



Fermi

Gamma-ray Space Telescope

SEARCH FOR  
SPATIALLY  
EXTENDED  
*Fermi*-LAT  
SOURCES USING  
TWO YEARS OF  
DATA

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## Search for Spatially Extended *Fermi*-LAT Sources Using Two Years of Data

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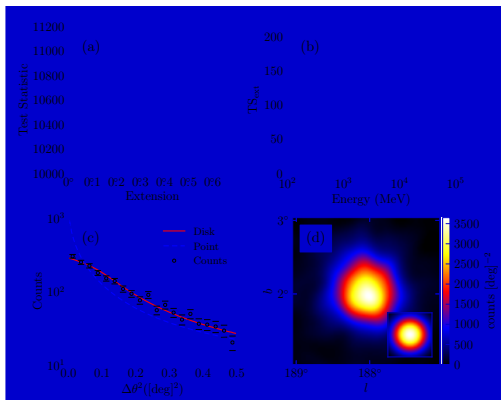
- ▶ Cat II paper
- ▶ Internal referees: Marianne Lemoine-Goumard + Johann Cohen-Tanugi (+ unofficially Jean Ballet)
- ▶ Submitted to ApJ

# SECTION 2.1. MODELING EXTENDED SOURCES IN THE POINTLIKE PACKAGE

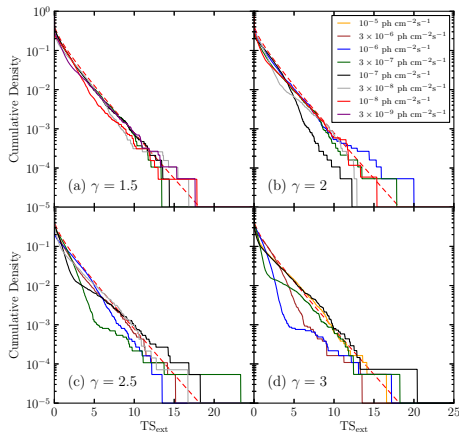
New method to study spatially-extended *Fermi*-LAT sources

- ▶ Description of `pointlike`
- ▶ Implementation of extended sources
- ▶ Simultaneously Fit position + extension
- ▶ speed up likelihood computation
- ▶ Cross check TS + spectral values using `gtlike`

# FIG. 1: IC 443

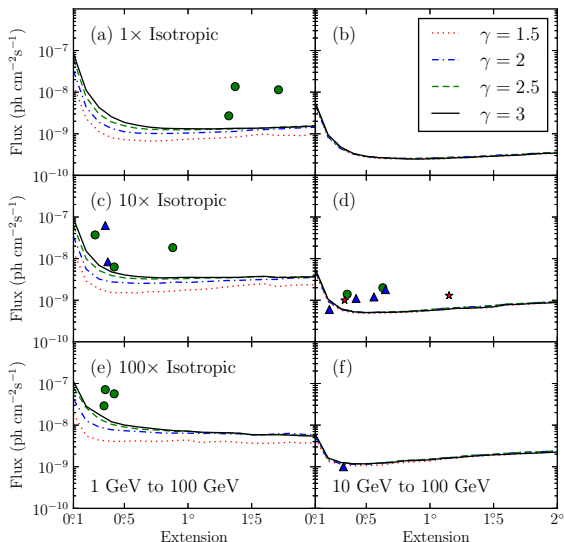


# FIG. 3+4: FALSE-DETECTION RATE



- ▶ Simulate point-like sources
- ▶ Test for extension
- ▶ Good agreement with Wilk's Theorem
- ▶ Use  $\sqrt{TS_{\text{ext}}}$  as a measure of significance
- ▶  $\sim 20,000$  Simulations per spectral model!
- ▶ Test in 1 GeV to 100 GeV + 10 GeV to 100 GeV energy range

# FIG. 5+6+7: DETECTION THRESHOLD

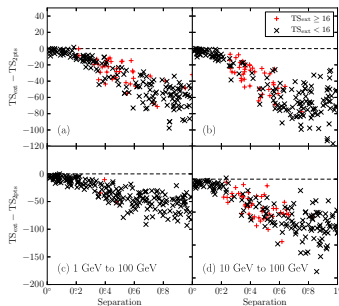


- ▶ Detection threshold to extension
- ▶  $\langle TS_{\text{ext}} \rangle = 16$
- ▶ Vary spectra, background, energy range
- ▶ Overlay extended sources
- ▶ Reference for future publications!

