

# PhD draft test title

To obtain the academic degree of

**Doctor of Science**

from the Faculty of Physics of the  
Karlsruhe Institute for Technology (KIT)

and

from the Institute of Technology "Prof. Jorge A. Sabato" of the  
Universidad Nacional de General San Martín (UNSAM)

submitted

**Dissertation**

of

**Paul Filip**

born in Breisach am Rhein

Day of the oral exam: 01.01.1970

Referent: Prof. Dr. Ralph Engel

Co-referent: Prof. Dr. Missi Ngno

Supervisor(s): Dr. David Schmidt



Universidad  
Nacional  
de San Martín



# PhD draft test title

Para optar por el título

## **Doctor en Ciencias Naturales**

del Instituto de Tecnología "Prof. Jorge A. Sábato" de la  
Universidad Nacional de General San Martín (UNSAM)

y

de la facultad de física del  
Instituto de Tecnología de Karlsruhe (KIT)

presentado

## **disertación**

de

**Paul Filip**

nacido en Breisach am Rhein

Día del examen:

Director: 01.01.1970

Co-Director: Prof. Dr. Ralph Engel

Co-referent: Prof. Dr. Missi Ngno

Colaborador(es): Dr. David Schmidt

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Zur Erlangung des akademischen Grades eines

## **Doktors der Naturwissenschaften**

an der Fakultät für Physik des  
Karlsruher Instituts für Technologie (KIT)

und

am Institut für Technologie "Prof. Jorge A. Sabato" der  
Universidad Nacional de General San Martín (UNSAM)

vorgelegte

## **Dissertation**

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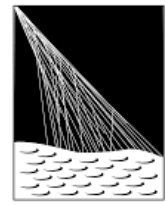
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# Abstract

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# Resumen

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# Zusammenfassung

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# Acronyms




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This is a list of alphabetically sorted acronyms used throughout this work.

<b>CR</b>	<i>Cosmic Ray</i> . . . . .	5
<b>DAQ</b>	<i>Data Acquisition</i> . . . . .	7
<b>EAS</b>	<i>Extensive Air Showers</i> . . . . .	8
<b>FD</b>	<i>Fluorescence Detector</i> . . . . .	7
<b>GAP</b>	<i>Giant Array Project</i> . . . . .	11
<b>SD</b>	<i>Surface Detector</i> . . . . .	7
<b>PAO</b>	<i>Pierre Auger Observatory</i> . . . . .	7
<b>UHECR</b>	<i>Ultra High Energy Cosmic Ray</i> . . . . .	5
<b>UV</b>	<i>ultra violet</i> . . . . .	8
<b>WCD</b>	<i>Water Cherenkov Detector</i> . . . . .	7

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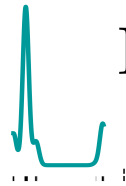


# Introduction

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# Part 1: Cosmic rays and extensive air showers

lyon

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*Cosmic Rays* (CRs) are particles of extraterrestrial origin that travel very close to the speed of light. Their relativistic kinetic energy  $pc$  far exceed their rest mass  $mc^2$ . In particular, *Ultra High Energy Cosmic Rays* (UHECRs) are typically defined as CRs with energies exceeding  $1 \text{ EeV} = 10^{18} \text{ eV}$  [P10]. These microscopic fragments are direct witnesses to the most violent processes known to date, and as such of great interest to researchers. Not only do they hold the key to understanding particle interactions at extremely high energies and small scales, but can also improve our understanding of the cosmos, and the universe at large scales.

It follows a discussion of the source mechanisms and origins of cosmic rays in Section 1.1 and Section 1.2. Various scenarios of CR creation at different sources are highlighted. In Section 1.3 we describe the transport of CRs through the cosmos from source to observer (i.e. earth). We finish with Section 1.4, where the interactions between CRs and the upper atmosphere that give rise to large cascades of secondary particles are explained.

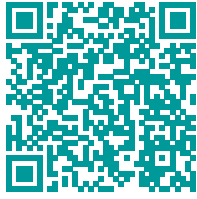
## 1.1 Sources of cosmic rays

## 1.2 Origin of cosmic rays

## 1.3 Propagation of cosmic rays

## 1.4 Extensive Air Showers





# Part 2: The Pierre Auger Observatory

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The *Pierre Auger Observatory* (PAO) is the (by area) largest scientific experiment in the world. It consists of an array of 1660 *Water Cherenkov Detectors* (WCDs), which form the *Surface Detector* (SD), and 27 fluorescence telescopes, that make up the *Fluorescence Detector* (FD).

With a region spanning roughly 3000 km<sup>2</sup> it offers a unique possibility to observe UHECRs at the tail-end of the CR energy spectrum with an unprecedented accuracy and precision.

