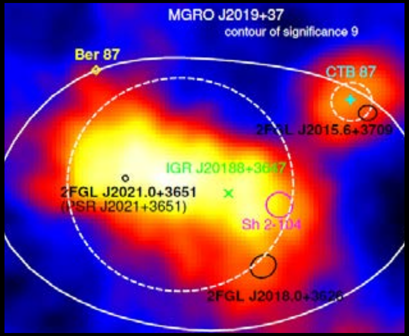
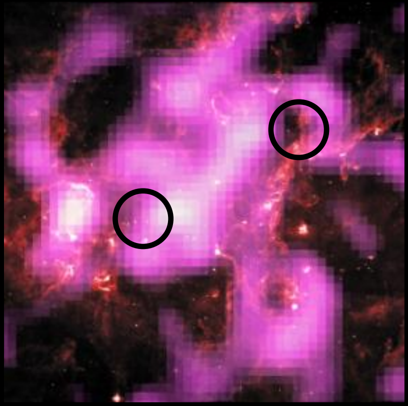
The Cygnus Region of the Galaxy: A VERITAS Perspective



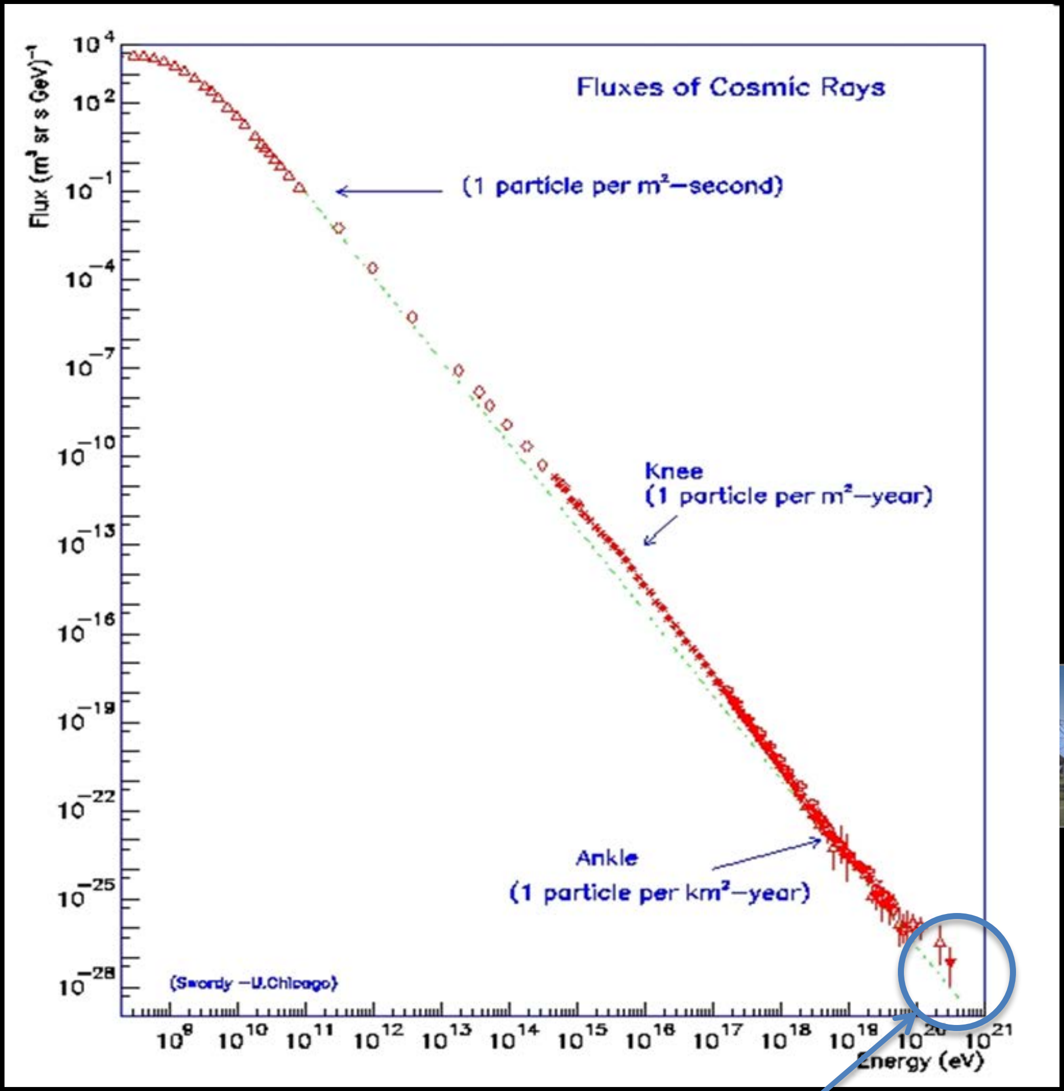


Amanda Weinstein
Iowa State University

SuGAR 2015
Geneva

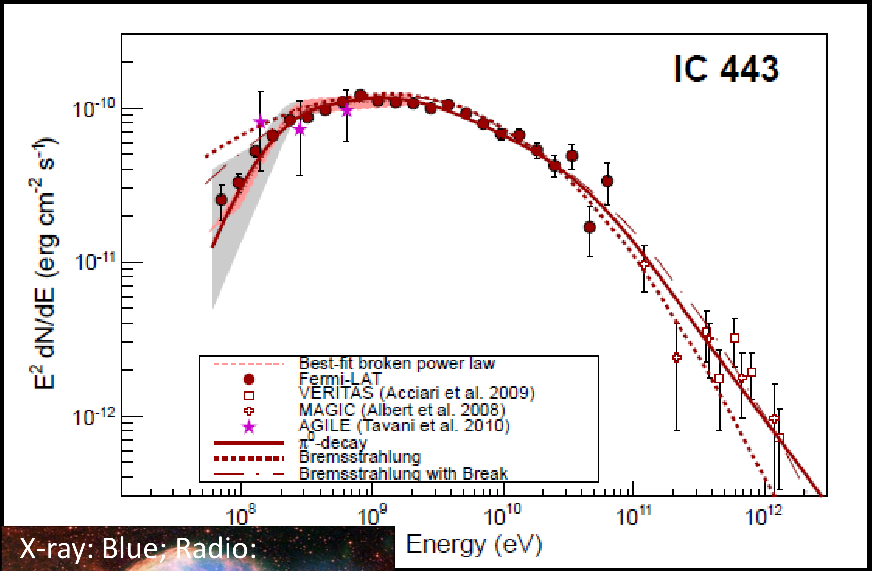
Hunting Cosmic Ray Accelerators

- Tracing particle populations with photons
- Information about acceleration mechanisms

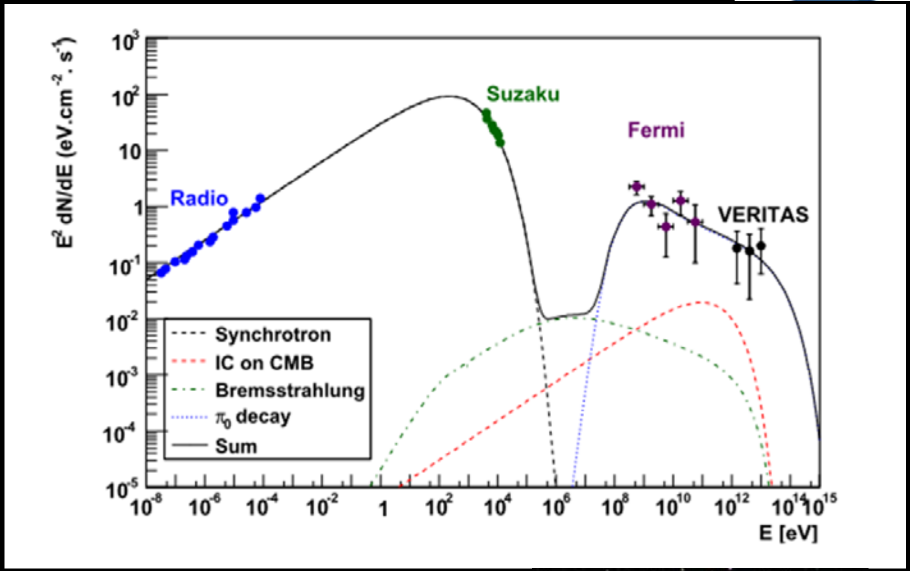


Charged particle anisotropies

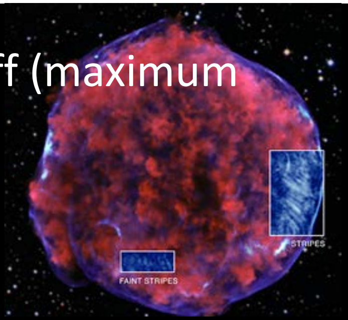
Finding PeVatrons with SNR?



IC443 and the “pion decay bump”

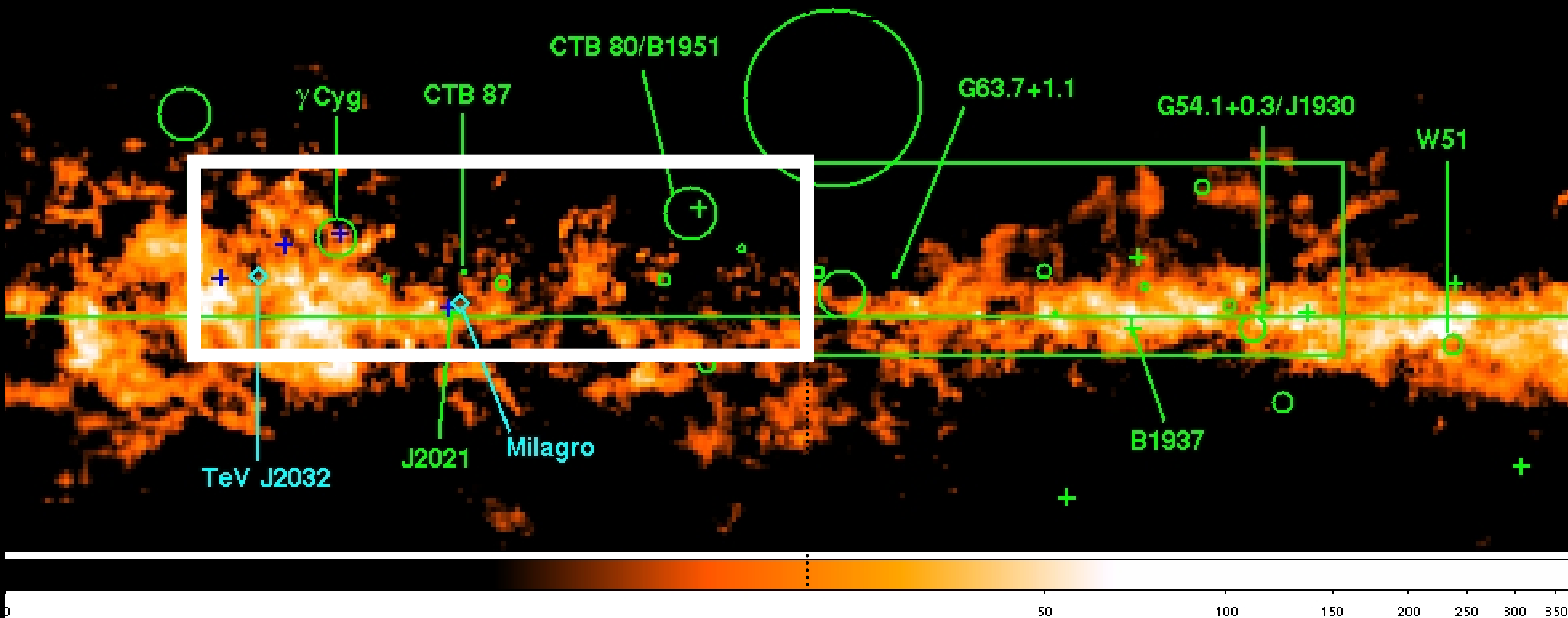


Tycho: hunting the cutoff (maximum proton energy)



