

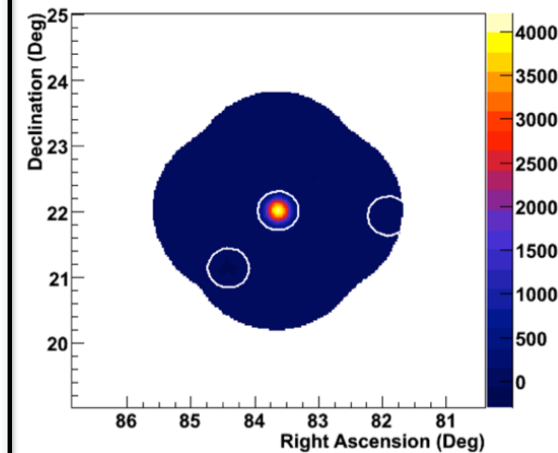
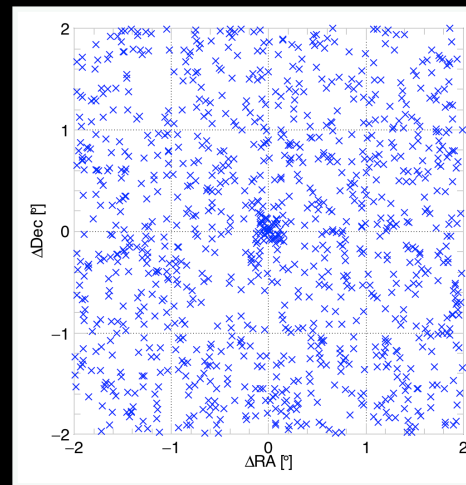
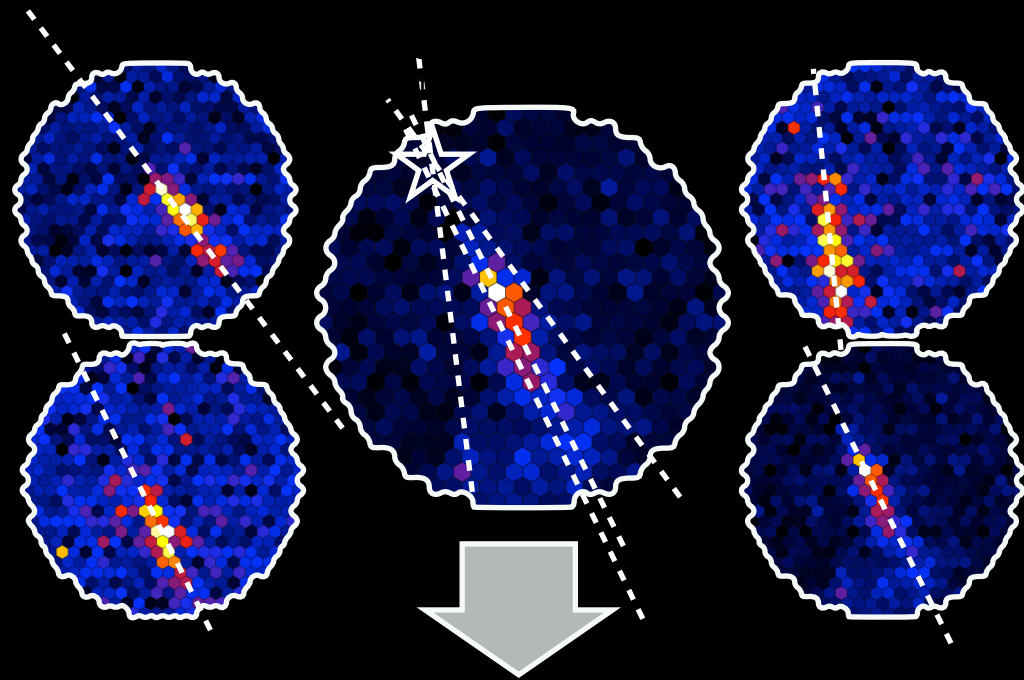
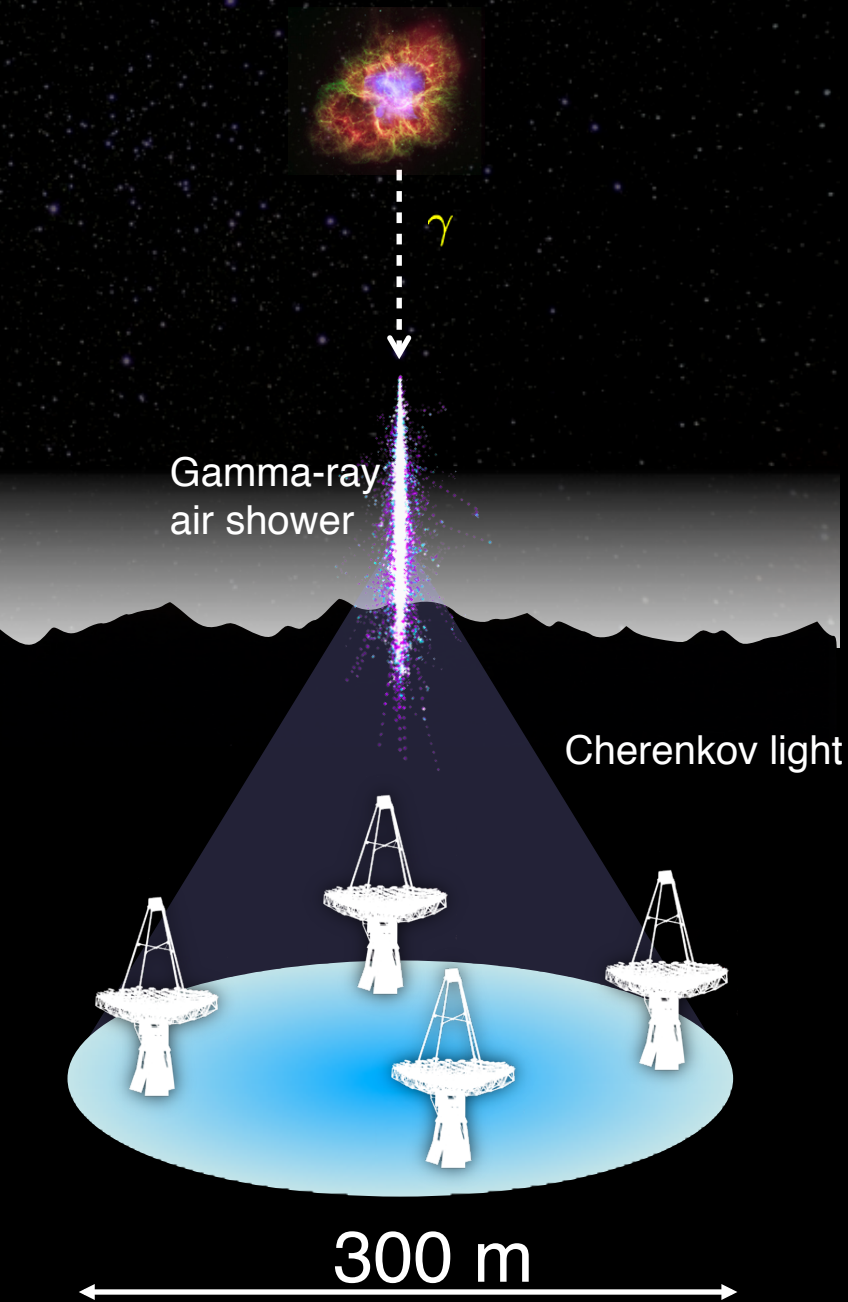


Introductions & Welcome

Reshmi Mukherjee

Barnard College, Columbia University

Imaging Air Cherenkov Technique



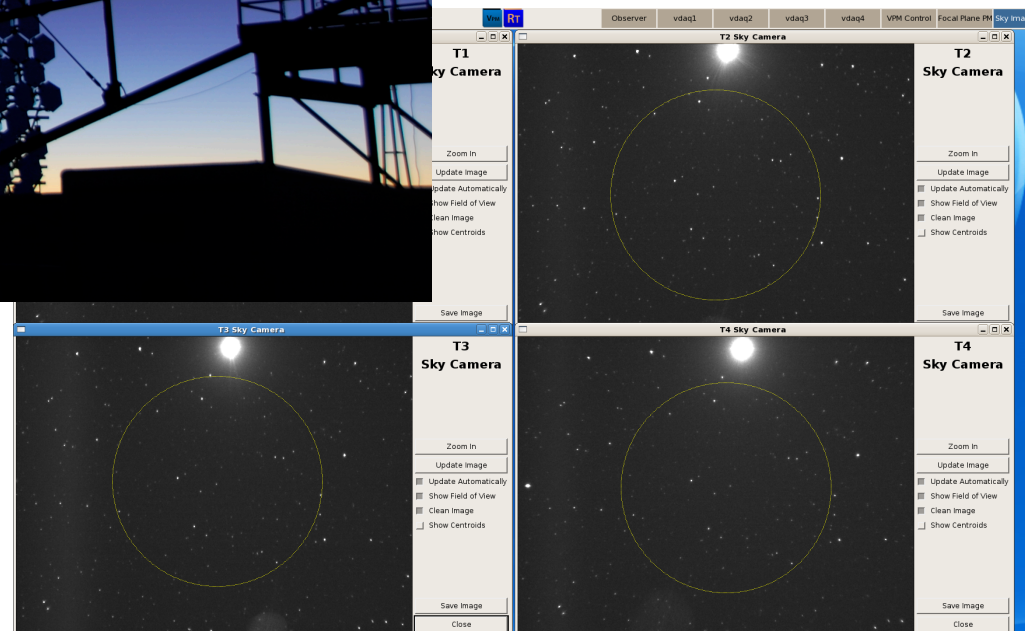
The Southern Arizona Night Sky



Photo: P. Fortin

Jupiter, during 3C 279 observations,
May 2017.

T4, the Moon, Jupiter, and
Venus in conjunction,
December 2008



The Southern Arizona Night Sky

Beautiful night sky....



Photo: J. Quinn

But sometimes ...



photo E. Roache



2007 to 2017

VERITAS First Light (April 2007)

April 28th, 2007
FLWO Basecamp



CERN COURIER

Jul 18, 2007

VERITAS telescopes celebrate first light

The latest in a series of VHE gamma-ray telescopes has come on line in Arizona. It will study gamma-ray sources ranging from supermassive black holes to dark matter.

Résumé

Inauguration de VERITAS

Hanna, Cern Courier 2007

The VERITAS Collaboration

V.A. ACCIARI^{1,21}, R.B. AMINI², G. BLAYLOCK³, S.M. BRADBURY⁴, J.H. BUCKLEY², V. BUGAEV², K.L. BYRUM⁵, O. CELIK⁶, A. CESARINI^{1,21}, L. CIUPIK⁷, Y.C.K. CHOW⁶, P. COGAN¹², P. COLIN¹¹, W. CUI⁸, M.K. DANIEL⁴, C. DOWDALL¹³, P. DOWKONTT², C. DUKE¹⁶, T. ERGIN³, A.D. FALCONE²², D.J. FEGAN¹³, S.J. FEGAN⁶, J.P. FINLEY⁸, P. FORTIN¹⁴, L.F. FORTSON⁷, D. GALL⁸, K. GIBBS¹, G.H. GILLANDERS²¹, J. GRUBE⁴, R. GUENETTE¹², G. GYUK⁷, J. HALL¹¹, D. HANNA¹², E. HAYS^{5,10}, J. HOLDER²³, D. HORAN⁵, S.B. HUGHES², C.M. HUI¹¹, T.B. HUMENSKY¹⁰, A. IMRAN⁹, P. KAARET¹⁸, G.E. KENNY²¹, M. KERTZMAN¹⁵, D. KIEDA¹¹, J. KILDEA¹, A. KONOPELKO⁸, H. KRAWCZYNSKI², F. KRENNRICH⁹, M.J. LANG²¹, S. LEBOHEC¹¹, K. LEE², G. MAIER¹², H. MANSERI¹¹, A. MCCANN¹², M. MCCUTCHEON¹², J. MILLIS⁸, P. MORIARTY²⁰, R. MUKHERJEE¹⁴, T. NAGAI⁹, J. NIEMIEC⁹, P.A. OGDEN⁴, R.A. ONG⁶, D. PANDEL¹⁸, J.S. PERKINS¹, F. PIZLO⁸, M. POHL⁹, J. QUINN¹³, K. RAGAN¹², P.T. REYNOLDS¹⁹, E. ROACHE¹, H.J. ROSE⁴, M. SCHROEDTER⁹, G.H. SEMBROSKI⁸, A.W. SMITH^{1,4}, D. STEELE⁷, S.P. SWORDY¹⁰, A. SYSON⁴, J.A. TONER^{1,21}, L. VALCARCEL¹², V.V. VASSILIEV⁶, R. WAGNER⁵, S.P. WAKELY¹⁰, J.E. WARD¹³, T.C. WEEKES¹, A. WEINSTEIN⁶, R.J. WHITE⁴, D.A. WILLIAMS¹⁷, S.A. WISSEL¹⁰, M. WOOD⁶ AND B. ZITZER⁸

Adler Planetarium and Astronomy
Museum, Chicago, IL
Argonne National Laboratory, IL
Barnard College, NY
De Pauw University, IN
Fred Lawrence Whipple Observatory
(SAO), AZ
Grinnell College, IA
Iowa State University, IA
Penn State University, PA



Purdue University, IN
University of California, Los Angeles, CA
University of California, Santa Cruz, CA
University of Chicago, IL
University of Delaware, DE
University of Iowa, IA
University of Massachusetts, MA
University of Utah, UT
Washington University, MO



University of Leeds, UK



Cork Institute of Technology, Ireland
Galway-Mayo Institute of
Technology, Ireland
National University of Ireland, Galway
University College Dublin, Ireland



