Highlights of VERITAS Results

M. Schroedter* for the VERITAS Collaboration#

* Iowa State University, # http://veritas.sao.arizona.edu

VERITAS Collaboration

~ 100 Scientists

22 Institutions in 4 Countries

Support from:

Smithsonian Inst.
U.S. NSF
U.S. DOE
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

U.S.

Adler Planetarium
Argonne Nat. Lab
Barnard College
DePauw Univ.
Grinnell College
Iowa St. Univ.
Purdue Univ.
SAO
UCLA
UCSC
Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Massachusetts
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

U.K.

Leeds Univ.

Ireland

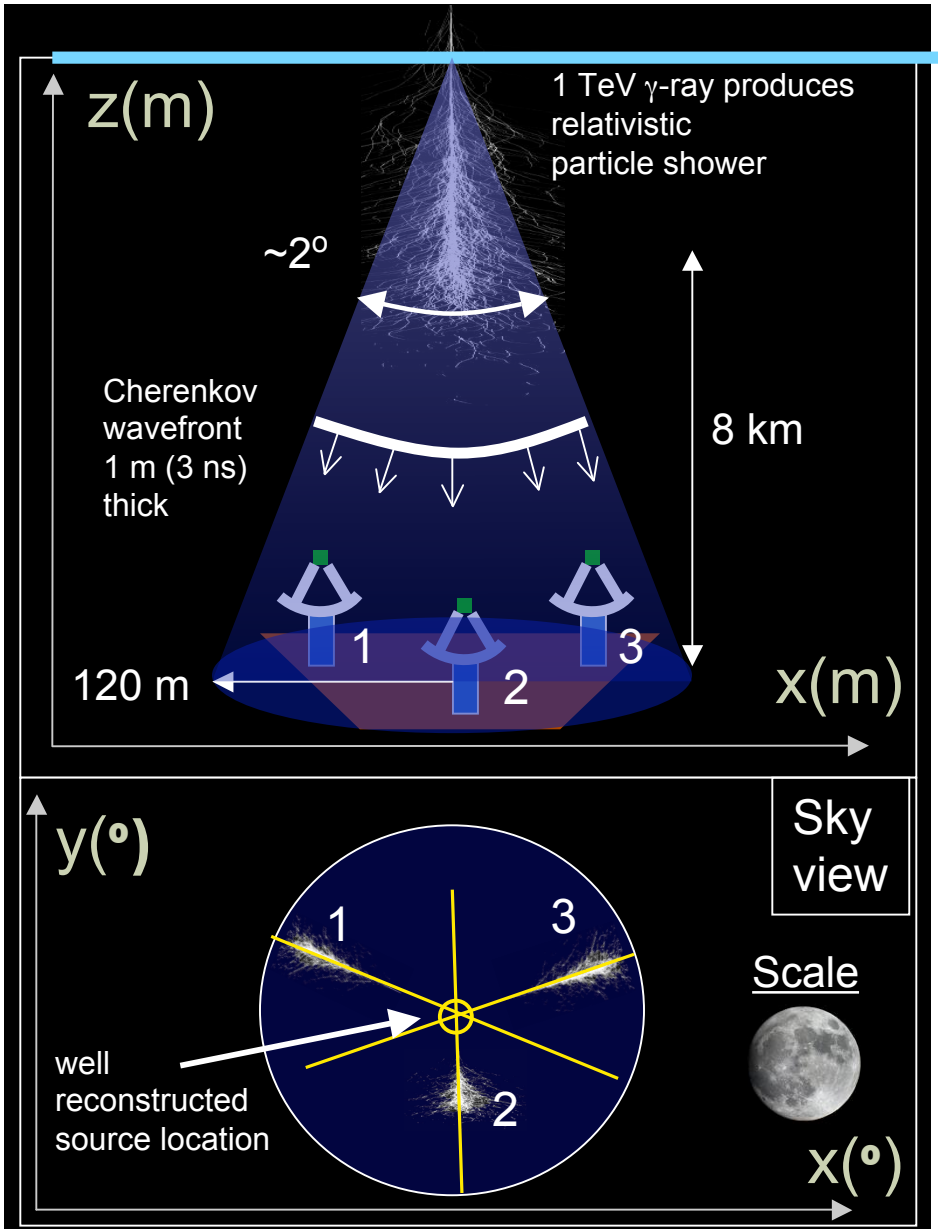
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

+ 25 Associate Members

Outline

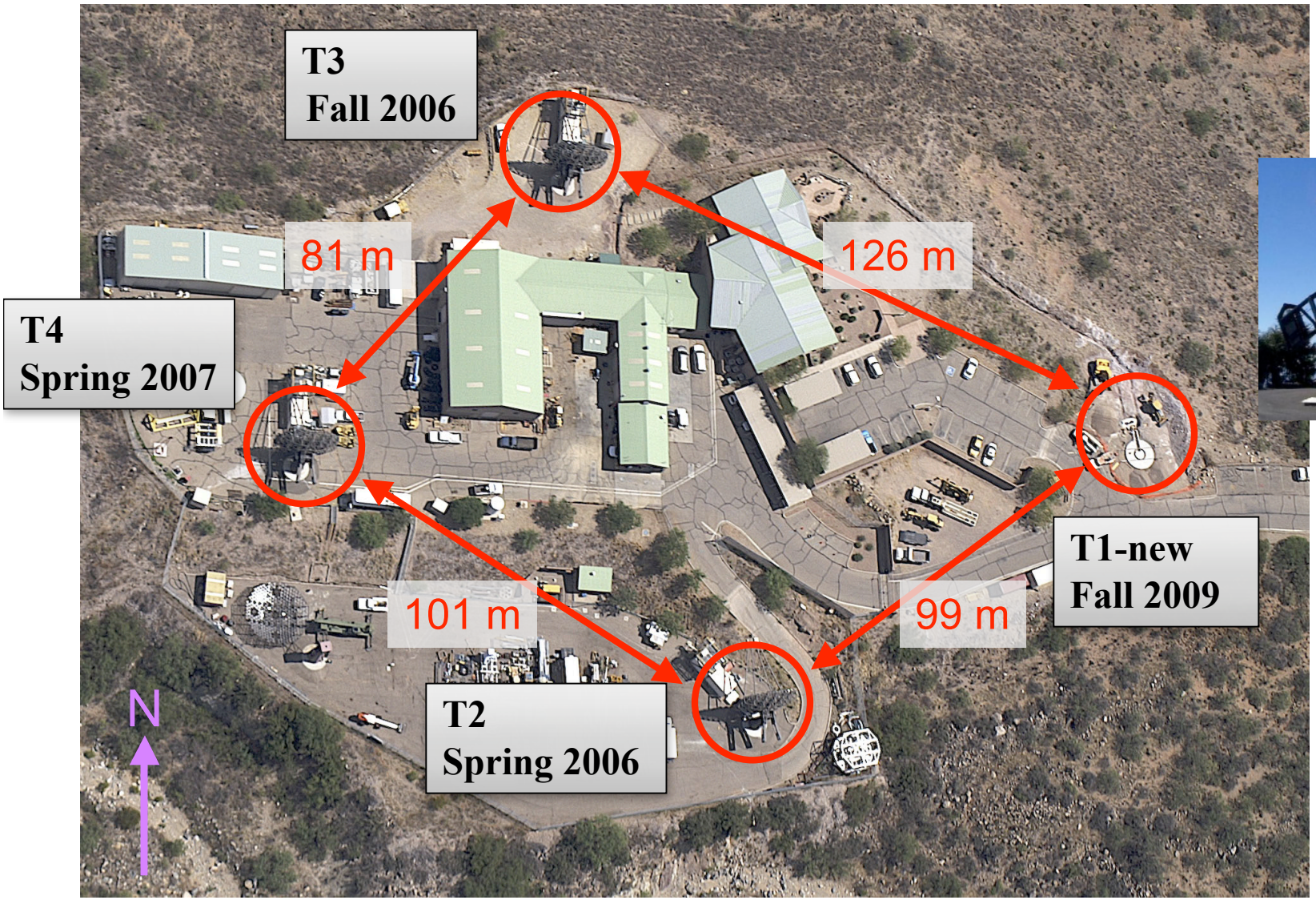
- Technique
- VERITAS Telescope Array
  - **Layout, technical details, performance**
- Science Highlights
  - **Extragalactic**
    - **Discovery of Starburst Galaxy M82**
    - **Radio Galaxy M87**
  - **Galactic Sources**
    - **Boomerang**
  - **Dark Matter Searches**
- VERITAS Upgrade Plans

Atmospheric-Cherenkov Technique



Detection area: 50,000 m^2
larger than football field!
Energy: 0.1-50 TeV
Energy resolution: ~18%
Angular res.: <0.12°

