the Eddington limit for a compact stellar-mass object. In these systems, the companion star overflows its Roche lobe, feeding matter to the black hole at super-Eddington rates. The radiation pressure inflates the accretion disk in the inner region within the critical radius, where powerful radiation-driven winds are ejected. The wind walls form a low-density conical funnel along the z-axis, where the radiation from the innermost region of the disk is geometrically beamed and reaches the observer. We show that in this funnel the X-ray photon field from the disk interacts with relativistic protons accelerated in the funnel, producing electron-positron pairs via the Bethe-Heitler mechanism, $p + \gamma \rightarrow p + e^{-} + e^{+}$. In this poster, we will present a model of the effects of the Bethe-Heitler mechanism within the funnels of ULXs and the resulting non-thermal MeV emission produced by the secondary pairs as they interact with ambient fields. Our results provide new insights into the high-energy processes occurring in these systems.

Advancements in GPU-accelerated particle-in-cell simulations with iPIC3D

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Particle-in-cell simulations are essential for studying kinetic-scale plasma behaviour in astrophysical and laboratory environments, where processes like relativistic magnetic reconnection and collisionless shocks can accelerate particles to extreme energies. We present the recent advancements in the semi-implicit iPIC3D code, which now supports GPU computation using CUDA (NVIDIA GPUs) and HIP (AMD GPUs). Comparisons with the CPU version of the code show a factor of 30 improvement in computational speed. We have integrated the exact energy-conserving semi-implicit method and the relativistic semi-implicit method that ensures energy conservation up to machine precision. This is essential to avoid artificial energy growth in the system over long time scales and obtain physically viable results. Furthermore, the code has undergone several methodological improvements that further boost its speedup by 10x. Owing to the implicit nature of the code and the recent algorithmic advancements, we are on course for exascale simulations of relativistic and nonrelativistic plasma, enabling unprecedented spatial resolution and temporal duration.

Achromatic and Delayed Gamma-ray burst afterglows from Relativistically moving thick-shells

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Gamma-ray bursts (GRBs) are luminous explosive phenomena caused by relativistic jets, the detailed physics of which remains unclarified. Since the launch of the Neil Gehrels Swift Observatory, well-sampled multiwavelength early afterglow light curves have been obtained, revealing discrepancies with predictions from the pre-Swift standard afterglow model. In particular, observational features such as achromaticity, gradual brightening (with a rising index of ~ 1), and delayed peak times ($\sim 10^3$ s) have long challenged interpretation within conventional models, often requiring ad hoc or fine-tuned assumptions to reproduce. However, these features offer critical insights into the structure and dynamics of relativistic jets. Recent numerical simulations of magnetized relativistic ejecta with finite shell widths have demonstrated that such geometrical and dynamical effects significantly affect jet evolution. In this study, we adopt a semi-analytical model based on such simulations and perform Bayesian parameter estimation for some GRBs exhibiting the above-mentioned features. Our results demonstrate that these observational characteristics emerge naturally from thick-shell dynamics, without invoking contrived scenarios, thereby offering a more unified and physically consistent interpretation. This work updates the conventional picture of GRB afterglows and provides a promising framework to understand their early-time diversity.

Looking around Cygnus X-3. How far is it?

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In this work, we investigate HI emission in the vicinity of Cygnus X-3, considering a range of distances proposed in previous studies. Our goal is to identify potential signs of interaction between the Wolf-Rayet wind and the microquasar outflows with the surrounding interstellar medium. Accurately determining the distance to Cygnus X-3 is essential, as it greatly affects both the interpretation of observational data and our understanding of the interaction mechanisms at play. By examining HI emission maps across these distance estimates, we aim to uncover evidence of dynamic processes and interactions that shed light on the complex relationship between massive stars, their stellar winds, and the ISM. Our findings will contribute to a broader understanding of how microquasars influence their environments and clarify their role within the Galactic ecosystem.

Exploring the environment of LS I +61303 at radio wavelengths

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We report deep radio images of the gamma-ray binary LS I +61303 created by stacking different archival observations at cm wavelength obtained with the Expanded Very Large Array. Our goal is to detect faint extended emission that could shed light on the true physical scenario behind this system: either microquasar or pulsar wind interaction. Arc-minute scale radio features are indeed present in the field of view at the tens of microjansky level. However, a physical connection with the binary system remains to be confirmed. Possible interpretations are discussed.