McGill University, QC, Canada

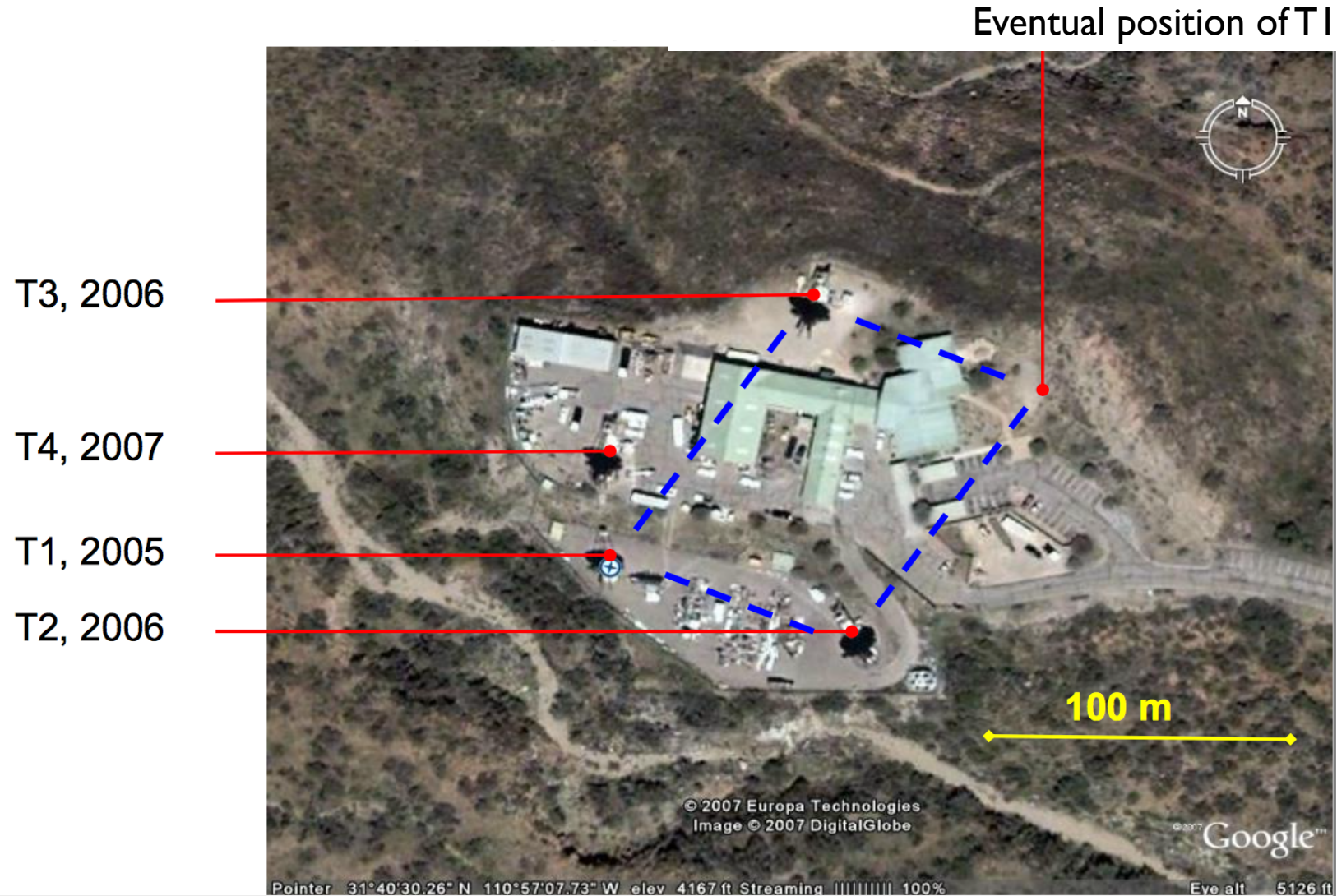


Collaboration in 2007



Collaboration meeting, Delaware, May 2007

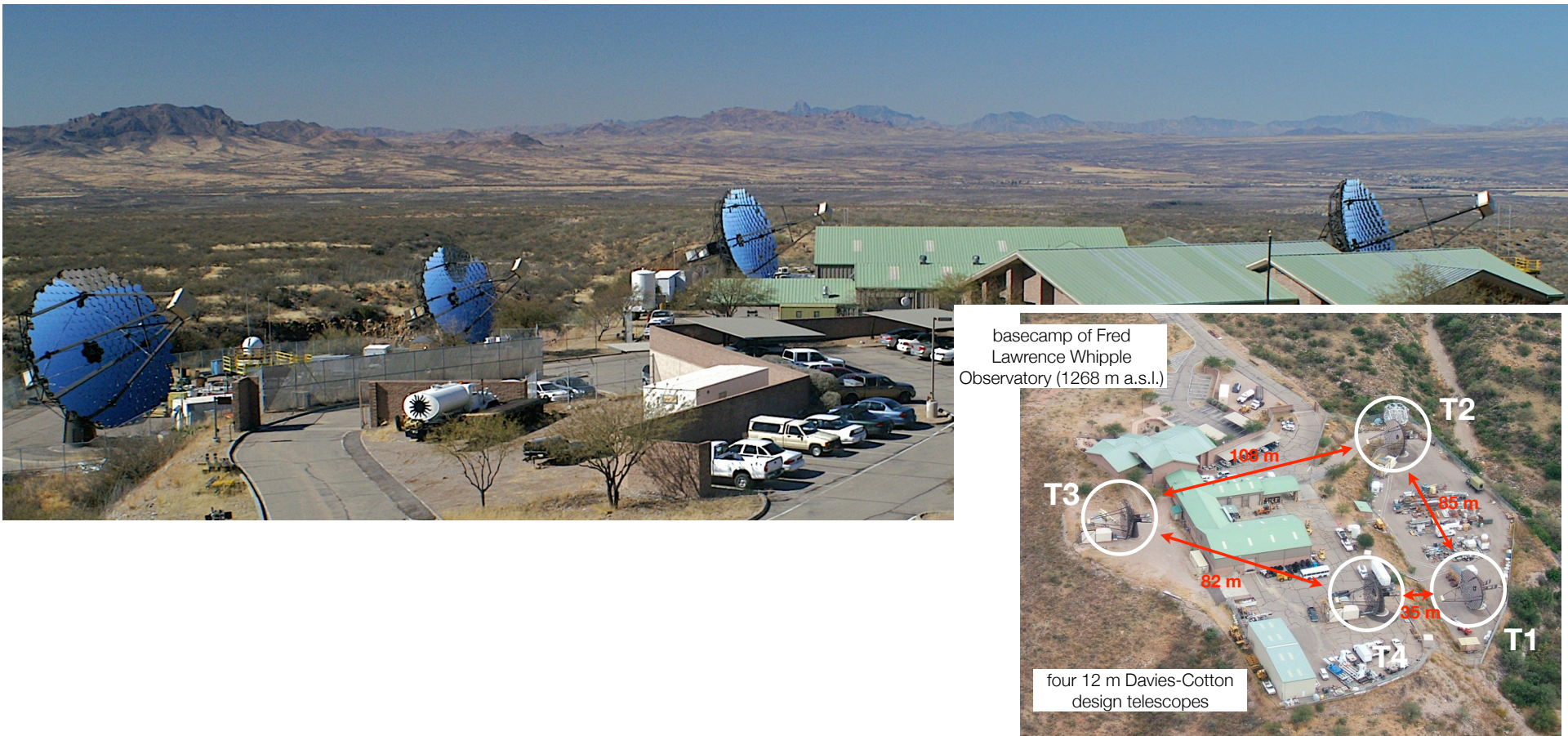
VERITAS Built Between 2005-2007



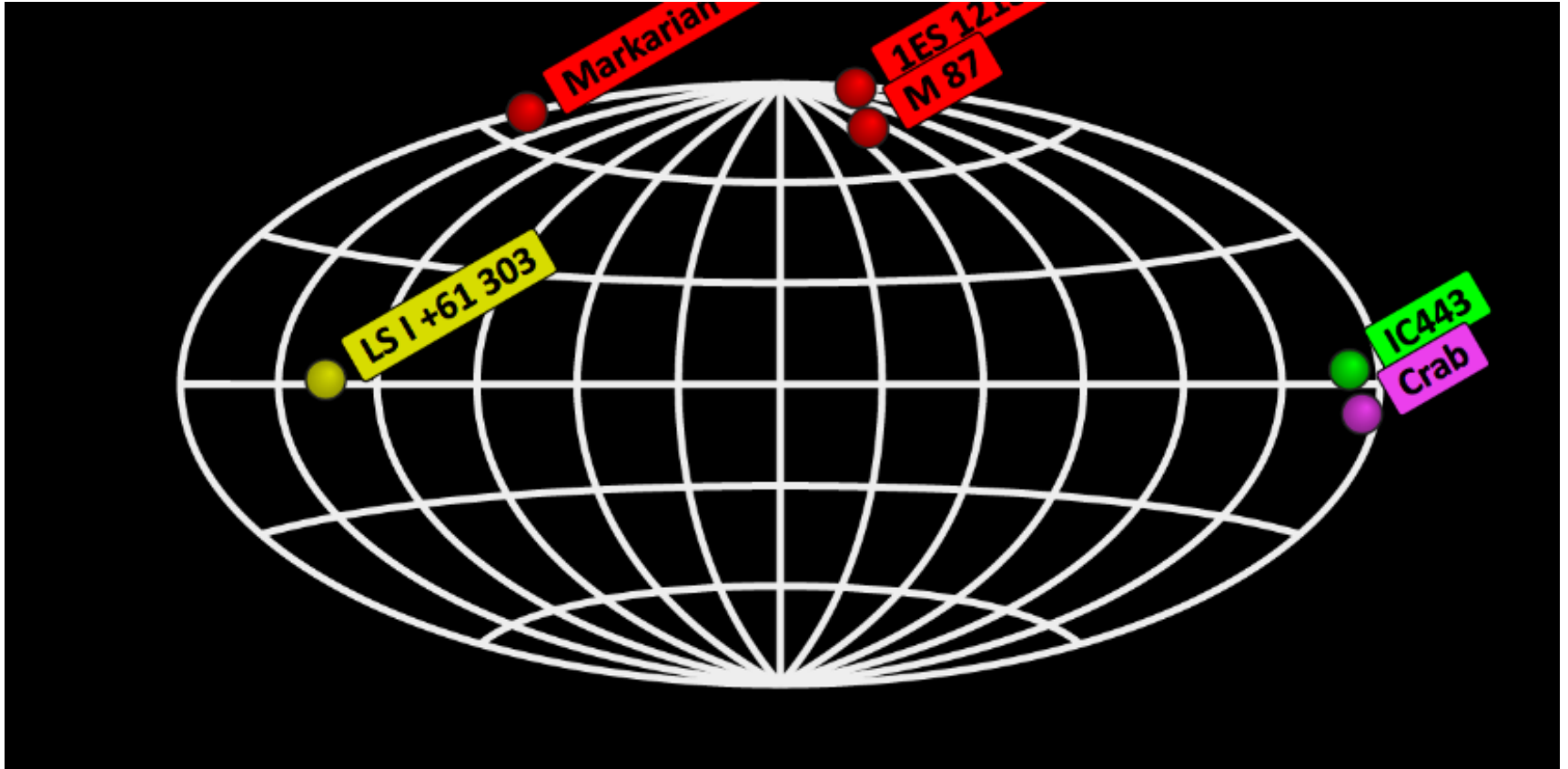


VERITAS in 2007

- VERITAS is fully operational with a broad scientific program.
- 30 contributions at the 2007 ICRC.



VERITAS Skymap c. 2007

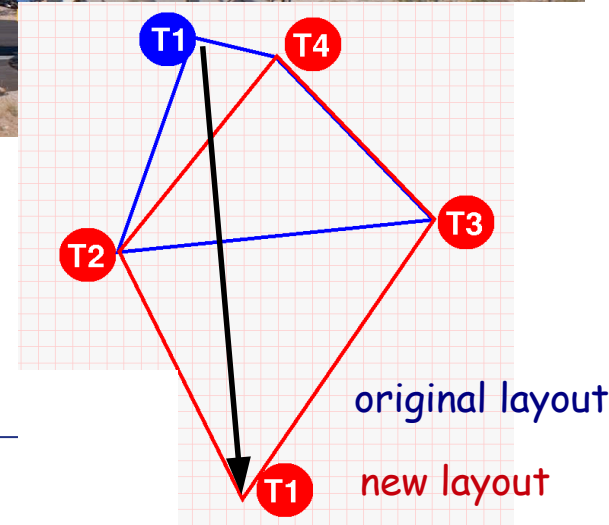


TeVCat

The Journey 2007-2017

Several improvements and upgrades completed:

- 2009: Original prototype telescope relocated.



The Journey 2007-2017

Several improvements and upgrades completed:

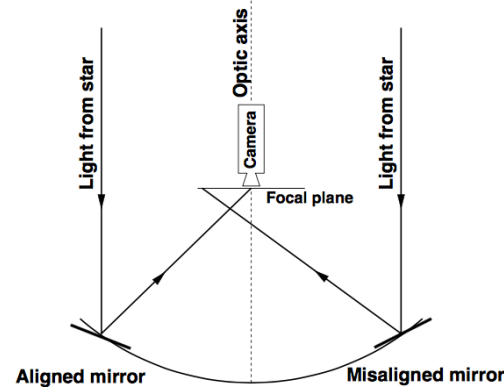
- 2009: Original prototype telescope relocated.



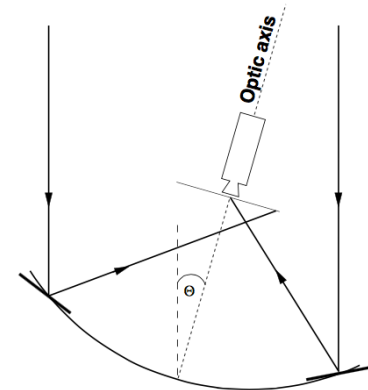
Upgrades & Improvements

Several improvements and upgrades completed:

- 2009: Original prototype telescope relocated.
- 2009 - 2010: New mirror alignment system .



(a) On axis



(b) Off axis

VERITAS Collaboration, arXiv:0910.3277

Upgrades & Improvements

Several improvements and upgrades completed:

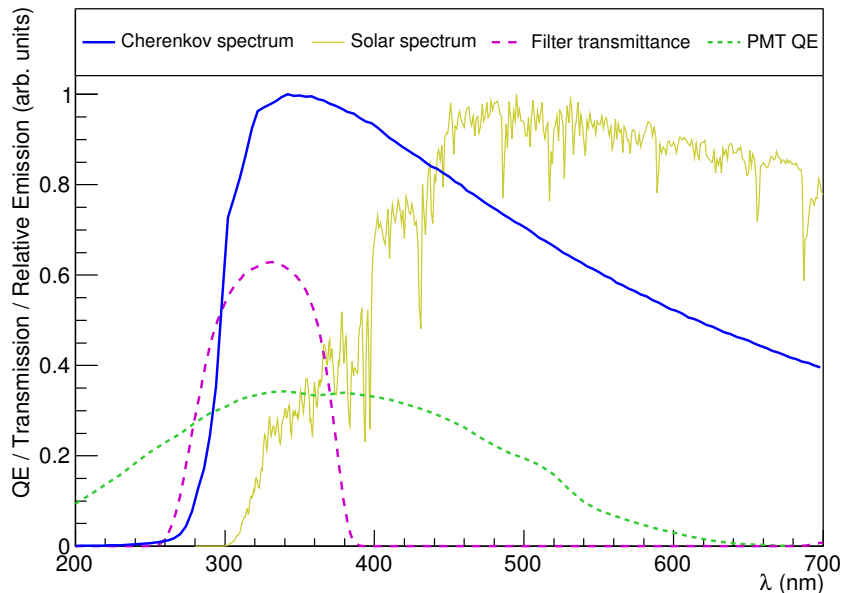
- 2009: Original prototype telescope relocated.
- 2009 - 2010: New mirror alignment system.
- 2011: New VERITAS building and control room (better safety, capabilities and quality of life).



Upgrades & Improvements

Several improvements and upgrades completed:

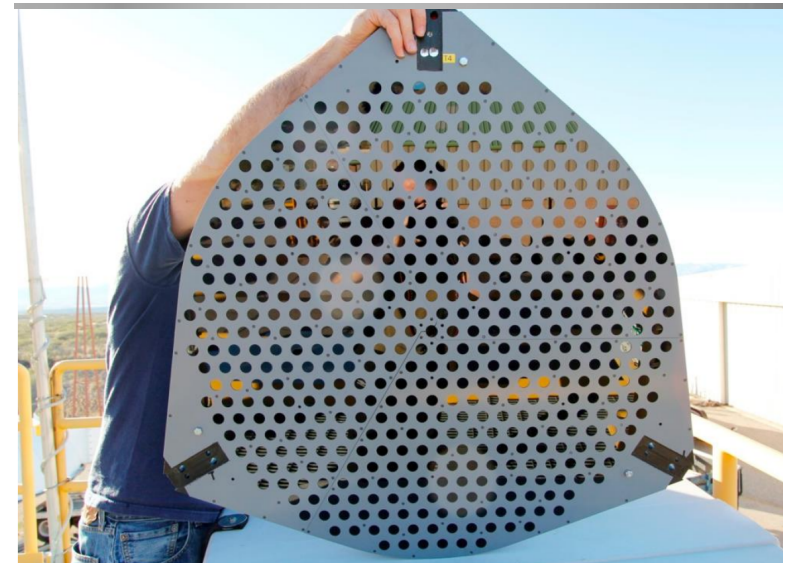
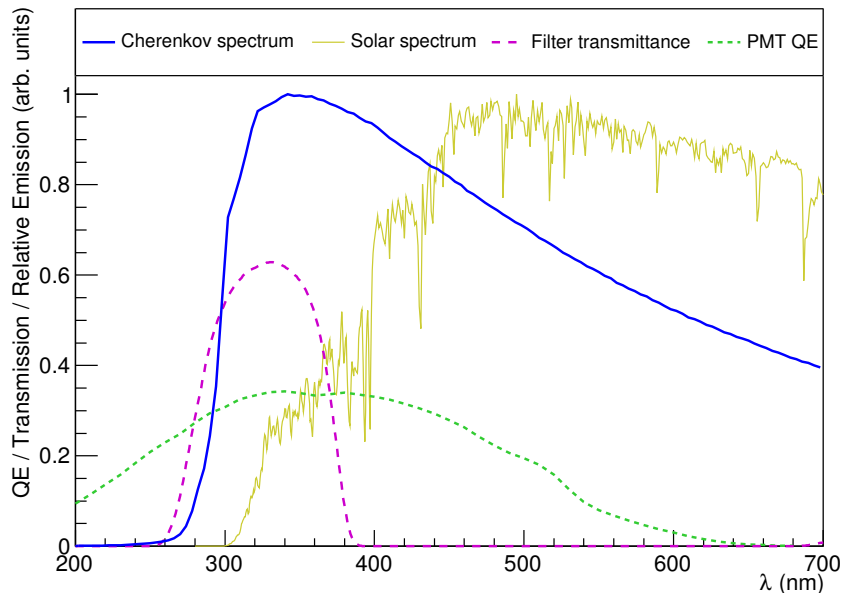
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- 2011: New telescope trigger systems. All photomultipliers replaced.
- 2012: Installation of UV filters, bright moonlight observations.



