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

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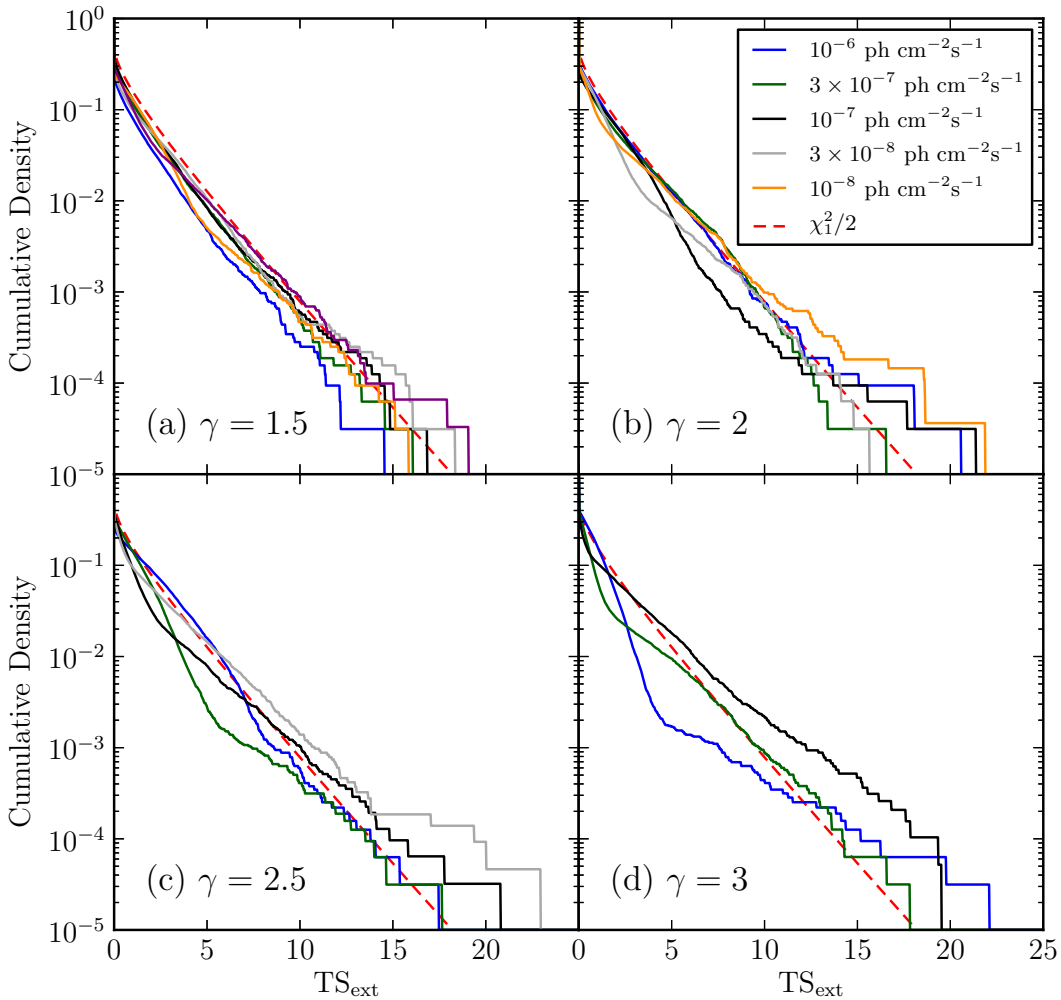
Overview

- Category II Paper
- Contact Authors: J. Lande, M. Ackermann, S. Funk
- Internal Referees: Marianne Lemoine-Goumard and Johann Cohen-Tanugi
- Target Journal: ApJ
- Currently submitted to internal referees
- Feedback welcome

Paper Outline

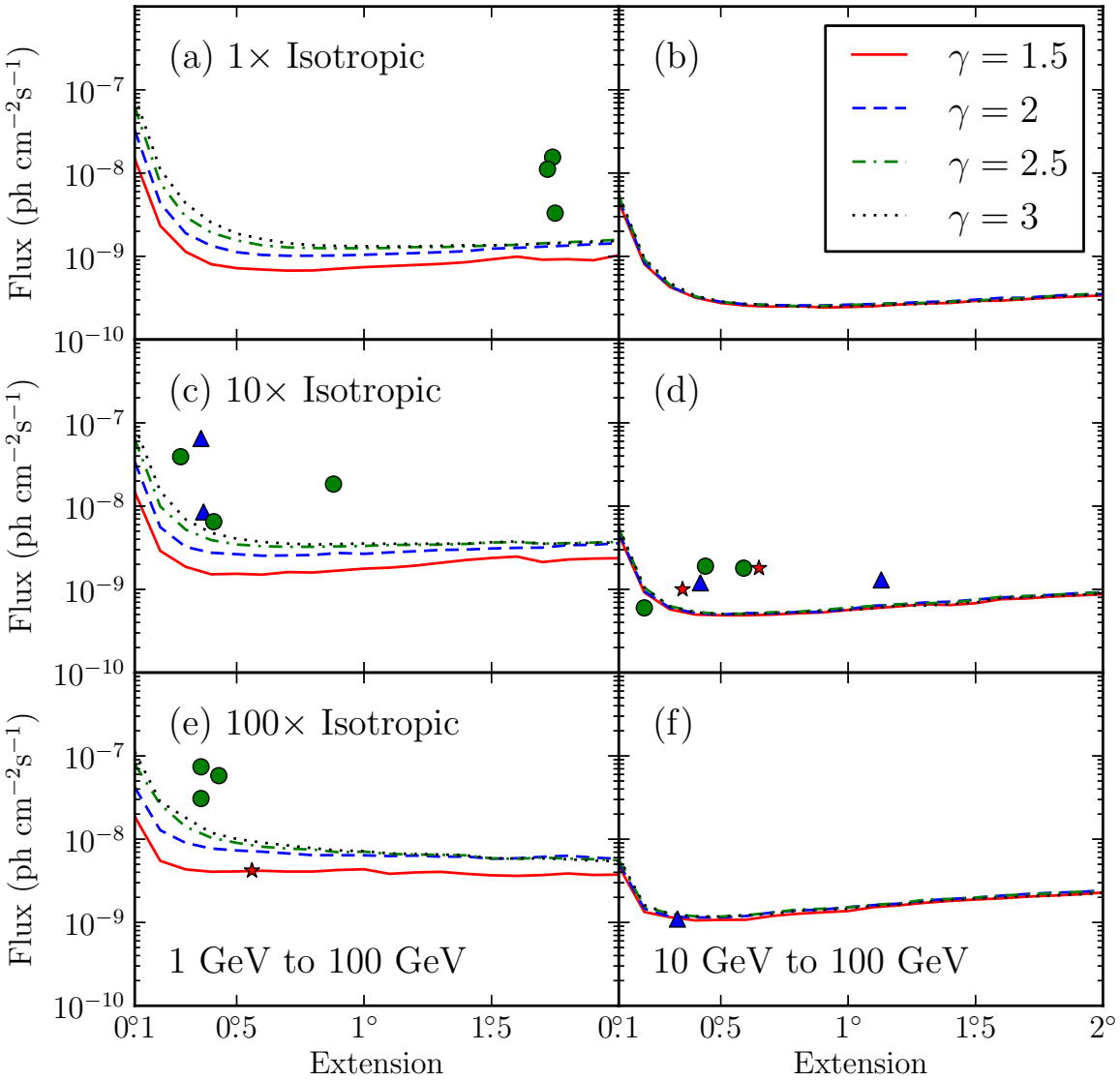
- Description of a new method (`pointlike`) for analyzing extended sources.
- Monte Carlo calculation of false detection rate for extended sources.
- Calculation of the LAT's detection threshold to spatially extended sources
- Presentation of a new search for spatially extended sources:
  - Reanalyzing extension of 12 extended sources in 2FGL
  - Test AGN from 2LAC for extension to validate the analysis
  - Present 9 extended sources not in 2FGL

