

# Book of Abstracts

## MuMeNTA: Multi-Messenger and Numerical Techniques in Astrophysics

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Harokopio University

The workshop is co-organized by members of:

Department of Physics of the National and Kapodistrian University of Athens  
Department of Informatics and Telematics of Harokopio University

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## Probing a cosmogenic origin of astrophysical neutrinos and cosmic rays using gamma-ray observations of TXS 0506+056

**Author:** Atreya Acharyya<sup>1</sup>

<sup>1</sup> *University of Southern Denmark*

In September 2017, a high-energy neutrino event detected by the IceCube Neutrino Observatory (IceCube-170922A) was associated, at the  $3\sigma$  level, with a gamma-ray flare from the blazar TXS 0506+056. Cosmic rays that are accelerated in astrophysical sources can escape from their jets and interact with background radiation fields. Interactions with the extragalactic background light can produce pions and hence neutrinos, while interactions with the cosmic microwave background predominantly drive inverse Compton scattering, contributing to electromagnetic cascades in intergalactic space. The resulting secondary gamma-ray emission can be detected with high-energy gamma-ray telescopes. In this study, we report on a new search for such cosmogenic cascade emission from the blazar TXS 0506+056, using a combined data set from the Fermi-Large Area Telescope and VERITAS. We compare the gamma-ray spectrum and neutrino observations with the predictions of cosmic-ray induced cascades in intergalactic space. The observed gamma-ray spectrum is modeled as a combination of the primary spectrum and the cascade spectrum. We apply a Monte Carlo simulation with a  $\Delta\chi^2$ -based likelihood analysis to jointly determine the best-fit parameters of a proton emission spectrum describing the data and derive constraints on the proton escape luminosity.

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## Numerical Advances in GRRT: Horizon-Scale Images of Resistive Accretion Flows Around Sagittarius A\*

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Sagittarius A has been investigated for years and is one of the most interesting sources in the Galactic Center, a region enriched by strong magnetic fields, dense gas and enhanced cosmic-ray activity. The black hole's shadow was imaged for the very first time in 2022 by the Event Horizon Telescope at a frequency of 230 GHz, demonstrating a characteristic ring morphology and a significantly small horizon-scale variability within the accretion flow. On the other hand, Sagittarius A exhibits bright flaring events in the Near Infrared (GRAVITY, Very Large Telescope Interferometer) and X-ray bands (Chandra X-ray Observatory) several times a day, with several bright flares tracing an orbit in the vicinity of the supermassive black hole. One of the most effective ways to investigate these phenomena is through General Relativistic Magnetohydrodynamic (GRMHD) simulations of the magnetized accretion disk coupled with General Relativistic Radiative Transfer (GRRT) calculations to create synthetic observables of the accretion flow near the horizon. A recent breakthrough in GRMHD simulations has been the implementation of resistivity within the accretion flow, providing a natural mechanism for magnetic field dissipation and describing its interaction with the disk plasma in the framework of General Relativity. We present the most recent code developments in resistive GRMHD and GRRT calculations and their implementation in state-of-the-art codes (BHAC and BHOSS, respectively). We show the first images of a resistive accretion flow in the vicinity of a black hole and discuss the effect of magnetic field dissipation on the highly variable MAD accretion state. Furthermore, we generate synthetic observables of resistive accretion disks for direct comparison with the horizon-scale images of Sagittarius A\* and investigation of the observed accretion flow variability. These numerical advances pave the way for a more

physical description of the intricate mechanisms that occur in the vicinity of an accreting black hole, providing a promising framework for understanding the vast spectrum of multi-messenger observations and characteristics of the supermassive black hole in the Galactic Center.

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## Modeling the Synchrotron Polarization of Blazars with AM<sup>3</sup>

**Author:** Frederike Apel<sup>1</sup>

<sup>1</sup> *Ruhr-Universität Bochum*

With the open-source software AM<sup>3</sup>, particle interactions and radiative emission in astrophysical objects like blazars can be simulated assuming a homogeneous and isotropic magnetic field. However, the synchrotron radiation from blazars is known to be polarized. Time-dependent multi-wavelength polarization measurements reveal magnetic field structures and shed light into the radiative processes in astrophysical objects. Our aim is to expand the capabilities of AM<sup>3</sup> and model the polarization from blazars considering required geometrical assumptions which were not included in the software before. Using a multi-zone model, the zones can be arranged in a way to mimic ordered or chaotic magnetic fields. In the future, this new feature could be used by everyone and would also be applicable to other astrophysical sources that emit polarized synchrotron radiation. In this talk, I will give an update on the project and present our approach, the first implementations and first application examples using AM<sup>3</sup> for modeling the synchrotron polarization from blazars.

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## Time-Dependent Leptonic Modeling of the Sub-Hour Spectral Evolution During the 2013 Outburst of Mrk 421

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In April 2013, the TeV blazar Mrk421 underwent one of its most powerful emission outbursts to date. An extensive multi-instrument campaign, which included MAGIC, VERITAS, and NuSTAR, provided comprehensive VHE and X-ray coverage over nine consecutive days.

In this talk I will present a detailed spectral analysis of the X-ray and VHE emissions on sub-hour timescales throughout the flare. We identify several clockwise spectral hysteresis loops in the X-rays. The VHE spectrum extends above 10 TeV, and its temporal evolution closely mirrors the behavior in the X-rays, thus revealing the first evidence of VHE spectral hysteresis simultaneous with the X-rays.

We apply a time-dependent leptonic model to 240 broadband SEDs binned at 15-minute intervals, allowing us to self-consistently track the particle distribution's history on sub-hour scales. The majority of the sub-hour flux and spectral variations are well reproduced by evolving the luminosity and slope of the injected electron distribution. To capture the VHE spectra at the highest energies, a Doppler factor of  $\sim 100$  is needed, implying relativistic motion of the emitting plasma in the jet frame. While this could be realized in plasmoid chains formed in current sheets during magnetic reconnection, the particle hardness evolution would require significant changes in the plasma magnetization during the flare.