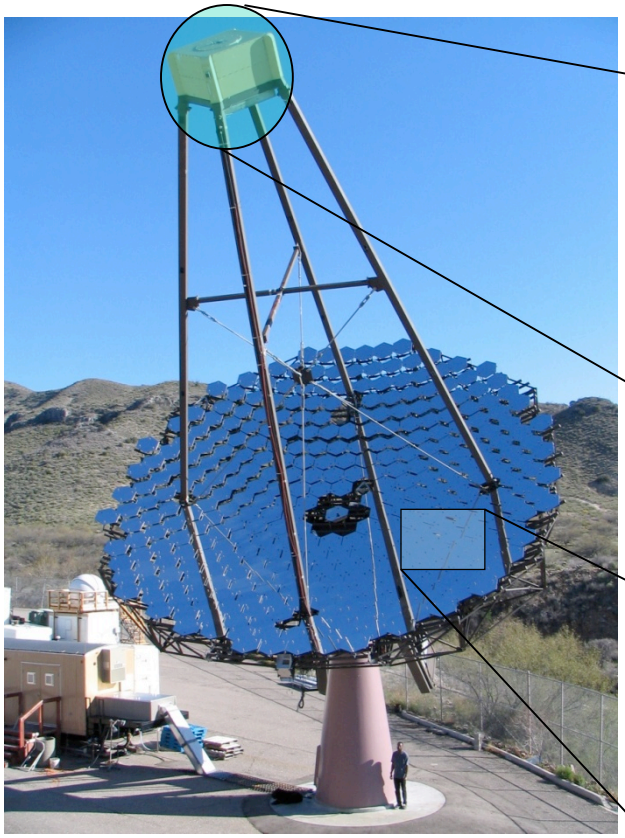
NEW VERITAS Telescope Array



7km

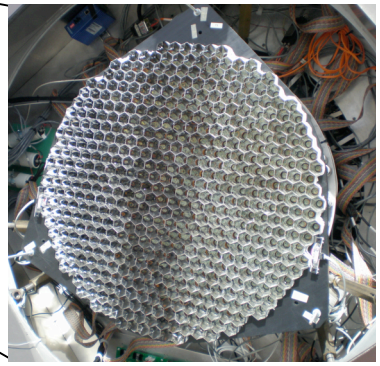
Whipple 10m

Technical Details



Telescope (x 4)
12-m diameter Davies-Cotton
f 1.0, 110 m^2 area

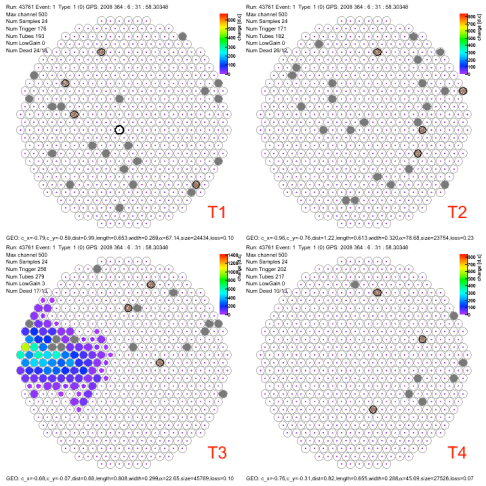
PMT Assembly



Camera (x 4)
499 PMTs, 3.5° FOV

Mirror Facets (x 350)
Reflectivity ~ 88%
(Recoated every 2 years)

Cosmic-ray event



FADC Readout
500 Msps, dual-gain

3-Level Trigger
Pixel, Telescope, Array
Deadtime ~10% @ 250 Hz

OLD VERITAS Performance

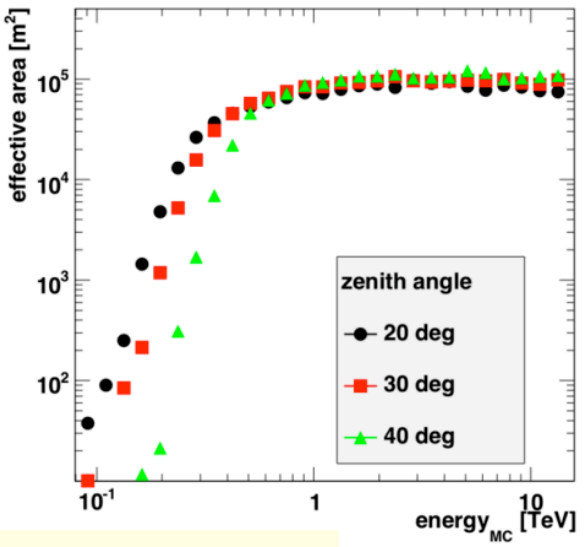
Canonical Performance Values:

- Energy Range: 100 GeV – 30 TeV (spectra >150 GeV)
- Energy Resolution: 15% – 20%

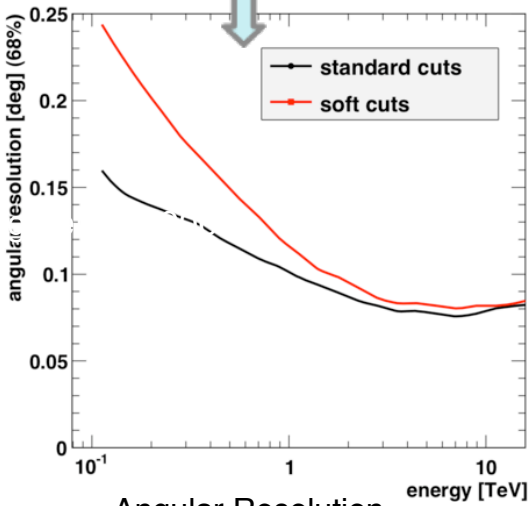
- Crab Rate ~ 40 / min (trigger)
- Sensitivity: 5% Crab in < 2.5 h
  1% Crab in < 50 h

- Angular Resolution: $r_{68} < 0.1^{o}$
- Pointing Accuracy: < 50″

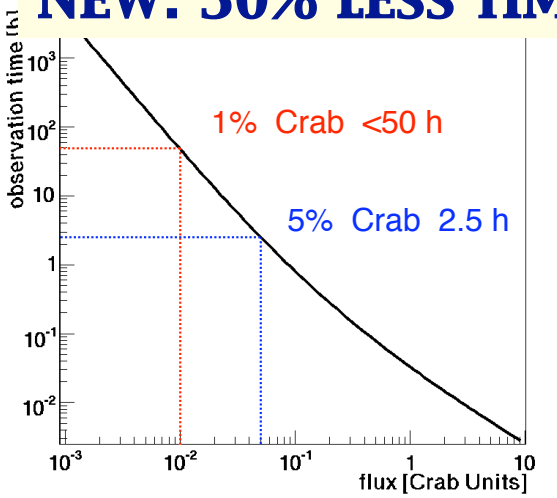
Effective Area (std. cuts)



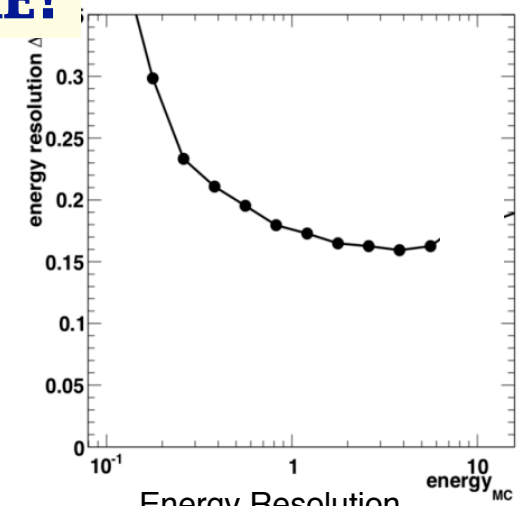
NEW: 30% LESS TIME!



