



# TeV Gamma-ray observations of PWNe with VERITAS

Ester Aliu for the VERITAS Collaboration



# TeV emission mechanisms in PWNe



Still in an early stage:

Leptonic origin (*early detections*):

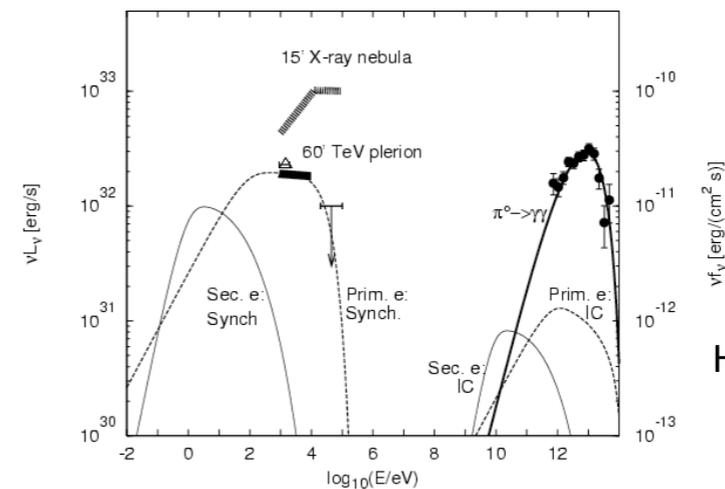
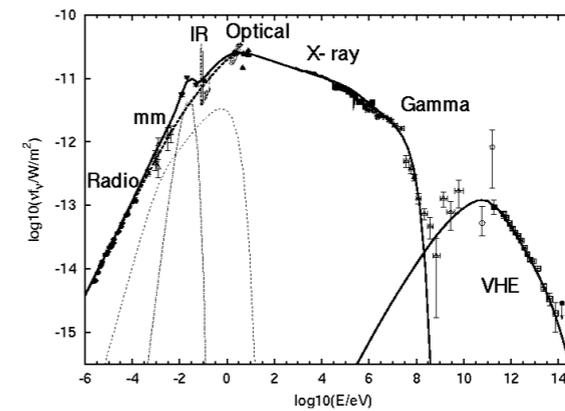
[de Jager & Harding, Aharonian]

- Inverse Compton emission
- Target photons: CMBR, interstellar IR, stellar photons, synchrotron (SSC)

Hadronic origin (*e.g. spectral features in Vela-X, interactions of PWNe with molecular clouds*):

[Bednarek, Horns]

- decay of  $\pi^0$  from interactions of relativistic ions with nebular matter



Horns et al.

TeV observations provide **new and independent** input into the physics of PWNe

- If IC and target photons known -> direct inference of the non-thermal electron spatial and spectral distributions

