The VERITAS Observatory:
Recent Stops along the Galactic Plane

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for the VERITAS Collaboration

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The VERITAS Instrument

Specifications:

- Energy range: 100 GeV to > 30 TeV
- Energy resolution ~ 15 % at 1 TeV
- Angular resolution (68% containment): 0.1º at 1 TeV, 0.14º at 200 GeV
- Source location accuracy: <50 arcseconds

Instrument design:

- Four 12-m telescopes
- 499-pixel cameras (3.5° FoV)
- FLWO,Mt. Hopkins, Az (1268 m)

Sensitivity:

- 1% Crab in < 30 hrs
- 10% Crab in < 30 min

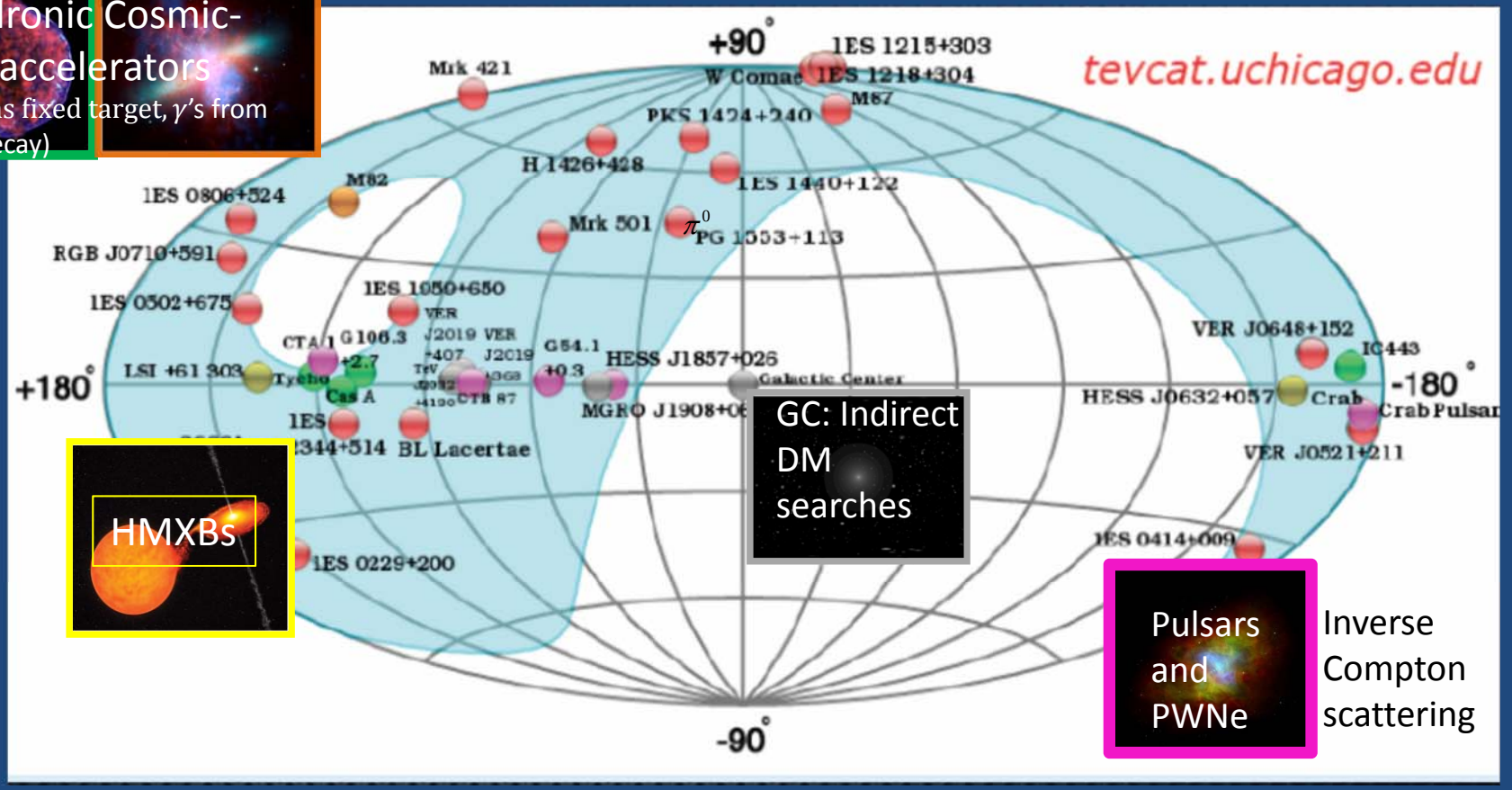
Yearly observing (good weather):

- **Dark time ~800 hours**
- **Moonlight ~400 hrs additional**

Supported by: NSF/DOE/Smithsonian, SFI(Ireland), NSERC(Canada), STFC (UK)

Galactic Accelerators and Beyond

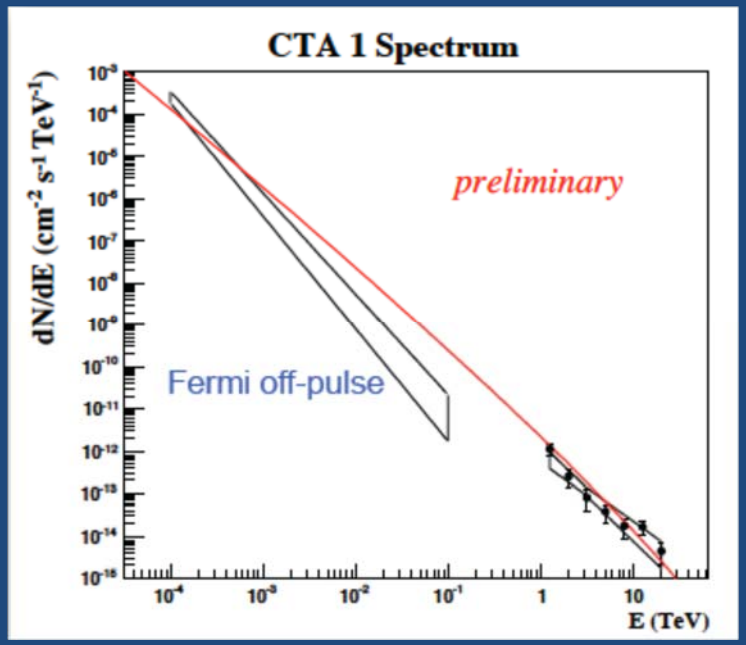
Hadronic Cosmic-ray accelerators
ISM as fixed target, γ's from π^0 decay)



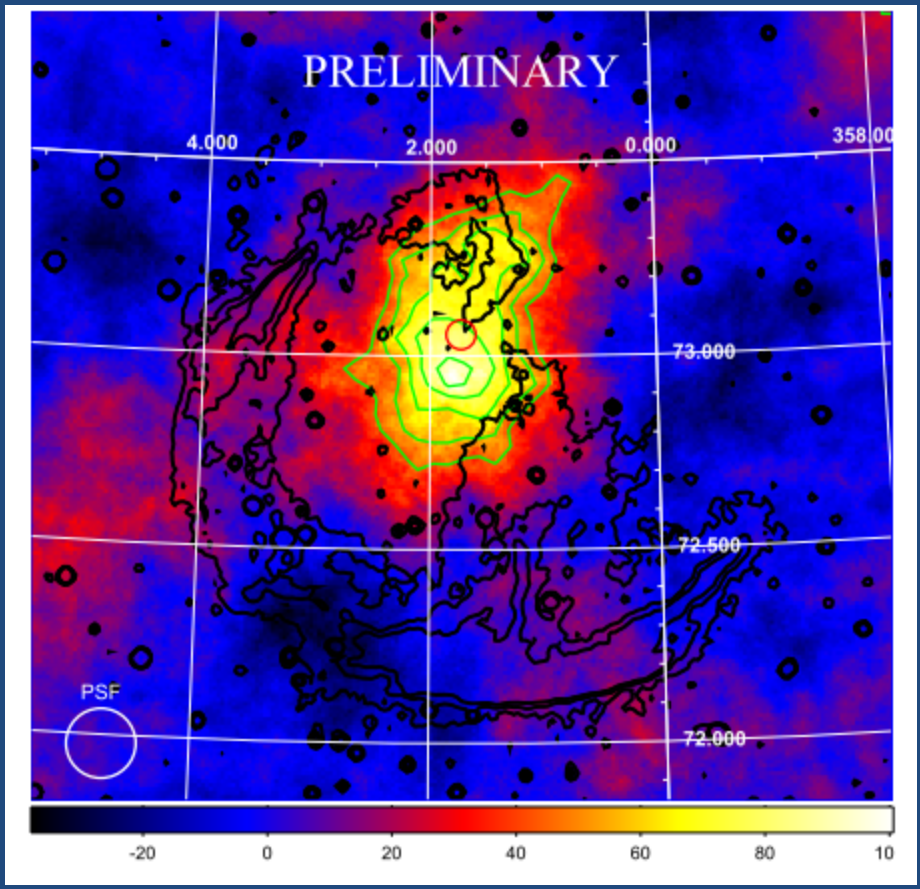
- Galactic CR accelerators, pulsars and PWNe, X-ray binaries, DM targets