Fig. 3: Monte Carlo Study of false detection rate



- Test simulated point sources for extension
- Lots of spectral parameters
- Good agreement with Wilks' Theorem
- $\sqrt{TS_{ext}} \rightarrow \#\sigma$

Fig. 5: Threshold vs background



- Large Monte Carlo study
- Calculate detection threshold to spatially extended sources
- Overlay LAT extended sources
- For future extended sources, can compare to threshold

Table. 3: Reanalyze 12 sources in 2FGL

Name	GLON (deg.)	GLAT (deg.)	σ (deg.)	TS	TS_{ext}	Pos Err (deg.)	Flux[(a)] (ph cm^{-2} s^{-1})	Index
			E>1 GeV					
SMC	302.68	-44.81	$1.75 \pm 0.07 \pm 0.02$	94.8	67.4	0.12	3.3 ± 0.4	2.41 ± 0.17
LMC	279.10	-32.61	$1.74 \pm 0.05 \pm 0.13$	1101.3	860.5	0.05	15.5 ± 0.6	2.48 ± 0.06
IC443	189.05	3.04	$0.36 \pm 0.01 \pm 0.04$	10719.8	510.4	0.01	64.8 ± 1.2	2.23 ± 0.02
Vela X	263.34	-3.11	0.88					
Centarus A	309.52	19.42	~ 10					
W28	6.50	-0.27	$0.43 \pm 0.02 \pm 0.03$	1324.8	177.4	0.01	58.0 ± 1.8	2.63 ± 0.03
W30	8.61	-0.20	$0.36 \pm 0.02 \pm 0.02$	465.4	73.3	0.02	30.7 ± 1.6	2.59 ± 0.04
W44	34.69	-0.38	$0.36 \pm 0.01 \pm 0.02$	1903.3	217.7	0.01	73.6 ± 1.8	2.68 ± 0.02
W51C	49.13	-0.45	$0.28 \pm 0.02 \pm 0.05$	1819.5	115.7	0.01	39.3 ± 1.3	2.35 ± 0.03
Cygnus Loop	74.22	-8.46	$1.72 \pm 0.05 \pm 0.07$	356.5	356.5	0.06	11.1 ± 0.7	2.53 ± 0.11
			E>10 GeV					
MSH 15−52	320.38	-1.22	$0.20 \pm 0.04 \pm 0.03$	76.2	6.5	0.03	0.6 ± 0.7	2.27 ± 0.73
HESS J1825−137	17.56	-0.46	$0.65 \pm 0.03 \pm 0.01$	83.6	55.9	0.05	1.8 ± 0.2	1.74 ± 0.19

- Test 12 2FGL sources for extension
- But always assume radially symmetric disk spatial model

Table. 4: New Extended Sources

Name	GLON (deg.)	GLAT (deg.)	σ (deg.)	TS	TS_{ext}	Pos Err (deg.)	Flux$^{(a)}$ (ph cm^{-2} s^{-1})	Index	Counterpart
				E>1 GeV					
2FGL J0823.0−4246	260.32	-3.28	$0.37 \pm 0.03 \pm 0.02$	320.9	46.3	0.02	8.5 ± 0.7	2.20 ± 0.09	Puppis A
2FGL J1627.0−2425c	353.08	16.78	$0.41 \pm 0.05 \pm 0.02$	144.5	31.1	0.04	6.5 ± 0.6	2.49 ± 0.14	Ophiuchus
2FGL J1712.4−3941	347.25	-0.54	$0.56 \pm 0.04 \pm 0.01$	75.0	39.6	0.05	4.2 ± 0.9	1.47 ± 0.12	RX J1713.7−3946
				E>10 GeV					
2FGL J0851.7−4635	266.29	-1.43	$1.13 \pm 0.08 \pm 0.05$	116.1	87.2	0.07	1.3 ± 0.2	1.76 ± 0.21	Vela Jr.
2FGL J1615.0−5051	332.38	-0.14	$0.33 \pm 0.04 \pm 0.01$	53.4	16.3	0.04	1.1 ± 0.2	2.24 ± 0.28	HESS J1616−508
2FGL J1615.2−5138	331.66	-0.66	$0.42 \pm 0.03 \pm 0.01$	76.6	48.0	0.05	1.2 ± 0.2	1.77 ± 0.24	HESS J1614−518
2FGL J1632.4−4753c	336.41	0.22	$0.44 \pm 0.04 \pm 0.03$	127.8	64.5	0.04	1.9 ± 0.2	2.29 ± 0.21	HESS J1632−478
2FGL J1837.3−0700c	25.08	0.13	$0.35 \pm 0.08 \pm 0.03$	46.2	18.8	0.07	1.0 ± 0.2	1.63 ± 0.29	HESS J1837−069
2FGL J2021.5+4026	78.18	2.19	$0.59 \pm 0.03 \pm 0.02$	222.2	116.4	0.04	1.8 ± 0.2	2.31 ± 0.19	γ-Cygni