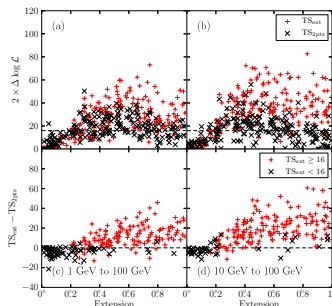
# FIG. 8+9: EFFECTS OF SOURCE CONFUSION

## Non-nested model comparison

$$TS_{2pts} = 2 \log(\mathcal{L}_{2pts}/\mathcal{L}_{ps})$$

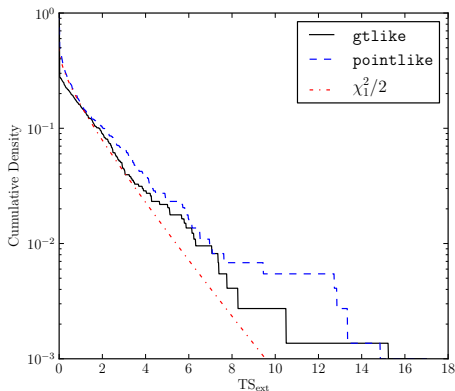


Simulate extended sources. Fit as point-like sources.



Simulate point-like sources. Fit for extension.

# FIG. 10: $TS_{\text{EXT}}$ FOR 2LAC AGN



- Use point-like AGN to validate extended source analysis
- Test clean 2LAC AGN for extension
- Don't find AGN to be extended!



# SECTION 7: EXTENDED SOURCES IN 2FGL

Table 3. Analysis of the twelve extended sources included in 2FGL

Name	GLON (deg.)	GLAT (deg.)	$\sigma$ (deg.)	TS	TS <sub>ext</sub>	Pos Err (deg.)	Flux <sup>(a)</sup>	Index
E>1 GeV								
SMC	302.59	-44.42	$1.32 \pm 0.15 \pm 0.31$	95.0	52.9	0.14	$2.7 \pm 0.3$	$2.48 \pm 0.19$
LMC	279.26	-32.31	$1.37 \pm 0.04 \pm 0.11$	1127.9	909.9	0.04	$13.6 \pm 0.6$	$2.43 \pm 0.06$
IC443	189.05	3.04	$0.35 \pm 0.01 \pm 0.04$	10692.9	554.4	0.01	$62.4 \pm 1.1$	$2.22 \pm 0.02$
Vela X	263.34	-3.11	0.88					
Centaurus A	309.52	19.42	$\sim 10$					
W28	6.50	-0.27	$0.42 \pm 0.02 \pm 0.05$	1330.8	163.8	0.01	$56.5 \pm 1.8$	$2.60 \pm 0.03$
W30	8.61	-0.20	$0.34 \pm 0.02 \pm 0.02$	464.8	76.0	0.02	$29.1 \pm 1.5$	$2.56 \pm 0.05$
W44	34.69	-0.39	$0.35 \pm 0.02 \pm 0.02$	1917.0	224.8	0.01	$71.2 \pm 0.5$	$2.66 \pm 0.00$
W51C	49.12	-0.45	$0.27 \pm 0.02 \pm 0.04$	1823.4	118.9	0.01	$37.2 \pm 1.3$	$2.34 \pm 0.03$
Cygnus Loop	74.21	-8.48	$1.71 \pm 0.05 \pm 0.06$	357.9	246.0	0.06	$11.4 \pm 0.7$	$2.50 \pm 0.10$
E>10 GeV								
MSH15-52	320.39	-1.22	$0.21 \pm 0.04 \pm 0.04$	76.3	6.6	0.03	$0.6 \pm 0.1$	$2.20 \pm 0.22$
HESS J1825-137	17.57	-0.45	$0.65 \pm 0.04 \pm 0.02$	82.9	44.9	0.05	$1.8 \pm 0.8$	$1.83 \pm 0.73$

<sup>(a)</sup>Integral Flux in units of  $10^{-9}$  ph cm $^{-2}$  s $^{-1}$  and integrated in the fit energy range (either 1 GeV to 100 GeV or 10 GeV to 100 GeV).

