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Using SKA-Low to detect PeV gamma-rays from Galactic Sources

F. Schlüter,[a,*] **P. Laub,**[b] **A. Nelles,**[b,m] **S. Bouma,**[b] **J. Bray,**[c] **S. Buitink,**[d,e] **A. Corstanje,**[d,e] **V. De Henau,**[d] **M. Desmet,**[d] **E. Dickinson,**[f] **L. van Dongen,**[e] **B. Hare,**[g,h] **H. He,**[i] **J.R. Hörandel,**[e] **T. Huege,**[j,d] **C.W. James,**[f] **M. Jetti,**[k,l] **H.-J. Mathes,**[j] **K. Mulrey,**[e] **O. Scholten,**[g] **C. Sterpka,**[h] **S. ter Veen,**[h] **K. Terveer,**[b] **P. Turekova,**[g,h] **T.N.G. Trinh,**[o] **S. Saha,**[j,p] **S. Sharma,**[b] **R. Spencer,**[c] **D. Veberic,**[j] **K. Watanabe,**[j] **M. Waterson,**[q] **C. Zhang,**[r,s] **P. Zhang**[t] **and Y. Zhang**[i,u]

E-mail: felix.schluter@icecube.wisc.edu

The Square Kilometre Array (SKA) is a next-generation radio telescope, and upon construction in 2030 the world's most sensitive one. SKA will comprise a low frequency component with almost 60 000 radio antennas on an extremely densely instrumented area of about 1 km^2 located in Australia. Sensitive to the radio emission in the 50 MHz to 350 MHz band, these astonishing dimensions offer intriguing capabilities for the detection of extensive air showers. While SKA will play a leading role in high-precision cosmic ray measurements, it may also play a role in gamma-ray astronomy. The particle cascade initiated by a gamma ray impacting on the Earth's atmosphere will emit radio waves, comparable to the emission observed from hadronically induced air showers. The energy threshold of current radio-air-shower experiments of tens to hundreds of PeV has limited those experiments to cosmic-ray science so far. With the interferometric measurement of air showers combining the coherent air-shower signals from thousands of individual antennas, we aim at lowering the energy threshold for the radio detection of air showers to PeV energies. The superior angular resolution of SKA may provide a way to both trigger on gamma-rays and separate them from hadronic cosmic rays. SKA's field of view of the Galactic Center provides a unique opportunity of obtaining a first detection at PeV energies. This contribution will sketch the challenges of as well as the necessary steps needed for gamma-ray detection with SKA and will highlight the scientific impact.

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*Speaker

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1. Introduction

In these proceedings, we are exploring the possibility of detecting PeV gamma-rays with the Square Kilometre Array Observatory (SKAO). SKAO will be the world's largest radio telescope, covering science cases from the Cosmic Dawn to extra-galactic and Galactic astronomy, to the local neighborhood. SKAO consists of two sites, SKA-Mid in South Africa (350 MHz - 15.4 GHz) and SKA-Low in Australia (50 MHz - 350 MHz). In particular the setup of SKA-Low with an extremely dense array of about 60,000 individual antennas also offers intriguing prospects for the detection of air showers.

The successful operation of an astronomical radio telescope as an air-shower detector has already been demonstrated by the Low Frequency Array (LOFAR) [1]. In the last decade, the radio technique has established itself next to traditional methods, such as particle detectors or fluorescence telescopes, to detect extensive air showers. It is sensitive to all relevant properties of the primary cosmic particle, i.e., the particle direction, energy, and type. It has been suggested before that one could use sensitive radio arrays to detect PeV gamma-rays from sources, such as the Galactic Center [2]. However, the comparatively high energy threshold remains an issue. The threshold is determined effectively by the shower energy at which the radio pulse amplitude exceeds the thermal fluctuations in the receiving system and becomes detectable. LOFAR has detected single showers at 10^{16} eV, but composition measurements, for example, have been reported starting just below 10^{17} eV [3]. Since the amplitude scales linearly with shower energy, showers at 10^{15} eV will be buried in the noise at LOFAR, requiring optimized detectors and advanced strategies.

