VERITAS Discovery of VHE Gamma Rays from the Starburst Galaxy M82

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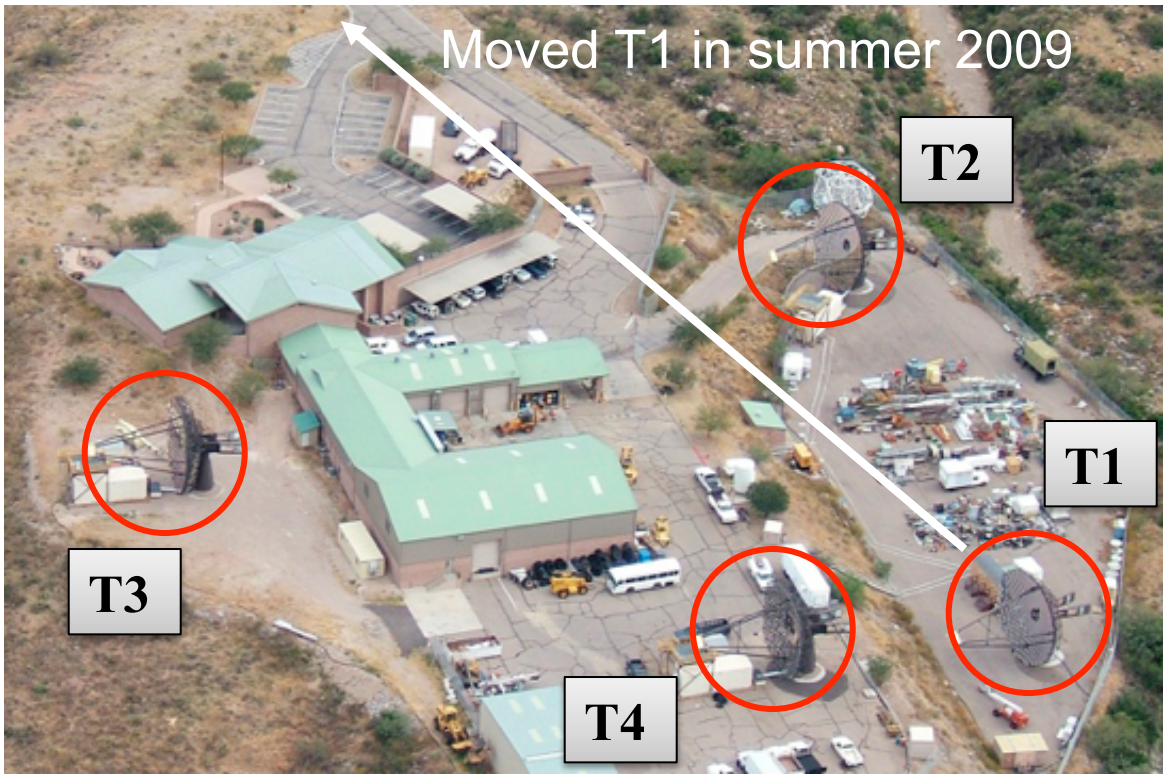
The 2009 Fermi Symposium - Washington, D.C. - 2-5 Nov 2009

VERITAS

Very Energetic Radiation Imaging Telescope Array System



- Mt. Hopkins, AZ
  - 1268 m a.s.l.
- Four 12m telescopes
  - f/D~1.0
- 350 mirrors; ~110m^2
- 499 pixel cameras
  - 3.5° FOV
- 3-level trigger system
  - ~250 Hz rate

- Energy threshold ~150 GeV
- Sensitivity 1% Crab (5σ) in < 50h
- Angular resolution <0.1° ($r_{68\%}$)
- Energy resolution ~15%