Note. — All sources were fit using a spatial model assuming a uniform radially symmetric intensity distribution. GLON and GLAT are Galactic longitude and latitude of the best fit extended source respectively. The first error on  $\sigma$  is statistical and the second is systematic (see Section 8). The errors on the integral fluxes and the spectral indices are statistical only. Pos Err is the error on the position of the source. Vela X and the Centaurus A Lobes were not fit in our analysis but are include for completeness.

- ▶ Test 12 extended 2FGL sources for extension
- ▶ Systematic reanalysis using 2 years of data.
- ▶ Assume uniform disk
- ▶ Extended sources are extended!

# SECTION 8: EXTENSION SYSTEMATICS

Test systematics due to not knowing PSF

- ▶ Compare best fit extension to MC based PSF
- ▶ Use difference as systematic
- ▶ Small effect on extension, large effect on statistical significance
- ▶ Probably too conservative. . .

Test systematics due to not knowing PSF

- ▶ Break up GALPROP diffuse model into multiple components
- ▶ Fit each component locally
- ▶ Tests systematics due to imperfect diffuse modeling

# SECTION 9: EXTENDED SOURCE SEARCH

- ▶ Run a dedicated search
- ▶ Find previously-unresolved extended 2FGL sources
- ▶ Search for  $E > 1$  GeV and  $E > 10$  GeV
- ▶ Many difficulties in search, discussed at length in text. . .
- ▶ Publish only good candidates

# SECTION 10: NEW EXTENDED SOURCES

Table 4. Extension fit for the nine additional extended sources

Name	GLON (deg.)	GLAT (deg.)	$\sigma$ (deg.)	TS	TS <sub>ext</sub>	Pos Err (deg.)	Flux <sup>(a)</sup>	Index	Counterpart
E>1 GeV									
2FGL J0823.0-4246	260.32	-3.28	$0.37 \pm 0.03 \pm 0.02$	322.2	48.0	0.02	$8.4 \pm 0.6$	$2.21 \pm 0.09$	Puppis A
2FGL J1627.0-2425c	353.07	16.80	$0.42 \pm 0.05 \pm 0.16$	139.9	32.4	0.04	$6.3 \pm 0.6$	$2.50 \pm 0.14$	Ophiuchus
E>10 GeV									
2FGL J0851.7-4635	266.31	-1.43	$1.15 \pm 0.08 \pm 0.02$	116.6	86.8	0.07	$1.3 \pm 0.2$	$1.74 \pm 0.21$	Vela Jr.
2FGL J1615.0-5051	332.37	-0.13	$0.32 \pm 0.04 \pm 0.01$	50.4	16.7	0.04	$1.0 \pm 0.2$	$2.19 \pm 0.28$	HESS J1616-508
2FGL J1615.2-5138	331.66	-0.66	$0.42 \pm 0.04 \pm 0.02$	76.1	46.5	0.04	$1.1 \pm 0.2$	$1.79 \pm 0.26$	HESS J1614-518
2FGL J1632.4-4753c	336.52	0.12	$0.35 \pm 0.04 \pm 0.02$	64.4	26.9	0.04	$1.4 \pm 0.2$	$2.66 \pm 0.30$	HESS J1632-478
2FGL J1712.4-3941 <sup>(b)</sup>	347.26	-0.53	$0.56 \pm 0.04 \pm 0.02$	59.4	38.5	0.05	$1.2 \pm 0.2$	$1.87 \pm 0.22$	RX J1713.7-3946
2FGL J1837.3-0700c	25.08	0.13	$0.33 \pm 0.07 \pm 0.05$	47.0	18.5	0.07	$1.0 \pm 0.2$	$1.65 \pm 0.29$	HESS J1837-069
2FGL J2021.5+4026	78.24	2.20	$0.63 \pm 0.05 \pm 0.04$	237.2	128.9	0.05	$2.0 \pm 0.2$	$2.42 \pm 0.19$	$\gamma$ -Cygni

<sup>(a)</sup>Integral Flux in units of  $10^{-8}$   $\text{ph cm}^{-2} \text{s}^{-1}$  and integrated in the fit energy range (either 1 GeV to 100 GeV or 10 GeV to 100 GeV).