Upgrades & Improvements

Several improvements and upgrades completed:

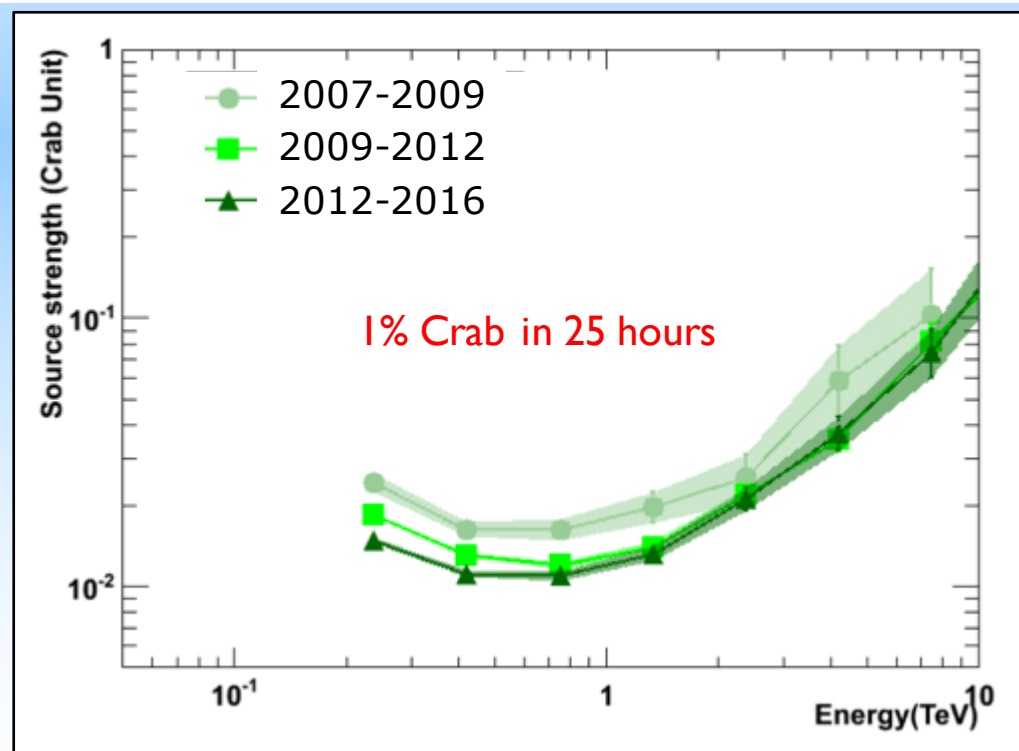
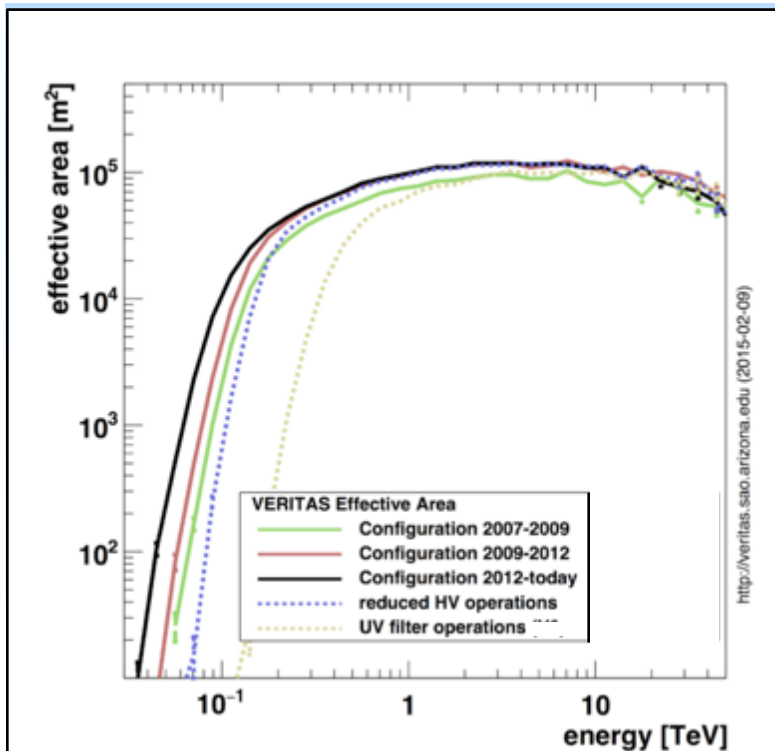
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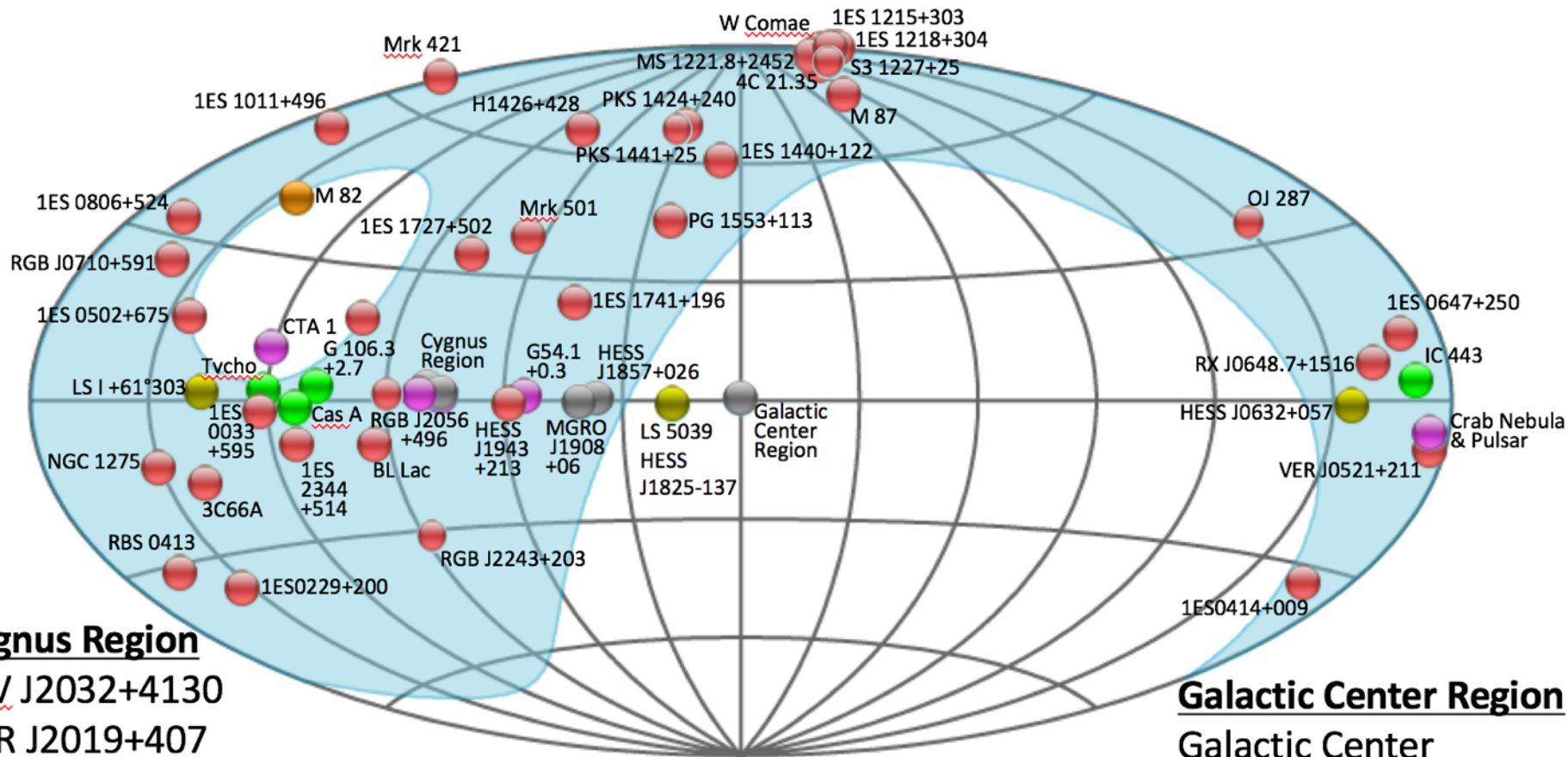
VERITAS Collaboration arxiv:1703.01307

VERITAS Sensitivity

- VERITAS now detects a source in less than half the time than in 2007.
(10% Crab source in 25 min, Crab Nebula in < 2 min)
- The low energy response has improved dramatically.

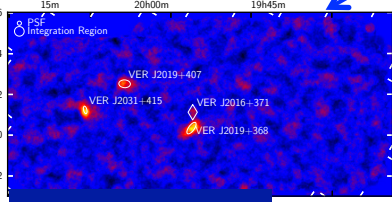


VERITAS Sky Map c. June 2017



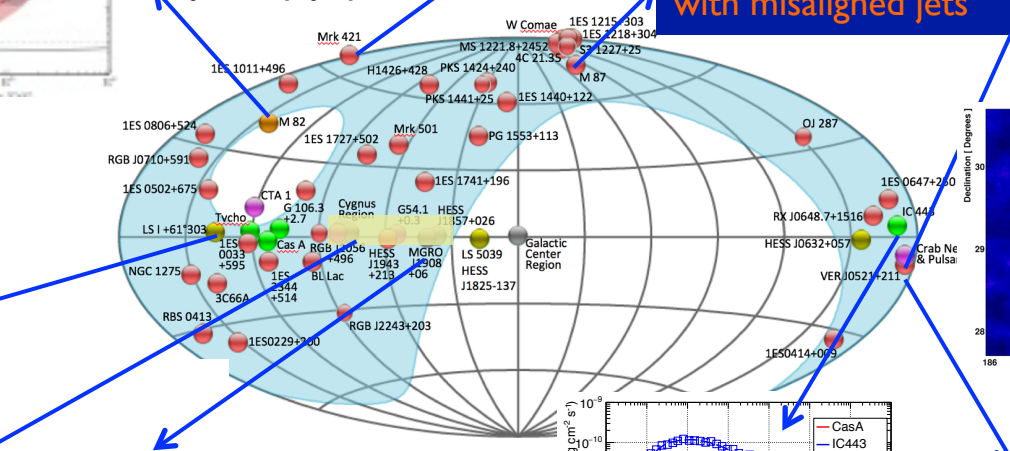
58 Sources

Fundamental Physics



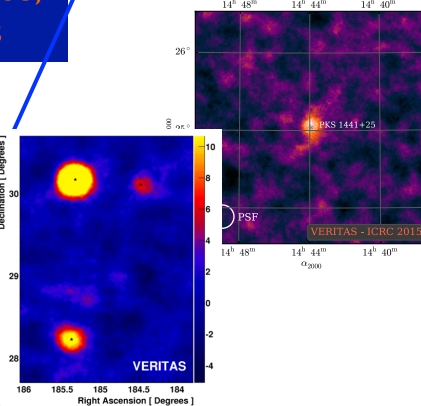
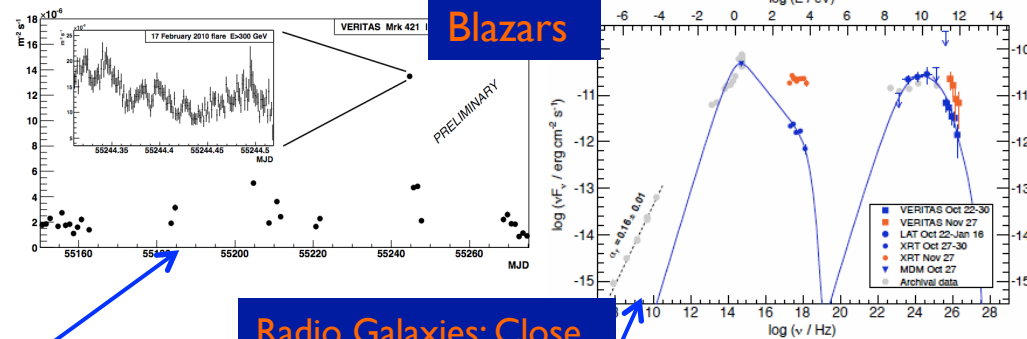
Cygnus Survey

Galactic sources

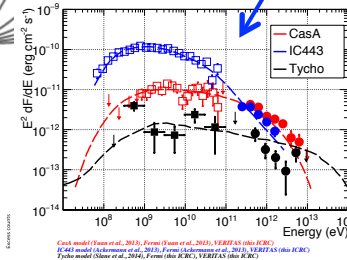


Radio Galaxies: Close, with misaligned jets

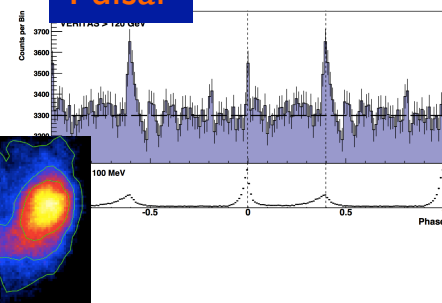
Blazars



Pulsar

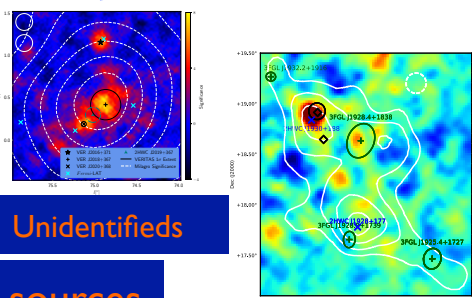


Supernova Remnant



Unidentifieds

HAWC Follow-ups

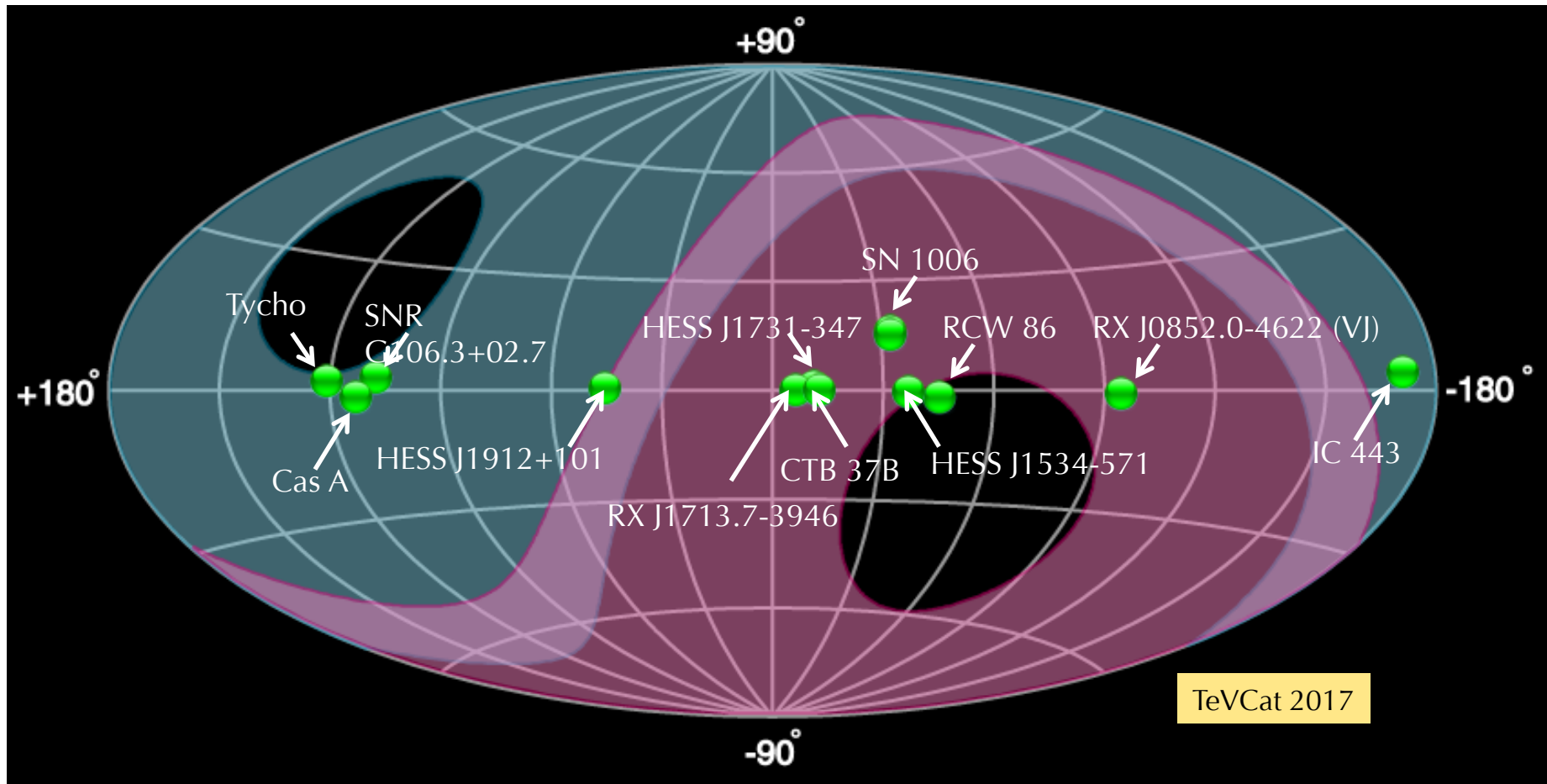




Some Highlights from the last 10 years

I. Sources of Cosmic rays: SNRs

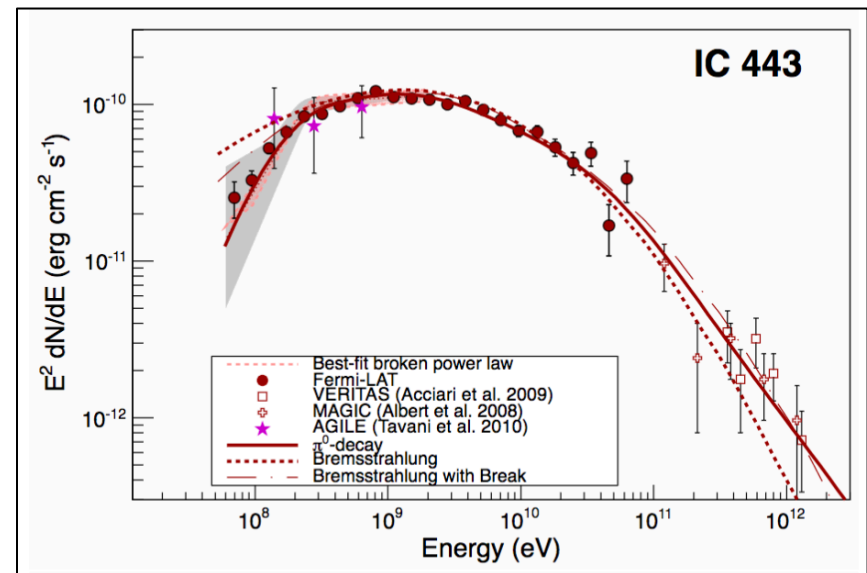
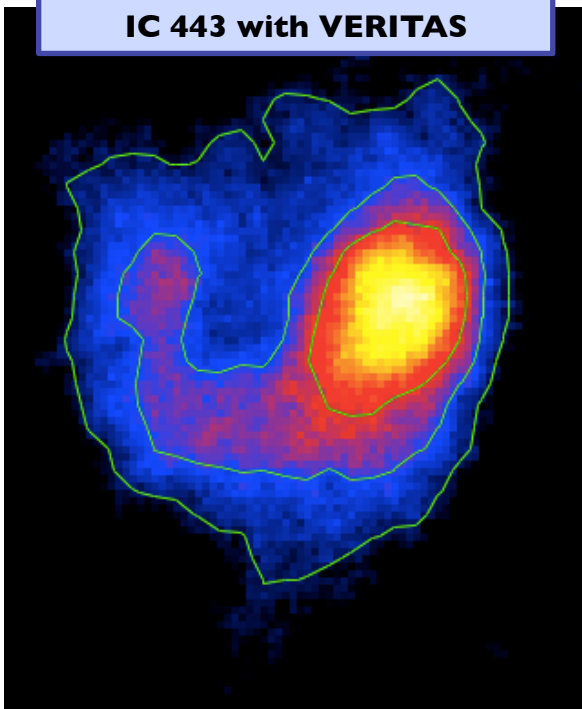
- γ -ray emission identifies the particle acceleration sites in SNRs.
- Leptonic or hadronic?



