

PAPER • OPEN ACCESS

Editorial DISCRETE proceedings

To cite this article: 2020 *J. Phys.: Conf. Ser.* **1586** 011001

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Editorial DISCRETE proceedings

Eberhard Widmann

Stefan-Meyer-Institute for Subatomic Physics (SMI), Austrian Academy of Science,
Boltzmannngasse 27, 1090, Vienna, Austria

E-mail: e.widmann@oeaw.ac.at

This volume contains the proceedings of the 6th Symposium on Prospects in the Physics of Discrete Symmetries, DISCRETE 2018. The symposium was held in Vienna from 26th to the 30th of November 2018, organized by the Stefan Meyer Institute for subatomic Physics of the Austrian Academy of Sciences. The topics of the DISCRETE conference series evolved from the previous meetings in Valencia (2008), Rome (2010), Lisbon (2012), London (2014) and Warsaw (2016), and covered in 2018

- [1] T, C, P, CP and CPT symmetries (conveners: E. Widmann (Vienna), J. Marton (Vienna))
- [2] Emergence of symmetries from entanglement (conveners: B. Hiesmayr (Vienna), A. Di Domenico (Roma))
- [3] Discrete symmetries in cosmology (dark matter, baryogenesis, leptogenesis etc.) (conveners: A. Rebhan (Vienna), J. Pradler (Vienna))
- [4] Neutrino masses, mixing and discrete symmetries (conveners: C. Giunti (Torino), M. Hirsch (Valencia))
- [5] Discrete symmetries and models of flavour mixing (conveners: Ch. Schwanda (Vienna), M.N. Rebelo (Lisbon))
- [6] Supersymmetry (convener: K. Sakurai (Warsaw))
- [7] Strings, branes, extra dimensions and discrete symmetries (conveners: A. Faraggi (Liverpool))
- [8] New results from LHC, new facilities (conveners: J.M. Lorenz (München), N. Saoulidou (Athens))
- [9] PT symmetric Hamiltonians (convener: C.M. Bender (St. Louis))
- [10] Multimessenger probes of the universe (conveners: A. Sakharov (New York), A. Pollmann (Wuppertal))

In comparison to previous years, topic [10] was added, and topic [3] was covered in a joint one-day session with the 14th Vienna Central European Seminar (VCES), an independent meeting on global and local symmetries organized by University of Vienna, TU Wien, the Institute for High energy Physics of the Austrian Academy of Sciences, the FWF doctoral school on Particle



and Interactions, and the EU COST Network Connecting insights in fundamental physics. The two conferences also shared a public evening talk by Malcom J. Perry (Cambridge) on “Black holes, fundamental physics, and the information paradox” which took place in the festive hall of the Austrian Academy of Sciences.

DISCRETE 2018 attracted 150 scientists from a variety of fields and countries, delivering 57 invited and 56 contributed talks. These talks were selected by the convenors together with the International Advisory Committee

Luis Alvarez-Gaume (Stony Brook CERN), José Bernabéu (Valencia), Gustavo Branco (Lisbon), Andrzej Buras (Munich), Antonio Di Domenico (Rome), Jonathon Ellis (King’s College London CERN), Domenec Espriu (Barcelona), David Hitlin (Caltech), Cecilia Jarlskog (Lund), Antonio Masiero (Padua), Nikolaos Mavromatos (King’s College London), Vasiliki Mitsou (Valencia), Hitoshi Murayama (Berkeley Tokyo DESY), Keith Olive (Minnesota), Antonio Pich (Valencia), Apostolos Pilaftsis (Manchester), Mariano Quirós (Barcelona), Fabio Zwirner (Padua), Francisco del Aguila (Granada), Werner Porod (Würzburg), Lola Magda (Patras), Adrian Bevan (Queen Mary University London),

and the DISCRETE Symposia Steering Committee

José Bernabéu (IFIC Valencia) [Chair]
G. Branco (IST Lisbon)
A. Di Domenico (Roma Sapienza)
G. Isidori (Zurich)
J. Kalinowski (Warsaw)
N.E. Mavromatos (King’s College London)
V.A. Mitsou (IFIC Valencia)
M.N. Rebelo (IST Lisbon)

The organisers wish to thank the convenors, speakers and participants of DISCRETE 2018 for providing an intellectually challenging and stimulating atmosphere through presentations and discussions during this meeting. We thank the convenors for acting as editors and reviewing the submitted manuscripts, special thanks go to Andreas Pichler for organizing the conference program and Dan Murtagh for coordinating the proceedings.

The next meeting in the DISCRETE series will be held in November 2020, organized jointly by the Department of Physics of the University of Bergen and Western Norway University in Bergen.

The local organising committee

Eberhard Widmann, Johann Marton, Andreas Pichler, Martin Simon, Daniel Murtagh

PAPER • OPEN ACCESS

Ultra High Energy Cosmic Rays and the Highest Energies Universe

To cite this article: R Aloisio 2020 *J. Phys.: Conf. Ser.* **1586** 012040

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection—download the first chapter of every title for free.

Ultra High Energy Cosmic Rays and the Highest Energies Universe

R Aloisio

Gran Sasso Science Institute, L'Aquila, Italy.

INFN - Laboratori Nazionali Gran Sasso, Assergi (AQ), Italy.

E-mail: roberto.aloisio@gssi.it

Abstract. We will discuss the main relevant aspects of the physics of ultra high energy cosmic rays. After a short recap of the experimental evidences, we will review theoretical models aiming at describing the sources of these extremely energetic particles opening a window on the highest energies universe. We will discuss the production of secondary particles and the possible tests of new physics that ultra high energy cosmic rays could provide. The present proceedings paper is mainly based on review papers written by the author in the last two years.

