Cosmic Rays origin studies in the W 44 region with Fermi-LAT and MAGIC observations

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Hands on the Extreme Universe with High Energies Gamma-Rays

Sexten, 19/07/2022

Outlines

- Project motivations
- Fermi-LAT analysis: procedure and results
- MAGIC analysis: procedure and results
- Modeling

Project motivations

- **Supernova Remnants (SNRs)** considered as **strong candidates** for **birthplaces** of **Cosmic Rays** in **Galactic** environments
- One of the strongest **HE γ-rays** emitters in the **Milky Way** is the **extended SNR W 44**
- **GeV emission** in the remnant **close-by region** reported in previous works (Uchiyama et al. 2012, Peron et al. 2020)
  - Probably due to **escaped CRs**
- Joint **Fermi-MAGIC** project:
  - Detailed morphological and spectral analysis of **W 44 region with Fermi-LAT**
  - **W 44 surroundings** observed with **MAGIC** telescopes
  - **Hadronic-based** model

Fermi-LAT analysis

Data selection & setup:

- 142 months of data (~**12 years**)
- **15° RoI** centered on W 44
- Energy range:
  - **Morphological** analysis: **1 GeV – 2 TeV** → in order to exploit better PSF and reduce source confusion
  - **Spectral** analysis: **100 MeV – 2 TeV**
- Latest **Galactic** and **Isotropic** background models
- Sources within 20° from RoI center from **4FGL-DR2 catalog**
- **Fermitools v 2.0.8** and **fermipy v. 1.0.1**

Morphological analysis

- Several templates adopted as possible **W 44 spatial models**:
  - 4FGL-DR2 catalog
  - Full ellipse template
  - Radio (1420 MHz) template
  - Catalog and elliptical templates divided along major axis and fitted separately
- Analysis procedure:
  - Catalogued **sources within 1°** from RoI center **removed**
  - Source-find algorithm to **look for new sources**
  - **Extension** test with a **disk** morphology (compared to a point-like source)

$$TS_{ext} = 2(logL_{disk} - logL_{ps})$$

  - **Curvature** test with a **log-Parabola** spectrum (compared to a simple PL spectrum)

$$TS_{curv} = 2(logL_{logP} - logL_{PL})$$

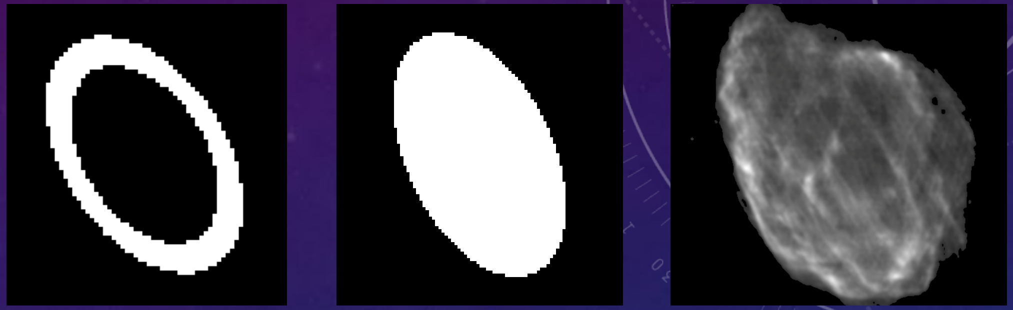
  - Akaike Information Criterion (**AIC**) used to **compare different models**

