**The working groups of the Astrophysics Department (AP) envision an attractive science program for the first extension phase of H.E.S.S. operations, and a longer term vision:**

Among the many domains in which H.E.S.S. plays a leading role, the **study of transient phenomena and time-domain astrophysics** in general have seen many breakthroughs over the last years. Studying the most violent phenomena in the Universe, observations in the VHE domain is an integral part and often plays a decisive role in understanding the physics that drives these events, through a multi-wavelength and multi-messenger approach. H.E.S.S. is receiving information and alerts from new detections throughout the entire electromagnetic spectrum, in addition to astrophysical neutrino and gravitation wave messengers. Our automatic alert system is continuously being improved and builds a solid basis for continued target-of-opportunity (ToO) programs targeting many time domain astronomy phenomena accessible to IACTs. Our extensive observation campaigns, involving many partners around the globe, benefit from the improved reliability and sensitivity of the upgraded CT5 camera, and continue to provide surprising, high-impact results.

Thanks to continuous efforts and improvements, *gamma-ray bursts (GRBs)* have now been established as VHE emitters. However, at the same time recent intriguing observational results raise questions on the dominant VHE production mechanism, its duration and evolution within the GRB phase of the system, necessary burst progenitor, burst and circumburst environment triggering VHE emission, maximum energy reached and its possible scaling with the jet opening angle, etc. The extension of H.E.S.S. operations over the next years allows for an observational program that systematically covers a larger burst parameter space, tailored to provide at least some answers to the science questions raised.

This quest for understanding the mechanisms that power GRBs will also be benefiting from new opportunities like those provided by the upcoming SVOM mission to be launched in late 2022. The associated ground segment will drastically improve the coverage of GRB observations in the optical domain and will thus significantly enhance the availability of crucial redshift measurements of GRBs. The emitted gravitational waves (GWs) encode important information (e.g., mass distribution, geometry, etc) about the system even before it triggers the explosions detected as GRBs, and could increase our understanding on how the progenitor system links to the observational appearance of the GRB. After significant upgrades, the global GW-interferometer network will restart science operations in late 2022. Improved sensitivities will lead to substantially more detections that allow a systematic study of the progenitors that drive such explosions. The addition of KAGRA as fourth GW observatory will help reduce the localization uncertainties. H.E.S.S. being the first ground-based pointing instrument to observe the location of the binary neutron star merger GW170817 has impressively demonstrated the current performance of the H.E.S.S. GW follow-up program. Further improvements will allow us to fully benefit from the opportunities during the upcoming physics runs of the GW detectors.

The dominant source population of the astrophysical high-energy neutrinos detected by IceCube, signatures of cosmic-ray acceleration, remains enigmatic. Uncovering the preferred cosmic environment where cosmic rays are accelerated to extreme energies is among the most urgent science quests today. Using the Earth as shield, the European KM3NeT neutrino telescope will provide increased sensitivity to sources in the Southern Sky perfectly accessible by H.E.S.S., while at the same time improving the angular resolution over the currently most sensitive detector, IceCube. In close collaboration with both neutrino instruments, H.E.S.S. is actively participating in the definition of improved alert schemes that take full advantage of existing MWL data as well as contemporaneous observations provided by monitoring instruments in the gamma-ray domain like Fermi-LAT, HAWC and LHAASO. This allows intensified searches for the identity of these powerful cosmic accelerators.

Overall, the H.E.S.S. transient program aims to strike a balance between continued efforts in well-established domains that provide assured science return and novel, higher risk endeavors. Along these lines continued coverage of flaring, Galactic and extragalactic objects expands our insight into the underlying physics that drives such outburst phenomena. In this regard, variability studies (including flare coverage complemented by continued monitoring and exploiting the extensive H.E.S.S. archive), and searches for periodicities of particular objects, are crucial. New data analysis tools and methods allow to cover the required broad range of timescales, ranging from milli-seconds to several years. Observations of particular phases or phase transitions in Galactic systems like gamma-ray binaries will continue to provide interesting insights into the evolution of such systems.

Observations of well-known supermassive black hole objects like Sgr A\* and M87 aim towards a deeper understanding on the link between black holes and their immediate environment, e.g., supporting jet formation. Correspondingly, these are now often embedded in global campaigns for example linked with observations of the Event Horizon Telescope (EHT), thus increasing their value for theoretical interpretations.

