Study of the PeVatron candidate SNR G106.3+2.7 observed at Large Zenith Angle with LST-1 and MAGIC

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2nd CTAO Symposium

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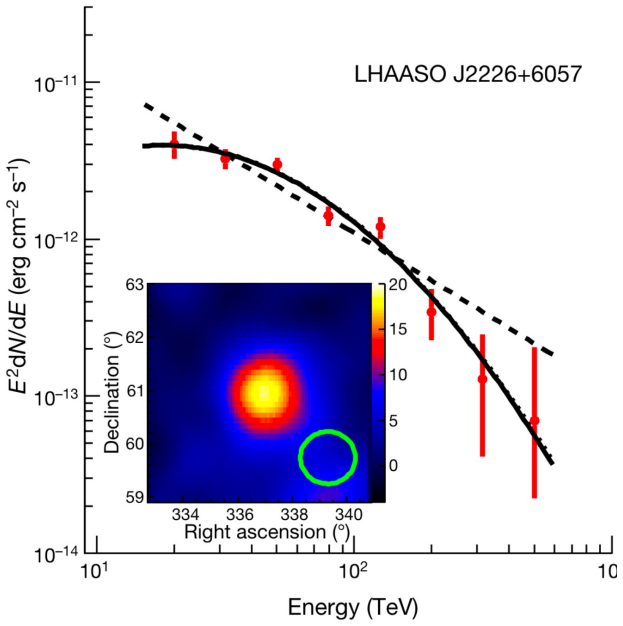
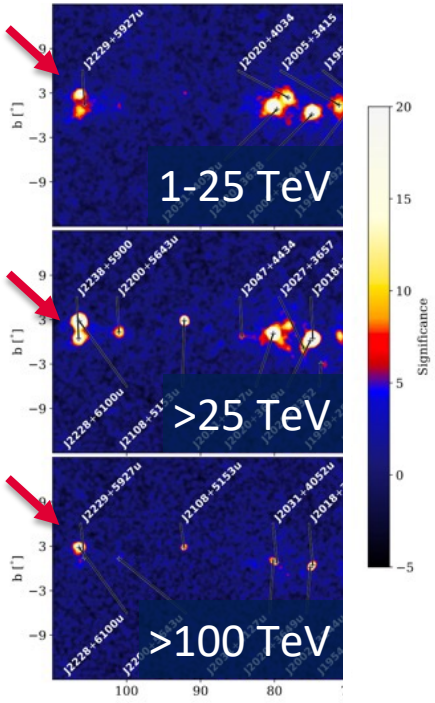
The confirmed PeVatron SNR G106.3+2.7

- **LHAASO** -> 43 UHE Galactic sources γ-rays between 1 TeV - 1.4 PeV
  - **SNR G106.3+2.7** among the sources
  - measured up to ~600 TeV

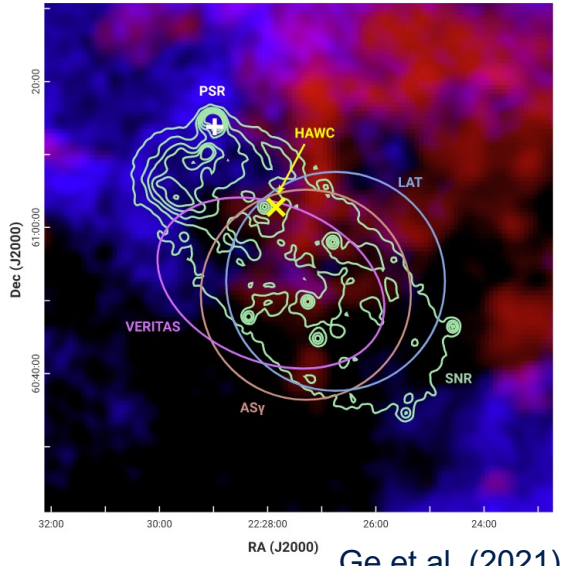


Cao et al. (2021)



Cao et al. (2023)

- Comet shaped **composite supernova remnant** (SNR)



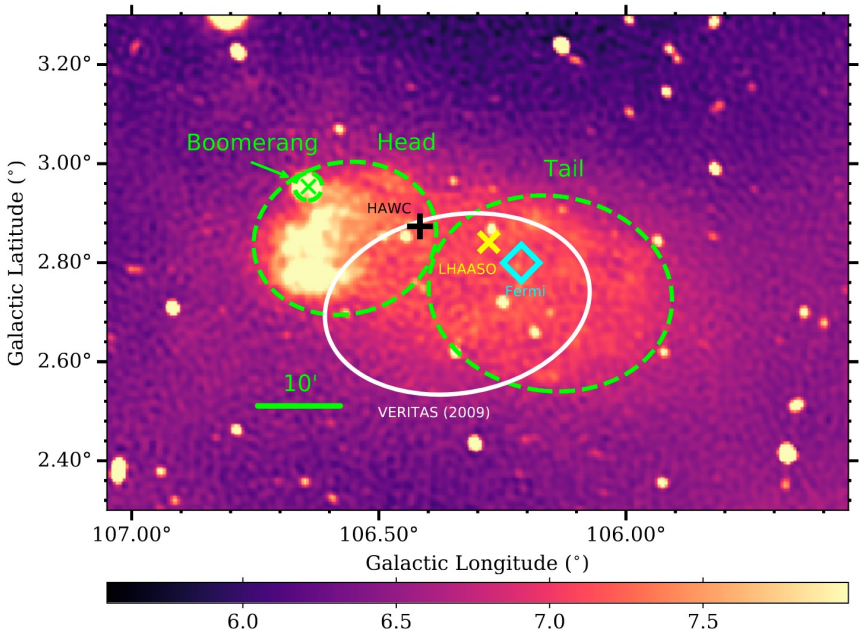
Ge et al. (2021)

head { pulsar (PSR) and its pulsar wind nebula (PWN) colliding in dense HI cloud (blue)

tail { expanding in low density HI cavity dense molecular cloud (red)

