Efficient particle acceleration from HESS J1640−465 and the PeVatron candidate HESS J1641−463

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Introduction : HESS J1640−465

- **HESS J1640−465** :

-Extended source detected by H.E.S.S. ($\sigma = 0.072° \pm 0.003°_{stat}$)

[Abramowski, A. et al 2014]

-Coincident with the radio SNR G338.3−0.0 and the associated X-ray pulsar PSR J1640−4631 (detected by *NuSTAR*)

[Gotthelf, E. V. et al 2014] :

$\tau_c = 3350$ years and $\dot{E} = 4.4 \times 10^{36} erg\ s^{-1}$

Estimated distance : $\sim$ 11 kpc (HI absorption)

[Kothes, R. et al, 2007]

Unidentified source

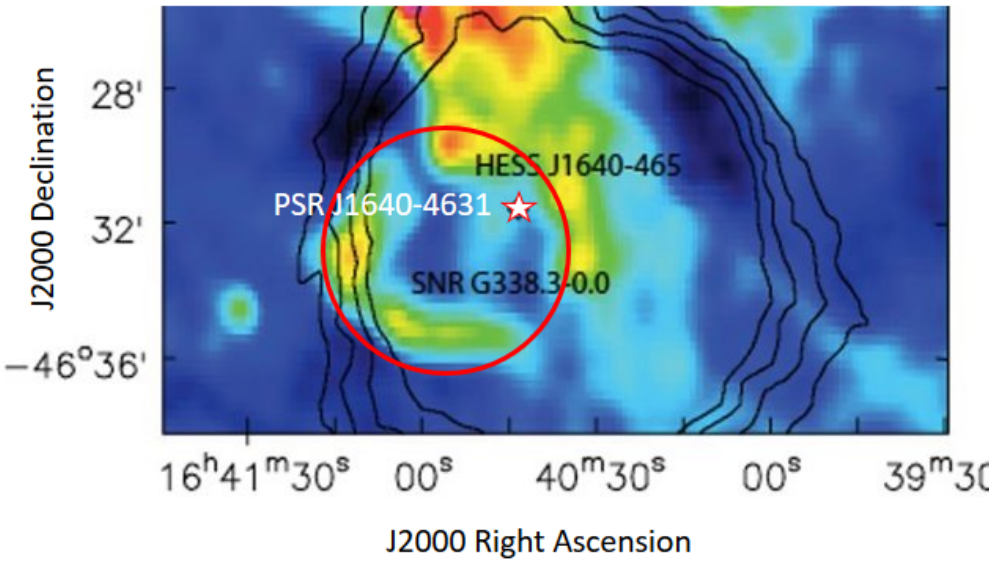

FIGURE – Radio view (*MOST* 843 MHz) of HESS J1640−465. Black contours : 6, 7 and 8 significance contours of the gamma ray emission > 4 TeV.

Introduction-2 : HESS J1640−465

In the GeV energy range :

- 2010 : Soft spectrum, $\Gamma \sim 2.3$, [Slane, P. et al. 2010]
  $\Rightarrow$ leptonic emission of a pulsar wind nebula
- 2014 : Harder ($\Gamma \sim 2$) after *HESS J1641−463* detection
  [Lemoine-Goumard, M. et al, 2014]
  $\Rightarrow$ hadronic or leptonic emission

Proton accelerator ?

Exceptionally luminous TeV gamma-ray supernova remnant [Abramowski, A., 2014]

- 2018 : Harder ($\Gamma \sim 1.4$) ($E \geq 10$ GeV) [Xin, Y.-L. et al 2018]
  $\Rightarrow$ leptonic emission of pulsar wind nebula

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Introduction-3 : HESS J1641−463

- **HESS J1641−463 :**

-Point source (H.E.S.S. [Abramowski, A. et al, 2014] and *Fermi* [Lemoine-Goumard, M. et al, 2014])