We begin this chapter in Section 2.1 by formulating open questions that the PAO aims to answer. Design details for the FD and for the SD are given in Section 2.2 and Section 2.3 respectively. After a discussion on the local *Data Acquisition* (DAQ) process and the centralized event detection in Section 2.4, we finish by detailing the procedure of the event reconstruction and higher level analysis in Section 2.5.

## 2.1 Science Goal and Open Questions

The flux of cosmic rays with energies exceeding the ankle,  $5 \times 10^{18}$  eV, is very low, and measures on average 6 events per km<sup>2</sup> yr [P11]. It is evident that one needs a large detector and a lot of time in order to make statistically relevant statements about the physics of UHECRs. Although only one of the initially planned two data taking sites came to reality [for white paper see P3], the Pierre Auger observatory has been be a world-leading experiment in terms

of measured exposure from the beginning of DAQ in January 2004 [P4], and will continue to yield results until decommission after 2030 [C1].

Many insights, such as the existence of the CR dipole discussed in Section 1.2, have been gathered from Augers event database as a consequence. Still, a plethora of mysteries remain. It follows a list of, in no particular order, important missing links of information that motivate not least this thesis, but the continued effort and daily work done by the Auger collaboration.

### 2.1.1 Flux suppression at highest energies

### 2.1.2 Validity of shower simulations

### 2.1.3 Exotic events

Photon showers

Neutrino showers

GZ effect

## 2.2 The Fluorescence Detector

The Fluorescence Detector of the PAO is a set of 27 reflector telescopes tuned to detect faint sources of *ultra violet* (UV) light. More specifically, the aim of the FD is to observe UV-emission of *Extensive Air Showers* (EAS). However, since the solar irradiance ( $120 \text{ W/m}^2$  @  $200 \text{ nm}$ – $400 \text{ nm}$  [P9]) and even the lunar irradiance ( $16 \text{ nW/m}^2$  @  $180 \text{ nm}$ – $300 \text{ nm}$  [P2]) in the UV-band far outshine the emission of UV-light by cosmic rays ( $0.32 \text{ nW/m}^2$  @  $337 \text{ nm}$  Appendix A.1), the FD can only operate in the astronomical night during third to first quarter moon. This consequently drops the duty cycle to approximately 20%.