The Jellyfish Nebula Resolved in γ rays

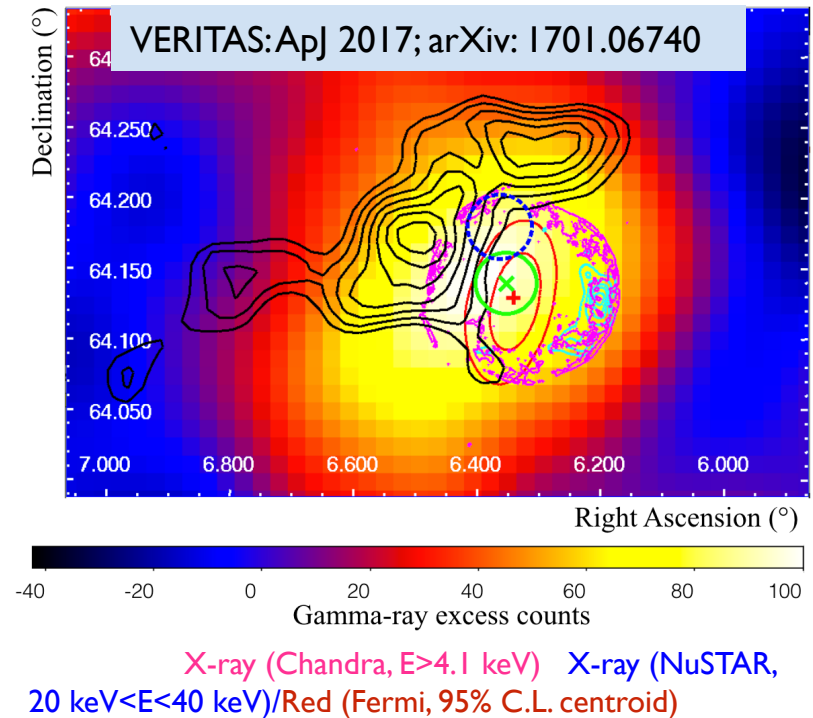
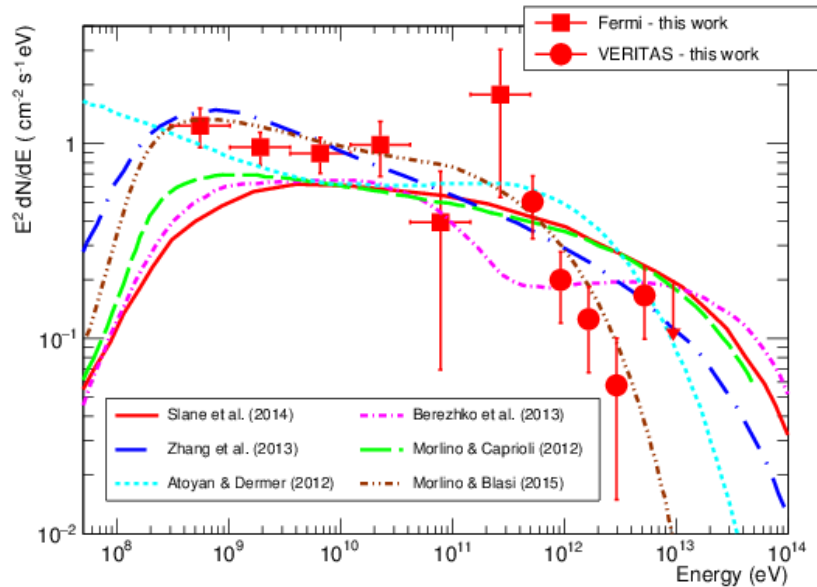
- Gamma-ray emission identifies the particle acceleration sites in SNRs.
- Particle population is ambiguous: leptonic or hadronic emission may dominate.
- Where hadronic emission is identified, the source spectra cut off at high energies.

IC 443 with VERITAS



Fermi-LAT Collaboration Science 339, 807, 2013

Tycho: Hadronic Accelerator?



- Possible interaction with Molecular Cloud.
- Detection in GeV-TeV energy by Fermi & VERITAS.
- Spectrum favors hadronic models.

What is the maximum energy of particles accelerated in Tycho?

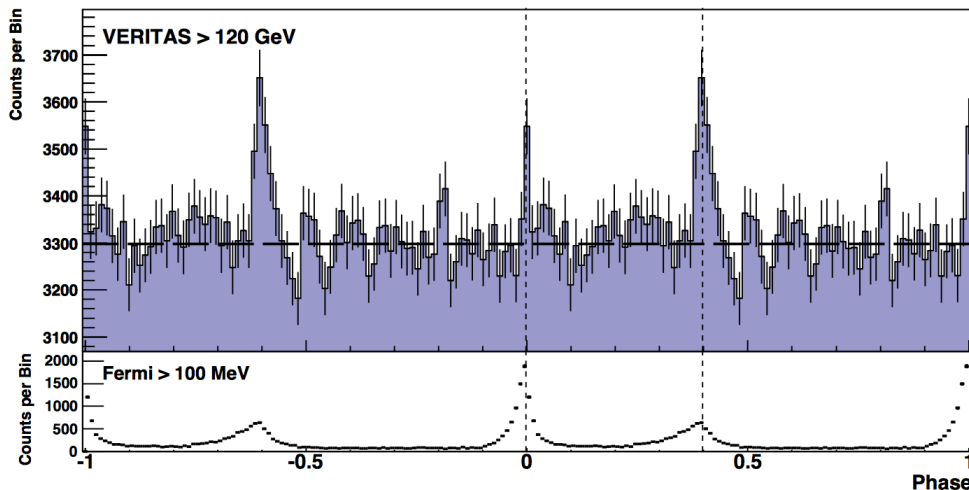
2011

2. Crab Pulsar:

Unexpected discovery of >100 GeV pulsed emission

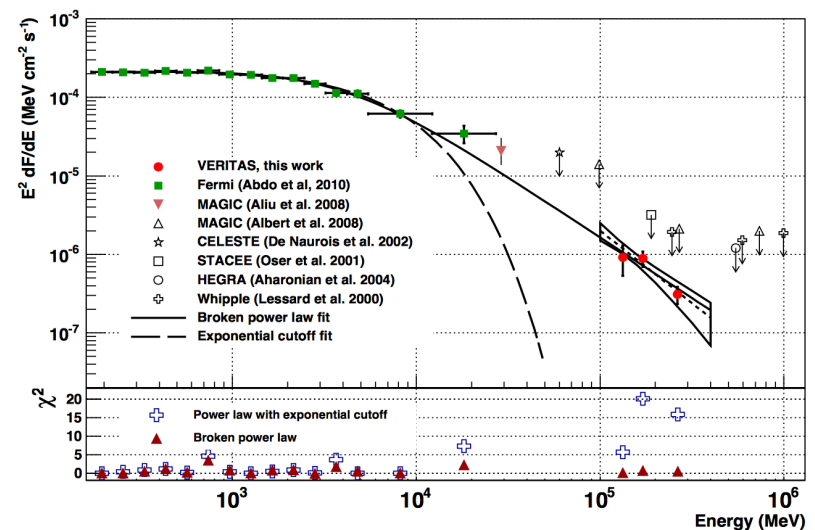
- Fermi-LAT measures a spectral break at 6 GeV.
- VERITAS measures unpredicted emission above 100 GeV.
- Latest MAGIC results extend to 1 TeV.
- Challenges emission models: Curvature radiation unlikely for pulsed VHE.
- Emission from the neighborhood of Light Cylinder ($r \sim 1600\text{km}$, > 10 stellar radii).

The Crab pulsar lightcurve >120 GeV



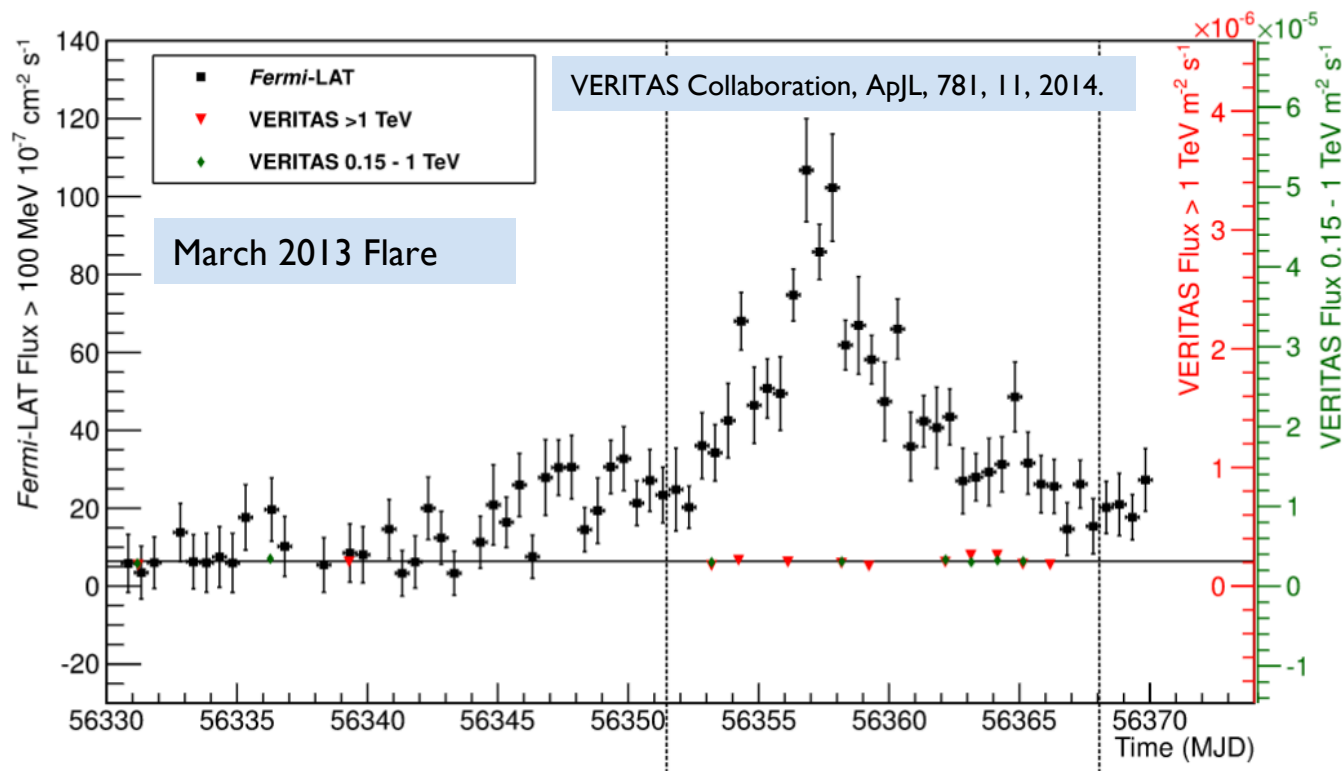
VERITAS Collaboration, Science, 334, 69, 2011

The Crab pulsar spectrum



3. The Steady Crab: No Flares at TeV

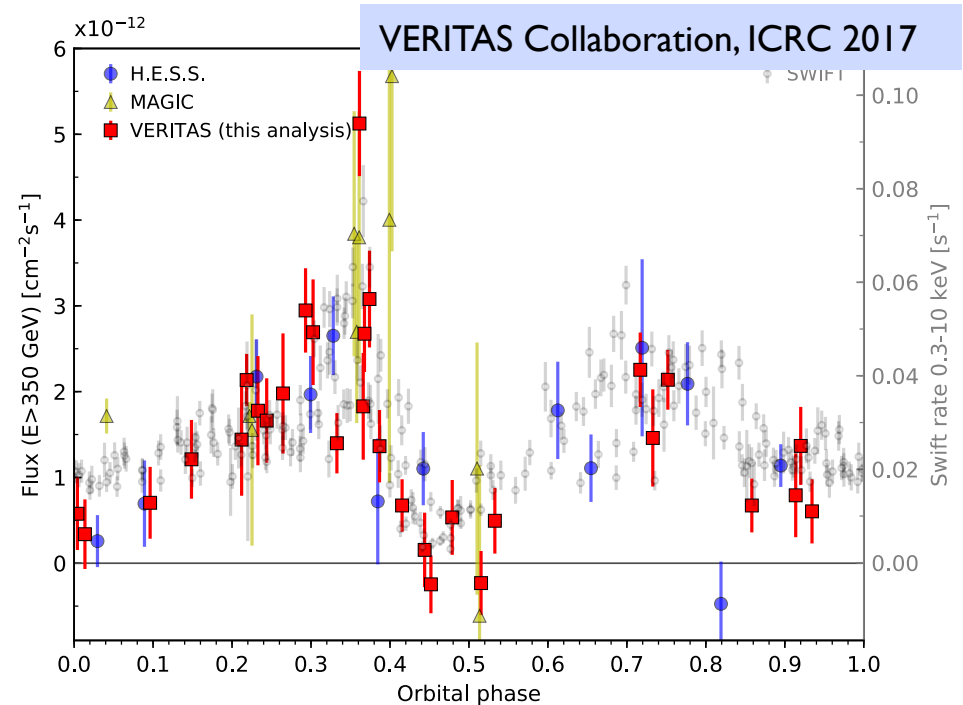
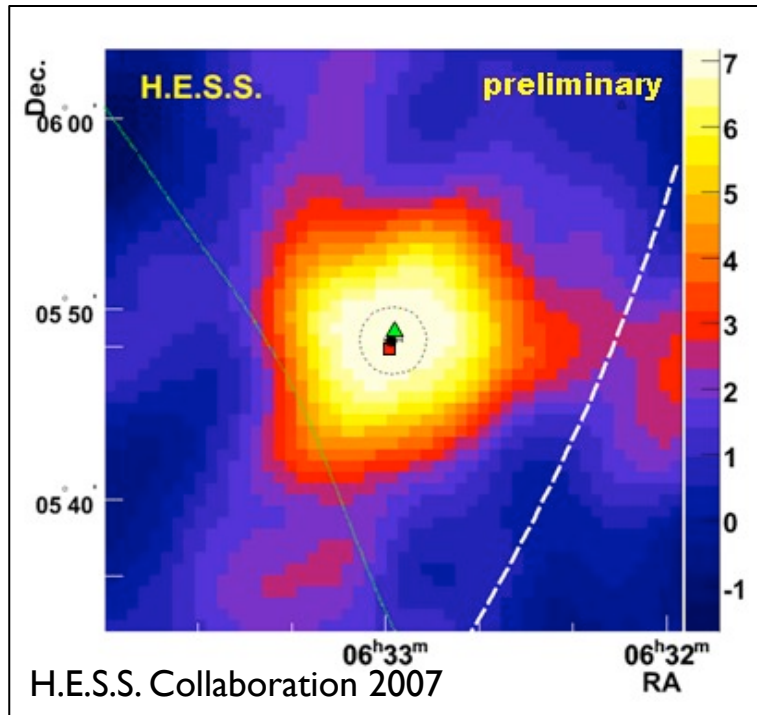
- The Fermi-LAT measured Crab flares have no counterpart at TeV.



- Light curve and reconstructed energy spectrum in between 1 TeV and 10 TeV do not indicate any flux enhancement at TeV energies.
- Flux above 100 MeV was six times elevated during observations.