Morphology and evolution of Relativistic Jets

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Most massive galaxies host a supermassive black hole (SMBH) at their centers, with masses ranging from millions to billions of solar masses. When these SMBHs actively accrete matter, they give rise to active galactic nuclei (AGN), which can launch collimated relativistic jets from the galactic core. These jets are capable of accelerating particles to high energies, either through shock interactions or electromagnetic processes. In this work, we present a qualitative study of relativistic jet dynamics, focusing on identifying regions favorable for particle acceleration and analyzing the internal and external jet environments. Using two-dimensional simulations with the PLUTO code, we varied the jet injection velocity, testing linear, precessing, and perturbed profiles to investigate how different dynamic conditions affect jet propagation and structure. Our results reveal how velocity variations influence internal jet morphology, stability, and interactions with the ambient medium. These insights contribute to a deeper understanding of the physical conditions that may lead to efficient particle acceleration in AGN jets.

PeVatron source LHAASO J1908+0621: a mixed scenario for gamma-ray emission?

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The study of Galactic cosmic rays currently relies on the observation and modelling of gamma-ray emission from molecular clouds. In order to find sources at energies $\sim$ 100 TeV, it is required to find sources known as PeVatrons, capable of accelerating the cosmic rays up to 1 PeV. Usually, the association between molecular clouds and supernova remnants are the favourite candidates as PeVatron sources. Unfortunately, due to source contamination and the angular resolution limitation of the current observatories, it is difficult to identify the exact accelerating source in many of the reported PeVatrons. A particularly notable case is LHAASO source J1908+0621 (MGRO J1908+06), as it was detected by several gamma-ray facilities and is associated with the SNR G40.5-0.5 in interaction with a MC and is also associated with two pulsars, PSR J1907+0602 and PSR J1907+0631. In this work, we aim to develop a model capable of distinguishing which accelerator is responsible for the detected emission or if it is a combination of both pulsar and SNR. Firstly, we calculated the high-energy emission produced in the interaction of SNR G40.5-0.5 with the ambient medium using a time-dependent diffusion model. We fitted the observed very-high emission in the range 10-100 TeV by assuming a total energy in protons of $\sim 10^{49}$ erg. As the source region also has another possible accelerator, we also considered the feasibility of the leptonic contribution from the pulsar PSR J1907+0602 in the detected emission as it would add a component to our pure hadronic model that could explain the lower energies. We conclude that the diffusion of the protons in the cloud should be slow.

Relativistic Hydrodynamic Simulations of FR0 Radio Galaxies

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Radio galaxies are a class of galaxies characterized by strong radio wave emission, primarily originating from active galactic nuclei (AGN) powered by supermassive black holes accreting matter. In these galaxies, AGNs often launch collimated jets that can reach relativistic speeds and emit high-energy particles. The traditional classifications: Fanaroff-Riley type I (FRI) and type II (FRII), feature powerful jets that typically extend beyond 30 kiloparsecs. Recently, a new subclass known as FR0 radio galaxies has been introduced to describe sources that exhibit compact radio jets with significantly lower power, usually confined within a maximum size of about 5 kpc. FR0 galaxies are predominantly found in the nearby universe (redshift z ¡ 0.05), and are typically hosted by elliptical galaxies with low-excitation optical emission lines. They exhibit radio luminosities at 1.4 GHz in the range 38.19 ¡ log(L) ¡ 40.27 and central black hole masses between 7.4 ¡ log(M) ¡ 9.0 (in solar mass units). Although FR 0s share many properties with FR I galaxies, their jet structures remain poorly understood. This work aims to investigate the physical conditions of FR 0 jets using relativistic hydrodynamic simulations with the PLUTO code, focusing on turbulence and jet-environment interactions. By modeling two specific FR0 sources based on available radio maps, we seek to reproduce their observed radio morphology and emissivity. This is particularly relevant given that some FR 0s have been detected emitting gamma rays in the TeV regime, suggesting they may act as efficient particle accelerators.

