Analysis of the W 44 Supernova Remnant and its surroundings with *Fermi*-LAT and MAGIC

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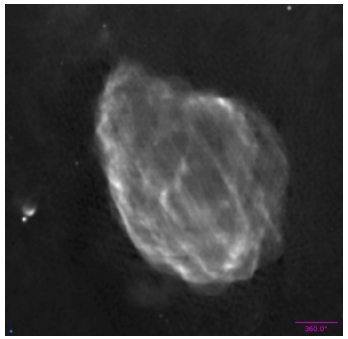
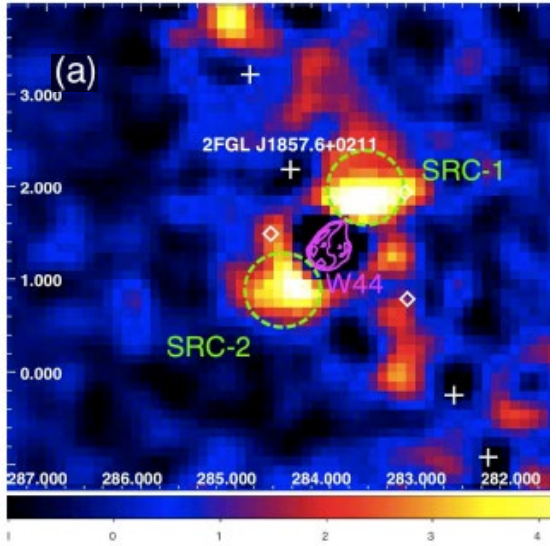
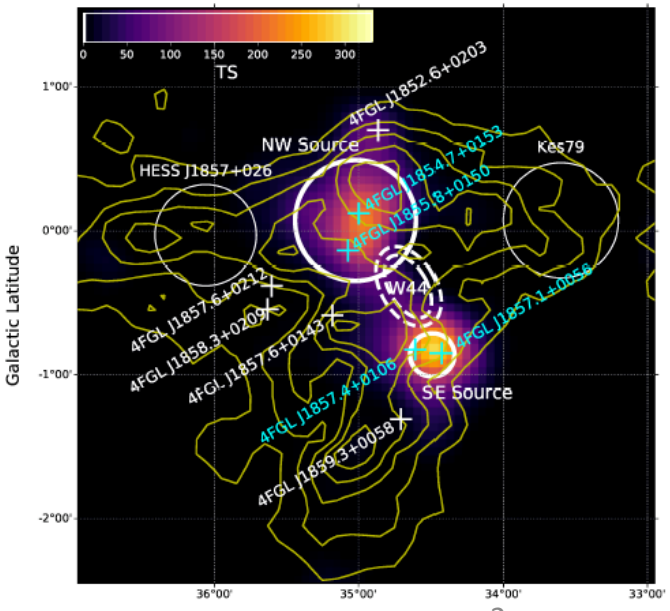
Context and motivation



- Supernova Remnants (SNRs) play a central role in the puzzle of Cosmic Ray origin
- W44 is one of the most luminous SNR in the GeV sky
- Previous works revealed the presence of GeV emissions in the SNR surroundings
  - Probably due to escaped CRs
- This work:
  - Detailed spatial analysis of W44 region with Fermi-LAT
  - Observations of W44 surroundings with MAGIC telescopes

