PhD project

High-energy transient phenomena

The core of the proposed thesis project will be the real-time search for transient high-energy emission linked to the detection of a gravitational waves and other multi-messenger astrophysical transients like high-energy neutrinos, gamma-ray bursts, fast radio bursts, stellar/nova explosions, etc. The combined observations across multiple instruments and cosmic messengers will unequivocally prove the existence of a high-energy particle accelerators related to these phenomena and will allow to derive novel insights into the most violent explosion in the universe.
Joining the H.E.S.S., CTA and SVOM collaborations the PhD candidate will be able to lead the exciting MWL and multi-messenger campaigns collected during the physics run O4 of the GW interferometers, the first high-energy neutrino events detected by KM3NeT and the first GRBs detected by the SVOM satellite. The PhD candidate will also have the opportunity to participate in the development of the Astro-COLIBRI platform allowing to follow transient phenomena in real-time via smartphone applications.

Introduction and context

F. Schussler, the proponent of this PhD project, is leading the working group and the observation program dedicated to searches for very-high-energy gamma-ray emission from transient phenomena with the H.E.S.S. observatory. Over the last years this program led to the detection of gamma-ray bursts (GRBs, [1,2]) and successful participation in various global campaigns following the detection of high-energy neutrinos, FRBs, and other phenomena. Complementing the detections of GRBs via X-ray satellites, the detection of gravitational waves allows to provide new and complementary insights into the pre-explosion phase, the initial conditions, and the geometry of the system. The proposed thesis project will exploit the exciting possibilities of combining the detection of GWs and the detection of the resulting GRB by VHE gamma-ray observatories in truly multi-messenger observations and analyses during the upcoming physics run of the Ligo/VIRGO/KAGRA interferometers. Being a central part of the "H.E.S.S. Legacy Program" that started in early 2022, these observations have been granted highest priorities and a significant amount of observation times has been allocated to them by both H.E.S.S. and CTA/LST. Similar to the H.E.S.S. observations of GW170817, these observations typically include fully automatic prompt observations and deep campaigns over several days [3], as well as long-term monitoring observations of the most exiting events [4]. Combining the lessons learned, the scientific results derived from these first GW observations and the recent breakthrough in detecting VHE emission from GRBS, significant improvements and prospects can be expected for these upcoming campaigns. The PhD student will be at the heart of these opportunities.

[1] H. Abdalla et al. (H.E.S.S. Collaboration), "A very-high-energy component deep in the gamma-ray burst afterglow", Nature 575 (2019) 476; arXiv:1911.08961
[2] H. Abdalla et al. (H.E.S.S. Collaboration), "Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow", Science 372 (2021) 6546; arXiv:2106.02510
[3] H. Abdalla et al. (H.E.S.S. Collaboration), "TeV Gamma-Ray Observations of the Binary Neutron Star Merger GW170817 with H.E.S.S.", Astrophys. Journal Letters 850 (2017) L22; arXiv:1710.05862
[4] H. Abdalla et al. (H.E.S.S. Collaboration), "Probing the Magnetic Field in the GW170817 Outflow Using H.E.S.S. Observations", Astrophys. Journal Letters 894 (2020) L16 ; arXiv:2004.10105

Scientific project and techniques

The core of the proposed project will be H.E.S.S., currently the world's most sensitive gamma-ray instrument, and CTA, the next generation, global high-energy gamma-ray observatory. We'll also collaborate closely with partners from around the world including obviously the gravitational wave instrument Advanced Ligo/VIRGO/KAGRA, but also the SVOM satellite to detect GRBs. The PhD candidate will be able to join the SVOM burst advocate activities and thus experience the detection of gamma-ray bursts first hand. Complementary observations will be conducted in collaboration with radio telescopes in Australia and South Africa, optical observatories around the globe, and many more. The group at IRFU, CEA Paris-Saclay is leading observations of transient phenomena by both H.E.S.S. and CTA and has long-standing experience with these challenging observations. The group is also driving changes and modernizations of the communication within the astroparticle community (e.g. via the Astro-COLIBRI web/smartphone application [1]).

The PhD student will first have the opportunity to participate in the development and improvement of the framework that allows to optimize the schedule of follow-up observations of astrophysical transients. Some of the most interesting events are being detected only with large localization uncertainties (i.e. especially GWs, but also GRBs, neutrinos and others). We therefore need specialized tools and algorithms that allow to point the follow-up instruments like H.E.S.S. into the right direction to rapidly catch the associated emission. This work is building on the expertise of the IRFU group that is leading the developments of these algorithms within H.E.S.S and CTA since several years [2]. A crucial observation period by the GW interferometers (called O4) is taking place from spring 2023 until end 2024. This timing is perfectly matching the PhD project presented here, as the selected student will have the opportunity to lead the H.E.S.S. and CTA/LST-1 follow-up observations searching for GRBs and other VHE gamma-ray counterparts to the GWs detected by LIGO/VIRGO/KAGRA during that period. A sizeable amount of observation time with both the H.E.S.S. and CTA/SLT-1 observatories has been reserved for these exciting searches. We'll thus have ample opportunities to optimize our follow-up procedures, gather lots of data to analyze, present our results at international conferences, and publish them in high-impact papers.