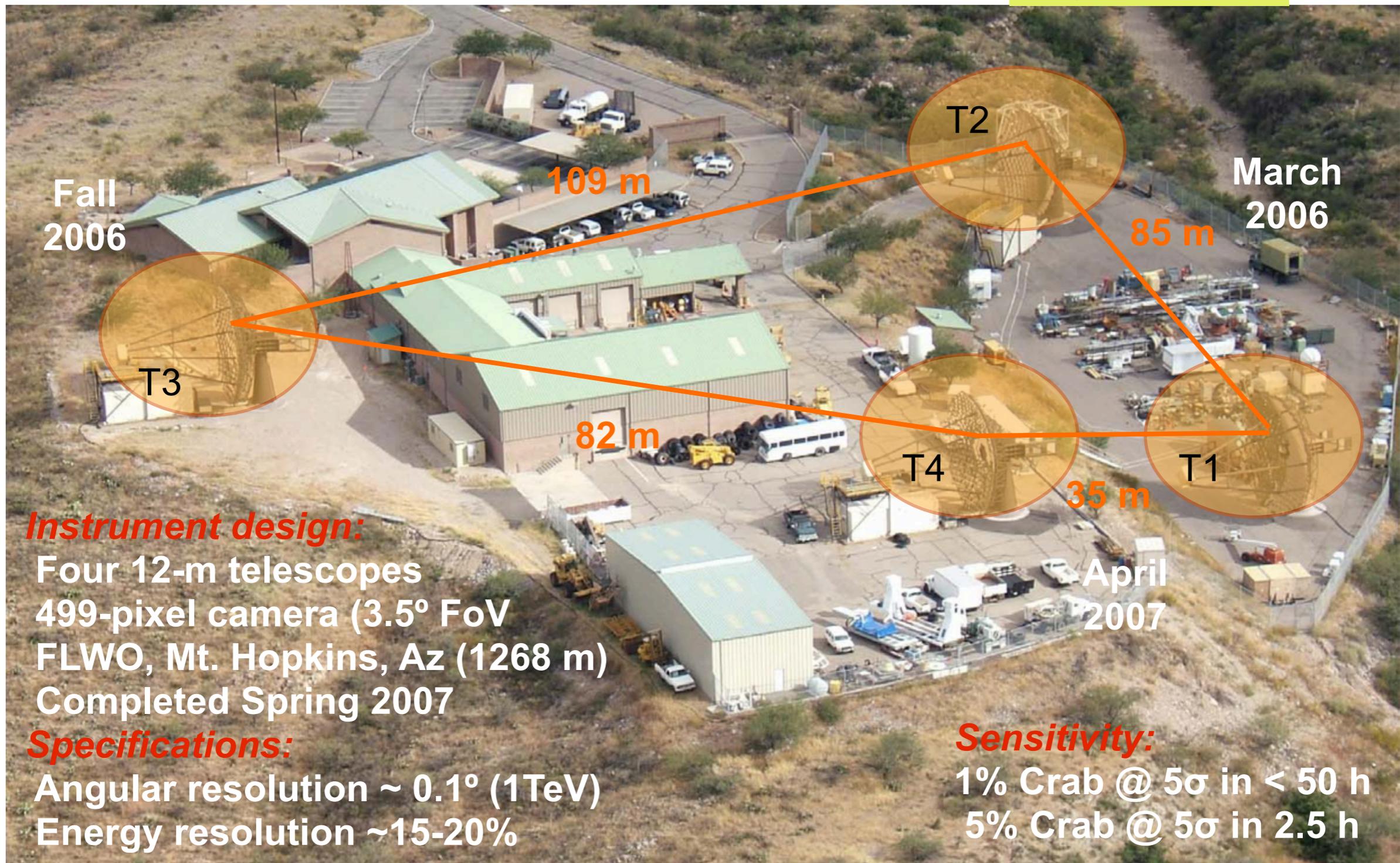
- If hadrons within the nebula (either ions within the wind or hadrons trapped in molecular clouds), PWNe should be considered serious candidates responsible for the bulk of the cosmic rays

Is the fastest-growing class of identified Galactic objects ( $\sim 30$ ), as revealed by HESS looking from the Southern Hemisphere

# VERITAS: A TeV Gamma-ray observatory



More details in the talk  
by R. Muhkerjee



**Instrument design:**

Four 12-m telescopes  
499-pixel camera (3.5° FoV)  
FLWO, Mt. Hopkins, Az (1268 m)  
Completed Spring 2007

