~~VERITAS Observations of Starburst Galaxies~~

The Discovery of VHE Gamma Rays from a Starburst Galaxy

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[1] *see R.A. Ong et al. (these proceedings) or http://veritas.sao.arizona.edu/conferences/authors?icrc2009*

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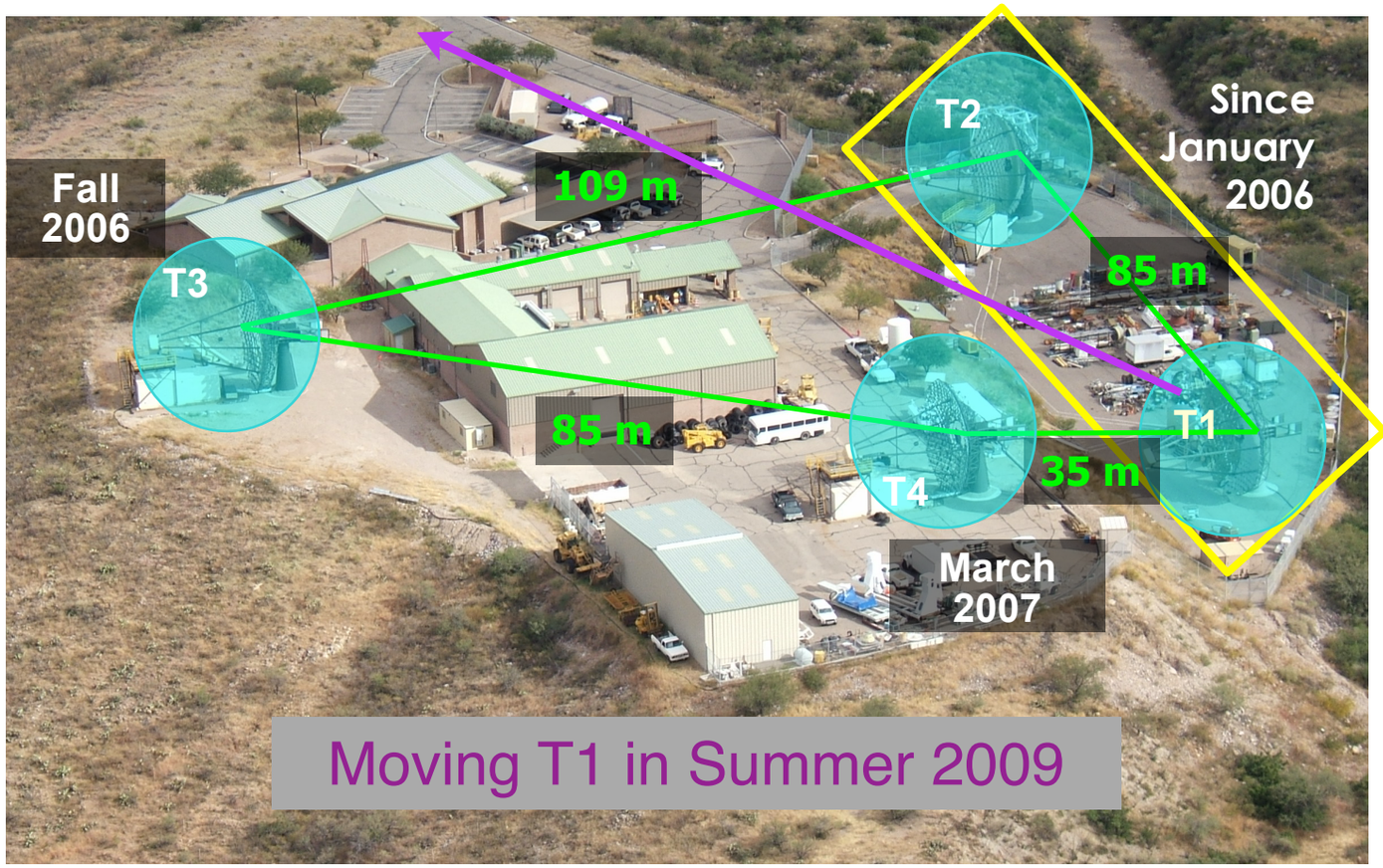
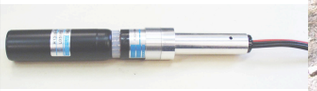
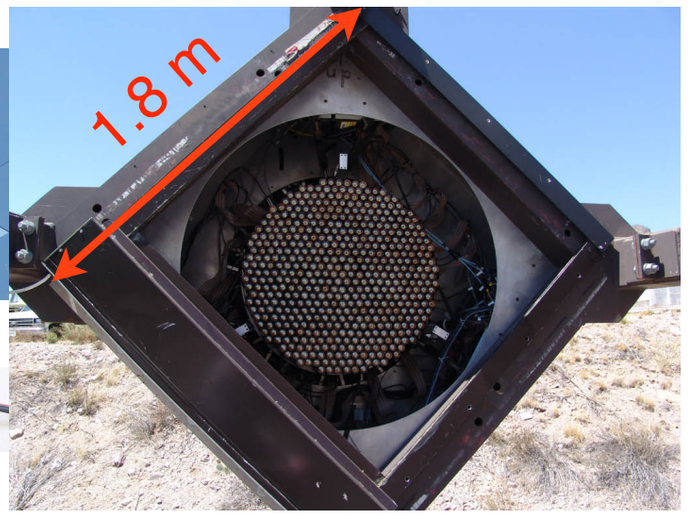
VERITAS: A Cherenkov Telescope Array