SNR and PWNe: CTA1

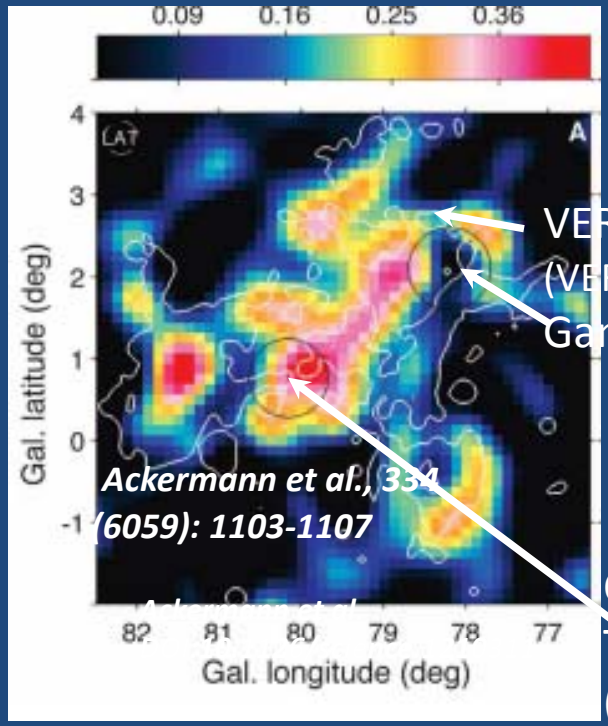
- Green contours: ASCA keV emission from pulsar wind nebula (PWN)
- Red: Fermi (GeV) pulsar
- TeV emission centers on pulsar and aligns with PWN
- Preliminary spectrum agrees well with Zhang et al. (2009) broad-band modeling of unpulsed Fermi component



- Supernova remnant (SNR) is ~13 kyr old and 4600 ly distant
- Black contours: 1.5° diam. radio shell at 1420 MHz (T. Landecker)



The Cygnus Region

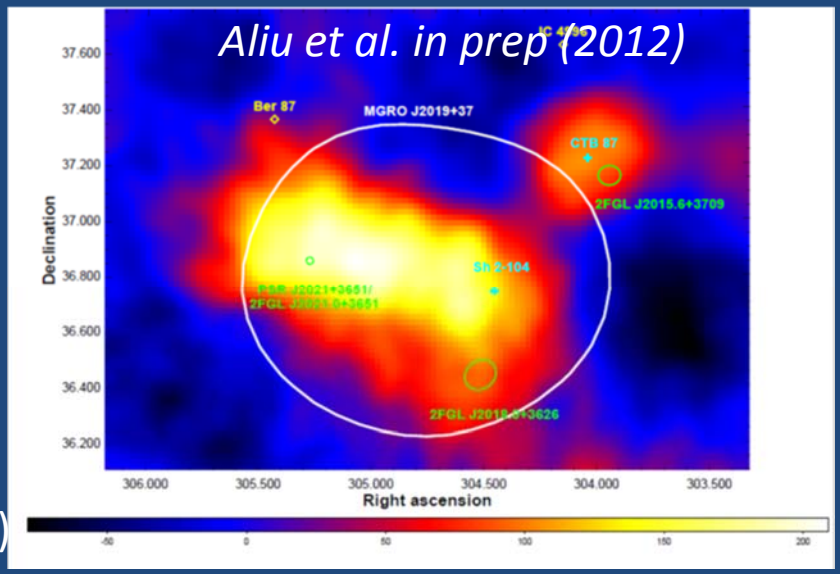


VER J2019+407
(VERITAS discovery)
Gamma Cygni SNR

Cygnus OB2
TeV J2032+4130
(VERITAS detection)

Ackermann et al., 334 (6059): 1103-1107

Cygnus cocoon (Fermi) with two potential accelerators seen in GeV and TeV



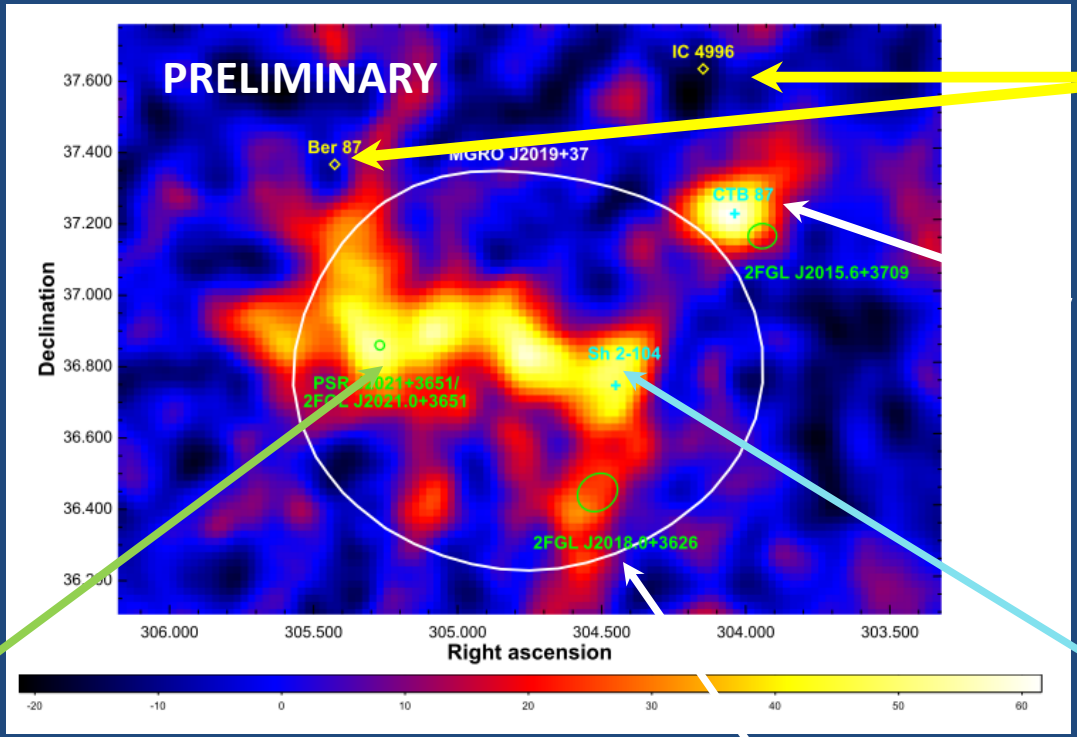
Extended source search of Cygnus OB1 region

- VERITAS observations from 2006 on
  - Survey: 67 < l < 82, -1 < b < 4 (2006-08)
  - Dedicated observations of specific regions (2009 and later)
- Two regions of complex GeV and TeV gamma-ray emission

The Cygnus Region: Cygnus OB1

- VERITAS observations of MGRO 2019+37 reveals complex TeV emission, poss. multiple sources

- **WR stars in region could also play a role**
- **Unresolved sources vs. highly extended source?**



Young stellar clusters in Cyg OB1 assoc.

