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Summary of Session 4: Particle physics from the sky and the cosmos

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The investigation of the origin and nature of neutrinos, cosmic rays, dark matter particles and gravitational waves spans several fields in Astrophysics and Cosmology. The combination of observations of different nature can provide strong insights in fundamental physics in a complementary way to terrestrial searches. Here we summarise the "Particle physics from the sky and the cosmos" session of the NOW 2024 edition.

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1. Introduction

The implications of astroparticle physics involve particle physics, Astrophysics and Cosmology. Neutrino sources cover a huge range of energies and are very different: astrophysical sources, atmospheric neutrinos, supernovae, cosmic neutrino backgrounds. Even if the models of particle physics and cosmology remain still uncertain, the complementarity of different ongoing and future experiments will soon shed light on neutrino properties and the nature of the dark matter and dark energy.

2. Cosmic Rays, Gamma Rays, and High Energy neutrinos

Cosmic photons, neutrinos and charged cosmic rays (CR) are all messengers carrying complementary information about properties and processes of the universe. The field of high energy astrophysics has been probably the most prolific of discoveries in the last fifteen years, thanks to experiments and observatories of unprecedented capabilities and a much refined theoretical framework. In this respect, **Roberta Sparvoli** provided a comprehensive lesson about gamma rays, CRs and other messengers showing how: i) direct detection results have created a picture of CRs in the Galaxy with a wealth of new insights in CR transport and acceleration; ii) gamma ray telescopes have led to the detection of sources in the energy range of 10-100 TeV up to PeV; iii) the High Energy (HE) neutrino universe has been revealed and is characterised by a diffuse flux with possible sources; iv) a very efficient multi-messenger approach towards astroparticle phenomena has finally started. In the context of such tremendous experimental and observational advances, **Pasquale Migliozzi** presented the Cubic Kilometre Neutrino Telescope (KM3NeT) [1] whose completion is expected by 2028. In-progress physics analyses will held competitive measurements of neutrino oscillation parameters, while an extraordinary event with energy larger than 10 PeV has been already detected.

Moving to current observations, **Ivan de Mitri** explained the CR and gamma ray measurements performed with the satellite-borne DArk Matter Particle Explorer (DAMPE) detector [2] which is smoothly taking data since December 2015. DAMPE so far showed evidence of: an energy cutoff at $\sim$ 1 TeV in the all electron spectrum; a softening in the proton spectrum at $\sim$ 14 TeV; a softening in the helium spectrum at $\sim$ 34 TeV. Moreover, the latest measurements of the energy spectrum of proton+Helium suggest a new spectral hardening around 100 TeV [3], while preliminary studies of gamma ray sources allowed the detection of new features in the Forbush decrease and provide upper limit for dark matter signatures. On the other hand, measurements of the fluxes of cosmic electrons and positrons represent unique probes for determining the local environment where CRs propagate in our Galaxy. The hypothesis that pulsars can source the observed excess of positrons above 10 GeV has found important confirmations after the observation of gamma ray halos at TeV energies of a few degree size around Geminga and Monogem pulsars. **Mattia Di Mauro** discussed analyses of diffusion properties around pulsars through gamma ray observations and presented how gamma ray halo detections can be used to derive information about the Galactic environment and the cosmic emission mechanism from pulsar [4]. Still in the context of high energy phenomena, **Francesco Villante** explained updated predictions for the very high energy neutrino and gamma ray flux from the Galactic Plane, including the diffuse emission produced by interactions of CRs

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with the interstellar gas, as well as the cumulative flux produced by sources that are too faint to be resolved by neutrino or gamma ray telescopes [5].

