PROCEEDINGS OF SCIENCE

Particle Physics in the Cosmos

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The Session V "Particles in the Cosmos", at the NOW 2016 workshop, is dedicated to the interplay among the theory and phenomenology of particle physics theories and cosmological models. The main topics faced during the sessions were addressed to the cosmological implications of the neutrinos and of other possible extra species in the Universe, and to the different Dark Matter candidates. A summary on the talks presented at the session is here reported.

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1. Introduction

To introduce our session, we evoke the words of E. Kolb: " *the relation between particle physics and cosmology may constitute a successful example of the unity of science. In a real sense the job of cosmology is to provide a canvas upon which particle physics can weave its individual threads into the tapestry of our understanding of the Universe. It might be that particle physics could somehow be used to derive cosmology and thereby function as the material of which the cosmological canvas is made*".

The "Particle physics in the Cosmos" session of the Neutrino Oscillation Workshop 2016 had exactly the purpose to cover this aspect, testing and constraining theories of particle physics through cosmology and viceversa, presenting current theoretical and phenomenological results and future perspectives. In the near future this connection can only be strengthened: cosmology is sensitive to both the number and masses of neutrinos (including possible sterile states), to the possible existence of other particles (such as axions..), to non standard interactions and properties for the particles, as well as the indirect search of dark matter particle with structure formations data and with neutrino telescopes is complementary to the direct detection providing more information as possible. In what follows we recapitulate the topics discussed and the highlights of the session. We devote the Section 1 to the cosmological implications of the neutrino proprieties, and of the existence of extra species in the Universe. The Section 2 focuses on the different Dark Matter candidates from both theoretical and experimental point of view.

2. Neutrinos, light particles and extra radiation

In the past decade, observational cosmology has donated us an accurate and amazing description of the evolution of the Universe pointing out existing issues but also raising new questions about the fundamental mechanisms behind the macroscopic phenomena. We can benefit from the Universe to learn about fundamental particle physics and than make use of what is learned to provide a better understanding of the Universe and its objects. A large number of cosmological probes, covering a wide range of redshifts, are used and also combined to constrain the content and the evolution of the Universe. In particular Cosmic Microwave Background, structures formation, gravitational lensing, Big Bang Nucleosynthesis, supernovae, Baryonic Acoustic Oscillations are contributing to shade light on the properties of particles and also on the possible existence of extra species.

The presence of a background of relic neutrinos is a basic prediction of the standard cosmological model. They are well established by cosmological observables at different epochs, contributing to radiation at early times and to matter at later times. In the Early Universe the three standard flavour active left-handed neutrinos, and their antiparticles, are thermally excited in the primeval plasma of particles, being in thermal equilibrium with charged leptons, baryons and photons by weak interactions. In this regime the neutrino distribution is the Fermi-Dirac one. Due the expansion of the Universe, the temperature decreases and the neutrino interaction rate decreases faster than the Hubble rate, leading to a decoupling of the neutrinos from the thermal bath. After the decoupling, neutrinos freely propagate becoming transparent to the Universe forming the Cosmic Neutrino Background (CνB). They represent an hot relic, in the sense that they decouple when they are relativistic particles. This picture is consistent with current CMB observations as showed in the plenary presentation of **M. Lattanzi** on “Neutrino cosmology”. Together with photons, in the standard case neutrinos fix the expansion rate while the Universe is dominated by radiation. Their contribution to the total radiation content can be parametrized in terms of the effective number of neutrinos N_{eff}.

As discussed by **M. Lattanzi**, neutrinos affect both the expansion history of the Universe (trough changes in the time of matter-radiation equality or in the distance to the last scattering surface) and the evolution of the perturbations, trough their free-streaming characteristic. The observed spectrum of CMB anisotropies permits to measure the parameters of the cosmological model and to provide information on neutrino physics. Currently, the most precise measurements of CMB anisotropies in both temperature and polarization, on a wide range of scales, are provided by the Planck satellite. In the analysis made by the Planck collaboration are also considered datasets from different cosmological probes, for example the BAO in order to get also geometrical information, as well as direct measurements of the Hubble constant. As pointed also by **A. Melchiorri** in his plenary presentation on “Future precision cosmology and neutrinos”, very important are also the Planck lensing information on the small-scale anisotropies, especially for the neutrino mass bounds. Indeed the CMB photons emitted at z=1100 are deflected by the gravitational lensing effect of massive cosmic structures, affecting the CMB anisotropy angular spectrum by smearing the high l-peaks. The CMB combined analysis provides strong constraints on neutrino masses (Σm_ν <0.19 eV) and also no indication for extra relativistic degrees of freedom at recombination (N_{eff} ~3). Some tensions among Planck data and other probes are still present which should be understood and overcome in the future CMB experiments. One concerns the value of σ_8 vs Ω_m plane between Planck and cosmic shear data from CFHTLenS. The other tension regards the value of the Hubble constant H_0. Indeed the recent astrophysical determination of the Hubble constant is more than 3σ away from the value determined by Planck assuming ΛCDM model.

