# A 3D Likelihood Analysis Tool for LHAASO-KM2A data

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## Abstract

The square kilometer array (KM2A) is the main array of the Large High Altitude Air Shower Observatory (LHAASO)[1], which is the most sensitive gamma-ray detector for energies above a few tens of TeV. We are developing a software pipeline based on the experimental data, Monte-Carlo simulations and the pointing track of the arrays. The pipeline is able to perform 3D (sky images at different energies) fits of KM2A data, similar to those used for Fermi-LAT and DAMPE gamma-ray analysis. This 3D likelihood analysis could fit source models of arbitrary morphology to the sky images, and get energy spectra information and detection significances simultaneously. The analysis with this software could give consistent results with those using traditional method[2].

## Introduction

The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation instrument, built at 4410 meters of altitude in the Sichuan province of China, with the aim of studying the energy spectrum, the elemental composition and the anisotropy of cosmic rays in the energy range between $10^{12}$ and $10^{17}$eV with unprecedented sensitivity, as well as to act simultaneously as a wide aperture (~2 sr), continously-operated gamma ray telescope in the energy range between$10^{11}$ and $10^{15}$ eV.

As a sub-array of LHAASO, The square kilometer array (KM2A) is mainly designed to cover a large fraction of the northern sky to hunt for gamma-ray sources at energies above 10 TeV. The whole KM2A array will consist of 5195 electro-magnetic detectors (EDs) and 1188 muon detectors (MDs), deployed over an area of 1.3 $km^2$. Even though the detector construction is still underway, a half of the KM2A array has been operating stably since the end of 2019.

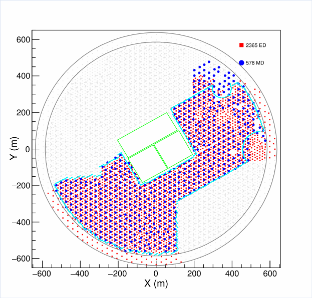


**Figure 1**:Planned layout of all LHAASO-KM2A detectors. The red squares and blue circles indicate the EDs and MDs in operation, respectively. The area enclosed by the cyan line outlines the fiducial area of the current KM2A half-array used in this analysis.

## Reference

[1] Bai X., Bi B. Y., et al, arXiv:1905.02773.
[2] Aharonian F., An Q., et al., arXiv:2010.06205.
[3] Abeysekara A.U., Albert A., et al., Nat. Astron., 5 (2021) 465.

## Instrument Response Functions from Simulation Data

Instrument Response Functions (IRFs) including the effective area, point-spread function and energy dispersion represent the performance of the detections like sensitivity, angular and energy resolution.

- Effective area, A(E, **v**)
- Point spread function, P(**v**', E, **v**)
- Energy dispersion, D(E', E, **v**)

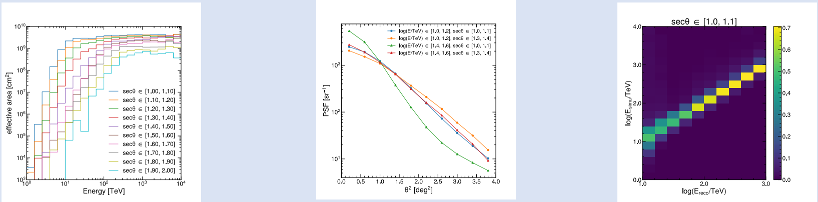


**Figure 2**:The IRFs obtained from the simulation gamma-ray data for KM2A half-array. The left panel is the effective area in different incident angle range, the middle panel is the PSF example in different energy and incident angle range, the right panel is the energy dispersion example in one incident angle bin.

## Exposure and Likelihood Analysis

Exposure for any given energy E and direction in the sky p as the integral of the effective area over the time range of interest, can also be expressed as an integral over the solid angle in the detector reference frame. $\epsilon(E,\hat{p}) = \int A_{\rm eff}(E,\hat{v}(t,\hat{p}))dt = \int A_{\rm eff}(E,\hat{v})t_{\rm obs}(\hat{v},\hat{p})d\Omega.$

We construct the binned likelihood function (in logarithm form) by summing over all $N_{bins}$ bins and $N_s$ sources: $\log L(\vec{\lambda}) = \sum_{i,j=1}^{N_{\rm bins}} \left( -\sum_{k=1}^{N_s} R_{ijk} + N_i \log \sum_{k=1}^{N_s} R_{ijk} \right)$ $TS_k = -2(\log L(\vec{\lambda}_{0,k}) - \log L(\vec{\lambda}_0))$

