Recent Results from the VERITAS Gamma-ray Observatory

RICAP 2016

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for the
VERITAS Collaboration

photo: P. Fortin

VERITAS Collaboration

~ 100 scientists

- 20 institutions

- 4 countries

US (DOE, NSF, SAO)

Adler Planetarium
Argonne Nat Lab
Barnard/Columbia
Bartol/Delaware
Georgia Tech
Iowa State U
Purdue U
SAO
UCLA
UCSC
U of Chicago
U of Iowa
U of Minnesota
U of Utah
Washington U

Canada (NSERC)

McGill U

Ireland

U College Dublin
National U Ireland Galway
Cork Inst Tech

Germany

DESY-Zeuthen

also ~ 40 associate members
theorists, MWL partners
(IceCube, Fermi, Swift etc)

VERITAS Detector

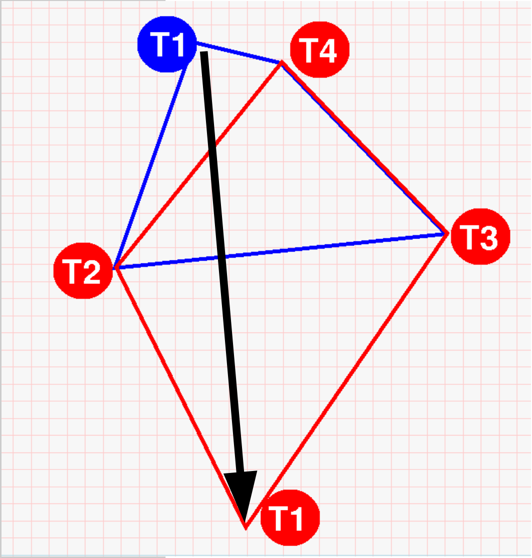
- four 12-m reflectors
- each with 499-PMT camera

located in southern Arizona

- 1.3 km asl on Mt Hopkins (Whipple Observatory basecamp)
- 1000 hours/year under dark skies
- 300 h/y under `bright' moonlight
- summer monsoon (July-August)

built between 2005 and 2007 (prototype in 2003)

- fully operational since September 2007
- T1 moved during summer 2009 to improve array layout
- cameras upgraded with HQE PMTs in 2012



VERITAS Performance

energy resolution: 15% - 20%

effective area ~ 100 000 m^2

spectral reconstruction: E > 100 GeV

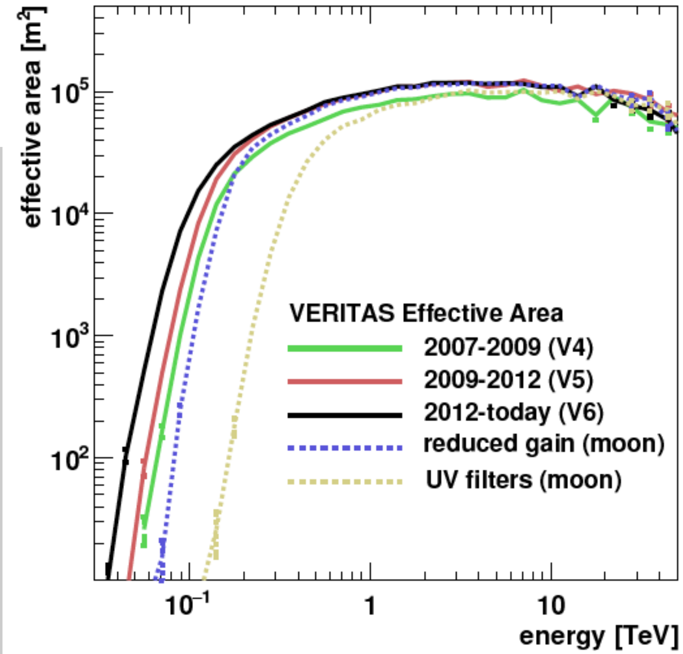
angular resolution (per event): r_{68} = 0.08° (@1 TeV)

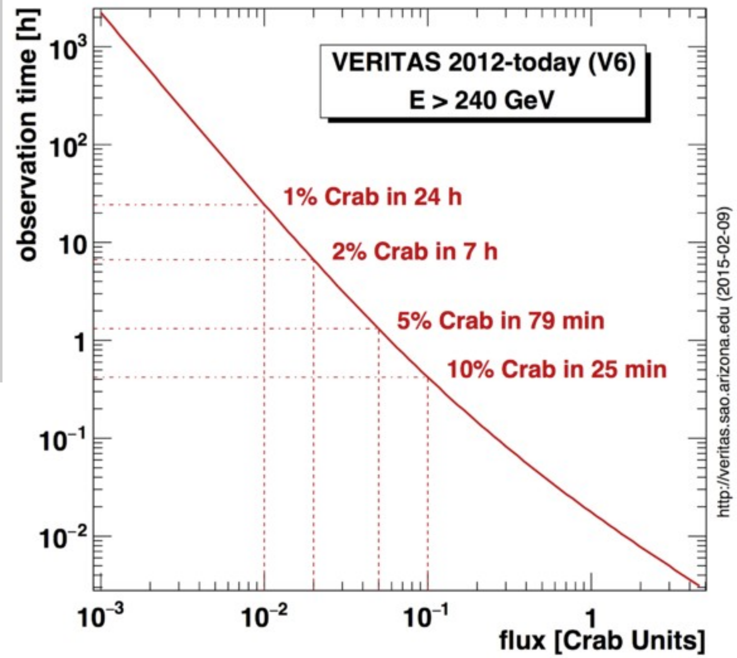
energy range: 85 GeV - 30 TeV

field of view 3.5°

sensitivity 1% Crab Nebula in < 25 h, 10% in 25 min

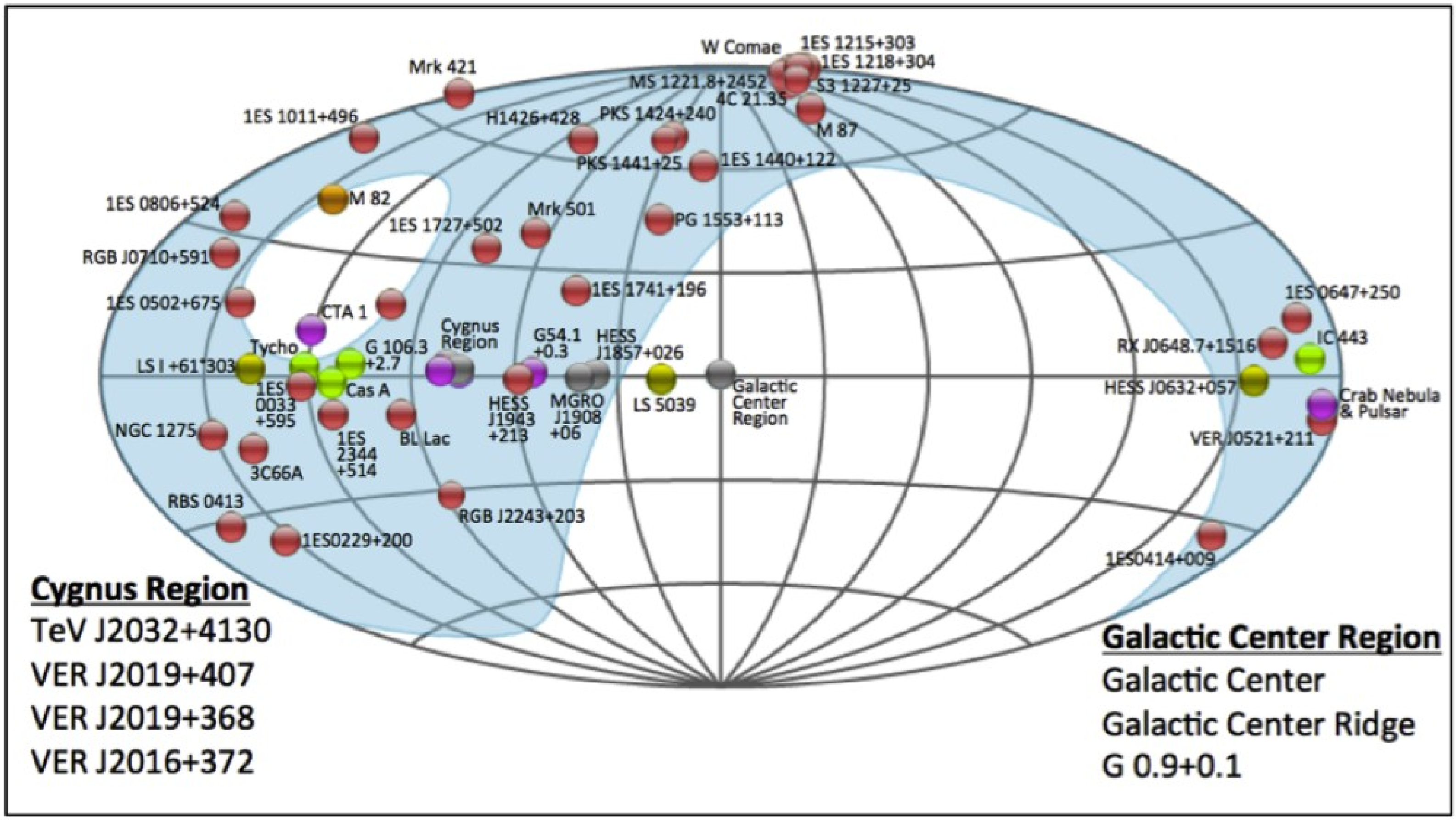
systematic errors: Flux ~20%; Γ ~ 0.1





VERITAS Catalog

54 sources from 8 source classes have been detected



http://tevcat.uchicago.edu

VERITAS Science

A mix of astrophysics and particle-astrophysics

- blazars and other AGN
  - acceleration
  - EBL and IGMF
  - flares (LIV)
- Galactic sources
  - acceleration (cosmic rays)
  - SNRs and PWNe
  - pulsars
  - binary systems
  - Galactic centre
- dwarf spheroidal galaxies
  - search for Dark Matter
- untargetted
  - cosmic-ray electrons
  - primordial black holes
- follow-up
  - GRBs
  - IceCube/LIGO/HAWC

time allocation

70% for 'long term plan'