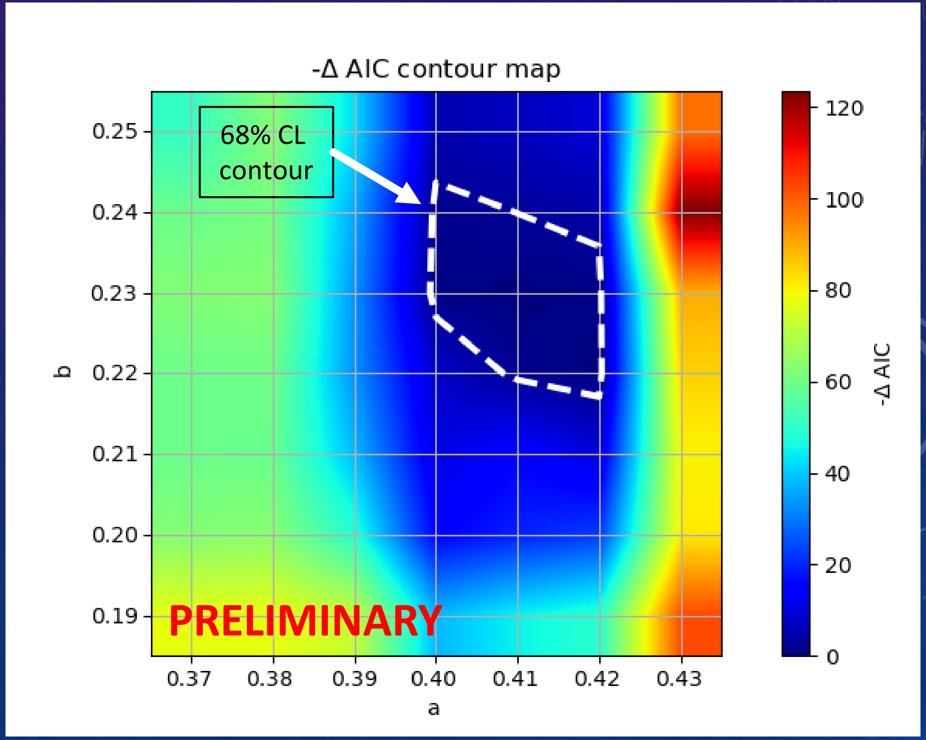
$$AIC = 2k - 2\ln(\hat{L})$$

Morphological analysis – W 44

- **W 44 elliptical template** derived varying inclination angle, semi-major and semi-minor axes of the ellipse → more than 150 templates: **best fit values (*a*,*b*,*θ*) = (0.41, 0.23, 115°)**
- Among the five templates the **Radio (1420 MHz)** provided the **best** results

Radio (1420 MHz)



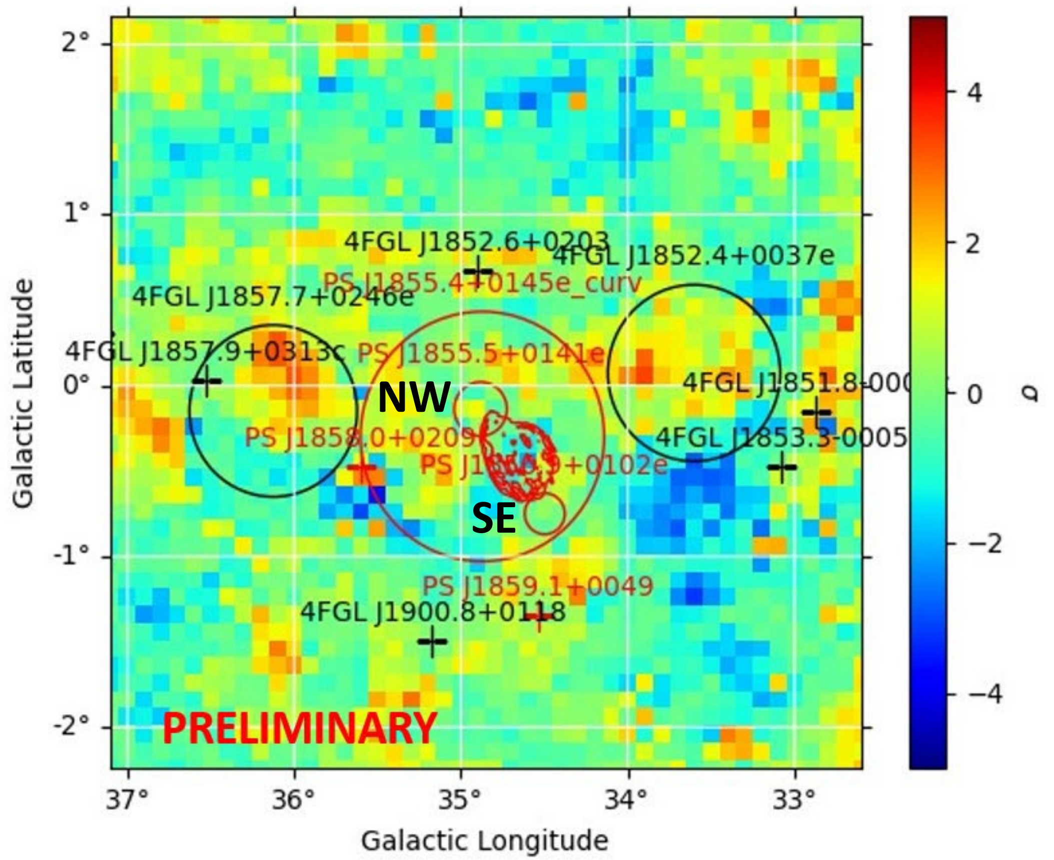


Template (W 44)	$ln\hat{L}$	$k\ (d.o.f.)$	*AIC*	Δ_{AIC}
4FGL	57702	18	−115368	289
4FGL divided	57755	25	−115460	197
Full ellipse	57743	18	−115450	207
Divided ellipse	57770	20	−115501	156
Radio	57856	27	−115567	0