**Specifications:**

Angular resolution ~ 0.1° (1TeV)  
Energy resolution ~15-20%

**Sensitivity:**

1% Crab @ 5σ in < 50 h  
5% Crab @ 5σ in 2.5 h

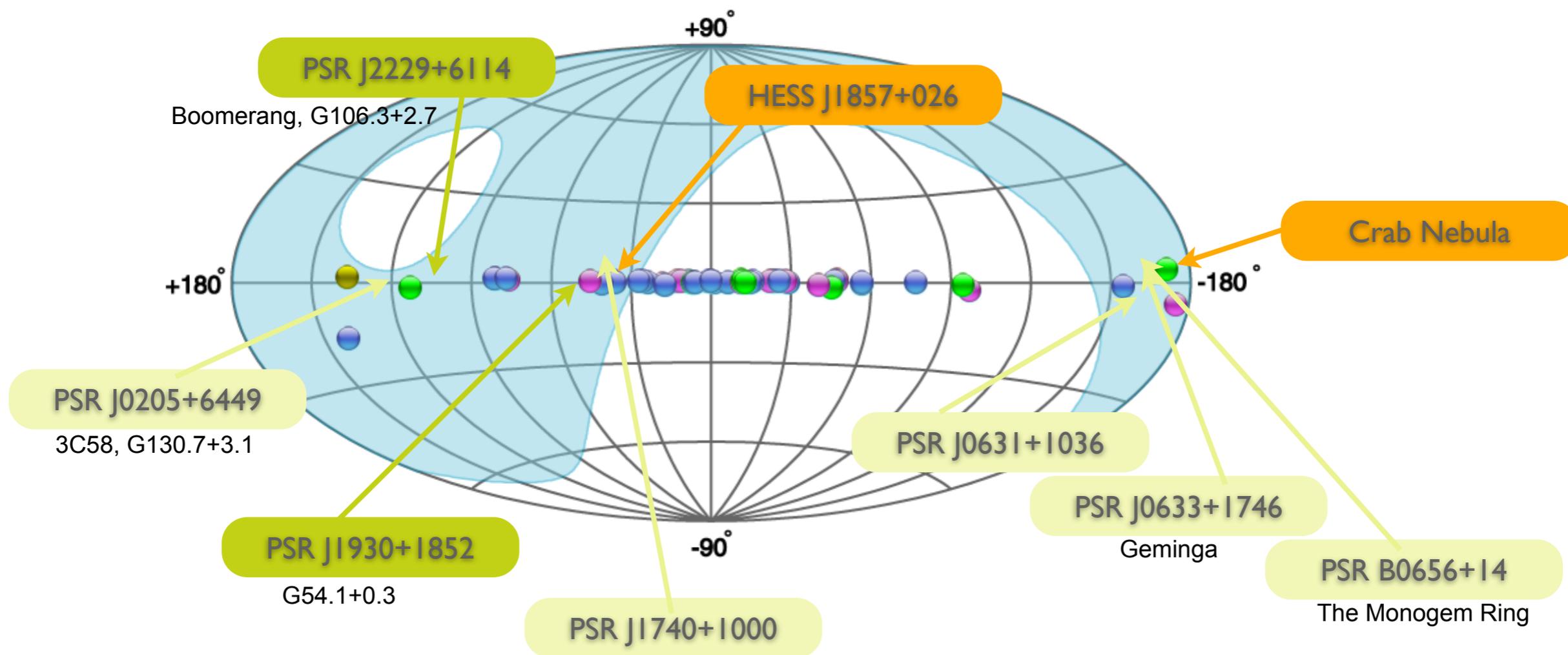
# A survey of Northern Galactic pulsars



VERITAS is performing observations in the vicinity of some selected Northern pulsars to look for steady TeV emission (SNRs and PWNe KSP)

Selection criteria is based on the  $\dot{E}/d^2 > 1.e35 \text{ ergs/s/cm}^2$

We report here the results of 7 of these objects whose analysis has already been completed.

