International conference PUMA22 Probing the Universe with Multimessenger Astrophysics

Monday, 26 September 2022 - Friday, 30 September 2022

Sestri Levante

Book of Abstracts

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The Moon: the new frontier for Gravitational Waves astrophysics with LGWA

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The Lunar Gravitational-Wave Antenna (LGWA) is a proposed detector which aims at revealing gravitational waves using the Moon as a detector and an array of seismic sensors as Moon-read-out. The concept is the same as that used for the gravitational waves bar detectors, which represent the first human attempt of measuring gravitational waves. With LGWA we will be sensitive in the deci-Hz frequency band, thus bridging a gap between current (and future) terrestrial gravitational wave detectors and space-based ones. In this talk we will discuss the LGWA project, the scientific results it can deliver along with the technologies needed for such an enterprise

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National Science Foundation support for Multi-messenger Astrophysics Research

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Physics prospects of KM3Net

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Binary black hole mergers in young star clusters

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Over the last six years, the LIGO and Virgo interferometers detected an increasing number of gravitational wave events. At the end of the third observing run, the wealth of GW candidates, most of which consist in the merger of binary black holes (BBHs), makes it possible to try to disentangle the formation channels of BBHs, thanks to their peculiar imprints.
In particular, the dynamical evolution in stellar clusters leaves a deep imprint on their BBH population, which turn out to present distinctive signatures with respect to the case of isolated evolution.

In my contribution, I will describe the properties of the population of BBH mergers from a new sample of N-body simulations of young star clusters. The simulated stellar systems present fractal

initial conditions to mimic the clumpiness of the observed star forming regions and include a realistic primordial population of binaries, characterized by observation-based orbital properties and a mass-dependent binary fraction. Two sets of star are considered to study the evolution of BBHs in stellar environments characterized by different dynamical activity: low-mass clusters (500-800 MSun) and high-mass clusters (5000-8000 MSun). Also, in order to take into account all the possible dynamical effects, the star clusters are evolved for 1500 Myr.

My study shows that the formation channels of BBHs in low-mass and high-mass star clusters are extremely different and lead to two completely distinct populations of BBH mergers. Low-mass clusters host mainly low-mass BBHs born from binary evolution, while BBHs in high-mass clusters are relatively massive (with chirp masses up to 50 MSun) and driven by dynamical exchanges.

Also, high-mass clusters produce a non-negligible number of BBH mergers with primary mass in the pair-instability mass gap, born either via stellar collisions, in which a main-sequence star merges with a more evolved star, or via BH mergers. A fraction of these massive BBHs also leave a merger remnant in the intermediate-mass BH range. These differences are crucial for the interpretation of the formation channels of gravitational-wave sources.

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Forecasting the detection capabilities of third–generation gravitational–wave detectors using GWFAST

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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, and the era of Multimessenger GW–EM Astrophysics has started with the observation of GW170817–GRB170817A. The discoveries during the first three observing runs already had an extraordinary impact on both 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 larger bandwidth, the Einstein Telescope and Cosmic Explorer will have outstanding potential, capable of triggering fundamental discoveries.

Forecasting the capabilities of these extraordinary instruments, which are able to detect hundreds of thousands of sources per year, is a crucial aspect. In this talk, I will present GWFAST, a novel Fisher-matrix code for GW studies, tuned toward third-generation detectors. After describing its main features and technical aspects, I will show the results of a comprehensive study of the capabilities of ET alone, and of a network made by ET and two CE detectors. In particular, to assess their potential, I will present the accuracy in the reconstruction of the parameters of both binary black hole, binary neutron star, and neutron star–black hole systems.

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Gravitational Waves and Cosmic Growth Combined

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As gravitational wave observatories discover more standard sirens, we recognize that they can be an incisive probe of dark energy and gravity in multimessenger combination with cosmic growth of structure. Gravitational wave distance deviations from general relativity can be related to growth deviations in many classes of gravity, providing deep insight into cosmic physics. I also discuss how exciting new instrumentation developments bring cosmic redshift drift closer to detection and measurement.

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Distinguishing Time Delays from Multi-Messenger Transients with Deep Learning

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Gravitationally lensed multi-messenger transients are promising probes for constraining cosmological parameters including the Hubble constant. We focus on developing a deep learning technique to estimate lensing time delays from various multiply imaged unresolved transients. We train convolutional neural networks and apply them to simulated supernovae lightcurves to determine whether there are one or two or four lensed images, and measure the corresponding time delays. We accurately identify the number of images and estimate the time delays exceeding ~6 days.

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Detecting long-duration gravitational wave signals

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Spinning neutron stars are sources of long-duration continuous waves that may be detected by interferometric detectors.
We focus on long-duration (transient) signals of unknown duration and start time.
We present a new method to identify them.

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CMB: theoretical aspects

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The NISP instrument of the Euclid mission

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Neutrinos and impact on cosmology

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A key tool to probe Euclid spectroscopy: Spectro-Photometric simulations of galaxies to unravel NISP's capabilities

