Large zenith angle observation of the PeVatron candidate SNR G106.3+2.7 with the LST-1 and the MAGIC telescopes

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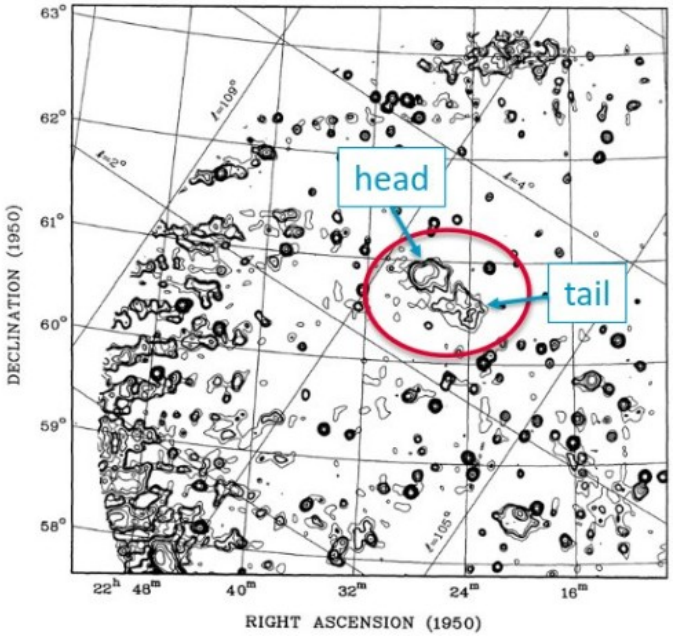
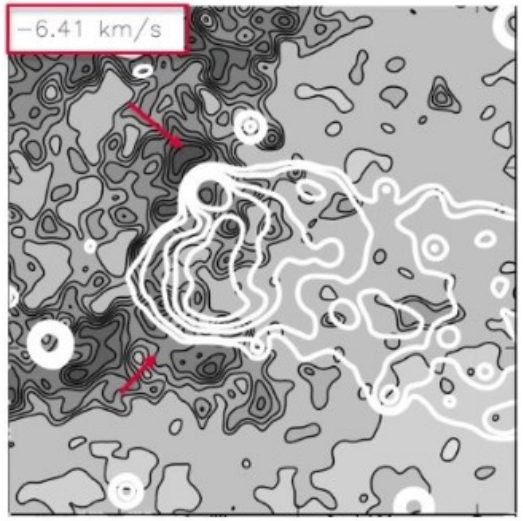
on behalf of the LST and MAGIC collaborations

SNR, Pulsar and PWN

- Super nova remnant SNR G106.3+2.6 first detected in radio
- Boomerang Pulsar Wind Nebula (PWN) identified in the head
- Pulsar detected close to the PWN
- Connected to molecular clouds (HI and CO)
  - Head : pulsar and its PWN colliding in dense HI cloud
  - Tail : expanding in low density HI cavity
  - CO cloud possibly around the tail or in foreground
- Distance : 0.8 – 10 kpc, Age < 10 400 years

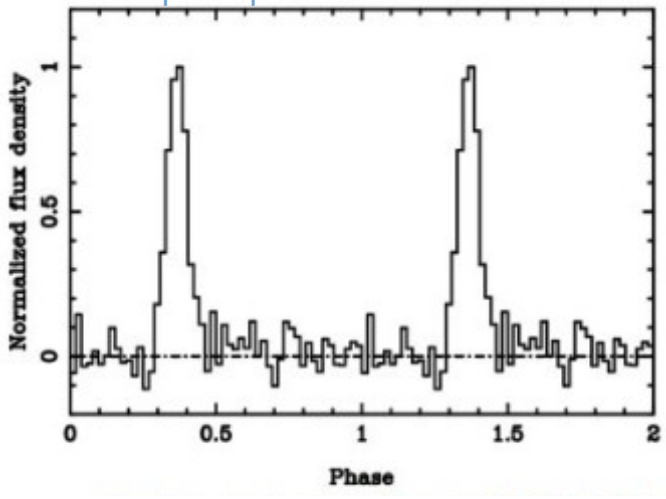
Joncas & Higgs (1990)





Khotes et al. (2001)
HI (grey) and radio continuum 1420 Hz (white)

Halpern et al. (2001b)
Radio pulse profile at 1412 MHz



Gamma-ray observations

Observed by multiple IACTs in the O(TeV):

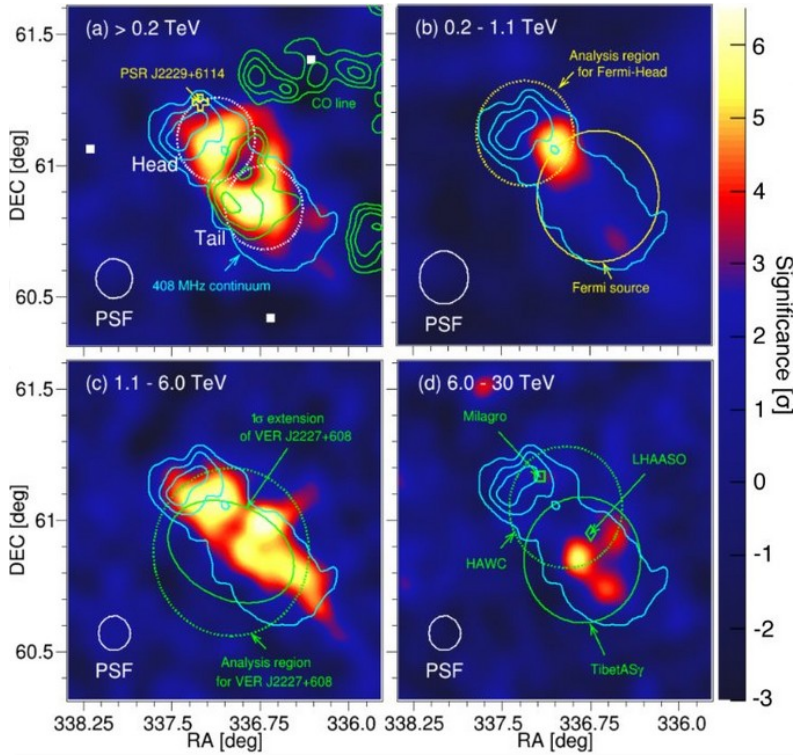
VERITAS, MAGIC

MAGIC detected the source up to 30 TeV showing energy dependent morphology

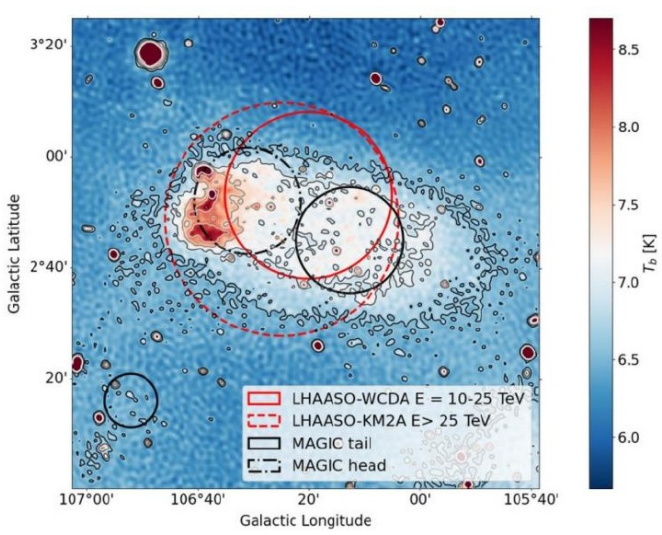
Observed by particle detectors in the O(10-100TeV):

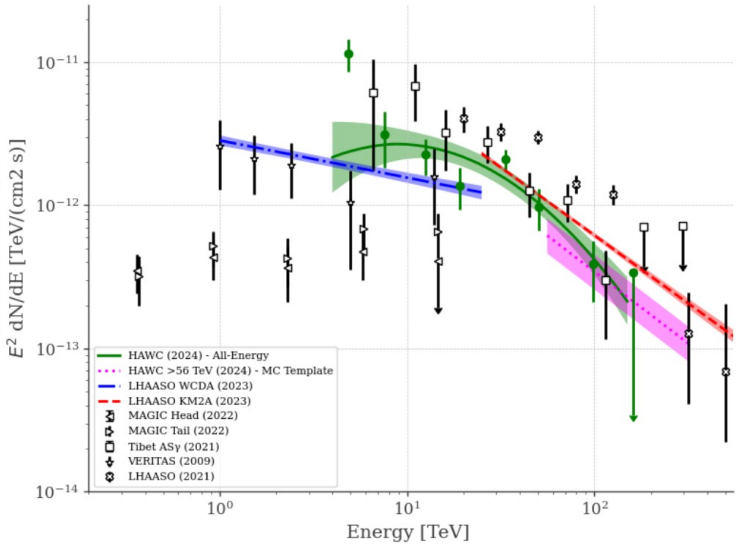
HAWC , Tibet ASγ, LHAASO

Clear detection by LHAASO at E>100 TeV



Maps with 120h of observations - MAGIC Collaboration (A&A, 2023)