1. Introduction

The study of the highest energies universe is inextricably tied to Ultra High Energy Cosmic Rays (UHECR) the highest energy particles ever observed with energies ranging from 10^{17} eV up to energies in excess 10^{20} eV. The observation of UHECR brings informations about the most energetic events in the universe and it could unveil new physical phenomena at energetic regimes not accessible otherwise.

The most advanced experiments to detect UHECR are, nowadays, the Pierre Auger Observatory in Argentina [1] and the Telescope Array (TA) experiment in the US [2], covering roughly 1/10 of the Auger area. The observation of UHECR is performed through their interaction with the Earth atmosphere, that produces an Extensive Air Shower (EAS) of particles in the atmosphere with a correlated fluorescence emission due to the excitation/de-excitation of nitrogen molecules in the atmosphere during the EAS development (see [3] and references therein).

Both Auger and TA are based on the hybrid concept, they combine the observation of the EAS particles that reach the ground and the observation of the fluorescence emission produced by the EAS in the atmosphere. This is obtained combining an array of surface detectors (SD) to sample EAS particles when they reach the ground and telescopes, overlooking the surface array, to collect the fluorescence light (fluorescence detectors, FD). The possibility of performing a combined measurement of SD and FD was one the most important breakthrough in the field of UHECR, this combination enables a better determination of the energy scale through the FD and the collection of high statistics through the SD.

The experimental study of UHECR clarified few important facts: (i) UHECR are charged particles, with a limit on photon and neutrino fluxes at 10^{19} eV at the level of few percent and well below respectively [4, 5, 6], (ii) the spectrum observed at the Earth shows a slight flattening



at energies around 5×10^{18} eV (called the ankle) with (iii) a steep suppression at the highest energies [7, 8].

The mass composition of UHECR is still not completely determined with experimental evidences showing a certain level of discrepancy. Before Auger published its results, experimental evidences were all pointing toward a prevalently light composition (proton dominated) with acceleration models characterised by steep injection spectra and high maximum acceleration energies (up to energies larger than 10^{20} eV) [3, 9, 10].

The observations of Auger, far the largest experiment set-up devoted to the detection of UHECR, have shown that the UHECR mass composition is dominated by protons only at energies around and below 10^{18} eV becoming progressively heavier starting from 5×10^{18} eV, with the highest energies dominated by nuclei [11]. On the other hand, the TA experiment, even if with 1/10 of the Auger statistics, collected data that seem to confirm the pre-Augger scenario [12], the mass composition is compatible with being light for energies above 10^{18} eV, with no apparent transition to a heavier mass composition. Nevertheless, a joint working group made of members of both collaborations, TA and Auger, has recently concluded that the results of the two experiments are not in conflict once systematic and statistical uncertainties have been taken into account [13]. This conclusion, though encouraging on one hand, casts serious doubts on the possibility of reliably measuring the mass composition at the highest energies, unless some substantially new piece of information becomes available.

It should be also noted that the spectra measured by the two experiments, though being in general agreement, differ beyond the systematic error at the highest energies (where mass composition differs the most) in such a way that TA claims a spectral suppression at energy $\geq 5 \times 10^{19}$ eV while Auger shows the suppression at sensibly lower energies [14].

In order to interpret the observations at the Earth, it is important a detailed modelling of UHECR propagation in the intergalactic medium, which is mainly conditioned by the interaction with astrophysical photon backgrounds. These interactions shape the spectrum observed at the Earth and are also responsible for the production of secondary (cosmogenic) particles: photons and neutrinos. This secondary radiation can be observed through ground-based or satellite experiments and brings important informations about the mass composition of UHECR and, possibly, on their sources.

Sources of UHECR are still a mystery, we do not know which kind of astrophysical object is responsible for the production of these particles. There are basically two different classes of astrophysical mechanisms that could be invoked to accelerate UHECR [3, 9]. The first class is based on the transfer of energy from a macroscopic object (that can move relativistically or not) through repeated interactions of particles with magnetic inhomogeneities; belongs to this class the diffusive shock acceleration mechanism. The second class is based on the interaction with electric fields that, through high voltage drops, can accelerate particles (at once) until the highest energies; belongs to this class the unipolar induction mechanism in fast spinning neutron stars. At the highest energies $E > 5 \times 10^{19}$ eV, the production of UHECR could also be connected with new physics not testable in Earth's laboratories. This is the case of the so-called top-down models in which UHECR are directly produced at high energy, as decay products of super-heavy relic particles (with mass $M_X \simeq 10^{12} \div 10^{14}$ GeV) predicted in a wide class of inflationary scenarios. These models connect the observations of UHECR with the Dark Matter (DM) problem and cosmological observations [15].

The paper is organised as follows. In section 2 we will discuss the main features of the acceleration models, compatible with observations, and their implications in terms of possible astrophysical sources. In section 3 we will discuss the production of secondary (cosmogenic) particles during the propagation of UHECR, mainly focusing on secondary neutrinos. In section 4 we will discuss the impact on the physics of UHECR of exotic models aimed at solving the DM problem. We will conclude in section 5.

2. Theoretical models and possible sources

To constrain the basic features of the sources of UHECR it is useful to adopt a purely phenomenological approach in which sources are homogeneously and isotropically distributed, characterised by few parameters: the injection of particles by the sources with a power law behaviour in energy $\propto E^{-\gamma_g}$, the maximum acceleration energy E_{max} and the source emissivity $\mathcal{L}_S(A)$, i.e. number of particles injected per unit volume and energy for each nuclei species labeled by the atomic mass number A . These parameters, that univocally identify a class of sources, are fitted to experimental data both spectrum and mass composition (see [3, 9] and references therein).

