PROCEEDINGS OF SCIENCE

Session V - Particle physics in the cosmos

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The investigation of fundamental physics via observations of particles of astrophysical and cosmological origin is an active research area that is independent from and complementary to terrestrial searches. Here we summarize the "Particle physics in the cosmos" session of the NOW 2022 edition. The focus of this session has been on recent advances, from both theoretical and experimental perspectives, in our understanding of neutrino and dark matter properties.

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1. Introduction

The tremendous experimental and observational advances in the past decades have shaped our understanding of the Universe at a fundamental level. Nevertheless, key aspects of the standard model of particle physics and of cosmology remain uncertain at the moment. Among those, two are the targets of ongoing and future endeavours from both a theoretical and experimental ground: unveiling neutrino properties and investigating the nature of the Dark Matter (DM).

2. Neutrinos in cosmology and astrophysics

Neutrinos are widely considered windows to beyond-standard-model physics [1] due to the difficulties in make them fit within the standard model of particle physics. At the same time, theoretical explanations of the origin of their masses can be linked to solutions to long-standing problems in cosmology, such as the origin of baryon asymmetry in the Universe (BAU). As explained in the contributions by **Juraj Klaric** and **Stefan Sandner**, the introduction of very massive right-handed neutrinos (RHN) required by the see-saw mechanism provides a good candidate that satisfies the necessary Sakharov conditions for dynamical creation of the BAU. Indeed, the RHN can lead to the BAU level observed today via leptogenesis mechanisms for RHN masses above $\mathcal{O}(\mathrm{MeV})$ [2–4]. Interestingly enough, resonant leptogenesis and leptogenesis via oscillations can be regarded as viable mechanisms while providing predictions that are testable with various laboratory searches [3–5]. Regardless of the BAU generation mechanism, we expect that no antimatter domains exist in the Universe [6]. Therefore, the observation of anti-nuclei in e.g., cosmic rays observatories such as AMS-02 [7] would be evidence of BSM physics and would require an explanation of its origin. A possible solution proposed by **Zurab Berezhiani** in their talk could be the hypothesis of creating anti-matter out of mirror (dark) matter [8, 9] during merger events of mirror neutron stars (neutron stars made of mirror neutrons) [10].

Lighter ($\mathcal{O}(\mathrm{keV})$) RHN can be also considered as viable DM candidates [11], produced e.g., with the Dodelson-Widrow mechanism [12] via oscillations with active neutrinos in the early Universe. However, **Joern Kernsten** explains that astrophysical constraints on the parameter space of the model do not allow for this mechanism to produce all the DM (see e.g., [13] for a review of current constraints). Alternative production mechanisms are required, such as those that involve the existence of non-standard BSM interactions in the neutrino sector, see e.g., [14]. While the simplest scenarios are already ruled out by X-ray searches, motivated extensions can be developed that can be tested by a plethora of astrophysical and cosmological observations.

The existence of a cosmic (active) neutrino background (CNB) is a key prediction of the standard model of cosmology [15]. As light yet massive relic particles, neutrinos affect the evolution of cosmological probes (see contributions by **Massimiliano Lattanzi** on the impact of the CNB on the cosmic microwave background and matter distribution, and by **Giampiero Mangano** on the role of the CNB in Big Bang Nucleosynthesis). Hence, observations of the latter can be used to constrain specific neutrino properties and even test for BSM neutrino behaviours. An interesting possibility is the investigation of the stability of cosmic neutrinos over cosmological timescales, something that cannot be easily achieved via terrestrial searches. Motivated by the extension of the standard model of particle physics to accommodate neutrino masses, BSM neutrino interactions can lead

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to cosmic neutrino decay, as discussed by **Isabel Oldengott**. The implications for the evolution of cosmological probes allow to put the most stringent bounds on the neutrino lifetime today with cosmological data [16, 17]. The direct detection of the CNB is a difficult endeavour due to the extremely low energy (well below the eV scale) of its flux [15]. Nevertheless, ongoing efforts are devoted to this ambitious observational target. The PTOLEMY project aims at detecting the CNB via neutrino capture over tritium [18, 19]. In their talk, **Marcello Messina** shows that, while the required sensitivity would be achieved on a longer time scale, a prototype is under development at LNGS and its detector, based on novel technology, will be ready in 2023. Assuming standard active neutrino properties, the average number density of the CNB today is about $113\,\mathrm{cm}^{-3}$ per neutrino family [15]. However, local clustering of the CNB may occur that can lead to a sizable overdensity. **Thierry Lasserre** points out that large-enough overdensities can be potentially observable with the β-decay experiment KATRIN exploiting again the (relic) neutrino capture process over tritium. Albeit only sensitive to very large overdensity values, KATRIN has already improved previous bounds by two orders of magnitude [20].