TeV emission associated with possible young PWN CTB 87 (~1% of Crab Nebula flux above 650 GeV)

HII region

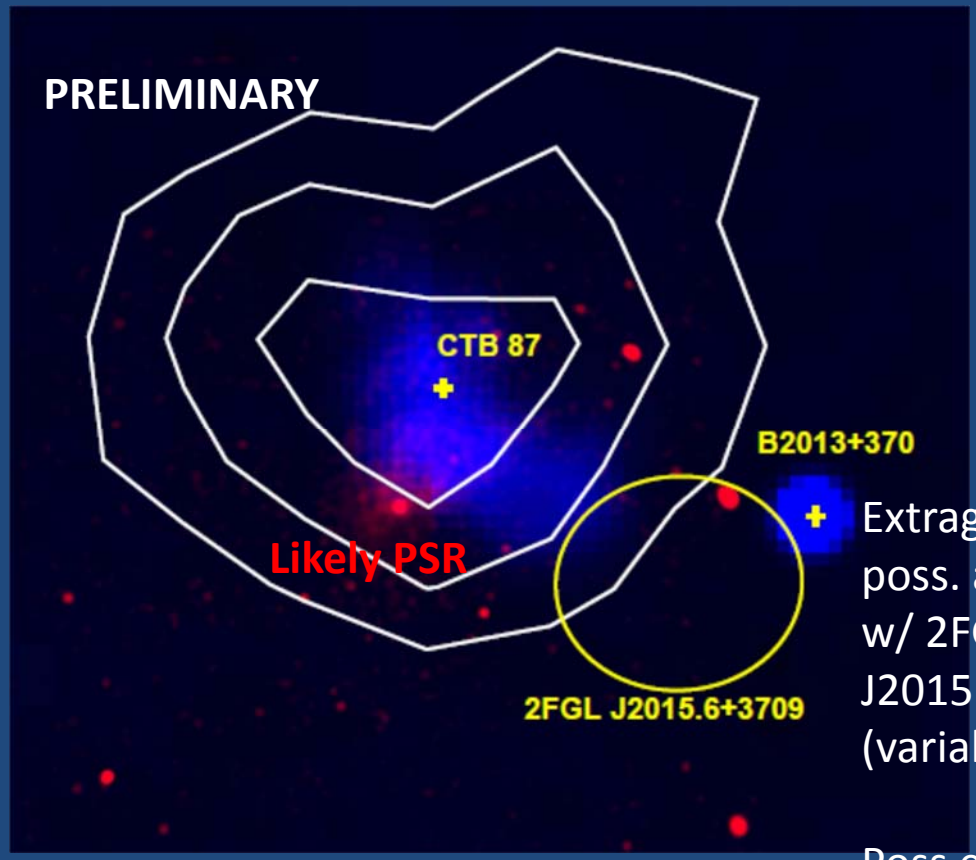
- PSR J2021 and 2FGL J2021.0+3651: young and energetic radio, GeV pulsar surrounded by PWN.

MGRO J2019+37

Closer View: VER J2016+372 and CTB 87

- Filled-center SNR at d~6kpc (Perseus arm)
- Pulsar recently located in X-rays (no pulsations yet detected)

- Red: X-ray (Chandra)
- Blue: Radio (NVSS)
- White: VERITAS TeV emission contours



Extragalactic: poss. association w/ 2FGL J2015.6+3709 (variable)?

Poss entangled with PWN contribution

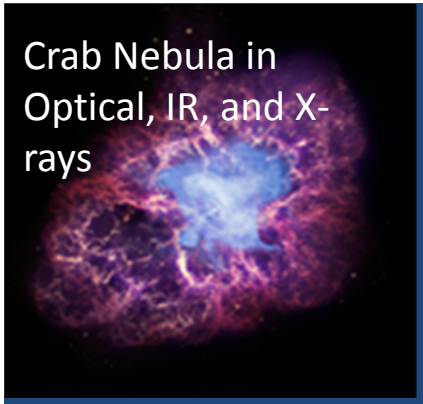
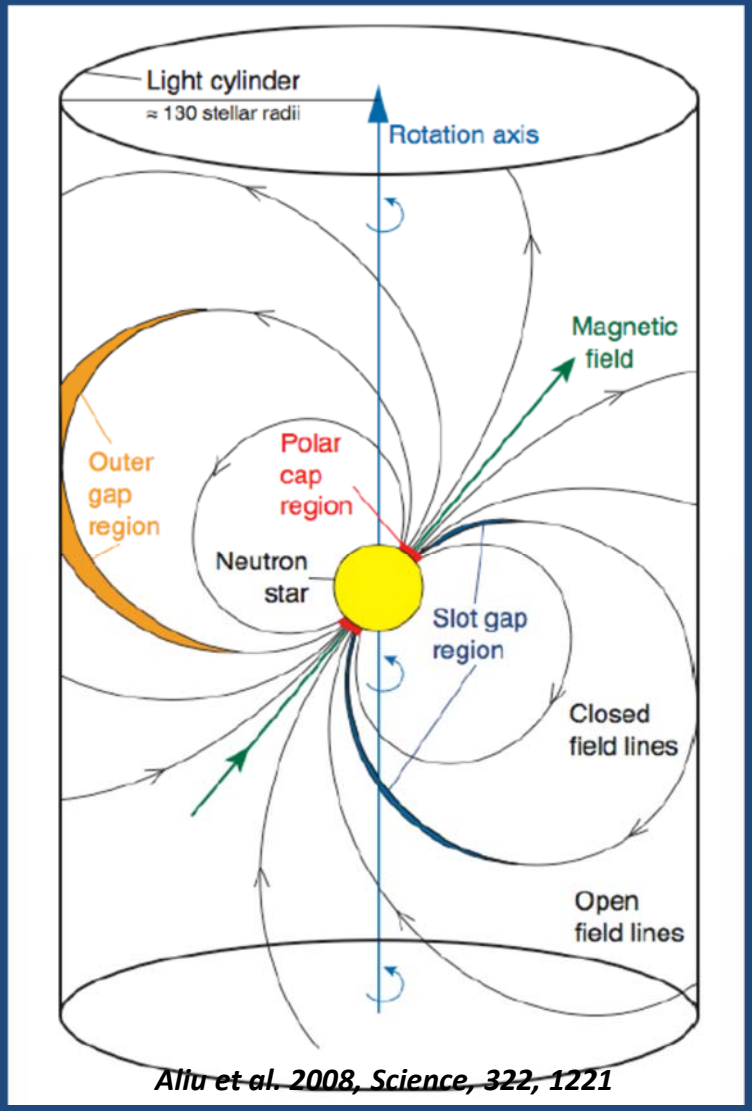


Image credits: X-ray: NASA/CXC/SAO/F.Seward; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehrz

An unscheduled stop: the Crab Pulsar above 100 GeV

- Remnant of historic supernova (1054 A.D.)
- One of the most energetic pulsars (4.6×10^{38} erg s^{-1}) and brightest gamma-ray pulsars

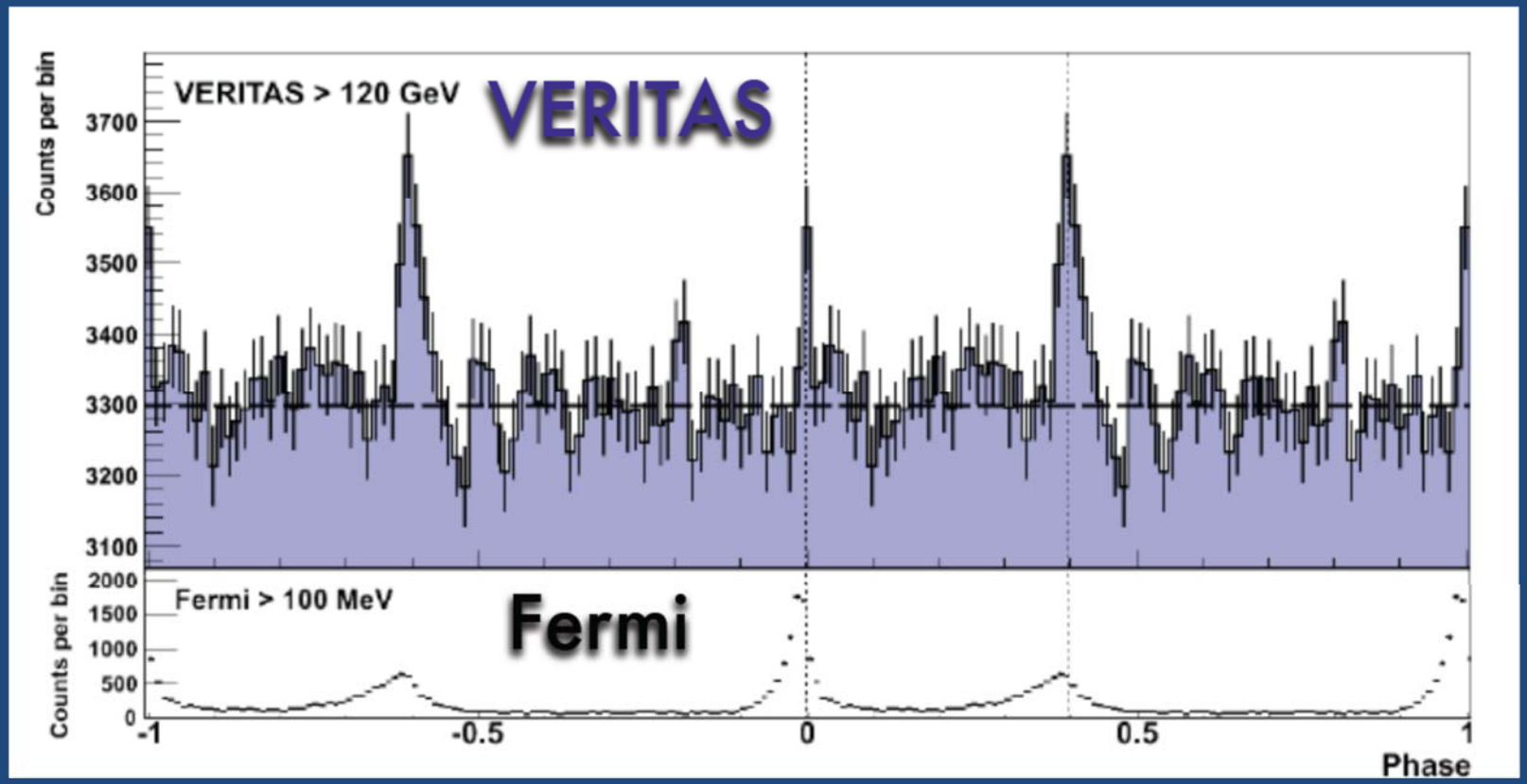
- Powers brightest VHE gamma-ray source, the Crab Nebula
- Conventional wisdom:
  - Break in pulsar spectrum described by exponential cutoff
  - Gamma-ray emission due to curvature radiation
  - Outer gap scenarios favored
    - Emission region > 6 stellar radii from star's surface