Exploratory searches for new source phenomena and source classes are benefitting from increased collaborations and joint observations with new facilities in the X-ray and radio bands (e.g. NICER, ASKAP, MeerKAT). These efforts include searches for potential, rare gamma-ray transients, like emissions associated to magnetar flares and Fast Radio Bursts. At the end of 2022 the Very Rubin Observatory (LSST) will commence its science operations and optical coverage of the H.E.S.S. sky will be deeper and with higher cadence than ever before. The enabled synergy between both observatories for the study of transient phenomena cannot be underestimated. In addition to H.E.S.S. reacting to new discoveries and alerts by LSST, many of our ToO observations will benefit from the long-term light-curves compiled during the LSST survey and joint studies are in preparation.

The H.E.S.S. program on transient phenomena combines thorough planning and preparation with exciting multi-wavelength and multi-messenger opportunities that will become available over the next years. It promises a rich program that will provide leading observations and results in a novel and rapidly evolving domain.

The gamma-ray band is certainly among the standard domains to explore phenomena that may hint towards **physics beyond the standard model (PBSM)**. The corresponding science program for the H.E.S.S. extension phase envisions cosmology (e.g. measuring the Hubble constant with gamma-ray spectroscopy), as well as particle physics (e.g., searching for ALPS/photon mixing) aspects using gamma-ray propagation.

The disparity of the *Hubble constant* from CMB and local measurements is the main driver to visit this question from the VHE perspective. In this context, the unequaled precision of spectral measurements with the H.E.S.S. telescopes and the unique and complementary methods related to individual and combined energy spectra are great assets. Furthermore, the upcoming launch of the JWST (October 2021) will lead to a completely new situation where the stellar contribution to the EBL will be completely resolved such that the model dependence of previous studies will be considerably reduced.

To this end an, the PBSM group is working towards proposing an optimized set of observations to achieve the goal of measuring the Hubble constant (possibly at various red shifts) with dedicated observations during the H.E.S.S. extension. In parallel we can use the available observational data from AGN to verify methods and expected performance.

The *search for ALPs*  remains a topic of considerable interest. The improvements in Galactic magnetic field tomography is going to provide additional opportunities to investigate spurious signals and improve constraints with dedicated observations. The era of eROSITA and low-frequency radio observations will also sharpen our view on the magnetic field present in the intra-cluster medium which is an essential input for searches of spectral signatures of photon-ALPs mixing. In the context of laboratory based photon-ALPs mixing, we will be able to explore the complementarity of these searches and possible spectacular results. While the actual observation program for this objective is difficult to foresee, it is going to be the motivation for upcoming observation proposals.

The PBSM confluence working area is regularly updated with further science topics that are going to be the focus points of this working group’s activities.

Much of the current knowledge on the *distribution of cosmic rays in the Galaxy* arises from the studies of the gamma-ray **diffuse emission** in the Galaxy. The knowledge of the diffuse gamma rays from a given direction on the sky and of the gas column density from the same direction yields information on the average cosmic ray density along the line of sight. Differently from diffuse emission the gamma-ray radiation from giant molecular clouds (MCs) helps determining a 3D view of the level of the CR background in the Galaxy: CR tomography on the level of the CR background. Giant MCs with their gas target density for cosmic ray interactions orders of magnitude higher than the surrounding interstellar medium, are crucial to enhance the gamma-ray emission arising from background CRs, and serve as *barometers of the Galactic cosmic ray pressure*. The spatial resolution of the tomography corresponds to the dimension of a typical MC in the Galaxy. The combination of novel clouds catalogues and of observations in the gamma-ray band allows obtaining an unprecedented view of the CR level and distribution. This procedure has been successfully tested in the GeV band, and is envisioned by the **diffuse emission and diffusion working group** to be carried out in the VHE band using H.E.S.S. over the next coming years.

How do *Galactic cosmic rays escape* their sources? According to the most popular view, SNRs accelerate the highest energy CRs at the transition between the free expansion and the Sedov phase, where the shock subsequently slows down and the magnetic field intensity decreases. Being not confined any longer, CRs may escape their injection sources, and may collide with the ambient gas. Studying these runaway cosmic rays, which form a *proton halo* around SNRs, allow to gain a deeper comprehension of the so far poorly understood mechanisms of cosmic ray escape. We plan to engage in such studies using a list of promising candidate SNR-cloud associations, designed for studies at extreme energies.