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To investigate the Euclid Near Infrared Spectrometer and Photometer (NISP) capabilities, Spectral Energy Distribution (SED) models of galaxies located at 0.3 ≤z ≤2.5 have been constructed, simulated using the TIPS simulator of the NISP red grism, and analyzed focusing on emission lines measurements.
These simulations will enable evaluating the spectroscopic survey performances of the Euclid mission and confirming that the slitless NISP spectrometer will match the requirements in terms of detection limits for the continuum and nebular emission lines.
The construction of the SEDs to be provided to the simulator consists in computing a continuum using the Bruzual & Charlot(2003) models, calling out best-fit SED parameters available in the publicly released catalogs from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), namely the BARRO2019 (Barro et al. 2019) covering the Great Observatories Origins Deep Survey North field (GOODS-N) and the COSMOS2015 (Laigle et al. 2016). The nebular emission Balmer, [NII]λλ6584,6549, [OII]λλ3727,3729, [OIII]λλ5007,4959, [SII]λλ6731,6717, [SIII]λλ9531,9069 and Paschen lines are added making use of calibrations available in literature. We refer to common tools and indicators for emission lines analysis such as the Star Formation Rate (SFR), the Baldwin-Phillips-Terlevich (BTP) diagram, the Mass-Metallicity Relation (MZR) and photoionization models. The emission lines are then integrated to the continuum accounting for the calculated velocity dispersion of each galaxy. A photometric and spectroscopic comparison and calibration of the constructed SEDs with observational data is then applied to ensure a realistic sample distribution of the fluxes calculated. The 1D simulated spectra are obtained using the Euclid official reduction pipeline. The simulated spectra are analyzed making use of the Python package specutils. These simulations are part of the Euclid Consortium pre-launch efforts to characterize systematics through an end-to-end analysis.
We provide a confirmation of the detection limit specifications for the continuum (i.e. H(AB) ≥19.5 mag) and emission lines (i.e. Flux ≥ 2 ×10−16 erg cm-2 s-1 for the Euclid Wide Survey configuration and of Flux ≥ 6 ×10−17 erg cm-2 s-1 for the Deep Field survey configuration. We also provide an estimate of the NISP spectral resolution and its dependance on morphological parameters (e.g. Disk size) and present an analysis stacking spectra located at 1.8 ≤ z ≤1.95, attesting the

great potential of the method in confirming redshift determination, a crucial aspect for the Euclid mission.

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Spectroscopic Simulations for the Euclid Mission

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Understanding the accelerated expansion of the Universe is one of the challenges of modern cosmology. The various existing cosmological models that can explain the accelerated expansion differ in small variations in experimental observations. Detecting such variations requires a precise astronomical survey capable of covering most of the sky. For this purpose, the Euclid space mission was designed, which will map large-scale structures over about one-third of the sky and over a cosmic time greater than 75% of the age of the Universe.
During the survey, Euclid, will extract the spectroscopic redshift of about 20 million galaxies with great precision. My work consists of performing simulations and extracting the spectra of the sources, including possible systematic effects. This work allows both to validate the simulation and to study the performance of the instrument. Specifically, in this presentation I will describe my thesis work, where I performed simulations to find the best observational sequence to use during the in-flight calibration phase of the instrument.

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Constraing Dark Energy parameters with needlet

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Euclid experiment will allow us to derive constraints on cosmological parameters and model selection through cross-correlation measurements between Cosmic Microwave Background (CMB) and Large Scale Structure (LSS). In this work we focalize on the detection of the late Integrated Sachs-Wolfe effect in order to constraint the density parameter for the dark energy Ω_{DE}, the equation of state w and the speed of sound c_s^2, by means of a needlet-based cross-correlation estimator.

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Cosmology with cosmic void statistics in galaxy survey

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Upcoming galaxy surveys will measure millions of spectroscopic galaxy positions over large sky areas and large redshift ranges, allowing to map in detail significant contiguous fractions of the observable Universe. High spatial resolution together with large volume allow to study cosmic voids in detail, making them a new effective probe for cosmology. In this talk, I focus on void abundance and void density profiles, and on their sensitivity to dark energy. Voids are a powerful cosmological probe to exploit for the next generation of surveys such as Euclid.

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Searching for Gravitational-Wave / Gamma-Ray-Burst associations in LIGO/Virgo and Fermi-GBM data

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The GW170817 event provided the first observation of gravitational waves from a neutron star merger with associated transient counterparts across the entire electromagnetic spectrum. This discovery demonstrated the long-hypothesized association between short gamma-ray bursts and neutron star mergers. More joint detections are needed to explore the relation between the parameters inferred from the gravitational wave and the properties of the gamma-ray signal, potentially ruling out some of the existing models of the physical processes responsible for these
events.
Groups in LIGO/Virgo/KAGRA, Fermi and Swift collaborations have developed many searches for joint gravitational-waves/gamma-ray- bursts detections. We will, first of all, give a general overview of all theses searches that assumed that at least one of gravitational-wave or gamma-ray-burst candidate is a confident event. We will finally present a new and deeper method aimed at detecting weak GW transients associated with weak gamma-ray- bursts. Contrary to other searches, this search for coincidences between the gravitational—waves and gamma-ray-bursts triggers does
not require a confident detection in one of the two channels.

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X-ray bursts

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Physics prospects of ELT

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Physics prospects of JWST

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On the hosts of neutron star mergers in the nearby Universe

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In the last years, with the advent of multi-messenger astrophysics, the characterisation of binary systems of neutron stars has become central in various fields such as gravitational waves, gamma-ray bursts (GRBs), and the chemical evolution of galaxies. In this work, we explore possible observational proxies that can be used to infer some characteristics of the delay time distribution (DTD) of neutron star mergers (NSMs). To do that, we construct a sample of model galaxies that fulfils the observed mass distribution function, star formation rate versus mass relation, and the cosmic star formation rate density. The star formation history of these galaxies is described with a log-normal function characterised by the logarithmic delay time (t_0) and the width of the function itself (τ). For the NSMs, we assume a theoretical DTD that mainly depends on the lower limit and the slope of the distribution of separation of the binary neutron stars systems at birth. We find that the current present rate of NSMs ($\mathcal{R} = 320^{+490}_{-240}$ Gpc^{-3}yr^{-1}) requires that ~ 0.3 per cent of neutron star progenitors lives in binary systems with the right characteristics to lead to a NSM within a Hubble time. The fraction of short-GRBs observed in late-type galaxies favours DTDs with a fair fraction of prompt events, along the lines suggested by chemical evolution models.