Relativistic Particle Acceleration in Flow-Collision Shocks: acceleration rates and correlations to local properties

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Magnetized large-scale shocks are turbulent and promote reconnection zones, creating favorable environments for the acceleration and diffusion of relativistic particles. In this work, we investigate the process of acceleration of ions in large-scale turbulent shocks based on high-resolution magnetohydrodynamic simulations integrated with particle trajectory integration. We analyze statistical correlations between the local acceleration rate of particles and physical plasma quantities such as current density, and intensity and topology of both magnetic and velocity fields. Our results show strongest correlations of acceleration to the magnetic field strength and current density (reconnection loci). This suggests that magnetic trapping (mirror effect) and turbulent magnetic reconnection play key roles in enhancing the efficiency of Fermi-like acceleration mechanism, by confining particles near the shock front and enabling multiple crossings with energy gain. Approximately 34% of the integrated particles presented peak acceleration rates above 10 GeV/s, and about 2% exceeded 1 TeV/s. Little correlation is found with respect to the velocity field topology, indicating that turbulence contributes mostly to transport and scattering of particles, but does not dominate the diffusive acceleration.

Probing the vacuum birefringence with the blazar optical polarization

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Although the Standard Model (SM) of particle physics provides a satisfactory theoretical fundament able to explain all known processes acting on elementary particles, it cannot be considered as the ultimate theory of fundamental interactions, as it does not really unify electroweak and strong interactions, does not include gravity and describes neither dark matter nor dark energy. Therefore, the SM should only be considered as a low energy approximation of a more fundamental theory describing and unifying all four fundamental interactions at the quantum level. There are several proposed extensions, aiming to complete the SM. Some of these extensions predict the existence of vacuum birefringence, which causes rotation of the polarization plane of photons of different energy. We use blazar polarization angle measurements, performed simultaneously in two optical bands (V and R) at different epochs to constrain the possible influence of the vacuum birefringence. Among the objects we monitored were S5 0716+714, S4 0954+65, B2 1308+32 and BL Lacertae. Our preliminary results do not show detectable vacuum birefringence but the work is ongoing.

Multiwavelength study of Mrk 501 's activity in 2014

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Markarian 501 (Mrk 501) is a bright blazar with a redshift of 0.034. Thanks to its brightness and proximity, the Very High Energy (VHE; E¿100 GeV) emission of Mrk 501 can be measured with higher accuracy than other blazars that are dimmer and/or located farther away. Collaborations such as the MAGIC telescopes, which concentrate on detecting photons from 50 GeV to a few TeV, have been able to do multiple multiwavelength campaigns to better understand the underlying particle acceleration and radiation processes. One of the many interesting campaigns happened in 2014, in which Mrk 501 presented intense flaring activity in the X-ray and VHE gamma-ray energy bands, similar to the activity level observed in 1997. Even so, on July 19th, a spectral 'feature' located approximately at 3 TeV was also detected, which was not clearly seen before or after this observation. Both of these aspects support the focus of this project. The research seeks to understand the radiative mechanisms within Mrk 501 in this MAGIC 2014 campaign, analyzing the multiwavelength data of the whole period, beyond July 2014, and understanding the temporal and spectral characteristics of the source.

Magnetic reconnection in blazar jets: the narrow TeV feature of Markarian 501

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On July 19th, 2014, the blazar Markarian 501 exhibited a spectral feature characterized by a narrow spike with a significance of $3-4\sigma$ near 3 TeV. This event occurred during one of the most active periods of the source, as observed by the MAGIC telescopes in a multiwavelength campaign, and it coincided with the most extreme X-ray flux ever detected from the source by Swift-XRT. Although several interpretations have been proposed, the origin of the TeV spectral spike remains inconclusive. In this work, we propose that the feature can be well explained by a transient magnetic reconnection event superimposed on the relatively quiescent blazar emission. Within this framework, we also reproduce the evolution of the source's multiwavelength SED over the days surrounding the observation of the peculiar spike.

Studying the Diverse PWNe Population with Chandra X-ray Observatory

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Pulsar Wind Nebulae (PWNe) are some of nature's most unique laboratories for studying production of the very high-energy particles by pulsars. By observing X-ray emission from PWNe we can learn about the underlying distribution of accelerated particles which constrains models for a yet unknown acceleration mechanism operating in pulsar winds. Our analysis shows that the properties (e.g., spectral indices) of these relativistic outflows vary significantly even for the most compact PWN structures where radiative cooling should play no role. In addition, the structures themselves show significant diversity (e.g. different relative strengths of the jet and torus components). Finally, the X-ray radiative efficiencies of PWNe range nearly 4 orders of magnitude. It may be that this diversity is an intrinsic feature of the dominant acceleration mechanisms (magnetic reconnection or shock acceleration) and/or pulsar geometry (magnetic obliquity angle) and spin-down properties. This can be tested by analyzing the uncooled spectra of compact PWNe, their morphology, and multi-wavelength pulse profiles. Here, we present preliminary results of PWN population properties studied with Chandra X-ray Observatory.

