Overview of the Observational Properties of UnID TeV Sources

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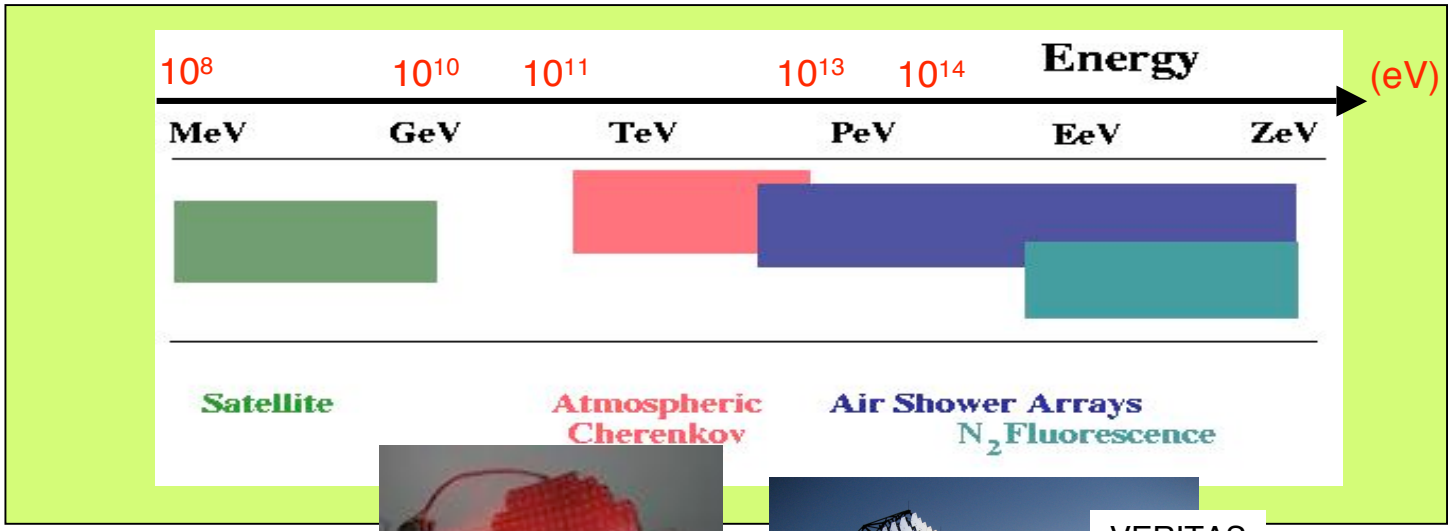
Outline

- Gamma-ray detectors
- Surveys of the γ-ray sky
  - HESS
  - MILAGRO
- Skymap & Galactic TeV source population characteristics
- Classes of Galactic TeV sources
- The remaining *unidentified* sources
- Identification strategies -- X-ray follow-ups
- Summary

Exploring the γ-ray Sky

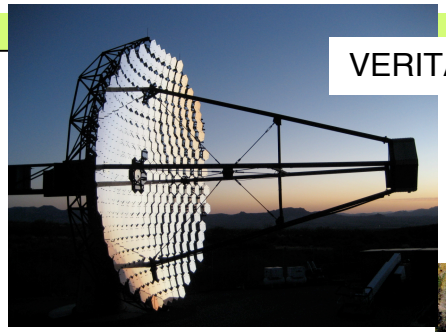



EGRET/CGRO


GLAST


MAGIC

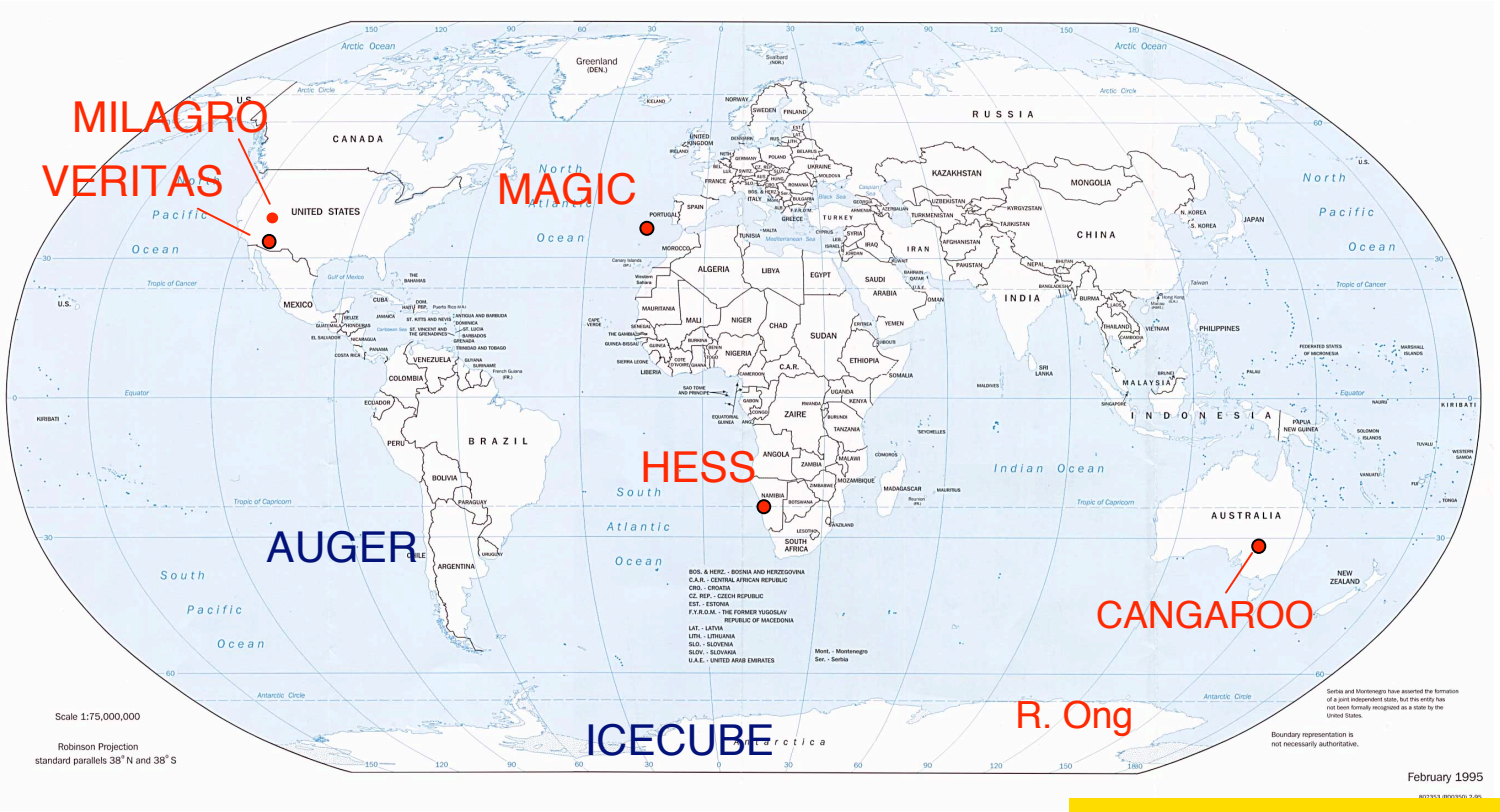

HESS


VERITAS


CANGAROO


MILAGRO

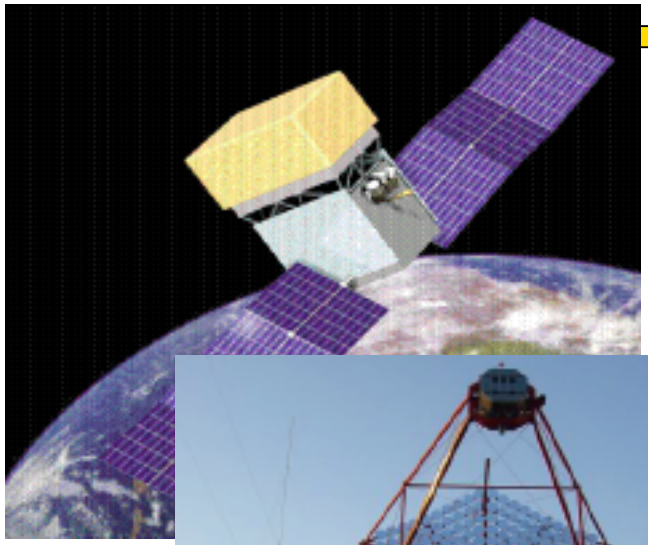
Exploring the γ-ray Sky



- Good global coverage - latitude & longitude.
- Northern TeV telescopes observe same sources as IceCube.
- GLAST + worldwide network of TeV telescopes.

See talks:
Cosmic rays: Holder
Neutrinos: DeYoung

Types of γ-ray Detector



Low-energy threshold: AGILE, GLAST (~10s MeV - 300 GeV)

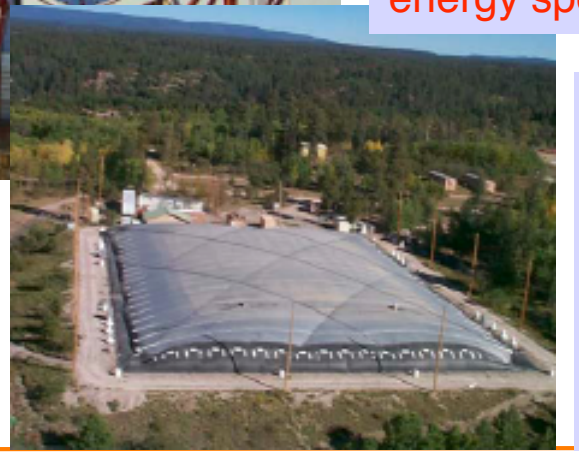
Space-based (small effective area), background-free, large duty cycle, large aperture

Sky survey < 10 GeV, transients

High sensitivity: HESS, MAGIC, VERITAS, CANGAROO (~100 GeV - 30 TeV)

Ground-based, large effective area, excellent background rejection, low duty cycle, small aperture

Survey limited regions of the sky, high resolution energy spectra

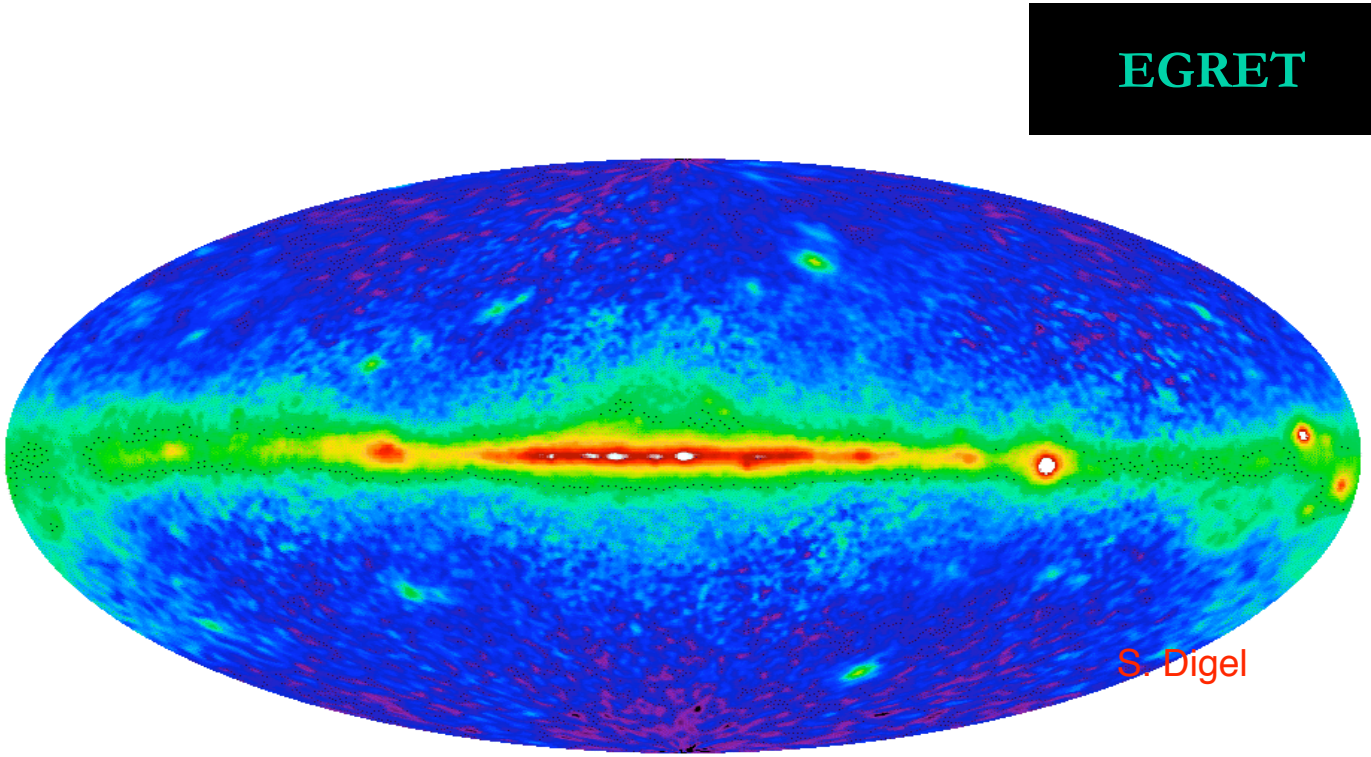


Large Aperture: MILAGRO (>20 TeV)

Large duty cycle, good background rejection, limited angular resolution

Unbiased sky survey, extended sources, transients

The Galaxy in high energy γ-rays



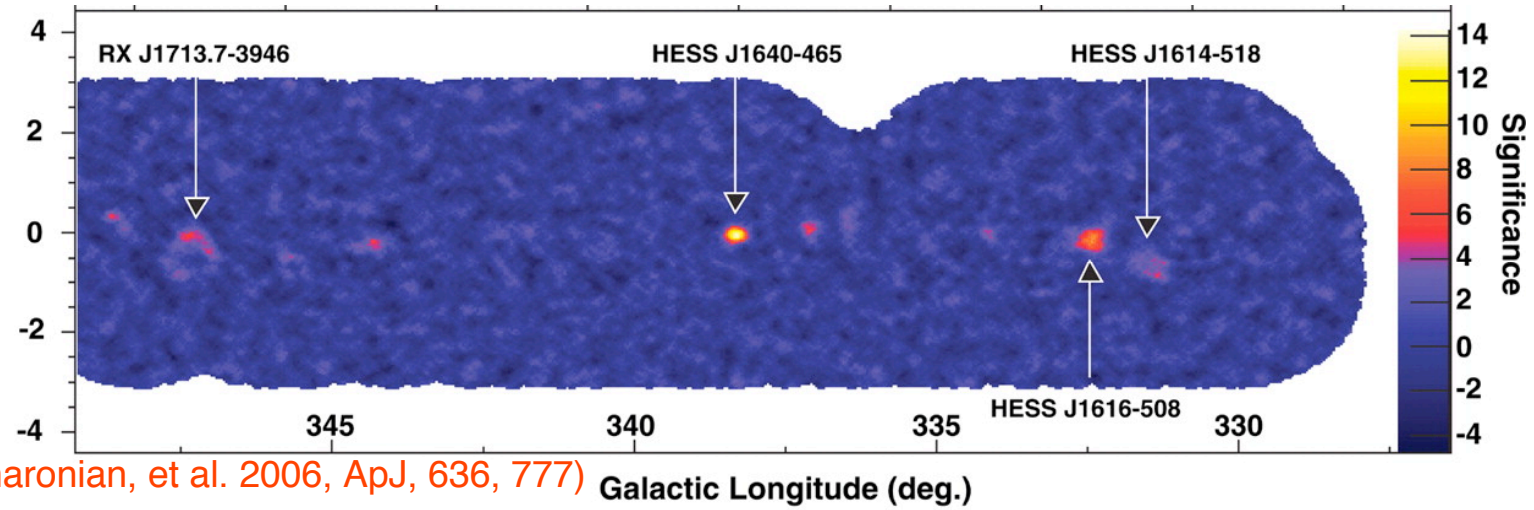
- ~1.4 Mγ, ~60% interstellar emission from the MW (Hartman et al. 1999)
- ~10% are cataloged (3EG) point sources
- 80 sources (>100 MeV), 28 sources (>1 GeV) within 10° of Galactic plane

Galactic TeV Astronomy (HESS)

Parameters of the HESS Sky Survey:

First stage - survey of the inner galaxy

- Years 2004-2005
- $-30^o < l < 30^o$, $-3^o < b < 3^o$
- 500 pointings, 230 h
- Avg flux sensitivity: ~2% Crab at > 200 GeV
- Detailed spectral and morphological information on sources
- 14 new sources detected
- Most of the HESS unidentified sources do not have EGRET counterparts