The SKA-Low is an interferometric detector and the signals from the individual receiving antennas will be combined using various techniques such as beamforming: signals across different receivers are time-shifted according to the signal arrival direction to be aligned in time and summed together. Coherent signals will add up linearly, incoherent signals will scale with the square root of the number of receivers (N), which provides an improvement of the signal-to-noise ratio of $\sqrt{N}$. This makes it possible to detect very faint, otherwise not detectable, coherent signals by combining a large number of individual receivers and thereby lowering the energy threshold for the radio detection of air showers. With SKA-Low, single air showers will be detected by thousands of dual-polarized radio antennas, which is orders of magnitude more antennas than any other air-shower experiment. With that, we hope to pioneer the radio detection of PeV air showers. This could open a new window for the detection of ultra-high-energy gamma rays in the Southern Hemisphere to study and potentially discover new Galactic PeVatrons.

While the order of magnitude estimates look very promising, technical, procedural, and algorithmic work is needed to fully enable a gamma-ray observing mode. Particularly, challenging are the triggering of SKA-Low, without disturbing on-going astronomical observations, as well as sufficient gamma-hadron separation at these (for radio) low energies. These proceedings report on the first steps towards simulating PeV showers in SKA-Low and highlighting the opportunities.

2. The SKA-Low detector

The Square Kilometre Array Observatory is an international, next-generation radio telescope located in South Africa featuring a mid-frequency component (350 MHz to 14 GHz) and Australia

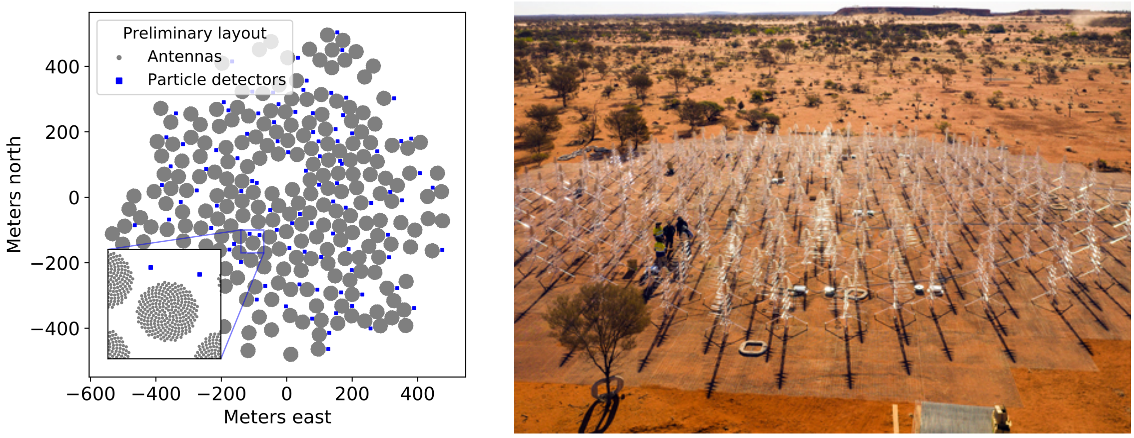

Figure 1: *Left*: The SKA-Low core plus satellite stations. Each gray circle indicates a station of 256 antennas. The squares indicate foreseen positions of the SKA-Low particle detectors consisting of a dense core, a ring around the core, and additional detectors near the satellite stations. Exact locations are still subject to discussion. *Right*: Picture of the first SKA-Low station with 256 antennas (SKAO Observatory).