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Spectral and Kinematic Properties of a Protostellar Jet in W3(H_2O)

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Astrophysical jets are observed across a wide range of scales, from young stellar objects to active galactic nuclei (AGN). While AGN jets are extensively studied, those associated with young, massive protostars remain challenging to characterize. This work focuses on the TW object in the W3(H_2O) region, a rare example of a protostellar system exhibiting synchrotron emission. Using multi-frequency observations from the Very Large Array (VLA) at 3, 6, 10, 15, and 22.25 GHz, we produced radio interferometric images with angular resolutions ranging from 0.11" to 0.86". Due to the complex structure of the source, we applied self-calibration techniques to enhance both sensitivity and dynamic range. We generated total intensity maps in all bands to trace the emission morphology. However, in some cases, image fidelity was limited by incomplete *u*-*v* coverage. Spectral index analysis revealed a negative value at low frequencies (3 GHz; $\alpha = -1.64 \pm 0.82$), confirming synchrotron radiation, and a positive index at higher frequencies (22.25 GHz; $\alpha = 1.06 \pm 0.40$), consistent with thermal free-free emission. Additionally, we imaged the 22.25 GHz water maser emission, identifying hundreds of maser spots aligned along the jet axis. These masers trace both the spatial distribution and velocity structure of the outflow, supporting the interpretation that they arise from shock fronts where the jet interacts with the ambient medium. The observed maser velocities span from -90 to -20 km/s, assuming a systemic velocity of -55 km/s for the central protostar. The observations were performed in full polarization mode, enabling future analysis of the magnetic field properties of the plasma. Ongoing work will focus on refining polarization calibration and improving

sensitivity in the higher-frequency bands, which will be essential for resolving jet structures and characterizing the field morphology.

Multi-wavelength light curve of Centaurus A

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Centaurus A (NGC 5128), at a distance of about 3.8 Mpc, is the closest Active Galactic Nucleus (AGN) to Earth. This object emits radiation at all frequencies of the electromagnetic spectrum, from radio waves to X-rays and gamma rays, and is also a possible source of cosmic rays. The aim of this work is to study the flux density variability of the core of this source at radio, X-ray and gamma ray wavelengths over the years, and to look for associations between these emissions. The 43 GHz radio frequency observations were made with the Pierre Kaufmann radio telescope in Atibaia using the 14-meter single-dish antenna. Soft X-ray (1.5-12 keV), hard X-ray (15-150 keV) and gamma rays (100 MeV-100 GeV) data were obtained, respectively, by spatial telescopes RXTE/ASM, Swift/BAT and Fermi/LAT. Cen A shows similar behavior at radio and X-ray bands of spectrum, with flares appearing at similar times, especially from the mid-2007 to mid-2012. However, there is no counterpart in the gamma ray observations, may be due to the fact that there were few observations at 43 GHz during the Fermi/LAT observations period. A Discrete Correlation Function (DCF) was used to quantify the correlation between the radio and X-ray frequencies and confirm the lack of correlation with gamma rays. The largest delay between the radio and X-ray signals was 32$\pm$35 days. Considering the uncertainty in the number of days of delay, we can conclude that the radio and X-ray emissions are practically simultaneous, suggesting a common origin.

A new gamma-ray source? The role of jet-outflow interaction in a protoplanetary nebula

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Recently, a multiwavelength study suggested an association between a *Fermi*-LAT source and a protoplanetary nebula, unveiling the possibility of a new type of high-energy emitter. In this source a jet-outflow morphology was revealed by radio and X-ray observations, along with the detection of a redshifted CO molecular outflow. According to the current theoretical framework, this could result from the interaction between the protoplanetary jet and a molecular outflow with the ambient gas in the stellar system, producing shocks that accelerate particles via the first-order Fermi mechanism.

Given this new scenario, we developed a radiative model of the source aiming to reproduce the multiwavelength spectrum. We fitted the spectrum using a Monte Carlo algorithm to determine the best-fit parameters describing the detection. Finally, we implemented a jet model

to explain the gamma-ray emission. Through this analysis, we were able to constrain the physical conditions in the source necessary to explain the gamma-ray detection. We conclude that this source is an ideal opportunity to study jets associated with planetary nebulae as potential gamma-ray emitters.