We release the entire MAGIC dataset ( $\sim 40$ hrs) to the community in DL3 file format, together with the large sample of broadband SEDs.

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## Constraining blazar jet physics through time-resolved blazar SED modeling with neural-network surrogates

**Authors:** Damien Bogue<sup>1</sup>; Narek Sahakyan<sup>2</sup>

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Comprehensive analysis of time-resolved spectral energy distributions (SEDs) of blazars is essential for understanding their underlying physical processes. However, when numerical kinetic models are combined with rigorous statistical inference—such as full posterior sampling instead of local optimization—the task of fitting large numbers of SEDs becomes computationally prohibitive. To address this challenge, we developed a surrogate-modeling framework based on convolutional neural networks. Trained on state-of-the-art time-dependent numerical simulations, these models accurately reproduce blazar spectra while reducing computational costs by several orders of magnitude, enabling the analysis of hundreds of SEDs. Using OJ 287, PKS 2155-304, and 1ES 1959+650 as case studies, I will demonstrate how time-resolved SED fitting uncovers systematic variations in jet microphysical and dynamical properties across different emission states.

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## A lepto-hadronic multi-zone framework for modelling multi-messenger emissions from AGN jets

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Active Galactic Nuclei (AGN) and their relativistic jets that emit radiation covering almost the entire electromagnetic spectrum, have been few of the most fascinating subjects in astronomy for decades, yet the composition of these relativistic jets is still not clearly known. The origin of the high energy peak in the Spectral Energy Distribution (SED) of blazars has been an open question in astronomy. Different models for the jet composition have been proposed in order to explain the high energy peak observed in the blazar SEDs, starting from the leptonic models, hadronic models to the lepto-hadronic model which combines both. The particles inside an AGN jet can be accelerated to high energies via different mechanisms, including shocks, stochastic turbulent acceleration and magnetic reconnection which can generate distinct multi-messenger observational signatures due to the rapid changes in magnetic field topology in the emission zone. These signatures can be used as pivotal diagnostic tools to study different jet composition models.

With the detection of high energy neutrinos with a significance of around 3.5 sigma coming from the direction of blazar TXS 0506+056 by IceCube Neutrino Observatory, it has reinvigorated the support and curiosity for the hadronic and lepto-hadronic models for AGN jets as unlike the leptonic scenarios, these models produce neutrino emission. While there exists numerical codes modelling single-zone lepto-hadronic scenarios in AGN jets, the availability of comprehensive multi-zone codes is limited. To tackle this notable gap in the field of lepto-hadronic modeling, particularly in the context of AGN jets and its observed multi-wavelength and neutrino emissions, we have developed a numerical multi-zone framework of the lepto-hadronic model for AGN jets by building upon the foundation of an existing single zone code called Katu. In this presentation, I shall describe our novel approach on integrating the multi-zone framework with the fluid dynamics code called PLUTO used for modeling the relativistic

jet. This framework serves as a bridge between jet dynamics and the microphysics within AGN jets, aiming to create synergy between relativistic magneto-hydrodynamic simulations and multi-messenger observations. We have applied this multi-zone framework to model the multi-wavelength photon as well as neutrino emissions arising from the jet which can provide valuable insights on how the complex interplay between the jet dynamics, particle acceleration mechanisms and jet composition effects the subsequent multi-messenger emissions from the jet.

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## Time-dependent modelling and other news from AGNPy

**Author:** Grzegorz Borkowski<sup>1</sup>

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I am going to discuss recent advancements in AGNpy, a Python library designed for modeling radiative processes in Active Galactic Nuclei (AGNs). I will focus on the new code dedicated to the time-dependent modelling of AGN processes, which can be used for searching for LIV signatures in AGN radiation. I will also cover other changes added recently to the code, and explain the plans for further development.

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## A leptohadronic perspective on the candidate neutrino-emitter blazar 5BZQ J0808+4950

**Author:** Margot Boughelilba<sup>1</sup>

<sup>1</sup> *DESY*

The role of active galactic nuclei in the production of high-energy neutrinos is crucial in the understanding of the excess of neutrinos seen by the IceCube observatory in the direction of the blazar TXS 0506+056 and the Seyfert galaxy NGC 1068. In particular blazars jets are potential sites of cosmic-ray acceleration, where neutrino production would be naturally explained along with the interaction of hadrons.

The blazar 5BZQ J0808+4950 is part of a blazar sample that has been highlighted as spatially correlated with neutrino hotspots in IceCube sky maps. In addition, a neutrino event, IC110929, was also reported in the direction of this blazar. With a luminous accretion disk serving as a photon field for the photo-hadronic interactions, 5BZQ J0808+4950, is a good candidate to test the relation between neutrino production and the radiative output of the blazar jet. We studied six contemporaneous epochs in which multi-wavelength data were available, in order to model the source's spectral energy distribution and its evolution over time. We find that the source exhibits two different gamma-ray states over the six epochs we consider.

We use leptohadronic models to model time-dependently 5BZQ J0808+4950, and find two types of solutions corresponding to the two gamma-ray states. The main variations between the six states are in the magnetic field strength and the spectrum of the injected primary particles. We predict a neutrino rate ranging from 0.01 to 0.04 neutrino per year, with the highest rate contemporaneous with the neutrino event observation.