The recent detections of VHE emission from GRBs has opened a new field of questions that we'll try to answer with this PhD project. In general, it is currently unclear how the initial parameters and the geometry of the pre-explosion system is linked to the observed characteristics of the GRB afterglow phase. Starting from basic questions like "What is the maximum energy reached in a GRB jet?" and "Are all, long and short, GRBs able to accelerate to TeV energies?" and leading up to detailed discussion of the influence of the viewing angle of the GRB jet, the jet opening angle, the inclination of the merger system, etc. Additional follow-up observations of GRBs, and especially those related to binary neutron star mergers, will allow us to tackle some of these topics. Depending on the number and quality of the detected events, we aim to link the parameters provided by the GW detection (i.e. the intrinsic, pre-merger parameters like the mass and mass distribution and the inclination of the system) with the post-merger system observable via the spectral and time structure of the MWL afterglow (e.g. jet opening angle, Lorentz factors, maximum energy, etc.).

The obtained high-energy gamma-ray data will be complemented by MWL observations covering the full electromagnetic range. We'll obtain use for example observations with optical telescopes (e.g. ATOM, GRANDMA), the Swift and SVOM X-ray satellites, public data from Fermi-LAT, etc. Driven by the multi-messenger observations led by the IRFU group over the last years, rapid data calibration and analysis procedures have been implemented. The student will be responsible for these data analyses and will thus be able to actively participate in the real-time exchanges within the global time-domain astrophysics community. Detailed offline data analyses

will possibly trigger additional mid and long-term monitoring observations before the results will be published in international conferences and papers [3].
Given the unpredictability of these phenomena (as we learned for example during the last GW observation run O3 during which no second GW170817-like event could be detected), a large range of additional possibilities will be assessed during the PhD project. The supervisor of the proposed project is for example leading a gamma-ray follow-up program of high-energy neutrino events. With the start of science observations of KM3NeT, prospects are very good for another global multi-messenger campaigns similar to the one connecting the flaring blazar TXS 0506+056 with the neutrino event IceCube-170922A [4]. If such an opportunity would occur during the PhD project, the student will have the possibility to lead the relevant data analyses and associated publications. Continuous and significant campaigns searching for gamma-ray emission from GRBs will see an increase in activity after the launch the of the SVOM satellite mid-2023. The close relations (the supervisor is member of SVOM and the science center emitting the crucial alerts is located at IRFU) will allow to conduct rapid follow-up observations with the high-energy gamma-ray instruments. These opportunities will help to shed light on the fundamental questions raised by the first VHE detections of GRBs outlined above.
Additional opportunities include searches similar to those performed over the last years and may for example involve FRBs. The origin of these milli-second long bursts of radio emission is still unknown and we are actively participating in several efforts to study the MWL properties of FRBs and their host galaxies. One of these are the Deeper-Wider-Faster campaigns that, twice per year, bring together a global consortium of observatories across all wavelengths and messengers to observe the same patch of the sky at the same time in search for transient phenomena. Another attempt are dedicated campaigns between MeerKAT, H.E.S.S., Swift and ATOM to study persistent behavior of FRB host galaxies and provide simultaneous MWL information for new bursts [5]. In 2020, an FRB could for the first time associated to a Galactic magnetar, SGR 1935+2154. During the campaign triggered by the X-ray activity of the source, a program led by F. Schussler allowed to obtain the first simultaneous VHE gamma-ray observations [6]. A last but not the least of these examples for possible additional science topics to be treated during the PhD project, is the recent discovery of very-high-energy emission from a Galactic nova [7]. After many years of continuous improvements and updates of the relevant H.E.S.S. program (which is part of the Transients WG led by F. Schussler), combined with novel tools like the Astro-COLIBRI platform, this breakthrough observation established a new class of VHE gamma-ray transients. These examples as well as continued programs with assured science return like follow-up observations of flaring active galactic nuclei (AGN), provide a very rich context for the outlined PhD project.
While this list of possibilities may look overwhelming, one has to realize that these efforts are imbedded in large working groups of the participating collaborations with sufficient manpower to tackle them efficiently. The decisions on the distribution of responsibilities within these groups are led by F. Schussler as working group convener and will be taken on a case-by-case basis jointly with the PhD candidate taking into account her/his interests as well as the work-load and overall advancement of the PhD project.

