ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2011. Т. 42. ВЫП. 4

DARK MATTER: THEORY

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The particle physics interpretation of the dark matter problem, which is intimately of cosmological and astrophysical nature, is going to be posed under deep scrutiny in the next years. From the particle physics side, accelerators like the LHC will deeply test theoretical ideas of new physics beyond the Standard Model, where particle candidates of dark matter are predicted to exist. From the astrophysical side, many probes are already providing a great deal of independent information on the foreseen signals which can be produced by the galactic or extragalactic dark matter. In all this, cosmology plays a central role in determining the relevance and the basic properties of the particle dark matter candidate. The ultimate hope is the emergence of dark matter signals and the rise of a coherent picture of new physics from and at the crossing of particle physics, astrophysics, and cosmology. A very ambitious and far-reaching project, which will bring to a deeper level our understanding of the fundamental laws which rule the Universe.

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INTRODUCTION

The presence of dark matter has been established on very different cosmological and astrophysical scales by a large number of experimental observations, most notably from the dynamics of galaxy clusters, from the flatness of the rotational curves of galaxies and from the observation of weak lensing phenomena, as well as by the theoretical understanding of structure formation. A significant amount of cold, collisionless and dissipationless dark matter is therefore needed in clustered systems: much more matter is present in these systems than luminous matter and sizably more than baryonic matter, as the comparison of the amount of dark matter in the Universe with the amount of baryons from primordial nucleosynthesis clearly shows.

Nonbaryonic cold dark matter is therefore needed, and this fact poses challenges not only to Cosmology and Astrophysics, but to Fundamental Physics as well, since no viable Dark Matter (DM) candidate is present in the Standard Model of particle physics. Extensions like supersymmetric theories or theories of extradimensions typically accomodate succesfull DM candidates, like neutralinos

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or sneutrinos in Supersymmetry (SUSY) or Kaluza–Klein (KK) excitations in theories of extradimensions. These particles may be present in our current Universe and act as DM if they have been produced during the early phases of the evolution of the Universe and then remain as relics from that early stage. They obviously need to be stable on cosmological time scales and to be produced in the early Universe in the right amount to form the whole amount of DM we see today in cosmic structures. Even though, these DM particles have very faint interaction with ordinary matter, hopefully they could have the chance to be revealed through some process: these sought-after signals are of astrophysical origin, since they are produced in galaxies or galaxy clusters, but they have a particle physics nature as well, since they must rely on the very particle physics properties of DM. At the same time, if DM is a new kind of elementary particle, a natural way to search for its existence and to determine its properties is at accelerators, which have the capabilities to directly discover new physics and to pinpoint the properties of new particles.

The studies to identify the nature of dark matter therefore stand at the intersection of three major fields of research: particle physics, cosmology and astrophysics. Fundamental particle physics has the responsibility to provide a suitable DM candidate. From the theoretical point of view, we need to identify and develop models of physics beyond the Standard Model, able to incorporate one (or more) suitable DM candidates. From the experimental side, accelerator searches are the main tools of investigation and discovery of new fundamental states of matter. Cosmology describes the environment where DM particles are formed in the early Universe and the evolution history of these DM particles along the structure formation history. The occurrence of the right amount of a particle DM candidate is a delicate balance between cosmological evolution, production mechanisms (thermal, nonthermal) and particle physics properties. The ability of a particle DM candidate to form the correct structures in the Universe depends both on the DM properties and on the gravitational evolution in the expanding Universe. Astrophysics describes the environment where the signals of the presence of DM (galaxies or galaxy clusters) are hopefully produced: the size and properties of these signals depend on the astrophysical context where they originate and the ability to observe them is limited by (typically overwhelming) backgrounds of astrophysical origin.

The «particle dark matter crossroad» is therefore a unique place where to put under deep scrutiny our ideas on the fundamental laws which rule the Universe. In these notes I will briefly report on the current status of some subjects which stands at this crossroad, starting from direct and indirect astrophysical signals of DM, and then moving to some brief comment of the connection between accelerator searches and cosmology. We will concentrate on the case of WIMP (Weakly Interacting Massive Particle) DM.

1. MULTICHANNEL SEARCH OF WIMP DARK MATTER

Galactic DM may be searched for in many ways: by looking at the recoil energy directly deposited in a low-background detector (direct detection) or by looking for annihilation products which are produced in the galactic environment (antimatter, gamma-rays, neutrinos) or in the Earth and Sun (neutrinos). Some of these annihilation products may further produce secondary signals: it is the case for electrons and positrons, which can produce secondary gamma-rays from inverse Compton scattering on radiation fields in the galaxy (CMB, infrared and starlight), or radio emission from synchrotron emission on galactic magnetic fields. An additional interesting effect on the CMB is represented by the possibility to distort the CMB spectrum again by means of Compton scattering on the electron/positron gas produced by DM annihilation in galaxy clusters. This version of the Sunyaev–Zeldovich effect is nevertheless small and very difficult to access [1, 2].