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## High-Resolution RMHD Modeling of AGN Jets: Numerical Advances and VHE Signatures

**Author:** Stella S. Boula<sup>1</sup>

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The macroscopic structure and dynamics of relativistic AGN jets regulate where and how particles reach very high energies. Recollimation shocks—and the turbulent regions that form downstream—act as natural sites of localized dissipation and non-thermal particle acceleration. Using high-resolution 2D and 3D RMHD simulations with PLUTO, we examine how external confinement, jet–ambient pressure imbalance, and magnetic-field geometry shape the emergence of time-dependent features capable of energizing particles. The results link global jet dynamics to the spectral, polarization, and variability signatures observed in the very-high-energy (VHE) band, providing a physically consistent framework for interpreting high-energy-peaked blazars and underscoring the need for global jet modeling in VHE studies.

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## From Models to Measurements: A Unified Framework for Blazar Polarisation Detectability

**Author:** Sara Capecchiacci<sup>1</sup>

<sup>1</sup> *IA-FORTH*

Multiwavelength polarimetric studies provide a powerful tool to probe the structure and physics of blazar jets, and in particular high-energy polarisation measurements allow us to discriminate between competing models for their multimessenger emission. A new generation of X-ray and gamma-ray polarimeters is currently under development to achieve that. In this work, we investigate the detectability of blazar polarisation as a function of flux and polarisation degree (PD), and we estimate the corresponding duty cycle expected for future instruments. We further explore how this duty cycle depends on SED class, typical variability levels, and the shape of the synchrotron component. This provides a unified way to compare theoretical expectations with real observing capabilities and to assess which sources, physical models, and flux states are most favourable for polarimetric studies. Our results offer practical guidelines for planning future multiwavelength polarisation campaigns to conclusively differentiate between competing theories.

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## Predictions of high-energy neutrino fluxes from blazars with LeHa-Paris code and stacking searches with KM3NeT/ARCA data

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Identifying the astrophysical sources of high-energy cosmic neutrinos remains a central challenge in multi-messenger astronomy. Following the association of a 290 TeV neutrino detected by IceCube with the flaring blazar TXS 0506+056, theoretical studies have focused on modelling the photon–neutrino connection in blazars. We present a computational framework combining advanced particle-interaction simulations and statistical analysis methods to investigate neutrino emission from High-frequency-peaked BL Lacs (HBLs). The LeHa-Paris

numerical code is employed to simulate photomeson interactions and radiative processes, enabling the computation of leptonic and hadronic contributions to the blazar Spectral Energy Distribution (SED), including the neutrino component. Starting from the well-characterized case of PKS 2155–304, a methodology is developed to compute neutrino flux templates, optimized with LeHa-Paris, for a subsample of HBLs from the 3HSP Catalogue. Thereafter, these predictions are coupled with a binned likelihood stacking analysis designed for KM3NeT/ARCA, a deep-sea Cherenkov detector under construction in the Mediterranean Sea and capable of observing neutrinos across an energy range from 100 GeV to multi-PeV. Its configurations with 6, 8, 19, and 21 instrumented detection units are analyzed, allowing for the comparison of simulated neutrino spectra with KM3NeT/ARCA data. The pipeline is aimed at enhancing sensitivity to cumulative neutrino signals beyond what is achievable from individual sources alone, thereby enabling possible connections between blazar emission models and neutrino observations.

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## Pulsars with PINNs

**Author:** Ioannis Contopoulos<sup>1</sup>

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We will present our efforts to obtain the reference solution for the ideal force-free 3D pulsar magnetosphere with Physics Inspired Neural Networks (PINNs). We will present our first results, we will show where and why they differ from all current state-of-the-art solutions, and we will discuss the potential of PINNs for astrophysics.

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## A 3D cone-based mapping framework for asymmetric structures in RATPaC: implementation and applications

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Supernova remnants are considered major contributors to the Galactic cosmic-ray population. However, many existing numerical models of particle acceleration at the remnants shocks still rely on over-simplified geometries that cannot reproduce the rich and asymmetric emission morphologies that many remnants show on account of their interaction with their inhomogeneous surroundings.

In this talk we present a way to address this limitation, thanks to a new addition to our RATPaC code, where we split-up the geometry of the remnant into cones, assuming a piecewise spherical symmetry. As a consequence, we solve the coupled system of hydrodynamics, cosmic-ray transport, magnetic fields, and turbulence in a fully time-dependent manner for each cone. This makes RATPaC a powerful tool for studying supernova remnants and cosmic-ray sources in the area in high-resolution astronomy, especially in the face of the upcoming CTAO.

We will describe the new feature and code architecture and we will show the first applications of it to both simulated data and observed data, such as that of SN1987A. We think that this 3D mapping tool enriches RATPaC's modeling capabilities by enabling systematic studies of geometry-driven effects in supernova remnants and other cosmic-ray sources.

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## A CNN Surrogate for Time-Dependent GRB Synchrotron Spectra

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We present a convolutional neural network (CNN) surrogate model designed to reproduce the time-dependent synchrotron spectra of GRB prompt emission. The training set consists of physically motivated simulations in which a single electron-injection episode and a decaying magnetic field generate the evolving spectra of FRED-shaped pulses. The CNN maps the physical parameters to the full energy-and time-dependent flux, enabling rapid reconstruction of spectral evolution. Compared with our earlier CNN developed for blazar spectral energy distributions, the GRB problem requires capturing strong temporal evolution, fast changes in spectral curvature, and a tight coupling between physical parameters and time. This surrogate model will shortly be used to analyze upcoming accumulated prompt-emission data from SVOM-GRM, in addition to archival data from Fermi-GBM.