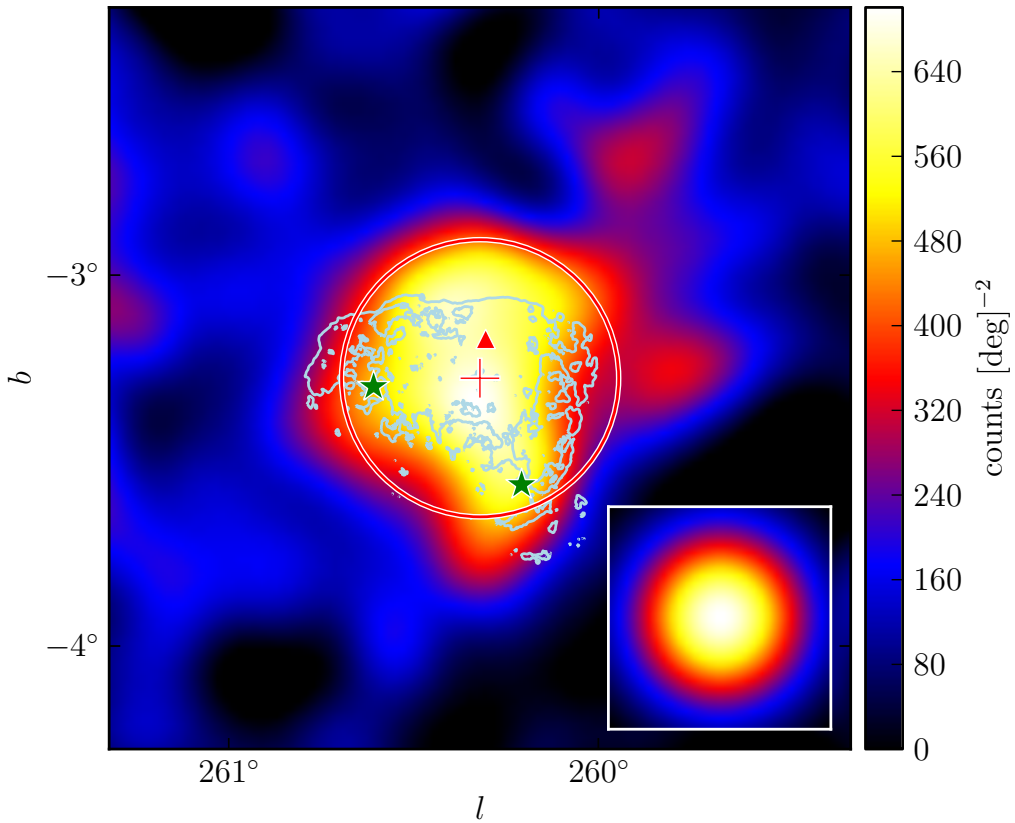
- 9 Extended Sources Not in 2FGL
- Skip in this talk
  - Vela Jr. - Dedicated Publication
  - RX J1713.7−3946 - Dedicated Publication
  - Ophiuchus - Most likely diffuse emission

Table. 5: Extension Errors

Name	$TS_{\texttt{pointlike}}$	$TS_{\texttt{gtlike}}$	$TS_{\text{alt,diff}}$	$TS_{\text{ext}\texttt{pointlike}}$	$TS_{\text{ext}\texttt{gtlike}}$	$TS_{\text{ext alt,diff}}$	σ (deg.)	$\sigma_{\text{alt,diff}}$ (deg.)	$\sigma_{\text{alt,psf}}$ (deg.)	TS_{inc}
				E>1 GeV						
2FGL J0823.0−4246	350.9	320.9	352.5	66.0	46.3	53.6	0.37	0.39	0.38	22.1
2FGL J1627.0−2425c	170.2	144.5	112.6	43.9	31.1	23.9	0.41	0.40	0.39	20.0
2FGL J1712.4−3941	80.9	75.0	43.4	47.4	39.6	22.2	0.56	0.56	0.54	6.4
				E>10 GeV						
2FGL J0851.7−4635	116.7	116.1	122.3	87.1	87.2	90.4	1.13	1.16	1.17	16.1
2FGL J1615.0−5051	52.4	53.4	55.6	17.5	16.3	17.4	0.33	0.32	0.32	11.9
2FGL J1615.2−5138	76.3	76.6	86.3	44.0	48.0	52.6	0.42	0.43	0.43	37.0
2FGL J1632.4−4753c	126.6	127.8	120.7	63.9	64.5	64.1	0.44	0.44	0.47	40.6
2FGL J1837.3−0700c	45.4	46.2	39.0	18.5	18.8	16.6	0.35	0.34	0.38	12.6
2FGL J2021.5+4026	234.3	222.2	235.6	135.9	116.4	121.4	0.59	0.60	0.60	24.3

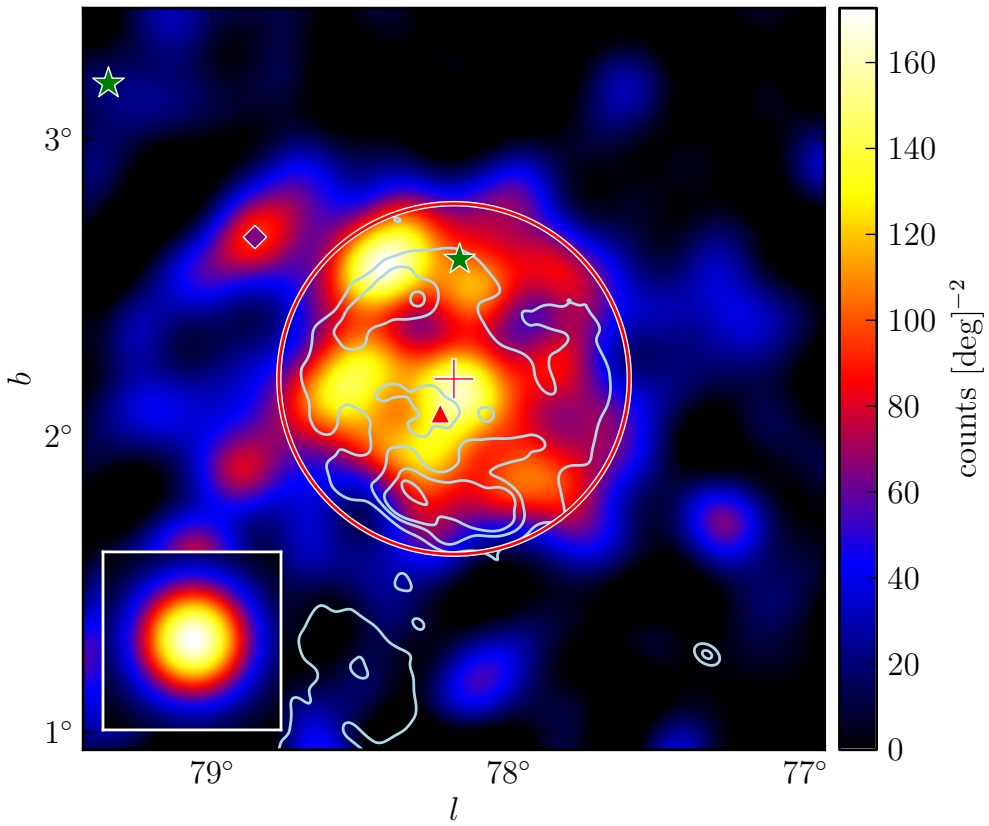
- Two Methods to estimate systematic error on extension
  - Alternate diffuse model (add degrees of freedom)
  - MC representation of the PSF