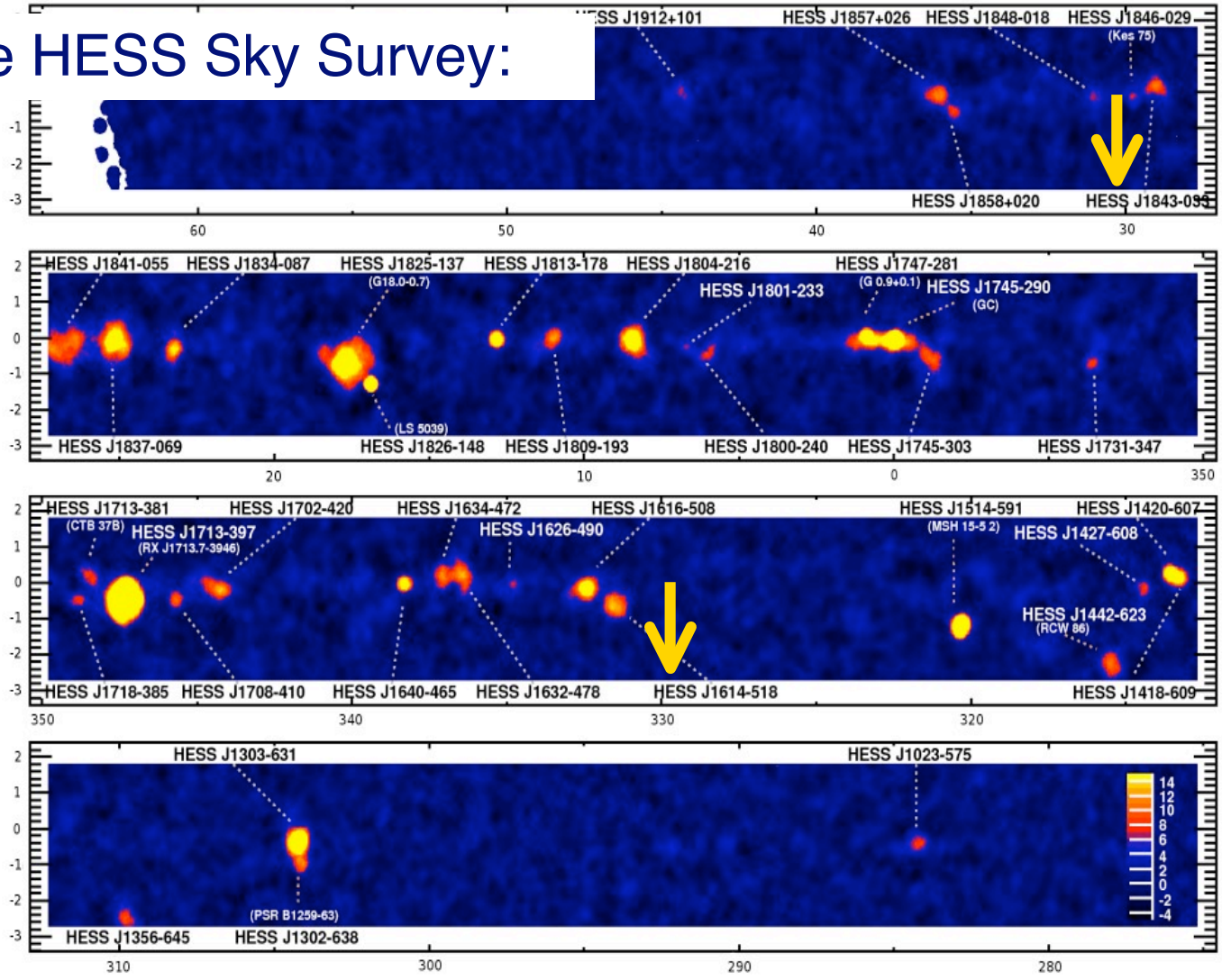
(Aharonian, et al. 2006, ApJ, 636, 777)

Galactic TeV Astronomy (HESS)

Parameters of the HESS Sky Survey:

Extended survey -

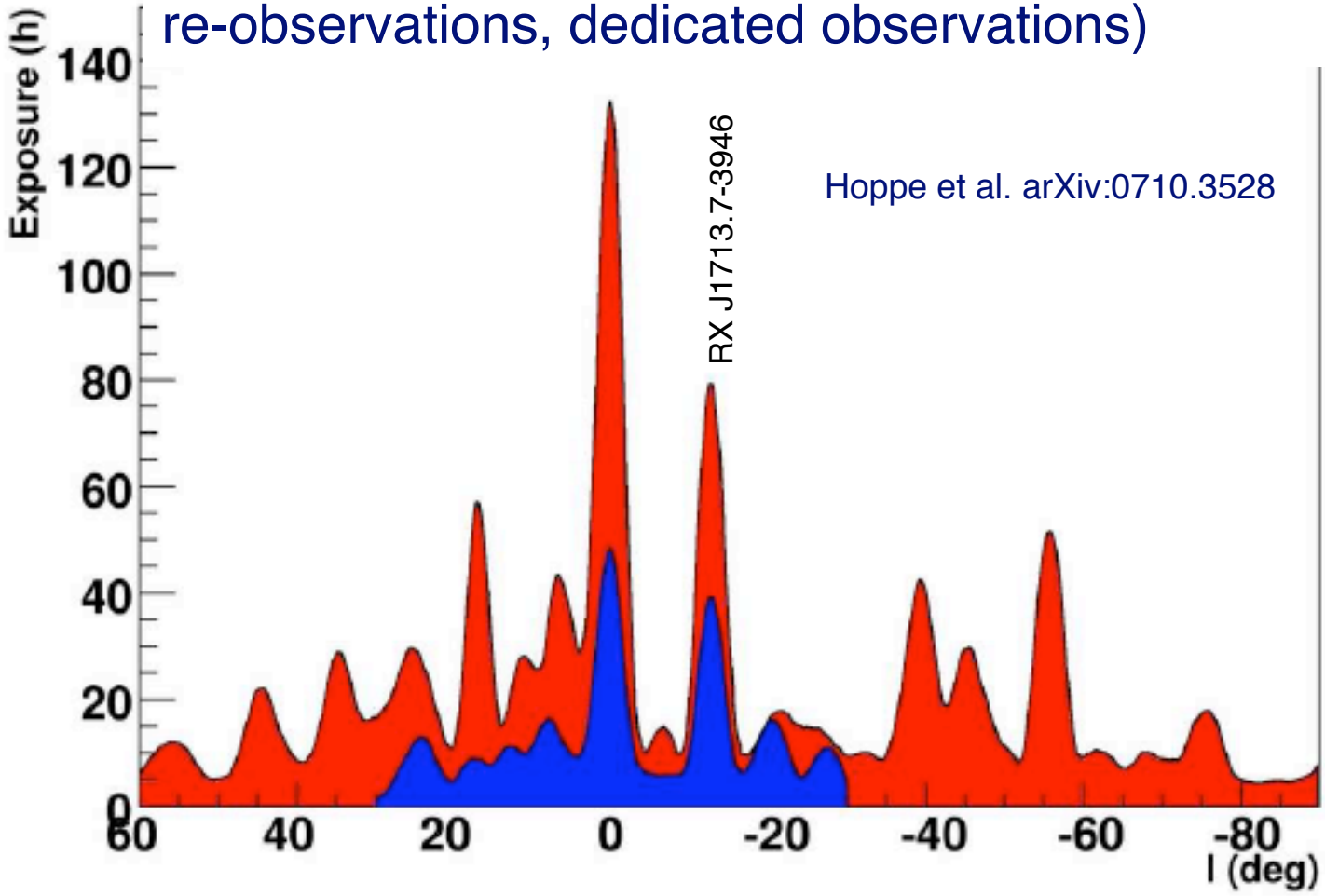
- Years 2005-2007
- l: –85º to 60º, b:±3º
- ~325 h survey, 625h pointed observations
- >14 new VHE sources



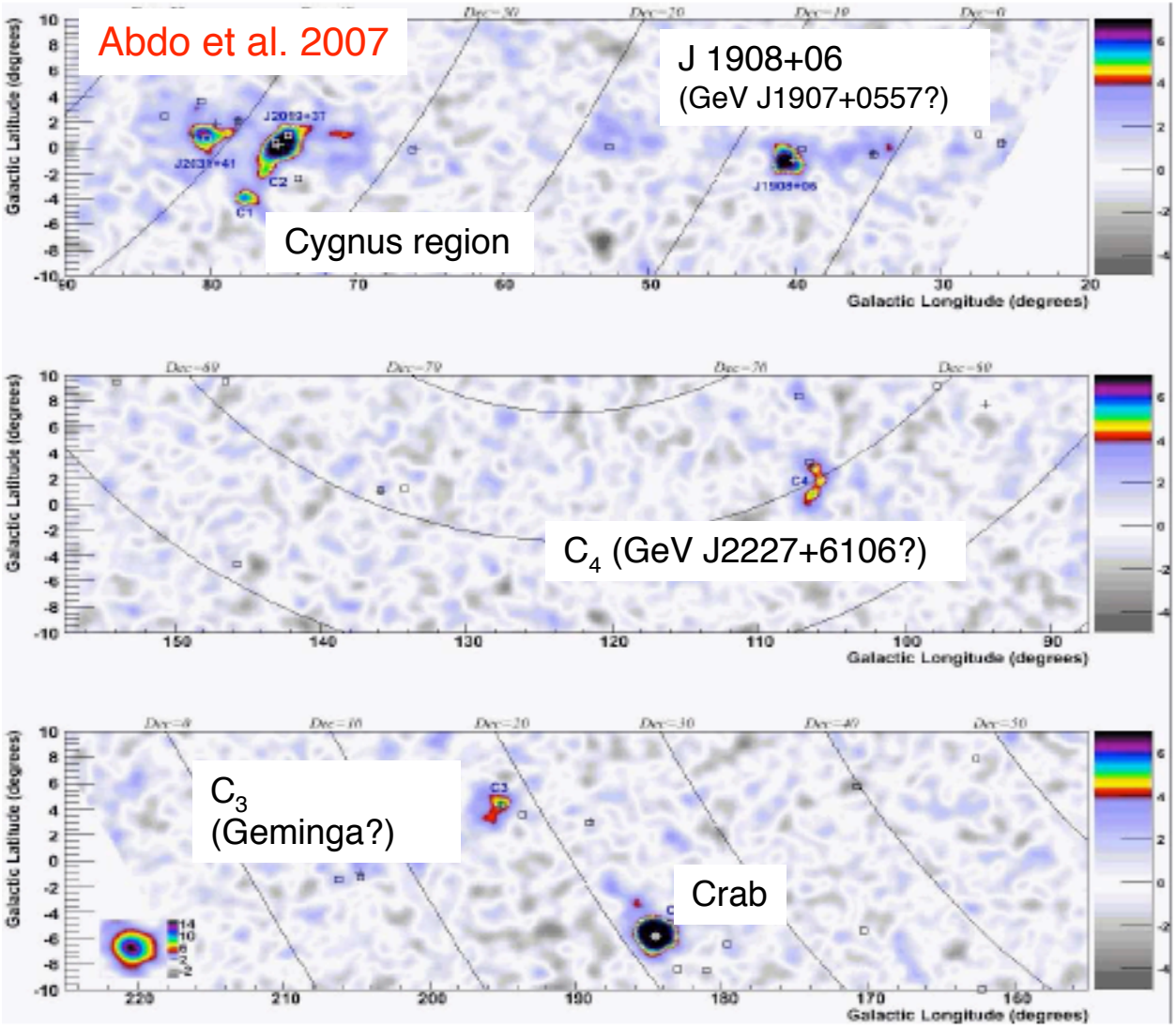
- Significant increase in TeV source catalog
- TeV J2032+4130 was the only unidentified "TeV" source prior to HESS
- New population of sources

HESS Sky Survey Exposure

Livetime along the Galactic Plane (includes survey, re-observations, dedicated observations)



Galactic TeV Astronomy (MILAGRO)

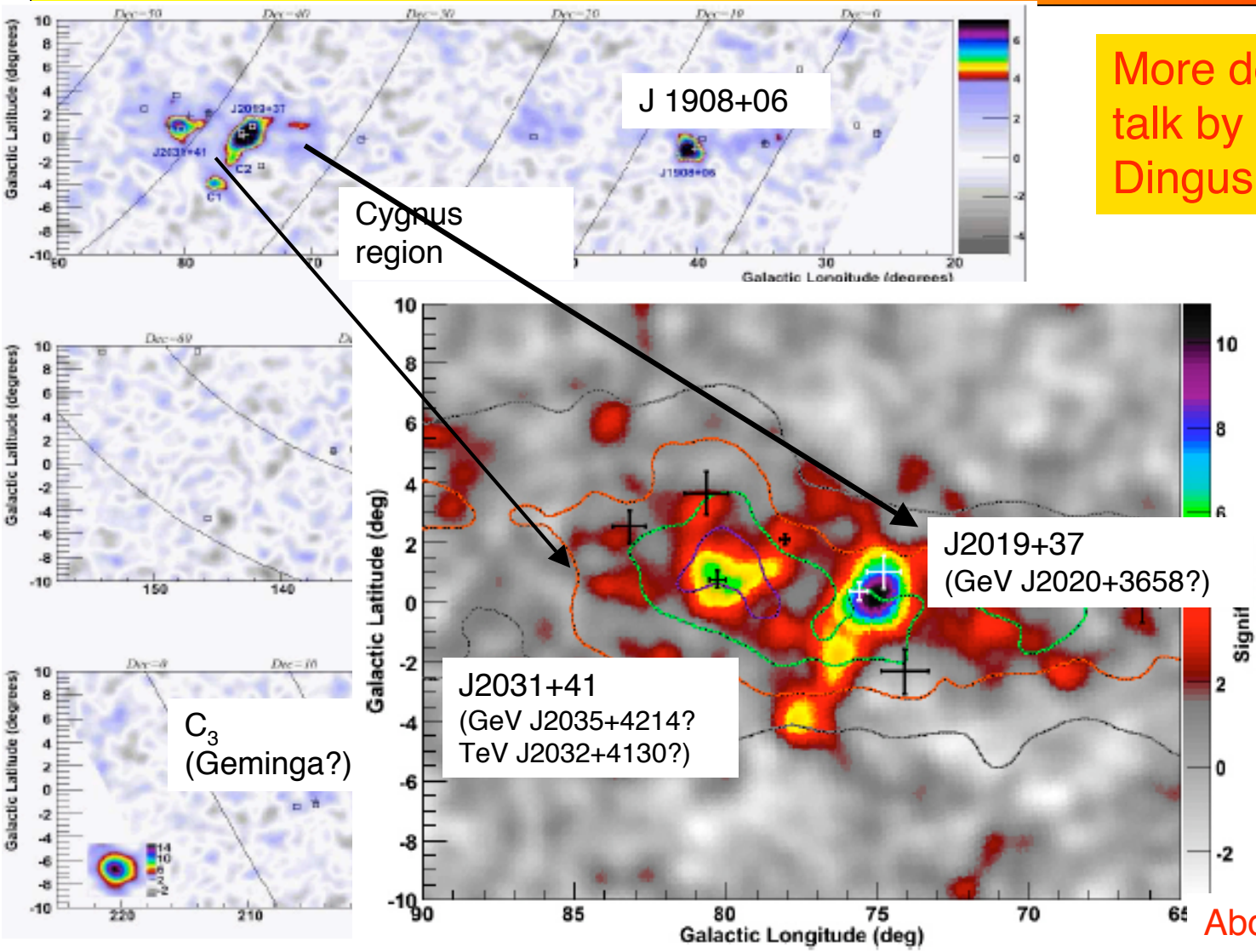


MILAGRO Survey:

- l: 30° to 220°
- Years 2001-2007
- b: ± 10°
- E> 20 TeV

- 4 sources at > 4σ
- 4 additional at lower significance
- 6 of the 8 sources are coincident with 3EG sources

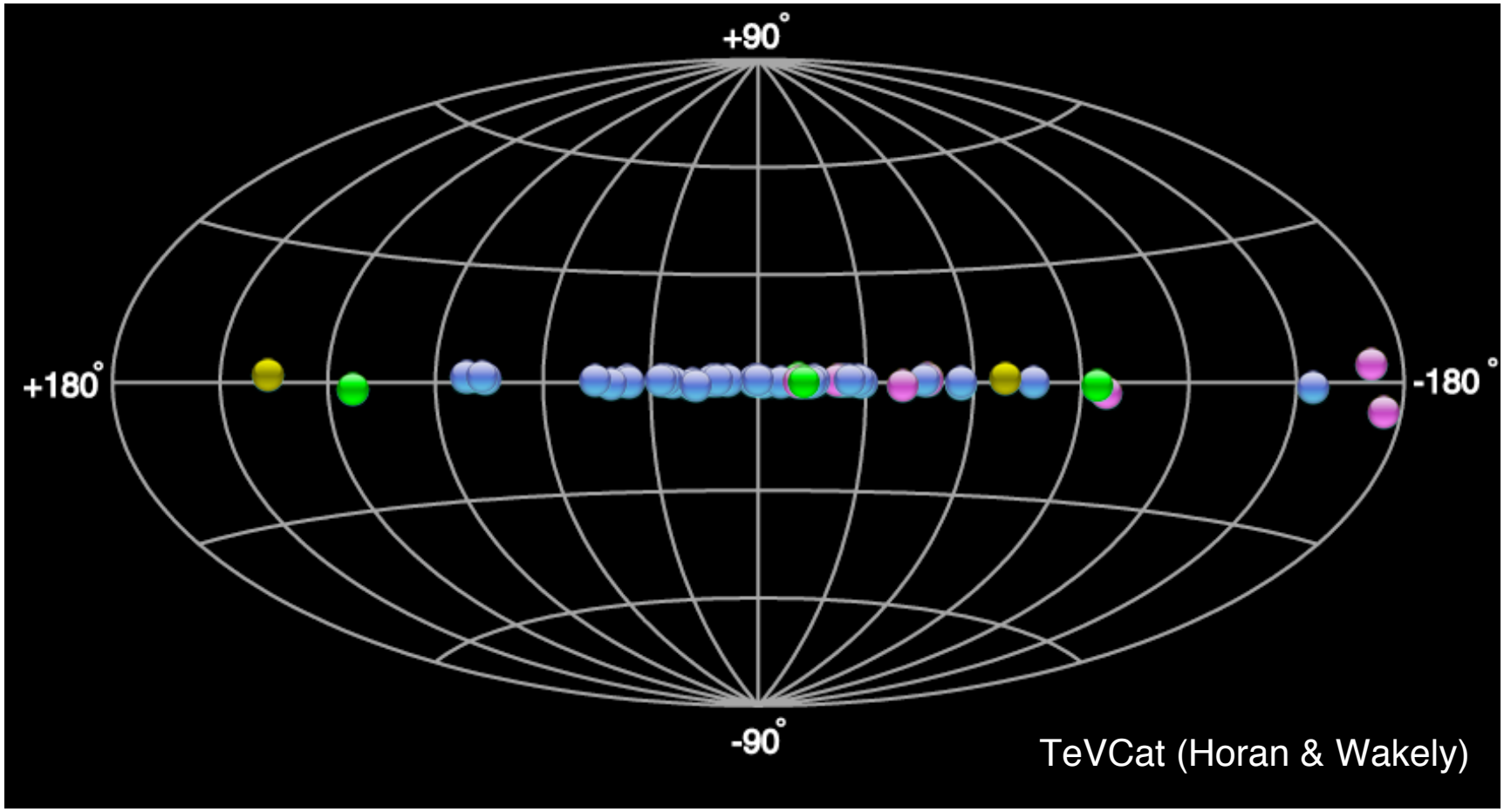
Galactic TeV Astronomy (MILAGRO)



