The Fourth Gravi-Gamma-Nu Workshop

Wednesday, 4 October 2023 - Friday, 6 October 2023

Gran Sasso Science Institute

Book of Abstracts

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Orbital Motion in the Reference Frame of a Blackhole

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I compare two versions of the analysis of the gravitational wave signal GW150914 presented previously by the LIGO/Virgo collaboration (LVC). The first version was presented in 2016 by this collaboration along with their announcement of the first experimental detection of gravitational waves [1]. It was based on rigorous general-relativistic treatment of the coalescing two-body problem. The second analysis of this signal by the same authors [2] was based on the quadrupole post-Newtonian (PN) approximation of General Relativity (GR). I revisit this post-Newtonian analysis and estimate the mass of the coalescing binary blackhole system using frequency values read directly from the time-frequency diagram of GW150914. My estimation, similarly to the PN-result from LVC [2], coincides with the rigorously calculated mass for this system from the LVC first publication. Additionally, I estimate the masses of other coalescing binary systems by using the same quadrupole PN-approximation formula applied to the data from the published gravitational wave transient catalogues. Practically all of myPN-approximation estimates coincide with the published masses based on the rigorous methods. In my view, this coincidence means that the rigorous theory for gravitational waveforms of coalescing blackhole binaries does not fully account for the difference between the source and detector reference frames because the PN-approximation, which is used for the comparison, does not make any distinction between these two reference frames: by design and by the principles and conditions for building the PN-approximation. I discuss possible implications of this conflict and find that the accuracy of the previously estimated characteristic (chirp) masses of coalescing binary blackhole systems is likely to be affected by a systematic error.

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Multimessenger view of neutron stars: from pulsars to GRBs / 2

The host galaxies of binary compact objects

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The merger rate density of binary compact objects and the properties of their host galaxies carry crucial information to understand the sources of gravitational waves. In this talk, I present galaxyRate, a new code that estimates the merger rate density of binary compact objects and the properties of their host galaxies, based on observational scaling relations. We generate synthetic galaxies according to the galaxy stellar mass function of star forming and passive galaxies. We estimate the metallicity according to both the mass-metallicity relation (MZR) and the fundamental metallicity relation (FMR). Also, we took into account the evolution of the galaxy properties from the formation to the merger of the binary compact object. We found that the merger rate density evolution changes dramatically depending on the choice of the star-forming galaxy main sequence, especially in the case of binary black holes (BBHs) and black hole neutron star systems (BHNSs). The slope of the merger rate density of BBHs and BHNSs is steeper if we assume the MZR with respect to the FMR, because the latter predicts a shallower decrease of metallicity with redshift. In contrast, binary neutron stars (BNSs) are only mildly affected by both the galaxy main sequence and metallicity relation. Overall, BBHs and BHNSs tend to form in low-mass metal-poor galaxies and merge in high-mass metal-rich galaxies, while BNSs form and merge in massive galaxies. We predict that passive galaxies host at least ~5-10%, ~15-25%, and ~ 15-35% of all BNS, BHNS and BBH mergers in the local Universe.

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Binary neutron star populations in the Milky Way

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Binary neutron stars (BNSs) wield a pivotal role in modern astrophysics. Merging BNSs not only can be loud sources of gravitational waves, but also trigger short gamma-ray bursts and kilonovae. A great example of such event is the renowned GW170817; the observation of its electromagnetic counterpart paved the way for new frontiers in multimessenger astrophysics.
Moreover, thanks to the timing precision of pulsars, BNSs are unique laboratories to probe gravitational physics. From the theoretical point of view, many open questions persist: what are the processes that most affect the evolution of a BNS, eventually leading to its merger? What are the birth spins and magnetic fields of neutron stars and how do they evolve?
In this talk, I will try to answer some of these questions through a new detailed analysis of the properties and evolution of BNSs. I combined cosmological simulations with the state-of-the-art population-synthesis code SEVN and explored the impact of binary star evolution prescriptions, such as the common envelope efficiency, the supernova kick model and neutron star spin and magnetic field properties on the population of BNSs. I will also show how my results compare against the Galactic pulsar population.
Finally, I will discuss the implications of my results for the next-generation gravitational wave detectors and radio observatories.

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Constraining the mass of neutron stars in compact binaries with multi-messenger observations

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Black widow systems are a class of rotation-powered pulsar binaries, consisting of a millisecond pulsar irradiating and ablating a sub-stellar mass companion. They are believed to be at the end of their recycling process, by which the neutron star has spun up and acquired considerable masses. Observations suggest that these systems potentially hold the most massive neutron stars in our Universe, with several systems reported to have neutron star greater than 2 solar masses based on optical photometric and spectroscopic observations. Nevertheless, the existing methods to determine the neutron stars'masses bear uncertainty due to complicated model systematics. In this research, we

focused on the compact black-widow-like systems with orbital period less than 1 hour and showed that these systems are potential gravitational wave sources detectable by LISA. By combining the binary mass function measured via optical observations with the complimentary mass function derived from the gravitational wave observations, we proposed a novel multi-messenger method to constrain the mass of the neutron stars in such binaries. We showed that our method has the potential to test the existing equation-of-state (EOS) models and to help us to understand the composition of the ultra-dense materials.

