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Review of the doctoral dissertation of Mr. Théo Hugues entitled "Search for Dark Matter with Liquid Argon Detectors"

The presented doctoral thesis was carried out at the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences and at the Université Paris Cité. The promoters of the work were respectively Dr. hab. Marcin Kuźniak and Dr. Davide Franco. The dissertation is in the form of a manuscript, containing around 140 pages of main text divided into six chapters and three appendices. Since I am not a native speaker I do not address language issues in the review. Also some minor editorial mistakes are not addressed in the review.

In a short, two-page introduction, the structure of the manuscript is presented. It is a bit of a pity that it does not include an introduction to the issues addressed in the thesis, which would have made it possible to outline the plan for the research and the dissertation at the outset.

The second chapter, entitled "Dark matter," is devoted to experimental and theoretical aspects of the dark matter issue. Firstly, the cosmological and astrophysical observation together with corresponding theoretical models are presented in Sec. 2.1. All the most important issues were presented correctly. Nevertheless, I would have preferred a more coherent and logical interpretation of the material presented, e.g. the meaning of Eq. 2.2 and Fig. 2.2. The description of nucleosynthesis appears to be inaccurate in some detail. In particular, the rather basic $p+p \rightarrow d+e^{+}+\nu_e$ process is missing. Moreover, there is an error in reactions 2.13, as the d+d reactions do not produce ^{4}He, but either ^{3}He+n or t+p. In contrast, ^{4}He is formed in d+t, t+t and many other reactions. On the other hand, the problem of microwave background is very nicely explained. Next, Sec. 2.2 contains the basic dark matter candidates and their properties. The new theory of gravity is well outlined, but it is a pity that the important phenomenon known as the External Field Effect in Modified Newtonian Dynamics is not mentioned here. It would have been better to develop this issue, important from the point of view of dark matter considerations, instead of, for example, the unnecessary presentation of Primordial Black Holes, a topic not very clearly, rather hastily presented. The description of sterile neutrinos is also inaccurate, e.g., it does not say that neutrinos are generally created by weak interaction processes, not just fusion and fission ones; neutrinos and antineutrinos have also opposite lepton numbers, not just electrical and magnetic properties; whether finally sterile neutrinos, which are not defined at all in the text, interact only through gravity and not through any other fundamental interactions of the Standard Model. Such definition of the dark matter candidate is nicely given in case of WIMP's. The last part of this chapter, Sec. 2.3, is devoted to DM detection methods. It is a brief but well-written introduction to the dark matter measurements currently underway and planned, which is a good introduction to the following chapters of the dissertation.

Chapter 3 is devoted to the properties and specific solutions of Liquid Argon detectors. There is a detailed description of scintillation mechanisms, although not without minor mistakes, e.g., according to [76] likelihood that an electron is captured by a Ar_2^+ dimer is not lower but equal to 1 in the absence of an electric field. It is a bit strange that the description of argon isotopes found in the atmosphere completely omits the stable isotope ^{38}Ar with an abundance of 0.06%. Of the radioactive isotopes only ^{39}Ar was discussed, but ^{37}Ar and ^{42}Ar were mentioned but omitted from the discussion. While the effect of the presence of ^{37}Ar is essentially negligible, ^{42}Ar is significant in the case of, for example, the GERDA experiment, which is an LAr detector - hence it was worth commenting on the effect of this isotope on LAr detectors measurements. In Sec. 3.2 and 3.3 the DarkSide-50 and DEAP-3600 detectors are described in detail. They are very well, though not perfectly written, while the detectors themselves are very respectful.