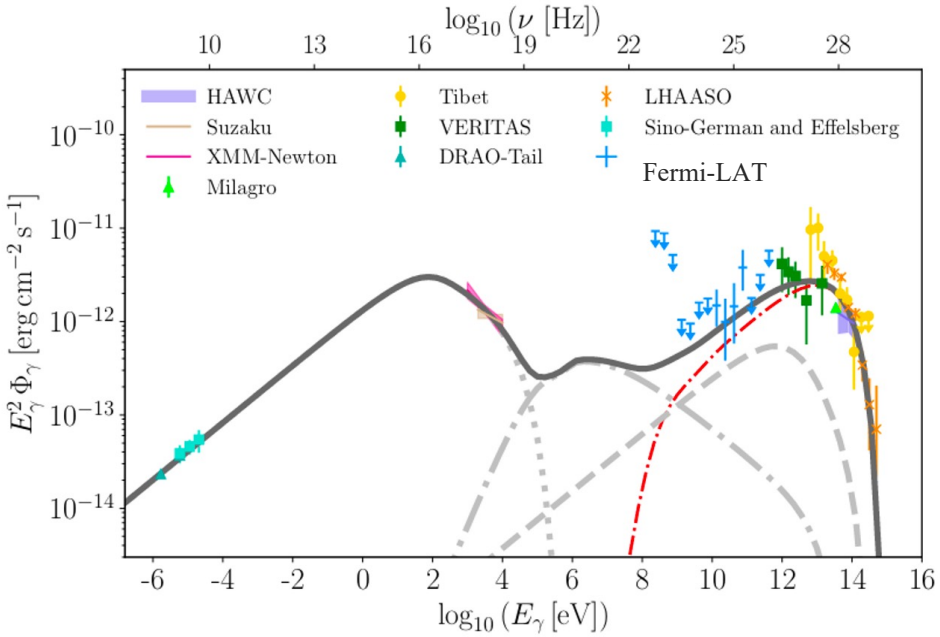
A hadronic PeVatron candidate

- UHE emission scenarios
  - from the **head** region: PSR+PWN -> **leptonic**
  - from the **tail** region: molecular cloud -> **hadronic**



Pope et al. (2023): CGPS 1420 MHz radio temperature brightness map

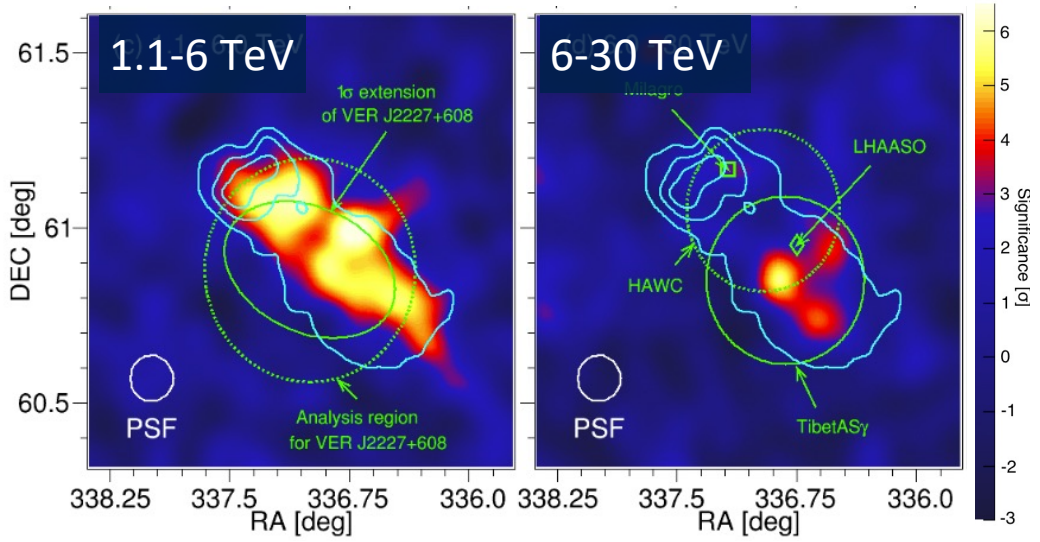
- **Hadronic** emission model **favored** by MWL SED analysis
- **Leptonic** scenarios still **not ruled out**



Fang et al. (2022): example of SED modelling the tail emission with lepto-hadronic scenario

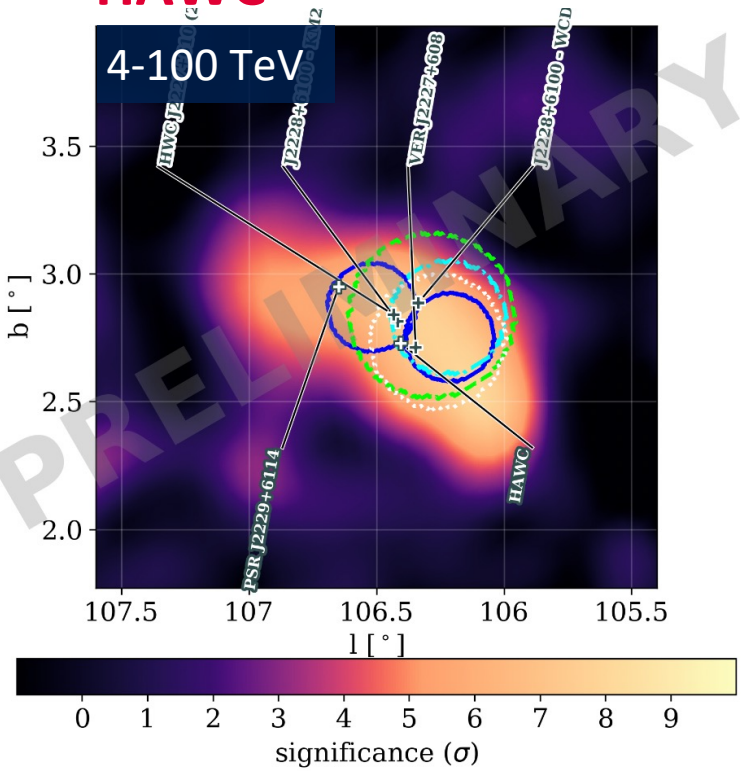
Recent VHE results

MAGIC



MAGIC Collaboration (2022)

HAWC



R. Turner (2023)

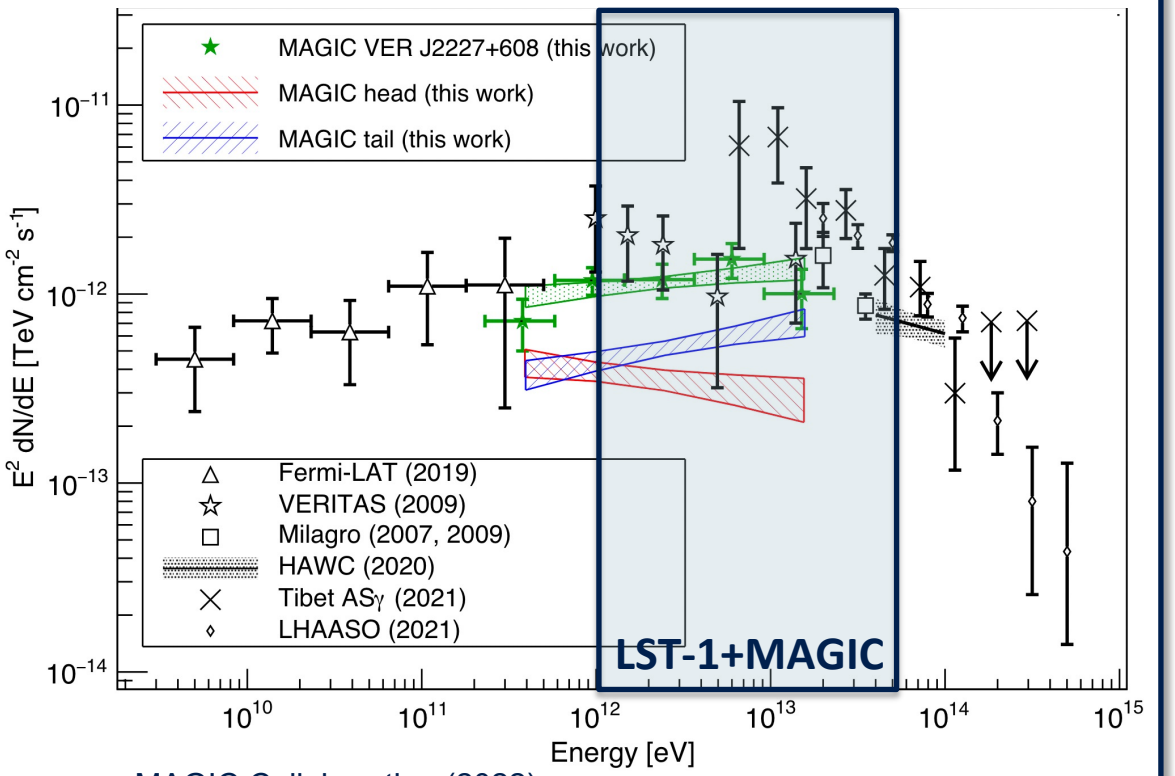
- VHE emissions from head and tail
  - **MAGIC**: tail, ~0.3° from PSR, correlated with molecular cloud
  - **HAWC**: head+tail, extended source

