LST COLLABORATION

Study of the hadronic PeVatron candidate

SNR G106.3+2.7

observed at Large Zenith Angle with LST-1 and MAGIC

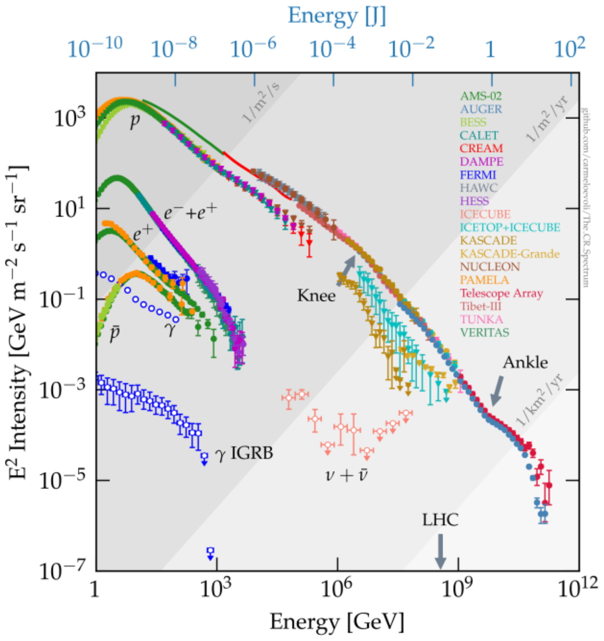
2024/12/09 3rd Year PhD Student Presentations

Marie-Sophie Carrasco, PhD student

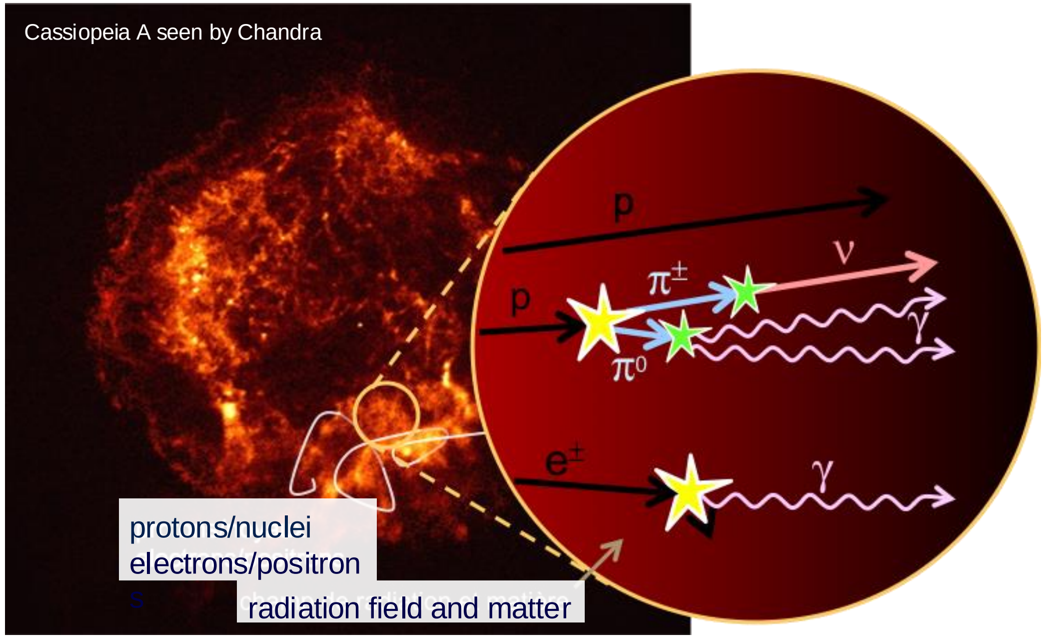
carrasco@cppm.in2p3.fr

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

The quest for Galactic PeVatrons



Evoli, C. (2023)



Diffuse cosmic ray (CR) flux on Earth

- Charged particles: hadrons (~98%, mainly p) and leptons (~2%, mainly $e^{\pm}$)
- Power law with first index break at ~3 PeV: the knee
- Galactic origin up to the knee, then Extra-Galactic
- PeVatrons**:** sources of ultra-high energy cosmic rays (UHE CRs, E $\gtrsim$ 0.1 PeV), still mostly unknown

Galactic Supernova Remnants (SNRs)

- Associated pulsars are known leptonic PeVatrons
- Main hadronic PeVatron candidates
- Strong particle acceleration by diffusive shock acceleration

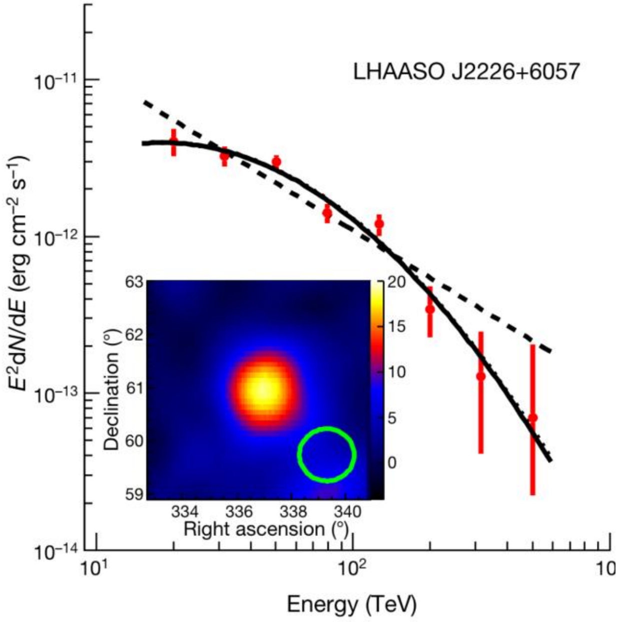
Gamma-ray astronomy ideal for PeVatron detection

- Gamma-ray emission by UHE CRs interactions: pion production, leptonic radiation
- CR ~1PeV → gamma ~100 TeV

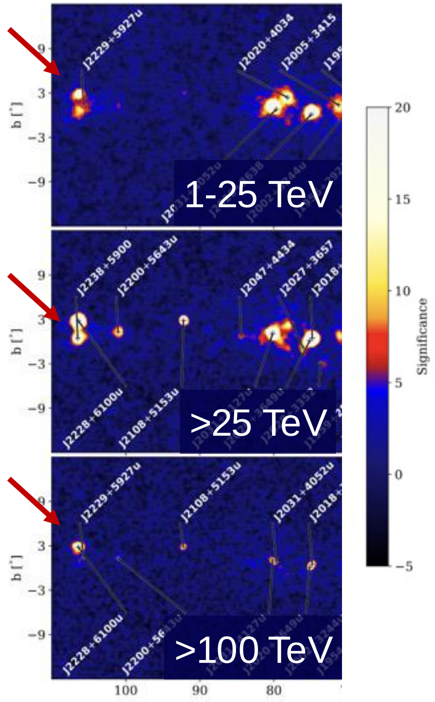
SNR G106.3+2.7
A confirmed PeVatron, hadronic or leptonic?

LHAASO -> 43 UHE Galactic sources
- ɣ-rays measured between 1 TeV - 1.4 PeV

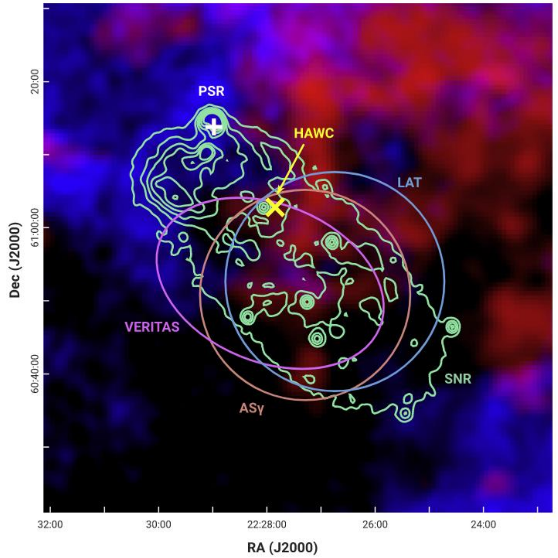
SNR G106.3+2.7 among the sources
- Measured up to ~600 TeV



Cao et al. (2021)



Cao et al. (2023)



Ge et al. (2021)

