Recent highlights from VERITAS

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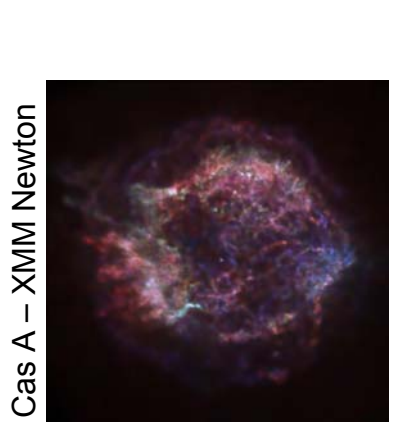
Outline

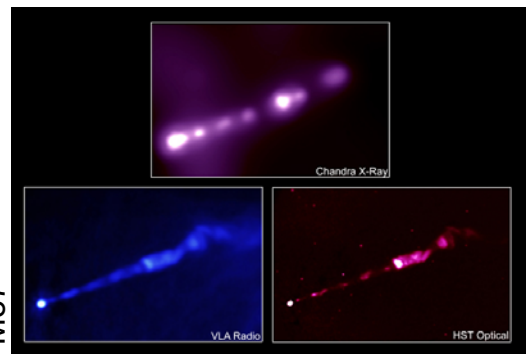
- Very high-energy (VHE) gamma-ray astrophysics
- Ground-based observations with Cherenkov arrays
- VERITAS & instrument performance
- Highlights of some recent science results
  - Extragalactic sources: AGNs, Mrk 421 flaring
  - Galactic sources: Cygnus, CTA1, Tycho, Crab pulsar
  - Astroparticle physics: dark matter searches
- VERITAS Upgrade & Outlook
- Conclusions

Very high-energy (VHE) gamma-ray astrophysics

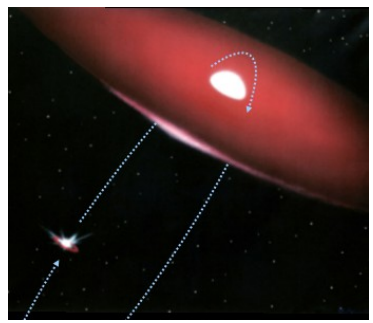
- At E> 50 GeV, several classes of sources known…
  - Galactic:
    - Supernova Remnants
    - Pulsar Wind Nebulae
    - Binary systems
  - Extragalactic:
    - Active Galactic Nuclei
    - Starburst galaxies
- …or expected:
    - Gamma-Ray Bursts
    - Dark-matter annihilation


Cas A – XMM Newton


Crab: HST + Chandra



M87

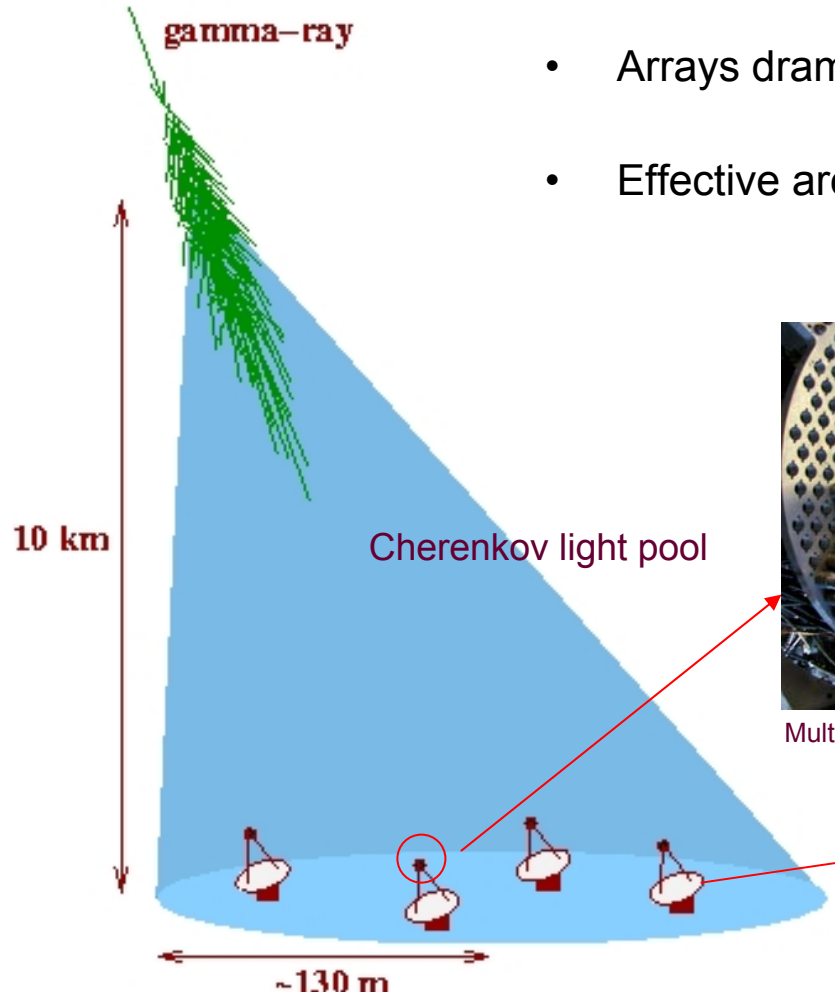

PSR B1259

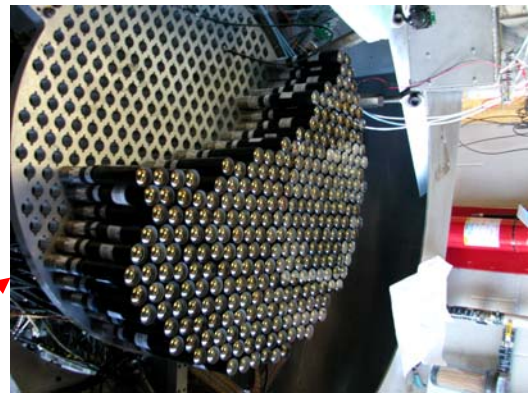
The scientific questions

- Origin of cosmic rays
  - What are the accelerators?
  - How do they work? To what energies?
- Understanding the nature of particle accelerators
  - What is being accelerated (electrons? protons?) ?
- Astrophysical sources for fundamental physics
  - eg. can use AGN flares to look for effects of quantum gravity (if start times are well understood)
- Discovery space for new physics
  - eg. large mass reach for WIMPs

Ground-based VHE observations

- VERITAS uses the air-Cherenkov *imaging technique:* shower is imaged in multi-PMT cameras at focus of telescopes
- Arrays dramatically enhance sensitivity and resolution
- Effective area ~ size of light pool ~ 10^5 m^2





