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# PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS AND ANISOTROPY STUDIES WITH THE PIERRE AUGER OBSERVATORY: THE MULTISCALE APPROACH

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# Abstract

The main goal of this thesis is the investigation of the arrival directions of ultra-high energy cosmic rays (UHECRs). The clustering of such events, collected by the Pierre Auger Observatory, is used to infer the nature of sources and their density, as well as other physical unknowns. Results are based on the comparison between real and simulated data. Hence, an *ad hoc* Monte Carlo code (HERMES) for the realistic simulation of UHECR propagation in the Universe and a novel method (MAF) to quantify the amount of clustering in a data set of few UHECR events have been developed.

In the first chapter, a general overview of UHECR physics will be given, with particular attention to the Pierre Auger Observatory and the most recent results regarding its measurements.

In the second and third chapters, we will present the general structure of our propagation code and we will discuss all the models, the parameterizations and the procedures adopted to simulate the propagation of UHECRs in a magnetized Universe. In the second chapter, magnetic fields are treated, and their impact on the propagation of UHECRs is discussed. In particular, we will simulate the diffusion of charged particles in both turbulent and structured magnetic fields for energy values ranging from $10^{17}$ eV to $10^{21}$ eV. In the third chapter, the propagation of protons, heavier nuclei, photons and neutrinos, will be treated in the absence of magnetic fields. We will define the cosmological framework of HERMES and we will treat the parameterizations adopted to simulate the extragalactic background radiation. The parameterizations for the cross section of $p\gamma_{\text{EBR}}$, $A\gamma_{\text{EBR}}$ and $\gamma\gamma_{\text{EBR}}$ interactions are discussed, as well as the relevant energy-loss processes. In particular, pair and pion production, as well as photo-disintegration in the case of heavy nuclei, are treated with great detail. Mean free path and energy-loss length are numerically estimated with HERMES: their dependence on nuclear mass and their evolution with redshift are also discussed. The impact of propagation effects on the GZK horizon of UHE protons is investigated, and some comparisons between our results and those obtained with other simulators available to the UHECR community are presented.

In the fourth chapter, a novel method is introduced to estimate the statistical significance of clustering in the arrival direction distribution of few events, a necessary requirement because of the current small number of events observed above $5\times10^{19}$ eV. The method involves a multiscale procedure, based on information theory and extreme value statistics, providing high discrimination power, even in presence of strong background isotropic contamination. It is naturally extended to allow multiscale cross-correlation analysis with candidate sources of UHECRs. Here, the term “multiscale” explicitly indicates the dependence on the angular scale adopted to investigate the arrival directions of UHECRs. It is shown that multiscale methods have some valuable features: i) they are semi-analytical, drastically reducing computation and allowing a larger parameter space to be explored in reasonable amount of time, ii) they are very sensitive to small, medium and large scale clustering, iii) they are not biased against the null hypothesis.

Finally, in the fifth, sixth and seventh chapters, Monte Carlo simulations, required because of the stochastic nature of some interactions between UHECRs and background photons, are extensively adopted to investigate real data. In the fifth chapter we use multiscale methods to explore the effects of experimental uncertainties on clustering and correlation of UHECRs with catalogs. In the

sixth chapter, energy losses due to secondary particle production (electron/positron pairs and pions) or photo-disintegration, as well as deflections due to galactic and extragalactic magnetic fields, are taken into account. All of such interactions, together with the distribution of (still unknown) sources, produce different distributions of arrival directions of events observed at Earth. Hence, multiscale clustering in events detected with the Pierre Auger Observatory and in simulated sky maps of UHECRs, mimicking realistic astrophysical scenarios, is used to put bounds on some relevant unknowns, as the fraction of protons in the data, the density of sources and the strength of the turbulent component of the extragalactic magnetic field. Moreover, the possibility that nearby active galactic nuclei and black holes could be responsible for the observed flux of UHECRs is explored in detail. In the seventh chapter, we perform a more extended study which takes into account additional observables, as the elongation rate and the energy spectrum. By varying the underlying assumptions, as for instance those ones on the mass composition and the intensity of magnetic fields, we have outlined an astrophysical scenario able to explain Auger data from a phenomenological point of view.

