Gamma-Ray Detective Work

Looking for counterparts to unidentified gamma-ray sources

Reshmi Mukherjee

2015 Fermi Summer School

Outline

I. Gamma-ray skymaps

II. Multifrequency strategies for identification

III. Population studies

IV. Other ideas

Some Readings

I. A couple of old reviews, but good introductions to multi -frequency strategies for unidentified gamma-ray sources:

"Multifrequency strategies for identification of unidentified gamma-ray sources," Mukherjee & Halpern, arxiv.org/abs/astro-ph/0408063

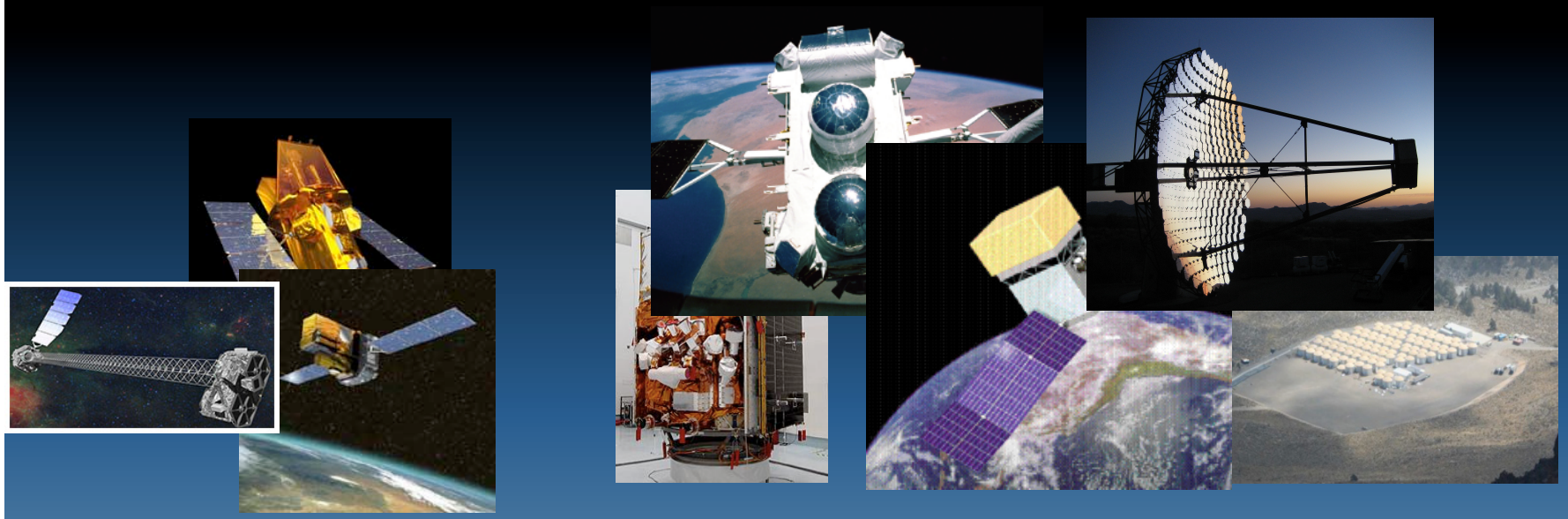
"High-Energy Gamma-ray Sources and the Quest for their IdentificationP.A. Caraveo, XXII Moriond Astrophysics Meeting, arXiv:astro-ph/0206236

II. Book:

Multiwavelength Approach to Unidentified Gamma-Ray SourcesA Second Workshop on the Nature of the High-Energy Unidentified SourcesEditors: K.S. Cheng, G.E. Romero

I. Gamma Ray Sky Maps

High Energy Instruments

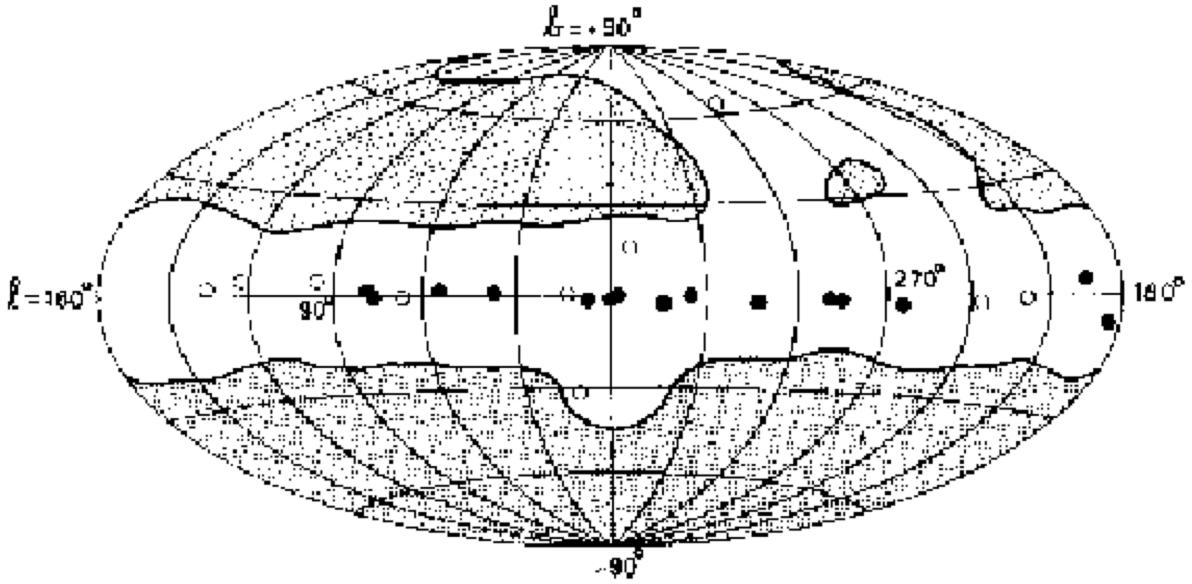


10^{-9} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20} m

100 keV 0.5 MeV 100 TeV

Cos-B Skymap

"Unidentified sources" are objects in the γ-ray sky with no identifications or known counterparts at other wavebands**. Some of the unidentified sources have remained so since the first surveys of the γ-ray sky carried out by the COS-B satellite in the 1970s.

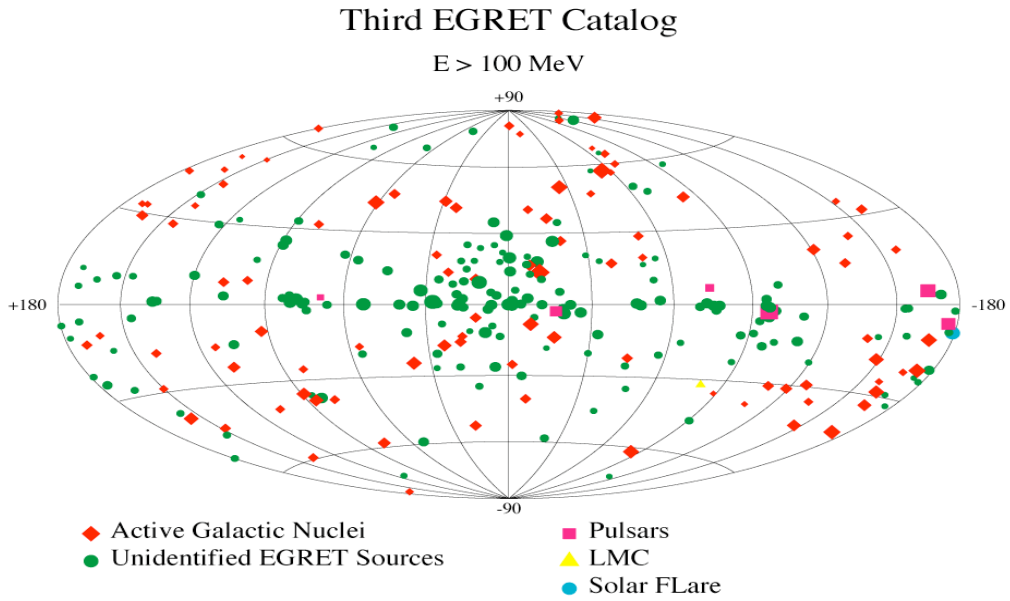


(Swanenburg et al. 1981

Of the total 25 sources detected by COS-B, only the pulsars, Crab and Vela, the molecular cloud ρ-Oph and the first extragalactic source, 3C 273 were identified (Bignami & Hermsen 1983).

EGRET Skymap

Following COS-B, the next major step in γ-ray astronomy came with the launch of the Compton Gamma Ray Observatory (CGRO) in 1991, when the on-board EGRET

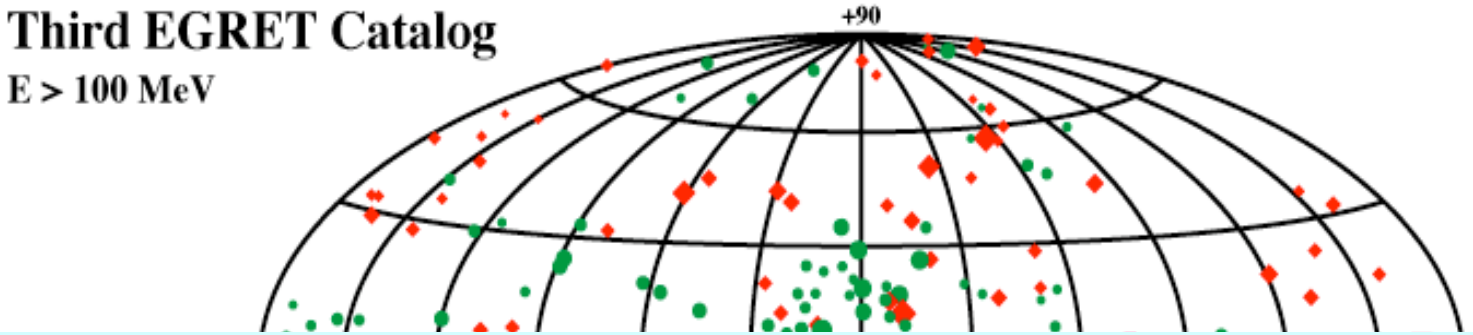


Hartmann et al. adsabs.harvard.edu/abs/1999ApJS..123...79H

Of the 271 point sources detected by EGRET, the majority were unidentified at the end of EGRET's mission. Some of these remained unidentified since COS-B days.

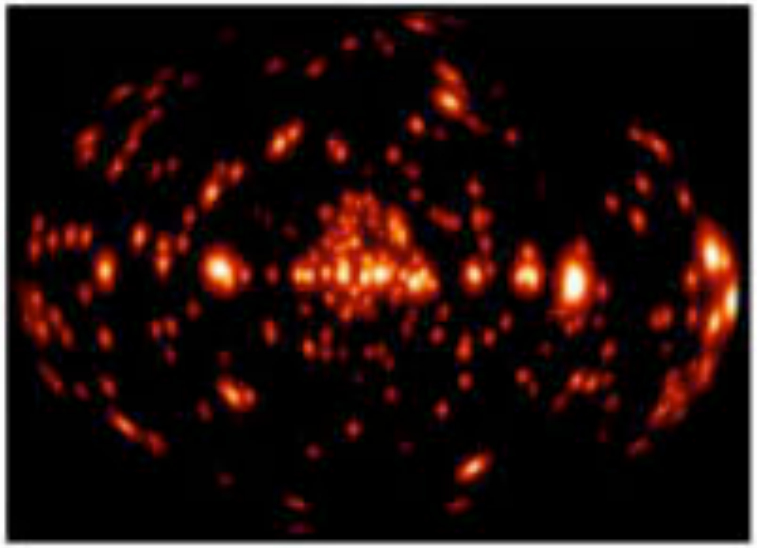
The nature of these unidentified sources was an outstanding mystery in the late 1990s, early 2000s.

A High Energy Enigma



- Error box of typical EGRET source is large ~ 0.5-1^0
- Identification of low-latitude sources hampered by bright Galactic diffuse emission.
- Lack of correlation between γ-ray flux & other frequencies.
- Counterpart searches of γ-ray sources usually start with looking for "more of the same" kinds of sources.
- Principle method of ID: Find positional coincidences between EGRET & flat-spectrum radio sources. Rely on the statistical evidence that blazars are the dominant population.

CGRO's Lingering Mysteries



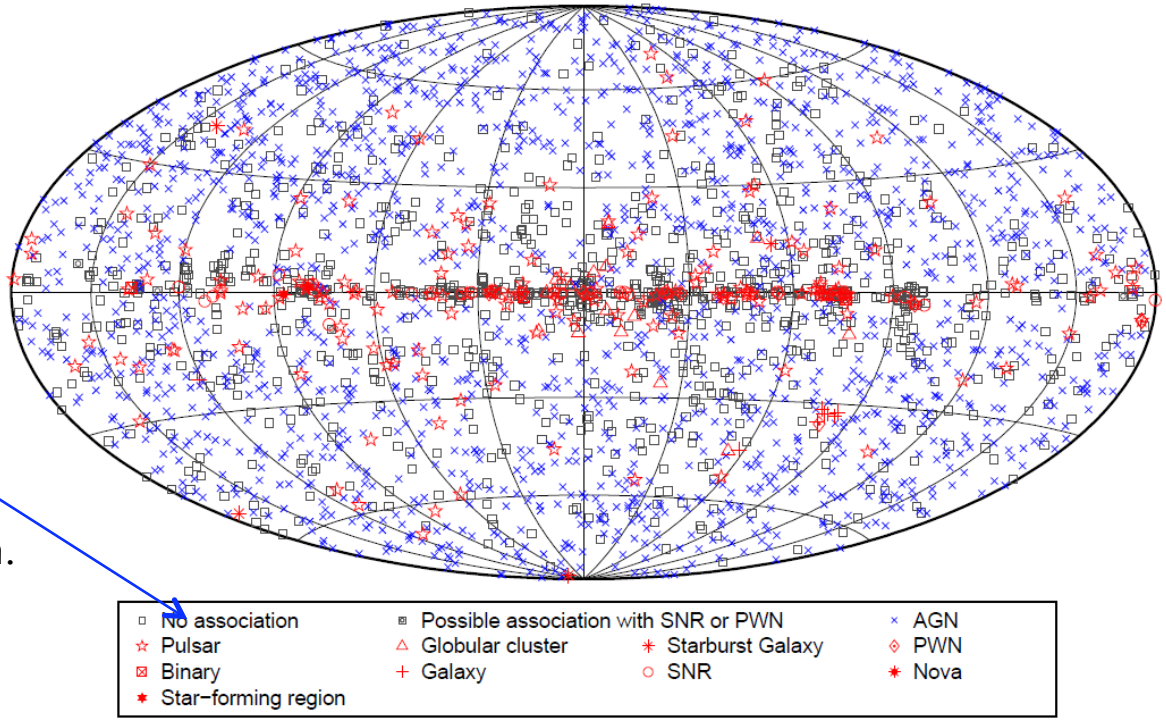
NASA/Honeywell Max Q Digital Group, Angela Cheyunski)

- Extragalactic ones are probably blazar AGNs
- Large fraction lie in a narrow band along the Milky Way plane
  - Star-formation regions surrounding the solar neighborhoods?
  - Geminga-like radio-quiet pulsars?
  - Pulsar wind nebulae?
  - Galactic microquasars?
  - Supernova remnants?
  - "dark accelerators?"

Fermi Catalog

The discovery of point-like high energy sources in the γ-ray sky has been one of the most exciting results in the field of γ-ray astronomy, since the advent of the first satellites in the 1970s.

Many different source classes, but the most enigmatic ones are the ones with no association.

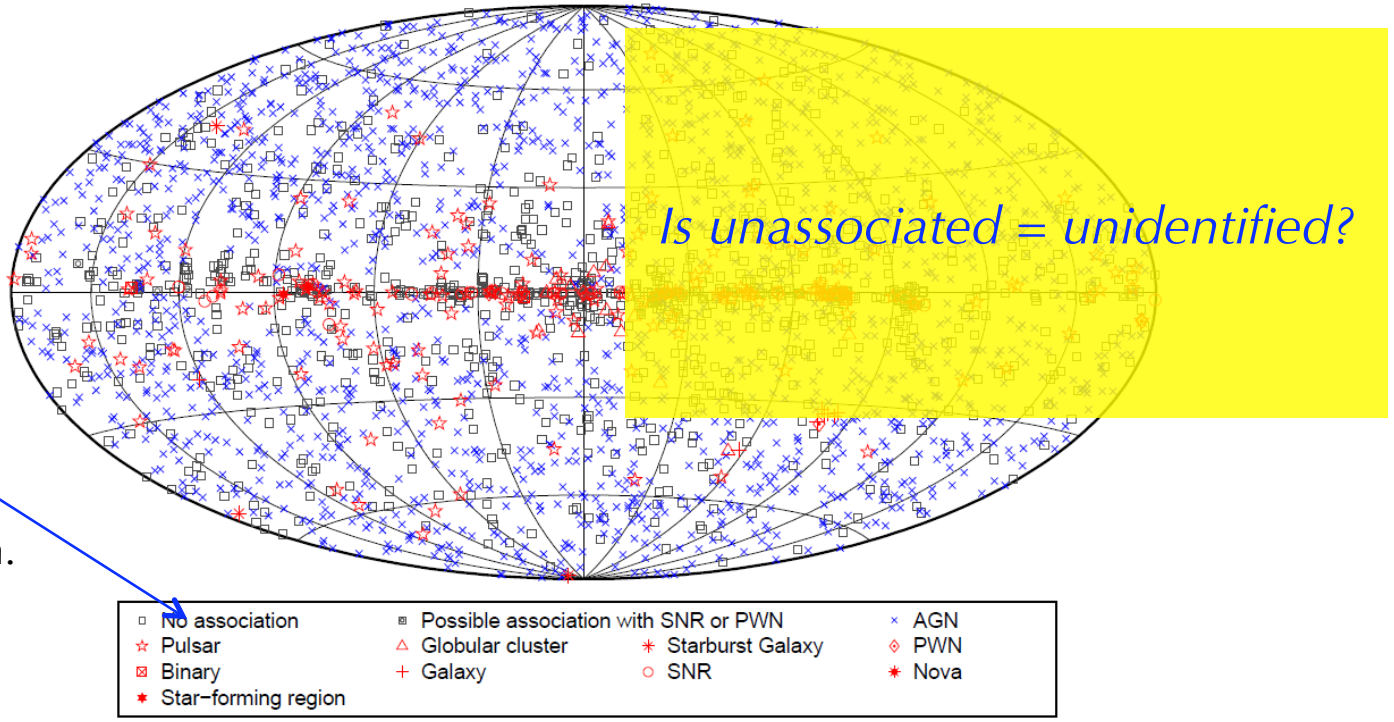


http://arxiv.org/abs/1108.1435

30% of the high-energy gamma-ray sources listed in the second Fermi LA (2FGL) catalog have not yet been associated with counterparts at lower energies.