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## Gamma rays as leptonic portals to energetic neutrinos: a new Monte Carlo approach

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High center-of-mass electromagnetic (EM) interactions could produce decaying heavy leptons and hadrons, leading to neutrino generation. These processes might occur in the most extreme astrophysical and cosmological scenarios, potentially altering the expected gamma-ray and neutrino fluxes in both the hadronic and the leptonic pictures. For instance, neutrinos could arise from high-redshift EM cascades, triggered by gamma rays beyond 1018eV scattering background photons, from low-radio to ultraviolet energy bands. Such energetic gamma rays are predicted in cosmogenic models and in scenarios involving non-standard physics. On astrophysical scales, leptonic production of neutrinos could take place in active galactic nuclei cores, where several-TeV gamma rays interact with the X-ray photons from the hot corona. We explore these scenarios within the CRPropa Monte Carlo code framework, developing dedicated tools to account for leptonic production and decay of heavy leptons and hadrons. In particular, decays are performed in synergy with the PYTHIA event generator. With these novel tools, we characterise the spectrum and flavour composition of neutrinos emerging from cosmological EM cascades and from leptonic processes in inner core of active galactic nuclei. Finally, we investigate the leptonic production of neutrinos in the context of the IceCube detection of NGC 1068.

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## A novel approach of the pulsar magnetosphere

**Author:** Ioannis Dimitropoulos<sup>1</sup>

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Neutron stars—pulsars—and their magnetospheres are key sources for multi-messenger astrophysics. Their emission spans the entire electromagnetic spectrum, they are strong candidates for contributing to the cosmic-ray positron excess, and theoretical models (though not yet confirmed observationally) suggest that they may also produce high-energy neutrinos in the TeV–PeV range. By combining these multi-messenger channels, we gain valuable insight into the structure of the pulsar magnetosphere, the physical mechanisms operating under extreme conditions, and the internal properties of the neutron star itself. In this talk, I will present our new methodology for computing the pulsar magnetosphere using machine-learning techniques, specifically Physics-Informed Neural Networks (PINNs). With this method, we achieved the first steady-state 3D solution of the pulsar equation and uncovered a new family of 2D solutions that confirm theoretical constraints which had not been verified until now. I will also show our study of gamma-ray emission from the equatorial current sheet and conclude by demonstrating the flexibility of our framework through comparisons with NICER observations of the stellar polar cap.

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## STRIPE: Modeling Relativistic Turbulent Acceleration in Extreme Astrophysical Sources

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Turbulent particle acceleration is widely invoked to explain high-energy emission from extreme astrophysical sources. However, standard second-order Fermi models based on Fokker–Planck equation neglect complex non-linear effects emerging in the high-amplitude ( $\delta B/B \sim 1$ ) and relativistic turbulence regimes, expected in many astrophysical environments. Recent MHD and PIC simulations of turbulence have revealed that particle energization under such conditions is dominated by non-resonant processes and is highly intermittent, proceeding through abrupt, localized, large-magnitude energy jumps. This phenomenology cannot be described within diffusion-coefficient-based approaches, and remains largely unexplored in astrophysical applications. We present STRIPE (Strong-Turbulence Relativistic Intermittent Particle Energization), a new Monte Carlo code implementing and extending the novel theoretical framework of Lemoine (2022) for turbulent acceleration in the high-amplitude regime. STRIPE computes stochastic evolution of particle momentum driven by random velocity-gradient fluctuations and includes synchrotron and inverse-Compton losses self-consistently. Combined with our radiation module, the framework provides time-dependent particle spectra and broadband SED predictions. We apply STRIPE to conditions characteristic of extreme blazars and LHAASO-detected PeVatron microquasars. The resulting particle spectra are found to strongly deviate from standard diffusion-coefficient-based predictions: relativistic high-amplitude turbulence naturally produces hard, extended power-law tails without curvature, reaching multi-PeV energies. The combined model is able to reproduce key spectral properties of these two source classes. In a first full modeling application, we successfully fit the TeV–PeV gamma-ray spectrum of V4641 Sgr, including its unusually hard spectral index. STRIPE provides a new open computational tool for exploring turbulent acceleration in a multi-messenger context, with planned extensions toward hadronic emission and neutrino-flux predictions for extreme astrophysical accelerators.

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## Diplodocus: development updates and some findings

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The DIPLODOCUS (Distribution-In-PLateauX methODOlogy for the Computation of transport eqUationS) framework, and its associated code `Diplodocus.jl`, for anisotropic particle transport and emission modelling of astrophysical sources (focused on jets), are now publicly available.

In this contribution, we will update the community on the project's status, development and direction, and provide some insightful results. This will include single and multi-zone code comparisons for leptonic blazar emissions and a study into the effects that structured, helical, magnetic field within a blazar jet may affect its observed spectrum and hence our parameterisation of their in-situ properties.

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## A multi-modal approach for the classification of multimessenger events involving gravitational waves and CTAO data

**Author:** Claudio Gasbarra<sup>1</sup>

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The first multimessenger observation involving gravitational waves, GW170817, demonstrated the essential role of combining information from different messengers and from the entire electromagnetic spectrum to achieve a comprehensive understanding of astrophysical phenomena. In the coming years, the Cherenkov Telescope Array Observatory (CTAO) — the largest and most sensitive ground-based very-high-energy gamma-ray facility — will begin operations, and is expected to observe a substantial number of events jointly with the gravitational-wave detector network. This motivates the development of fast and robust analysis strategies capable of promptly extracting data features, including the ability to distinguish genuine multimessenger events from coincidental detections.

In this work, I present an implementation of a multimodal machine-learning (MMML) approach that combines CTAO and gravitational-wave data to classify candidate multimessenger events and extract source features.

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## From Photons to Neutrinos: Advancing Multi-Messenger Blazar Modeling with Gammapy

**Author:** Lea Heckmann<sup>1</sup>

**Co-authors:** Bruno Khelifi ; Justin Albinet ; Matteo Cerruti

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Blazars are among the most powerful objects in the Universe and are prime candidates for producing ultra-high-energy cosmic rays and astrophysical neutrinos. In today's multi-messenger era, combining data from different cosmic messengers with advanced modeling tools is key to unlocking the secrets of these extreme sources.