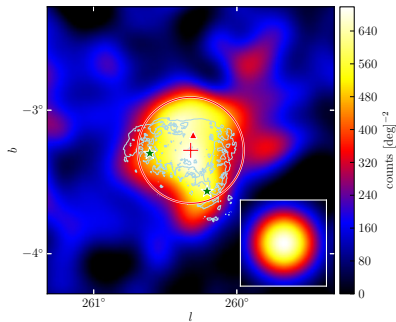
<sup>(b)</sup>The discrepancy in the best fit spectra of 2FGL J1712.4-3941 compared to [Abdo et al. \(2011c\)](#) is due to fitting over a different energy range.

Note. — The columns in this table have the same meaning as those in Table 3. RX J1713.7-3946 and Vela Jr. were previously studied in dedicated publications [Abdo et al. \(2011a\)](#).

- ▶ 6 new extended sources
- ▶ + RX J1713-3946 & Vela Jr (not extended in 2FGL)
- ▶ + 1 source in Ophiuchus region  $\rightarrow$  diffuse emission

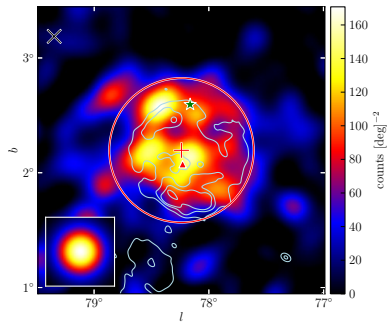
# 2 EXTENDED SNRs

## Puppis A



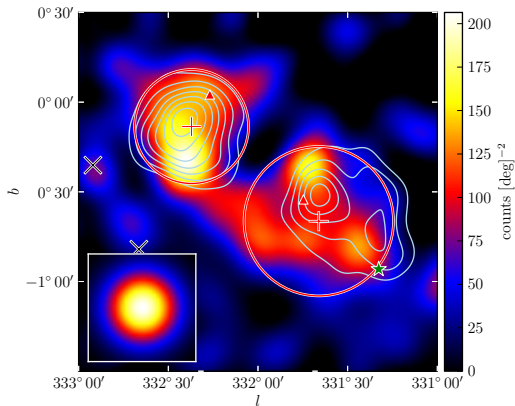
- ▶ X-ray contours
- ▶ Mid-aged SNR
- ▶ Not observed to directly interact with molecular clouds

## $\gamma$ -Cygni



- ▶ Radio contours
- ▶ SNR interacting with molecular clouds?
- ▶ Veritas + Milagro detections

# TWO NEARBY LAT EXTENDED SOURCES

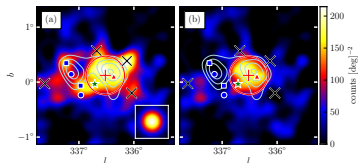


- ▶ (left):  
2FGL J1615.0–5051
- ▶ Coincident with  
HESS J1616–508
- ▶ + X-ray pulsar  
PSR J1617–5055 +  
~ 1' PWN
- ▶ PWN Candidate

- ▶ (right): 2FGL J1615.2–5138
- ▶ Coincident with HESS J1614–518
- ▶ No other compelling multiwavelength counterpart

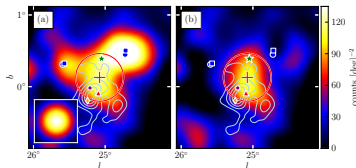
# 2 MORE PWN CANDIDATE

## 2FGL J1632.4–4753c



- ▶ Coincident with HESS J1632-478
- ▶ *XMM-Newton* point-like + extended emission
- ▶ (but no pulsations)
- ▶ PWN Candidate

## 2FGL J1837.3–0700c



- ▶ Coincident with HESS J1837-069
- ▶ + X-ray pulsar PSR J1838–0655
- ▶ +  $\sim 2'$  X-ray PWN
- ▶ PWN candidate
- ▶ Second X-ray PSR + PWN candidate in region (but no pulsations)

# THANK YOU

See text for more details:

- ▶ [https://www-glast.stanford.edu/cgi-prot/pub\\_download?id=662](https://www-glast.stanford.edu/cgi-prot/pub_download?id=662)