Aliu et al. 2008, Science, 322, 1221

An unscheduled stop: the Crab Pulsar above 100 GeV

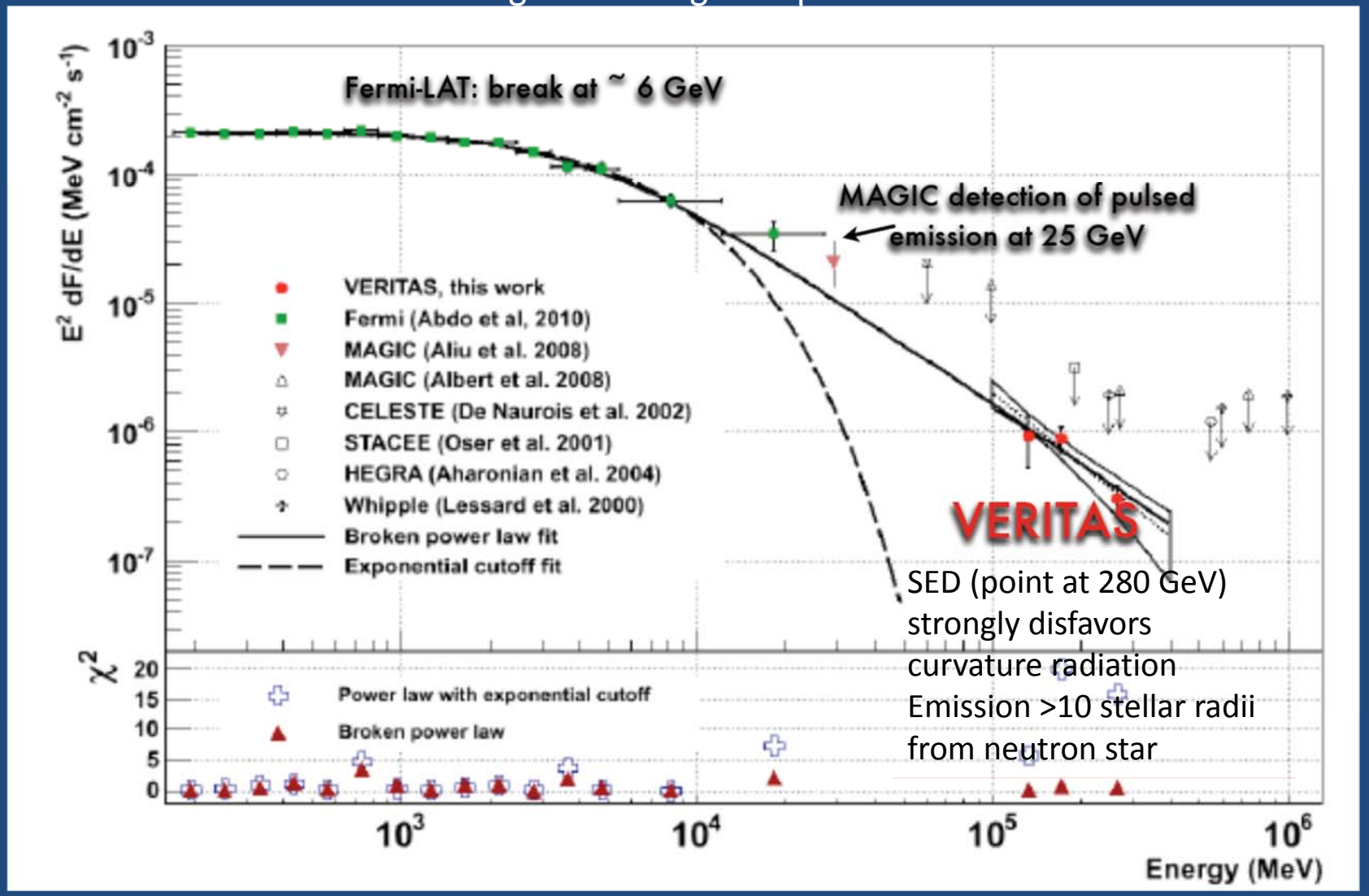
- First pulsed VHE source above 100 GeV
- Pulse profile significantly (2-3 times) narrower than GeV pulse profile



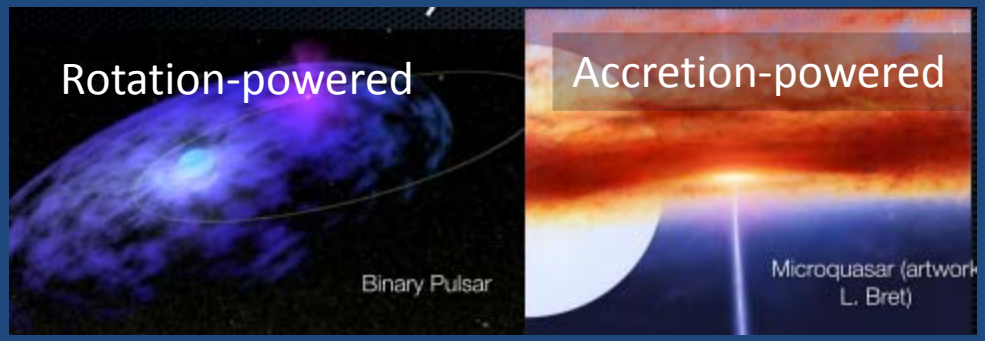
- Energy-dependent narrowing of pulse profile strong probe of nature of magnetospheric particle acceleration region (tapering?)

Crab Pulsar: Altering Paradigms

- Stringently constrains:
  - gamma-ray emission mechanisms (new component above a few GeV)
  - location of emission regions in magnetosphere