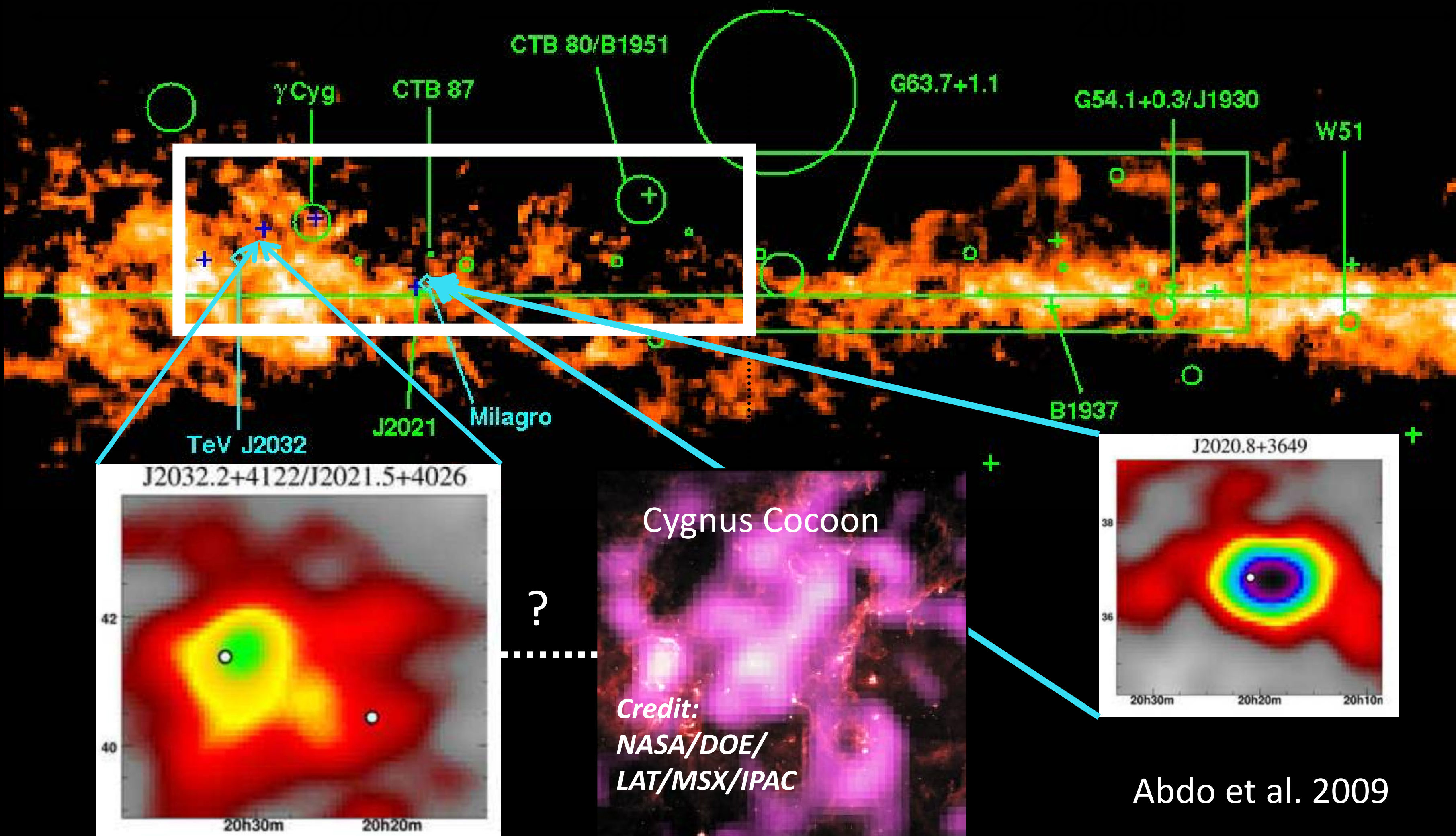
- Problem: most energetic particles escape first (~30 yrs)
  - Hunting baby SNRs is hard!
- Cosmic ray escape signatures from accelerators? (individual, aggregate)

VERITAS Cygnus Region Survey: Motivations



- Source-agnostic look at a potentially source-rich region
  - High density of material
  - EGRET catalog sources, SNR/PWNe, &c.
  - Cygnus superbubble

High Energy Picture



Abdo et al. 2009

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:

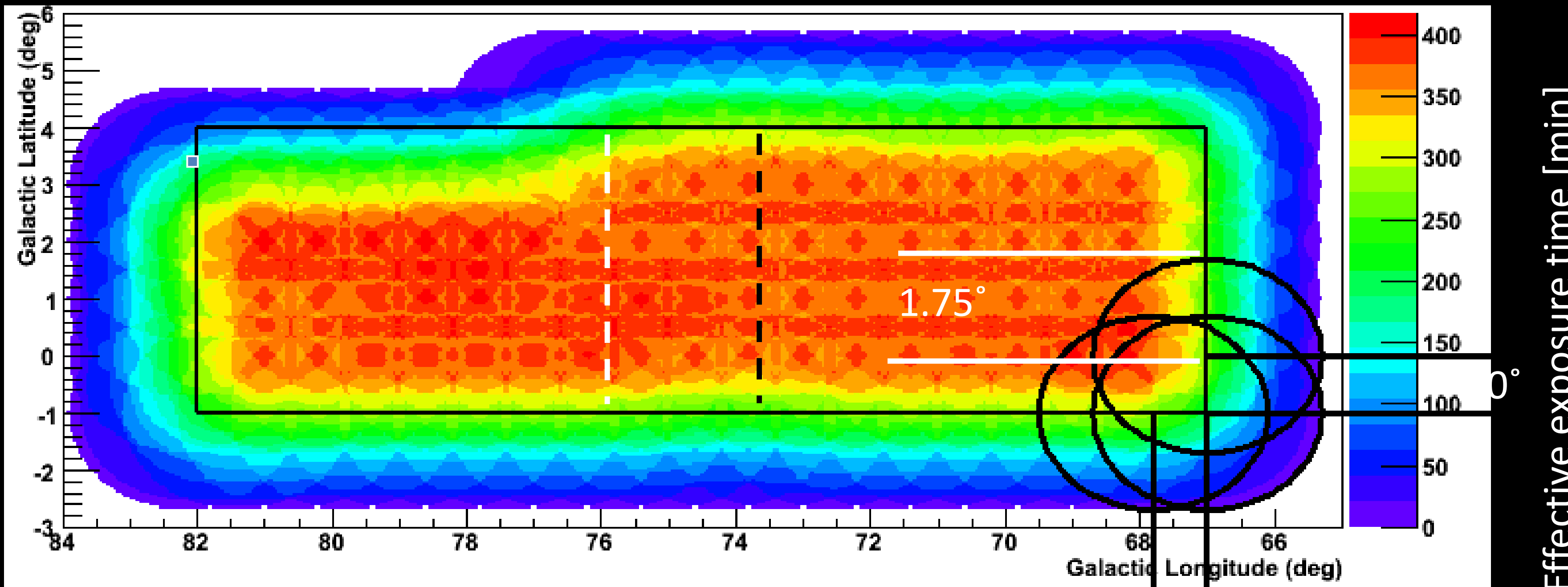
- 1% Crab in < 30 hrs
- 10% Crab in < 30 min

Yearly observing (good weather):

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

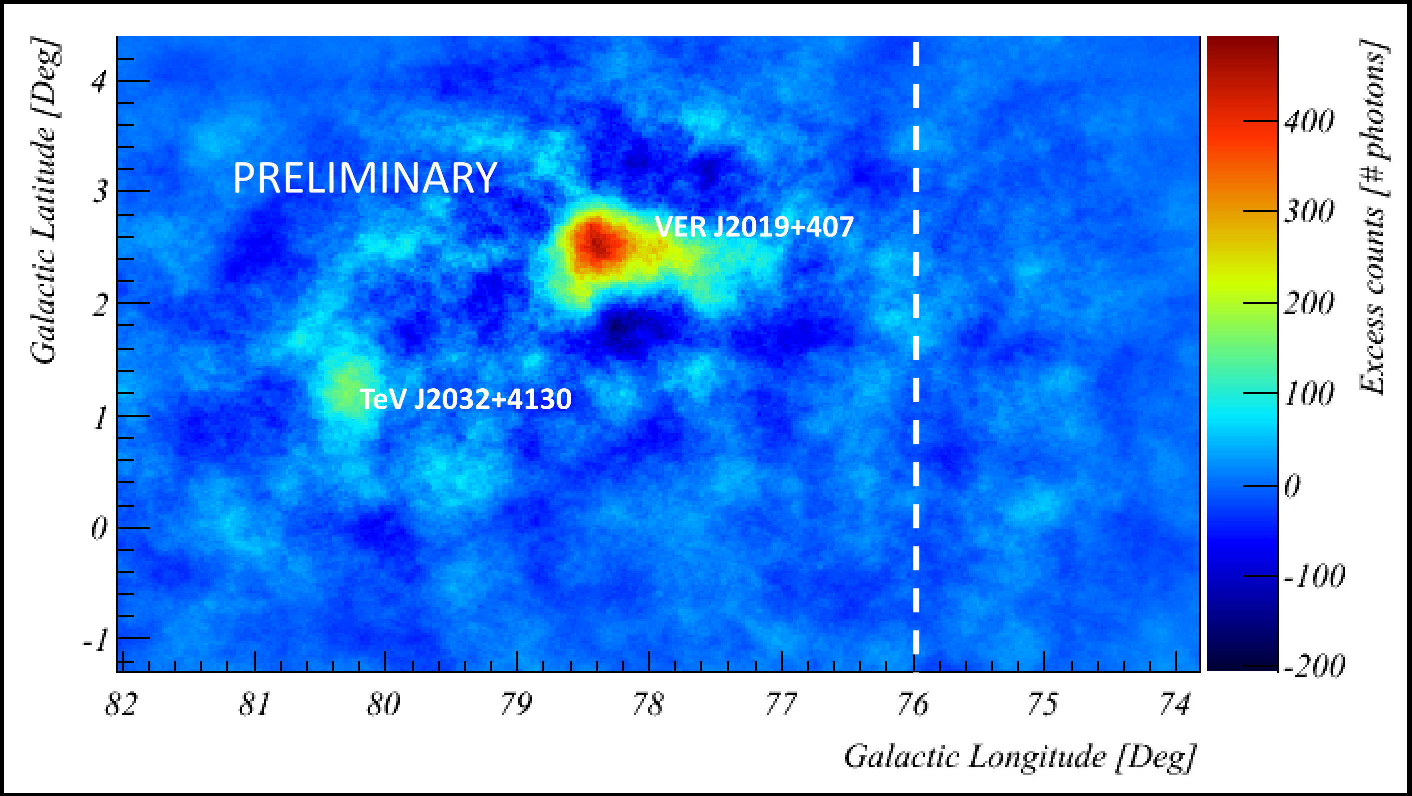
Supported by: NSF/DOE/Smithsonian, SFI(Ireland), NSERC(Canada), STFC (UK)