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

Our study of SNR G106.3+2.7

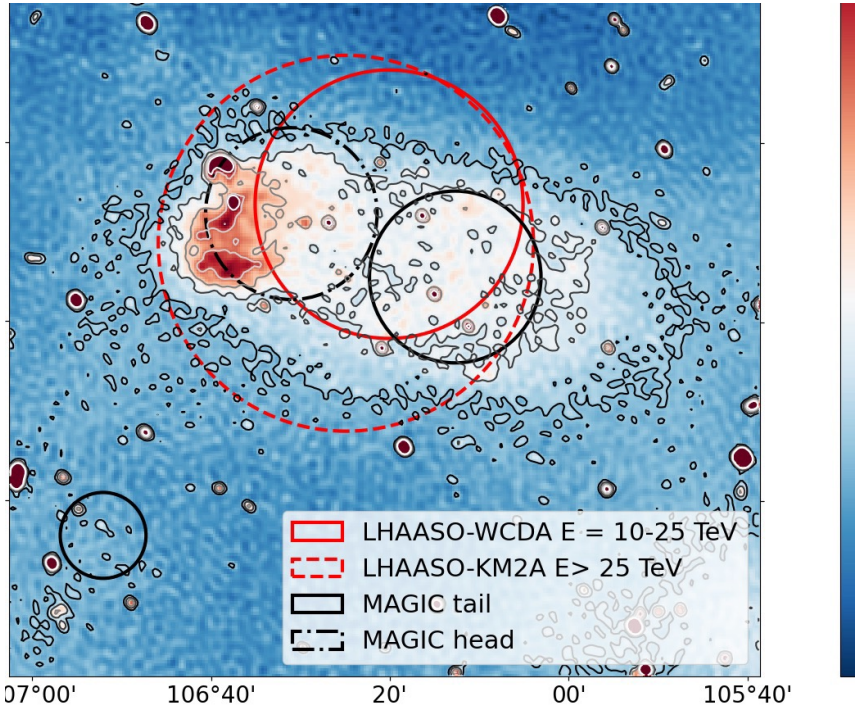
- Understanding the **nature of the source** by resolving its **energy-dependent morphology**

➢ exploration of the **1-50 TeV energy range**



MAGIC Collaboration (2022)

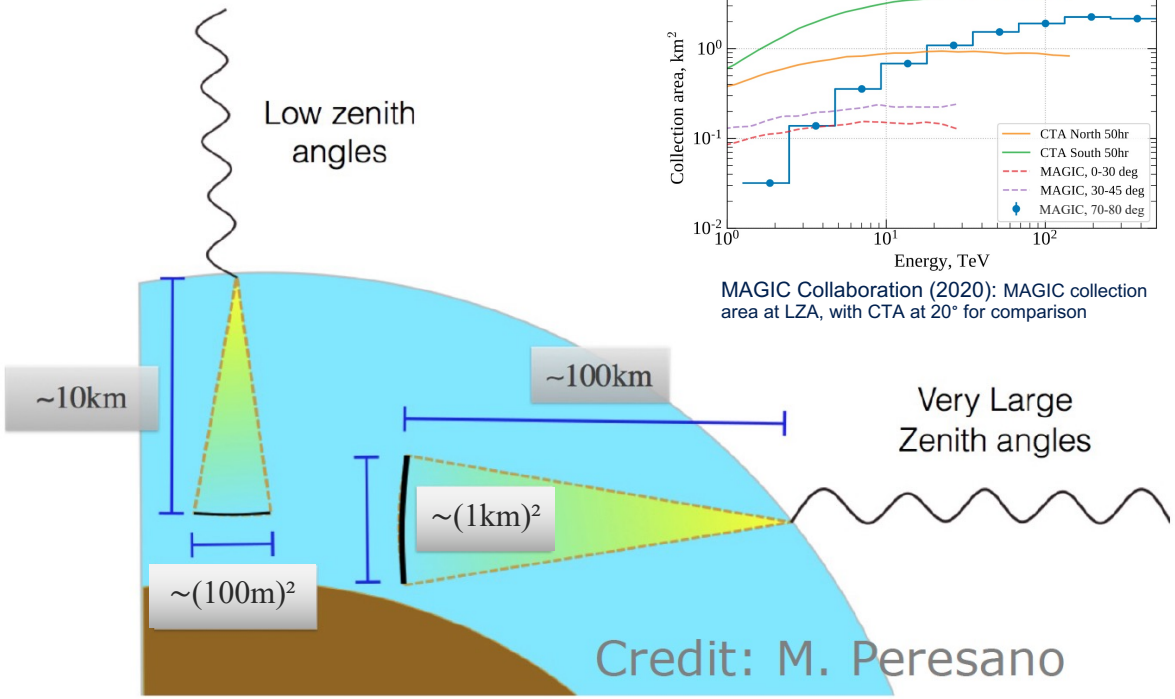
➢ with an **angular resolution <0.1 deg**



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

The observation campaign

- **On-going multi-year observation campaign** with LST-1 and MAGIC
  - At Large Zenith Angle (**LZA**) -> higher effective area at higher energies
  - Stereo **LST-1+MAGIC** -> higher sensitivity