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Decomposing the origins of gamma-rays from the Galactic Centre with neutrino imaging and implication on the millisecond pulsar population

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Molecular clouds in the Galactic Centre will glow in neutrinos and gamma-rays when bombarded by energetic hadrons. Gamma-ray imaging of the Galactic Centre has therefore been employed to study the cosmic-ray energy spectrum and density distribution around Sgr A*. While part of the gamma-rays may be contributed by leptons, leading to uncertainty that is challenging to estimate, neutrinos serve as clean messengers of hadronic interactions and are thus better tracers of cosmic rays in the Galactic Centre. IceCube's recent announcement of the Milky Way's first neutrino map highlights our advanced capability to discern Galactic emissions. Future neutrino observations will achieve an angular resolution below 0.1 degrees, enabling us to resolve the central region of our galaxy. We explore the potential role of millisecond pulsars as cosmic-ray accelerators, and use neutrino imaging to constrain their population. Their population bears significant implications for the gamma-ray excess problem and the formation of extreme mass ratio inspirals in galaxies similar to Milky Way.

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Gamma-ray pulsar glitches: a study of variability in Fermi-LAT data

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Pulsars are the largest class of Galactic sources detected by NASA's Large Area Telescope (LAT) on the Fermi mission. Pulsars are generally acknowledged as very stable astrophysical rotators, and they gradually slow down by emitting radiation at the expense of their rotational energy. Occasionally, pulsars can undergo transient events called glitches, which consist in rapid changes in their rotational parameters and are often followed by a relaxation. Variability in the emission features correlated to glitches has been observed in a small family of radio pulsars and in the radio-quiet PSR J2021+4026, which is the only variable pulsar observed by the LAT. Here we present a novel analysis of LAT gamma-ray pulsars consisting of a study of variability correlated with changes in the spin-down rate. We perform a maximum likelihood spectral analysis of LAT data around detected glitches, aiming at measuring variations in the gamma-ray flux and spectral parameters. We present results for a subset of glitches that we consider particularly promising. Our study suggests the importance of variability analysis to achieve a deeper understanding of pulsar physics.

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A multi-messenger view of NGC 1068

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I will present a comprehensive multi-messenger view of NGC 1068, the prototype Seyfert II galaxy recently associated with high-energy IceCube neutrinos. Various aspects of the source, including its nuclear activity, jet, outflow, and the starburst region, will be analised in detail using a multi-wavelength approach.
I will also explore its gamma-ray and neutrino emissions to try to understand which astrophysical component is responsible for the IceCube neutrinos.

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The Compton Spectrometer and Imager (COSI)

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The Compton Spectrometer and Imager (COSI) is a gamma-ray telescope, selected by NASA as a Small Explorer satellite mission to be launched in 2027. COSI employs a novel Compton telescope, consisting of a compact array of cross-strip germanium detectors. Owing to its wide field-of-view and excellent energy resolution, COSI will achieve an unprecedented sensitivity in the 0.2-5 MeV energy band. In particular, it will improve narrow-line sensitivity by about one order of magnitude over existing searches, mapping the full sky uniformly with an energy-dependent angular resolution on the degree scale. The mission requirements enable four key science goals: the origin of Galactic positrons, nucleosynthesis in the Galaxy, polarization studies of accreting black holes, and multi-messenger astrophysics. In this talk, I will provide an overview of the instrumental design and science of COSI. I will present the current status of the project and the publicly-available data challenges released every year

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The fourth Data Release of the fourth Fermi LAT source catalog

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The new data release four (DR4) of the Fourth catalog of gamma-ray sources of the Fermi Gamma-ray Space Telescope Large Area Telescope (4FGL), is based on gamma-ray photons detected with energy between 50 MeV and 1 TeV, and accumulated during the first 14 years of the Fermi all-sky survey. The analysis methods are inherited from the first 4FGL catalog (8-year list), with several new features introduced in DR3 and a few in this release. We present first insights, both about the characteristics of the entire source population, and the sources (about 500) that are new, with respect to the previous DR3 (12-year list).

About 40% of the new sources of DR4, are statistically associated with counterparts at other electromagnetic wavelengths (generally radio and/or X-ray sources), and are largely represented by blazars or candidate blazars. In this view, initial highlights on the companion catalog, the data release four of the Fourth LAT AGN Catalog (4LAC-DR4), are also briefly introduced.

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Exploring Cosmic Ray acceleration and escape in the W44 region with Fermi-LAT and MAGIC

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W44 is a middle-aged Supernova Remnant (SNR) largely investigated to probe acceleration of Cosmic Rays (CRs). Previous studies already showed the presence of gamma-ray emission not only from the remnant, but also from its surroundings, thought to be due to high-energy CRs escaping from the forward shock of the remnant.
We present a detailed morphological and spectral analysis of Fermi-LAT data above 100 MeV related to the W 44 region. The morphological analysis was performed for energies above 1 GeV, to exploit the improved angular resolution of the instrument, deriving an accurate description of the region's morphology.
The W 44 region was also observed in the very high-energy gamma-ray band by the MAGIC telescopes. We carried out a likelihood analysis exploiting the spatial information derived from the Fermi-LAT analysis above 1 GeV, focusing on the northwestern side of the remnant. The combined Fermi-LAT and MAGIC spectra provide useful constraints on the diffusion of the escaped CRs.
In this talk we describe the analysis results and a model that includes the temporal evolution of the acceleration and escape process of high-energy particles from the remnant's shock.

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Future Multimessenger Detections with SVOM

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SVOM is a joint French-Chinese mission dedicated to the study of gamma-ray bursts (GRBs) and high-energy transients. SVOM boasts a suite of space-based instruments spanning from hard X-rays to visible light that will be complemented by a ground segment of optical telescopes. With an expected launch in early 2024, SVOM will also contribute to multimessenger observations of gravitational waves (GWs) detected by LIGO/Virgo/KAGRA in the second half of the O4 observing run. Here, we present the observational strategy for SVOM follow-up of GWs with the Microchannel X-ray Telescope (MXT) and the Visible Telescope (VT). We also present the development of a ground-based subthreshold search of SVOM ECLAIRs data.