30% for proposals (time allocation committee) and director's discretionary time

blazars	40%
Galactic	32%
Dark Matter and particle astrophysics	22%
calibration	2%
GRBs etc	2%

Galactic SNRs

charged cosmic rays

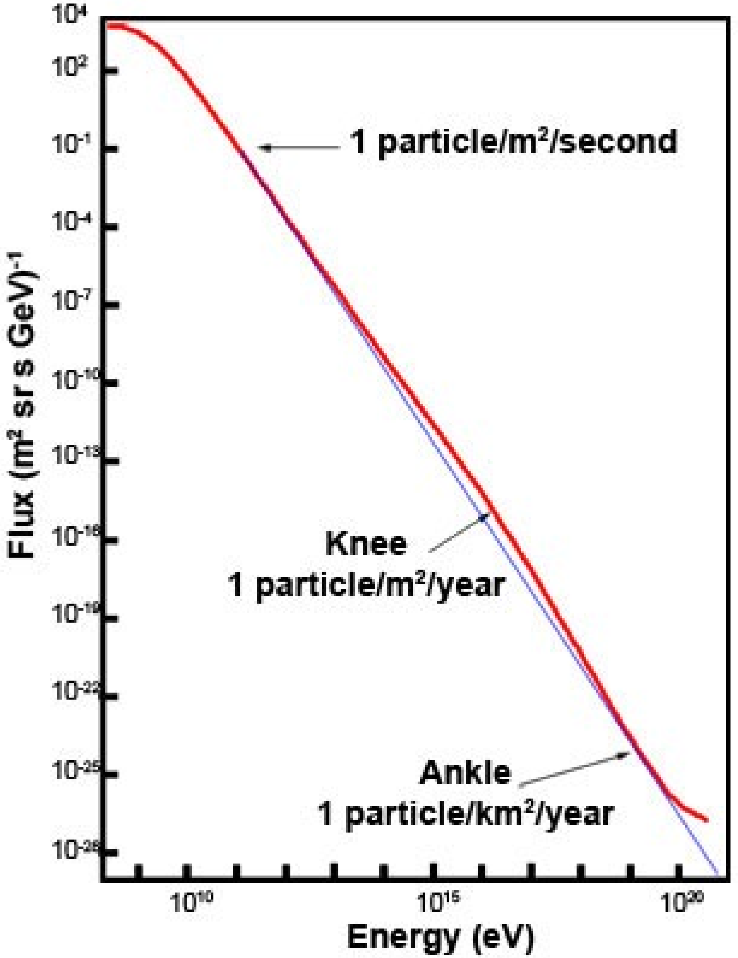
- mostly protons and helium
- energies up to 10^{20} eV
- discovered in 1912 but origin still unknown

original motivation for gamma-ray astronomy was to find the sources of cosmic rays

- neutral - they point back to their origin

SNRs are the preferred candidates for Galactic cosmic rays - below the 'knee'

- energy output and frequency of SN explosions are approximately matched to the energy and lifetime of the CRs

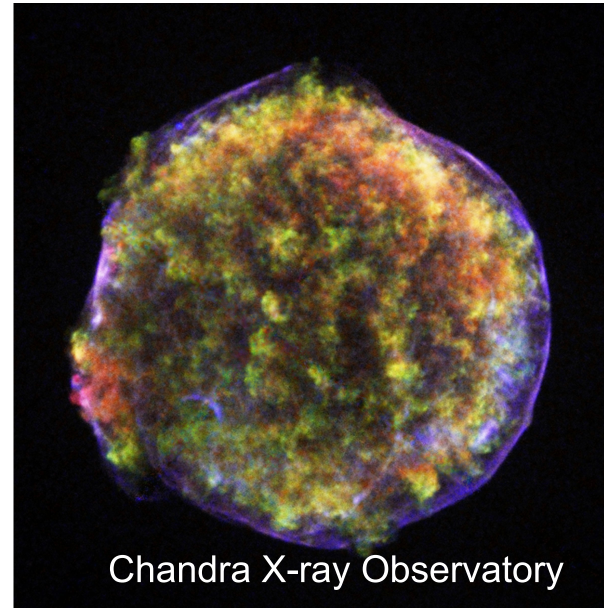


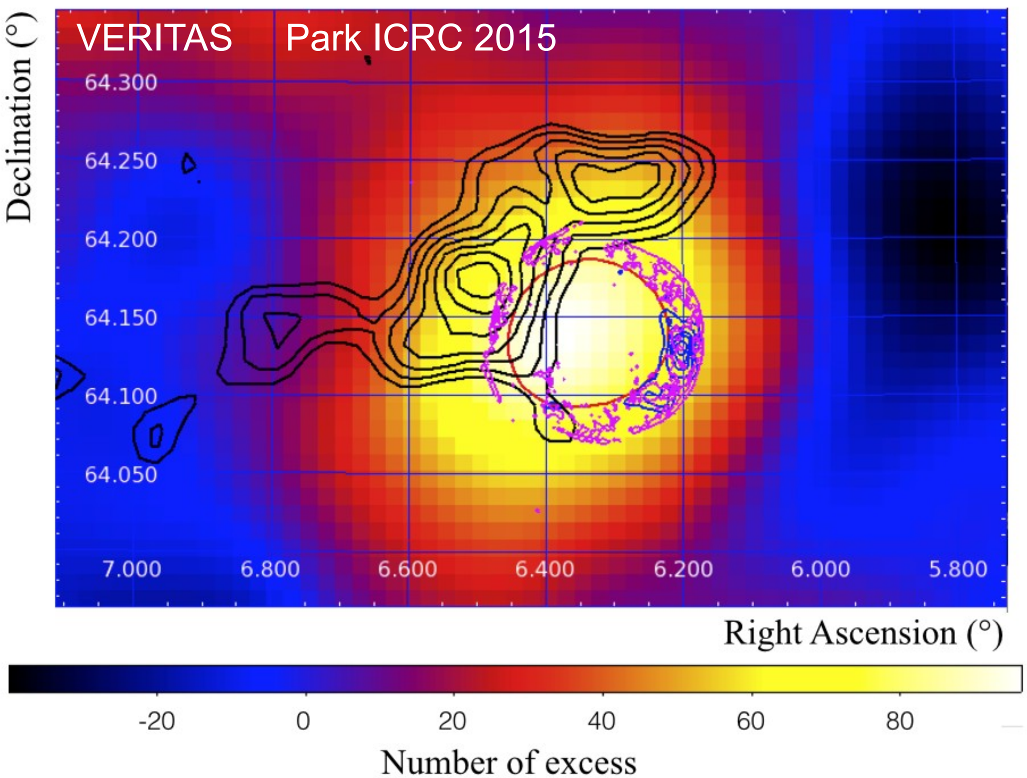
Tycho's SNR (SN1572)