- **Arizona:** ~32° N, ~111° W, 1268 m a.s.l.
- **Four identical telescopes:**
  - f/D ~ 1.0; D = 12 m; f = 12 m
- **Mirror Area:** ~106 m²; 350 mirrors
- **Camera:** 499 pixels (0.15°) & 3.5° FoV
  - Readout: Dual-gain; 500 MHz FADC
- **3-level trigger:** ~10% dead time; ~300 Hz
- **Data:** ~750 h / year + 35% in moonlight
- **Metrics:** Studies from ~100 GeV to ~30 TeV
  - Detect (5σ) 1% Crab source in <50 h @zenith
  - Angular resolution: $r_{68} < 0.1°$
  - Energy resolution: ~15%







M 82: A Starburst Galaxy

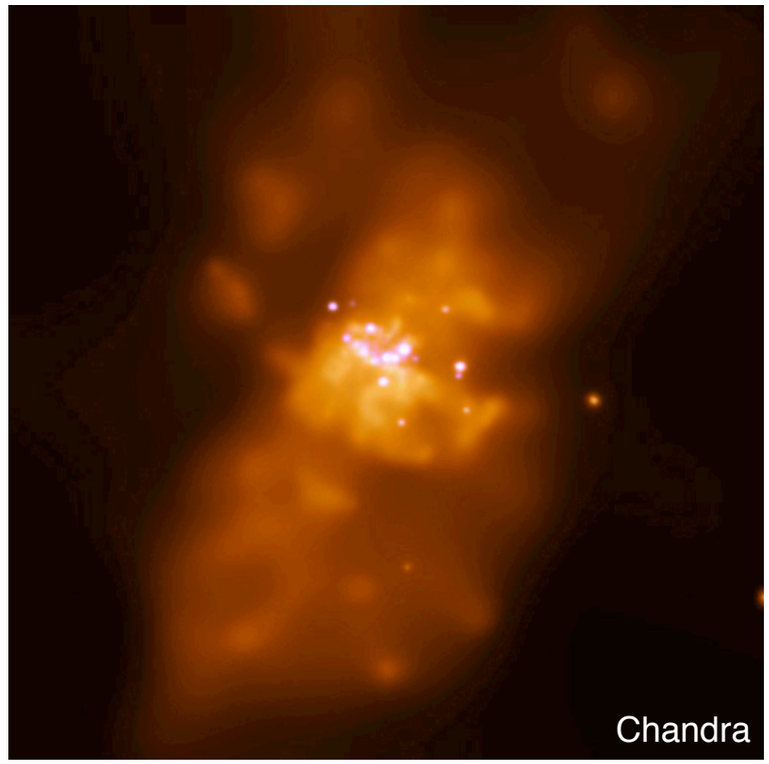
- M 82 is the prototype starburst galaxy
  - δ ~ 70º => Culminates at θ ~ 40º
  - D = ~3.9 Mpc towards Ursa Major: EBL a non-issue
  - Diameter ~1' => Point-like for VHE γ-ray studies
  - Central SMBH: <3 x 10^7 M_{sun}; No evidence of an AGN
- M 82 interacting with group of galaxies
  - Over hundreds of millions of years
  - At least 1 major interaction with larger spiral M 81
- Tidal forces => Active starburst region
  - Diameter ~ 1000 light years
  - HST => Contains >200 massive star clusters
    - 10^4 -10^6 M_{sun}; brighter than most in Local Group