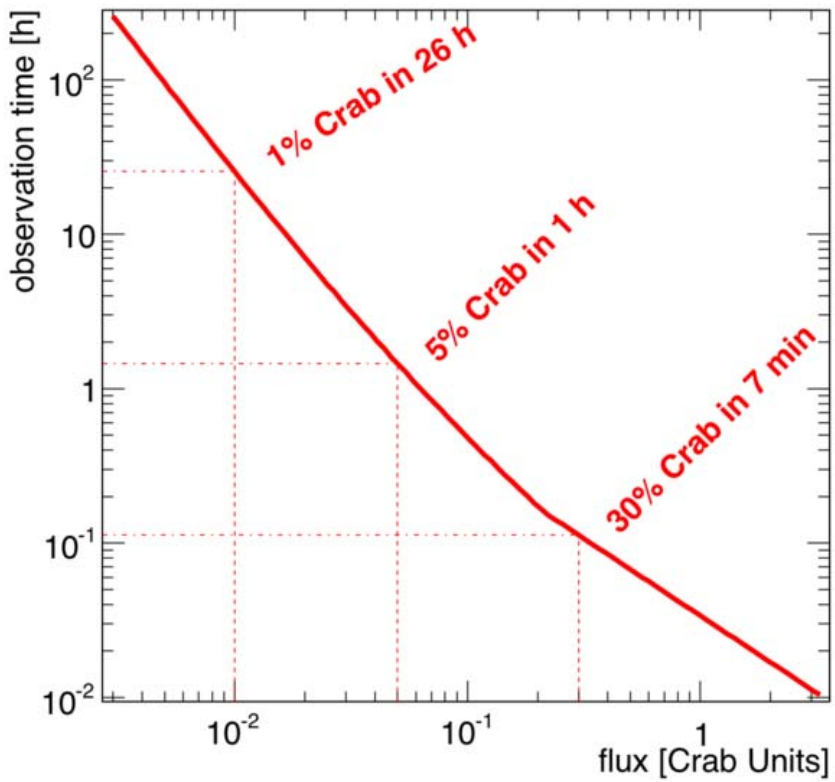
Multi-PMT camera

12m reflector

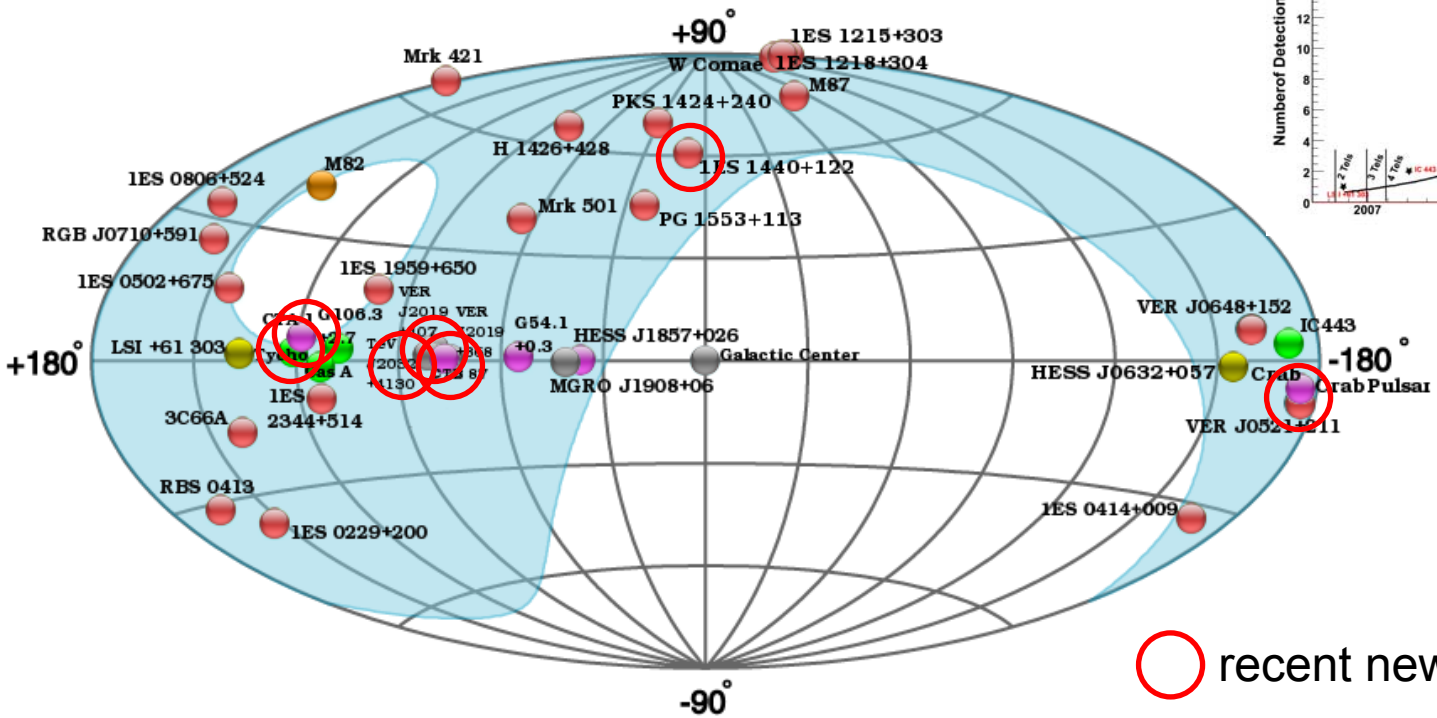
VERITAS

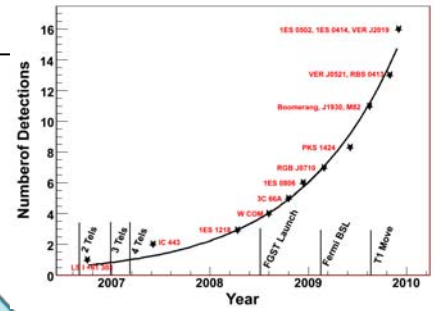
VERITAS
- Four 12-m imaging air-Cherenkov telescopes
- Sited at Whipple Observatory, Az
- International collaboration (US, Canada, UK, Ireland, Germany)
  ~ 80 collaborators at 20 institutions
- Fully operational since 2007
- ~1000 observing hours/yr

Performance
- Energy range: 100 GeV → 30 TeV
- 3.5^{o} field of view
- Angular resolution: < 0.1^{o} (68% containment)
- Energy resolution: 15%-25%
- Sensitivity (5σ detection):
  - Crab Nebula: ~ 60 sec
  - 1% Crab Nebula flux: < 30 h



The (current) VERITAS Sky





recent new detections

- As of May, 2011: 39 source detections:
  - Extragalactic: 22 (20 blazars, 2 non-blazars)
  - Galactic: 12 (9 PWN/SNR, 2 binaries, 1 pulsar)
  - Unidentified: 5

Extragalactic observations

- Extragalactic objects make up majority of VERITAS sources
- Primarily blazars, mostly HBL
- Aim: understand jet production by supermassive black holes and the physics behind gamma-ray production
  - leptonic?
  - hadronic?
- Regular monitoring campaign on TeV blazars
- Multiwavelength campaigns important
- Major goal: measure the extragalactic background light (EBL) through its effect on blazar spectra

  $\gamma_{TeV}\ \gamma_{EBL} \rightarrow e+e-$

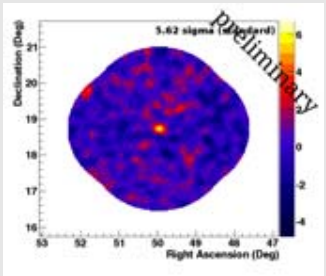
Extragalactic results: the blazar list

Source	Type	Redshift z	Discovery?
Markarian 421	HBL	0.031	Whipple
Markarian 501	HBL	0.034	Whipple
1ES 2344+514	HBL	0.044	Whipple
1ES 1959+650	HBL	0.048	
H 1426+428	HBL	0.129	Whipple
1ES 1218+304	HBL	0.182	
1ES 0806+524	HBL	0.138	Y
W Comae	IBL	0.102	Y
3C 66A	IBL	0.444 (?)	
RGB J0710+591	HBL	0.125	Y
PKS 1424+240	IBL	unknown	Y
RGB J0521.8+2112	HBL	unknown	Y
RBS 0413	HBL	0.190	Y
1ES 0502+675	HBL	unknown	Y
1ES 0229+200	HBL	0.140	
RXS J0648.7+1516	HBL	0.179	Y
1ES 0414+009	HBL	0.287	
PG 1553+113	HBL	unknown (>0.43)	
1ES 1440+122	IBL	0.162	Y
1ES 1215+303	HBL	0.130 (?)	

- Several blazars at z>0.18
- Will allow strong constraints on EBL

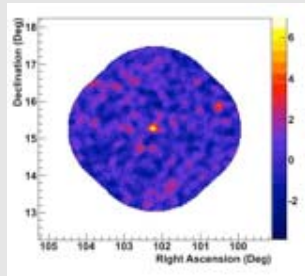
Extragalactic results I: AGN discoveries

RBS 0413



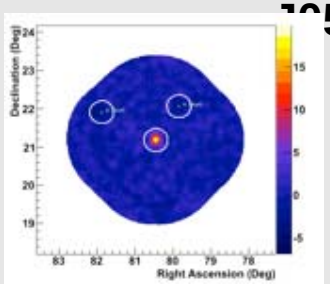
- ~5.5σ in 25 h
- 1.6% Crab Nebula
- X-ray-bright HBL @ z=0.19
- brightest LAT extrapolation
- ATEL #2272 with Fermi

RX J0648.7+1516



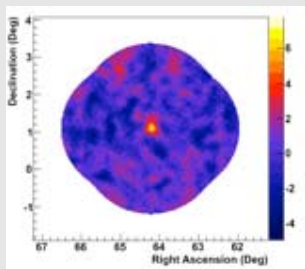
- ~5.2σ in 18 h
- 2% Crab Nebula
- Keck: Blazar
- z=0.179 (Lick 3m)
- ATEL #2486

VER J0521+211 (RGB J0521.8+2112)



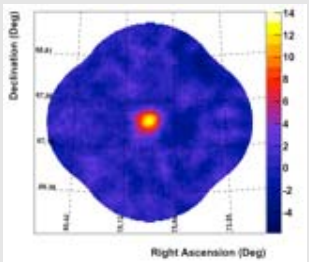
- ~8σ in 15h
- 4% Crab Nebula
- z=? (unsuccessful MMT, MDM, IR efforts)
- bright flare (>20% Crab)
- ATELs #2260 & #2309

1ES 0414+009



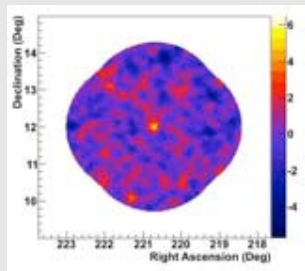
- ~7σ in 45 h; 2% Crab
- among X-ray-brightest HBL
- z=0.287
- EBL! high-z Mkn 421
- H.E.S.S. detection

1ES 0502+675



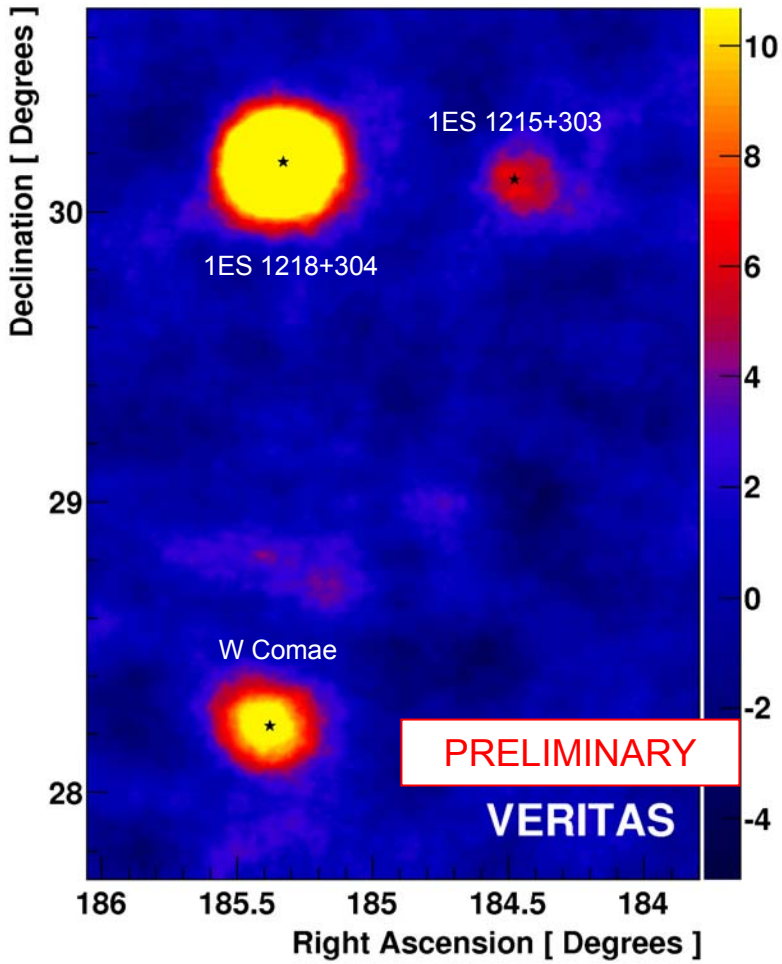
- ~12σ in 30 h
- 5% Crab Nebula
- z≠0.341? (1h MMT exposure – no features, no redshift)
- ATEL #2301