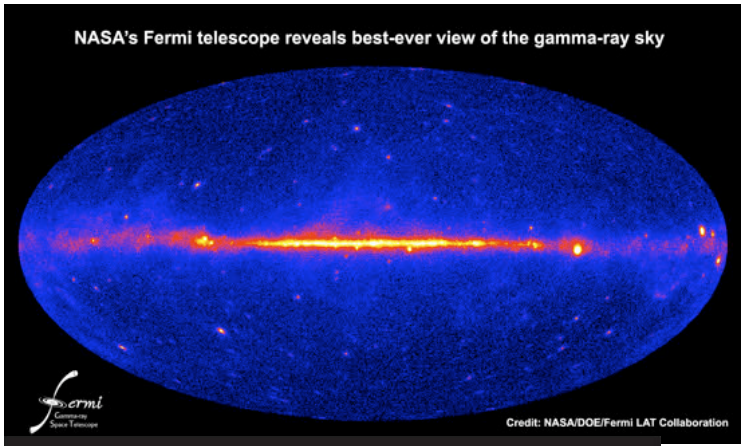
Currently the most sensitive array

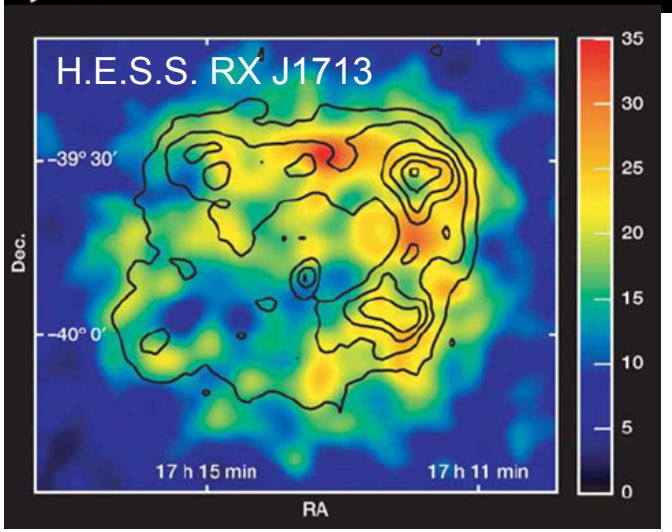
30% improvement in integral flux sensitivity above 300 GeV

See Perkins et al. poster "VERITAS Telescope 1 Relocation"

Origin of Cosmic Rays

- Existence well established near Earth
  - First evidence in 1912 (Hess)
  - But the origin has eluded us for 100+ years!
- Diffuse γ-rays from the Milky Way
  - Interpreted as mainly coming from CRs interacting with interstellar gas
    - CRs + ISM $\rightarrow \pi^0 \rightarrow \gamma$-rays
    - electrons + ambient photons $\rightarrow \gamma$-rays
- Where are these CRs accelerated?
  - Supernova remnants
  - Massive star winds
- Can we look elsewhere for more evidence?
  - LMC - nearby, observed with EGRET and Fermi-LAT
  - Other galaxies



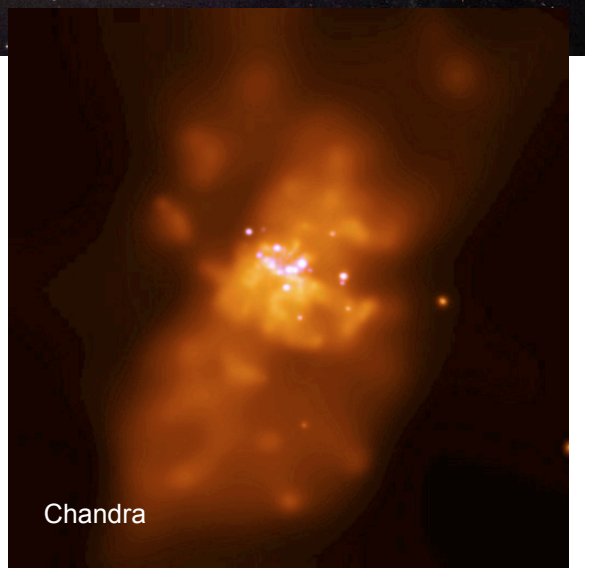


Why Starburst Galaxies?