Angular Resolution



Pt. Source Sensitivity



Energy Resolution

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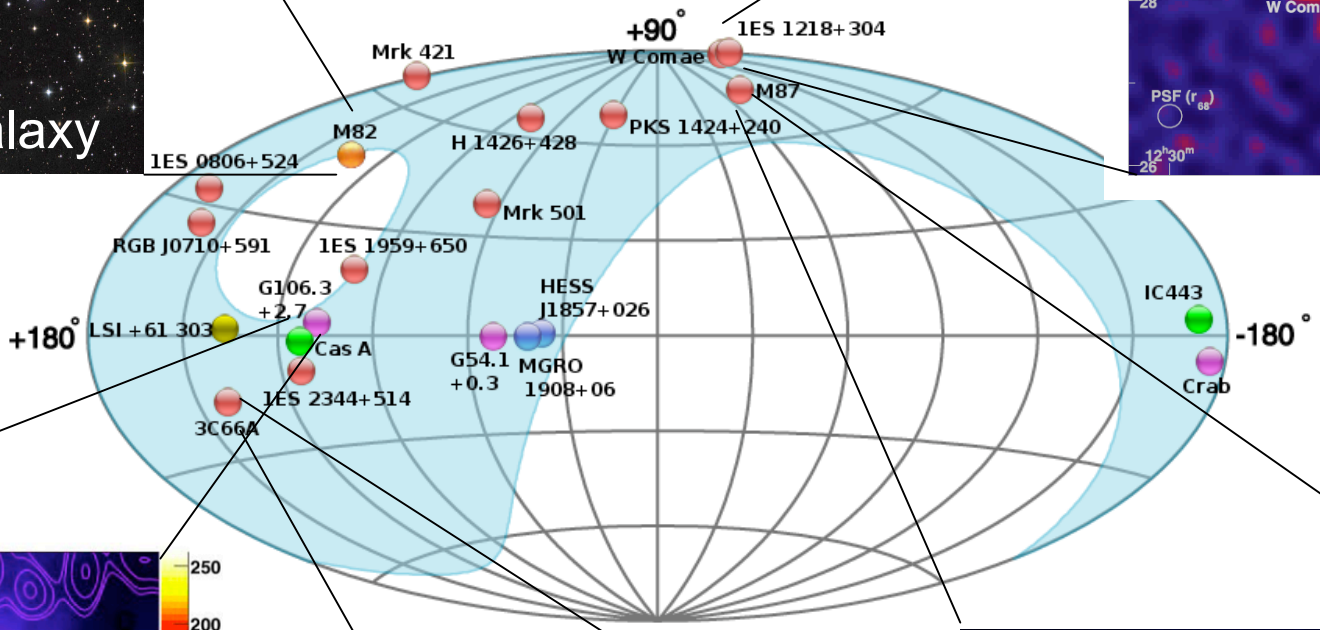
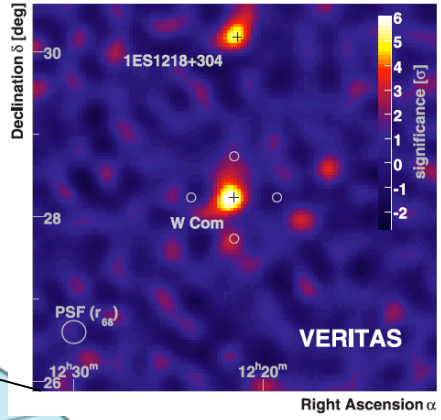
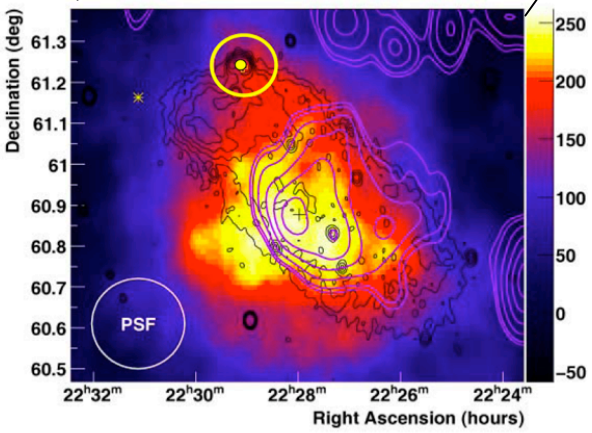
    - **Boomerang**
  - **Dark Matter Searches**
- VERITAS Upgrade Plans

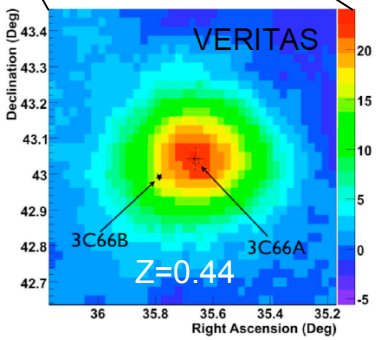
VERITAS Science Highlights

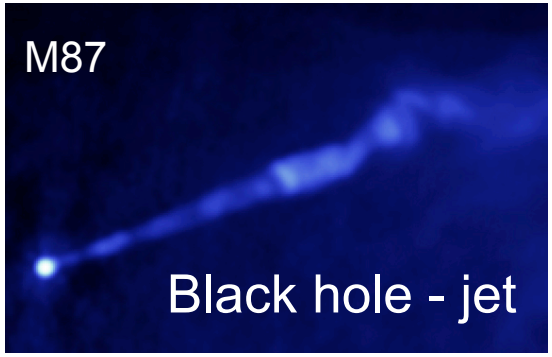
21 Sources
6 Classes











Extragalactic Sources

- Active Galactic Nuclei
  - BH accretion powers relativistic jet & VHE particle acceleration.
  - Science goals: emission mechanism, jet physics, BH engine.
  - Sources of UHE cosmic rays?
  - Double-peaked SED
    Simultaneous MWL data crucial.

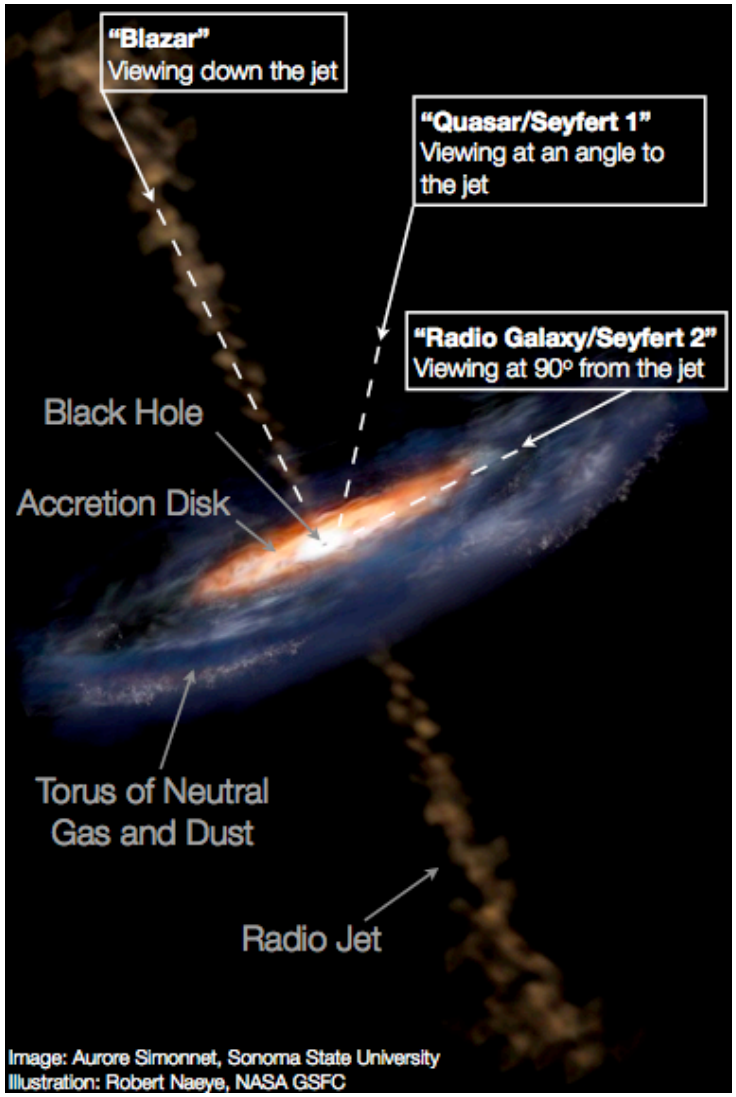
a) Blazars (10)

- Highly variable emission: 3 min
- Probe EBL from spectra via:
  $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ e^-$

b) Radio Galaxies: M87, Cent-A

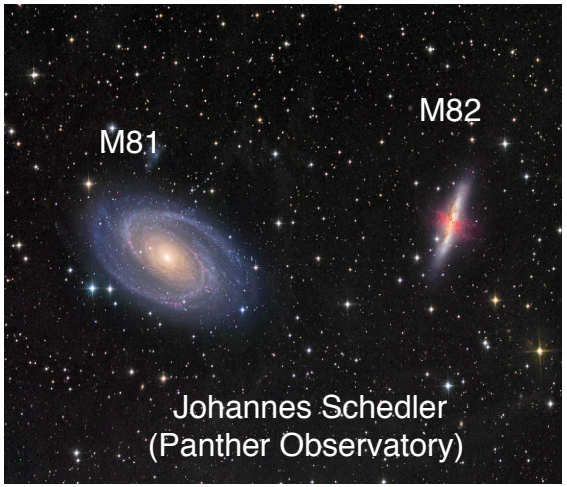
- Closer, so structure can be better resolved.

