Letter of intent

**Acronym and title:** PHANTASY – PHotonuclear-hAdroN physics for asTroAstrophYSics

**Name(s) of the project leader(s):** Gianluca Gregori (Oxford); Catalina Curceanu (LNF, INFN); Brian Reville (MPIK)

**In the sections below, please provide details on** *(2 pages max.):*

**1. Research objectives**

*Introduction*: Photonuclear reactions, and their inverse radiative-capture processes, serve as a unique window into hadronic and nuclear dynamics governed by the interplay between electromagnetic and strong interactions. These processes not only underpin our understanding of the origin of the elements through nucleosynthesis but also provide sensitive probes of hadronic structure and reaction mechanisms. In particular, the photodisintegration of light nuclei is governed by the response of the nucleus to electromagnetic probes, which is inherently linked to hadronic degrees of freedom—nucleon-nucleon interactions, meson-exchange currents, and short-range correlations. The study of photon-induced reactions offers complementary access to key aspects of hadron physics, especially in extreme environments where the role of resonant and non-resonant photon-hadron couplings becomes prominent. For example, in high-temperature astrophysical sites such as the early universe, stellar cores, and Gamma-Ray Bursts (GRBs), photons with energies up to hundreds of MeV can break apart atomic nuclei. These reactions are sensitive to the hadronic interaction models and nuclear structure inputs that define (γ,n), (γ,p), and (γ,α) cross sections—critical quantities for modeling the γ-process responsible for synthesizing rare, proton-rich nuclei. Moreover, photonuclear reactions act as well-controlled analogues for neutrino-induced processes, offering a bridge between electromagnetic and weak interactions in a hadronic medium. Since the same nuclear transition operators are often involved, studying γ-induced reactions allows us to infer properties of ν-induced reactions, which are far more difficult to measure. This connection is essential for constraining supernova dynamics and the ν-process contributions to nucleosynthesis. Hence, photonuclear data can inform both astrophysics and hadron structure by benchmarking theoretical nuclear response functions across different interaction regimes.

*Proposed experimental platform*: We propose to exploit the Beam Test Facility (BTF) at the Laboratori Nazionali di Frascati (LNF) to develop a novel γ-ray source for studying photonuclear reactions in a controlled laboratory environment that replicates key features of high-energy astrophysical scenarios. The photon beam will be generated via Inverse Compton Scattering (ICS), wherein a high-power optical laser interacts with an ultra-relativistic pair plasma produced by converting a primary electron beam through a high-Z target. The resulting γ-ray spectrum follows a power-law distribution extending up to several hundred MeV, resembling the energetic photon fields found in GRBs and stellar explosions. This approach offers a unique advantage in probing hadronic response in the regime where photon energies are sufficient to excite nucleon resonances and break nuclear binding, but below the deep-inelastic scattering threshold. Such an energy window is rich with hadron physics phenomena: the excitation of Δ and higher resonances, meson production thresholds, and contributions from multi-nucleon and meson-exchange processes. By tuning the γ-ray spectrum and nuclear targets, we aim to isolate specific channels that test models of hadron-induced nuclear reactions under electromagnetic excitation. Detection of the photonuclear events will be performed with a high-resolution Time Projection Chamber (TPC), using a gas target composed of light nuclei such as ^4He or ^12C. These systems are ideal for benchmarking theoretical models of few-body nuclear systems where hadronic interactions can be computed with high precision using ab initio approaches. The TPC provides full 3D reconstruction of charged-particle final states, enabling detailed kinematic analysis of the reaction channels, including nucleon emission, cluster breakup, and potential meson production.

D*ata Analysis*: The TPC will yield high-dimensional, image-like data capturing the 3D trajectories and energy depositions of charged particles produced in photonuclear events. This raw information encodes signatures of the underlying hadronic dynamics, including track multiplicity, angular correlations, and vertex topology. To extract this information efficiently and systematically, we will deploy advanced deep learning techniques such as Convolutional Neural Networks (CNNs) and Graph Neural Networks (GNNs). These models are particularly adept at processing complex spatial and temporal data, enabling robust event classification, noise reduction, and accurate reconstruction of particle kinematics. Beyond reconstruction, machine learning algorithms will be trained to identify specific hadronic final states and reaction mechanisms—distinguishing between quasi-elastic nucleon knockout, inelastic resonance excitation, and multi-particle breakups. This level of analysis is crucial to disentangle the contributions of various hadronic processes and to validate nuclear interaction models across different energy regimes. The ability to correlate event features with theoretical predictions will enhance our understanding of hadronic responses to electromagnetic probes, bridging low-energy nuclear structure with high-energy hadron physics.

1. **Connection to Transnational Access infrastructures (TAs) and / or Virtual Access projects (VAs)**

This project establishes a vital programme at the Transnational Access (TA) at INFN Frascati – upgrading its capabilities to address critical problems at the interface of hadron and nuclear physics with high energy astrophysics – with contributions from the groups at the University of Oxford and the Max Planck Institue for Nuclear Physics (MPIK) in Heildelberg, Germany. This synergy will not only accelerate innovation across multiple scientific fields (hadron physics, particle astrophysics, detector’s development, and machine learning techniques) but will also foster a more integrated European research community, provide critical hands-on training for the next generation of engineers and physicists, and reinforce the leadership of the European research areas in particle astrophysics.

**3. Estimated budget request**

INFN-LNF: Personnel: €60,000

Consumables: €60,000

Travel: €7,000

University of Oxford: PhD student: €132,000

Consumables: €55,000

Travel €15,000

MPIK: Personnel: €20,000

Compute access: €15,000

Travel: €8,000

Indirect costs: €92,750

**Total: €463,750**

**4. Participating and partner institutions**

Participating institutions: INFN-LNF, University of Oxford and MPIK. Interest in PHANTASY physics, more generically, includes team from the following institutions: CERN, GSI, Desy, University of Iceland, IST Lisbon, Science and Technology Facilities Council, Imperial College London, University of the Bundeswehr Munich, University of Rochester, University of Michigan.