R. Alfaro et al. 2024

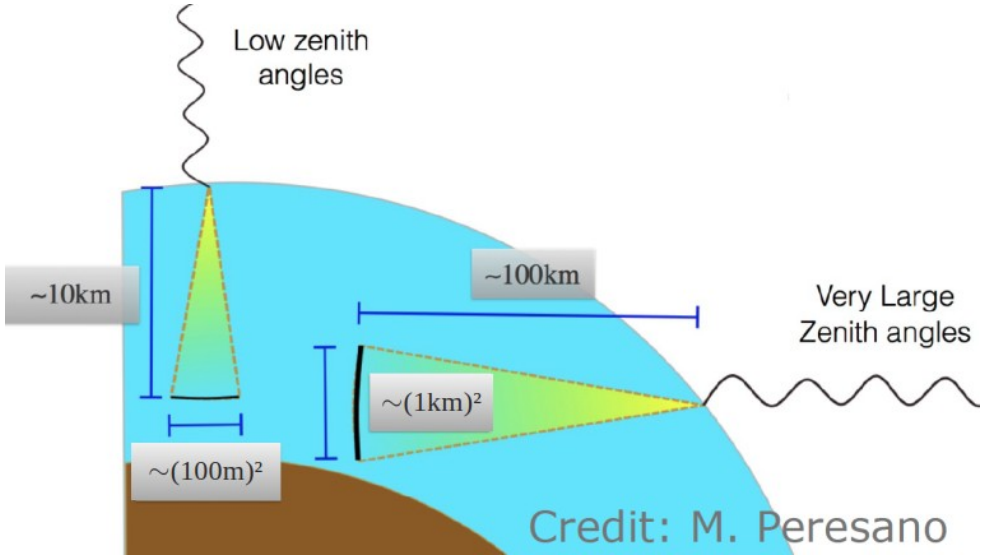
Observation strategy

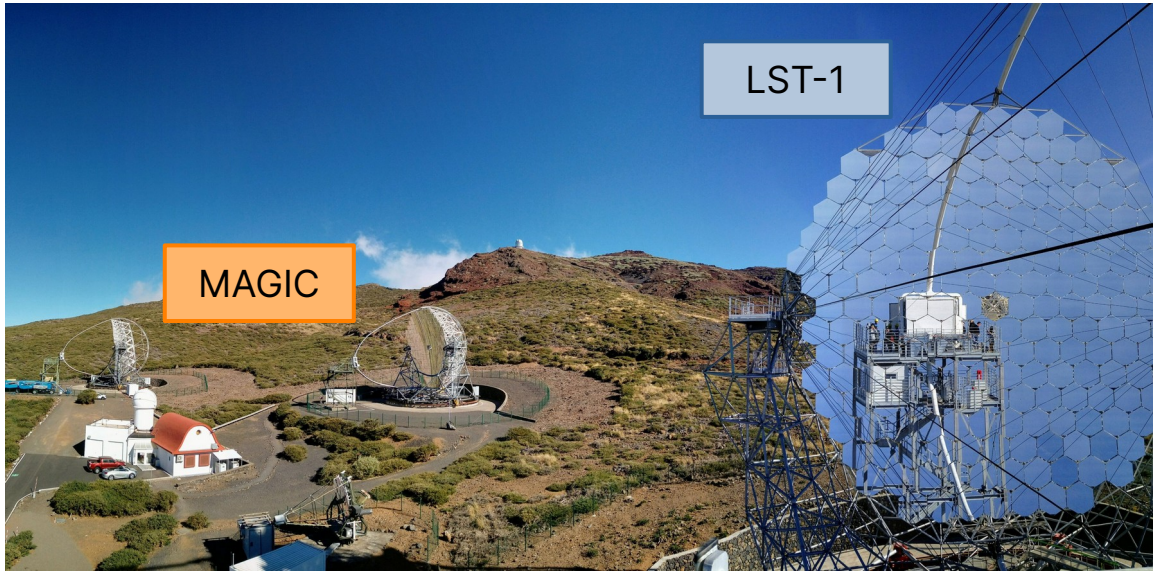
Goal and strategy

Resolve the energy-dependent morphology of the source for E > 10 TeV :

Extend the high angular resolution measurements of IACTs to the energy range only covered by particle detectors

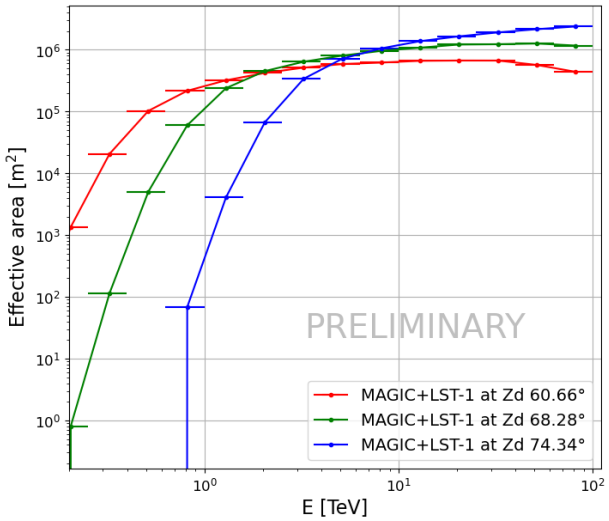
- Profit from simultaneous LST-1 and MAGIC observations to increase telescope multiplicity
- Observe at large zenith angle (LZA) to increase sensitivity at E>10 TeV

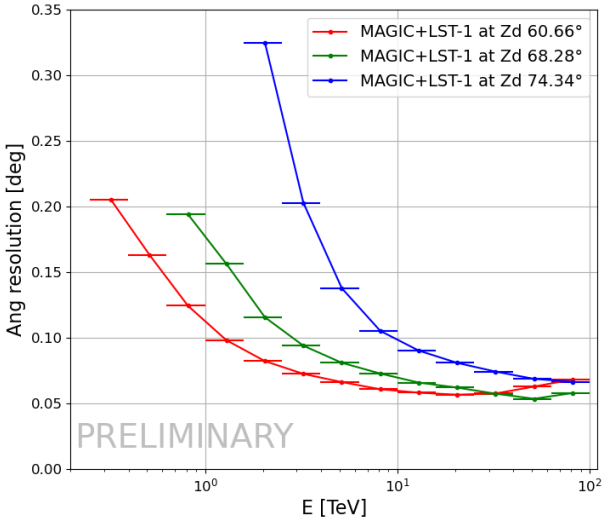


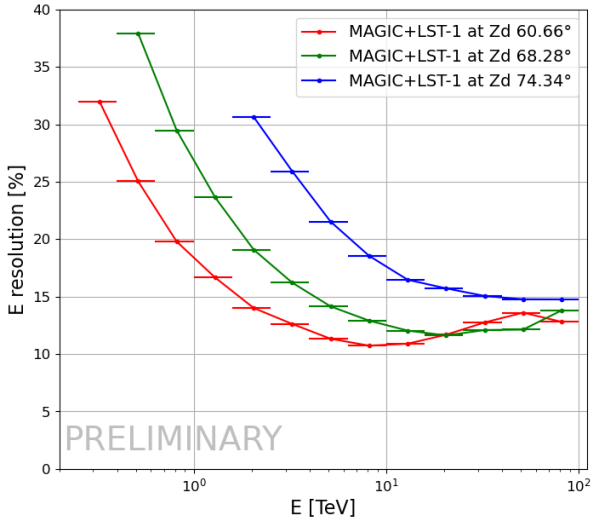


Credit : Alicia López Oramas – From MAGIC telescopes on X (link)

Large Zenith Angle performance





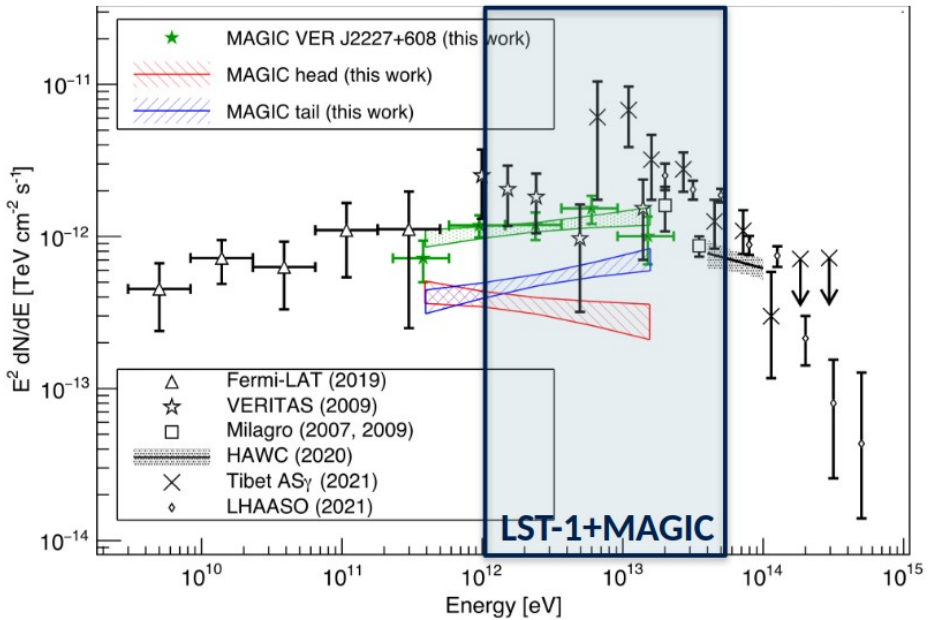


Performance estimates using MC simulation of LST-1 + MAGIC stereo data reconstructed with magic-cta-pipe

In the LZA region (60-75°):

- Effective area increases compared to lower zenith
- Angular resolution still reaches < 0.1°
- Energy resolution< 15%
- We can explore the 1-50 TeV region

MAGIC Collaboration (2022)



Available dataset and pipelines

Analysed dataset :

After data quality selection and combination of simultaneous LST-1 and MAGIC data, the data are combined, excluding common time intervals in subsequent subarrays.