A Catalogue of Variable Active Galactic Nuclei Based on Multi-Timescale Variability Analysis from Fermi-LAT Data

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We present a catalogue of variable active galactic nuclei (AGN) based on an analysis of gamma-ray light curves from the Fermi-LAT Light Curve Repository. Our work focuses on characterizing variability across multiple temporal scales, extending beyond the yearly fractional variability publicly available in the Fermi-LAT catalogs. Specifically, we systematically estimate variability parameters on monthly, weekly, and three-day cadences.

Our analysis confirms and extends the known correlation between variability amplitude and timescale, contributing to the characterization of high-energy outflows in AGN jets across different temporal regimes. These results also reinforce the established dichotomy between flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs), with FSRQs predominantly showing larger variability than BL Lacs at all time scales.

Furthermore, we present subsamples of the most luminous and variable sources in each timescale, representing primary targets for follow-up observations for the next generation of ground-based observatories, including the Cherenkov Telescope Array Observatory (CTAO), ASTRI Mini-Array, and the Southern Wide-field Gamma-ray Observatory (SWGO). While luminosity ensures detectability, strong variability can reveal compact emission regions and extreme particle acceleration processes. This catalogue serves both as a tool for optimizing observational strategies and as a step towards developing a unified variability metric applicable across different timescales.

Numerical simulations of the non-linear DSA process: connecting kinetic scales with astrophysical scales through a modified PIC-MHD approach

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The origin of cosmic rays remains one of the central open questions in high-energy astrophysics. It is believed that most galactic cosmic rays (with energies up to PeV) are accelerated in non-relativistic shocks produced by the expansion of supernova remnants into the interstel-

lar medium, through the non-linear Diffusive Shock Acceleration (DSA) mechanism, although many details of the process are not yet fully understood. A significant challenge in numerical simulations is the connection between "micro-scale" phenomena, such as instabilities and resonant waves that govern cosmic ray transport, and the "macro-scale" evolution of the supernova remnant shock interacting with the interstellar medium. To better connect these scales in multidimensional magnetohydrodynamic (MHD) simulations that include cosmic rays, we have developed a modified Particle-in-Cell-MHD (PIC-MHD) approach based on the guiding-center approximation for particles. The effects of cosmic ray-induced waves and instabilities are incorporated via a subgrid model. In this research, we compare the evolution of particle acceleration in a two-dimensional shock, using this modified PIC-MHD approach, with fully self-consistent PIC-MHD simulations, where kinetic phenomena are explicitly resolved. This new approach enables the modeling of the particle acceleration process over spatial and temporal scales much larger than the kinetic scales of the particles injected into the acceleration process, providing a method for investigating the non-linear DSA acceleration mechanism.

LAST-P: measuring powerful outflows with a large field-of-view polarimetric instrument

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Optical polarimetry is a key tool for probing the structure of powerful outflows in AGN, GRBs, supernovae, TDEs, novae, and microquasars. Existing data show polarization degrees ranging from 0% to 30% for different source types. Population studies, which are required to distinguish between possible source models, are currently limited by the lack of high-cadence, wide-field polarimetric surveys.

I present here the Large Array Survey Telescope Polarization telescope (LAST-P). LAST-P will achieve polarization degree and angle precisions of 0.4% (0.7°), 0.7% (1.1°), and 1.1% (1.7°) for sources with magnitude 17, 18, and 19 over a 15 x 1 minute exposure, respectively. LAST-P will be a cost-effective instrument, having a 89.8 deg^2 field of view. It will be capable of monitoring 75% of the polarization sky over a period of 15 days, enabling unprecedented time-domain polarimetric studies.

Generation of a Look-Up Table for water Cherenkov detectors at SWGO for the highest energy gamma rays

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The reconstruction of atmospheric showers from high-energy gamma rays is essential for optimizing the design and performance of the Southern Wide-field Gamma-ray Observatory (SWGO). Several layout options are under consideration for SWGO's outer array, each involving different detector configurations. This work focuses on simulating the detector response of a cylindrical tank measuring 3.6 m in diameter and 1.78 m in height, equipped with two multi-photomultiplier tube (multiPMT) modules, each containing seven 3-inch PMTs. These simulations contribute to the FastSim project, which uses a lookup table (LUT) to capture detector responses from single particles, enabling a much faster alternative to full shower simulations. The results show that the multiPMT configuration captures valuable directional information through distinct patterns in photoelectron counts and timing, improving reconstruction capabilities. Future work will validate the LUT method against full simulations to assess its accuracy and performance benefits.

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