### 2.2.1 Telescope and camera design

### 2.2.2 Calibration of measurements

Drum calibration

XY-scanner

## 2.3 The Surface Detector

roughly mention design, duty cycle

## 2.4 Central Data Acquisition System

## 2.5 Offline and Event Reconstruction

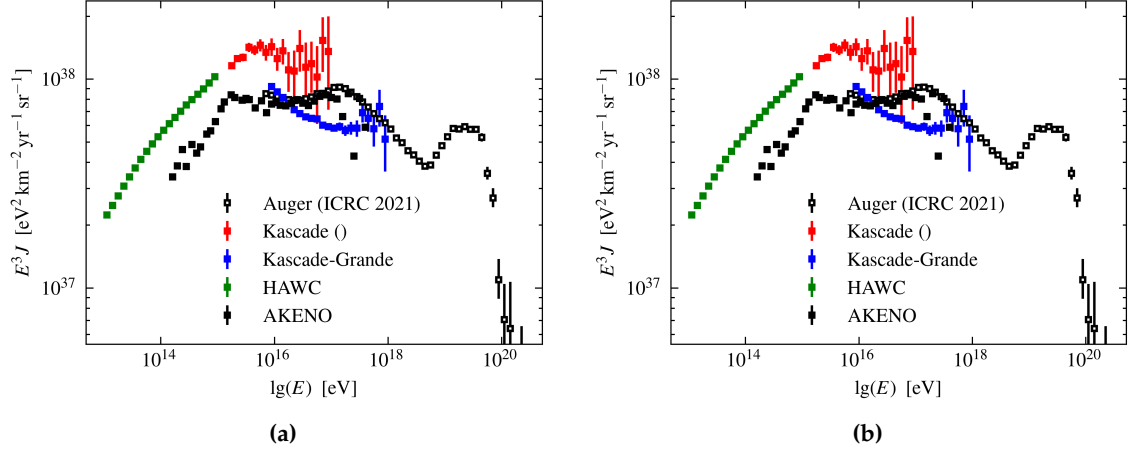


Figure 2.1: (b) asdasd (b) asdasd

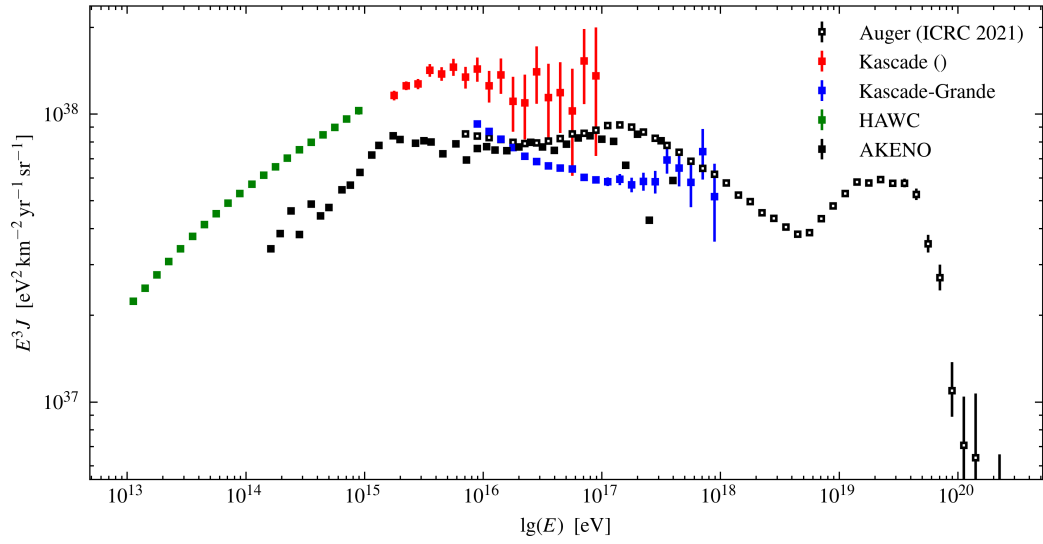


Figure 2.2: asdasdasdasd



# Bibliography

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The Pierre Auger observatory hosts an internal database of papers. These typically short reports serve to accelerate the exchange of knowledge within the collaboration, and are called *Giant Array Project* (GAP) notes. Since they contain information that is not freely accessible outside the Pierre Auger collaboration, they are listed in a special category with the prefix *G*. Similarly, sources from personal correspondence are grouped with the prefix *C*. Physical references, also containing official publications by the Pierre Auger collaboration, can be found with label *P*. All other references are indexed under the label *O*.

## Personal Correspondence

[C1] Antonella Castellina. “Outcome of the Finance Board”. Dec. 2023.

## Physics References

- [P1] William Alvin Baum. “Attenuation of ultraviolet light by the lower atmosphere”. en. PhD thesis. 1950. DOI: [10.7907/99T9-5S60](https://doi.org/10.7907/99T9-5S60).
- [P2] J. Lean. “Contribution of Ultraviolet Irradiance Variations to Changes in the Sun's Total Irradiance”. In: *Science* 244.4901 (Apr. 1989), pp. 197–200. ISSN: 1095-9203. DOI: [10.1126/science.244.4901.197](https://doi.org/10.1126/science.244.4901.197).
- [P3] Danilo Zavrtanik and P. Auger Collaboration. “The Pierre Auger Observatory”. In: *Nuclear Physics B-Proceedings Supplements* 85.1-3 (2000), pp. 324–331.
- [P4] J. Abraham et al. “Properties and performance of the prototype instrument for the Pierre Auger Observatory”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 523.1-2 (2004), pp. 50–95. DOI: <https://doi.org/10.1016/j.nima.2003.12.012>.
- [P5] J. Matthews. “A Heitler model of extensive air showers”. In: *Astroparticle Physics* 22.5–6 (Jan. 2005), pp. 387–397. ISSN: 0927-6505. DOI: [10.1016/j.astropartphys.2004.09.003](https://doi.org/10.1016/j.astropartphys.2004.09.003).
- [P6] M. Risse et al. “Photon air showers at ultra-high energy and the photonuclear cross-section”. In: *Czechoslovak Journal of Physics* 56.S1 (Sept. 2006), A327–A336. ISSN: 1572-9486. DOI: [10.1007/s10582-006-0166-7](https://doi.org/10.1007/s10582-006-0166-7).
- [P7] M. Ave et al. “Spectrally resolved pressure dependence measurements of air fluorescence emission with AIRFLY”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 597.1 (Nov. 2008), pp. 41–45. ISSN: 0168-9002. DOI: [10.1016/j.nima.2008.08.052](https://doi.org/10.1016/j.nima.2008.08.052).
- [P8] B. Keilhauer et al. “Nitrogen fluorescence in air for observing extensive air showers”. In: *EPJ Web of Conferences* 53 (2013). Ed. by K.-H. Kampert et al., p. 01010. ISSN: 2100-014X. DOI: [10.1051/epjconf/20135301010](https://doi.org/10.1051/epjconf/20135301010).