-0.25° away from HESS J1640−465

-Coincident with the radio SNR G338.5+0.1 and the dense HII region G338.4+0.0

-Soft spectrum ⇒ hidden by HESS J1640−465

-Very hard spectrum at TeV energy (H.E.S.S. Γ ∼*2.1*), no break up to 30 TeV

Best H.E.S.S. PeVatron candidate

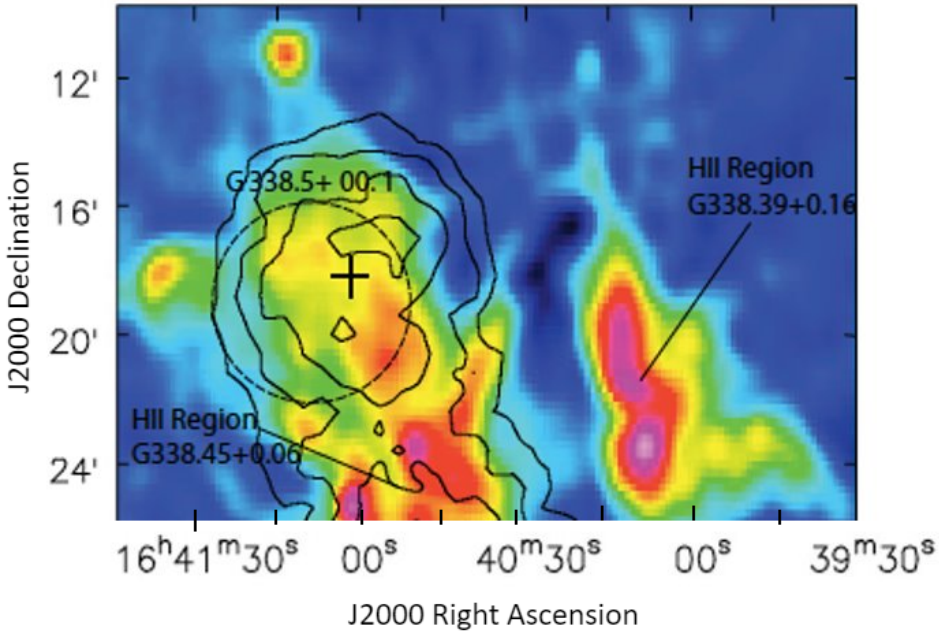

FIGURE – Radio map (*MOST*). Position and extension of G338.5+0.1 is indicated as a dashed black circle, the best fit position of HESS J1641−463 is shown as a black cross.

Unidentified source

Data selection

Morphological and spectral analysis :
FermiPy package V 0.17.3 , *gtlike (SCTOOLS 11-07-00)*

Requirements

Data	Pass 8, 100 months
Zenith angle	<90°
Energy	1 GeV − 1 TeV (morphology)
Energy	200 MeV − 1 TeV (spectra)
Region of interest	$15^\circ \times 15^\circ$
Sources	4FGL [The Fermi-LAT collaboration, 2019]

Description of the diffuse emission :

Isotropic : *iso_P8R3_SOURCE_V2_v1.txt*

Galactic : *gll_iem_v07.fits*

Summed Likelihood binned analysis using the data divided into four angular resolution reconstruction qualities

Source model improvement

- In order to improve the fit quality of the region ⇒ additional sources in the source model

Grey crosses : sources from the 4FGL catalog

- *FermiPy* : residual Test Statistic[1] map

With TS $\geq$ 25 :

9 sources added above 1 GeV (white crosses)
+
2 sources added above 200 MeV (green crosses)