2013

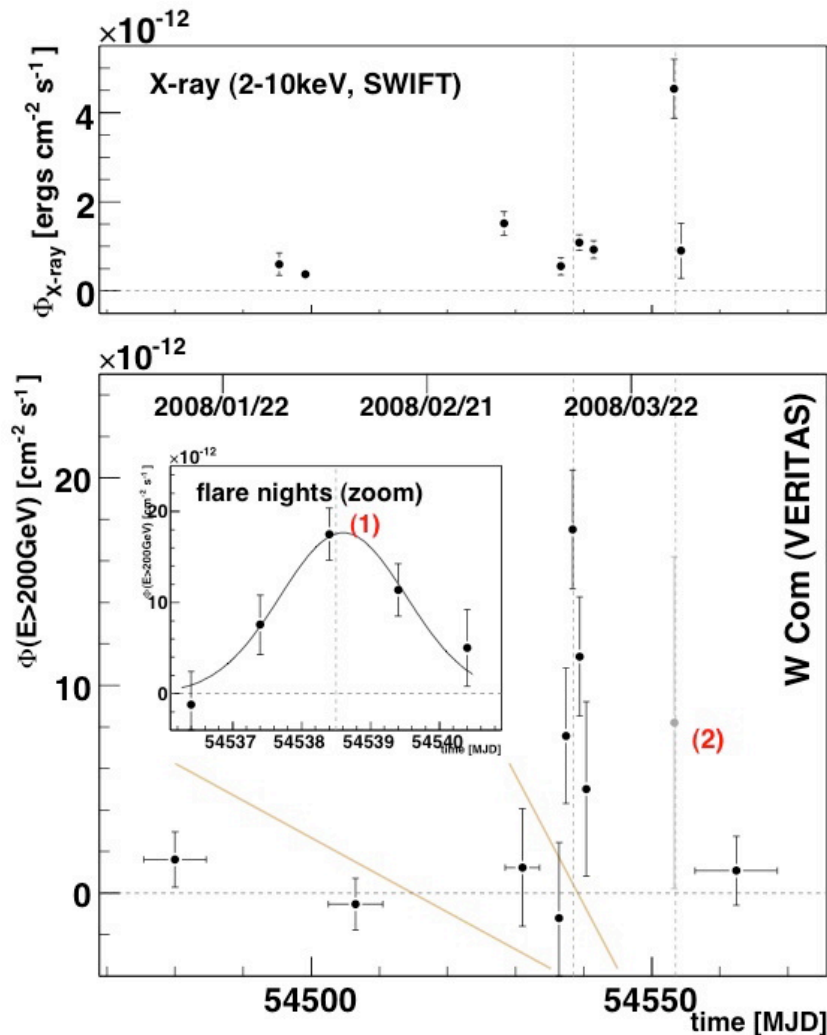
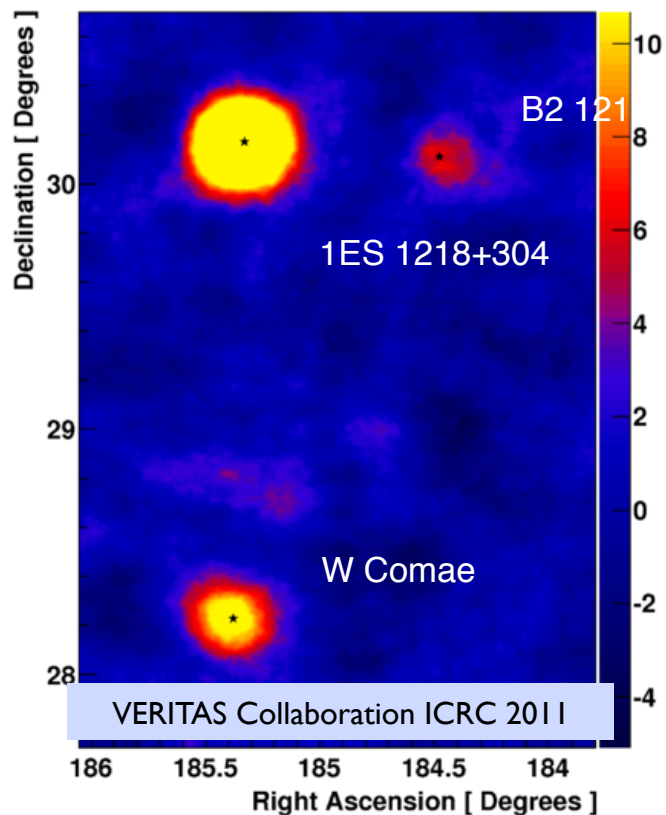
4. Identification of a Gamma Ray Binary



- HESS J0632+057: unidentified, located in the Monoceros region.
- Associated with massive Be star MWC 148.
- VHE & Swift X-ray data indicate that the source is a binary period of 315 days.
- VERITAS has more than 220 hours of observations.

5. IBLs: VERITAS Discovery of W Com

- Intermediate-peaked (IBL).
- First IBL to be detected > 200 GeV.
- Strong flare 2008 March (ATel 1422).

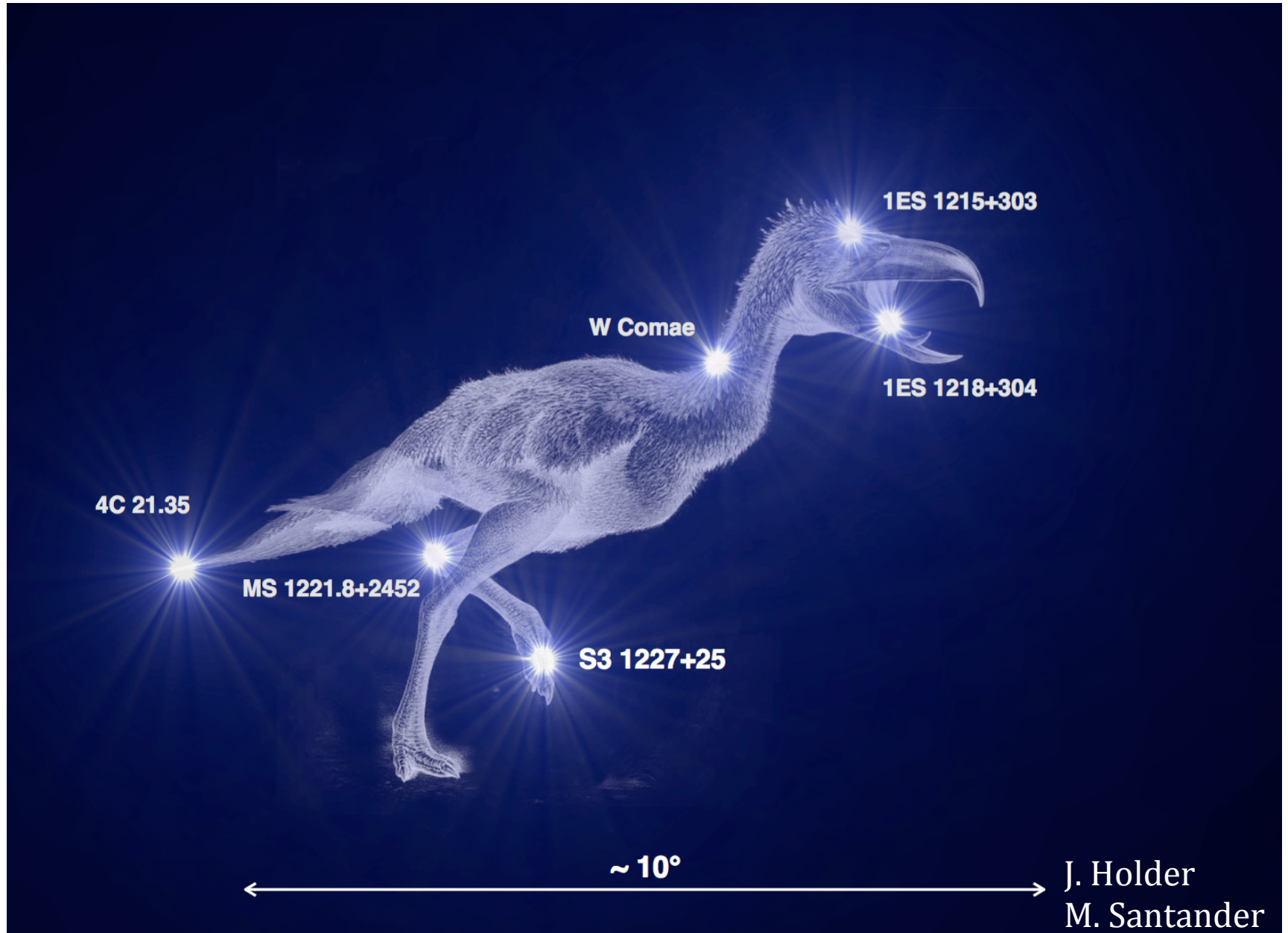


- 70% of excess from 4-night flare in 2008 March.
- $\tau \approx 1.3 \pm 0.3$ days, 9% CU.

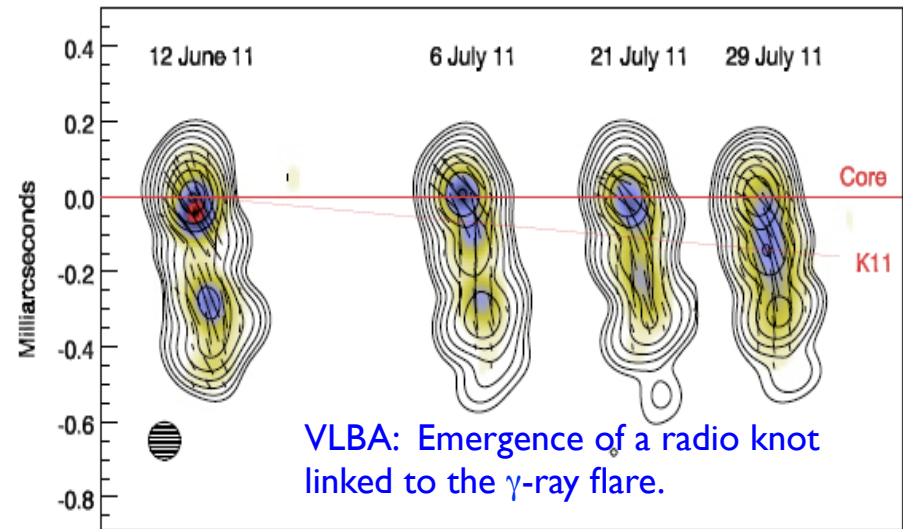
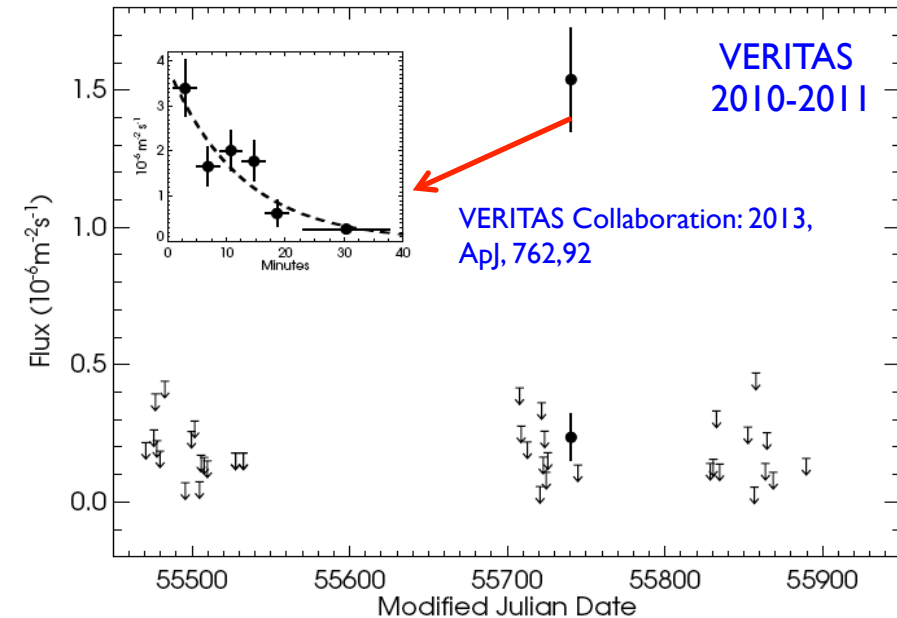
VERITAS Collaboration, 2008 ApJ 690, L73

2008

The Terabird – A VERITAS Constellation!



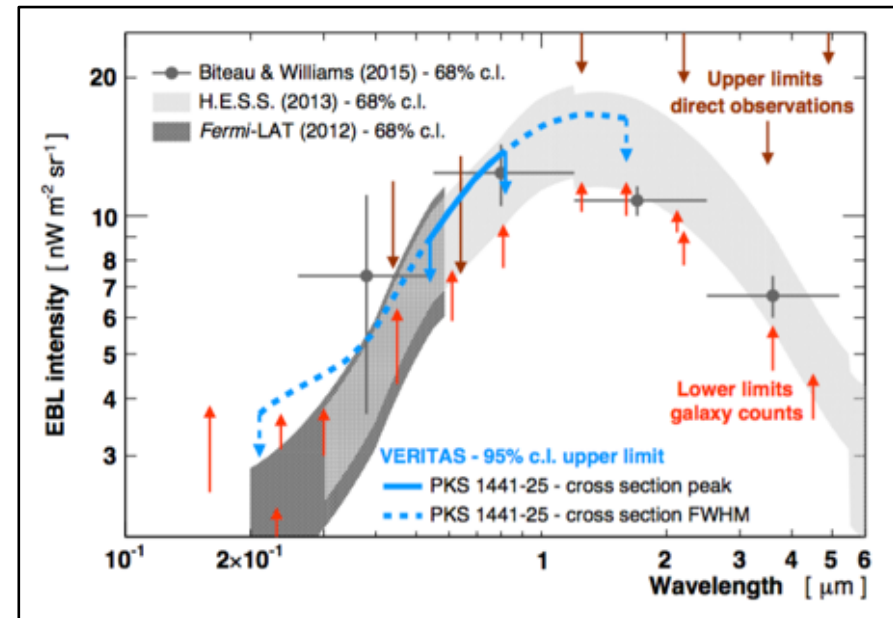
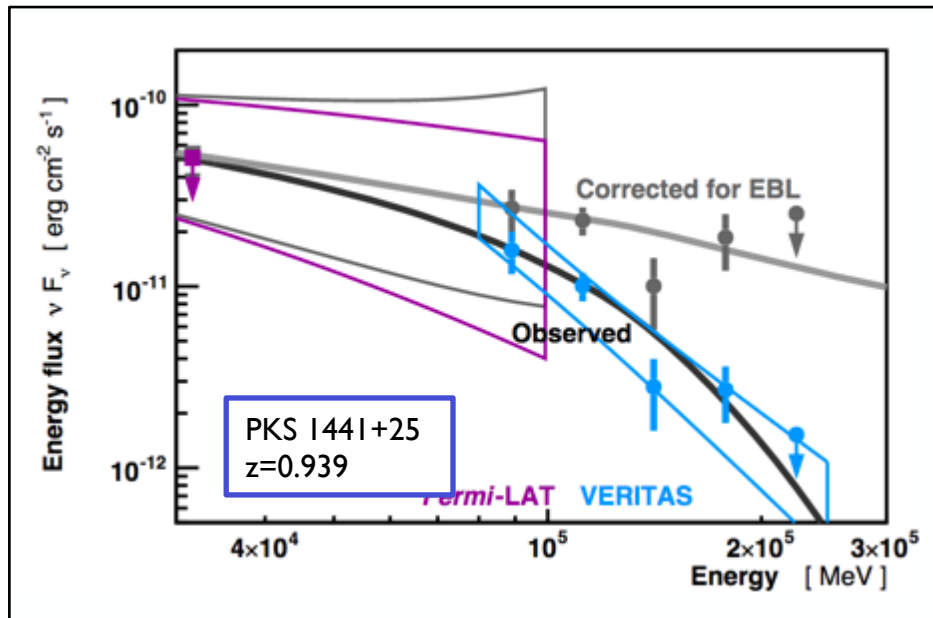
6. Locating the Emission Region in the Jet



- Flare on June 28, 2011 picked up by VERITAS monitoring; 125% Crab flux ($> 200 \text{ GeV}$)
- Flux decayed by factor of 10 in $\tau = 13 \pm 4 \text{ min}$
- Flares + MWL coverage provide remarkable tomography of jet.
- New SL component near core (43 GHz) - new knot K11, shows a different polarization position angle (20° compared with 44° for the core).

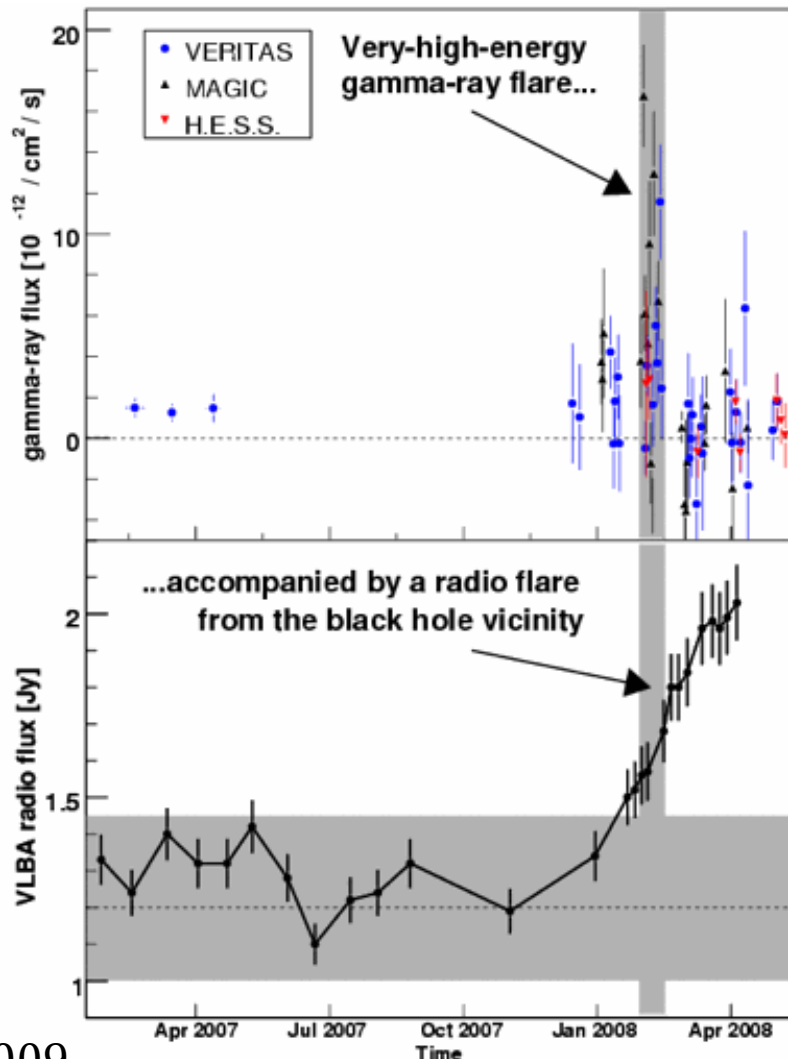
7. Discovery of TeV γ rays from a quasar at $z \sim 1$

- Above 10 GeV, gamma-ray photons are absorbed by pair production EBL.
- Powerful cosmological constraints from a single source.
- AGN with redshifts of ~ 1 have been detected by the current generation.
- 5% Crab flux (> 85 GeV). Gamma rays must be from outside BLR

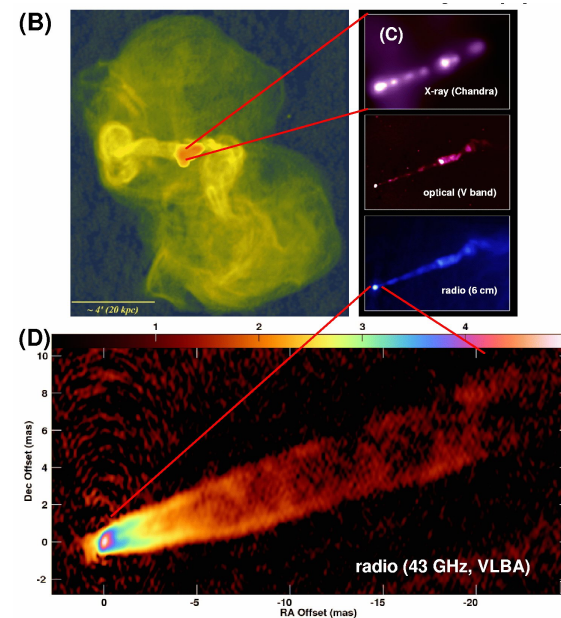


8. M 87: Gammas from the Edge of a Supermassive Black Hole

- High-resolution radio and gamma-ray observations reveal the site of relativistic particle acceleration in the galaxy M87.