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Einstein Telescope: science objectives and designs

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The detection of gravitational waves in 2015, thanks to the LIGO and Virgo interferometers, opened a new window on our Universe. The discoveries during the first three observing runs already had an extraordinary impact on astrophysics, cosmology, and fundamental physics.

The GW community is now looking at the next long–prepared step: 'third–generation'detectors. Thanks to an increase of more than one order of magnitude in sensitivity and a larger bandwidth, Einstein Telescope (ET) and Cosmic Explorer (CE) will have an outstanding potential, capable of triggering fundamental discoveries.

I will give a broad overview of the main science targets of ET, ranging from Astrophysics to Cosmology and Fundamental Physics. I will then show recent forecasts for the observational prospects of ET, also comparing the reference triangular design with a geometry consisting of two widely separated L-shaped interferometers. Finally, I will focus on more specific aspects of the science case, namely nuclear physics and primordial black holes.

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Potential biases and prospects for the Hubble constant estimation from a joint EM and GW analysis of neutron star merger

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GW170817 is an outstanding event as it paved the way for multi-messenger astrophysics. It is a binary neutron stars merger, that saw the detection of a gravitational wave (GW), a gamma ray burst (GRB) and an afterglow. Such events are interesting also from a cosmological point of view, as we can derive an Hubble constant (H_0) measurement (the current expansion rate of the Universe), independently from any cosmic distance ladder. In this work we estimate H_0 using the broad band afterglow emission and the relativistic jet centroid motion from the very-large-baseline interferometry (VLBI) and HST images of GW170817. Compared to previous attempts, we join these two messengers with the GW in a simultaneous Bayesian fit. We focus on the H_0 estimation robustness depending on the unknown jet structure and the possible presence of a late time flux excess. We find $H_0 = 70.1^{+4.6}_{-4.4}\ km/s/Mpc$, a viewing angle of 18 deg and a distance of 44 Mpc, fitting the complete data set. This H_0 measure is about 3 times more precise than a GW-only estimation. Not including the jet motion in the analysis, the H_0 posterior peaks above 90 $km/s/Mpc$, because of the preference for high viewing angles, caused by the possible presence of a late-time excess in the afterglow flux. In general, the afterglow, no matter the jet structure, tends to prefer high viewing angles, leading to an unreliable H_0 measurements. Therefore, careful modeling of the afterglow is needed. Moreover, the larger the number of counterparts included in the analysis, the more robust and reliable is H_0.

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Time-evolving photoionisation in GRB afterglows

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GRB absorption spectra are powerful probes of the circumburst medium of their progenitor and the host galaxy's ISM. The column densities as derived from the X-ray and the optical spectra differ by up to an order of magnitude, suggesting the presence of a highly ionised region close to the GRB. This happens because the X-ray absorption probes the total column along the line of sight, including the immediate vicinity of the GRB, while optical absorption probes the neutral ISM within the host, thus providing a complementary method to study the nature of the medium. In this study, we present a combined analysis by using a newly developed time-evolving photoionisation model to fit the X-ray afterglow spectra of a flux-selected sample of seven GRBs (including the record-breaking GRB221009A) within a physically-motivated picture, which also takes into account the optically-derived absorption. Our model independently constrains a high-ionisation region in the immediate vicinity of the burst, consistent with the GRBs exploding in a dense environment (10^{3-4} cm^{-3}) that is typical of high-mass star-forming regions. Furthermore, time-evolving modelling significantly improves over cold or equilibrium ionised absorber models.

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GeV emission from a compact binary merger

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The origin of gamma-ray bursts (GRBs) is still mysterious. We believe that binary neutron star (BNS) mergers produce short GRBs, while long GRBs are associated to the collapse of massive stars.
This GRB dichotomy, based on the duration of the prompt pulse, was recently challenged by the detection of the bright and relatively close (z=0.076) GRB 211211A. Despite its long duration (~30 s), the discovery of an optical-infrared kilonova (KN) points to a compact object binary merger origin.
We have analysed the radio-to-GeV afterglow emission of this source. In particular, the analysis of the high energy (HE, 0.1-10 GeV) data, provided by Fermi/LAT, revealed a significant emission ($> 5\sigma$) detected in two epochs at late times (~10^3 and ~10^4 s after the burst) with approximately constant flux (~5e10 erg/cm^2/s).
The multi-wavelength afterglow emission is well modelled by synchrotron emission from electrons accelerated in the forward shock (FS). The model includes also the optical/NIR KN emission, which accounts for the excess in the r-band, and synchrotron-self-Compton, which is not dominant at these energies (< 10 GeV).
Nonetheless, the LAT emission in the second epoch (~10^4 s) is in substantial excess with respect to the FS+KN best-fit model.
This intrinsically faint excess (Liso~10^{46} erg/s) was never observed before in neither short nor long GRB populations.
We interpret this new spectral component as external Inverse Compton (EIC) emission from KN optical photons and electrons accelerated in the low-power jet.
The discovery of the late-time HE excess in GRB 211211A strongly challenges our current understanding
of emission processes occurring in gamma-ray burst, especially at high energies, and opens a new observational window for kilonovae, which can possibly be observed also in the ~GeV spectrum.

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Multimessenger science with LISA

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In this talk, I will first give a brief update on the the Laser Interferometer Space Antenna mission status. Afterwards, I will review the different ways in which electromagnetic and gravitational wave information are synergistically used to gather unique scientific inshight into the variety of sources present in the LISA Gravitational wave band. Broadly speaking these are divided in two categories: collecting electromagnetic (EM) information (much) ahead of LISA's launch in the mid 2030s, and collecting them afterwards, when LISA detections can act as trigger.