Survey Exposure as of Summer 2009



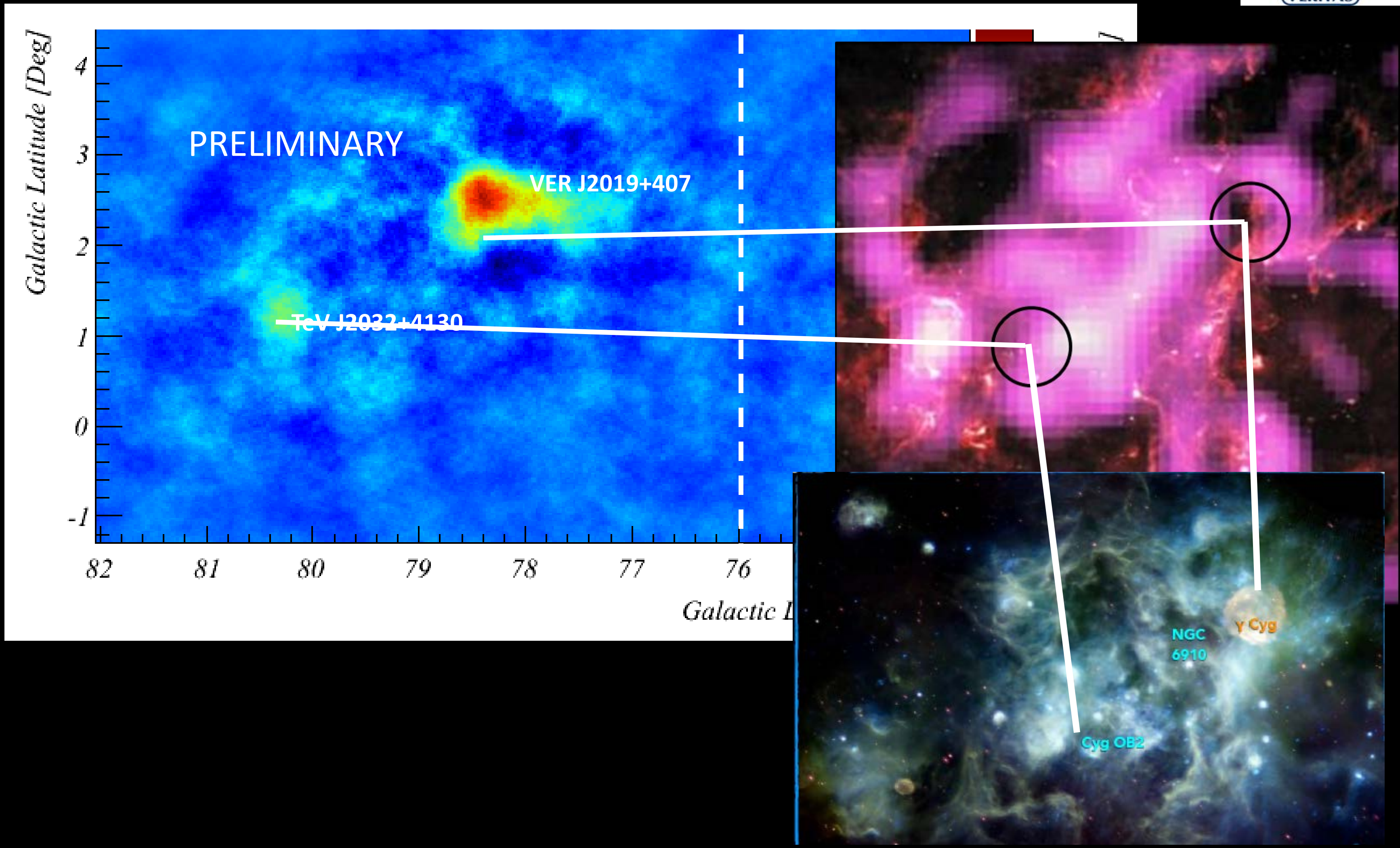
- Survey covers region 67˚ < l < 82˚, -1˚ < b < 4˚
- ~6 hrs effective exposure before followup
- ~2 yr program

Survey Results (Partial)

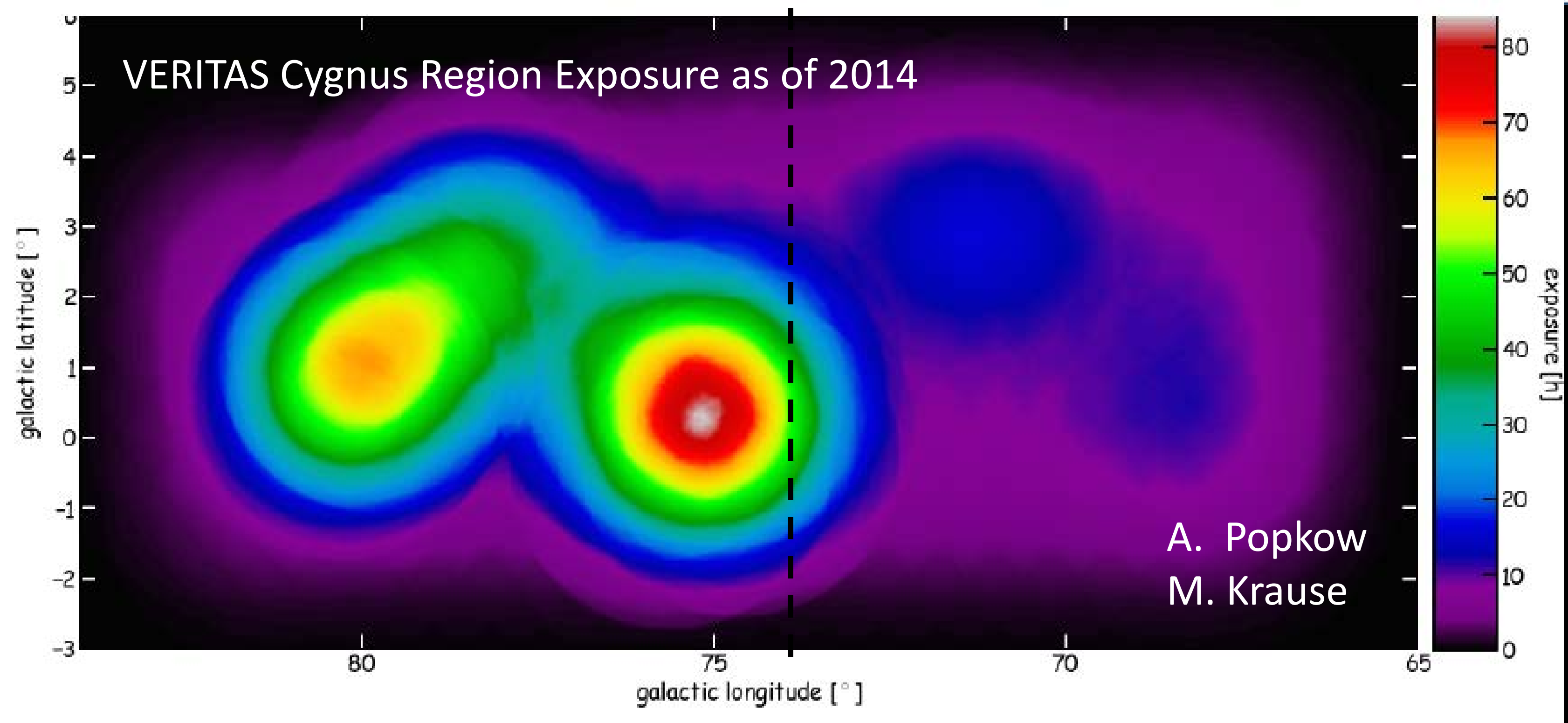


- Based on data through Fall 2009
  - Uneven exposure due to follow-up on VER J2019+407 and TeV J2032
- First shown at 2009 Fermi Symposium

Survey Results (Partial)

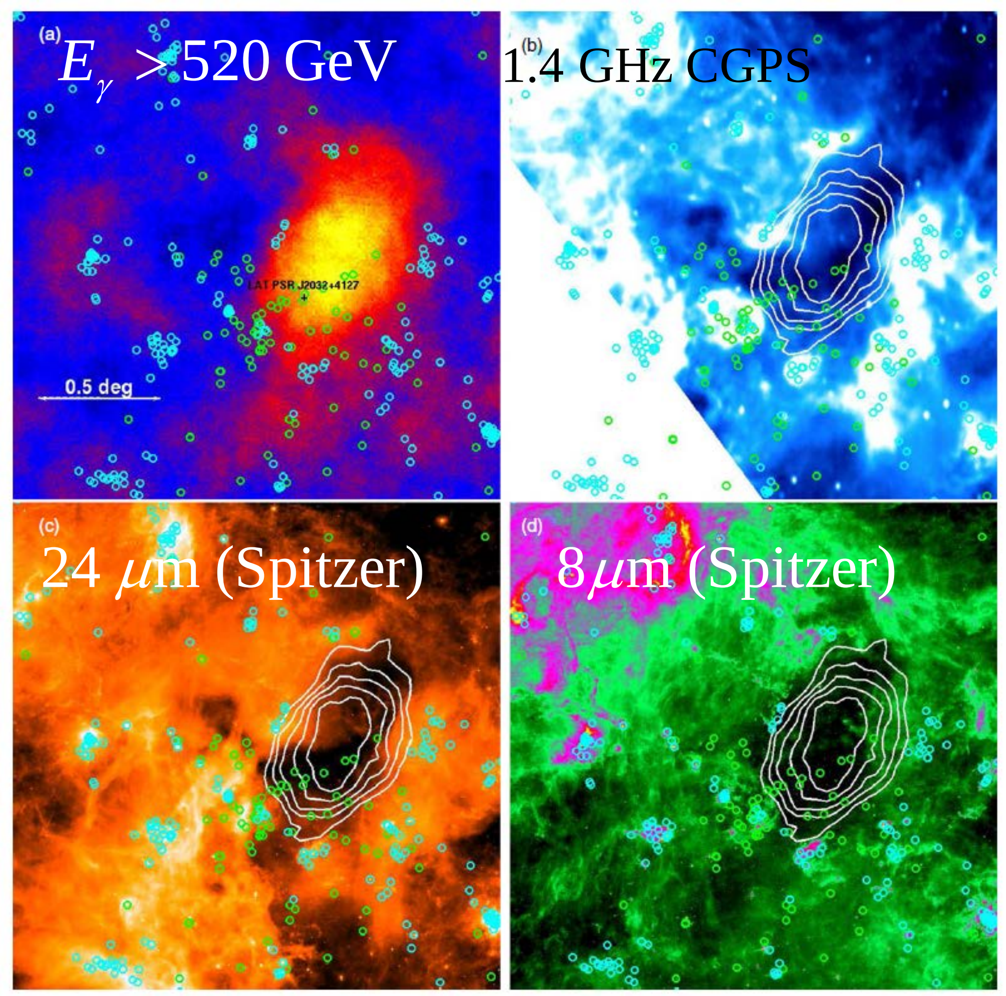


Where are we now?