Livetime in final analysis (and **total livetime**) per subarray and analysis pipeline :

- LST-1 + MAGIC stereo **18.7 hours** : magic-cta-pipe
- LST-1 Mono **24.9h** (total : **43.4h**) : cta-lstchain
- MAGIC **6.9h** (total : **44.5h**) : MARS

Joint LST-1 + MAGIC, LST-1 Mono, MAGIC : 50.4 hours

High level analysis :

High level analysis with gammapy v1.1 and background IRFs produced with the package acceptance_modelisation

Background estimation

Background IRF :

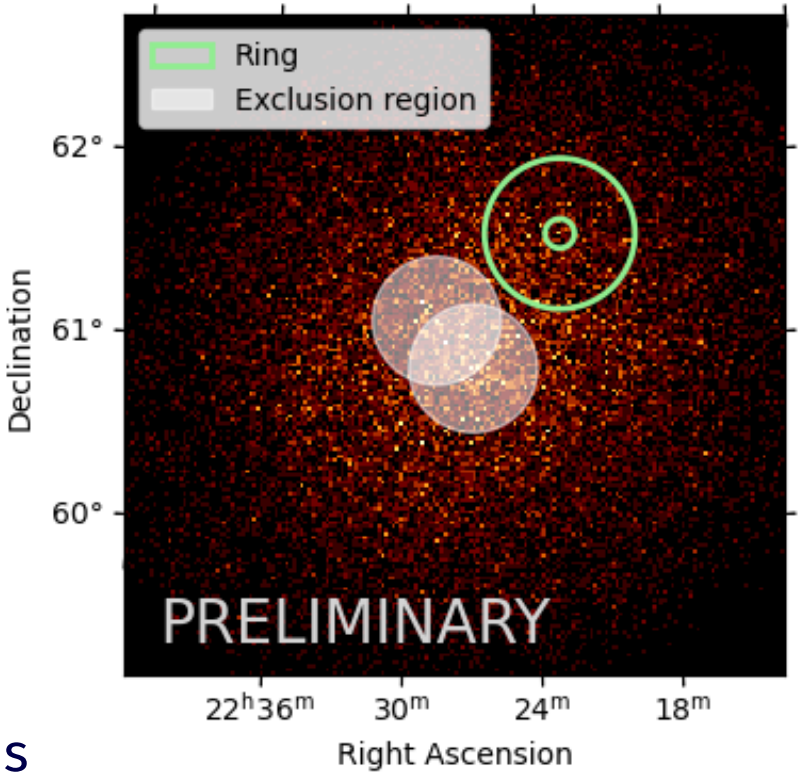
Obtained with the code acceptance_modelisation

- Create background IRFs from DL3 data (event list) using the **total time** for each sub-array
- Output a zenith dependent 3D IRF (E, Alt, Az) fitting a model per energy bin
  - 2D Gaussian with linear gradient along the Alt and Az axes (LST-1 Mono, LST-1 + MAGIC)
  - 1D Gaussian along the field of view radius (MAGIC only)

Background maps :

Apply the ring background method using the background IRF

- Exclude a region around the source
- Integrate over a ring (green circles) for each pixel of the map
- Normalize counts using the background IRF

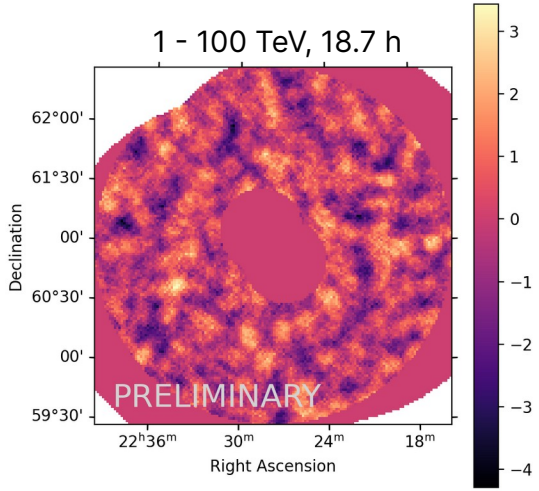


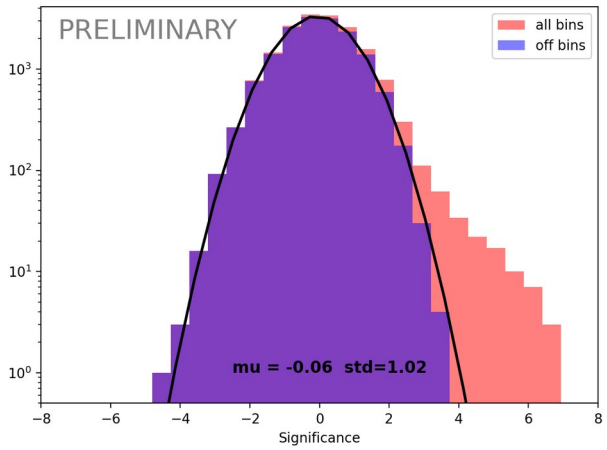
Spectral analysis :

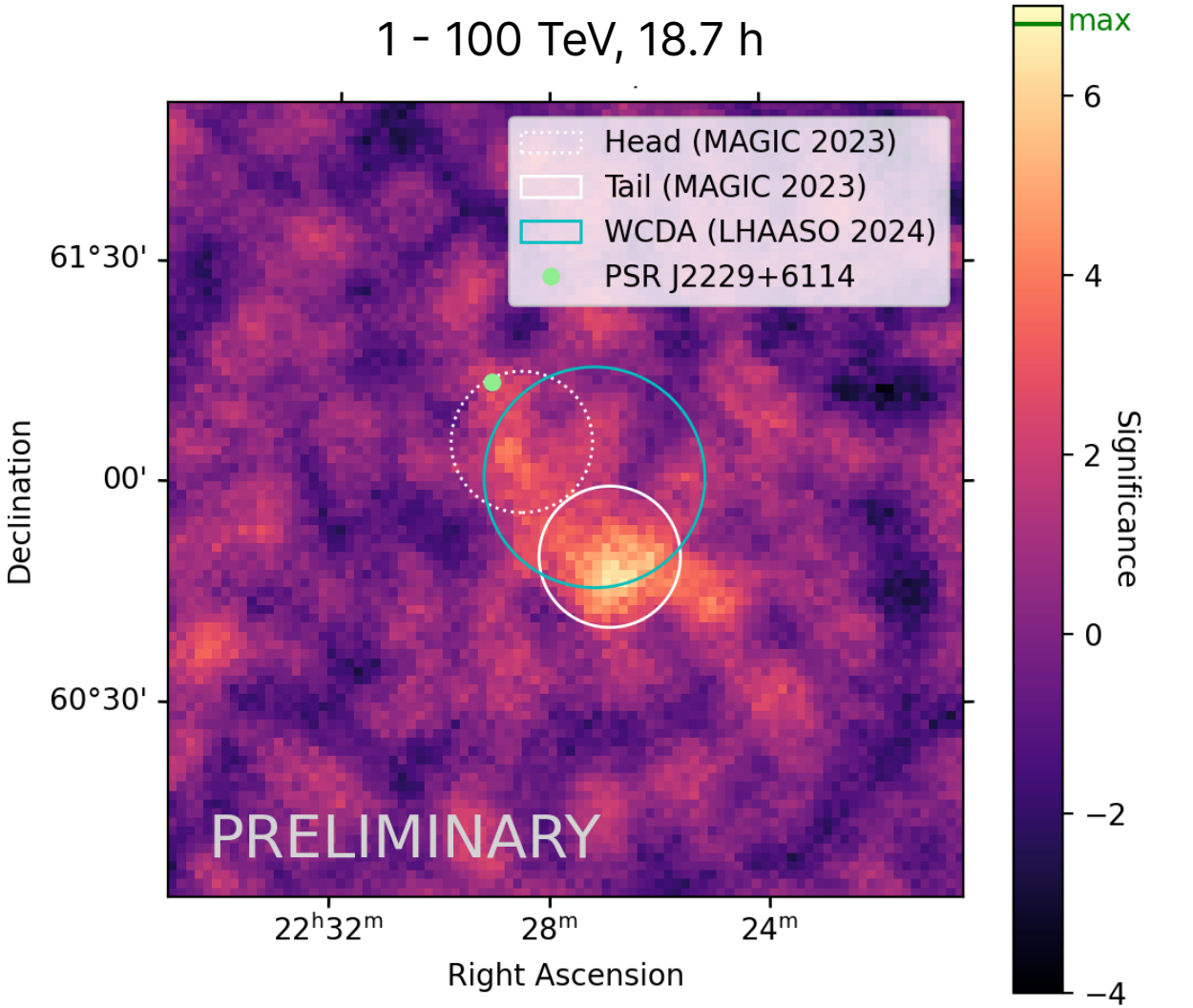
- In addition to skymaps, the background obtained with the ring background method is used in spectral analysis to estimate background counts vs energy in regions of interest
- This is an alternative to the reflected background method which is biased at LZA