In this contribution, we present a novel, user-friendly multi-messenger modeling approach built on the open-source package `Gammapy`. Our framework brings together observations from optical to very-high-energy gamma rays operating directly on instrumental counts. The possibility to then directly fit theoretical models to these data inside `Gammapy` enables us to minimize biases and assumptions.

Focusing on blazars as key multi-messenger targets, we showcase how our framework enhances the ability to constraint emission models and present its extension to (lepto-)hadronic models

and neutrino data. Hadronic models are computationally expansive and therefore cannot be easily fit on the fly. We present our current solutions for hadronic fits and discuss possible future implementations.

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## From Vacuum to Force-Free: Neural Surrogates for Physically Grounded, Multiwavelength Constraints on Neutron-Star Structure

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Constraining neutron-star structure requires models that are physically faithful yet fast enough for the evaluations required by Bayesian sampling. We begin with static vacuum field (SVF) magnetospheres, where direct light-curve synthesis is too slow for practical MCMC; our neural-network (NN) surrogate matches SVF profiles with high fidelity and provides  $\sim 400\times$  speedups, enabling multipolar fits to NICER X-ray pulse profiles. We then extend to force-free (FF) magnetospheres and promote mass  $M$  and radius  $R$  to free parameters that enter GR ray tracing and the multipole-dipole balance at the light cylinder. Because FF simulations are  $\sim 2000\times$  costlier than vacuum, we pretrain on SVF and fine-tune the full network on a compact FF dataset to obtain surrogates with  $\sim 10^6\times$  speedups. We also train an NN to emulate FF gamma-ray light curves, making joint NICER-Fermi-LAT likelihoods feasible at MCMC scale. In FF, the current-sheet geometry specifies where gamma rays originate and their light-curve morphology, so the combined fit yields stricter, physically grounded constraints on  $M$ ,  $R$ , and magnetic topology; we illustrate the workflow on PSR J0030+0451. Tools are in place for energy-dependent X-ray modeling, and the framework extends to future radio observables, enabling comprehensive multiwavelength studies and a clear path to equation-of-state constraints.

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## Astrophysical Jets as Laboratories for Light Dark Matter

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Relativistic jets from black hole X-ray binaries (BHXBs) and active galactic nuclei (AGN) are powerful accelerators of cosmic rays (CRs), reaching energies up to the PeV scale and shaping the multiwavelength (MW) and multimessenger sky. Recent observations – including TeV detections of BHXBs and refined AGN spectra – motivate unified modeling frameworks capable of capturing jet physics across scales while probing potential interactions with light dark matter (DM). In this work, we extend the BHJet model to consistently describe BHXB and AGN jets, incorporating CR interactions with their environments and with sub-GeV DM candidates. We analyse both quiescent and active source states and test different statistical approaches, including nested sampling, to robustly explore parameter degeneracies. Applying the model

to Markarian 421 we achieve simultaneous fitting of jet dynamics and DM–electron interactions. This yields competitive constraints on DM-induced CR cooling, strengthening existing limits by up to an order of magnitude depending on DM mass. Our results demonstrate that joint MW modeling of jets is a powerful avenue for identifying astrophysical PeVatrons and constraining physics beyond the Standard Model.

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## Photo-hadronic neutrino production in magnetospheric current sheets of accreting black holes

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Non-jetted AGN exhibit hard X-ray emission with a power law spectrum above  $\sim 2$  keV, which is thought to be produced through Comptonization of soft photons by electrons and positrons (pairs) in the vicinity of the black hole. The origin and composition of this plasma source, known as the corona, is a matter open for debate.

Our study focuses on the role of relativistic protons accelerated in black-hole magnetospheric current sheets in the pair enrichment and neutrino production of AGN coronae. We present a model that has two free parameters, namely the proton plasma magnetization  $\sigma_p$ , which controls the peak energy of the neutrino spectrum, and the Eddington ratio  $\lambda_{\text{Edd}}$  (defined as the ratio between X-ray luminosity  $L_X$  and Eddington luminosity  $L_{\text{Edd}}$ ), which controls the amount of energy transferred to secondary particles.

Our results indicate a strong dependence of the neutrino luminosity produced on the Eddington ratio. More specifically, the fraction of the X-ray energy transferred to the high-energy neutrinos produced in the coronal environment is proportional to the Eddington ratio for  $\lambda_{\text{Edd}} \leq 10^{-2}(\sigma_p/10^5)^{-1}$  while constant otherwise. Furthermore, we discuss our results in light of the recent IceCube observations of TeV neutrinos from NGC 1068, NGC 4151 and CGCG 420-015. We, also, combine our coronal model with a luminosity function in order to provide an estimation of the diffuse neutrino flux measured on Earth.

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## News from AM<sup>3</sup> and M87 TeV flare modelling

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The super-fast ( $\sim$ day), very-high-energy (VHE;  $>0.1$  TeV) photon flares from the nearby active galactic nucleus M87 provide a unique, exciting opportunity to fast-forward our understanding of particle acceleration in jets. After a long break since 2010, the Event Horizon Telescope (EHT) multiwavelength (MWL) campaign captured a new VHE flare in 2018 with unprecedented frequency coverage including cm/mm-VLBI, EHT, Swift/Chandra/NuSTAR, Fermi-LAT and H.E.S.S./MAGIC/VERITAS. However, the angular resolution at TeV energies cannot resolve the emission region more precisely than within the entire galaxy itself. Also, the causality argument from the short VHE flare duration can only limit the size of the emission region to be small ( $\sim 10$  gravitational radii,  $r_g$ ), leaving the location uncertain from somewhere between the black hole vicinity (few  $r_g$ ) out to the knots ( $10^6 r_g$ , HST-1). It is thus only the simultaneous MWL facilities, with much smaller angular resolution at other

frequencies, that can help narrow down the location and physical nature of the VHE flares. The recent publication of the 2018 EHT MWL data set in 2024 provided only phenomenological 2/3-zone modelling, calling for a more physically grounded interpretation. I will discuss precisely such modelling, with a component of persistent emission from an MHD driven multi-zone jet in combination with a time-dependent flaring component. Along the way, I will give updates on the new developments of the AM<sup>3</sup> software. Looking ahead, this work is also particularly relevant as a preparation for the confirmed 2-month EHT/MWL/VHE movie campaign in Spring 2026, with even better temporal and spectral coverage to finally fully reveal the physics of M87's super-fast VHE flares.