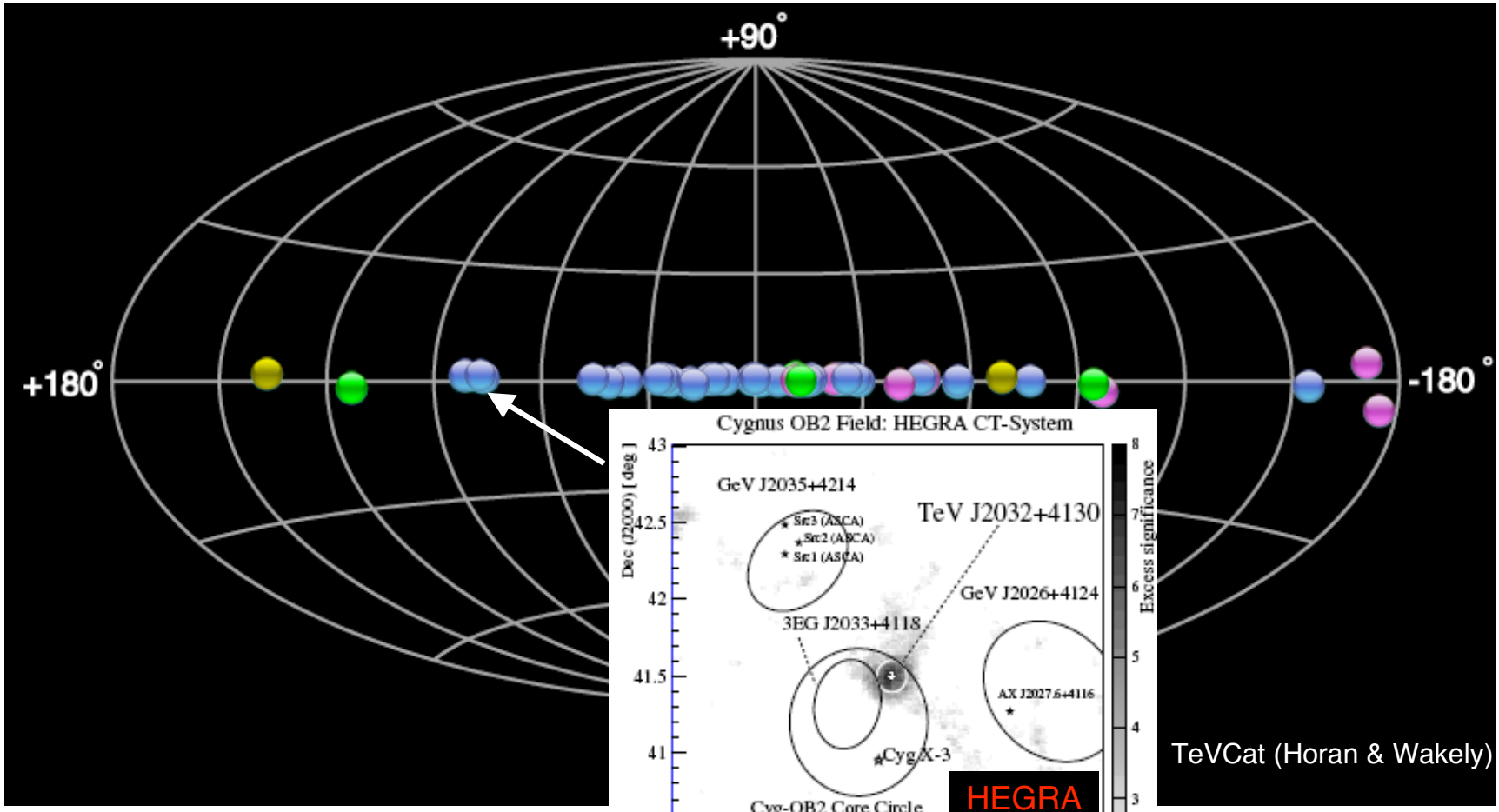
More details in talk by Brenda Dingus

Abdo et al. 2006

TeV Skymap of Galactic Sources



TeV Skymap of Galactic Sources



Aharonian et al. 2005

Catalog of Galactic TeV sources

Name	RA	Dec	l	b	Crab fux	radius	Assoc.
LSI +61 303	02:40:31.7	61:13:46					X-Ray Binary
Crab	05:34:31.9	22:00:52	184.56	-5.78	1	0	Crab nebula
IC443	06:16:43	22:31:48					
HESS J0632+057	6:32:58	5:48:20	205.66	-1.44	0.03	0	
HESS J0835-455	8:35:00	-45:36:00	263.86	-3.09	0.75		la X
HESS J0852-463	8:52:00	-46:22:00	266.28				J0852.0- la Junior)
HESS J1023-575	10:23:18						WR 20a; Westerlund 2;
HESS J1302-638	13:02:				0.07	0	PSR B1259-63 / SS 2883
HESS J1303-631	13:03:0		304.24	-0.36	0.17	9.6	
HESS J1418-609	14:18:02	-60:58:12	313.25	0.16	0.06	4.2	G313.3+0.1 (Rabbit)
HESS J1420-607	14:20:12	-60:45:32	313.56	0.27	0.07	3.6	PSR J1420-6048 ? (Kookaburra)

51 sources including 4 Milagro sources plus an additional 17 extragalactic sources

Compiled from online HESS Source Catalog & TeVCat

Catalog of Galactic TeV sources

Name	RA	Dec	l	b	Crab fux	radius	Assoc.
HESS J1427-608	14:27:52	-60:51:00	314.41	-0.15	0.035	4.8	
HESS J1514-591	15:14:07	-59:09:27	320.33	-1.19	0.15	6	MSH 15-5 2
★ HESS J1614-518	16:14:19	-51:49:12	331.52	-0.58	0.25	12	
★ HESS J1616-508	16:16:24	-50:54:00	332.39	-0.14	0.19	8.2	PSR J1617-5055 ?
HESS J1626-490	16:26:04	-49:05:13	334.77	0.05	0.13	6	
★ HESS J1632-478	16:32:10	-47:49:12	336.38	0.19	0.12	12.6	IGR J16320-4751 ?
★ HESS J1634-472	16:34:58	-47:16:12	337.11	0.22	0.06	6.6	IGR J16358-4726 ?; G337.2+0.1 ?
★ HESS J1640-465	16:40:43	-46:31:48	338.32	-0.02	0.09	2.7	G338.3-0.0 ?; 3EG J1639-4702 ?

★ *Sources detected in the initial HESS survey of the inner galaxy (Aharonian et al. 2006)*

Catalog of Galactic TeV sources

Name	RA	Dec	l	b	Crab fux	radius	Assoc.
HESS J1702-420	17:02:46	-42:04:12	344.26	-0.22	0.24	18	
HESS J1708-410	17:08:14	-41:04:48	345.67	-0.44	0.07	4.8	
HESS J1713-381	17:13:58	-38:12:00	348.65	0.38	0.018	3.6	CTB 37B (G348.7+0.3) ?
HESS J1713-397 RX J1713.7-3946	17:13:00	-39:45:00	347.28	-0.38	0.66	15	RX J1713.7-3946, G347.3-
HESS J1718-385	17:18:07	-38:33:36	348.83	-0.49	0.015	9	PSR J1718-3825 ?
HESS J1731-347	17:31:55	-34:42:36	353.57	-0.62	0.16	10.8	
HESS J1745-290	17:45:41	-29:00:22	359.95	-0.05	0.05	0	Sgr A* / Sgr A East ?
HESS J1745-303	17:45:02	-30:22:12	358.71	-0.64	0.05	12.6	3EG J1744-3011 ?
HESS J1747-281	17:47:23	-28:09:06	0.87	0.08	0.02	0	G0.9+0.1
HESS J1800-240A	18:01:58	-23:57:43	6.14	-0.63	0.03	9	G006.1-006; (W 28)

Catalog of Galactic TeV sources

Name	RA	Dec	l	b	Crab fux	radius	Assoc.
HESS J1800-240B	18:00:26	-24:02:20	5.90	-0.37	0.03	9	W 28-A2
HESS J1800-240C	17:58:52	-24:03:07	5.71	-0.06	0.018	1	(W 28)
HESS J1801-233	18:01:42	-23:20:06	6.66	-0.27	0.03	10	W 28; GRO J1801-2320
HESS J1804-216	18:04:31	-21:42:00	8.40	-0.03	0.25	12	G8.7-0.1 / W30 ?; PSR J1803-2137 ?
HESS J1809-193	18:09:21	-19:27:00	10.92	0.08	0.14	32	PSR J1809-1917 ?
HESS J1813-178	18:13:36	-17:50:24	12.81	-0.03	0.06	2.2	G12.8-0.02; AX J1813-178
HESS J1825-137	18:26:02	-13:45:36	17.82	-0.74	0.17	9.6	PSR J1826-1334; 3EG J1826-1302 ?

Catalog of Galactic TeV sources

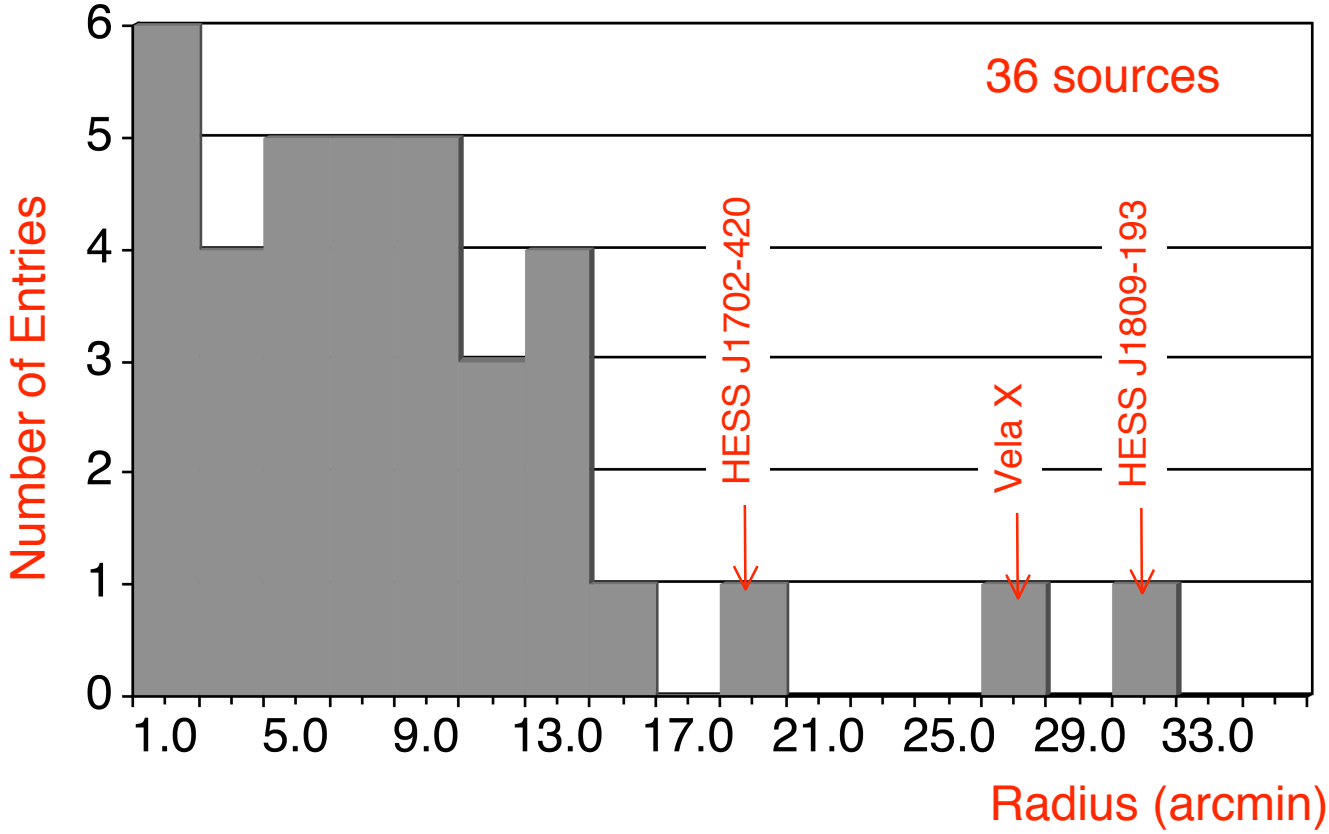
Name	RA	Dec	l	b	Crab fux	radius	Assoc.
HESS J1826-148	18:26:15	-14:49:30	16.90	-1.28	0.03	0	LS 5039
★ HESS J1834-087	18:34:46	-8:45:36	23.24	-0.31	0.08	5.4	G23.3-0.3 / W41?
★ HESS J1837-069	18:37:38	-6:57:00	25.18	-0.12	0.132	7.2	G25.5+0.0 ?; AX J1838.0-0655 ?
HESS J1841-055	18:40:55	-5:33:00	26.80	-0.20	0.13	25	
HESS J1857+026	18:57:11	2:40:00	35.96	-0.06	0.16	6.6	
HESS J1858+020	18:58:20	2:05:24	35.58	-0.58	0.016	4.8	
MGRO J1908+06	19:08:00	06:00:00					
HESS J1912+101	19:12:49	10:09:06					
MGRO J2019+37	20:19:00	37:00:00					
MGRO J2031+41	20:31:00	41:00:00					
TeV J2032+4130	20:32:07	41:30:30					

47 Galactic sources!

First unidentified TeV source

VHE Source Population Characteristics

Most of the Galactic TeV sources are extended
(Size is resolved if > 2-3')

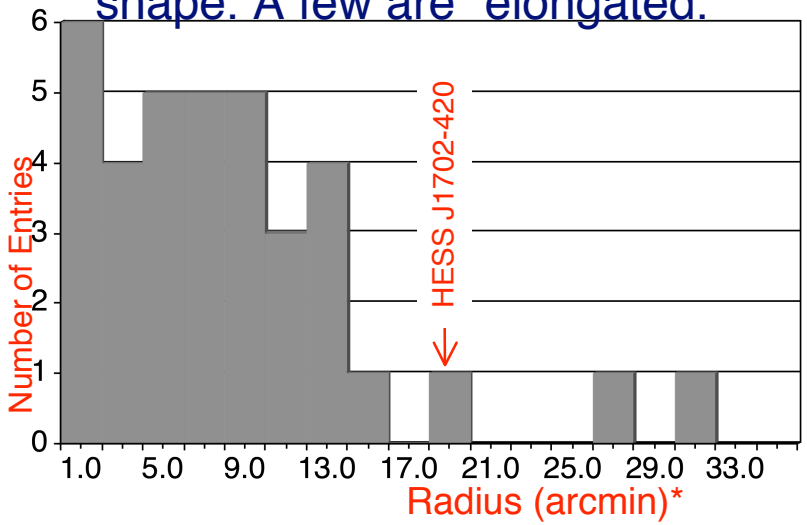


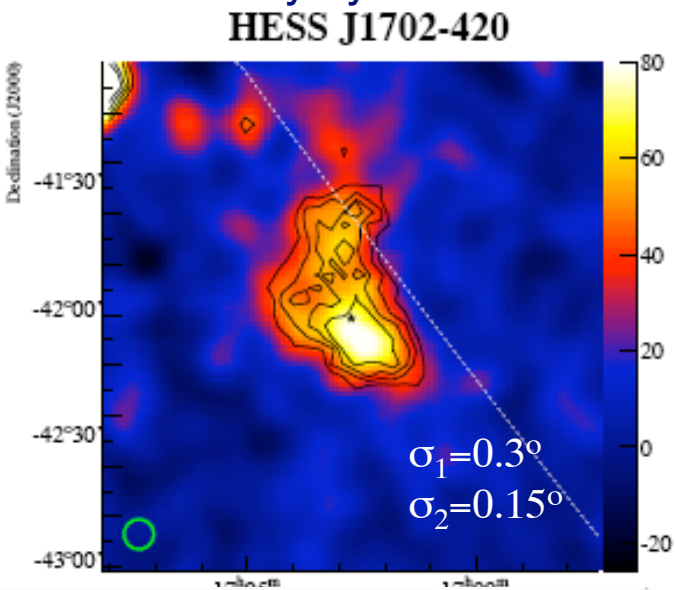
* For extended sources, take average of sem-major and -minor axes

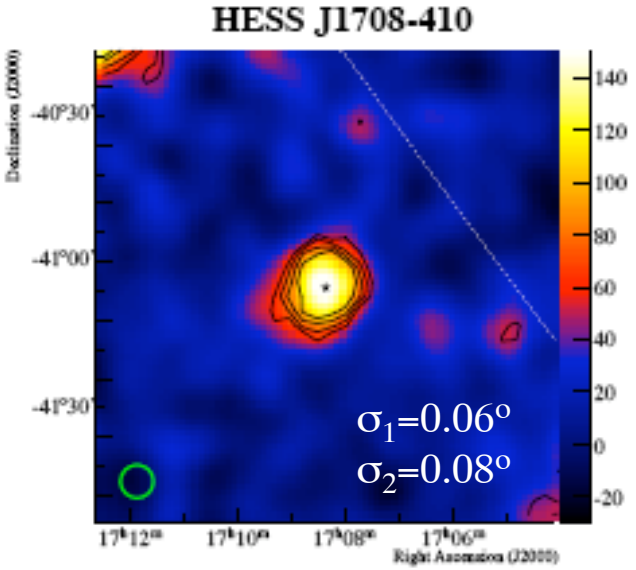
Data: HESS Source Catalog http://www.mpi-hd.mpg.de/hfm/HESS/public/HESS_catalog.htm

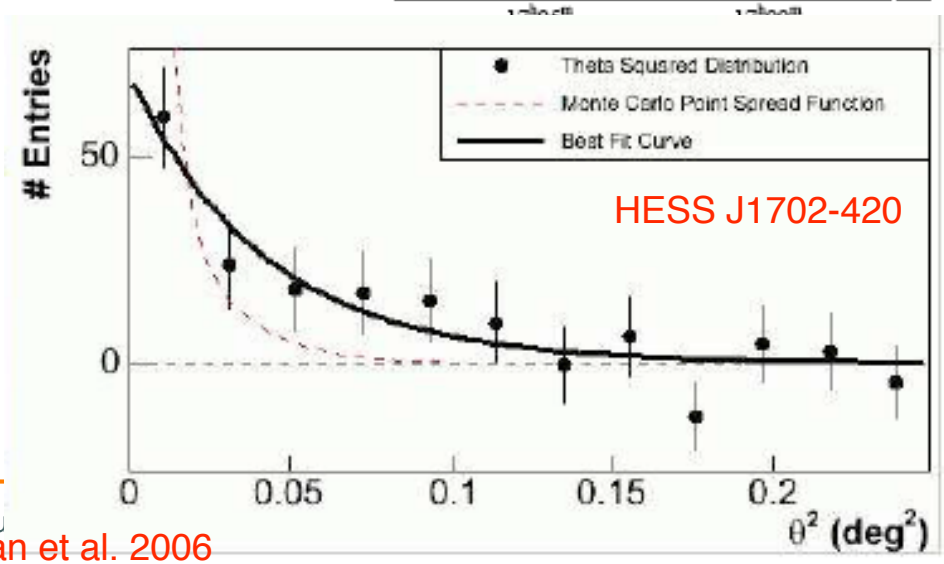
VHE Source Population Characteristics

Most extended HESS sources are compatible with radially symmetric shape. A few are "elongated."