- Exposure increased
  - candidate follow-up, independently motivated observations
- Results from new (non-survey) datasets
- Future plans with full set of archival data in survey region

TeV J2032+4130

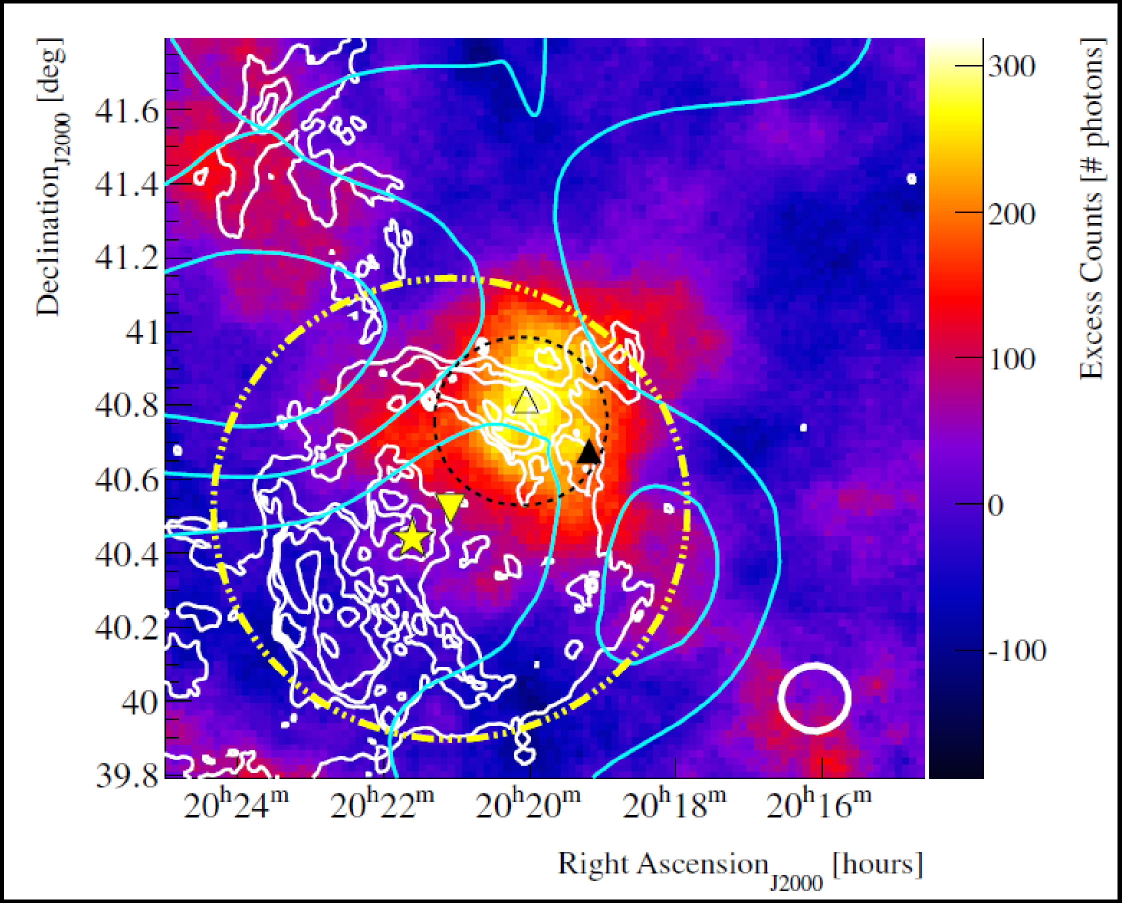


Aliu et al 2014

Star forming regions OB stars

- VHE gamma-ray emission confined in a "void" of radio, IR emission
- Likely PWN of PSR J2032+4127
  - Faint X-ray PWN consistent w/spin-down properties of pulsar
  - TeV/X-ray luminosity consistent w/PWN expectations
- No significant detection of PWN in Fermi data from 500 MeV – 100 GeV

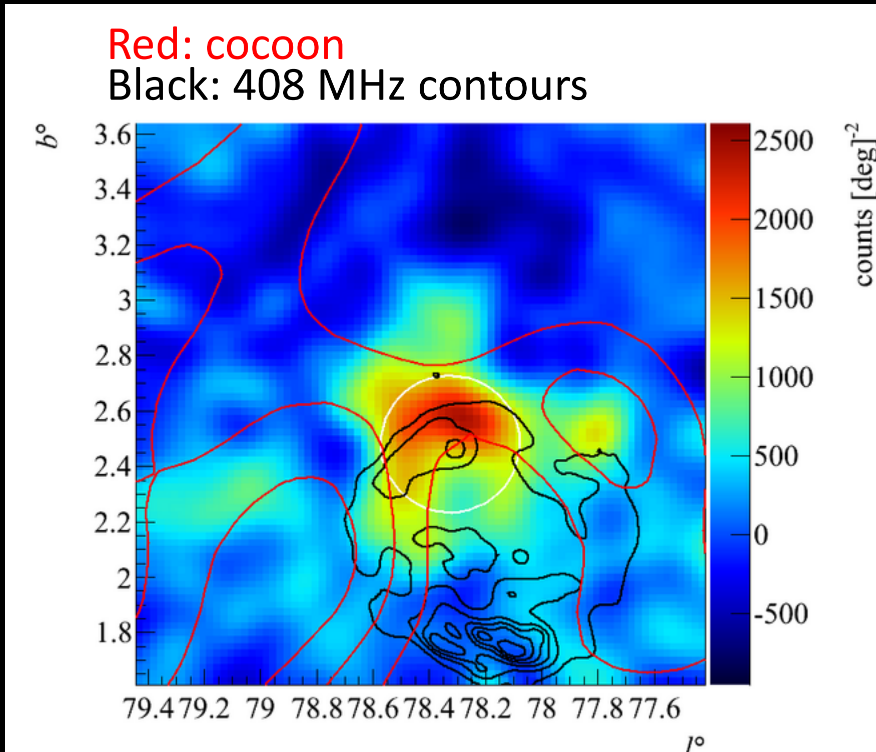
VER J2019+407



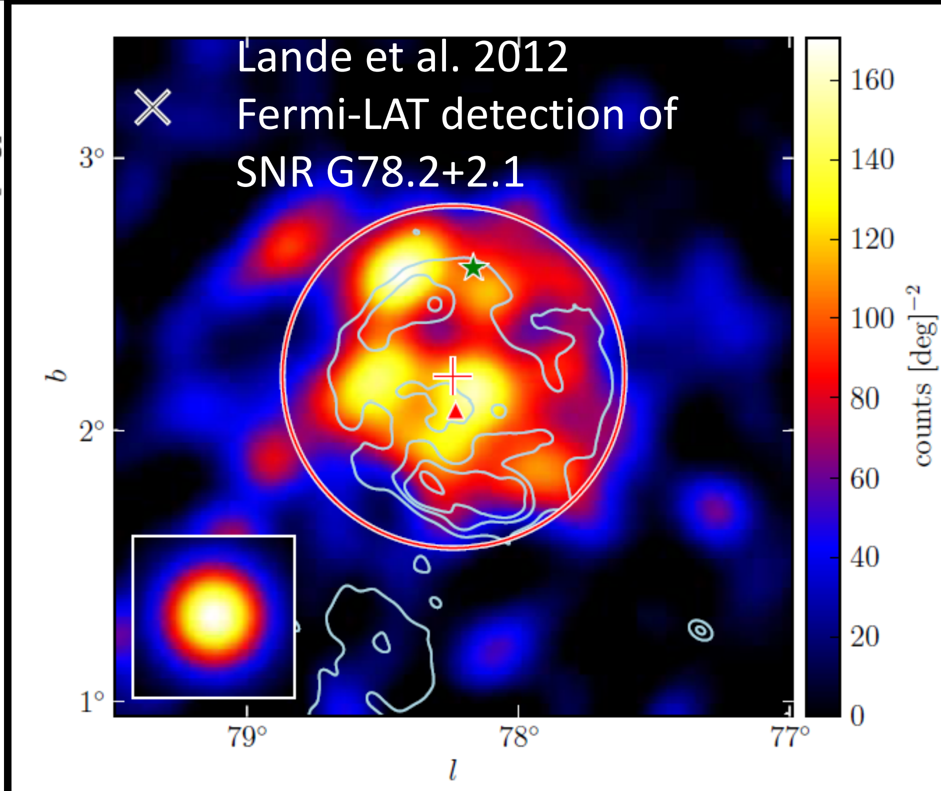
Aliu et al 2013

- Emission from SNR?
  - TeV flux consistent with material density
  - Diffuse X-ray emission is thermal
- Offset PWN?
  - Large offset from PSR J2021+4026
  - Leahy et al. 2013—hard X-ray point source with distance consistent with SNR
    - Just outside VER J2019+407 1σ extensions
    - Pulsar? No pulsations seen as yet.

VER J2019 and 1FHL J2021.0+4031e

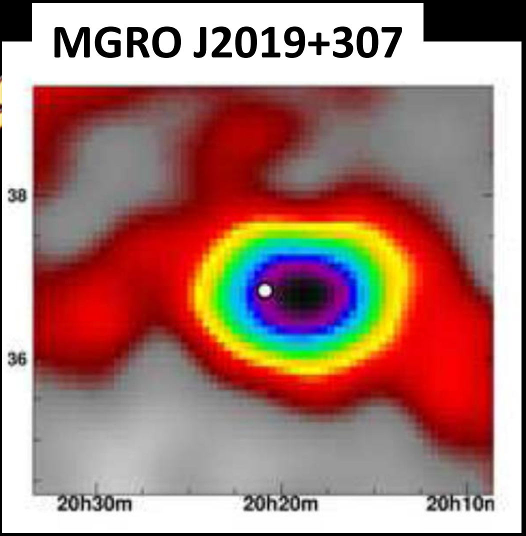


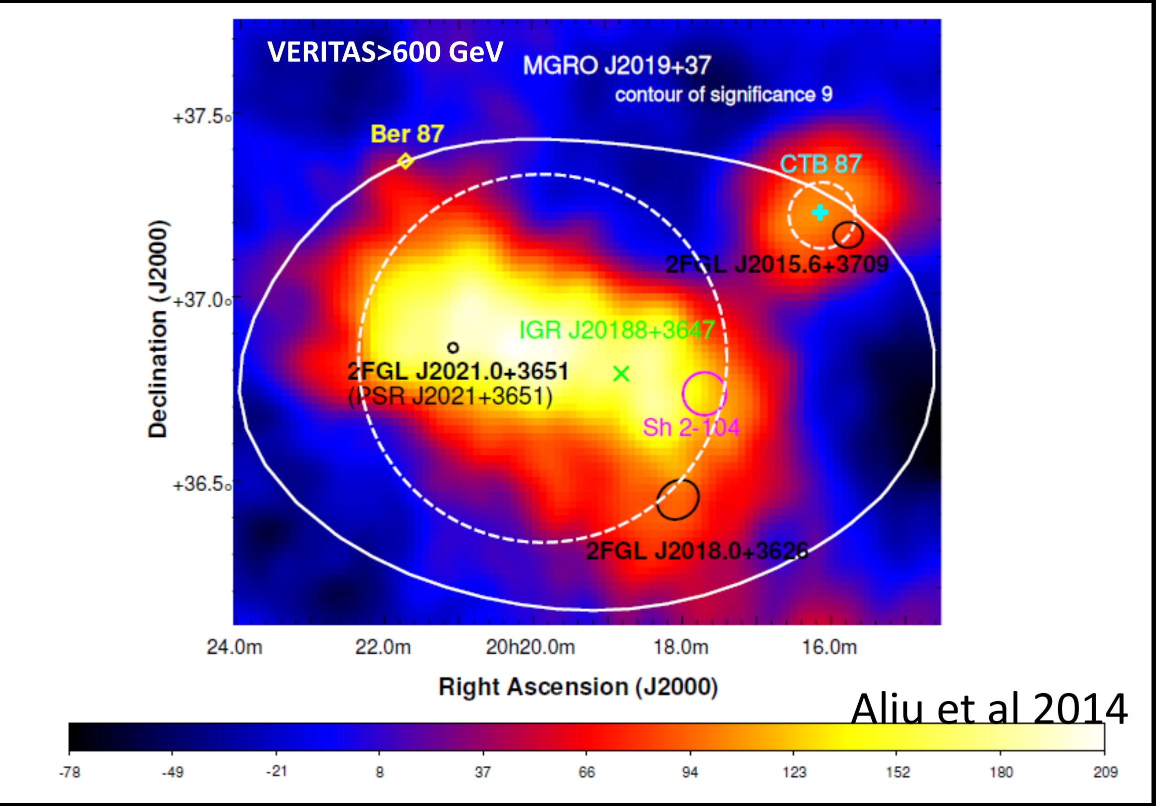
VERITAS Spatial Residual Map (spatial likelihood)



- Same source, energy-dependent morphology?
- Or different origins entirely for emission?