Fermi Unassociated Sources

The discovery of point-like high energy sources in the γ-ray sky has been one of the most exciting results in the field of γ-ray astronomy, since the advent of the first satellites in the 1970s.



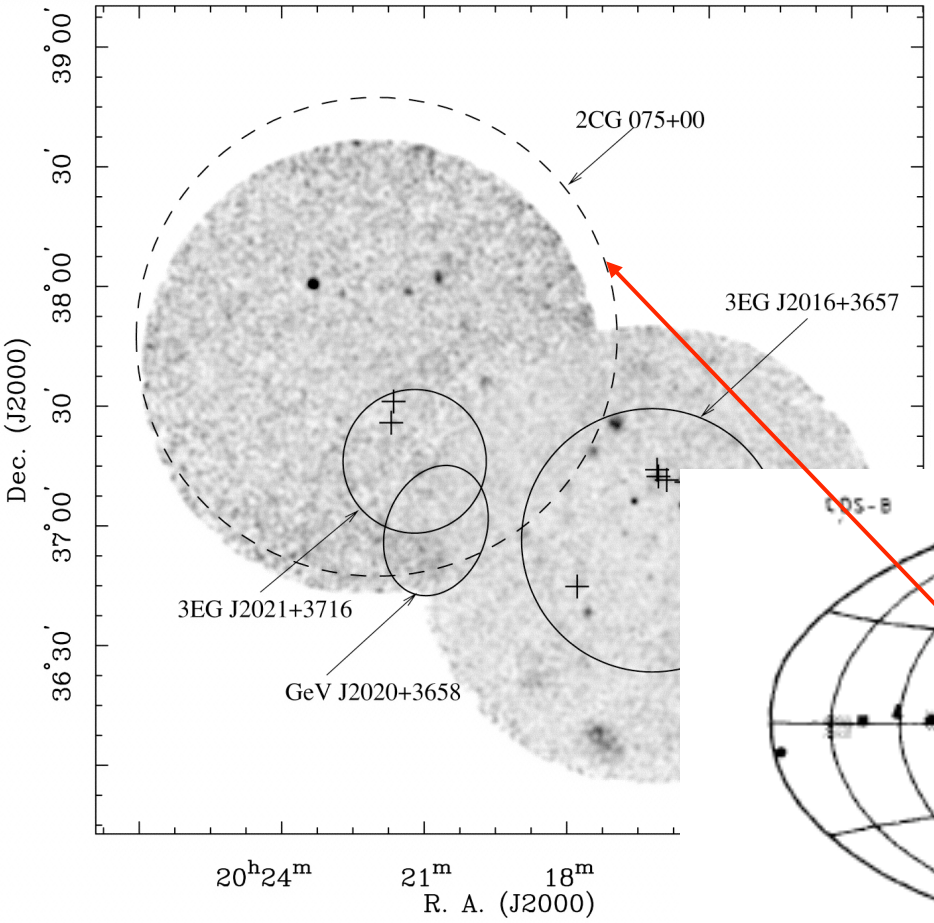
Many different source classes, but the most enigmatic ones are the ones with no association.

30% of the high-energy gamma-ray sources listed in the second Fermi LA (2FGL) catalog have not yet been associated with counterparts at lower energies.

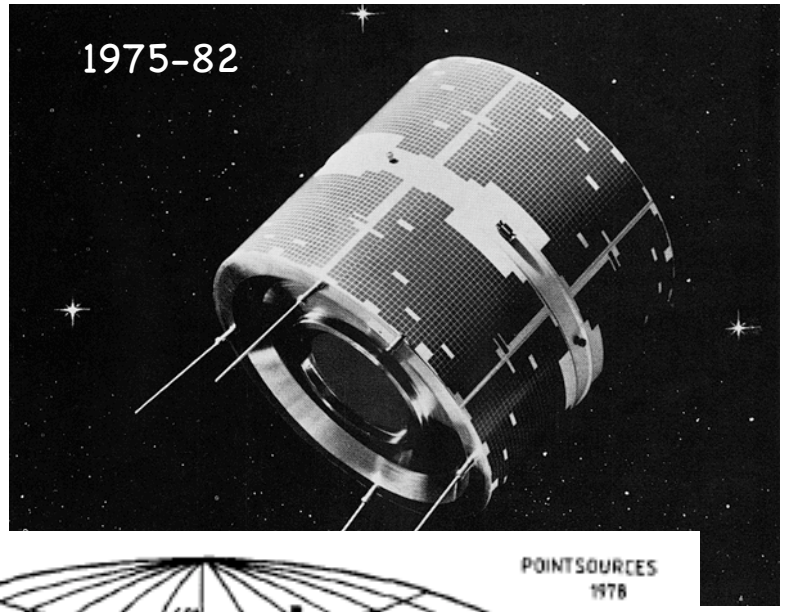
II. Multiwavelength Strategies for Source Identifications

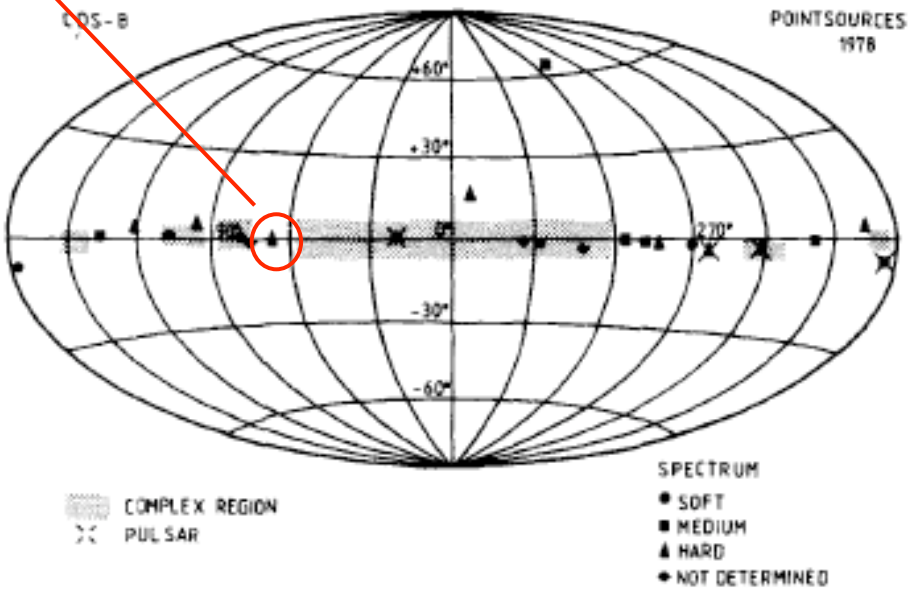
Case 1:The COS-B field: 2CG 075+00

ROSAT PSPC Image of the COS-B Field



(Mukherjee et al. 2000).



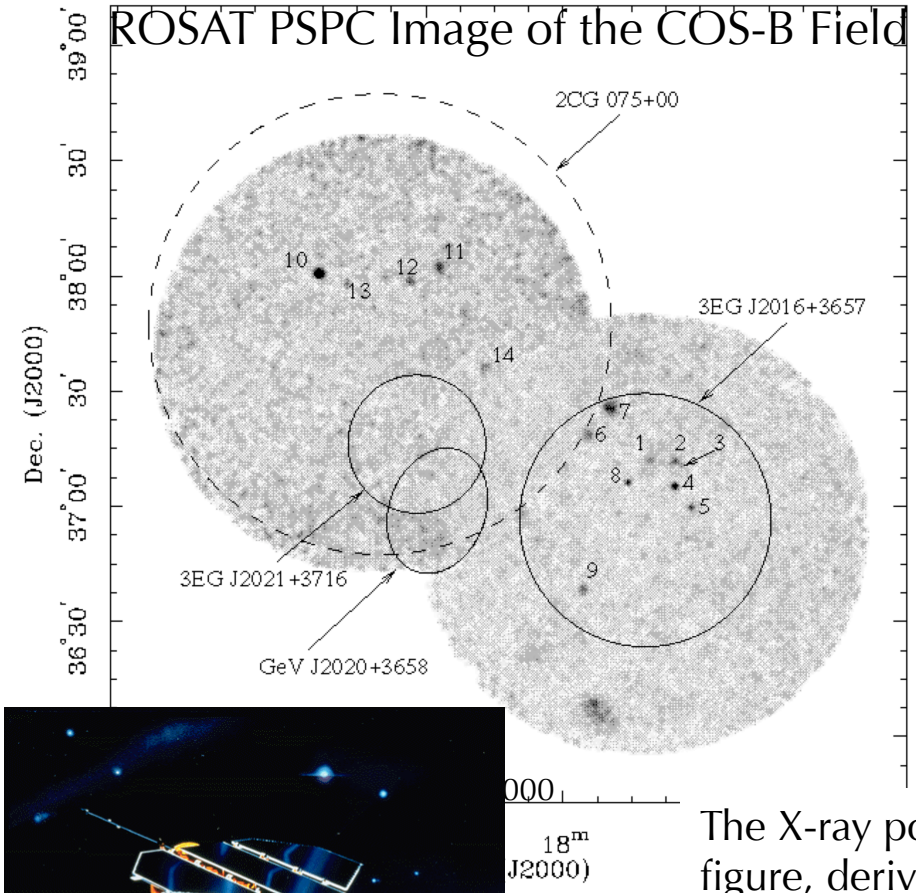


Mayer-Hasselwander et al. 1980

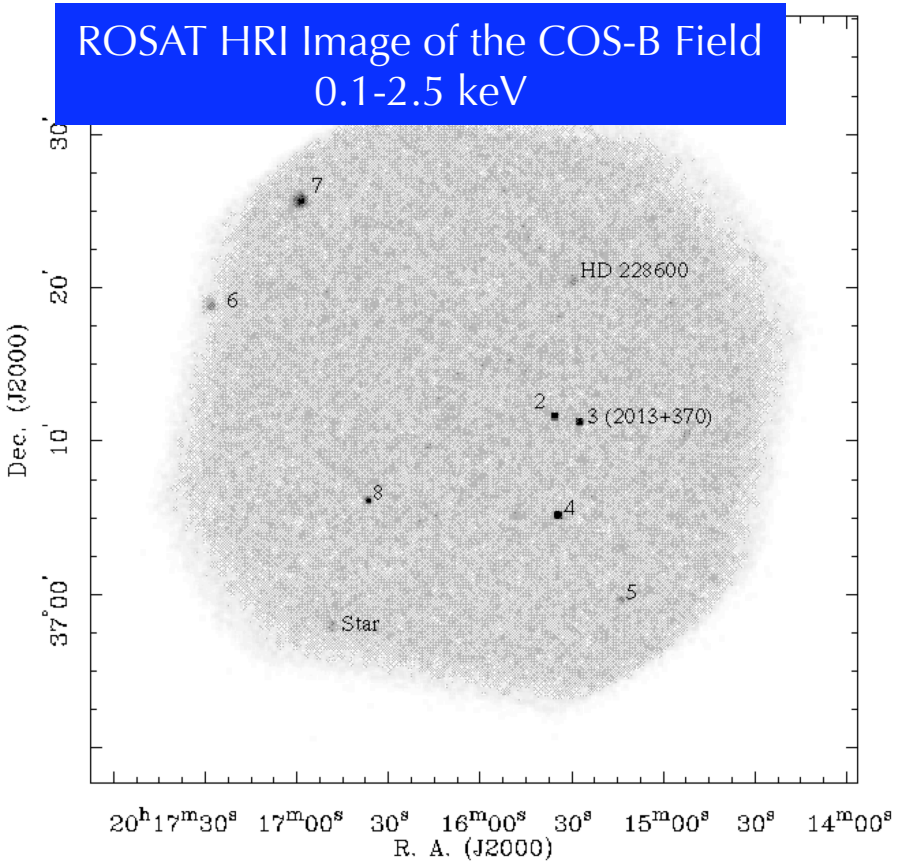
The COS-B field: 2CG 075+00

EGRET: 100 MeV – 10 GeV

ROSAT PSPC Image of the COS-B Field



ROSAT HRI Image of the COS-B Field
0.1-2.5 keV

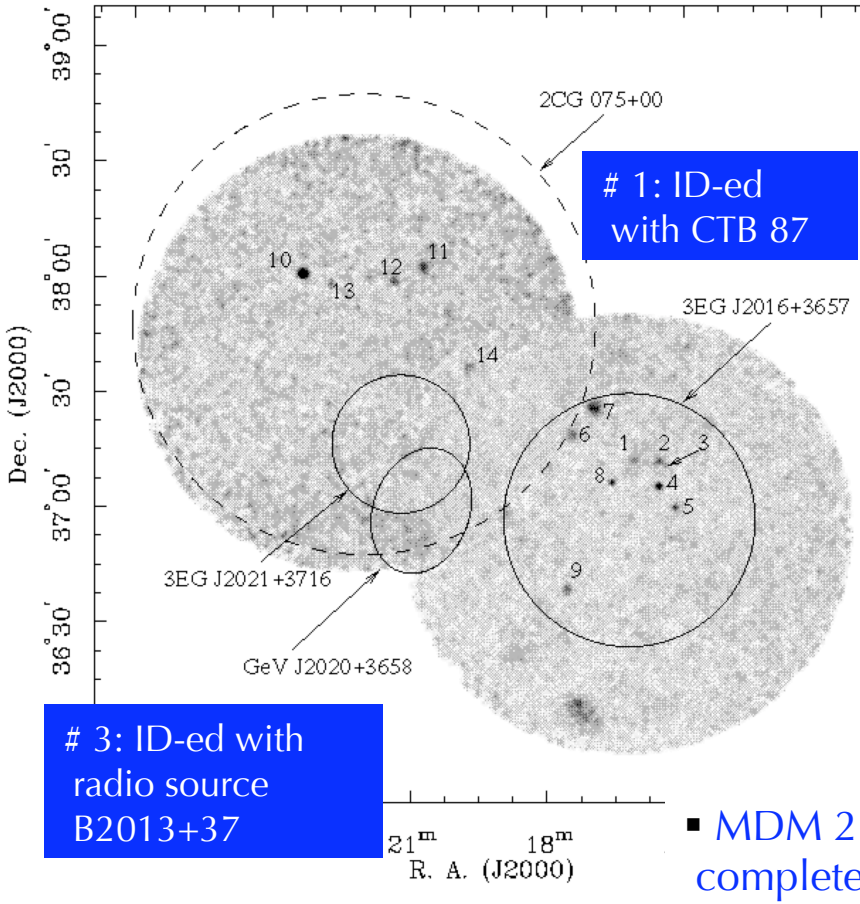


The X-ray point source positions, marked in the figure, derived from the ROSAT analysis were used to search for counterparts to the X-ray sources.

(Mukherjee et al. 2000).

The COS-B field: 2CG 075+00

ROSAT PSPC Image of the COS-B Field

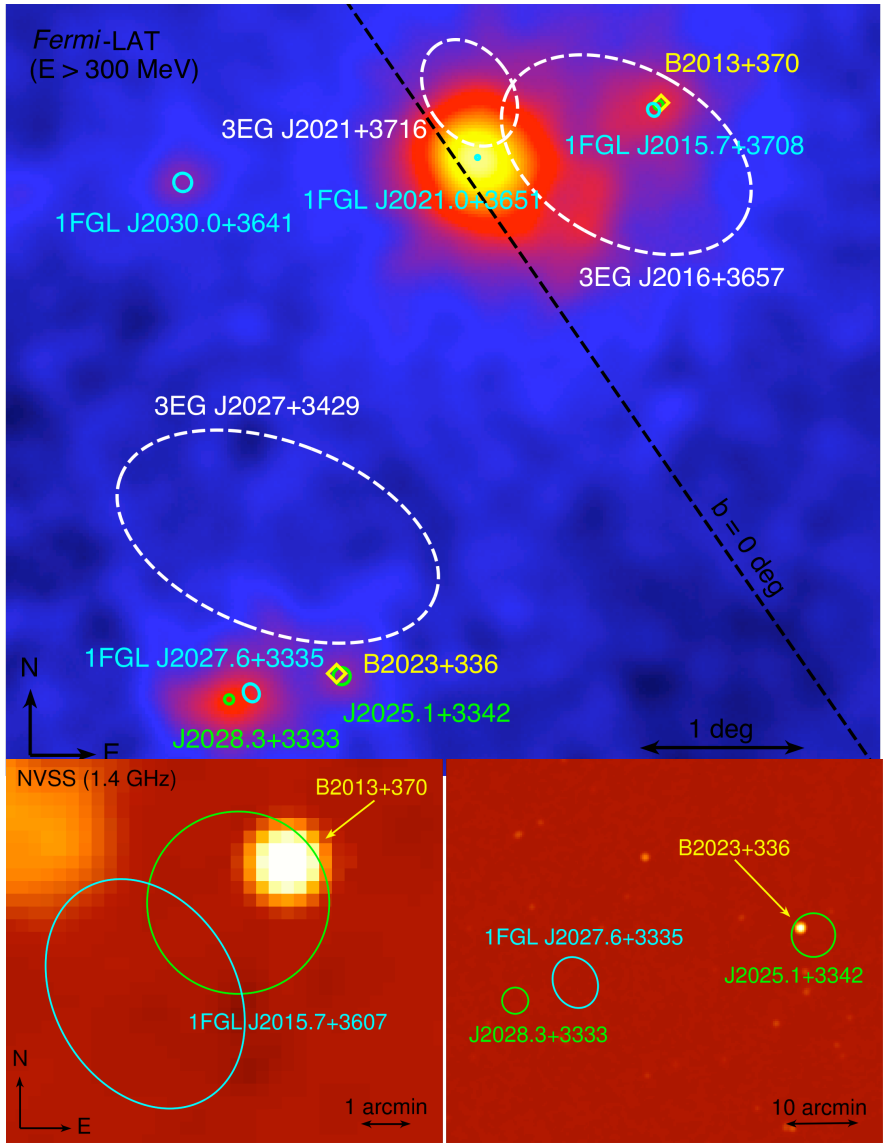


(Halpern et al. 2001).