Morphological analysis – W 44 surroundings

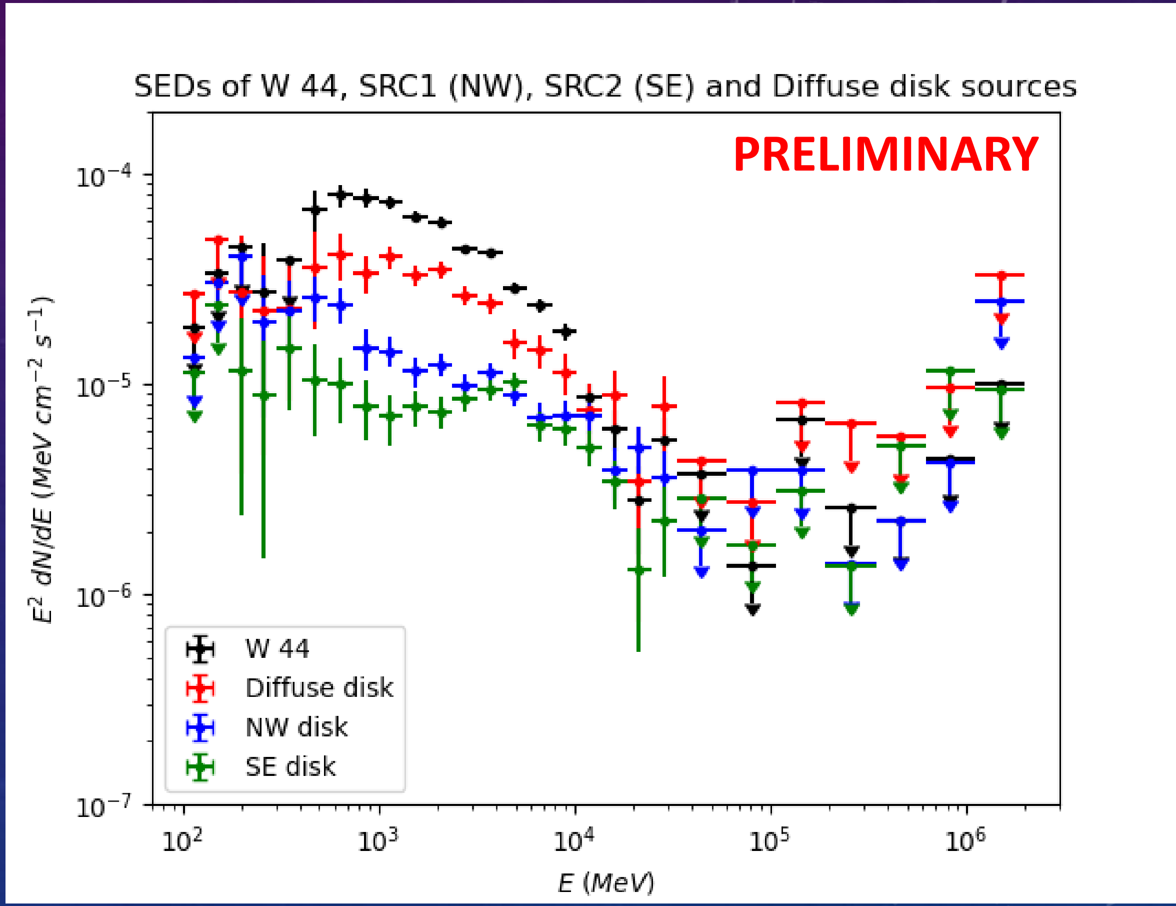
- Best configuration:
  - **Radio** template used for **W 44**
  - **Two small Radial Disk** sources found in the **NW** and **SE** regions
  - Large extended diffuse source
    - Probably **associated** with **CO** emission
    - Alternative template: from CO data (NRO FUGIN survey)
    - Large disk statistically preferred with a $\Delta AIC = 10.6$

Deviation probability map



Spectral analysis

- Energy range: 100 MeV – 2 TeV
- Based on best morphology derived from HE analysis
- **Weighted likelihood** procedure for mitigating effect of systematics (mainly due to imperfect knowledge of Galactic background emission)
- Sources reasonably well resolved above 1GeV