MGRO J2019+307



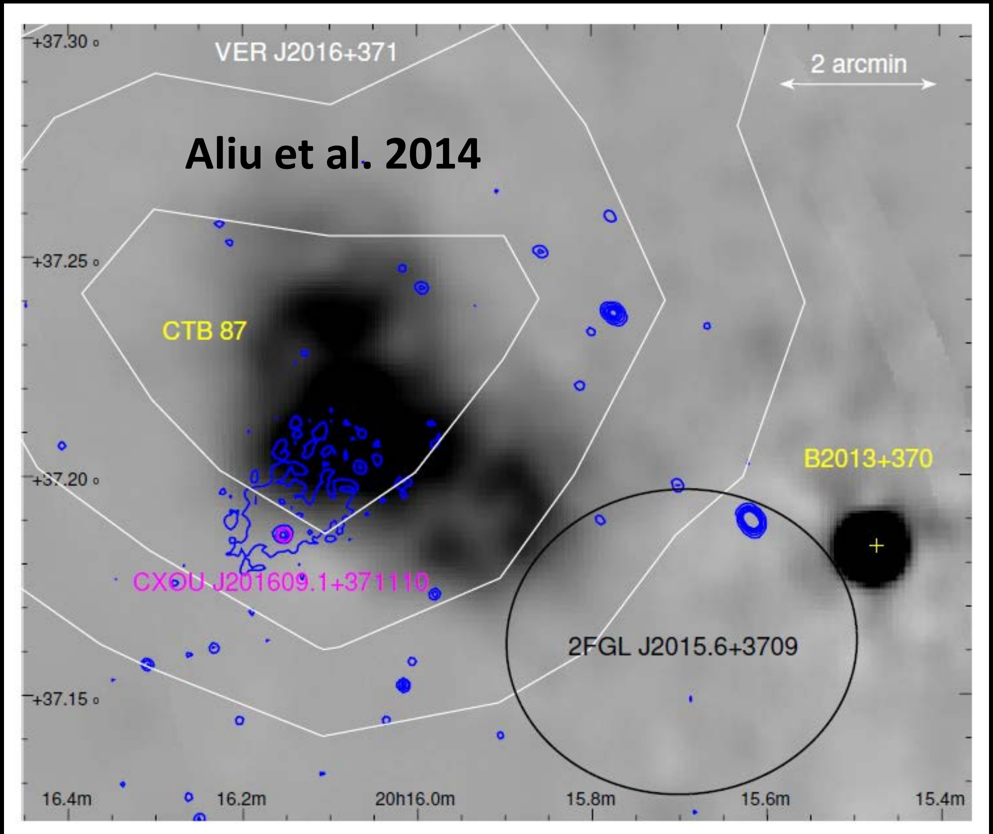


Aliu et al 2014

Two sources discovered:
VER J2016+371 (point)
VER J2019+368 (extended, complex)

- MGRO J2019+307: Brightest diffuse source in Galaxy
- Located towards Cyg OB1, overlaps PSR J2021+3651

VER J2016+371 and CTB 87



Grayscale: 610 MHz GMRT

Chandra: 0.3-7.5 keV

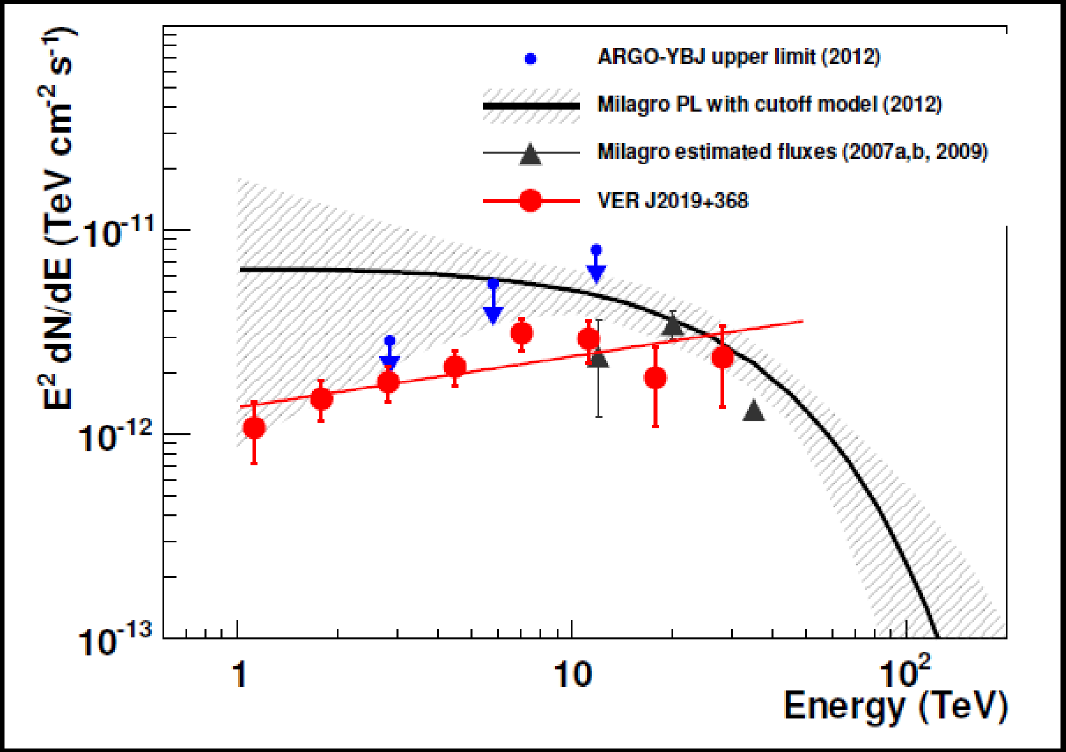
X-ray pulsar candidate

White: VERITAS contours

- Matches up with radio emission (no shell, ID'd as PWN)
- Multiwavelength properties in line with other VHE PWNe

→ Offset radio, TeV PWN: relic population

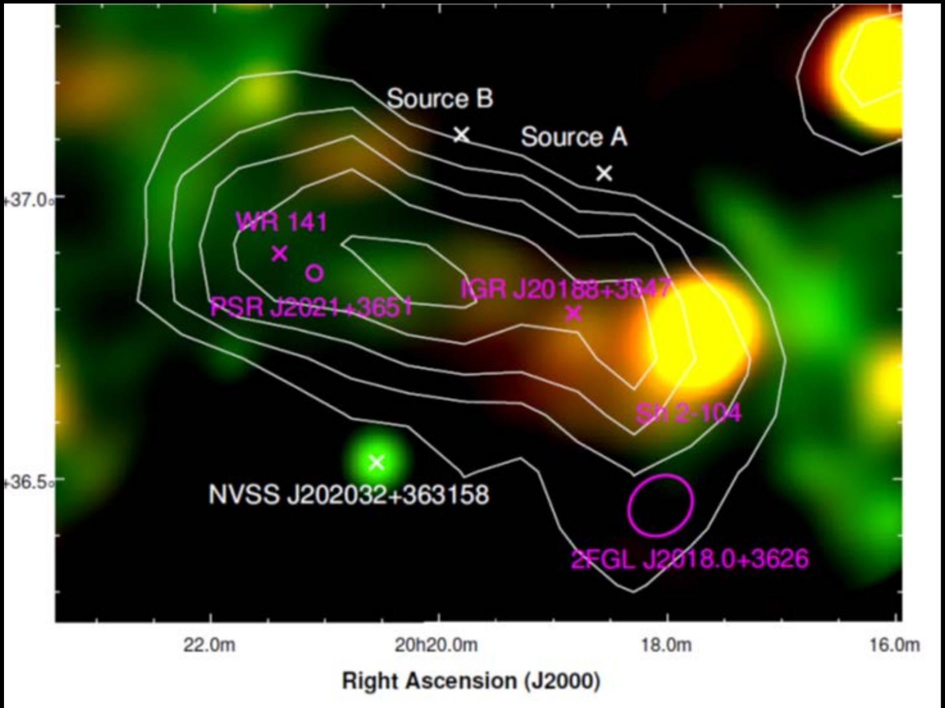
VER J2019+368 in Context



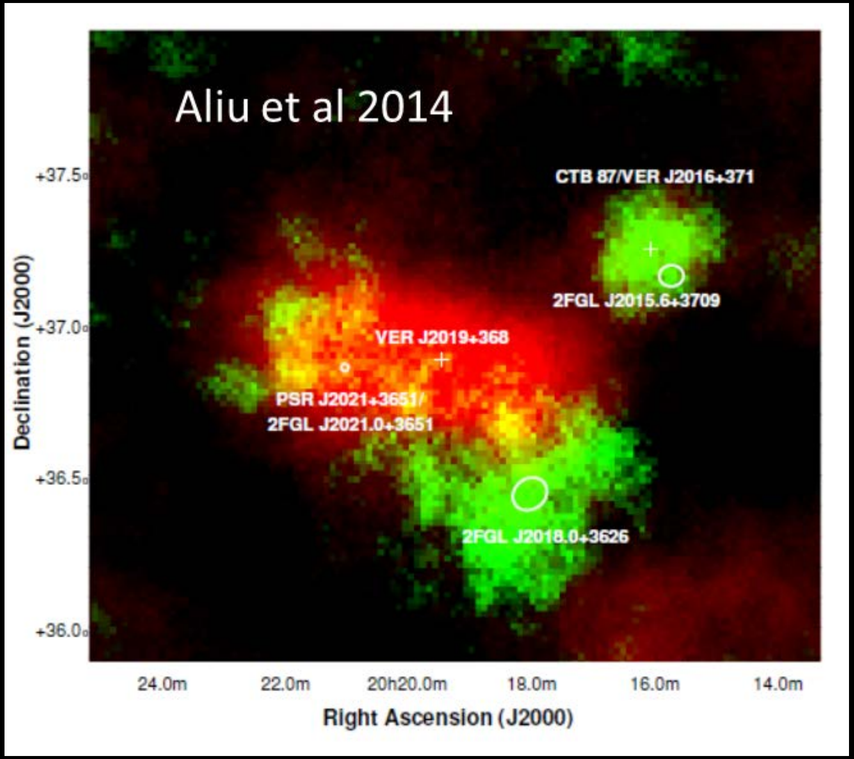
- Consistent with spectral points, flux limits from Milagro and ARGO
- VER J2019+368 clearly main contributor to MGRO J2019+307
- So what is it?

Breaking down VER J2019+368?

