

VERITAS Galactic Physics



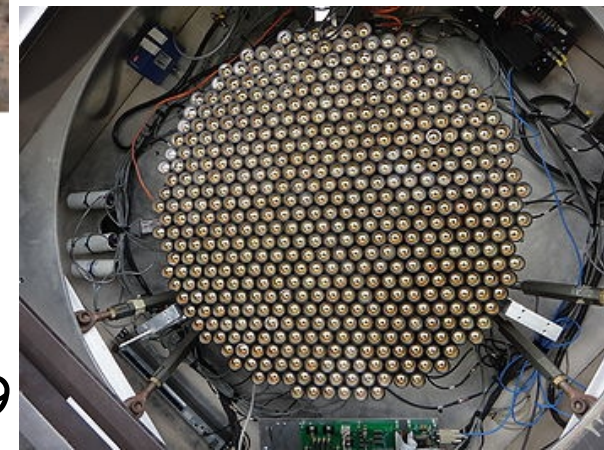
Farzaneh Sheidaei¹
for the VERITAS Collaboration
¹University of Utah



Outline

- Brief introduction to VERITAS
- VERITAS Galactic Science program
- Selection of new Galactic Source Results
 - ♦ Pulsar Wind Nebulae (**Tycho**)
 - ♦ Supernova Remnants (**CTA 1**)
 - ♦ Binary System (**HESS 0632+057/VER J0633+057, LSI +61° 303**)
 - ♦ Cygnus region (**TeV 2032+4130, VER J2016+371, VER J2019+407**)
 - ♦ Crab Nebula flaring

VERITAS



- Four 12-m imaging atmospheric Cherenkov telescopes.
- Located at Whipple Observatory, Arizona, USA (1268 m)
- Full operations began Fall 2007.
- One telescope was moved to new location in summer 2009
- Upgrade High QE PMTs and a New Tel Trigger in 2011-2012
- Energy Range: 85 GeV-30 TeV Energy Resolution 15-25%
- Angular Resolution < 0.1 deg (68%) Sensitivity < 25 hr for 1% Crab

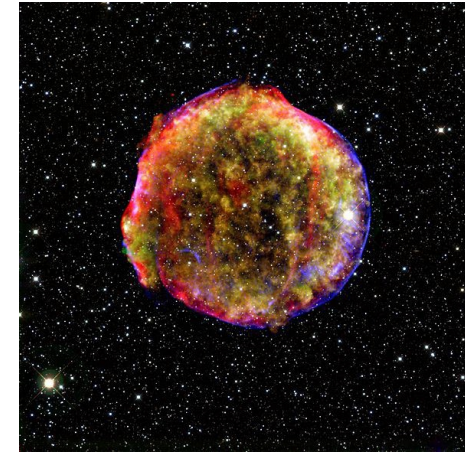
VERITAS Galactic Science program



- **SuperNova Remnants (SNRs)**

Galactic Cosmic-Ray Accelerators

There are ~8 SNRs in VHE detected yet



- **Binary systems**

The least numerous class but very puzzling system

Two scenarios: Micro-quasar or pulsar binary

4 VHE Binary systems



- **Pulsar Wind Nebulae**

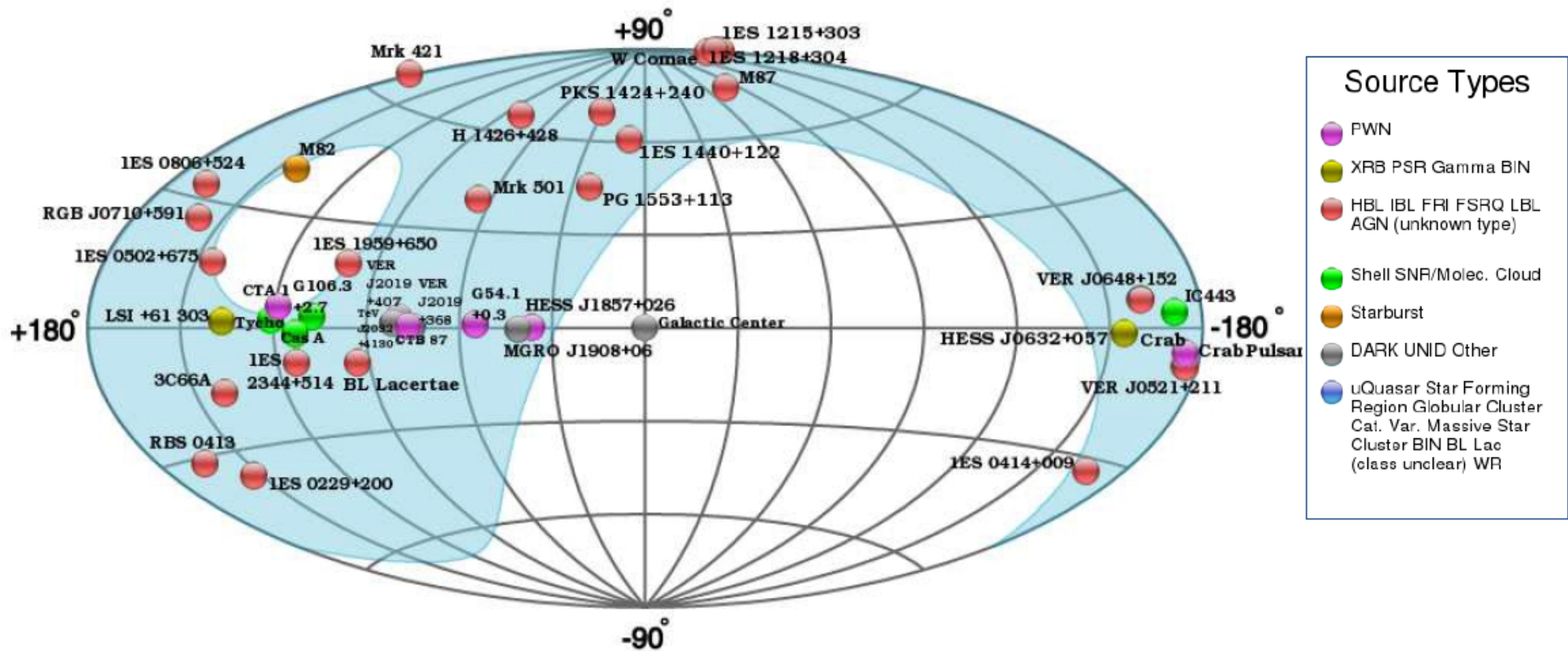
The largest class of identified Galactic VHE gamma-ray sources