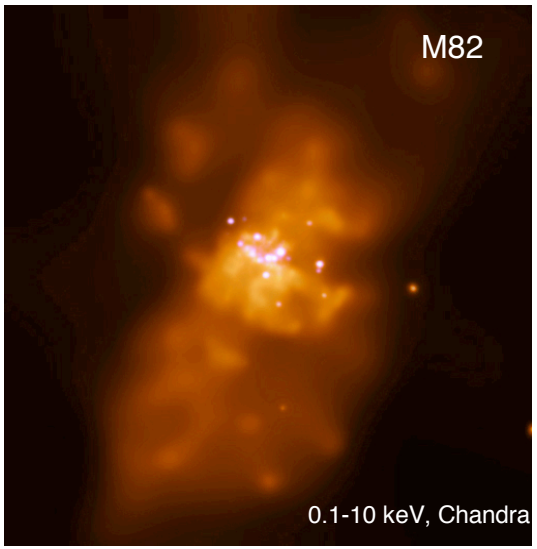
- Starburst Galaxy: M82



M82: Starburst Galaxy

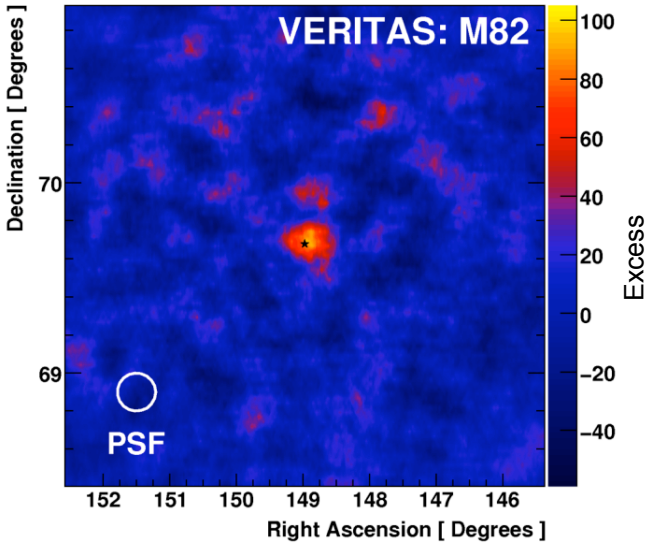
- M82: Prototype starburst galaxy
  - Interacting with group of galaxies over hundreds of Myrs.
  - Tidal forces → active starburst region (HST shows > 200 massive star clusters.
  - SMBH < 3 x 10^7 M_{sun}, no AGN activity.
- Starburst Region
  - High star formation and SNR rate.
  - High CR density (from radio emission).
  - High gas density ~ 150 #/cm^3
  - γ-rays from cosmic rays (p^+ and e^-) interacting with gas and B-field Clues on origin of CR's.
  - Previous limits < 10% Crab (HEGRA, Whipple). Also limits on NGC 253.

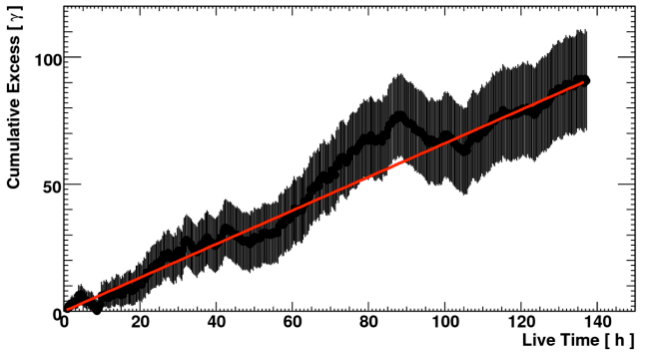




M82: Starburst Galaxy

- VERITAS Data & Analysis
  - 2007-09: 137 h live time.
    Only dark time (no moonlight).
  - "Hard cuts" from *a priori* study
    of Crab data at similar zenith (θ ~ 40º).
- Detection !
  - 5.0 σ excess (pre-trials), 4.8 σ (post-trials).
    Consistent with point source at M82.
  - Many systematic checks of analysis procedure, background method, and potential biases.
    (E > 700 GeV)
  - Among weakest VHE sources ~0.9% Crab.
- Interpretation
  - **First detection of an extragalactic VHE source not clearly associated with AGN activity.**
  - Consistent with predictions, general nature of CR interactions.





"Discovery of Gamma-ray Emission from a Starburst Galaxy,"
Acciari et al., submitted to Nature.

M82: Starburst Galaxy

- Energy spectrum
  - Range: 0.9 to 5 TeV
  - Well fitted by pure power law

    $\Gamma = 2.5 \pm 0.6_{stat} \pm 0.2_{sys}$
- Hadronic emission

  $p_{CR} + p_{ambient} \rightarrow \pi^0 \rightarrow \gamma\ \gamma_{TeV}$

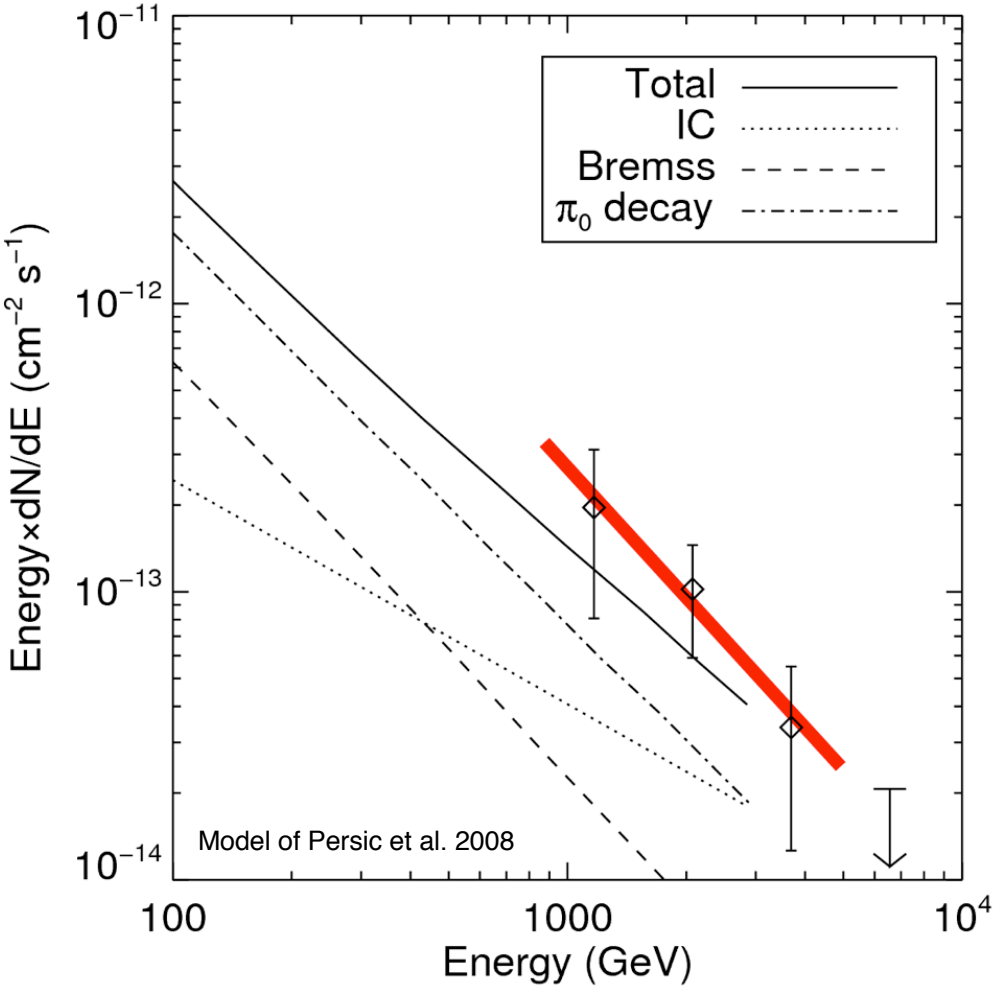
  $\rightarrow \pi^{+/-} \rightarrow e, \nu$

  e + B-field → radio/IR synchro

  Measured 32 GHz flux is consistent with VHE γ-ray spectrum extrapolated to 20 GeV if $\Gamma = 2.3$ and B~8nT.
- Leptonic signature (IC)