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## Probing the Statistical Correlation of Tidal Disruption Events with High Energy Neutrinos

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High energy (HE) neutrinos have been observed by neutrino observatories for over a decade. Nevertheless, their origin and mechanisms responsible for their production still remain a mystery. Tidal disruption events (TDEs) have been proposed as candidate HE neutrino emitters, however a statistical association between the two has yet to be established. I will discuss results from the statistical association of a large sample of optical TDEs with neutrinos using TDECat and HE neutrino events observed by IceCube. While our analysis disfavors the association between neutrinos and the TDE population, we still find interesting associations with individual events including the jetted TDE Sw J2058+05. Our results highlight the need of upcoming surveys like LSST and next-generation neutrino observatories (e.g. KM3NET, IceCube-Gen2) to further test this potential correlation.

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## Detailed Modeling of Stochastic Particle Acceleration and Multi-Messenger Emission in AGN Coronae

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Stochastic particle acceleration in magnetized turbulent plasmas, and its resulting multi-messenger signatures, has received increased attention in recent years. A detailed modeling of this process is however made complex by the need to treat simultaneously particle acceleration and radiative processes.

We present here a hybrid numerical code that couples AM3 [1], a state-of-the-art, open-source, time-dependent lepto-hadronic radiative modeling tool, with a particle acceleration solver based on a momentum-space transport equation. The acceleration module incorporates recent theoretical developments, in particular the non-linear feedback of accelerated particles on the turbulent cascade [2] and a generalized transport equation in momentum space to model particle acceleration in strong turbulence [3]. This new framework therefore enables a self-consistent modeling of particle acceleration and the associated multi-wavelength and multi-messenger emission, making it a powerful tool to study turbulence-driven acceleration and to produce predictive signatures for comparison with observations.

Recent observations by the Ice Cube collaboration of multi-TeV neutrinos associated with nearby Seyfert galaxies provide specific motivation for this tool [4]. The inferred neutrino flux is at least an order of magnitude larger than the photon flux at similar energies, indicating that neutrinos originate from a region opaque to  $\gamma$ -ray photons. A natural candidate for such an environment is the accreting corona surrounding the central supermassive black hole, where photo-hadronic interactions can occur between the intense radiation field and protons stochastically accelerated by turbulence [5].

Using the hybrid code, we model the coronal plasma including stochastic proton acceleration, feedback on the turbulent spectrum, interactions with the local photon field, and the flow dynamics. The model successfully reproduces the IceCube neutrino flux within a physically motivated corona scenario. This provides a self-consistent explanation for the neutrino emission from NGC 1068 and offers a general framework for studying turbulence-driven particle acceleration and multi-messenger signatures in other astrophysical sources.

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- [2] M. Lemoine, K. Murase, F. Rieger: Nonlinear aspects of stochastic particle acceleration, *Phys. Rev. D* 109, 063006 (2024)
- [3] M. Lemoine: First-Principles Fermi Acceleration in Magnetized Turbulence, *Phys. Rev. Lett.* 129, 215101 (2022)
- [4] IceCube Collaboration: Evidence for neutrino emission from the nearby active galaxy NGC 1068, *Science* 378, 6619, 538-543 (2022)
- [5] A. Das, T. Zhang, K. Murase: Revealing the Production Mechanism of High-Energy Neutrinos from NGC 1068, *Astrophys.J.* 972 (2024) 44

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## The hunt for extraterrestrial high-energy neutrino sources

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The origin of high-energy neutrinos is fundamental to our understanding of the Universe. Immense effort has been put into identifying extragalactic sources of TeV-PeV neutrinos but still to no avail. Blazars has been proposed as one of the most promising candidates, however, the original association of a blazar with a high-energy neutrino has generated more questions than answers. I will discuss current efforts to test blazars as neutrino emitters across the electromagnetic spectrum using the largest sample of blazars compiled to date, as well as recent insights on the problem from multiwavelength polarimetry.

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## A VHE gamma-ray perspective of neutrino emitting Seyfert candidates: Insights into the hidden accelerator NGC 4151

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The Seyfert galaxies NGC 1068 and NGC 4151 have emerged as the most promising counterparts of 4.2 and 3.0 neutrino excesses detected by IceCube in the TeV energy range.

Gamma rays and neutrinos are co-produced at the same flux level via hadronic interactions between the parent proton population and the ambient matter and radiation in the neutrino-emitting region. Observations of NGC 1068 with the MAGIC telescopes have set stringent upper limits on its very-high-energy (VHE,  $E > 100$  GeV) gamma-ray flux, revealing the presence of a gamma-ray obscured accelerator.

With the latest MAGIC observations, similar evidence is found in NGC 4151. In this talk, I will present the first results from MAGIC observations of NGC 4151, which led to the estimation of stringent upper limits on its VHE emission. The unabsorbed gamma-ray spectrum is calculated directly from the neutrino spectrum by IceCube (Abbasi 2025). The MAGIC upper limits are used to constrain the neutrino-emitting region to the vicinity of the SMBH, to about  $\sim 10^4$  Schwarzschild radii of the SMBH at the center of NGC 4151, using relatively model-independent opacity arguments derived from multi-wavelength observations of the vicinity of the AGN core.

These findings strongly suggest that, like NGC 1068, NGC 4151 harbors a neutrino production site that is optically thick to gamma rays, reinforcing the idea that Seyfert galaxies could be a new class of hidden cosmic-ray accelerators.