LST-1 + MAGIC : 18.7 hours, Energy : 1 - 100 TeV
Maximum significance on map : 6.8σ
Signal concentrated in the tail

Well normalized background



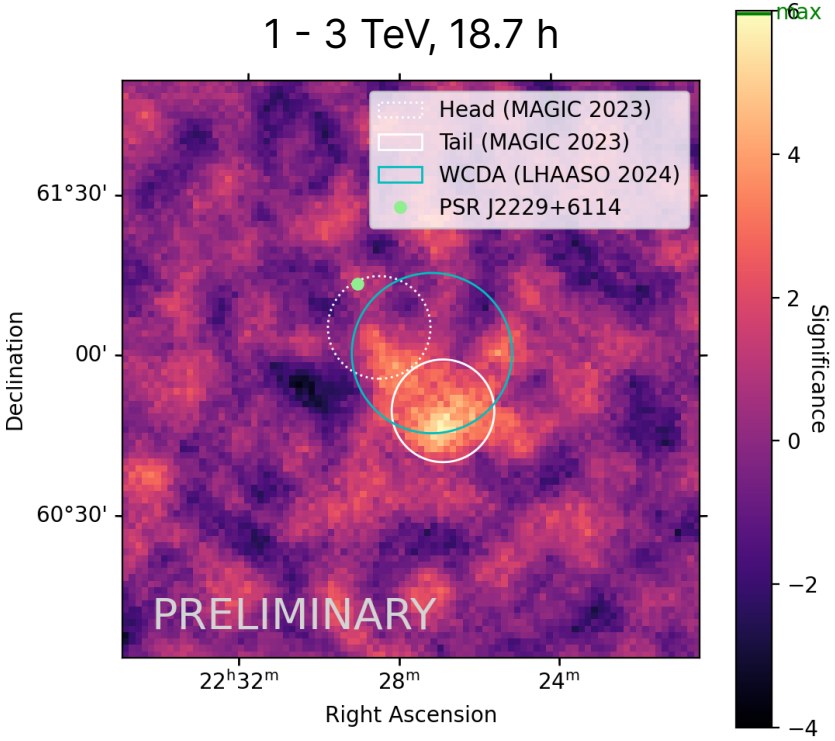


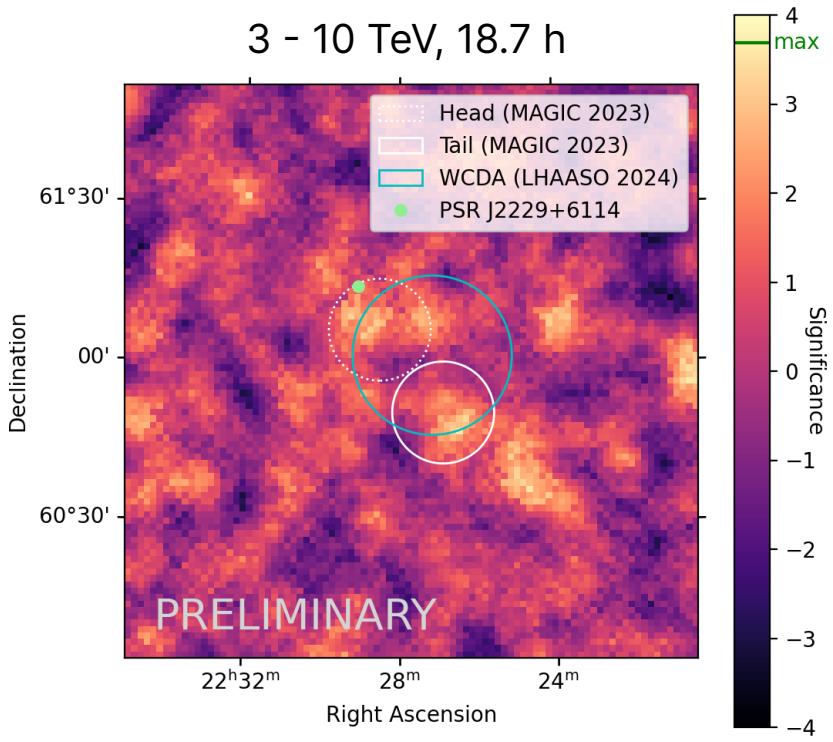


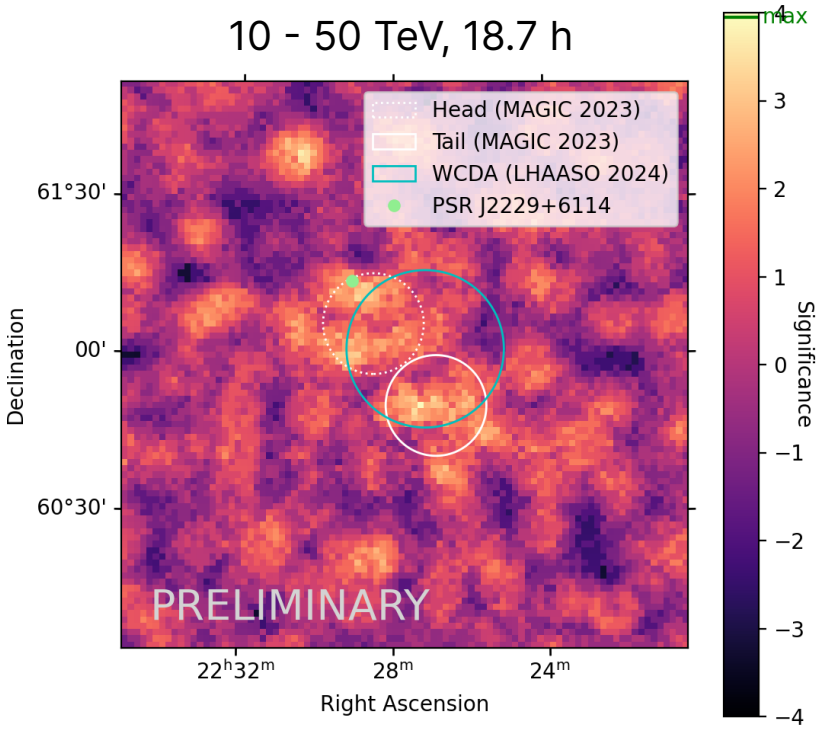
Skymaps vs energy

LST-1 + MAGIC : 18.7 hours

Signal dominated by the 1-3 TeV range







Skymaps

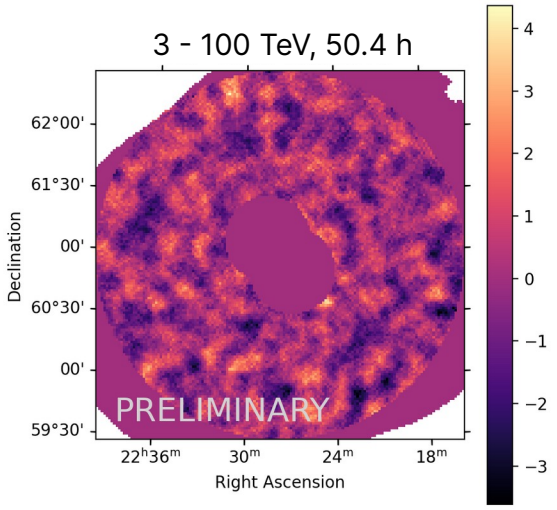
Joint dataset : 50.4 hours , Energy : 3 – 100 TeV