# Contents

**Abstract** **i**

**1 Ultra-high energy cosmic rays and the Pierre Auger Observatory** **1**
1.1 Historical highlights . . . . . 1
1.2 The energy spectrum and the mass of CRs . . . . . 3
1.3 UHECR acceleration mechanisms . . . . . 7
1.4 Candidate sources of UHECR . . . . . 8
1.5 Extensive air showers . . . . . 11
1.6 UHECR detection: the Pierre Auger Observatory . . . . . 18
1.6.1 The detector . . . . . 19
1.6.2 Event selection of the surface detector array . . . . . 20
1.6.3 Event reconstruction . . . . . 25
1.6.4 Main results . . . . . 32

**2 Simulating the propagation of UHECRs I: magnetic fields** **37**
2.1 General structure of the HERMES code . . . . . 37
2.2 Origin of cosmic magnetic fields . . . . . 39
2.3 Simulating the motion of charged particles . . . . . 40
2.4 Modeling the diffusion in the irregular field . . . . . 41
2.5 Simulating the Galactic magnetic field . . . . . 46
2.6 Simulating the extragalactic magnetic field . . . . . 50
2.7 Conclusions . . . . . 54

**3 Simulating the propagation of UHECRs II: energy-loss in the EBR** **56**
3.1 Modeling the cosmological framework . . . . . 56
3.2 Modeling the extragalactic background radiation . . . . . 60
3.2.1 Cosmic microwave background . . . . . 60
3.2.2 Cosmic infrared/optical background . . . . . 61
3.2.3 Cosmic radio background . . . . . 65
3.2.4 Summary of the parameterizations included in HERMES . . . . . 66
3.3 Modeling and simulation of energy-loss processes . . . . . 67
3.3.1 Cross section of $p\gamma$ interactions . . . . . 68
3.3.2 Interaction lengths for $p\gamma$ interactions . . . . . 69
3.3.3 Cross section of $A\gamma$ interactions, photo-disintegration and decay chain . . . . . 73
3.3.4 Interaction lengths for $A\gamma$ interactions . . . . . 77
3.4 Propagation of secondary neutrinos and photons . . . . . 80
3.5 Impact of propagation on the spectrum of UHECR . . . . . 83
3.5.1 Protons and heavy nuclei . . . . . 83

3.5.2 Neutrinos and $\gamma-$rays . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 84
3.6 Investigating the GZK horizon of UHE protons . . . . . . . . . . . . . . . . . . . 86
3.6.1 Influence of extragalactic magnetic field . . . . . . . . . . . . . . . . . . . . 87
3.6.2 Influence of cosmology . . . . . . . . . . . . . . . . . . . . . . . . . . . . 89
3.6.3 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 92
3.7 Comparison of HERMES with other propagation codes . . . . . . . . . . . . . . . 92
3.8 Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 95

**4 Search for UHECR anisotropies: the multiscale method 97**
4.1 Hypothesis testing . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 97
4.2 Review of anisotropy and correlation estimators . . . . . . . . . . . . . . . . . 100
4.3 MAF: a new approach to anisotropy studies . . . . . . . . . . . . . . . . . . . 104
4.3.1 Dynamical counting . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 105
4.3.2 Interpretation of MAF . . . . . . . . . . . . . . . . . . . . . . . . . . . . 107
4.3.3 Statistical analysis of MAF . . . . . . . . . . . . . . . . . . . . . . . . . 109
4.3.4 Discussion and conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . 113
4.3.5 Additional information . . . . . . . . . . . . . . . . . . . . . . . . . . . . 114
4.4 Discrimination power of MAF in different astrophysical scenarios . . . . . . . . . 115
4.4.1 Existing methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 116
4.4.2 Astrophysical models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 116
4.4.3 Statistical analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 119
4.4.4 Comparison with other methods . . . . . . . . . . . . . . . . . . . . . . . 120
4.4.5 Discussion and conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . 120
4.5 Probing cosmological parameters with MAF . . . . . . . . . . . . . . . . . . . . 126
4.6 Multiscale cross-correlation function . . . . . . . . . . . . . . . . . . . . . . . 127
4.7 Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 128