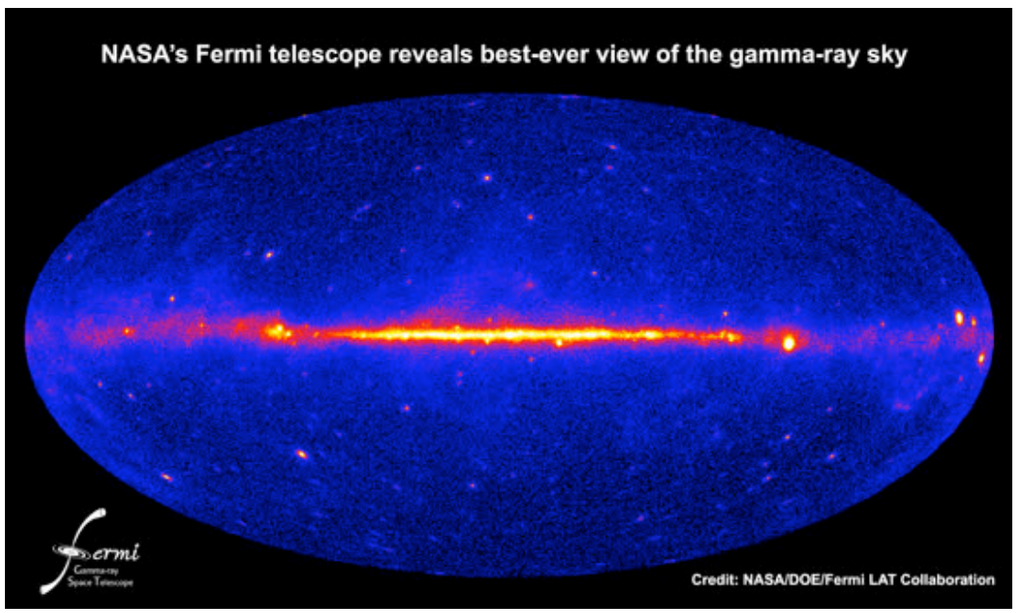

Johannes Schedler (Panther Observatory)


NASA, ESA, The Hubble Heritage Team, (STScI / AURA)