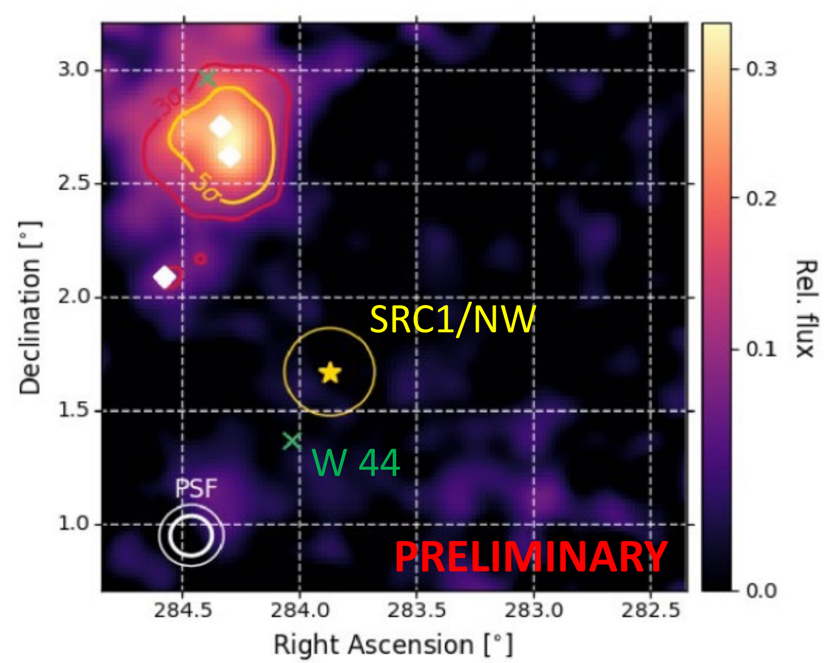


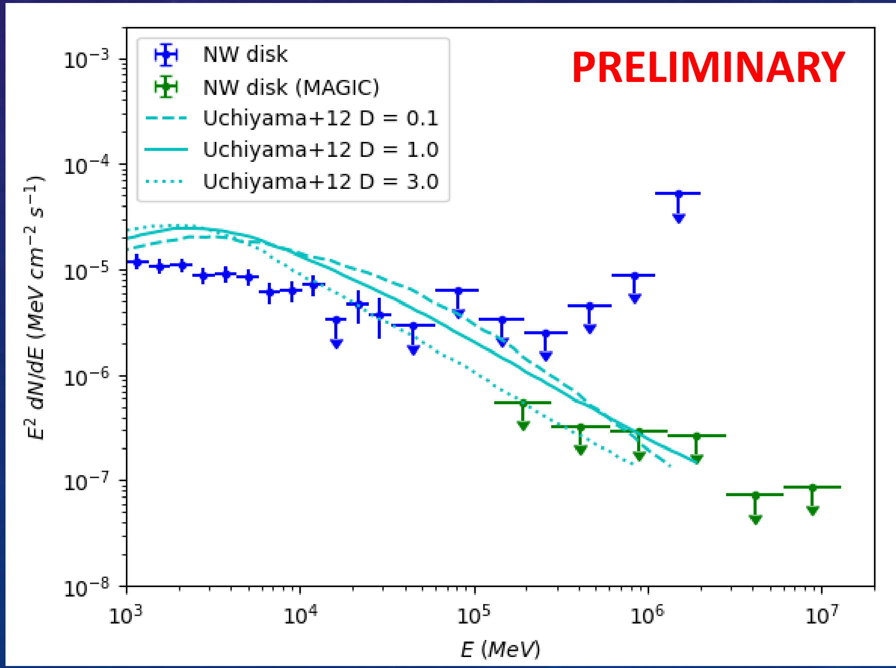
MAGIC observations and analysis

- Time of observations: April 2013 – August 2014 for 173.7 h after quality cuts
- Analysis software:
  - MAGIC Analysis and Reconstruction Software (MARS) for low level analysis
  - SkyPrism for high-level analysis (spatial likelihood analysis)
- Analysis based on Fermi HE results
- Source region model: MAGICJ1857.3+027, HESSJ1858 and NW (SRC1)
- NW at same location and extension as in Fermi
- W 44 and Large Diffuse Disk were not excluded nor modeled due to their curved spectra in the GeV range

MAGIC results

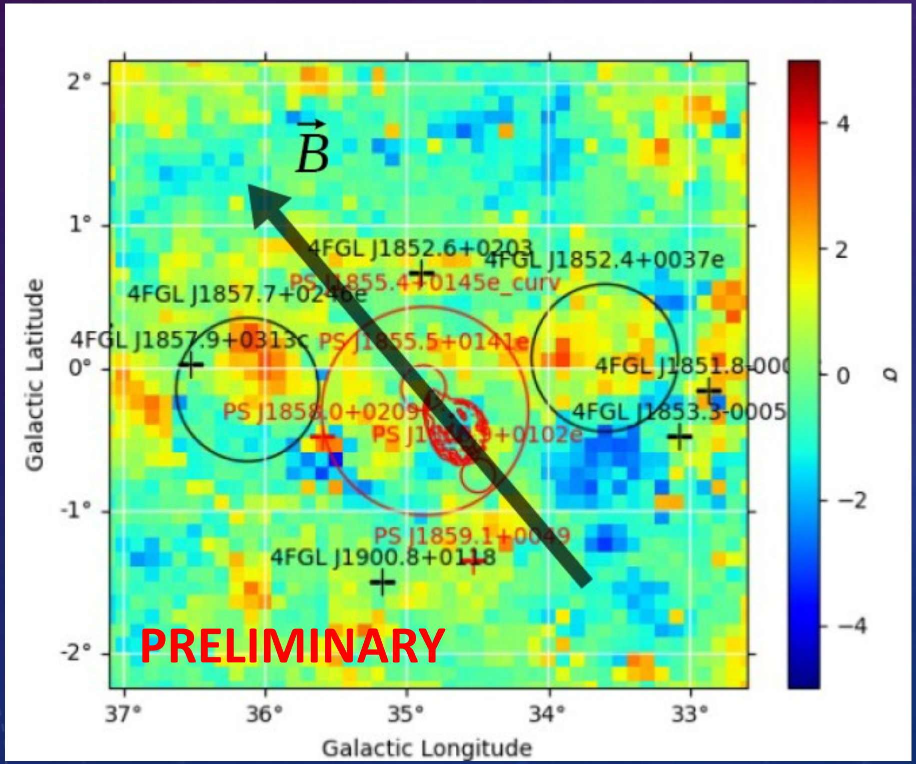
- Looking for a signal corresponding to NW source
- No significant detection was found
- ULs at 95% CL derived in SED
- ULs provide **constraints on CRs diffusion coefficient**