- [P9] Martin Snow et al. "Absolute Ultraviolet Irradiance of the Moon from the LASP Lunar Albedo Measurement and Analysis from SOLSTICE (LLAMAS) Project". In: *Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere*. Springer New York, 2013, pp. 227–253. ISBN: 9781461463849. DOI: [10.1007/978-1-4614-6384-9\\_8](https://doi.org/10.1007/978-1-4614-6384-9_8).
- [P10] Rafael Alves Batista et al. "Open questions in cosmic-ray research at ultrahigh energies". In: *Frontiers in Astronomy and Space Sciences* 6 (2019), p. 23.
- [P11] Francesco Fenu and P. Auger Collaboration. "The cosmic ray energy spectrum measured with the Pierre Auger Observatory". In: *Advances in Space Research* 72.8 (2023), pp. 3531–3537. ISSN: 0273-1177. DOI: <https://doi.org/10.1016/j.asr.2023.06.020>. URL: <https://www.sciencedirect.com/science/article/pii/S0273117723004581>.

# Derivations and calculations

## A.1 Approximating the upper limit of the UV irradiance of an EAS

In the following, we estimate the UV irradiance,  $I_{UV}$ , or Wattage deposited per area, from fluorescence light stemming from an extensive air shower. To illustrate that telescopes need to be incredibly sensitive to observe this phenomenon, we assume fantastic to unrealistically good conditions for the UV light yield and related parameters. This thus results in a very optimistic upper limit to  $I_{UV}$ .

Consider a cosmic ray with energy  $E_0 = 10^{18}$  eV impinging almost vertically ( $\theta = 15^\circ$ ) on the upper atmosphere. We assume the behaviour of the particle cascade resulting from the deeply inelastic scattering processes of the primary particle is completely determined by the Heitler-Matthews model (see and [P5, P6]). We then arrive at the following value for the atmospheric depth (height), at which the EAS reaches its maximum in multiplicity:

$$X_{\max} \approx 700 \text{ g/cm}^2 \quad (\approx 18.5 \text{ km above earth surface}^1). \quad (\text{A.1})$$

At  $X_{\max}$ , the EM component of the shower contains roughly  $1 - (E_0 / \xi_C^\pi)^{\beta-1} \approx 92\%$  of the primary particle energy, with photons and electrons sharing the fraction to equal parts. Continuing, we assume that only electrons contribute meaningfully to excitations of air molecules. Muons in the hadronic component of the EAS are minimally ionizing and can therefore be neglected, similar arguments apply for photons in the EM component.

It thus follows that  $E_{UV} = 0.92 \cdot 0.5 \cdot 10^{18} \text{ eV} = 4.6 \times 10^{17} \text{ eV}$  are available a priori to create fluorescence light. As per [P8], optimistic numbers for the fluorescence light yield are about  $FY = 8\gamma / \text{MeV}$ . Most of these photons stem from the  $2P(0,0)$  transition of  $N_2$  [P7], which has a characteristic wavelength of 337.1 nm, and an average radiation time of 42 ns [P2].

Assuming that all available energy  $E_{UV}$  is immediately converted to molecular excitations of  $N_2$  at  $X_{\max}$ , and then gradually released according to an exponential decay, we recover an expression for the (UV) power output of the air shower.

$$P(t) = FY E_{UV} \frac{hc}{337.1 \text{ nm}} \cdot \frac{e^{-42 \text{ ns}/t}}{t} \quad (\text{A.2})$$

<sup>1</sup>The calculated height above surface that corresponds to the given atmospheric depth varies a lot based on atmospheric variables. We have assumed a purely isothermic atmosphere with  $T = 278 \text{ K}$ , and a standard density of  $\rho = 0.86 \text{ kg/m}^3$  at an altitude of 1400 m above sea level.

For the example at hand, this results in a maximum power output of  $P_{\max} \approx 19.4 \text{ W}$ . This macroscopic number might seem optimistic for such a microscopic process, but in reality is not surprising, as the shower itself is incredibly short lived.

In a last step, we convert the maximum power output to an irradiance measured on ground. For this, we must take into account that the area illuminated by the UV-light grows proportional to the distance squared to the source (location of  $X_{\max}$ ). Furthermore, UV-light is attenuated by the atmosphere. More specifically, UV light with a wavelength of 337 nm drops in intensity by about 13%/km in clear conditions [see Fig. 83 on page 103 of [P1](#)]. Supposing that an observer is at least  $d = 18.5 \text{ km}$  away from  $X_{\max}$  (compare Eq. [\(A.1\)](#)), we estimate the total irradiance this observer measures as

$$I_{\text{UV}} = P_{\max} \frac{e^{-0.14 \frac{d}{\text{km}}}}{4\pi d^2} \approx 0.32 \text{ nW/m}^2. \quad (\text{A.3})$$

## Additional Figures

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## Tabulated Data

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## Additional Content

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