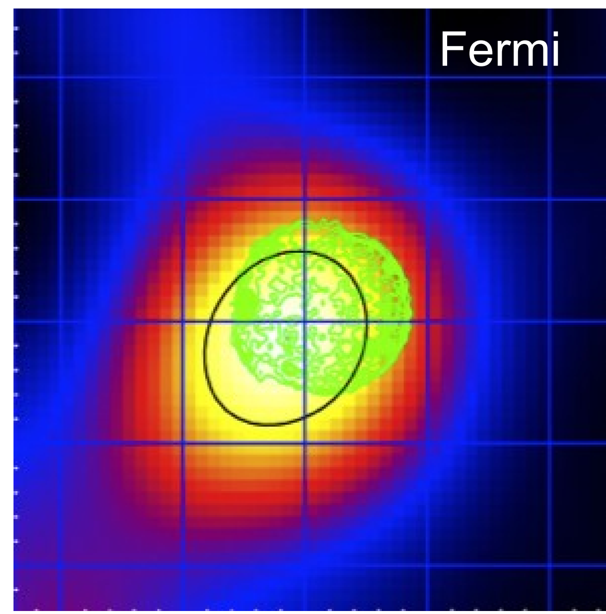
age	444 years
distance	2-5 kpc

explosion into clean environment - relatively symmetric

extensively studied at many wavelengths



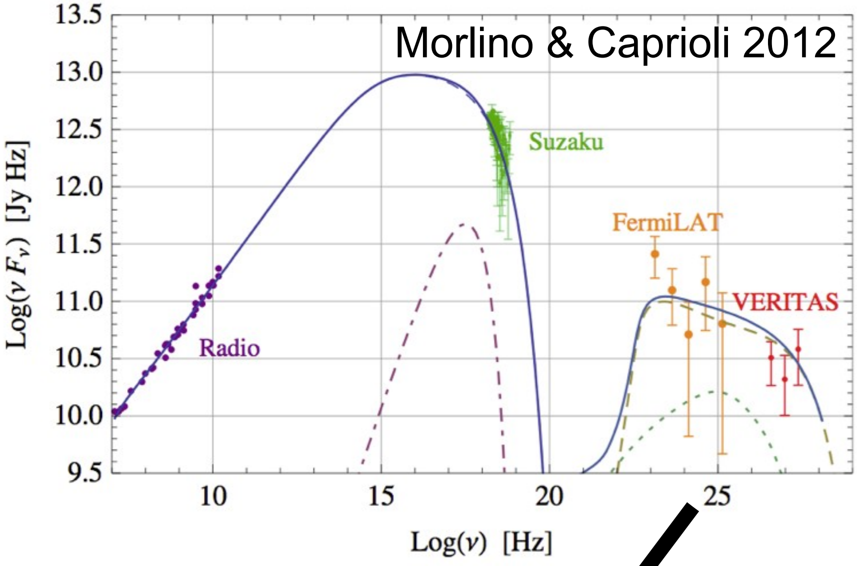


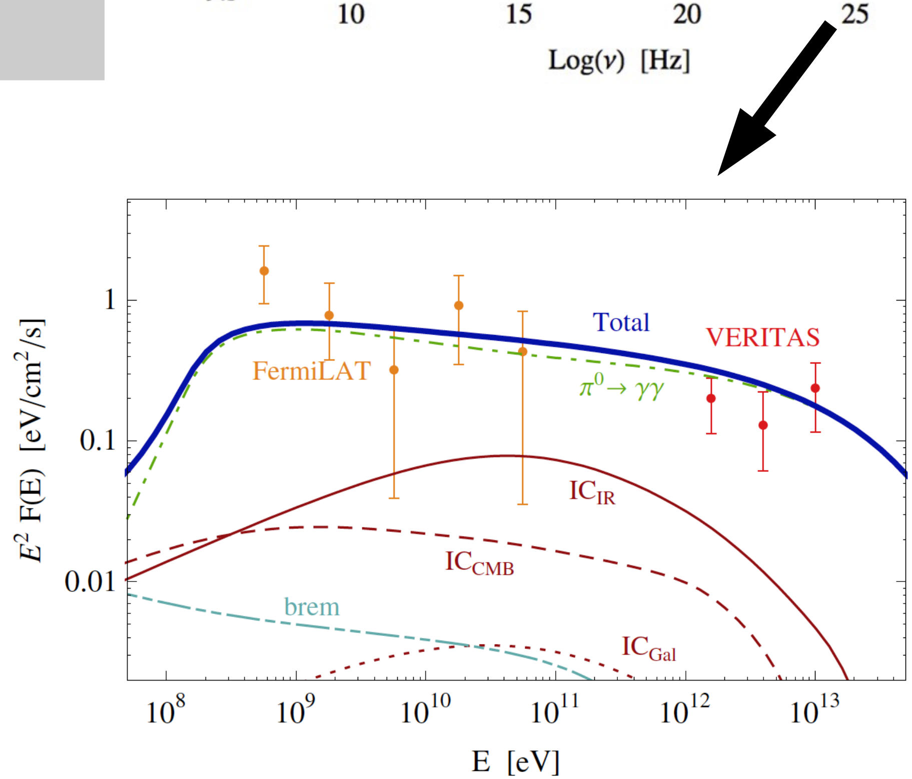


Tycho's SNR (SN1572)

VERITAS detection of 10 TeV photons and no evidence of a cutoff in the spectrum imply that hadrons are accelerated to several hundred TeV

One of many models - most have a pion-dominated gamma-ray production but maximum proton energy can be lower





Tycho's SNR (SN1572)

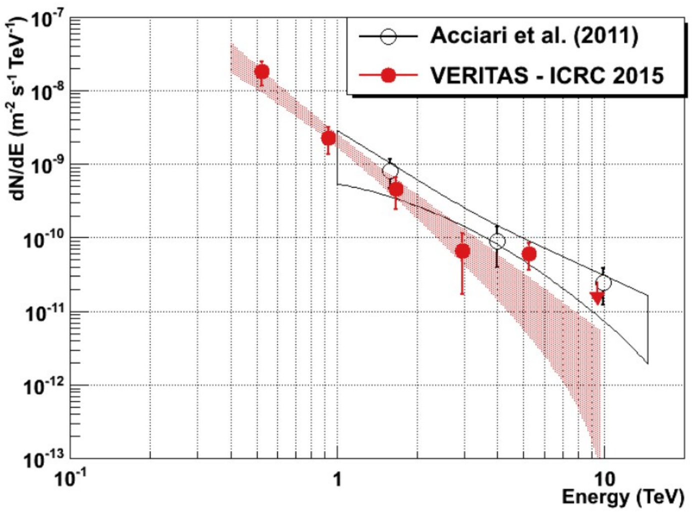
VERITAS has deepened its exposure 74 h --> 150 h

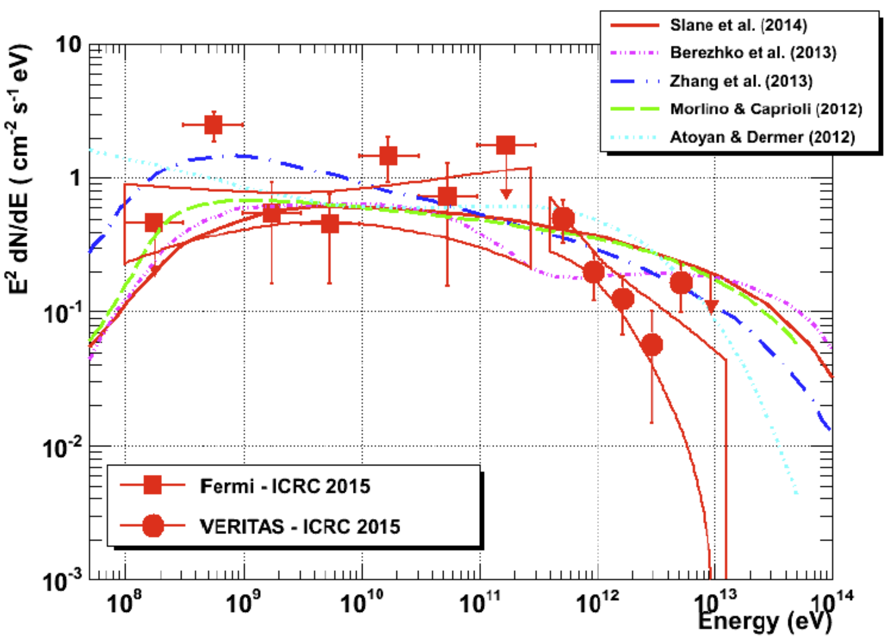
extension of spectrum to lower energies (new PMTs)

softer power law is a better fit to new data

Fermi also has released new and better data

results are consistent with previous measurements





CAS A

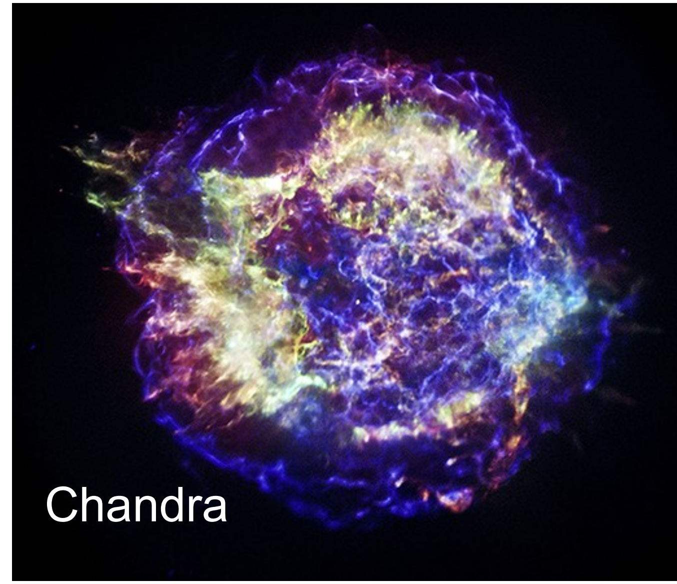
remnant of type IIb core-collapse supernova

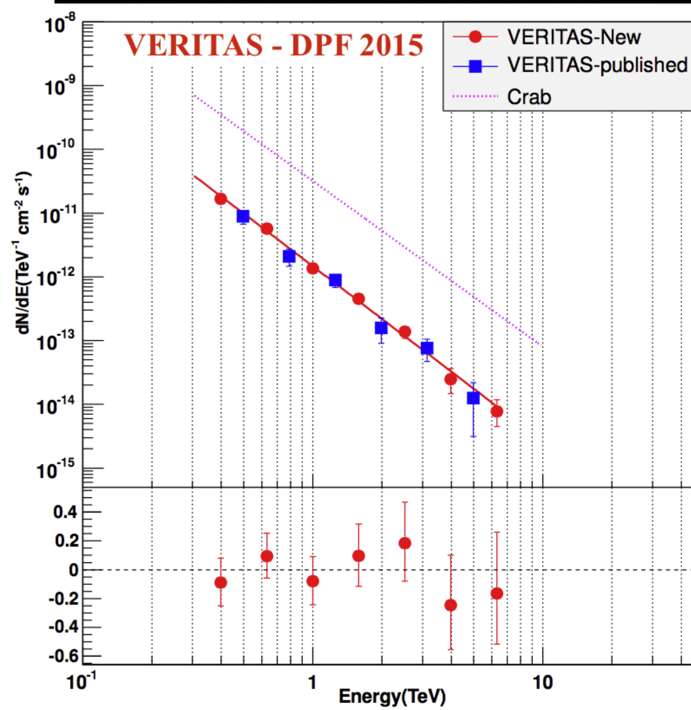
young (350 y), close (3.4 kpc)