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Quantum noise reduction in Gravitational Wave Interferometers

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The sensitivity of gravitational wave detectors is ultimately limited by
the quantum noise, which arises from the quantum nature of light and it is driven by vacuum fluctuations of the optical field entering from the dark port of the interferometer.
Quantum noise has two complementary features: the shot noise, which depends on phase fluctuations of the optical field disturbing the detector at high frequencies, and radiation pressure noise, which depends on amplitude fluctuations of the optical field perturbing the position of suspended mirrors at low frequencies. One way to improve the sensitivity is to inject squeezed vacuum into the dark port, with reduced phase fluctuations (frequency-independent squeezing). At the same time, due to the Heisenberg's uncertainty principle, the amplitude fluctuations are larger and we need to produce frequency-dependent squeezing to achieve a broadband mitigation of quantum noise.
I will present quantum noise reduction methods that have already been implemented in current interferometers and those that will be introduced in future gravitational wave detectors.

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The multimessenger astrophysics potential of the JUNO experiment

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JUNO will be the largest ever built liquid scintillator detector for neutrino physics. It will be sensitive to various astrophysical neutrino sources, including solar neutrinos, the diffuse supernova neutrino

background, pre-supernova neutrinos and the all-flavor neutrino flux from a Galactic core-collapse supernova (CCSN) with high statistics. For the purpose of maximizing the physics reach of JUNO when used as a neutrino telescope, two trigger systems will operate in JUNO to search for a transient astrophysical signal in real time: a dedicated multimessenger (MM) trigger system and a Prompt CCSN monitor, the latter embedded in the global trigger system. This talk will report the expected performance of JUNO for the detection of the different neutrino fluxes from the mentioned sources, highlighting the unique contributions it will bring to the understanding of the physics behind the various astrophysical phenomena.

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Fast emulation of two-point angular statistics for photometric galaxy surveys

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We develop a set of machine-learning based cosmological emulators, to obtain fast model predictions for the C(ℓ) angular power spectrum coefficients characterising tomographic observations of galaxy clustering and weak gravitational lensing from multi-band photometric surveys (and their cross-correlation). A set of neural networks are trained to map cosmological parameters into the coefficients, achieving a speed-up O(10^3) in computing the required statistics for a given set of cosmological parameters, with respect to standard Boltzmann solvers, with an accuracy better than 0.175% (<0.1% for the weak lensing case). This corresponds to ~2% or less of the statistical error bars expected from a typical Stage IV photometric surveys. Such overall improvement in speed and accuracy is obtained through (i) a specific pre-processing optimisation, ahead of the training phase, and (ii) a more effective neural network architecture, compared to previous implementations.

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Measuring the beta-decay properties for exotic rare-earth isotopes

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The rapid neutron capture (so-called *r*-) process produces about half the heavy isotopes beyond the iron peak. The solar *r*-process abundance distribution has a local maximum around A $\approx$ 160 which originates from freeze-out during the late phases after neutron exhaustion. This rare-earth abundance peak (REP) provides a unique probe of the astrophysical conditions in the latter stages of the *r*-process [1-4].

According to the most recent sensitivity study the most influential nuclei to the REP formation can be found in the 55 ≤ Z ≤ 64 neutron rich region [3]. To constrain the peak formation models, in recent measurements at RIKEN Nishina Center using the BRIKEN array [5], the beta-decay parameters (delayed neutron emission probability and half-life) of 28 exotic neutron-rich Pm-Sm-Eu and Gd isotopes were measured. The half-life values and the neutron emission probabilities of the isotopes were obtained by fitting the time distribution of implantation-beta (i-β) and implantation-beta-neutron (i-β-n) correlation events using a sum of Bateman formulae. Furthermore, two CLOVER-type HPGe detectors are also mounted in the BRIKEN array, that are used to measure γ-spectra, thus the half-life results could be verified by exponential fitting the time distribution of implantation-beta-gamma (i-β-γ) correlation events [6]. The experimental results and astrophysical interpretation will be presented [7].

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[6] A. Vitéz-Sveiczer et al., in preparation
[7] G. G. Kiss et al., submitted to The Astrophysical Journal

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Semi-analytic modeling of kilonovae with the radiative transfer equations

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Matter expelled from binary neutron star (BNS) and black hole-neutron star (BHNS) mergers is one confirmed site capable of harboring r-process nucleosynthesis in the universe, due to its extreme conditions and abundance of neutrons. The freshly produced nuclei are unstable and undergo nuclear decay, releasing an amount of energy sufficient to power a thermal transient known as kilonova (KN). A kilonova shines from a few hours ("blue" KN) to a few weeks ("red" KN) after merger and represents a major electromagnetic counterpart to gravitational wave signals.
We start from an analytic solution of the radiative transfer equations to develop a NR informed kilonova model which considers multiple ejecta components, the general anisotropy of their dynamical properties and the projection in the observer viewing direction. We propose an ejecta structure such that the total luminosity is the combination of two contributions, one emitted at the photosphere, delimiting the optically thick bulk of the ejecta, and one coming from the optically thin layers outside of it. The impact of the ejecta thermodynamical properties on the light curves is explored by employing parametrized radioactive heating rates derived from nuclear reaction network calculations. We validate our model by comparing our results with multy-frequency radiative transfer simulations, pointing out the improvements with respect to other simpler semi-analytic models.