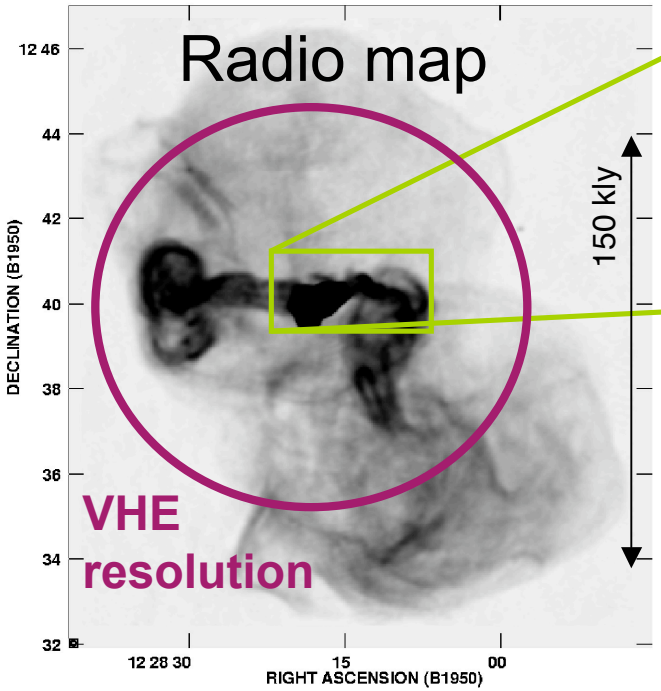
  $e_{CRs} + \gamma_{IR} \rightarrow e + \gamma_{IC}$

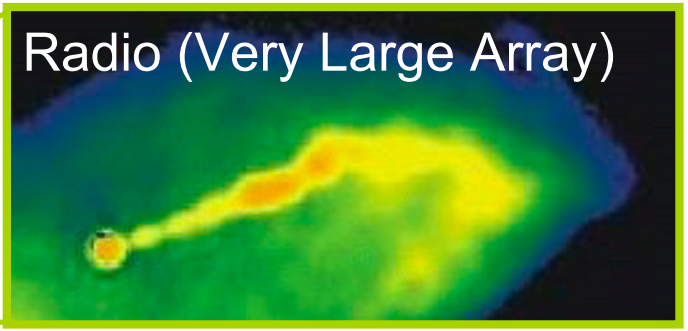
  Consistent with Chandra 5 keV flux for 1 GeV CR-electrons, 8 nT.

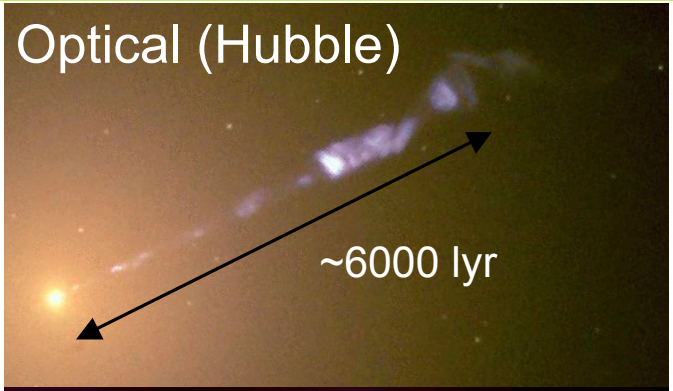


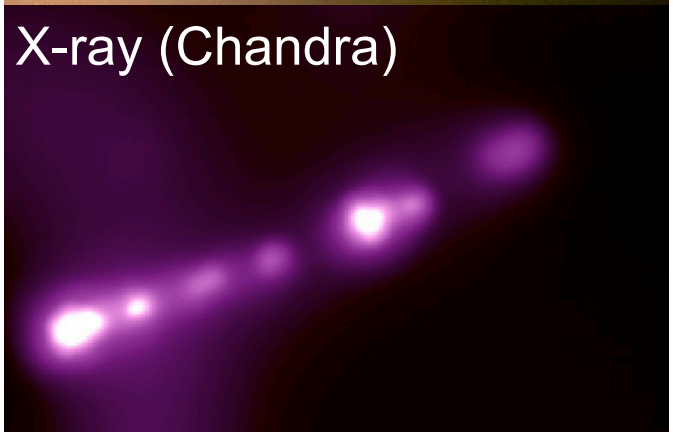
Pohl (1994), Völk et al. (1996), Persic et al. (2008), de Cea del Pozo et al. (2009)

M87: Radio Galaxy



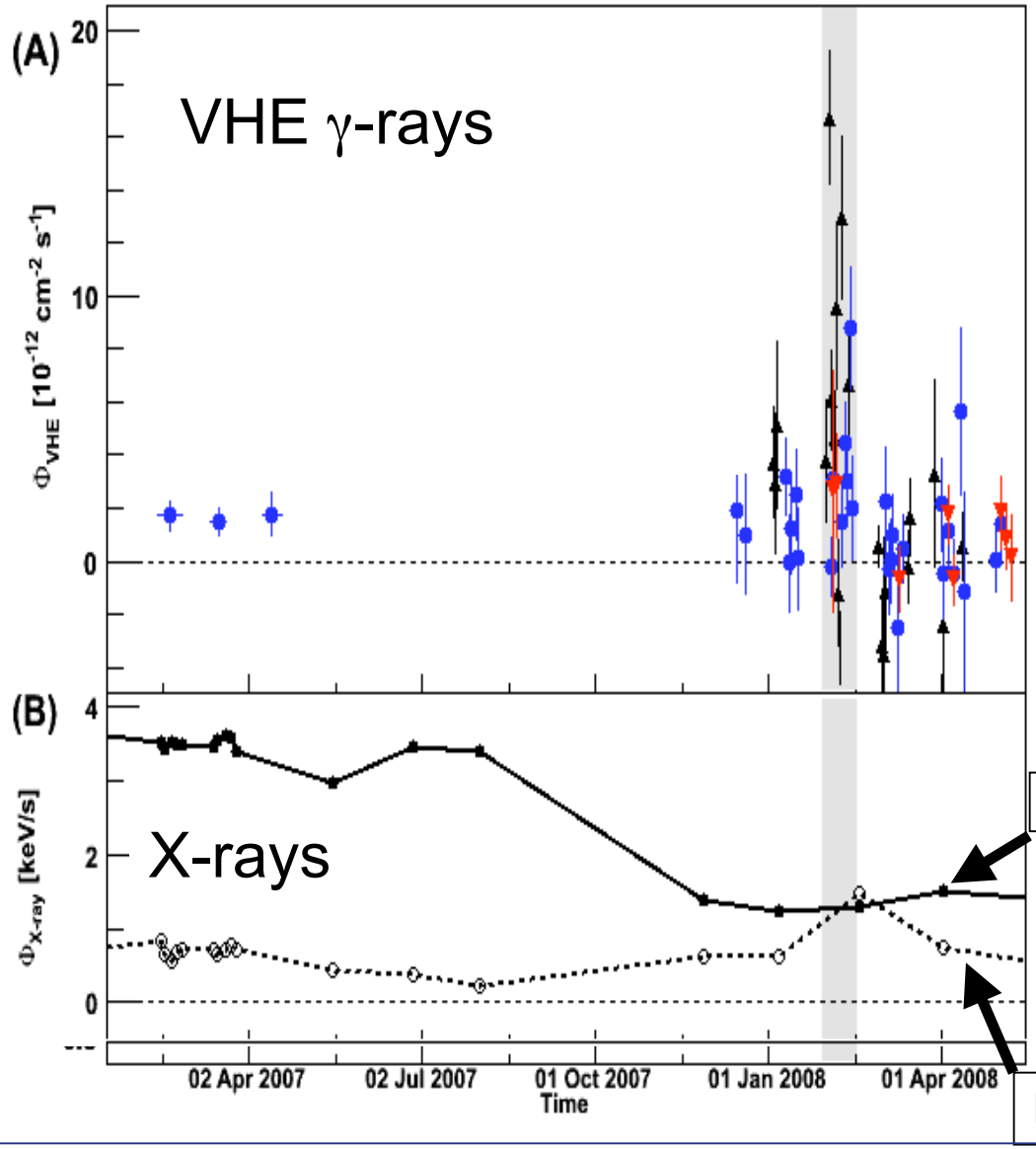






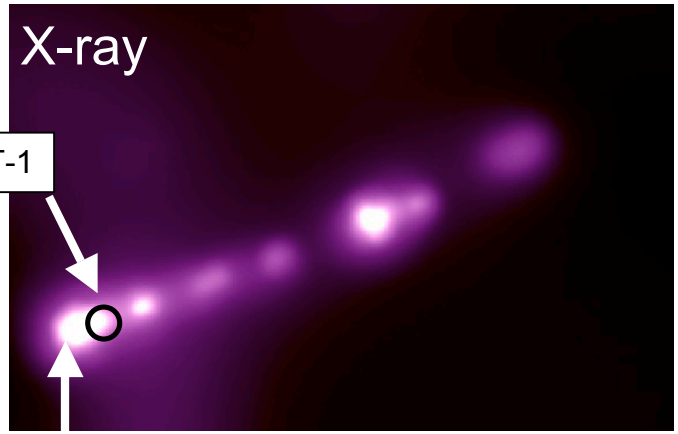
- Giant elliptical radio galaxy
  - Jet angle ~30°
  - Super massive BH ~6×10^9 $M_\odot$
- 17 Mpc (z=0.004)
- International multi-λ campaign

M87: Radio Galaxy



- TeV γ-ray outburst
  - Duration ~ a week
  - Nucleus active in X-rays, 43 GHz
- VLBA resolution at $6R_S$
  - Variability confined to nucleus
  - R_S = 44,000 km

VERITAS, VLBA, HESS, and MAGIC, Science **325**, July 2009.