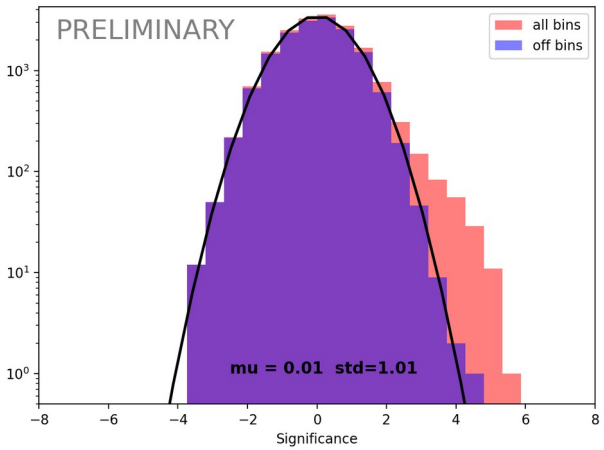
Maximum significance on map : 5.5σ

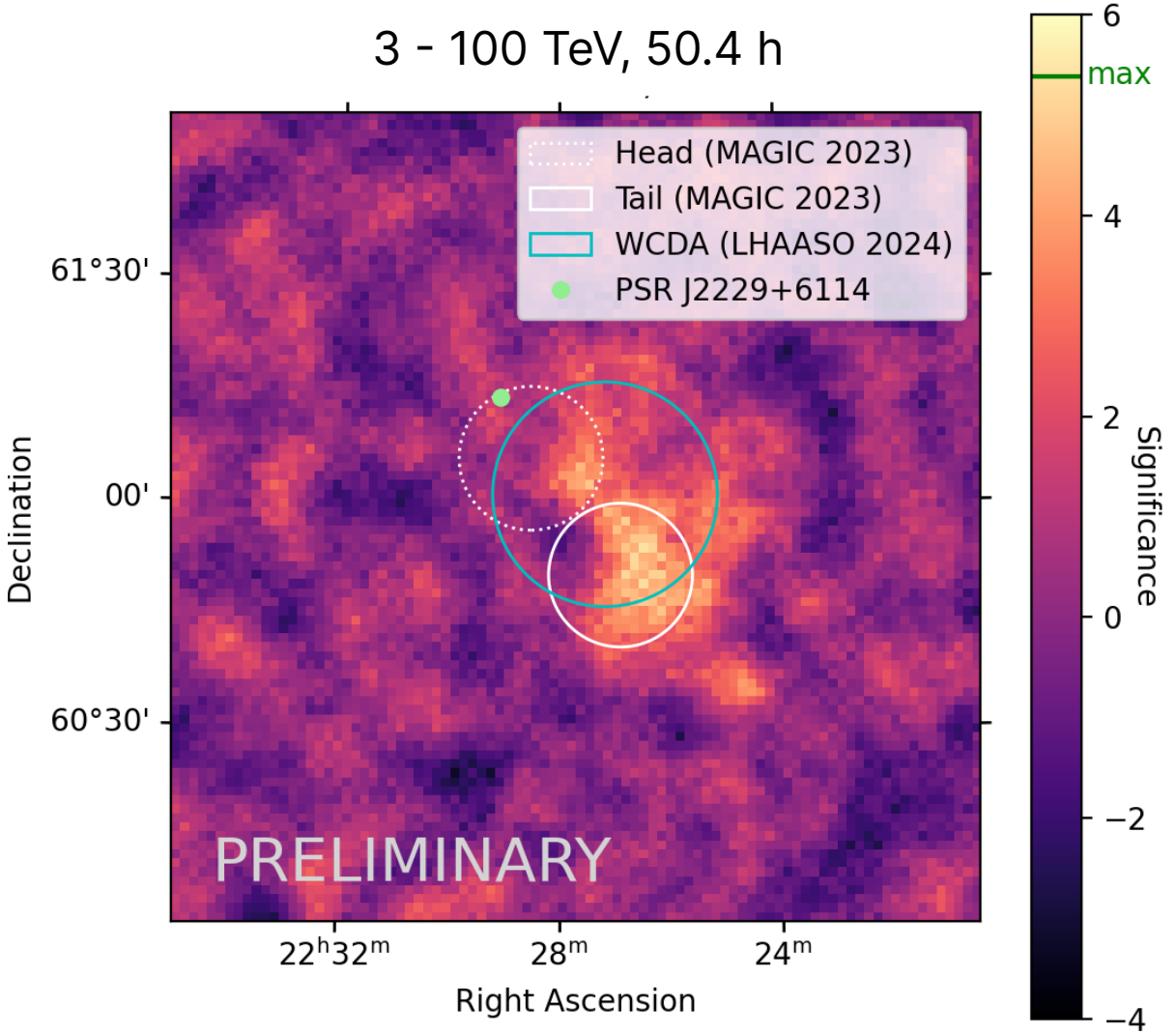
Background degraded below 3 TeV due to the different energy thresholds of the added observations → increase threshold

Signal more extended

Well normalized background





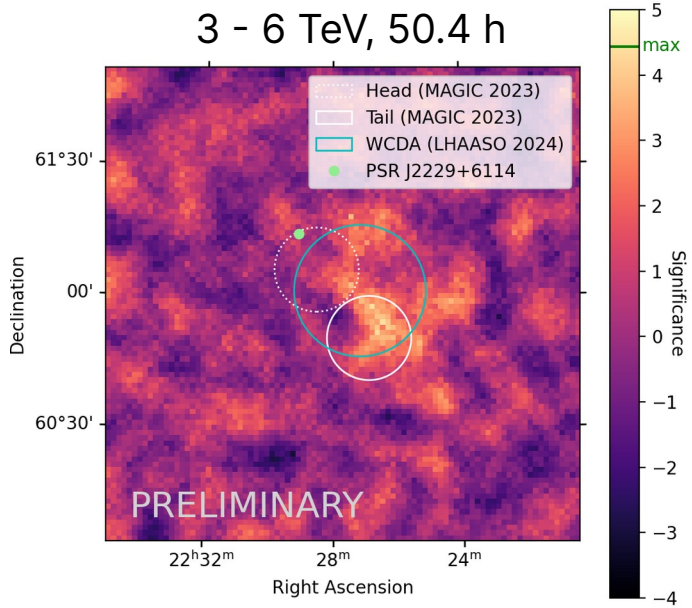


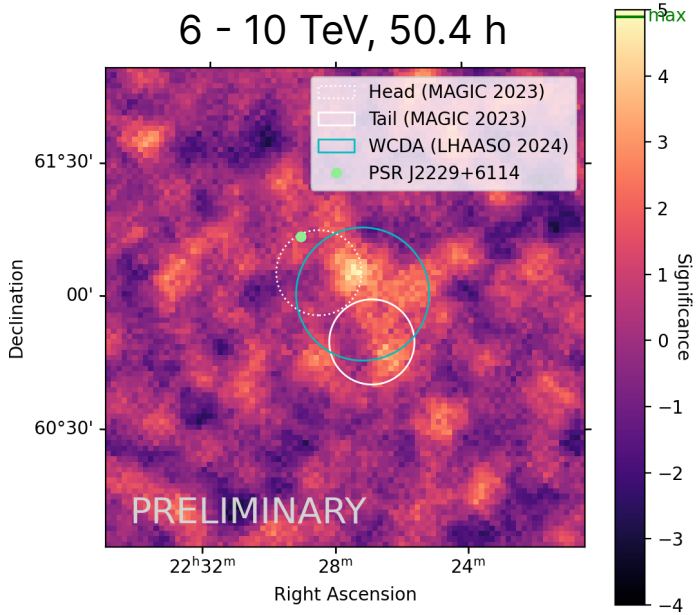
Skymaps vs energy

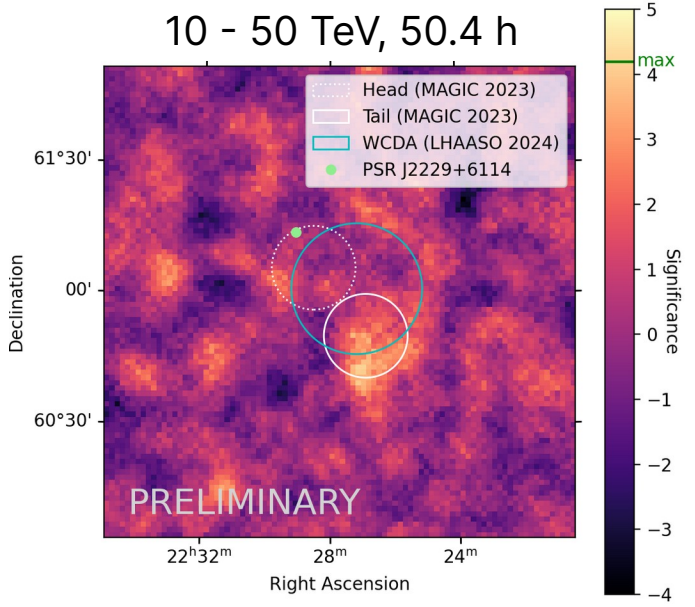
Joint dataset : 50.4 hours

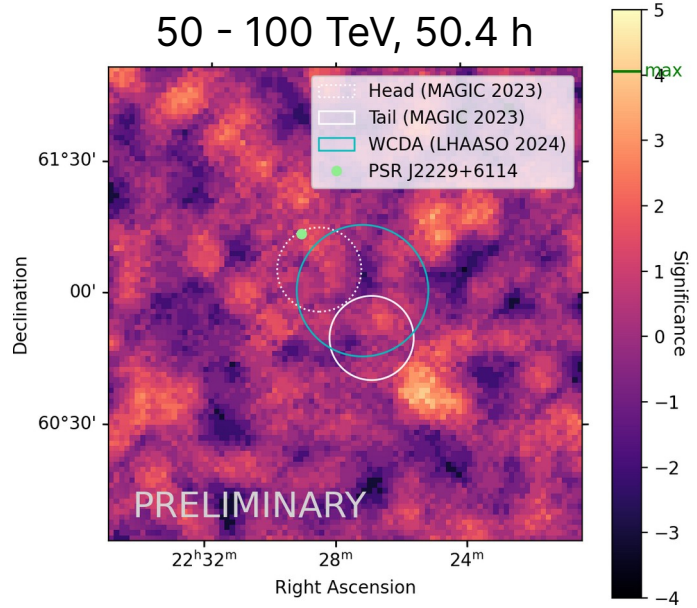
We observe:

- more than 4σ in each energy bins
- the maximum of the significance is moving away from the pulsar with increasing energy above 6 TeV



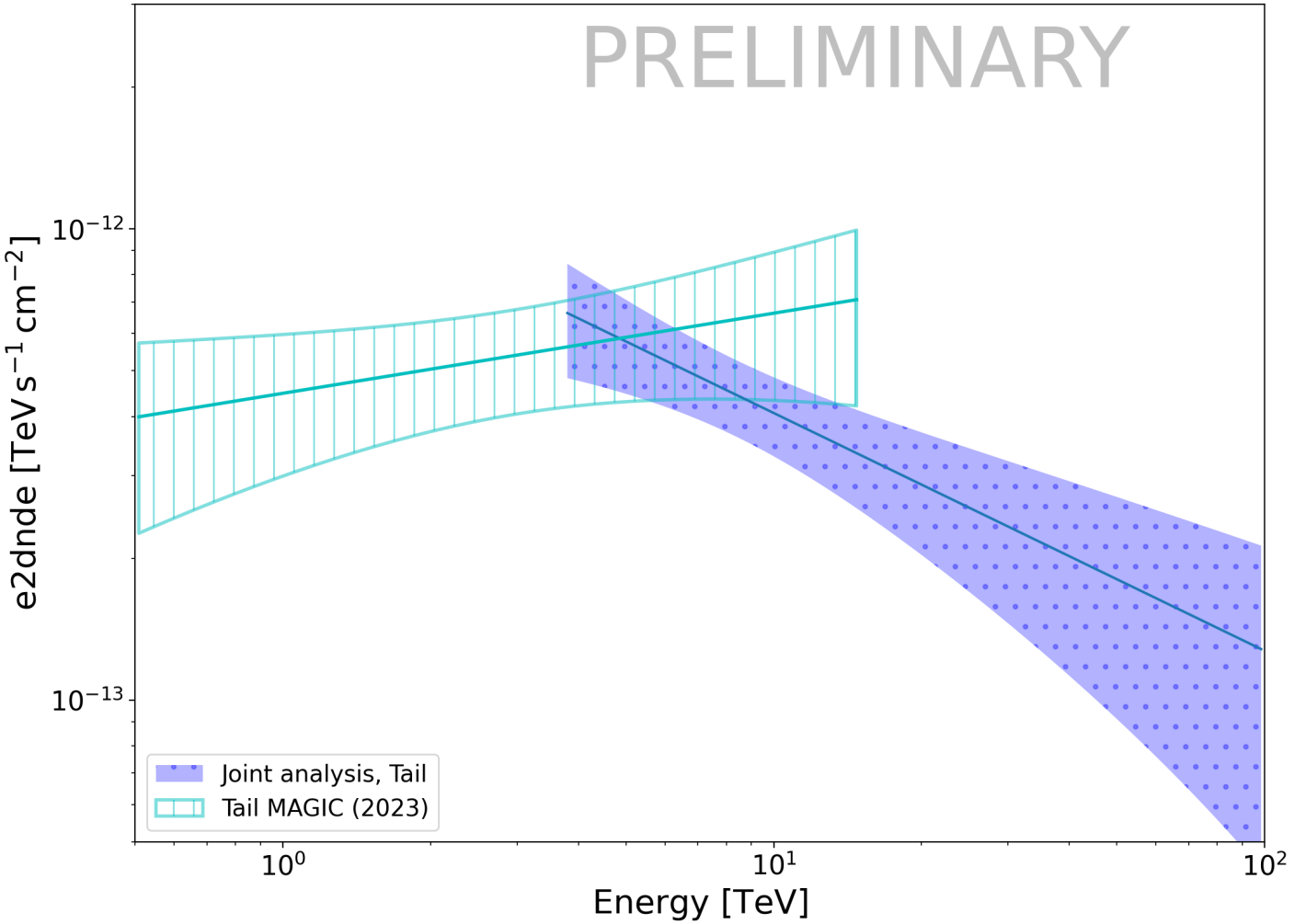


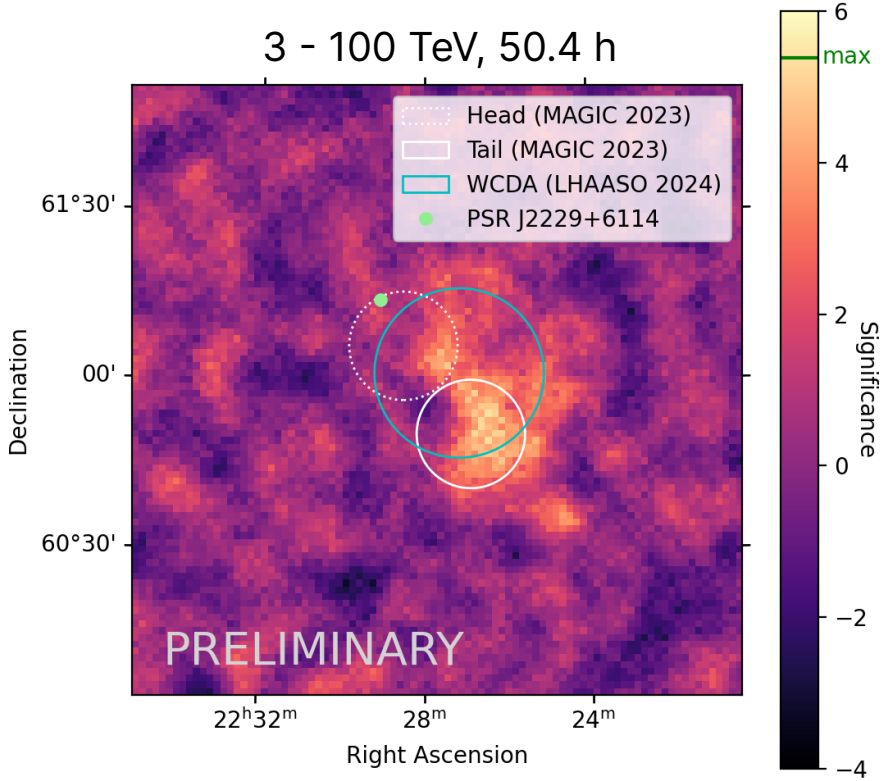




Spectra - Tail

Joint dataset : 50.4 hours spectra in 3 regions

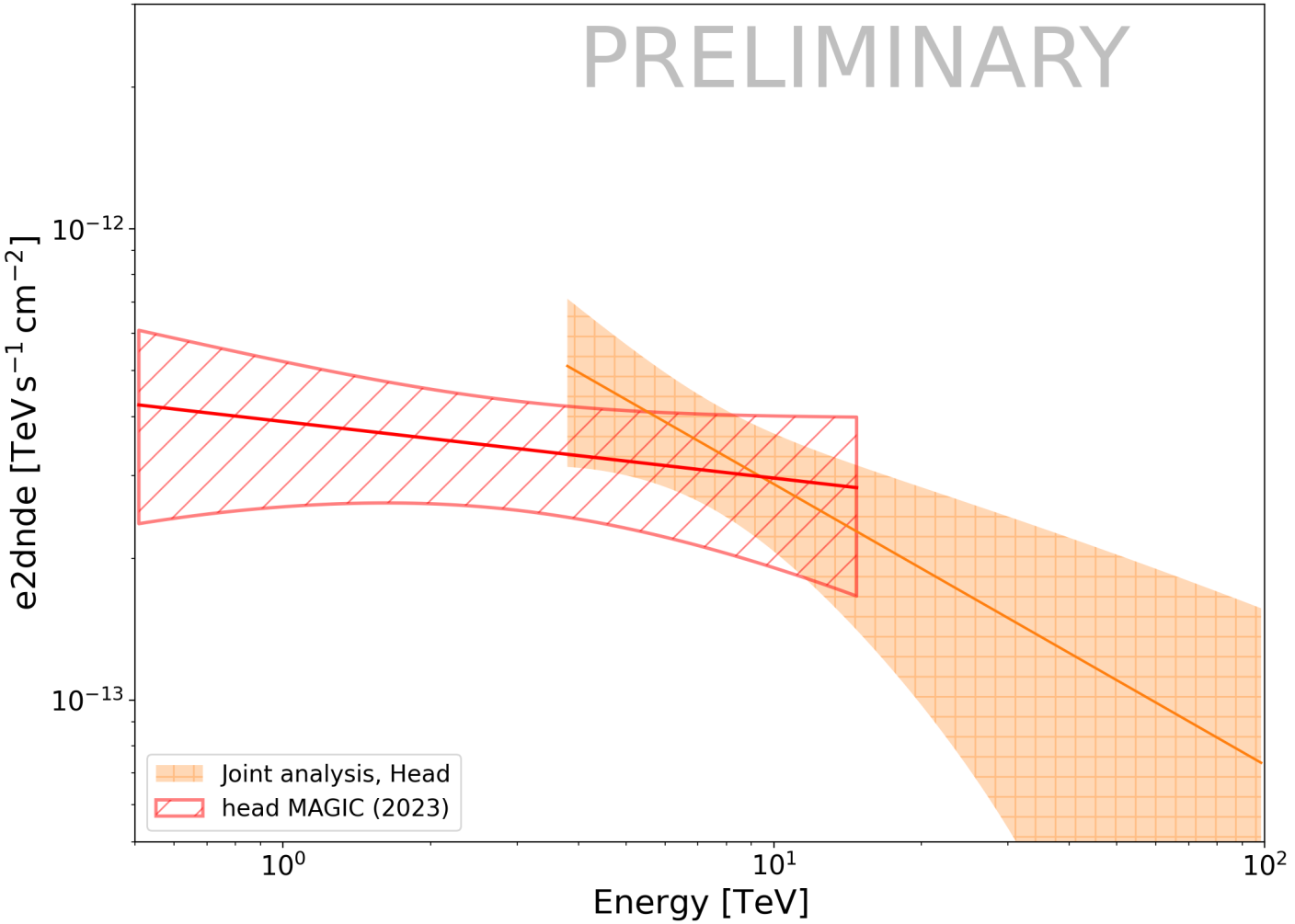


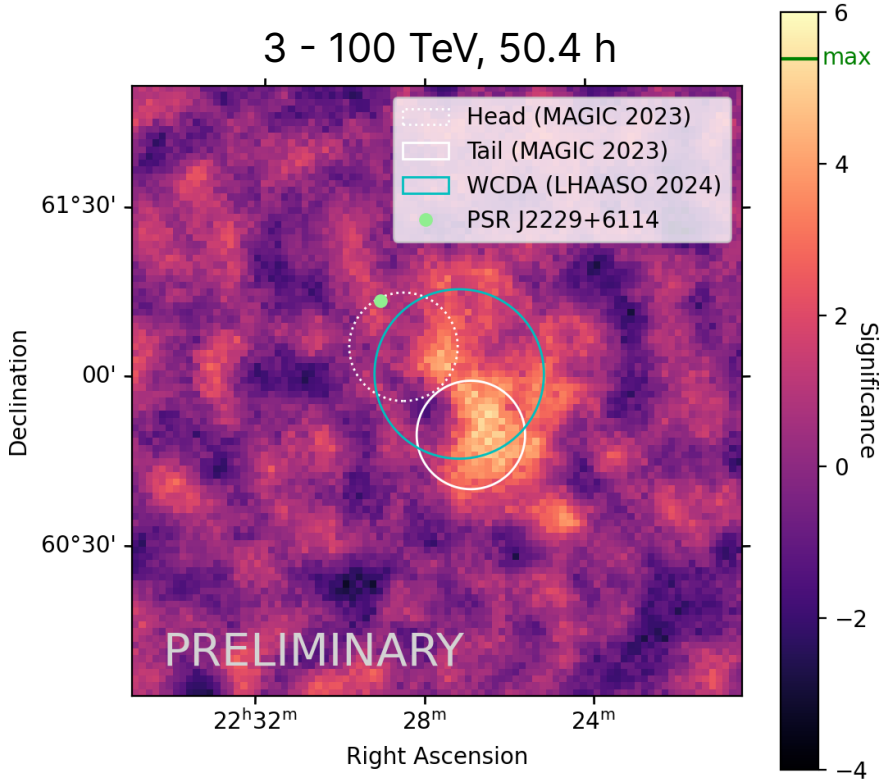


Spectra connect well with the published spectra by MAGIC and LHAASO on the same region.