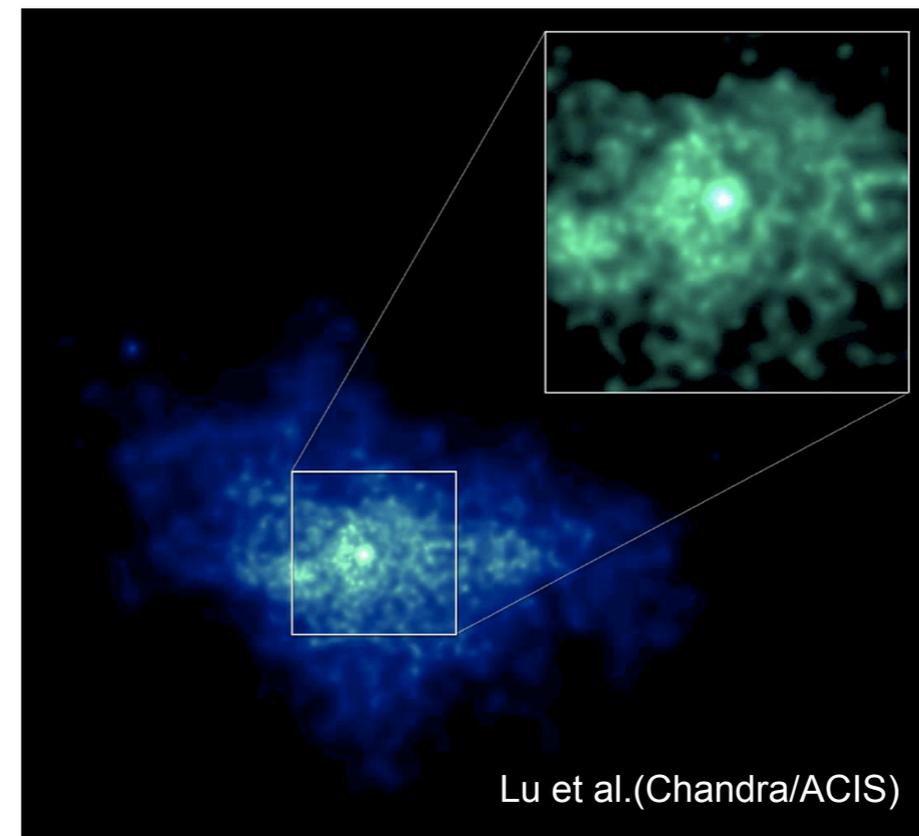


# The Crab-like system G54.1+0.3/PSR J1930+1852

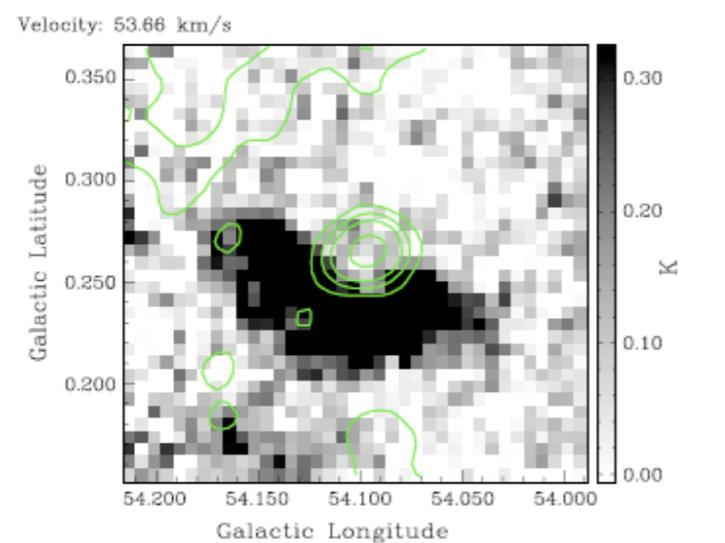


## Closest cousin of the Crab Nebula

- Elliptical radio & x-ray morphology  
2'x1.5' (not resolvable by TeV instruments)
- X-ray jet/torus, no thermal shell
- Age ~2900 years
- $\dot{E} = 1.2 \times 10^{37}$  ergs/s
- Distance ~ 6.2 kpc



## Also, nearby Molecular Cloud



Leahy et al. (FCRAO)

## Observations at the GeV and TeV

- None EGRET box ( lies outside the 99% CL error box 3EG J1928+1746 - possibly associated with PSR J1928+1748)
- Not among the bright Fermi catalog
- $F(>0.6 \text{ TeV}) < 20\%$  of the Crab by HEGRA