2FGL J0823.0−4246 - Puppis A



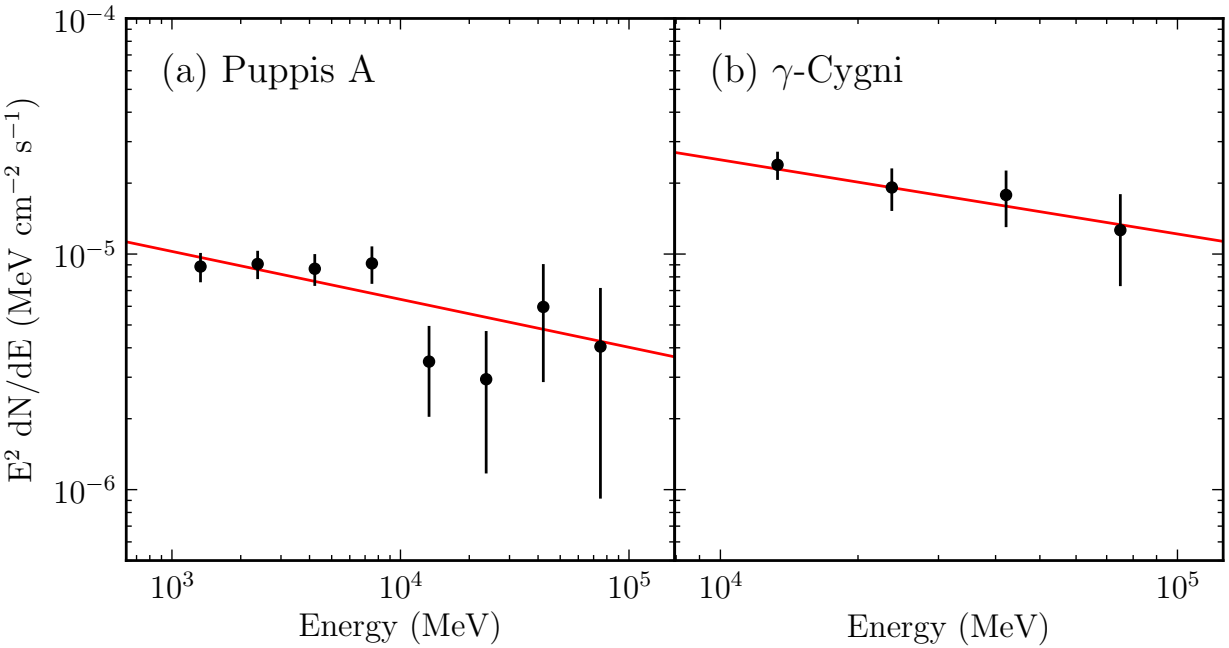
- 1 GeV to 100 GeV
- Middle-age SNR Puppis A
- ROSAT X-ray contours (Petre+1996)
- SNR not observed to interact with molecular clouds (Paron+2008)
- Similar to Cygnus Loop SNR

2FGL J2021.5+4026 - γ-Cygni

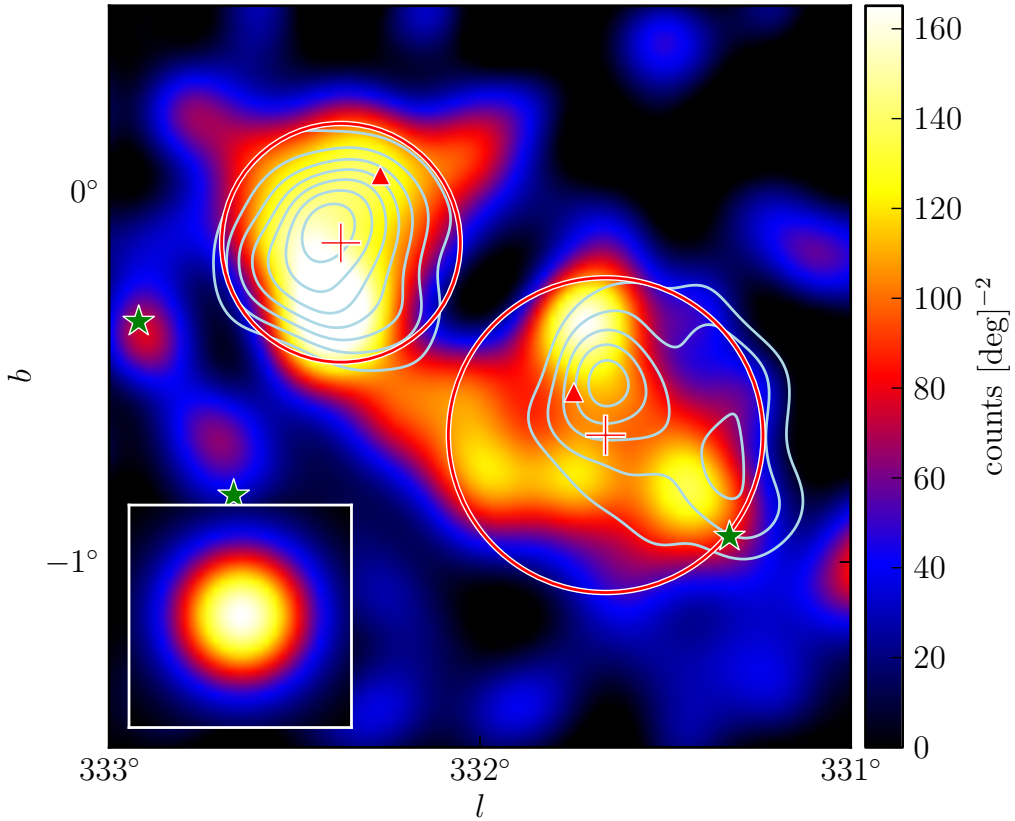


- 10 GeV to 100 GeV
- PSR J2021+4026 at lower energies
- Radio contours (Taylor+2003)
- SNR interacting with Molecular cloud
- Milagro: 4.2σ excess at $\sim$ 30 TeV (Abdo+2009)
- VER J2019+407 detected by Veritas at 200 GeV (Weinstein 2009)

Puppis A + γ-Cygni



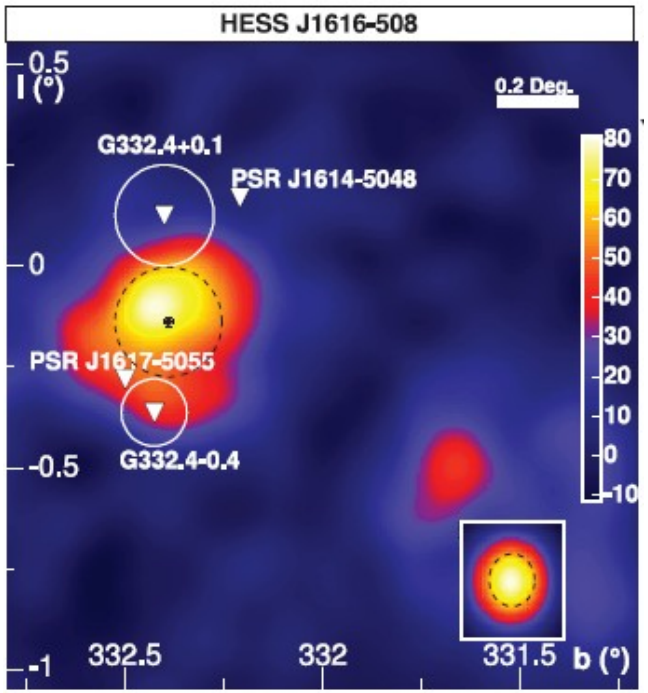
HESS J1614−518 & HESS J1616−508



- 10 GeV to 100 GeV
- Two nearby LAT extended sources
- both coincident with extended TeV sources.