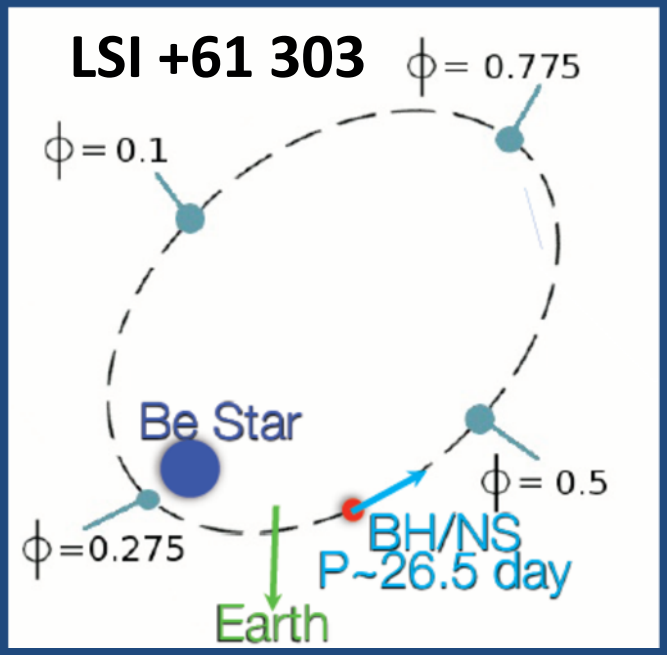


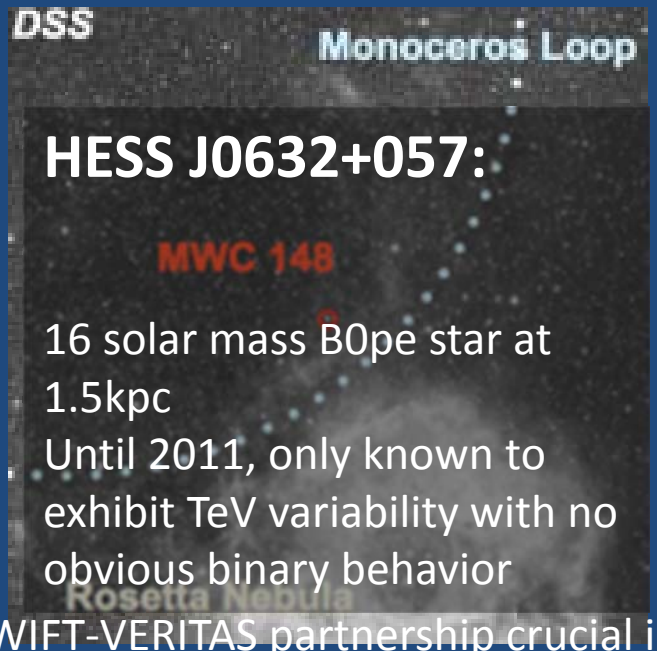
X-Ray Binaries



- 4 XRBs confirmed by IACTs
- 1 with confirmed nature (HESS PSR B1259 is a binary pulsar)
- Periodicity and variability of emission is our best clue