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Lunar Gravitational-wave Antenna

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The Virgo and LIGO instruments and their first observations are amazing, but they are only the very first step into the new era of GW science and astronomy. The prospect to detect signals from kilometer-scale sources out to redshifts of 100 with the proposed Einstein Telescope and Cosmic

Explorer, or the merger of massive black holes with LISA is mind-boggling. These detectors are part of a wider effort to expand the frequency band of gravitational-wave observations, but so far, the decihertz band is left out, which harbors many interesting sources of GWs. In this talk, we will present the Lunar GW Antenna (LGWA), which was proposed in 2020 to observe GWs on the Moon also in the decihertz band. It exploits the Moon itself as a giant antenna for GWs. Its pathfinder mission Soundcheck was recently selected by ESA into the Reserve Pool of Science Activities for the Moon. The LGWA collaboration is now working hard to establish the LGWA science case and to develop the technologies that will enable breakthrough GW science on the Moon.

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The IXPE view of GRB 221009A

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GRB 221009A is an exceptionally bright gamma-ray burst (GRB) that reached Earth on 2022 October 9th after traveling through the dust of the Milky Way. The Imaging X-ray Polarimetry Explorer (IXPE) pointed at GRB 221009A on October 11th and measured, for the first time, the 2-8 keV X-ray polarization of both a GRB afterglow and rings of dust-scattered photons which are echoes of the GRB prompt emission. We set upper limits to the polarization degree of the afterglow and the prompt emission of respectively 13.8% and 55% at a 99% confidence level, providing constraints on the jet opening angle of the GRB and other properties of the emitting region. In this contribution, I present on behalf on the IXPE Collaboration the results of the analysis and interpretation of the IXPE observation of GRB 221009A.

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Search for dark matter lines in the energy spectra of Galactic gamma rays with 13.75 years of Fermi-LAT data

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Although there is indirect experimental evidence on the existence of dark matter, the debate on its nature is still open. One class of possible candidates is represented by Weakly Interacting Massive Particles (WIMP).

Our galaxy is largely composed of Dark Matter. Assuming that pairs of WIMPs can annihilate to produce gamma rays, or that WIMPs can directly decay into photons, monochromatic lines in the galactic gamma-ray spectrum should be observed. To search for these lines, we analyzed the spectra of gamma rays from our galaxy, constructed using a sample of data collected by the Fermi Large Area Telescope (LAT) in the energy range 1 GeV - 1 TeV in the first 13.5 years of collecting data. The search was carried out in 5 regions of the sky, optimized for different dark matter profiles. We report no evidence of significant signals. Therefore, upper bounds on the annihilation cross section and decay rate of the WIMPs were obtained.

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Astrophysical clues of axion-like particles

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Axion-like particles (ALPs) are a common feature in several extensions of the Standard Model, arising, for example, as a solution to the strong CP problem in quantum chromodynamics or as a prediction of string theories. Astrophysical and cosmological signatures of axion-like particles might be found in many observations, including gravitational wave spectra, but most importantly in the electromagnetic spectrum ranging from radio waves to gamma rays. A significant property for the experimental detection of ALPs is indeed their coupling to photons, which enables, among other phenomena, ALP-photon conversions in ambient magnetic fields.

In this talk we review the relevance of ALPs in high-energy astrophysics. In particular, we focus on the potential to detect spectral modifications of extragalactic sources due to ALP-photon conversions in intergalactic magnetic fields using the latest generation of Cherenkov telescopes.

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JWST and prospects for multi-messenger astrophysics

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JWST opens up a new window to study near and mid-IR emission with exceptional sensitivity. This window may be crucial to unveiling several multi-messenger sources, perhaps most notably because this is where signatures of heavy element production may arise in either compact object mergers or extreme supernovae. I will present JWST observations of two recent GRBs; GRB 221009A - the Brightest of All Time (BOAT) and GRB 230307A a long GRB arising from a compact object merger. I will discuss the insights that these observations have already enabled, as well as the possibilities that future observations will provide.

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GRB221009A: The brightest GRB ever detected by Fermi-LAT

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In this contribution we present the analysis of GRB221009A, the brightest Gamma-Ray Burst (GRB) ever detected by the Fermi Large Area Telescope (LAT). The burst triggered the Gamma-Ray Burst

Monitor (GBM), and the high-energy emission of the triggering pulse started in the LAT before the associated low-energy component detected by the GBM. During the prompt phase, we identified a Bad Time Interval (BTI) of 63 seconds due to the very high intensity of hard X-rays. However, we were able to determine sub-intervals where standard analysis could be performed. The late time emission decays as a power law, but its extrapolation based on the first 450 seconds suggests that the afterglow started during the prompt emission. Furthermore, we found that the high-energy events detected by the LAT cannot have a Synchrotron origin but, during the prompt emission, they are probably associated with an additional Self Synchrotron Compton (SSC) component. Late time high-energy events are instead harder to explain as products of SSC or TeV electromagnetic cascades, which raises questions regarding their origin. Overall, GRB221009A, stands out compared to other Fermi-LAT GRBs, indicating that it is an exceptionally rare event.

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High-energy spectral component of GRB prompt emission.

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Prompt emission of GRB is believed to be produced from electrons accelerated up to non thermal energies in the internal shocks. This emission peaks in the keV-MeV energy band, but a high energy component is theoretically expected. While photons in the very high energy domain have been detected by Cherenkov Telescopes in recent years, prompt-related VHE photons have not been observed yet. Their detection would be crucial for the understanding of the physics related to the prompt emission.
In the last years, there have been many Fermi/LAT detections of high energy photons, temporally coincident with the prompt emission phase, but with different spectral properties. This GeV emission has been interpreted by several authors as mostly dominated by the afterglow. I will present new results based on a systematic study of GRBs with an early GeV emission detected by Fermi/LAT, including the exceptionally bright GRB221009A. By studying the temporal evolution of the GeV emission from the first seconds up to days, prompt GeV candidates can be found.