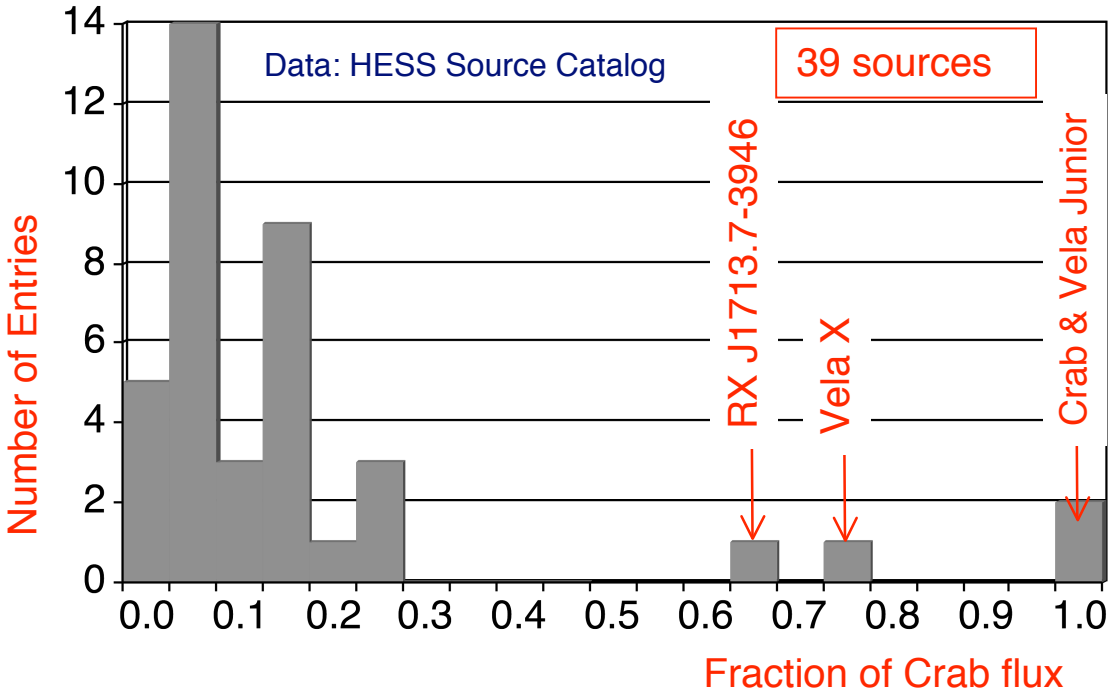




Aharonian et al. 2006

VHE Source Population Characteristics

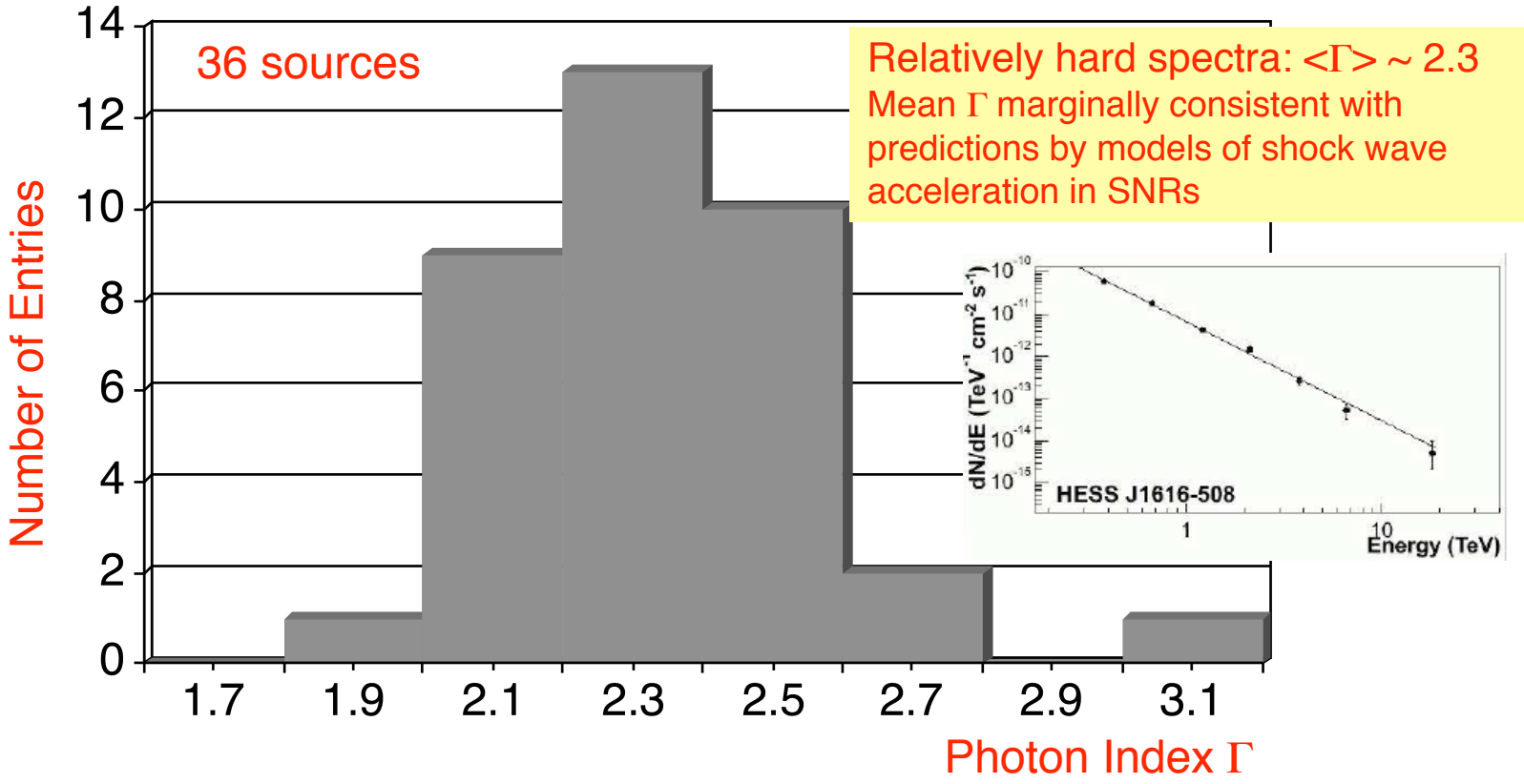
Most of the Galactic TeV sources are < 10% of the Crab flux



- Integral fluxes (>200 GeV) ranges: (0.6 to 60)X10^{-12} cm^{-2} s^{-1}
  - This corresponds to ~2 - 25% of Crab Nebula flux
- Most likely associations of the γ-ray sources lie at ~4-10 kpc within our Galaxy, and exhibit luminosities in the range 2-30 X 10^{34} erg s^{-1} (Aharonian et al. 2006)

VHE Source Population Characteristics

Distribution of the photon index of Galactic TeV sources



Data compiled from: HESS "new" VHE sources: Aha 2006 ApJ 636, Aha 2008 A&A 358.

IC 443 (MAGIC), LSI (VERITAS), Crab (HESS), LS 5039 (HESS), MSG 15-52 (HESS), Vela X (HESS), Other HESS sources from HESS publications available via TeVCat.

X-ray Observations of TeV Fields

Goal: Understand the physical nature of the emission mechanisms in unidentified TeV sources.

What we have learnt from TeV sky surveys:

- TeV sources could be extended or point-like γ-ray sources.
- Fields that include catalogued X-ray sources (ASCA, ROSAT, EXOSAT, …).

Motivation for X-ray follow-ups:

- Detailed search for X-ray counterparts, follow-up of the known X-ray sources.
- Spectral analysis -- might establish the electronic or hadronic nature of the parent particles of the TeV source.
- Timing studies.
- Morphology.

or…

TeV sources with no plausible counterparts: “dark” accelerators ?

Galactic TeV Source Classes

- Supernova Remnants (SNRs)
- Pulsars and PWNe
- Young Star clusters
- Unidentified *but several are PWNe)*
- Dark Accelerators/new source class ??

- Binary pulsar PSR B1259-63, microquasars
- X-ray binaries
- Diffuse emission
- Galactic center

See Chuck Dermer's talk

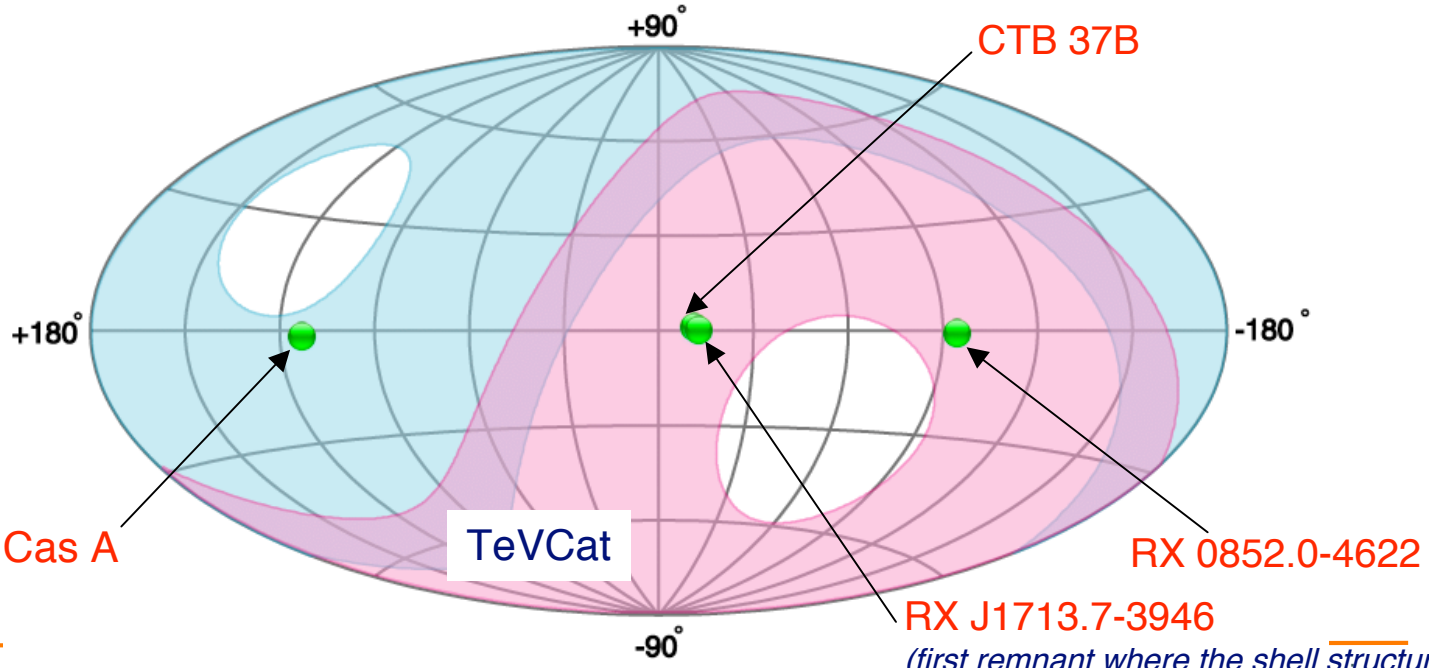
Galactic TeV Sources: SNRs

- Supernova Remnants (SNRs):
  - Shell-type morphology detected in TeV image.
  - X-ray image also shows shell morphology
  - Evidence of SNR shock waves accelerating particles
  - Well-resolved SNRs RX J1713.7-3946 and RX J0852.0-4622 by HESS Cas A (VERITAS & MAGIC)

More on SNRs in Pat Slane's talk

SNRs suspected to be cosmic ray acceleration sites (e.g. Drury, Aharonian. Volk 1994)

Also, IC 443, HESS J1731-347, HESS J1801-233 W28, RCW 86

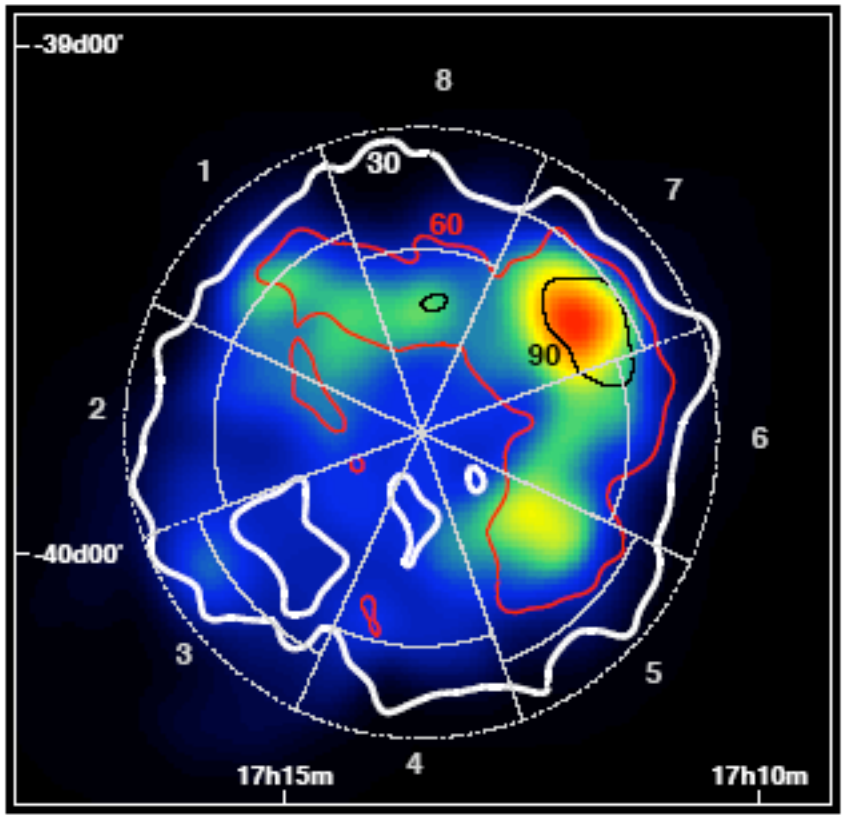


(first remnant where the shell structure was detected in VHE gamma rays)

Detailed spectral and morphological study of SNR RX J1713.7-3946 with H.E.S.S:

Galactic shell-type SNR (G347.3-0.5):

- Shell-Type Supernova Remnants: Particles accelerated to at least 100 TeV



γ-rays detected throughout the whole SNR - resembles shell structure.

No decisive conclusions yet about the parent particle population dominantly responsible for the γ−ray emission from RXJ1713.7−3946:

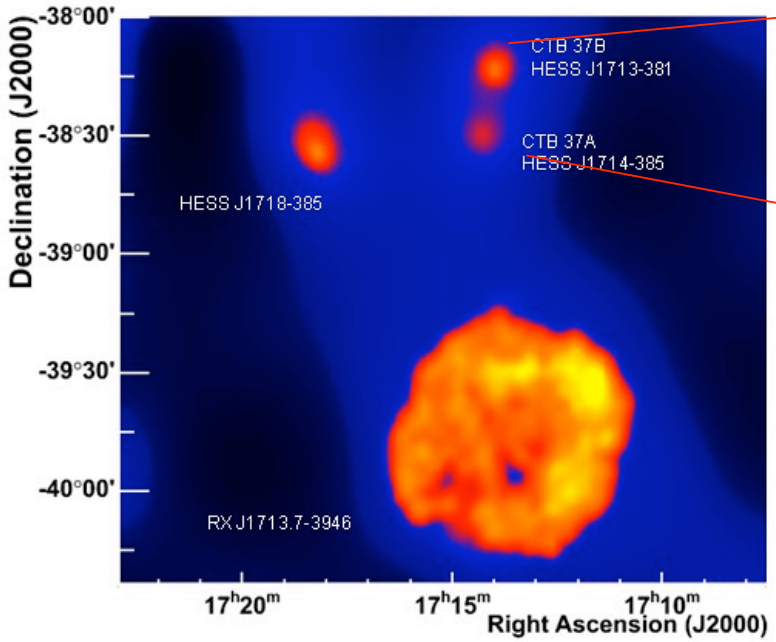
Both leptonic (IC scattering off VHE electrons) and hadronic π^0 decay) could explain the spectrum.

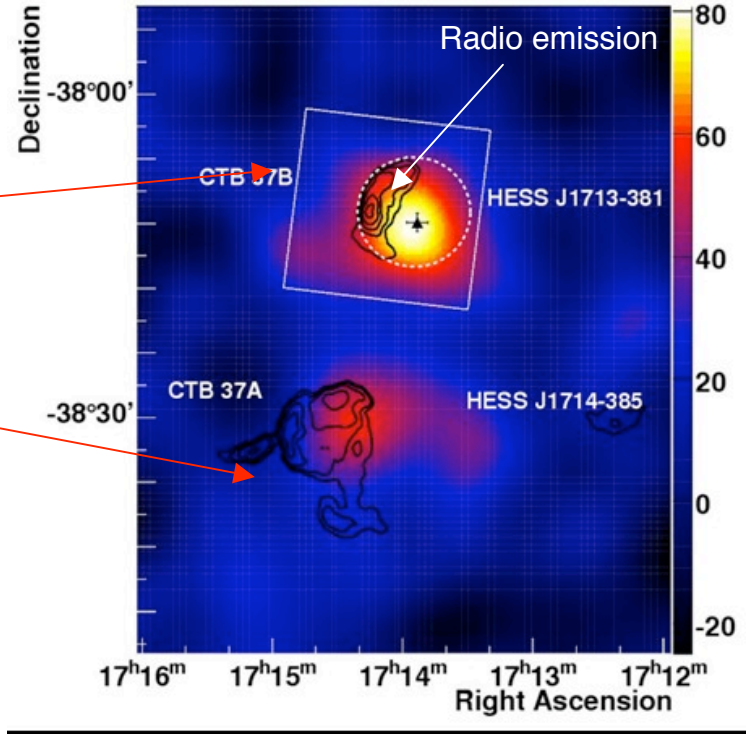
astro-ph/0411533

Spectrum measured in 190 GeV-40 TeV.
Striking correlation between X-ray and γ-ray image.
Radial profiles in both wavelength regimes reveal the same shape almost everywhere in the region of the SNR.