bright, well-studied at most wavelengths

new VERITAS data

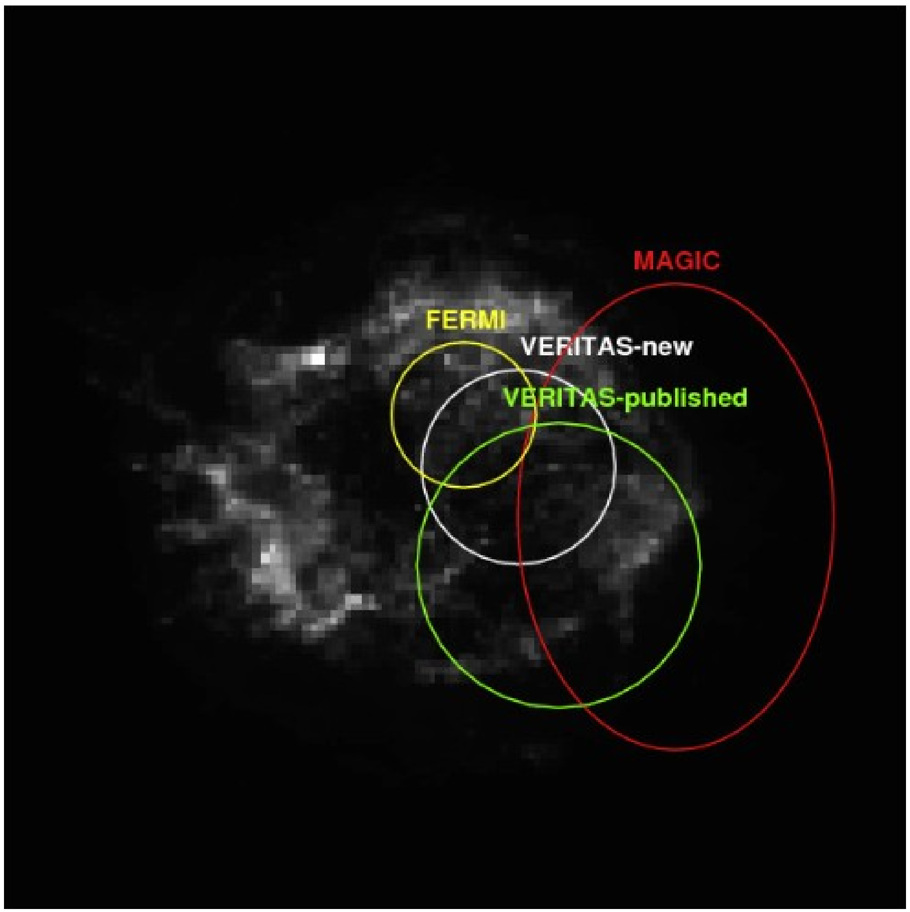
- triples data set (total of 60 h)
- large-zenith-angle observations (boosts effective area at high energies)
- range is increased (at both ends)
- statistical errors reduced by 60%
- energy spectrum consistent with previous

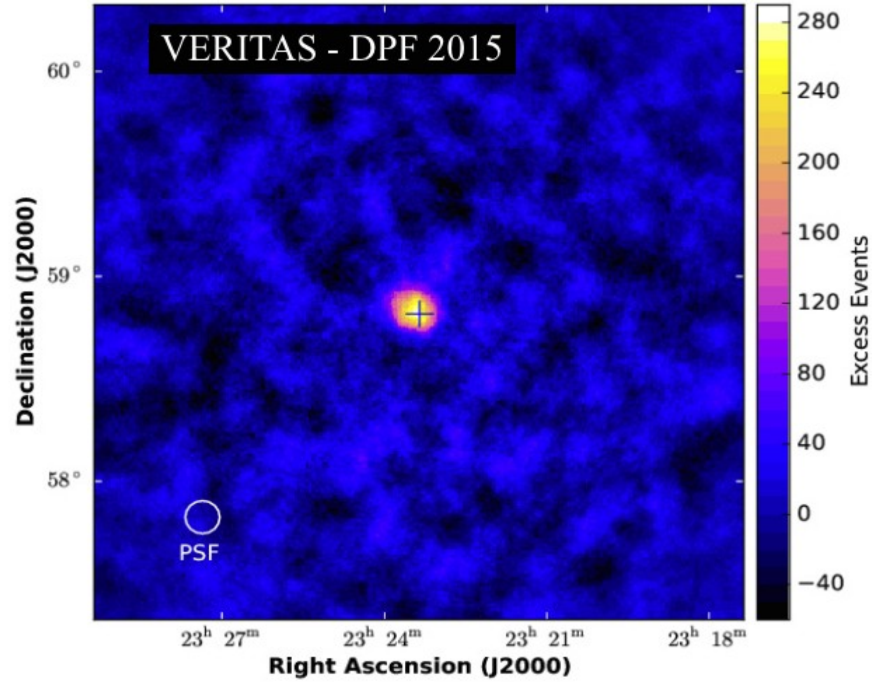




CAS A

updated position now limited by telescope pointing systematics (50")

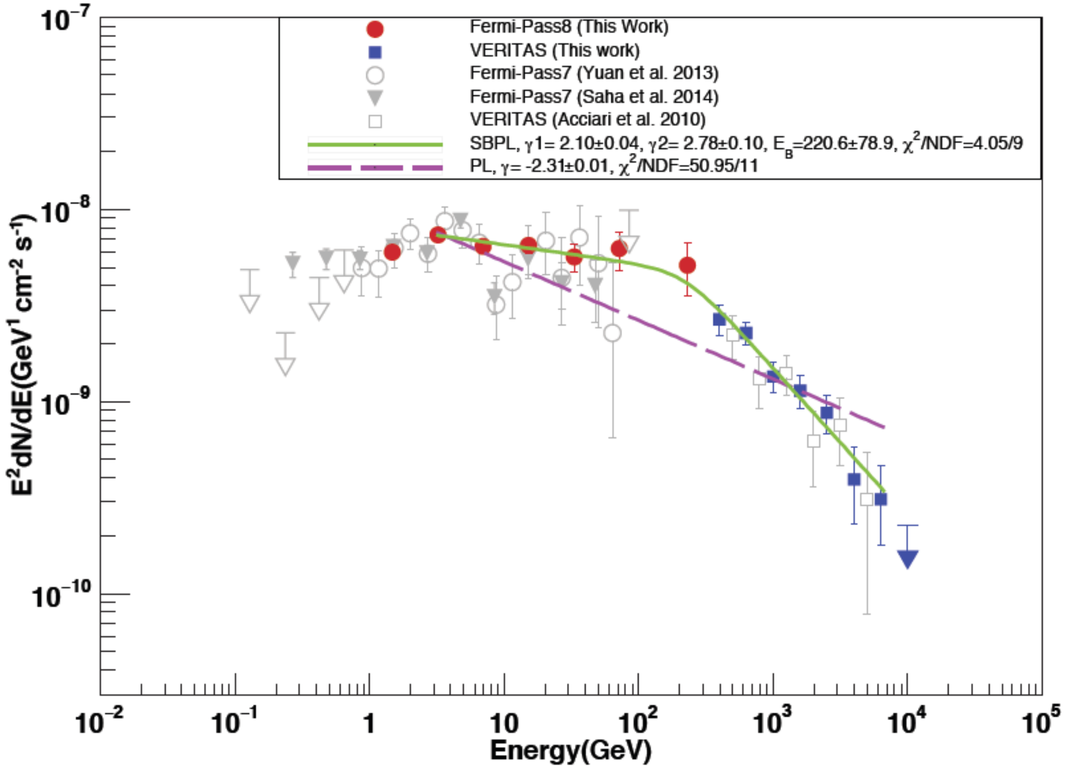




CAS A

spectrum follows a broken power law

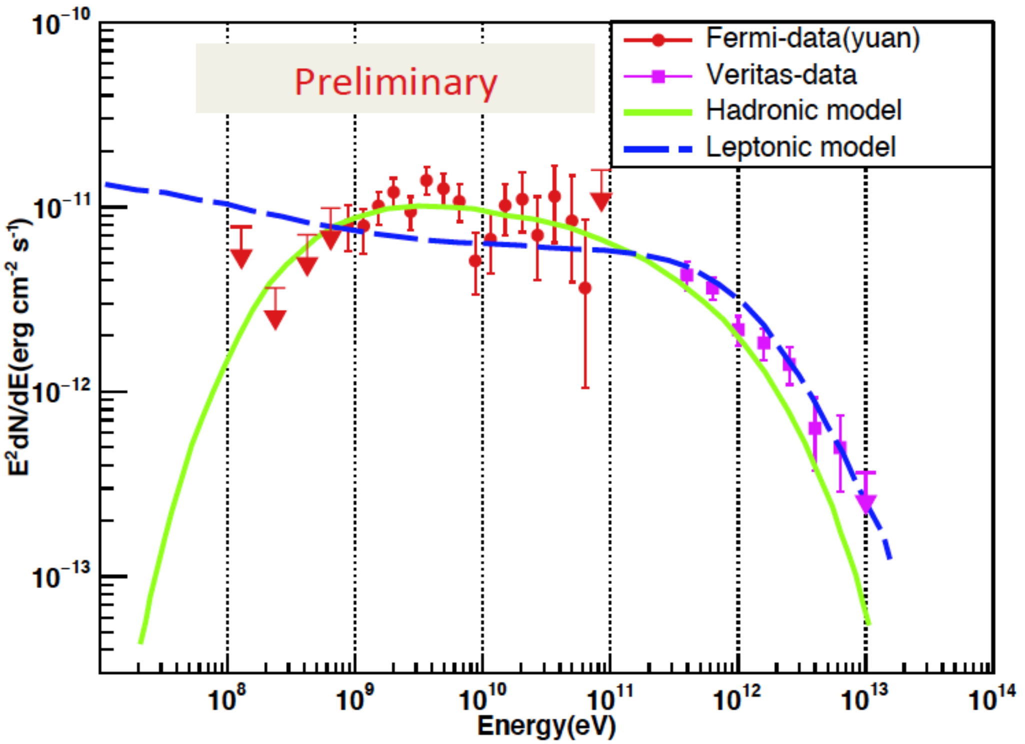
VHE part is steep (Γ = 2.78 +/- 0.10)