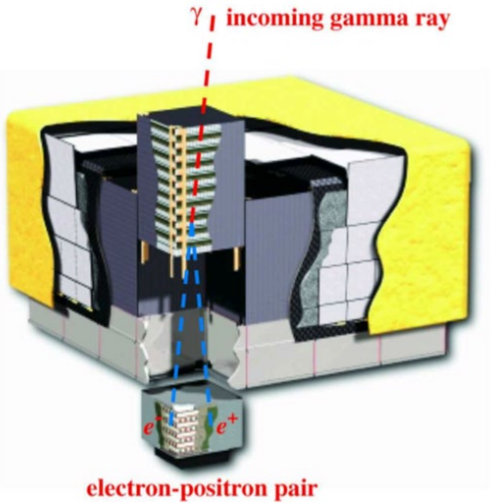


Uchiyama+12 ApJL, 749, L35,



Peron+20 ApJL, 749, L35

Fermi-LAT analysis



- *Fermi*-LAT is sensitive to gamma-rays from tens of MeV to few TeV
- Data selection:
  - 142 months of data (~12 years), SOURCE class
  - 15° RoI centered on W44
  - Energy range: 1 GeV – 2TeV
  - Maximum zenith angle: 105°
- Analysis setup
  - Galactic and Isotropic background models
  - Sources within 20° from ROI center from 4FGL-DR2 catalog
  - Summed likelihood with PSF event types
  - *fermitools* v2.0.8 and *fermipy* v1.0.1 packages

Morphological analysis

- W44 morphology investigated adopting several templates:
  - 4FGL-DR2 catalog template, having an elliptical ring (Abdo+10 Science, 327)
  - Full ellipse template
  - Radio (1420 MHz) template
  - Catalog and elliptical templates divided along the major axis and fitted separately
- Analysis procedure:
  - All known sources within 1° from W44 center were removed
  - Source-find algorithm to search for new sources
  - Extension test with a disk morphology (compared to a point-like source)

$$TS_{ext} = 2\left(\log L_{disk} - \log L_{ps}\right)$$

  - Curvature test with a log-parabola spectrum (compared to a simple power-law spectrum)

$$TS_{curv} = 2\left(\log L_{logP} - \log L_{PL}\right)$$

  - Akaike Information Criterion (AIC) used to compared different models:

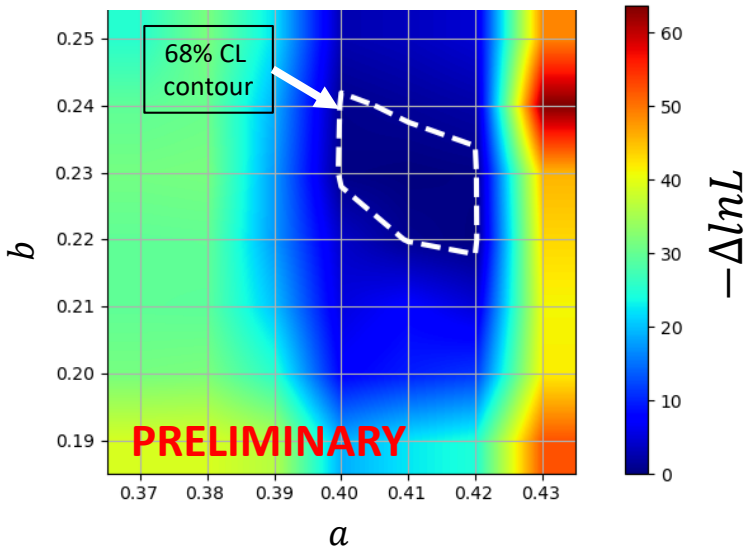
$$AIC = 2k - 2ln(\hat{L})$$

Morphological analysis – W44 template

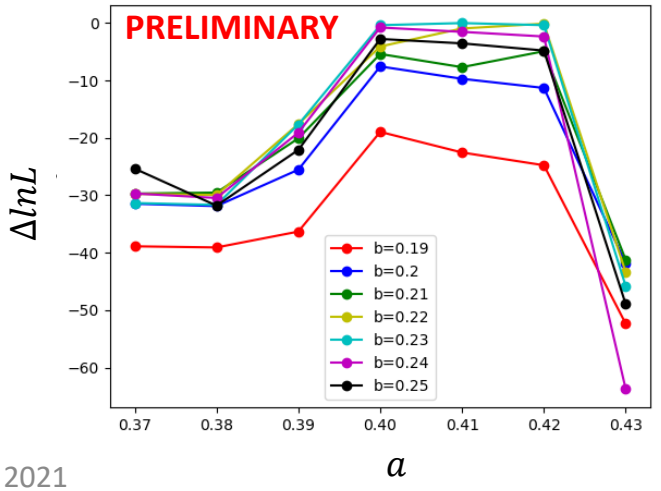
- W44 elliptical template fitted varying the semi-major and semi-minor axes and the inclination angle of the ellipse
  - Best-fit value: (a,b,θ)=(0.41,0.23,115°)
- AIC used to compare all templates
  - Radio template provided the best result