TeV emission from the nebulae of energetic pulsars

> 28 PWNe detected in VHE observatories

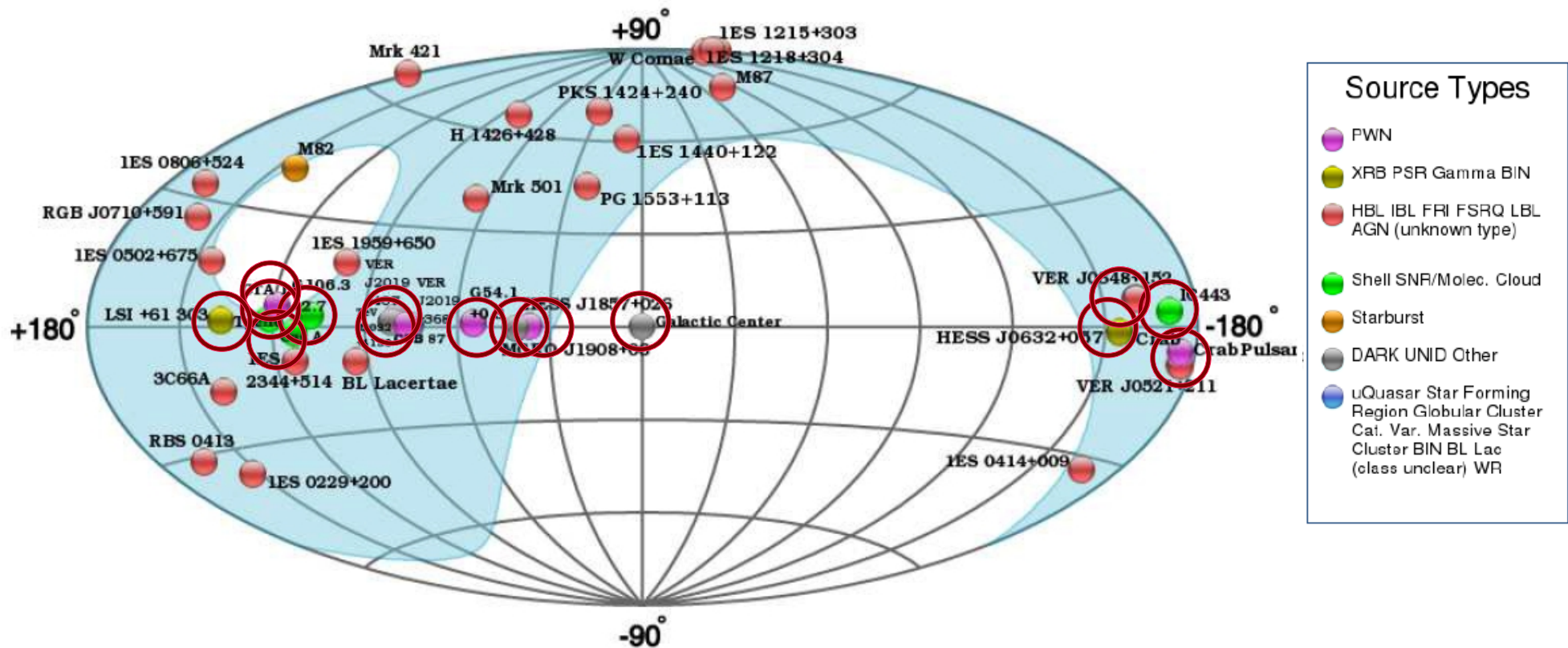


VERITAS Galactic Sources



- 46 VHE sources from 8 astrophysical classes
- 28 Extragalactic (62%): 25 blazars, 2 radio galaxies & a starburst galaxy(M82)
- 17 Galactic (38%): Crab pulsar, 2 gamma-ray binaries, 5 pulsar wind nebulae, 4 SNRs & 5 unidentified objects
- Program (~350 h / yr) covers PWNe (~100 h), SNRs (~100 h), binaries (~100 h) and unidentified objects (~50 h)

VERITAS Galactic Sources

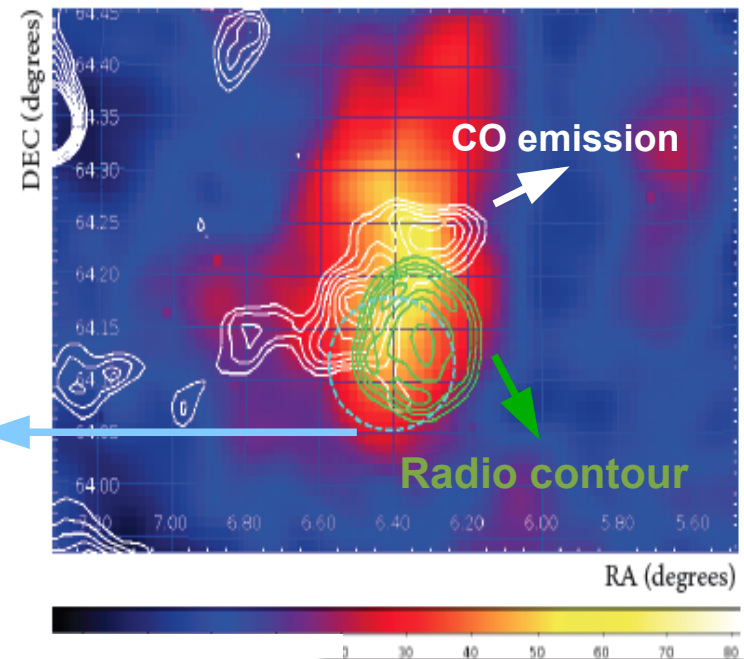


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Tycho Supernova Remnants

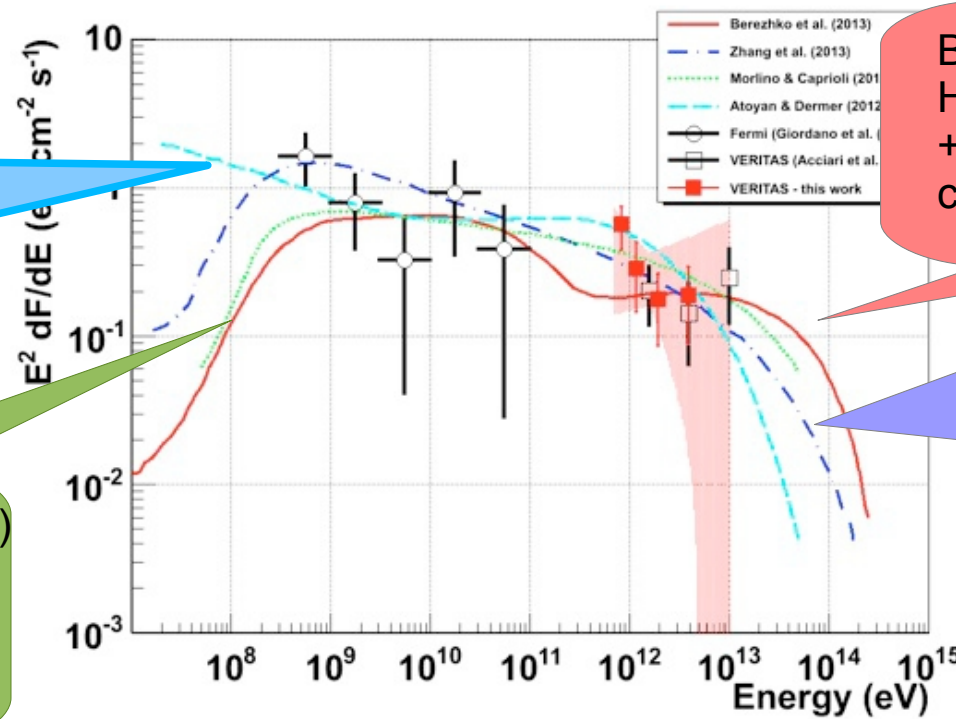
- Historical Type 1a SN (441 yr, $d \sim 2-5$ kpc)
- 61 hr +20 hr (2009-13)
- $E \sim 800$ GeV-10 TeV
- 0.9% Crab, hard spectrum
- $\Gamma = 1.95 \pm 0.51$
- Hadronic Scenario $p+p \rightarrow \pi^0 + \dots$
 $\pi^0 \rightarrow 2\gamma$
- Leptonic Scenario $e^- + \gamma \rightarrow e^- + \gamma$

Fermi-LAT
emission



Atoyan & Dermer (2012)
Pure leptonic model
with multiple emission
zones

Morlino & Caprioli (2012)
Hadronic dominant,
Multiwavelength
spectrum,
 $P_{\text{max}} = 470$ TeV



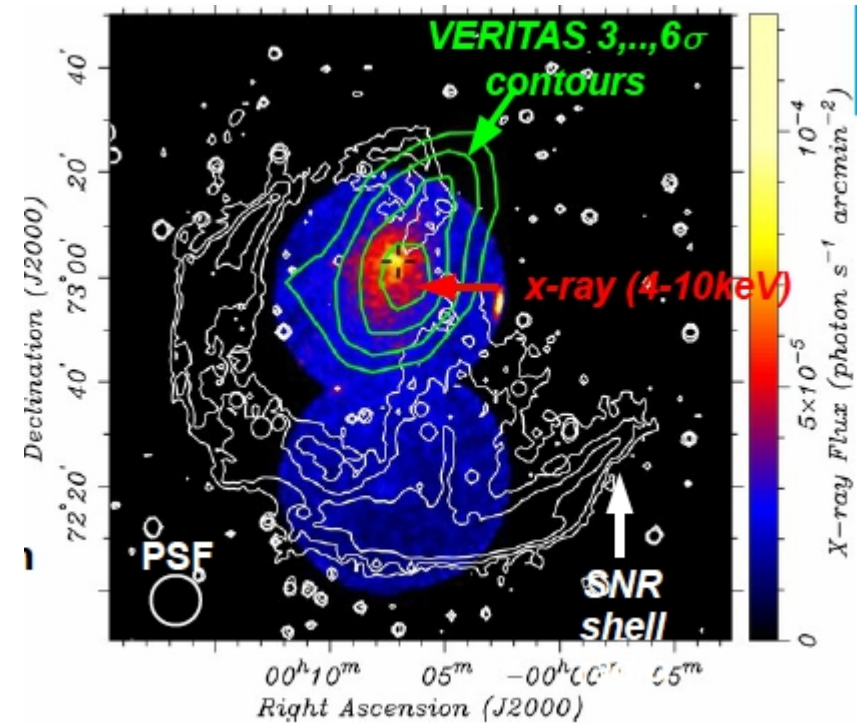
Bereziko et al (2012)
Hadronic dominant,
+ Interactions with dense
clump around SNR