There is an intensive and impressive plan for Proposed/Future CMB experiments with a stronger sensitivity for Σm_ν and for N_{eff}. Moreover improvements for the measurement of H0 should be obtained. They are divided in 3 categories: 1) Ground based (such as SPT, BICEP/Keck at the South Pole, ACT in Chile), 2) Balloon borne (as for example PIPER, SPIDER, 3) Satellites (such as Litebird, CORE).

We have seen that relic standard neutrino are well established by cosmological probes, however they are not detected so far. A direct detection is a challenging task and this is the ultimate goal of PTOLEMY project devoted to gather information on neutrinos generated during the beta decay of tritium. At this purpose a highly effective detector must be employed to detect the energy and position of electrons emitted during the beta decay. As discussed by **A. Cocco** the neutrino capture on a tritium target consists of a relic neutrino and a tritium nucleus in the initial state, and two particles in the final state, an electron and a ^{3}He nucleus. If the kinetic energy of the electrons emitted from tritium nuclei are measured with a precision comparable to the masses of the relic neutrino eigenstates, then the process of tritium beta-decay, a three-body final state, can be distinguished from neutrino capture by looking for electron energies above the beta decay endpoint with a separation set by twice the neutrino mass, for the neutrino mass eigenstates with electron flavor.

The number of light neutrinos sensitive to weak interactions equals three from the analysis of the invisible Z-boson width at LEP. Any strong departure of N_{eff} from this value would be due to the contribution of other relativistic relics (totally or partially thermalized light sterile neutrinos, axions, pseudoscalar particles) or to non-standard neutrino features (primordial neutrino asymmetries, non-standard interactions with electrons, reheating scenarios). We will devote the last part of this contribution to this topic, namely the determination of N_{eff} and possible deviations.

The simple picture of 3 standard free streaming neutrino species is perfectly consistent with all the available data. It is however desirable to investigate more complicated scenarios for the neutrino sector.

A recent and complete theoretical computation of N_{eff}, including also neutrino flavor oscillations, with a full collisional term, and also in presence of non-standard neutrino-electron interactions, is presented by **S. Pastor**, providing a value of N_{eff}= 3.045 in the standard case and a value of N_{eff}= 3.049 in presence of non-standard neutrino-electron interactions. These predictions are full compatible with the CMB data as observed by the Planck satellite.

F. Forastieri in his presentation considers the possibility that neutrinos have interactions beyond the standard ones (named “hidden” or “secret” interactions) in the context of cosmological observations. In particular, he presents a specific version of secret interactions, namely a (pseudo)scalar interaction mediated by the Nambu-Goldstone boson of new broken U(1) symmetry, The limits on the strength of neutrino non-standard interactions are obtained by directly modifying the Boltzmann equation in the cosmological code in order to account for neutrino collisions, following in this way the transitions from collision-less to perfectly tightly coupled regimes. Using CMB temperature and polarization anisotropies data from Planck combined with other surveys data, he shows that all the models considered are consistent with no interactions.

Scenario with eV sterile neutrinos, as suggested by some anomalous data from neutrino oscillation experiments, is incompatible with cosmological data, in particular with structure formation data and with observations of the Cosmic Microwave Background anisotropies. However, this conclusion can change by invoking new physics. A possible reconciliation could be achieved suppressing the sterile neutrino thermalisation in the early Universe. Among different possibilities, **S. Gariazzo** focuses on the introduction of a secret interaction only confined in the sterile sector and mediated by a light pseudoscalar ($m < 0.1$ eV) of a new U(1) broken symmetry. The new interaction induces a large matter potential which can suppress equilibration of the sterile state until after active neutrino decoupling. Moreover, at late times the interaction becomes very strong leading to a coupled fluid of neutrinos and pseudoscalars. A better agreement of the cosmological posterior for the sterile neutrino mass with the squared-mass difference isobtained from the analysis of short- baseline neutrino oscillation data. In addition, this model also predicts a value of the Hubble parameter much higher than the one obtained in the ΛCDM model and so more compatible with the astrophysical measured value.

A possible contribution to N_{eff} can be given by thermal axions while they are still relativistic, as presented by **E. Di Valentino**. At this regard she presents the CMB constraints on the thermal axion mass, exploiting the full Planck mission data, which include polarization measurements. Relic axions constitute a hot dark matter component and their masses are strongly degenerate with those of the three active neutrinos, as they leave identical signatures in the different cosmological observables. Using a combination of data sets, she present a stringent bound on the thermal axion mass, $m_a < 0.529$ eV at 95 % CL.