All these astrophysical signals depend on the way the nonrelativistic DM particles are distributed in the galactic (or extragalactic) environment. Moreover, charged signal (positrons, antiprotons, antideuterons) and those secondary effects due to these antimatter signals, are affected by their propagation in the galactic environment. Large uncertainties in the theoretical prediction arise from the modelling of the DM distribution and galactic propagation. Some examples will be given in the next subsections.

2. DIRECT SEARCHES

Direct detection of DM relies on the ability to detect the recoil of a nucleus induced by the elastic (or even inelastic) scattering of a DM particle. The expected recoil spectrum is an almost exponential function of the nuclear recoil energy and the main source of background arises from neutron interactions. The motion of the Earth with respect to the galactic system induces typical signatures in the recoil, with peculiar features which are not expected to be shared by the neutron background. The motion of the local group inside the Galaxy would induce a backward/forward asymmetry in the direction of the recoils (directionality), the motion of the Earth around the Sun induces an annual modulation of the rate, of the order of a few percent and energy-dependent, while the rotation of the Earth around its axis would induce an even smaller diurnal effect.

Currently annual modulation is studied by the DAMA Collaboration. A clear evidence for an annual dependence of the rate is observed along 13 annual cycles, with a cumulative exposure of 427050 kg · day [9]. Modulation is observed only on single-hit events in the signal energy-window, while multiple-hit events and detector stability parameters do not modulate. The evidence has

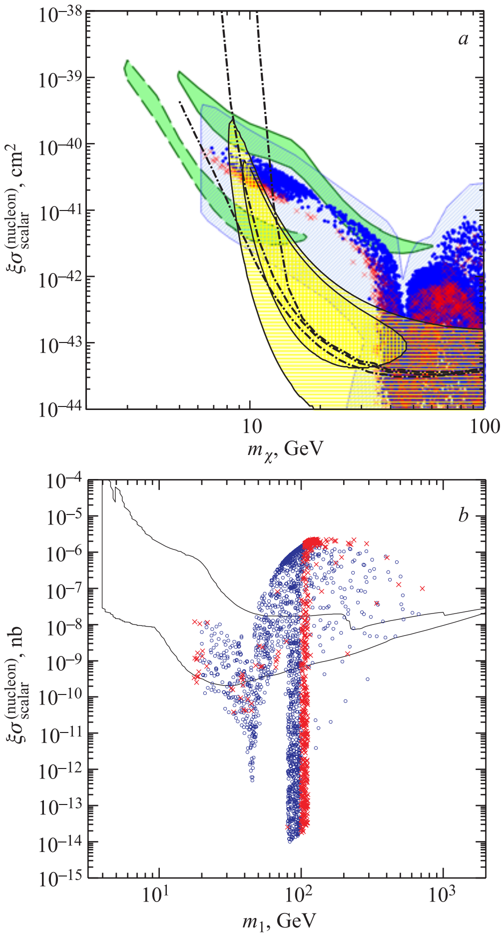

Fig. 1.

a 8.9σ CL and the modulation amplitude in the 2–6 keV energy window is $S_m = (0.0116 \pm 0.0013)$ cpd/kg/keV, the modulation phase is (146 ± 7) days (compatible with 152 days, the expected phase for an isotropic halo — notice that this value can change if the halo is not isotropic [9, 10]) and the period of modulation is (0.999 ± 0.002) y. When interpreted as due to DM, the DAMA annual modulation effect defines compatibility regions in the plane DM mass vs. DM-nucleon scattering cross section, as shown in Fig. 1*. On the panel *a*

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*The colored version of the figures is available only at http://www.jinr.ru/published/.