Template (W 44)	lnL	k (d.o.f.)	AIC	Δ_{AIC}
4FGL	57702	18	-115368	289
4FGL divided	57755	25	-115460	197
Full ellipse	57743	18	-115450	207
Full ellipse divided	57770	20	-115501	156
Radio (1420 MHz)	57856	27	-115657	0

2D Log-likelihood profile



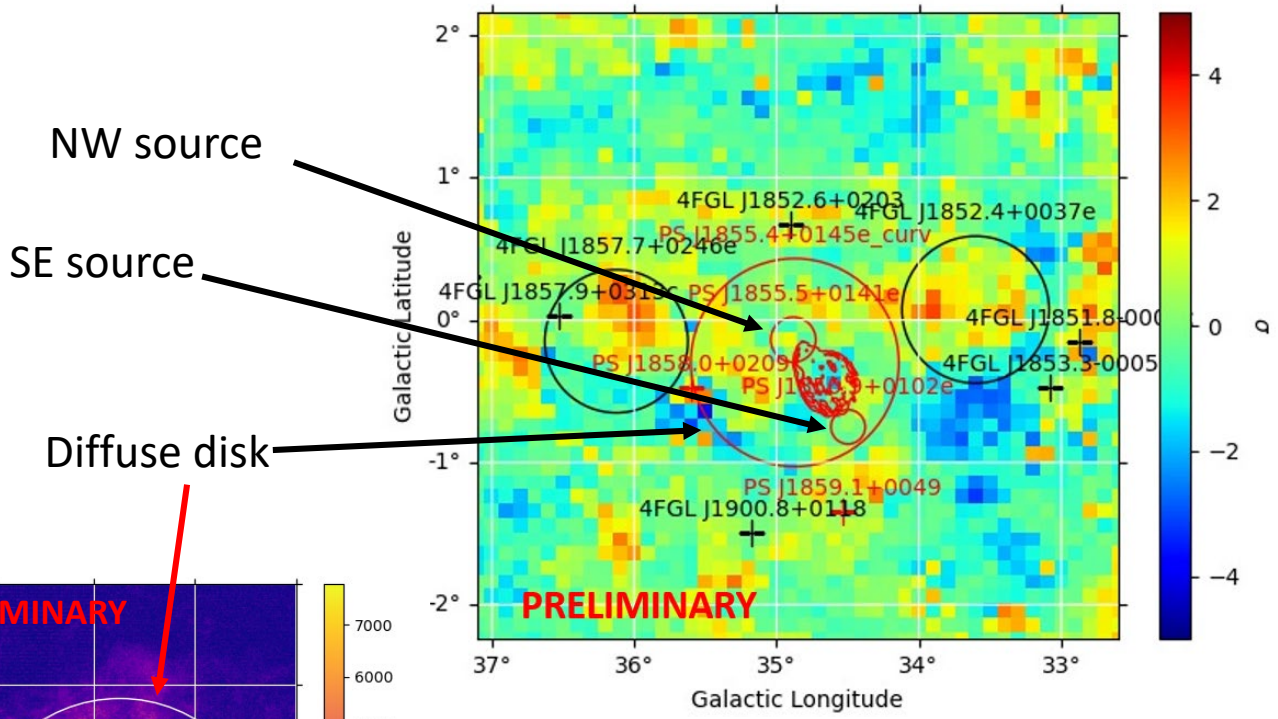
Log-likelihood profile

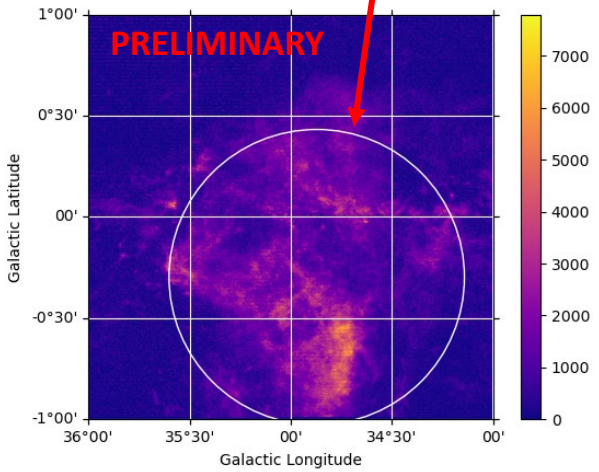


Morphological analysis – W44 surroundings

- Radio (1420 MHz) template used for W44
- Two small extended sources (disk) found close to W44, coincident with previously detected sources