Following [16, 17], taking into account all possible channels of energy losses and solving the transport equations for UHECR (protons or nuclei) we can determine the theoretical flux and mass composition expected at the Earth, to be compared with observations. While the flux directly follows solving the transport equations, mass composition is inferred from the mean value of the depth of shower maximum (elongation rate) $\langle X_{max} \rangle$ and its dispersion $\sigma(X_{max})$, computed as shown in [18]. The combined analysis of $\langle X_{max} \rangle$ and $\sigma(X_{max})$, even if not conclusive allows to obtain less model dependent information on the mass composition [19, 20]. A relevant source of uncertainties comes from the dependence of the depth of shower maximum and its fluctuations on the hadronic interaction model used to describe the shower development in the atmosphere. Most of such models fit low energy accelerator data while providing somewhat different results when extrapolated to the energies of relevance for UHECR (see [3, 9] and references therein).

As discussed in the Introduction, the results of Auger showed a mass composition progressively dominated by heavy nuclei. The qualitative new finding that mass composition might be mixed has served as a stimulus to build models that can potentially explain the phenomenology of Auger data. These models all show that the Auger spectrum and mass composition at $E \geq 5 \times 10^{18}$ eV can be fitted at the same time only at the price of requiring very hard injection spectra for all nuclei and a maximum acceleration energy $E_{max} \leq 5Z \times 10^{18}$ eV [16, 21], being Z the charge of the nucleus. The need for hard spectra can be understood taking into account that the low energy tail of the flux of UHECR reproduces the injection power law. Therefore, taking $\gamma \geq 2$ cause the low energy part of the spectrum to be polluted by heavy nuclei thereby producing a disagreement with the light composition observed at low energy.

One should appreciate the change of paradigm that these findings imply: while in the case of a pure proton composition it is needed to find sources and acceleration mechanisms able to energise CR protons up to energies larger than 10^{20} eV with steep injection [22] ($\gamma_g \simeq 2.5 \div 2.7$), the Auger data require that the highest energy part of the spectrum ($E > 5 \times 10^{18}$ eV) has a flat injection ($\gamma_g \simeq 1.0 \div 1.6$) being dominated by heavy nuclei with maximum energy not exceeding a few $\times Z \times 10^{18}$ eV [16].

In order to reproduce Auger observations, the additional light contribution to the flux at energies below 5×10^{18} eV should exhibit a steep power law injection with $\gamma_g \simeq 2.6 \div 2.7$ and a maximum acceleration energy not exceeding a few $\times 10^{18}$ eV, as for the heavier component [16, 23, 24]. The origin of this radiation that, as for the heavier one, should be extragalactic [3, 9], can be modelled essentially in two ways: (i) assuming the presence of different classes of sources: one injecting also heavy nuclei with hard spectrum and the other only proton and helium nuclei with soft spectrum [16, 23] or (ii) identifying a peculiar class of sources that could provide at the same time a steep light component and a flat heavy one [24, 25, 26]. The second approach is based on a specific hypothesis on the sources that should be surrounded by an intense radiation field that, through photo-disintegration of heavy nuclei in the source neighbourhood, can provide a light component of (secondary) protons with a steep spectrum together with a hard and heavier component [24, 25]. It should be also noted that the diffusive shock acceleration

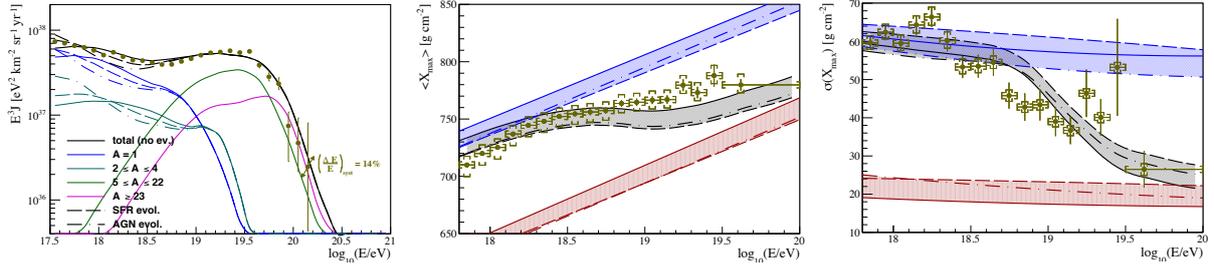


Figure 1. Comparison of the flux (left panel), elongation rate (central panel) and its dispersion (right panel) as observed by Auger and computed assuming the model with two classes of different extragalactic sources. Figures taken from [17].

mechanism produces steep injections of particles with $\gamma_g > 2$, while acceleration due to potential drops typically imply $\gamma_g \simeq 1$ (see [3, 9] and references therein).

In figure 1 we plot the flux and mass composition as observed by Auger and as reproduced theoretically assuming two classes of extragalactic sources with different injection characteristics as discussed above.

3. Cosmogenic secondary neutrinos

The propagation of UHECR is mainly conditioned by the interaction with astrophysical photon backgrounds: the Cosmic Microwave Background (CMB) and the Extragalactic Background Light (EBL). The interaction of UHECR with such backgrounds shapes the spectrum expected at the Earth and produces several unstable particles that in turn decay into high energy photons, electrons/positrons and neutrinos. The possible detection of these signal carriers, realised already at the end of sixties, is extremely important to constrain models for UHECR sources, composition and the details of propagation (see [3, 9] and references therein). In the following we will mainly discuss the case of neutrinos.