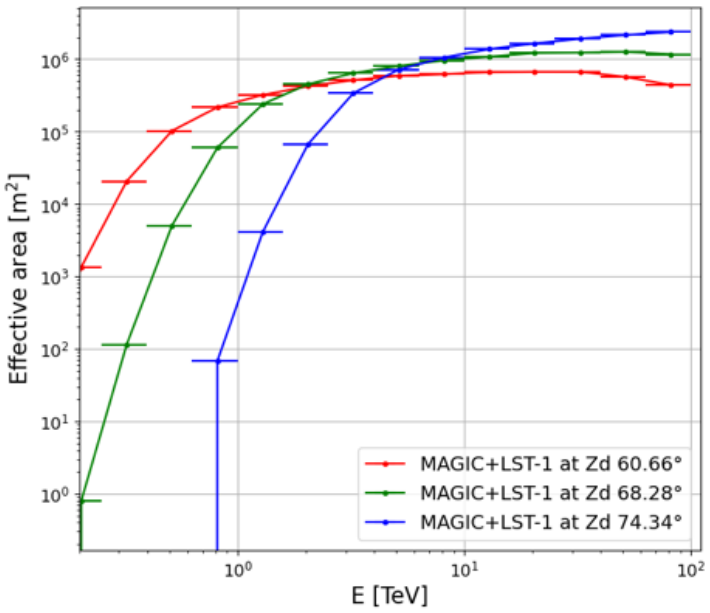


MAGIC Collaboration (2020): MAGIC collection area at LZA, with CTA at 20° for comparison

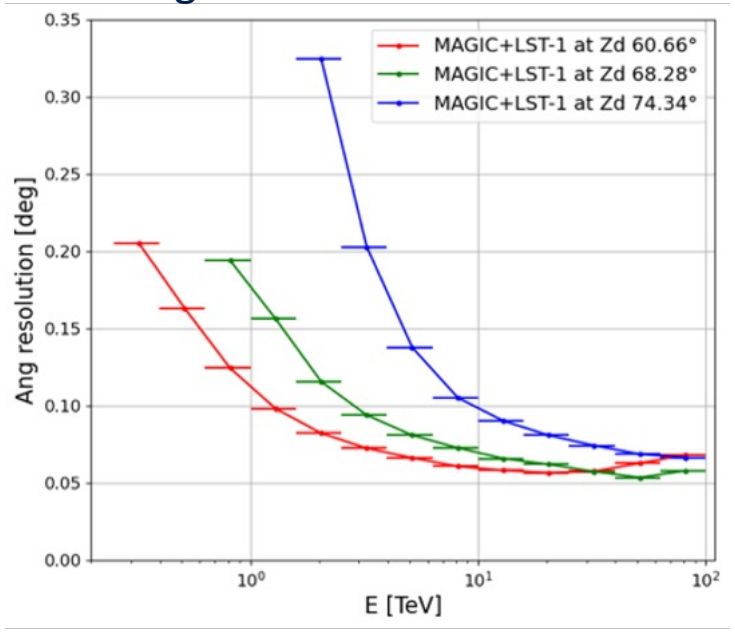
LZA observation with LST-1+MAGIC

- The **effective area** strongly increases with zenith at VHE
- The **angular resolution** is expected to be < 0.1° for highest energies
- The **energy resolution** is also expected to be better than 15% for highest energies at all zd