is shown the DM-nucleon scattering cross section $\xi\sigma_{\rm scalar}^{\rm (nucleon)}$ as a function of the WIMP mass. The [green] shaded regions denote the DAMA/LIBRA [3] annual modulation regions, under the hypothesis that the effect is due to a WIMP with a coherent interaction with nuclei; the region delimitated by the solid line refers to the case where the channeling effect is not included; the one with a dashed contour, to the case where the channeling effect is included [4]. The [violet] band displays the region related to the two CDMS candidate events [5], obtained under the hypothesis of a backgound contribution as in [6], normalized to 0.8 events in the whole energy window of CDMS II. The contours refer to 68 and 85% CL. The dash-dotted lines show the bounds from XENON100 [7] under three different choices of the scintillation efficiency. The scatter plot represents supersymmetric configurations calculated in a Minimal Supersymmetric Standard Model (MSSM) where gaugino universality is not assumed. The [red] crosses denote configurations with a neutralino relic abundance which matches the WMAP cold dark matter amount ($0.098 \leqslant \Omega_\chi h^2 \leqslant 0.122$), while the [blue] dots refer to configurations where the neutralino is subdominant ($\Omega_\chi h^2 < 0.098$). The region covered by a [blue] slant hatching denotes the extension of the scatter plot upwards and downwards, the hadronic uncertainties in the scattering coherent cross section are included. On the panel b is shown sneutrino–nucleon scattering cross section $\xi\sigma_{\rm nucleon}^{\rm (scalar)}$ as a function of the sneutrino mass m_1 for a full scan of the supersymmetric parameter space [8]. [Red] crosses refer to models with sneutrino relic abundance in the cosmologically relevant range; [blue] open circles refer to cosmologically subdominant sneutrinos. The solid curve shows the DAMA/NaI region, compatible with the annual modulation effect observed by the experiment [9]. In the same figure, the DAMA regions are confronted with theoretical predictions in models where light neutralinos arise as a consequence of gaugino non-universality [4]. The DAMA regions shown in Fig. 1 refer to a specific galactic halo model. In the case of different halo models, the regions are accordingly modified [9]. The right panel of the same figure shows the comparison of the DAMA region with sneutrino DM.

Currently, all other direct DM detectors are not directly testing the presence of annual modulation in their recoil rate. Instead, they rely on sophisticated techniques of background rejection and/or interpretation. Recently the CDMS Collaboration reported the results of their final exposure (612 kg · day) with 2 events which pass all cuts (for an expected background of 0.8 events) [11]. The statistics is definitely extremely small and the CDMS data should cautiously be used to set bounds, but it is interesting to notice that these two events would be compatible with the DAMA result for low-mass DM, as shown in Fig. 1. Just after CDMS presented their final exposure result, CoGeNT (exposure of 18.48 kg · day) reported an irreducible excess of bulk-like events at very low recoil energies, which also are compatible with DAMA in the 10 GeV DM mass range [12]. Also CRESST (exposure of 333 kg · day) has recently reported an excess of events over the expected background [13]. Since these events refer to interaction with oxygen, they would be compatible with DAMA and CoGeNT for the same DM masses and similar scattering cross sections. Even though these results from CDMS, CoGeNT, and CRESST, with a low statistic, cannot be currently considered as possible evidences, it is nevertheless interesting that with the current sensitivities direct detection detectors start showing some excesses, which appear to be compatible among themselves and with the long-standing and much more strong DAMA effect, in the case of WIMP DM in the 10 GeV range.

This year also XENON100 reported its first results (exposure of 170 kg · day) [7]: in this case no event passed all cuts. The 90% CL bound posed by XENON100 is also shown in Fig. 1. The actual bound from the XENON detector is currently limited by the knowledge of the scintillation efficiency at low energies (L_{eff}), a quantity for which there are currently different determination with a large spread among them [7]. Figure 1 shows the impact of this large uncertainty for the interesting low DM mass range. A precise determination of L_{eff} at low recoil energies for the xenon experiments will then be very relevant in assessing the bound (or the compatibility region, in case of detection of a signal) from this type of detectors [14].

Directional detectors are currently under study, while diurnal modulation may be accessible to the DAMA setup, if the mass of the detector is increased in the ton range.

3. NEUTRINOS AS DARK MATTER MESSENGERS

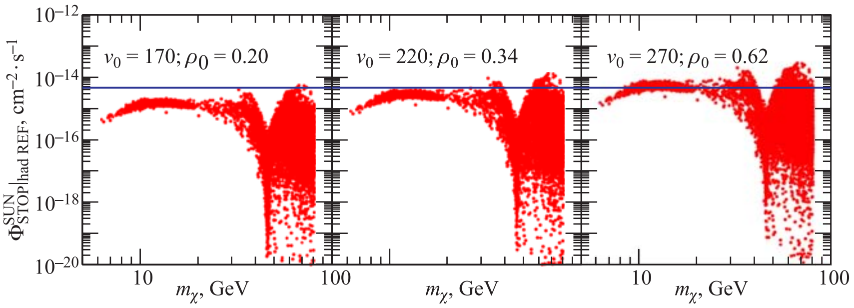

Fig. 2. Stopping-muons flux, generated by light neutralino pair-annihilation inside the Sun [17]. The three panels show the dependence of the muon flux on the local rotational velocity v_0 (in units of km · s^{-1}) and the local density ρ_0 (in units of GeV · cm^{-3}) of the dark matter halo. The horizontal line represents the experimental limit on through-going muons from the Earth obtained using the SK data [18]