Galactic TeV Sources: SNRs

- CTB 37B





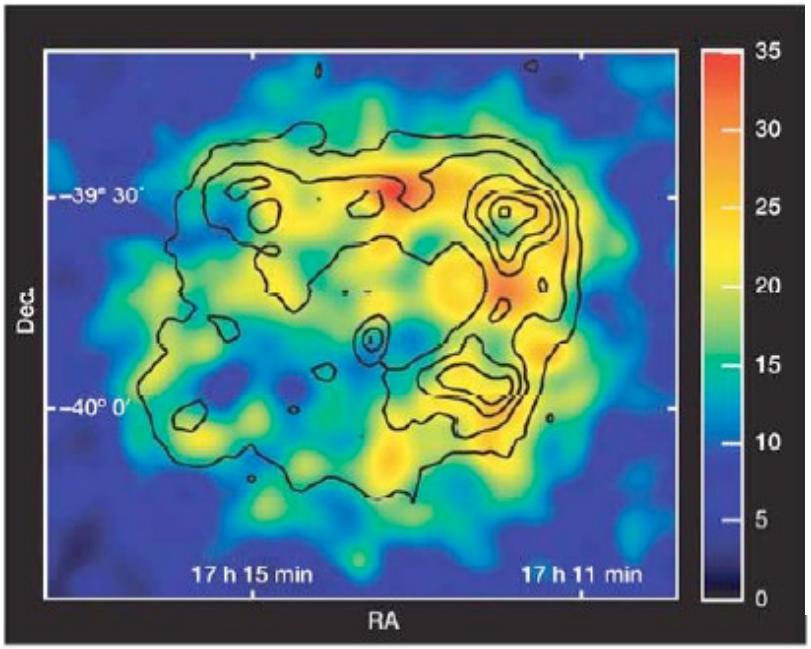
Aharonian et al. arXiv:0803.0682

- Extended source ~2.6'
- Part of 5' shell is visible in radio
- Chandra X-ray observations shows interesting point source and thermal diffuse emission

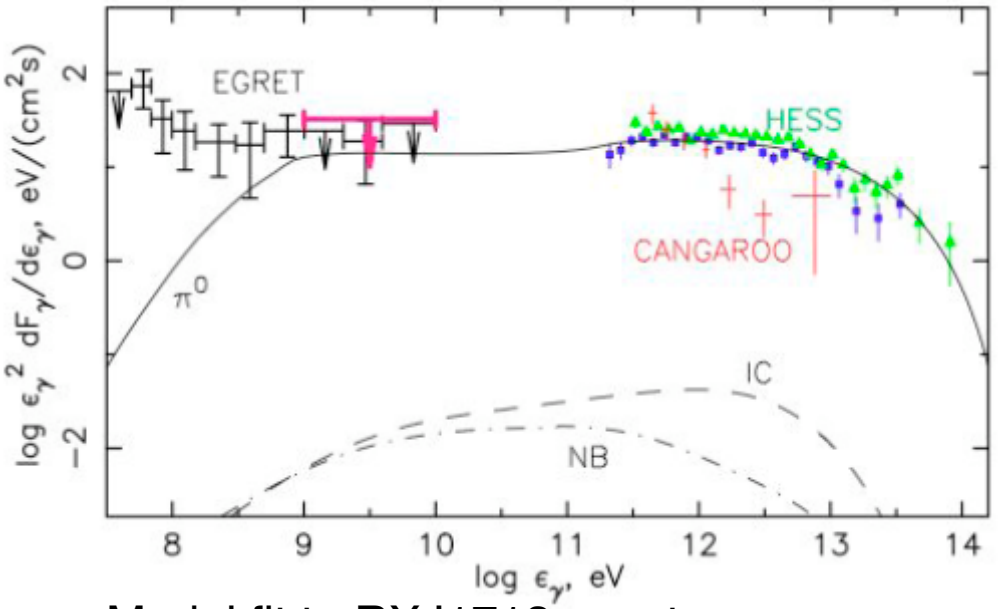
Galactic TeV Sources: SNRs

- Shell-Type Supernova Remnants: Particles accelerated to at least 100 TeV

Well-resolved SNRs RX J1713.7-3946 and RX J0852.0-4622 by HESS
Cas A (VERITAS & MAGIC)



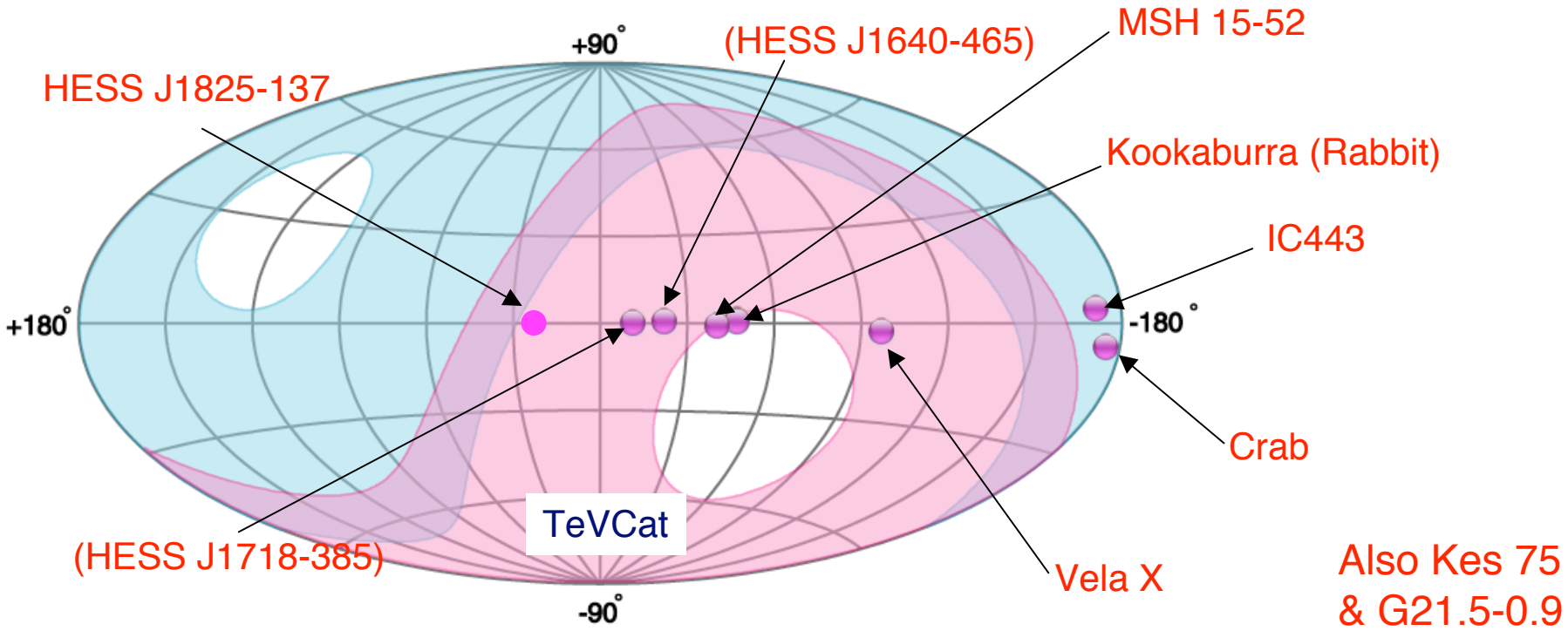
RX J1713.7-3946 HESS image + ASCA 1-3 keV contours



Model fit to RXJ1713 spectrum (Berezhko and Völk)
Primary population: e^- or p?

Galactic TeV Sources: Pulsars and PWNe

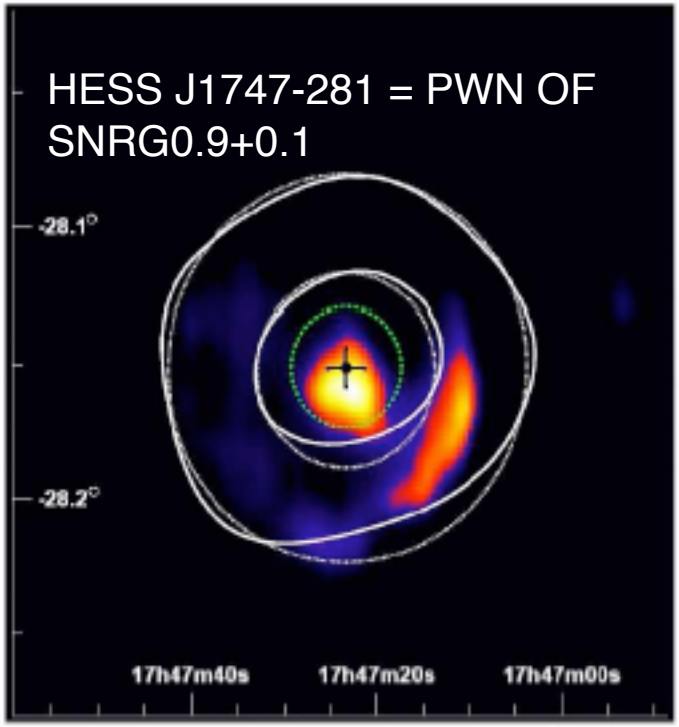
- PWNe are the largest class of the identified Galactic TeV sources.
- No pulsed emission detected at TeV, except for recent detection from Crab by MAGIC.
- Several PWNe are offset from pulsar position.



Galactic TeV Sources: Pulsars and PWNe

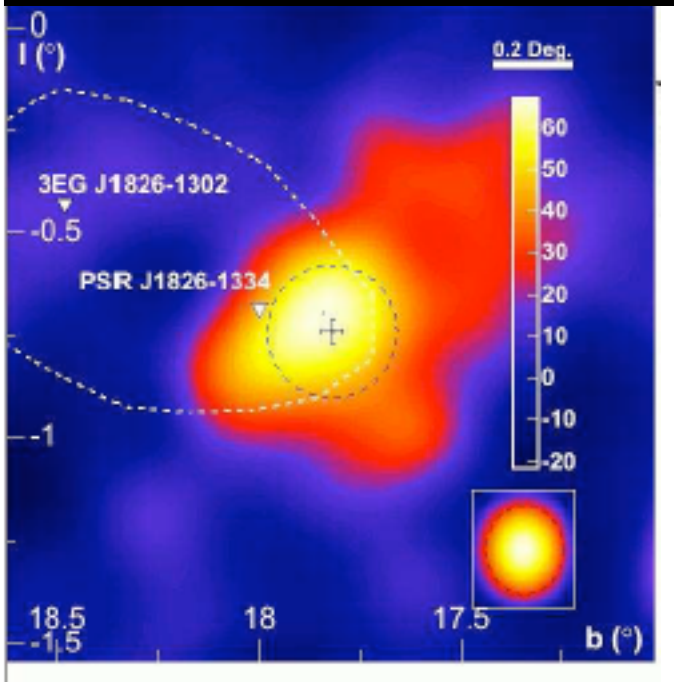
Acceleration of relativistic jets:

- Jets accelerated by pulsars which power PWN
- Black hole jets from microquasars (LS 5039)*



The 90 cm radio flux map of G0.9+0.1 with HESS confidence contour.
Green dashed : 95% UL HESS size.

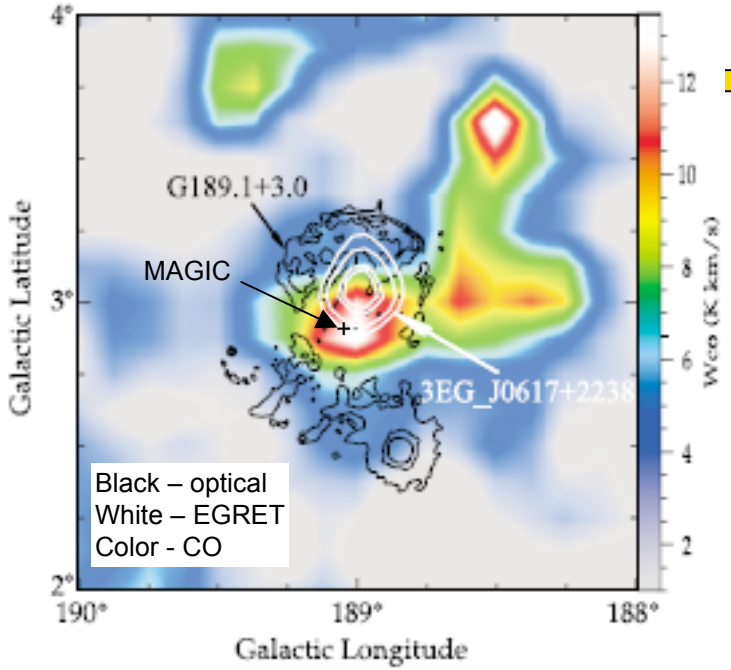
HESS J1825-137 =(?) G18.0-0.7
= PWN OF PSR B1823-13

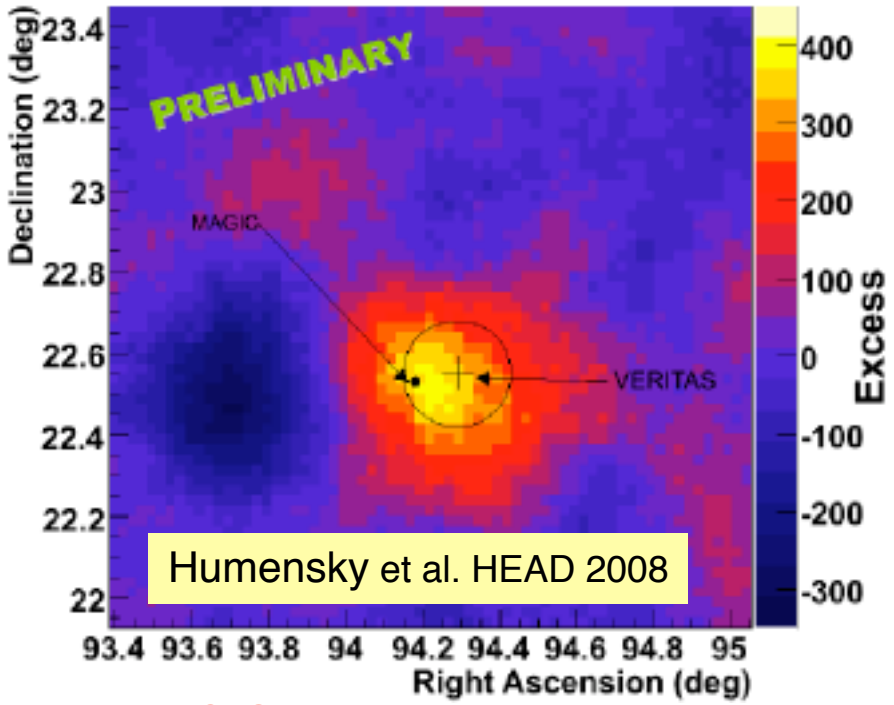


PWN - a nebula generated by the stream of relativistic electrons and positrons from the pulsar.

de Jager et al. astro-ph/0602078

SNR IC 443





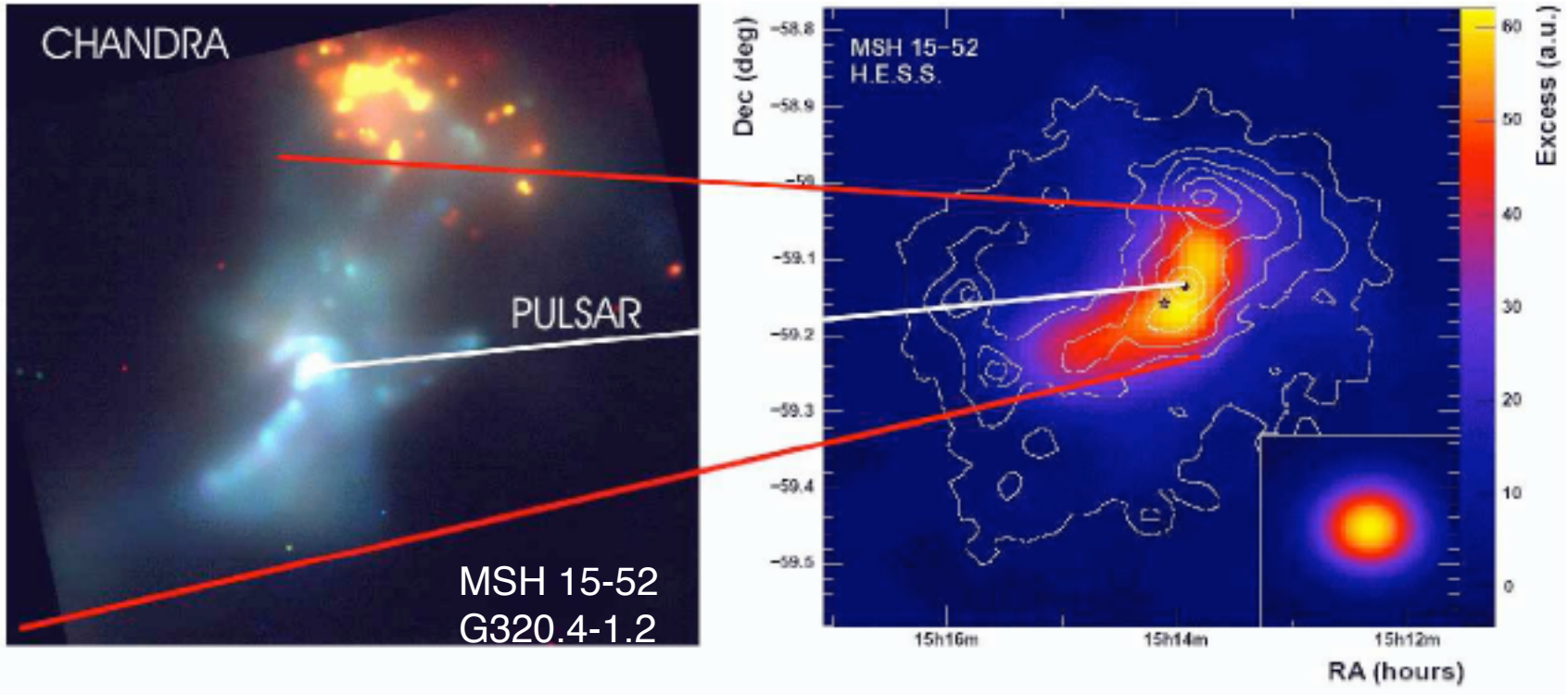
- Shell interacting with molecular cloud -> potential target material
- EGRET emission centered on remnant, overlaps cloud
- MAGIC emission centered on cloud
- PWN at southern edge of shell, inferred Edot~10^{36} erg/s

VERITAS Observations

- ~ 34 hrs data (2007)
- 8.25σ excess, 0.19 +/- 0.02 γ/min
- Flux (>200 GeV) ~ 3% Crab.
- Extended source
- VERITAS consistent with MAGIC and cloud.