A comet shaped SNR

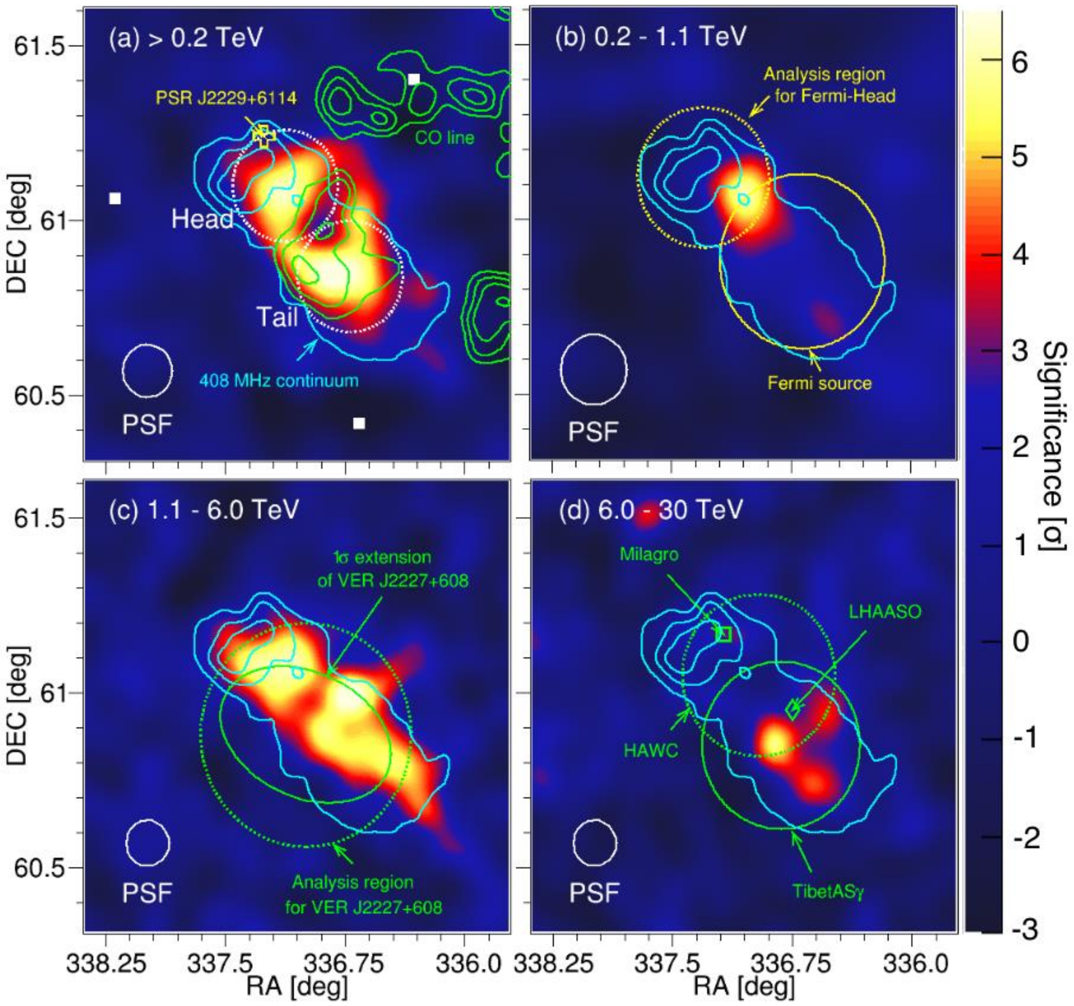
Head
- pulsar (PSR) and its pulsar wind nebula (PWN)
- colliding in dense HI cloud (blue)

leptonic PeVatron?

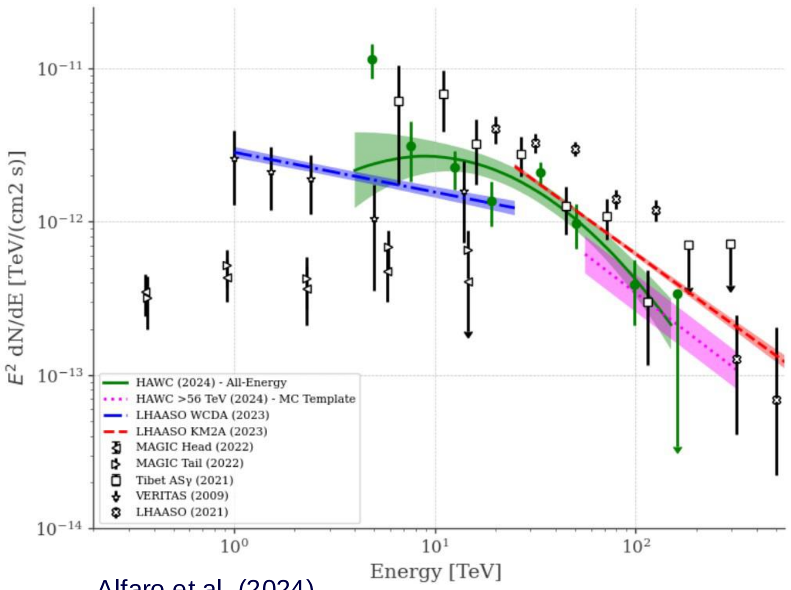
Tail
- expanding in low density HI cavity
- dense molecular cloud (red)

hadronic PeVatron?

SNR G106.3+2.7
Recent VHE results



MAGIC Collaboration (2022)



Alfaro et al. (2024)

Very high energy (VHE, E≥0.1 TeV) emission from head and tail

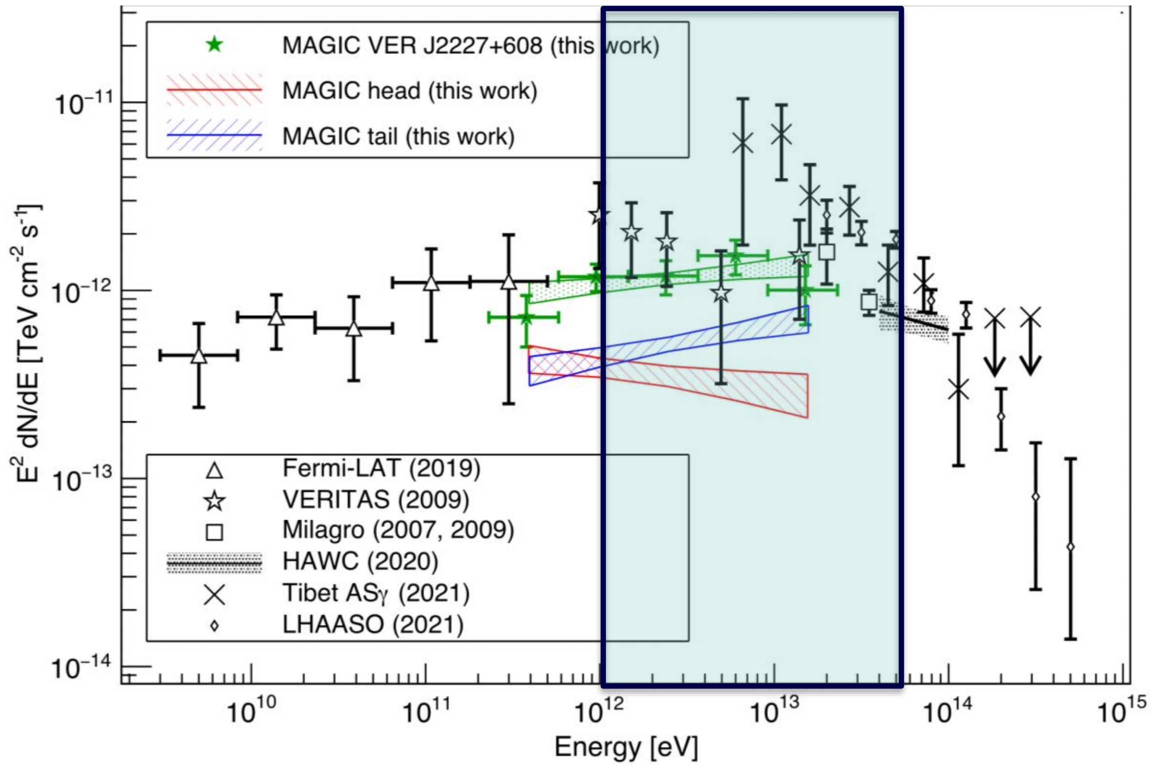
- MAGIC: detection up to 30 TeV, showing an energy-dependent morphology
- HAWC, Tibet ASɣ, LHAASO: detection at O(10-100TeV), with angular resolution too low for morphology