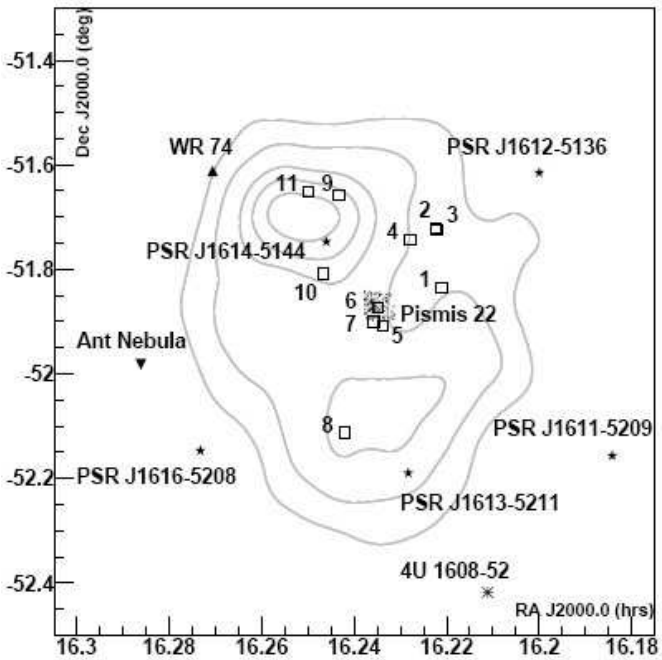
- (left): 2FGL J1615.0−5051 → HESS J1616−508
- (right): 2FGL J1615.2−5138 → HESS J1614−518

2FGL J1615.0−5051 → HESS J1616−508



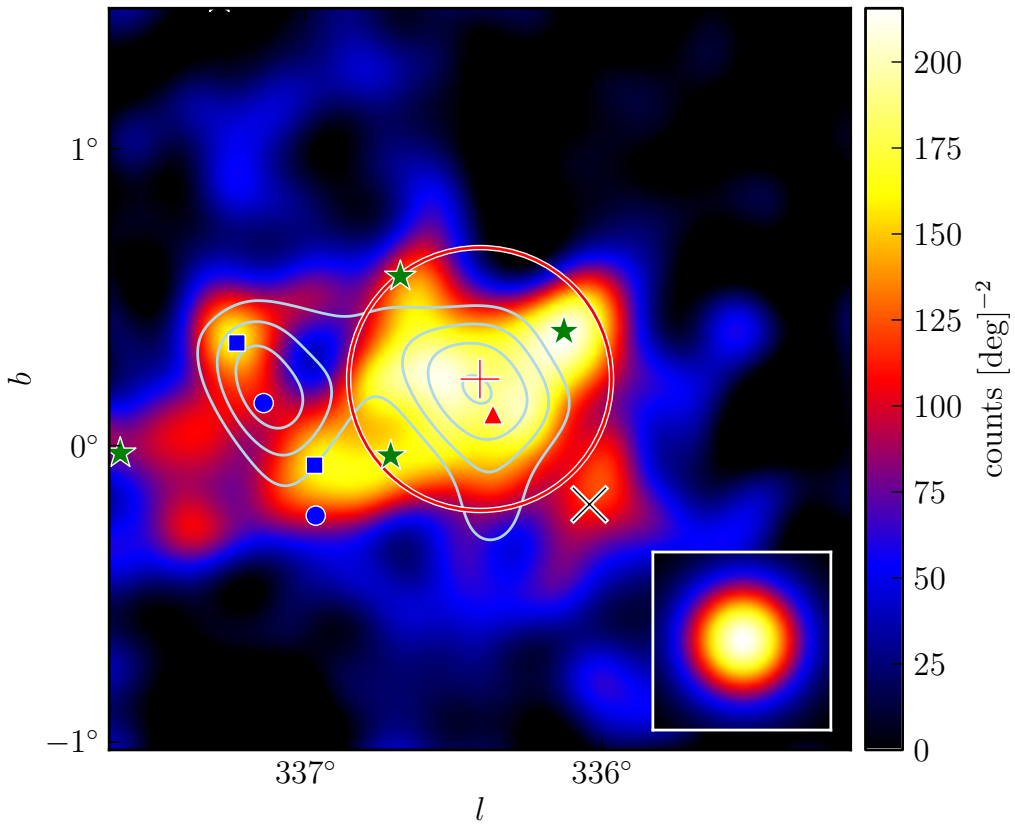
- 2 nearby SNRs: RCW103 and Kes 32 - not spatially coincident (Aharonian+2006)
- 3 Nearby Pulsars: only PSR J1617−5055 energetically powerful enough
  - 9' away → offset PWN?
  - *Chandra* detected $\sim 1'$ PWN
  - not oriented towards HESS J1616−508
- Other diffuse emission in region (Kargaltsev+2009)

2FGL J1615.2−5138 → HESS J1614−518



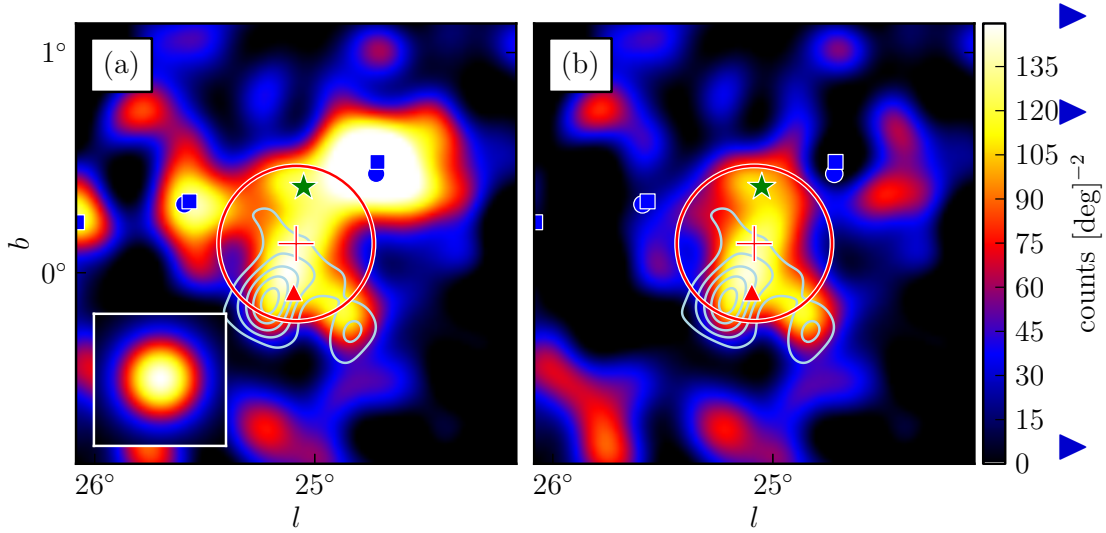
- 5 nearby pulsars, but none powerful enough (Rowell+2008)
- Open cluster Pisim 22
- Suzaku: 2 X-ray sources, one towards peak of HESS J1614−518 and one coincident with Pisim 22 (Matsumoto+2008)
- SNR? PWN? Acceleration in Stellar Winds of Pisim 22?