In the field of Ultra High Energy (UHE) neutrinos, the Pierre Auger Observatory [6] is the largest astroparticle detector in operation providing a very good sensitivity to the detection of neutrinos with energies above 100 PeV. The identification is efficiently performed for neutrinos of all flavours and, since the neutrino fluxes are correlated to the acceleration mechanisms of charged particles, searches for these neutral particles enhance the multi-messenger understanding of UHE CR sources and of transient astrophysical phenomena. As pointed out by **Camilla Petrucci**, an upper limits to the UHE neutrino flux from diffuse and point-like sources has been reported, placing constraints on theoretical models of neutrino production at EeV energies and on the properties of the sources of UHE CRs. Concerning Extremely HE neutrinos (in the range of EeV), when approaching higher energies, the fluxes fall off and there is the need of very large detectors to probe fluxes beyond the GeV scale. There are still many open questions related to the origins of these neutrinos and their role in the universe. In this context, **Colton Hill** described the status of HE neutrinos searches at IceCube Neutrino Observatory [7], which represents an ideal environment to investigate the high energy frontiers in neutrino physics from TeV to EeV. These neutrinos originate from UHE cosmic rays interacting with the cosmic microwave background photons. There has been huge progress in the last ten years with a first detection of a candidate neutrino produced via the Glashow resonance, as well as a signicant observation of neutrinos consistent with the Galactic plane.

Recent studies show how environments such as Star-Forming and Starburst Galaxies (SFGs and SBGs) can act as sources of HE neutrinos [8]. As explained by **Antonio Ambrosone**, they experience intense phases of stellar formation activity, which is expected to increase the amount of gas and magnetic turbulence leading to confinement of HE CRs and high probability of proton-proton collisions, making these environments powerful emitters of HE gamma rays and neutrinos. Using Fermi-LAT data the correlation between these emissions with the star formation rate has been measured, showing also that the SFG and SBG contributions cannot saturate the isotropic gamma ray background (IGRB) measured by Fermi-LAT, while being consistent with a 20% contribution to the 6-yr Cascade diffuse neutrino flux measured by IceCube. Other studies, show the possibility that the extreme energy cosmic rays can be induced by a particular type of dark matter from a parallel sector. **Zurab Berezhiani** discussed how dark cosmic rays can source the ordinary ones within the GZK radius of our Galaxy, and how this mechanism can be the potential source of HE astrophysical neutrinos observed by IceCube [9].

3. Neutrinos and Supernovae

Neutrinos are elementary particles that constitute our matter world. They have many peculiar properties, such as flavour oscillations. In this respect the Jiangmen Underground Neutrino Observatory (JUNO), an experiment under construction in the south of China, will be able to measure neutrino oscillation parameters with an unprecedented precision of less than 1%, and observe thousands Supernova (SN) neutrinos if a SN explodes in our Galaxy [10]. JUNO will detect also thousands of neutrinos from the Earth, the so-called geoneutrinos, and a copious number of neutrinos coming from the Sun and other sources. However, the main aim of the JUNO experiment is to determine the neutrino mass hierarchy and perform precision measurements of the

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Pontecorvo–Maki–Nakagawa–Sakata matrix elements. The Juno scientific potential was presented by **Marco Malabarba** explaining how its large mass, superior energy resolution, and low detection threshold will make it an excellent detector to study neutrinos from a variety of natural sources such as the Sun, Supernovae, and the interactions of cosmic rays with the atmosphere. In particular: in the case of solar neutrinos, it will overcome Borexino results thanks to good radiopurity of the liquid scintillator; in case of nearby SN explosions, JUNO will be able to detect both pre-SN and SN neutrinos, and pointing to the source can also be provided; in the case of atmospheric neutrinos, measurements will be combined with reactor antineutrinos to boost the neutrino mass ordering sensitivity; finally, in the case of Diffuse Supernova Neutrino Background (DSNB), Juno as an expected high sensitivity and its discovery could be achieved in a few years. Indeed, from a theorethical side, the DSNB is hypothesised to be a theoretical population of neutrinos (and antineutrinos) cumulatively originating from all core-collapse (CC) supernovae (SN) events throughout the history of the universe. It is supposed to be isotropic and time independent, produced by an estimated SN rate of 1 SN/s, and consisting of neutrinos with typical energies on the scale of 10^7 eV. The DSNB can provide information about the star formation rate, the fraction of SNe forming Black Holes (BH), the history of our universe, and the exotic neutrino properties. As discussed by **Antoine Beauchêne**, the Super-Kamiokande (SK) new Gadolinium (Gd) phase (Sk-Gd) allows us to get larger statistics in less time, helping to probe DSNB models more quickly, but disfavours background-only hypothesis at 2.3σ [11].