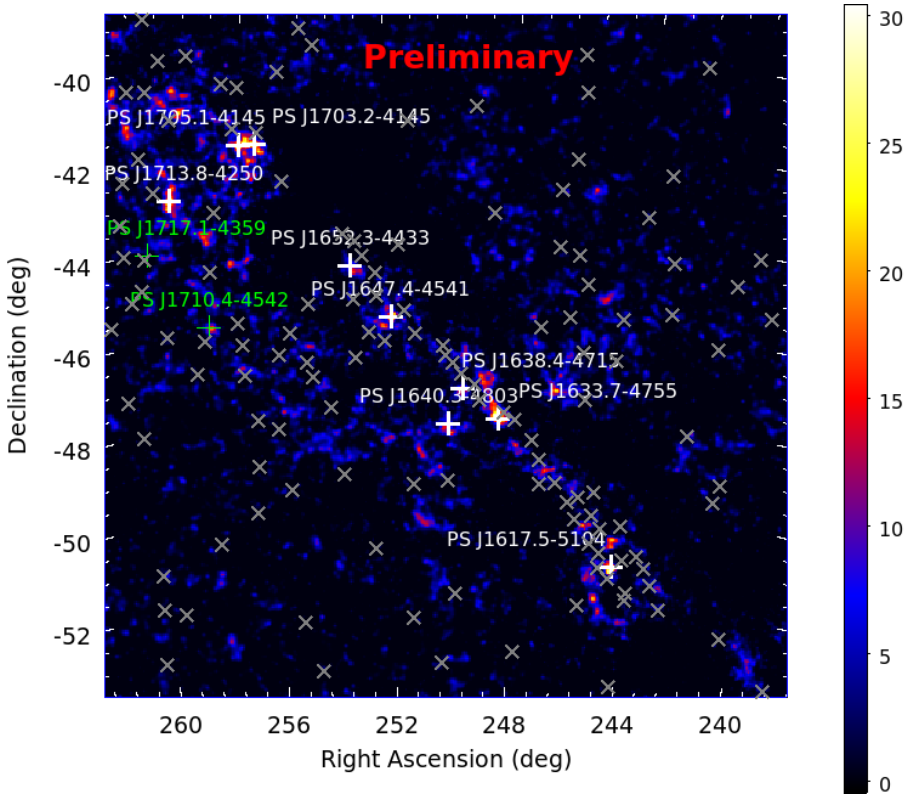

FIGURE – Residual TS map of the region centered on HESS J1640−465 above 1 GeV.

1. $TS = 2 \times (log(\mathcal{L}_{test\ \ model}) - log(\mathcal{L}_{reference\ \ model}))$

Best fit localization and extension : HESS J1640−465

Position and extension of HESS J1640−463

	4FGL	*FermiPy*	H.E.S.S.
RA	$250.16° \pm 0.02°_{stat}$	$250.18° \pm 0.01°_{stat}$	$250.180° \pm 0.004°_{stat}$
Dec	$-46.55° \pm 0.02°_{stat}$	$-46.56° \pm 0.01°_{stat}$	$-46.530° \pm 0.004°_{stat}$
σ	none	$0.068° \pm 0.013°_{stat}$	$0.072° \pm 0.003°_{stat}$

For the first time, we see the extension of HESS J1640−465 using the *Fermi*-LAT data

Model comparison for HESS J1640−465

Model	N_{dof}	TS_{ext} (point vs model)
Point (relocalized)	4	/ / /
2D Gaussian	5	39
HESS template	2	37

FermiPy localization/extension is not significantly better than the H.E.S.S. template

⇒ We use H.E.S.S. extension and position of HESS J1640−465 for the spectral analysis

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Best fit localization : HESS J1641−463

Position of HESS J1641−463

	4FGL	*FermiPy*	H.E.S.S.
RA	$250.26^\circ \pm 0.02^\circ_{stat}$	$250.25^\circ \pm 0.01^\circ_{stat}$	$250.26^\circ \pm 0.01^\circ_{stat}$
Dec	$-46.32^\circ \pm 0.02^\circ_{stat}$	$-46.29^\circ \pm 0.01^\circ_{stat}$	$-46.30^\circ \pm 0.01^\circ_{stat}$