Future of multimessenger science / 24

Multi-Messenger Astrophysics and Cosmology with next-generation GRB missions

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The huge luminosity, the redshift distribution extending at least up to z~10 and the association with the explosive death of very massive stars make long GRBs extremely powerful probes for investigating the early Universe (pop-III stars, cosmic re-ionization, SFR and metallicity evolution up to the "cosmic dawn") and measuring cosmological parameters. At the same time, as demonstrated by the GW170817 event, short GRBs are the most prominent electromagnetic counterpart of gravitational-wave sources like NS-NS and NS-BH merging events, and both long and short GRBs are expected to be associated with neutrino emission. Moreover, the combination of extreme distances, huge number of photons emitted over wide photon energy range and the variability down to few ms makes these phenomena a promising tool for performing tests of fundamental physics like Lorentz Invariance Violation (LIV). My review will include the status, concepts and expected performances of space mission projects (e.g, THESEUS) aiming at fully exploiting these unique potentialities of the

GRB phenomenon, thus providing an ideal synergy with the large e.m. facilities of the future like LSST, ELT, TMT, SKA, CTA, ATHENA in the e.m. domain, advanced second generation (2G++) and third generation (3G) GW detectors and future large neutrino detectors (e.g.,Km3NET)

Future of multimessenger science / 25

ET-WST synergy for next generation multi-messenger observations

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The Einstein Telescope (ET) will be an innovative next generation gravitational wave (GW) interferometer. With ET it will be possible to explore a large volume of the Universe and detect thousands of binary neutron star systems mergers (BNS) per year. The corresponding electromagnetic (EM) counterparts will likely be faint and to be searched in the large error regions of ET GW signals. Beyond the detection, the bottleneck of MM science will be to gather the spectroscopic data required to identify and characterize EM counterpart candidates. Integral Field Spectroscopy (IFS) and Multi-Object Spectroscopy (MOS) can play a key role in achieving this goal. I will present the study I am carrying out to assess the impact of the next generation IFS and MOS (such has the WST) on the detection, identification and characterisation of EM counterparts of ET BNSs, with the aim to provide the specifications required, and to prepare the synergy with ET.

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GLADEnet: a progressive web app for multi-messenger cosmology and electromagnetic follow-ups of gravitational-wave sources

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The rare multimessenger event GW170817 showed a new way of making cosmology with the potential to resolve the tension between different measurements of the expansion rate of the Universe given by the Hubble constant.

However, most of the detected gravitational wave signals from compact binaries up to date do not have a multi-messenger counterpart, earning them the designation of dark standard sirens and in order to infer cosmological parameters from them statistical approaches are used by requiring the knowledge of galaxies within the event localization volume.

In the multi-messenger context, evaluating the completeness of catalogues of galaxies is of paramount importance, as it plays crucial i) for correctly optimizing observational strategies and maximising the chance to detect a counterpart and ii) for the postobservation data analysis, for example, to evaluate the efficiency of galaxy-targeted searches or
to correctly infer cosmological parameters.

In this work we describe the progress on the new interactive web tool, named GLADEnet, which enables us to evaluate galaxy incompleteness in real-time across the gravitational-wave sky-localization. In particular, we introduce a parameter, referred to as Completeness coefficient C. This measurement is of particular importance when we use catalogs such as GLADE (Galaxy List for the Advanced Detector Era) catalogue which comprises a collection of various catalogues. Hence, its completeness differs across different regions of the sky.

Here we present a comprehensive guide on how to use the web app detailing its functionalities geared towards managing the vast collection of over 22 million objects in GLADE. The completeness coefficient and the GLADE galaxy list will be disseminated in real-time via GLADEnet–https://virgo.pg.infn.it/gladenet/catalogs/ powered by the Virtual Observatory (VO) standard and tools.

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The KM3NeT experiment and its prospects for multi-messenger physics

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The KM3NeT collaboration is building two underwater neutrino detectors in the Mediterranean: the ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss) detectors.
ARCA is located off the Sicilian coast of Capo Passero and aims to detect and identify astrophysical neutrino sources. The ORCA detector, located off the French coast of Toulon, has been optimised for the detection of atmospheric neutrinos in the GeV range, with the main aim of studying the fundamental properties of neutrinos. The two detectors, ARCA and ORCA, will allow the study of neutrino astronomy from MeV to tens of PeV.

The first detection units, which are strings containing the optical sensors, have already been deployed by the KM3NeT collaboration at the French and Italian sites. The two detectors are currently taking data in partial configurations and have already produced some physics results, demonstrating the great potential of the two detectors for the coming years.

The multi-messenger programme, which involves real-time analysis of interesting astrophysical sources seen by other experiments in gravitational waves, X-rays, gamma rays and other wavelengths, is already active. The sending of real-time neutrino alerts to the astronomy community to trigger follow-up observations of interesting neutrino events is ongoing.

The status, physics results and scientific perspectives of KM3NeT will be presented, with particular emphasis on the multi-messenger programme.

Multimessenger view of neutron stars: from pulsars to GRBs / 28

Speed of Gravity and Cosmology Constraints from Binary Neutron Stars using Time Delays between Gravitational Waves and Short Gamma-ray Bursts.