Modeling

- Particles **acceleration** and **escape** from the **W 44 forward shock**
- NW (SRC1) and SE (SRC2) emissions due to **clouds close to W 44** and illuminated by **CRs escaping along local magnetic field**



- Spectrum at the shock:

$$f_{sh}(p,t) \propto \xi_{cr} p^{-\alpha} e^{-p/p_{max}(t)}$$

- Maximum energy:

$$p_{max} = p_M (t/t_{Sedov})^{-\delta}$$

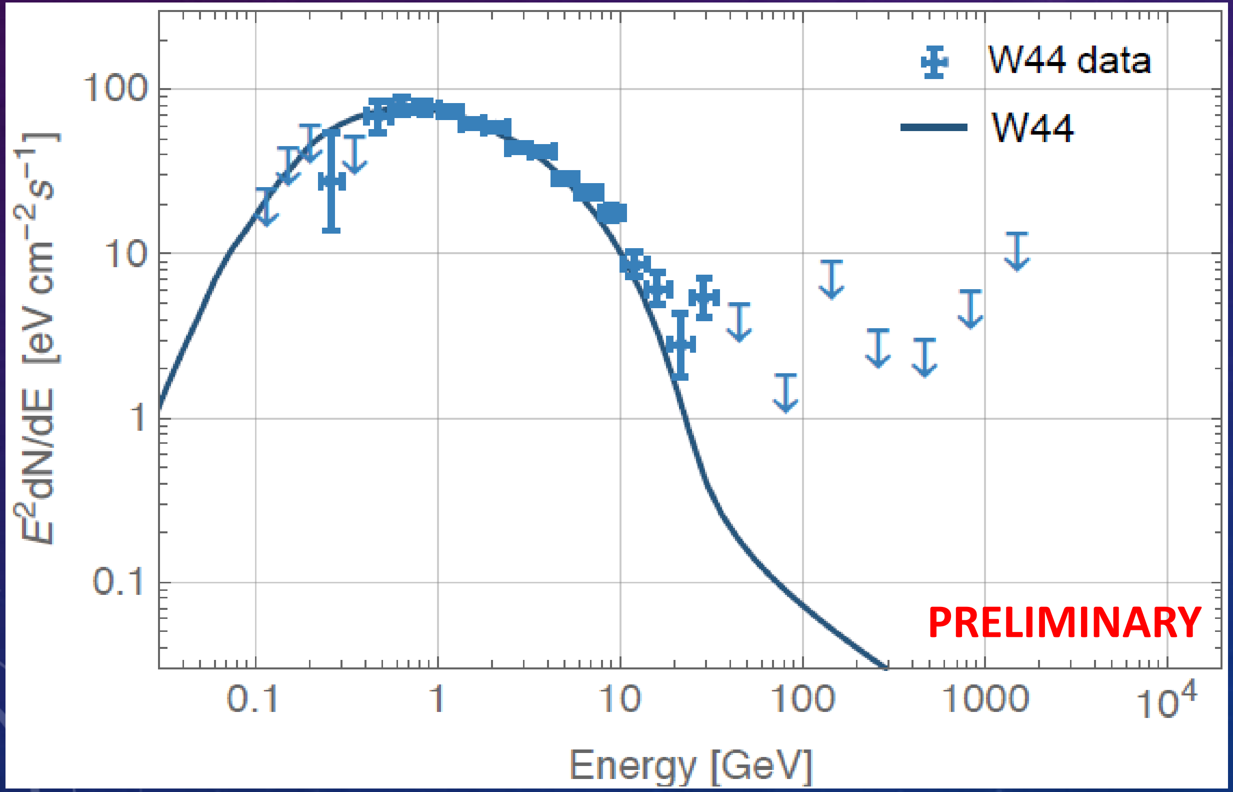
- Diffusion coefficient at W 44 forward shock estimated self-consistently using streaming instability
- External diffusion coefficient:

$$D_{ext}(p) = \chi D_{gal}(p)$$

- $\alpha, p_M, \delta, \xi_{cr}, \chi$ free parameters, fixed to fit the emission from the SNR → emission from clouds depends only on distance from W 44 and their masses

Modeling – W 44

- For particles acceleration and escape from W44 forward shock, model developed in Celli et al. 2019 has been adopted