There are two processes by which neutrinos can be emitted in the propagation of UHECR: (i) the decay of charged pions, produced by photo-pion production, $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$ and the subsequent muon decay $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$; (ii) the beta-decay of neutrons and nuclei produced by photo-disintegration: $n \rightarrow p + e^- + \bar{\nu}_e$, $(A, Z) \rightarrow (A, Z - 1) + e^+ + \nu_e$, or $(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e$. These processes produce neutrinos in different energy ranges: in the former the energy of each neutrino is around a few percent of that of the parent nucleon, whereas in the latter it is less than one part per thousand (in the case of neutron decay, larger for certain unstable nuclei). This means that in the interaction with CMB photons, which has a threshold Lorentz factor of about $\Gamma \geq 10^{10}$, neutrinos are produced with energies of the order of 10^{18} eV and 10^{16} eV respectively. Interactions with EBL photons contribute, with a lower probability than CMB photons, to the production of neutrinos with energies of the order of 10^{15} eV in the case of photo-pion production and 10^{14} eV in the case of neutron decay (see [17] and reference therein).

The flux of secondary neutrinos is very much sensitive to the composition of UHECR. In figure 2 we plot the flux of cosmogenic neutrinos expected in the case of a pure proton composition (left panel) and in the case of mixed composition (right panel). Comparing the two panels of figure 2 it is evident the huge impact of the composition on the expected neutrino flux: heavy nuclei provide a reduced flux of neutrinos because the photo-pion production process in this case is subdominant.

The production of cosmogenic neutrinos is almost independent of the variations in sources' distribution because the overall universe, up to the red-shift of the first stars (pop III) $z_{max} \simeq 10$,

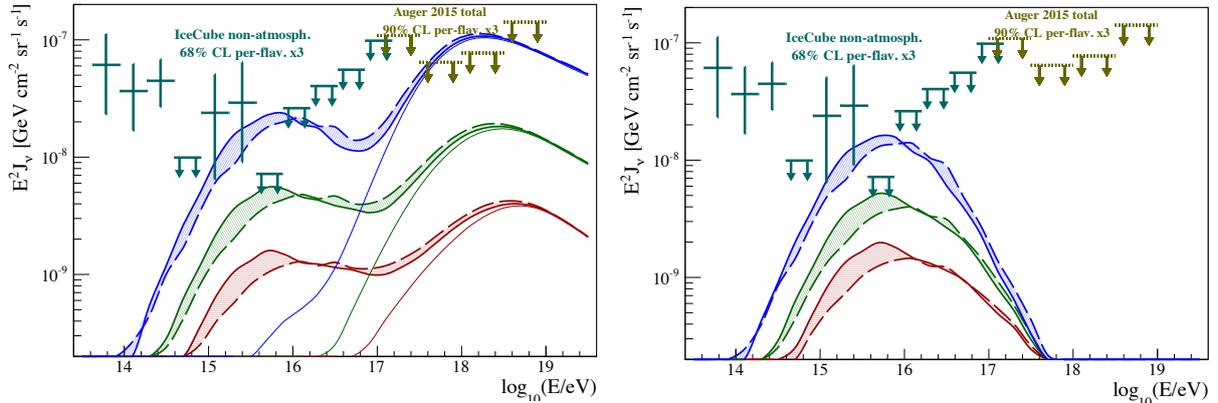


Figure 2. [Left panel] Fluxes of neutrinos in the case of a pure proton composition. The three different fluxes correspond to different assumptions on the cosmological evolution of sources (from bottom to top): no evolution (red), star formation rate evolution (green) and active galactic nuclei evolution (blue), coloured bands show the uncertainties due to the EBL model (see [9, 3] and references therein). Thin solid lines are neutrino fluxes obtained taking into account the sole CMB field. [Right Panel] Neutrino fluxes in the case of mixed composition, as shown in figure 1, with the same color code of left panel. Experimental points are the observations of IceCube on extra-terrestrial neutrinos [27] and the Auger limits on neutrino fluxes [6]. Figures taken from [17].

could contribute to the flux. Once produced at these cosmological distances neutrinos travel toward the observer almost freely, except for the adiabatic energy losses and flavour oscillations, the opacity of the universe to neutrinos being relevant only at redshifts $z \gg 10$. This is an important point that makes neutrinos a viable probe not only of the mass composition of UHECR but also of the cosmological evolution of sources. In figure 2 three different hypothesis on the cosmological evolution of sources are taken into account: no cosmological evolution (red bands), evolution typical of the star formation rate (green band) and of active galactic nuclei (blue band).

There is a solid consensus about the light composition of UHECR in the low energy part of the observed spectrum. This assures a flux of cosmogenic neutrinos in the PeV energy region, produced by the protons' photo-pion production on the EBL photons. Coloured bands in figure 2 show the uncertainties connected with the EBL background (see [3, 9] and references therein). Another important uncertainty in the expected neutrino flux comes from the contribution of UHECR sources at high red-shift. Given the energy losses suffered by UHE protons and nuclei, sources at red-shift larger than $z > 1$ can be observed only in terms of cosmogenic neutrinos [17].