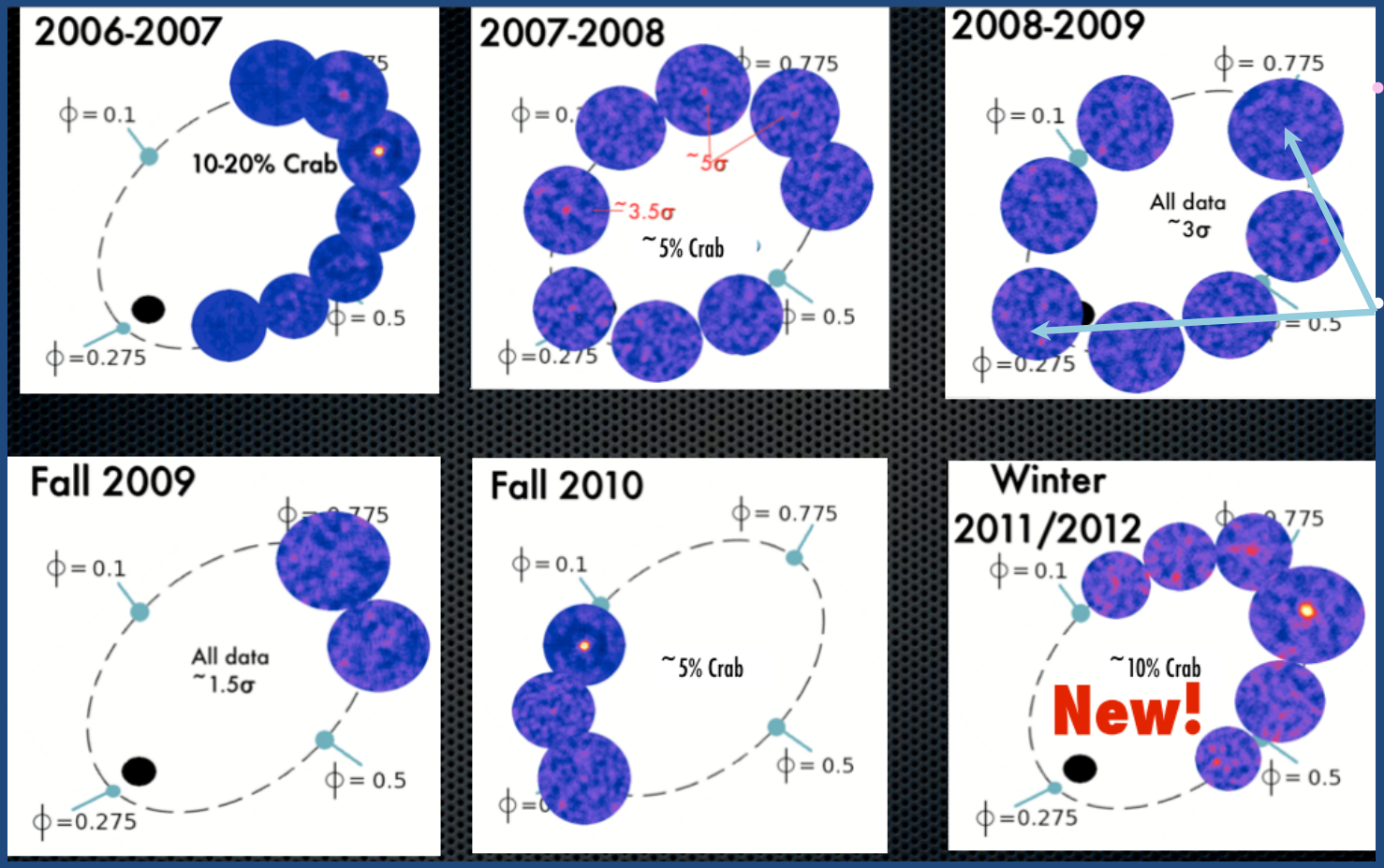
Competing emission models





SWIFT-VERITAS partnership crucial in identifying this as 4th TeV binary

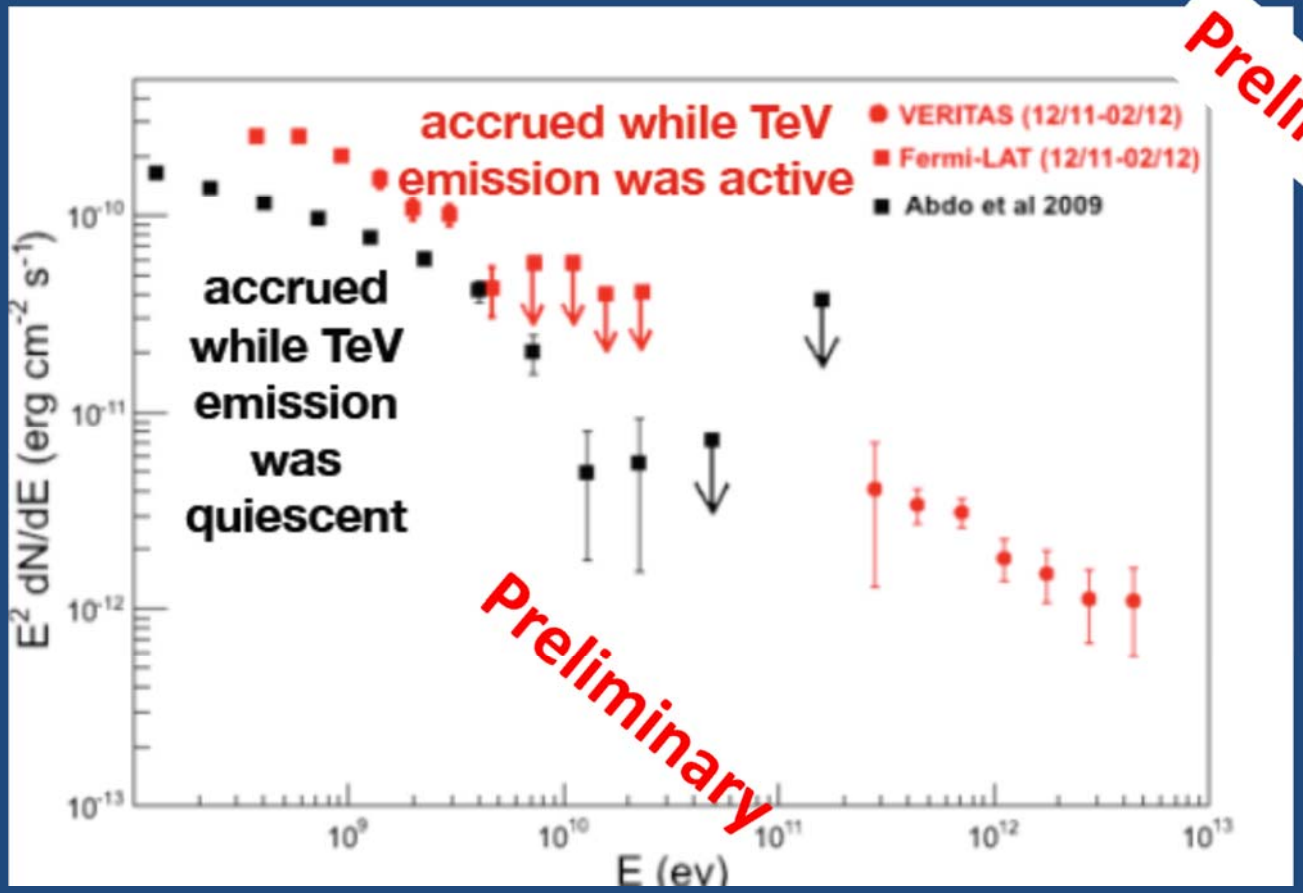
LSI +61 303



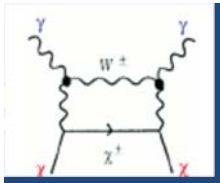
- Radio outbursts near apastron, ~4yr modulation (Gregory 2002)
- High X-ray activity throughout orbit
  - Strongest at apastron
  - Secondary peak near periastron

- Apparent multi-year modulation of TeV emission (typically near apastron)

LSI +61 303



- Connection between GeV and TeV could be the key to resolving the microquasar/binary pulsar model debate
- Fermi-LAT shows emission shoulder coincident with VERITAS detection
- System still shows cutoff at a few GeV



DM searches and the Galactic Center

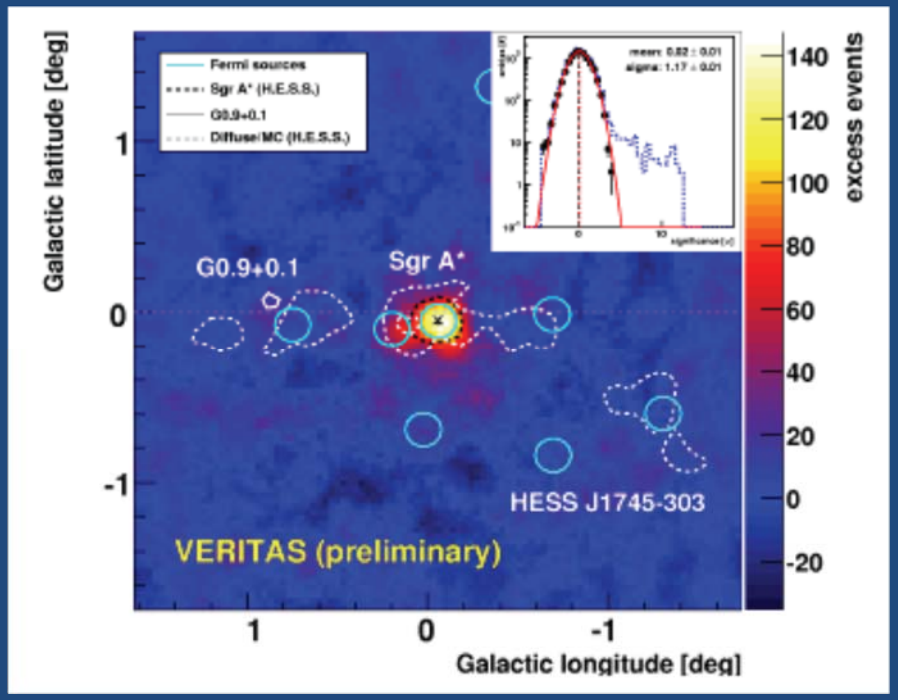
- WIMPs with masses between 50 GeV and 10 TeV well-motivated DM candidates
- Some candidate WIMPS (e.g. neutralino) self-annihilate, producing a potentially detectable gamma-ray signature in astrophysical regions of high DM density
  - Spectral cutoff ($q\bar{q}$ continuum) or line signature ($\pi^0 \rightarrow \gamma\gamma$, suppressed)
- No detections as yet, but may set meaningful limits
- Galactic Center (GC) remains an attractive DM target for TeV observatories
  - Strongest potential signal
  - BUT complex astrophysical backgrounds (must constrain extremely well for best DM results)

- VERITAS observations of GC taken at large zenith angle (increased threshold, eff. area at high energies)

Sgr A* (radio source) $4 \times 10^8\ M_\odot$ black hole

SNRs and PWNe

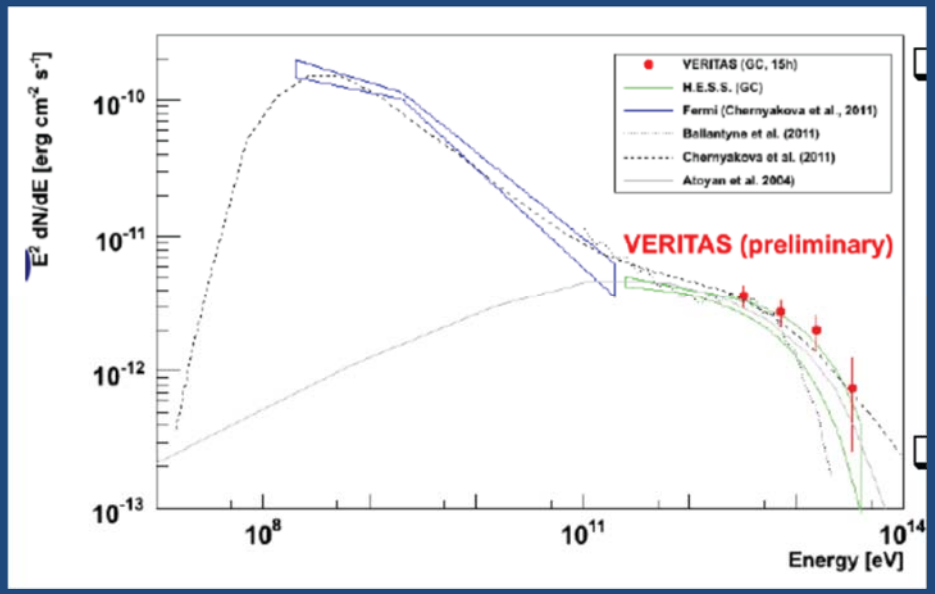
Transients (flaring emission)

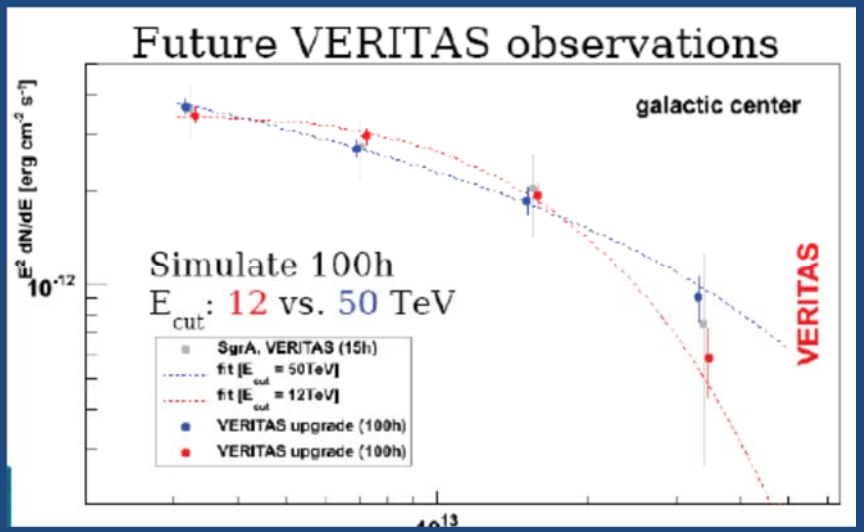


- VERITAS
  - 12σ excess at GC
  - 2-3σ at G0.9+0.1
- White: HESS GC +diffuse
- Blue: Fermi sources

- Increased level of CR density, molecular clouds (Aharonian et al. 2006)