➢ Study with high angular resolution needed at E>10 TeV

Study goal

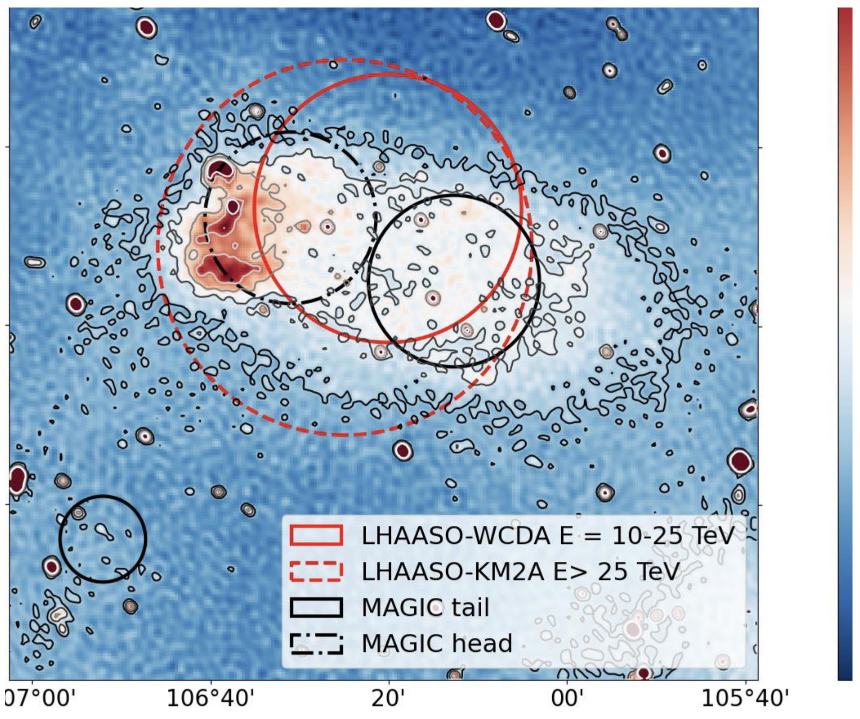
Understanding the **nature of the source** by resolving its **energy-dependent morphology**

- Exploration of the **1-50 TeV energy range**



MAGIC Collaboration (2022)

- With an **angular resolution <0.1 deg**

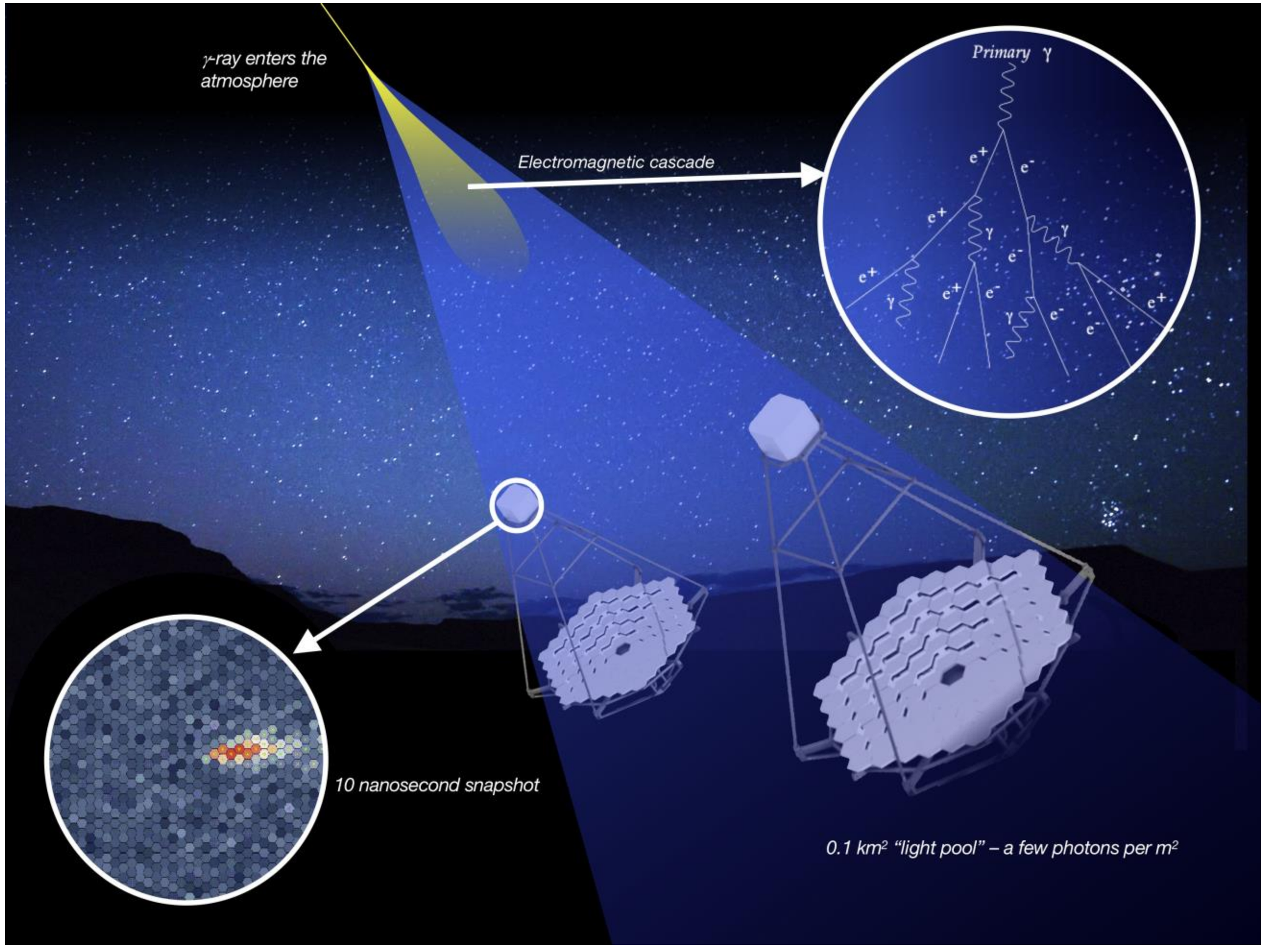


Cao et al. (2023): LHAASO data from catalog, CGPS 1420 MHz radio contours

Gamma-ray astronomy with IACTs

Imaging Air Cherenkov Telescopes (IACTs)

- Gamma-ray interaction with atmosphere generates an extensive air shower
- Electromagnetic cascade of particles with velocity greater than light in atmosphere → optical Cherenkov light pool
- Shower development imaged in camera by each IACT of the array
- Gamma-ray energy and direction well constrained by shower parameters → **good angular resolution**



The LST-1 + MAGIC IACT array

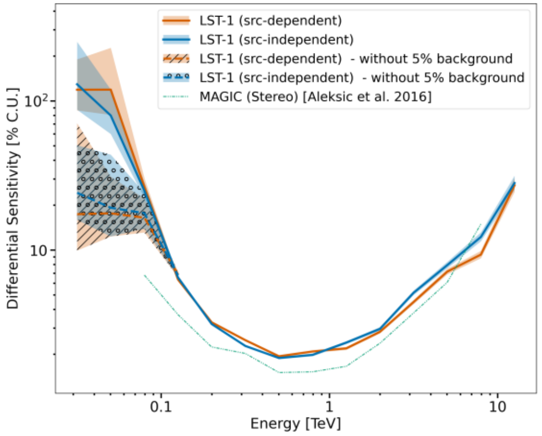
Ongoing multi-year observation campaign with IACT array

- **LST-1**: first Large-Sized Telescope prototype of the Cherenkov Telescope Array Observatory (CTAO), inaugurated end of 2018
- **MAGIC**: two IACTs neighbors to LST, stereo observations since 2009
- Located at the Roque de los Muchachos Observatory (La Palma, Spain)

Antonio Glez. / PDALP - SODEPAL-Cabildo La Palma

Observation strategy

Reaching high energies with LZA observation



LST-1 differential sensitivity for the Crab Nebula
(Abe et al., 2023)