Radio



VHE



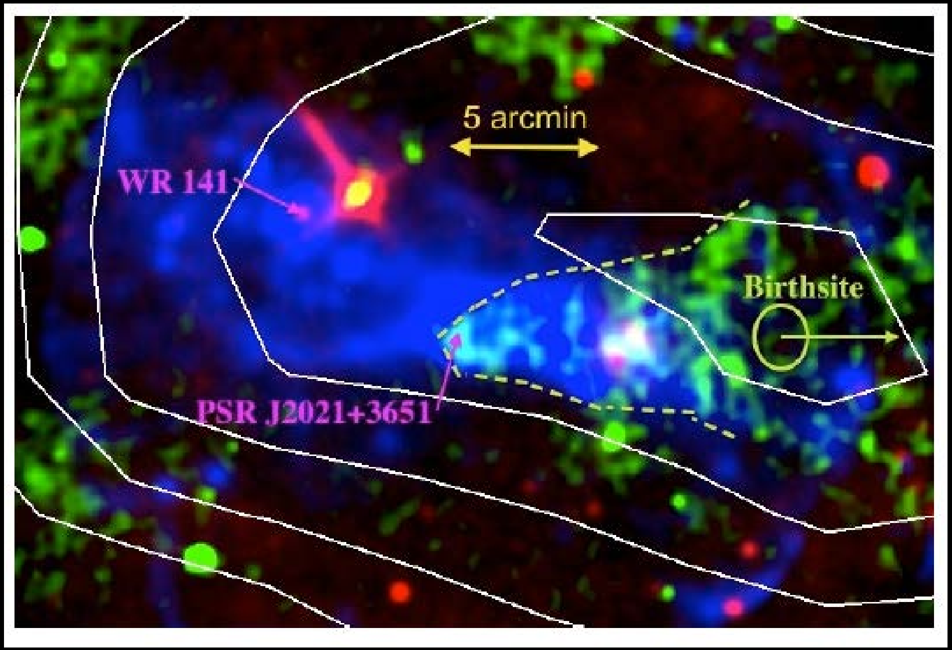
White: VHE contours

Red: >1 TeV Green: 600 GeV-1 TeV

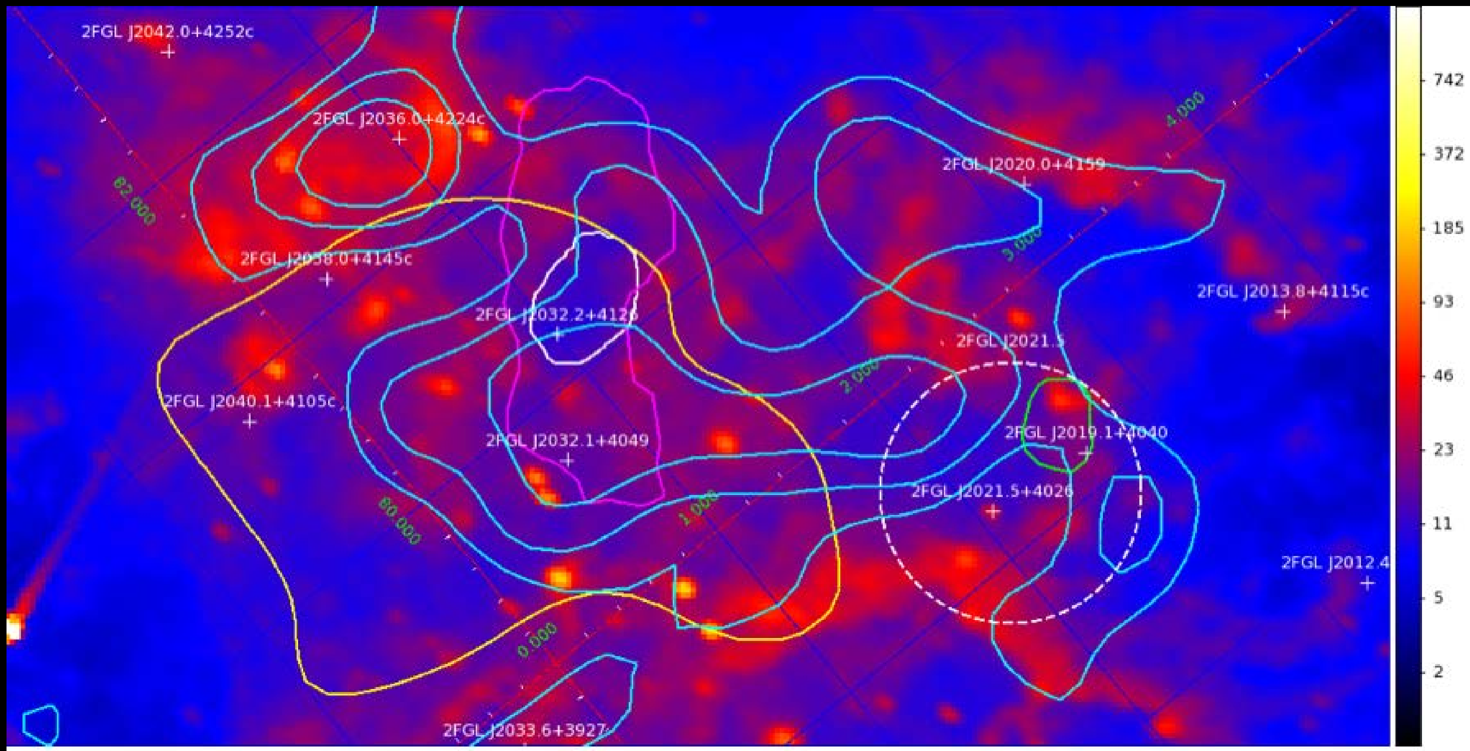
TeV PWN of high E-dot pulsar PSR J2021+3651 may account for significant portion of VHE

However, given likely birth position of pulsar not likely to account for all.

Breaking down VER J2019+368?



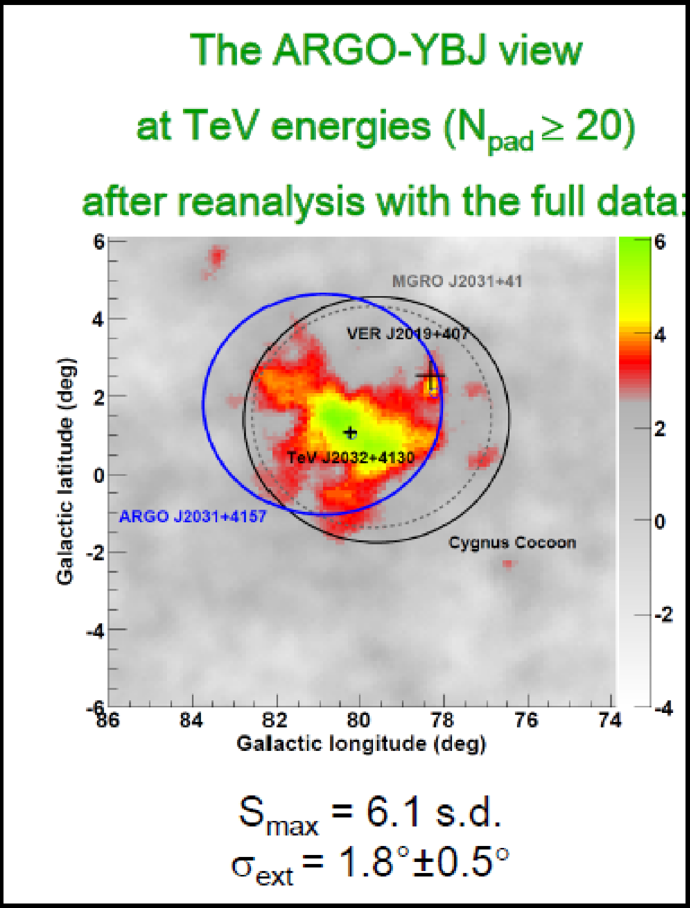
The Cocoon: The Big Picture

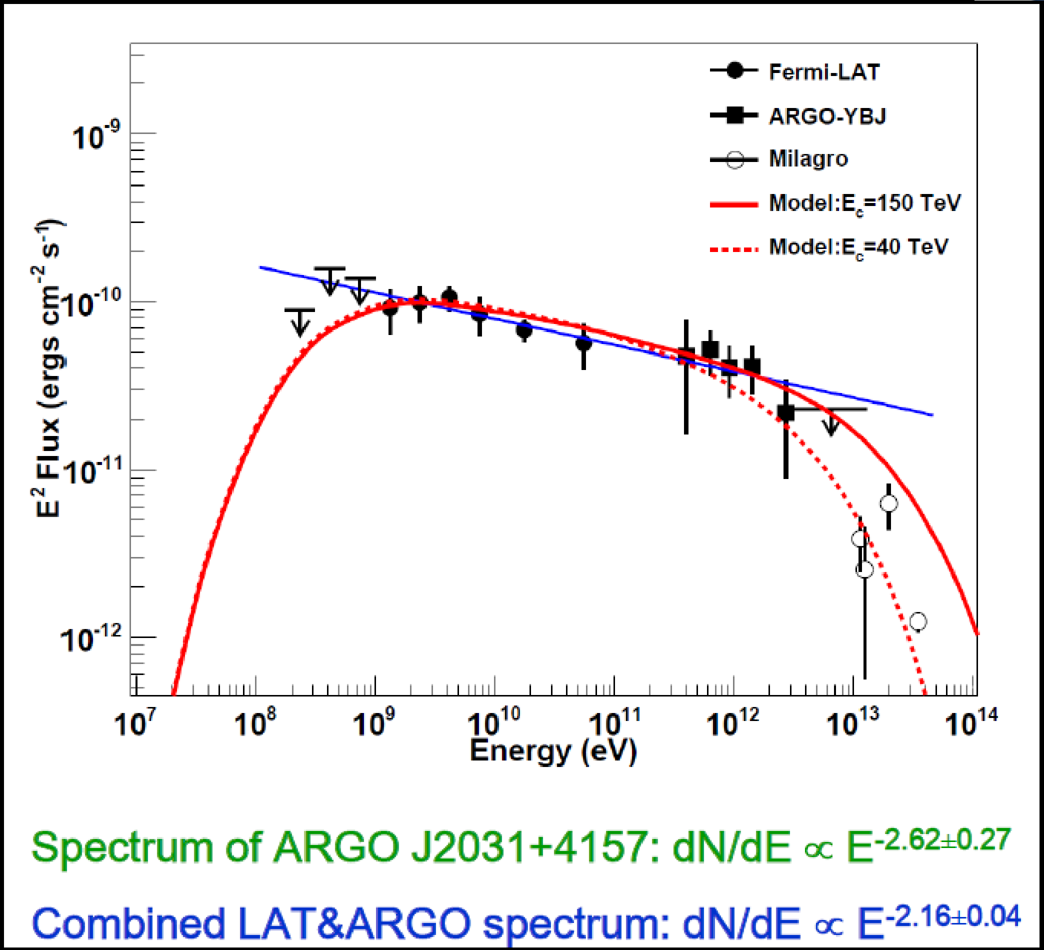


Yellow: MGRO J2031+41 5σ
White: TeV J2032+4130 5σ (Aliu et al. 2014)
Magenta: ARGO 5σ
Cyan: Cocoon contours (Ackermann et al.)
Green: VER J2019+407 (Aliu et al. 2013)
White dashed: Lande et al. 2012 best fit
Color: 8 micron MSX

- What powers the cocoon (stellar winds in young superbubble environment)?
- What contributes to MGRO J2031+41?
- Important caveats (e.g. distance uncertainties)

Big Picture II

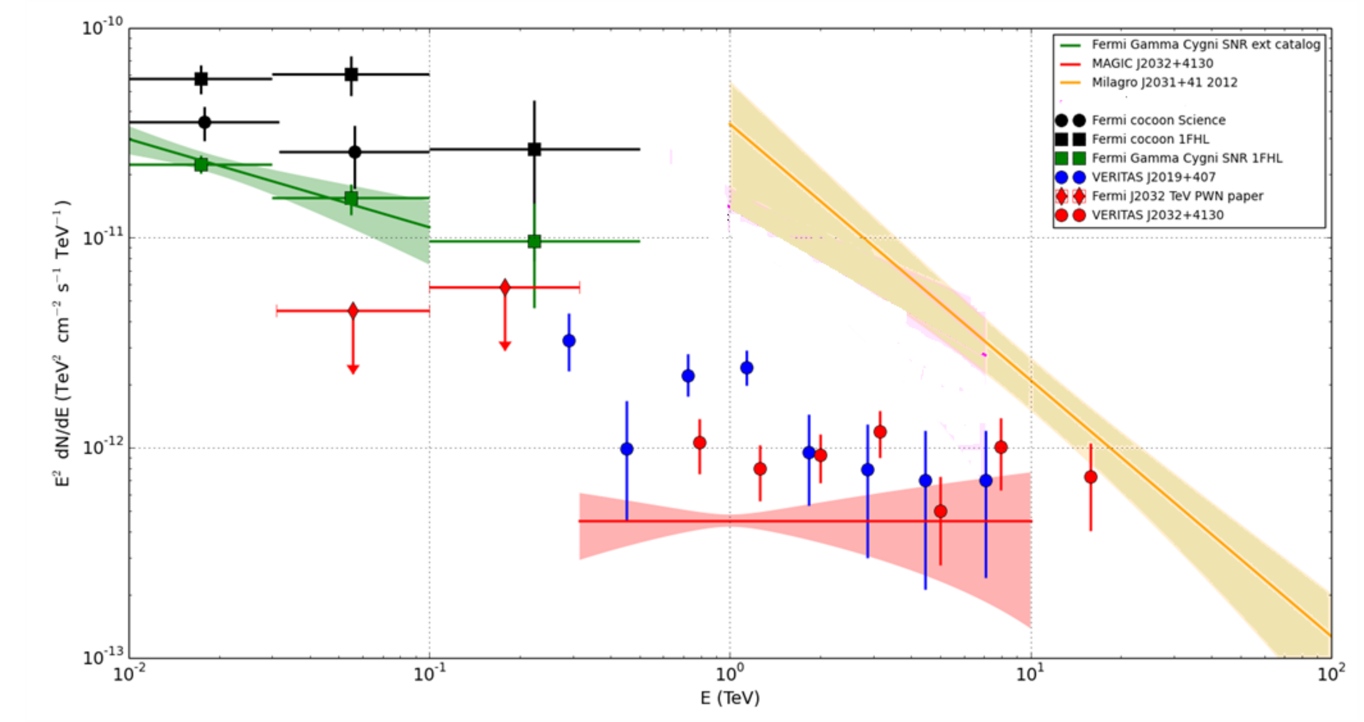




Di Girolamo SciNeGHE 2014
Bartoli et al. 2014

Milagro points corrected for TeV J2032+4130
ARGO points corrected for nearby sources