- Starbursts activity induced by galaxy interactions/mergers
  - Strong tidal forces
  - Active star-forming regions
- Leads to high gas densities & star formation rates
  - High supernova rate
  - Shocks from massive star winds and supernovas
- Enhanced cosmic-ray flux ⇒ enhanced gamma-ray flux
- Requirements for good candidates
  - Distance - nearby
  - High CR density
    - Measure via synchrotron emission in radio frequencies
  - High mean gas densities
    - Form far infrared (FIR) emission
- Modeling
  - M82 (Persic et al. 2008)
  - NGC 253 (Domingo-Santamaria et al. 2005)

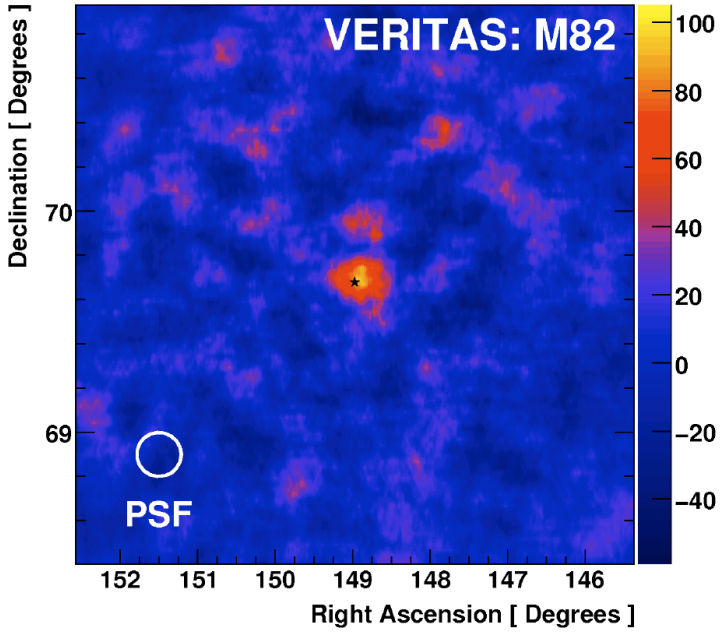
M82 - prototypical starburst

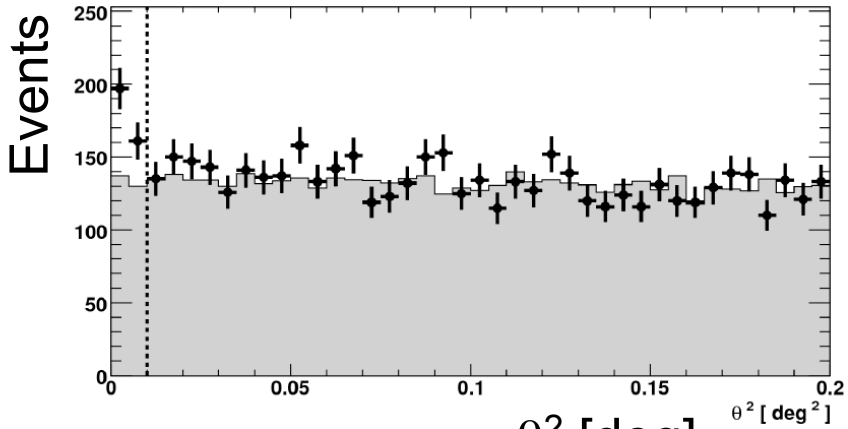
- Among the closest starbursts
- Core starburst region
  - SF rate ~10x Milky Way
  - SN rate ~0.1/yr
  - CR density ~100x Milky Way
    - Inferred from synchrotron emission
  - Gas density ~150 cm^{-3}
- Weak upper limits from previous generation observatories
  - EGRET (HE)
  - HEGRA & Whipple (VHE)
    - flux <10% Crab