featuring a low-frequency component (50 to 350 MHz) [4]. Construction of the, for this work relevant, low-frequency component with more than 100 000 receivers, i.e., dual-polarized antennas has already started and its completion is expected in 2030. Almost 60 000 receivers will be deployed in an extremely dense core region of about one square kilometer. The array is organized in stations with 256 receivers arrange on a spiral grid making up one station. Each receiver consist of two orthogonal-oriented SKALAv4 antennas. A map of the SKA-Low array[1] and an image of the first deployed station with SKALAv4 antennas can be seen in Fig. 1. Within the scope of these proceedings, we assume that the antennas in each receiver unit, are orientated along North-South and East-West axis respectively, while in reality all stations will have an individual rotation with respect to local north. For this study, we simulate the response of each receiver unit to the electromagnetic radiation from air showers. To this end, we are take into account a model for the direction- and frequency- dependent sensitivity of the SKALAv4 antenna and sample the signals at 800 MHz. No additional filter or amplifier are simulated (the antenna model acts a band-pass filter between 50 MHz and 350), as some system parameters will only be shared after science verification. While SKA is expected to digitize signals at 8-bit resolution, no digitization is simulated yet. We do not expect the limited resolution - or the lack of simulating it - to have a significant effect on our results as with the large amount of signals any effect will be averaged out. A limited dynamic range as imposed by a digitizer is also no issue as our signals are well within the noise floor.

To improve the capability of SKA-Low to detect air showers the High Energy Cosmic Particle (HECP) science working group is planing to construct an additional particle detector. The baseline configuration features $\mathcal{O}\,(100)$ units of $\mathcal{O}\,(\mathrm{m}^2)$ scintillator panels. However, this configuration might change in the future to improve air-shower detection and in particular discrimination capabilities (also driven by this project).

[1]The map shows the AA4 array configuration which we used in this work for our simulations. After a rebaseling of the construction plans for SKA-Low, a new configuration AA* with slightly fewer stations is meant to be build. We do not expect a noticeable difference due to that change for our results.

3. Simulating PeV air showers for SKA-Low

To simulate the radio emission from extensive air showers, numerical Monte-Carlo codes, such as CoREAS[2], have become the gold-standard in recent years providing the best fidelity. However, these codes are computational expensive and the very large number of receivers in SKA-Low prevents simulating the signals for all or even a sizable fraction of all receivers with such codes. To circumvent this limitation we are making use of a recently developed algorithm which allows to interpolate the full electric field traces from a specific grid of simulated signals to arbitrary receiver positions [5]. With this it is possible to use a single simulated air shower several times while each time changing its position w.r.t. the detector array. This interpolation, as well as the simulation of the instrumental response of an SKA-Low receiver as described in the aforementioned section, is performed with NuRadio, an open-source, python-based simulation and reconstruction framework framework for radio detection from neutrinos-induced in-ice particle cascades as well as air showers [6]. In addition to the electromagnetic radiation from air showers, we simulate the thermal radiation from the sky impinging on the antennas. For the radio brightness of the sky we are using the GSM2016 model as implemented in NuRadio. We randomly vary the time, for which we integrate the sky brightness at the location of SKA-Low. We are not simulating any electronic noise contribution.

For this work, we use a set of 99 1 PeV gamma-ray showers with 15° zenith and 0° azimuth angle. Different energies are simulate by scaling the Galactic noise by a factor of s, resulting in a simulated energy (relative to noise) of $E_{\mathrm{sim}} = s^{-1} \cdot 1\,\mathrm{PeV}$. This is motivated by the fact that the signal amplitude and therefore the signal-to-noise ratio (SNR) scales in first order linearly with the energy of the primary gamma ray. Per shower we simulate five positions, randomly distributed in the range $x, y \in [-500\,\mathrm{m}, 500\,\mathrm{m}]$. To save storage space we only interpolate antennas within a 400 m radius. This is more than sufficient to contain the footprint, since the shower is very vertical.

4. Detecting PeV gamma rays with SKA-Low

To study the prospect of detecting gamma rays with SKA-Low, a couple of key questions have to be addressed: I) Is the flux of gamma rays at PeV energies sufficiently strong to be detected by a square-kilometer detector? II) Is it possible to detect gamma ray-induced air showers down to PeV energies with SKA-Low? III) Can one identify gamma-ray induced air showers over a large background of hadron-induced air showers?