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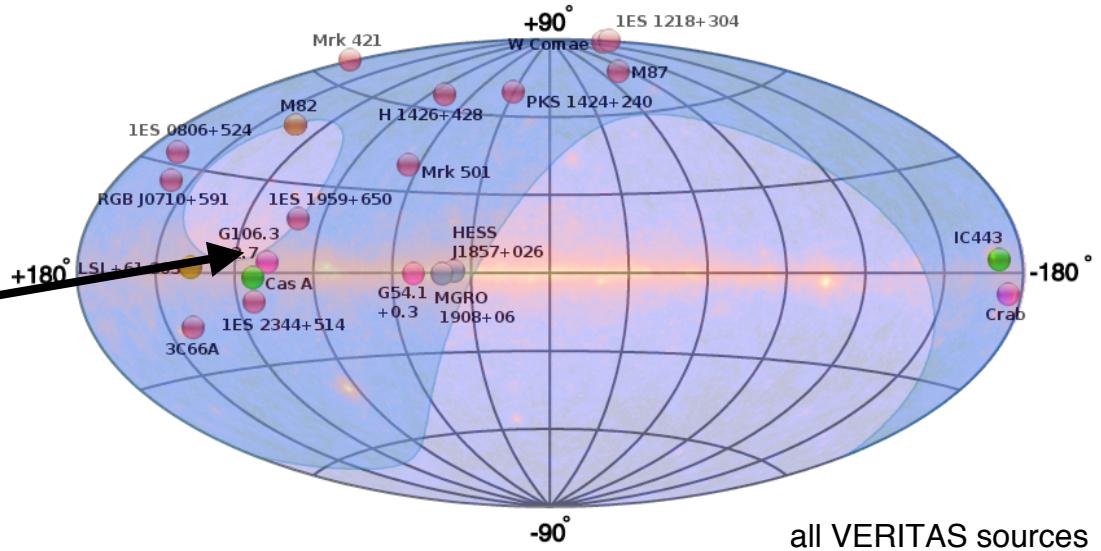
Galactic TeV Sources

Supernova remnants (5)

- Shell-type
  (IC 443, Cassiopeia A)
- Pulsar-wind nebulae
  (Crab, Boomerang, G54.1)

- X-ray Binary
  - LSI +61 303
  - Be star + compact companion

- Unidentified
  - MGRO 1908, HESS J1857
  - Bright in VHE γ rays
  - Dark otherwise



all VERITAS sources

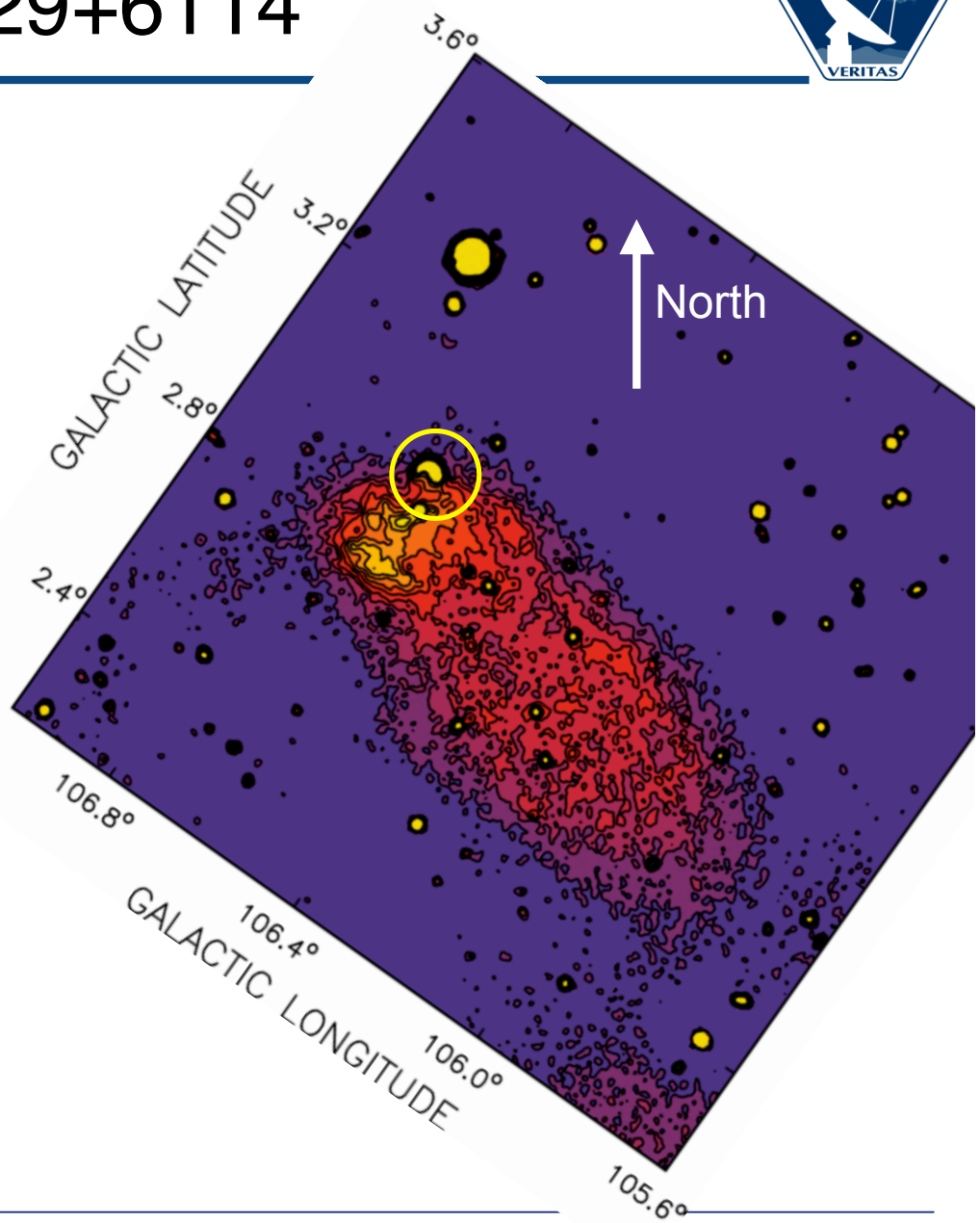
Extragalactic
Blazars, Radio galaxies
Starburst galaxy

- Galactic plane is rich in γ-ray emission:
  - 90% photons seen at GeV energies.
  - Probe acceleration of e, p in shock fronts, colliding winds, superbubbles

Hope to pin down CR Origin:
need ν-signature!

