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Report on PhD thesis submitted by Alena Bakalová

Dear Members of the PhD Committee,

It was a pleasure to read the PhD thesis of Alena Bakalová about the *"Connection between Arrival Directions and Mass of Ultra-high-energy Cosmic Rays"*. The topic is very timely and up to date since this thesis studies, among other things, the recent discovery of a dipolar anisotropy in the arrival direction of ultrahigh-energy cosmic rays. To learn about the distribution of flux arriving at the edge of our Galaxy, Alena Bakalová used sophisticated models of the Galactic magnetic field to simulate the propagation of charged particles. These fields distort both the amplitude and direction of the signal and therefore the investigation of the de-amplification and deflection of the dipole is very valuable to understand its origin. One of the major goals of the thesis was to provide, for the first time, a systematic study of the possible origin of the dipole for different plausible assumptions on the Galactic magnetic field and the mass composition of ultrahigh-energy cosmic rays and indeed, the thesis (and the corresponding publication in JCAP) discusses this subject thoroughly and in-depth. These results, along with the other studies presented, are original and novel scientific research.

Some more detailed comments and minor suggestions can be found the appendix. In summary, I evaluate the thesis overall as very good and I can recommend it for presentation at a public PhD defense.

Best regards,

Michael Unger

Detailed comments: The thesis is very well written and pleasant to read. The first chapter gives an excellent introduction to cosmic rays including a historical background beyond the balloon flights of Hess. I learned a lot of new things in this chapter and found it very refreshing and original. After Eq.(1.7) it could have been noted that this is the vertical depth and introduce the more general concept of the *"slant depth"*. And after Eq.(1.12) it would have been worthwhile to point out that the mass-dependence is $A^{1-\beta}$ before giving the numerical value of $A^{0.15}$.

Chapter 2 is appropriately concise for this thesis. Since it is mentioned, one or two explanatory sentences regarding the *"Constant Intensity Cut"* would have helped to illuminate the origin of f_{CIC}.

Chapter 3 gives a good and complete overview of the propagation of cosmic rays. It would have been good to motivate the use of TF17 a bit more. In my opinion, this model is not exactly on equal footing with the JF12 model. It did not use the synchrotron data for tuning and even the extragalactic RMs are masked at low latitude ($|b| < 10°$) which means that the disk component is not very well-constrained. I also did not understand the motivation to use this model without a random field. The authors of TF17 do not imply that there is no random field, but they just concentrate on the coherent field. Could one for instance combine TF17 with the JF12 random field or the estimate from Pshirkov et al? And whereas this chapter has a very good and short explanation of rotation measures and polarized synchrotron emission, it does not discuss the total synchrotron emission from which the random field is derived. In light of the Kolmogorov spectrum used in the later chapters, it would have also been useful to introduce the power spectrum of the turbulence and its relation to the coherence length. And on page 43, the half-sentence *"... smaller than the radius of the galaxy"* should read *"... smaller than the height of the Galactic disk"* or similar.

Chapter 4 provides a well-written overview of the state-of-the-art of cosmic ray observations at the highest energies. A large amount of information is presented, demonstrating a very good understanding of the field. What a pity that the collaborations provide the maps in Fig.4.10 in different projections!!

As said in the main part of this letter, I consider chapter 5 to be the most important result of this thesis. The analysis is very well explained. Maybe Tab.5.1 could be removed, as it just shows what can be said in one sentence (the spectrum remains unchanged due to the absence of energy losses). Please note that no comparison with the polarized intensity was done in Ref.[78], therefore I did not understand the sentence *"able to reproduce the X-shape behavior in the polarized light [78]."*. One should also be precise about the different parts of the model. The coherent field has an uncertainty due to the uncertainties of the model parameters (and of course other assumptions). And then there is the random field, for which we only know the strength, but not the particular realization. In that context, a sentence like *"To account for the uncertainties of the GMF model, multiple realizations of the field were simulated."* is a bit confusing. Moreover, it should be noted that the coherence length influences the turbulent field, but of course not the coherent field. Therefore, in sentences like *"Lowering the coherence length acts in a similar manner as decreasing the overall strength of the field"* and *"...the uncertainties of the model were implemented by using multiple coherence lengths of the random turbulent component of the field."* it could maybe be made clear, that the coherence length is not related to the overall field strength (only the turbulent one) and it is not a proxy for the uncertainty of the model. An interesting future direction, surely beyond the scope of this already detailed study, could be the investigation of the quadrupolar component of the anisotropy. How does the amplitude depend on the magnetic field? Does some of the quadrupolar power "leak" into the dipolar one after propagation through the GMF?

Chapter 6 addresses a very interesting subject, the effect of a local source on the UHE spectrum. The premise of the study is the discrepancy between the spectra measured by the Telescope Array and the Pierre Auger Observatory. But since the latter measures a lower flux, I would find it more natural to study a local source in the Northern hemisphere to explain the discrepancy like e.g. in ApJ 953 (2023) 2, 129 or ApJ 836 (2017) 2, 163. And since the study is only performed above $10^{19.5}$ eV it is unclear how the spectrum of the source would fit to the lower energies, in particular for very soft spectra. Moreover, it could be expected that the flux above $10^{19.5}$ eV is the sum of a diffuse component and the one flux from the local source. These could be interesting future directions to expand the study to the full energy range. Furthermore, I would be interested if for e.g. Fig. 6.11 several realizations of the turbulent GMF were combined (maybe also different coherence length?). Whereas for some purposes, like marginalizing over the realizations to find the 1-σ contours of origin, it makes sense to combine the simulations, it could be more interesting to see for this figure the image of a particular lens as e.g. in Farrar and Sutherland JCAP 05 (2019) 004.

Chapter 7 provides a very solid analysis of the response of water-Cherenkov detectors using two simulation frameworks. Could another comparison also be performed in the future with the software of the Pierre Auger Observatory in which also water-Cherenkov detectors are simulated with GEANT? The chapter finishes with an interesting study of the amplification of the photon density in binary systems.

The conclusions in chapter 8 give a clear and comprehensive summary of the work.