# G54.1+0.3/PSR J1930+1852: Results



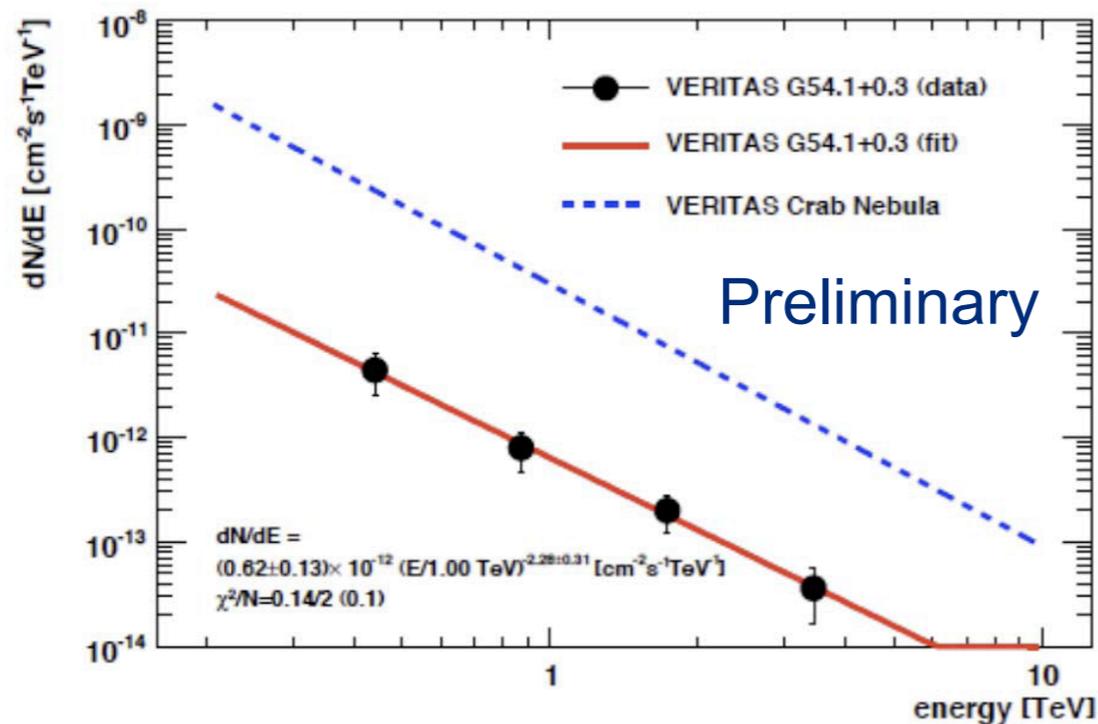
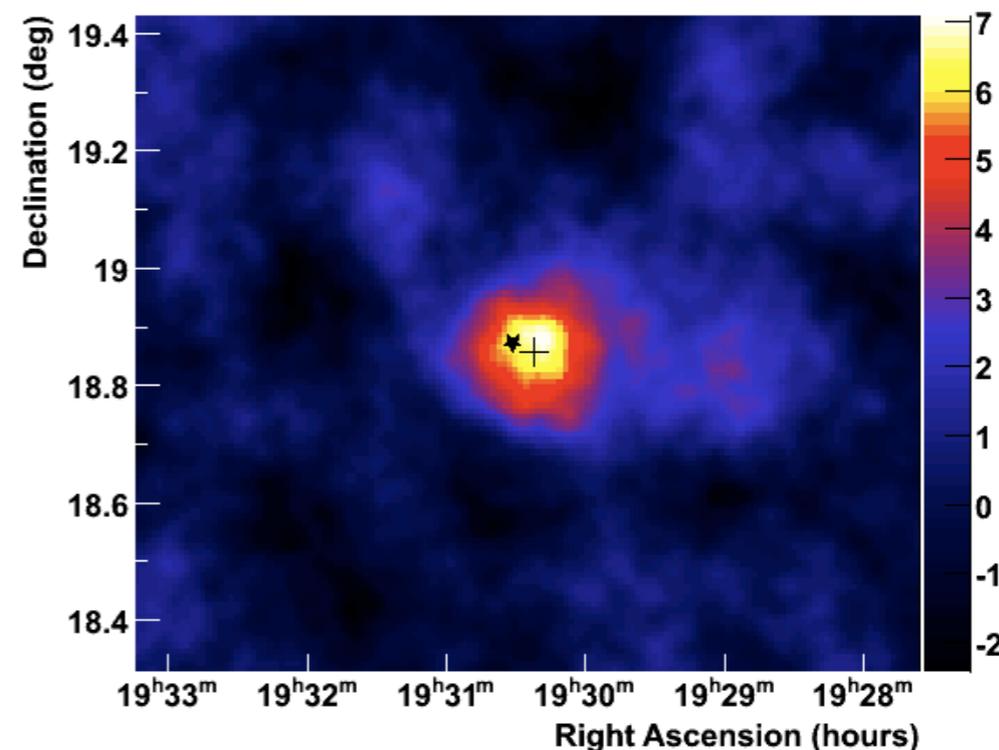
## 2007/08 Evidence of signal

- First pointed observations (~14 hr) show  $>4\sigma$  post-trials

## 2009 Follow-up

- Confirms the signal  $>5\sigma$  post-trials in 22 hours
- Combined dataset yields a  $7\sigma$  detection in 36 hours

The emission is compatible with the G54.1+0.3 position and the extension is consistent with a point source