4. New physics: the super heavy dark matter hypothesis

The extreme energies of UHECR, as high as 10^{11} GeV, eleven orders of magnitude above the proton mass and "only" eight below the Planck mass, are a unique workbench to probe new ideas, models and theories which show their effects at energies much larger than those ever obtained, or obtainable in the future, in accelerator experiments. An interesting class of exotic models that can be tested through UHECR are top-down models for the production of these extremely energetic particles. The idea of top-down models arose in 90s to explain the lacking of the high energy suppression in the flux observed by the AGASA experiment (see [3, 9] and reference therein). Nowadays, with the firm experimental observation of the high energy suppression in

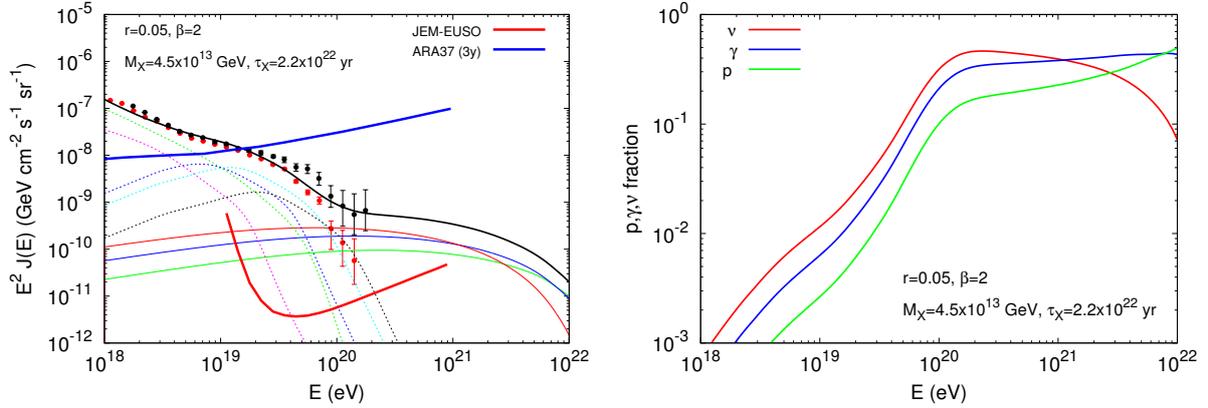


Figure 3. [Left Panel] Flux of UHECR from the decay of SHDM (thin solid lines) with parameters as labeled together with the flux expected in the framework of the mixed composition model of [17]. Also shown is the sensitivity to SHDM decay products: of the proposed JEM-EUSO space mission (thick red solid line) and, for UHE neutrinos, the upcoming ARA observatory (thick blue solid line). Experimental data are those of Auger (red points) and TA (black points). [Right Panel] Fraction over the total flux of protons, photons and neutrinos by SHDM decay as follows from fluxes in right panel. Figures taken from [15].

the UHECR flux, the scientific case for super-heavy relics is connected with the problem of DM and cosmological observations.

The leading paradigm to explain DM observations is based on the Weakly Interactive Massive Particle (WIMP) hypotheses, which consists of two basic assumptions: (i) WIMPs are stable particles of mass M_χ that interact weakly with the Standard Model (SM) particles; (ii) WIMPs are thermal relics, i.e. they were in Local Thermal Equilibrium (LTE) in the early Universe. Imposing that the WIMP density today is at the observed level, using a simple unitarity argument for the WIMP annihilation cross section $\sigma_{ann} \propto 1/M_\chi^2$, one obtains an estimate of the WIMP mass in the range of 10^2 to 10^4 GeV. This result, also called the WIMP “miracle”, links the DM problem to the new physics scale expected in the context of the “naturalness” argument for electroweak physics. Triggering in this way the strong hope that the search for WIMP DM may be connected to the discovery of new physics at the TeV scale. Searches for WIMP particles are ongoing through three different routes: direct detection, indirect detection, and accelerator searches. None of these efforts have discovered a clear WIMP candidate so far. In addition, no evidence for new physics has been observed at the Large Hadron Collider. Although not yet conclusive, the lack of evidence for WIMP may imply a different solution for the DM problem outside of the WIMP paradigm.

An alternative to WIMP models is represented by the scenario based on super-heavy relics produced due to time varying gravitational fields in the early universe: the so-called Super Heavy Dark Matter (SHDM). This approach is based on the possibility of particle production due to the non-adiabatic expansion of the background space-time acting on the vacuum quantum fluctuations (see [9, 15] and references therein). In the framework of inflationary cosmologies, it was shown that particle creation is a common phenomenon, not tied to any specific cosmological scenario, that can play a crucial role in the solution to the DM problem as SHDM (labeled by X) can have $\Omega_X(t_0) \simeq 1$ [28, 29]. This conclusion can be drawn under three general hypotheses: (i) SHDM in the early universe never reaches LTE; (ii) SHDM particles have mass of the order of the inflaton mass, M_ϕ ; and (iii) SHDM particles are long-living particles with a lifetime exceeding the age of the universe, $\tau_X \gg t_0$.

Precision measurements of CMB polarisation and observations of UHECR up to energies $\simeq 10^{20}$ eV enable a direct experimental test of the three hypothesis listed above. As discussed in [15], the first two hypothesis can be probed through the measurements of CMB polarisation. The third hypothesis, particle life-time longer than the age of the universe, is a general requirement of any DM model based on the existence of new particles. As in the case of WIMP, discrete gauge symmetries protecting particles from fast decays work equally well for SHDM particles (see [15, 28, 29, 30] and references therein).

The best way to test the existence of SHDM is through the indirect detection of its annihilation and/or decay products (direct detection is unattainable). Since the annihilation cross section of a (point) particle is bounded by unitarity, $\sigma_{ann} \propto 1/M_X^2 \sim 1/M_\phi^2$, the annihilation process results in an unobservable small annihilation rate [28].