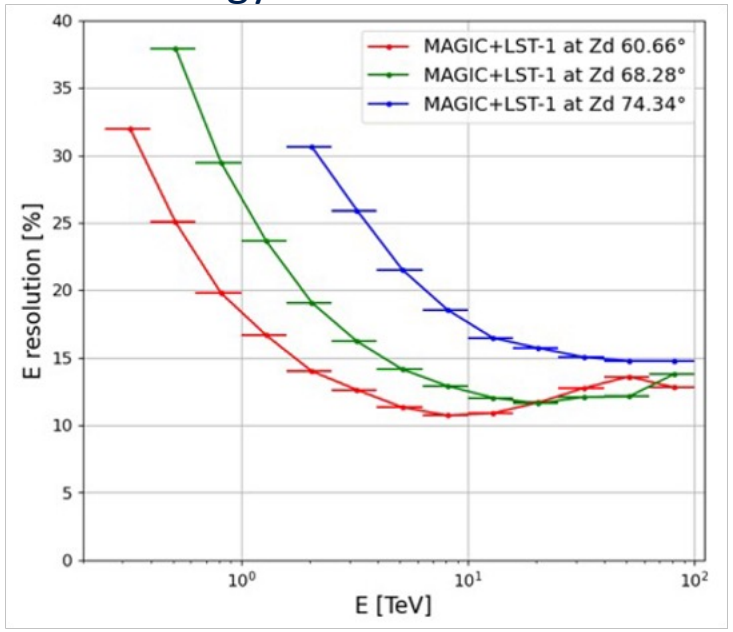
Effective area vs zenith



Angular resolution vs zenith



Energy resolution vs zenith

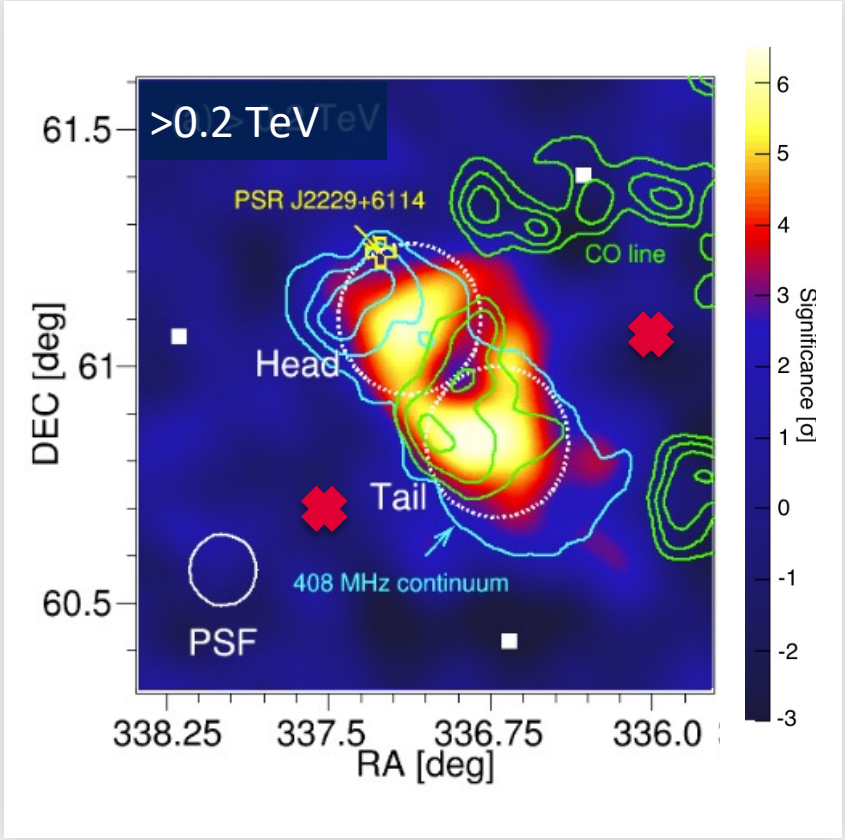


MC simulation of MAGIC+LST stereo data reconstructed with magic-cta-pipe

Data analysis

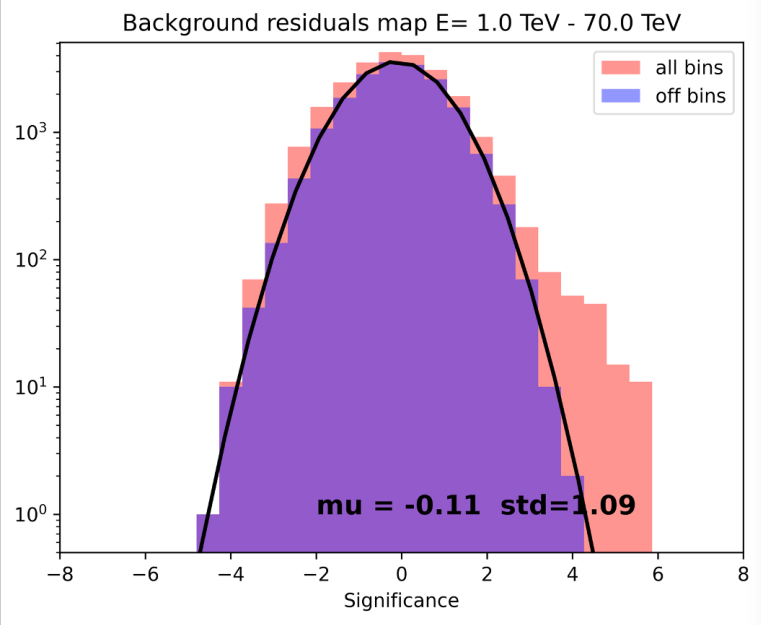
- Observation performed in **wobble mode**
  - **2 wobbles** to study both head and tail
- 3 datasets, 3 reconstruction pipelines (cf. backup)
  - **LST-1** data reconstructed with lstchain
  - **MAGIC + LST-1** data reconstructed with magic-cta-pipe
  - **MAGIC** data also reconstructed with MARS for crosscheck
- **High level analysis** (spectrum, maps) performed with gammapy

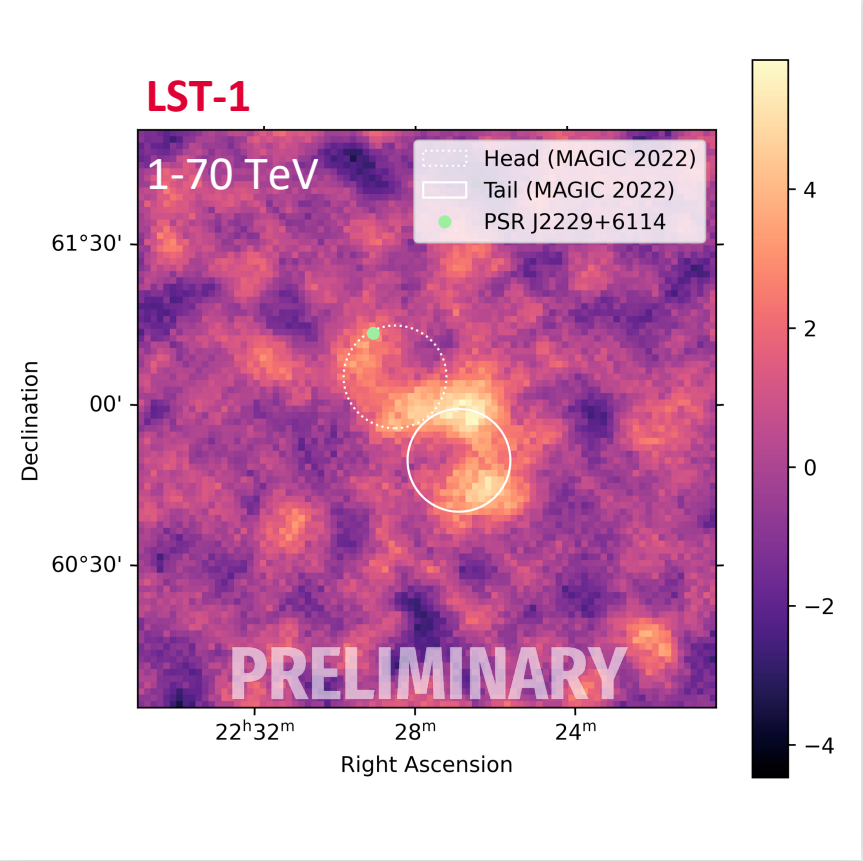
- **This work** presents preliminary results
  - **38h LST-1 data** (final target is 120h)
  - maps and spectrum with point-like study (for now)
- Stereo analysis of LST-1+MAGIC and MAGIC data is ongoing

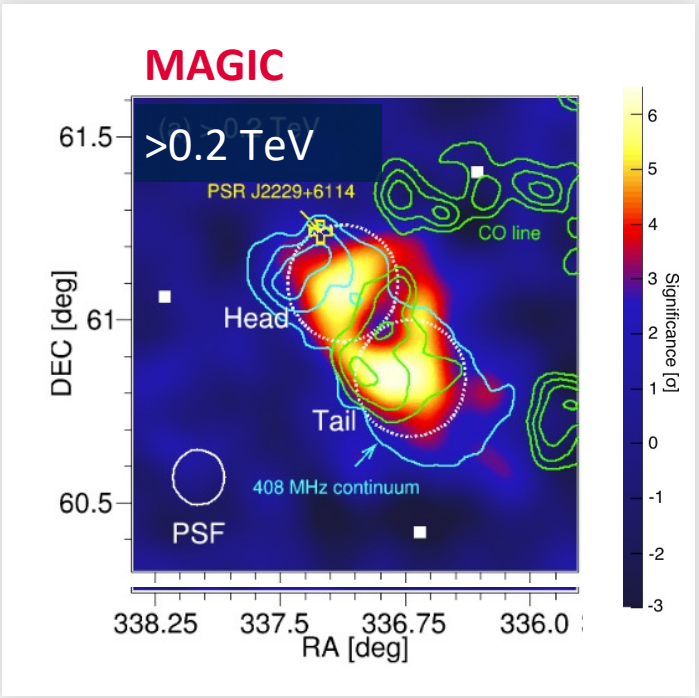


MAGIC Collaboration (2022)