The problem of MGRO J2031+41



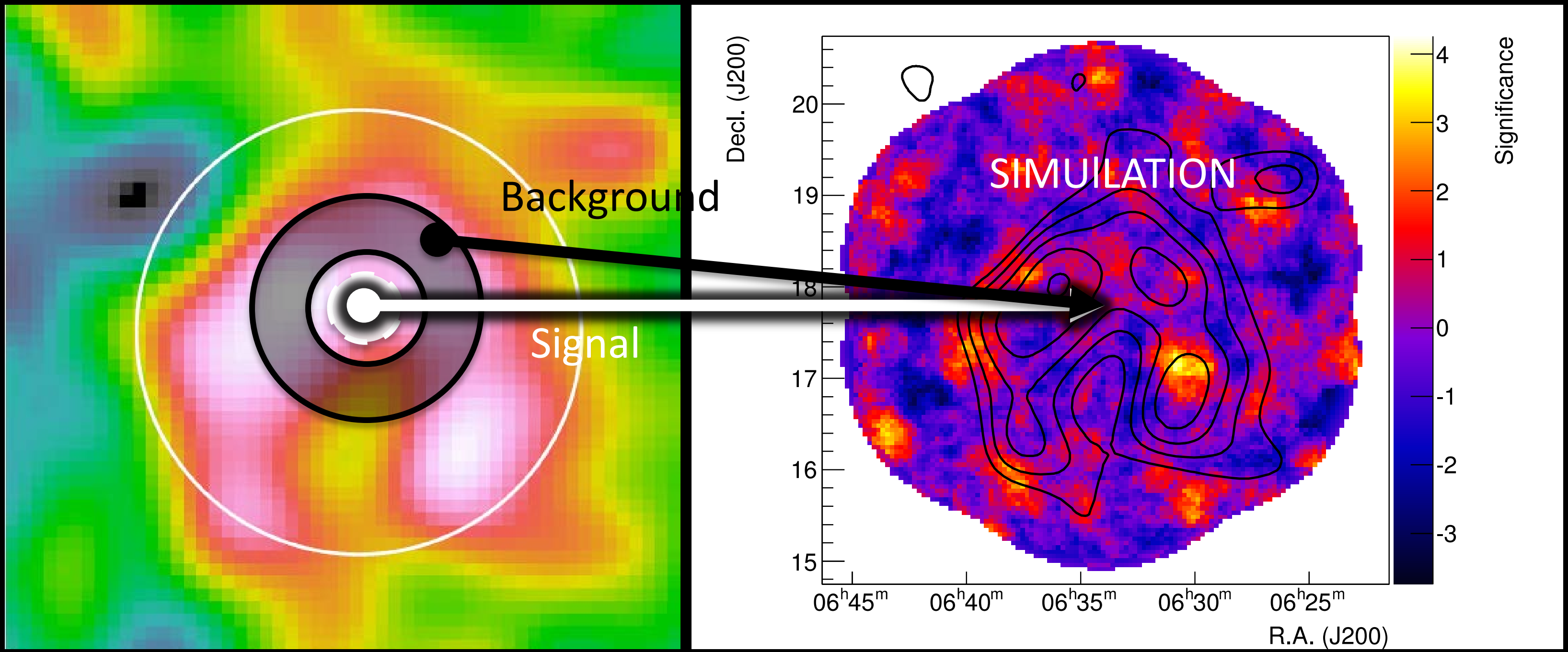
- ARGO corrects spectrum using IACT fluxes (tricky!)
  - Flux discrepancies between techniques
  - Don't know cutoffs or how to continue to low energy

courtesy L. Tibaldo

- Wish list
  - Better constrain cocoon and gamma Cygni spectra between 500 GeV and 10 TeV
  - Better-resolved morphology of all sources, esp. > 1 TeV

VERITAS and the Cygnus Cocoon

- Yesterday upon a stair I met a man who wasn't there. He wasn't there again today, I wish, I wish he'd go away." --- *Antigonish*, Hughes Mearns
- What happens with sources comparable to VERITAS field of view?



Analysis technique matters!

Unbinned 3D Maximum Likelihood

- Maximizes, with respect to a set of free parameters, the "likelihood" that a particular dataset originates from a particular model.

$$L = \frac{N_{\exp}{}^{N} e^{-N_{\exp}}}{N!} \prod_{i=1}^{N} \frac{p(x_i | s)}{N}$$

(s) are a set of free parameters (e.g. flux strength, spectral index)

$p(x_i | s)$ is the probability for a given photon candidate

- In practice, minimize

$$-2 \ln L$$

- Wilk's Theorem: a test-statistic formed by comparing the likelihood of a "null" hypothesis and a "test" model will be normally distributed

$$TS = -2 \ln \left(\frac{l_{null}}{l_{test}} \right)$$

  - Permits a statistical significance to be assigned to the signal component of the fit

3D Unbinned Maximum Likelihood

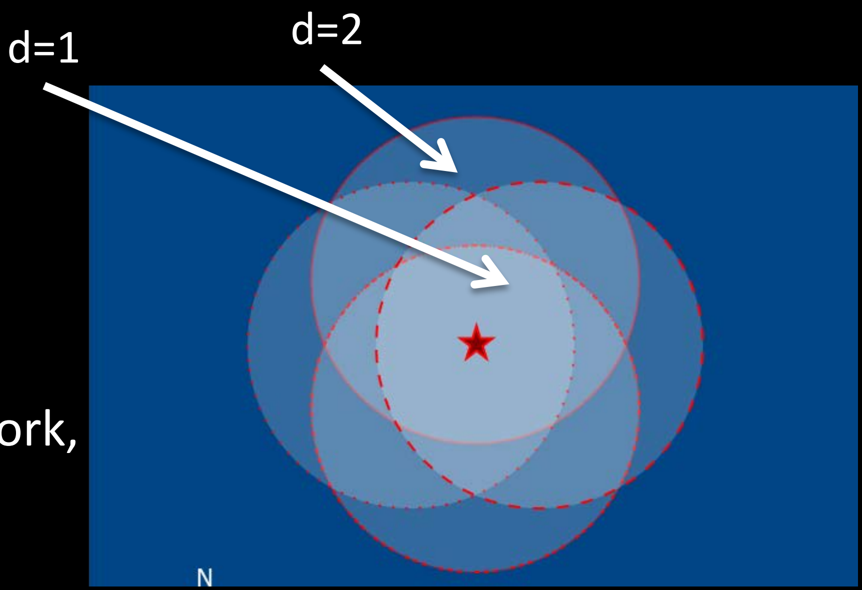
- "Simultaneous fitting:" group data into datasets *d*
  - Share a subset of key parameters *s* across sets
  - Other parameters α_d vary

Physics-driven

$$-2\ln L = -2\sum_{d}\sum_{i=1}^{N^d}\ln p(x_i^d \,|\, s, \alpha_d) + 2N_{\text{exp}}^d + 2\ln N^d!$$

Extended likelihood term

- Choice of subdivision driven by
  - **Observation position**
  - Changes in instrument response

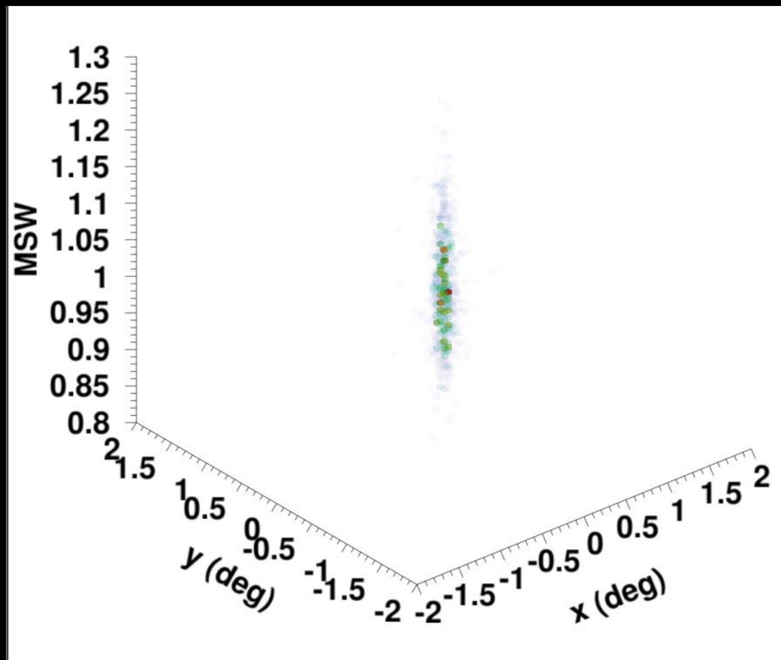


- Current version based on RooFIT
  - MINUIT-based likelihood framework,

Expectation for each Dataset

Gamma-ray source

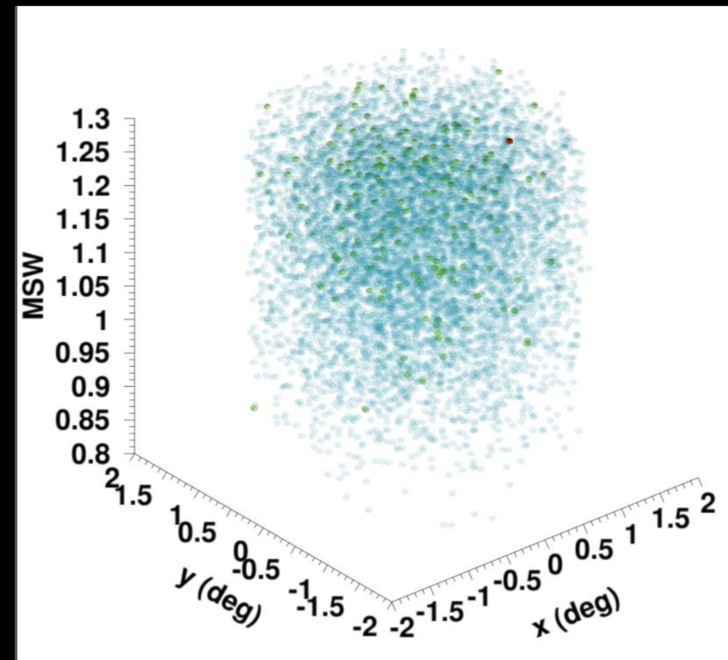
MSW: templates from gamma-ray simulations