B2013+370
- Blazar-like characteristics, typical of 3EG IDs
- Compact, extragalactic, non-thermal radio source
- Variable at optical and mm (90 GHz, 142 GHz)
- 5 GHz flux of ~ 2 Jy
- SED of 3EG J2016+3657 characterized by a synchrotron peak at lower energies, IC peak at higher energies. Most power output in γ-rays.

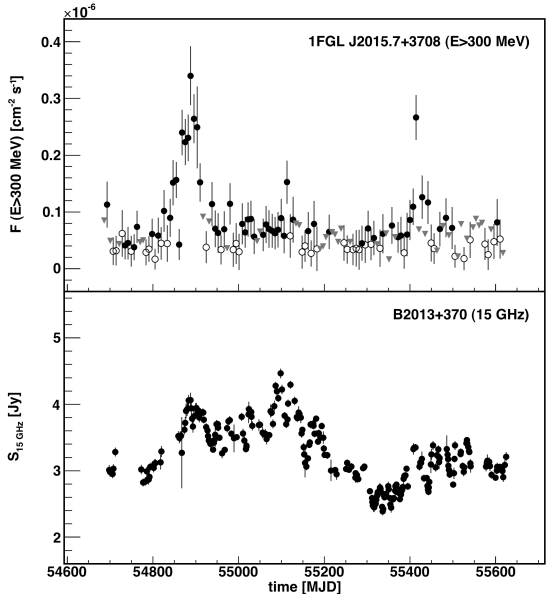
- MDM 2.4 m and KPNO 2.1 m telescopes used to obtain a complete set of optical identifications of all X-ray point sources within error circles of 3EG sources.
- Other than # 1 and # 3, all other sources in the EGRET fields are either cataclysmic variables (CVs), or Wolf-Rayet stars or binary O stars, all unlikely to be γ-ray emitters.

Information from Fermi-LAT

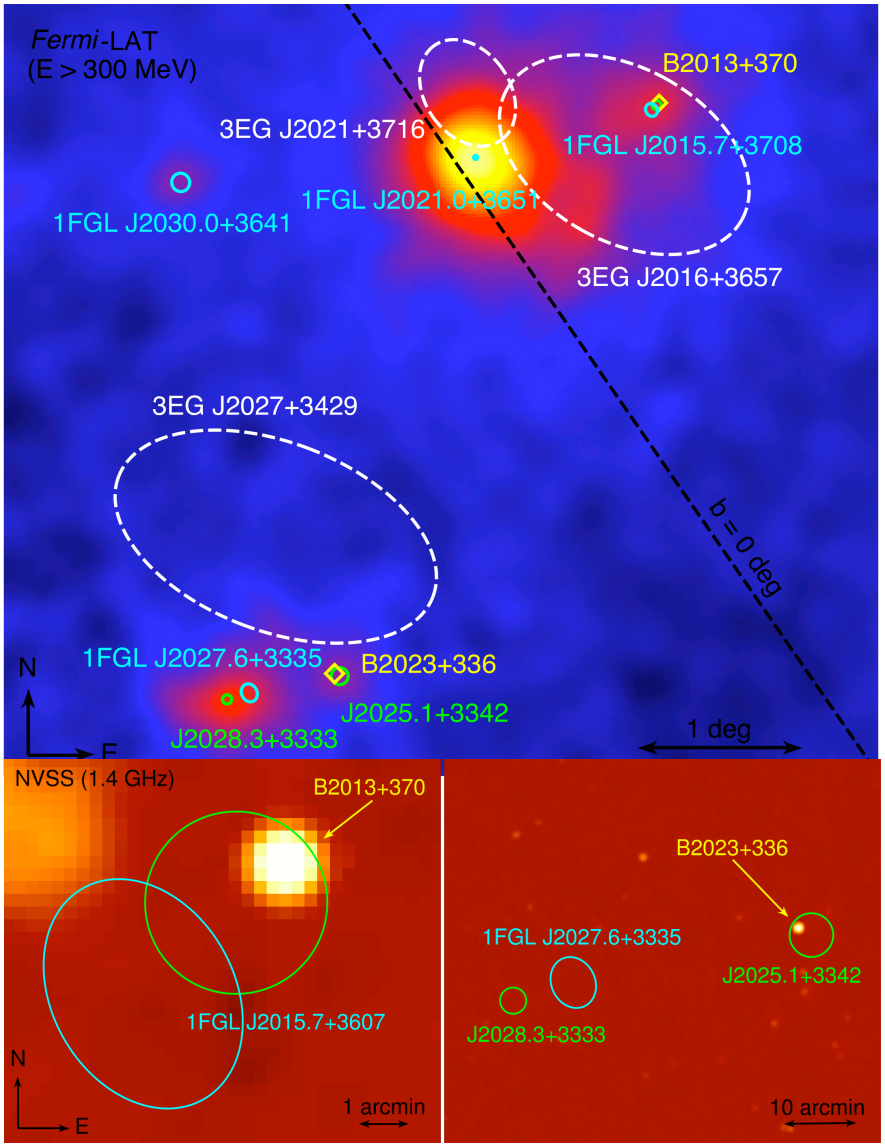


Kara et al. 2011, arXiv:1112.3312

- Firm associations for the blazar B2013+370 established with previously unidentified EGRET and Fermi-LAT source.
- Spatial association and the observed variability in the γ-ray and radio bands allow us to establish a firm association between B2013+370 and the previously unidentified γ-ray source 3EG J2016+3657 (1FGL J2015.7+3708)

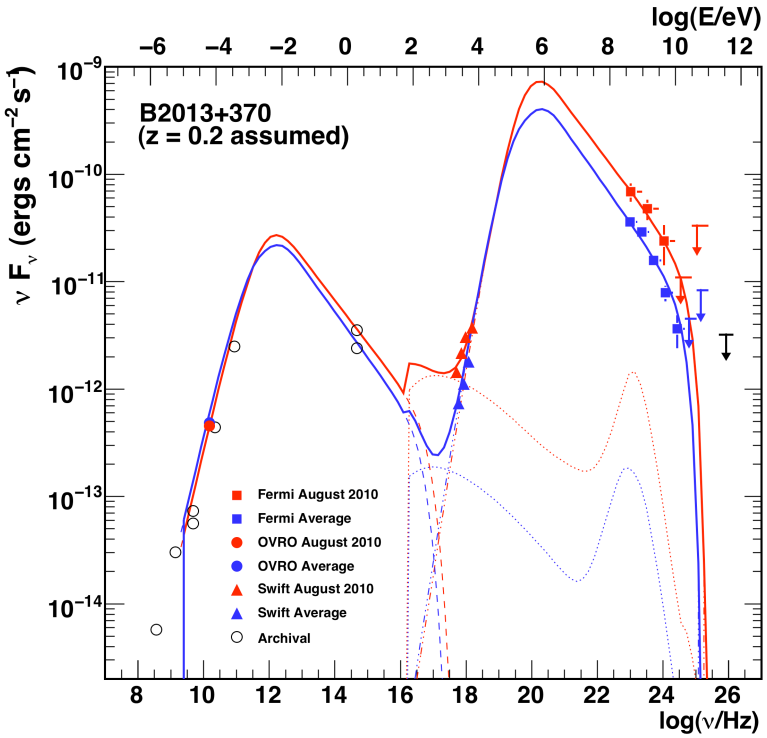


Identification!



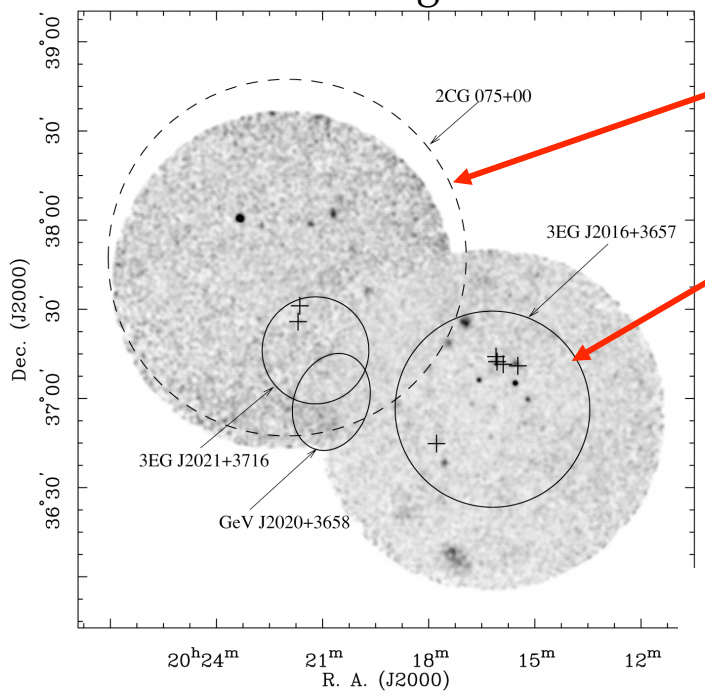
Kara et al. 2011, arXiv:1112.3312

The γ-ray dominated SED, hard X-ray spectrum, and preference for EC models point towards B2013+370 being an LBL or an FSRQ.



The COS-B field: 2CG 075+00

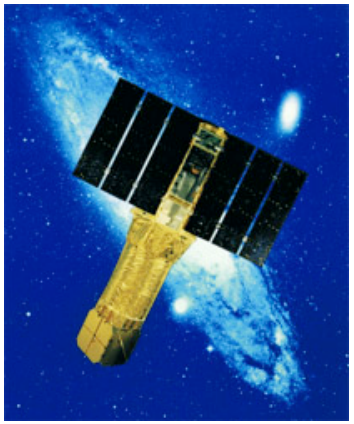
ROSAT PSPC Image of the COS-B Field



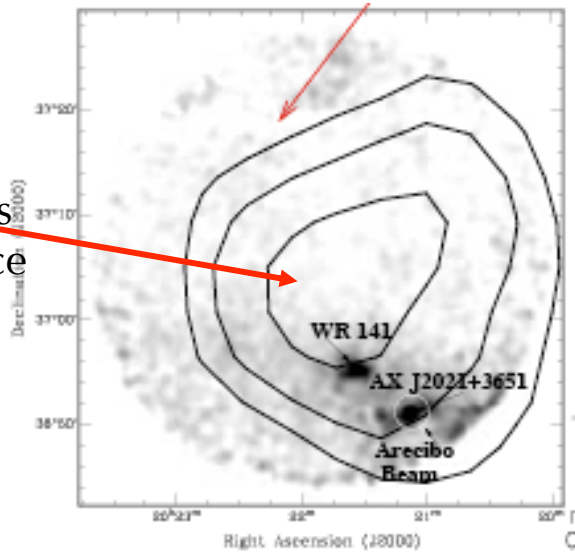
Unidentified, since COS-B times

EGRET source 3EG J2016+3657: Probably a blazar behind the Galactic plane.

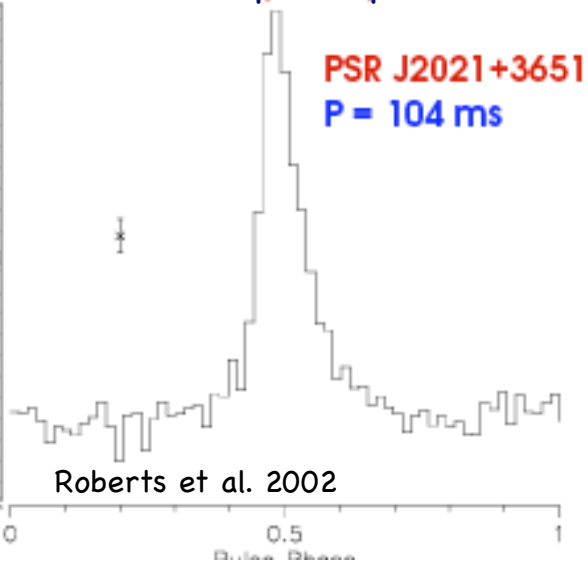
New observations with Arecibo radio telescope led to the discovery of a young & energetic pulsar: PSR J2021+3651 = AX J2021+3651 = ?3EG J2021+3716 = 2CG 075+00



ASCA image shows a hard X-ray source AX J2021+3651 plus a WR star.



1.4 GHz pulse profile

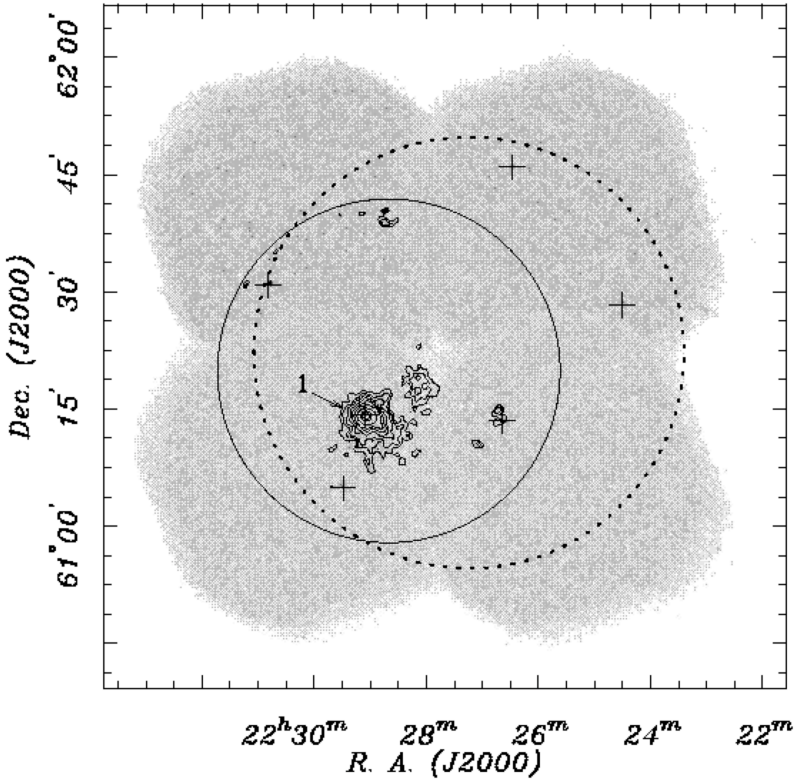


Roberts et al. 2002

Case 2: The case of 3EG J2227+6122

- 3EG J2227+6122 unidentified source at low Galactic latitude
- X-ray, radio, and optical observations of the EGRET field together point to the possibility that 3EG J2227+6122 is most likely a young, energetic pulsar, with an associated X-ray pulsar wind nebula (PWN), enclosed in a small non -thermal radio shell.

Halpern et al. 2001

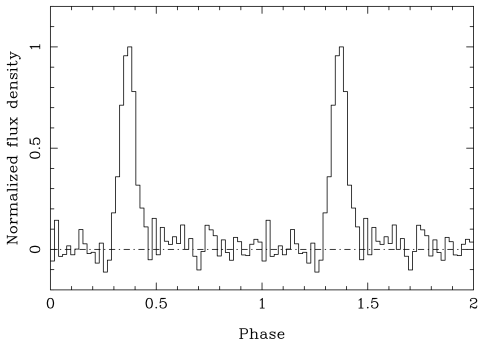


Composite ROSAT HRI image of the 3EG J2227+6122. Except for #1, all the X-ray point sources (plus signs) are bright stars.
#1 is the only unidentified HRI source, and is coincident with a bright, hard source seen in the ASCA GIS image (contours).