Astrophysical neutrinos can be also measured by DM direct detection experiments through the coherent elastic neutrino-nucleus scatter (CEνNS) process. Hence, as emphasized by **Louis Strigari**, they can also act as neutrino telescopes. As the sensitivity improves, such detectors will be able to observe solar neutrinos, low-energy atmospheric neutrinos and supernova neutrinos [21, 22], thus providing new remarkable insight on such sources. Precision measurements of CEνNS cross section at colliders are therefore crucial as well as the development of directional detectors, which for instance have the ability to disentangle DM events from solar neutrino ones. Supernova neutrinos represent one of the most challenging open problems in neutrino physics thanks to which it is possible to understand how these particles behave in extreme conditions. In particular, As pointed out by **Basudeb Dasgupta**, in the inner region of a supernova, the neutrino density is so high, that their self-interactions affect the flavour evolution making it a non-linear phenomenon. As a consequence, and intriguing behavior, known as “collective oscillations” can occur [23, 24]. Remarkably, neutrino oscillations could provide crucial information on the explosion mechanism of supernovae. Moreover, another laboratory to probe cosmology and fundamental particle physics would be also provided by the still-undetected diffuse supernova neutrino background (DSBN), i.e. the MeV neutrino cumulative emission from all supernova explosions in the Universe. In this context, **Manibrata Sen** shows that the DSBN measurements will allow one to place stringent limits on neutrino lifetime and possibly to shed light on the origin of neutrino masses [25, 26].

3. Dark Matter

Although DM is one of the pillars of the standard cosmological model, its nature is still unknown having no clue about its non-gravitational interactions and its mass [27]. Among the different ways to search for DM, direct detection experiments (see e.g., [28] for a review) are very sensitive to Weakly Interacting Massive Particles (WIMPs), i.e. DM particles with O(GeV) mass. In their talk, **Carla Macolino** has presented the first results from the XENONnT detector [29]. The first blinded analysis of low-energy electronic-recoil data has not only excluded the XENON1T 2020 excess in the electron events, but also placed competitive limits on several new physics models including Axion-Like Particles (APLs) and dark photon. At the same time, the DarkSide program

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has reported new remarkable updates as discussed by **Francesca Dordei**. Thanks to the lower atomic mass of the target, liquid Argon detectors exhibit a better sensitivity to low-mass WIMPs. After the successful campaign of the DarkSide-50 experiment [30–32], the DarkSide-20k detector is currently under development.

Other DM candidates that have recently become very popular are Primordial Black Holes (PBHs). They are hypothetical black holes formed soon after the inflationary epoch through the gravitational collapse of density fluctuations in the early Universe. In their talk, **Philippa Cole** has pointed out that the slow-roll approximation for inflation needs to be broken to achieve the right enhancement in the primordial power spectrum on small scales to produce PBHs [33]. Interestingly, the formation of PBHs will be crucially tested by upcoming experiments such as SKA, LISA and ET [34]. In this context, **Ninetta Saviano** has also shown that the Hawking radiation of PBHs with masses between 10^{14} and 10^{18} is an efficient source of boosted sub-GeV dark particles which can be then observed in direct detection experiments thanks to their higher velocities [35, 36]. Hence, the presence of PBHs would lead to very stringent constraints on the interaction of light DM and ordinary matter.

Tremendous efforts have been also dedicated in recent years to search for axions and ALPs, which are well-motivated DM candidates arising in many standard-model extensions. In their talk, **Igor Irastorza** has reviewed the current status and the near-future developments of axion experiments [37]. Concerning laboratory axion experiments based on the light-shining-through-wall method, the recently-commissioned ALPS-II detector will be able to probe the axion-to-photon coupling $g_{a\gamma}$ at the level of 10^{-11} GeV^{-1}. Haloscope experiments (e.g. ADMX, HAYSTAC and CAPP), which aim at detecting relic axions, are now probing the well-established KSVZ and DFSZ models for the QCD axion. Finally, significant improvements in the axion constraints are expected to be provided by the future IAXO helioscope detector. Such experimental developments are also accompanied by recent theoretical advances in modeling the ALP impact on astrophysical environments. In this context, **Giuseppe Lucente** has discussed a ballistic model to account for both energy-loss and energy-transfer regimes caused by ALPs in stellar environments, including the photon coalescence process together with the standard Primakoff one [38, 39]. Applying such a refined calculation to global cluster stars has been able to ruled out the “cosmological triangle”, i.e. the region in the ALP parameter space with $m_a \lesssim 0.4$ MeV and $g_{a\gamma} \simeq 10^{-5}$ GeV^{-1}.

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