Zhang et al (2012)
Hadronic dominant,
emission from MC with
energy conversion
efficiency of 1%
($n=12 \text{ cm}^{-3}$)

CTA 1: A VHE emitting Pulsar Wind Nebula



- ◆ Composite/shell type SNR with an X-ray filled radio shell of $\sim 1.8^\circ$
- ◆ Age $\sim 13\text{ky}$, $D \sim 1.4 \pm 0.3\text{ kpc}$
- ◆ Fermi γ -ray pulsar (2008)
- ◆ $P = 316.9\text{ms}$, $E_{\text{cutoff}} \sim 5\text{ GeV}$;
- ◆ 40 hrs data 2010-2011, $6.5\sigma \rightarrow \text{VER J0006+729}$
- ◆ $\delta = 0.25^\circ - 0.3^\circ$
- ◆ $\Gamma = 2.2 \pm 0.2_{\text{stat}} \pm 0.3_{\text{syst}}$ 4% of the Crab Nebula
- ◆ $\mathcal{E} = 0.2\%$ of the spin down power.
- ◆ 5 arcmin offset from TeV emission
- Properties of CTA 1 nicely fit in the middle of those of known TeV/X-ray PWN

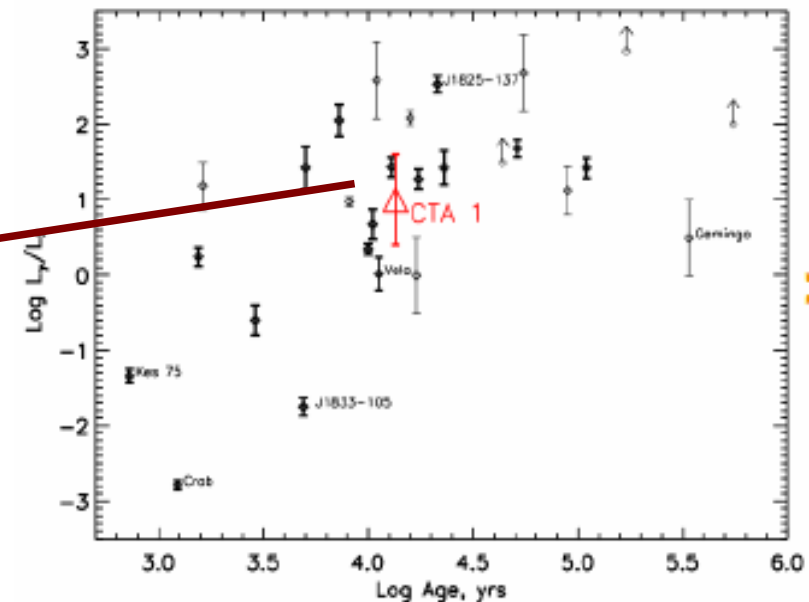
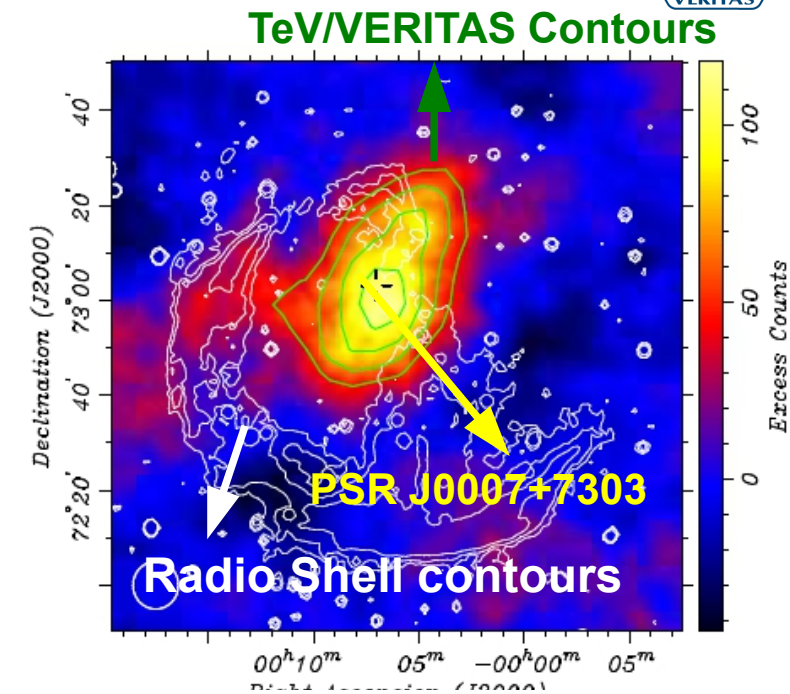


Aliu, E. et al., ApJ 764 p38 (2013)

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Gamma-ray Binaries (GeV-TeV)



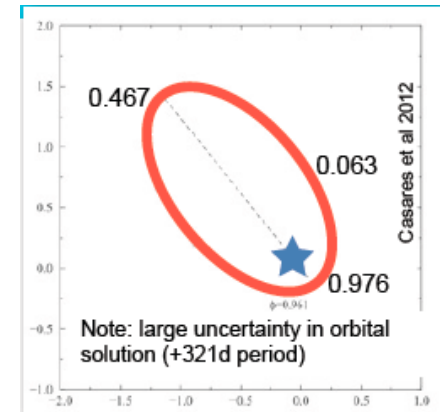
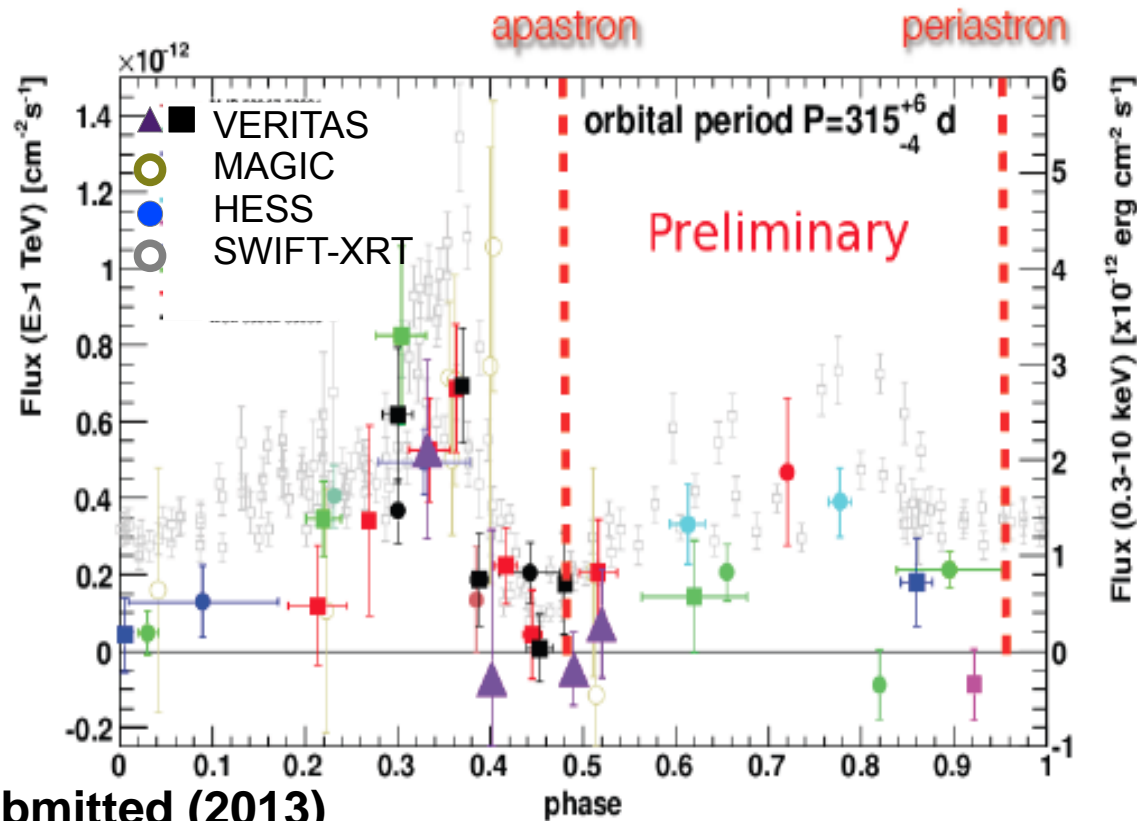
	type	D (kpc)	orbital period [d]	Radio (10^{31} erg/s)	1-10 keV (10^{33} erg/s)	1-10 GeV (10^{33} erg/s)	0.2-10 TeV (10^{33} erg/s)
LS 5039	O6.5V+neutron star? BH?	2.5	3.9	1-3	5-50	70	4-11
LS I +61 303	Be?+neutron star? BH?	2 (?)	26.5	1-17	3-9	60	3-8
PSR B1259-63	Be + 48ms pulsar	1.5	1237	0.02-0.3	0.3-6		2-3
Cygnus X-1	O9.7Iab+black hole	2.2	5.6	0.3	$\sim 1 \times 10^4$	no detection	12 (??)
Cygnus X-3	Wolf-Rayet + BH?; rel. jet (MQ)	7	0.2 (4.8h)	70	$\sim (3-8) \times 10^4$	5	no detection
1FGL J1018.6-5856	O6.5V+neutron star? BH?	5	16.6	1-4	variable	150-200	HESS J1018-589?
HESS J0632+057	B0pe + ??	1.5	315	0.03	0.05-1	<9	~ 0.9