TABLE – Position of HESS J1641−643

Good agreement between the H.E.S.S. and the *Fermi* localisation ⇒ same source

No significant extension for HESS J1641−463 using a 2D Gaussian : TS_{ext} = 6

GeV emission of HESS J1640−465 & HESS J1641−463

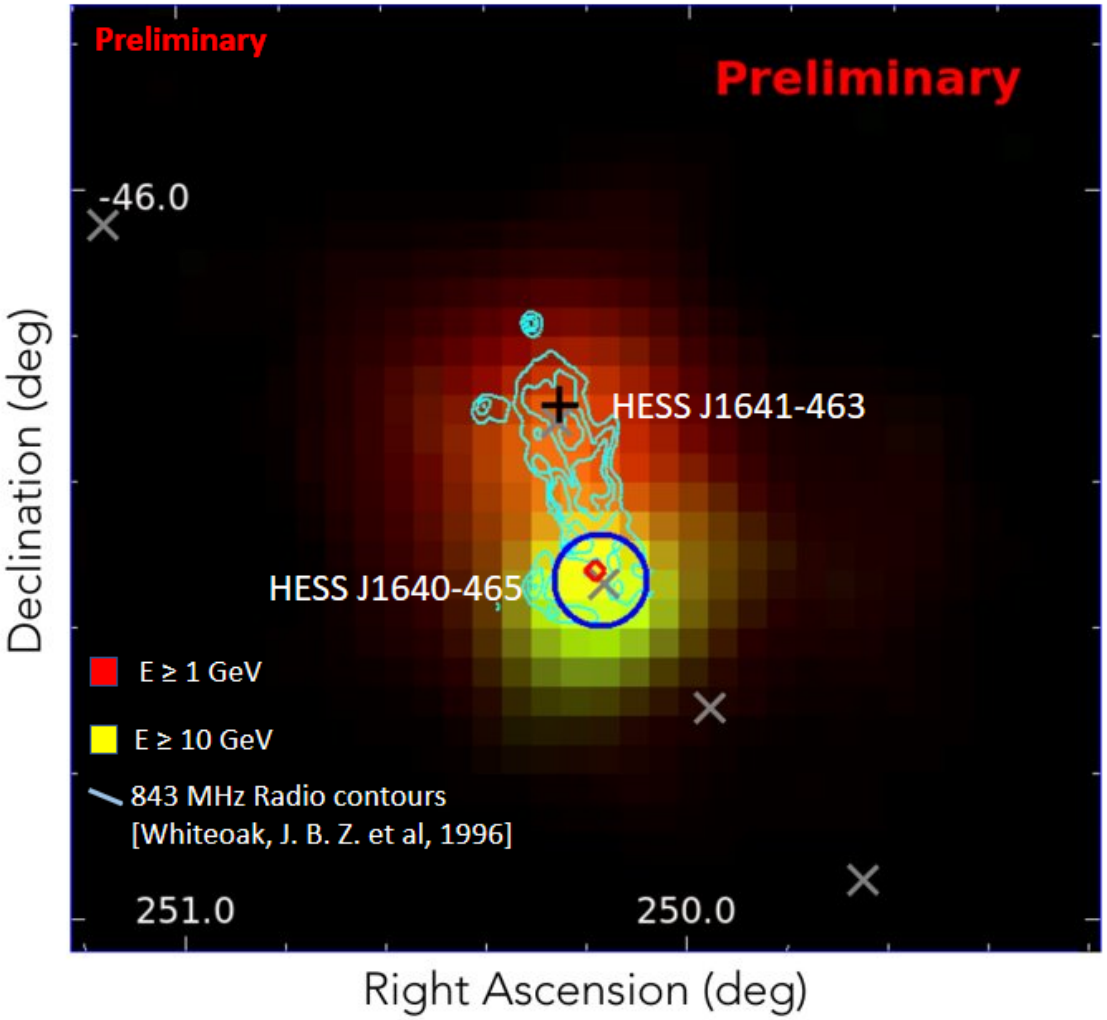


FIGURE – 1.5° × 1.5° TS map centered on HESS J1640−465. Black