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Multimessenger Parameter Estimation of GW170817: From Jet Structure to the Hubble Constant

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The electromagnetic radiation that followed the neutron star merger event GW170817 revealed that gamma-ray burst afterglows from jets misaligned with our line of sight exhibit a light curve with slowly rising flux. The slope of the rising light curve depends sensitively on the angle of the observer with respect to the jet axis, which is likely to be perpendicular to the merger plane of the neutron star binary. Therefore, the afterglow emission can be used to constrain the inclination of the merging system. Here, we calculate the gamma-ray burst afterglow emission based on the realistic jet structure derived from general-relativistic magnetohydrodynamical simulations of a black hole torus system for the central engine of the gamma-ray burst. Combined with gravitational wave parameter estimation, we fit the multi-epoch afterglow emission of GW170817. We show that with such a jet model, the observing angle can be tightly constrained by multimessenger observations. The best fit observing angle of GW170817 is $\theta_\mathrm{v} = 0.38 \pm 0.02$ rad. With such a constraint, we can break the degeneracy between inclination angle and luminosity distance in gravitational wave parameter estimation, and substantially increase the precision with which the Hubble constant is constrained by the standard siren method. Our estimation of the distance is $D_\mathrm{L} = 43.4 \pm 1$ Mpc and the Hubble constant constraint is $\mathrm{H}_0 = 69.5 \pm 4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. As a result, multimessenger observations of short-duration gamma-ray bursts, combined with a good theoretical understanding of the jet structure, can be powerful probes of cosmological parameters.
https://arxiv.org/abs/2009.04427

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Simulating the recollimation shocks, instabilities and particle acceleration in relativistic jets

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AGN jets are the most powerful persistent emitters in the Universe, but the mechanisms through which they dissipate part of their energy flux and convey it to relativistic particles are still elusive. Despite advances on the numerical and theoretical side, the identification of the processes at work is made difficult by the huge range of spatial and temporal scales involved and by the strong interplay between kinetic-scale processes and large-scale dynamics, with the important role of instabilities. Numerical simulations are therefore the natural tool for exploring the vast range of jet phenomenology.
In this framework, 3D MHD simulations of relativistic jets surprisingly reveal that the (intensively studied in 2D) recollimation caused by pressure unbalance with the external medium triggers a rapidly growing instability that leads to the development of strong turbulence, eventually resulting in the complete disruption of the flow (Komissarov et al. 2019). Existing simulations are inadequate to fully characterize the instability and the level of turbulence injected in the plasma, therefore in order to understand the impact of this newly discovered instability, we are pursuing a vigorous program of relativistic MHD simulations. Preparatory 2D and complete 3D simulations are carried out with the state-of-the-art PLUTO code, and the treatment of particle acceleration and transport is included via a hybrid approach. In particular the setup we are considering is designed to be applied to the most extreme and still enigmatic blazars, the EHBL. Their observational properties are different from the bulk of the blazar population, challenging the standard emission scenarios, and the multiple-shock model proposed by Zech &Lemoine, justified by 2D simulations, is instead questioned by the results of these 3D simulations. In addition, the presence of strong turbulence downstream of the recollimation shock is an interesting feature for building a new model for the VHE-emission of the EHBL.

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Using low frequency scatter broadening measurements for precision estimates of DM and its implications on GW detection using PTAs

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Pulsars are rotating neutron stars emitting a beam of radio light from their magnetic axis. As the pulsar signal passes through the interstellar medium (ISM), it gets smeared due to the variation of the group velocity of the radiation with wavelength caused by the electrons in the line of sight. This smearing can be due to dispersion by the integrated column density of electrons or multipath propagation due to inhomogeneities in the electron distribution across the line of sight. The dynamic nature of the ISM makes both these effects vary with observation epochs. This variation can mimic a slowly varying noise in ToA covariant with GW signature of an isotropic stochastic gravitational wave background (SGWB). We present a new method to estimate the DM accurately in presence of scatter broadening in the pulse profile by compensating for variable scatter broadening, estimated using 300-500 MHz wide-band upgraded Giant Metrewave Radio Telescope (uGMRT) measurements. We evaluate this method in comparison with traditional DM estimation methods, ignoring such effects, using simulated data. We also present results from this method using Indian Pulsar Timing Array (InPTA) data set on PSR J1643-1224 and discuss implications of our results.

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Towards experimental study of compact binary ejecta opacity relevant for kilonova transient signals

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Joint observations of gravitational-wave (GW) event to compact binary objects mergers, and of their electromagnetic counterpart, known as kilonova (KN) lead to a new avenue in the multi-messenger astronomy era to constrain the astrophysical origin of the r-process elements and the equation of state of dense nuclear matter [1]. Coalescence of double neutron star releases n-rich ejecta which undergoes r-process nucleosynthesis, driving the quick evolution of the KN transient powered by freshly synthesized decaying radionuclides. KNe act as spectral probes to explore the merger environment, hence of fundamental relevance for future detection and for providing sounder nucleosynthetic yields occurring in these loci [2]. However, largely heterogeneous post-merging ejecta composition, of both light and heavy-r process nuclei, propagates strong effects on the KN light-curve prediction through the ejecta opacity, till today hard to be fully addressed by theoretical models. Here we will present some peculiar features of the KN studies, focusing on the opacity issue, from the atomic and plasma physics perspectives. We report on the paradigm of early-stage timescale KN emission at optical wavelengths from light r-process ejecta component, and we present the work carried out in the framework of the PANDORA collaboration [3] to support planned experimental measurements of plasma opacity with in-laboratory plasmas resembling these KN-stage conditions [4]. In this view, the results of recently performed experiments at the INFN-LNS on the Flexible Plasma Trap (FPT) to reproduce suitable early-stage ejecta conditions for the designed first-of-its-kind opacity measurements of under-dense and low-temperature plasmas are here reported. We will also discuss some of the experimental progresses on the problem, including instruments and methods opening to an interdisciplinary approach for tackling astrophysical problems in laboratory plasmas.

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Stability of hypermassive neutron stars against a prompt collapse

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Highly differentially rotatig neutron stars can be produced in core-collapse supernova explosions. These objects may be significantly more massive than rigidly rotating neutron staers. Even for a modest degree of differential rotation we find equilibrium solutions with masses up to 4 times larger then the TOV limit. While the rotation profile evolves into uniform rotation on secular timescales, the immediate fate of the hypermassive remnant may have impact on the gravitational wave and electromagnetic emission from core-collapse supernova.