Compelling reason to search for TeV emission from IC 443: γs from cosmic rays, or PWN?

HESS J1514-591 = PWN of PSR B1509-58



HESS image of the PWN of PSR B1509-58 shows a similar jet structure as seen in the Chandra image. Contours are ROSAT PSPC data.

First time that an astrophysical jet has been resolved in the γ-ray domain?

de Jager et al. astro-ph/0602078

Galactic TeV Sources: Pulsars and PWNe

- Several unidentified HESS sources are associated with PWNe candidates

VHE Source	PSR Name	Required efficiency for VHE PWN candidate
HESS J1303-631	J1301-6305	7%
HESS J1616-508	J1617-5055	1%
HESS J1702-420	J1702-4128	11%
HESS J1718-385	J1718-3825	0.5%
HESS J1804-216	B1800-21	2%
HESS J1809-193	J1809-1917	2%
HESS J1837-069	J1838−0655	2%
HESS J1912+101	J1913+1011	2%
HESS J1640-465	Possible VHE PWNe with undetected pulsars	
HESS J1813-178		

See Review talk on PWNe by Jules Halpern & Oleg Kargaltsev

References:
Kargaltsev et al. (2008),
Kargaltsev et al. (2007),
Gotthelf & Halpern (2008),
Gallant et al. (2008)

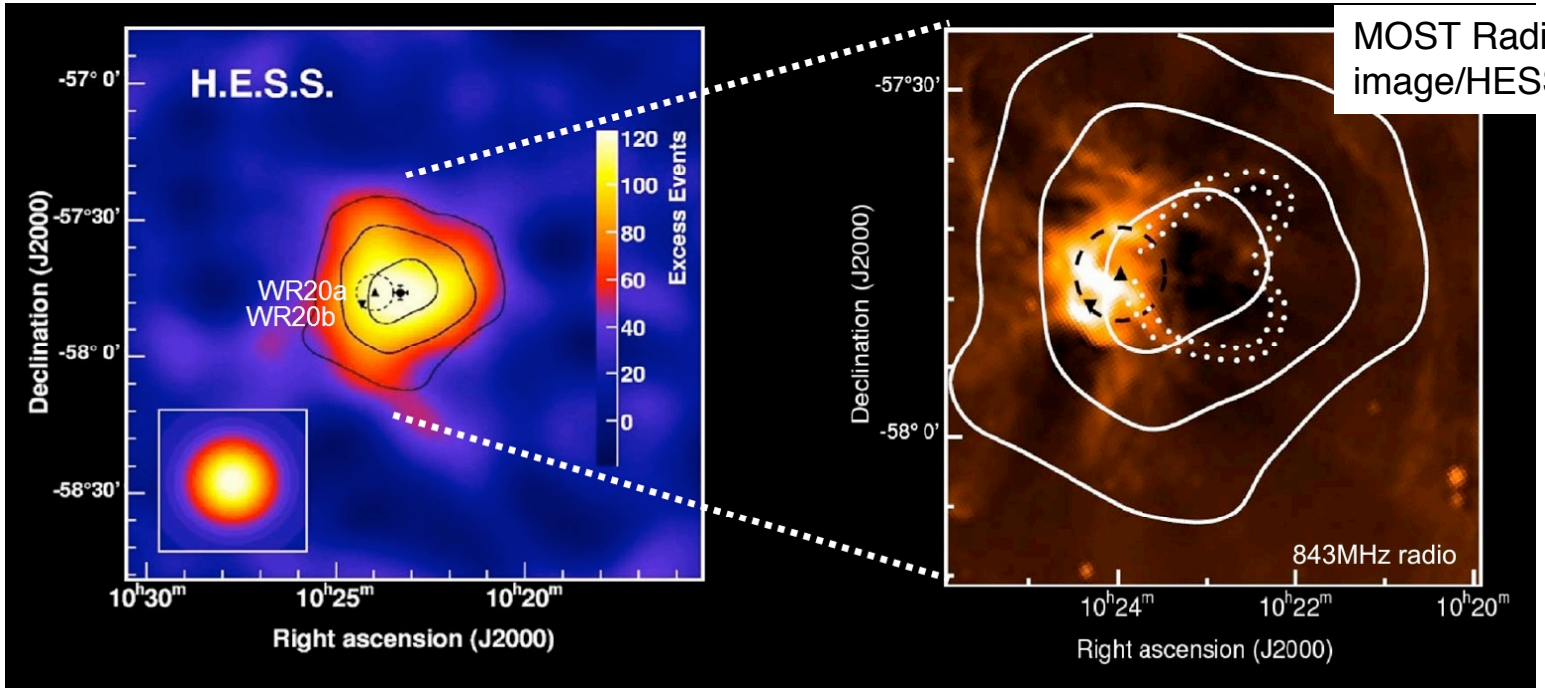
Chandra & RXTE data, X-ray pulsar. First pulsar located by its γ-ray emission

See talk X-ray studies of HESS fields by Eric Gotthelf

Other types of sources …

Galactic TeV Sources: Young Stellar Clusters

- Discovery of a new type of very-high-energy γ-ray emitter: Westerlund2 stellar cluster/HESS J1023-575



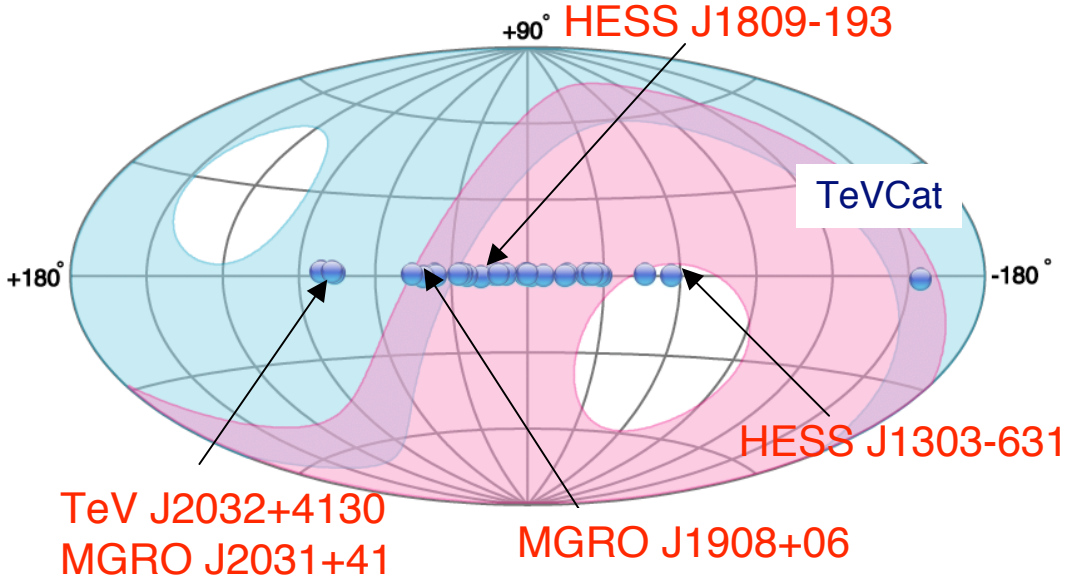
- High energy γ-ray emission associated with a stellar cluster characterized by ongoing star formation and presence of massive Wolf-Rayet stars.
- Stellar winds could be sites of extreme particle acceleration.

Reimer et al., arXiv:0710.3518

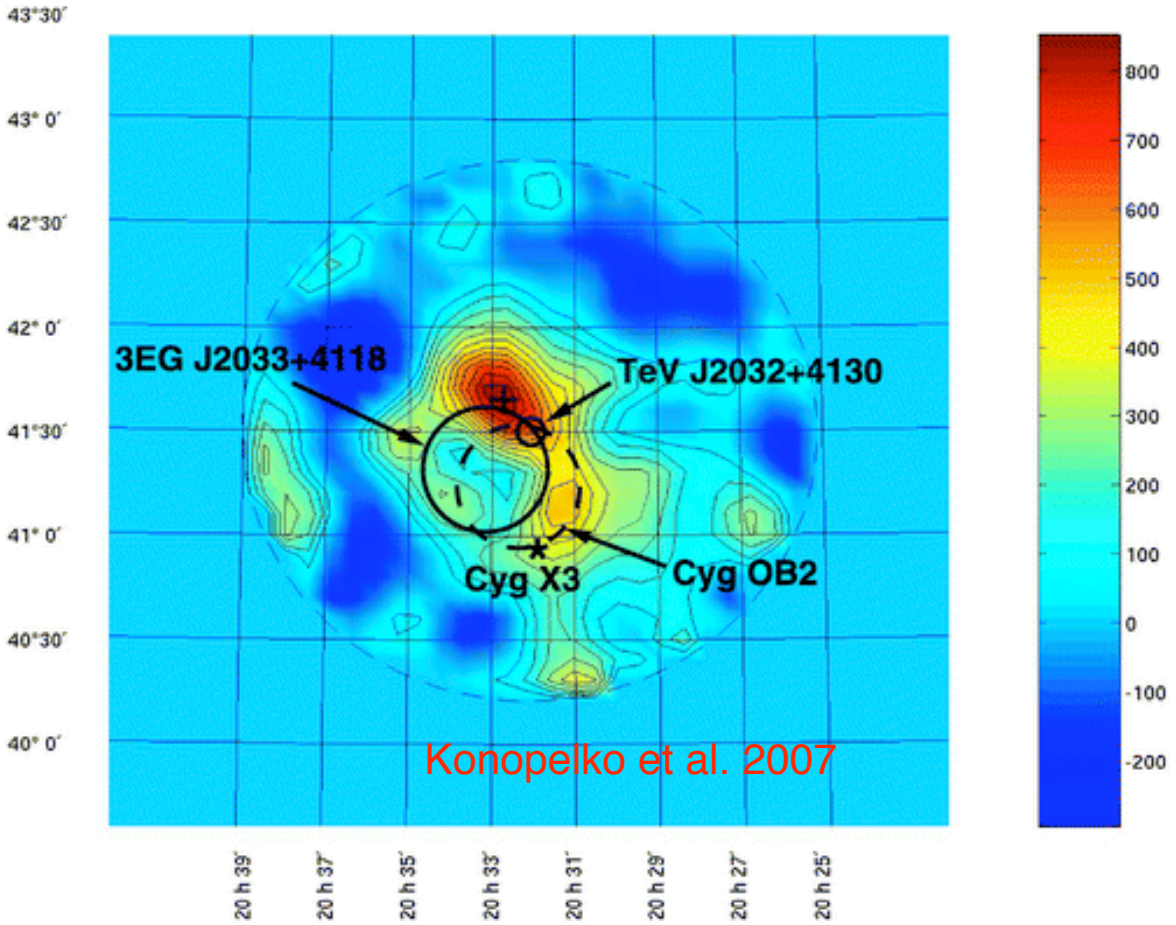
TeV Sources with no Counterparts: *Dark Accelerators?*

- 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.

~ 13 sources
(including Milagro
with no counterparts)



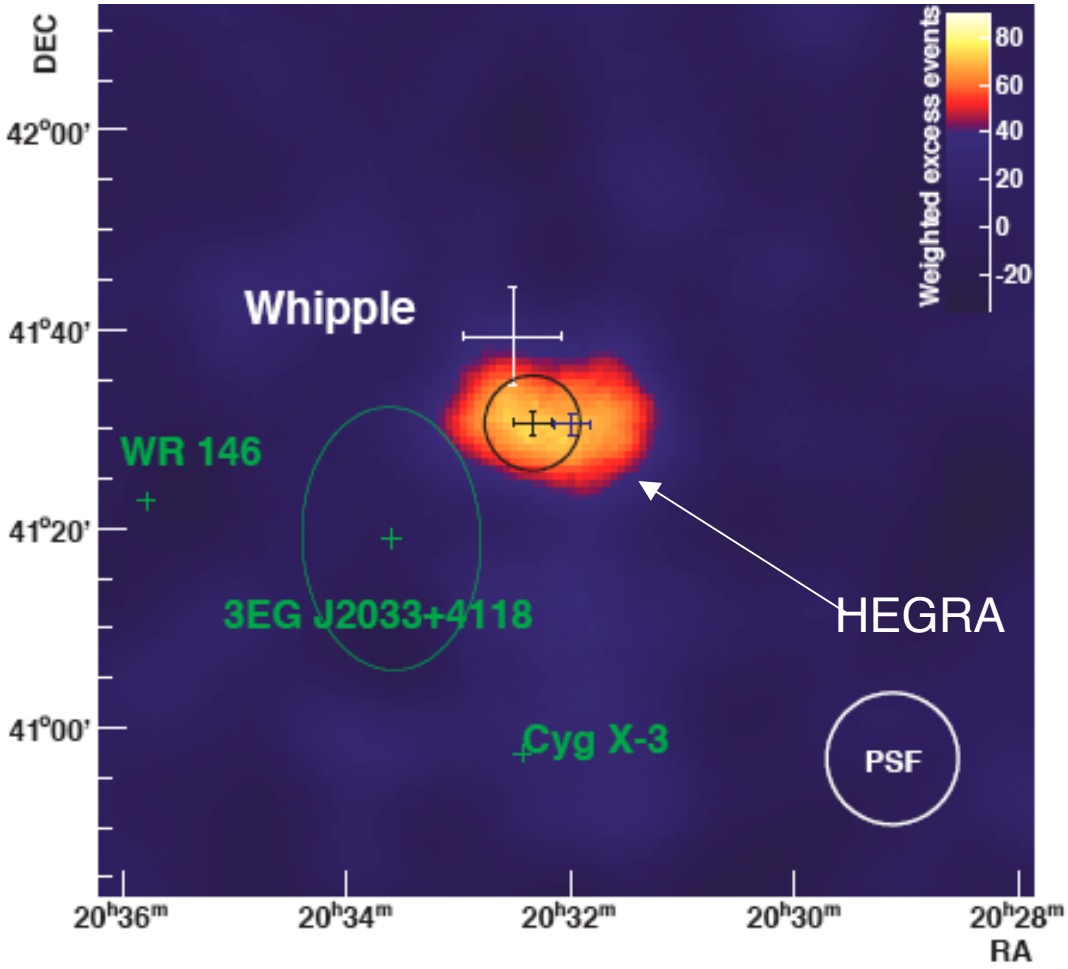
TeV Sources with no Counterparts: *Dark Accelerators?*



Whipple Skymap of region around TeV J2032+4130

TeV Sources with no Counterparts: *Dark Accelerators?*

MAGIC Skymap of region around TeV J2032+4130



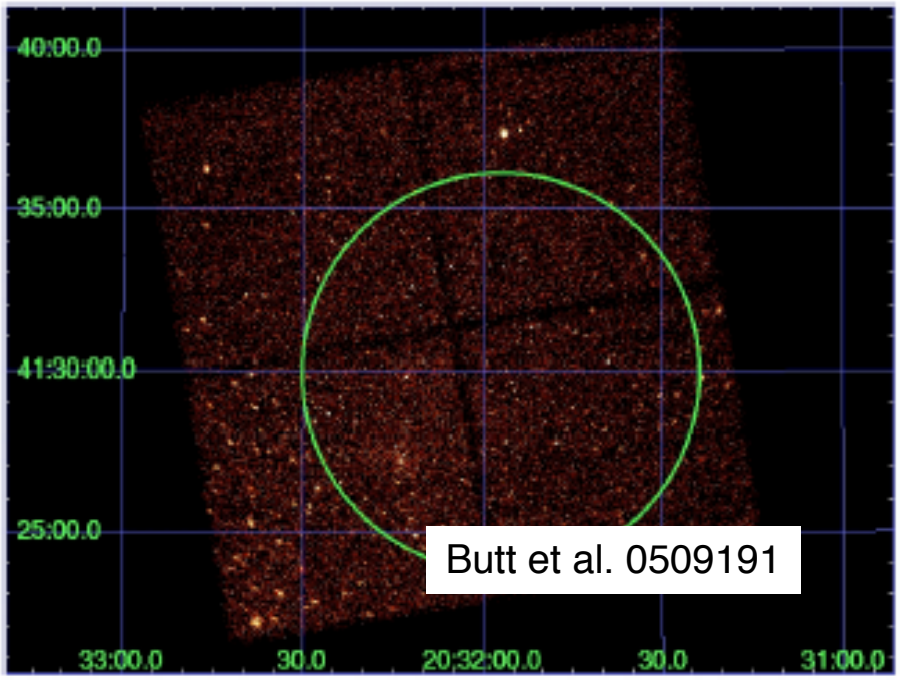
E> 500 GeV
extended source

Albert et al. 2008

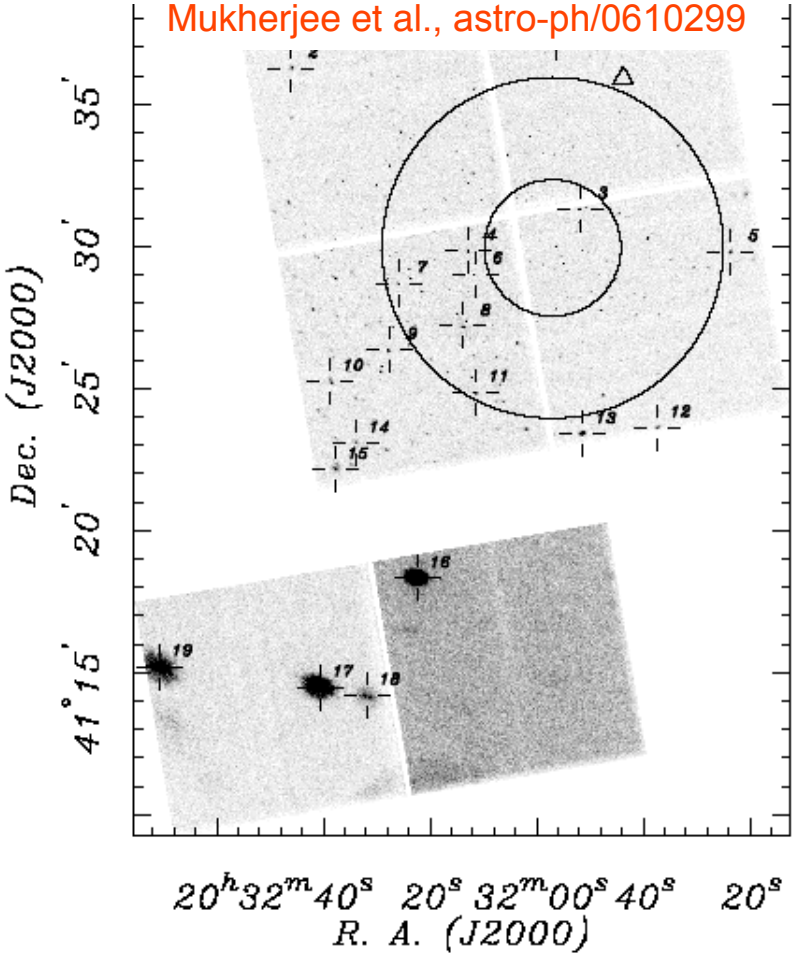
TeV Sources with no Counterparts: *Dark Accelerators?*

In some cases….