1ES 1440+122



- ~5.2σ in 50 h
- <1% Crab Nebula
- hard-spectrum IBL (LAT)
- z=0.162
- ATEL #2786

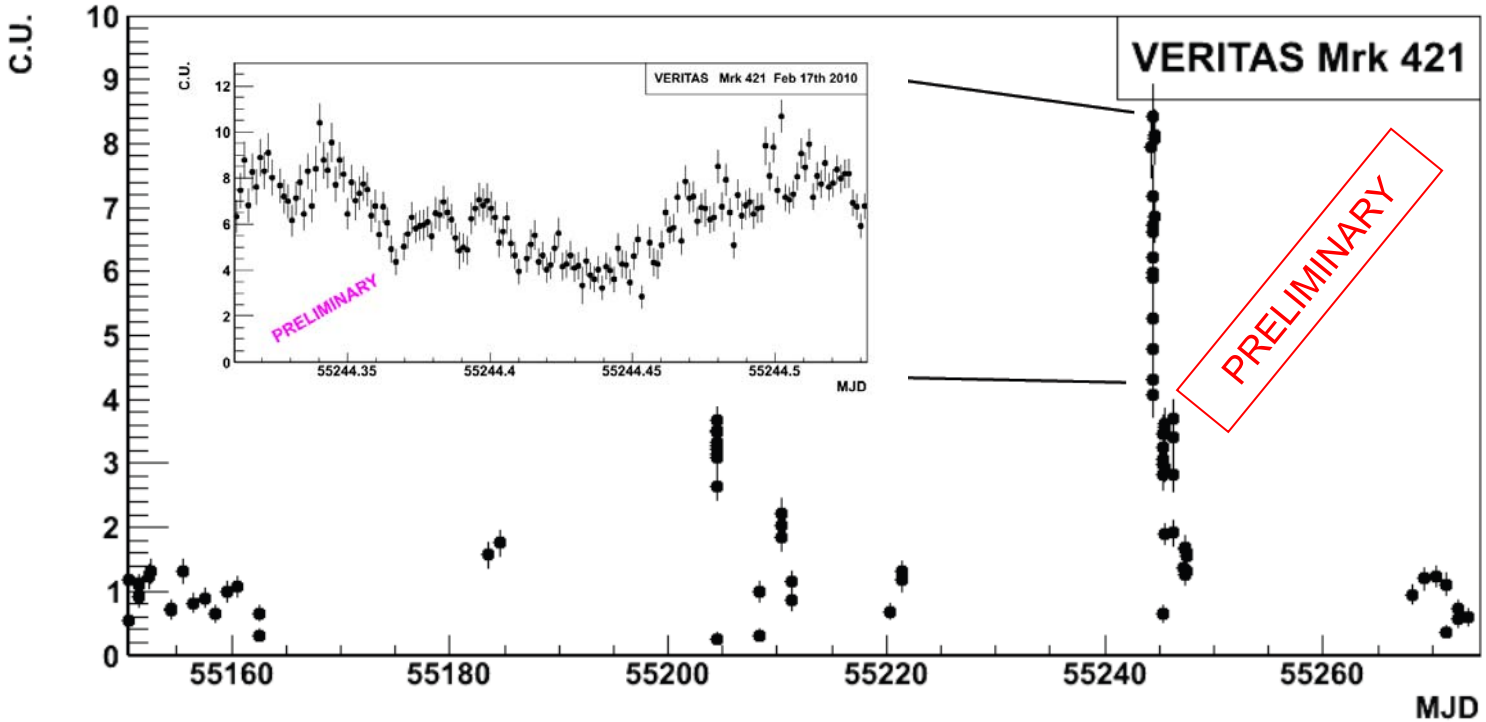
Extragalactic results II: the first triple-AGN field!



"Make that a trio…"

Extragalactic results III: Mrk 421 flaring

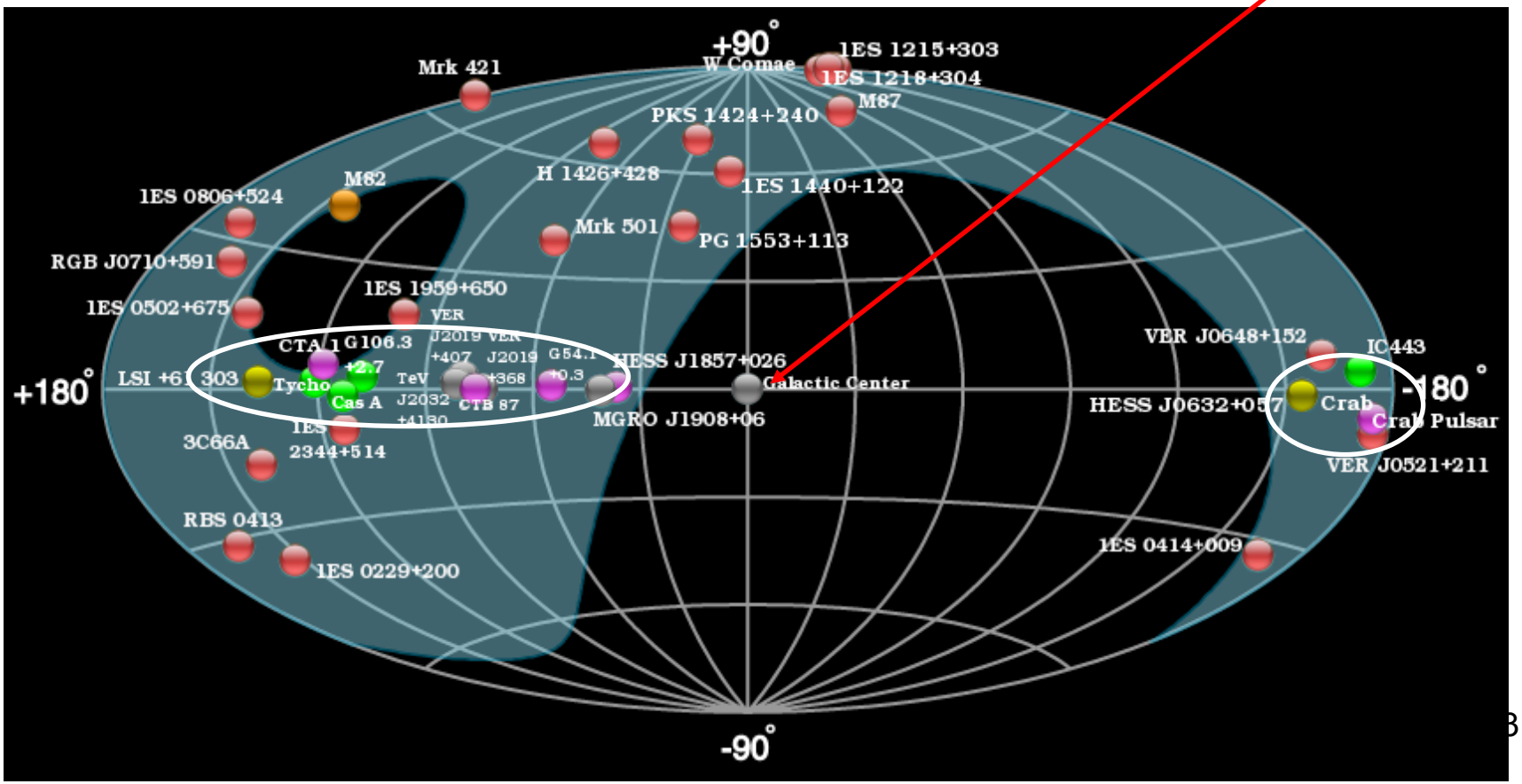
- Regular monitoring allows detections of flares
  → Deep observations and multiwavelength campaigns
- Ex.: Markarian 421 (Feb 2010) – flared to > 10x Crab Nebula
- Strong enough to allow 2-minute binning!
- Spectral-evolution studies in progress