We investigate the dynamical stability against radial and axisymmetric pertutbations of differentially rotating neutron stars. We use the 2D CoCoNuT code to perform a series of hydrodynamical simulations of hypermassive neutron stars. We check whether the object undergoes a prompt collapse or stays stable on dynamical timescales.
I will present our preliminary results of our stability studies for masses up to 2 times larger than TOV limit. The threshold to collapse that we find is close to the limit estimated by turning-point criterion.

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A phenomenological inspiral-merger-postmerger gravitational waveform model for binary neutron star coalescence

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Gravitational waves provide us with an extraordinary tool to study the matter of neutron stars. In particular, the postmerger signal will reveal a lot of information about matter at such high densities. Although current detectors are mainly sensitive to the signal emitted by binary neutron stars during the inspiral and merger phase, the detectors'improvements planned for the next observing runs and future generation detectors, like Einstein Telescope and Cosmic Explorer, will allow us to detect postmerger signals too. We present a new model for the inspiral-merger-postmerger signal emitted by binary neutron stars systems. The inspiral part of the model is described by one of the state-of-the-art waveform models employing a closed-form expression for the tidal contribution, while the postmerger is modeled with a three-parameters Lorentzian, with two different approaches: in one case the Lorentzian parameters are kept as free parameters, in the other one we model them via quasi-universal relations. We test the performance of both versions of our model in parameter estimation analysis, employing a set of signals obtained from hybrid waveforms, and simulated at different distances. We compare the results for the LIGO-Virgo network with aLIGO+ sensitivity to

a network including also LIGO-India and KAGRA. We also study the possible improvement given by the high-frequency detector NEMO, and we finally compare results to what we will obtain for the same sources with third-generation detectors.

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Novel cosmological bounds on thermally-produced axion-like particles

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Cosmological observations represent a powerful probe to test the presence of new light species beyond the Standard Model (SM) of particle physics. In this talk I will focus on thermal axion-like particles (which I will simply refer to as axions), that can arise from various extensions of the SM and include, as a special case, the QCD axion. Thermal axions can be produced in the early Universe from scatterings involving particles belonging to the primordial thermal bath, at temperatures much larger than the axion mass (i.e., when axions are relativistic). Considering both the possibilities that axions are produced via axion-photon or axion-gluon processes, I will show and discuss the constraints on the axion couplings obtained using the latest CMB and BAO data. The bounds on the axion-gluon coupling are the most stringent ones in the mass range considered ($10^{-4} - 100$ eV). The constraints on the axion-photon coupling are competitive with the results from the CAST collaboration for axion masses larger than 3 eV. Finally, I will briefly comment on the forecast reaches that will be available given the sensitivity of future CMB-S4 missions.

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DEMNUni: CMB-galaxy cross-correlation in the presence of massive neutrinos

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We present an analytical modelling of the cross-correlation between the total (linear and nonlinear) ISW/Rees- Sciama effect and the galaxy distribution, in the presence of massive neutrinos. The modelling has been compared against sky-maps of CMB and galaxies extracted from the "Dark Energy and Massive Neutrino Universe"(DEMNUni) N-body simulations. We found a significant difference, in the amplitude of the cross- spectrum and in the position of its characteristic sign inversion, as the neutrino mass varies. Our results represent a leap forward from previous modelling in literature, which could be useful to produce forecasts and, especially, to exploit future ISW/Ress-Sciama observations for inference of cosmological parameters, the neutrino mass in particular.

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Testing the cosmological principle with the CMASS galaxy sample

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The cosmological principle that the universe is homogeneous and isotropic at large scales is a fundamental assumption of modern cosmology. Recent observations of the galaxy redshift survey provide relevant data to confront the cosmic homogeneity with observation. Several previous studies claim that the homogeneity scale is reached at a radius around 70 Mpc/h. Here we present a homogeneity test for the matter distribution using the Baryon Oscillation Spectroscopic Survey CMASS galaxy sample. As a homogeneity criterion, we compared the observed data with similarly constructed random distributions by counting the number of galaxies in the truncated cones. Comparisons are also made with three theoretical results using the same method: (i) the dark matter halo mock catalogs from the N-body simulation, (ii) the log-normal distributions derived from the theoretical matter power spectrum, and (iii) the direct estimation from the theoretical power spectrum. We show that the observed distribution is statistically impossible as a random distribution up to 300 Mpc/h in radius, whereas it is consistent with three theoretically derived results based on the cosmological principle. The observed galaxy distribution (light) and the simulated dark matter distribution (matter) are quite inhomogeneous even on a large scale. We discuss the ontological status of the cosmological principle. Based on Y. Kim, C.-G. Park, H. Noh & J. Hwang, CMASS galaxy sample and the ontological status of the cosmological principle, A&A 660, A139 (2022).

Session 7 / 22

The LISA orbiting observatory for low frequency gravitational waves

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The Laser Interferometer Space Antenna, LISA, is the ESA "L3" large mission, destined to be an orbiting observatory for gravitational waves in the 0.1 mHz to 1 Hz band. This will open a scientifically rich and deep window for astronomy, cosmology, and fundamental physics in a gravitational wave band that can only be reached from space. We present here the observatory science potential – including multi-messenger opportunities – and the main experimental challenges in making it work as we prepare for launch around 2035.

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Physics prospects of the Einstein Telescope

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Supernova remnants

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Supernovae explosions: an observational perspective

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GWSkySim: a fast simulator of gravitational wave sources with multimessenger applications

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The observation of the GW170817 event has shown how multimessenger astronomy is a powerful tool to investigate the most energetic phenomena in the Universe. Simulations are an important tool to study multimessenger emission and understand the constraints that can be put using joined electromagnetic and gravitational-wave observations. For that purpose, we developed the Gravitational Wave Sky Simulator (*gwskysim*), a numerically efficient and user-friendly software for simulating realistic gravitational emission from astrophysical sources and their electromagnetic counterparts. The output produced by the simulator can be read and manipulated with the most important analysis tools used in the field. We will give an overview of the software package and present some examples of possible applications.