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The landmark detection of a gravitational wave (GW) from the Binary Neutron Star Merger (BNS) GW170817 and its electromagnetic counterparts allowed us to study the Universe in a totally new way. Among the several discoveries made possible by GW170817, we can find the tightest constraints on the speed of gravity and the first measure of the Hubble constant (H0). Both these two measures were possible thanks to several assumptions that might not be granted with future detections. In fact, the speed of gravity was measured using agnostic assumptions on the prompt-time delay between the GW and the short Gamma-ray burst (sGRB), while the measure of H0 was possible thanks to the identification of the source host galaxy. In this talk, I will discuss how by relaxing the assumptions on GW-sGRB prompt time delay and identification of host galaxy still permits to infer the speed of gravity and H0 with populations of GW sources. By simulating populations of GW-sGRB detections with future observing runs, we find that: (i) it will be possible to jointly fit the GW-sGRB prompt-time delay distribution together with the speed of gravity and (ii) it will be possible to measure the Universe expansion even if the case that the source host galaxy is not observe. In particular, the latter result is made possible thanks to a new technique that I explored able to assign a redshift to the source using the GW-sGRB observed time delay.

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Follow-up of gravitational waves alerts with IACTs using Astro-COLIBRI

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Follow-up of gravitational wave alerts has proven to be challenging, primarily due to the large uncertainty on the localisation, which is often significantly larger than the field of view of most instruments. A smart pointing strategy significantly enhances the chance of rapidly observing the true position of the underlying compact binary merger event and so to detect an electromagnetic counterpart.

To address this challenge, we introduce tilepy, a software solution that has been developed and successfully deployed by the H.E.S.S. collaboration during the O2 and O3 observational runs to search for a very-high energy counterpart to GWs events. The optimised tiling strategies implemented in tilepy allowed H.E.S.S. to be the first ground facility to point toward the true position of GW170817. In this presentation, we outline the key features of the now publicly available tilepy software package and showcase its adoption by multiple Imaging Atmospheric Cherenkov Telescopes (IACTs) for GW alert follow-up during the ongoing O4 observational campaign.

In addition, the tilepy software is now also integrated into the Astro-COLIBRI platform. This tool helps in the planning of follow-up of a large range of transient phenomena including GW alerts. The platform also provides an overview of the multi-wavelength context by grouping and visualising information coming from different observatories alongside GW alerts. We will illustrate the use of Astro-COLIBRI in searches for counterparts to GWs.

Future of multimessenger science / 30

Perspectives for kilonovae multimessenger detection

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The detection of the gravitational wave (GW) signal GW170817 and the electromagnetic (EM) signal AT2017gfo confirmed the association between binary neutron star (BNS) mergers and kilonovae (KNe) and showed the potential of joint detection to unveil the nature of neutron stars and the nucleosynthesis of heavy elements in the Universe. The next-generation GW interferometers, such as the Einstein Telescope, are unprecedented resources to enhance the chances of detecting EM counterparts significantly enlarging the horizon of detectable BNS mergers, and dramatically improving the source parameter estimation. In this context, providing reliable predictions about GWs and KNe joint detections is pivotal to developing detection strategies and evaluating the multi-messenger science potential. Starting from BNS merger populations based on population synthesis codes, we compute the number of detected mergers and estimate the source parameters within a Fisher-matrix approach for different configurations of ET. We evaluate the KNe emission both assuming AT2017gfo-like signals or modelling the KN parameters via numerical-relativity-informed fits for two different EOSs. We evaluate the perspectives for ET observing in synergy with the Vera Rubin Observatory (VRO) looking at the impact of GWs and KNe joint detections on constraining the EOS and for cosmology studies.

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Multi-wavelength studies of Cosmic Ray accelerators

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The study of cosmic-ray accelerators is done with a multi-wavelength approach which provides a more complete view of the physical phenomena that involve the acceleration of charged particles. Cosmic-ray accelerators are both galactic, for example Supernova Remnants, and extragalactic, for example Active Galactic Nuclei and Gamma-Ray Bursts. To get a larger sample of Galactic cosmic-rays, researchers are studying them using telescopes in the southern hemisphere.

In this study we focus on the TeV energy band through simulations of two Supernova Remnants, RCW86 and Vela Junior, with the Middle-Sized Telescopes (MSTs) of the southern array of the Cherenkov Telescope Array (CTA) to be installed at Paranal, Chile. These simulations allow us to investigate which MST configuration results in the best performance for studying gamma-ray emission from new Galactic sources and for a better understanding of the mechanisms at the basis of the acceleration of Galactic cosmic rays.

In particular, we compared the performance of a configuration composed of single-mirror MSTs and dual-mirror MSTs, the latter called Schwarzschild-Couder Telescopes (SCTs). Thanks to their better sensitivity and angular resolution, SCTs would be the preferred option to investigate in detail the morphology of extended sources. Indeed, we find that the mixed configuration performs better than the one composed of only single-mirror MSTs. We compared different spatial models in order

to distinguish between different sources, such as a Supernova Remnant and a Pulsar Wind Nebula with the different telescope configurations.

These studies are complementary to MeV-GeV energy band analysis, which are being investigating with Fermi-LAT datasets.

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From HERMES Pathfinder to DAMA

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I will present an update on the HERMES Pathfinder + SpIRIT projects, currently in phase-D. These projects are in-orbit demonstrations, with the goal of demonstrating that Gamma Ray Bursts can be efficiently observed and localized by miniaturized instrumentation hosted by CubeSats. This can allow the design and implementation of a sensitive all-sky, all-time X-ray/Gamma-ray observatory, based on distributed architectures. The operation of a flexible and sensitive X-ray/gamma-ray all-sky monitor will have a pivotal role in providing high-energy counterparts of the second generation gravitational wave interferometer events during this decade, and third generation events during the next decade.