The Starburst Region of M 82

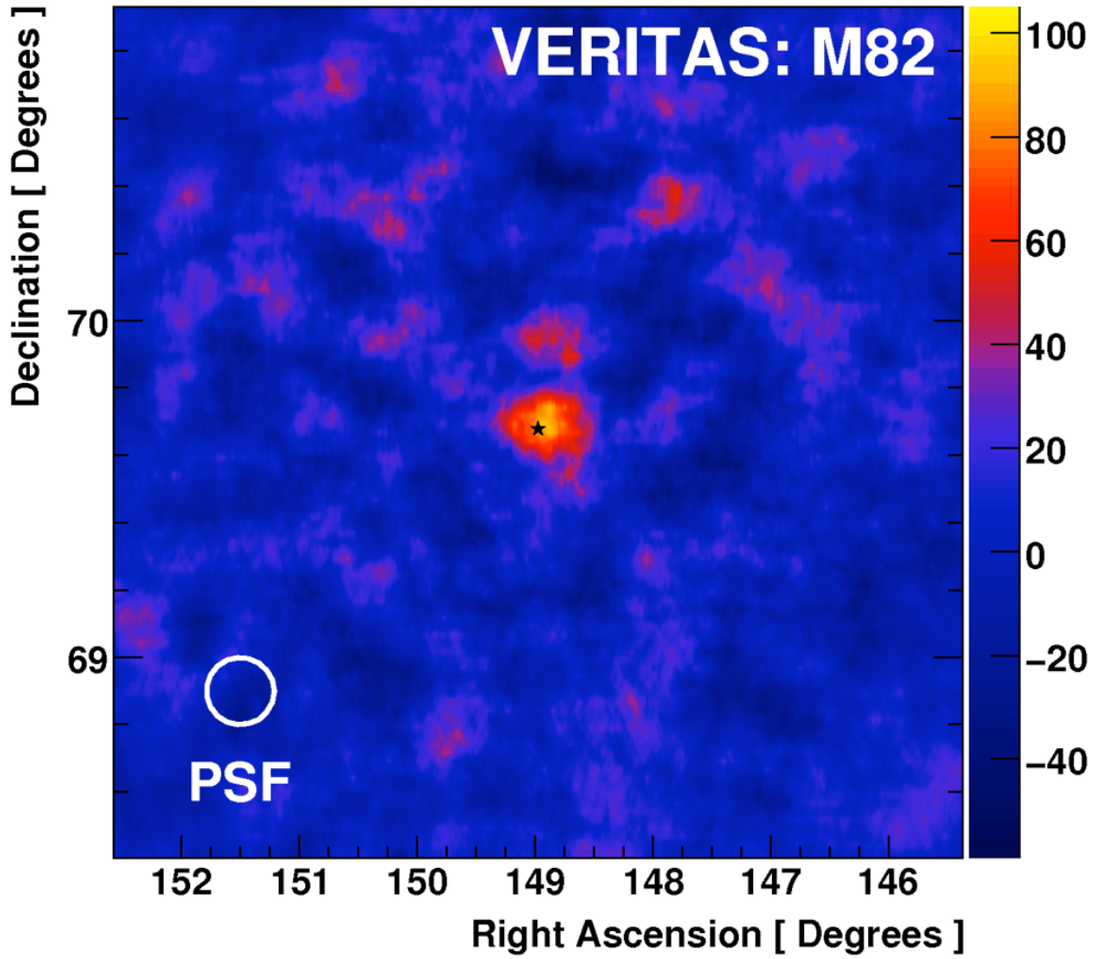
- High star formation rate: ~10x Milky Way
- High supernova rate: ~0.1 to ~0.3 / year
- Cosmic-ray (CR) origin? 100-year old question
  - Preferred theory: SNR & wind-zones of massive stars
- High CR density: ~100x Milky Way
  - Inferred from intense radio-synchrotron emission
- High gas density: ~150 particles / cm^3
- CR hadrons + gas => pions => γ-rays
- CR electrons + ambient photons => γ-rays
- >60% of EGRET γ-rays from CR
- HEGRA & Whipple: VHE flux <10% Crab