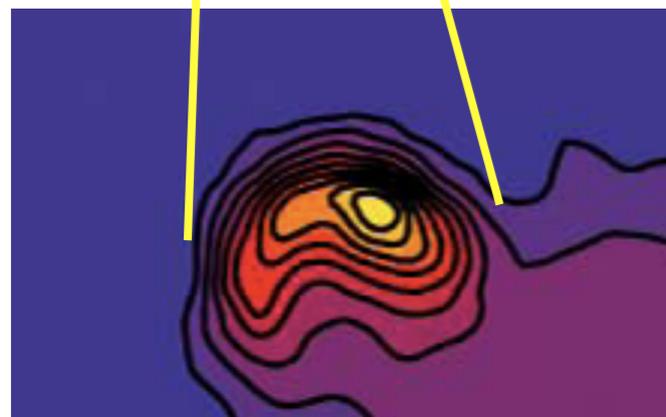
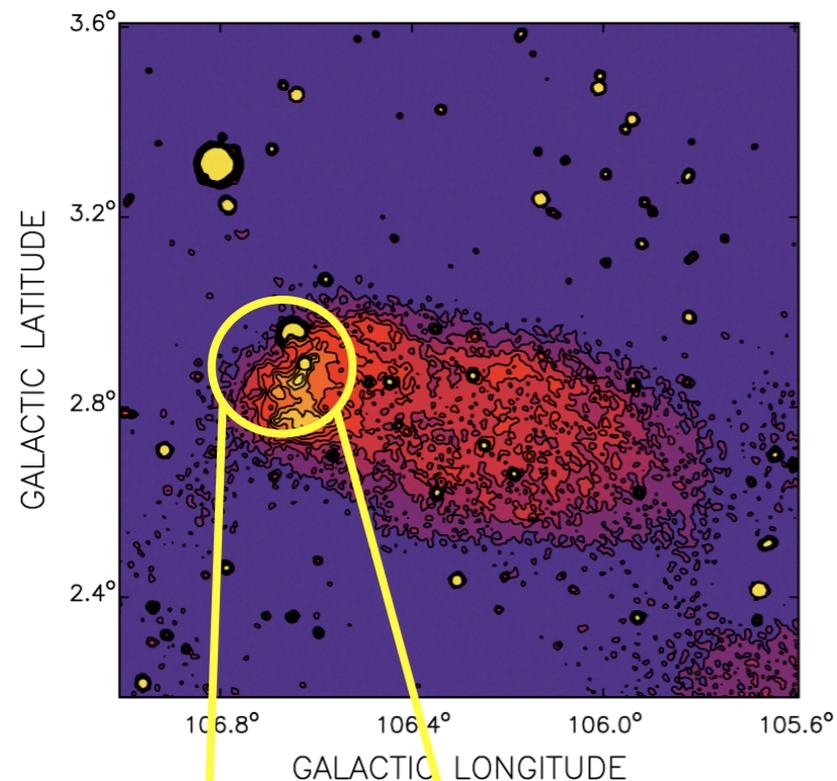
## Preliminary spectrum

- Flux ( $>1$  TeV)  $\sim 3\%$  Crab
- Index  $\sim 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$

Efficiency of TeV production relative to the spindown-power consistent with being a young object

- $L/\dot{E} \sim 2\%$ , which is very similar to other similar young detected objects like Crab and G21.1+0.5

# The Vela-like system Boomerang/PSR J2229+6114



Energetic pulsar+wind nebula  
discovered in the error box of source  
3EG J2227+6122

- Age  $\sim 10000$  years
- $\dot{E} = 2.2 \times 10^{37}$  ergs/s
- Distance  $\sim 800$  pc (Kothes et al.)
- Likely part of the larger SNR G106.3+2.7

On Fermi/LAT Bright Source List

Emission at  $\sim 35$  TeV reported by  
Milagro near former C4 hot spot location

# Boomerang/PSR J2229+6114 : Results



2007 Evidence of extended signal

2008 Follow-up

- Resolve TeV emission overlapping the radio shell of G106.3+2.7

- $7.3\sigma$  detection in 33 hours (6.0 post-trials)