DM captured and accumulated inside bodies like the Earth and the Sun may annihilate and produce a neutrino flux which can escape the body. Spectral and angular features may be exploited to desentangle the signal from the atmospheric neutrino background [15, 16]. Neutrino oscillation, and transport in the Sun, have been shown to be relevant effects, which cannot be neglected [15, 16]. The typical signal relies in the search for a muon neutrino flux, which induces upgoing muons in the neutrino telescope. An explicit example of a signal coming from the Sun, and relevant for the same light DM neutralinos discussed in the previous section, is shown in Fig. 2, where predictions for stopping muons in the SK detector are shown for different DM halo properties [17].

4. ANTIPROTONS

Annihilation in the galactic environment may produce antimatter, thus adding an exotic contribution to cosmic rays. The antiproton signal at low energies has a mild feature and when compared to the background the capability to clearly disentagle a signal from the background is hard, expecially when considering that astrophysical uncertainties will still be a major component in the theoretical determination of the signal [19]. This can be seen in Fig. 3, where predictions for the differential flux both for the secondary production (the background) and for the signal for some representative DM masses is shown. On the panel a, are shown the primary Top-Of-Atmosphere (TOA) antiproton fluxes as a function of the antiproton kinetic energy, for some representative spectra from neutralino annihilation [19]: the solid, long-dashed, short-dashed, dotted lines refer to $m_\chi = 60$, 100, 300, 500 GeV, respectively. The astrophysical parameters correspond to the median choice. Solar modulation is for minimal solar activity. The upper dash-dotted curve corresponds to the antiproton secondary flux [20, 21]. Full circles, open squares, stars, and empty circles show the data from BESS 1995–1997 [22], BESS 1998 [23], AMS [24] and CAPRICE [25]. On panel b is shown antiproton flux at $T_{\bar{p}} = 0.23$ GeV vs. the neutralino mass, at solar minimum and for the best fit set for the astrophysical parameters [26]. A spherical isothermal DM density profile has been used. The scatter plots are derived by a full scan of the parameter space of non-universal gaugino models which predict low-mass neutralinos [27–29]. Crosses [red] and dots [blue] denote neutralino configurations with $0.095 \leqslant \Omega_\chi h^2 \leqslant 0.131$ and $\Omega_\chi h^2 < 0.095$, respectively. The shaded region denotes the amount of primary antiprotons which can be accommodated at $T_{\bar{p}} = 0.23$ GeV without entering in conflict with the experimental BESS data [22, 23] and secondary antiproton calculations [30]. The scatter plot has an astrophysical uncertainty which can shift it either up or down by one order of magnitude. For heavy DM, the spectral feature could allow discrimination against the background, but this requires pretty strong boost factors, which appear

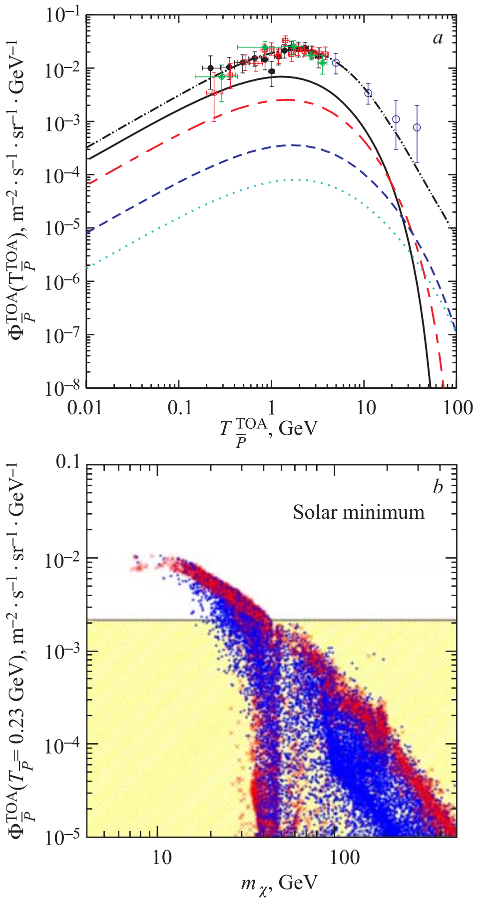

Fig. 3.

to be disfavoured by recent studies [31]. Special annihilation mechanism, like the Sommerfeld enhancement [32], could prevent the necessity of large astrophysical boost factors.