If SHDM particles decay, under general assumptions on the underlying theory (see [15, 28, 29, 30] and references therein), we can determine the composition and spectra of the standard model particles produced. Typical decay products are neutrinos, gamma rays and nucleons with a flat spectrum, that at the relevant energies can be approximated as $dN/dE \propto E^{-1.9}$, independently of the particle type, with a photon/nucleon ratio of about $\gamma/N \simeq 2 \div 3$ and a neutrino nucleon ratio $\nu/N \simeq 3 \div 4$, quite independent of the energy range [30]. The most constraining limits on SHDM lifetime are those coming from the (non) observation of UHE photons and, even to a lesser extent, neutrinos. Auger observations provide us with very stringent limits on the photons flux at energies above 10^{19} eV, which are at the level of 2% [31], this fact already constrains the SHDM life-time to values $\tau_X \geq 10^{21} \div 10^{22}$ yr depending on the underlying inflationary potential.

In the left panel of figure 3, as discussed in [15], we plot the flux of UHECR coming from the decay of SHDM in a specific model of inflation with $M_X = 4.5 \times 10^{13}$ GeV and $\tau_X = 2.2 \times 10^{22}$ yr (solid lines); we also show the expected sensitivities of the proposed JEM-EUSO space mission (thick red solid line) [32] and, for UHE neutrinos, of the upcoming ARA observatory (thick blue solid line) [33]. In the right panel we show the corresponding fraction over the total flux of protons, photons and neutrinos by the decay of SHDM. From figure 3 it is clear that SHDM models can be effectively probed only by the next generation of UHECR experiments, those designed to maximise statistics at the highest energies [34], together with new and more refined observations of the CMB polarisation pattern as they constrain the inflationary scenario.

5. Conclusions

One of the main goals in the study of UHECR is a clear identification of the sources. In this ambit, as discussed above, a key observable is the mass composition. A pure proton composition is, theoretically, a natural possibility. Proton is the most abundant element in the universe and several different astrophysical objects, at present and past cosmological epochs, could provide efficient acceleration even if it requires very high luminosities and maximum acceleration energies. The complexity of the scenario based on a composition with heavy nuclei disfavors astrophysical sources placed at high redshift because of the lacking of heavy elements. To reproduce observations, mixed composition requires sources with flat injection spectra for heavy nuclei, or needs particular dynamics in the source environment, such as photo-disintegration on strong local photon fields. A remarkable feature of the mixed composition scenario is the relative low maximum energy required at the source.

After the first detection of astrophysical neutrinos at energies below few $\times 10^{15}$ eV by the IceCube collaboration [27], the study of HE and UHE neutrinos attracted a renewed interest. The observations of IceCube, being at relatively low energy, can be only marginally explained in the framework of cosmogenic neutrinos coming from UHECR interactions, also given the large uncertainties on the EBL background at high red-shift [17]. At high energies ($E \geq 10^{18}$) neutrino production is critically related with the mass composition of UHECR and with cosmological

evolution of sources.

The study of UHECR has an impact also in fundamental physics, as it involves tests of models and theories that extend beyond the standard model of particle physics. This is the case of SHDM that, being a viable alternative to the WIMP paradigm for DM, can be tested only through the combined observations of the CMB polarisation pattern and UHECR at the highest energies [15].

We conclude highlighting the two principal avenues on which the study of UHECR should develop in the near future. From one hand, as discussed above, a firm experimental determination of the mass composition is an unavoidable step forward in this field of research. On the other hand, the highest energy regime, typically energies $E \geq 5 \times 10^{19}$ eV, still remains less probed with not enough statistics to firmly detect possible anisotropies in the arrival directions and the exact shape of the suppression. Current technologies, such as Auger and (extended) TA, can reach, in several years, one order of magnitude more in the number of observed events at the highest energies, which seems not enough to firmly detect anisotropies, to probe new physics or to detect neutrinos. New technologies are needed and future space observatories, with improved photon detection techniques, like the proposal POEMMA (Probe of Extreme Multi-Messenger Astrophysics) [34], promise a new era in the physics of UHECR, allowing the needed statistics to detect anisotropies, cosmogenic neutrinos and to probe new physics [3, 9, 34].