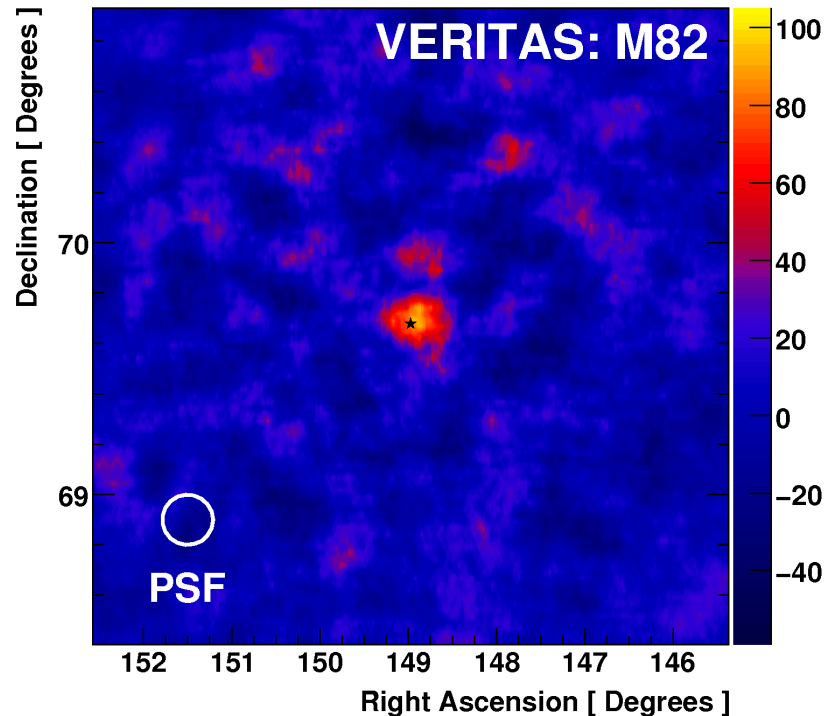


- A TeV flare occurred simultaneous with the birth of a knot in radio (VLBA) on the "rim" of the central supermassive black hole of M87.



Science, 325, 444, 2009 (The VERITAS Collaboration, VLBA, H.E.S.S. + MAGIC)

9. Discovery of TeV Gamma Rays from M 82



One of only two TeV starburst galaxies.

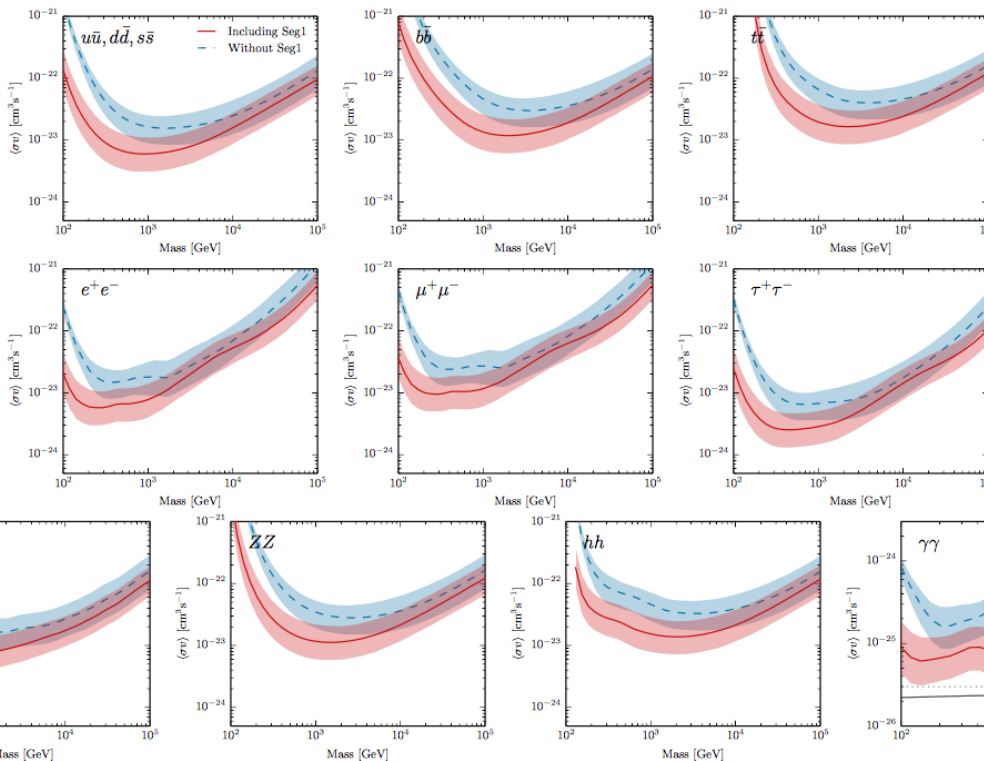
- Hard spectrum, emission > 700 GeV.
- Among the weakest VHE sources detected, $\sim 0.9\%$ Crab Nebula flux.
- Cosmic ray density $\sim 250 \text{ eV cm}^{-3}$ (~ 500 times average Galactic density).
- Strongly suggests supernova & stellar winds are the dominant accelerators of cosmic rays.

Astroparticle Physics, Cosmology

- Dark matter searches (Classical & ultra faint dwarf spheroidals; PRD 2017)
- Lorentz Invariance Violation (Energy dependent speed of light differences; targets – GRBs, pulse widths of γ -ray pulsars, AGN variability)
- Primordial Black Holes (could evaporate and produce bursts of VHE γ s)
- Extragalactic Background Light ($\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+ + e^-$)
- Intergalactic Magnetic Fields (look for pair cascades/halos; ApJ 2017)
- Direct Cherenkov emission (produced by the primary particle, CR heavy nuclei)
- Electron-positron measurements (Galactic CR studies)

10. A Decade of Dwarf Galaxy Observations: 2007 to 2017

- Indirect detection of dark matter is a key science program.
- Five dwarf galaxies observed: Segue I, Ursa Minor, Draco, Boötes and Willman I.



216 hours of data analyzed (92 hours on Segue I).

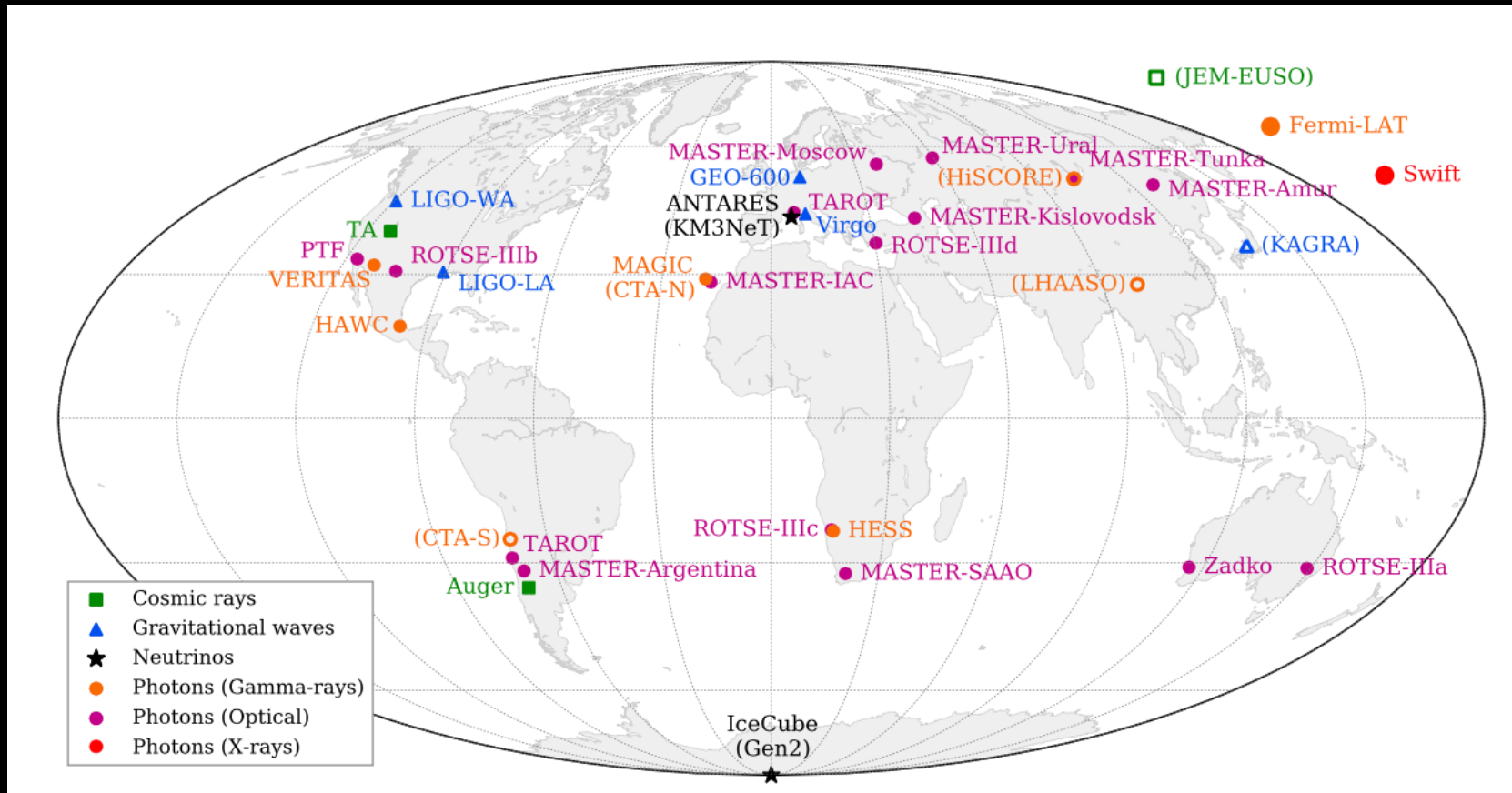
No significant γ -ray excess was seen in the direction of any of the five dSphs.

VERITAS Collaboration, PRD 2017, ICRC 2017



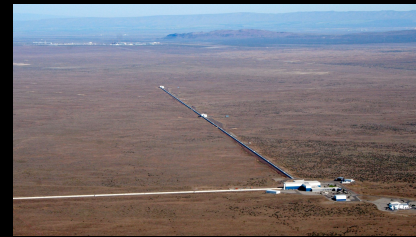
New Partners

Multi-Messenger Astronomy



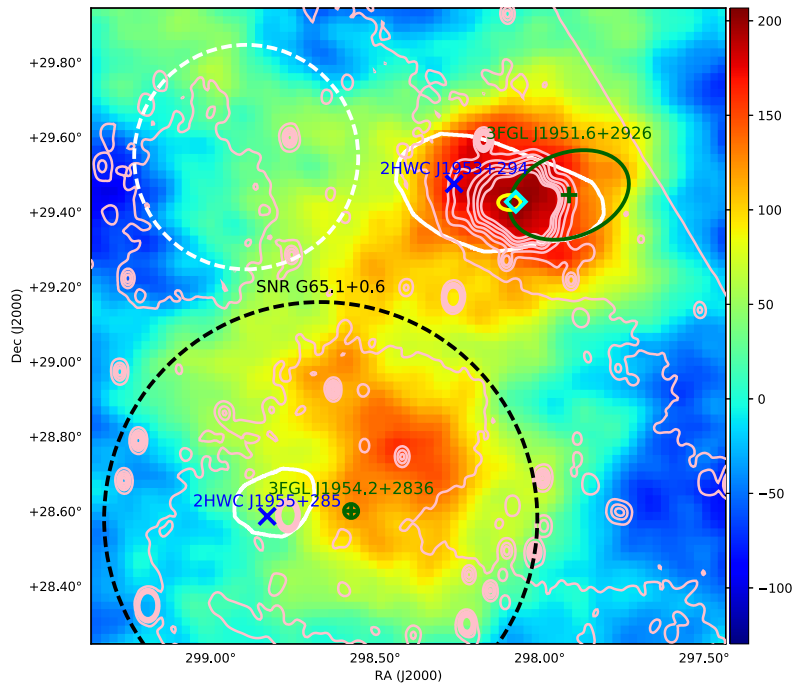
From “Dawn of Multi Messenger Astronomy,” Santander, 2016

VERITAS Multi-Messenger Program



- **Cosmic ray sources:** Follow up of HAWC sources of TeV γ rays.
- **Astrophysical Neutrinos:** Observation of IceCube neutrino positions. Prompt follow-up of neutrino alerts.
- **Gravitational Waves:** Planned follow-up observations of LIGO-VIRGO alerts.

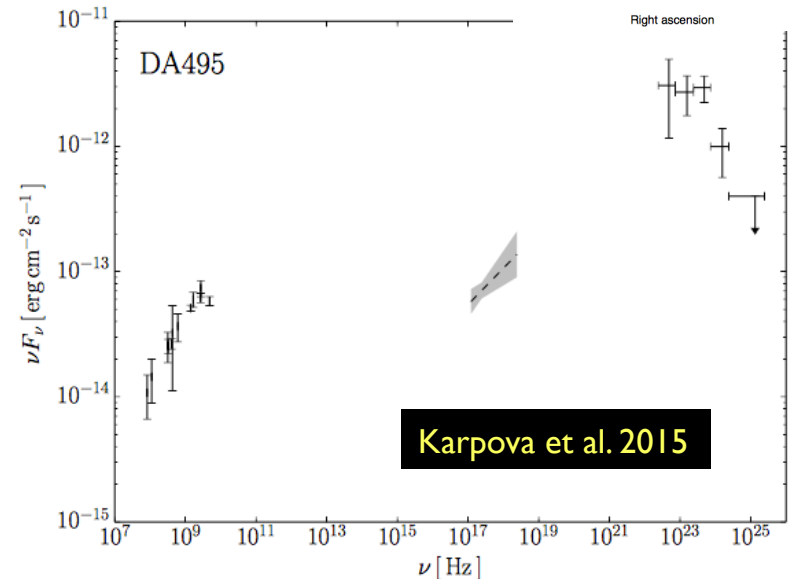
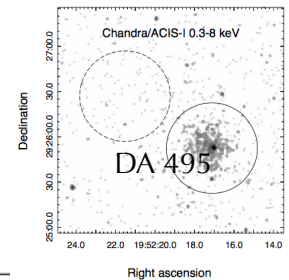
VERITAS: 2HWC J1953+294



- No pulsations detected from X-ray source. SED similar to typical PWNe such as G76.9+1.0 & MSH 11-62.
- Is the Fermi source associated with the pulsar or PWN?