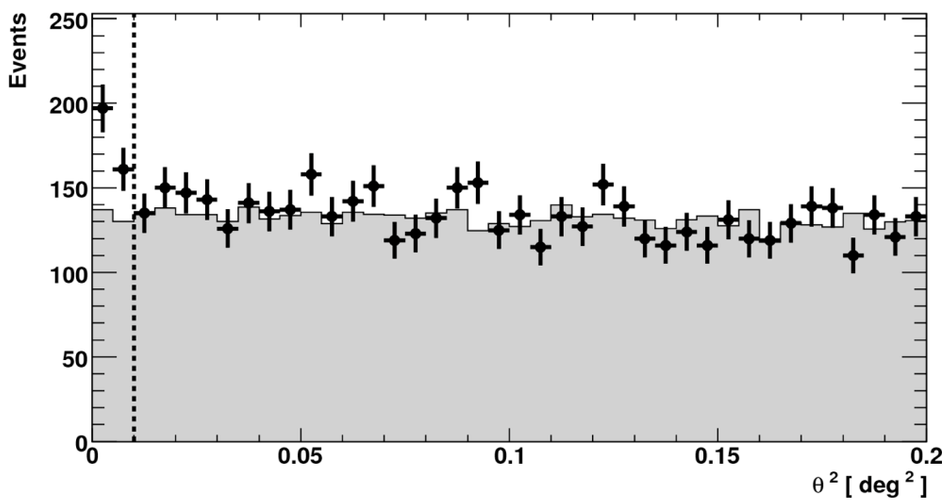




VERITAS Discovery of VHE Gamma-rays

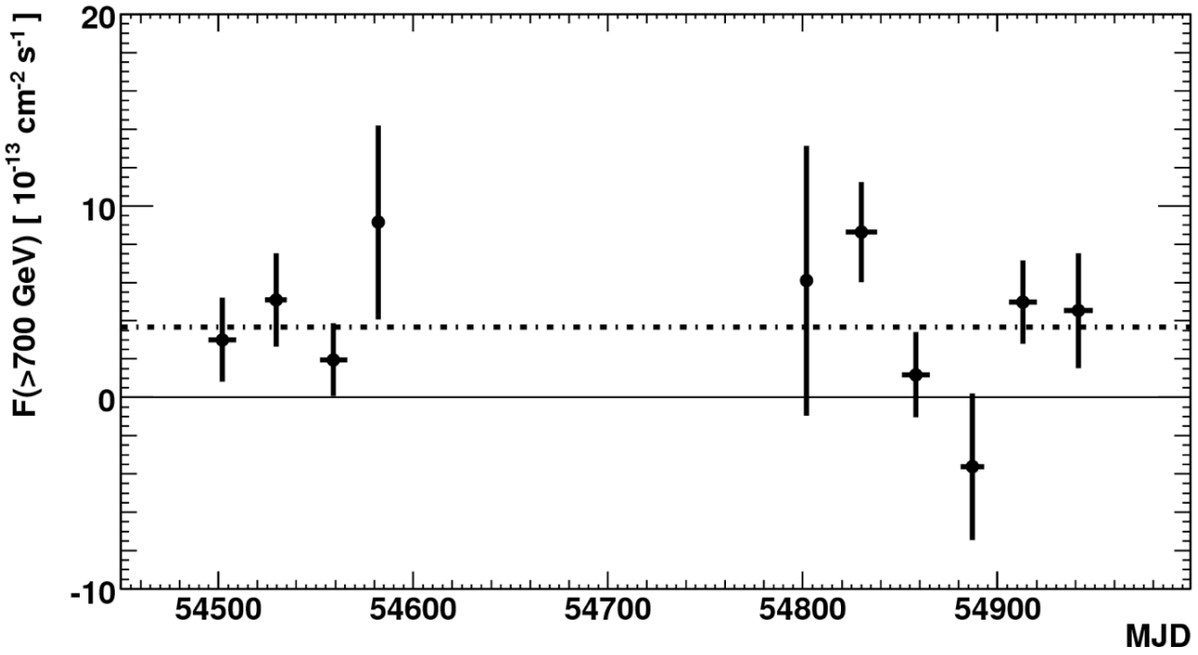
- VERITAS (2007-09): ~137 h live time
  - Only in astronomical darkness; Mean θ ~ 39º
  - Bad weather data removed (via FIR data)
- Standard VERITAS analysis + "hard cuts"
  - E_{th} ~ 700 GeV; NB: Sensitivity less at θ ~ 39º
  - Cuts *a priori* optimized using Crab at θ ~ 40º
    - For detection of weak, hard-spectrum sources
      - Theoretical expectation for M 82
  - Standard practice, but 3 trials: "std" & "soft" cuts
- Point-like excess of 91 γ; 5.0σ pre-trials
- Post-trials significance of 4.8σ
  - Chance probability of 7.7 x 10^{-7}