cross : HESS J1641−463. Blue circle : HESS J1640−465. Red diamond : pulsar. Grey crosses : sources of the 4FGL.

Spectral analysis

Model comparison

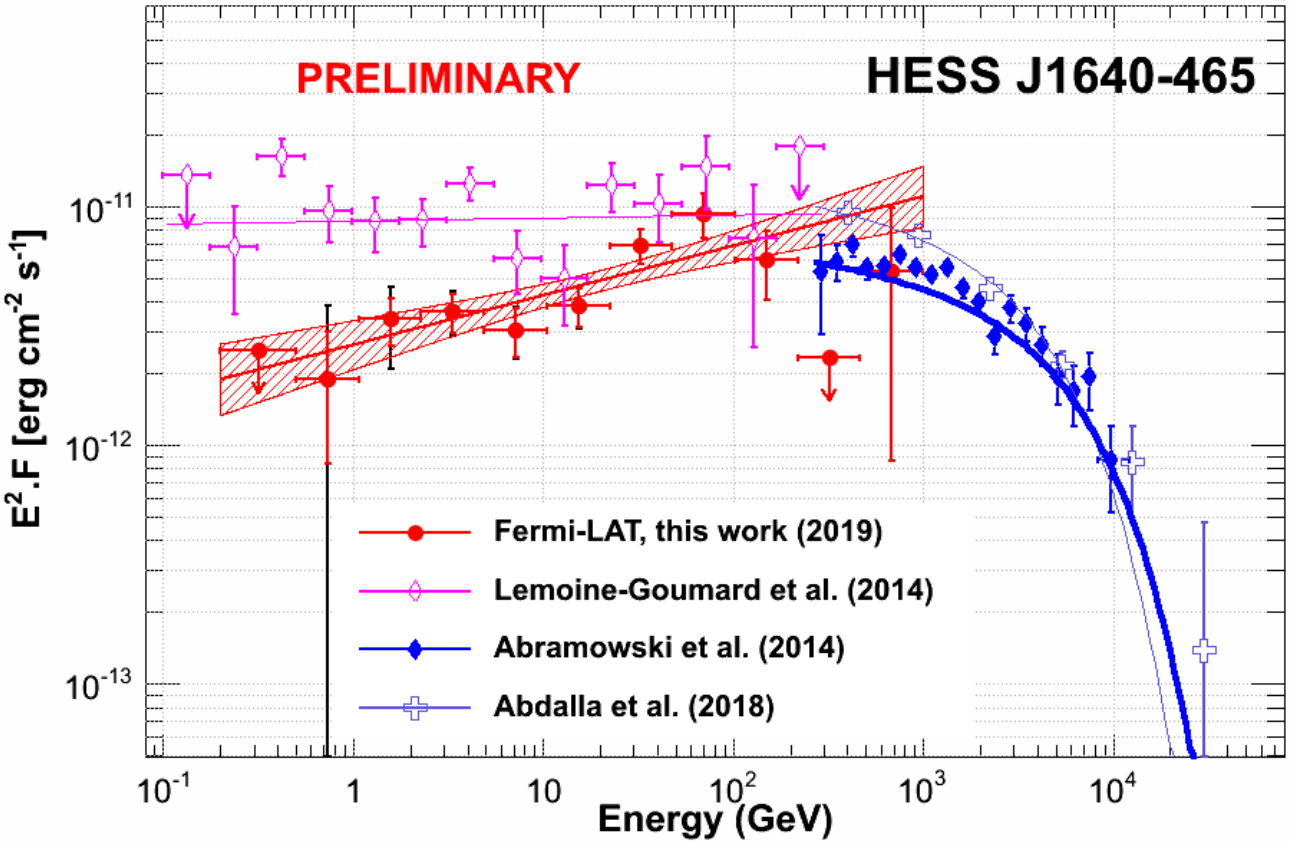
HESS J1640−465	HESS J1641−463	N_{DoF}	$\Delta\ TS_{model\ vs\ PLPL}$
Power-law	Power-law	4	////
Power-law	Log-parabola	5	18
Log-parabola	Log-parabola	6	26