CAS A

spectrum is better fit by a hadronic model

especially at Fermi energies



IC 443 (Jellyfish Nebula)

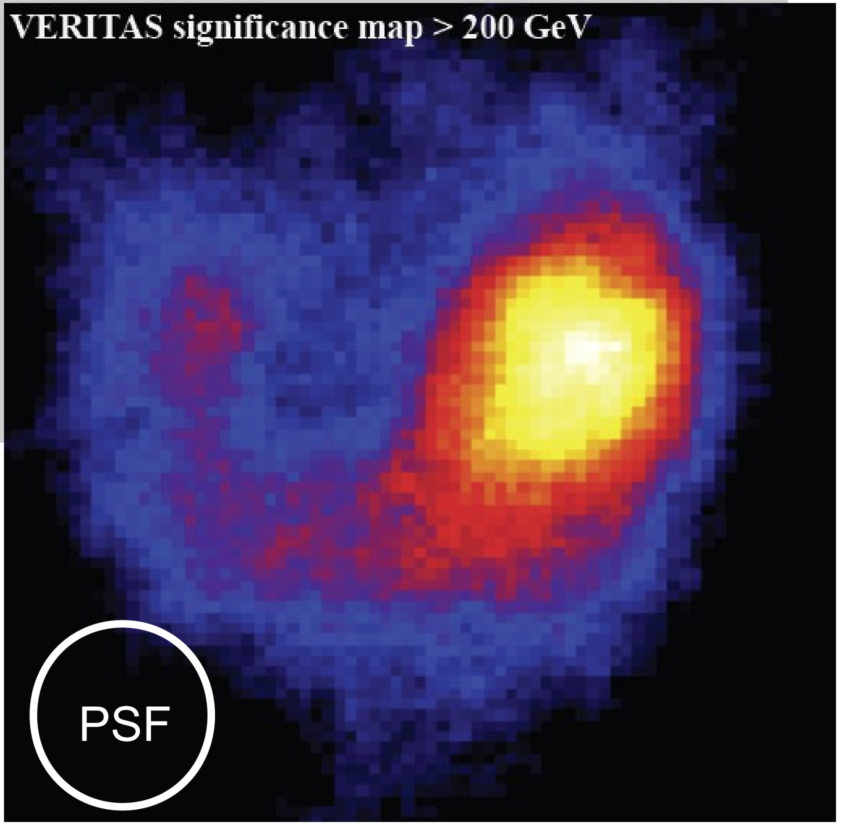
middle-aged shell-type SNR
expanding into complicated environment at 1.5 kpc

presence of gas clouds revealed by OH-maser emission and molecular lines

finite extension (diameter ~ 0.75°) permits morphology studies

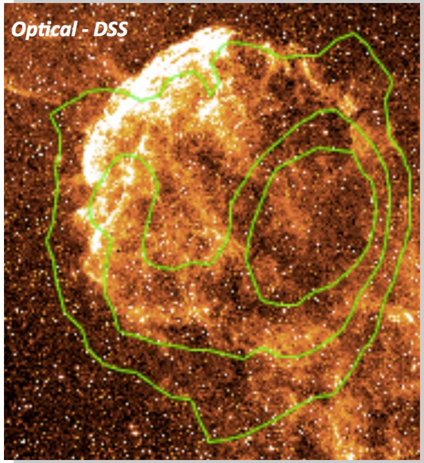
VERITAS data have been acquired since 2007

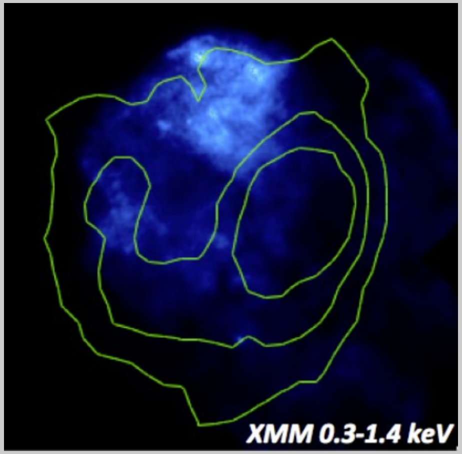
- 155 h after quality cuts
- factor of 4.5 over that used in previous sky maps
- factor of 9 over that used in previous spectral studies

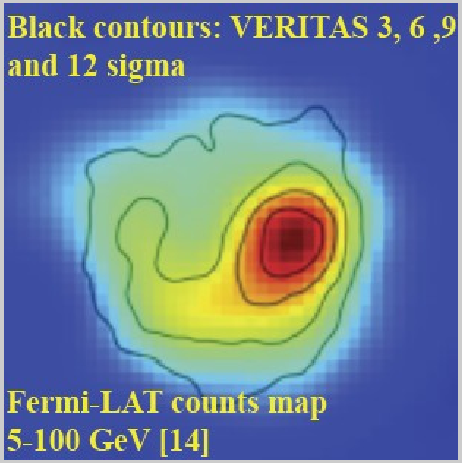


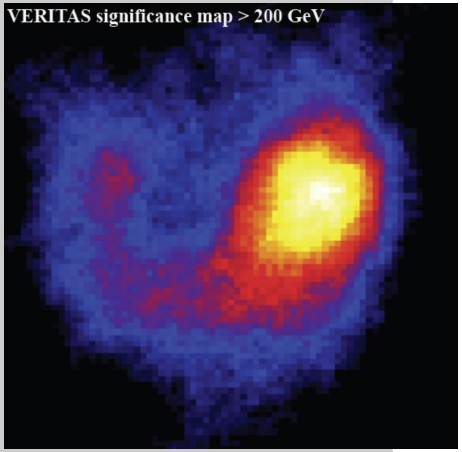
IC 443

multiwavelength data from IR to VHE gamma rays









molecular cloud blocking visible light in northeast quadrant seems to be where GeV-TeV gamma rays originate

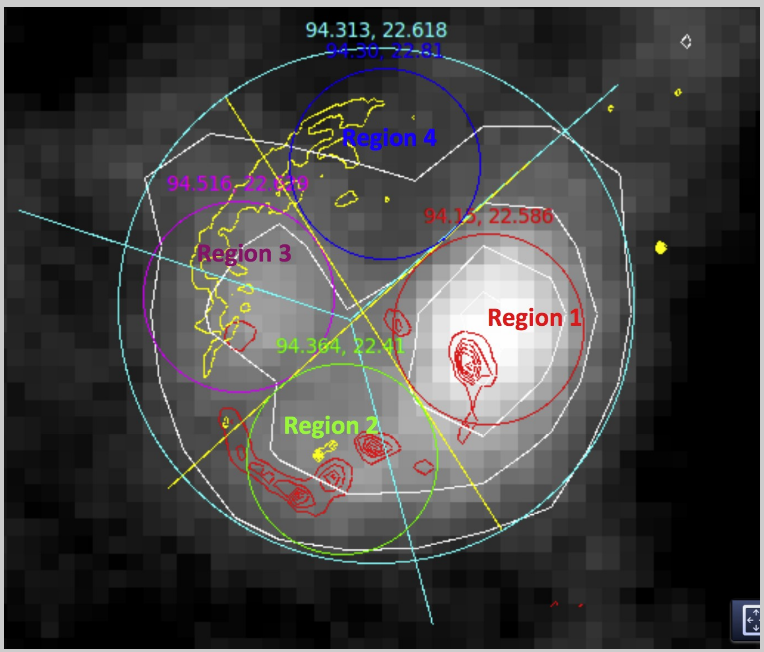
likely hadronic acceleration with π^0 production in the `beam dump' (Fermi sees a 'pion bump')

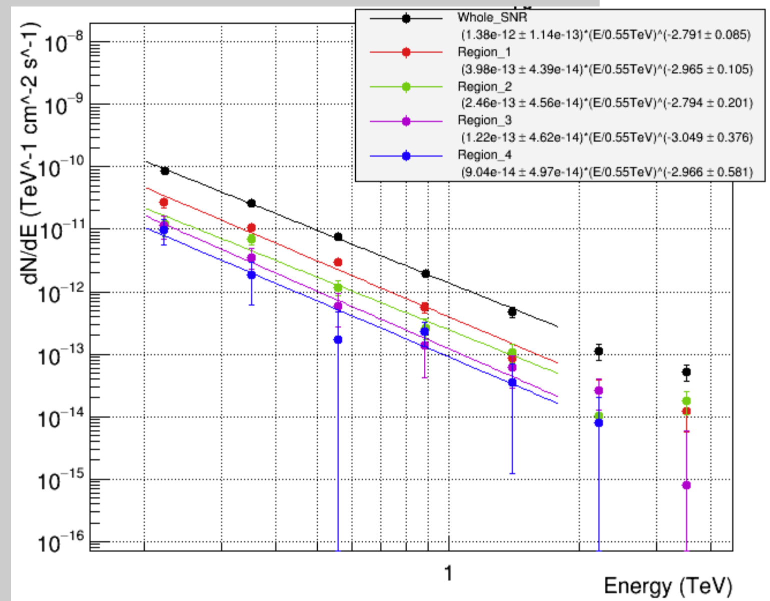
soft X-rays are anticorrelated with the gamma rays

IC 443

- gamma-ray spectrum is well fit with a single power law (broken power law needed if combined with Fermi data)

- power-law index is independent of the quadrant (surprising? the environments are quite different!)