Spectra - Head

Joint dataset : 50.4 hours spectra in 3 regions

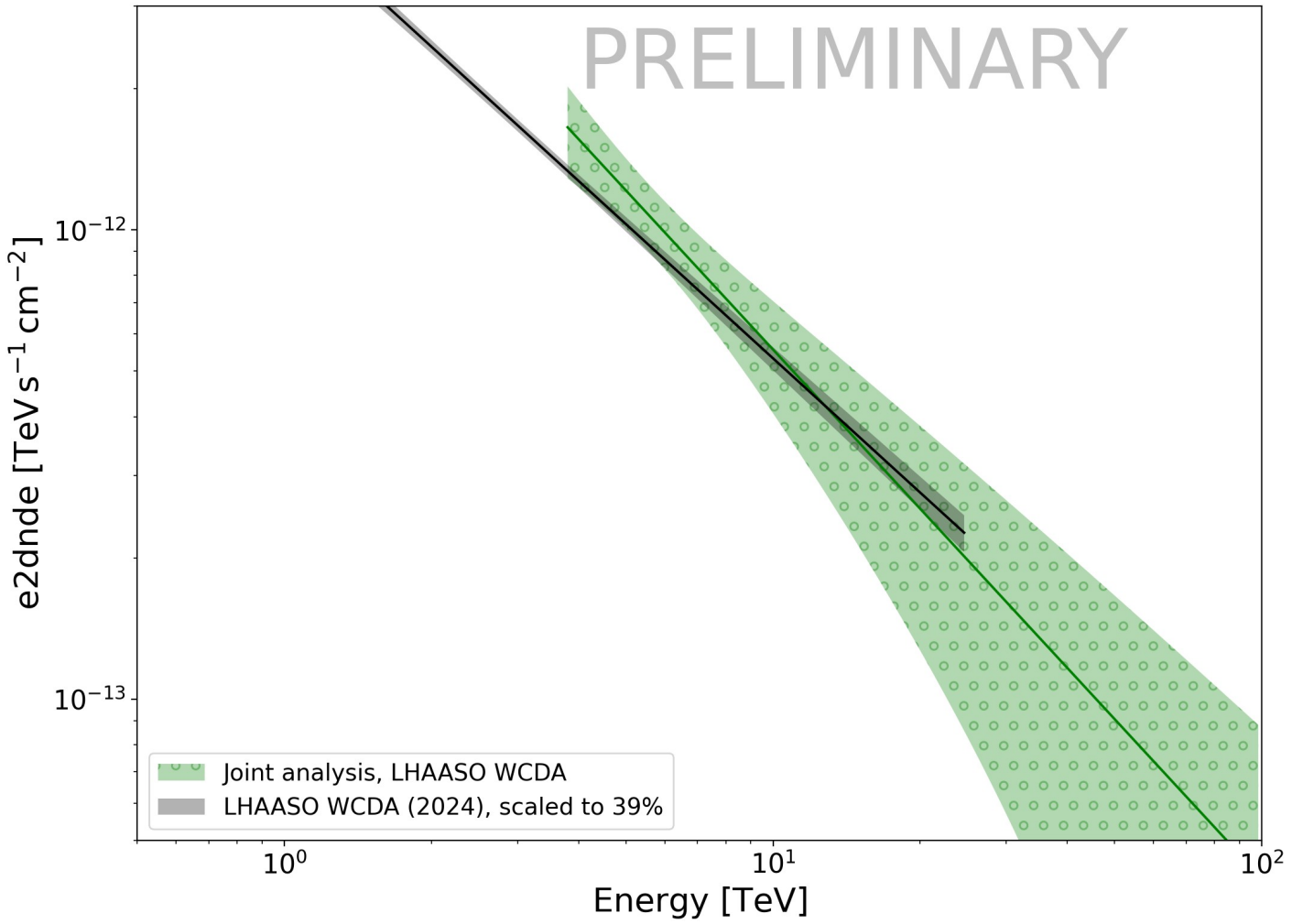


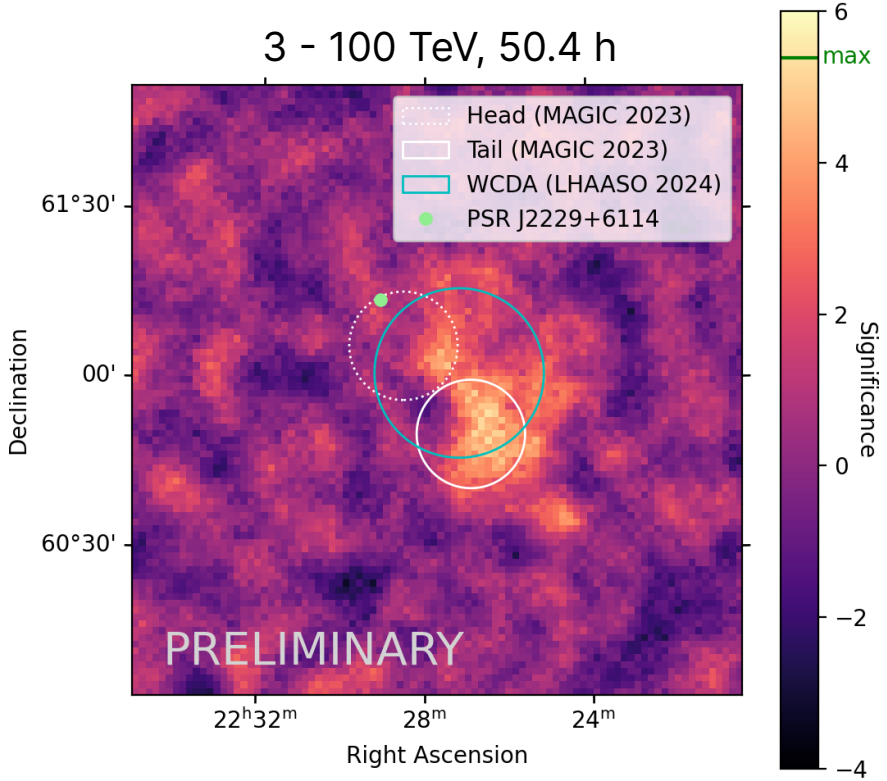


Spectra connect well with the published spectra by MAGIC and LHAASO on the same region.

Spectra – LHAASO WCDA

Joint dataset : 50.4 hours spectra in 3 regions



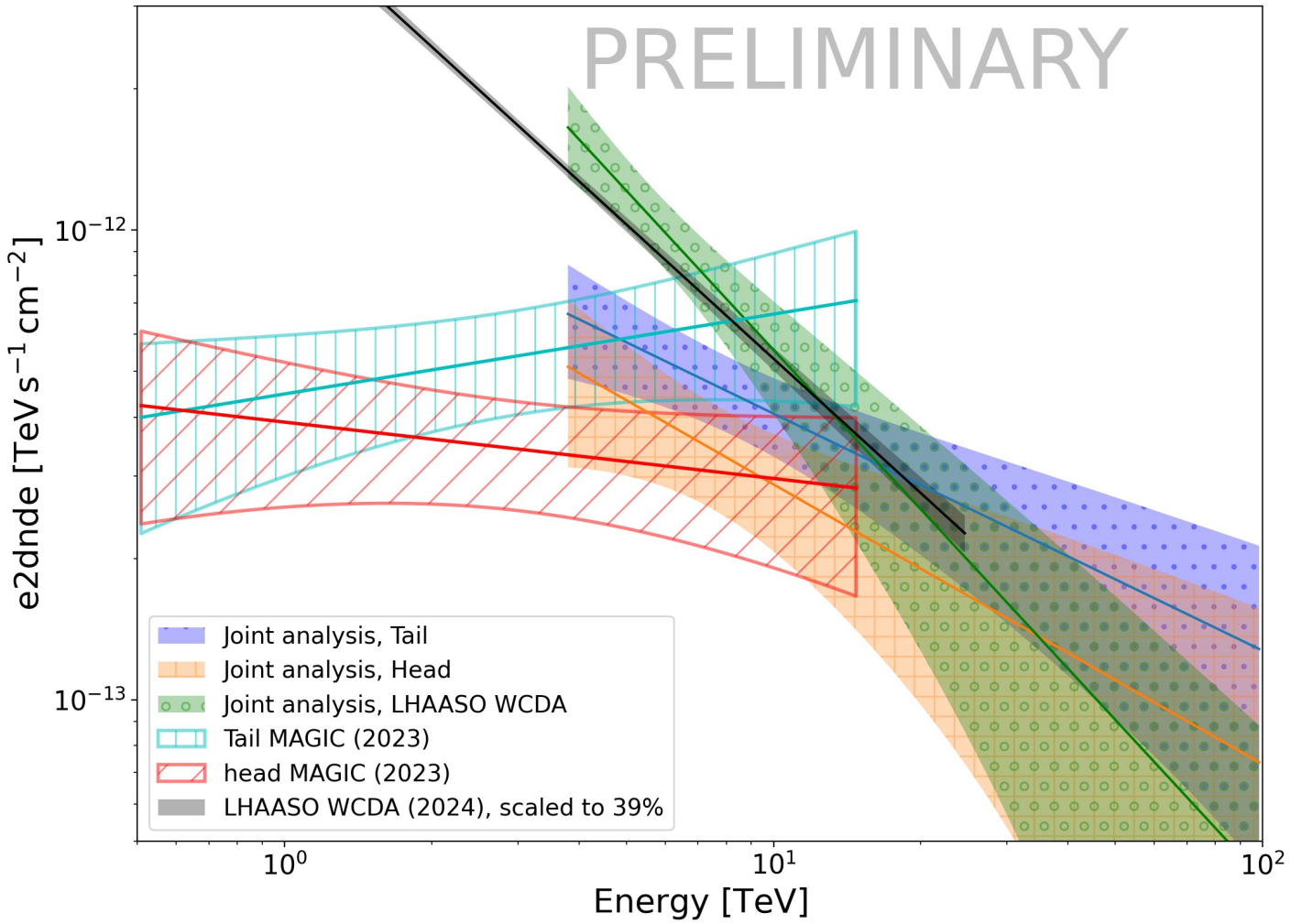


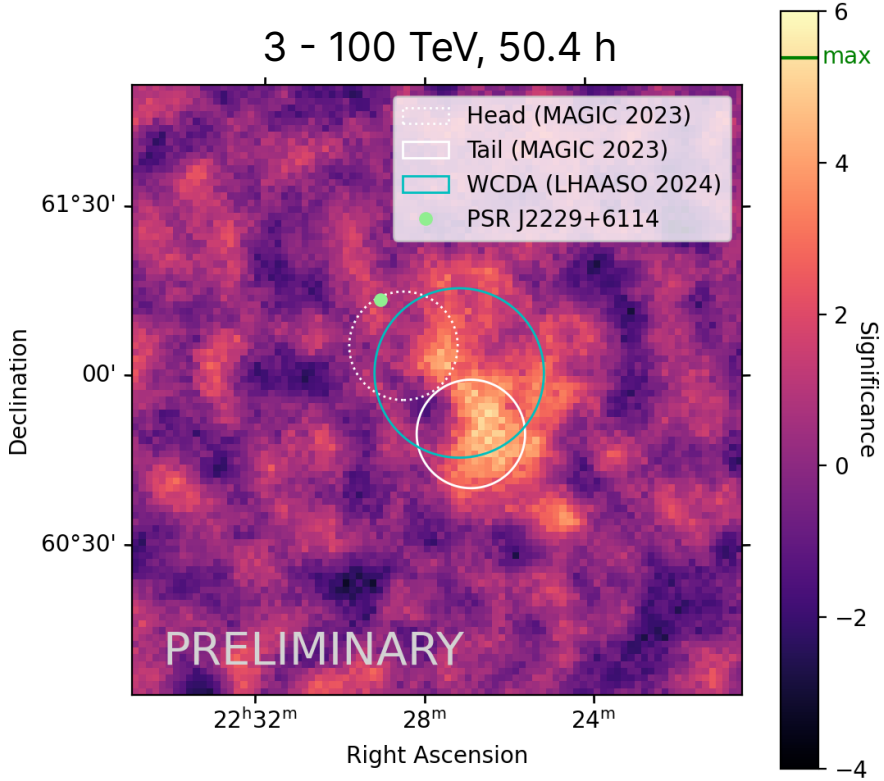
Spectra connect well with the published spectra by MAGIC and LHAASO on the same region.

LHAASO flux scaled down to 39% since the reported flux is for a 2D gaussian spatial model and we use only the 1σ radius.

Spectra

Joint dataset : 50.4 hours spectra in 3 regions





Spectra connect well with the published spectra by MAGIC and LHAASO on the same region.

Conclusion

We presented the first joint analysis of LST-1 + MAGIC, LST-1 Mono and MAGIC datasets acquired at LZA on the SNR G106.3+2.7 region.

We have shown the capacity of LST-1 + MAGIC to detect the source in a short period of time (19.7h) with high angular resolution.

Using all the data available, 50 hours distributed between the different sub-arrays, we have seen :

- A clear detection of an extended source
- More than **4σ of significance in multiple energy bins**
- A **shift of the emission region away from the pulsar with increasing energy**
- Spectral energy distributions compatible with the published spectra from MAGIC and LHAASO

These results are very promising, the acquisition campaign will continue up to 120 hours of MAGIC+LST-1 equivalent observation time.

Backup

Backup : software

magic-cta-pipe : version 0.4.1
https://github.com/cta-observatory/magic-cta-pipe/tree/v0.4.1

cta-lstchain : version 0.10.11
https://doi.org/10.5281/zenodo.11149874

gammapy : version 1.1
https://doi.org/10.5281/zenodo.8033275

acceptance_modelisation : development version toward version 0.3
https://github.com/mdebony/acceptance_modelisation