Galactic observations

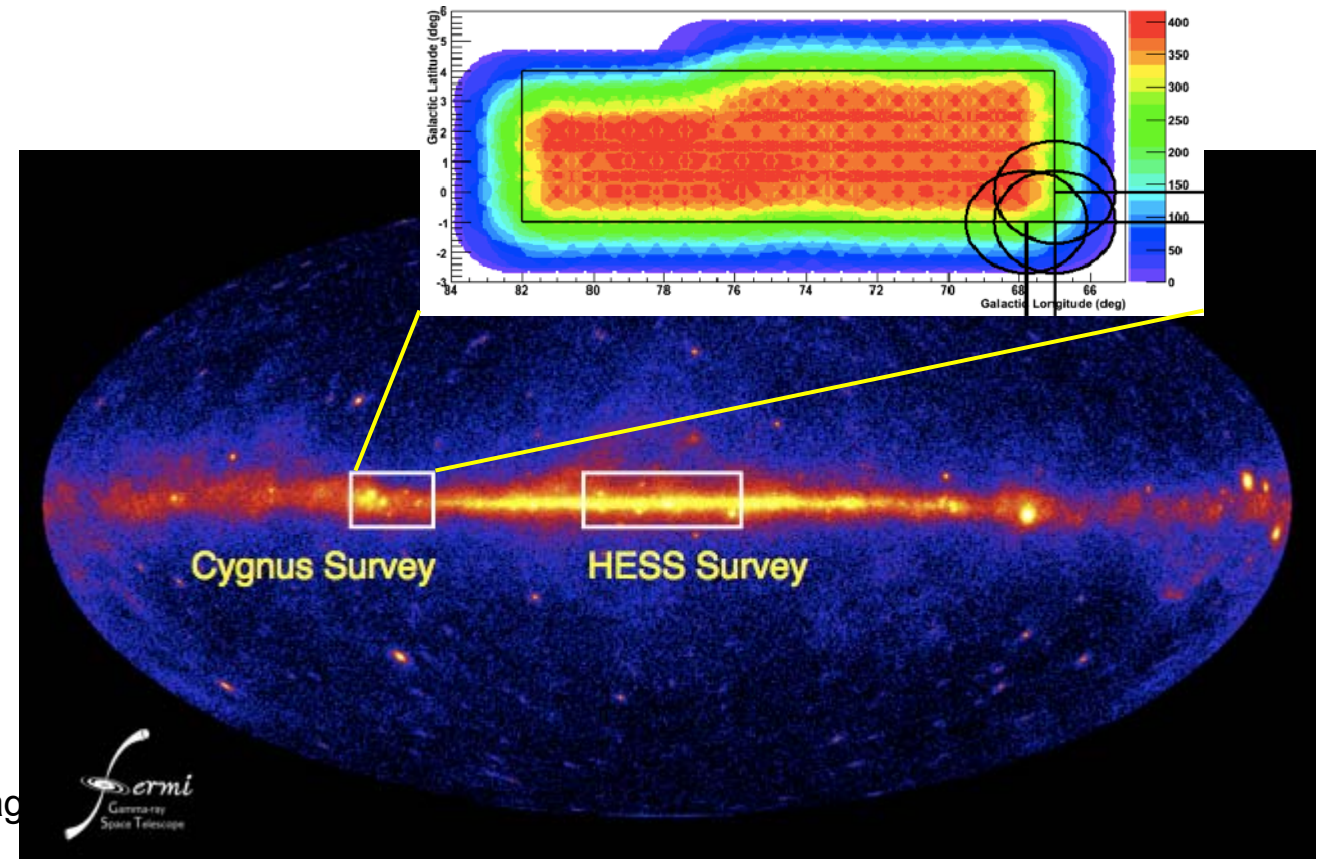
- Extensive targeted observations as well as Sky Survey (Cygnus region)
- 13 sources observed to date
- Several galactic source types: SNR, PWN, binary systems, pulsar

Galactic center: see talk by M. Beilicke this PM



Galactic observations (Cygnus survey)

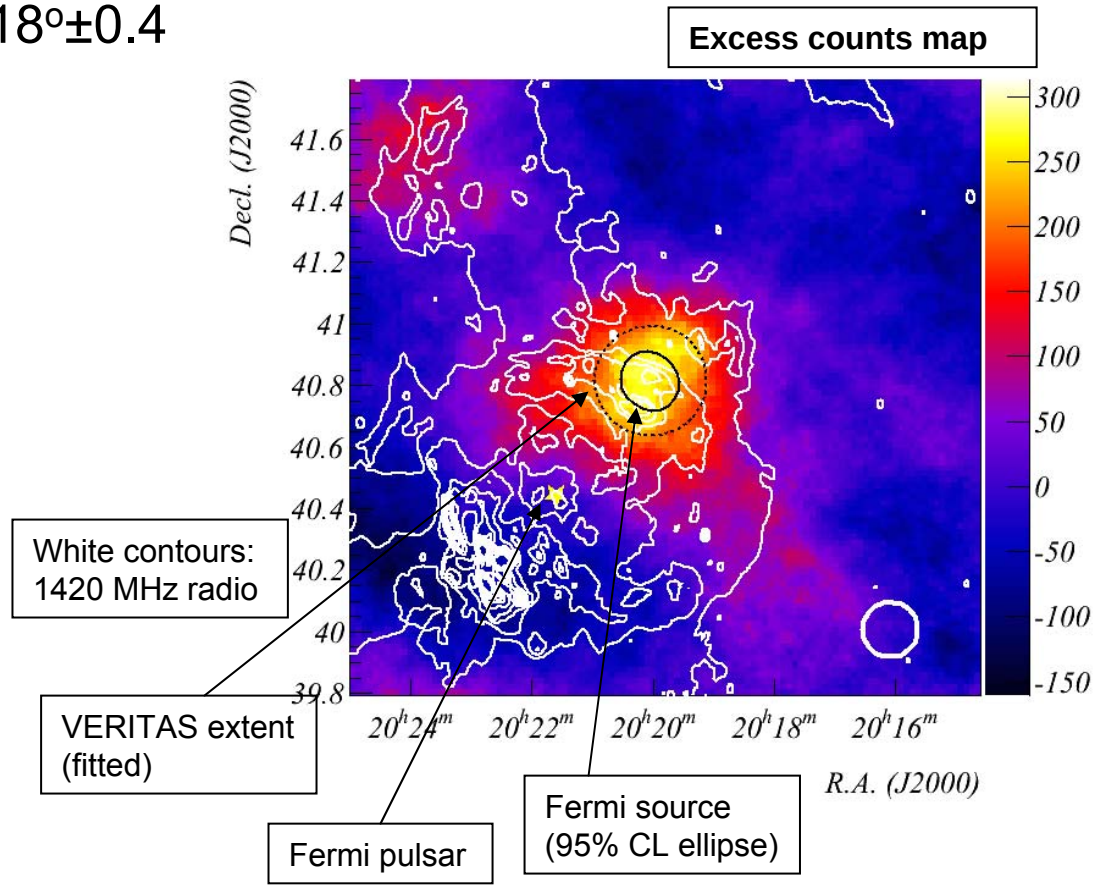
- Cygnus region: site of VERITAS Sky Survey in 2007-2009
- 112 hr base survey (+56 hrs follow-up)
- Depth: <3% Crab Nebula flux (E>200 GeV, point sources)



Galactic results I: VER2019+407 & γ-Cygni

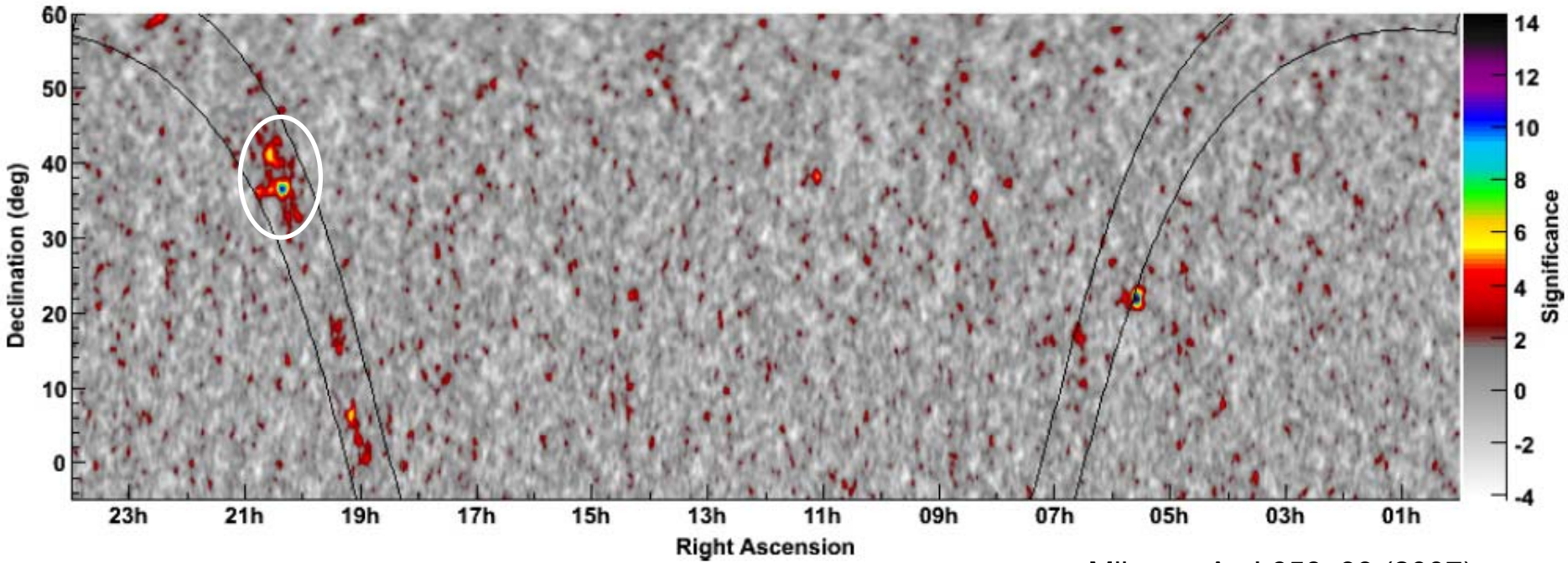
- G78.2+2.1 (gamma-Cygni): SNR of age 5-10 kyr
- VERITAS: 18.6 hrs (2009)
- Detection: 9.6σ (7.5σ post-trials): VER2019+407
- Extended emission: $\sigma \sim 0.18^{o} \pm 0.4$