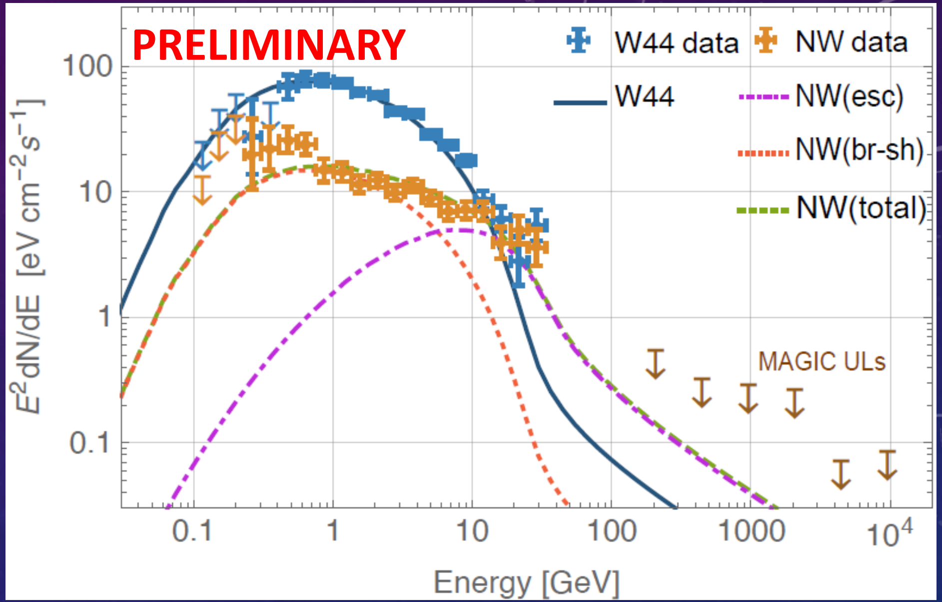


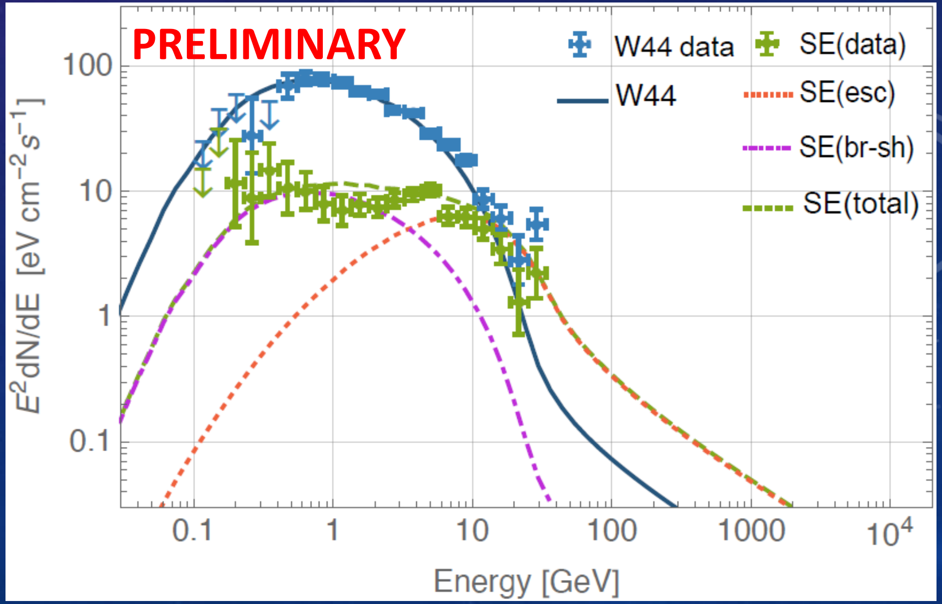
- Assumptions:
  - Age ≃ 2 x 10^4 yr
  - Distance = 2.2 kpc
  - Explosion energy = 10^{51} erg
  - Average circumstellar medium density = 10 cm^{-3}

- Parameters' values:
  - $f_{sh}(p,t) \propto \xi_{cr} p^{-4.2} e^{-p/p_{max}(t)}$
  - $\xi_{cr} = 1.3\%$
  - $p_{max} = p_M (t/t_{ST})^{-\delta}$ where:
    - $p_M = 100\ TeV\ ,\quad \delta = 2$
    - $p_{max}(t_{age}) = 44\ GeV$

Modeling – SRC1 (NW) and SRC2 (SE)

- **SRC1** and **SRC2**, both located **along SNR's major axis**, assumed at same distance from us as W 44 (d = 2.2 kpc)
  - **Distances** W 44 – clouds
    - NW: 17.3 pc
    - SE: 15.7 pc
  - Almost identical values for **clouds radii**
  - $D_{ext}(p) = 0.2\ D_{gal}(p)$
- Emission due to **hadrons escaping along local magnetic field** and interacting with circumstellar gas (supported by Liu, Hu, Lazarian 2022)
- Low energy gamma-ray emission, in particular from SRC1, requires **broken-shock scenario**:
  - Particles having $E < E_{br}$ allowed to escape from a small portion of the shock surface
  - Possible in middle-aged SNR expanding in a highly inhomogeneous medium





Conclusions

- **W 44 region** analysed with **Fermi-LAT** and **MAGIC** telescopes
- Detailed **morphological analysis** performed on Fermi-LAT data for energies **above 1GeV**
- **Spectral analysis** carried out **above 100 MeV** with better understanding of systematic uncertainties thanks to **weighted likelihood** procedure
- W 44 **surroundings**, in particular **NW region**, observed with **MAGIC** telescopes in the **VHE band → ULs constraining emission models**
- **Model**
  - Particles acceleration and **escape** from W 44 forward shock along **local magnetic field**
  - Emission from **SRC1** and **SRC2**: **CRs escaped from the SNR** and **illuminating nearby clouds**
  - **Broken shock scenario** for low-energy emission

Thank you for your attention!