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Status of the Cryogenic AntiCoincidence detector for ATHENA X-IFU: DM and SM models

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The study of the X-ray sky, in particular transient sources, is an important part of the multimessenger astrophysics concurrent to Gravitational Waves and Neutrino Observations. It helps to understand different phenomena, e.g. the central engine and jet physics in compact binary mergers, the equation of state of neutron stars, cosmic accelerators, and the origin of Cosmic Rays (CRs), the Cosmic distance scale and tests of General Relativity and the Standard Model. Athena (Advanced Telescope for High ENergy Astrophysics) will be an X-ray telescope mounted on a satellite that will be launched in 2030 decade towards an L1 orbit. One of the two detectors mounted on the focal plane will be a cryogenic spectrometer (X-ray Integral Field Unit, X-IFU) to perform high resolution spectroscopy and imaging. To reduce the particle induced background, thus enhancing the X-IFU sensitivity, a Cryogenic Anti-Coincidence detector (CryoAC) is planned. It consists of a hexagonal 4-pixel silicon microcalorimeter sensed by Ir/Au TES network that will work as veto system. A demonstration model (DM) having square active area of 1 cm2 has been developed and tested showing that it is fully compliant with its requirements. Further, a structural model (SM) of final form has been developed and tested for mechanical and thermal stress. Here we report the CryoAC general status and in particular the results of the DM and SM tests.

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Cosmology from the weak lensing of gravitational waves

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Planned and proposed future gravitational wave detectors will observe huge numbers of binary mergers. It is timely to explore cosmological tests that can be performed with this forthcoming plethora of data, in combination with present and future galaxy surveys. We forecast a combined standard siren + weak lensing analysis, where perturbations in the propagation of gravitational waves by intervening matter allows their use to probe large scale structure. We find that 3rd generation detectors, combining sources with and without an electromagnetic counterpart, will outperform future galaxy/intensity mapping surveys using this joint analysis method. We also show for the first time how merging binaries could constrain the sum of neutrino masses independently from other probes, should DeciHz detectors be launched. Finally, we demonstrate how the cosmology dependence in the redshift distribution of mergers can be exploited to improve dark energy constraints if the cosmic merger rate is well known.

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Very High Energy Gamma-Ray Astronomy and the search for PeVatrons

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Gamma-ray astronomy studies the most extreme and violent phenomena in the Universe. Thanks to the continuous improvement in experimental techniques in the last decades a growing number of sources have been detected at very high energy showing a large variety of different types of emitters proving that particle acceleration and transport is occurring in different astrophysical conditions and environments. The last few years have been particularly exiting with the spectacular detection by LHAASO of a dozen of PeV particle accelerators (PeVatrons) in our Galaxy. This discovery has opened the ultra-high energy frontier in gamma-ray astronomy contributing to shed light on the 100 years old question on the origin of galactic cosmic ray sources. In the presentation a review of present operating instruments will be given focusing on the latest results on the PeVatron search. In particular the complementarity and the need of the different experimental techniques will be highlighted. Finally, the next generation ground based gamma-ray telescopes will be presented together with the expected science potential in the search and characterization of galactic cosmic ray sources.

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A population of pulsar wind nebulae, issues and prospects

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Latest Results from the Pierre Auger Observatory

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In the new scientific era of multi-messenger astronomy, ultra-high-energy cosmic rays offer a very rare opportunity to investigate the nature of astro- physical sources and particle interactions at energies far from current particle accelerators capabilities. With almost 20 years of operation, the Pierre Auger Observatory is the world's largest cosmic ray detector providing a unique data set of the most energetic particles in the Universe. The Observatory employs a hybrid technique: a Surface Detector consisting of 1660 Water Cherenkov de- tectors and covering an area of 3000 km2 and 27 Fluorescence telescopes. A review of selected results is presented, focusing on the energy spectrum, mass composition measurements, search for sources, neutral particles and fundamen- tal physics. The future prospects of the Observatory will also be discussed in light of the AugerPrime upgrade currently under construction.

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Multi-messenger studies at the Pierre Auger Observatory

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The connection between ultra-high energy cosmic rays, photons, neutrinos and gravitational waves, in particular after the successful detection of gravitational waves, is nowadays widely investigated. Since all these signals may originate from the same sources, a multi-messenger approach, combining data from different experiments is undoubtedly the most appropriate technique for a better understanding of the physics behind the production and propagation of these messengers.
The Pierre Auger Observatory is the largest and most precise detector of ultra-high-energy cosmic rays. Thanks to its sensitivity to photons and neutrinos of very high energy, it is possible to perform diffuse and targeted searches above 10^{17} eV.
In this talk, we will focus on the search for diffuse fluxes of photons and neutrinos and report about the follow-up analyses in the context of the multi-messenger framework.

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Extreme TeV Blazar: a stochastic acceleration model

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Active Galactic Nuclei are the most powerful persistent sources in the Universe. Among them, blazars, AGN whose jet is pointed towards the Earth, present the most energetic emission. Lately a specific kind of blazar drew the attention of the gamma ray astronomy community: the extreme TeV blazars. These sources exhibit a peak of radiation at TeV energies and a hard intrinsic spectrum at sub-TeV range. In most cases their exceptional TeV emission appear to be steady over years.

Explaining the features of the extreme TeV blazars is still an open challenge, in fact the most used phenomenological models, based on shock acceleration alone, are not able to totally reproduce their SED and the parameters required by the fit are close to the theoretical limits.

In our model we suppose that the non-thermal particle are firstly accelerated by a jet recollimation shock caused by the difference between the jet and the external pressure, which then induces turbulence in the rest of jet, presuming a low plasma magnetization. Non-thermal particles are therefore reaccelerated by the turbulence, which harden the particle spectra and accordingly the radiative emission.