☒ GRS 1915+105, SS 433, PSR B1259-63

- Fascinating but complicated systems, where the number of models to explain them is much larger than the number of sources
- The emission can involve processes associated with a jet, a stellar wind, a stellar disk, or a pulsar or some combination of these.

HESS J0632+057 / VER J0633+057

A new gamma-ray Binary



Aliu, E. et al., submitted (2013)

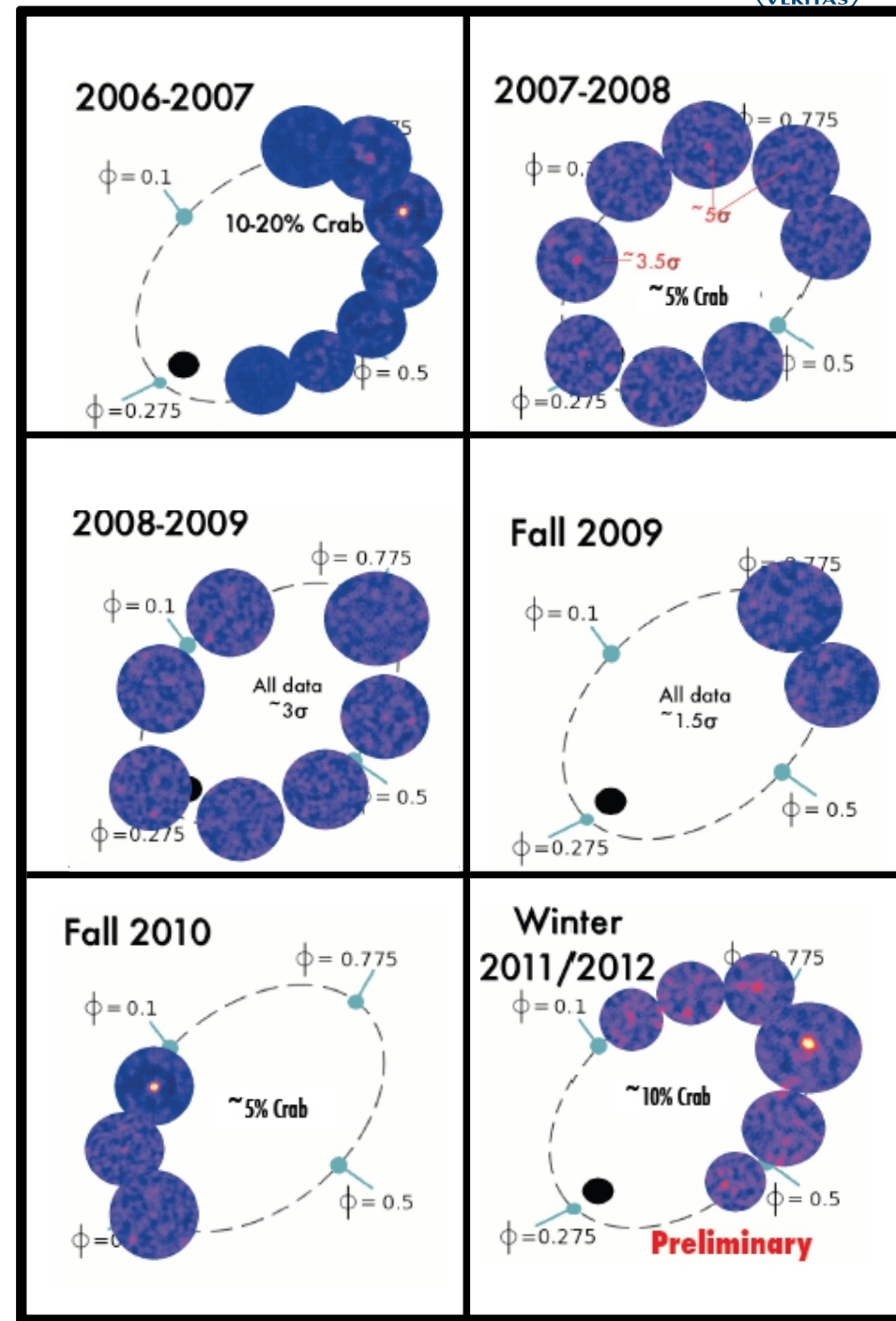
- Discovered by HESS in 2004-05, 3% Crab
- VERITAS 2008-09 (U.L. < 1.1% Crab), 2010, 11 and 2012 show up
- >3 years of intense X-ray coverage → 321 ± 5 days by *swift*-XRT (soft x-ray)
Bongiorno et al. 2011, ApJ, 737, L11
- Not detected by Fermi
- Strong correlation between TeV and X-ray emission

LSI +61° 303



- High-mass X-ray binary system included Be star and unknown compact object (BH or NS)
- Elliptical orbit: $e=0.537\pm0.034$
- 2 kpc distance
- 26.5 day orbit
- A variable TeV source (2-20% Crab) near the apastron (typically)

The emission from the system may go through a complex, multi-year modulation, similar to that seen in radio