[1] P. Reichherzer et al., "Astro-COLIBRI—The COincidence LIBrary for Real-time Inquiry for Multimessenger Astrophysics", Astrophys.J.Supp. 256 (2021) 1; arXiv:2109.01672
[2] H. Askar et al., "The H.E.S.S. Gravitational Wave Rapid Follow-up Program", JCAP 03 (2021) 045; arXiv:2010.16172
[3] H. Abdalla et al. (H.E.S.S. Collaboration), "H.E.S.S. Follow-up Observations of Binary Black Hole Coalescence Events during the Second and Third Gravitational-wave Observing Runs of Advanced LIGO and Advanced Virgo", Astrophys. Journal 923 (2021) 1, 109; arXiv:2112.08307
[4] IceCube, Fermi-LAT, MAGIC, H.E.S.S. et al., "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", Science eaat1378 (2018); arXiv:1710.05833

[5] J. Chibueze et al, "A MeerKAT, e-MERLIN, H.E.S.S. and Swift search for persistent and transient emission associated with three localised FRBs", arXiv: 2201.00069; MNRAS (2022)
[6] H. Abdalla et al. (H.E.S.S. Collaboration), "Searching for TeV gamma-ray emission from SGR 1935+2154 during its 2020 X-ray and radio bursting phase", Astrophys. Journal 919 (2021) 2; arXiv:2110.00636
[7] S. Wagner et al. (H.E.S.S. Collaboration), "Detection of VHE gamma-ray emission from the recurrent nova RS Ophiuchi with H.E.S.S.", Astronomers Telegram #14844; Science (2022à

Organization of the PhD project and preliminary timeline

Providing a timeline for an observation program of transient phenomena is inherently uncertain and only rough estimates can be given. To prepare for various exciting opportunities, the PhD project will start with a period during which the student will get to know the available tools that have been developed in the group over the last years. These will be used to analyze the exciting dataset of observations conducted during the O4 GW run. Supported by other members of the collaborations, the PhD student will also act as responsible burst advocate for the H.E.S.S., CTA/LST and the SVOM collaborations. He/she will thus have the opportunity to guide the relevant observations first hand. The subsequent data analyses will be led by the student and will be published on behalf of the involved collaborations.
As outlined above the student will also join the development of the Astro-COLIBRI platform and (if interested) its outreach activities towards the amateur astronomer community.

[1] Abbott, B.P., Abbott, R., Abbott, T.D. *et al.* Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev Relativ* **23,** 3 (2020)

Environment and training opportunities

The PhD student will become a member of the H.E.S.S., CTA and SVOM collaborations. This unique combination will allow her/him to participate and lead the preparation of observations in close collaboration with external partners and be in charge of the subsequent data analyses across several wavelength ranges and instruments. The student will thus learn how to manage large volumes of complex data in a cloud-based computing environment on the Grid. Participation in the onsite operation of the experiments in Namibia and La Palma is possible. The student will have an extensive set of data analysis tools at his disposal but will also have the opportunity to develop novel methods and techniques taking full advantage of the information provided by multiple messengers. The participation in the Astro-COLIBRI development will expose her/him to modern tools like cloud computing and the publication of smartphone apps.
Thanks to existing collaborations, additional MWL coverage to the gamma-ray observations is naturally provided by radio facilities like MeerKAT, ATCA, ASKAP, etc., via the onsite optical telescope ATOM, dedicated observations requested from the Swift X-ray satellite, automatized analyzed of Fermi-LAT data, etc. This context will allow the student to gain experience with very diverse data sets and a large variety of analysis techniques. Combined with the access to the first data from CTA, this prepares the student for future research positions in many domains of (high-energy) astrophysics.

Local and international partners, thesis supervision

The PhD student will evolve within the astroparticle physics group at IRFU/CEA-Saclay, which is one of the major groups within H.E.S.S. and CTA and the lead institute for the French/Chinese SVOM satellite. The proposed project will benefit from existing strong links with various other groups in the Paris and Paris-Saclay area. We will for example be able to leverage the complementary expertise in follow-up observations of GW events by the Virgo and LSST/FINK groups at IJCLab. Another synergy exists with the group at LLR/Ecole Polytechnique especially via the postdoc H. Ashkar, former PhD student of F. Schussler and expert on GW follow-up scheduling with H.E.S.S. and CTA. Preparation and exploitation of the first GRB detections by SVOM will benefit from close collaborations with groups at IJCLab and IRFU/DAp. Interaction with external partners and members of other collaborations (Desy-Zeuthen/Berlin, MPIK/Heidelberg, Univ. Alabama/US, Univ. Adelaide/Australia, etc.) as well as within the active astrophysics community of Paris-Saclay will allow the student to enlarge his horizon and become a key member of the new and rapidly growing multi-messenger community. The multi-messenger astroparticle group at IRFU embraces the opportunities enabled by bringing together people from a wide range and diversity of thought, culture, background, experience and identity.

The thesis director, Fabian Schüssler (fabian.schussler@cea.fr), is member of the H.E.S.S., CTA, ANTARES and SVOM collaborations. He is the official H.E.S.S. contact for multi-messenger studies and is responsible for the H.E.S.S. science working group on transient phenomena and the related observation program. He is leading several projects bringing the global multi-messenger and astroparticle physics together and is developing novel tools to manage the increasing flow of information about transient astrophysical events. In this context he is co-supervising a PhD thesis jointly with researches from LISN/CNRS/Paris-Saclay on artificial intelligence and machine learning approaches to analyze astronomical observation reports written in natural language.

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