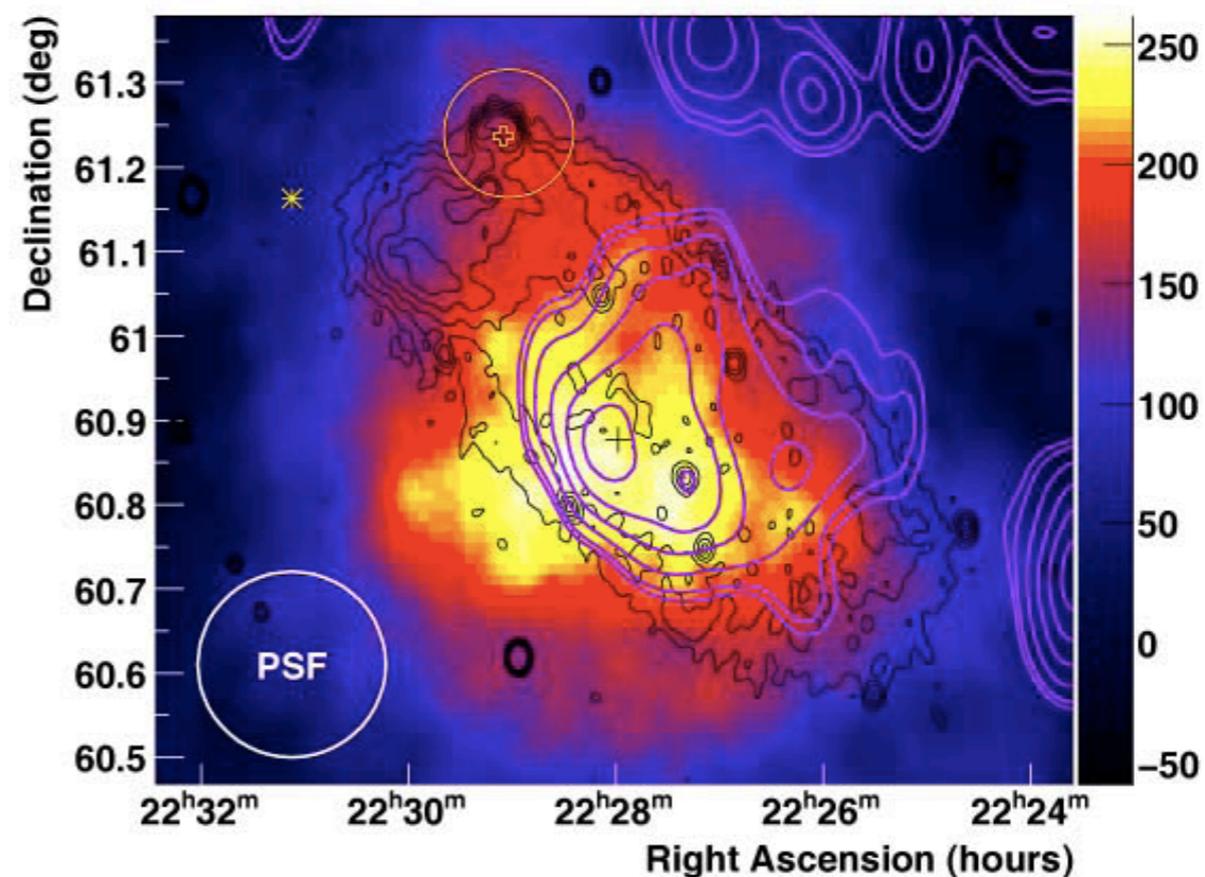
The emission is measured extended

- Spans a  $0.4^\circ \times 0.6^\circ$  region

- Peak is  $0.4^\circ$  away from PSR

- Overlaps with region of high CO density

Multiwavelength Excess Map



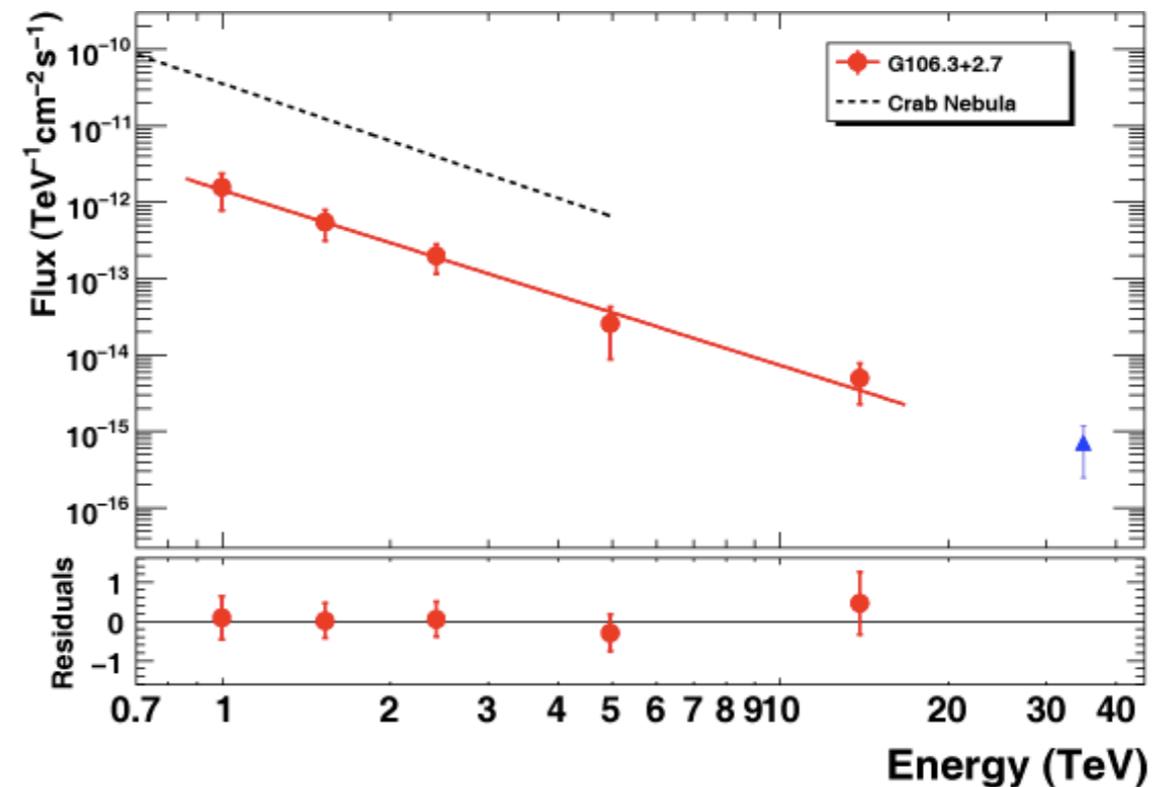
Black - Radio(DRAO)  
Circle -FGST Error Box  
Dot - Pulsar position  
Purple -  $^{12}\text{CO}$  emission

# Boomerang/PSR J2229+6114 : Results (II)



## Energy Spectrum

- Integrate over 0.32deg radius centered on emission peak
- Flux above 1 TeV is ~5% of the Crab Nebula
- Well fit by pure power law  
 $\Gamma \sim 2.29 \pm 0.31_{\text{stat}} \pm 0.3_{\text{sys}}$



Consistent within errors with Bednarek & Bartosik PWN model (they assumed a different distance...)

Extension of spectrum is consistent within errors with Milagro point at 35 TeV  
- hadronic origin?

# Upper Limits



The search for emission in the vicinity of 5 other significant objects has ended in non-detections

Why we do not detect them? high magnetic fields? low density medium? too extended and too close?

PSR name	$\log_{10}\dot{E}/d^2$ [erg/s/kpc <sup>2</sup> ]	T [hrs]	$\langle Z \rangle$ [°]	S [ $\sigma$ ]	F(>E <sub>th</sub> ) [% crab]
<b>J0205+6449</b>	36.4	12.8	35.2	1.1 (1.5)	2.3 (4.1)