- Likely emission from SNR acceleration, then collision with ambient material
- Partial HI shell to NW may suggest hadronic emission



Galactic results II: The Cygnus region

- Region seen as extended source (multiple sources?) by Milagro at E>10 TeV (90% Crab flux at E>20 TeV)
- VERITAS data: 75 h (summer/fall 2010)

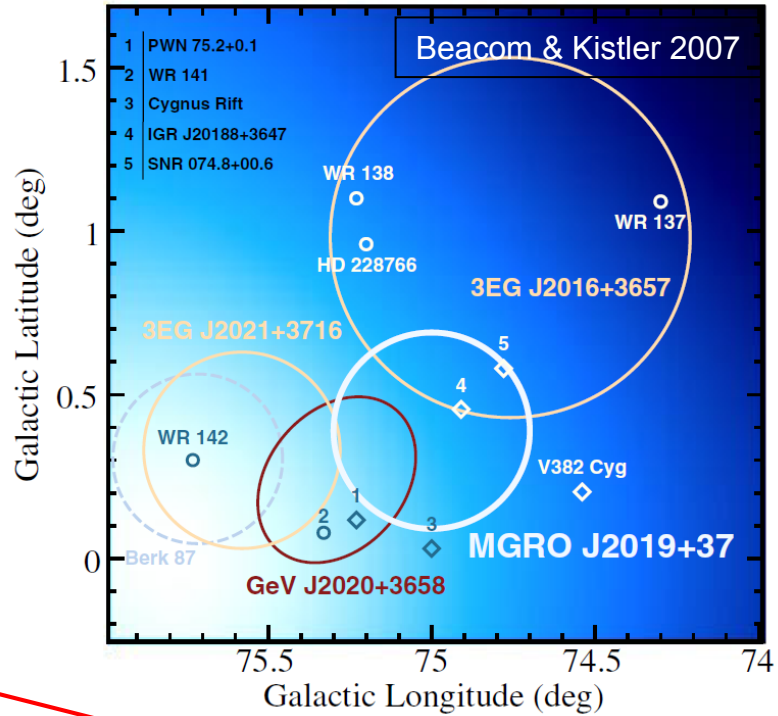


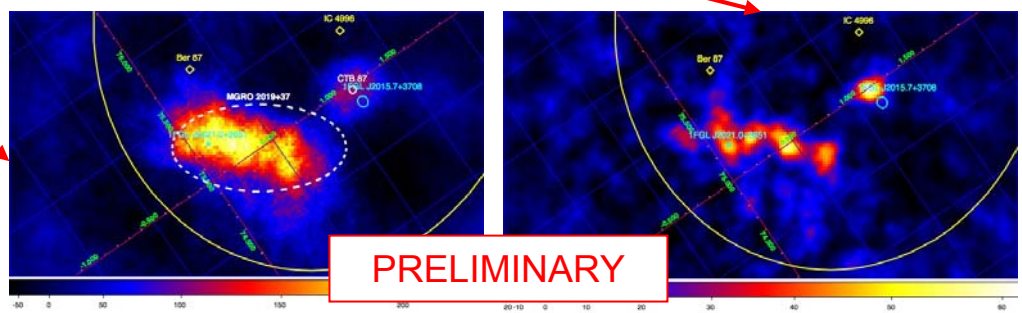
Milagro, ApJ 658, 33 (2007)

Galactic results II: Cygnus region

- Complicated region!
  - radio- and gamma-ray pulsar PSR J2021+3651
  - PWN CTB 87
  - several WR stars
  - several EGRET sources

- VERITAS: 75 hrs of data (2010)
- Search for both point and extended emission; see two new sources:
  - CTB 87 (PWN)
  - Cyg OB1 complex

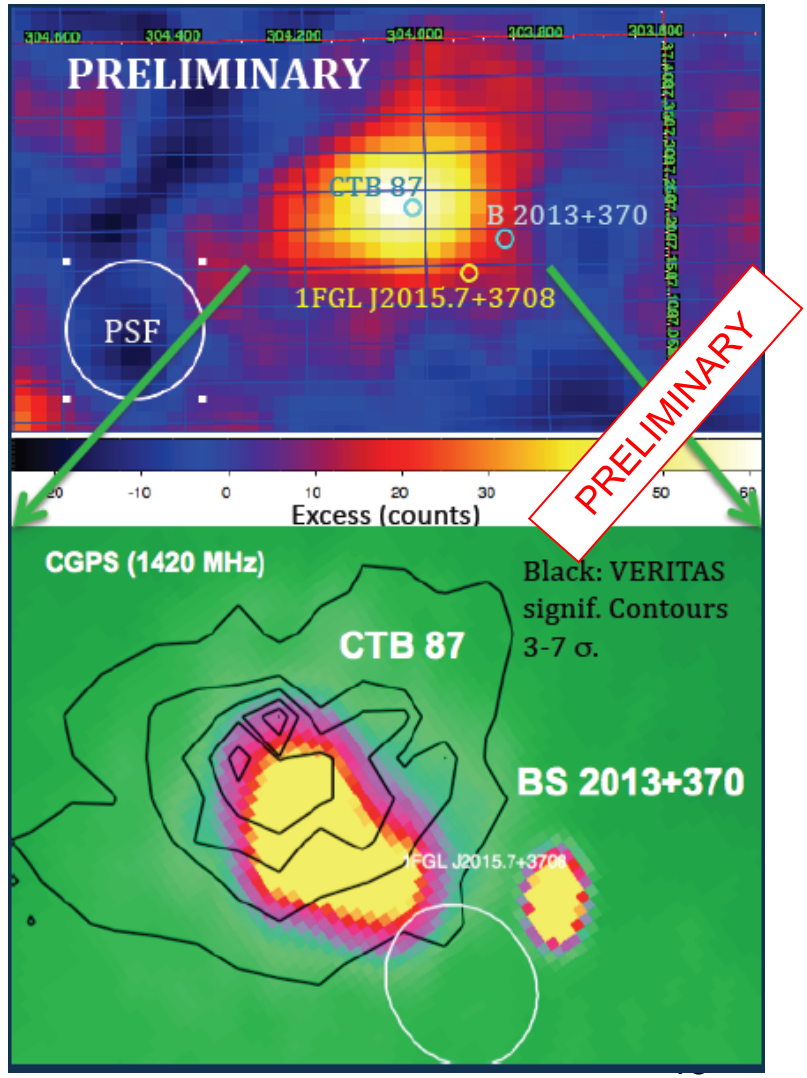




Galactic results IIa: CTB 87

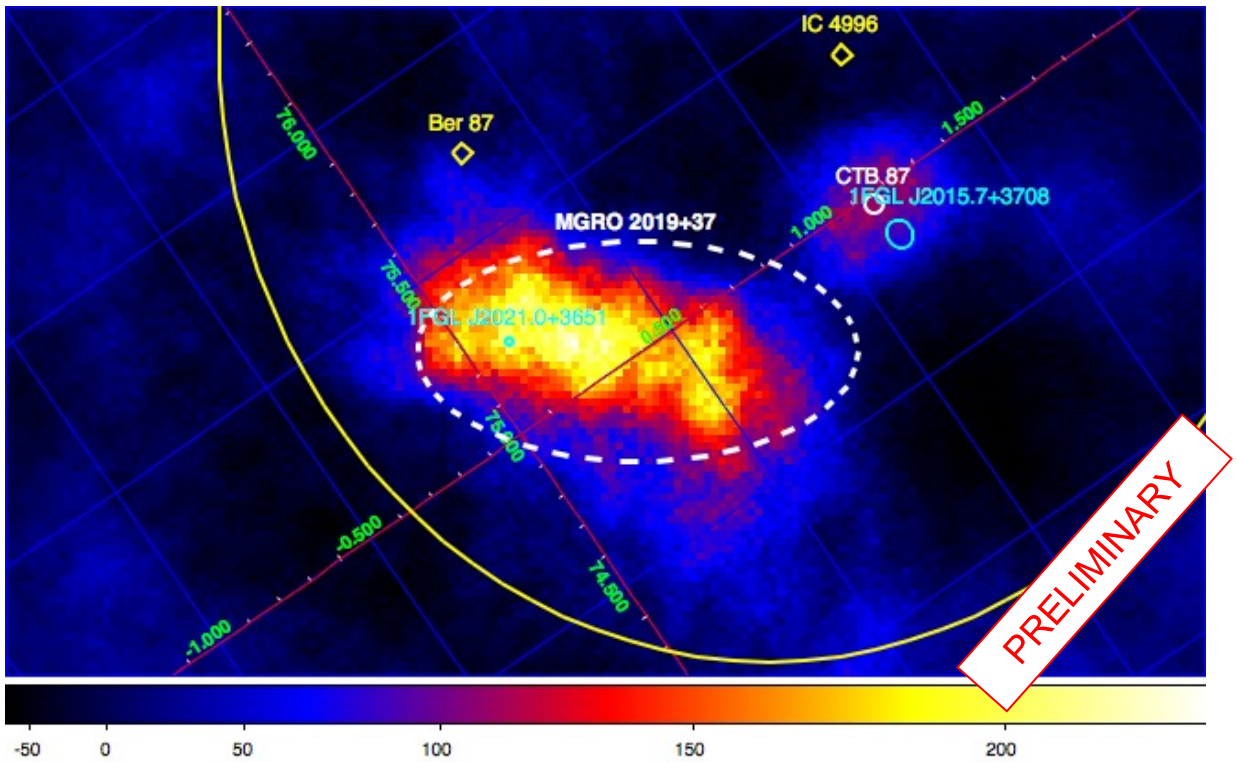
- VERITAS sees point source coincident with CTB 87
- Detection at 6.1σ
- Flux at E> 1 TeV: ~ 0.8% of Crab Nebula
- Power-law spectrum (Γ ~ 2.1±0.5), lack of variability