Concerning the connection between SNe and CRs at a more observational level, the structures resulting from the explosion of a star in a supernova, the so-called supernova remnant (SNR), represent also a paradigm for the origin of Galactic CRs. As explained by **Silvia Celli**, the particle release process from SNR shocks is energy dependent, such that high-energy particles are expected to leave the shock region before low-energy ones, the absolute temporal scale depending on the diffusion coefficient in the region surrounding the shock. The presence of dense gas targets, such as interstellar clouds nearby the accelerators, might provide evidence for the escaping flux of particles through the production of gamma rays and neutrinos at hadronic collisions. In this respect, recent wide field-of-view survey instruments have revealed an unexpectedly large population of Galactic gamma ray sources at UHE (larger than 100 TeV) with no counterpart and the scenario of molecular clouds illuminated by nearby SNRs appears to be a viable explanation [12].

Finally, SNe can source not only neutrinos but also Gravitational Waves (GW). **Alessandro Lella** explained as the theory of CCSNe can nowadays be considered a field mature enough to be studied at the interface of gravitational, particle, nuclear and numerical physics. Recent realistic 3D SNe simulations have revealed that successful explosions can be self-triggered only by accounting for the heating by neutrinos anisotropically emitted from the protoneutron star (PNS) and large neutrino-driven convective instabilities. Both these phenomena are characterised by a non-vanishing quadrupole momentum, which could generate a large GW emission in the range of frequencies $1 - 10^3$ Hz, and might be in the reach of current and future GW detectors for a future Galactic SNe event, providing information on different explosion phases, neutrino emission and PNS oscillation modes. Moreover, recent advancements have brought to light the crucial role of Neutrino Flavour Conversions (NFFCs) in CCSNe and Neutron Star Merger (NSM) simulations. As discussed by **Sajad Abbar**, NFCs cannot be ignored blindly in CCSN simulations but integrating these conversions into the simulations remains a formidable computational task that can be fulfilled

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through Artificial Intelligence (AI) methodologies [13]. This represents an important step forward in our understanding of the intricate dynamics of CCSNe and NSMs, with profound implications for astro- and particle-physics.

Finally, in the context of unlocking ultra-high-resolution astrophysical phenomena, **Domenico Della Volpe** presented the so-called Quantum Assisted Intensity Interferometry (HBT effect) which exploits a purely quantum mechanical effect arising from the indistinguishability of particles. To perform this technique, researchers look for temporal correlations between photons detected at two different locations separated by a distance known as the baseline. The strength of this correlation depends on the distance between the telescopes and the size of the source. The advent of light detectors operating in the picosecond domain has revolutionised our scientific capabilities, enabling us to achieve micro-arcsecond and even nano-arcsecond resolutions in the optical domain using the HBT effect.

4. Dark Matter Searches

The composition of the universe is a central question of Astrophysics and Cosmology and, to make sense of cosmological observations, one has to introduce Dark Matter (DM) and Dark Energy (DE), both of still unknown nature. From and experimental side, DM particles populating our Galactic halo could be directly detected by measuring their scattering off target nuclei or electrons in a suitable detector. However the detection is challenging since this interaction is expected to occur with very low probability and would generate very small energy deposits [14]. Of great importance in DM searches could be the role of the DSNB. In fact, as explained by **Tim Herbermann**, diffuse neutrinos from past SNe in the universe provide a unique opportunity to test DM interactions. These neutrinos can scatter off DM particles in the Milky Way halo and boost them to (semi-)relativistic energies, allowing us to detect them in terrestrial laboratories. Focusing on a generic model of DM-lepton interactions mediated by a vector boson, energy-dependent scattering cross sections have been implemented and a detailed numerical analysis of DM attenuation due to scattering in medium has been performed. Limits on DM-lepton interactions for light DM in the MeV mass range have been set using xenon based direct detection experiments [15].