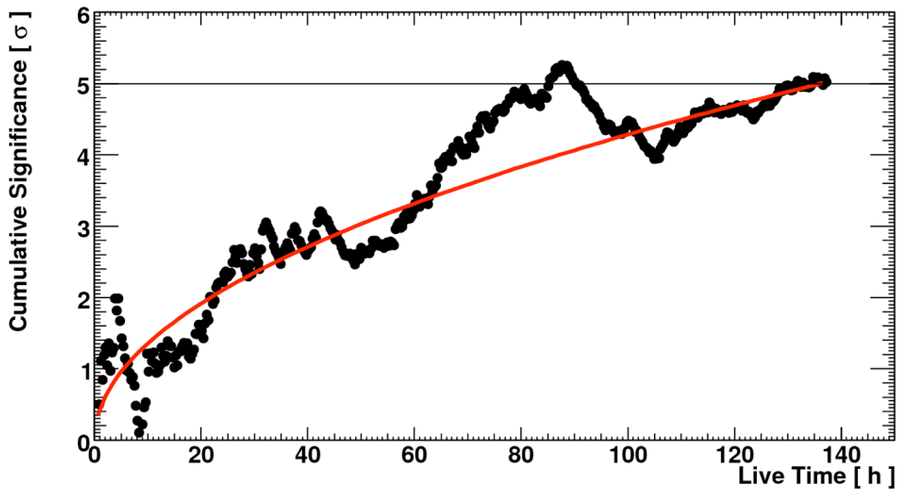


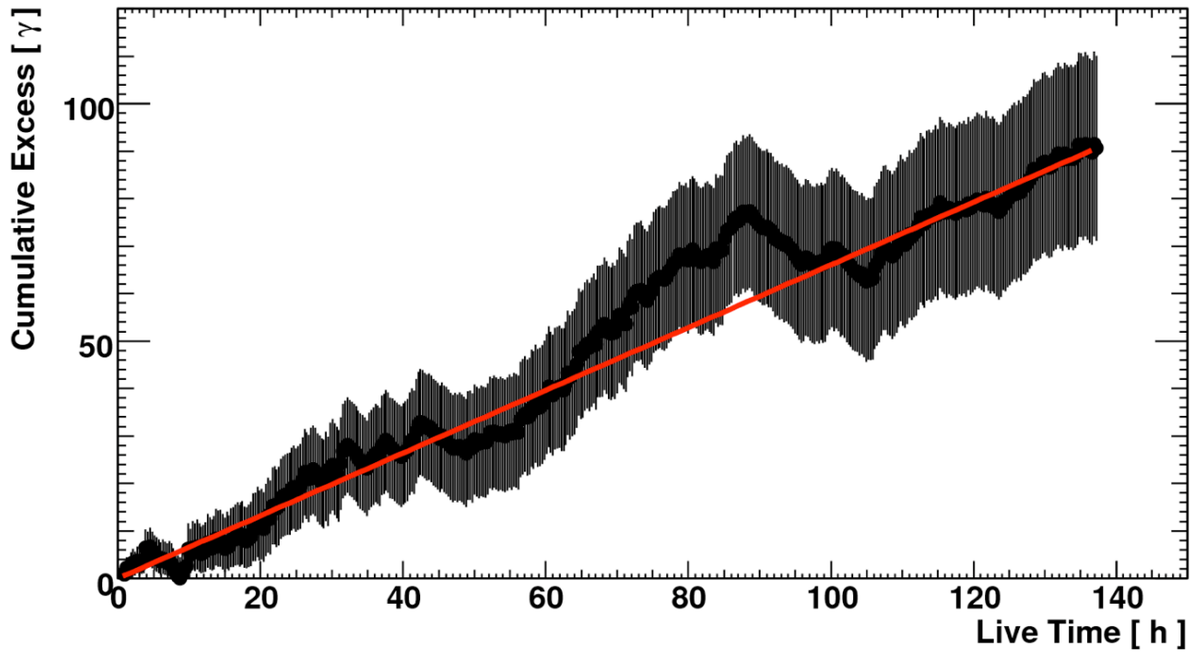


M 82: A Steady VHE Flux

- Among weakest-ever VHE sources
- $F(>700\ \text{GeV}) = (3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}$
  - 0.9% of Crab Nebula (>700 GeV)
  - Gamma-ray rate: 0.7 / hour
- No variations in monthly flux
  - $\chi^2 = 11.5$, 9 d.o.f.; $P(\chi^2) = 0.24$
  - Factor of “a few” variations not ruled out
- Steady signal accumulation