- Nearby blazar (BS 2013+370) excluded as TeV source at 99% CL



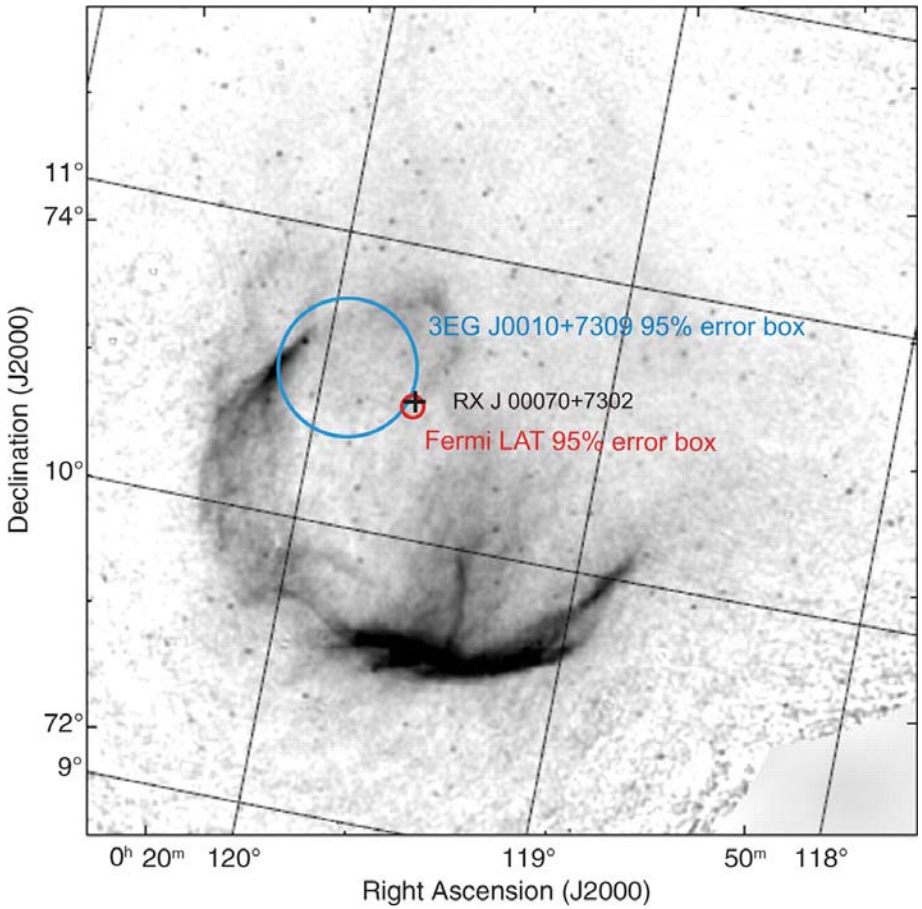
Galactic results IIb: Cyg OB1 region

- VERITAS extended-source analysis sees broad emission region
- Detection at 8.3σ (7.4σ post-trials)
- Coincident with MGRO J2019+37
- Multiple sources likely – need more data!



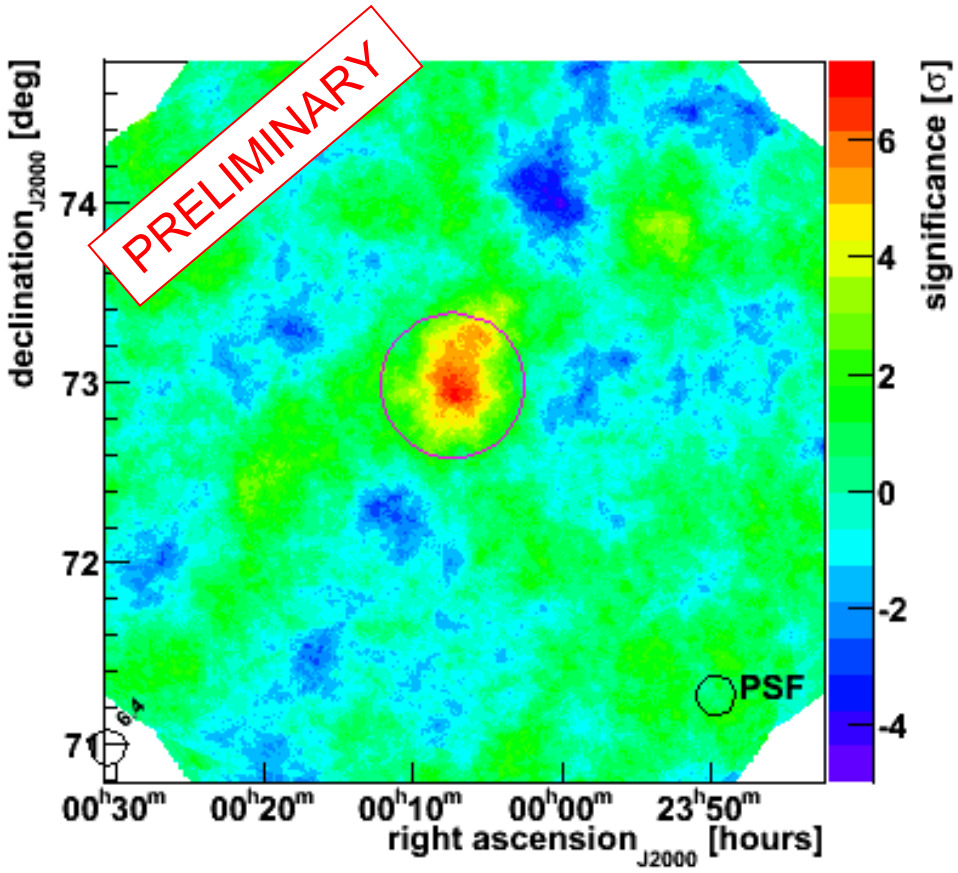
Galactic results III: CTA1

- young SNR (~13 kyr)
- composite SNR: radio shell, center-filled X-ray emission
- Fermi & X-ray (XMM-Newton) pulsar
- VERITAS data:
  26.5 hr (2010-2011 season)



Galactic results III: CTA1

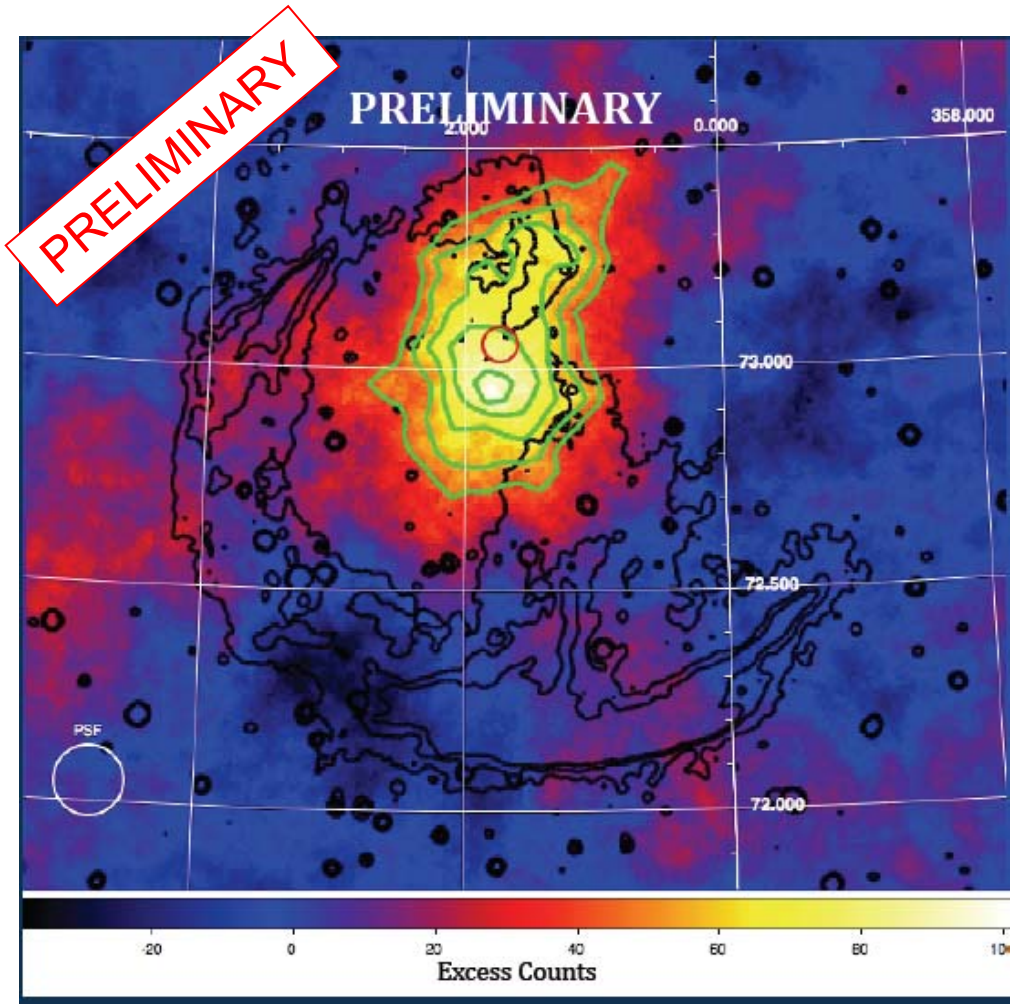
- VERITAS detection: 7.3σ (6.3σ post-trials)
- Flux (E > 1 TeV): ~4% of Crab Nebula
- Extended emission