Current data from PAMELA on the $\bar{p}/p$ ratio show no deviation from expectations on the secondary component: this implies that antiprotons may be used to set relevant constraints on the presence of DM and on its properties, once theoretical uncertainties are properly taken into account [19, 26, 33]. Figure 3 shows a scan of the SUSY parameter space of a low-energy realization of the Minimal Supersymmetric Standard Model (MSSM), where neutralino is the DM candidate [19, 26]. Theoretical uncertainties of astrophysical origin are sizeable [19]. For example, in panel b of Fig. 3 the scatter plot can be shifted upward or downward by about a factor of 6–10 [19], due to uncertainties in galactic propagation.

5. ANTIDEUTERONS

Antideuterons as a DM indirect signal have been proposed in [34]. Recently, a reanalysis has been developed, where also theoretical uncertainties have been quantified [35]. Some results are reported in Fig. 4. On the panel a are shown Top-Of-Atmosphere (TOA) primary (solid lines) and secondary (dashed line) antideuteron fluxes, modulated at solar minimum, for a Weakly Interacting Massive Particle (WIMP) with $m_\chi = 50$ GeV and for the three propagation models which

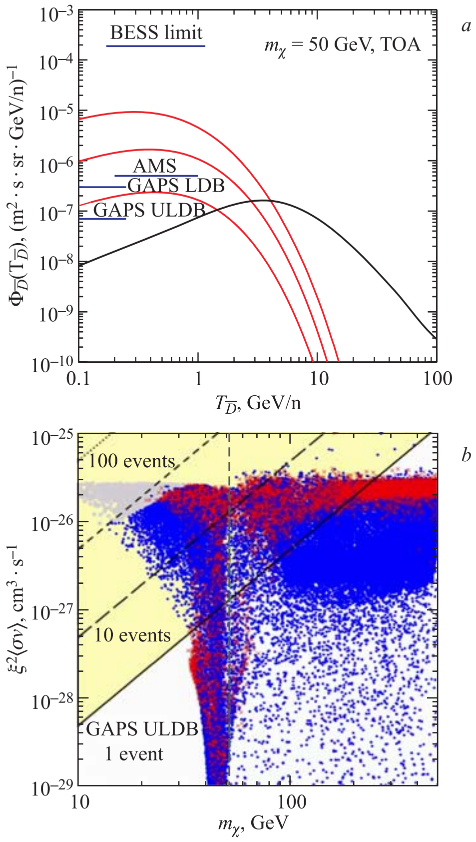

Fig. 4.

encompass astrophysical uncertainties [35]. The secondary flux is shown for the median propagation model. The upper dashed horizontal line shows the current BESS upper limit on the search for cosmic antideuterons [36]. The three horizontal solid [blue] lines are the estimated sensitivities for (from top to bottom): AMS-02 [37], GAPS on a long (LDB) and ultralong (ULDB) duration balloon flights [38–40]. Panel b: GAPS ULDB reach compared to predictions for neutralino DM in low-energy supersymmetric models, shown in the plane effective annihilation cross section $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ vs. neutralino mass m_χ [35]. The solid, long-dashed, and short-dashed lines show the estimate of the capability of GAPS ULDB of measuring 1, 10, and 100 events, respectively, for the median propagation model. The scatter plot reports the quantity $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ calculated in a low-energy MSSM (for masses above the vertical [green] dashed line) and in nonuniversal gaugino models which predict low-mass neutralinos [27–29]. [Red] Crosses refer to cosmologically dominant neutralinos, while [blue] dots stand for subdominant neutralinos. Grey points are excluded by antiproton searches. In Fig. 4 it is shown that the low-energy spectrum offers a unique opportunity to desentangle a signal from the background, since at kinetic energies below 1–3 GeV the production of secondary antideuterons (the background) suffers from a kinematical suppression. Therefore low kinetic energies are the place where experimental efforts should concentrate. Antideuterons appear to offer the best possibility to detect a signal, even in the absence of a boost factor. Foreseen experiment (GAPS, AMS) will have a unique chance to probe this signature directly in the next decade [35]. An example of the capability to probe the SUSY parameter space with a future experimental mission (GAPS) is shown in the rigth panel of the same figure. Neutralino consifurations with masses up to a few hundreds of GeV may be probed, and signals as large as 100 events are possible.

6. POSITRONS AND ELECTRONS

Positrons offer a very interesting possibility and have recently gained a lot of attention as a consequence of the release of the PAMELA data on the positron fraction [45] first and then of FERMI [55], ATIC [54], and HESS [56] on the sum of electrons and positrons.