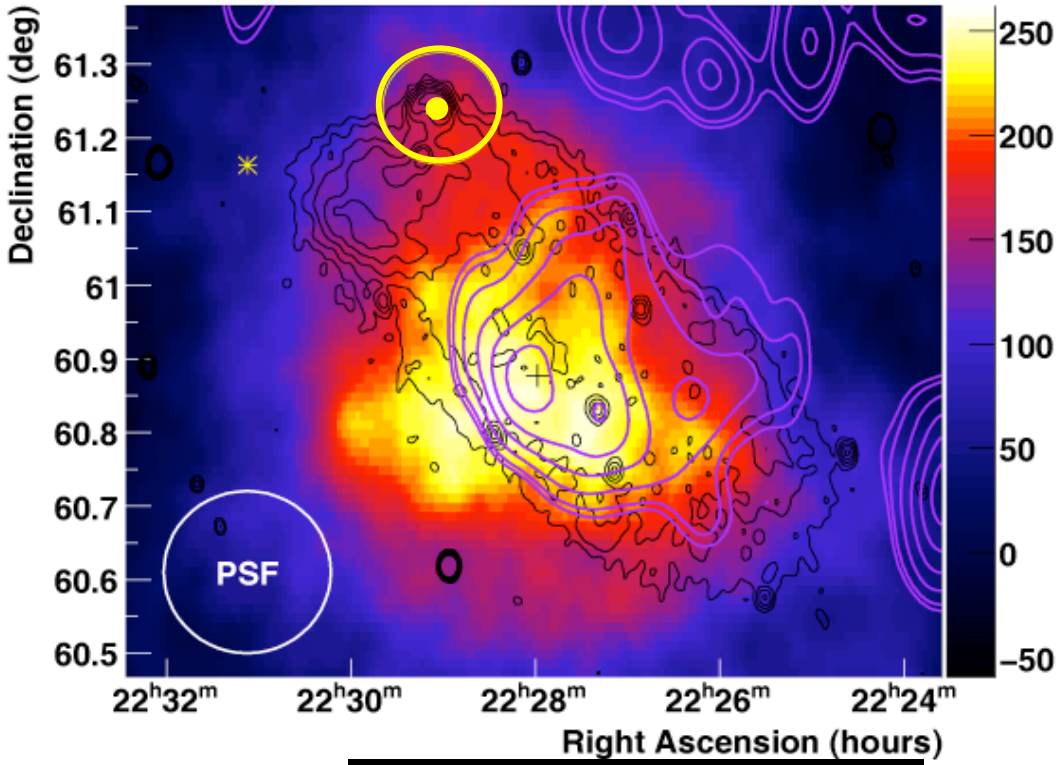
Boomerang/PSR J2229+6114

- Energetic pulsar + wind nebula discovered by EGRET
  - Age ~ 10,000 years
  - Period: ~50 ms
  - E-dot = 2.2×10^{37} erg/s
  - Distance ~800 pc (Kothes et al.)
- Likely associated with large SNR G106.3+27
- Fermi-LAT Bright Source list
- Emission at ~35 TeV reported by Milagro (Abdo et al., 2009)



Boomerang/PSR J2229+6114

- VERITAS Observations
  - Observations overlap radio shell
  - 33 h, 6.0σ post-trials
  - Flux ~5% Crab above 1 TeV
- TeV emission is extended
  - Spans a 0.4° x 0.6° region
  - Peak is 0.4° from pulsar
  - Overlaps region of high CO density



Color map: VERITAS
Circle: Fermi error circle
Dot: Pulsar position
Black: 1.4 GHz DRAO
Purple lines: CO

V. A. Acciari et al., sub. to ApJ.

Boomerang/PSR J2229+6114

- Energy spectrum
  - Integrate over 0.32o radius centered on emission peak
  - Well fitted by pure power law

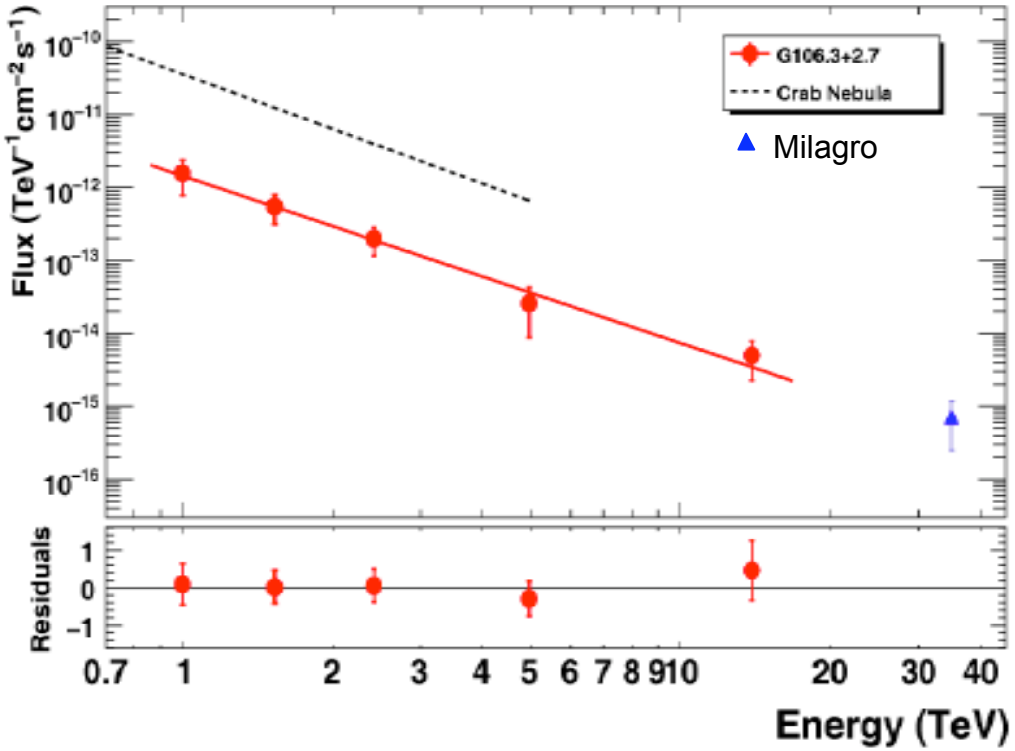
    $\Gamma = 2.3 \pm 0.3_{stat} \pm 0.3_{sys}$,

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

- If associated with pulsar

  Favors hadronic origin of VHE γ ?

  $p_{CR} + p_{ambient} \rightarrow \pi^0 \rightarrow \gamma\,\gamma$



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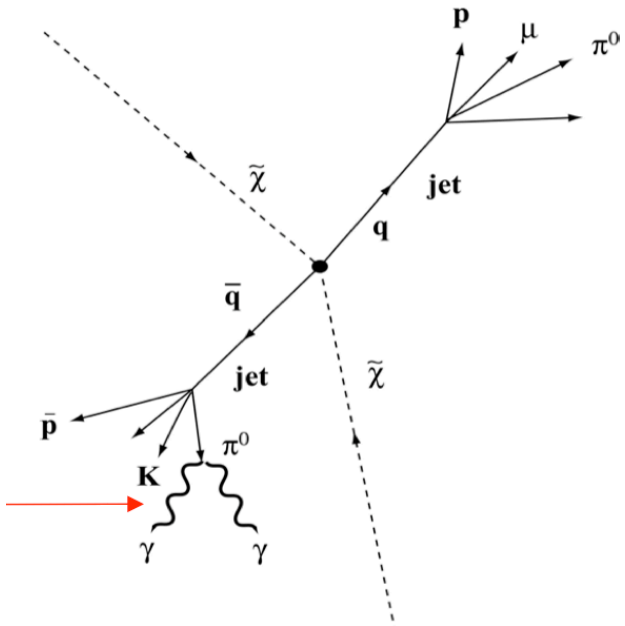
VERITAS Dark Matter Searches



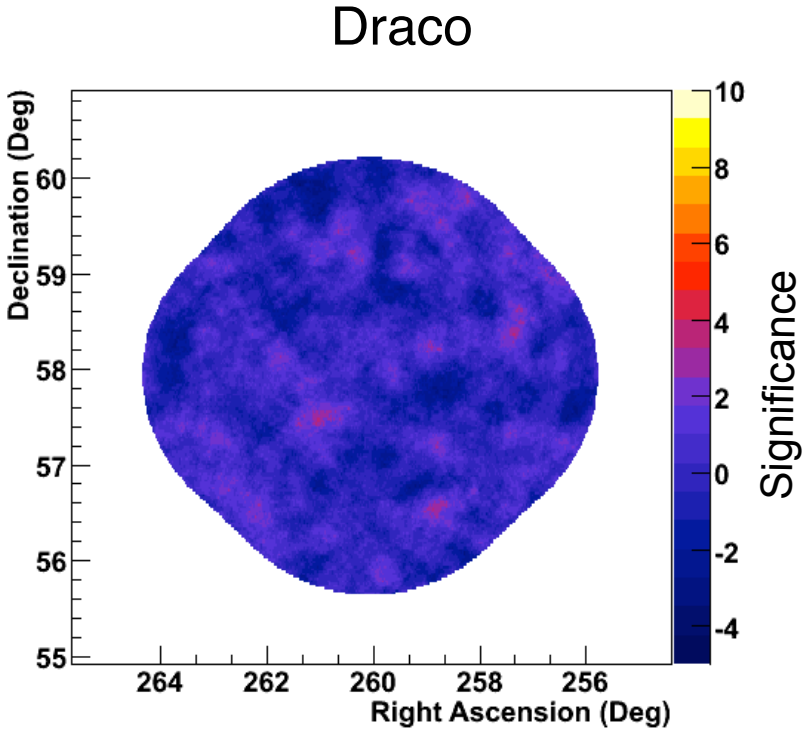
- Complementary approaches
  - Accelerators (Tevatron, LHC,…)
  - Underground labs (CDMS, COUPP,…)
  - Astrophysical DM annihilation
- Dark matter annihilation
  - WIMP candidates (KK, SUSY)
  - Unique HE γ-ray signature
    50 GeV - 10 TeV
  - Direct link to galactic halo structure

$$\gamma \text{ flux} \propto \left[\frac{\langle \sigma v \rangle}{8\pi m_\chi^2}\right] \times \rho_\chi^2$$