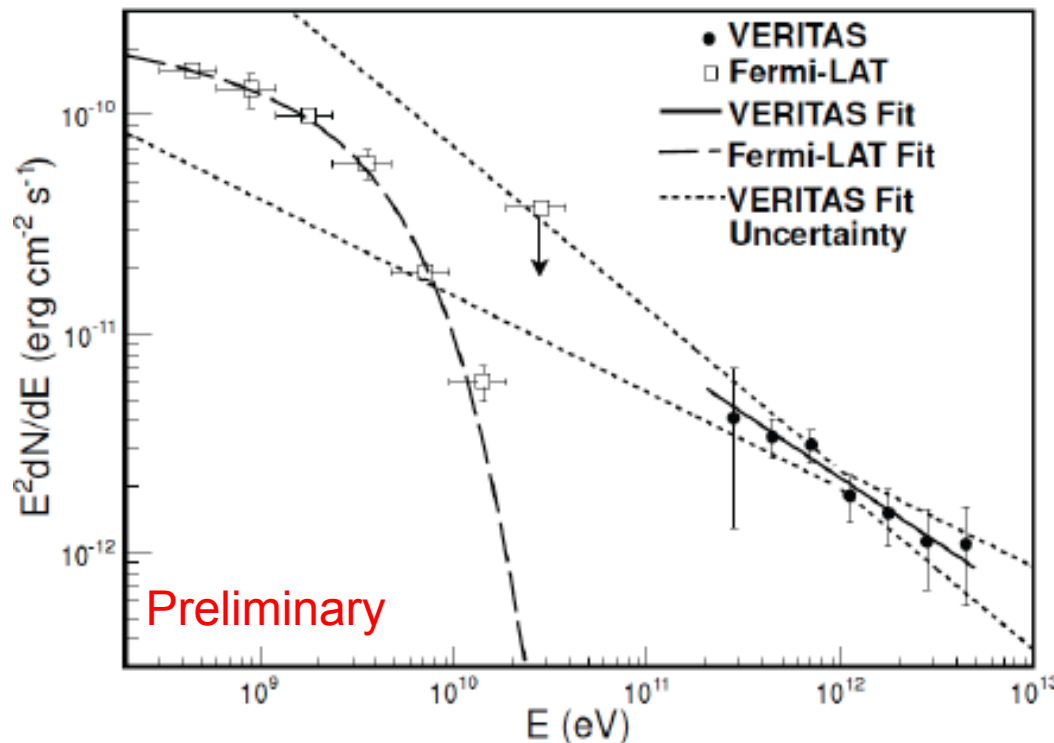


LSI +61° 303



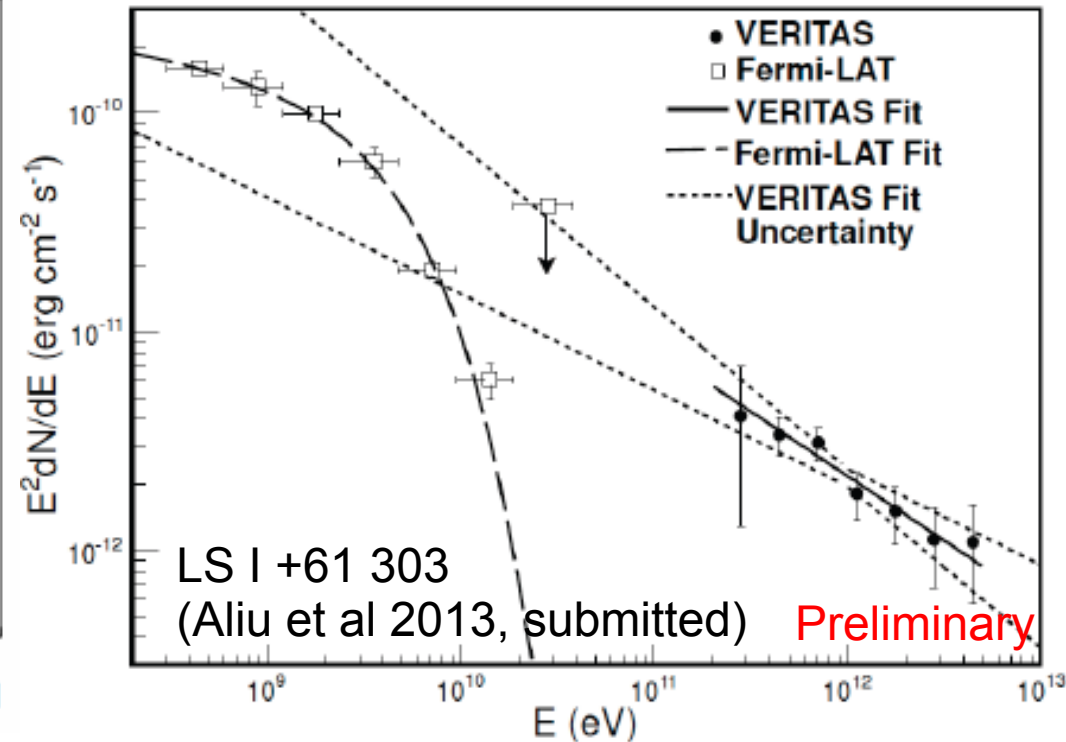
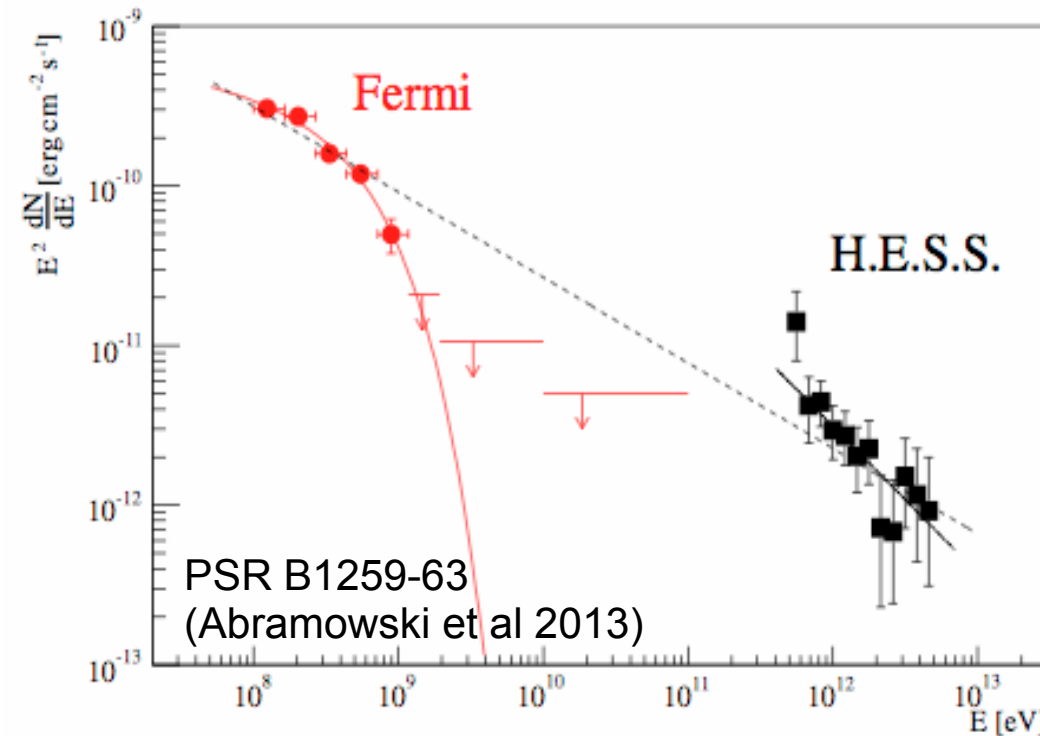
Fermi-LAT/VERITAS Contemporaneous Data

- ◆ Night to night variability (MJD 55918/55919, MJD 55944/55945)
- ◆ No strong evidence for correlation between *Swift*-XRT and VERITAS or Fermi-LAT and VERITAS observations.
- ◆ TeV Spectrum: Power-law $(1.37 \pm 0.14) \times 10^{-8} (E/1\text{TeV})^{-2.59 \pm 0.15} \text{ TeV}^{-1} \text{ m}^{-2} \text{ s}^{-1}$
- ◆ GeV Spectrum exponential cut-off @ 4 GeV
 - **very similar to GeV pulsars spectrum**
- ◆ Indication of multiple populations in LSI 61 303
- ◆ → explain the lack of correlation between GeV and TeV observations