Similarly to the case of the other indirect detection signal, astrophysical uncertainties largely affect also the positron flux [41], as well as the background flux of secondary origin [42], and they have to be taken into consideration when comparison with data is attempted. When theoretical and experimental uncertainties are considered [42], theoretical determinations agree with available data on the single positron flux [42], which is available up to a few tens of GeV. At higher energies, both the positron fraction (shown by PAMELA up to 100 GeV) and the total lepton flux (shown by FERMI, ATIC, and HESS up to a few TeV) clearly show an excess over the pure secondary background [51,59]. The lepton fluxes at high energies clearly indicate the presence of local sources of electrons/positrons, which show up in the fluxes above a few tens of GeV. A natural explanation of this effect comes from astrophysical sources (pulsars, supernova remnants) which have been shown to be able to reproduce the experimental data in a natural way [51, 59, 60]. Figure 5 shows the agreement between pure astrophysical contributions (secondary leptons and sources) with the FERMI and HESS data. Other astrophysical mechanisms able to explain the rise of the positron flux at high energies have also been discussed [61]. On the panel a of Fig. 5 is presented the positron fraction $e^+/(e^- + e^+)$ versus the energy E for a DM particle with a mass of 100 GeV and for a Navarro–Frenk–White (NFW) profile [41]. The four cases refer to different annihilation final states: direct e^+e^- production (top left), $b\bar{b}$ (top right), W^+W^- (bottom left) and $\tau^+\tau^-$ (bottom right). In each panel, the

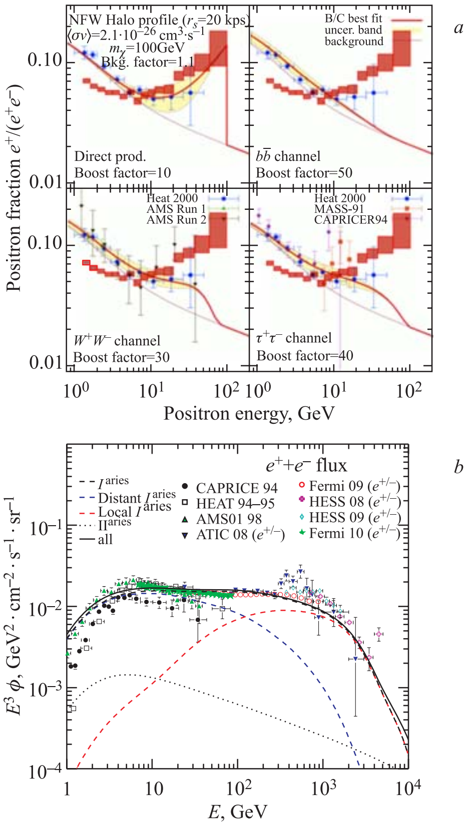

Fig. 5.

thick solid [red] curve refers to the best-fit choice of the astrophysical parameters. The colored [yellow] area features the total uncertainty band arising from positron propagation. In each panel, the thin [brown] solid line stands for the background of [43, 44]. The [red] boxes denote the PAMELA data [45]. Experimental data from HEAT [46], AMS01 [47,48], CAPRICE [49], and MASS [50] are also plotted. On plot b is shown the electron + positron flux vs. the energy E. The solid line shows a template flux of pure astrophysical origin, while the various dashed and dotted curves break up the total flux into contributions from local and distant astrophysical sources (pulsars supernova remnants and secondaries) [51]. Data are taken from CAPRICE [49], HEAT [52], AMS [53], ATIC [54], FERMI [55], and HESS [56].

A contribution to the positron (and electron) fluxes may also be originated by DM annihilation. The positron flux from DM annihilation may possess spectral features, depending on the final state of the particle DM annihilation [41]. Figure 5 shows the case of a DM particle of 100 GeV mass which annihilates dominantly in pure final states. Hard spectra, like the annihilation into e^+e^- or into gauge bosons or also to $\tau^+\tau^-$ are potentially able to reproduce the PAMELA result [41, 62], while instead hadronic final states produce softer spectra. Typically, however, the positron signal requires sizable boost factors in order to prevail over the background: this implies that if also hadrons are produced, strong bounds come from antiproton searches [62,63]. Analyses of the PAMELA data, in combination with other types of indirect searches, show that large boost factors are needed and the DM needs to produce mostly leptons (and not hadrons) unless it is very heavy, with masses above a few TeV [62].

From the point of view of particle physics, a WIMP DM which annihilates rather dominantly into leptons is typically difficult to realize: the most natural candidates, like neutralinos or sneutrinos, do not produce sizeable amounts of leptons, and it is therefore necessary to resort to different types of candidates. A great deal of theoretical activity has been devoted to the identification of suitable DM candidates to explain the leptonic «anomaly».