Galactic results III: CTA1

- VERITAS contours: green
- Fermi pulsar: red circle
- Radio (1420 MHz) contours: black

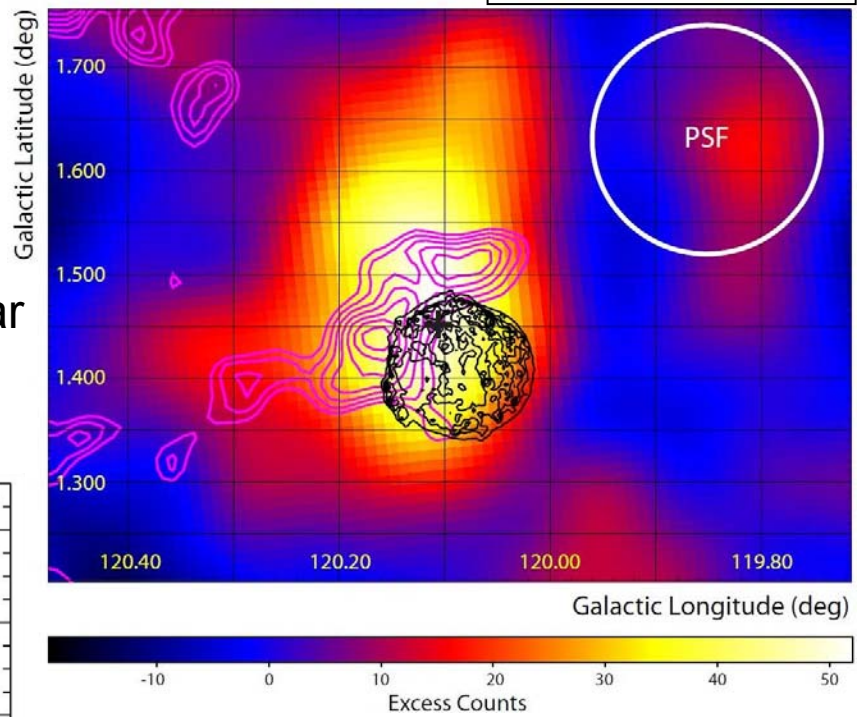
- Consistent with young PWN: <u>new TeV source</u>



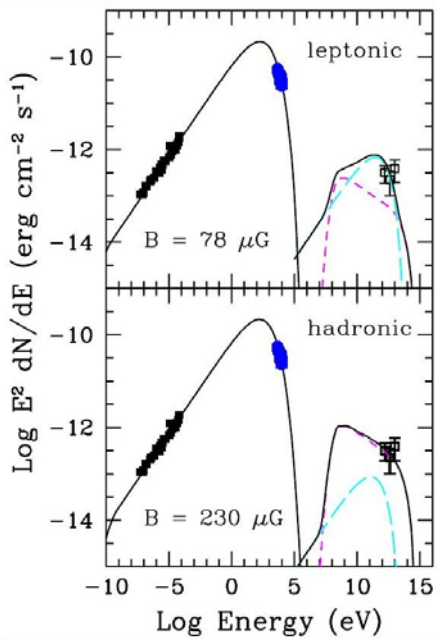
Galactic results IV: Tycho's SNR (G120.1+1.4)

- Type 1A SN, observed in 1572
- VERITAS data: 68 hr (2008, 2010)
- Detection: 5.0σ (post-trials)
- Flux (E> 1TeV): 0.9% of Crab Nebula
- Power-law spectrum: Γ=1.95±0.5±0.3
- Peak significance close to where molecular cloud is interacting with SNR
- Both leptonic and hadronic models fit data

Excess counts map



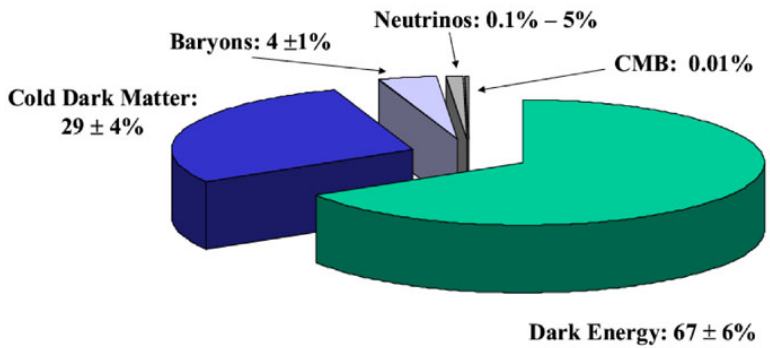
Black contours: X-ray (Chandra)
Magenta contours: 12CO emission



Cyan: Inverse Compton
Magenta: π^0

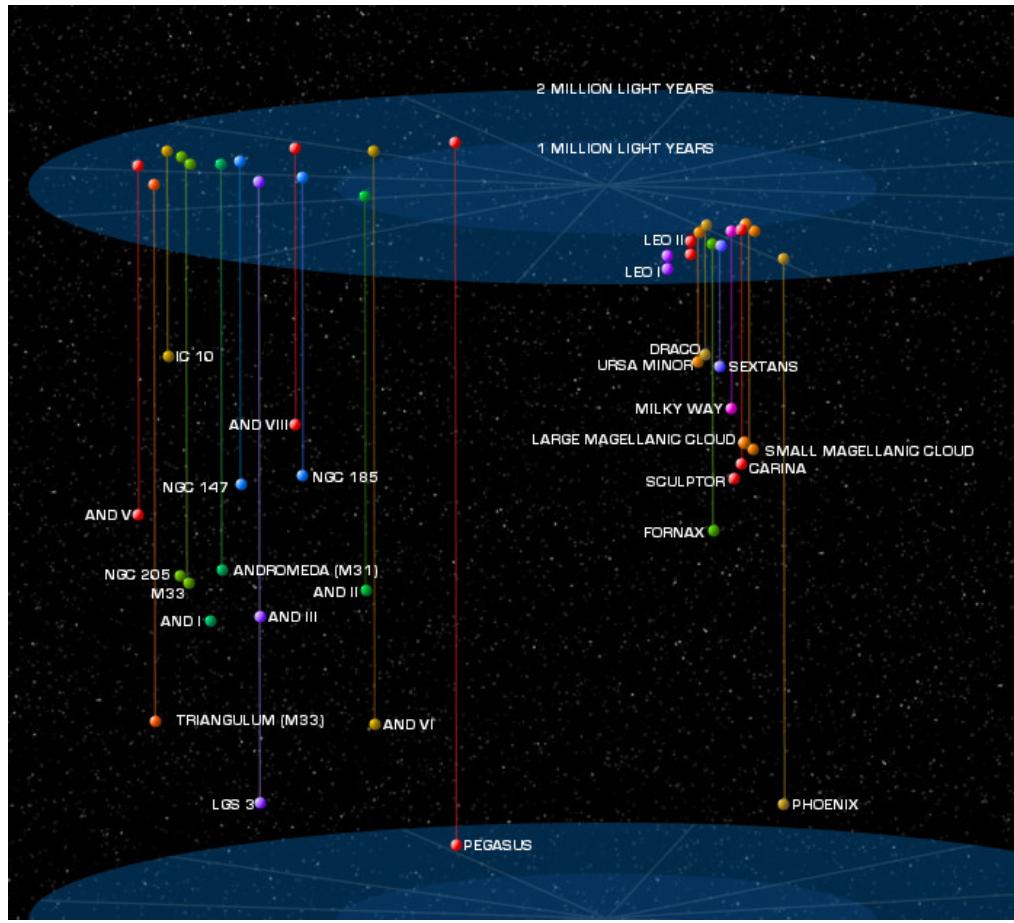
Astroparticle observations: Dark Matter Searches

- Dark matter ~25% of energy density of Universe
- Must be non-baryonic, cold, heavy, gravitationally bound
- WIMPs (eg. neutralino) in 50 GeV – 10 TeV range are well-motivated candidates
- Self-annihilation could lead to GeV/TeV gamma signal
- Cherenkov arrays well suited for this search



Astroparticle observations: Dark Matter Searches

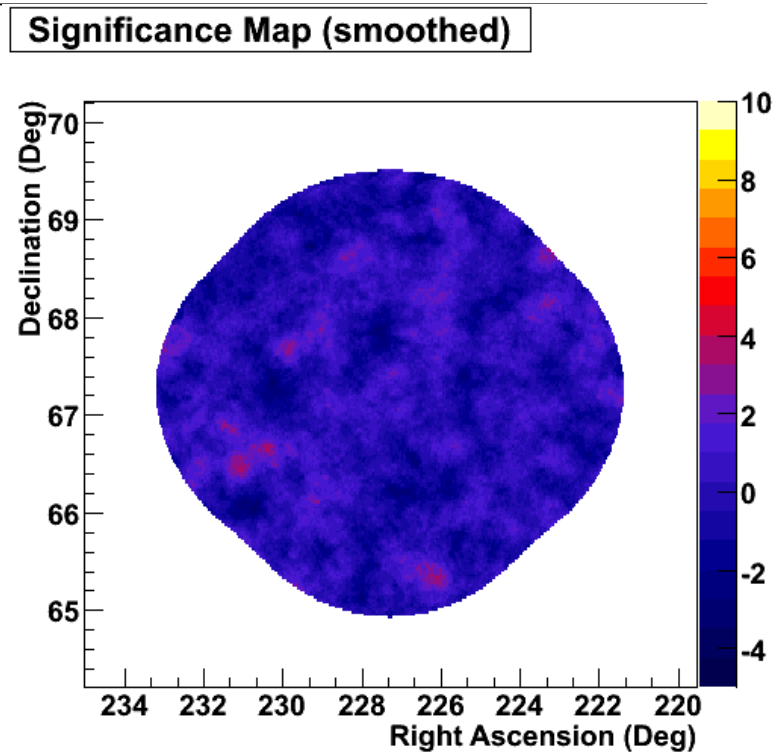
- Good targets are nearby galaxies with high mass-to-light ratios:
- Candidates: dwarf spheroidals (small astrophysical backgrounds)
- Ursa Minor, Draco, Willman I, Bootes I, Segue 1