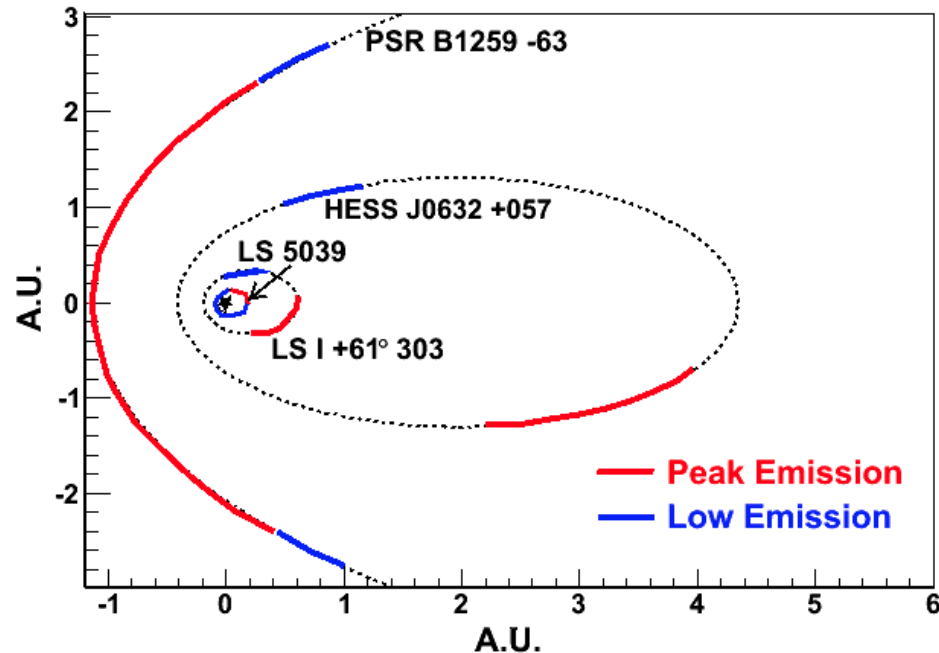
Aliu, E. et al., submitted (2013)

Connection between Sources



- LSI +61 303/HESS J0632+057: Strong TeV sources near apastron
- HESS J0632+057 no emission in Fermi-LAT data
- LSI +61 303/PSR B1259-63: Very similar SED, with a cut-off in ~few GeV
- Fundamentally different type of binary objects and/or different emission geometry

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Galactic sources in Cygnus Region



Cygnus Region

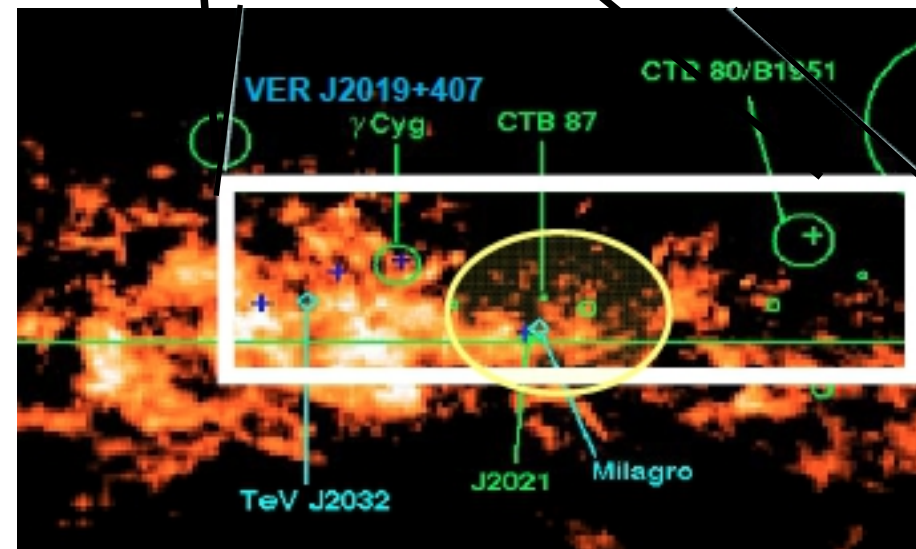
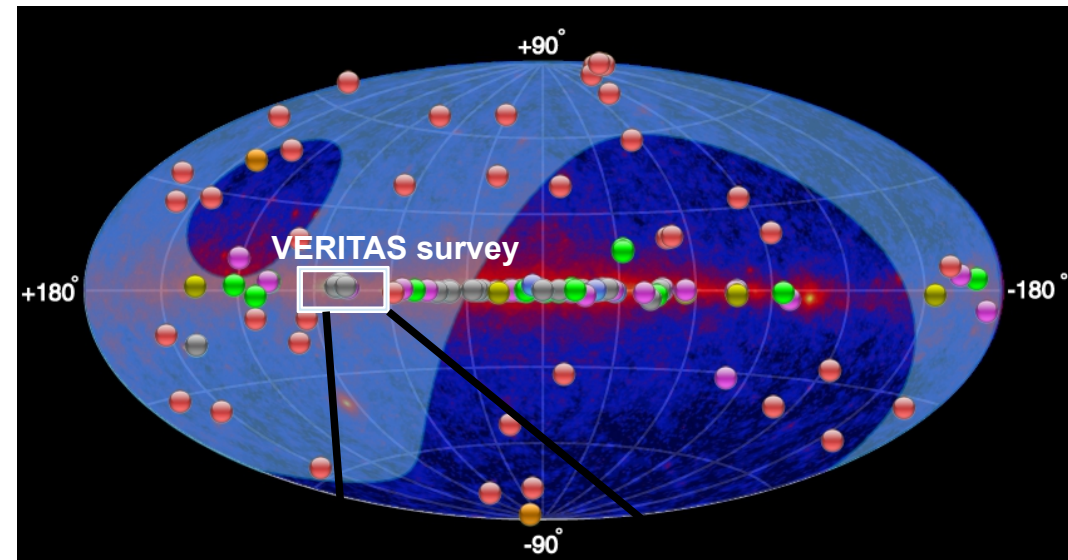
- Rich in star forming activities
- Many potential VHE accelerators

Sky Surveys

- GeV range: EGRET and Fermi-LAT
- TeV range: VERITAS (4% Crab)
- TeV range: HEGRA (~25% Crab)
- Multi-TeV: Milagro (35% Crab)

VERITAS sky survey

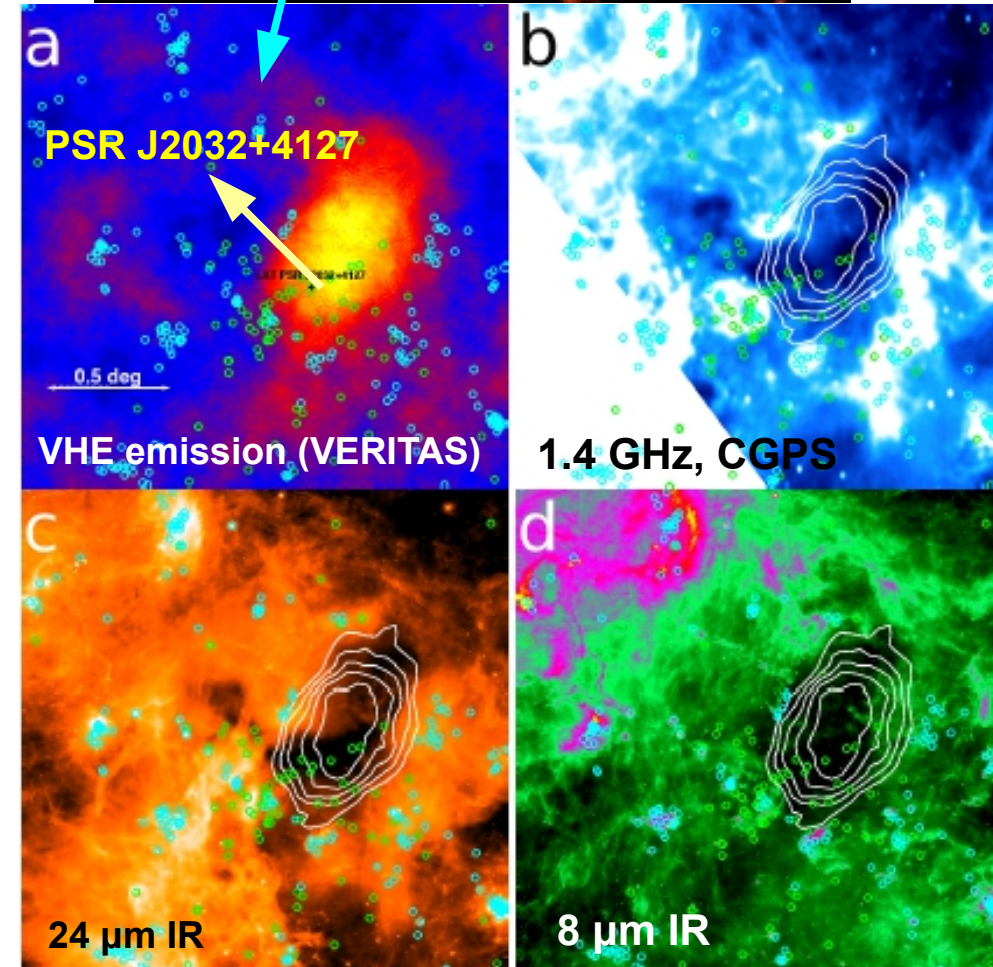
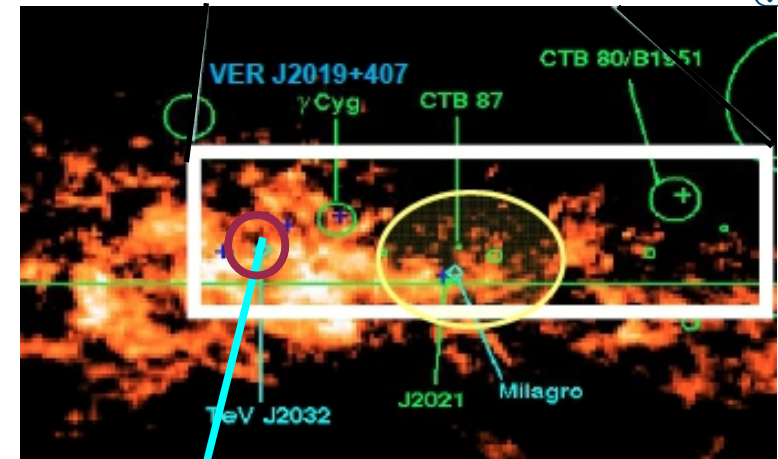
- 2007-09: $15^\circ \times 5^\circ$ (l, b)
115h (survey) + 50 h (follow-up)
- ★ Extended source near SNR G78.2+2.1 (γ -Cygni)
- ★ Extended source on TeV J2032+4130 (HEGRA)
- ★ Extended source on MGRO J2019+37 (MILAGRO)