LST-1 and MAGIC designed for lower end of the energy spectrum

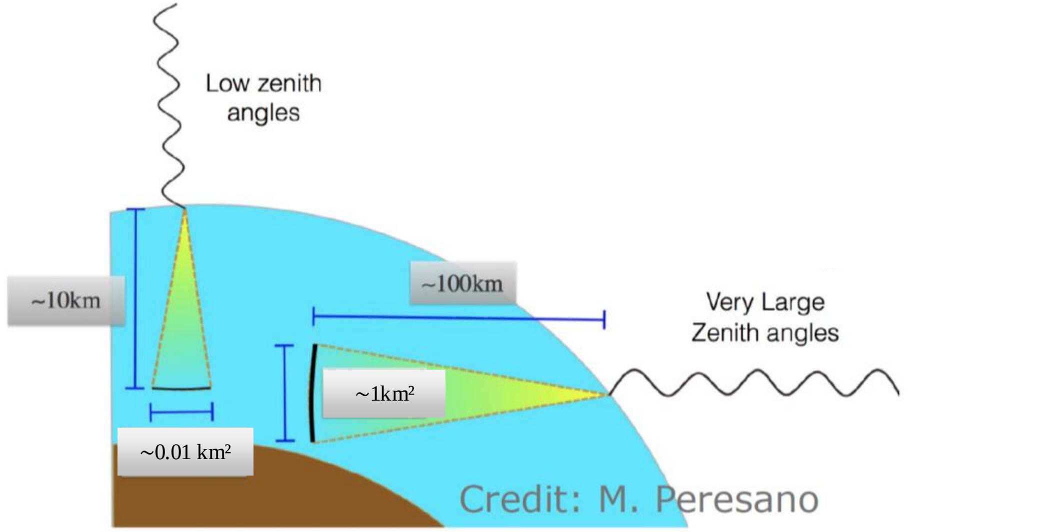
- optimal sensitivity for ~0.1 – ~10 TeV

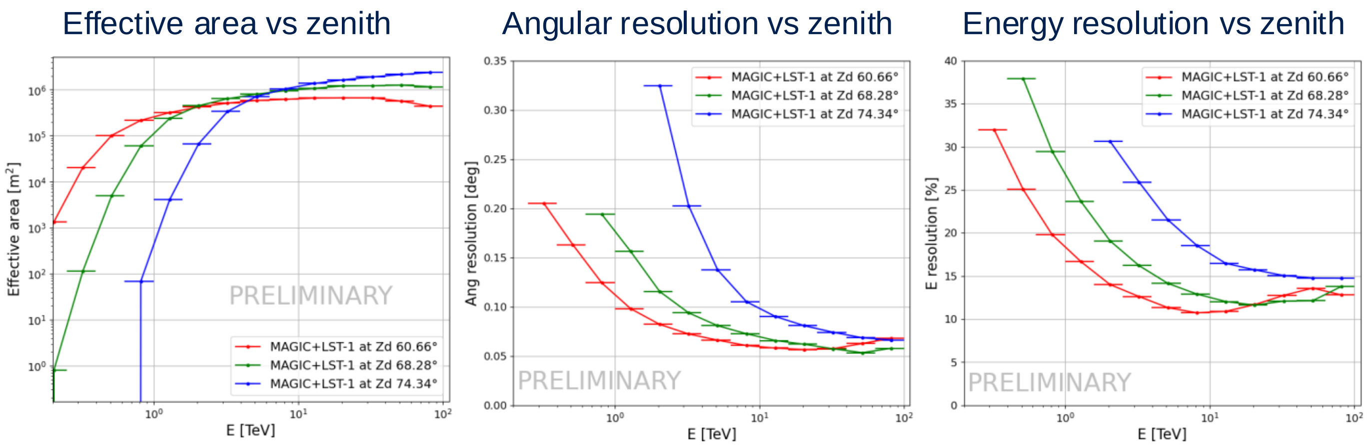
Large zenith angle (LZA, zenith = 55°-75°) observation

- Increases the effective collection area up to a factor 10 for the highest energies

Expected performance

- Effective area strongly increases with zenith at VHE
- Angular resolution is expected to be < 0.1° for highest energies
- Energy resolution is also expected to be better than 15% for highest energies at all zenith

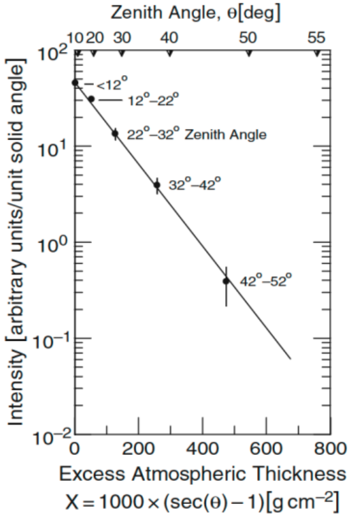




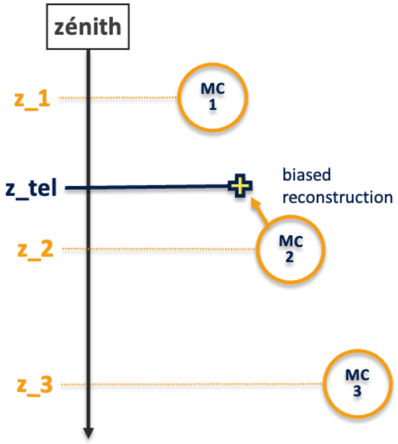
MC simulation of MAGIC+LST-1 stereo data reconstructed with magic-cta-pipe

LZA observation: the main source of difficulties for our study

- Greater depth of atmosphere
- Density profile of the atmosphere varies exponentially with zenith
- Higher Cherenkov light absorption
- Increased sensitivity to bad weather conditions



Intensity attenuation with zenith angle
Grieder, P.K. (2010)



Zenith-dependent bias in reconstruction via random Forest trained on discrete pointing MC simulation

Impact at every level

Data quality

- Degraded signal-to-noise ratio → lot of bad quality data
- Data quality parameters behave differently → need for custom selection

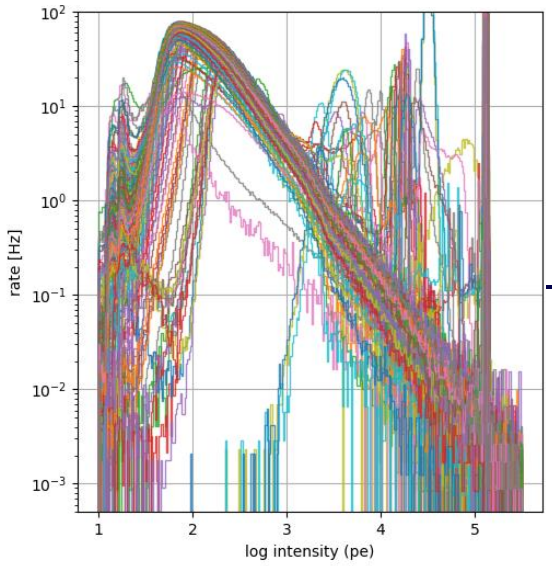
Reconstruction

- Smaller amount of p.e. collected in the camera → higher energy threshold
- Event reconstruction uses random forest (RF) trained on MC simulation → bias introduced by fast-varying zenith-dependent features

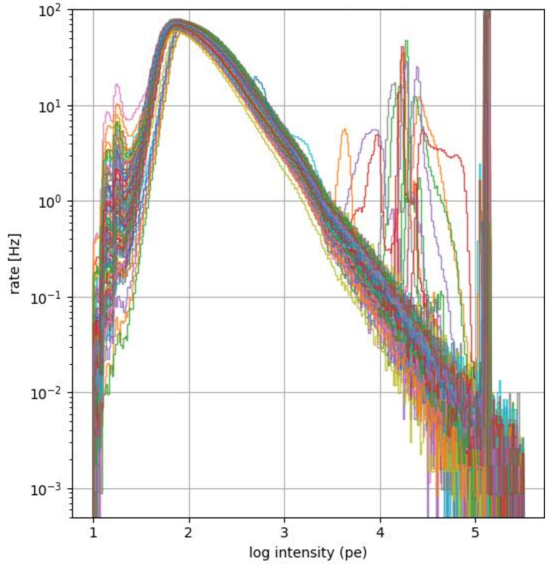
Analysis

- Inhomogeneities in large field of views (FoVs) → need for precise background model

