Prof Jan Trlifaj, Vice Dean 31 August 2018
To whom it may concern.

Opponent's Review on Dalibor Nosek's Habilitation Thesis:
Mass Composition and Arrival Directions of the Highest Energy Cosmic Rays

The thesis presented, addresses a very topical open problem in cosmic ray and astroparticle physics: The origin of high energy cosmic rays. This is an extremely difficult and stubborn problem, as already in 1962 a cosmic ray was unambiguously recorded that had an energy of about 10^{20} eV, an incredibly high energy at the time, yet, still today, almost 60 years later, we do not know what the sources are, we can only hypothesize on the mechanisms of their production and to detect them requires huge detectors that go to the limits of what today can be built in large international collaborations. Although we know that the highest energy cosmic rays are nuclei (from protons to about iron and beyond), we still cannot clearly identify what the elemental composition beyond about 10^{15} eV is

A reason for the difficulty is that cosmic rays, charged particles, do not travel in straight lines, and therefore do not normally point back to their sources. Cosmic rays "diffuse" in the magnetic fields of the galaxy and of intergalactic space for a long time before arriving at Earth, and therefore a direct connection of a cosmic ray to their source has been lost. Cosmic rays arriving at Earth are a mix from many galactic and extragalactic sources with different spectra and arrive largely isotropic.
Unless, of course, the CR energy is so high that the deflection remains small (of order few degrees). With current knowledge, one would have expected that particles of 10^{20} eV indeed are only deflected little in the cosmic magnetic fields and should start to point back at their source, thus enabling charged-particle astronomy.
At low energies ($<10^{12}$ eV), cosmic rays are mainly protons, with heavier nuclei making only a few % of the total flux. Assuming that at high energies also protons ($z=1$) are a good fraction of the cosmic rays, one would certainly expect those to be deflected very little from their source to us, whereas nuclei with $1<z<26$ … would be deflected z times more, and are thus expected to point back to their sources less well. Thus, the two ways to make progress in the search of the origin of highest energy cosmic rays it, to identify the cosmic ray particles and measure the arrival direction of their smallest-z fraction, and to look for anisotropies in the overall arrival direction of cosmic rays as a function of energy, that may indicate a referred arrival direction.

For any further analysis, the primary energy of each comic ray particle, its arrival direction and its identity are "a priori" unknown and need to be reconstructed from the reaction products (the extensive air shower) the primary particle creates in the atmosphere. Unfortunately, also the hadronic interaction and secondary particle production in the atmosphere are partly unknown at high energies, as cosmic rays go well beyond of what man-made accelerators can produce. The combination of all these factors makes cosmic ray physics so difficult and challenging.

The Pierre Auger Observatory is the best existing observatory for ultra-high energy cosmic rays (UHECRs; $E>10^{18}$ eV). It covers 3000 km^2 with detectors of two types: the surface detectors (SD) that are operational all the time and the fluorescence detectors (FD) that are only operational during dark moonless nights, only about 10% of the time. Scientists in the

Auger Collaboration work to identify the mass composition of cosmic rays and search for signs of preferred arrival directions. Also, the improvement of the shower simulation to be able to reproduce the Auger measurements is a key ongoing project. These are the three remaining chief directions of research. (The shape of the overall energy spectrum of cosmic rays from about 10^{17} to beyond 10^{20} eV has been measured and the spectral features "ankle" and "cut-off" have clearly been detected and characterized.) A hardware upgrade is currently underway to improve the sensitivity to measurements of the mass composition. Hopes are high, that with this upgrade cosmic ray protons can be selected, pointing back at one (or more) sources. The combination of the various SD and FD observables, and the comparison of measurements with Monte Carlo simulations, has so far not delivered a coherent and unambiguous result on the cosmic ray composition at high energies.

This thesis explains well the situation in ultra-high-energy cosmic ray research und the status of the Pierre Auger Observatory in chapter 2 and 3. The main chapters 4 and 5 address the two main directions of research of Auger that currently are pursued vigorously. Dr Nosek has been a member of the Pierre Auger Collaboration since many years and UHECR physics has been his main topic of research. He has co-authored all the collaboration papers of Auger which have been published in het last few years. In many, the work of Dr Nosek, which is demonstrated in the listed conference reports and internal Auger notes (GAPs). They prove the breadth and productivity of Dr Nosek over the years.

He also published a number of few-author papers in refereed journals, that are to form the basis of this habilitation thesis (papers A01, A02, B01, B02). The papers have been published from 2015 to 2017. Dr Nosek tries to introduce statistical concepts that are well proven in other areas of science to the analysis of cosmic ray composition data. They all address aspects of the highly non-trivial analysis of multivariate data. The combination of the various observables in Auger promises enhanced mass and directional sensitivity. Over the years, several attempts have been made within the UHE community to analyze their data, but no convincing result could be achieved so far.

In chapter 4, Dr Nosek explains very concisely the status of the Auger mass composition analysis and its current limitations. In chapter 4.3 and 4.4 he comments on the papers A01 and A02, respectively. In sec. 4.3, a Monte Carlo study hints at a way to determine mass composition by comparing SD data at different zenith angles, masses and energies. With the ongoing detector upgrade at Auger, it becomes even more promising to disentangle electromagnetic and muonic signals and get a handle on the mass composition. In sec. 4.4 the maximum entropy method is investigated for composition analysis of data from the fluorescence detectors.

In chapter 5, De Nosek describes the exciting course of recent events in cosmic ray arrival directions and point source search. Propagation effects and influence of ambient magnetic fields are discussed and the latest version of the all-particle energy spectrum is presented. Also here the uncertainty of the composition hampers further scientific progress and source identification. A number of potential sources, nearby powerful AGNs, are discussed. In sec. 5.4. new analysis approaches from publications B01 and B02 are explained. They use a Bayesian approach to disentangle a "source" and a "background" population of cosmic rays.

Considerable supporting work has been described in a number of GAP notes (internal Auger reports). The publications and the supporting reports are of a high quality, with substantial potential to improve the Auger mass composition and source search analyses.

In summary, I am very pleased with the report at hand, which is certainly of international standard for a habilitation. Dr Nosek proves considerable breadth and has made valuable contribution to the Pierre Auger Observatory and its data analysis. I valuate this thesis as an important contribution for the benefit of students and experts in the field. **Therefore, I support with emphasis the appointment of Dr Nosek as an associate professor.**

Topics of discussion during the defense could be the following:

So far there is no visible impact yet of the four key publications in the Auger Collaboration or the wider community. They have not been cited yet by other publications (may be partly due to their rather recent publication?). It would be interesting to know how Dr Noseks work has been received in the Auger Collaboration and how it will be used in upcoming analyses and publications.

How does Dr Nosek judge the potential of the recently developed radio technique in detecting air showers and how could Auger benefit from it after the upgrade?

What will the Auger upgrade mean for the search for UHE photons and neutrinos?
By how much will its detection sensitivity be improved?

What would be a logical next step in experiments for UHECRs after the Auger upgrade?
Is a ground-based 30,000 km^2 array for UHECR still desirable?
What are advantages and disadvantages of a space observatory of UHE cosmic rays?

With best regards

Dr Johannes Knapp

Astroparticle Physics
Deutsches Elektronensynchrotron (DESY)