- One large diffuse disk
  - Likely associated with CO emission
  - CO template derived from NRO FUGIN survey and tested instead of the large disk → diffuse disk is statistically preferred with a ΔAIC=10.6

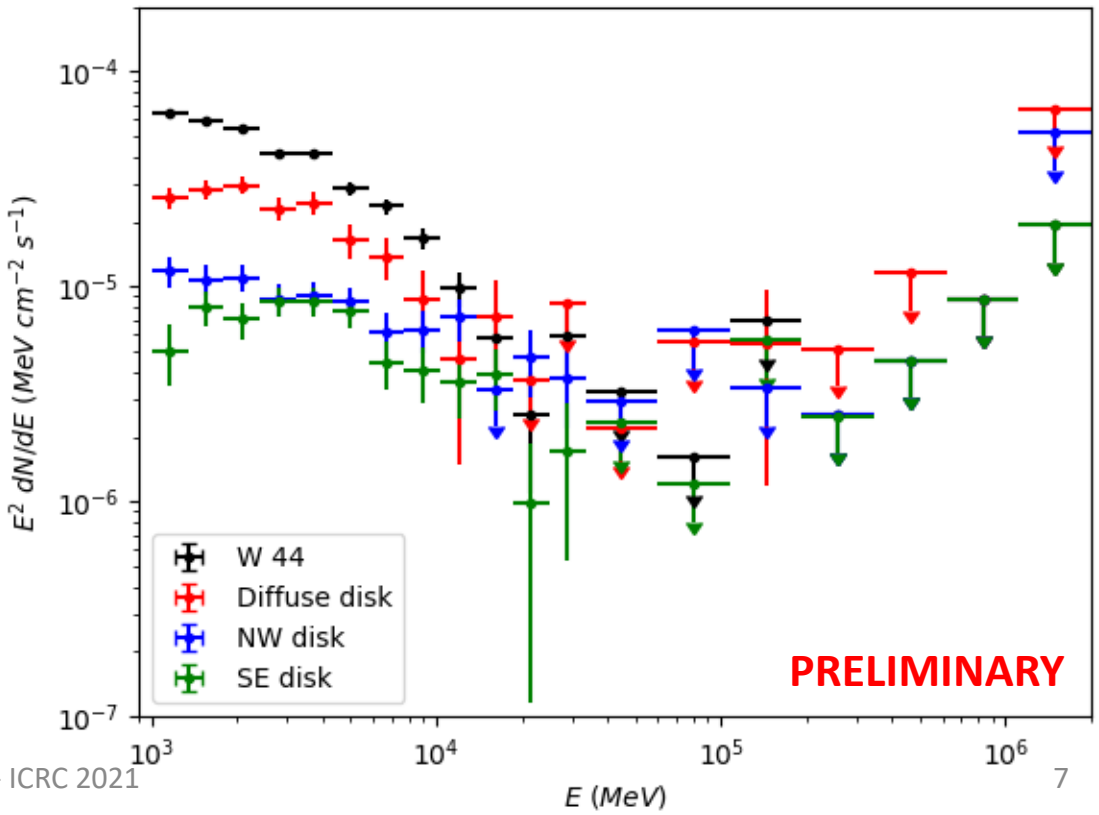
Deviation probability map





Spectral analysis

- Spectral Energy Distribution (SED) for W44 and surrounding sources
  - 8 bins/decade for $E \leq 30$ GeV
  - 4 bins/decade for $E > 30$ GeV
- Results compatible with previous papers