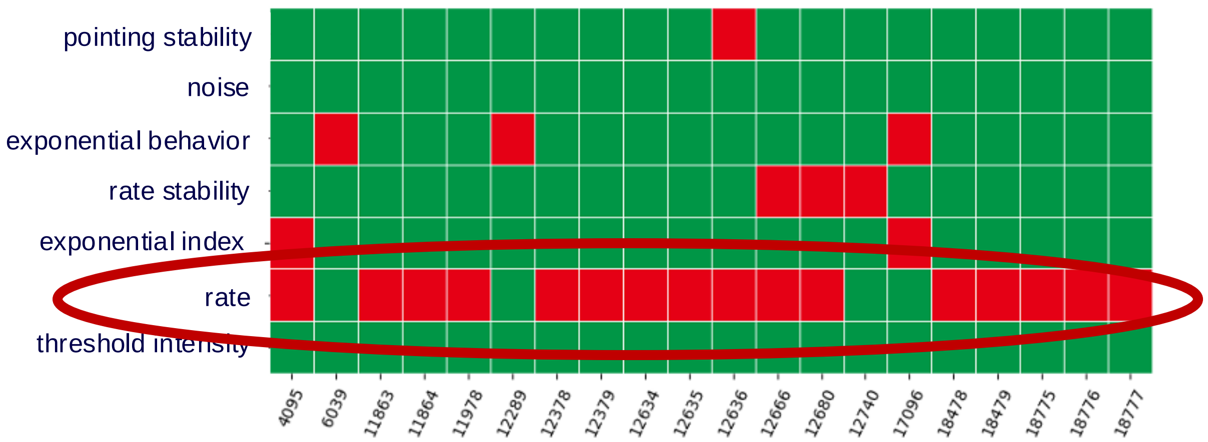
Full Crab LZA dataset



Selected Crab LZA dataset



"Recovered" runs: passing (green) and rejecting (red) standard selection cuts



Log-intensity rates = good quality indicators

- Distribution of the rate of Cherenkov photo-electrons measured in each run event
- Maximum rate value and position: sky conditions
- Behavior before max rate: energy threshold
- Behavior after max rate : calibration, car flash, sky condition

Custom selection tool development

- Gaussian containment of key rate features
- Zenith-dependent

Tool validation on Crab Nebula

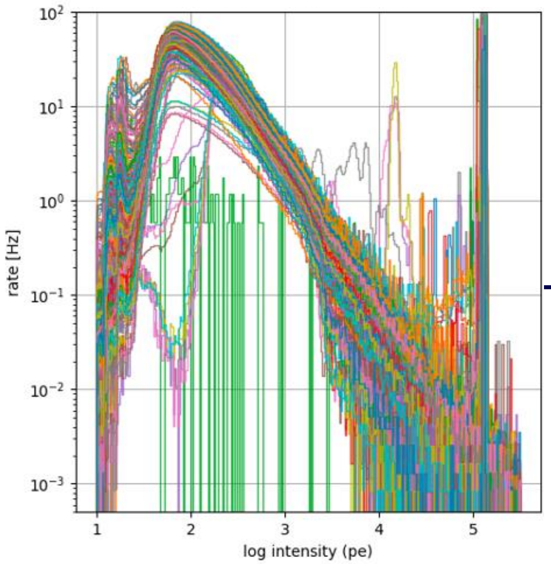
- 94.5% match with standard selection and standard zenith
- 81.2% match with standard selection and LZA
- More permissive to low rates, otherwise very good agreement

3.9% "recovered" LZA data

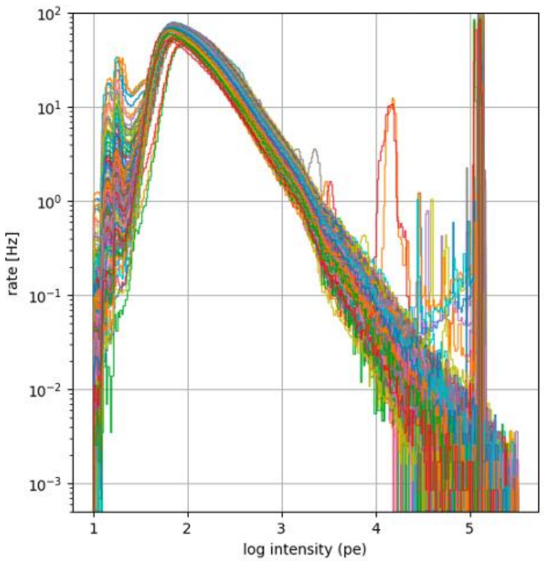
- Slightly lower performances due to lower rates
- Still usable with appropriate analysis

Data quality and selection
SNR G106.3+2.7 LZA LST-1 data

Full G106 LZA dataset



Selected G106 LZA dataset



“Recovered” runs: passing (green) and rejecting (red) standard selection cuts

SNR G106.3+2.7 observation up to 2024-12-03

- 271 runs taken at LZA (zenith = 55° -75°)
- 68.8 h total livetime
- final target: 120 h

Selected dataset

- 64.4% selected
- 25.2% of “recovered” data → significantly larger statistics

Background estimation performed on events map

1. at source region level to perform spectral analysis

1D analysis

- No background model assumed
- Events are just binned in energy

$$N_{Signal} = N_{ON} - N_{Bkg}$$

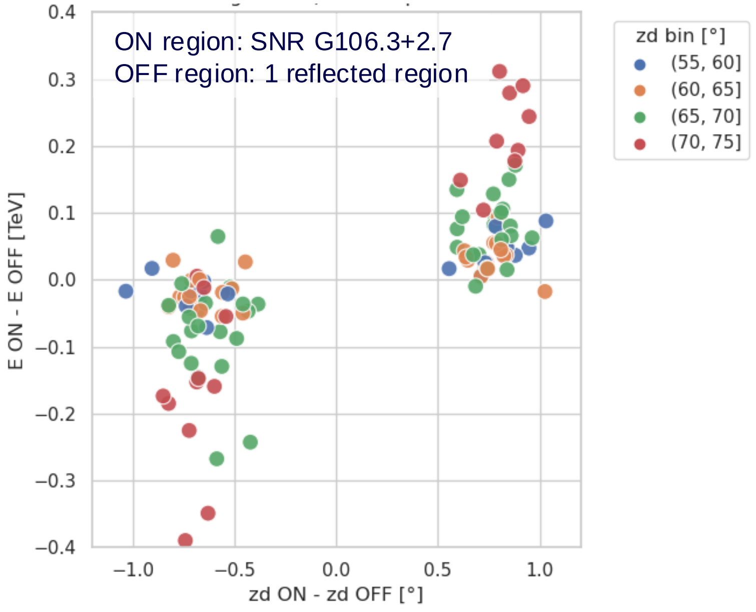
$$N_{Bkg} = \frac{N_{OFF}}{\alpha}$$

$$\alpha = \frac{\Omega_{OFF}}{\Omega_{ON}}$$

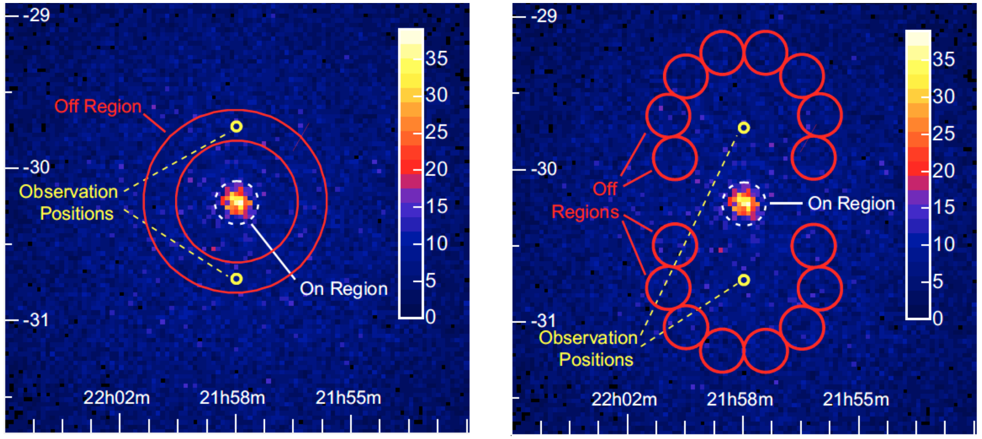
Two regions

- ON: the region in which we want to detect signal
- OFF: region(s) where background is expected to be equivalent