**5 Search for UHECR anisotropies in Auger and experimental uncertainty effects 130**
5.1 Smearing the arrival directions of UHECRs . . . . . . . . . . . . . . . . . . . . 130
5.1.1 Directional statistics . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 131
5.1.2 Applications . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 134
5.2 The Auger dataset . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 135
5.3 Search for an anisotropy signal with the MAF and effects of uncertainties . . . . . 136
5.3.1 Search for anisotropy with the MAF method . . . . . . . . . . . . . . . . . 136
5.3.2 Effects on the anisotropy signal due to angular resolution . . . . . . . . . . 137
5.3.3 Effects on the anisotropy signal due to energy resolution . . . . . . . . . . . 139
5.3.4 Discussion and conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . 144
5.4 Search for correlations with AGNs with the MCF and uncertainties effects . . . . . 144
5.4.1 Effects on the correlation signal due to angular and energy resolutions . . . . 144
5.4.2 Discussion and conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . 145
5.5 Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 147

**6 Clustering and correlation of UHECR in Auger: astrophysical scenarios 150**
6.1 Bounds on the density of UHECR sources with MAF . . . . . . . . . . . . . . . 150
6.1.1 Relating the density of UHECR sources to the observation of clustering . . . . 150
6.1.2 Relating our work to existing studies . . . . . . . . . . . . . . . . . . . . . 151
6.1.3 Astrophysical models and simulations . . . . . . . . . . . . . . . . . . . . 152
6.1.4 Clustering analysis of simulated sky maps and Auger data . . . . . . . . . . 154
6.1.5 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 162

6.2 Bounds on source density of UHECR and EMF with MAF . . . 163
    6.2.1 Simulation of magnetic fields . . . 163
    6.2.2 Clustering analysis of simulated sky maps and Auger data . . . 164
    6.2.3 Conclusion . . . 168
6.3 Can nearby black holes be sources of UHE protons? . . . 169
    6.3.1 Data selection . . . 170
    6.3.2 Simulation of UHECRs . . . 172
    6.3.3 Clustering analysis of simulated sky maps and Auger data . . . 174
    6.3.4 Conclusion . . . 179
6.4 Influence of catalogues on the correlation between UHECRs and AGN . . . 180
6.5 Conclusions . . . 182

**7 A phenomenological global picture of Auger data above 60 EeV 184**
7.1 Introduction . . . 184
7.2 Simulation of sources and UHECRs . . . 185
7.3 Simulation of magnetic fields . . . 185
7.4 Description of the methods adopted for the clustering analysis . . . 186
    7.4.1 The global approach . . . 187
    7.4.2 The local approach . . . 187
7.5 Clustering analysis of simulated sky maps and of Auger data . . . 188
7.6 The elongation rate predictions from different hadronic models . . . 190
7.7 The energy spectrum in different scenarios . . . 191
7.8 The correlation with AGN . . . 192
7.9 Conclusion . . . 196

**Conclusions and outlook 197**

**Appendix A: Relativistic kinematics 199**

**Appendix B: Probability, Statistics and Information theory 202**
B.1 Probability and Statistics hints . . . 202
B.2 Information theory hints . . . 206

**Bibliography 209**

# List of Tables

3.1 Six-Parameter $\Lambda$CDM fit to *WMAP* data . . . . . . . . . . . . . . . . . . . . . . . . . . . 62
3.2 Flat cosmological models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90
3.3 Curved cosmological models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90

4.1 Main differences between p-value and $\alpha-$level approaches [217]. . . . . . . . . . . . . . . . 100
4.2 Worldwide surface detectors . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 111
4.3 Statistical power for several anisotropy estimators . . . . . . . . . . . . . . . . . . . . . . . 119

5.1 Auger data: number of events above a given energy . . . . . . . . . . . . . . . . . . . . . . 135
5.2 MAF: impact of angular uncertainty, CDF from VCV . . . . . . . . . . . . . . . . . . . . . 138
5.3 MAF: impact of angular uncertainty, CDF from Auger data . . . . . . . . . . . . . . . . . . 139
5.4 MAF: impact of energy uncertainty, CDF from Auger data . . . . . . . . . . . . . . . . . . 139
5.5 MAF: impact of energy uncertainty, CDF from Auger data with $\Delta E/E = 0.10$ . . . . . 143
5.6 MCF: impact of experimental uncertainties, CDF . . . . . . . . . . . . . . . . . . . . . . . 148