Since we are treating stochastic acceleration, in order to study the time evolution and the steady state of the system, we must describe the phase-space distribution of the non-thermal particles and of the turbulence through diffusion equations. Supposing isotropy and homogeneity, their interaction and spectra have been studied solving a system of two non-linear and entangled Fokker Planck equations, while the radiative emission has been calculated through the Synchrotron Self Compton model. The emission from our model has been compared with prototype extreme TeV blazar 1ES 0229+200.

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Recent progress on BSM and dark matter searches in CUORE

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The Cryogenic Underground Observatory for Rare Events (CUORE) is the first bolometric 0νββ experiment to reach the one-tonne mass scale. The detector, located underground at the Laboratori Nazionali del Gran Sasso in Italy, consists of 988 TeO2 crystals arranged in a compact cylindrical structure of 19 towers, operating at a base temperature of about 10 mK. After beginning its first physics data run in 2017, CUORE has since collected the largest amount of data ever acquired with a solid state detector and provided the most sensitive measurement of 0νββ decay in 130Te ever conducted.
The large exposure, sharp energy resolution, segmented structure and radio-pure environment make CUORE an ideal instrument for a wide array of searches for rare events and symmetry violations. New searches for low mass dark matter, solar axions, CPT and Lorenz violations, and refined measurements of the 2νββ spectrum in CUORE have the potential to provide new insight and constraints on extensions to the standard model complementary to other particle physics searches. In this talk, we discuss recent progress on BSM and dark matter searches in CUORE.

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Cosmology and Multi-Messenger Astrophysics with Gamma-Ray Bursts

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Gamma-Ray Bursts constitute one of the most fascinating and relevant
phenomena in modern science, with strong implications for several fields of astrophysics, cosmology and fundamental physics.
In this review, I will focus on the perspective key-role of GRBs for
cosmology and multi-messenger astrophysics. Indeed, 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 (i.e., those lasting up to a few minutes) potentially extremely powerful probes for investigating the early Universe (pop-III stars, cosmic reionization, SFR and metallicity evolution up to the "cosmic dawn") and cosmological parameters. At the same time, as demonstrated by the GW170817 event, short GRBs (lasting no more than a few s) are the most prominent electromagnetic counterpart of gravitational-wave sources like NS-NS and NS-BH merging events.
Moreover, both long and short GRBs are expected to be associated with neutrino emission. I will also report on the status, concepts and expected performances of space mission projects (e.g, THESEUS, Gamow Explorer) 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).

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Galactic archeology: overview and chemical evolution

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Prospects of present and future underground labs for nuclear astrophysics

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Planck observations of the Galactic polarized synchrotron emission and constraints on Dark Matter

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The Planck collaboration has produced precise observations of the polarized synchrotron emission in the microwave band.
This emission is sensitive to the presence of a possible signal from Dark Matter annihilation or decay. We use, for the first time, synchrotron polarization to constrain the DM annihilation cross section by comparing theoretical predictions with the latest polarization maps obtained by Planck. We find that synchrotron polarization is typically more constraining than synchrotron intensity by about one order of magnitude, independently of uncertainties in the modeling of electron and positron propagation, or of the Galactic magnetic field. Our bounds compete with Cosmic Microwave Background limits in the case of leptophilic DM.

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Multimessenger astrophysics at LNS from a nuclear physics point of view

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The detection of the gravitational event GW170817 is a turning point in nuclear astrophysics. Its observation triggered the investigation of the bright optical transient AT2017gfo using a broad number of diagnostic tools, opening the era of multimessenger astronomy. In particular, the follow-up of the lightcurve evolution made it possible to pinpoint the contribution from freshly synthesized heavy elements to the heating rate and opacity.
From a nuclear physics perspective, this event is the first record of the in-situ operation of the rapid neutron-capture process (r-process), responsible of the production of about 50% of elements heavier than iron. The kilonova associated with GW170817 proved that neutron star (NS) mergers are primary sites for the production of heavy elements, thanks to the large neutron densities leading to the production of neutron-rich isotopes far from the beta-stability valley.
This very brief overview shows the large number of nuclear and atomic physics input necessary to model the blast and its subsequent evolution. Among these, a primary role is played by the nuclear equation of state necessary for the description of NS structure and dynamical properties, and ruling the dynamics of binary NS mergers. Indeed, one of the main novelty offered by the binary NS merger event detection is the possibility to access NS tidal polarizability and, from that, NS radii and EOS of neutron rich matter.
The other fundamental ingredients to understand the blast followup are r-process yields (fixing the heating term of the light curve) and opacities (fixing the optical properties of the expanding plasma). In turn, r-process yields are strongly influenced by neutron capture cross sections, beta-decays and in particular those followed by neutron emission, and fission rates.
Besides constraints from observations, the comparison of predicted and experimental r-process yields is a fundamental tool to understand the explosion conditions. At present, the tighter constraints on r-process nucleosynthesis is based on solar system heavy-element abundances, once the calculated slow neutron-capture process (s-process) yields have been subtracted. Therefore, accurate modelling of the s-process is pivotal to the understanding of the r-process as well.
The Laboratori Nazionali del Sud of INFN are a unique place for the investigation of multimessenger astrophysics from a nuclear physics point of view, thanks to the expertise and the presently available and forthcoming experimental setups focused on the study of these many ingredients necessary to the understanding of the physics of the explosion and of its time evolution.
While the CHIRONE experiment studies the nuclear EOS at both low densities, using reactions among heavy nuclei with different N/Z ratios at Fermi energies available at LNS, and high densities, carrying out dedicated experiments at GSI to constrain NS radii, to be compared with the astrophysical ones, the nToF and ASFIN experiments measure n-capture and n-producing reaction cross sections, for both the r- and the s-process, the latter using mainly indirect methods to cover energies of astrophysical interest. ASFIN and PANDORA experiments will measure beta decays under different conditions: the former experiment will focus on beta-delayed neutron emissions, while the latter is the only facility that will measure beta decays in plasmas, where atoms are ionized as under stellar conditions leading to significant changes in lifetime for some isotopes of astrophysical interest. PANDORA is also undertaking a program of measurement of opacities of plasmas under temperature and densities similar to those characterizing kilonova ejecta, that would be one of its kind as well.
Special attention has been also devoted to the investigation of those reactions influencing the evolution of the NS progenitors and constraining their physical properties (such as masses and number), e.g., the 12C+12C fusion and the reactions leading to 26Al production and destruction. The ASFIN collaboration applied indirect methods to cast light on these related topics.
In this presentation I will briefly report on recent results these experiments have achieved towards a better understanding of multimessenger astronomy.