VERITAS Discovery

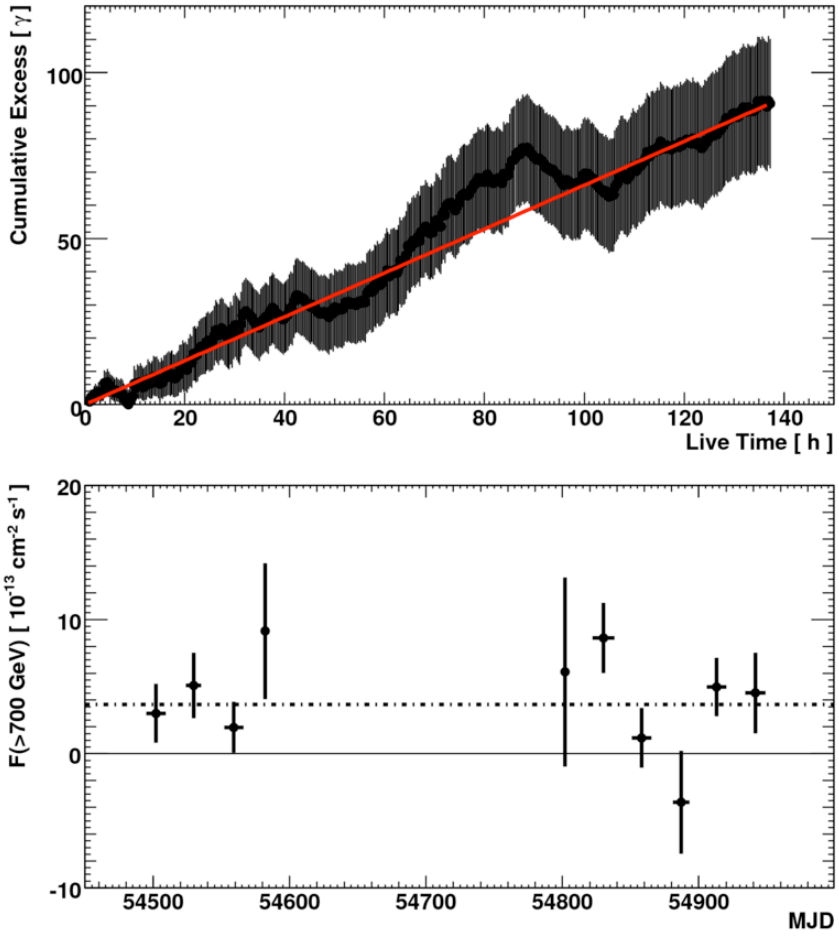
- M82 observed 2007-2009
  - Quality selection (weather etc.)
  - ~137 h live time (deepest VERITAS exposure to date)
- Standard VERITAS analysis
  - Std. practice to use 3 sets of cuts
    - Theoretical prediction of a hard spectrum
    - Expect a hard cut to be the best
  - Cuts a priori optimized using Crab data at $\theta \approx 40°$
  - $E_{th} \approx 700$ GeV (lower sensitivity at $\theta \approx 40°$)
- Point-like excess of 91 $\gamma \Rightarrow 5.0\sigma$
  - 4.8σ post-trials significance
- The results are now published in Nature online.