3. Dark Matter

A wide range of astronomical observations show that the visible stars and gas in all galaxies, including our own, are immersed in a much larger cloud of non-luminous matter. The existence of this "dark matter" is consistent with evidence from large-scale galaxy surveys and microwave background measurements, indicating that the majority of matter in the universe is non-baryonic. The nature of this non-baryonic component is still unknown, and the variety of proposed theoretical particles as dark matter candidates is wide. However, some constraints on the properties of the candidate directly arise from the astronomical observations: being "dark", it can not be charged under both electromagnetic and nuclear interactions; it has to be "cold", or non–relativistic, to explain the non-homogenous distribution of the matter in the Universe; it has to be "stable" over the lifetime of the Universe.

The "zoo" of dark matter particles counts a wide range of candidates. Three plenary talks have discussed three among the leading ones: "keV sterile neutrinos" (**A. Merle**), "Axions" (**A. Ringwald**), and "WIMP's" (**M. Messina**).

As discussed by **A. Merle**, sterile neutrinos with mass of the order of keV can be a natural candidate of dark matter. They are usually classified as warm candidates because they can generate an important free-streaming, damping the distribution of matter on small scales. However, the free-streaming length not only depends on the mass of the particles, but also on the momentum, and therefore on the their phase space distributions. Different production mechanisms (i.e flavor conversions with active neutrinos, scalar decay) produce warm or cold distributions functions, with a different impact on the structure formations. Furthermore, mixed scenarios there could exist in which dark matter is composed by several candidates with a cold and warm nature. Experimentally, the constraints on keV sterile neutrinos comes from the observation of X-rays expected from the sterile neutrino two–body decay into active neutrinos and photons.

The impact of different production mechanisms on structure formation is discussed in the presentation of **A. Schneider**. He focuses more on the resonant production mechanism and on the scalar decay one, in particular he shows the allowed region for the sterile angle-mass parameter space delimited by X-ray observation and by structure formation data.

Axions arise as a solution of the (not yet observed) strong-CP problem in particle physics. The Peccei-Quinn extensions of the Standard Model introduces a pseudo-scalar field to solve the problem. The so–added new global symmetry is spontaneously broken, resulting in a new particle, called axion, able to interact with gluons, fermions, and, at loop–level, with photons.

Axions acquire a small mass from mixing with the pion with $\mathrm{m}_a \sim \mathrm{meV}\left(\frac{10^9 GeV}{f_A}\right)$, where f_A is a new mass scale: the axion decay constant.

The thermal production of axions is disfavored by the their relic density, which would imply hot dark matter. There are, however, several way to non-thermally produce axions as dark matter, like from the "vacuum realignment", or from topological defects. The Standard Model-Axion-Seesaw-Higgs Portal Inflation (S.M.A.S.H.), a minimal extension of the Standard Model, adds three right-handed neutrinos, a new color triplet, and a complex SM-singlet scalar, with a vacuum expectation value of 10^{11} GeV, which simultaneously breaks the lepton number and the Peccei-Quinn simmetries. S.M.A.S.H. is able to solve 5 problems at one: dark matter, the smallness of the neutrino masses, baryogenesis, cosmic inflation, and the strong CP problem. Refer to the A. Ringwald proceeding for more details.

Axions may be detected by looking at direct scattering with SM particles. Currently there exist a wide experimental activity in the field. Different techniques have been developed or are under development to look at direct scattering of axions with SM particles. CASPEr will detect the spin precession caused by axion dark matter using nuclear magnetic resonance techniques. In particular, it will look for the direct coupling of the axion and the spin of the nucleus, and for the time-varying nucleon electric dipole moment caused by the axion. Similarly, QUAX will also exploit magnetic resonances, but this time induced by the interaction of cosmological axions with the spin of electrons in a magnetized sample. Resonant microwave cavity experiments, like ADMX, look for the axion resonant conversion in photons in cavities placed in a magnetic field (the so–called Primakoff process). ADMX currently provides the most stringent limits in the 1–100 μeV mass range. Other experiments will be based on dish antennas and resonators. As **A. Ringwald** stated in his talk, *in the upcoming decade a sizable fraction of the parameter space of interest for axion dark matter will be probed.*

Weakly Interacting Massive Particles, or WIMP's, are appealing dark matter candidates because well motivated by cosmological considerations, well supported by several particle physics theories, and experimentally detectable in laboratory. **K. Petracki**, showed in her presentation that, if the dark matter mass is larger than a few TeV, relic abundance of thermal dark matter annihilating via a long-range interaction is affected by the formation and decay of dark matter bound states in the early Universe.