Median energy difference vs mean zenith difference between ON and OFF regions



OFF regions determined with the ring (left) and reflected (right) background methods



Berge et al. (2007)

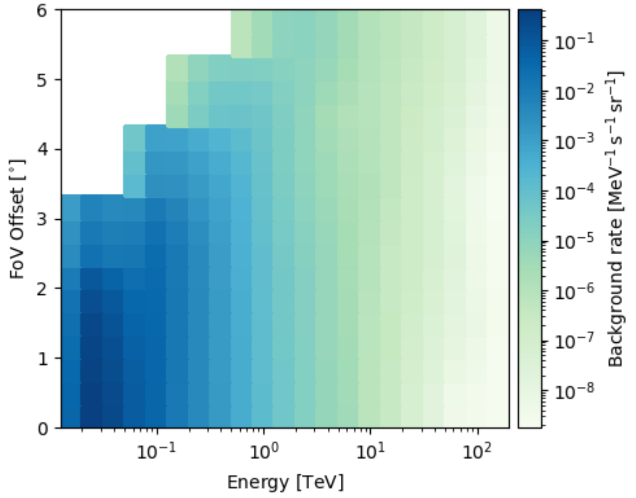
Bias issue at LZA

- Event distribution is zenith-dependent → inhomogeneities between ON-OFF regions
- Complex FoV events need to be normalized with precise background instrument response functions (IRF)

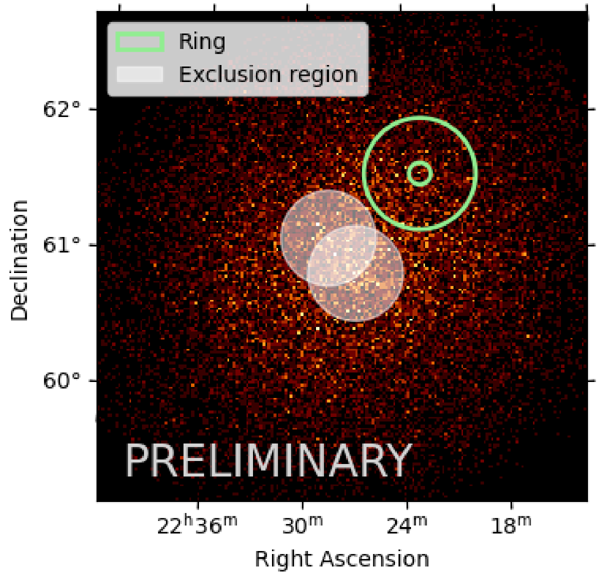
Background estimation for high level analysis (2)

Background estimation performed on events map

1. at source region level to perform spectral analysis
2. at field-of-view (FoV) level to produce full skymaps with significance



Background IRF for simulated CTAO-South observations (50 h at zenith=20°) (gammapy-data)



SNR G106.2+2.7 events map with exclusion region (white circles) and ring kernel (green circles)

$$\alpha = \frac{\int_{OFF} IRF_{Bkg}(E,\Omega,t)\ dE\ d\Omega\ dt}{\int_{pixel} IRF_{Bkg}(E,\Omega,t)\ dE\ d\Omega\ dt}$$

Background IRF

- Model the background rate per solid angle as a function of reconstructed energy and detector coordinates (FoV coordinates)
- 2D (E, offset) or 3D (E, lon, lat)
- Computed on events map

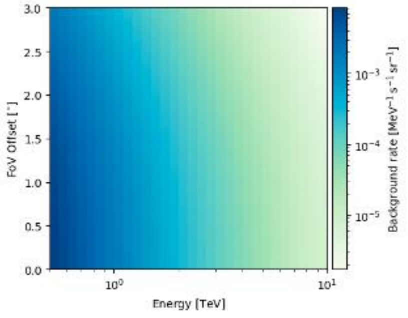
Normalization

- Rate from IRF used instead of solid angle ratio
- Each pixel becomes an ON region
- Integration over FoV or ring OFF region like before
- Source region masked to prevent signal contamination

Background modeling

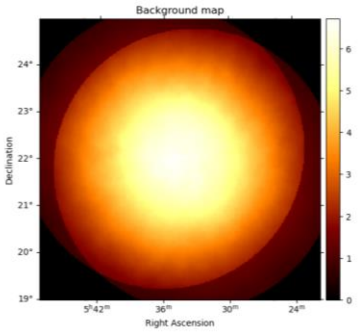
SimBMVtool + accmodel: Simulation

Analytical background model



SimBMVtool →

Simulated background data



SimBMVtool

- Custom analytical background IRF
- Full observation simulation

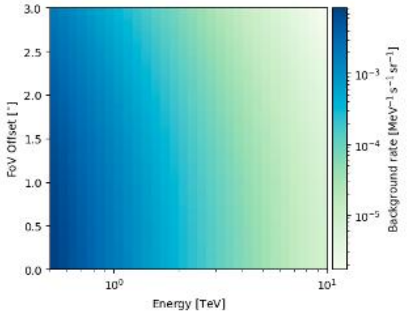
Simulation and background model validation tool (SimBMVtool) needed to test the performances of our background IRF modeling tool

acceptance_modelisation (accmodel)

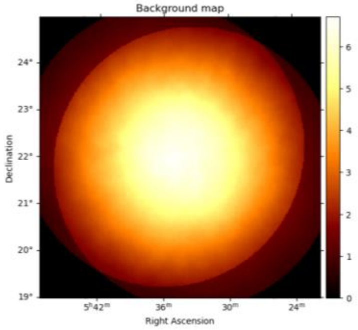
- Background IRF modeling package developed by M. De Bony (new post-doc at CPPM)
- Option for zenith-binned modeling
- G. Emery (previous post-doc) and I joined the development to improve performance and add features
- Paper in preparation