Log-parabola instead of power-law for HESS J1641−463 : $\sim 4\sigma$
$\Rightarrow$significant curvature

Systematics : uncertainties in our model of the Galactic diffuse emission, on the morphology of HESS J1640−465 and in our knowledge of the *Fermi*-LAT Instrument Response Functions.

Spectrum of HESS J1640−465

HESS J1640−465	
TS	233
Index	$\Gamma = 1.8 \pm 0.1_{stat} \pm 0.2_{syst}$
Energy flux [200 MeV − 1 TeV]	$[4.44 \pm 0.15_{stat} \pm 0.33_{syst}] \times 10^{-11}$ erg cm^{-2} s^{-1}



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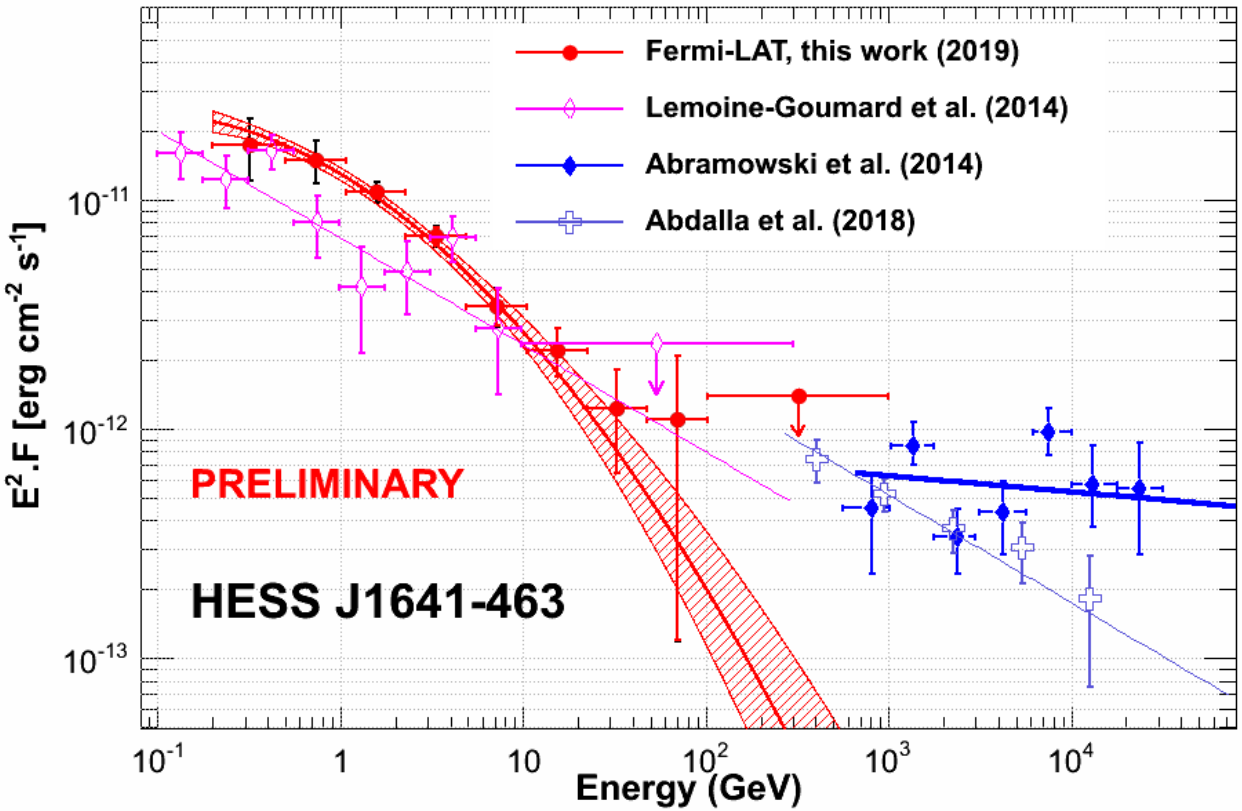
Spectrum of HESS J1641−463