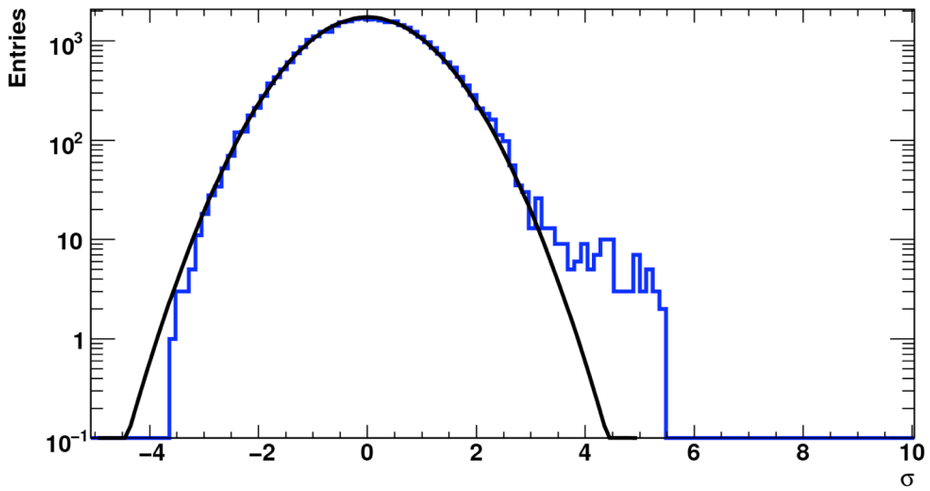






Systematic Checks

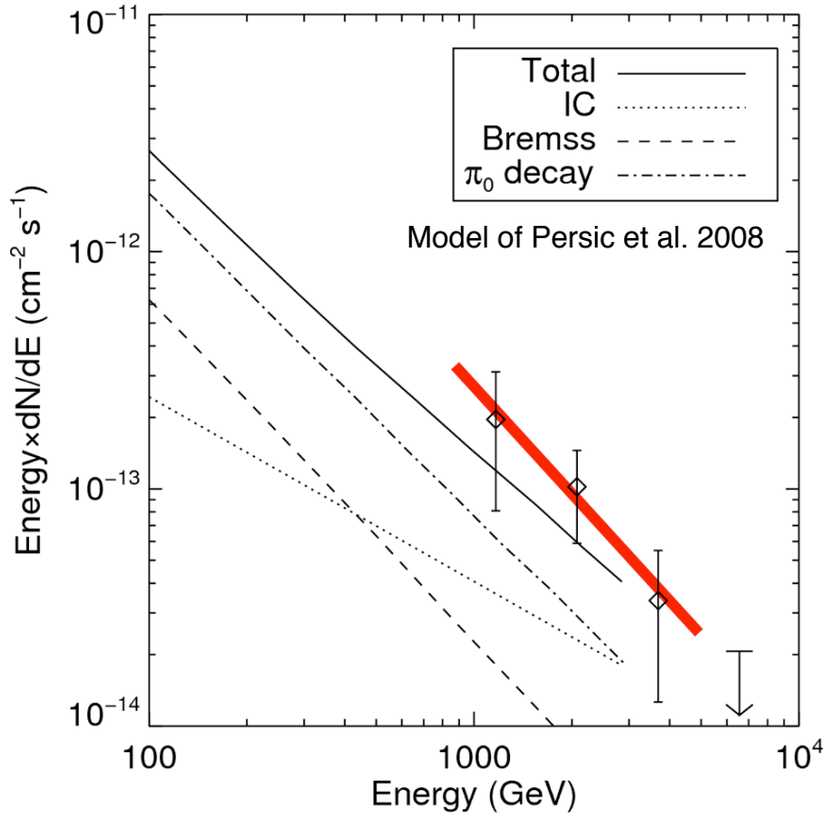
- All hardware operating normally, no moonlight data & dark NSB region
- "Hard cuts": Enormous images (>200 PE); bright star effects mitigated; very low background (S/N ~ 1/3)
- Result verified (5.2σ) by independent analysis/calibration/simulation package(s)
- Alternate background estimation: Ring method => 5.1σ on-source
  - Also ~5σ using a binned maximum-likelihood method
  - Reflected-region BG method always has 11 off-source regions
  - Significance distribution is Gaussian (mean 0, σ = 1)