6.1 Source density study: astrophysical scenarios . . . . . . . . . . . . . . . . . . . . . . . . . 155
6.2 Source density study: bounds from *global* method . . . . . . . . . . . . . . . . . . . . . . 162
6.3 Density of several candidate sources of UHECR . . . . . . . . . . . . . . . . . . . . . . . . 162

7.1 Predicted fractions of protons from different hadronic models . . . . . . . . . . . . . . . . 191

# List of Abbreviations

| | |
|---|---|
| $\Lambda$CDM | $\Lambda-$Cold Dark Matter |
| ACF | AutoCorrelation Function |
| ASS | AxiSymmetric Spiral |
| BSS | BiSymmetric Spiral |
| CEL | Continuous Energy Loss |
| CR | Cosmic Rays |
| CGB | Cosmic $\gamma-$ray Background |
| CIB | Cosmic Infrared Background |
| CIOB | Cosmic Infrared/Optical Background |
| CMB | Cosmic Microwave Background |
| COB | Cosmic Optical Background |
| CRB | Cosmic Radio Background |
| CUVOB | Cosmic UltraViolet/Optical Background |
| CXB | Cosmic X-ray Background |
| EAS | Extensive Air Shower |
| EBL | Extragalactic Background Light |
| EBR | Extragalactic Background Radiation |
| EMF | Extragalactic Magnetic Field |
| GMF | Galactic Magnetic Field |
| GZK | Greisen-Zatsepin-Kuzmin |
| HECR | High Energy Cosmic Rays |
| HMR | Harari-Mollerach-Roulet |
| IRB | InfraRed Background |
| ISM | InterStellar Medium |
| LDF | Lateral Distribution Function |
| MHD | MagnetoHydroDynamics |
| SFR | Star Formation Rate |
| SNR | SuperNova Remnant |
| UHECR | Ultra HECR |

By striving to do the impossible,
man has always achieved what is
possible. Those who have
cautiously done no more than
they believed possible have
never taken a single step forward

M. A. Bakunin

# Conclusions and outlook

The subject of this thesis has been the investigation of the arrival directions of ultra-high energy cosmic rays (UHECRs) detected by the Pierre Auger Observatory. The study of UHECR at Earth cannot prescind from the study of their propagation in the Universe. We have developed an ad hoc Monte Carlo code (HERMES) for the realistic simulation of UHECR propagation (Chaps. 2 and 3). For the search for clustering in the observed arrival directions and for a correlation with astrophysical objects considered as possible UHECR accelerators, we have introduced a novel method, a multi-scale one (Chap. 4). Besides for the actual search of anisotropies, we have used such method to infer the nature of the sources and their density (Chaps. 5 and 6). Finally, we have considered the obtained results on anisotropy in the more general frame of Auger results (including the observed energy spectrum and the inferred mass composition) to constrain astrophysical scenarios compatible at the same time with these three main observables (Chap. 7). Into more details:

- In chapter 2 and 3 we have described the HERMES propagation code, presenting the modeling we have adopted for i) the cosmological framework, ii) the cosmic background radiation (microwave, infrared/optical and radio), iii) the regular component of the Galactic magnetic field and the irregular component of both the Galactic and the extragalactic magnetic fields, iv) the cross sections describing the interactions between UHE nuclei and photons of extragalactic background radiation, v) the production of secondary particles because of such interactions.
- In the same chapters we have shown several simulations of nuclei propagating in a magnetized Universe and in our Galaxy, by varying the relevant parameters, putting in evidence impact of magnetic fields and energy-loss processes. We have included all the relevant energy losses, as the adiabatic loss (due to the expansion of the Universe), the pair and photo-pion production, and, in the particular case of heavy nuclei, the photo-disintegration processes. We have estimated the surviving probability of UHECRs as a function of their energy and their propagation distance, and we have investigated the impact of energy-loss processes on the propagation of nuclei and, in particular, on the GZK horizon of UHE protons. The agreement between our results and those ones obtained with other simulator available to the community is remarkable.
- In chapter 4 we have introduced a new multiscale method for the investigation of the anisotropy in the arrival direction distribution of UHECR events. It has been designed to perform both catalog-independent and catalog-dependent analyses, and it is based on information theory and extreme value statistics. We have shown that the multiscale method is a competing tool for the study of both small and large scale anisotropies and correlations, providing a great discrimination power even in presence of a strong background contamination and for quite different astrophysical scenarios. As a possible application of our method, we have shown how to probe the Hubble parameter with clustering analysis, by assuming that AGN in the nearby Universe are the sources of UHECRs.
- In chapter 5 we have extensively used multiscale methods to search for an anisotropy signal in