No counterparts, even after deep X-ray observations: (5ks DDT, 50 ks *Chandra)*



Mukherjee et al., astro-ph/0610299



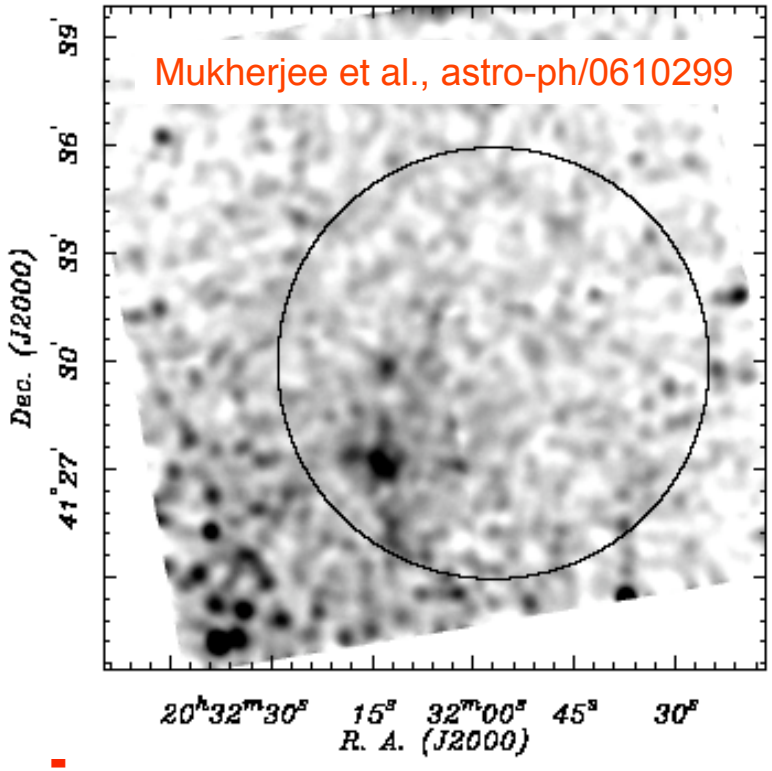
- TeV J2032+4130: 50 ks Chandra reveals no compelling counterpart. Related to multiple stellar X-ray sources associated with Cyg OB2?

TeV Sources with no Counterparts: *Dark Accelerators?*

In some cases….

No counterparts, even after deep X-rav observations:

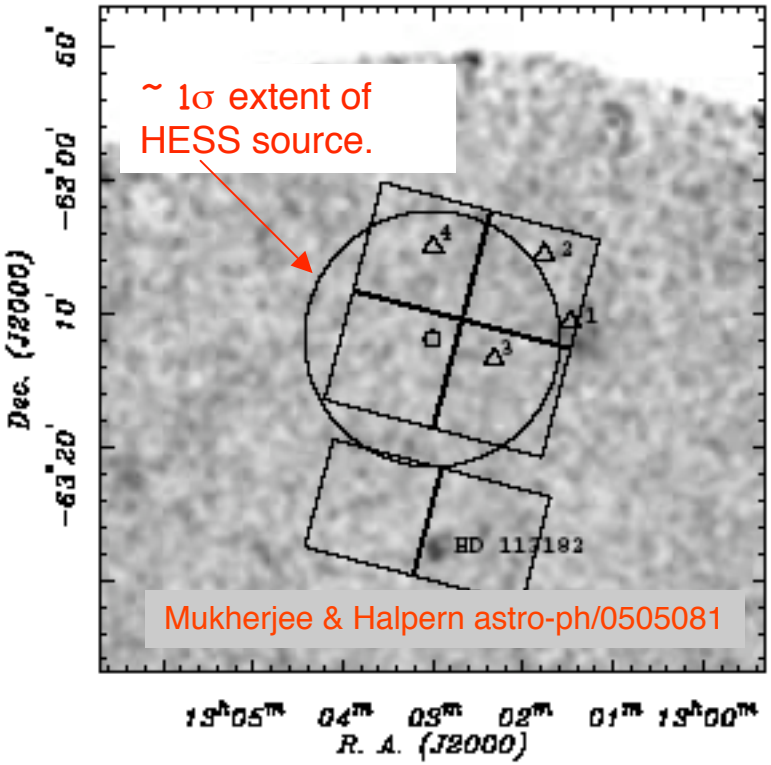
- No convincing point source counterpart to TeV J2032+4130 in the X-ray band.
- Unlikely to be a blazar.
- Significant hard diffuse X-ray emission within the error circle of TeV J2032+4130. High energy particles are being accelerated in the stellar winds associated with the massive stars in the region.
- If the source of the diffuse emission is embedded in the Cygnus OB2 association at d = 1740 pc (MT91), the corresponding luminosity is 3×10^{31} erg s^{-1}.

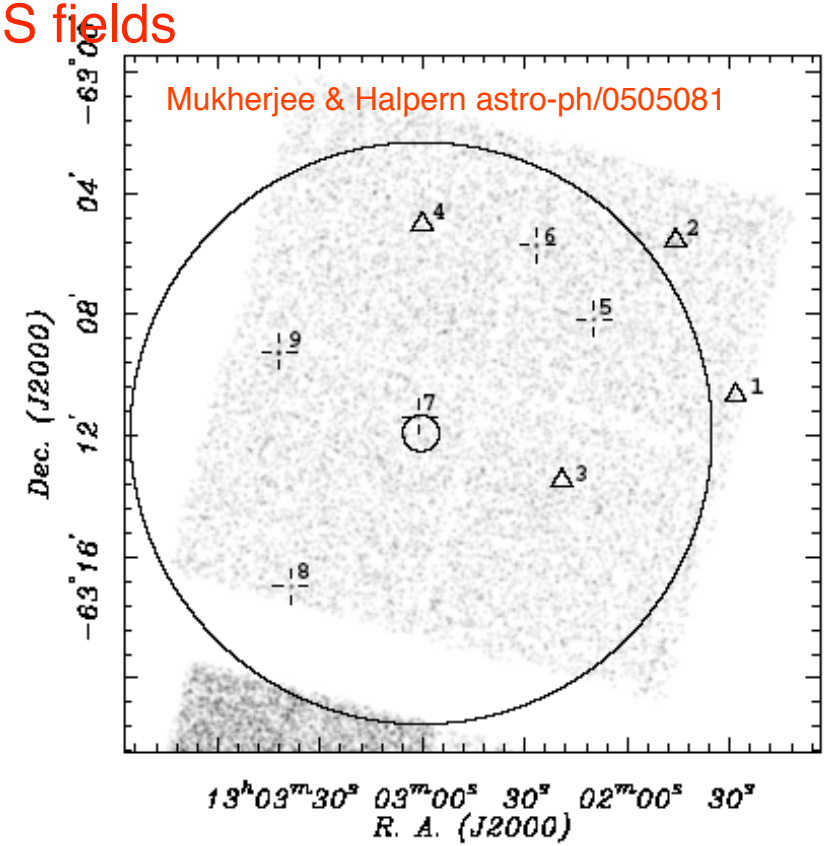


- ….
- Dual-lobed radio source? (Butt et al. 2008)
- Dark accelerators?
- GRB remnants ?? (astro-ph/0509615)

TeV Sources with no Counterparts: HESS J1303-631?

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)

TeV Sources with no Counterparts: HESS J1303-631?

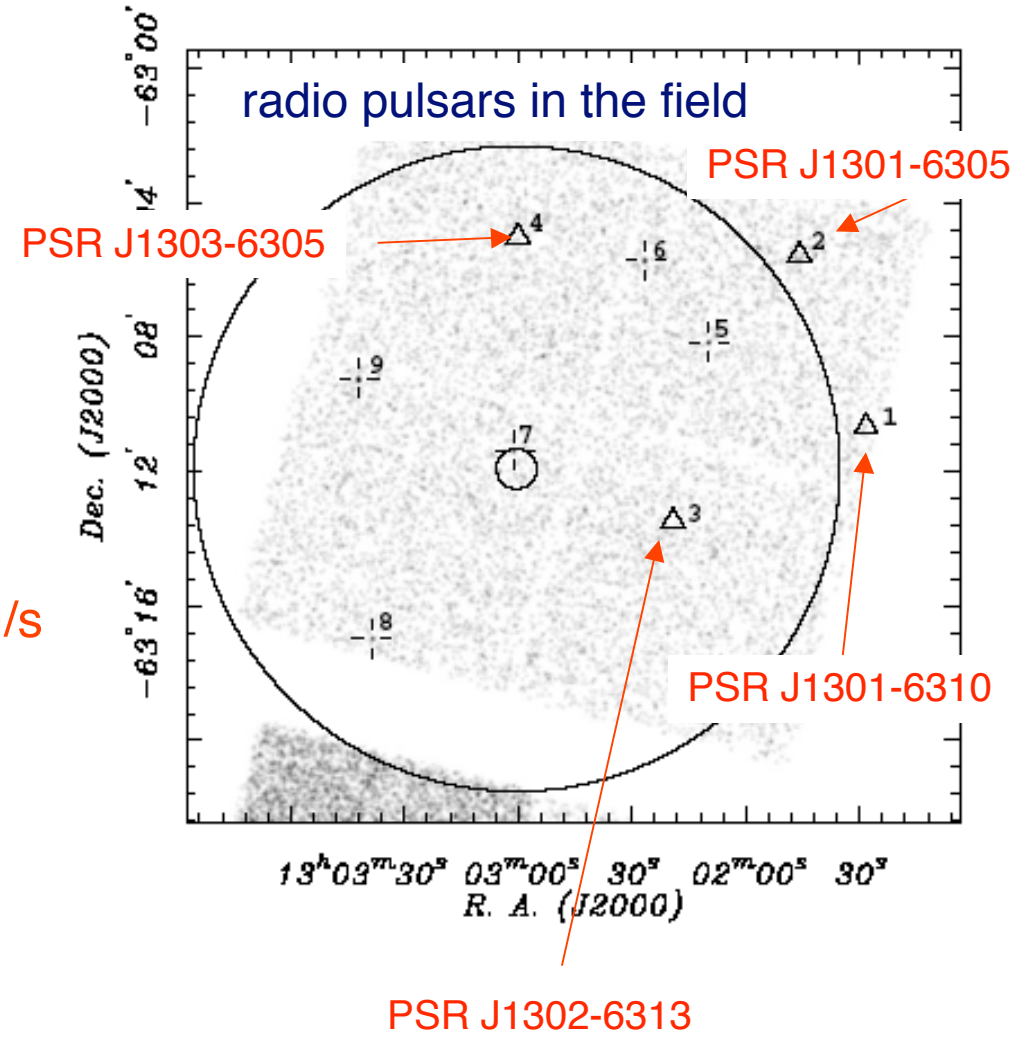
PSR J1303-6305:

d=15.8 kpc
(Taylor & Cordes 1993)

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

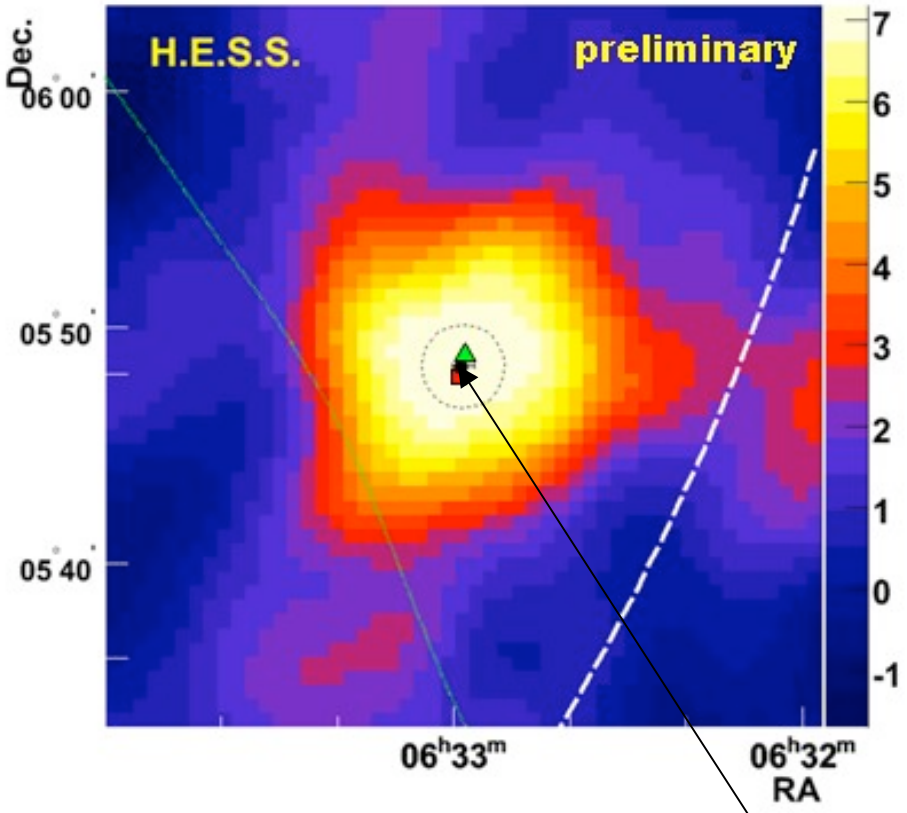
initial spin-down power: ~10^{38} erg/s

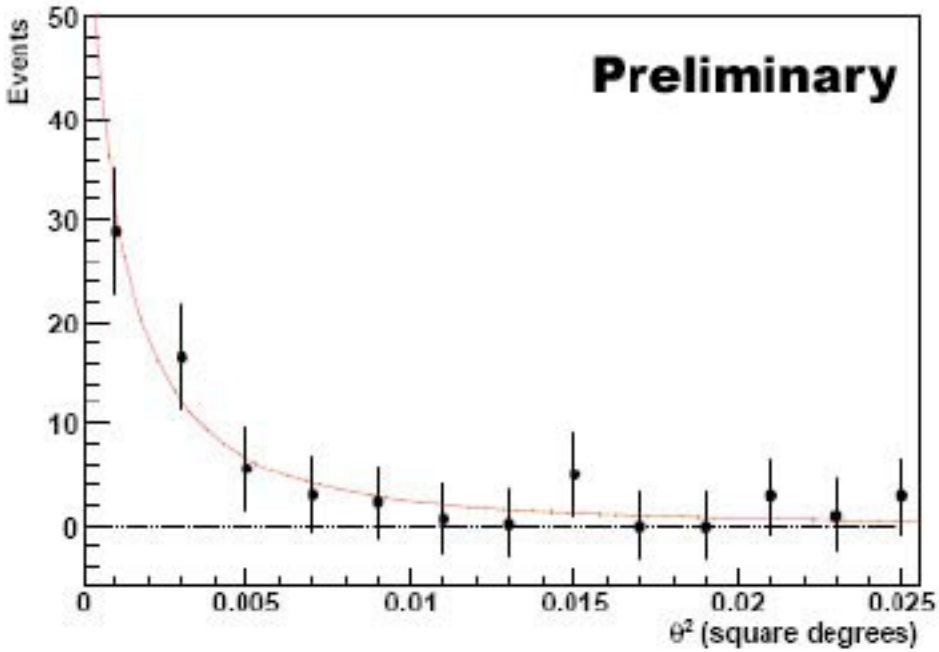
HESS J1303-631 -- “dark” accelerator or PWN?



TeV Sources with no Counterparts: HESS J0632+057?