References

- [1] Aab A *et al.* (Pierre Auger) 2015 *Nucl. Instrum. Meth.* **A798** 172–213 (*Preprint* 1502.01323)
- [2] Tinyakov P (Telescope Array) 2014 *Nucl. Instrum. Meth.* **A742** 29–34
- [3] Aloisio R, Blasi P, De Mitri I and Petrerá S 2018 *Springer Book* (*Preprint* 1707.06147)
- [4] Abraham J *et al.* (Pierre Auger) 2009 *Astropart. Phys.* **31** 399–406 (*Preprint* 0903.1127)
- [5] Abu-Zayyad T *et al.* (Telescope Array) 2013 *Phys. Rev.* **D88** 112005 (*Preprint* 1304.5614)
- [6] Abreu P *et al.* (Pierre Auger) 2013 *Adv. High Energy Phys.* **2013** 708680 (*Preprint* 1304.1630)
- [7] Aab A *et al.* (Pierre Auger) 2013 *ICRC 2013 Proceedings* (*Preprint* 1307.5059)
- [8] Abu-Zayyad T *et al.* (Telescope Array) 2015 *Astropart. Phys.* **61** 93–101 (*Preprint* 1305.7273)
- [9] Aloisio R 2017 *PTEP* **2017** 12A102 (*Preprint* 1707.08471)
- [10] Berezhinsky V, Gazizov A and Grigorieva S 2006 *Phys. Rev.* **D74** 043005 (*Preprint* hep-ph/0204357)
- [11] Aab A *et al.* (Pierre Auger) 2014 *Phys. Rev.* **D90** 122005 (*Preprint* 1409.4809)
- [12] Abbasi R U *et al.* 2015 *Astropart. Phys.* **64** 49–62 (*Preprint* 1408.1726)
- [13] Abbasi R *et al.* (Pierre Auger, Telescope Array) 2016 *JPS Conf. Proc.* **9** 010016 (*Preprint* 1503.07540)
- [14] Verzi V 2016 *PoS ICRC2015* 015
- [15] Aloisio R, Matarrese S and Olinto A V 2015 *JCAP* **1508** 024 (*Preprint* 1504.01319)
- [16] Aloisio R, Berezhinsky V and Blasi P 2014 *JCAP* **1410** 020 (*Preprint* 1312.7459)
- [17] Aloisio R, Boncioli D, di Matteo A, Grillo A F, Petrerá S and Salamida F 2015 *JCAP* **1510** 006 (*Preprint* 1505.04020)
- [18] Abreu P *et al.* (Pierre Auger) 2013 *JCAP* **1302** 026 (*Preprint* 1301.6637)
- [19] Aloisio R, Berezhinsky V, Blasi P and Ostapchenko S 2008 *Phys. Rev.* **D77** 025007 (*Preprint* 0706.2834)
- [20] Kampert K H and Unger M 2012 *Astropart. Phys.* **35** 660–678 (*Preprint* 1201.0018)
- [21] Aloisio R, Berezhinsky V and Gazizov A 2011 *Astropart. Phys.* **34** 620–626 (*Preprint* 0907.5194)
- [22] Aloisio R, Berezhinsky V, Blasi P, Gazizov A, Grigorieva S and Hnatyk B 2007 *Astropart. Phys.* **27** 76–91 (*Preprint* astro-ph/0608219)
- [23] Taylor A M 2014 *Astropart. Phys.* **54** 48–53 (*Preprint* 1401.0199)
- [24] Globus N, Allard D and Parizot E 2015 *Phys. Rev.* **D92** 021302 (*Preprint* 1505.01377)
- [25] Unger M, Farrar G R and Anchordoqui L A 2015 *Phys. Rev.* **D92** 123001 (*Preprint* 1505.02153)
- [26] Blasi P, Amato E and D’Angelo M 2015 *Phys. Rev. Lett.* **115** 121101 (*Preprint* 1508.02866)
- [27] Aartsen M G *et al.* (IceCube) 2015 (*Preprint* 1510.05225)
- [28] Aloisio R, Berezhinsky V and Kachelriess M 2006 *Phys. Rev.* **D74** 023516 (*Preprint* astro-ph/0604311)
- [29] Kolb E W, Starobinsky A A and Tkachev I I 2007 *JCAP* **0707** 005 (*Preprint* hep-th/0702143)
- [30] Aloisio R, Berezhinsky V and Kachelriess M 2004 *Phys. Rev.* **D69** 094023 (*Preprint* hep-ph/0307279)
- [31] Abraham J *et al.* (Pierre Auger) 2008 *Astropart. Phys.* **29** 243–256 (*Preprint* 0712.1147)
- [32] Ebisuzaki T, Medina-Tanco G and Santangelo A (JEM-EUSO) 2014 *Adv. Space Res.* **53** 1499–1505
- [33] Allison P *et al.* (ARA) 2015 *Astropart. Phys.* **70** 62–80 (*Preprint* 1404.5285)
- [34] Olinto A V *et al.* 2018 *PoS ICRC2017* 542 (*Preprint* 1708.07599)

This site uses cookies. By continuing to use this site you agree to our use of cookies. To find out more, see our [Privacy and Cookies policy](#).



Table of contents

Volume 1586

2020

◀ Previous issue Next issue ▶

6th Symposium on Prospects in the Physics of Discrete Symmetries - DISCRETE 2018 26-30 November 2018, Vienna, Austria

Accepted papers received: 30 June 2020

Published online: 11 September 2020

[Open all abstracts](#)

Preface

OPEN ACCESS 011001

Editorial DISCRETE proceedings

+ [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS 011002

Peer review statement

+ [Open abstract](#) [View article](#) [PDF](#)

Papers

OPEN ACCESS 012001

Symmetry properties of non-Hermitian PT -symmetric quantum field theories

P Millington

+ [Open abstract](#) [View article](#) [PDF](#)

-
- OPEN ACCESS** 012002
Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN
Z Kucerova
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012003
Violation of lepton number in 3 units
R M Fonseca
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012004
 PT -symmetric quantum field theory
C M Bender
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012005
On the systematic construction of basis invariants
A Trautner
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012006
Measurement of charge asymmetry for the $K_S \rightarrow \pi e \nu$ decay and test of CPT symmetry with the KLOE detector
A Di Domenico
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012007
Test of discrete symmetries in transitions with entangled neutral kaons at KLOE-2
A De Santis
[+ Open abstract](#) [View article](#) [PDF](#)
-
- OPEN ACCESS** 012008

Tests of discrete symmetries in positronium decays with the J-PET detector

E Czerwiński and for the J-PET collaboration

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012009

Chiral symmetry-breaking schemes and dynamical generation of masses and field mixing

M Blasone, P Jizba and L Smaldone

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012010

Influence of Cosmic Radiation while Testing the Time Reversal Symmetry in the Decay of Ortho-Positronium Atoms using the J-PET detector