VERITAS Collaboration, ICRC 2017

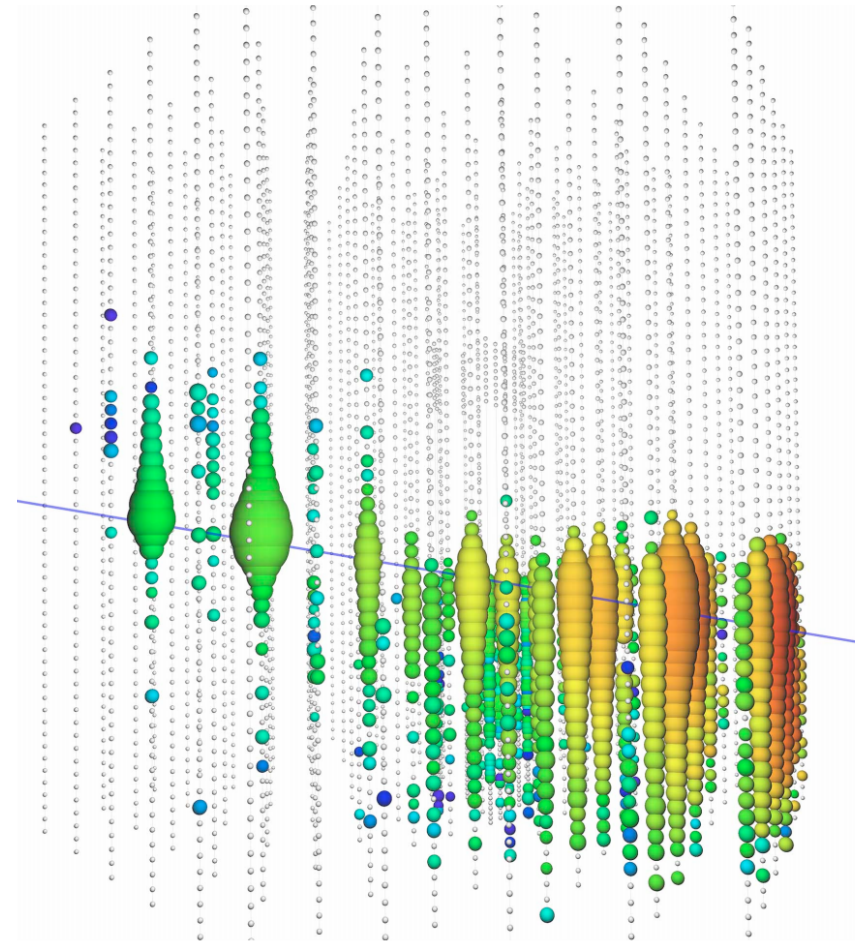
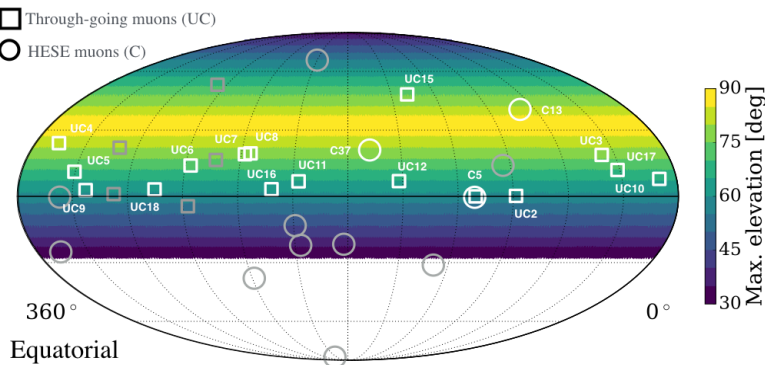
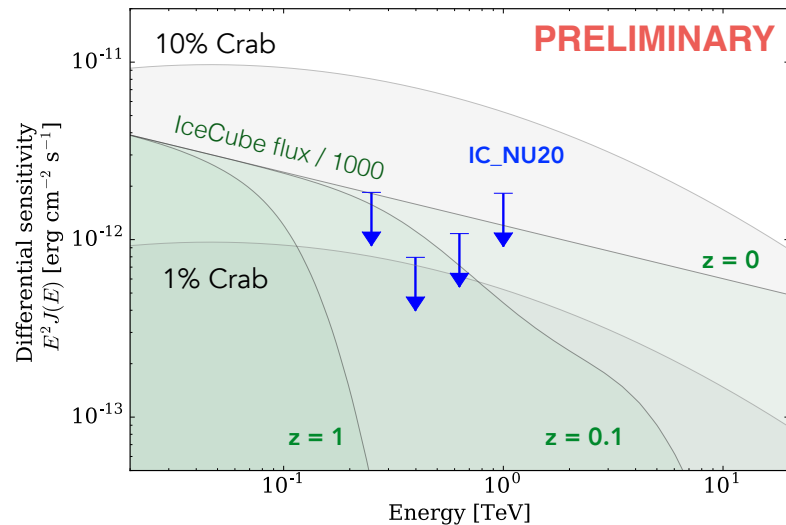
- VERITAS confirms HAWC detection.
- Nearby PWN DA 495(G65.7+1.2 – Galt & Kennedy 1968) is likely counterpart.
- XMM/Chandra source J1952.2+2925 possibly a pulsar, likely associated with 3FGL J1951.6+2926.



VERITAS IceCube Neutrino Follow-up

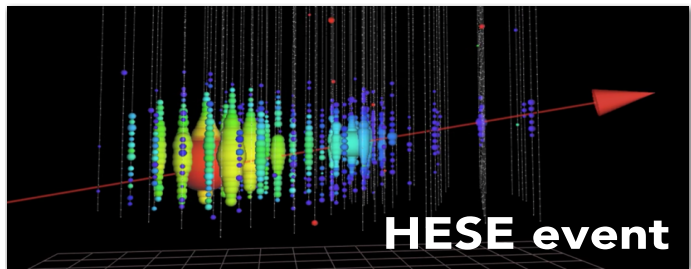
- Observation of multi-PeV muon positions
- Total of **~64 hours** have been taken on 28 HE muon neutrino events
(non-contemporaneous, time scale years).

IceCube Collab. (2016)
[arxiv/1607.08006](https://arxiv.org/abs/1607.08006)



VERITAS IceCube Neutrino Follow-up

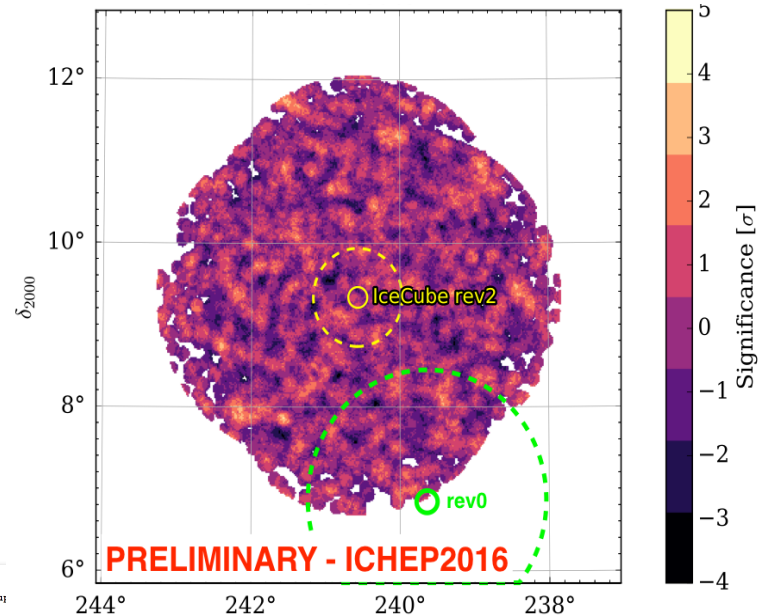
- Real-time follow-up of IceCube alerts with VERITAS (time scale seconds).
 - GCN events through AMON.
- Multi-wavelength follow-up of rare IceCube neutrino multiplet (Feb 2016) (time scale weeks). (arXiv:1702.06131).



04/27/2016 AMON GCN Circular

TITLE: GCN CIRCULAR
NUMBER: 19363
SUBJECT: ICECUBE-160427A neutrino candidate event: u
DATE: 16/04/29 16:29:47 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufu@umd.edu>

IceCube detected a candidate cosmic neutrino IceCube-160427A on 16/04/27 (http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon). The event was a high-energy neutrino candidate with track-like characteristics and it arrived when the IceCube detector was in a normal operating state. More sophisticated reconstruction algorithms have been applied offline, with the direction refined to RA=240.57d and DEC=+9.34d and the position uncertainty reduced to an estimated 0.6 degrees or 36 arcminutes radius (stat+syst, 90% containment). We encourage by ground and space-based instruments to help identify a possible astrophysical source for the neutrino.



VERITAS follow-up

TITLE: GCN CIRCULAR
NUMBER: 19377
SUBJECT: VERITAS rapid follow-up observations of IceCube event 160427A
DATE: 16/05/03 00:39:16 GMT
FROM: Reshmi Mukherjee at Columbia U/VERITAS <muk@astro.columbia.edu>

Title: GCN CIRCULAR
Subject: VERITAS rapid follow-up observations of IceCube event 160427A
From: VERITAS Collaboration

On April 27th, 2016, the IceCube collaboration reported the detection of a high-energy neutrino of potential astrophysical origin (GCN #19363). The neutrino event (run ID: 127853, event ID: 67093193) was detected at 05:52:32 UTC and follow-up observatories, VERITAS among them, were notified at 05:53:53 through a GCN/AMON notice. See http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon for details.

VERITAS performed follow-up observations of the alert position (RA: 239.6639°, Dec: 6.8528°, in J2000 coordinates) between 05:55:45 UTC, 193 s after the neutrino detection, and 07:39:36 UTC in normal "wobble" mode, where the pointing direction of the telescope is offset from the source

<http://gcn.gsfc.nasa.gov/gcn3/19377.gcn3>

Detection: 05:52:32 UT

Alert sent: 05:53:53 UT

Follow-up start: 05:55:45 UT

112 seconds

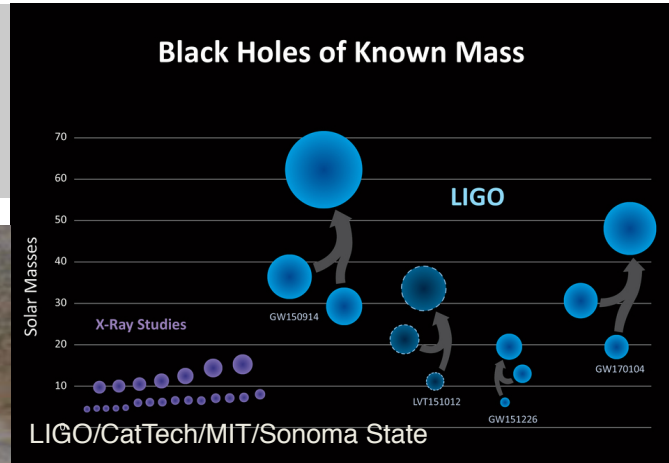
LIGO Gravitational Wave Follow Up

1 June 2017: GW170104 Press Release

LIGO Detects Gravitational Waves for Third Time
Results confirm new population of black holes.



Abbott et al., PRL 2017



VERITAS carried out follow up observations on UT Jan 5

TITLE: GCN CIRCULAR

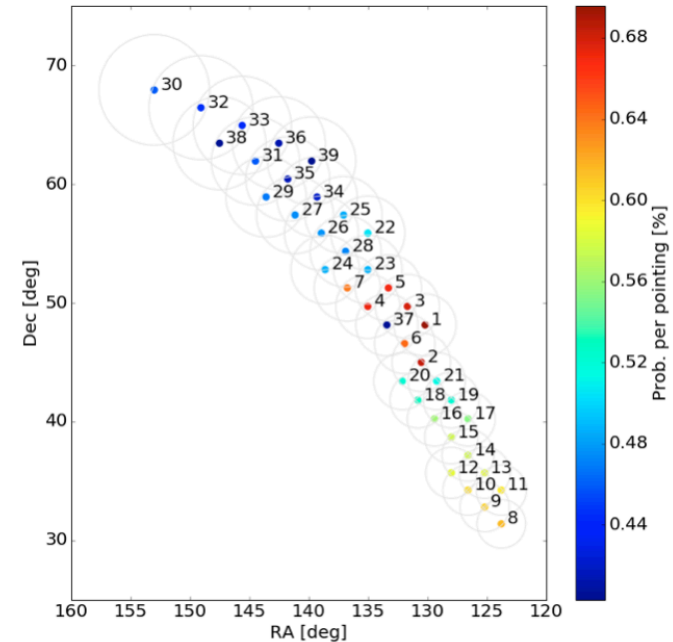
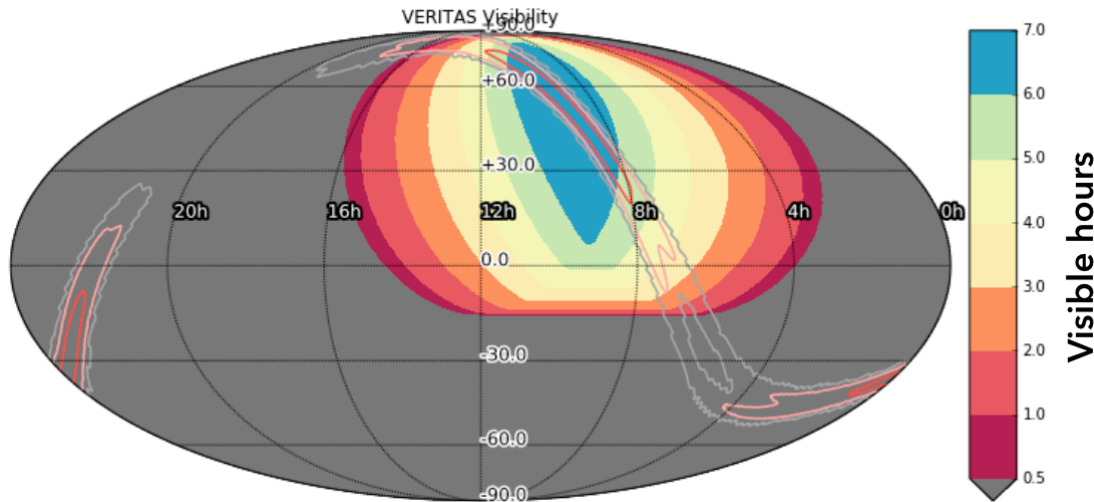
NUMBER: 21153

SUBJECT: LIGO/Virgo G268556: VERITAS Very-High-Energy Gamma-Ray Observations

DATE: 17/05/27 00:20:02 GMT

FROM: David A. Williams at UC Santa Cruz <daw@ucsc.edu>

LIGO Gravitational Wave Follow Up

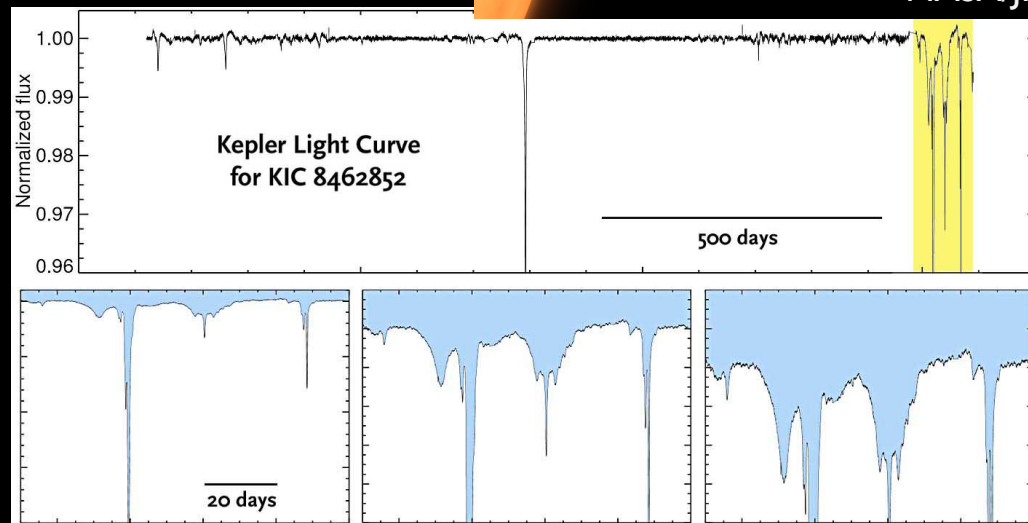
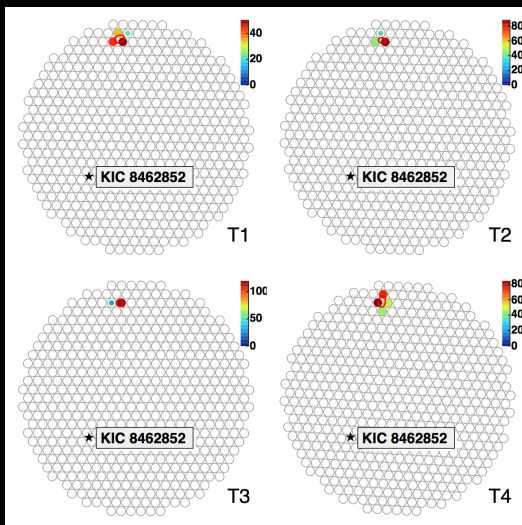
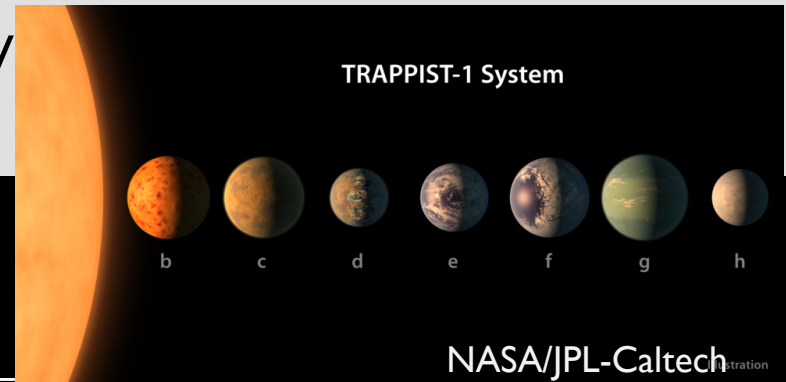


- Observable at $> 50^\circ$ elevation from the VERITAS site.
- 39 consecutive exposures performed to tile the localization region.
- Each pointing observed 5 min. Avg spacing between pointings 1.83° .
- Observations cover $\sim 27\%$ of the containment probability of the event.