TeV J2032+4130 (VER 2031+415)



- ◆ First unidentified source (HEGRA)
- ◆ Confirmed by MAGIC, Whipple and MILAGRO (MGRO J2031+41)
- ◆ Extended source ~6 arcmins
- ◆ Detected in the Sky Survey (2007-09)
- ◆ Follow-up of 48.2 hr $\rightarrow 8.7\sigma$
- ◆ Asymmetric extension
 - major axis: $0.16^\circ \pm 0.02^\circ$ (NW)
 - minor axis: $0.066^\circ \pm 0.009^\circ$
- ◆ ~4% Crab nebula
- ◆ No clear picture of the nature from other wavelength
- ◆ A new VHE PWN



Aliu, E. et al., in preparation (2013)

MGRO J2019+37



- One of the three sources discovered by MILAGRO
Not resolved, broad feature ($1.2^\circ \times 0.7^\circ$)

VERITAS

- VER J2016+371: point source (5.7σ) consistent spatially with SNR CTB 87
- VER J2019+368: extended and consistent spatially with MGRO J2019+37

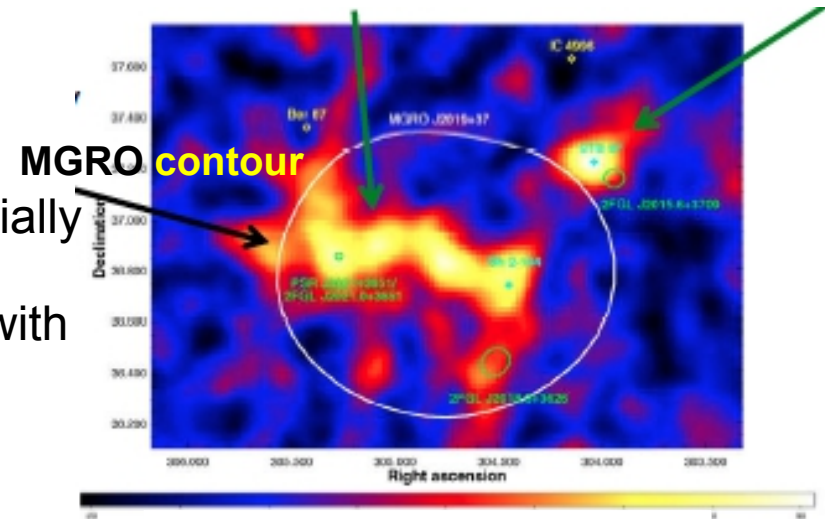
Multi-wavelength study and interpretation

- CTB 87:** \blacktriangle PWN in X-ray and VHE γ -ray
 \blacktriangle No pulsar detected yet!
- VER J2019+368**

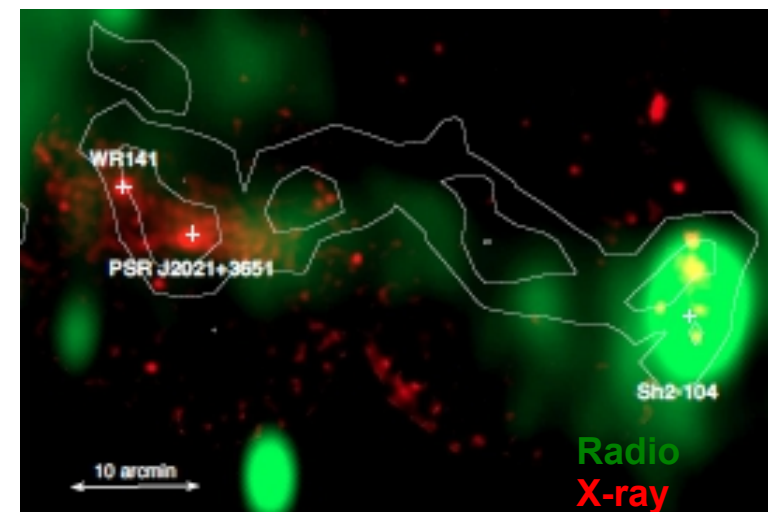
- Multiple sources
- Power law spectrum ($\delta=0.5^\circ$)
- $\Gamma = 1.75 \pm 0.08_{\text{stat}} \pm 0.3_{\text{sys}}$
- $\phi = (1.4 \pm 0.1 \pm 0.3) \times 10^{-12} \text{ ph TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$
- Objects in the region: PSR J2021+3651, Wolf-Rayet star WR141, IGR J20188+3647, HII region (sh2-104)
- Extensive multi-wavelength needed

VER J2019+368

VER J2016+371



Aliu, E. et al., in preparation (2013)