First view of the Boomerang SNR with LST-1





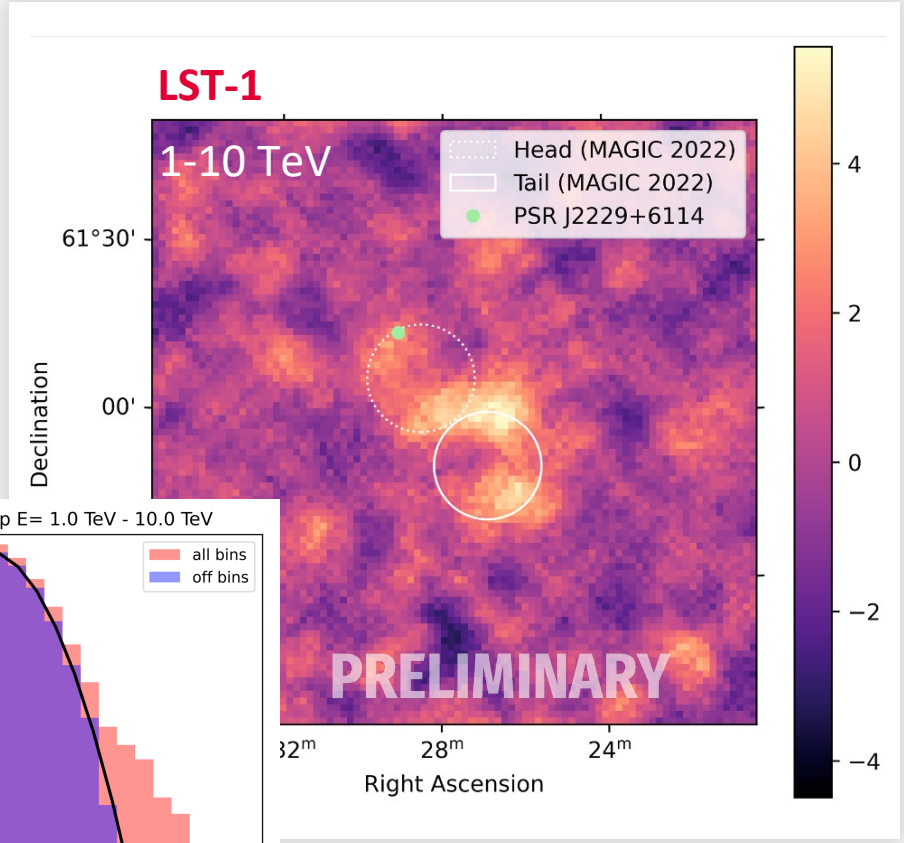


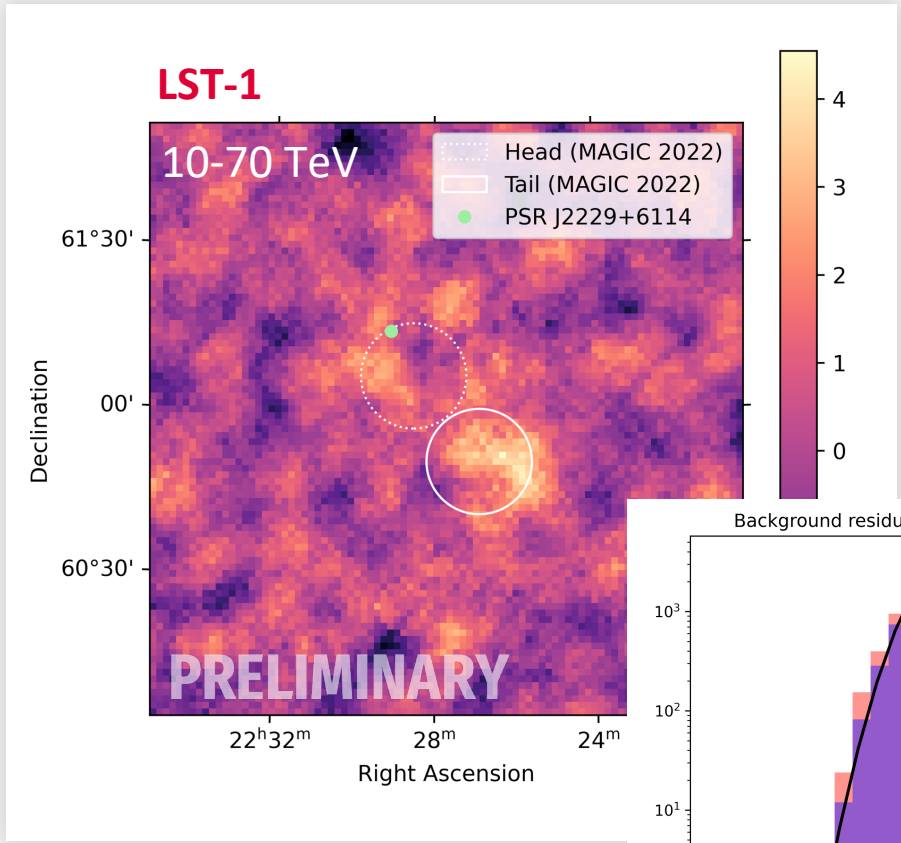
MAGIC Collaboration (2022)

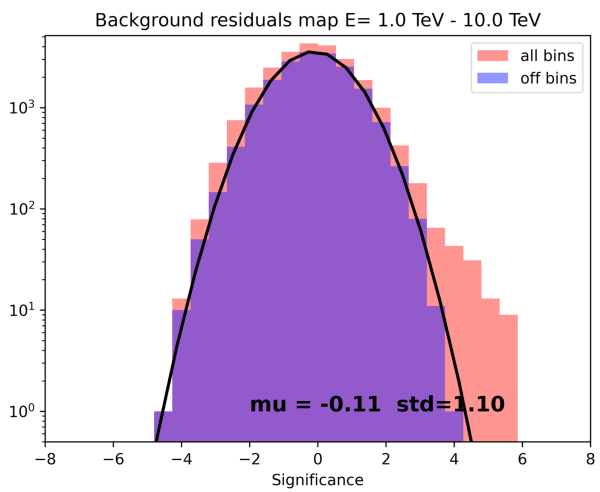
LST-1 results with 38 h of data at large zenith angle (cf. backup)

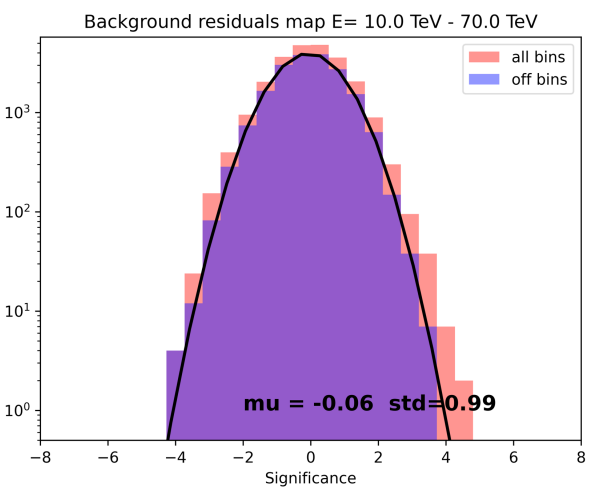
MAGIC map with 121 h of data at low zenith angle