HESS J1641−463	
TS	860
Alpha	$\alpha = 2.7 \pm 0.1_{stat} \pm 0.2_{syst}$
Beta	$\beta = 0.10 \pm 0.03_{stat} \pm 0.1_{syst}$
Energy flux [200 MeV − 1 TeV]	$[4.73 \pm 0.15_{stat} \pm 1.53_{syst}] \times 10^{-11}$ erg cm^{-2} s^{-1}



Conclusion

For HESS J1640−465 :

- First detection of the extension with the *Fermi*-LAT data
- Good connection between the H.E.S.S. and the *Fermi* spectra ⇒ same source ?
- Hard spectrum suggests a leptonic emission rather than hadronic ⇒ pulsar wind nebula or supernova remnant ?

For HESS J1641−463 :

- No significant extension
- Significant curvature in the GeV energy band
- Two spectral components
- Pulsar-like spectrum (*Fermi*) + PeVatron (H.E.S.S.) ?

Hypotheses :

-Pulsar (GeV) + nebula (TeV) ? ⇒ no pulsar seen, no extension
-Binary system ? ⇒ no star in all wavelengths
-Coinciding SNR (GeV energy band) + protons escaping from HESS J1640−465 (TeV energy band) ?

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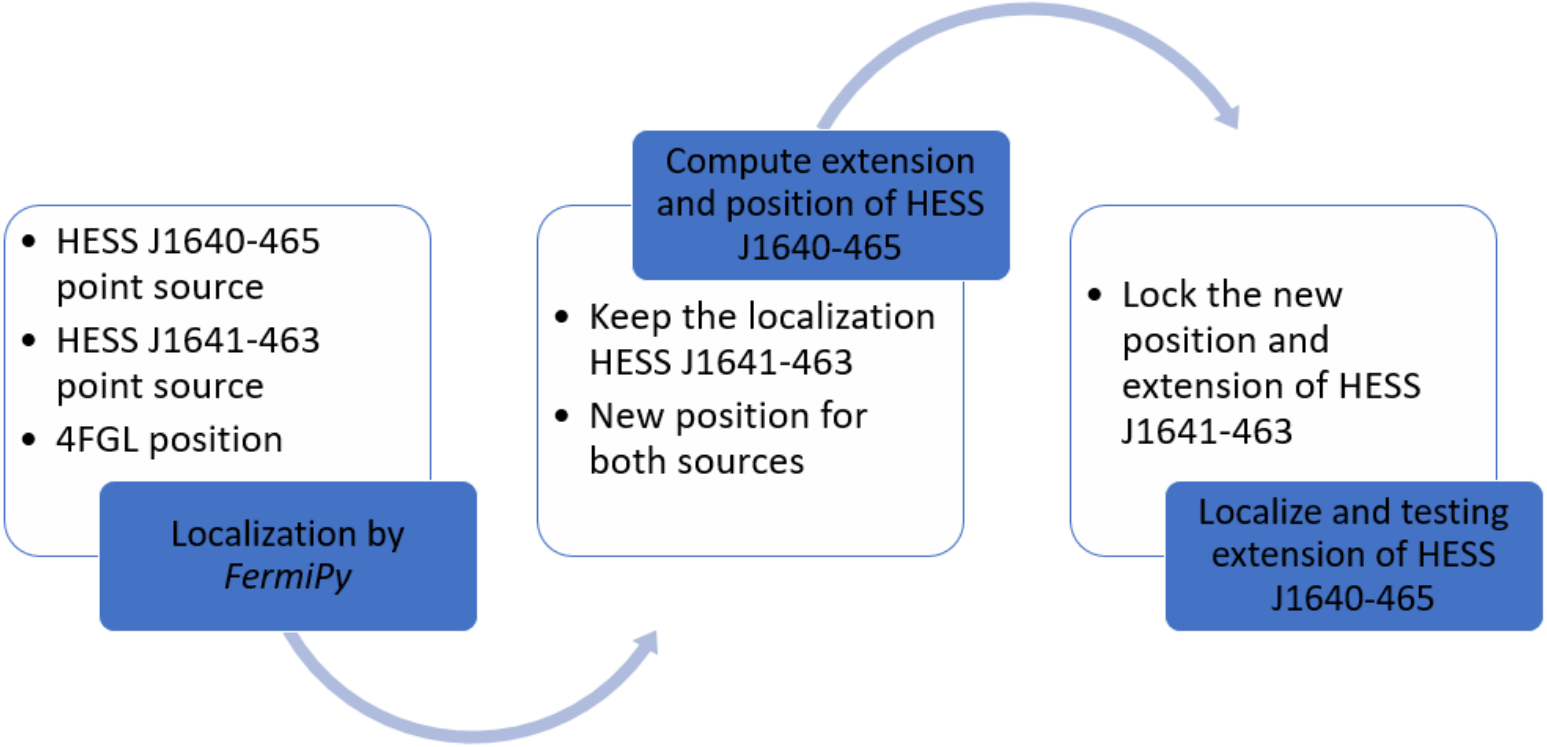
Search for extension