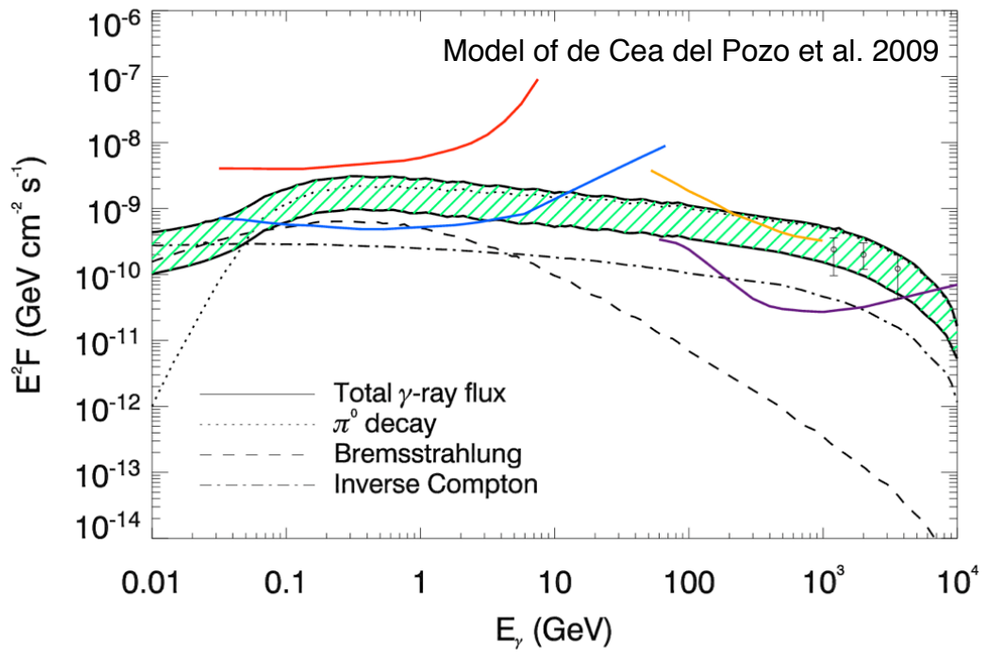


- No bias in long data set: Stack extragalactic non-blazar data
  - With the same analysis: Combined excess of -4 events (-0.2σ) in ~121 h of live-time (no moonlight data)
- Not due to brightness of M 82 (V=9.3) when integrated over its extent => V ~ 8.2
  - Two V < 9 stars in FOV: Excesses of 1.1σ & 0.8σ at their locations (>0.7° from M 82)
- Not due to dodgy behavior in a telescope: Signal still present when each tel. is individually excluded

The VHE Gamma-Ray Spectrum

- Fit Range: 875 GeV to ~5 TeV
  - Fit to $dN/dE \sim (E / TeV)^{-\Gamma}$
  - $\chi^2 = 0.1$, 1 NDF; $P(\chi^{2}) = 0.7$
- $\Gamma = 2.5 \pm 0.6$
- VHE flux close to predictions
  - Incl. both leptonic & hadronic channels
    - Pohl 1994
    - Völk et al. 1996
    - Persic et al. 2008
    - de Cea del Pozo et al. 2009





Some Quick Interpretation

- Leptons or hadrons? We can't say, yet....
- Hadronic channel: Protons + Matter => Pions => γ-rays; but also => Pions => Secondary Electrons
  - Use radio emission from secondary electrons to limit γ-ray flux from CR hadrons @ 20 GeV
  - Extrapolate VERITAS spectrum downwards: Γ = 2.5 => Flux ~2x higher; Γ = 2.3 => OK
  - Either the true gamma-ray spectrum from 10 GeV to 1 TeV is "harder" than the VERITAS measurement, or the VHE flux is not predominantly from CR hadrons
- Leptonic channel: CR electrons + ambient photons => X-rays & γ-rays via IC scattering
  - Use non-thermal X-ray flux => limit number of electrons @ 1 GeV, but need 10 TeV electrons for VHE
  - Theory & comparison to CR-induced X-ray flux to VHE flux => IC spectrum: Γ ~ 2 from 100 keV to 100 GeV
    - Electron energy losses (IC & synchrotron) => Steepening + cut-off in IC spectrum above some energy
  - If Fermi sees a cut-off, the particles responsible for VHE γ-rays could be identified
- Dark Matter annihilation? In concentrations near the central SMBH, or from formation of an identified IMBH
  - HESS didn't see DM-related γ-rays from the GC, or from IMBH's in Galactic Plane & M 82 is far more distant!

Conclusions

- Enormous VERITAS exposure on M 82: ~137 h quality-selected live time over 2 years
- VERITAS has detected M 82 (91 γ, 4.8σ post-trials, P ~ 7.7×10^{-7});
  - The observed flux is steady: $F(>700\ \text{GeV}) = (3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}$; ~0.9% Crab
    - Luminosity is ~2×10^{32} W; Approximately 0.03% of the optical luminosity
  - The observed photon spectrum has large errors: $\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{syst}}$
- 1st VHE γ-ray detection of an object that is not clearly related to an AGN
- Measurement of CRs outside the galaxy => Help solve 100-yr old mystery of CR origin
  - VHE detection confirms a long standing prediction of the theory of CR acceleration in SNR
- Detection helps address a number of scientific questions:
  - Role of CRs: in driving large-scale galactic winds; in feedback of star formation on the structure of galaxies
  - Whether smaller shocks (e.g. in SNR) are the predominant CR acceleration sites?
    - or, if CR acceleration occurs on larger scales (>30 ly) in a more distributed fashion?