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## Time dependent modelling of PKS 1510-089 July 2019 flare

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PKS 1510-089 is a blazar located at a redshift of  $z=0.361$ . It belongs to the blazar class of flat spectrum radio quasar (FSRQ) and is one of the few FSRQs detected at very high energy (VHE) gamma-rays with Cherenkov telescopes. In July 2019, it underwent a flare in high energy (HE) gamma-rays as seen with Fermi-LAT. The source was detected by H.E.S.S. (High Energy Stereoscopic System) during the flare and data analysis reveals fast intra-night variability in the VHE band as well as complex multiwavelength spectral behavior.

These characteristics make the flare an excellent laboratory to probe the physical conditions in the emitting region and the properties of the particle distribution within the jet.

In this contribution, I will present the observational campaign, together with a time-dependent leptonic model of the flare, implemented with the AM3 framework, which allows us to follow the evolution of the underlying electron population in detail.

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## Multi-Messenger, Multi-Instrument Blazar Modelling

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We present updates to the stationary lepto-hadronic code from *Boettcher et al. (2013) (B13)*. We demonstrate the implementation of the semi-analytical Bethe-Heitler pair production calculation from *Karavola & Petropoulou (2024)*.

B13 has also been implemented in Gammapy, as a callable model, enabling precise modelling of multi-wavelength data following *Nievas Rosillo et al. (2025)*. The neutrino output from B13 has also been utilized to allow for even a non-detection in the neutrino regime to be useful in parameter space restrictions.

Pipelines have also been written to process *Fermi-LAT* and *Swift-XRT/UVOT* products to Gammapy datasets.

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## AstroGenesis: A Domain-Aware Multi-Agent Model for Data-Driven Astrophysics

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Astrophysics is entering a data-rich era driven by multi-wavelength observatories and multi-messenger experiments. These facilities produce vast, heterogeneous datasets that challenge traditional analysis pipelines. General-purpose AI systems, while powerful, often lack the contextual reasoning and scientific rigor required for astrophysical interpretation. AstroGenesis is an AI-powered, domain-aware multi-agent research assistant designed to revolutionize how astrophysicists access, analyze, and interpret astronomical data. Built upon a Retrieval-Augmented Generation (RAG) framework and a modular multi-agent architecture, AstroGenesis integrates literature retrieval, data access, theoretical modeling, and hypothesis generation into a unified ecosystem. Each specialized agent autonomously handles dedicated tasks—such as spectral fitting, time-series analysis, or model inference—under the coordination of a central supervisory agent that ensures transparency and reproducibility. Key innovations include a domain-aware RAG system that grounds responses in peer-reviewed literature; seamless integration with multi-wavelength and multi-messenger archives for both raw and processed data; and neural-network-based modeling agents trained on large-scale radiative simulations for real-time, physics-consistent inference. It is possible to inspect the machinery with a human-on-the-loop for validation, and feedback to further enhance reliability. Demonstrated through a prototype for blazar research, AstroGenesis can be generalized to diverse astrophysical phenomena. By unifying reasoning, data retrieval, and theoretical modeling within a scalable framework, it lowers the barrier to advanced analysis and fosters transparent, reproducible, cross-disciplinary discovery in modern astrophysics.

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## News from CRPropa

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We present recent developments in CRPropa, highlighting a range of new tools for modelling the propagation of cosmic rays, gamma rays, electrons, and neutrinos from GeV to ZeV energies through galactic and extragalactic environments, as well as the surroundings of astrophysical sources. Since the last major CRPropa release, several significant features have been introduced to enhance its multi-messenger capabilities, including updated models of the extragalactic background light (EBL), cosmic-ray nuclei heavier than iron, spatially dependent photon fields, new Galactic magnetic field models, and improved cosmic-ray tracking performance.

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## Gammapy: Current status and future plans

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Gammapy is an open-source Python framework for gamma-ray astronomy. Built on the scientific Python ecosystem and using community-supported open data standards, it provides a unified platform for data reduction and modeling across a wide range of high-energy instruments, enabling interoperability between observatories and supports comprehensive joint analyses. Since its start in 2014 as a lightweight toolbox for TeV data studies, Gammapy has matured into a powerful, flexible analysis environment backed by an active and steadily expanding user community, and provides analysis support for major Imaging Atmospheric Cherenkov Telescopes including H.E.S.S., VERITAS, MAGIC, LST1, ASTRI; Water Cherenkov Telescopes like HAWC and SWGO, as well as Fermi-LAT.

In this contribution, we present the main concepts and features of the library and expose the variety of scientific use cases it supports. We will highlight the features of the latest stable release, and discuss plans for future development like support for Bayesian analysis, unbinned likelihood, improved timing analysis and interoperability with other packages for using physical models.

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## On the connection between high-energy neutrinos and delayed radio flares: the case of TXS 0506+056

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TXS 0506+056 is the first blazar associated with a high-energy neutrino detection (IceCube-170922A) in 2017. Notably, no immediate radio brightening accompanied this neutrino producing -ray flare but instead, a major radio outburst occurred about 2.5 years later. We investigate whether the 2017 flare accompanied by a high-energy neutrino event can lead to such a delayed radio flare. Using parameters from a published multi-messenger model of the 2017 flare, we simulate the evolution of a relativistic “blob” of plasma ejected during the flare. We propose a two-stage scenario in which the blob travels outward in the jet and becomes transparent, then undergoes a fresh particle acceleration in the optically thin regime on parsec scales. A mild deceleration of the jet (as hinted by very-long-baseline radio imaging) is also introduced. This re-acceleration model reproduces the time lag and spectrum of the radio flare. Our results suggest that production of high-energy neutrinos in blazars can lead to a delayed radio flare, but only after the emitting region propagates downstream and encounters new energization.