Spatial: Intrinsic source model, convolve with IRFs at each stage of fit

Cosmic-ray background

MSW: Templates from "blank field" data



Spatial: templates from "blank field" data---source and cosmic-ray IRFs pre-convolved

- Multi-component model

Key Advantages of MLM

- We fit a model to the entire extended or diffuse source
  - **Higher Sensitivity:** Signal/background ratio for any category controlled by flux of **full source** (or fraction of source in field of view).*
  - **Reduced Trials Factors:** Test coarse grid of extended source model positions rather than checking at many (correlated) points within the extended source.
- **Powerful diagnostic tools** to address systematic errors from modeling
- Technique **naturally extends to multiple overlapping sources**
  - Can test assumptions
- Simultaneous fitting approach provides **potential extension to multi-instrument datasets** (Fermi, HAWC)

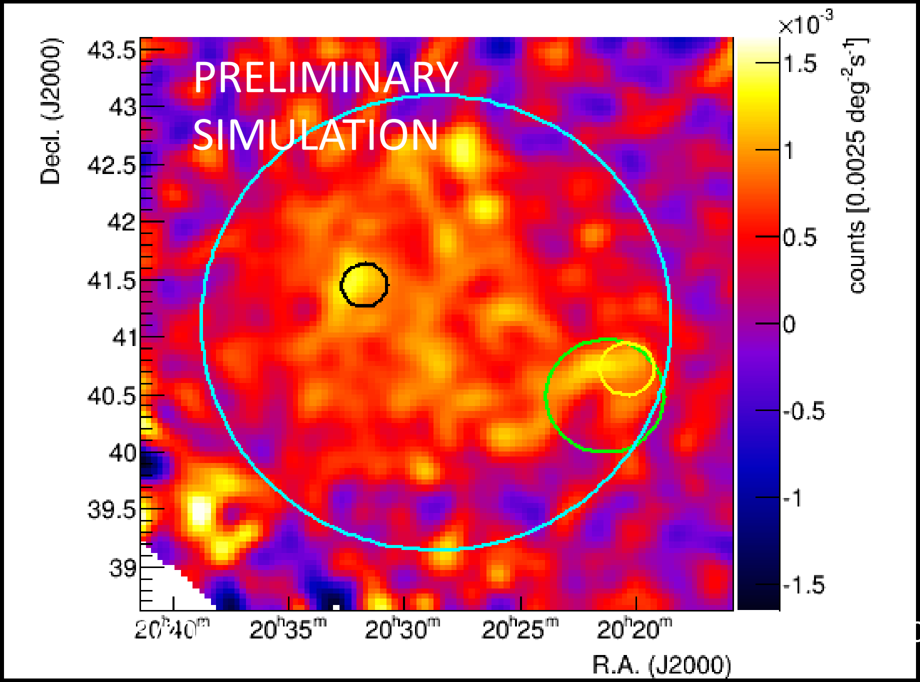
How much does it help?

Toy model simulation of observations in the Cygnus region between 500GeV-1TeV.

Source	MLM Sqrt(TS)	RBM Significance (nominal position)
TeV J2032+4130	4.47	3.33
VER J2019+407	2.82	3.6
Cocoon (2°Gaussian)	33.2	-0.05
Gamma Cygni	5.1	3.43

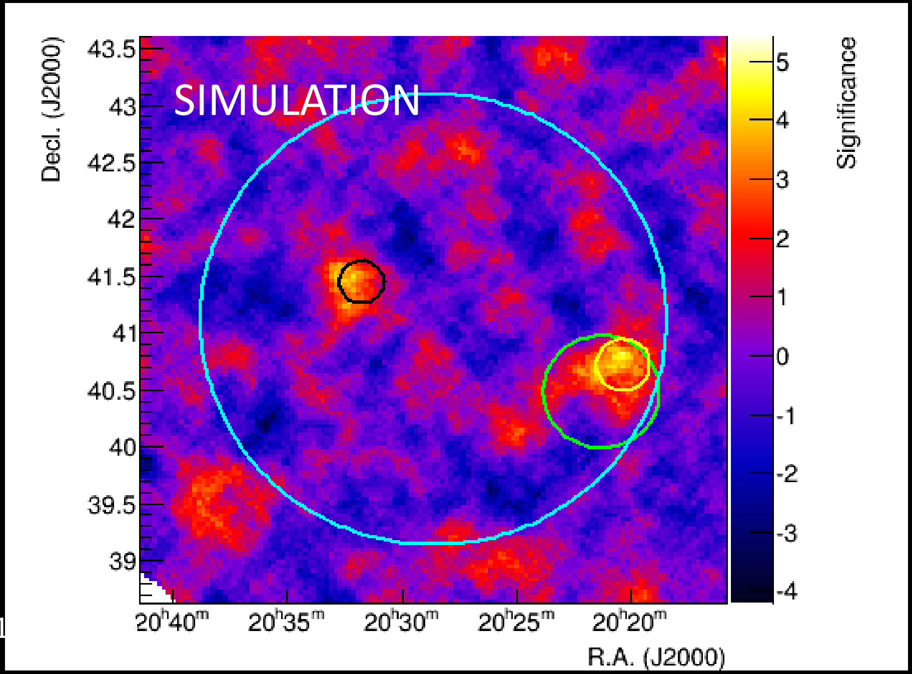
MLM

Shows evidence of extended emission



RBM

No evidence of extended emission



Outlook

- Active work to repeat the standard analysis of all VERITAS data in Cygnus region
  - Survey proper
  - Follow-up data
  - Target date: Summer 2015 for first preliminary results

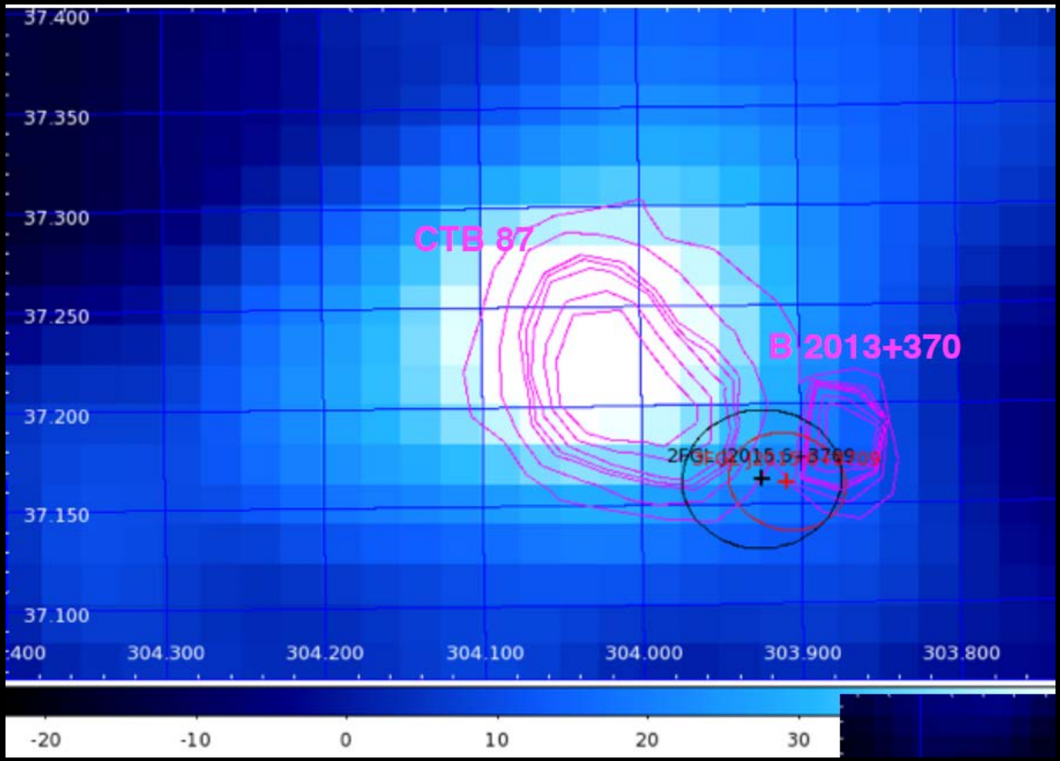
- 3D MLM approach will provide a significantly different view of this same dataset
  - Target date: by the end of 2015

Conclusions

- The Cygnus region above a GeV remains science-rich, challenging, and full of mysteries
  - E.g. the “Cygnus cocoon”
    - Evidence for CR acceleration in superbubbles?
    - A snapshot of recently escaped or re-accelerated cosmic rays?
  - VERITAS and HAWC both have a critical role to play
- VERITAS is rising to the challenges posed by this region
  - Stay tuned!

BACKUP SLIDES

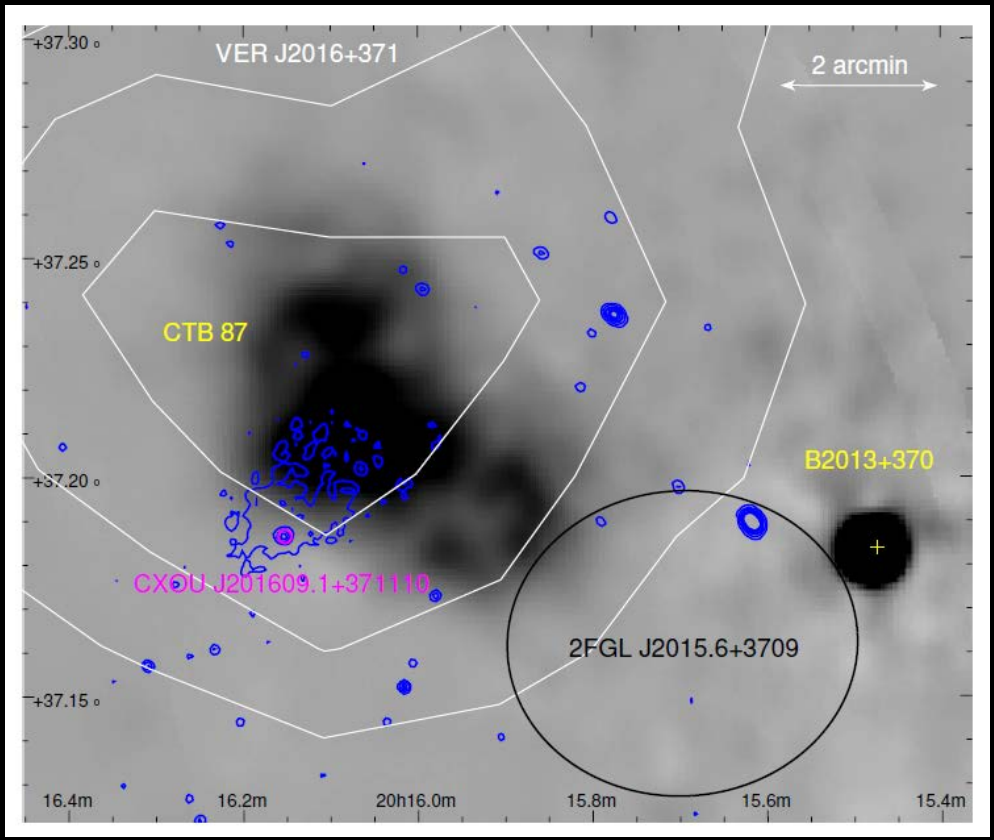
VER J2016+371 continued



Black: 2FGL 2015.6+3709
Red: 3FGL 2015.6+3709
Magenta: 1420 MHz radio contour
Color: VERITAS

- 2FGL/3FGL error circles consistent with VER J2016+371
  - 3FGL some what less so
- 2FGL/3FGL source identified (on basis of spectral variability) with FSRQ B2013+370

VER J2016+371 and CTB 87



Grayscale: 610 MHz GMRT

Chandra: 0.3-7.5 keV

X-ray pulsar candidate

White: VERITAS contours

- What about 2FGL J2015.6+3709?