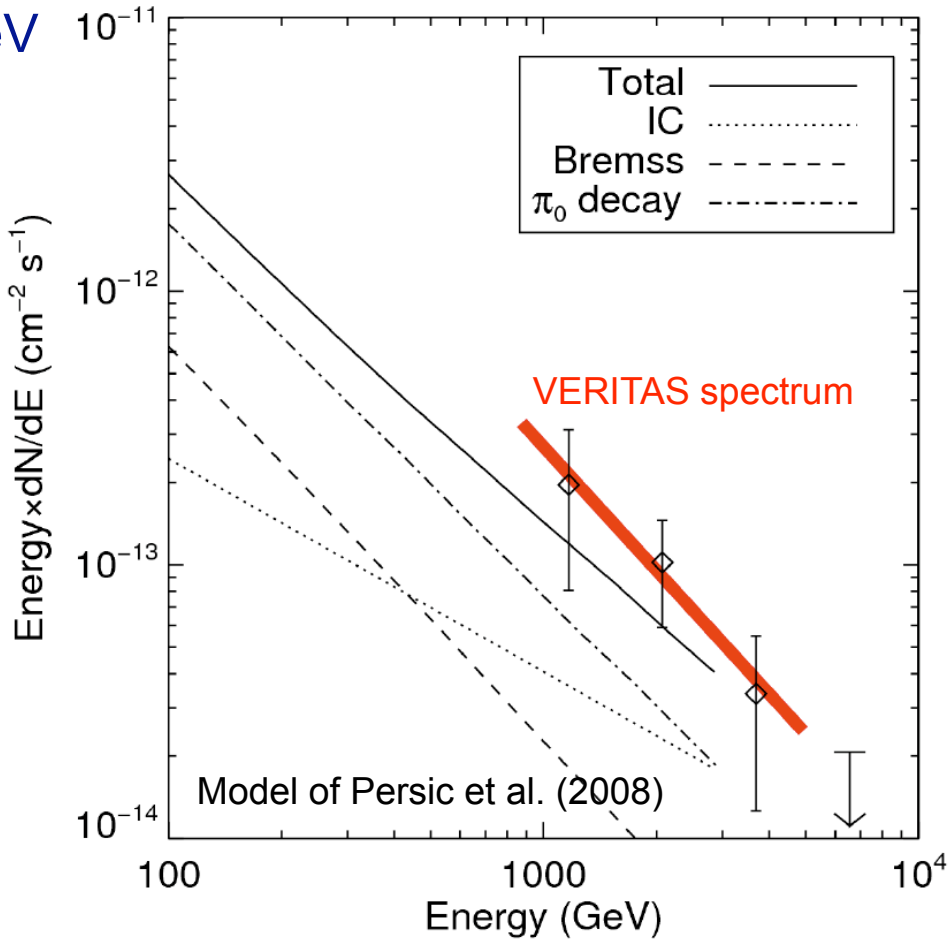
M82: Steady VHE γ-ray Source

- One of the weakest VHE γ-ray sources ever detected
  - 0.9% of the Crab Nebula (E>700 GeV)
  - 0.6 γ/hour
- Cumulative excess consistent with a steady flux
- Lightcurve is consistent with no monthly variation
  - χ^2=11.5 with 9 d.o.f.
  - P(χ^2)=0.24



VHE γ-ray Spectrum of M82

- Energy range 875 GeV to 5 TeV
- Power-law fit
  - $dN/dE \propto (E/TeV)^{-\Gamma}$
  - $\Gamma = 2.6 \pm 0.6$
- Close to model predictions
  - Pohl (1994)
  - Völk et al. (1996)
  - Persic et al. (2008)
  - de Cea del Pozo et al.(2009)



Interpretation

Hadronic channel

- CR ions + matter → π
- π → γ and sec. electrons
- Secondary electron emit synchrotron radiation
  - Radio frequency 32 GHz
  - Constrain γ-ray flux from CRs at 20 GeV
- Extrapolated VERITAS spectrum gives ~2x too high flux
  - Γ = 2.3 ok though
- Spectrum is harder at Fermi-LAT energies OR VHE flux not predominantly from CR ions

Leptonic channel

- Inverse Compton scattering
  - CR electrons + photons → X-rays and γ rays
- Use non-thermal X-ray emission to constrain the electron population
  - Lower limit on magnetic field (8 nT)
  - Upper limit on absolute number of electrons at about 1 GeV
  - But 10 TeV electrons required for VHE gamma rays
- Theory predicts Γ = 2.0 in the 100 keV to 100 GeV energy band
  - Steepening of IC spectrum and a cut off at some energy due to cooling

Summary

- VERITAS has discovered VHE γ-ray emission from M82
  - 91 γ's in 137 h of quality-selected live time
  - Post-trial significance is 4.8σ
  - Steady flux F(E>700 GeV)=$(3.7\pm0.8_{stat}\pm0.7_{syst}) \times 10^{-13}$ cm^{-2}s^{-1}
  - Luminosity is ~2 $\times 10^{32}$ W; approx. 0.03% of the optical luminosity
- Weakest VERITAS source to date
- First clear detection of VHE gamma rays from an extragalactic object of non-AGN type
- Hard spectrum source
  - $\Gamma = 2.6\pm0.6$

Systematics 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 (>0.7º from M 82)
- Not due to dodgy behavior in a telescope: Signal still present when each telescope is individually excluded

Backup slides

VERITAS After the move

Improved Sensitivity