2FGL J1632.4−4753c - HESS J1632-478



- 10 GeV to 100 GeV
- *XMM-Newton* point-like + extended emission ($32'' \times 15''$) towards center of H.E.S.S source (Balbo+2010)
- Extended radio source in archival MGPS-2 data
- PWN? No pulsations (yet) in point-like X-ray source

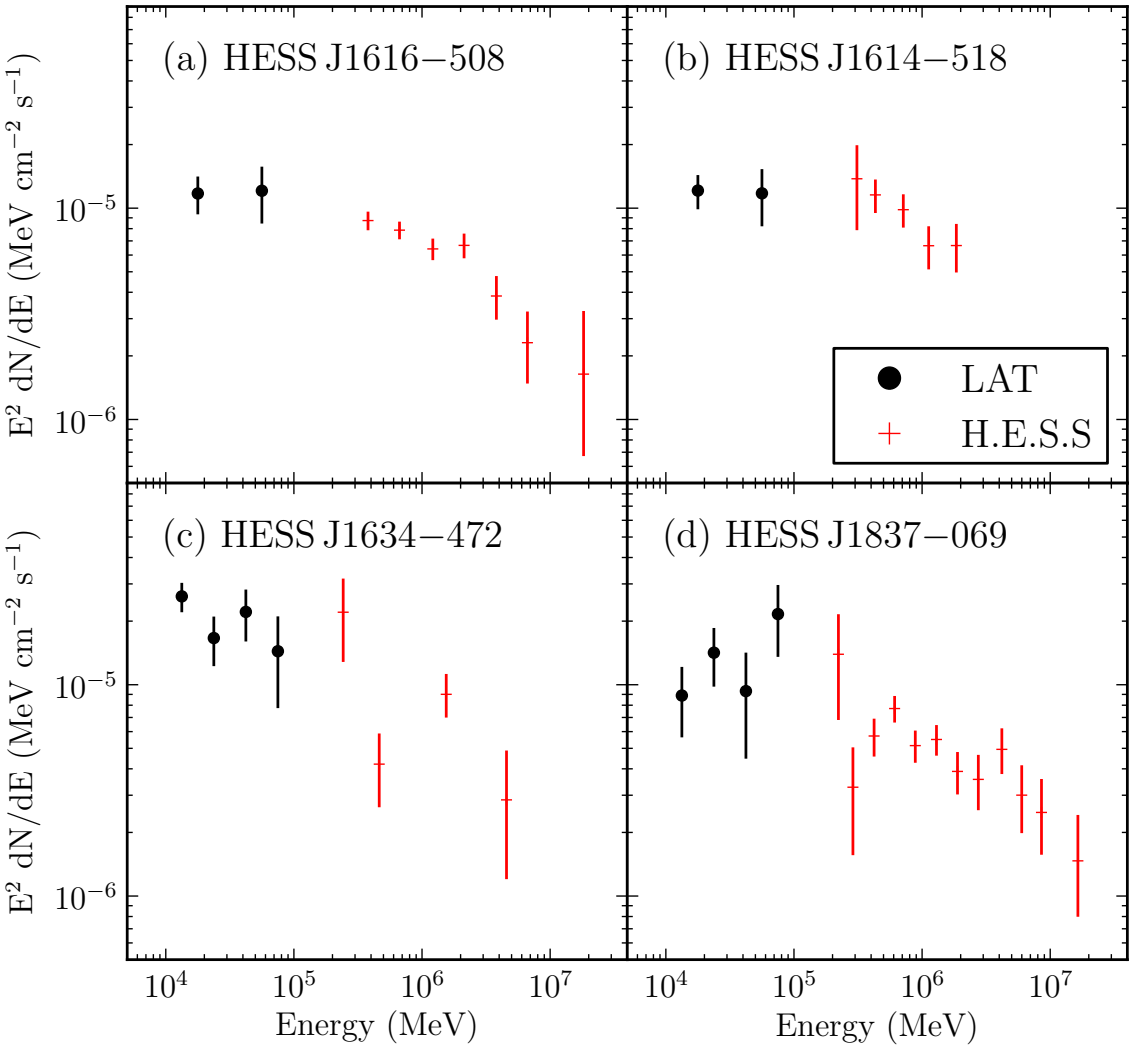
2FGL J1837.3−0700c - HESS J1837-069



- 10 GeV to 100 GeV
- Coincident with X-ray source AX J1838−0655 (Hertz & Grindlay 1988)
- X-ray Pulsations: PSR J1838−0655

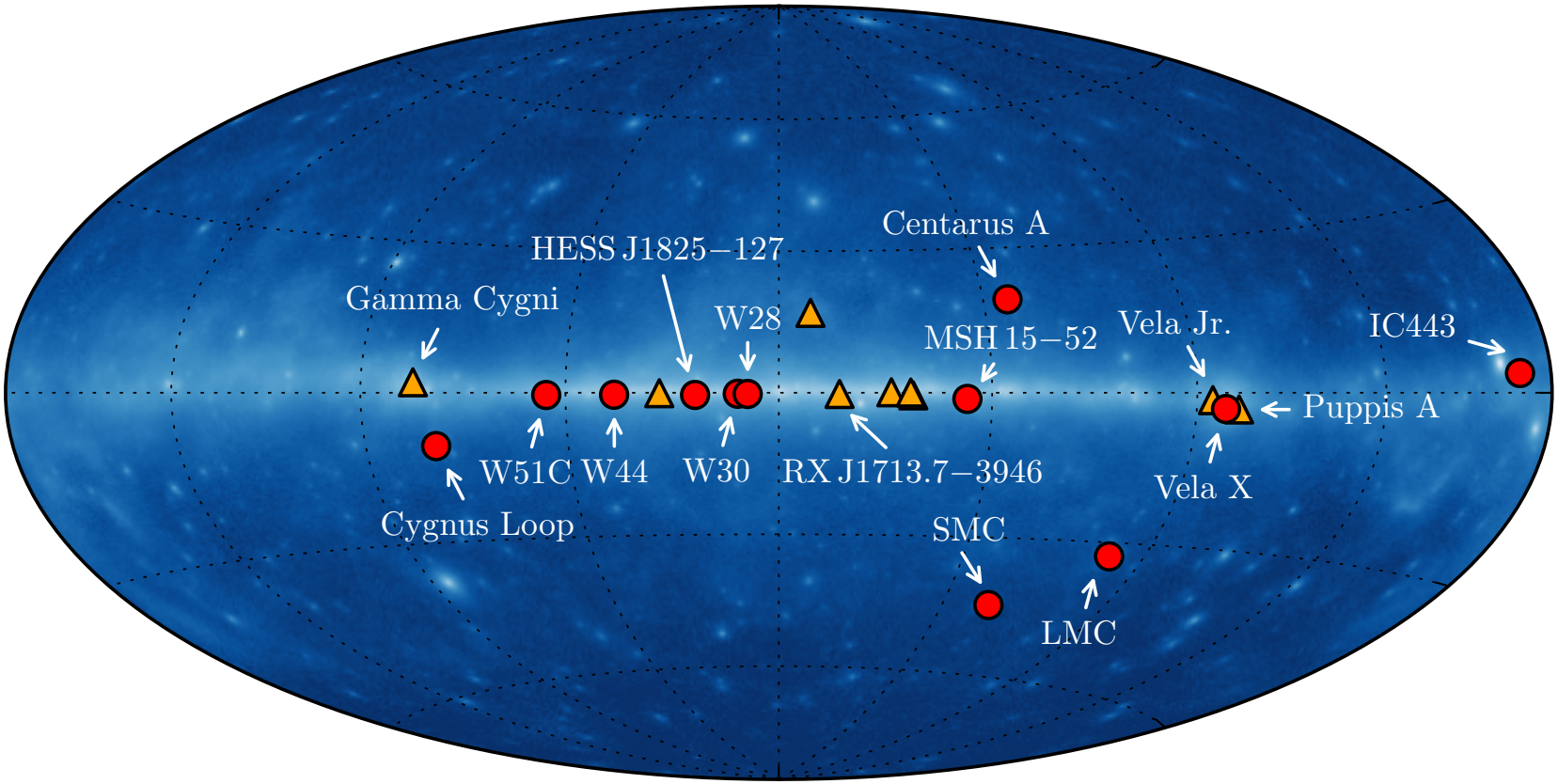
- also: X-ray PWN $\sim 2'$ (Gotthelf & Halpern 2008)
- γ-rays from PWN?
- Second X-ray source AX J1837.3−0652 resolved into point + extended component (no pulsations yet)
- γ-rays from multiple PWN