VERITAS at the Galactic Center

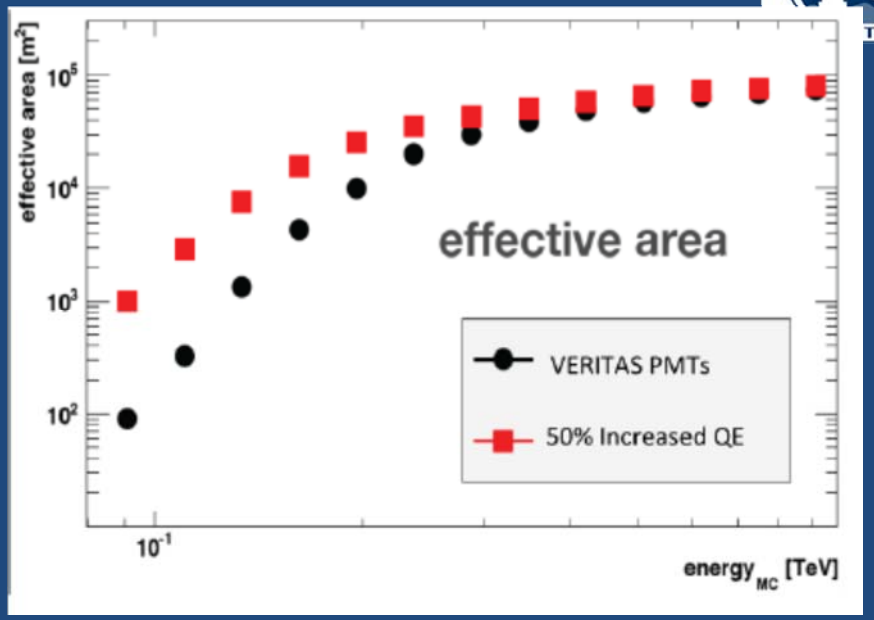




- Preliminary VERITAS spectrum, 40% systematic error (conservative estimate from Crab LZA observations)
  - Thanks to LZA, spectrum competitive now above 10 TeV with HESS with a significantly smaller dataset
- Future plans
  - Constrain astrophysics (models provide different predictions for)
    - cutoff at high energies
    - variability at > 10 TeV
  - obtain DM annihilation upper limit for E > few TeV
- With 100hrs of observations (after VERITAS upgrade) expect to do quite well

The VERITAS Upgrade

- Fall 2011:
  - new FPGA-based camera-level (L2) trigger
  - Improved flexibility, NSB rejection, threshold
  - Successfully commissioned



- Summer 2012:
  - PMT replacement with high-efficiency PMTs
  - Photon collection increase by ~50%
  - Improved background rejection, threshold

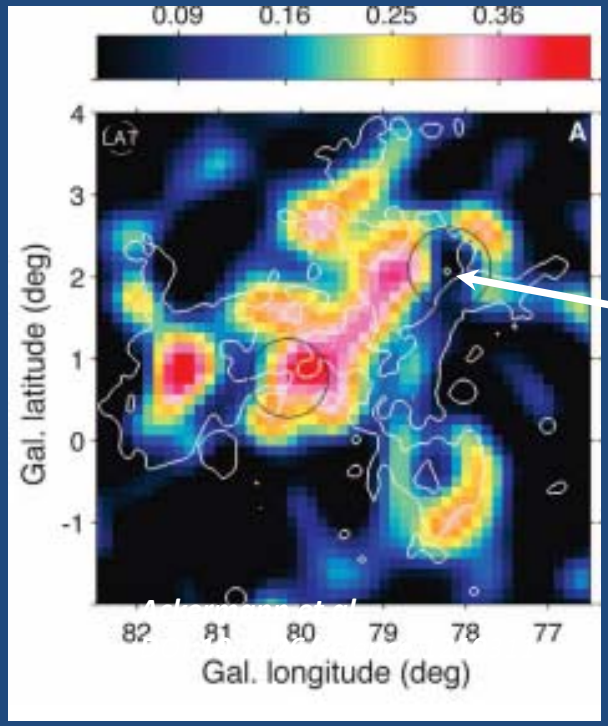
Conclusions and Outlook

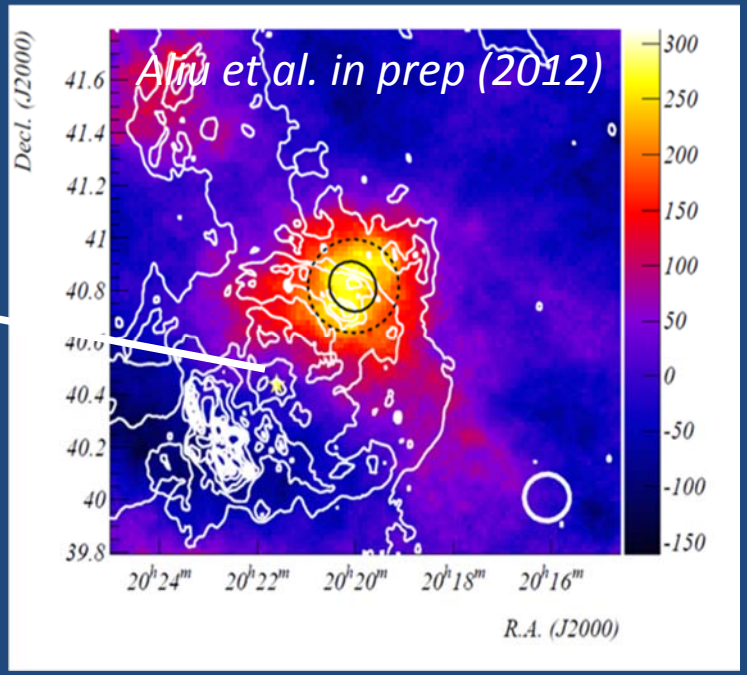
- The VERITAS Galactic science program continues to expand and improve
- Cygnus region has yielded two highly complex regions of GeV-TeV emission
  - The region surrounding VER J2019+407 and TeV J2032+4130 /Cygnus OB2
  - The region surrounding Cygnus OB1/MGRO J2019+307
  - Disentangling PWNe, potential cosmic-ray accelerators (SNRs, WR stars, etc.), and even recently-escaped CR populations in GeV and TeV will be a delightful challenge.
- Detection of Crab pulsar above 100 GeV has fundamentally changed our thinking on pulsar emission mechanisms at high energies.
- Unusual variability in the GeV - TeV regime continues to teach us how much we have left to learn about the mechanisms of emission in gamma-ray emitting binaries.
- The Galactic Center promises
  - Further insights into CR acceleration processes, related astrophysics
  - DM annihilation upper limits

The ongoing VERITAS upgrade promises more rapid journeys into exciting new territory.