4.1 Extrapolating fluxes from known TeV sources

The sky map in Fig. 2 (*left*) shows the position of potential sources observable by SKA-Low. Those include the high energy LHAASO sources from [7] within the SKA-Low FOV of $\theta \leq 65°$ around the zenith, as well as selected HESS sources from the galactic plane with a hard spectral index [8]. The background color indicates the daily observation fraction at SKA-Low. To estimate whether it is possible to detect PeV gamma rays with SKA-Low, we extrapolated the fluxes of the LHAASO sources from TeV to PeV energies without a spectral break and neglecting any attenuation due to propagation effects. This follows the analysis approach in [9], but extending it by taking

[2]The radio extension of the widely used air-shower simulation code CORSIKA.

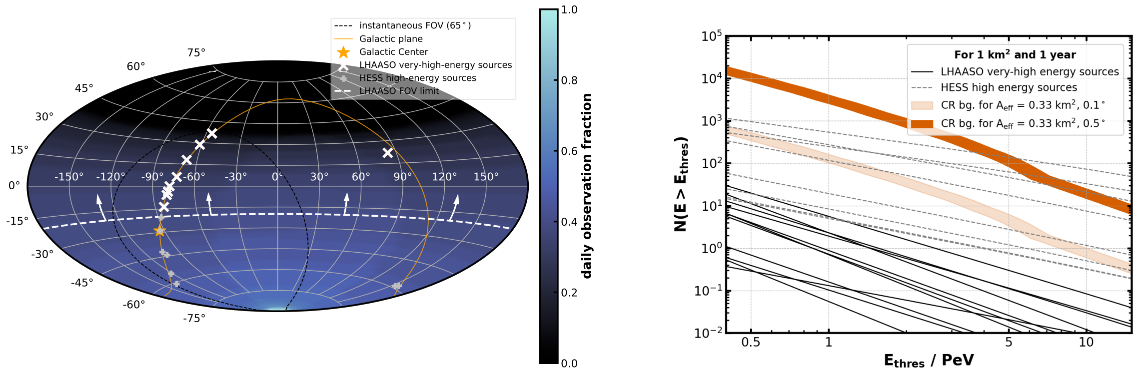

Figure 2: *Right*: Sky map in equatorial coordinates showing the location of LHAASO (white "x") very-high-energy gamma ray sources and the Galactic center in the SKA-Low field of view. The LHAASO FOV limit, SKA-Low instantaneous FOV and Galactic plane are indicated. The colored background represents the fraction of time a given location in the sky is in the FOV of SKA-Low. No very-high-energy gamma ray sources have been identified in the Southern Sky due to a lack of experiments in the Southern Hemisphere. Energetic sources from the HESS Galactic plane survey with a hard spectral index are potential source candidates and are indicated as well (grey "+"). *Left*: Number of expected events per year over a given threshold energy for LHAASO's very-high-energy gamma ray sources, HESS high energy gamma ray sources and the cosmic ray background with an effective area of $A_{\text{eff}} = 0.33\,\text{km}^2$ (this is a representative value for the gamma ray sources taking into account the average inclination and observation fraction) and a pointing resolution of 0.1° and 0.5°, respectively. The width of the band reflects the fact that a hadron requires 10 - 30% more energy than a gamma ray to produce the same signal amplitude (because less energy is lost to the hadronic and muonic shower component for gamma rays). The kink in the CR bands is due to the transition from a low-energy to a high-energy flux measurement by IceTop.

into account the exact location of SKA-Low, the maximum FOV of $\theta \leq 65°$, and an inclination-dependent aperture $A(\theta) = A_0 \cos(\theta)$. Fig. 2 (*right*) shows that the most promising LHAASO source is expected to produce a couple of gamma rays per year detectable by SKA-Low above 1 PeV. The FOV of SKA-Low and LHAASO are only partially overlapping and most LHAASO sources are only observable under unfavorable inclinations at SKA-Low. It makes sense to expect more LHAASO-like source in the SKA-Low FOV, potentially in more favorable locations for SKA-Low - especially in the Galactic Center which is not observed by LHAASO.