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NGC 1068 as a neutrino source and the emerging class of Seyfert galaxies

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While the existence of a diffuse flux of high-energy astrophysical neutrinos has been established for over a decade, the sources of this signal still need to be discovered. Last year, the IceCube Collaboration reported evidence for TeV neutrinos from the nearby active galaxy NGC 1068 at 4.2 sigma. After the blazar TXS 0506+056, NGC 1068 is the second extragalactic neutrino source identified. It belongs to the class of the Seyfert galaxies, and it is intrinsically bright in X-rays. Follow-up analyses looking for neutrino emission from other X-ray luminous AGN in general and Seyferts in particular hint at the possibility that other Seyfert galaxies might have similar properties to NGC 1068 and be the next promising candidates as cosmic neutrino sources.

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Tidal disruption event rates under the magnifying glass

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A tidal disruption event (TDE) occurs when a star is destroyed by the strong tidal shear of a massive black hole (MBH). TDE detections can unveil otherwise dormant MBHs, and they constitute unique probes for constraining the MBH demographics, especially towards the low-mass end of the MBH mass function. In order to do so, it is fundamental to theoretically constrain the expected TDE rates across different environments, MBH masses, stellar properties. In this talk, I will review the main formation mechanisms of TDEs and I will present new advances that allow for more precise estimates of their rates. Finally, I will stress the importance of combining upcoming observations by wide-field transient surveys with theoretical estimates of TDE rates to shed new light on the demographics of the lightest MBHs.

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X-ray quasi-periodic eruptions: a potential electromagnetic counterpart of extreme mass ratio inspirals

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X-ray quasi-periodic eruptions (QPEs) are a new variability phenomenon observed around low-mass ($M_{BH} < 10^7\ M_\odot$) supermassive black holes. They appear as sharp and intense bursts of soft X-ray emission ($E\ <\ 2$ keV), that last about one hour and repeat quasi-periodically every few hours. Each QPE emits a luminosity of 10^{42-43} erg s^{-1}, typically one order of magnitude above a much more stable quiescent flux level. So far they have been observed in eight galaxies, about a half of which are associated to tidal disruption events. Much work has been done on the theoretical side, but the physical explanation for the QPE appearance is not clear yet, as their phenomenology is quite complex. Among the possible explanations, significant attention has been drawn to the case of extreme mass ratio inspirals (EMRIs), where the secondary object $-$ that could be a star or a black hole much smaller than the primary one $-$ could either transfer mass or impact onto the inner accretion flow around the primary massive black hole. In this talk I will review the history of the discovery of the known QPEs and the theoretical explanations offered so far, with particular emphasis on the EMRI scenario(s) where QPEs could reveal to be the electromagnetic counterparts of gravitational wave sources detected in the future from space.

Multimessenger view of neutron stars: from pulsars to GRBs / 36

Long-duration gamma-ray bursts from compact object mergers

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The duration distribution of gamma-ray bursts is bimodal, and the general consensus has been that the two groups stem from separate progenitors: binary compact object mergers and supernovae for short and long GRBs, respectively. A number of events discovered in the recent past has however proven this distinction to be imperfect. Kilonovae, the smoking-guns of mergers, were detected following the long, bright GRB 211211A and 230307A. Another long GRB stemming from a merger was identified via its host galaxy properties (the first case where dynamical formation of the binary could be ascertained). I will review this newly identified, rapidly expanding population of nearby cosmic explosions.

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The Radio to GeV Afterglow of GRB 221009A: Observations and Multi-wavelength Modeling

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As the most energetic explosions in the Universe, long-duration Gamma-ray Bursts (GRBs) provide a unique opportunity to explore physics at extreme energy scales that are otherwise impossible to investigate in Earth-bound laboratories. The radiation produced by the interaction of their ejecta with the environment contains clues to their progenitors and to the mechanisms responsible for producing and collimating their relativistic jets. Whereas this radiation has traditionally been interpreted in the framework of synchrotron radiation from relativistic shocks, the discovery of VHE gamma-rays from GRBs complicates this model.

The recent bright, nearby GRB 221009A provides an excellent opportunity to test our understanding of processes responsible for GRB afterglow radiation. I will summarize our understanding of this path-breaking event with a special emphasis on new insight from radio observations, which reveal unexpected and unusual spectral and temporal evolution. I will combine our radio data with optical to GeV observations to explore the jet physics of this remarkable explosion. I will conclude with a discussion of the role of radio observations and modeling in GRB science, highlighting the current and future role of radio observations in the ongoing multi-messenger revolution in extragalactic time-domain astrophysics.

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A Luminous Relativistic Tidal Disruption Event Discovered by the ZTF Optical Survey

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Tidal disruption events (TDEs) are bursts of electromagnetic energy released when supermassive black holes (SMBHs) at the centers of galaxies violently disrupt a star that passes too close. TDEs provide a new window to study accretion onto SMBHs and may be associated with high energy neutrinos. In some rare cases, this accretion leads to launching of a relativistic jet, but the necessary conditions are not fully understood. The best studied jetted TDE to date is Swift J1644+57, which was detected in gamma-rays more than a decade ago, but was too obscured by dust to be seen at optical wavelengths. I will present the discovery of AT2022cmc, a rapidly fading source at redshift z~1.2 found in Zwicky Transient Facility survey data, whose unique light curve transitioned into a luminous plateau within days. Observations of an exceptionally bright counterpart at X-ray, sub-millimeter, and radio wavelengths supported the interpretation of AT2022cmc as a rare jetted TDE containing a synchrotron afterglow, likely launched by a rapidly spinning SMBH.