SimBMVtool + accmodel: Background modeling and model data validation

Analytical background model



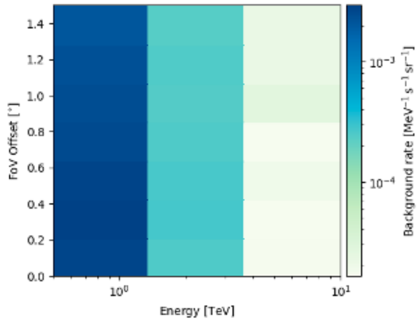
Simulated background data



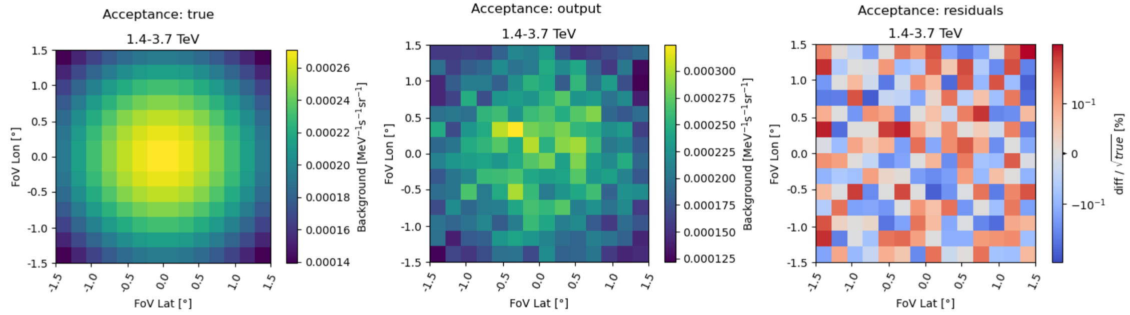
SimBMVtool

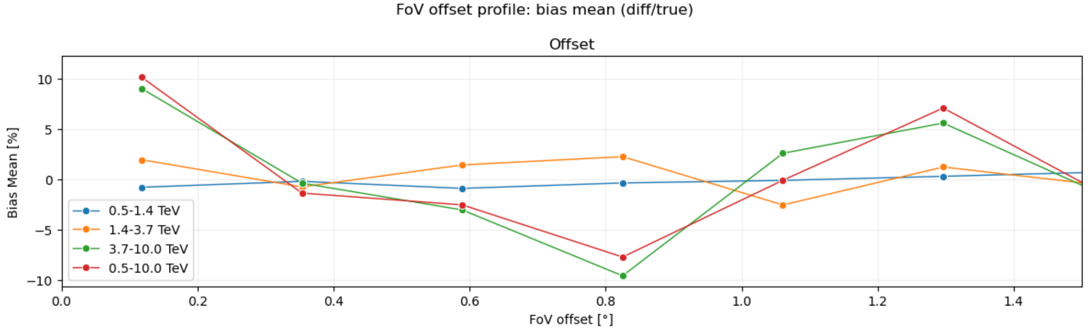
accmodel

Output background model



SimBMVtool

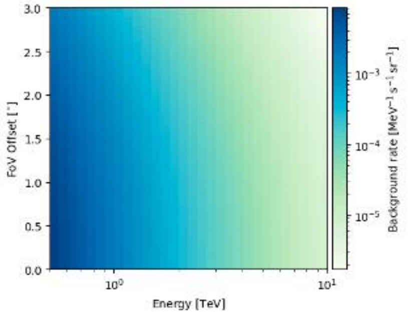




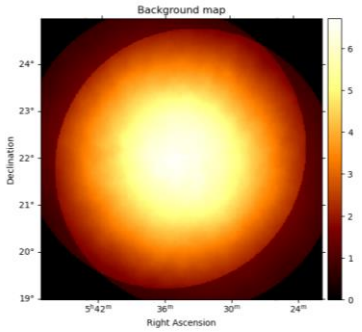
SimBMVtool

- Custom analytical background IRF
- Full observation simulation
- Background modeling on simulation
- Output to true IRF comparison

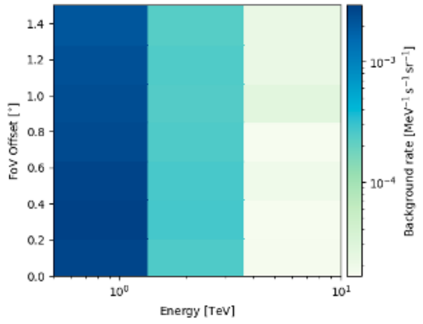
Analytical background model



Simulated background data

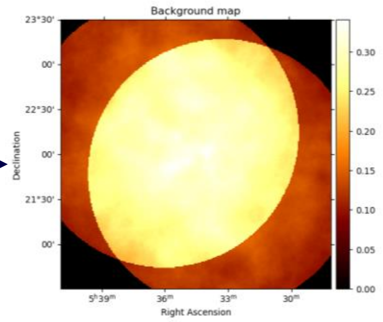


Output background model

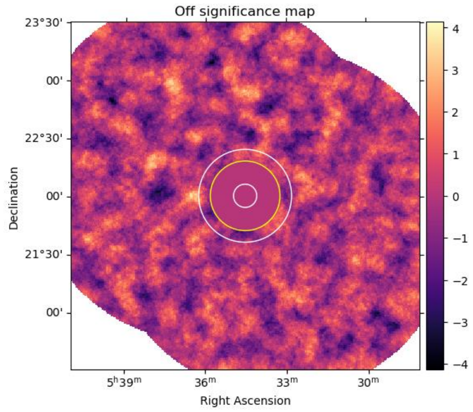


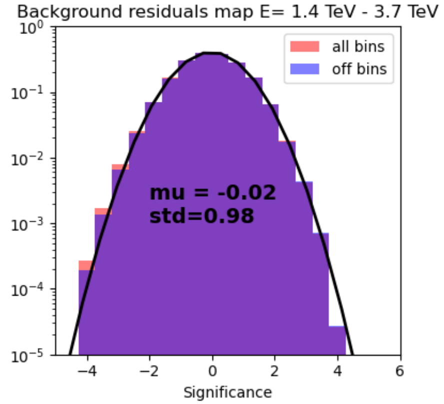
SimBMVtool

Output background data



SimBMVtool

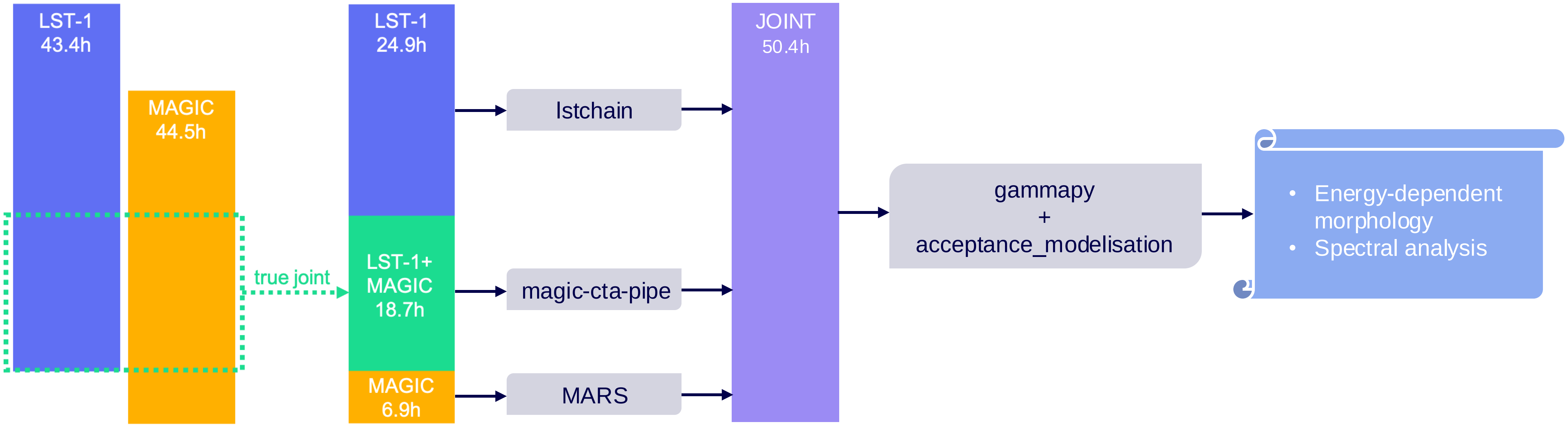




SimBMVtool

- Custom analytical background IRF
- Full observation simulation
- Background modeling on simulation
- Output to true IRF comparison
- Background estimation with the output model
- Skymap production with event significance
- Background model figure of merit: residuals should follow normal law if purely statistical fluctuations

SNR G106.3+2.7: Data analysis



Joint analysis: 50.4 hours

- Combination of simultaneous LST-1 and MAGIC data
- 3 datasets: LST-1 + MAGIC, LST-1 Mono, MAGIC
- Combined after specific analysis pipeline
- High level analysis with gammapy

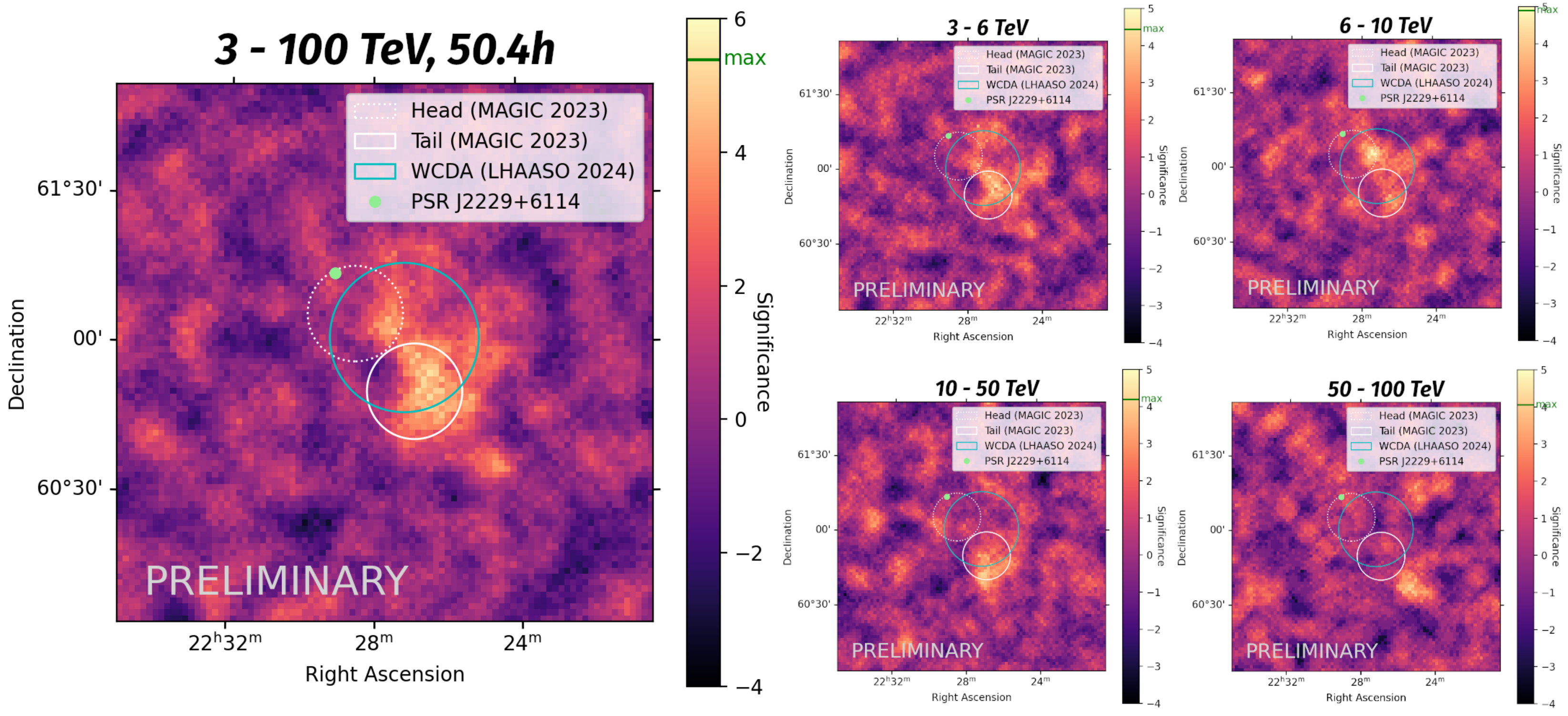
Results presented this summer at Gamma24 by G. Emery