Galactic Centre

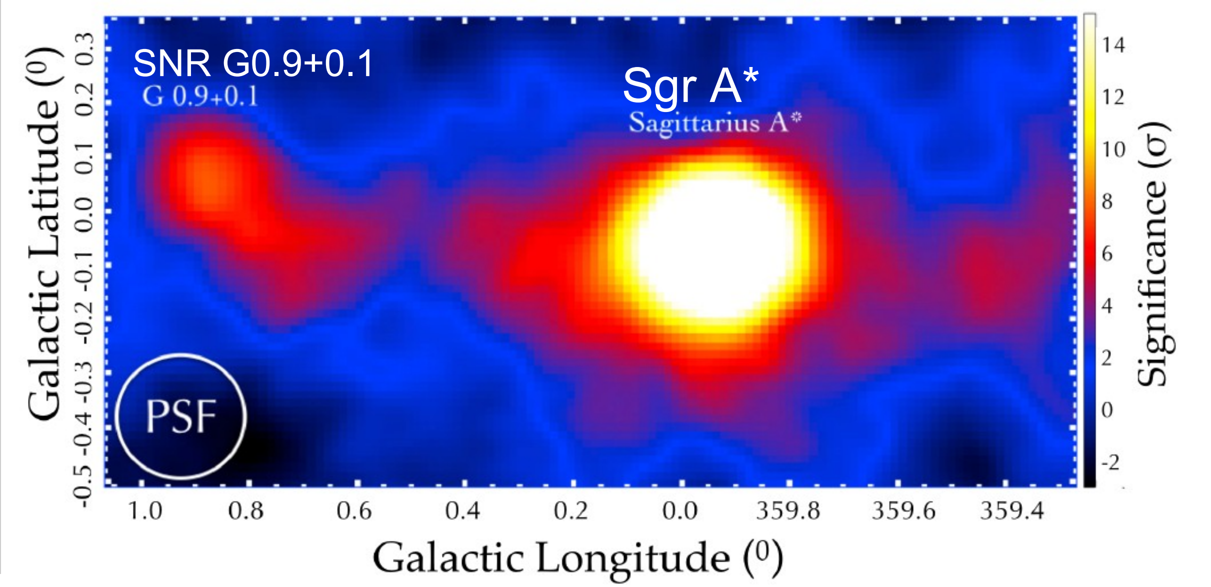
- complicated place dominated by a supermassive black hole (Sgr A*)

- never above 30° elevation for VERITAS (large zenith-angle observations)

- elevated energy threhold (2 TeV) but increased collection area

- observed for 85 hours

    - 735 excess gamma-ray events
    - 25 σ detection



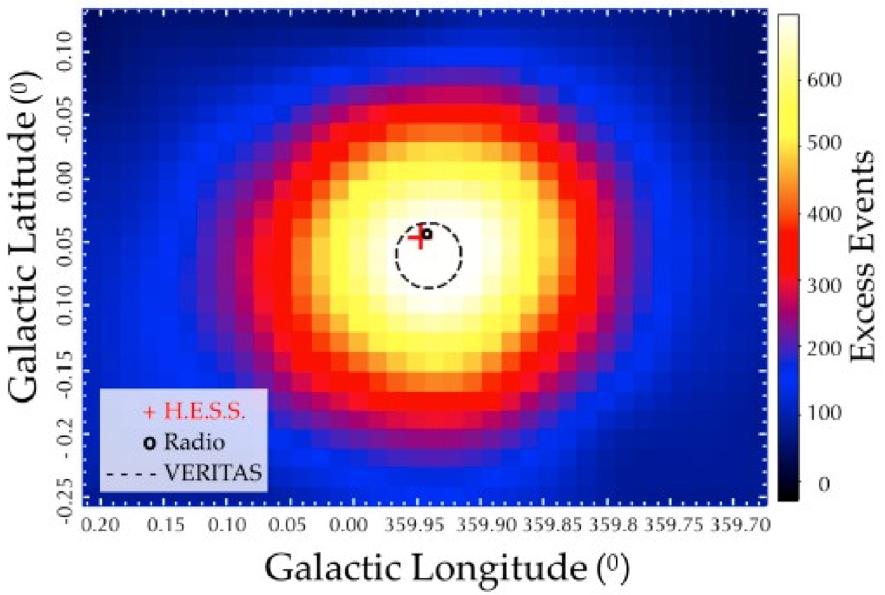
Galactic Centre

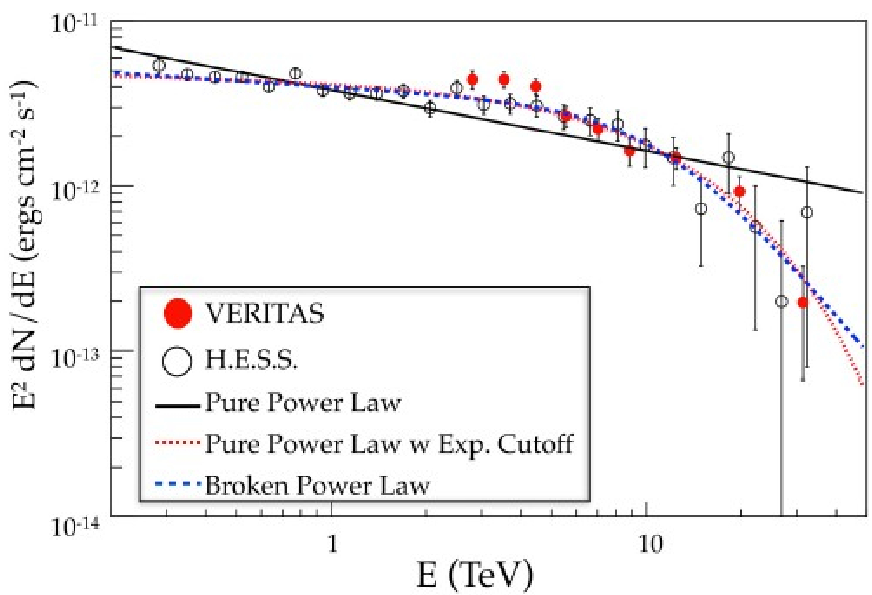
Sgr A* - associated with a $4x10^6$ solar-mass black hole

- constant flux at TeV energies (not so at lower E)

- spectrum needs a broken power law or an exponential cutoff

- recent H.E.S.S. announcement of PeV proton acceleration is confirmed by VERITAS results