Evidence for such WIMPs may come from experiments at the Large Hadron Collider at CERN or from sensitive astronomical instruments detecting radiation produced by WIMP-WIMP annihilations in galaxy halos. For instance, **M. Chianese** in his presentation interpreted the slight excess of Ice-Cube neutrino events in the energy range 10-100 TeV as annihilating dark matter particles.

Direct detection experiments look for WIMP scatters off ordinary matter, producing a nuclear recoil that deposits energy in a sensitive detector. The background is the major problem for these experiments, since the expected signal rate is extremely low and only a fraction of the events can be discriminated on an event–by–event basis.

Background suppression relies on several techniques, some of them shared by all the experiments. For instance, all of them are located deep underground, to be shielded against cosmic rays, and are built with extremely low background materials. Generally, the sensitive target is surrounded by active shielding: water Cherenkov detectors and/or liquid scintillators loaded with isotopes with high neutron capture cross sections. Neutrons, in fact, are the most dangerous background since induce nuclear recoils that can perfectly mimic WIMP events.

Other background suppression techniques are more related to the specific active target and detection approach. There exist three main observables used by direct dark matter search experiments to detect WIMP events: charge (ionization), light (scintillation), phonon (heating). There is a net advantage in exploiting two of these observables at the same time, since the repartition of the energy in the different channels, strongly depends on the nature of the particle, and thus providing an efficient particle discrimination power.

M. Messina, in his talk, implicitly subdivided the direct dark matter search in three main branches: experiments dedicated to prove/disprove the DAMA/LIBRA signal; bolometers with an enhanced sensitivity at low WIMP masses (<10 GeV); noble liquid target (xenon and argon) more sensitive at larger masses (> 10 GeV). DAMA/LIBRA has observed at more than 9 σ, an annual modulation signal, compatible with the expectations from dark matter interactions. The dark matter interpretation of this signal, however, was rejected by several other experiments, which did not observed any compatible excess of events with respect to the background, and, very recently by Xenon100 directly looking for annual modulation. The final answer on this controversy will be given by future experiments using exactly the same target (NaI) and technique of DAMA. Among them, SABRE, (see the proceeding by **Davide D'Angelo**) is aimed to detect annual modulations with twin NaI detectors at LNGS in Italy and at SUPL in Australia. The two northern and southern hemisphere locations will verify if the DAMA signal is induced by other non dark matter seasonal effects.

At mK temperature, bolometric experiments are exploiting different strategies mostly dedicated to lower down the detection energy threshold to a fraction of keV. A so low energy threshold allows to gain in sensitivity at large WIMP masses and to access to very low masses (at the GeV and sub-GeV scale). CDMS and Edelweiss, which simultaneously detect photons and charge, are running with Germanium detectors. CRESST is using $CaWO_4$ and looks for phonons and photons. CDMS has produced a new results showing the possibility to reach $\sim$50 eV by exploiting the Neganov-Luke effect, which increases the phonon yield, but does not allow anymore to discriminate between electron and nuclear recoils. In the future, SuperCDMS will use Germanium and Silicium detectors in the two configurations, with/without the Neganov-Luke effect. CRESST has recently reached a threshold of $\sim$300 eV in the nuclear recoil energy scale. The goal is to reach a threshold of $\sim$100 eV_{nr} and to reduce the intrinsic background by a factor 100.

In the noble liquid sector, a number of experiments, such as XENON100, PandaX, and LUX, successfully profit from liquid xenon target masses, which guarantee an excellent radio-purity, high stopping power for penetrating radiation, and high ionization and scintillation yields. The mentioned experiments are currently leading in terms of sensitivity at WIMP masses >10 GeV. The limited use of liquid argon was justified by the important contamination of the cosmogenic ^{39}Ar, an issue recently solved by the DarkSide collaboration, as shown in the presentation by **B. Bottino**, using underground argon, naturally depleted in ^{39}Ar. This opened the way to the technology based on liquid argon, which provides the highest electron recoil rejection power, thanks to the scintillation pulse shape discrimination.

The next generation of noble liquid experiments is beginning and consists of tonne / multi–tonne scale detectors, like Xenon-1t, Xenon-nt, DarkSide-20k, and LZ. These generations will start to suffer by the presence of background due to solar, atmospheric, and Supernovae neutrino coherent scatterings off nucleus. This irreducible background can not be shielded and perfectly mimics WIMP signals. A possible solution was explained by **G. Fiorillo** and consists in exploiting the WIMP directional information. This may be inferred in liquid argon dual–phase TPC by looking at nuclear track direction with respect to the electric field orientation. Laboratory setups, like ReD and ARIS, will investigate this possibility in the future years.

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