In Chapter 4 the author turns to the measurements made with the DEAP-3600 detector. But first, the inelastic boosted dark matter model is presented. This description is well-written, however it would be better if Figure 4.1 more closely resembled Figure 1 from publications [87] or even [93], which are much more in line with the text provided. Various calculations and simulations are presented to test the simulation programs and compare them with the results presented in other publications – this will allow to verify the results obtained for other scenarios of the searched phenomenon. Conducting such a multiple check was a very good idea. However, the presentation of some of the results is not clear. A_{tot} is the acceptance after applying a cut at 10 MeV on the total deposited energy, but why the same threshold was applied while calculating A_{pr} acceptance? Are the experimental triggers and background levels the same in case of both kinds of events? It doesn't say how these acceptances were calculated? $A_{tot/pr}$ was calculated from the spectrum depicted in Fig. 4.6, but this quantity is not shown or used anywhere. In turn, it is not clear how Fig. 4.6 was calculated? The description of the colors in Fig. 4.9 is by reference to the publication [100] (I think it is Fig. 8), which is quite a breakneck procedure.

Chapter 5 describes the search for dark matter with the DarkSide-50 detector, which is the main part of the dissertation. The use of the blinding technique is beneficial in the analysis of data, although too few details are given to understand the procedure used. After a brief explanation of why the annual modulated signal should be expected, a low-mass analysis strategy is presented in Sec. 5.2 and the Lomb-Scargle periodogram in Sec. 5.3. The standard methods of periodogram analysis used in the astrophysics are presented in many aspects. The description gives the reader a good overview, but it is necessary to read the cited publications to understand these methods, since the description is limited and sometimes chaotic. For example, some variables, such as τ, appear without definition and further use. Figures 5.5, 5.12, 5.13, 5.14 and several others appearing further down, as well as Table 5.2, are not cited at all in the text, and Figure 5.7 is not from publication [85], which is a shortcoming in the quality of the text. Next, Section 5.4 presents the behavior and especially investigation of the long-term stability of the DarkSide-50 detector subsystems, which is crucial to the analysis presented here. The very important part of the analysis is investigation of the correlation between particular variables. First, the correlation between detector parameters and environmental data is presented - one-day binning was used. Very important correlations between data and slow-control readings were examined in detail. Not only the standard linear correlation coefficient, but also the Spearman and Kendall coefficients were considered. The null hypothesis was tested by analyzing artificial Monte Carlo data, as well as the Scipy methods. The latter is somewhat questionable because it is based on a publication [153] that is not mathematically rigorous. But since the search for correlations included pessimistic results among those obtained by various methods, the results of the analysis are certainly safe. Then, an analogous search for correlations was carried out, allowing for a time shift between the SLC and the data, which is possible and even expected under certain conditions. The conclusions of the analysis are obviously correct, although some statements are questionable, e.g., it can be seen that certain parameters, like temperatures, vary sinusoidally with a period of about 300 days, so it should not be written that "these parameters do not have any sinusoidal variations." The final section of this chapter, Sec. 5.5, describes the analysis of annual modulation of measured data. After a nice presentation of the of analysis of the obtained periodograms and description of Monte Carlo data, the obtained amplitudes of the searched signal are presented and shown to be statistically insignificant. The upper limits of dark matter interactions were set for three energy regions – no dark matter was found. The unsatisfactory part is left by the end of this chapter, where a very important result shown in Fig. 5.46 is not explained at all. The author refers to another publication, where the method is presented and the reader would have to perform this analysis for himself. Also unfortunate is the reference in the next paragraph to the publication [1], which does not exist - it is just some hidden file on the disk of the author.

The presented dissertation is about the search for dark matter with the DarkSide-50 detector. This research is very important from the point of view of modern fundamental physics and cosmology. Finding or not finding dark matter is a key to our understanding of the Universe. The dissertation presents the detections system, data analysis, sources of systematic effects and the results in the right way. It was not simple, but rather difficult and tedious work done by the author. There are some shortcomings in the description of some parts of his work, but they do not significantly reduce its value. It seems that the author wrote the dissertation in some haste, which happens.

In conclusion, I consider the doctoral thesis of Mr. Théo Hugues to be a valuable contribution and to meet the criteria prescribed by law for a doctoral dissertation. Accordingly, I request that this dissertation be admitted to public defense.