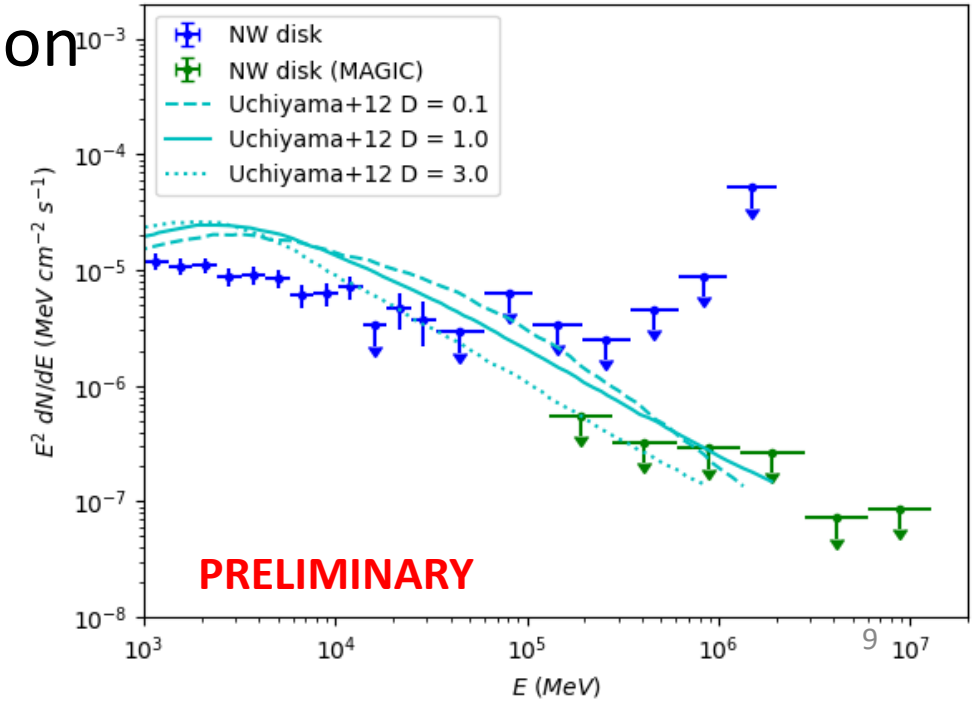


MAGIC observations

- Time of observations: April 2013 - August 2014 for 173.7 h after quality cuts
- Zenith angle: 25°– 45°
- Centered on the coordinates of NW source from Uchiyama+12
- Standard wobble distance: 0.4°
- Software:
  - MAGIC Analysis and Reconstruction Software (MARS) for low level analysis
  - *SkyPrism* for high-level analysis (spatial likelihood analysis)
- Background camera exposure model derived using an Exclusion Map
  - known sources in our field of view excluded
    - HESS J1857+026 with a radius of 0.45°, including MAGIC J1857.2+0263 and MAGIC J1857.6+0297
    - HESS J1858+020 with a radius of 0.17°,
    - NW and SE sources with their position and extension from the Fermi-LAT analysis
    - W44 and large diffuse disk were not excluded nor modeled due to their curved spectra in the GeV range

MAGIC results

- We searched for a signal originating from the NW source, using the spatial information from our previous *Fermi*-LAT analysis
- No significant detection was found
- Upper limits at 95% confidence level were derived in SED
- Upper limits are compatible with CR diffusion hypothesis (Uchiyama+12)
- Constraints on the CR diffusion coefficient can be derived



Summary and Outlook

- We have analysed W44 region with *Fermi*-LAT and MAGIC telescopes
- A careful morphological analysis of the W44 region was carried on with *Fermi*-LAT for energies above 1 GeV
- Observations in the VHE gamma-rays were carried out with MAGIC telescopes focusing on the NW emission in the W44 surroundings
- No significant detection was found but constraining upper limits were derived
- Study on the CR diffusion coefficient in the hypothesis of escaped CR already ongoing