Another difficulty with the DM interpretation of the PAMELA and FERMI data stands in the necessity of large boost factors: the signal has to be largely boosted over the standard production: this may be realized by DM overdensities (which are very unlikely and basically excluded [31]), by peculiar effects in the low-velocity annihilation cross section (Sommerfeld enhancement) [32]) or by a nonstandard cosmology at the time of DM production in the early Universe [57]. The whole host of indirect detection signals may be used to set bounds on these possibilities. This may be rephrased into bounds on the annihilation cross section of the DM particle: if the boost factor is due to the Sommerfeld enhancement or to an enhanced annihilation cross section due to alternative cosmologies, the bounds are directly on the cross section; if the boost is due to DM overdensities, the bound is actually on the product of the an-

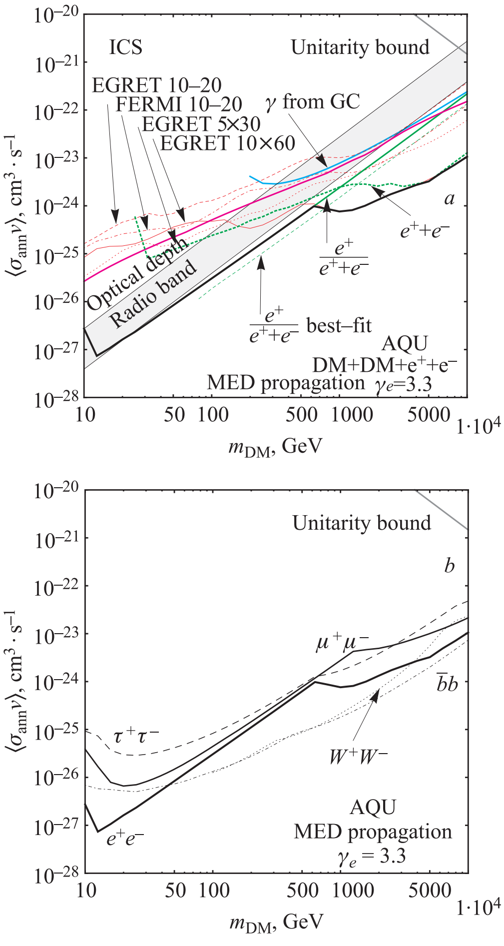

Fig. 6.

nihilation cross section times the astrophysical boost factor. Figure 6 shows one of these analyses [57], where a whole set of different bounds are applied. On the panel a are presented upper limits on the DM annihilation cross section (versus the DM mass) coming from different astrophysical observations, for the Aquarius DM distribution and for DM annihilations into e^+e^- [57]. The MED propagation model for cosmic rays has been used. The region above the thick black line is excluded by the convolution of all the implemented constraints. The shaded band labelled as «radio band» denotes the uncertainty on the radio constraint. The dashed line labelled as «$e^+/(e^+ + e^-)$ best fit» denotes the values of the DM annihilation cross section required to explain the

PAMELA data on the positron fraction. The unitarity bound assuming s-wave annihilations [58] is also shown. On the plane b is presented the summary of the astrophysical bounds on the DM annihilation cross section vs. the DM mass, for the Aquarius DM distribution and for different DM annihilation channels: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^-, and $\bar{b}b$. Cosmic rays are propagated in the MED model.

7. GAMMA RAYS

Gamma rays are another important tool for studying DM annihilation in the Galaxy and to probe regions of the galactic environment which are partly different from those explored by charged cosmic rays. Spectral features of the gamma-ray signal are not typically very strong, except for the case of direct annihilation into a gamma line, which instead would be a striking signature of DM annihilation. The gamma line is typically strongly suppressed for suitable DM candidates, and therefore very hard to be probed. The gamma-ray signal typically requires (sizable) boost factors in order to be observable on the top of the astrophysical gamma rays. FERMI will be in the next years a unique laboratory to study gamma rays and it will provide valuable insight also on the DM problem [64]. Currently, FERMI is providing an interesting bound on the extragalactic (or high-latitude) gamma-rays flux [65], which starts to set interesting bounds on the amount of gamma rays produced by DM annihilation [66].