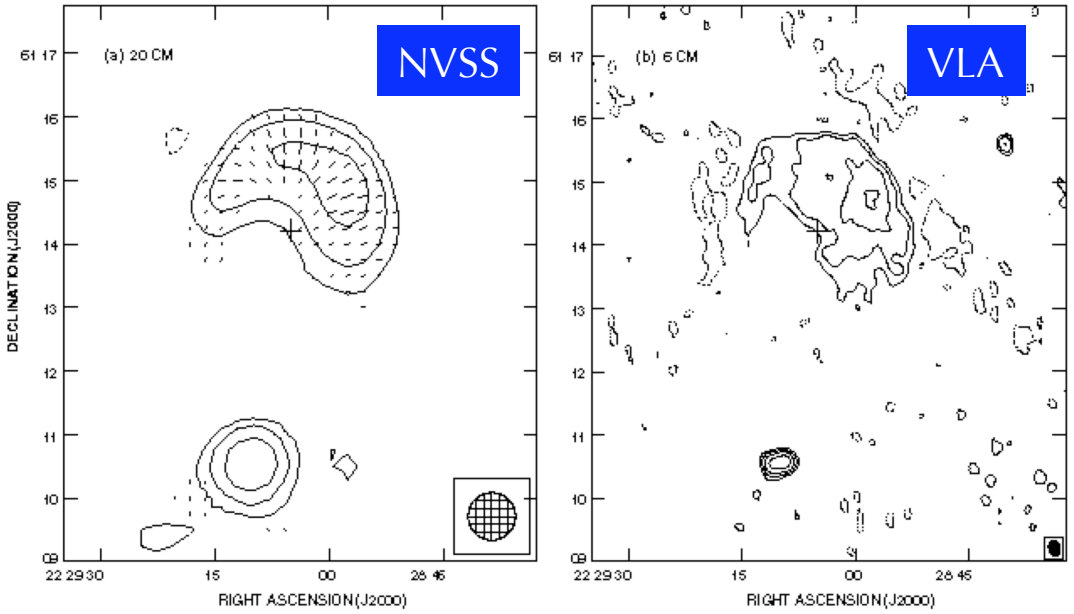
The case of 3EG J2227+6122

- 3EG J2227+6122 found to be = RX/AX J2229.0+6114 = VLA J2229.0+6114
- Radio source VLA J2229.0+6114 has an incomplete circular shell-like structure, with a high degree of linear polarization evident throughout the shell
- X-ray pulsations detected with a period of 51.6 ms from RX/AX J2229.0+6114
- Morphology, together with the non-thermal spectrum of the X-ray nebula indicates a "composite" supernova remnant = G106.6+2.9
- 3EG J2227+6122 = young and energetic 51.6 ms X-ray/radio pulsar PSR J2229+6114. Confirmed by Fermi-LAT

Halpern et al. 2001

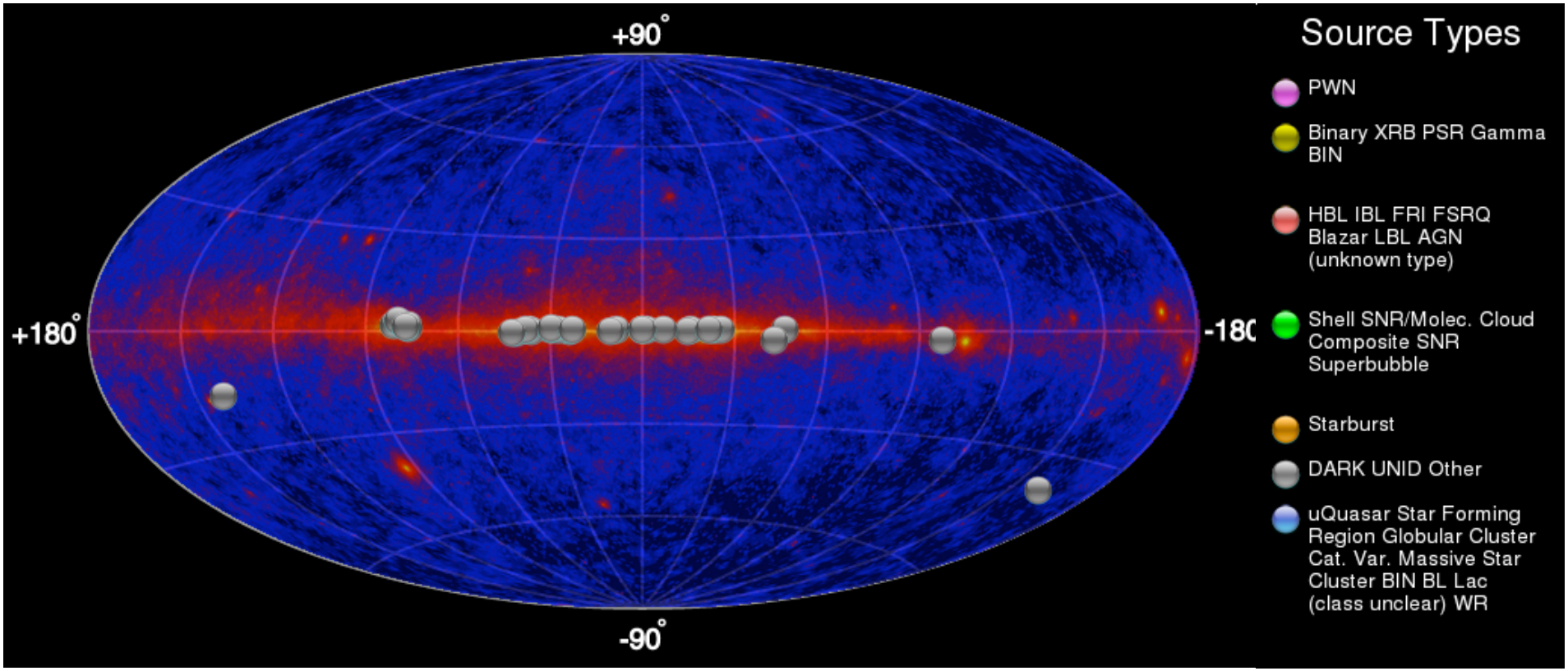


Radio pulse profile of PSR J2229+6114 at 1412 MHz observed with the Lovell radio telescope at Jodrell Bank



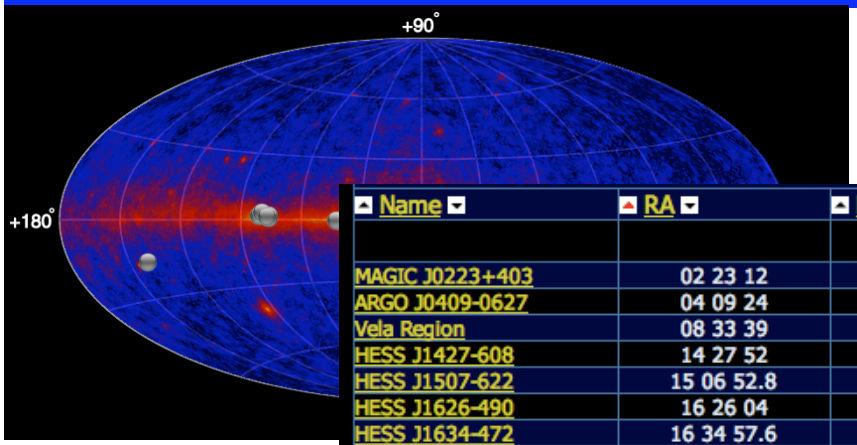
V. TeV Unidentified Sources

The Unidentified TeV Sky



TeV sources with no known counterparts overlaid on the Fermi-LAT skymap
cite: TeVCat

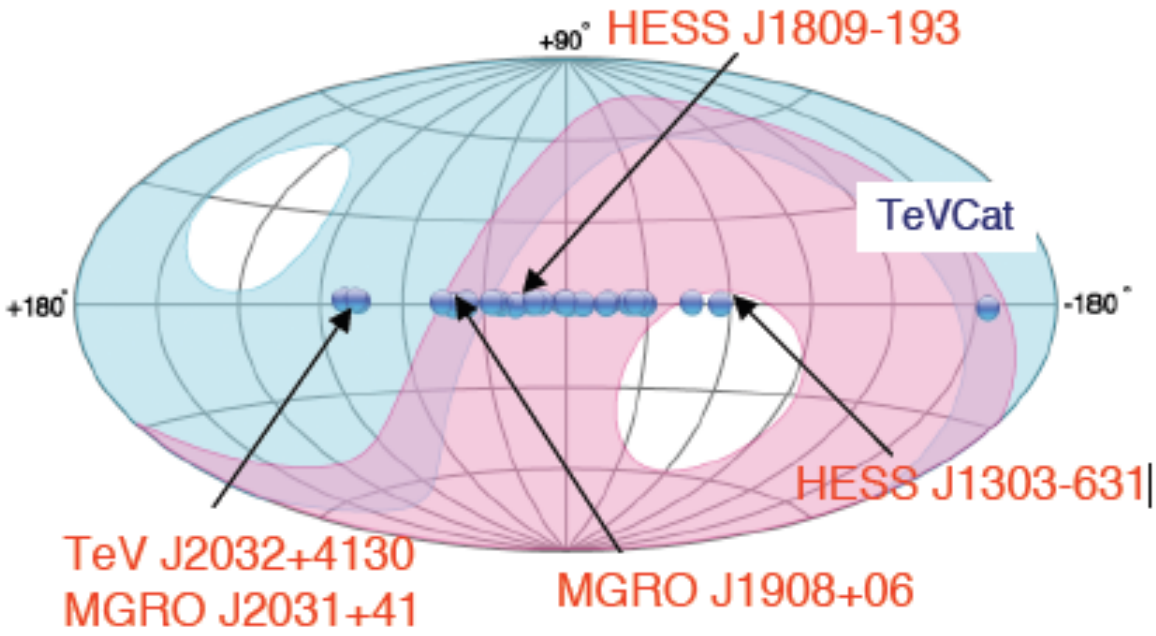
The Unidentified TeV Sky



Name	RA	Dec	Type	Date	Dist	Catalog
			UNID			...
MAGIC J0223+403	02 23 12	+43 00 42	UNID	2009.02		Default Catalog
ARGO J0409-0627	04 09 24	-06 27 00	UNID	2013.11		Source Candidates
Vela Region	08 33 39	-45 00 10	UNID	1997.09		Other Sources
HESS J1427-608	14 27 52	-60 51 00	UNID	2007.07		Default Catalog
HESS J1507-622	15 06 52.8	-62 21 00.0	UNID	2009.12		Default Catalog
HESS J1626-490	16 26 04	-49 05 13	UNID	2007.07		Default Catalog
HESS J1634-472	16 34 57.6	-47 16 12	UNID	2006.01	8.6 kpc	Default Catalog
HESS J1641-463	16 41 01.7	-46 18 11	UNID	2012.10		Newly Announced
HESS J1702-420	17 02 44	-42 00 57	UNID	2006.01		Default Catalog
HESS J1708-410	17 08 24	-41 05 24	UNID	2006.01		Default Catalog
HESS J1729-345	17 29 35	-34 32 22	UNID	2011.05		Default Catalog
HESS J1741-302	17 41 00	-30 12 00	UNID	2008.07		Newly Announced
Galactic Centre Ridge	17 45 39.6	-29 00 22	UNID	2006.02	8.5 kpc	Default Catalog
Galactic Centre	17 45 39.6	-29 00 22	UNID	2004.05	8.5 kpc	Default Catalog
HESS J1804-216	18 04 31.2	-21 41 60	UNID	2005.03	6 kpc	Default Catalog
HESS J1808-204	18 08 36.24	-20 26 44.9	UNID	2012.07		Newly Announced
HESS J1832-093	18 32 50	-09 22 36	UNID	2011.10		Default Catalog
HESS J1834-087	18 34 45.6	-08 45 36	UNID	2005.03	4 kpc	Default Catalog
HESS J1841-055	18 40 55	-05 33 00	UNID	2007.07		Default Catalog
HESS J1843-033	18 43 00	-03 18 00	UNID	2008.07		Newly Announced
0FGL J1844.1-0335	18 44 08.87	-03 35 21.4	UNID	2009.04		Source Candidates
HESS J1857+026	18 57 11	+02 40 00	UNID	2007.07		Default Catalog
HESS J1858+020	18 58 20	+02 05 24	UNID	2007.07		Default Catalog
0FGL J1900.0+0356	19 00 02.21	+03 56 48.3	UNID	2009.04		Source Candidates
MGRO J1908+06	19 07 54	+06 16 07	UNID	2007.08		Default Catalog
ARGO J1910+0720	19 10 36	+07 21 00	UNID	2013.11		Source Candidates
VER J2016+371	20 16 02	37 11 52	UNID	2011.08		Default Catalog
VER J2019+368	20 19 25	+36 48 14	UNID	2014.04		Default Catalog
MilagroDiffuse	20 20 00	+38 00 00	UNID	2005.12		Default Catalog
VER J2019+407	20 20 04.8	+40 45 26	UNID	2009.11		Default Catalog
MGRO J2031+41	20 28 43.2	+41 18 36	UNID	2007.08		Default Catalog

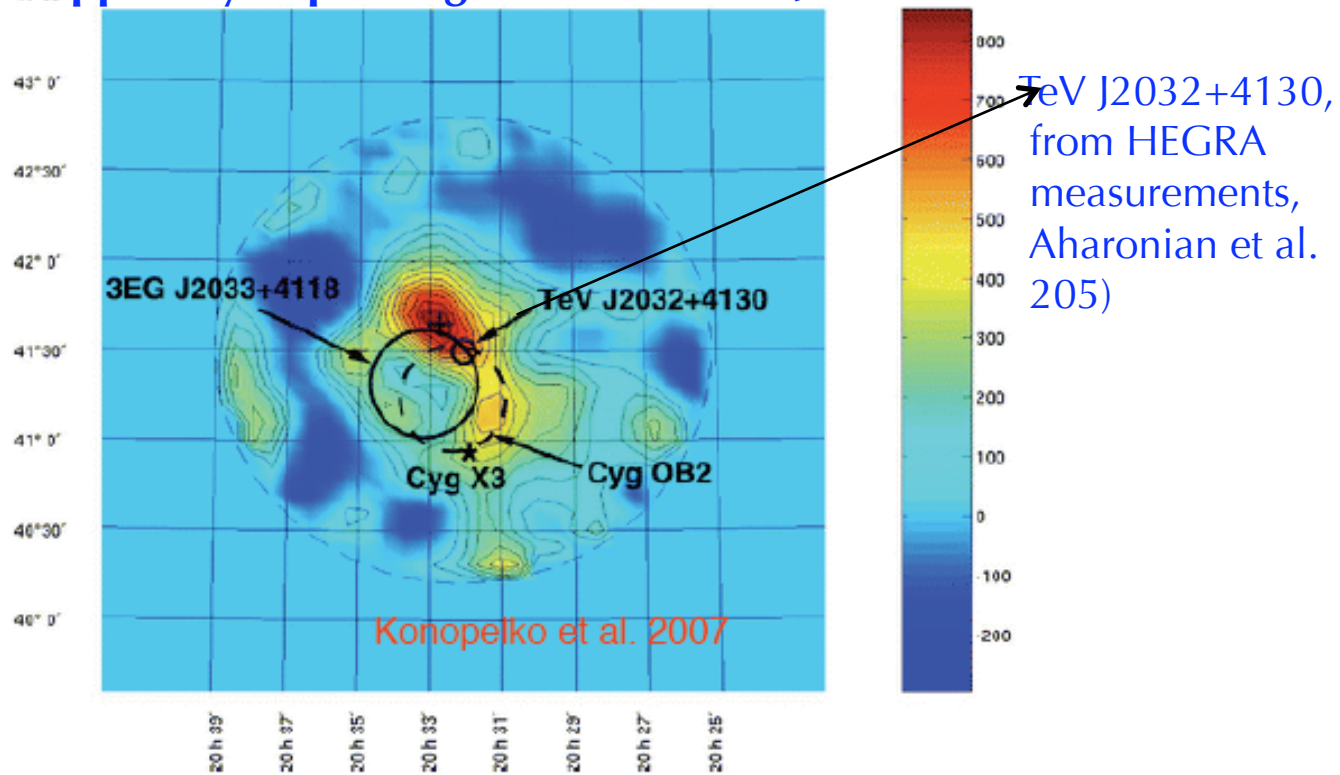
TeV Sources with no Counterparts: *Dark Accelerators*?

- TeV sources with no counterparts.
- All extended?
- May not be "Dark" -- at the limit of X-ray surveys, hadronic sources, new source class?
- Deeper X-ray observations and/or new information may reveal counterparts.



Case 1: The First Unidentified TeV Source

Whipple Skymap of region around TeV J2032+4130

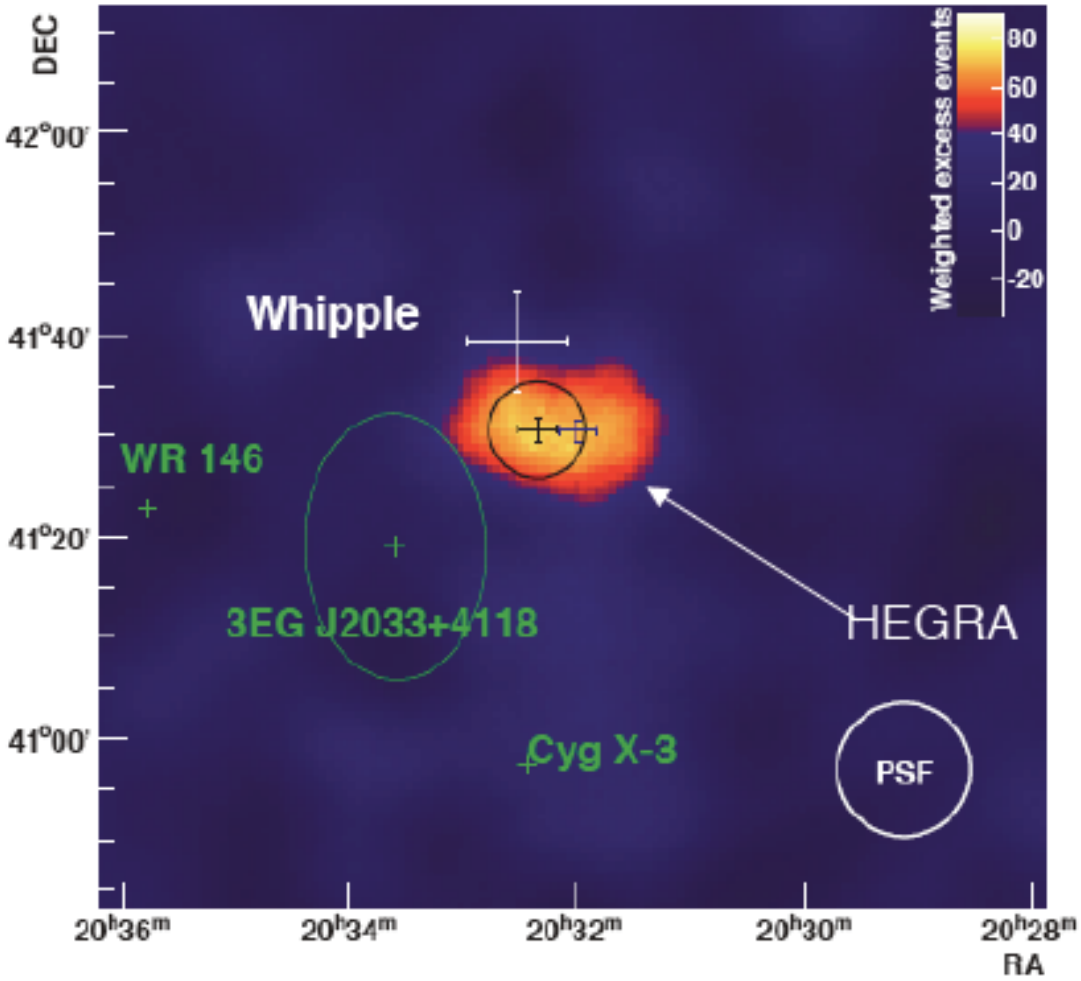


TeV J2032+4130, from HEGRA measurements, Aharonian et al. 205)

TeV J2032+4130 was the first unidentified source discovered at very high energies, reported by HEGRA (E>100 GeV), with no obvious counterpart in any other wavelength.