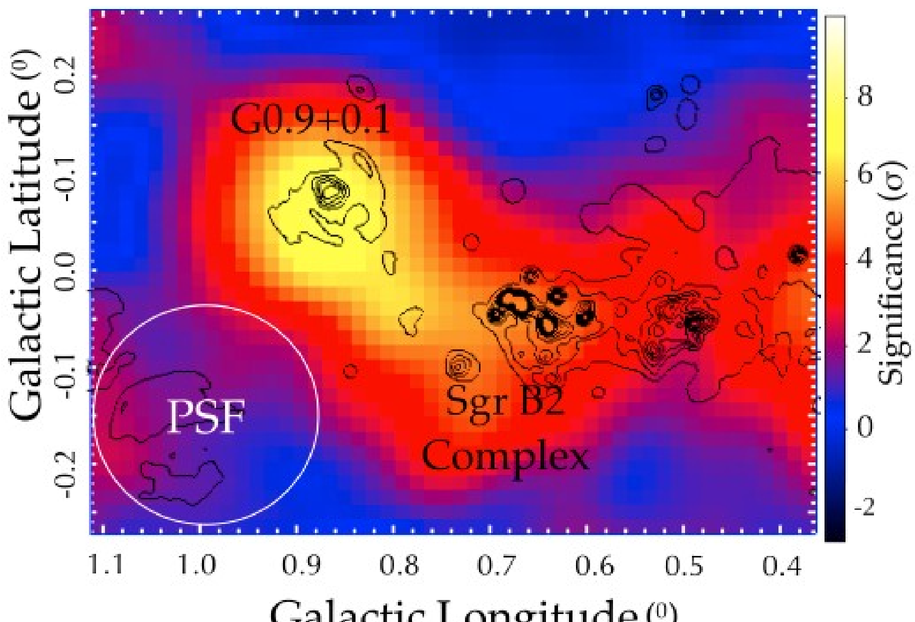


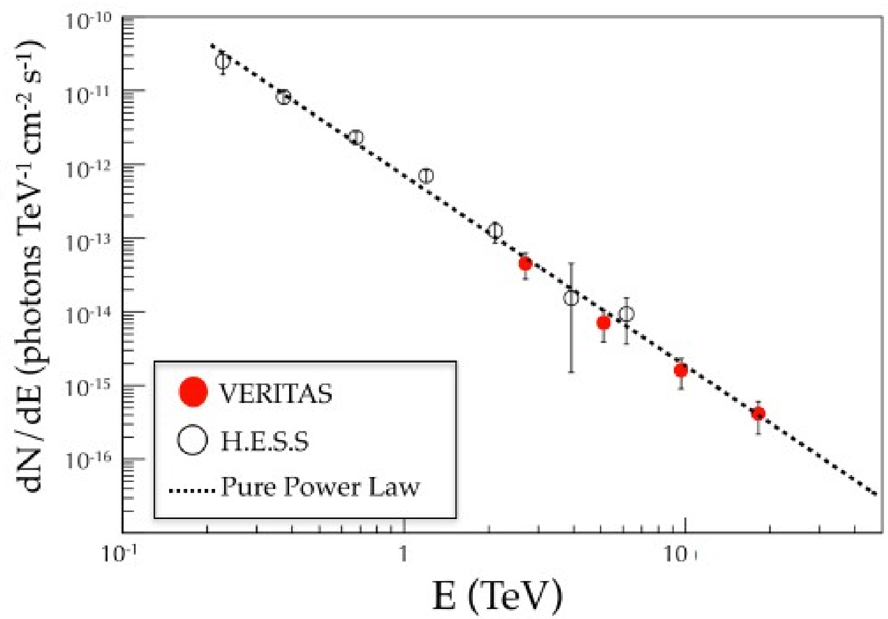


Galactic Centre

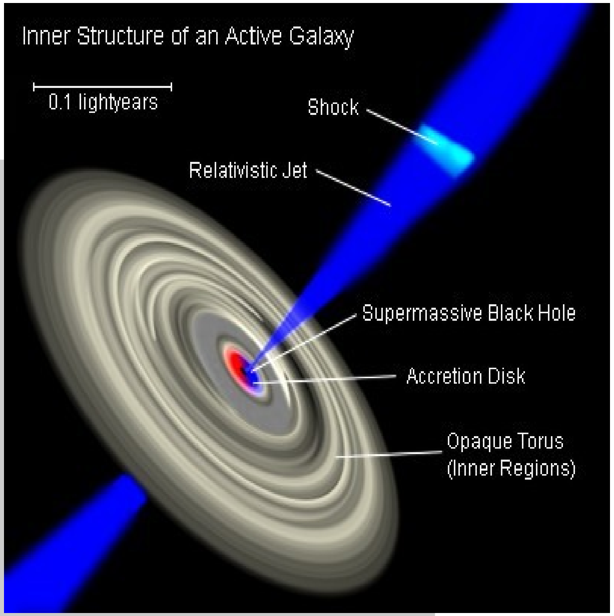
G0.9 +0.1 - supernova remnant

- 7 σ detection in 85 hours
- spectrum above 2 TeV matches and extends the H.E.S.S. measurement
- no deviation from simple power law up to 20 TeV





AGN (active galactic nuclei)



- most extragalactic sources are AGN of the blazar class

- VERITAS has detected 34

- time allocation plan going forward:

  > 50% regular monitoring of known blazars

  MWL coordination to produce long-term MWL light curves

  intense observations during flares (at any wavelength)

  ~30% target-of-opportunity observing

  ~20% VHE discovery observing

- Fermi is the primary pathfinder

- FACT is a valuable real-time monitor

PKS 1441+25

One of five flat-spectrum radio quasars (FSRQs) detected in the VHE band

FSRQs are a subclass of blazars where the supermassive black hole (SMBH) is in a field of optical-to-ultraviolet photons radiated from the surrounding disk

PKS 1441+25

- $z = 0.939$ (farthest of the VHE FSRQs - 7.5 Gy travel time)

- detected by VERITAS April 2015

    - observations triggered by MAGIC and Fermi

    - MWL campaign with other instruments triggered

PKS 1441+25

VERITAS results

400 gamma rays (8σ) in 15 h (Apr 21-28, 2015)

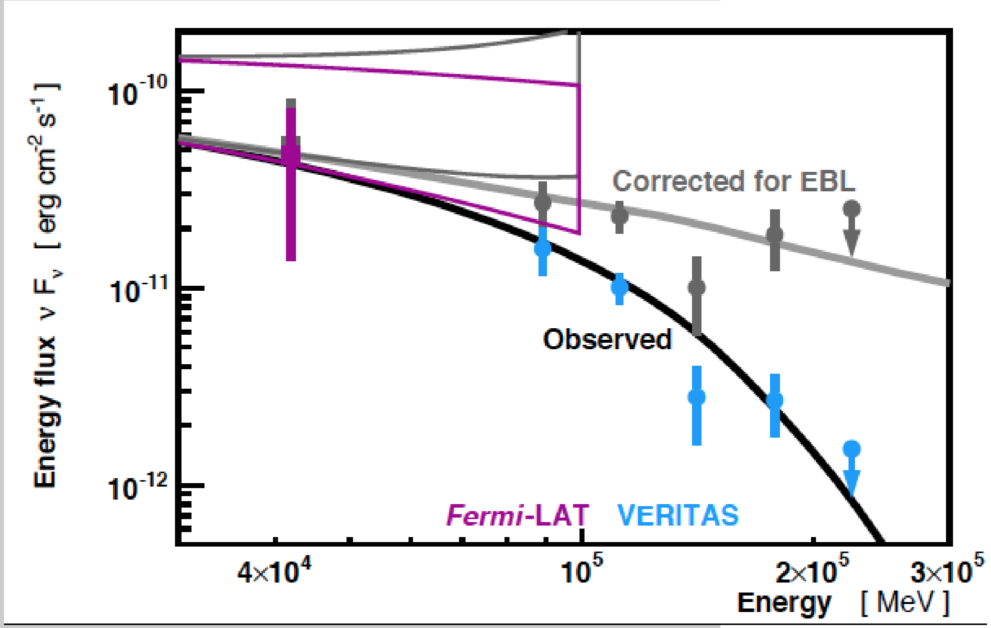
MAGIC 2600 (26σ) in 30 h

80 < E < 200 GeV

5% Crab flux

Γ = 5.3 +/- 0.5

steep power law is likely due to EBL absorption (corrected using model from Gilmore et al. connects smoothly to Fermi spectrum).



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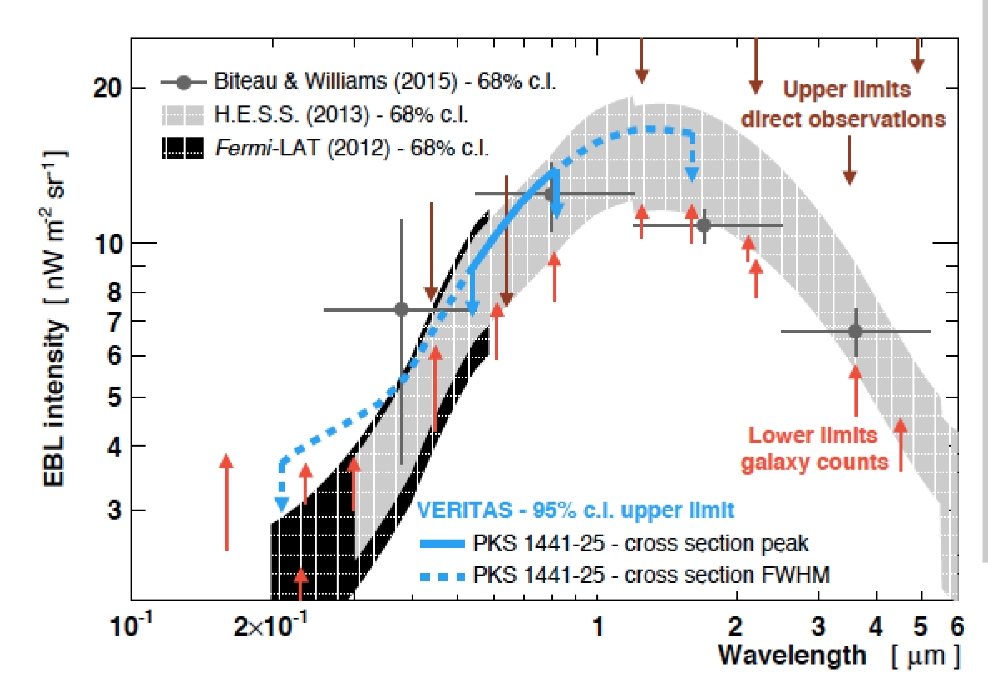
PKS 1441+25

Detection of gamma rays between 80 and 200 GeV implies

a) the source is 10^4 - 10^5 Schwarzschild radii from the SMBH - otherwise they would be absorbed by pair-production off the local photon field

b) the extragalactic background light (EBL) is at a level near the lower limit given by galaxy counts (higher would mean more attenuation from pair production)



Cosmic-ray Electrons (CRE)

small component of the total CR flux at GeV-TeV energies

probe local environment

- lose energy rapidly from inverse-Compton scattering and synchrotron radiation

- maximum range is ~1 kpc - this restricts the number of candidate sources (secondary production, pulsars, dark matter, . . .)

measurements from orbiting detectors (AMS-02, Fermi-LAT) are statistics-limited above ~100 GeV

ground-based detectors (H.E.S.S., MAGIC, VERITAS) have large areas ($> 10^5$ m^2) but poor signal-to-noise and no charge discrimination

- positrons are interesing - HEAT, PAMELA, Fermi and AMS see the fraction rising

Cosmic-ray Electrons (CRE)

VERITAS measurements

- the challenge is that CREs appear to come from every part of the sky; there is no ON-OFF cut as for gamma rays from a source of finite size