Log-likelihood profile for the extension of HESS J1640−465

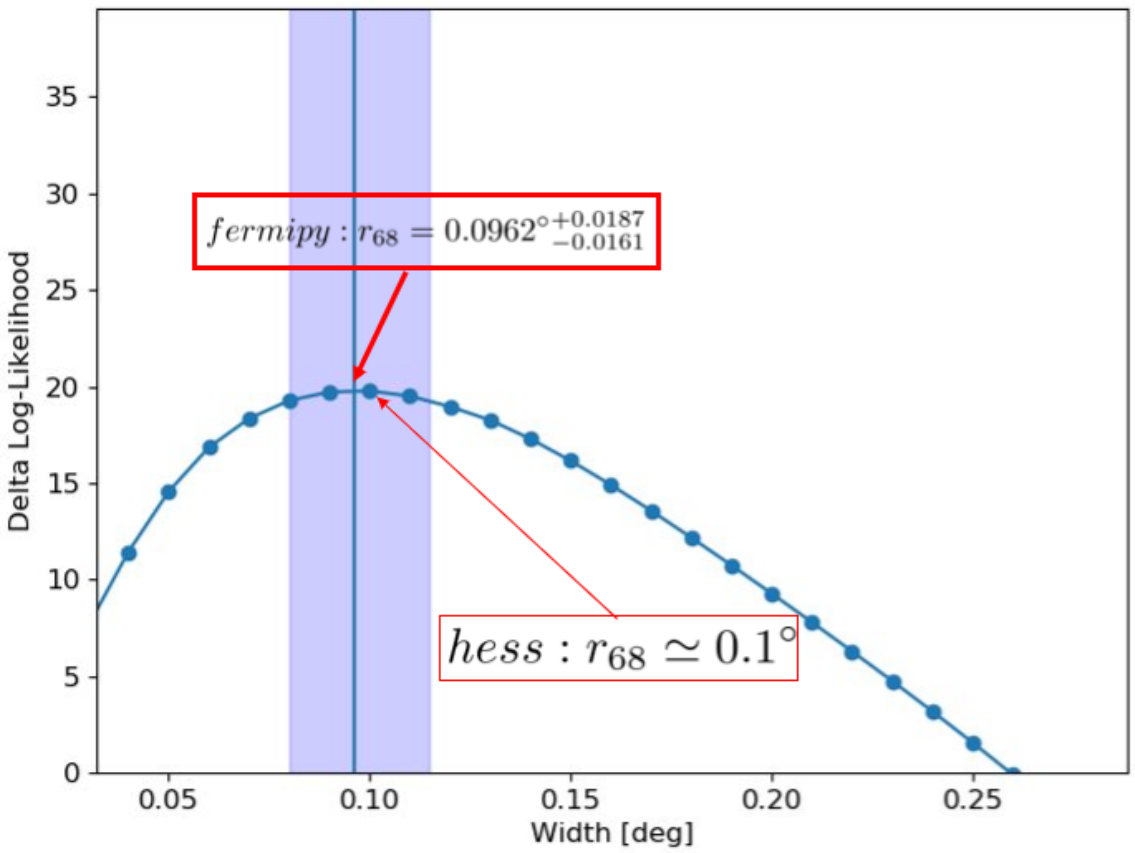


FIGURE – Evolution of the likelihood with the extension

Extension $\sim 0.068^{\circ}$ measured with *FermiPy* above 1 GeV

Analyses comparison

Lemoine, M. et al, 2014 :	**Xin, Y.-L., 2018 :**	**This work :**
5 years of data	8 years of data	8 years of data
Pass 7	Pass 8	Pass 8
No summedlikelihood	No summedlikelihood	Summedlikelihood
3FGL source list	3FGL source list	4FGL source list
No curvature for HESS J1641−463	No curvature for HESS J1641−463	Curvature for HESS J1641−463

For HESS J1640−465 :

Lemoine, M. et al, 2014 : $\Gamma = 1.99 \pm 0.04_{stat}$

Xin, Y.-L., 2018 : $\Gamma = 1.4 \pm 0.2_{stat}$

4FGL (2018) : $\Gamma = 1.8 \pm 0.1_{stat}$

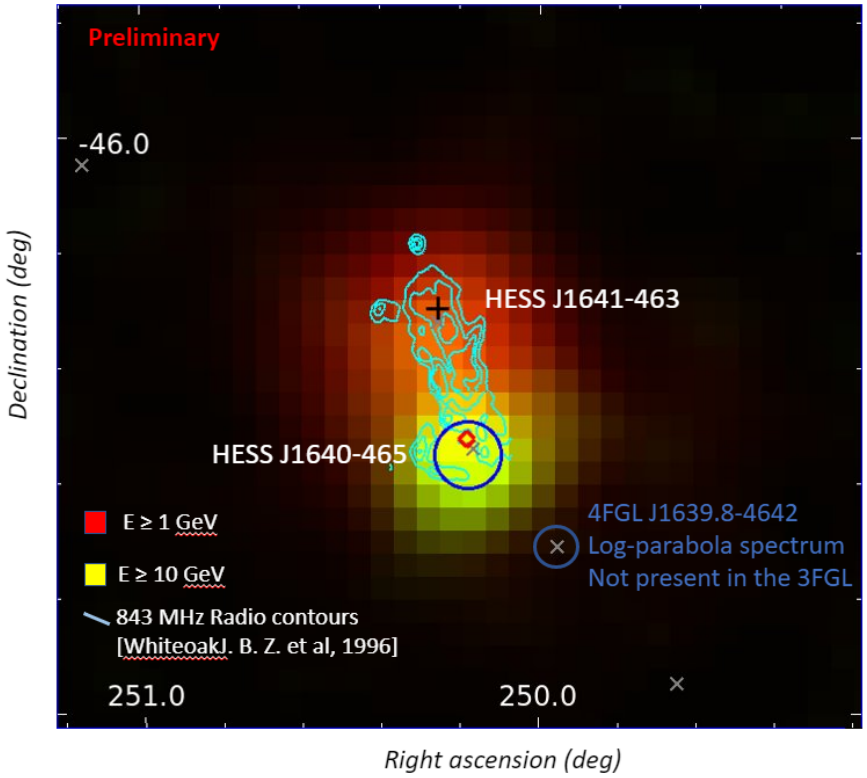
This analysis, 2019 : $\Gamma = 1.8 \pm 0.1_{stat}$

HESS J1641−463 :

Lemoine, M. et al, 2014 : $\Gamma = 2.47 \pm 0.05_{stat}$

4FGL (2019) : $\alpha = 2.6 \pm 0.1_{stat}$, $\beta = 0.14 \pm 0.05_{stat}$

This analysis, 2019 : $\alpha = 2.7 \pm 0.1_{stat}$, $\beta = 0.10 \pm 0.03_{stat}$



Objects caracteristics

PSR J1640-4631 :

- x-ray pulsar (*Nustar*) assicated x-ray PWN (*WMN-Newton, Chandra)*
- = 4.4×10^{36} erg s^{-1}, τ_c=3350 years, $B_s = 1.1 \times 10^{13}$ G
- no γ or radio pulsation
- $\Gamma_{psr} = 1.1$, $\Gamma_{pwn} = 2.4$

SNR G338.3-0.0 :

- shell age : 1000 - 8000 yr
- distance : 8 - 13 kpc using 21cm HI absorption
- shell : no x-ray emission (low T + large column density)