J Raj, E Czerwiński and On behalf of the J-PET collaboration

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012011

Searches for pair production of charginos and top squarks in final states with two oppositely charged leptons at CMS experiment

B Chazin and on behalf of the CMS Collaboration

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012012

Disentangling genuine from matter-induced CP violation in neutrino oscillations

A Segarra and J Bernabeu

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012013

Leptogenesis in CPT violating backgrounds

T Bossingham

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012014

Spontaneous CP Violation and Scalar FCNC

M Nebot

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012015

Bounding CPT and Lorentz symmetry violations through ultra-high-energy cosmic rays

C A Escobar and R Potting

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012016

High precision test of the Pauli Exclusion Principle for electrons

K Piscicchia, A Amirkhani, S Bartalucci, S Bertolucci, M Bazzi, M Bragadireanu, M Cargnelli, A Clozza, C Curceanu, R Del Grande, L De Paolis, J Egger, C Fiorini, C Guaraldo, M Iliescu, M Laubenstein, J Marton, T Mazzocchi, M Miliucci, E Milotti, A Pichler, D Pietreanu, A Scordo, H Shi, D Laura Sirghi, F Sirghi, L Sperandio, O Vazquez Doce, M Veith and J Zmeskal

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012017

Three Higgs doublet model with horizontal S_3 symmetry

A Alvarez-Cruz, M Gómez-Bock, M Mondragón and A Pérez-Martínez

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012018

SUSY discovery prospects with MoEDAL

K Sakurai, D Felea, J Mamuzic, N E Mavromatos, V A Mitsou, J L Pinfeld, R Ruiz de Austri, A Santra and O Vives

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012019

Flavor mixed sleptons and its consequences at one-loop level

R Espinosa-Castañeda, F V Flores-Baez, M Gómez-Bock and M Mondragón

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012020

S₄ modular symmetry, seesaw mechanism and lepton masses and mixing

P P Novichkov and J T Penedo

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012021

Sterile neutrinos as a source of CP violation

A Palazzo

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012022

Master Majorana neutrino mass parametrization

I Cordero-Carrión, M Hirsch and A Vicente

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012023

The Inert Doublet Model at current and future colliders

J Kalinowski, W Kotlarski, T Robens, D Sokolowska and A F Żarnecki

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012024

Fifth forces and discrete symmetry breaking

P Millington

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012025

An Inert Scalar In The S₃ Symmetric Model.

C Espinoza, E A Garcés, M Mondragón and H Reyes-González

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012026

Spinor–vector duality and sterile neutrinos in string derived models

Alon E. Faraggi

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012027

Tests of the electroweak sector with precision measurements and diboson final states at the ATLAS Experiment.

L Fabbri

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012028

Measurements of the Higgs Boson Properties at the ATLAS Experiment

M Biglietti and on behalf of the ATLAS Collaboration

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012029

Recent results from SUSY searches with ATLAS and prospects for the HL-LHC

A Ventura and on behalf the ATLAS Collaboration

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012030

Nonexistence of locally but not globally supersymmetric orbifolds

S Groot Nibbelink

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012031

Tests of lepton flavour universality at LHCb

A. Buonaura and on behalf of the LHCb collaboration

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012032

Towards machine learning in the classification of $Z_2 \times Z_2$ orbifold compactifications

A E Faraggi, G Harries, B Percival and J Rizos

[+ Open abstract](#) [View article](#) [PDF](#)**OPEN ACCESS**

012033

Probing modified dispersion relations in vacuum with high-energy γ -ray sources: review and prospects

J Bolmont and C Perennes

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012034

Overview on solar, geo, and reactor neutrino experiments

L Ludhova

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012035

Study of η -meson Decays at KLOE/KLOE-2

X Kang and on behalf of KLOE-2 Collaboration

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012036

Quantum stability in open string theory with broken supersymmetry

H Partouche

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012037

KLEVER: An experiment to measure $BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$ at the CERN SPS

M W U van Dijk and on behalf of the KLEVER project

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012038

Collider physics at the intensity and energy frontier – the HL-LHC and beyond

F Meloni and on behalf of the ATLAS and CMS collaborations

[+](#) [Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012039

Gravitational waves from cosmic domain walls: a mini-review

K Saikawa

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012040

Ultra High Energy Cosmic Rays and the Highest Energies Universe

R Aloisio

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012041

Pushing the Energy and Cosmic Frontiers with High-Energy Astrophysical Neutrinos¹

M Bustamante

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012042

Natural supersymmetric Twin Higgs

M Badziak and K Harigaya

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012043

Electric Dipole Moment Measurements at Storage Rings

J Pretz and on behalf of the JEDI and CPEDM collaboration

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012044

Impact of new physics on $B + L$ violation at colliders

D G Cerdeño, P Reimitz, K Sakurai and C T amarit

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012045

The dispersion method and dimensional regularization applied to the decay $H \rightarrow Z\gamma$

I Boradjiev, E Christova and H Eberl

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

The CP-symmetries of the 2HDM

012046

B Grzadkowski, O M Ogreid and P Osland

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012047

Status and physics potential of the JUNO experiment

F Perrot and on behalf of the JUNO Collaboration

[+ Open abstract](#) [View article](#) [PDF](#)

OPEN ACCESS

012048

Implications of symmetries in the scalar sector

H E Haber, O M Ogreid, P Osland and M N Rebelo

[+ Open abstract](#) [View article](#) [PDF](#)

JOURNAL LINKS

[Journal home](#)

[Information for organizers](#)

[Information for authors](#)

[Search for published proceedings](#)

[Contact us](#)

[Reprint services from Curran Associates](#)