8. ACCELERATOR PHYSICS AND COSMOLOGY

Dark matter candidates are potentially present in almost any extension of the Standard Model of particle physics. In supersymmetric theories with R-parity conservation, both neutralinos and sneutrinos are successful cold dark matter candidates, although other possibilities are present, like, e.g., gravitinos. In the next years LHC, and hopefully in the future the ILC, will probe these new physics models and a quite intriguing interconnection between high-energy physics studies, astophysics and cosmology will be posed under deep scrutiny. An example of this interplay is depicted in Fig. 7, where a section of the minimal SUGRA parameter space is shown, together with the expected reach of the LHC. A fraction of this parameter space is already excluded by LEP, Tevatron and studies of rare processes. In the allowed region, Fig. 7 shows the sector which is compatible with a relic neutralino able to explain the dark matter content of the Universe, a sector which is just a small fraction of the relevant parameter space. The same figure also shows the effect induced by the thermal history of the Universe: alternative cosmologies, different from the FRW cosmology, imply a modified decoupling epoch and an ensuing different relic abundance:

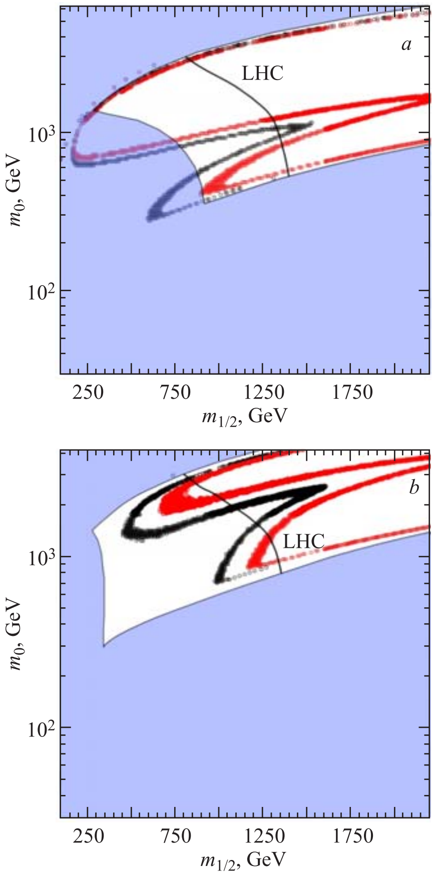

Fig. 7. Minimal SUGRA parameter space m_0 (universal soft scalar mass) vs. $m_{1/2}$ (gaugino mass) for $\tan\beta = 45$ (a) and $\tan\beta = 53$ (b) and common trilinear coupling $A_0 = 0$. The shaded areas are excluded by bounds on supersymmetry searches and supersymmetry contribution to rare processes. The dark [black] circles show the region of parameter space where the neutralino relic abundance matches the WMAP range for cold dark matter in standard cosmology. The light [red] points refer to the same situation in a scalar-tensor cosmology. From [67]. The solid line denotes the expected reach of LHC

therefore, the cosmologically relevant regions in parameter space are shifted. The example shown in Fig. 7 refers to scalar–tensor cosmologies. Reconstruction of the particle physics properties of dark matter and the underlying particle physics model represent a window also on the early Universe physical properties [57, 67, 68].

CONCLUSIONS

In these notes, we have briefly discussed the study of particle dark matter, which stands at the intersection of the fields of particle physics, cosmology and astrophysics. Rich theoretical and experimental activities are currently undertaken, with the ultimate goal to discover the nature of dark matter and the new physics which underlies it.

We have seen that astrophysical DM searches may be proficiently used to set constraints on the properties of particle DM, as long as a signal is not observed. If a signal is detected, this may guide us toward the identification of some of the properties of the DM candidate (and to some extent of the underlying new physics model): the most direct information will likely be on the mass of the DM particle and on the size of its interactions. A fine structure of the DM particle properties will be difficult, and to this aim more than one type of astrophysical signals (if accessible) would likely be necessary.

Different detection signals probe different properties of the DM particle and feel different features of the galactic environment. To identify a DM signal it is therefore of greatest importance to exploit specific and typical signatures of the various types of signals, like annual modulation or directionality in direct detection, or the low-energy signal-to-background behavior of antideuterons in cosmic rays. In any case, a better knowledge of the astrophysical environment and of the astrophysical backgrounds will be very important.

Cosmological properties and astrophysical signals of particle DM candidates can either guide or complement accelerator physics searches. LHC has recently started its operations and will be fully operational in the next years. A great wealth of data will then be available and in case of detection of a signal from new physics, a first indication on the nature of the underlying model may hopefully arise. These results will necessarily have to be analyzed also in the context of the presence of a suitable DM candidate. Accelerators, with their unique capability of identifying (at least part of the) new physics particles and their properties, will allow one to shape out the predictions also for DM signals. The two approaches are therefore both fundamental and complementary in the study of the DM hypothesis: only accelerators can prove the existence of new physics beyond the Standard Model and directly discover the new physical states, but only astrophysical DM searches can prove that the new physical states explain the DM puzzle and explicitly identify the DM presence in the astrophysical environment. The interplay between the two approaches may even be able in the future to tell us something on the cosmological evolution of the early Universe. The «particle dark matter crossroad» is therefore an interesting place to visit in the next years.

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