- use tight cuts on detector and observing conditions

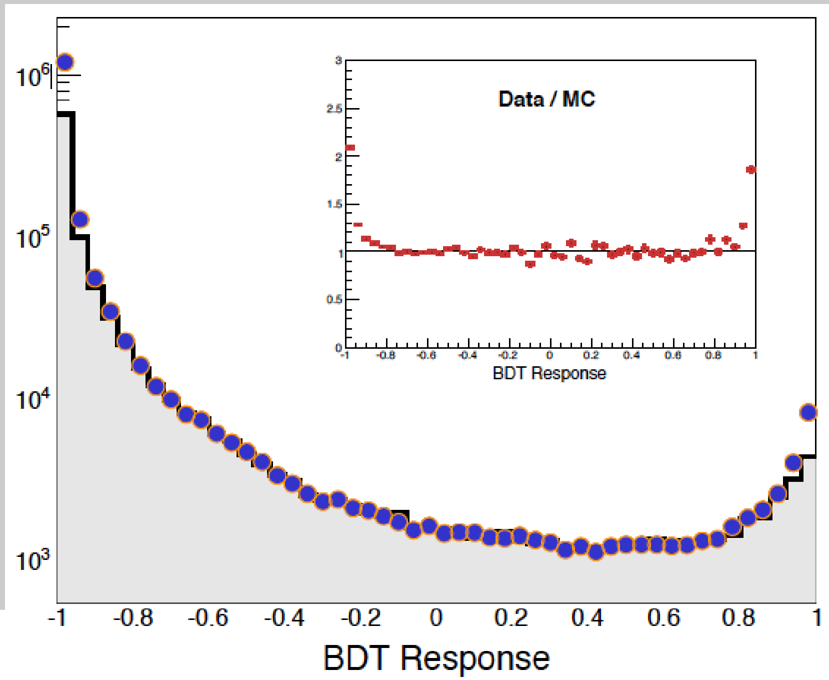
analysis

- use boosted decision trees (BDTs) trained with a combination of simulations (EM and hadronic showers) and randomly chosen data (background)

grey area = proton monte carlo

-1 = proton-like
(excess is from helium)

+1 = electron-like
(excess is the electron signal)



Cosmic-ray Electrons

VERITAS results

300 h of data

0.3 < E < 5 TeV

broken power law

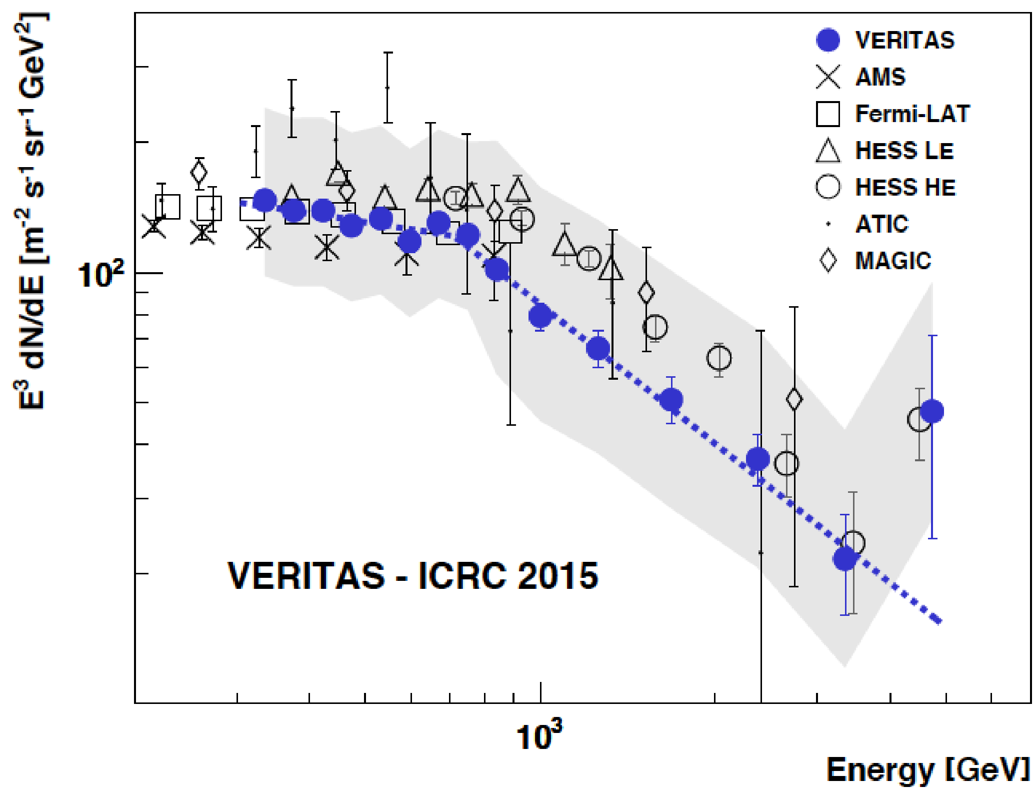
- break at 710 +/- 40 GeV

- indices

$-3.2 +/- 0.1_{stat}$

$-4.1 +/- 0.1_{stat}$

- systematics dominated by energy scale uncertainties (20%)



results are in approximate agreement with other measurements

- in particular, this is the second (after H.E.S.S.) high-statistics measurement of a break in the CRE spectrum at ~ 1 TeV

Dark Matter

Gamma-ray telescopes can search for photons coming from the mutual annihilation of dark-matter particles such as WIMPS.

Results depend on annihilation cross-sections so are complementary to results from underground nuclear-recoil experiments and accelerator-based production experiments.

For annihilation signals in objects like dwarf galaxies the connection to astrophysics (where it all began) is direct.

VERITAS observes

- the Galactic Centre
- galaxy clusters
- dwarf spheroidal galaxies

Dark Matter

Dwarf Spheroidal Galaxies

- relatively nearby (20-200 kpc)
- DM-dominated (order 1000 times more dark matter than ordinary matter)
- astrophysically 'clean' - no conventional gamma-ray sources

VERITAS targets - 230 hour total

- Segue 1	92 h	23 kpc
- Draco	50	80
- Ursa Minor	60	66
- Bootes	14	62
- Willman 1	14	38

Dark Matter

Analysis

- based on Geringer-Sameth et al. (2015)

- each event is weighted according to

    - the dSph it came from
    - energy
    - angular distance from dSph

- test statistic = sum of weights

- compare two hypotheses (bkgd only vs bkgd+DM) for entire data set

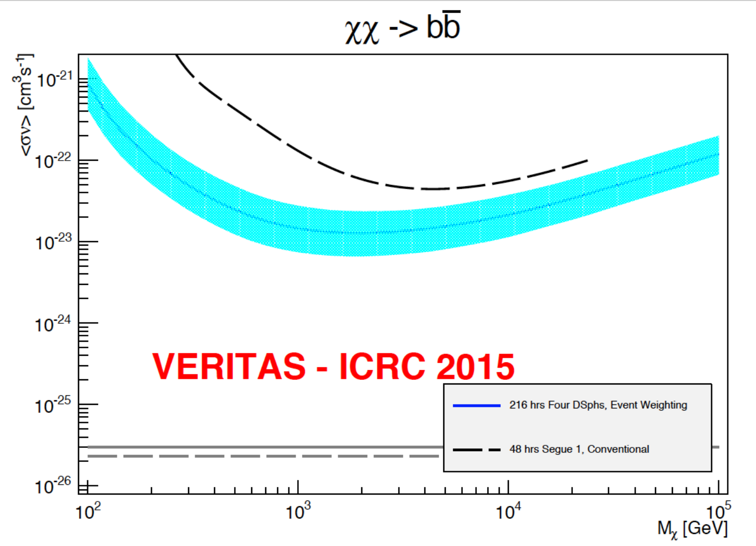
Dark Matter

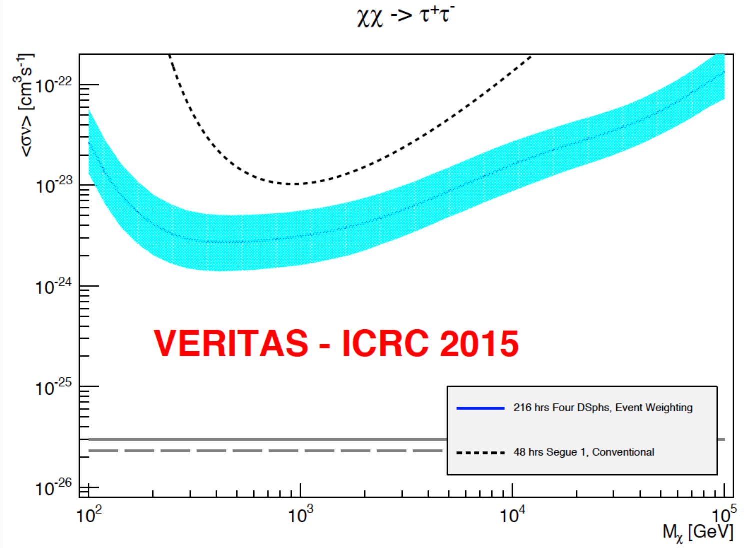
Results

- 95% CL upper limits assuming 100% branching ratio into specified channel

- width of curve comes from DM profile uncertainty

- horizontal lines show upper limits for two models of thermally-produced dark matter





Conclusions and future plans

VERITAS is running smoothly and maintains its sensitivity.
A long-term science plan is in place to provide a legacy science product but does not preclude reaction to new developments.

MWL partnerships and follow-up observations for other observatories (IceCube, HAWC, LIGO) are becoming a significant part of our program.

Operations until summer 2019 are planned.