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Vera Rubin Observatory and Einstein Telescope: kilonova observation strategies to understand ET detector design

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The Vera Rubin Observatory will be a powerful instrument in the discovery and follow-up of kilonovae (KNe), especially in the perspective of third generation gravitational wave (GW) observatories which will come online towards the end of the tenure of Rubin's decadal survey (LSST WFD) in the mid 2030s. Follow-up of electromagnetic (EM) counterparts of binary neutron star (BNS) mergers provides a unique window into the population studies of kilonova and gamma ray-burst (GRB) central engines and their properties. We have been working on optimizing observation strategies to follow up BNS merger triggers with Rubin and other next generation optical observatories to search and observe KNe and GRB optical afterglows with different configurations of GW detectors, in particular focusing on the Einstein Telescope (ET) which is proposed to be the first underground interferometer.
Exploring these strategies has helped us compare different detector designs for ET and how it will perform in networks with the other ground-based GW observatories which will be its contemporaries. An extensive theoretical framework for kilonova modelling has helped us compare how ET-Rubin synergies will help us understand and compare the different conditions under which BNS systems form and merge, as well as potentially give us a handle on a better understanding of neutron star equations of state (EOS). I will be presenting our results and projections drawn from a BNS population of 10 years and present optical observation strategies that will help us make meaningful predictions using Rubin.

Multimessenger view of neutron stars: from pulsars to GRBs / **40**

Ultrahigh-energy cosmic-ray signature in GRB221009A

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The brightest long gamma-ray burst (GRB) detected so far by the \textit{Swift}-BAT and \textit{Fermi}-GBM telescopes, GRB~221009A, provides an unprecedented opportunity for understanding the high-energy processes in extreme transient phenomena. We find that the conventional leptonic models for the afterglow emission from this source, synchrotron and synchrotron-self-Compton, have difficulties explaining the observation of
$gtrsim10$ TeV γ rays (as high as 18 TeV) by the LHAASO detector. We modeled the γ-ray spectrum estimated in the energy range 0.1-1 GeV by the \textit{Fermi}-LAT detector. The flux predicted by our leptonic models is severely attenuated at > 1 TeV due to $\gamma\gamma$ pair production with extragalactic background light, and hence an additional component is required at
$gtrsim10$ TeV. Ultrahigh-energy cosmic rays can be accelerated in the GRB blast wave, and their propagation induces an electromagnetic cascade in the extragalactic medium. The line-of-sight component of this flux can explain the emission at
$gtrsim10$ TeV detected by LHAASO, which requires a fraction of the GRB blast wave energy to be in ultrahigh-energy cosmic rays. This could be an indication of ultrahigh-energy cosmic-ray acceleration in GRBs.

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Review on short-long dichotomy

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Search and characterization of massive black hole binary candidates

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Massive black hole (MBH) binaries are among the loudest expected sources of low frequency gravitational waves. The rate of MBH coalescences is still very uncertain, and EM observations of close MBH binaries have the potential to strongly reduce the current uncertainties. I will discuss the physical consequences of the presence of a binary on the surrounding gas, deriving the observational features associated with massive black hole binaries proposed in literature. I will then report on the results of MBH binary searches in large observational datasets. It must be stressed that the proposed observational features are not unique to binary systems. I will therefore discuss follow up strategies to test the binary scenario. Single massive black hole binary candidates that made it to the news will be discussed in detail, including the results of unpublished observational tests. The talk will end with the discussion of the limitations of current searches and with an overlook to complementary searches that next generation EM surveys will allow for.

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BBH coalescence - observations

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Progress in understanding tidal disruption events using observations

Mentoring programs in the scientific community: Case study of the Fermi-LAT collaboration / 46

The Fermi-LAT Collaboration mentoring program

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The most luminous AGN do not produce the majority of the detected stellar-mass black hole binary mergers in the local Universe

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Despite the increasing number of GW detections, the astrophysical origin of the Binary Black Hole (BBH) mergers detected by the LIGO and Virgo interferometers remains elusive. A promising formation channel for these BBHs is inside accretion discs around supermassive black holes, that power AGN. Investigating the spatial correlation between the positions of these potential host environments and the localisation volumes of detected BBHs allows to put constraints on the GW-AGN connection. In this talk I will present how we used this approach to obtain the first observational constraints of the fractional contribution of the so-called AGN channel to the total stellar-mass BBH merger rate. We have found that the fraction of the detected mergers originated in AGN brighter than 10^45.5 (10^46) erg/s cannot be higher than 0.49 (0.17) at a 95 per cent credibility level. Our upper limits imply a limited BBH merger production efficiency of the brightest AGN, while most or all GW events may still come from lower luminosity ones. Alternatively, the AGN formation path for merging stellar-mass BBHs may be actually overall subdominant in the local Universe.

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Detection of early (prompt) very-high-energy gamma-ray emission from compact mergers

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The production of VHE early emission of gamma-ray bursts (GRBs) is still highly debated. Nowadays, we mostly rely on observations in the range of 10 keV-10 MeV while at higher energies (above 100 GeV), the current instruments have difficulties due to time spent repositioning the telescope. I will discuss the multi-messenger observational strategies to detect the early emission of short GRBs at very-high-energies (VHE; E > 30 GeV) in the era of the third-generation gravitational wave detectors Einstein Telescope (ET) and Cosmic Explorer (CE) in association with Cherenkov Telescope Array (CTA). I will describe the capabilities to detect 0.1-100 GeV by using gravitational-wave early warning alerts and the localization pre-merger estimated by the next generation of gravitational-wave detectors. I will discuss possible VHE components from the synchrotron self Compton components in the leptonic GRB model, the high energy tail of the hadronic GRB model as well as external inverse Compton emission as viable candidates in the energy band of 10 GeV - 10 TeV and their detection limits by CTA.