<b>J0631+1036</b>	35.2	13.0	24.5	0.3 (0.4)	1.3 (2.1)
<b>J0633+1746</b>	36.1	14.5	17.9	1.1	1.6
<b>B0656+14</b>	35.6	9.4	22.4	-1.8 (-2.6)	0.2 (0.7)
<b>J1740+1000</b>	35.1	10.5	24.6	0.2 (0.0)	1.0 (1.4)

point source u.l. at PSR

slightly extended source u.l. at PSR

# Summary

---



VERITAS has made high-significance detections/discoveries of two galactic sources at the TeV band. Deeper studies are needed to understand the origin of the TeV emission

G54.1+0.3/PSR J1930+1852 (Crab-like object  $\sim 1e3$  yr)

Steady and consistent with a point source emission (limited resolution of TeV instruments)

Flux  $\sim 3\%$  of Crab above 1 TeV

L/E  $\sim 2\%$  (0.3-10 TeV band), consistent with pulsar powering the nebula

Boomerang/PSR J2229+6114 (Vela-like object  $\sim 1e4$  yr)

Steady and extended emission along the radio shell and also coincident with nearby molecular cloud emission

Flux  $\sim 5\%$  of Crab above 1 TeV

If associated with MGRO J2229+611, hadronic origins may be favored

5 upper limits have been reported, more notably VERITAS does not detect 3C58 with current exposure

VERITAS survey of Northern Galactic pulsars is ongoing and more results will be reported in the future aiming to cover uniformly and with high sensitivity the whole Northern sky population