Next to the expectations for gamma-rays the expected background from cosmic-ray induced air showers is indicated in Fig. 2 (*right*) with two red bands. The bands indicate the amount of cosmic rays a pointing resolution of 0.1° and 0.5°, respectively. The width of the band reflects the fact that a hadron requires 10 - 30% more energy than a gamma ray to produce the same signal amplitude (because less energy is lost to the hadronic and muonic shower component for gamma rays).

4.2 Detecting PeV air showers with interferometric techniques

To investigate the possibility to detect PeV gamma rays with SKA-Low, the signals from the individual receivers are beamformed using the radio-interferometric technique (RIT) [10, 11]. RIT assumes a spherical wavefront to align the receiver signals, and thus uses for a given beamforming direction (at least) 3 parameters, like every non-planar wavefront. Those describe the wavefront's center, i.e., shower core, and the curvature. In the following, we are assuming perfect knowledge

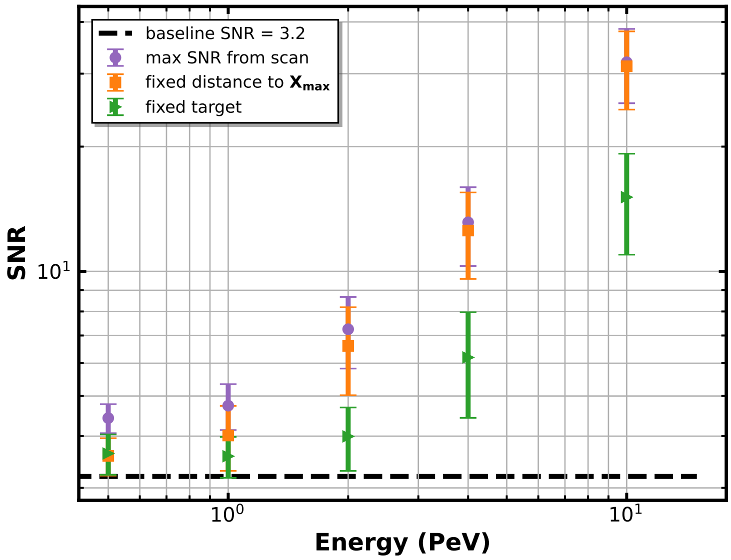

Figure 3: The SNR of the beamformed signal as function of the shower energy. The horizontal line indicates the median SNR when beamforming in an off-source direction, i.e., of waveforms without a coherent signal.

of the shower geometry, i.e., the shower direction and shower core. While the shower direction is well constraint when searching for gamma rays from point sources, the shower core is generally not well known. Later, we estimate the level of precision with which the core position is required.

To improve the SNR of the beamformed signal we are upsampling the receiver signals to 3.2 GHz. The radio emission from air showers is strongly forward-beamed, such that only a fraction of the array is illuminated by a single air shower. Hence, removing receivers that lack a coherent air shower signal increases the SNR of the beamformed signal. Here, only receivers within 300 meters around the shower axis are taken into account. Furthermore, we only use showers with a core within 400 meters of the array core at (0 m, 0 m) to consider only contained events. Fig. 3 shows the beamformed SNR for all showers in our aforementioned simulation set as a function of the shower energy. The SNR is calculated using three different approaches: First the beamformed signal is calculated along the shower axis, this produces a longitudinal profile of the shower development (see Refs. [10, 11]) and allows to find the highest SNR. Second, instead of scan the entire longitudinal space, we calculate the beamformed signal at a specific distance to the shower maximum (which is obviously inaccessible for triggering). And third, you use a fixed depth in the atmosphere across all showers. For the higher energies, the first two approaches yield very similar results. That demonstrates that the beamformed, longitudinal profiles are well behaved and correlate well with the shower development. For lower energies, the second method yields lower SNR, a result of less well behaving profiles. The third method, which does not require any information about the shower depth results in the lowest SNR. The dashed horizontal line indicates the mean SNR value when intentionally beamforming off source.