VERITAS Dark Matter Searches

- Source Characteristics
  - High mass/light ratio > ~100
  - Low astrophysical background (low baryonic mass)
  - Very near
- VERITAS DM Program
  - Huge collection area over Fermi: ~10,000m^2
  - Comprehensive program, 7% of observing time
    - Dwarf Galaxies (e.g. Draco…)
    - Local Galaxies (e.g. M32, M33)
    - Globular Clusters (e.g. M5)
    - Galaxy Clusters (e.g. Coma)

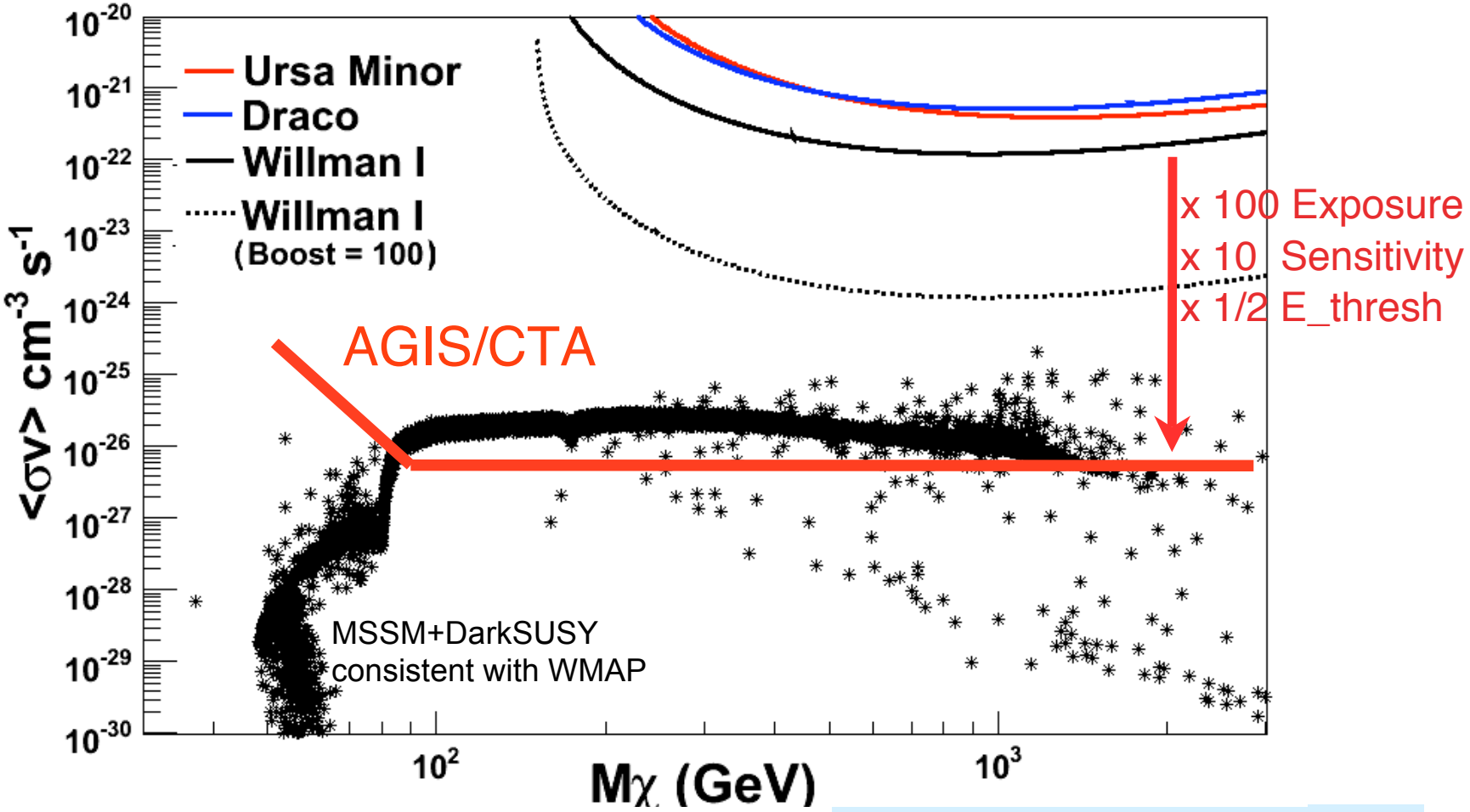
- **So far, no Detections**
  → Limits on 7 candidate sources



Dwarf-Sph <100 kpc	95% CL UL Flux at 1 TeV (Crab)
Draco	0.3%
Ursa Minor	0.5%
Willman I	1%
Bootes I (200kpc)	0.5%

VERITAS Dark Matter Limits

Assuming NFW profile



2009 ICRC Talk: R. Wagner, HE 2.3 (#0625)

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VERITAS Upgrade Plans

- VERITAS operates very well with excellent sensitivity.
- With the excitement in the field and the unique capabilities of Fermi, we want to improve VERITAS.

Plans to improve the sensitivity and to extend the energy range are ongoing:

1. Improved optical point spread function - accomplished
2. Relocating telescope T1 ← accomplished
3. Upgrading cameras with high efficiency PMTs ← proposed
4. New trigger system ← proposed

Summary

- VERITAS is the most sensitive γ-ray detector between 0.1 - 30 TeV.
- Major scientific highlights

- Detection of 5 new blazars:
  1ES 0806+524, W Com (IBL), 3C 66A (IBL), RGB 0170+541, PKS 1424+240.
- Detection of starburst galaxy: M82.
- Truly simultaneous MWL campaign pin-points VHE engine (M87).
- Detection of 2 new PWN/SNR: G106.3+2.7 and G54.1+0.3
- Best measurements to date of IC 443 and Cas-A.

- VERITAS upgrade will significantly improve sensitivity.
- Future discoveries driven by closer collaboration between GeV, TeV γ-ray and ν telescopes.

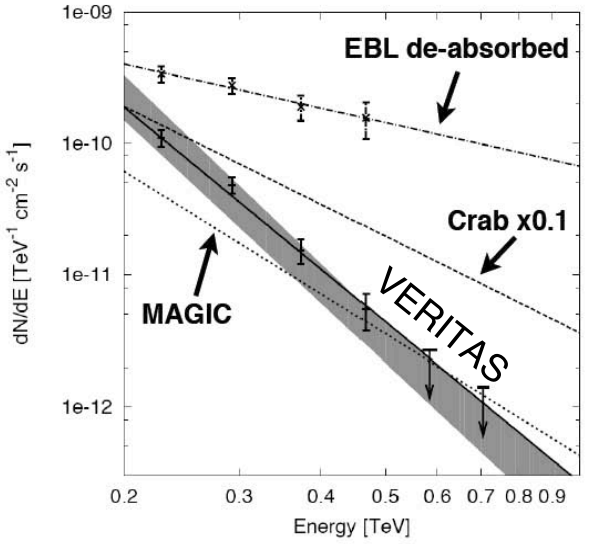
Backup: IBL 3C66A

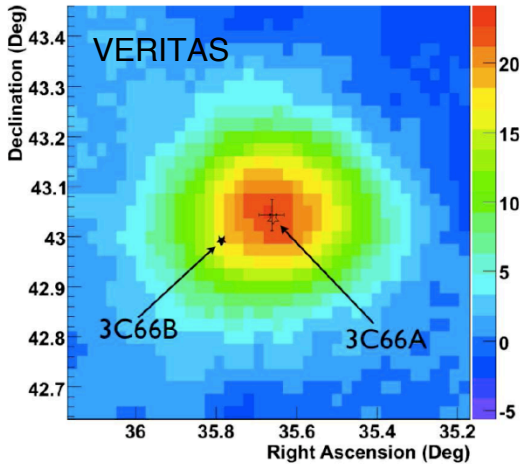
3C 66A: Distant Blazar

- 3C 66A
  - IBL at nominal z=0.44.
  - Seen by EGRET and Fermi-LAT.
  - **VERITAS flare discovery, 2008**
    21σ, 33h, E_{th} ~ 120 GeV.
    (ATEL #1753, ApJ 693, L104).
  - Soft spectrum: $\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{sys}$
    (due to EBL ?) .
  - Joint Fermi-VERITAS study;
    SSC model disfavored (see L. Reyes' talk).

ICRC Talk: J. Perkins OG 2.3 (#0490)

ICRC Talk: L. Reyes OG 2.3 (#0637)





- MAGIC reported 3C66B 0.12° away.
  5.4σ in 54 h from 2007 data.
- Source confusion?
  VERITAS excludes 3C66B at 4.3σ.