LAT + H.E.S.S. SEDs

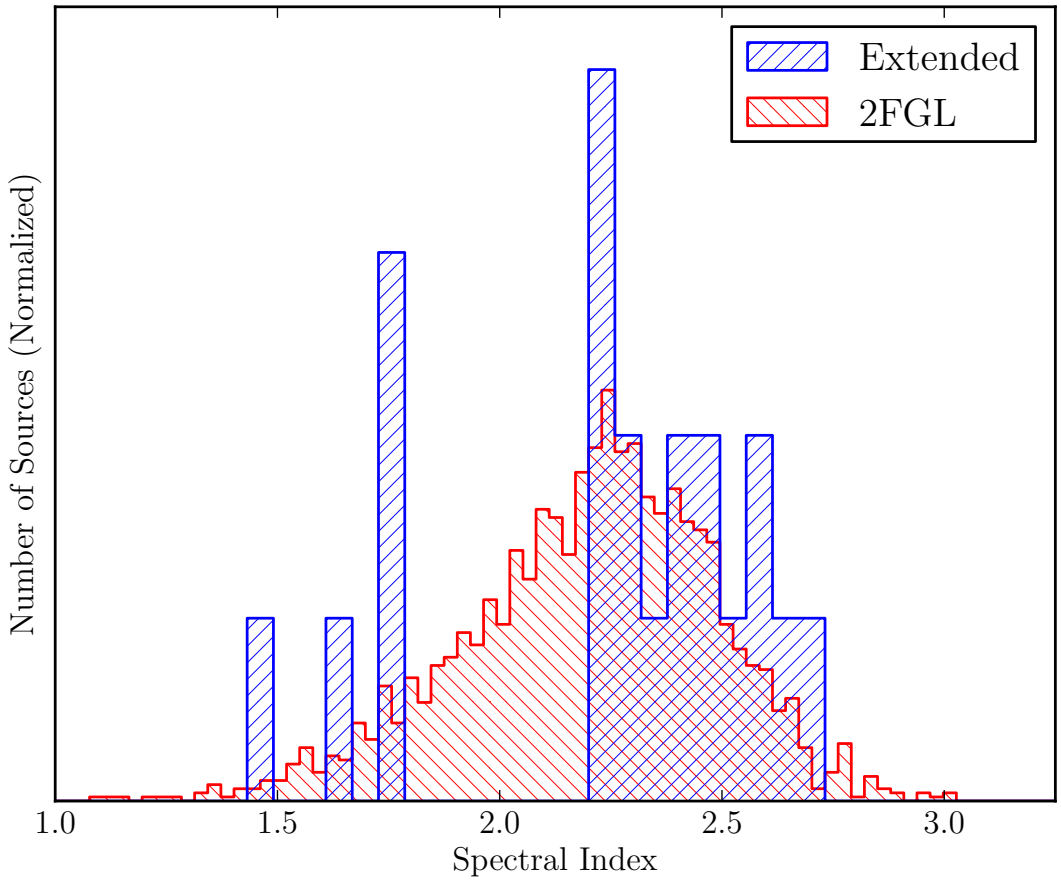


- GeV + TeV spectrum connect for these souces
- (Statistical Errors Only)
- Future work: take SEDs to lower energies