Our preliminary results indicate a good core estimate of better than $\lesssim$ 20 m is required to maintain $\gtrsim$ 50% of the maximum signal. While extensive scans of the multi-dimensional parameter space are possible in an offline reconstruction, options are limited at trigger level.

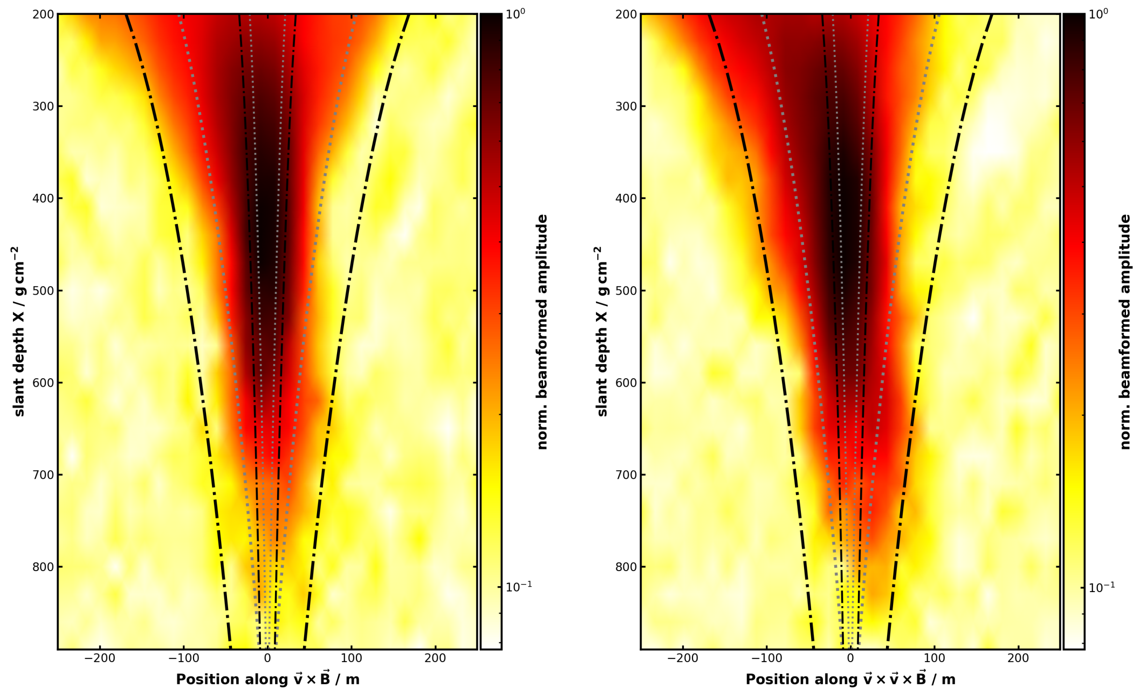

Figure 4: Interferometric maps of a 10 PeV gamma ray shower. The normalized amplitude of the beamformed waveforms for various positions along the shower development are shown. The gray dotted and back dashed-dotted lines indicate a deviation by 0.1° and 0.5° from the air shower direction for a 15° (gray) and 45° (black) air shower. The left plot shows the lateral distribution along the $\vec{v} \times \vec{B}$-axis and the right plot along the $\vec{v} \times \vec{v} \times \vec{B}$-axis. The latter points roughly into the direction of the shower.