It is also the first extended source to be observed in VHE gamma rays.

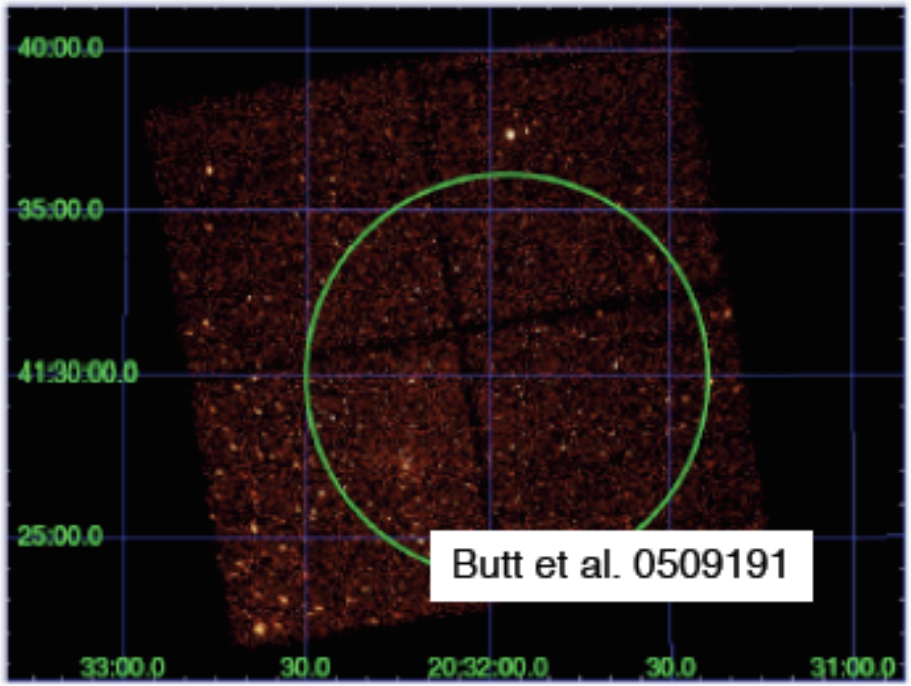
TeV J2032+4130 – Early Studies

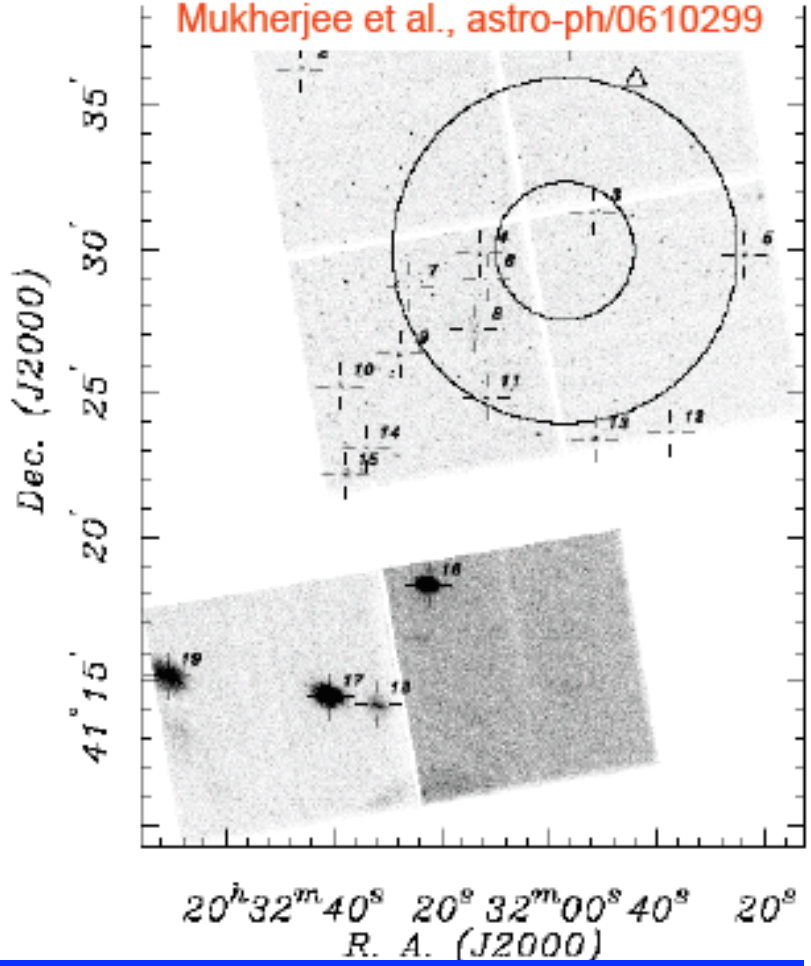


E> 500 GeV
extended source
Albert et al. 2008

MAGIC Skymap of region around TeV J2032+4130

TeV J2032+4130 – Search in X-rays



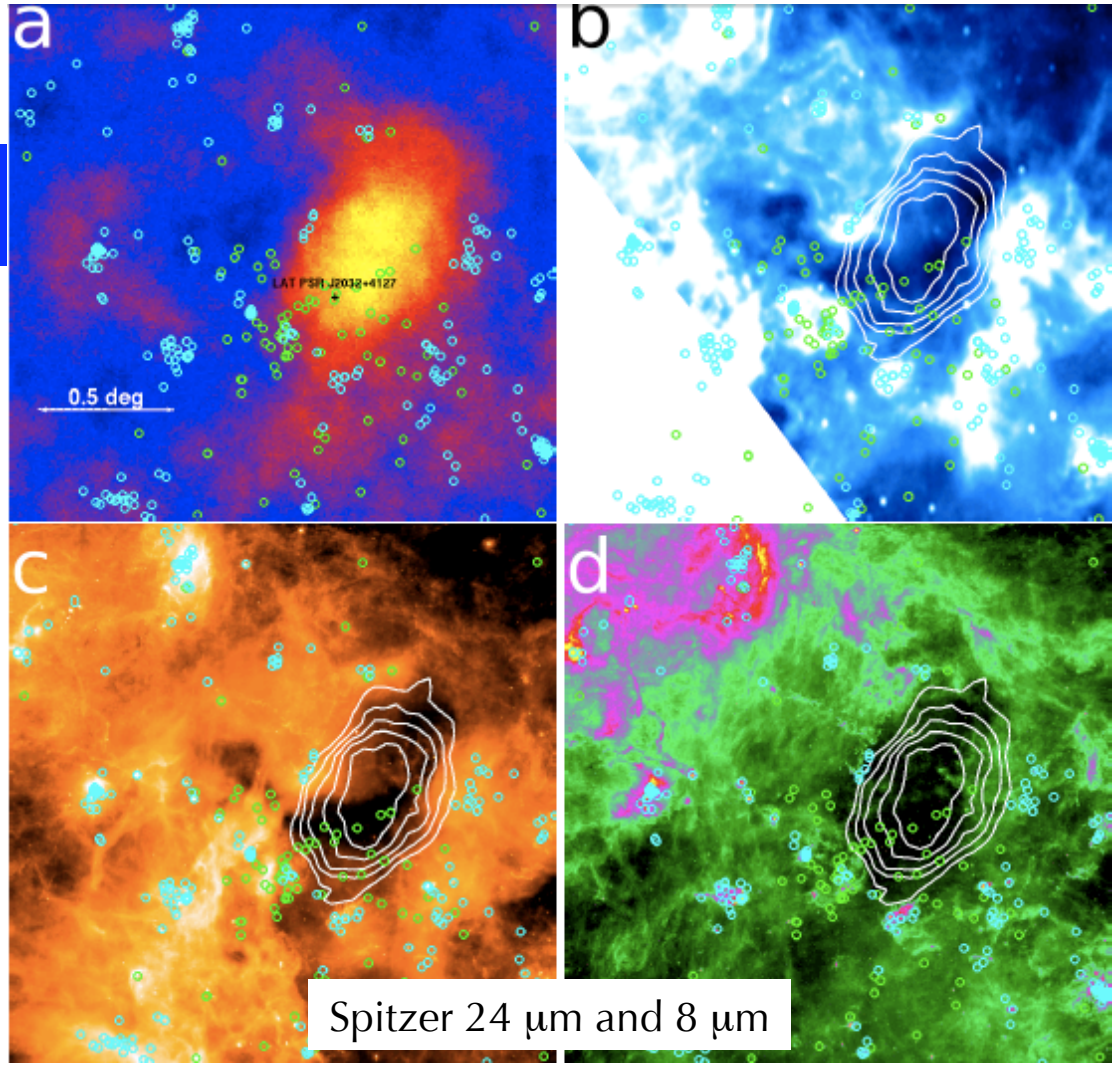


- TeV J2032+4130: 50 ks Chandra reveals no compelling counterpart. Related to multiple stellar X-ray sources associated with Cyg OB2?

No counterparts, even after deep X-ray observations: (5ks DDT, 50 ks Chandra)
-Dual-lobed radio source? (Butt et al. 2008)
- Dark accelerators?
- GRB remnants ?? (astro-ph/0509615)

TeV J2032+4130 – PWN Association?

LAT pulsar:
J2032+4127



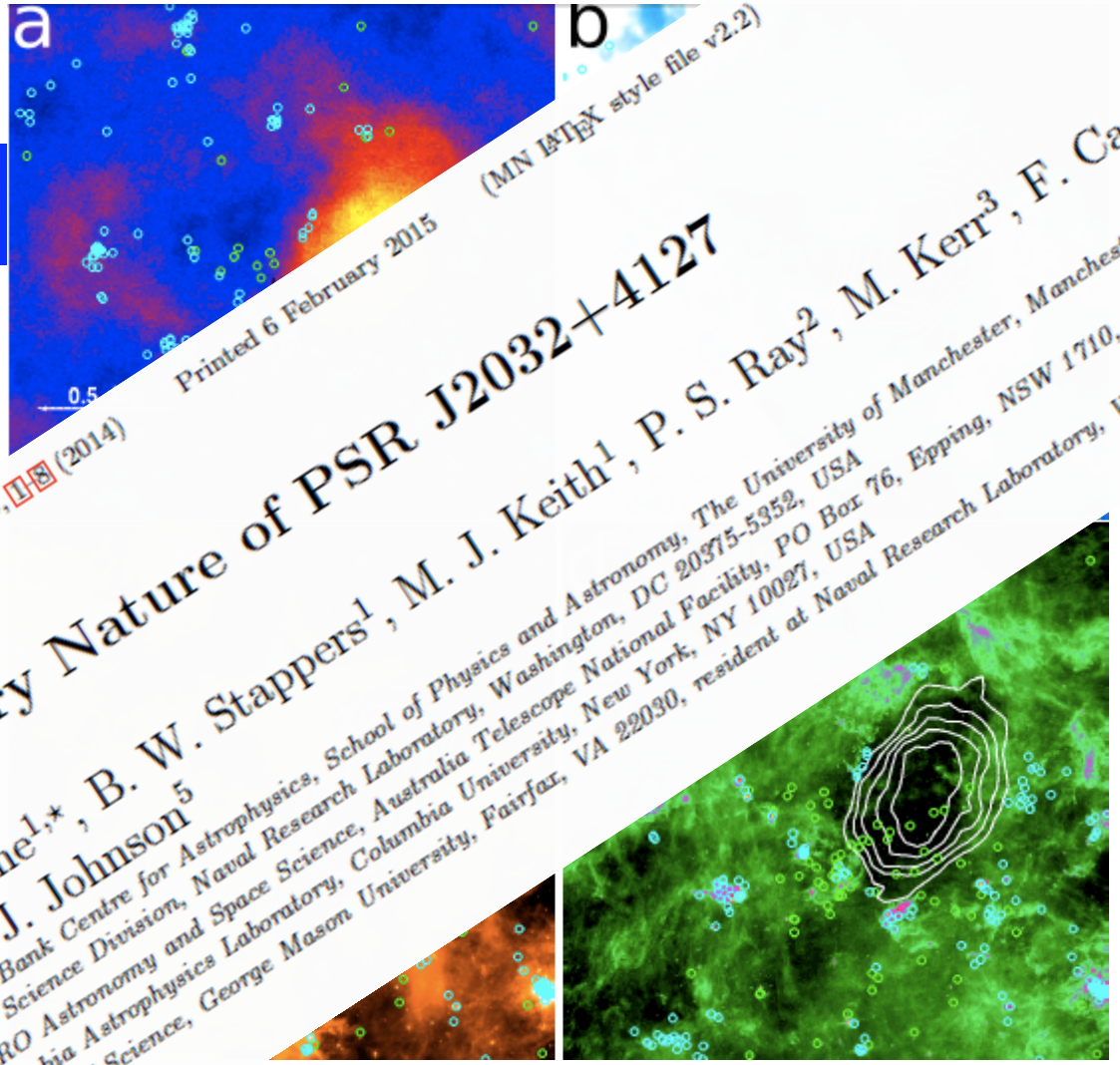
Spitzer 24 μm and 8 μm

1.4 GHz image from the Canadian Galactic Plane Survey

TeV J2032+4130 – PWN Association?
Perhaps not quite.

See: astro-ph /1502.01465

LAT pulsar: J2032+4127



Mon. Not. R. Astron. Soc. 000, 1–8 (2014) Printed 6 February 2015 (MN LATEX style file v2.2)

The Binary Nature of PSR J2032+4127

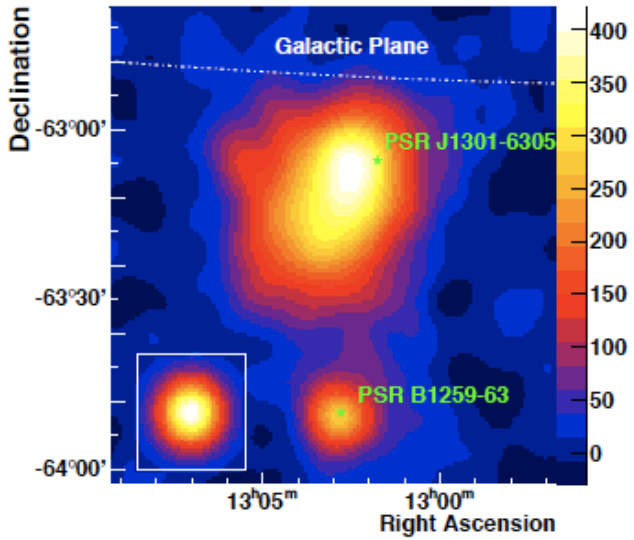
A. G. Lyne[1,*], B. W. Stappers[1], M. J. Keith[1], P. S. Ray[2], M. Kerr[3], F. Camilo[4], and T. J. Johnson[5]

[1] Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
[2] Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA
[3] CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia
[4] Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[5] College of Science, George Mason University, Fairfax, VA 22030, resident at Naval Research Laboratory, Washington, DC 20375, USA

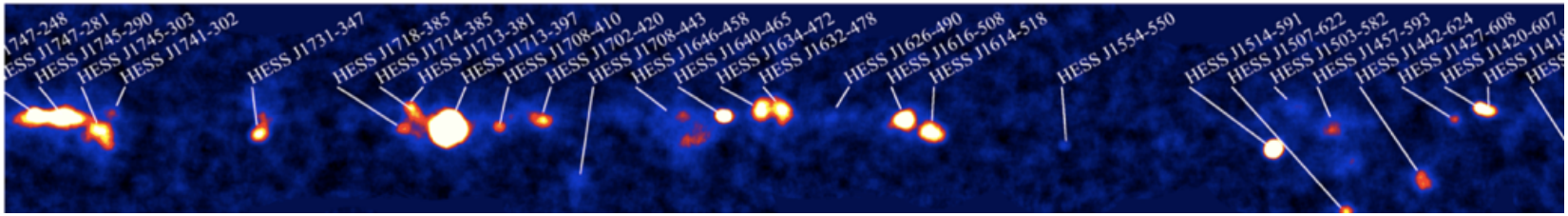
Case 2: Nature of HESS J1303-631

- HESS J1303-631, serendipitously discovered by H.E.S.S. during an observation campaign of the pulsar PSR B1259-63