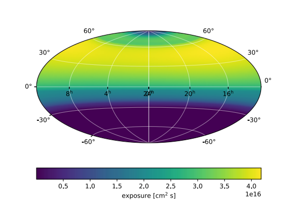


**Figure 3**:The exposure map of KM2A half-array at 10 TeV in the equator coordinate with Aitoff projection.

## Summary

The very-high-energy gamma-ray sky is an important observation target for KM2A, the sub-array of LHAASO. To facilitate analyzing the KM2A gamma-ray data, we have developed a dedicated software, which implements maximum likelihood analysis to extract the parameters of sources that contribute to the observed gamma-rays. The KM2A IRFs that are essential to the gamma-ray data analysis are also derived based on statistics from simulation data. Applying the KM2A IRFs and the software that are detailed in this paper, scientific analyses of the gamma-ray data could be carried out to obtain the best-fit parameters, fluxes and corresponding statistical uncertainties, and further the spectral energy distribution, promoting our understanding of the nature of very-high-energy gamma-ray phenomena.

## Implementation and examples

The code is written with python, based on the NumPy, SciPy, AstroPy, and iminuit package. For expandability, the software are structured with modules.

Modules:
Input: `SkyMap, IRFs, SpatialModel, Spectrum, Model`
Process: `Exposure, LikelihoodBase, BinnedLikelihood`
Output: `LikelihoodAnalysis`
Scripts:
`BinnedAnalysis.py, plotCountsMap.py, plotfitRegion.py, plotSpatialMap.py, plotSpectrum.py`

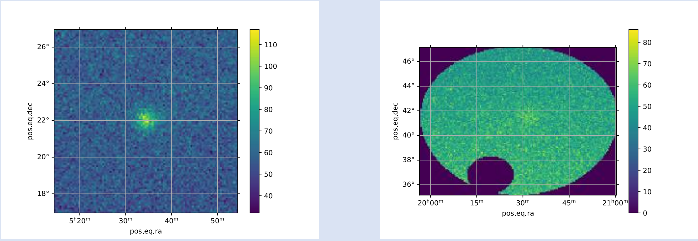


**Figure 4**:Left panel shows the counts map around the Crab Nebula binned with 0.1*0.1 $degree^2$ with CAR projection, right panel shows the fit region around Cygnus Cocoon which is in a 6° radius circle region around (RA=307.17°, DEC=41.17°) and removed a 1.5° radius circle region around (RA=304.85°, DEC=36.80°).

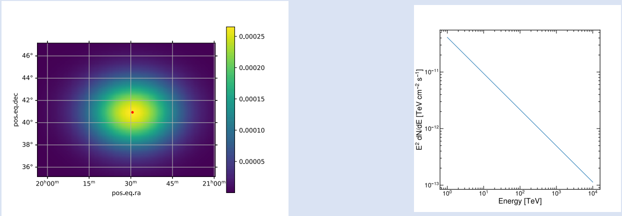


**Figure 5**:Cygnus Cocoon spatial map which is a extended source centered at (RA=307.65°, DEC=40.93°)with a Gaussian width of 2.13° and power-law spectrum $dN/dE=N_0(E/E_0)^{\Gamma}$with $N_0=9.3\times10^{-13}$ $cm^{-2}$ $s^{-1}$ $TeV^{-1}$, $\Gamma=-2.64$, $E_0$=4.2 TeV of Cygnus Cocoon[3].

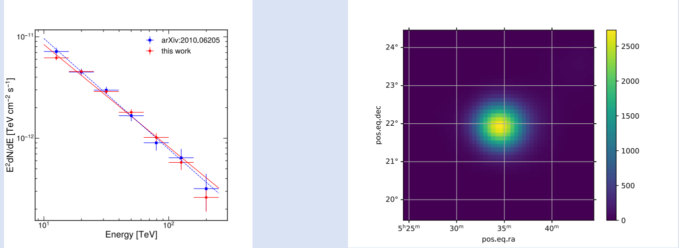


**Figure 6**:The spectral energy distribution (SED) and test statistics (TS) map of the Crab Nebula.