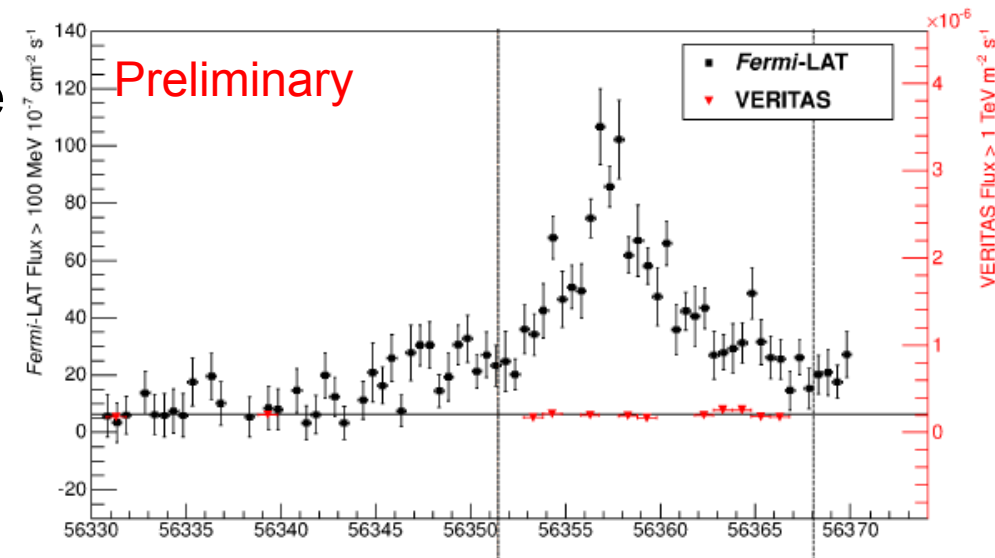
March 2013 Crab Nebula Flare



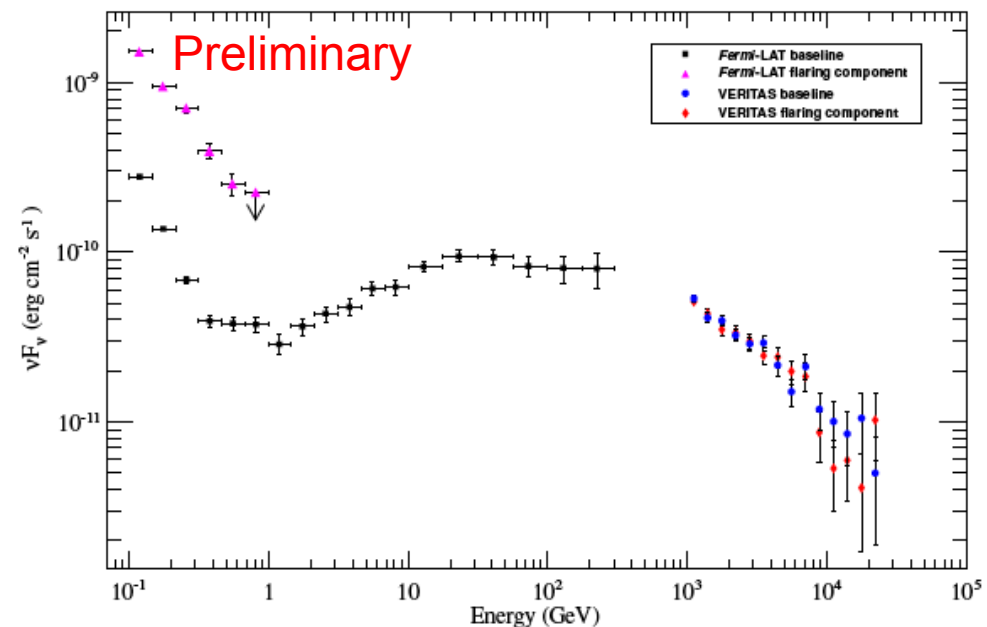
- ◆ Fermi-LAT: 2-week flaring in March 2013
- ◆ VERITAS: 10 days in the flaring episode
- ◆ No GeV/TeV flux correlation
- ◆ Relative flux change:
VERITAS $< \sim 5\%$
Fermi-LAT $\sim 600\%$

- ◆ The lifetime for 200MeV sync.
Radiation: $T_{\text{sy}} = (3 \times 10^5 \text{s})(B/1 \text{mG})^{-1.5}$

- ◆ Increasing the magnetic field and injection of a large number of excess electrons at PeV energies.
- ◆ The flare electron with $\gamma_{\text{sy}} \sim 10^9$ can produce VHE emission in the PeV band with IC mechanism.



Aliu, E. et al., in preparation (2013)



Conclusions



- VERITAS is a state-of-the-art ground-based VHE gamma-ray telescope Array, with wealth of new information about Galactic sources
- VERITAS has taken ~350 hr/year on Galactic sources leading in detecting 17 Galactic sources:
 - **Deep exposure on Tycho SNR**: Expand high energy gamma-ray measurements ~100 GeV-10 TeV to test the existing models
 - **Deep observation on CTA 1** in the form of PWN
 - **Binary systems**: still unknown and continue to surprise us!
 - **LSI 61303**: multiple populations from GeV to TeV, indication of short-time variation.
 - **HESS J0632+057**: Strong correlation between VHE and X-ray emission. Stable spectral energy distribution
 - **Cygnus Region**: **TeV 2032+4130** is a new PWN, **VER J2016+371** as a PWN for CTB 87, **VER J2019+407** (SNR interaction)
 - No flare from simultaneous VHE coverage of a GeV **Crab flare**



Thank you

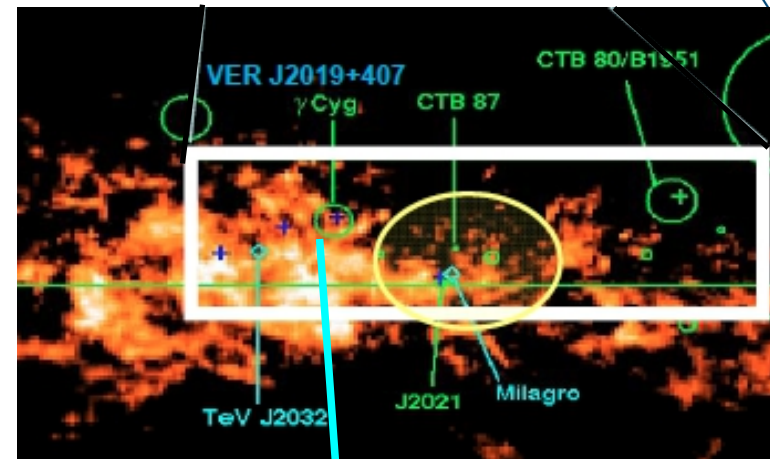
Backup

VER J2019+407



VERITAS:

- 21.4 hr follow-up observations with 7.5σ
- Extension of $0.23^\circ \pm 0.03^\circ$
- Source at north-west of the SNR
G78.2+2.1(γ -Cygni)



MC+SNR✓

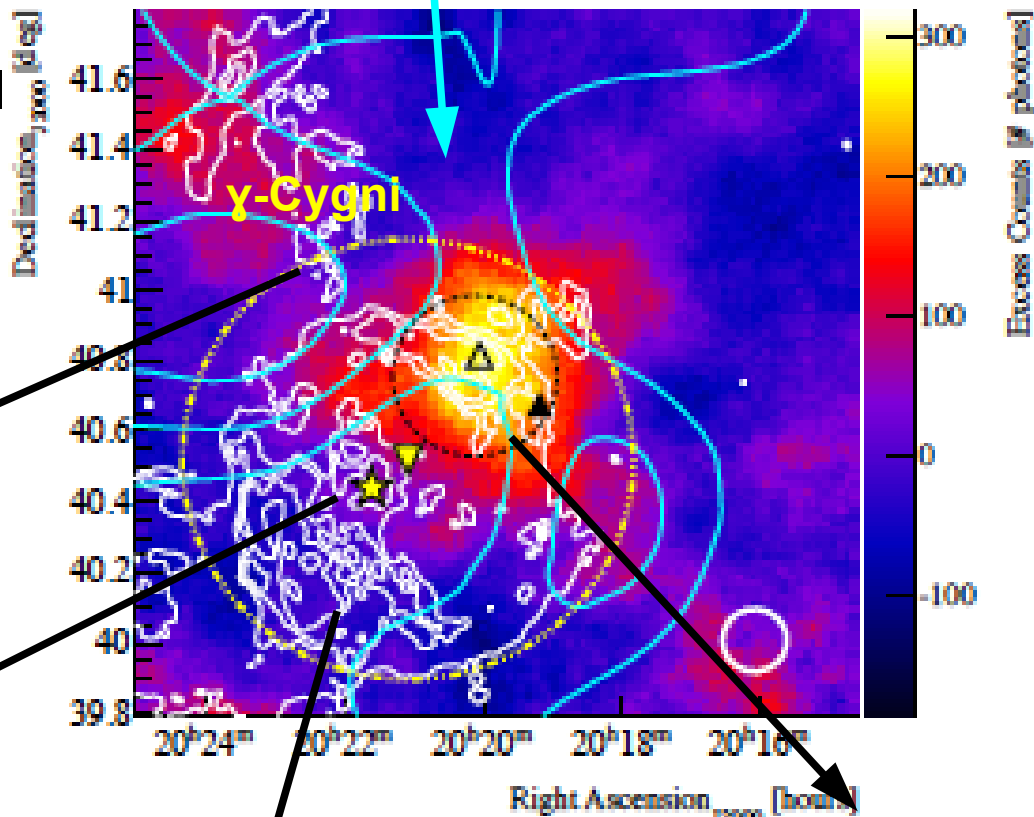
Shock interaction of ejecta with dense HI shell

Hadronic scenario: $\rho = 1.0\text{--}2.2 \text{ cm}^{-3}$

In consistent with optical observation

Fermi extended source

PSR J2021+4026



Radio SNR contour

VERITAS
source