Abramowski et al. arXiv:1210.6513v2.pdf

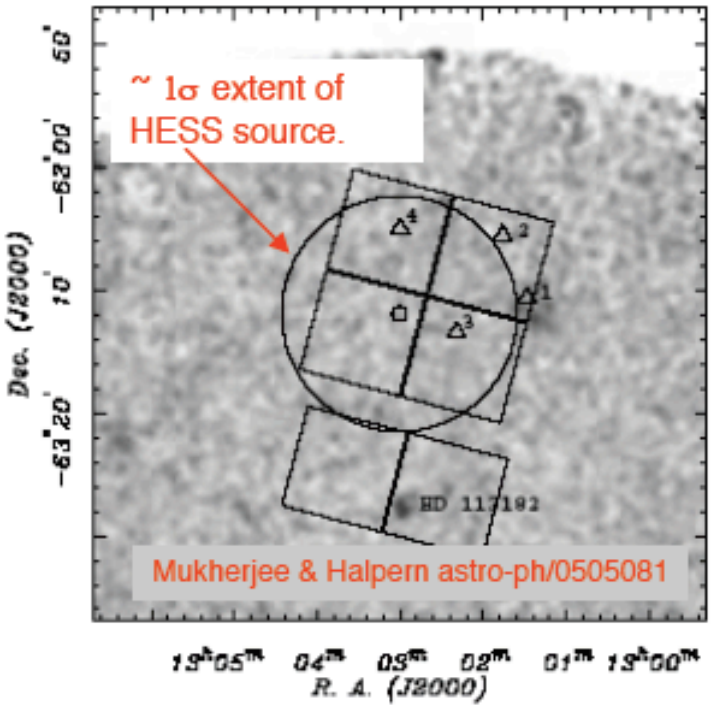


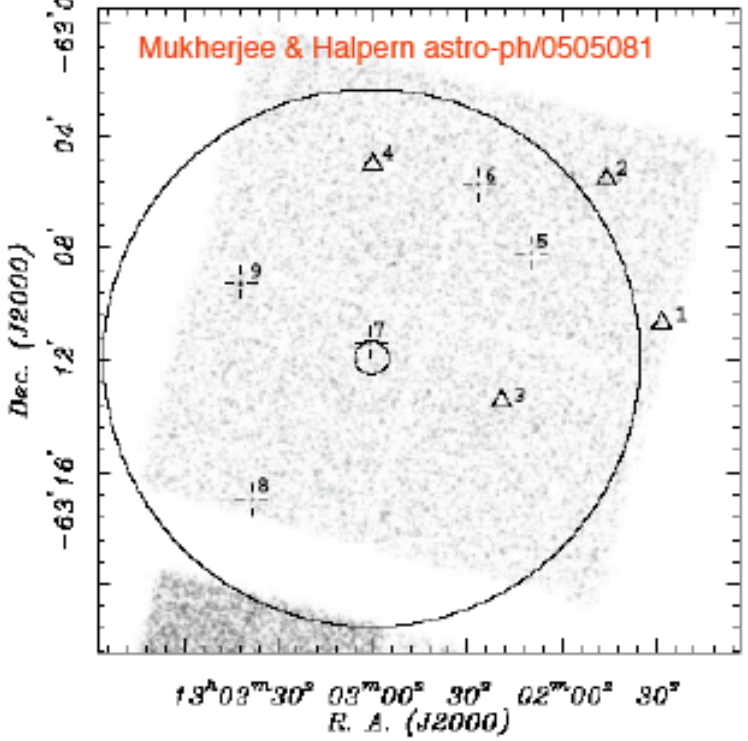
- The first so-called "dark source" discovered by H.E.S.S.
- More of these sources were discovered by the H.E.S.S. collaboration in the following years
- Identifying and understanding this new class of sources has become an important task for modern ray astronomy



A long-lasting mystery …

X-ray observations studies of HESS fields





Archival ROSAT image, plus new Chandra image FOV (squares).
Several radio pulsars - but none with sufficient spin-down flux for powering detectable TeV emission from a PWN

- HESS J1303-631 does not appear to have a point source counterpart at X-ray energies.
- Suggested to be a GRB remnant? (astro-ph/0509615)

A long-lasting mystery …

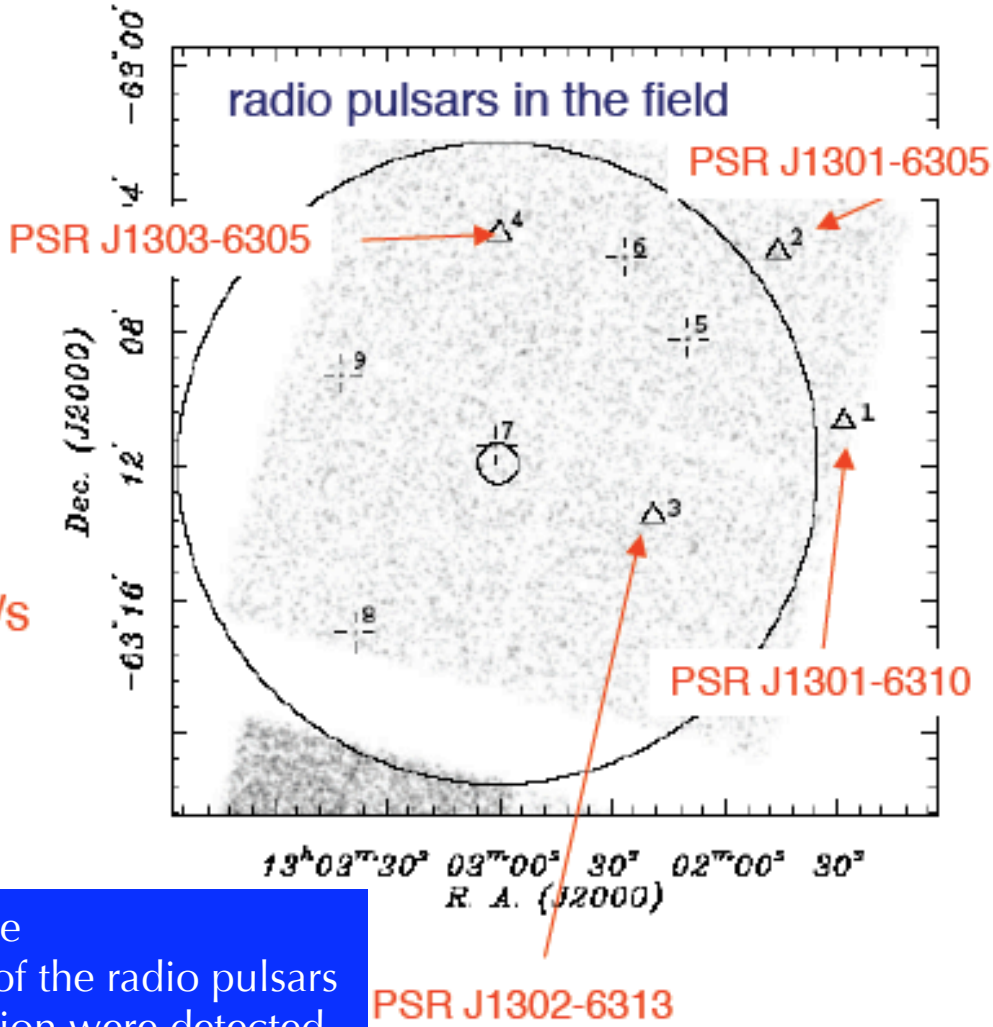
PSR J1303-6305:

d=15.8 kpc
(Taylor & Cordes 1993)

Revised distance:
d=6.6 kpc
(using NE2001, Cordes & Lazio 2002)

initial spin-down power: ~10^{38} erg/s

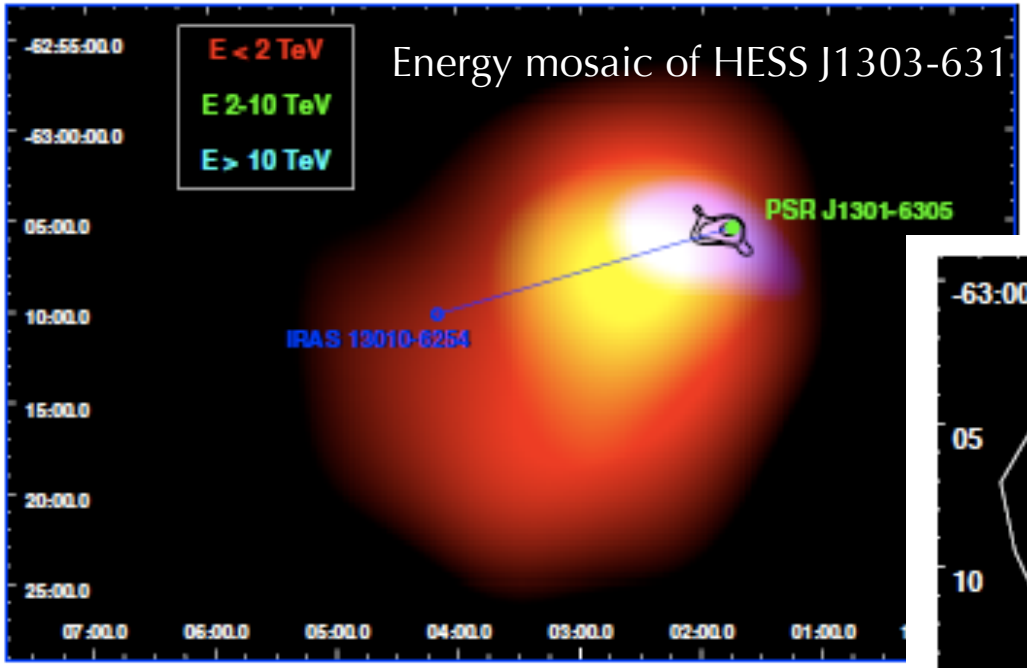
HESS J1303-631 -- "dark" accelerator or PWN?



- No extended emission corresponding to the γ-ray emission region was found, and none of the radio pulsars in the field of view of the Chandra observation were detected.

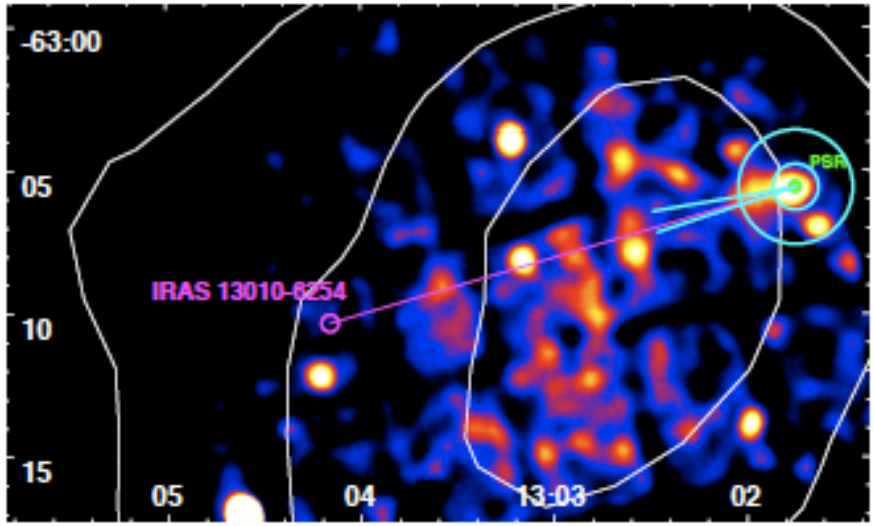
- The possibility of an annihilating clump of dark matter as the origin of the γ-ray signal was explored by Ripken et al. (2008).

And finally …



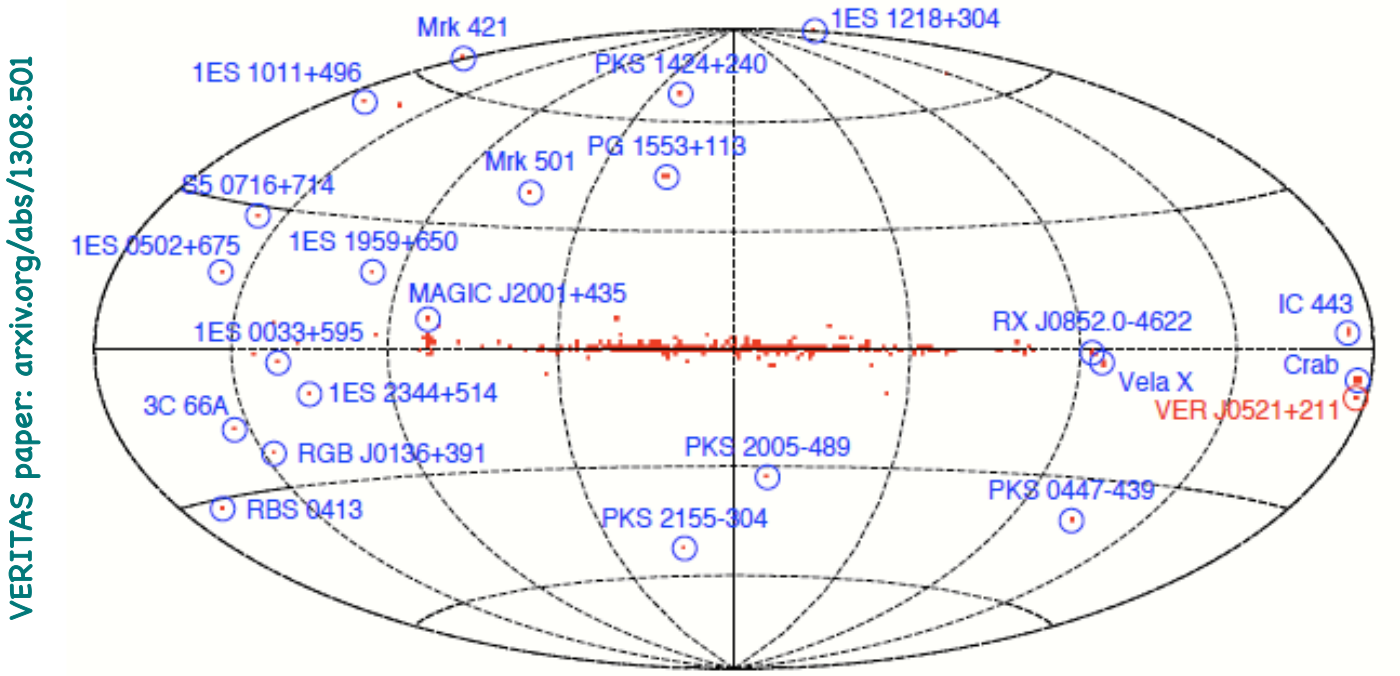
HESS Collaboration, arXiv: 1210.6513v2.pdf

The 2 - 8 keV XMM-Newton X-ray count map in the region of the pulsar



- Significant energy-dependent morphology of the source, as well as the identification of an associated X-ray PWN from XMM-Newton observations enable identification of the VHE source as an evolved PWN associated to the pulsar PSR J1301-6305
- HESS J1303-631, now appears also to belong to the “not-so-dark” group

Case 3: VERITAS Discoveries: Finding new blazars (Follow up of Fermi Sources)

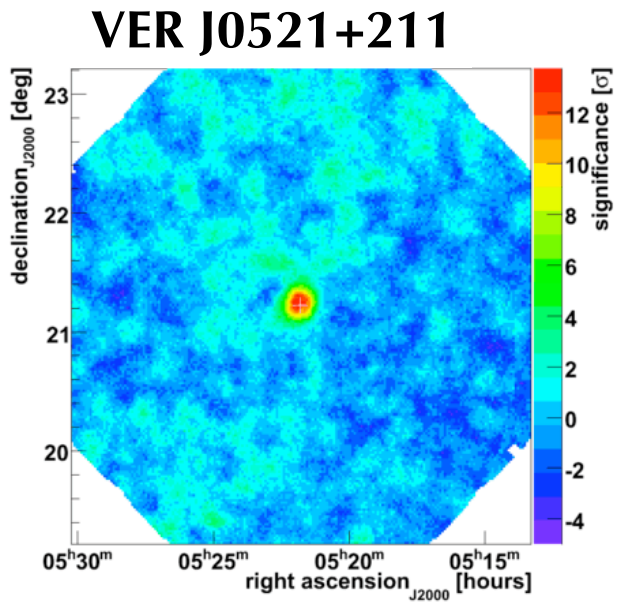


A number of unidentified Fermi sources are expected to be blazars behind the Galactic plane.

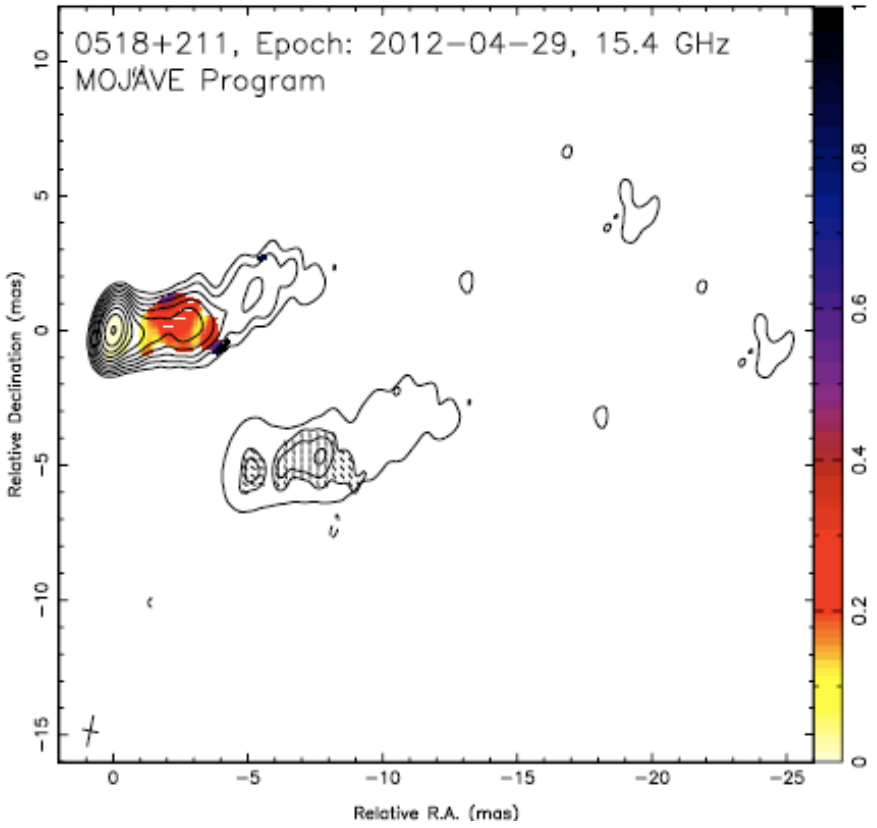
VHE telescopes are a good tool for identifying blazars at low latitudes (better localization, higher sensitivity to flux variability).