Auger UHECR data, as well as for a correlation with candidate objects in astronomical catalogues. We have investigated the influence of angular and energy uncertainties on both the anisotropy and the correlation signals of events detected with the Pierre Auger Observatory. We have shown that such uncertainties have an impact on the estimated signal. In particular, the energy resolution significantly affects the clustering, whereas the angular resolution negligibly affects such studies.

- In chapter 6 we have investigated several astrophysical scenarios that could be responsible for the observed clustering and correlation in Auger data. We have performed several different studies to estimate the density of UHECR sources by varying the underlying hypotheses on the mass composition, the intensity of magnetic fields and distribution of sources. We have found that the lower bound on the source number density is of the order of $10^{-4}$ Mpc$^{-3}$ at 95% confidence level, hence excluding some classical candidate astrophysical objects as BL Lac and colliding galaxies, in favor of active galactic nuclei (AGN) and gamma-ray bursts (GRB). Additionally, we have explored the possibility that nearby black holes are the sources of UHECRs detected with the Auger Observatory. We have found that the mass of black holes plays an important role in anisotropy analysis. In fact, the luminosity of black holes is proportional to their mass, as well as the density of such objects in the nearby Universe, and both quantities have a direct impact on the clustering of UHECRs. Our results suggest that, even in the more extreme cases, black holes with mass smaller than $\approx 10^{7.3} M_\odot$ or larger than $\approx 10^{8.75} M_\odot$ are unlikely to be the only sources of UHE protons. Conversely, black holes with mass larger than $M_{\mathrm{BH}}$, with $10^{7.3} < M_{\mathrm{BH}}/M_\odot < 10^{8.75}$ are candidate sources of UHE protons observed at Earth above 60 and 80 EeV.
- Finally in chapter 7 we have performed a more extended study, taking into account the two other most relevant observations of the Pierre Auger Observatory, namely the average maximum of the shower development and the energy spectrum. By varying the underlying assumptions, as for instance those ones on the mass composition and the intensity of magnetic fields, we have simulated the production of UHECRs and their propagation in a $\Lambda$CDM cosmology. Hence, we have outlined the astrophysical scenarios able to explain Auger data from a phenomenological point of view. We have found two plausible scenarios, corresponding to two different models for galactic and extragalactic magnetic field: more intense GMFs requires a higher fraction of protons (around 50%) in the data to obtain the observed clustering and correlation signals, whereas less intense GMFs requires a smaller fraction of protons (around 20%) to achieve the same result. In the first case, results are in agreement with predictions from SIBYLL and QGSJET hadronic models, whereas in the second case, there is agreement only with predictions from EPOS. In any case, the more likely spectral injection index is 2.4. However, if a global comparison is performed, the scenario with a weak turbulent GMF, together with the corresponding compatible models, is the most suitable candidate to reproduce the observed data.

As widely discussed in the present thesis, a final answer about the origin and the composition of UEHCRs is still missing. The analyses presented in this thesis have had the aim of shedding more light on the problem of UHECR origin. This has been possible especially thanks to the access to the data of the largest ever built cosmic ray experiment, the Pierre Auger Observatory. Our studies have provided results about the propagation of UHECRs, their clustering and their possible sources in the energy region of highest attraction in astroparticle physics, namely the trans- and super-GZK region (approximatively above $10^{19.7}$ eV). They have also shown that the modeling of both sources and propagation, coupled to clustering and correlation analysis, may be able to open new insights to the solution of the still unsolved UHECR puzzle.

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