Still in the context of neutrino backgrounds and DM searches, the DarkSide-20k detector [16] will reach in less than one year a world leading sensitivity to low mass (1-10 GeV/c^2) Weakly Interacting Massive Particles (WIMPs), but, as discussed by **Mattia Atzori Corona**, a detailed characterisation of the Coherent Elastic Neutrino Nucleus Scattering (CEνNS) and Neutrino Elastic Scattering (νES) backgrounds will be needed. In fact, the search for light DM particles presents many experimental challenges, such as the loss of discrimination power, the selection of few-electron events and the need to have control over the various background components such as the signals due to solar neutrino interactions and the beta decay of argon-39. Similarly, also the XENONnT experiment [17] is aiming for the direct detection of DM particles in the form of WIMPs, and has already completed its first science run. However, as explained by **Carla Macolino**, solar neutrinos can interact with liquid xenon through CEνNS, producing signals similar to DM-nucleus interactions. Known as the “neutrino fog”, this phenomenon represents an irreducible background for direct DM detection. The XENONnT detector, noted for its substantial exposure and low background, provides for the first time the opportunity to probe this interaction.

5. Neutrinos, Gravitational Waves, and Cosmology

Over the last two decades, the continuous improvement of the precision and accuracy of cosmological observations has opened a window to constrain neutrino properties via cosmological data. In particular, the sum of the three neutrino masses, $\sum m_\nu$, can be well constrained due to its effect of suppressing the clustering of Cold Dark Matter (CDM) after the neutrino non-relativistic transition. Despite the great progress in the precision of β-decay experiments, cosmology provides the most stringent, model-dependent, constraints to date on the absolute neutrino mass scale. Recently, the DESI Collaboration reported an upper limit of $\sum m_\nu < 0.082$ eV at the 95% CL from the combination of Cosmic Microwave Background (CMB) and DESI baryon acoustic oscillations (BAO) data. This bound mildly favours the normal ordering (NO) scenario and shows that there might be a possibility of indirectly constraining the neutrino mass hierarchy using cosmological data. Future galaxy surveys and CMB experiments are expected to improve this limit. In particular, **Massimiliano Lattanzi** explained how different combinations of next-generation CMB and Large Scale Structure (LSS) measurements will provide a sensitivity for $\sum m_\nu$ between 15–50 meV. The lower-end sensitivities rely on a cosmic-variance limited measurements of the reionisation optical depth from LiteBIRD. This is enough for a up to 4-σ measurement of the minimum mass in NO allowed by oscillation experiments ($\sim$ 60 meV), and will also allow to determine the mass ordering if $\sum m_\nu$ is close enough to 60 meV. However, it is important to point out that changing the underlying cosmological model can potentially relax the constraints obtained from many of the cosmological probes. In addition, future measurements of the effective number of relativistic species, $N_{\rm eff}$, will provide tight constraints on theories beyond the Standard Model(SM) and the ΛCDM cosmological model. In fact, a deviation from the standard value of $N_{\rm eff}$ might be due to additional light species (e.g. sterile neutrinos, thermal axions), non-standard expansion history, new physics affecting neutrino decoupling, large lepton asymmetry.

Concerning forecasts from upcoming data, **Sefa Pamuk** discussed how the Euclid mission [18] has a great complementarity between the spectroscopic and the imaging/photometric surveys and between Euclid and CMB experiments. This complementarity will allow Euclid to achieve unprecedented precision in constraining neutrino properties, with a great potential for $\sum m_\nu$ measurements and the possible exclusion of many theoretically well-motivated additional relativistic particles. As such, Euclid will strongly impact the theoretical landscape of cosmology [19].

Finally, a very important field in Cosmology is the supposed Stochastic Gravitational Wave Background (SGWB) produced in the very early universe, during the so-called cosmological inflation epoch. **Giampiero Mangano** presented a study about the impact of stochastic quantum noise due to trans–Planckian effects on the primordial power spectrum for gravity waves during inflation. This noise can be described in terms of a source term in the evolution equation for comoving modes k which changes its amplitude growth from early times as long as the mode physical wavelength is smaller than Λ^{-1}. At large energy scales, the source term can be modelled as due to a gas of black holes in the trans–Planckian regime and the corresponding Hawking radiation. At later times the evolution follows the standard sourceless evolution. It is possible to show that this mechanism still leads to a scale-invariant power spectrum of tensor perturbations, with an amplitude that depends upon the ratio $\Lambda/m_{\rm P}$.

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