Blazars behind the Galactic plane

VERITAS paper: arxiv.org/abs/1308.501

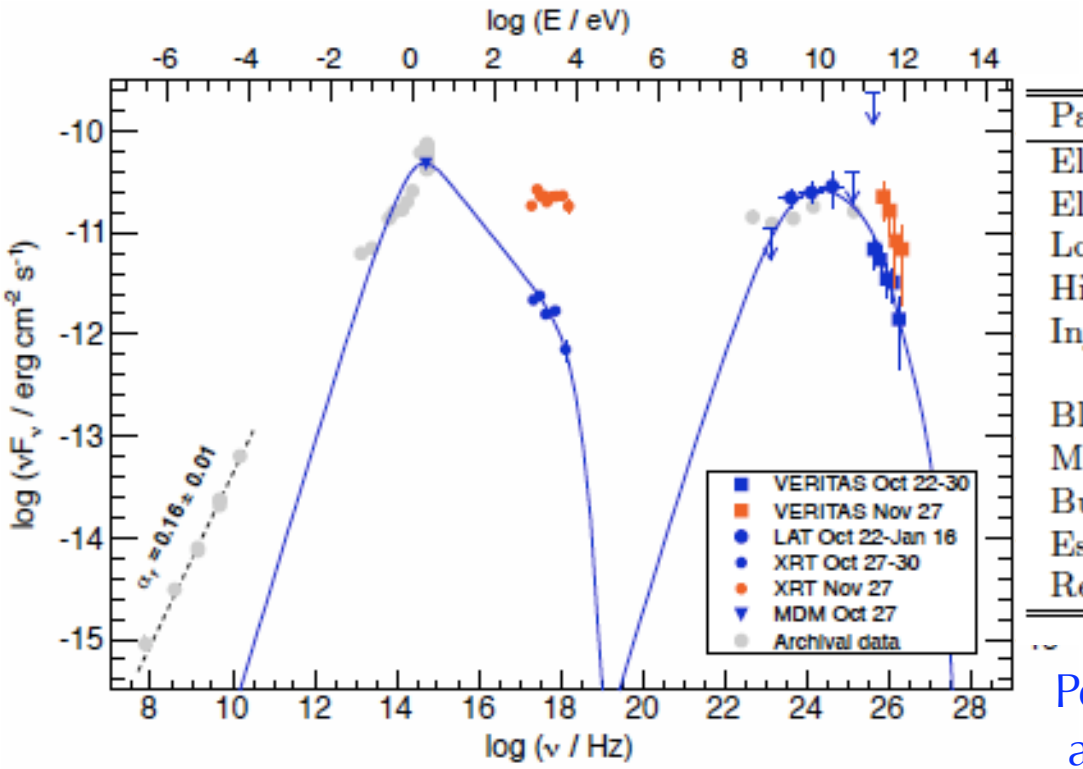


- Discovered in 2009. Flare detected ~10% Crab in 2012.
- Strongly variable from optical to TeV bands, with a peak flux corresponding to ~ 0.3 time bands the steady Crab (at TeV energies).
- Recent optical spectroscopy - typical of BL Lacs, z~0.108



15 GHz MOJAVE VLBA image of RGB J0521.8+2112 on 2012 April 29. The radio morphology consists of a bright radio core + apparent one-sided jet that extends for ~20 mas to the west

SED of VER J0521+211



Archaumbault *et al.* 2013

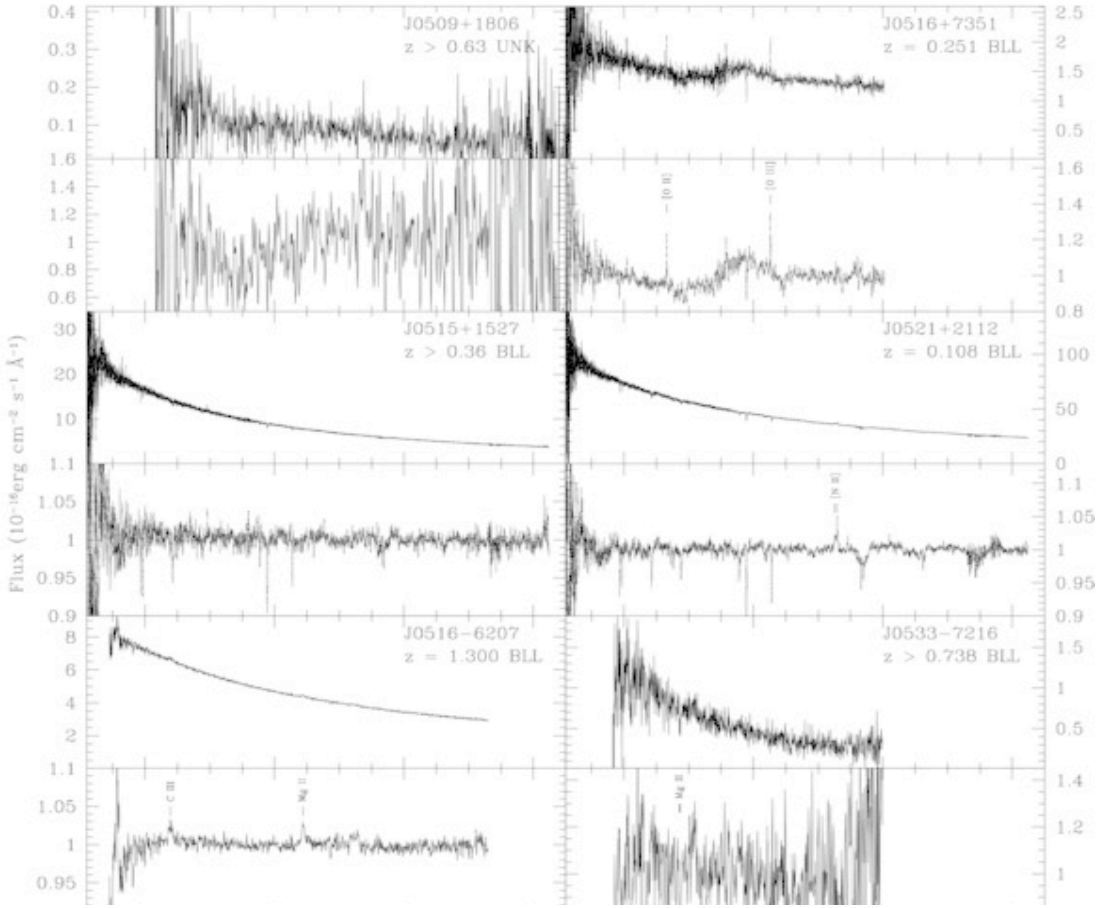
Parameter	Symbol	Value
Electron distribution		
Electron power	L_e [erg s^{-1}]	7.7×10^{44}
Low-energy cutoff	γ_{min}	3.5×10^4
High-energy cutoff	γ_{max}	2.0×10^6
Injection index	q_e	3.0
Blob radius	R_b [cm]	4.0×10^{17}
Magnetic field	B [G]	0.0025
Bulk Lorentz factor	Γ	30
Escape parameter	η_{esc}	300
Redshift (assumed)	z	0.10

- Shift in VHE power not as dramatic - Could be from onset of KN suppression ($h\nu \sim m_e c^2$ in e^- rest frame)
- Min value of Doppler factor: $\delta \sim 30$
- Energy budget: $u_e/u_b < 0.01$

Peak in the γ-ray band, between 10 and 200 GeV -- leptonic one-zone SSC emission model.

Model parameters indicate a relatively weak magnetic field of ~ 0.01 G and a particle dominated jet.

Blazar Confirmation: VER J0521+211



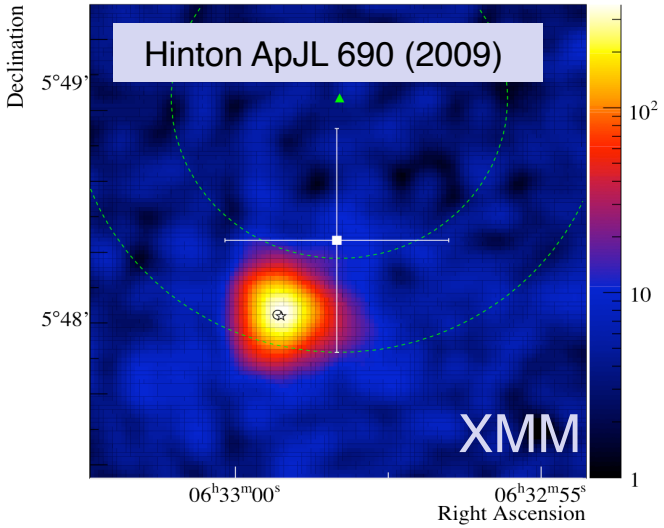
Recently published observations with the Low Resolution Imaging Spectrograph at the W. M. Keck Observatory) show aweak emission feature identified as [N II] $\lambda\ \lambda$ 6548, 6583, which would indicate a redshift of z = 0.108.

Figure 1.14 from Spectroscopy of the Largest Ever γ-Ray-selected BL Lac Sample Michael S. Shaw et al. 2013 ApJ 764 135

Case 4: HESS J0632+057: ??

HESS J0632+057: Only unidentified TeV source in Galactic plane that is point-like.

- Discovered by H.E.S.S. in 2004/2006 (Γ=2.53, F(>1 TeV) ~3% Crab.
- MWL follow-up shows a hard spectrum X-ray source & faint radio source coincident with a massive Be star (MWC148) (Hinton et al 2009).
- Faint point-like, variable radio source (<2" extension, 0.2-0.4 mJy, Skilton et al 2009)
- Not detected by Fermi LAT
- No binary system identified (e.g. Aragona et al 2010)
- VERITAS non-detection 2006-2009, VERITAS detection in 2010. Implies variability.
- Variable X-ray emission measured by Swift. (Falcone et al 2010))

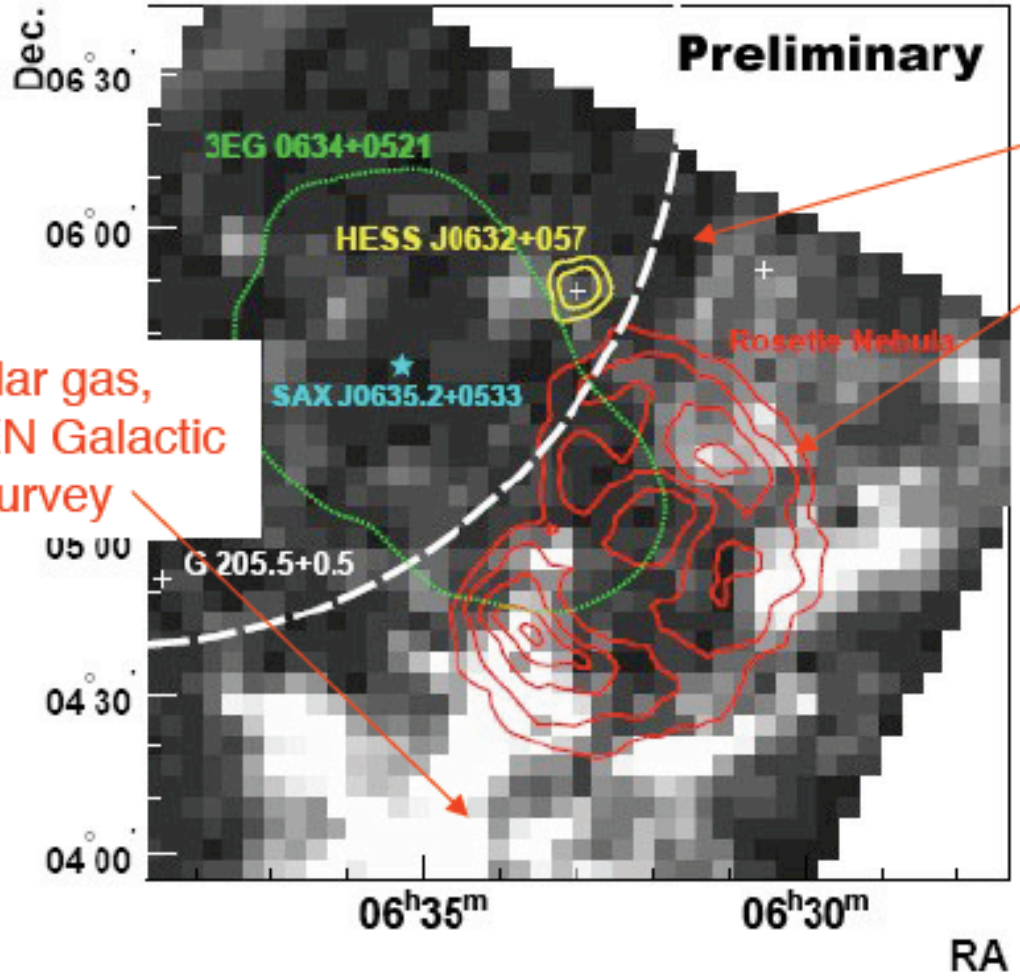


A new TeV binary system? Coincident with Be star MWC 148? (Hinton et al 2009).

An unusual isolated massive star? (confined stellar wind, Townsend et al 2007)

HESS J0632+057: Dark accelerator or ?

The Monoceros Loop SNR?Rosette Nebula region



Green's Catalog position of SNR

radio observations 8.35 GHz

Molecular gas, NANTEN Galactic plane survey

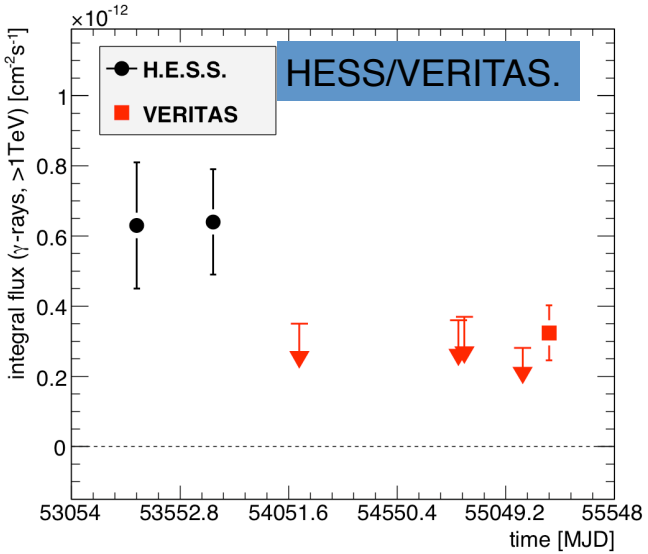
- 30-150 kyrs old
- Distance ~1.5 kpc
- Interaction with the Rosette nebula?

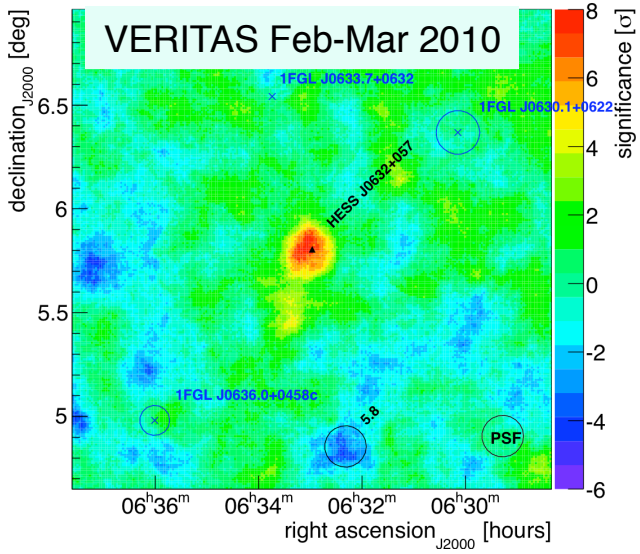
Dark? Identified? No confirmed source type.

Puehlhofer et al. 2007 - First GLAST Symposium

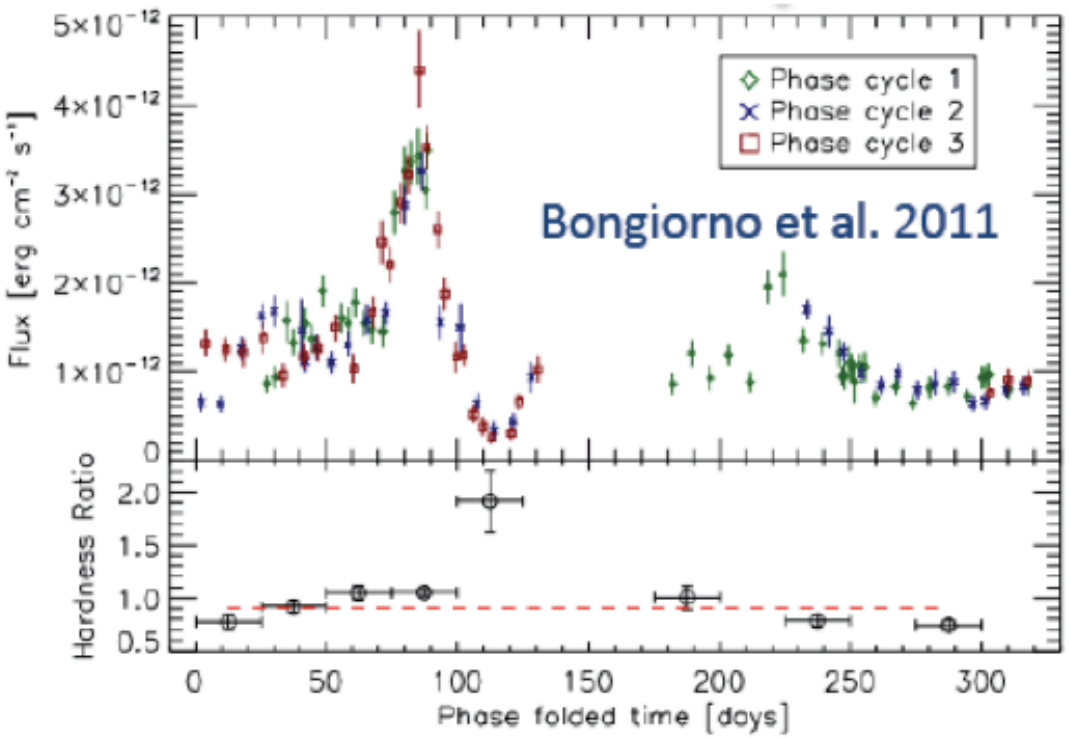
TeV Variability – a new binary??