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New 3D White Dwarf Deflagration Models for Type Iax Supernovae

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Type Ia supernovae (SNe Ia) play a number of key roles in astrophysics. These include contributing substantially to cosmic nucleosynthesis, injecting kinetic energy in galaxy evolution and acting as cosmological distance indicators. Thanks to modern transient surveys it has become clear that type Ia supernovae are a diverse population with many different explosion scenarios proposed to explain normal SNe Ia as well as the various sub-classes. Nucleosynthesis constraints can help to understand the progenitors as different scenarios produce different elemental yields. In particular, explosion scenarios involving a deflagration phase produce relatively large amounts of neutron rich iron-group isotopes. Type Iax supernovae (SNe Iax), which are a sub-class of SNe Ia, are suggested to arise from pure deflagrations of Chandrasekhar mass CO white dwarfs. If this is the case SNe Iax are candidates for contributing to the enrichment of the Universe with neutron rich iron-group isotopes. Type Iax supernovae are estimated by Foley et al. (2013) to make up approximately 30% of the total SNe Ia rate. SNe Iax primarily occur in late-type host galaxies which implies they are a relatively young population and are spectroscopically similar to SNe Ia (although there are some differences) but generally have lower peak magnitudes. SNe Iax however have a much larger spread in their luminosity than normal SNe Ia: the faintest and brightest SNe Iax differ by more than 4 magnitudes at peak. Their infrared (IR) light curves don't show the secondary peak commonly seen in SNe Ia and the long-term evolution is different, potentially suggesting there is some form of luminous bound remnant left behind (in agreement with what is predicted by pure deflagration models). A key theoretical challenge is understanding the origin of this diversity across a wide range of wavelengths and epochs. One way to understand the diversity in the SNe Iax population is to explore how diversity in their initial conditions can impact the synthetic observables produced by models. To this end we present new 3-Dimensional, Carbon-Oxygen White Dwarf deflagrations (Lach, Callan et al. 2022) with varying geometric conditions including ignition radius of the deflagration and central density. We comment on the light curves and spectra produced from this series of models and compare the synthetic observables to the SNe Iax population. Finally, we discuss the possible causes of systematic differences between our model sequence and SNe Iax, the understanding of which are key to supporting or ruling out the pure deflagration scenario.

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Looking for Orphan gamma-ray burst in the Rubin LSST data with the FINK alert broker

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Gamma-ray bursts are highly energetic cosmological objects that provide us with different paths towards a better understanding of fundamental physics and the evolution of the universe. The most recent, promising and innovative path developed, consists in estimating the Hubble cosmological constant from gravitational wave events for which the distance can be estimated through electromagnetic observations. The perfect case was the one of GW170817/GRB170817A, and indeed several initiatives are well underway to try to optimize the matching of on-axis GRB signal (prompt, afterglow, kilonova) with potentially sub-threshold gravitational waves.
What we propose here is to provide new electromagnetic candidates for this matching by trying to identify off-axis GRBs in the Rubin LSST data through their so−called orphan optical afterglow emission. We will present our early work on this topic, starting with simulations with the afteglowpy

package of off-axis GRB afterglow light curves on a large part of the phase space of the parameters : energy, distance, jet nature and geometry, burst environment. This set of simulation helped us to understand that indeed some orphan afterglows should appear in Rubin LSST data as faint and slow transients that could be observable for several months.
We then produced a population of short GRBs off-axis afterglows for which we ran pseudo-observations using the "rubin_sim" package that offers a realistic schedule of the 10 years long observations of the LSS, and generated fake alerts ingested by the FINK alert broker. With that setup we are ready to dive into the characterization and identification of orphan afterglow light curves, we'll present our views on the most promising paths forward.

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Toward an independent reconstruction of the expansion history of the Universe

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A cosmological-model independent reconstruction of the expansion history of the Universe can help to shed light on the dark sector and the current cosmological tensions. I will discuss past, present, and future efforts to constrain the Hubble parameter $H(z)$ using two optimal astrophysical probes: cosmic chronometers and gravitational waves. Massive and passive galaxies can be used as chronometers to obtain direct measurements of the Hubble parameter without any cosmological model assumptions, $H(z) = -1/(1+z)\,\mathrm{d}z/\mathrm{d}t$. However, robust $\mathrm{d}t$ estimates require deep spectroscopy to break internal degeneracies between stellar population parameters (e.g., age and chemical content). I present a recent analysis of the stellar ages, [Z/H], and $[\alpha/\mathrm{Fe}]$ of 140 cosmic chronometers at $z \sim 0.7$ from the LEGA-C survey using an optimized set of Lick indices (arXiv:2106.14894). From the age-z relation of this population, a new measurement of $H(z)$ is derived, assessing in detail its robustness and dependence on systematic effects (arXiv:2110.04304). Finally, I will present the synergies betheen cosmic chronometers and gravitational wave cosmology in the context of current and future galaxy surveys and detectors.