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## Investigating the Hadronic Origin of VHE Emission in HBL Blazars: A Multi-Zone Lepto-Hadronic Framework

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The origin of Very High-Energy (VHE) gamma-ray emission in High-frequency peaked BL Lac objects (HBLs) remains debated. While standard leptonic models successfully explain the synchrotron peak, they often struggle to reproduce hard TeV spectra without extreme parameters. We explore a hybrid scenario where the VHE emission arises from the interaction of stochastically accelerated protons with a target photon field provided by shock-accelerated electrons.

We present a newly developed numerical framework designed to model these multi-messenger signatures. Our code couples a stochastic acceleration model for protons with a standard shock scenario for electrons. By implementing the analytical parameterisations of proton-photon interactions (Kelner & Aharonian 2008), we calculate the resulting photomeson cascades and secondary gamma-ray spectra. We apply this model to characteristic HBL spectral energy distributions to assess whether hadronic components can naturally account for the observed VHE hardening. Furthermore, we provide estimates for the accompanying neutrino flux, aiming to constrain the baryon loading of the jet using current limits from the IceCube Neutrino Observatory. This study offers a diagnostic tool to distinguish between leptonic and hadronic origins of blazar emission in the multi-messenger era.

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## Using VLBI observations for modeling emission properties of neutrino candidate blazars

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There have been recent population studies supporting the idea that radio-loud blazars can be the potential source of high-energy astrophysical neutrinos being observed by IceCube. The understanding of neutrino production from these sources is intimately connected to explaining their multi-wavelength spectra as well. In this talk, ongoing work will be presented in modelling the lepto-hadronic spectral energy distribution (SED) for the neutrino-candidate blazar PKS 1749+096 in which both, the bulk properties and the particle distribution in the emission region, are anchored directly using parsec-scale VLBI observations of the jet and the corresponding spectral index map. When combined with physically motivated assumptions about jet processes, this approach allows modeling the SED from radio to gamma-rays without using numerical fitting to archival data. Thus, the talk attempts to motivate using radio observations as an anchor for improving our understanding of multi-messenger emission from neutrino-candidate blazars.

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## Accelerating multi-messenger modeling of blazars with neural networks

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Modeling the spectral energy distributions (SEDs) of blazars with physically motivated models is computationally expensive, as it requires solving coupled differential equations numerically and scanning high-dimensional parameter spaces.

In this contribution I will present our recent application of machine learning to accelerate the evaluations of blazar SED. Our method relies on a neural network (NN) architecture based on Gated Recurrent Units (GRUs), trained on a large sample of lepto-hadronic blazar simulations computed with the publicly available codes *AM<sup>3</sup>* and *LeHaMoC*. The resulting NN offers a strongly reduced run time while maintaining high accuracy in SED prediction. This efficiency enables Bayesian inference to be performed efficiently, making the method suitable for real-time analysis of blazar data.

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## Coupled Proton Acceleration and Leptonic-Hadronic Radiation in Turbulent Supermassive Black Hole Coronae

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Turbulent coronae around supermassive black holes can accelerate non-thermal particles to high energies and power observable emission, but the comparable timescales of acceleration, cooling, and electromagnetic cascades make this process hard to capture. In this seminar, I will introduce a time-dependent framework that self-consistently couples proton acceleration—modeled with the Fokker–Planck equation—to lepto-hadronic radiation and cascading. Applied to the neutrino-emitting active galactic nucleus (AGN) NGC 1068, the model reproduces IceCube’s observed neutrino spectrum while remaining consistent with gamma-ray limits. I will also discuss a transient-corona scenario, potentially arising in non-jetted tidal disruption events such as AT 2019dsg, where early cascade feedback regulates proton acceleration in weaker coronae and imprints delayed optical/UV, X-ray, and neutrino signals on ~100-day timescales. The framework efficiently models multi-messenger emission from both steady and transient sources, offering a flexible way to connect particle-acceleration physics with radiation mechanisms in AGN and TDE environments.

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## The OneHaLe Code: Towards version 2.0

**Author:** Michael Zacharias<sup>1</sup>

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In this presentation, I will show a (brief) update regarding the new capabilities of the OneHaLe (one-zone hadro-leptonic) code including some applications. New features include full hdf5 compatibility (output is written to a single file), easier handling of the injection particle distribution as well as the variability input, and others. The easier handling allows the user to have direct control of these inputs (with minimal C coding skills).

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## Numerical advancements in GRMHD simulations: Application of robust primitive recovery methods.

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General Relativistic MagnetoHydroDynamic (GRMHD) simulations solve the time-dependent electro- and hydrodynamic partial differential equations in arbitrary spacetimes. They usually employ conservative integration routines to advance the solution in the time domain, which are known to produce mostly numerically stable results. The most common one is the Finite Volume Method, which accurately evolves the conserved quantities in time, but in return requires the precise recovery of the primitive variables (pressure, velocity and density) in each time step and every grid cell, by solving a complex system of algebraic equations. This procedure is known for its numerical difficulty, especially in the context of GRMHD simulations. Although the currently used Newton-Raphson solvers prove to be very useful, they fail to provide accurate solutions in highly magnetized, low-density, or high Lorentz factor regions. These regions, that are commonly found in highly energetic astrophysical environments such as black hole accretion systems, require advanced techniques for primitive variable recovery, which often rely on approximations. In our work, we employ the robust method proposed in Kastaun et al. 2021 and implement it in the Black Hole Accretion Code (BHAC). The novelty of this approach is to transform the system of equations to a single equation and provide a bisection bracketing interval for accurate convergence in numerically unstable domains. We apply our implementation in high-resolution GRMHD simulations of magnetically arrested disks, whose variable accretion flow creates quasiperiodic flux eruptions and strongly magnetized regions within the disk and funnel.