First look at the morphology in two energy bins



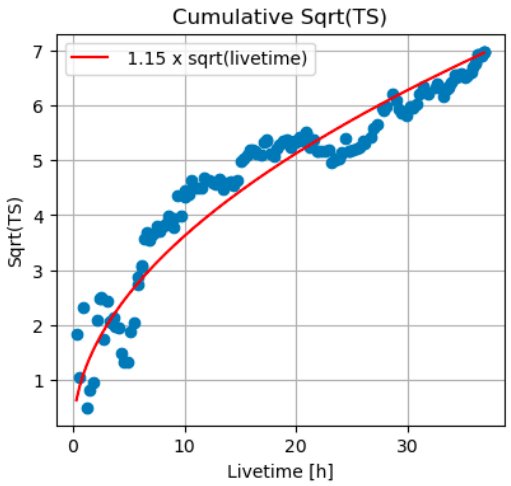


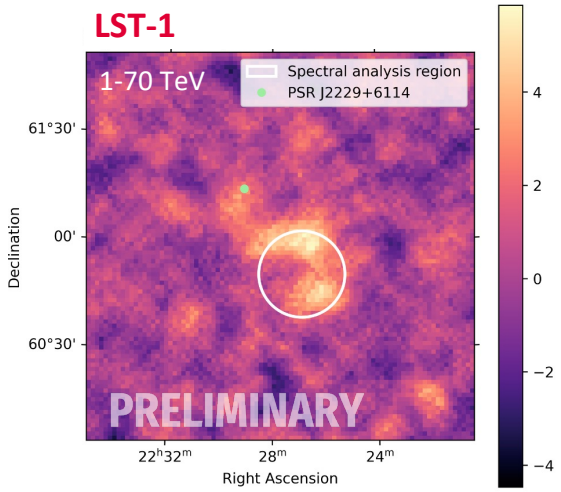




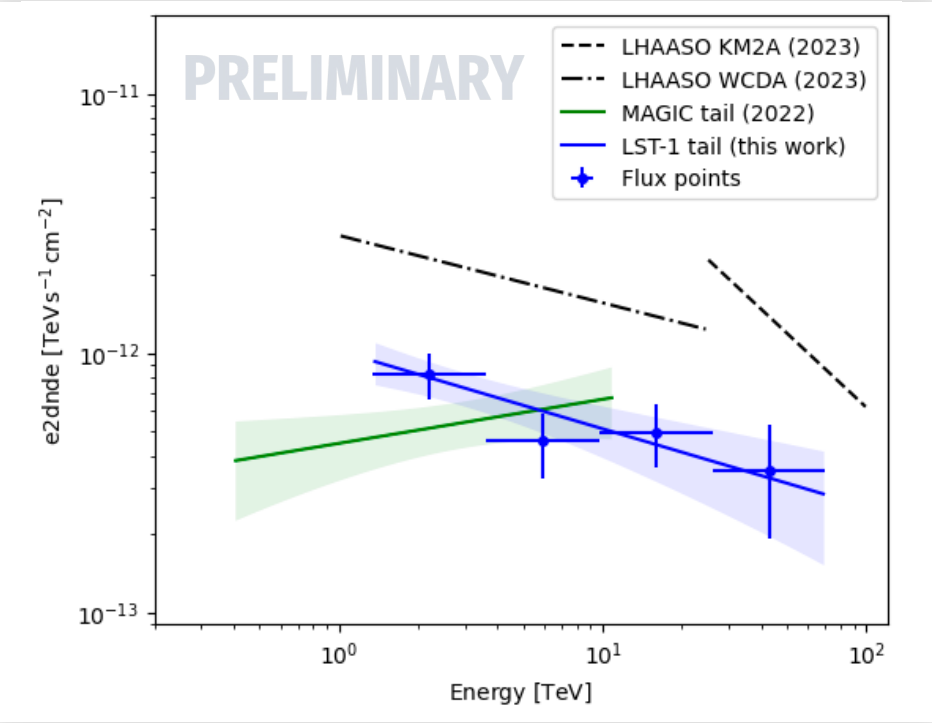
We begin to see the energy-dependent morphology, with a shift of the emission towards the tail for **E>10 TeV**

Looking at the spectrum with point-like analysis





- Stacked analysis SED with **38h of LST-1 data** (cf. backup)
- ON region:
  - 0.2° radius
  - centered on the tail
- Fit in the 0.5-70 TeV energy range



- Simple power law: $dN/dE = N_0 (E/3\ \text{TeV})^{-\Gamma}$
  - $\Gamma = 2.30 \pm 0.14$
  - $N_0 = (8.13 \pm 1.20) \times 10^{-14}$ TeV s^{-1} cm^{-2}
- Index consistent with LHAASO
- Flux consistent with MAGIC, extended at higher E

Conclusions and outlook

- The Boomerang SNR is a promising hadronic PeVatron candidate
- Successful ongoing LST-1+MAGIC observation campaign at LZA
- We already detect the source up to ~50 TeV and begin to see its energy-dependent morphology
- First spectral analysis covers MAGIC and LHAASO energy range

Next:

- ➢ Joint LST-1+MAGIC data analysis
- ➢ Optimization of the background modelling
- ➢ Optimization for extended source analysis
- ➢ Modelling of possible gamma-ray emission scenarios
- ➢ New data to come (final target 120h)

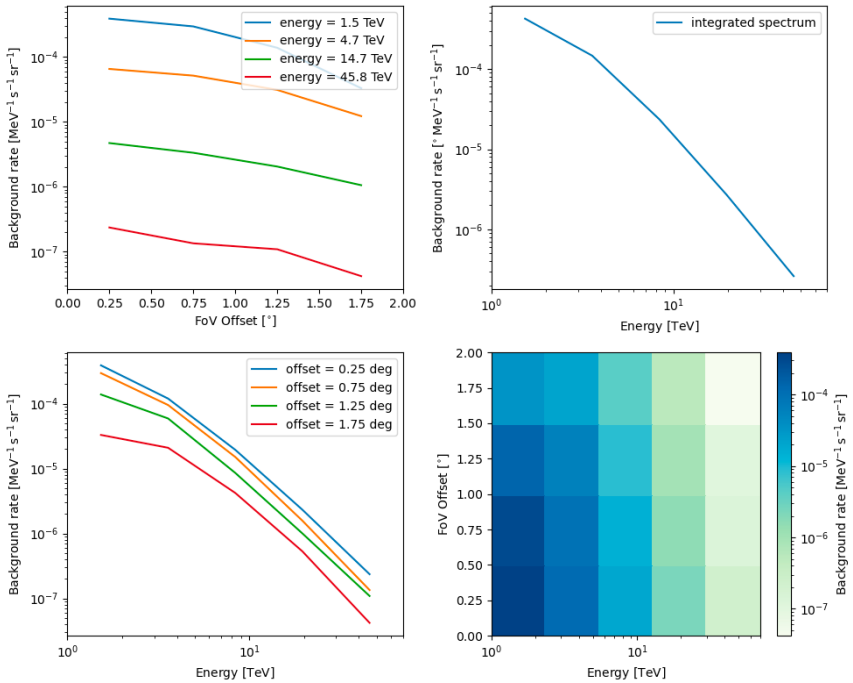
LST-1 moments before operations (S. Menchiari, apr. 2023)

Thank you for your attention !