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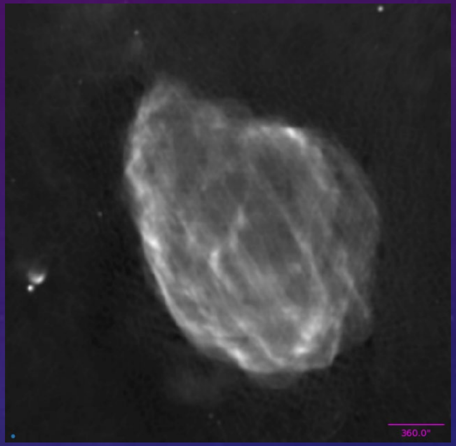
Backup material

THE EXTENDED SNR W44

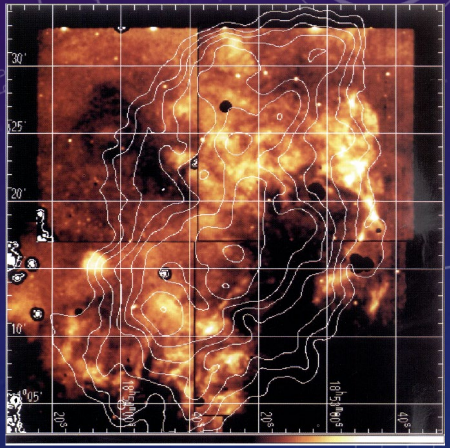
- Age ~ $2 \cdot 10^4\ yr$
- $(GLON, GLAT) = (34.65°, -0.38°)$
  $(RA, DEC) = (284.0°, 1.37°)$
- Distance ~ $2 - 3\ kpc$
- Composite SNR:
  - ➢ shell
  - ➢ PWN surrounding PSR B1853+01 extending ~ $1' - 2'$
- W44 observations:
  - ➢ *Radio and IR*: distorted shell elongated SE-NW, extent ~ $25 - 30\ pc$, filamentary and clumpsy emission
  - ➢ *Optical*: filaments immersed in a diffuse emission
  - ➢ *X-rays*: centrally concentrated
- SNR-MC observations:
  - ➢ SNR interacting with parent MC complex
  - ➢ Extent ~ $100\ pc$
  - ➢ Molecular studies: $J = 1 \longrightarrow 0$ lines of ^{12}CO ^{13}CO

Radio $1420\ MHz$
THOR survey - VLA

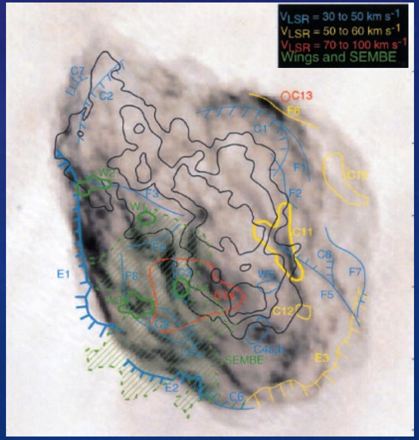


Multi channel IR
(green: $4.5\ \mu m$)
Spitzer IRAC

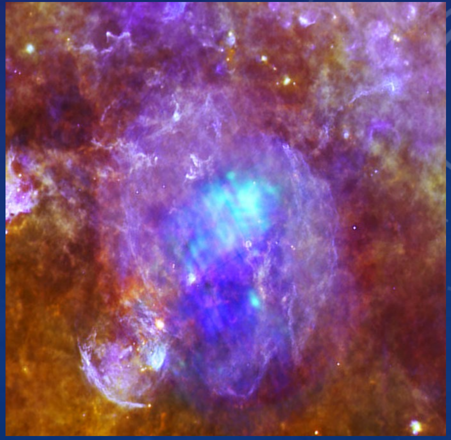
Optical $H\alpha$ $656nm$
PFUEI - Palomar



CO emission lines
J = 1 - 0 NRO



Far IR + X-rays
Herschel + XMM-Newton



Fermi-LAT analysis

Data selection:

- 142 months of data ($\sim$ **12 years**), SOURCE class
- **15° RoI** centered on W 44
- Energy range:
  - **Morphological** analysis: **1 GeV – 2 TeV**
  - **Spectral** analysis: **100 MeV – 2 TeV**
- Maximum zenith angle:
  - **Morphological** analysis: **105°**
  - **Spectral** analysis:
    - **100 MeV – 300 MeV: 90°**
    - **300 MeV – 1GeV: 100°**
    - **1GeV – 2TeV: 105°**

Analysis setup:

- **Galactic** and **Isotropic** background models
- Sources within 20° from RoI center from **4FGL-DR2 catalog**
- **Summed likelihood** i.e. separated PSF event types
- **Fermitools v 2.0.8** and **fermipy v. 1.0.1**

Morphological analysis – W 44 surroundings

- Best configuration:
  - **Radio** template used for **W 44**
  - **Two small Radial Disk** sources found in the **NW** and **SE** regions
  - Large extended diffuse source
    - Probably **associated** with **CO** emission
    - Alternative template: from CO data (NRO FUGIN survey)
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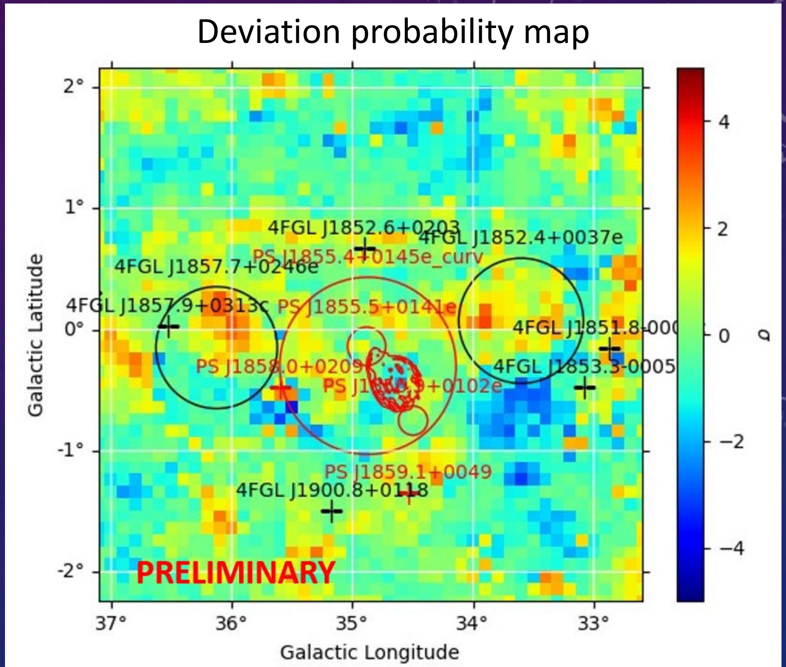

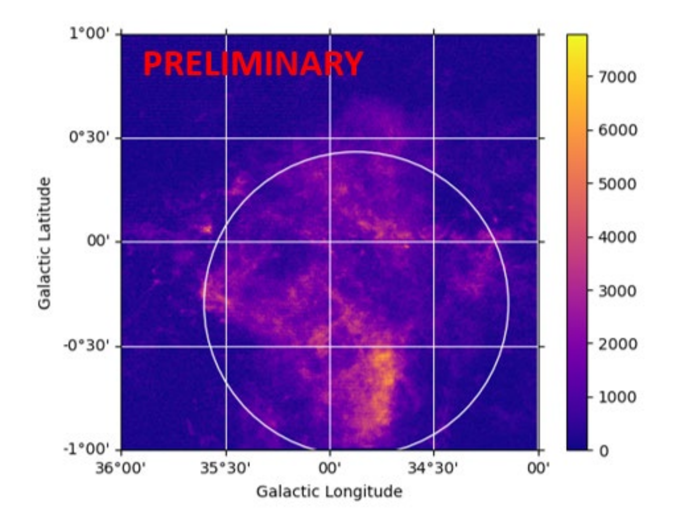

Spectral analysis

- **Weighted log-likelihood** procedure
- It allows to account for systematic errors, whose main origin is our imperfect knowledge of Galactic diffuse emission
- Below few hundred MeV, where the PSF increases up to several degrees, due to the large number of photons the source-to-background ratio is small (at the percent level) so systematic errors on the background model are critical
- Following prescriptions contained in: https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/weighted_like.pdf

MAGIC observations and analysis

- Time of observations: April 2013 – August 2014 for 173.7 h after quality cuts
- Zenith angle: 25° - 45°
- Standard wobble distance: 0.4°
- Analysis software:
  - MAGIC Analysis and Reconstruction Software (MARS) for low level analysis
  - SkyPrism for high-level analysis (spatial likelihood analysis)
- Analysis based on Fermi HE results
- Background camera exposure model derived using an Exclusion Map
  - Exclusion region around SE a.k.a SRC2 source (PS J1856.9+0102e)
- Source region model: MAGICJ1857.3+027, HESSJ1858 and NW (SRC1)
- NW at same location and extension as in Fermi
- W 44 and Large Diffuse Disk were not excluded nor modeled due to their curved spectra in the GeV range

Modeling – local magnetic field

- NW and SE emissions due to **clouds close to W 44** and illuminated by **CRs escaping along local magnetic field**
- Scenario suggested by
  - Locations of NW and SE
  - W 44 elongated along the magnetic field direction (from Liu, Hu, Lazarian 2022 https://doi.org/10.1093/mnras/stab3783)