BACKUP

The Cygnus Region

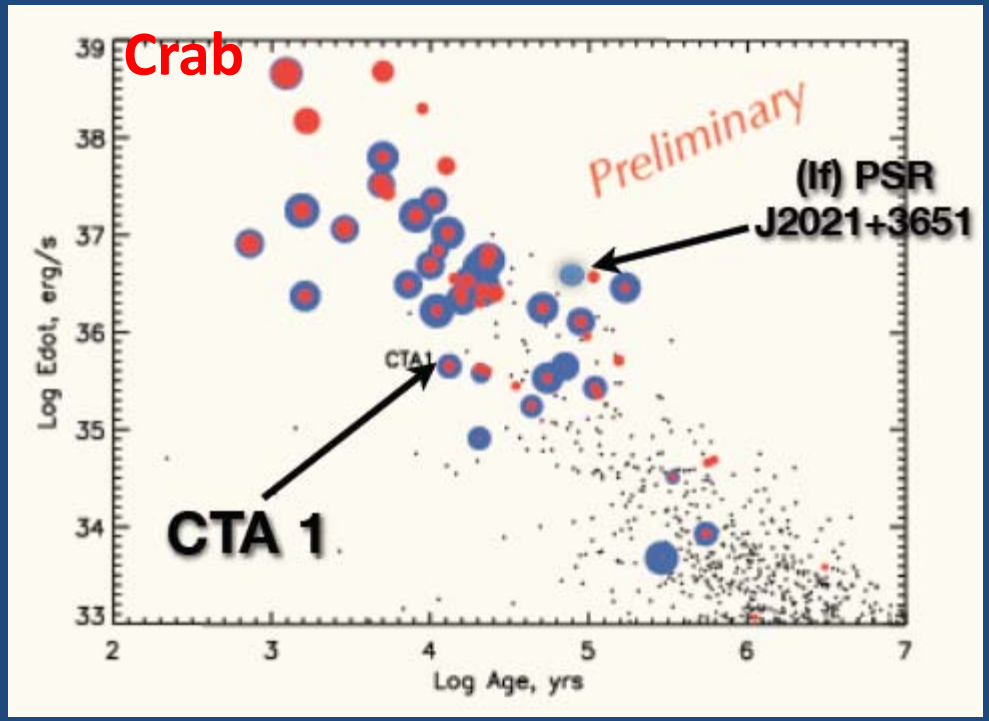




Recent results in context

- X-Ray detected PWN (red)
- TeV PWN (Blue)
- Luminosity scales with circle size

Modified from Kargaltsev and Pavlov 2010

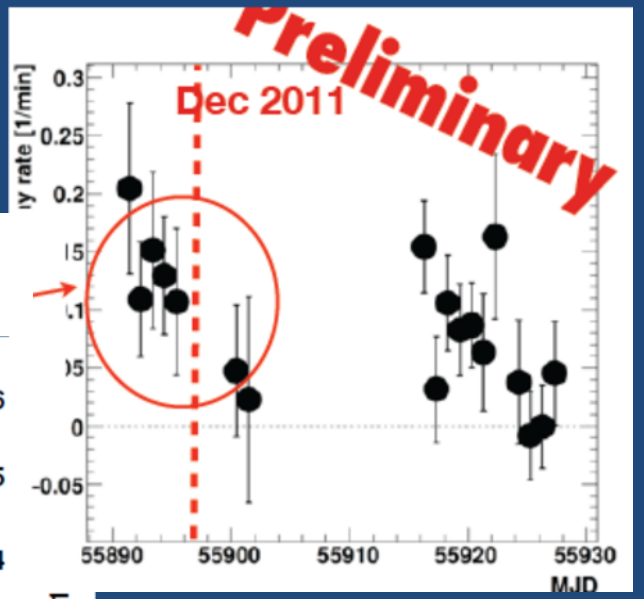


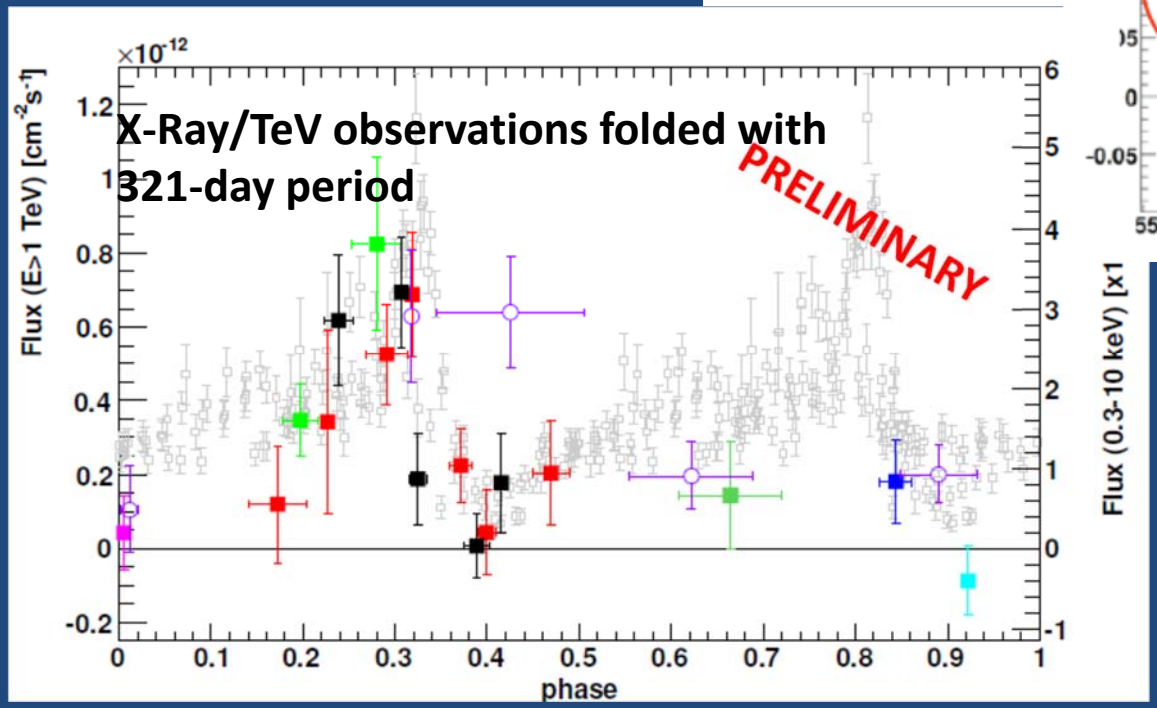
- Young, high E-dot pulsars appear more likely to have observable TeV PWNe

HESS J0632+057

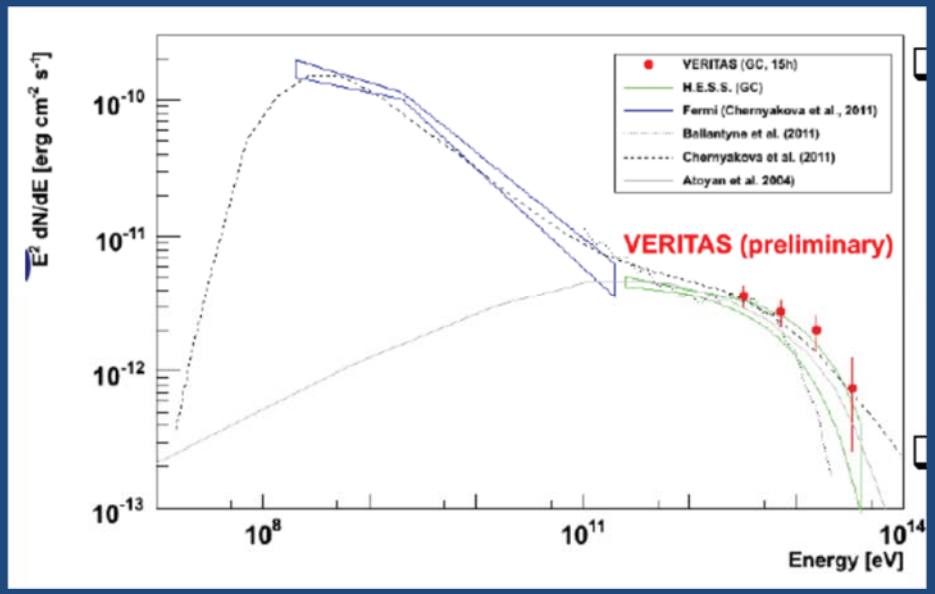
- Latest VERITAS observations: Nov 2011-Jan 2012
- SWIFT-VERITAS partnership crucial in identifying this as 4th TeV binary
- Possible TeV-X-ray lag?

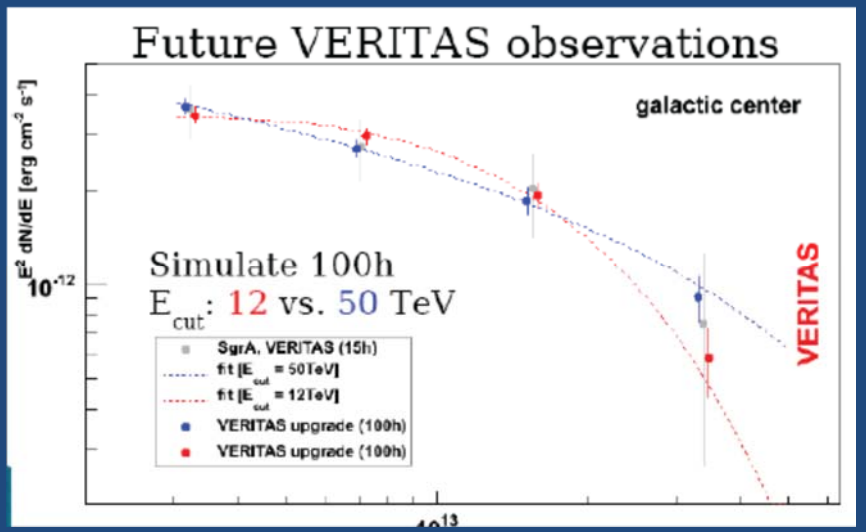
321 days after last TeV emission peak





VERITAS at the Galactic Center





- Preliminary VERITAS spectrum, 40% systematic error (conservative estimate from Crab LZA observations)
- Models:
  - M. Chernyakova et al. ApJ 726 (2011): BH accelerator, variability timescale 10^4 yr @ Mev/GeV, ~10 yr above 10 TeV
  - Ballantyne et al. MNRAS 410, 152 (2011): protons accelerated within ~20 Rs; spectral variability > 10 TeV
  - Atoyan et al., ApJ, 617, L123 (2004) :BH plerion (leptonic wind)
- Constrain astrophysics
  - cutoff at high energies
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