4.3 Gamma-hadron separation

At PeV energies, the diffuse cosmic ray background exceeds the potential flux of gamma rays by many orders of magnitude. The flux of cosmic rays is so intense that it is not possible to trigger and readout every single air shower which falls within the SKA-Low array. Hence, the rejection of a large fraction of cosmic-ray induced air-shower at trigger level is necessary. This can be realized, but is not limited to, by selecting events with a beamformed trigger arriving only from a narrow patch in sky from the direction of a potential gamma-ray source. To provide a first estimation of the pointing resolution with beamforming we are evaluation the beamformed signal distribution for a 10 PeV gamma ray shower around its shower axis in Fig. 4. The spatial extend of the signal distribution, in which the signal is strong is compared to angular deviations from the shower axis. The gray dotted lines indicate a 0.1° and 0.5° deviation form the shower axis. It can be seen that the latter fully envelops the signal distribution. The black lines indicate the same angular deviations for an air shower with a 45° zenith angle (instead of 15°). Since the spatial extend of the beamformed signal does not strongly change with the zenith angle, the pointing resolution improves for more inclined air showers as the shower develops further away from the detector.

The expected number of cosmic ray events with a pointing resolution of 0.1° and 0.5° is already demonstrated in Fig. 2 (*right*). The reduced background flux should be sufficiently reduced to trigger and store all events. While the most optimistic gamma-ray flux models predict fluxes at the same level than the cosmic ray background at 0.1 ° at ~1 PeV, the background at 0.5 ° is at least on order of magnitude higher. Furthermore, predicted fluxes from LHAASO sources would require an additional background subtraction of $\sim 10^{-2} - 10^{-3}$. This has to be accomplished in an offline analysis using more refined methods to investigate the longitudinal profile of the triggered air showers and incorporate information of the auxiliary particle detector.

5. Conclusion and Outlook

We have presented the idea to detect PeV gamma rays with SKA-Low to study the acceleration sites of the highest Galactic cosmic ray. We have demonstrated that the astonishing number of radio antennas available at SKA-Low to detect air showers can be sufficient to detect air showers with energies down to PeV, a novelty in radio detection of air showers. It is clear, that with the here-presented preliminary feasibility study, a firm conclusion about the prospect of gamma ray detection with SKA-Low can not be drawn yet. This is the goal for future work. We are anticipating considerable potential to improve methods and analysis strategies.

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Affiliations

[a] Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium
[b] ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
[c] Jodrell Bank Centre for Astrophysics, Dept. of Physics & Astronomy, University of Manchester, UK
[d] Vrije Universiteit Brussel, Astrophysical Institute, Pleinlaan 2, 1050 Brussels, Belgium
[e] Department of Astrophysics/IMAPP, Radboud University Nijmegen, The Netherlands
[f] International Centre for Radio Astronomy Research, Curtin University, Bentley, 6102, WA, Australia
[g] Kapteyn Astronomical Institute, University of Groningen, Netherlands
[h] Netherlands Institute for Radio Astronomy (ASTRON), Dwingeloo, The Netherlands
[i] Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, No. 10 Yuanhua Road, Nanjing, China
[j] Institut für Astroteilchenphysik, Karlsruhe Institute of Technology (KIT), Germany
[k] Max-Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany
[l] Ludwig-Maximilians-Universität München (LMU), München, Germany
[m] Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany
[n] Department of Physics, Khalifa University, P.O. Box 127788, Abu Dhabi, United Arab Emirates
[o] Physics Education Department, School of Education, Can Tho University, Campus II, 3/2 Street, Ninh Kieu District, Can Tho City, Viet Nam
[p] Department of Physics, Indian Institute of Technology Kanpur, Kanpur, UP-208016, India
[q] SKA Observatory, Jodrell Bank, Lower Withington, Macclesfield, SK11 9FT, UK
[r] School of Astronomy and Space Science, Nanjing University, Nanjing 210023, China
[s] Key laboratory of Modern Astronomy and Astrophysics, Nanjing University, Ministry of Education, Nanjing 210023, China
[t] School of Electronic Engineering, Xidian University, No.2 South Taibai Road, Xi'an, China
[u] School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China

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