Puehlhofer et al. 2007 -
First GLAST Symposium



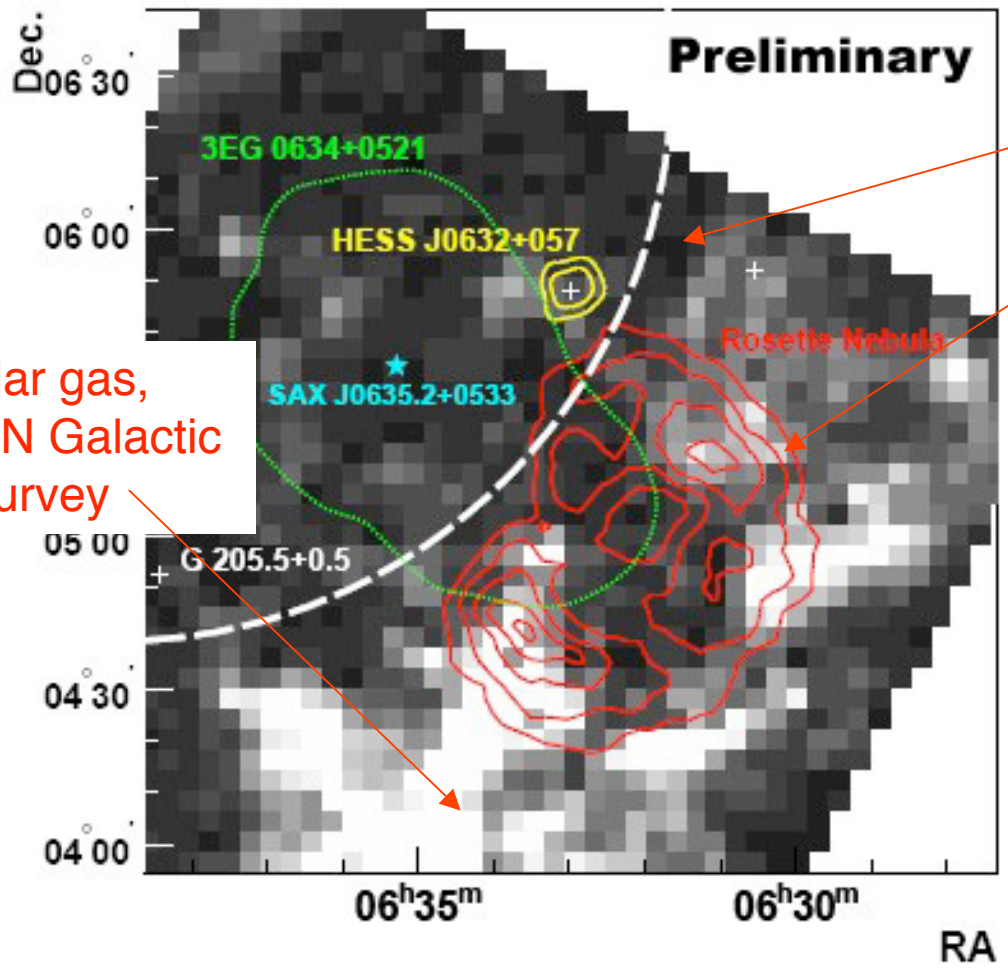


- Point-like source
- Limit on rms size of emission region: 2’

weak RX source, Be star

HESS J0632+057: Dark accelerator or ?

The Monoceros Loop SNR?Rosette Nebula region



Green's Catalog position of SNR

radio observations 8.35 GHz

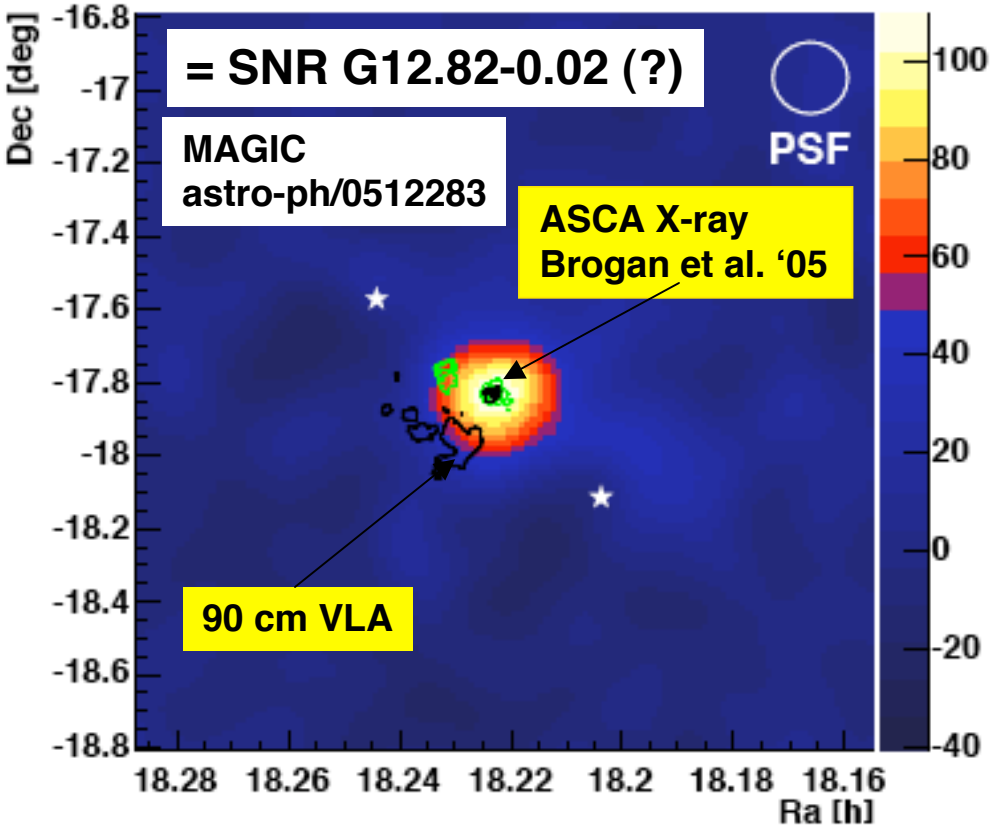
Molecular gas, NANTEN Galactic plane survey

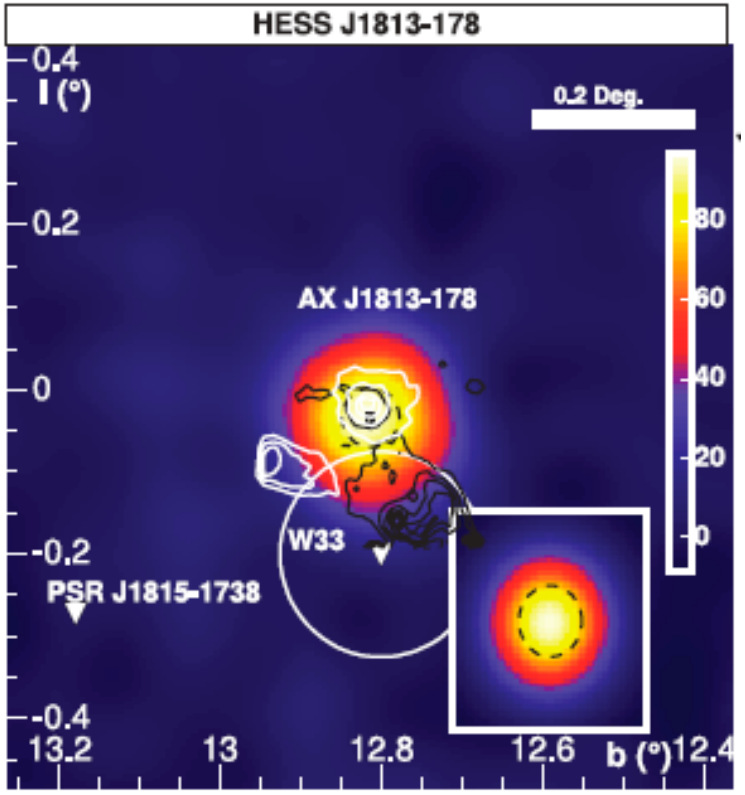
- 30-150 kyrs old
- Distance ~1.5 kpc
- Interaction with the Rosette nebula?

Dark? Identified? No confirmed source type.

Puehlhofer et al. 2007 - First GLAST Symposium

MAGIC Observations of HESS Unidentified Sources

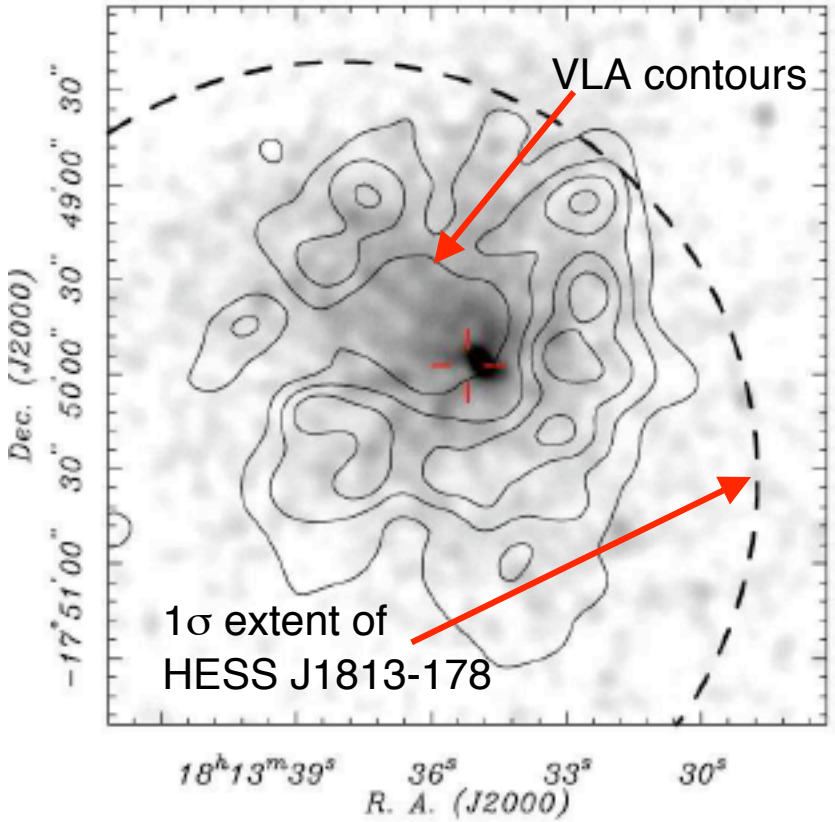




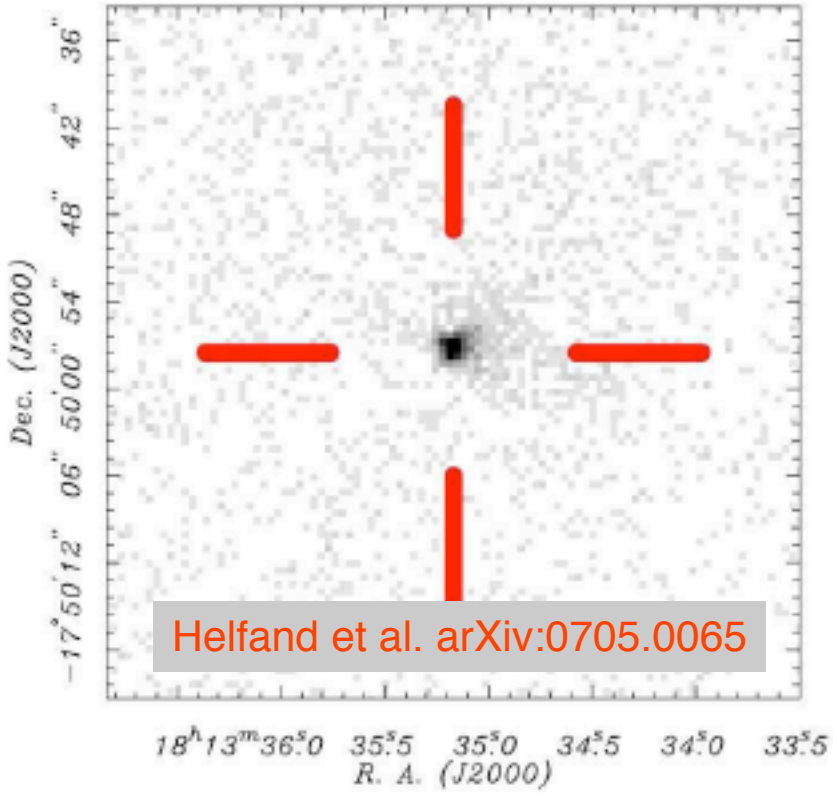
- The brightest and most point-like unidentified HESS sources of the survey.
- Coincident with archival ASCA source.
- Turned out to be coincident with previously un-catalogued radio shell type SNR G12.82-0.02.
- MAGIC confirms HESS detection. 25h observation, Jun-Jul '05.
- Hard γ-ray spectrum: $\Gamma = -2.1 \pm 0.2$. Integral flux > 400GeV ~ 8% Crab.

X-ray observations of HESS/MAGIC Field

Putative pulsar coincident with HESS J1813-178



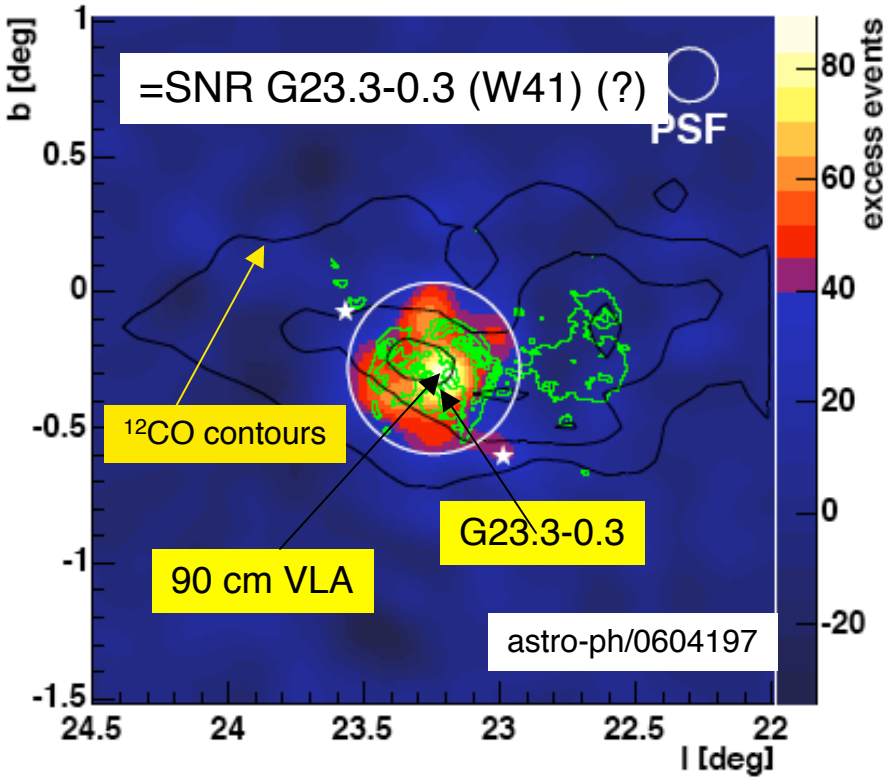
Chandra resolved X-ray emission component from G12.82−0.02. The morphology of the diffuse emission strongly resembles that of a PWN.

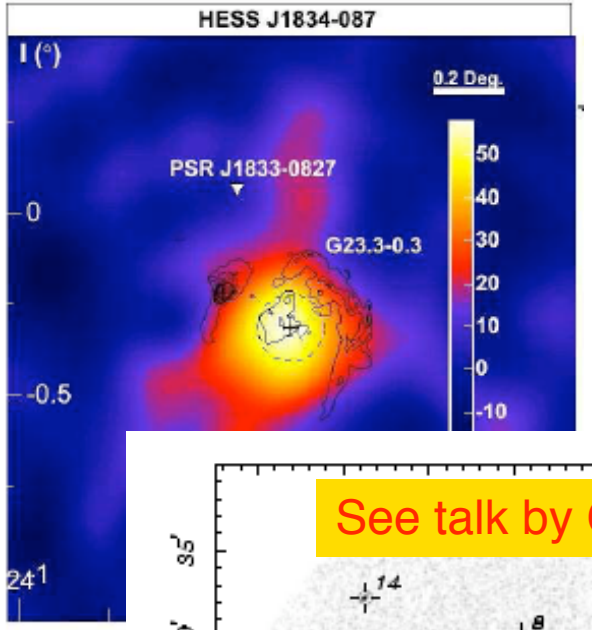


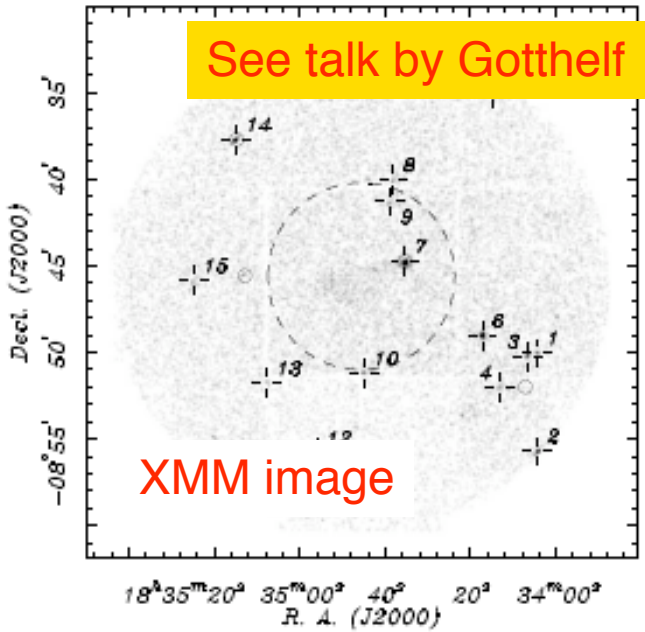
Zoom-in at full resolution of the X-ray image centered on the point source, a candidate pulsar.

MAGIC Observations of HESS Unidentified Sources

X-ray follow-up







Observation of VHE γ-rays from HESS J1834-087 with the MAGIC. Associated with asymmetric shell-type SNR, W41 (?), or PWN?
Spectrum > 200 GeV: $\Gamma = -2.5 \pm 0.2$

TeV Sources -- What have we learnt ...

- Several of the TeV sources now have likely counterparts.

- This was a result of follow-up studies of the the HESS fields using:
  - Archival X-ray, radio data
  - New X-ray studies (XMM, Chandra, Swift-XRT,RXTE)

- Source Classes (plausible counterparts):
  - Pulsar Wind Nebulae (PWN)
  - X-ray binaries - highly absorbed hard X-ray sources
  - Microquasar (XRB, BH)
  - Molecular Clouds
  - Star formation regions
  - SNR

  - Dark accelerators ?
    - no plausible SNR, pulsar, EGRET counterpart
    - no associated X-ray or radio emission
      e.g. HESS J1614-518, HESS J1708-410
    - Or new source classes with $F_{TeV} >> F_X$??
    - Or are these PWNe?

Future Directions ....

- TeV sky surveys are on-going.

- More results expected in the future from VERITAS, MAGIC, HESS

- Study of GLAST & AGILE transients

- Study of archival X-ray data + new observations at lower energies are important for understanding the nature of TeV sources

End