LAT Detected Extended Sources

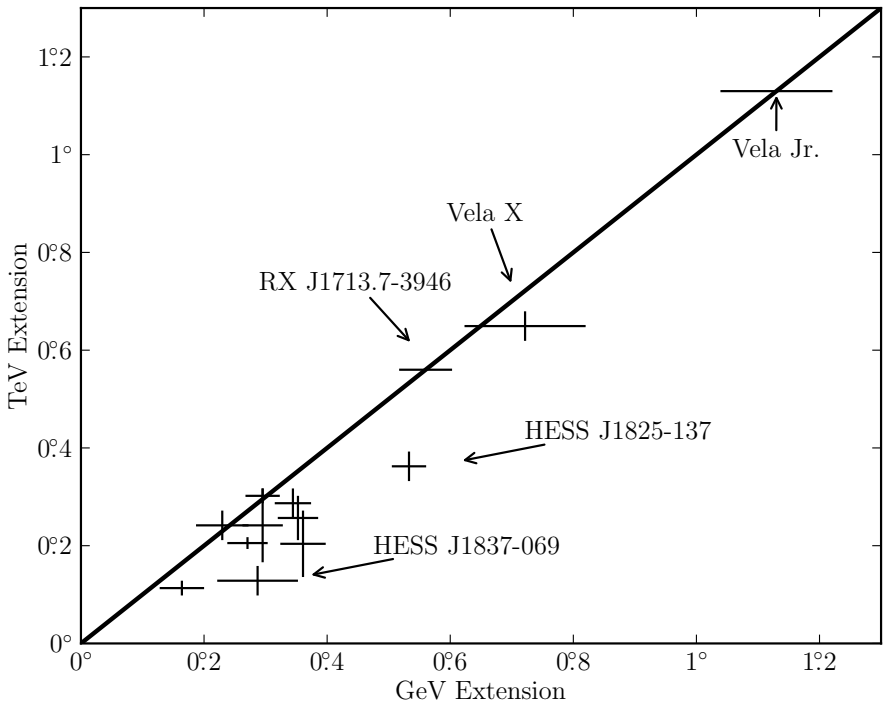


Spectral Index of extended sources



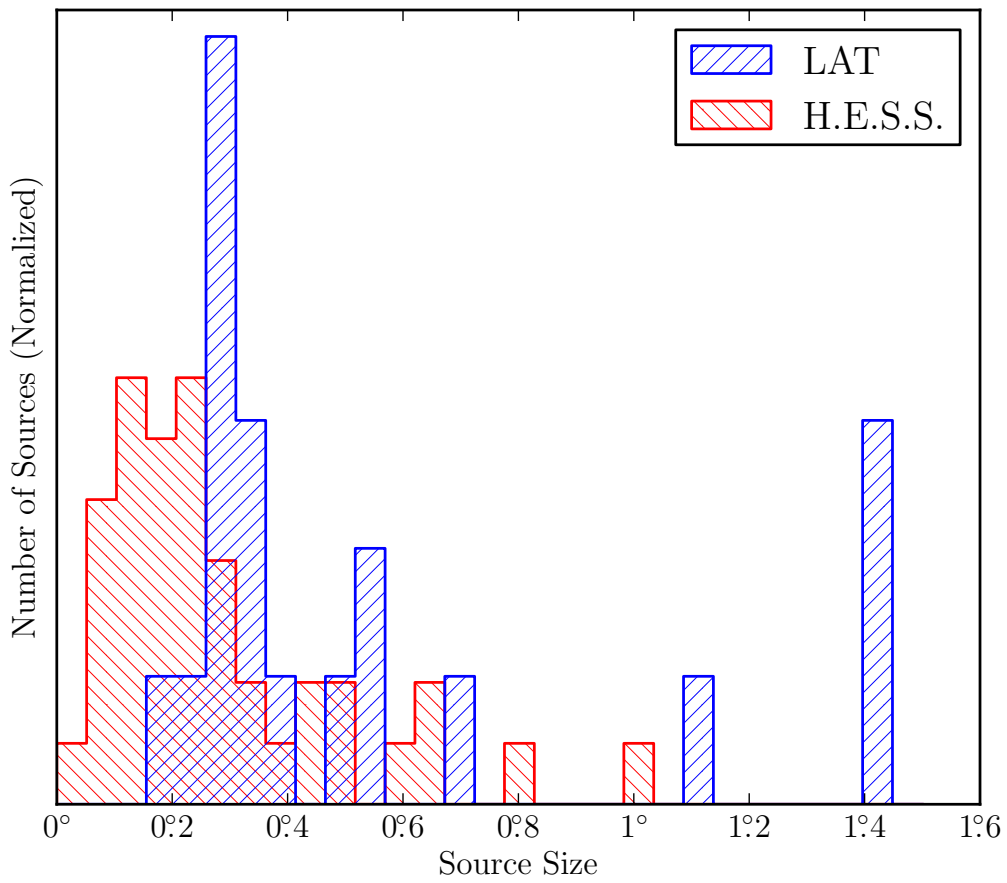
- Compare Index to 2FGL
- Seems like there is roughly a divide between softer SNRs and harder PWN
- Have not quantified

LAT + H.E.S.S. Sizes



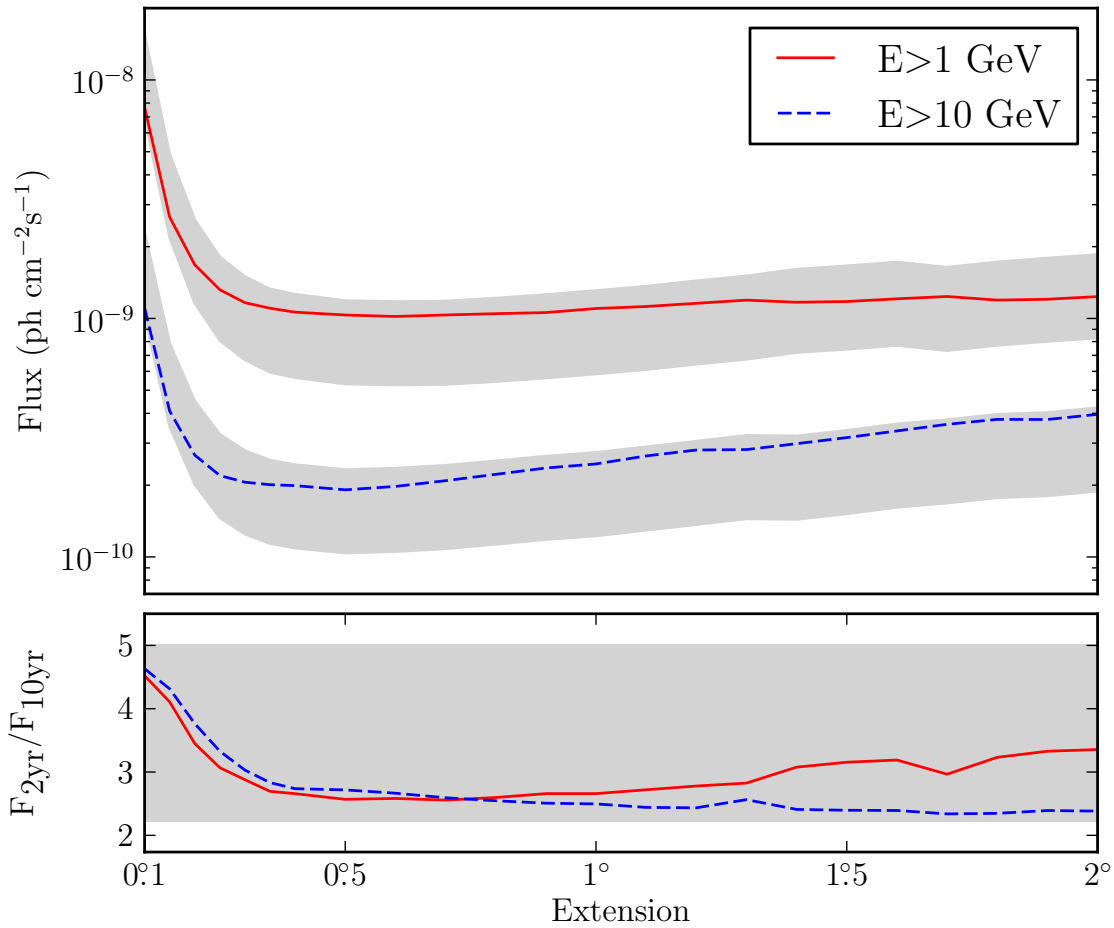
- Compare GeV and TeV sizes
- Generally, good agreement
- HESS J1825−137 significantly larger at GeV than TeV
- Other PWN expected to be larger at GeV than TeV energies, but
- Would require improving systematics on the analysis (source confusion, elliptical spatial models, etc)

LAT + H.E.S.S. Distributions



- Compare GeV and TeV sizes
- LAT detectes larger sources
- H.E.S.S. detects smaller sources
- Population of small TeV extended sources we can't resolve
- Presumably, currently outside our detectability

Sensitivity after 10 years



- Calculate extension threshold with 10 year simulation
- Also, project from 2 year threshold by $\sqrt{time}$ and time
- Sensitivity $> \sqrt{time}$ for small sources
- Many future discoveries!
- Think about putting in senior review