Background IRF modeled with acceptance_modelisation

- Used for both skymaps and spectral analysis
- Zenith-dependent 3D IRF (E, Alt, Az)
- Model fitted per energy bin
- Zenith-binning and fit methods implemented by us
- Fit method validated with SimBMVtool

Scientific preliminary results

SNR G106.3+2.5: Energy-dependent morphology

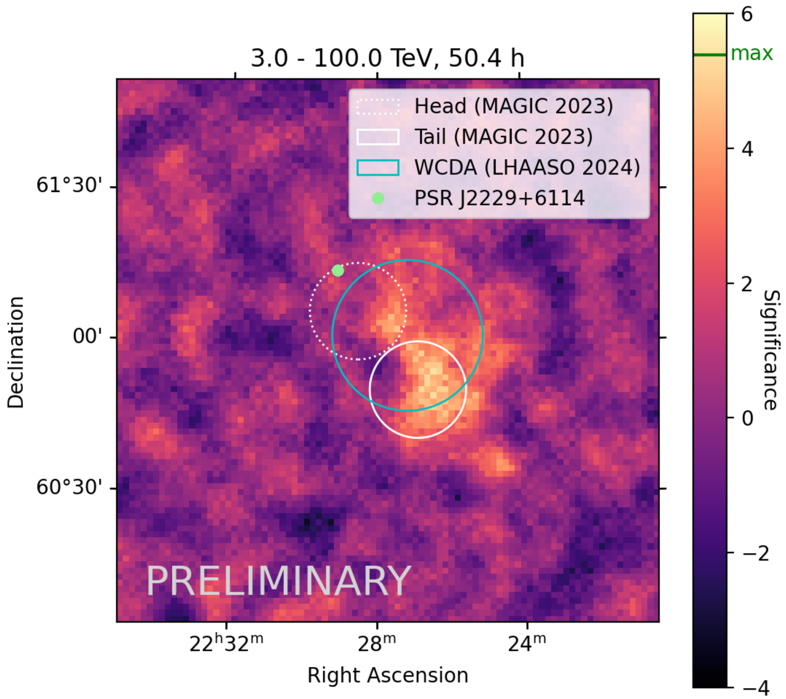


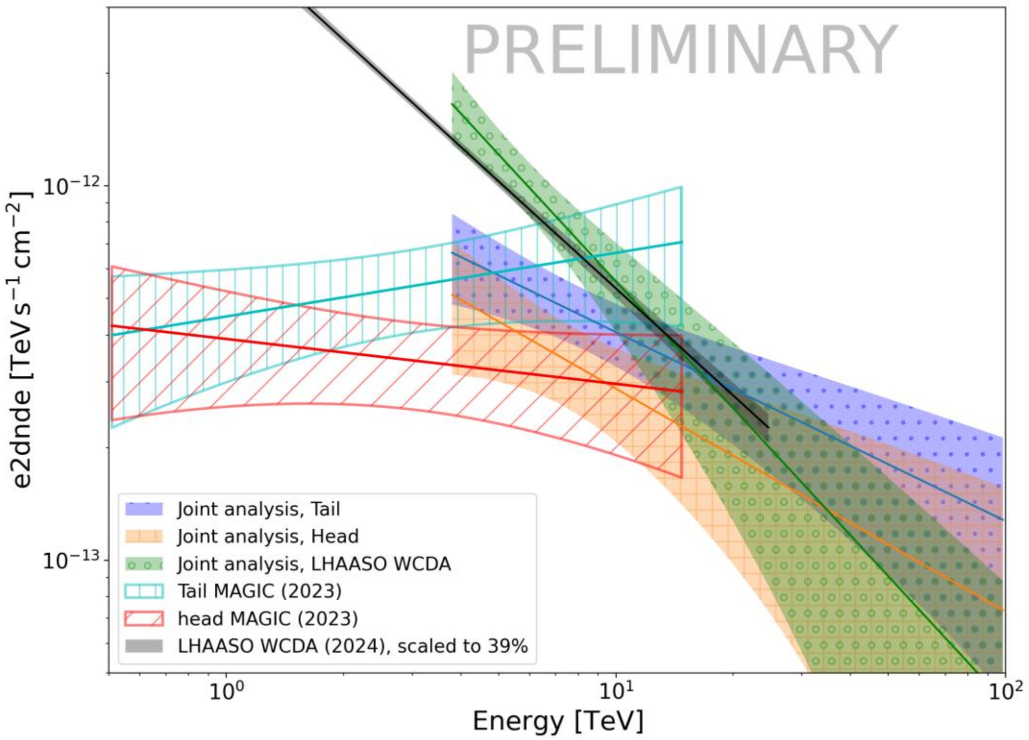
Results with 50.4 hours
- 3-100 TeV range
- 5σ detection overall

Energy-dependent morphology
- 4 energy bins
- More than 4σ in all energy bins
- Significance maximum moving away from the pulsar with increasing energy above 6 TeV

We begin to see the energy-dependent morphology, with a shift of the emission towards the tail for E>6 TeV → **promising hadronic PeVatron**

SNR G106.3+2.5: Spectral analysis





Comparison with literature
- MAGIC results with head and tail region spectra
- LHAASO result with WCDA instrument region spectrum

Good connection with published spectra
- Good agreement regarding the norm
- Power law indices vary due to different energy ranges but are consistent

My PhD work from low to high data level

The hadronic PeVatron candidate SNR G106.3+2.7 observed at Large Zenith Angle with LST-1 and MAGIC

Data quality and selection

- Development of a data quality selection tool
- Data selection specific to LZA observations allowing to recover data

Data reconstruction

- Reconstruction pipeline improvement (1st year, not shown here)

Background modeling

- Contribution to modeling package development
- Development of a simulation and model validation tool
- Diffusion of the tool within the LST collaboration
- Speaker at the LST analysis school

Scientific preliminary results

- First look at signs of the energy-dependent morphology
- Preliminary source spectra consistent with literature
- Promising results for hadronic PeVatron

What's next ?

- Background estimation parametrization final study
- acceptance_modelisation paper with M. De Bony and G. Emery
- Prepare SNR G106.3+2.7 study paper while waiting for data
- Presentation request for ICRC

Thank you for your attention!

Software libraries

lstchain: https://zenodo.org/doi/10.5281/zenodo.6344673
magic-cta-pipe: https://github.com/cta-observatory/magic-cta-pipe (cf. LST-1+MAGIC performance paper)
MARS: https://arxiv.org/abs/0907.0943

gammapy: https://zenodo.org/doi/10.5281/zenodo.8033275
gammapy-data: https://github.com/gammapy/gammapy-data

acceptance_modelisation: https://github.com/mdebony/acceptance_modelisation