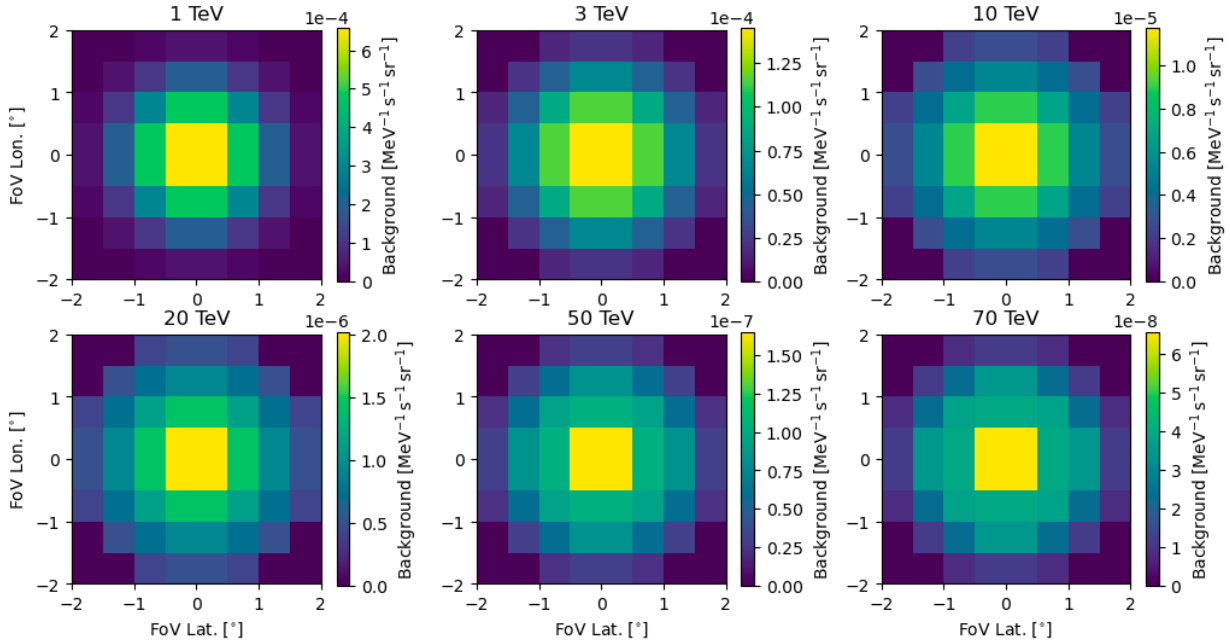
Backup

Skymap analysis method

- 2D acceptance (energy, offset) estimated with [acceptance modelisation library]
- Background estimated with gammapy [ring background model]



Example of produced IRF



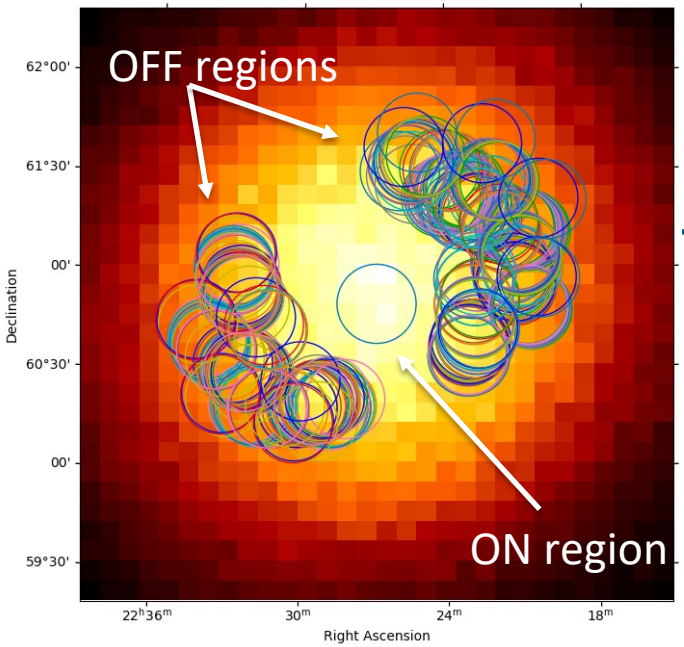
Estimated acceptance map vs energy

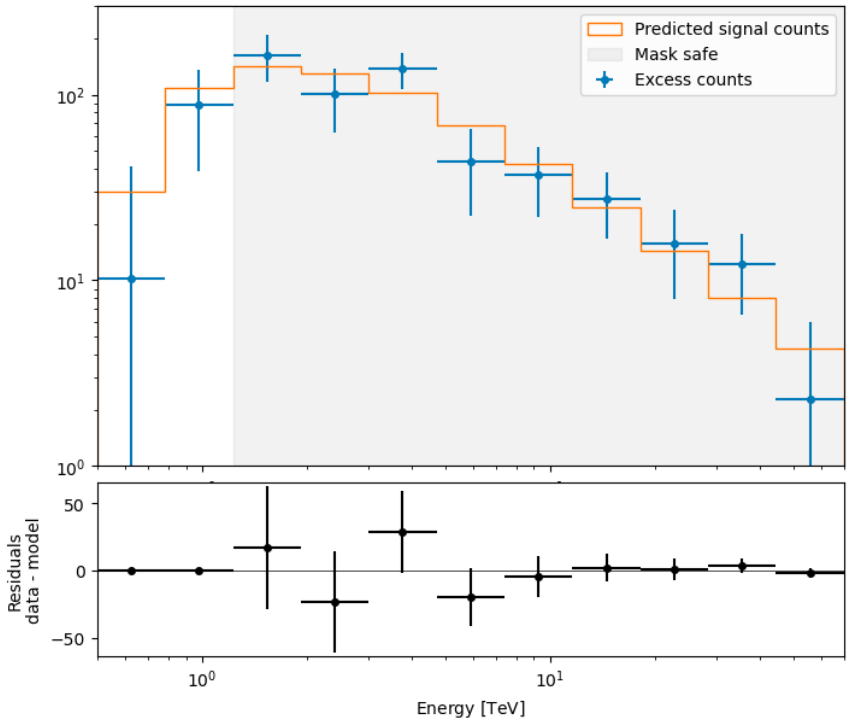
Spectral analysis method

- We followed the gammapy tutorial for [1D spectral analysis]
  - extended source analysis not possible with point-like IRFs

- Source coordinates:
  - head: (RA, DEC) = (337.13°, 61.10°)
  - tail: (RA, DEC) = (336.72°, 60.84°)
- ON region:
  - Target position is the tail region
  - 0.2° radius
- OFF regions:
  - exclusion region:
    - 2 circles centered on head and tail
    - 0.3° radius
  - no limit on number of reflected background regions

- SED:
  - Safe mask: 10% of the maximum effective area
  - 0.5 – 70 TeV reco energy range
  - 5 bins per decade for fit, 2 for final SED flux points





Reconstruction 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.4701488