VERITAS: Exploring new ideas

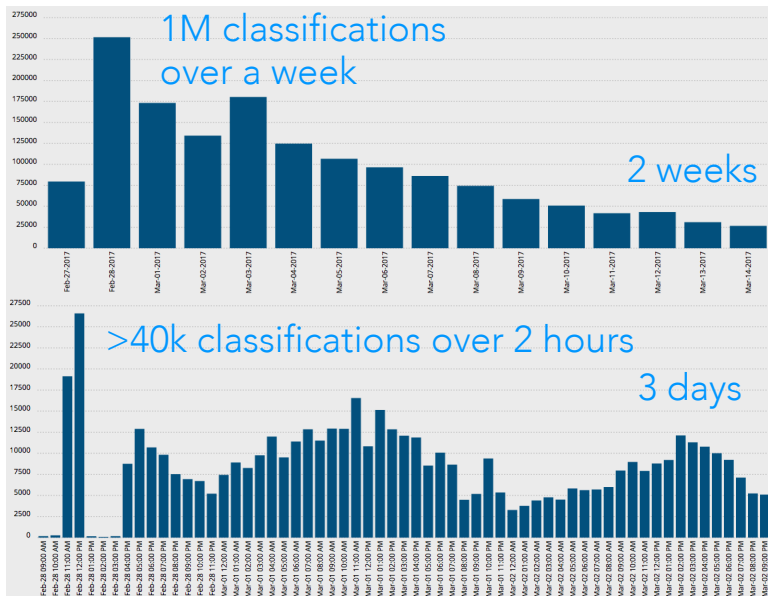
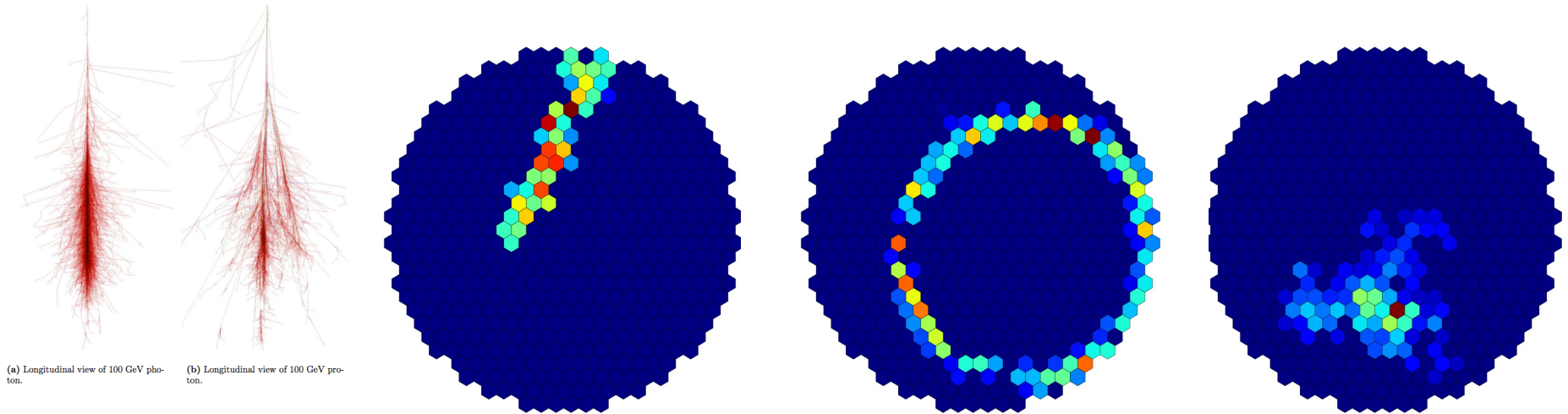
- A Search for Brief Optical Flashes Associated with the SETI Target KIC 8462852 (VERITAS Collaboration: arXiv:1602.00987).
- Testing optical photometry (Data taken on Z V
- Data taken on TRAPPIST-I.

VERITAS: looking for very short timescale astrophysical phenomena.



Boyajian et al. MNRAS 2015

Citizen Science: Muon Hunter

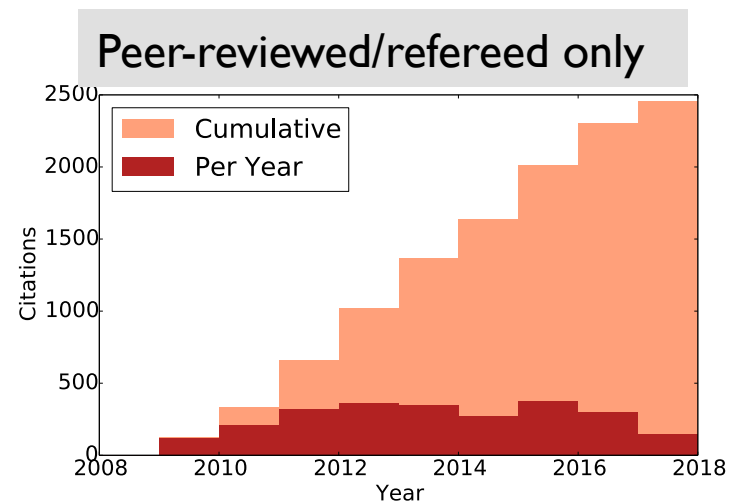
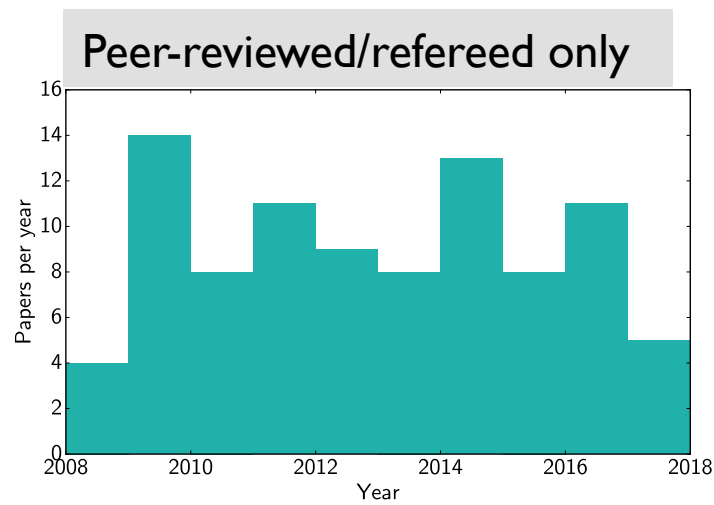


- A citizen science project hosted on the Zooniverse platform.
- VERITAS data are classified multiple times by individual users in order to select and parameterize muon events.
- Use this dataset to train and validate a convolutional neural-network model.

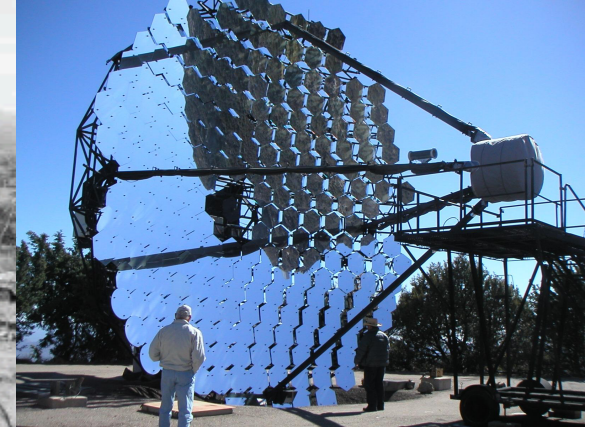
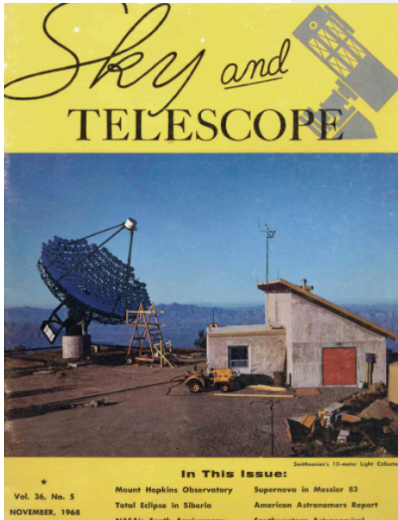
VERITAS by the Numbers

It has been an outstanding ten years.

- 90 authors at the 2007 ICRC
- 92 authors at the 2015 ICRC
- 55 Ph.D.Theses (since 2006)
- 90 peer-reviewed publications (since 2007)



1967 - 2017



Standing on the shoulders of giants



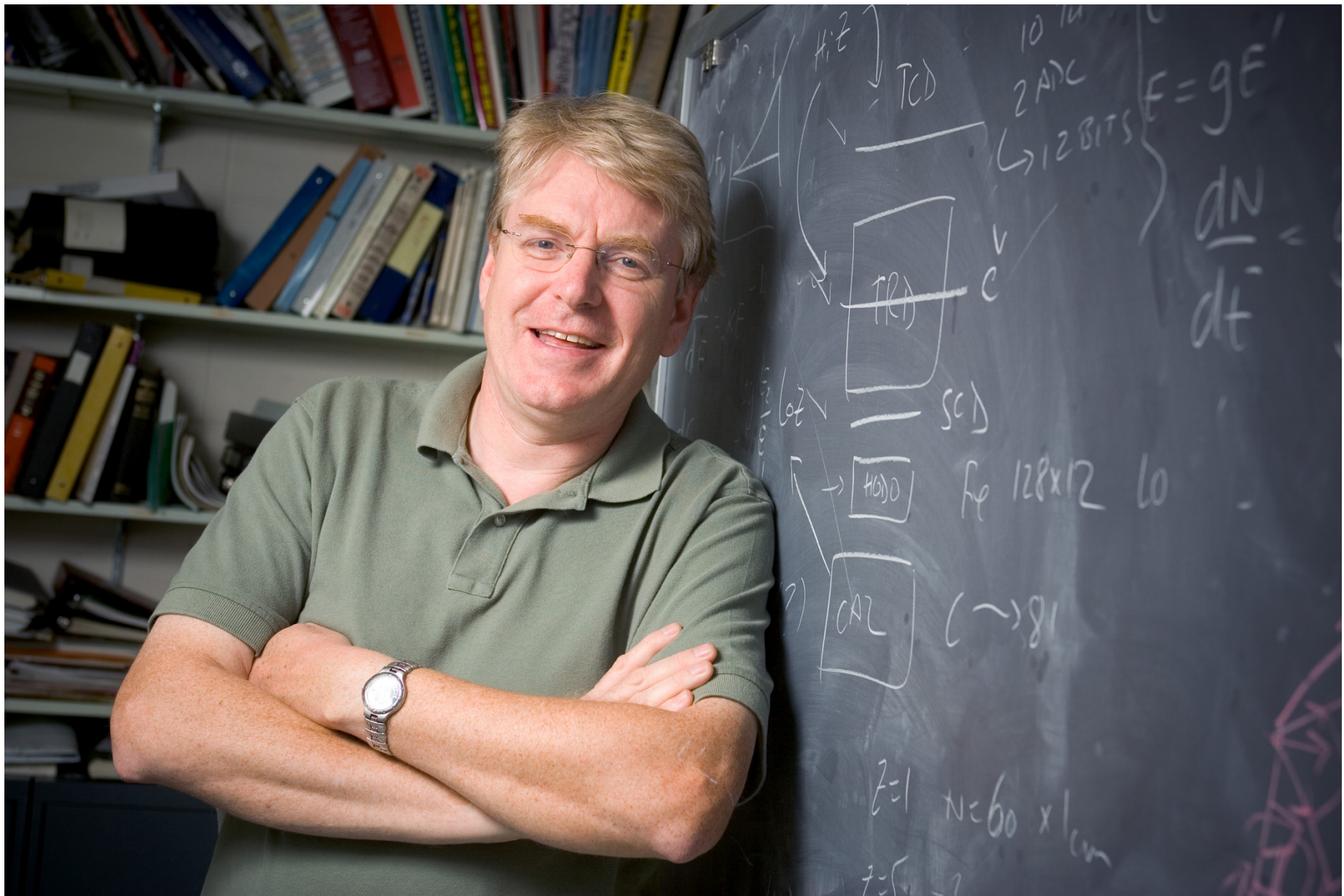
Dan Harris, 1934-2015



John Huchra, 1948-2010



Alexander Konopelko, 1962 - 2012



Simon Swordy, 1954-2010



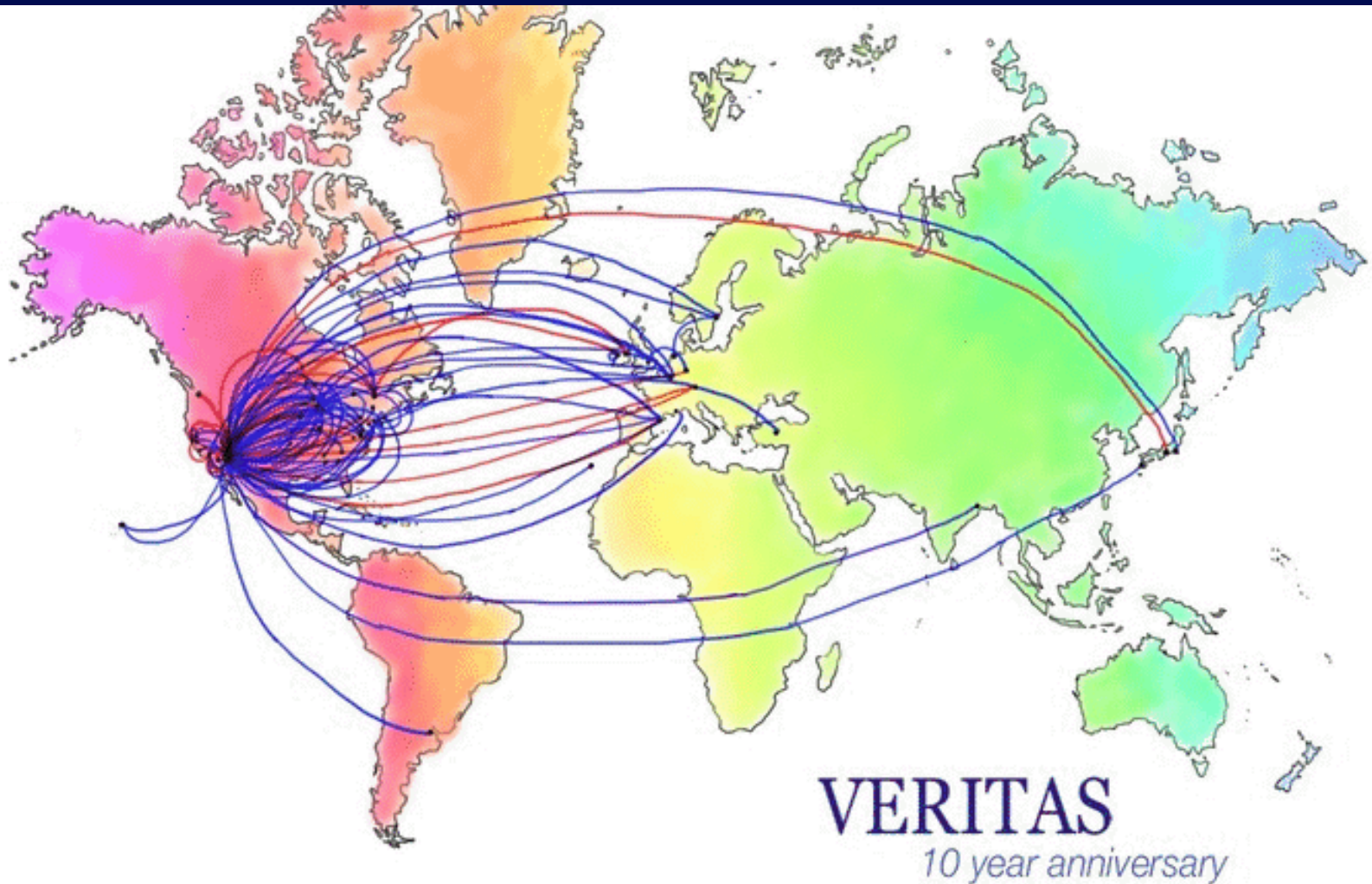
Trevor Weekes, 1940-2014

The Current People of VERITAS



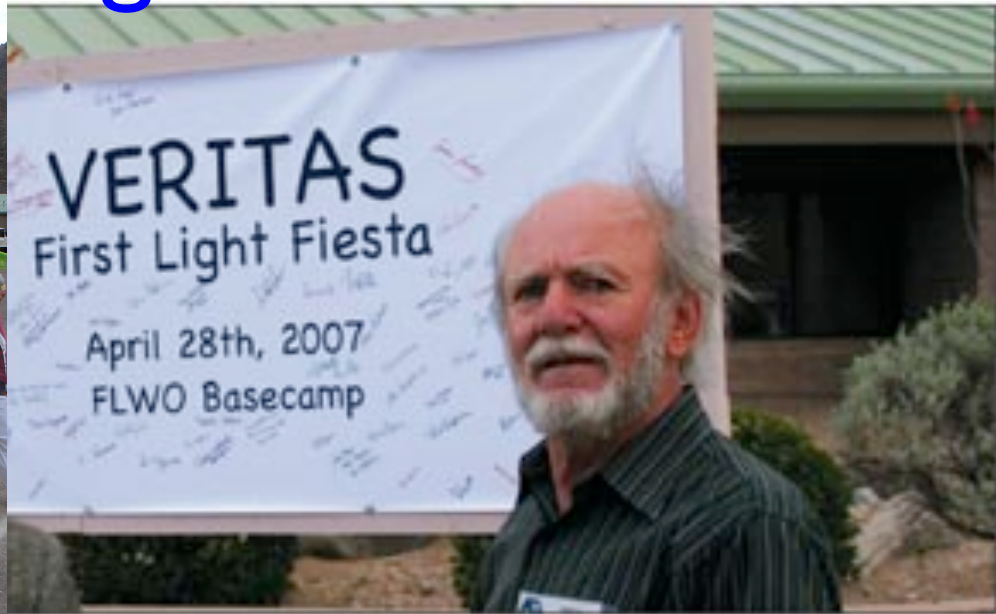
c. 2017. Please let me know if I missed someone.

VERITAS Students and Postdoc Journeys



Reshmi Mukherjee 2017

Celebrating 10 Years



Thank you for
celebrating with us.

Thank You

- To our funding agencies

U.S. National Science Foundation

U.S. Department of Energy Office of Science

The Smithsonian Institution

NSERC in Canada

Science Foundation Ireland

Irish Research Council



U.S. DEPARTMENT OF
ENERGY



- Thanks to Project Office staff for exceptionally smooth operations
- Thanks to all our University Groups
- The VERITAS ESAC (External Science Advisory Council)

Backup