- 30 h in Dec 2006 - Jan 2009: not detected by VERITAS (ApJ 687 L94 (2009))
- Excluded with ~4σ confidence that HESS J0632+057 is a steady gamma-ray emitter
- H.E.S.S./VERITAS campaign in 2009/2010
- 8h in Oct 2009: no detection (UL~1.3% Crab)
- 20 h in Feb/March 2010: clear detection (7.5 σ, 1.5% Crab)
- Clearly variable in VHE gamma rays
- Is it a VHE binary? Need detection of orbital modulation (at any wavelength)





And finally…

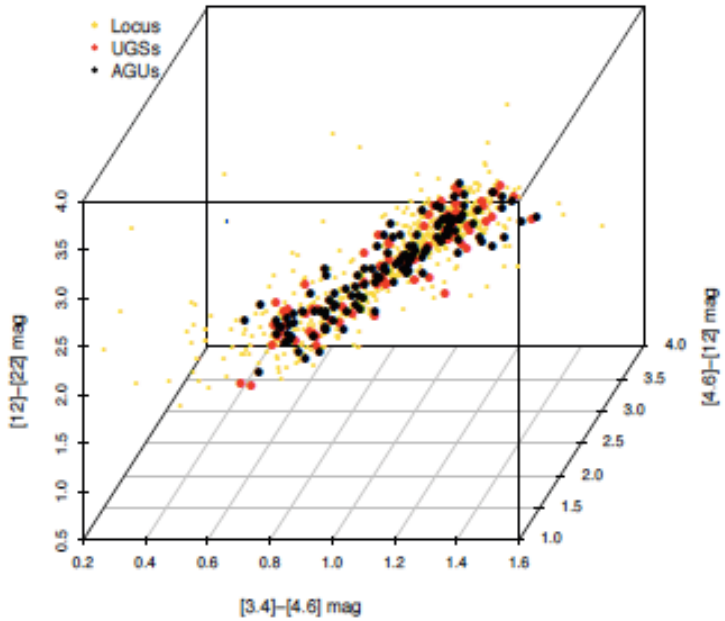


- Swift X-ray monitoring establishes periodic behavior (T=320±5 days) (Bongiorno, 2011) Atel #3153
- VERITAS observations Feb 7/8, 2011 triggered by X-ray activity (Atel #3152)
- > 8σ, F (E> 300 GeV) ~ 4% Crab
- Confirmed by MAGIC (Atel #3161)

Population characteristics

Radio, infrared and optical counterparts of the γ-ray blazar candidates

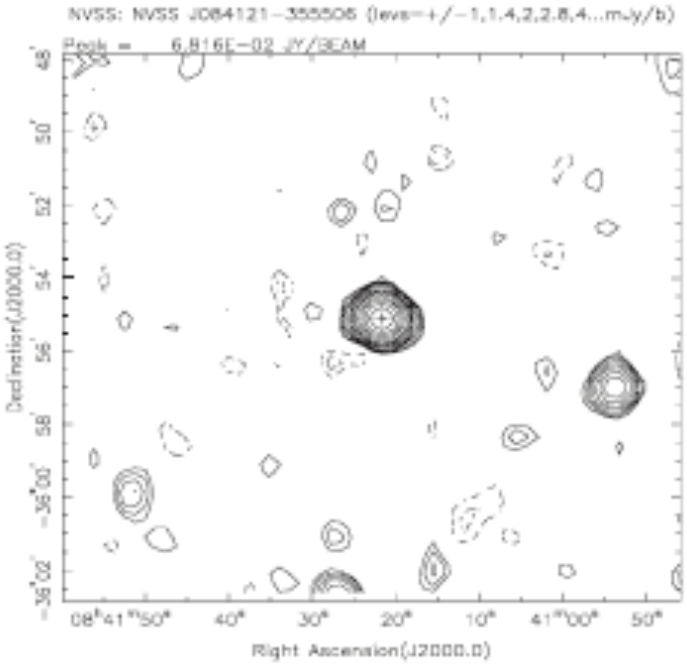
- New association method to identify if there is a γ-ray blazar candidate within the positional uncertainty region of a generic 2FGL source.
- Method entirely based on the discovery that blazars have distinct infrared colors with respect to other extragalactic sources (from Wide-field Infrared Survey Explorer (WISE) all-sky observations).
- Method applied to 2FGL unidentified γ-ray sources (UGSs) and to active galaxies of uncertain type (AGUs).

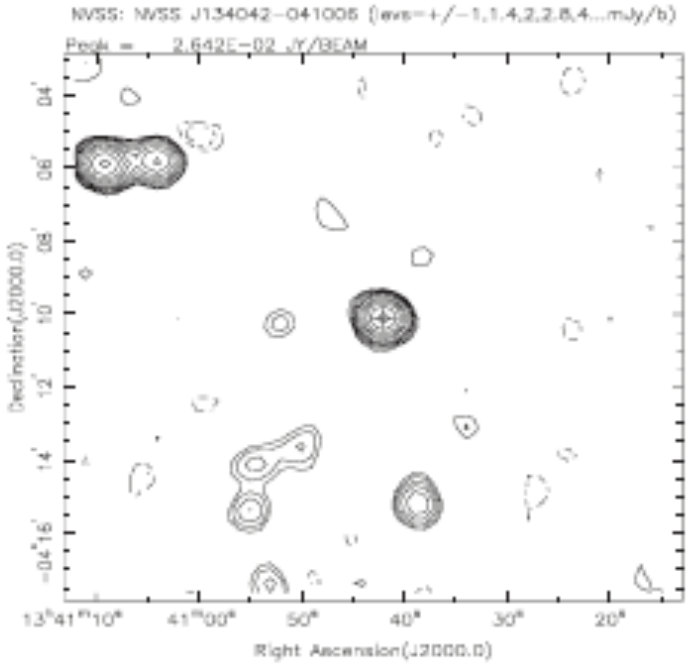


The 3D representation of the locus (known γ-ray blazars are indicated in yellow) in comparison with the selected γ-ray blazar candidates: UGSs (red) and AGUs (black).

See Massaro et al. arXiv:1303.3585

Radio, infrared and optical counterparts of the γ-ray blazar candidates





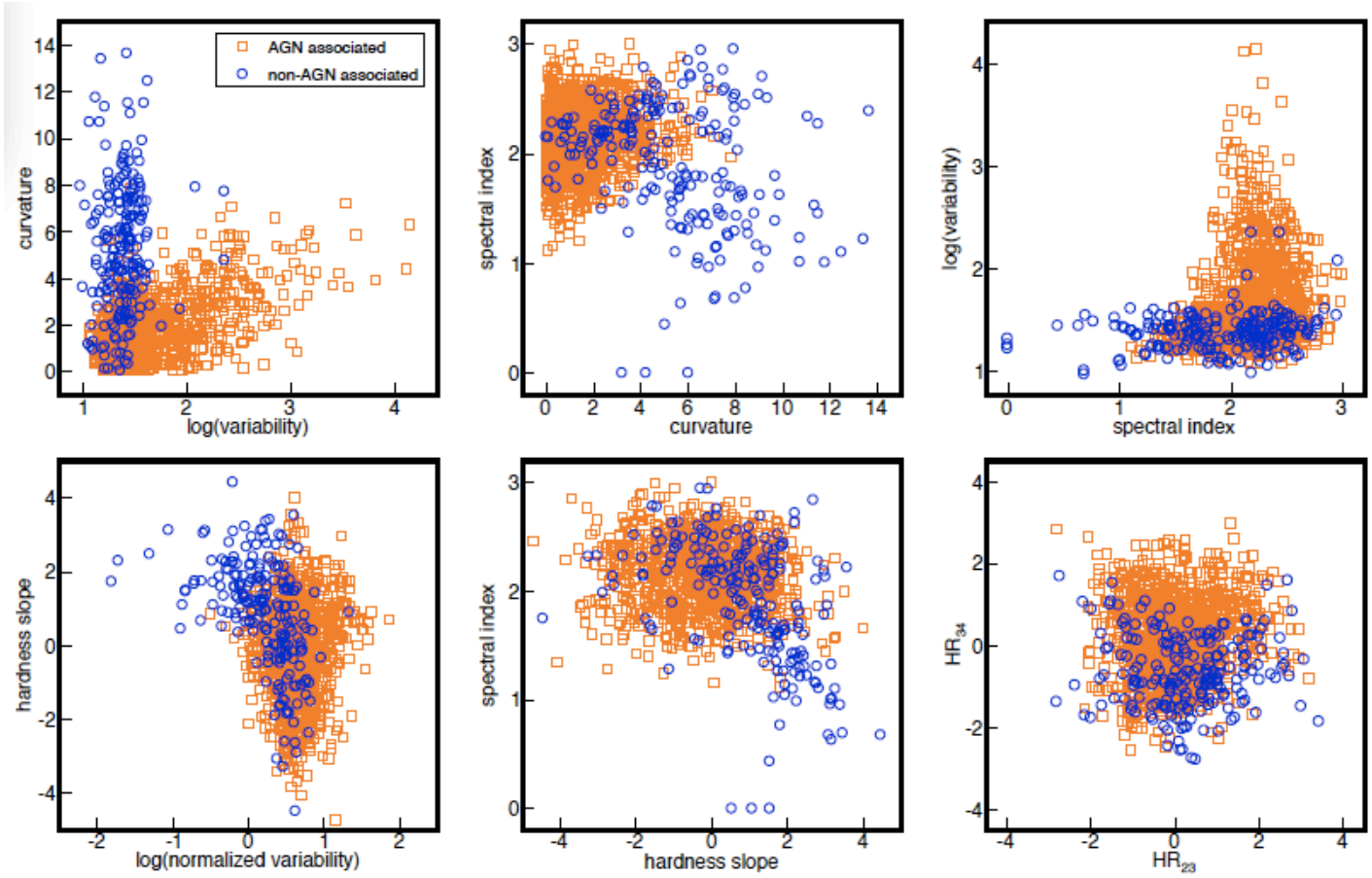
The archival NVSS radio observations (15′ radius) of the γ-ray blazars candidates: WISE J084121.63-355505.9 (left) and WISE J134042.02-041006.8 (right), associated with the Fermi sources 2FGLJ0841.3-3556 and 2FGLJ1340.5-0412, respectively.

The black crosses point to the radio counterpart of the γ-ray blazar candidates selected according to the procedure of Massaro et al. arXiv:1303.3585. Both are clear examples of core dominated radio sources similar to blazars in the radio band also at 1.4 GHz.

See Massaro et al. arXiv:1303.3585

Automated Searches

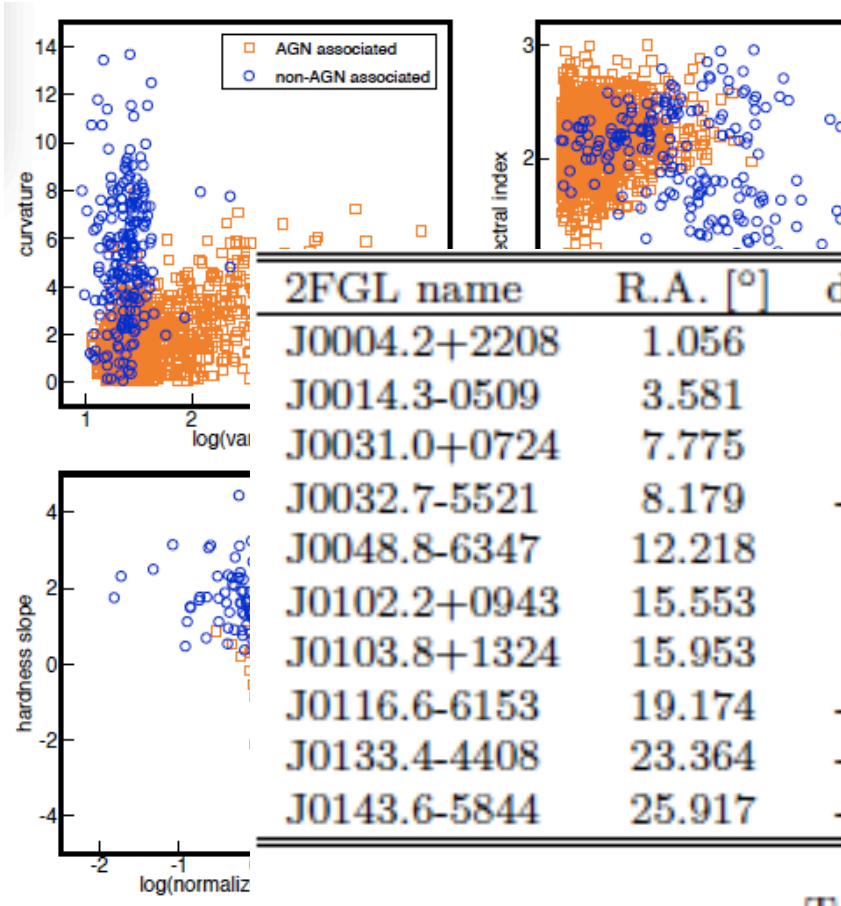
SEARCH FOR GAMMA-RAY-EMITTING ACTIVE GALACTIC NUCLEI IN THE FERMI -LAT UNASSOCIATED SAMPLE USING MACHINE LEARNING (Doert & Errando 2013)



Scatter plots showing some gamma-ray properties listed in the 2FGL catalog (*top panels) and parameters used by the machinelearning* algorithms (*bottom panels) for AGN and non-AGN sources.*

Automated Searches

SEARCH FOR GAMMA-RAY-EMITTING ACTIVE GALACTIC NUCLEI IN THE FERMI -LAT UNASSOCIATED SAMPLE USING MACHINE LEARNING (Doert & Errando 2013)



Scatter plots sl

algo

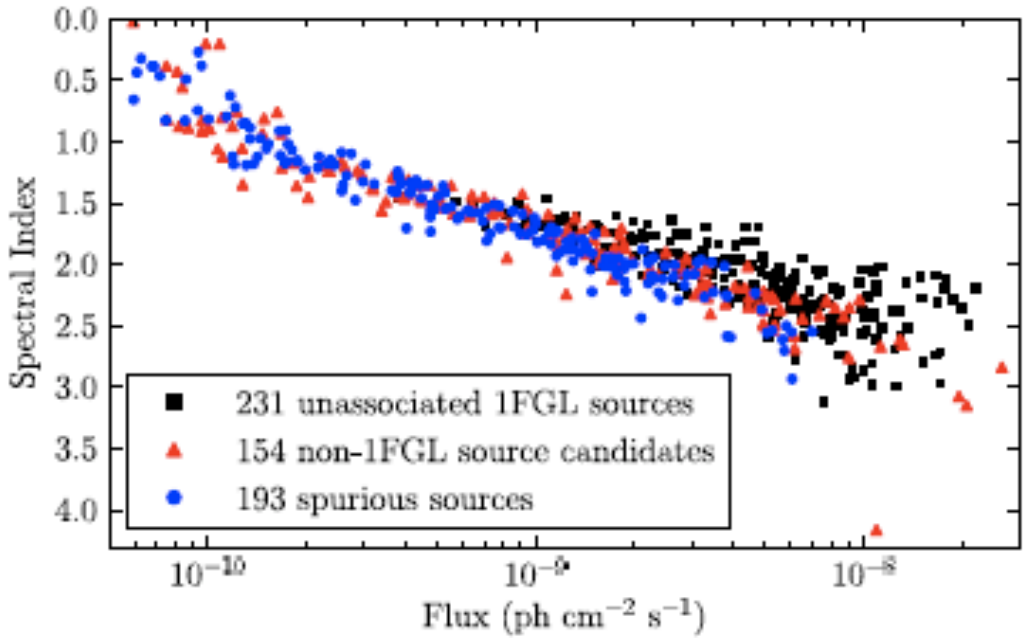
2FGL name	R.A. [°]	decl. [°]	L_{RF}	L_{NN}	(1)	(2)
J0004.2+2208	1.056	22.137	0.98	0.97	A	
J0014.3-0509	3.581	-5.153	1.00	1.00	A	
J0031.0+0724	7.775	7.414	0.99	1.00	A	b
J0032.7-5521	8.179	-55.356	1.00	1.00	A	
J0048.8-6347	12.218	-63.79	0.90	0.92	A	b
J0102.2+0943	15.553	9.726	1.00	1.00	A	b
J0103.8+1324	15.953	13.401	0.96	1.00	A	b
J0116.6-6153	19.174	-61.887	1.00	1.00	A	ab
J0133.4-4408	23.364	-44.142	0.99	1.00	A	ab
J0143.6-5844	25.917	-58.745	0.98	1.00	A	abc

TABLE 3
LIST OF HIGH-CONFIDENCE AGN CANDIDATES, ORDERED BY R.A.
(THIS TABLE IS AVAILABLE IN ITS ENTIRETY IN A
MACHINE-READABLE FORM IN THE ONLINE JOURNAL. A PORTION IS

Other ideas ....

SEARCH FOR DARK MATTER SATELLITES USING FERMI-LAT

THE ASTROPHYSICAL JOURNAL, 747:121 (11pp), 2012 March 10



Ackermann et al. 2012: Numerical simulations based on the ΛCDM model of cosmology predict a large number of as yet unobserved Galactic dark matter satellites.

- Search for these satellites via the γ -ray emission expected from the annihilation of weakly interacting massive particle (WIMP) darkmatter.
- Some dark matter satellites are expected to have hard γ -ray spectra, finite angular extents, and a lack of counterparts at other wavelengths.