Astroparticle results: Dark Matter Searches

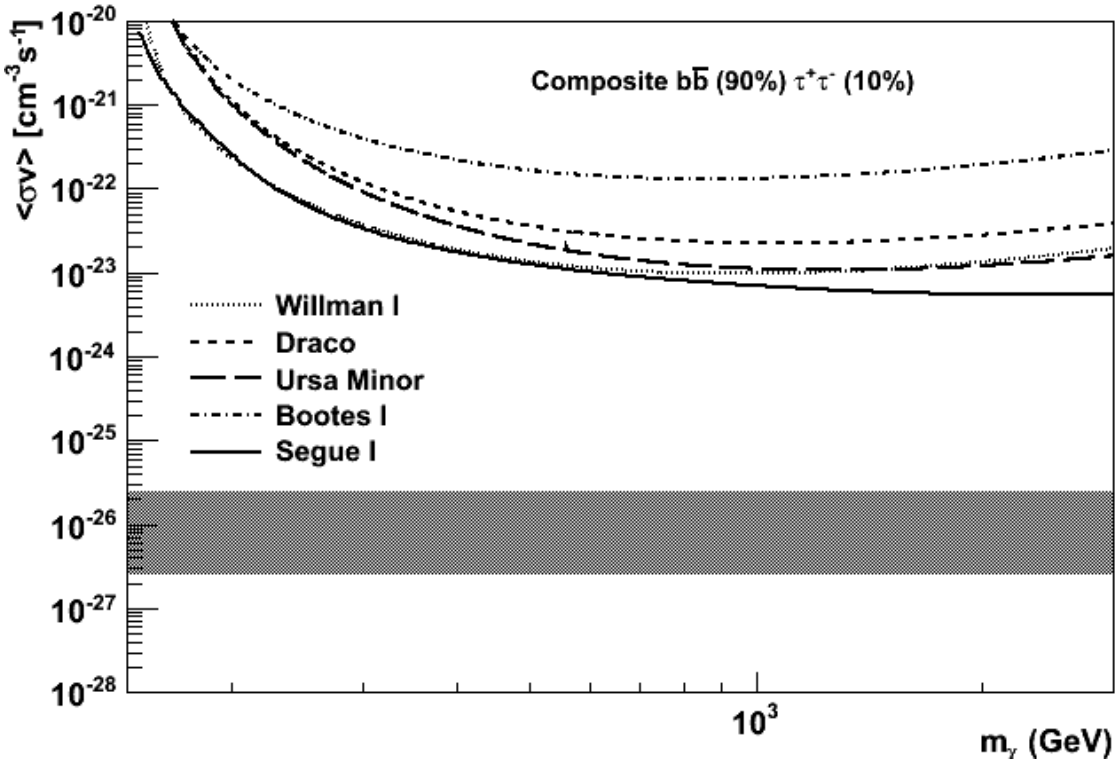
- eg: Ursa Minor
- ~20 hrs data; no detection
- Flux limit: 1-2% Crab Nebula (95%)
  (0.4 x 10^{-12} $cm^{-2}s^{-1}$)

- Turning flux limit into DM limit needs
  - Particle-physics modeling
  - Astrophysical factor J (DM density distribution squared), ~10^{18} GeV^2cm^{-5}
- Usually use NFW profile
  (Segue 1: Einasto profile)



Astroparticle: Dark Matter Searches

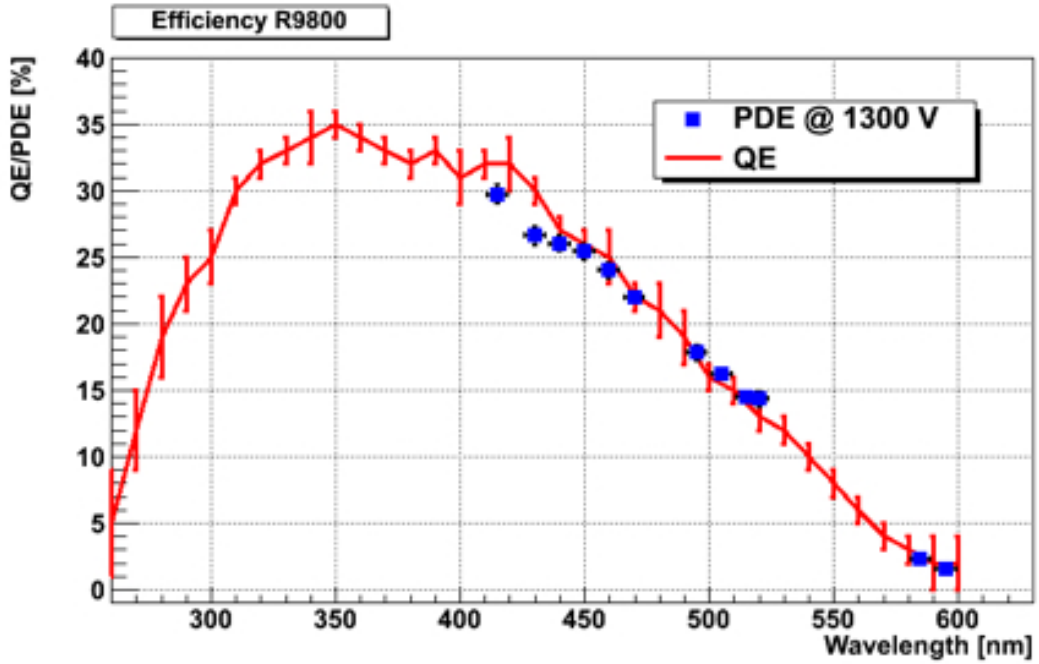
- VERITAS limits on $\langle\sigma v\rangle \sim 10^{-23}$ cm^{-3}s^{-1}
- Need significant astrophysical boost factor to constrain models



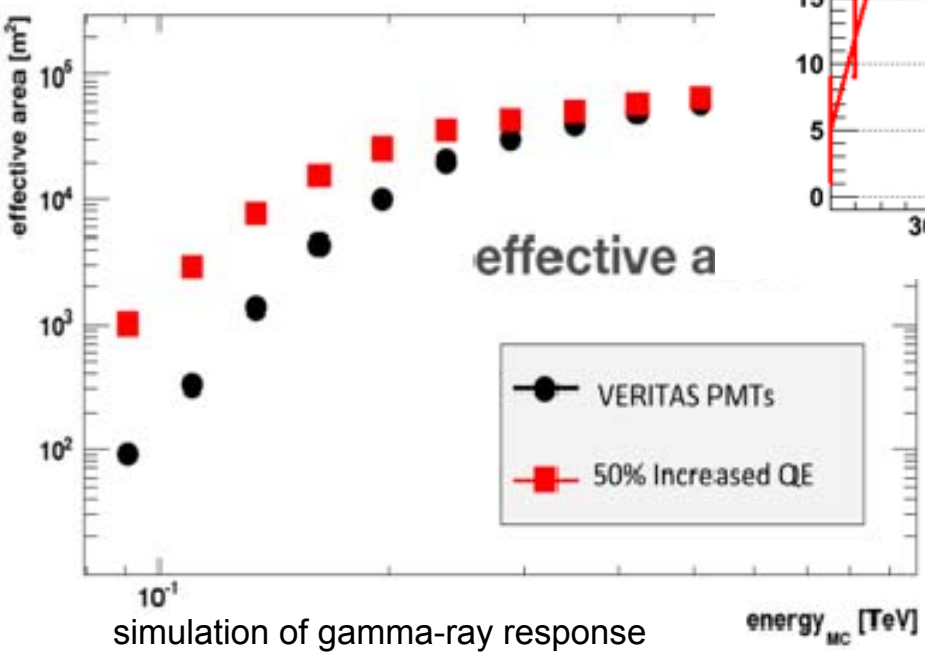
The future: VERITAS Upgrades

- FPGA-based Trigger upgrade (partially installed, commissioning underway)
  - improved CR event rejection
- PMT replacement with high-efficiency PMTs (summer 2012, funded)
  - ~50% increase in QE over current tubes
  - lower energy threshold (trigger threshold to < 100 GeV)
  - improved sensitivity
- LIDAR System (2011, funded)
  - Improved atmospheric monitoring
- Telescope drive upgrade (study phase)
  - shorter response time to GRBs, etc.

VERITAS PMT upgrade



Hamamatsu R9800
(QE and PDE measurement:
WashU and UCSC)



simulation of gamma-ray response

Conclusions

- VERITAS operating well, improved sensitivity since 2010
- Many new sources and exciting results on known sources
- Active collaboration with other VHE instruments, Fermi/LAT and instruments at other wavelengths
- Upgrade underway w/several years of stable operation following