Highlights of The Very Energetic Radiation Imaging Telescope Array System (VERITAS)

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On behalf of the VERITAS Collaboration

Talk Outline

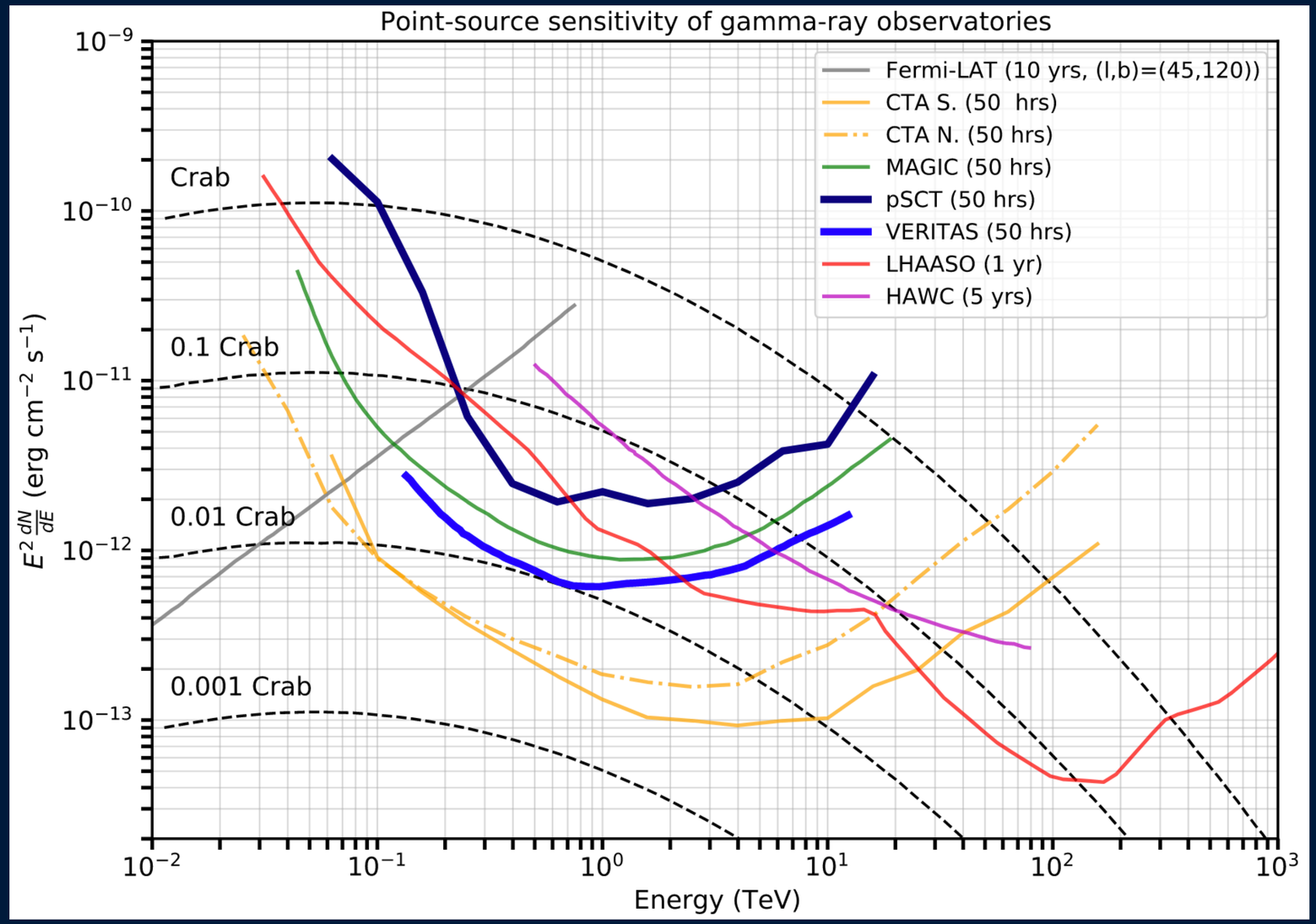
1. What is VERITAS - Performance and Science Program
2. Galactic Science Topics
3. AGN Science Topics
4. Astroparticle Physics
5. Transients and Multi-Messenger Astronomy
6. Optical Capabilities
7. Future Plans

VERITAS

Energy Range	85 GeV - 30 TeV
Angular Resolution (R_{68}%)	< 0.1° @ 1 TeV
Pointing accuracy	< 50''
Effective Area	~10^5 m^2 @ 1 TeV
Field-of-view	3.5°

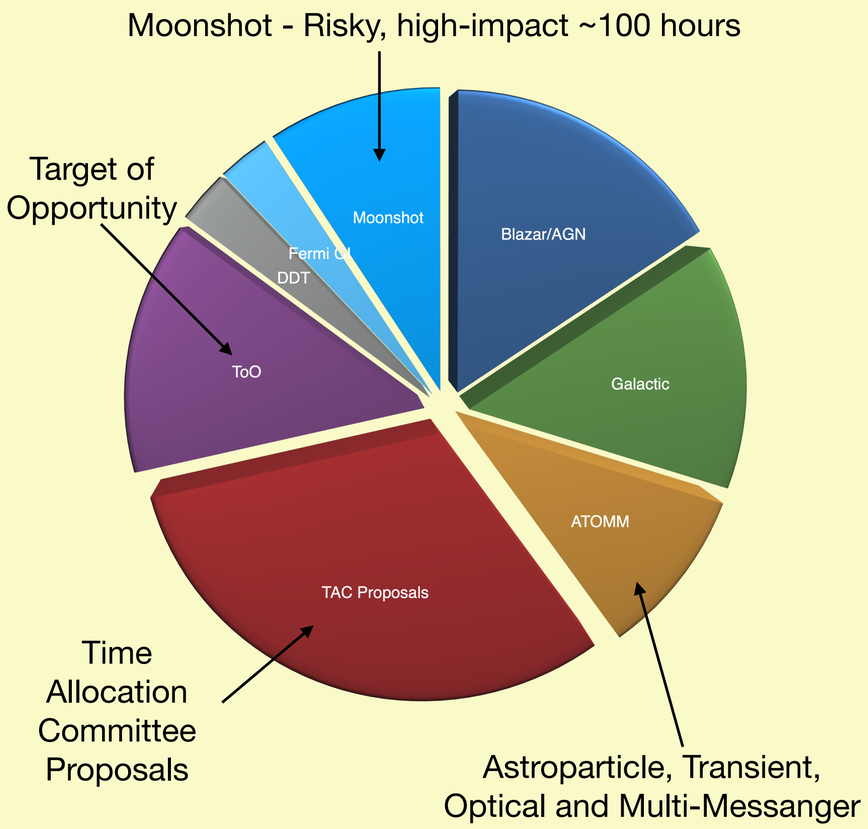
- Array of four 12m IACTs
- Located at Fred Lawrence Whipple Observatory (FLWO) in southern Arizona USA (31 40N, 110 57W, 1.3 km a.s.l.)
- Key dates:
  - 2007 - Start of full 4-telescope operations
  - 2009 - Relocation of T1 to improve array symmetry (increased sensitivity)
  - 2009 - Improved mirror alignment system (reduce PSF by 30%, increased sensitivity)
  - 2011 - Trigger system upgraded (increased sensitivity)
  - 2012 - Camera upgrade (reduced energy threshold)
  - 2019 - Inauguration of prototype Schwarzschild-Couder Telescope (pSCT)
- Funded through 2022
- In it's current configuration VERITAS can detect (5σ) a 1% Crab source in 25 hours

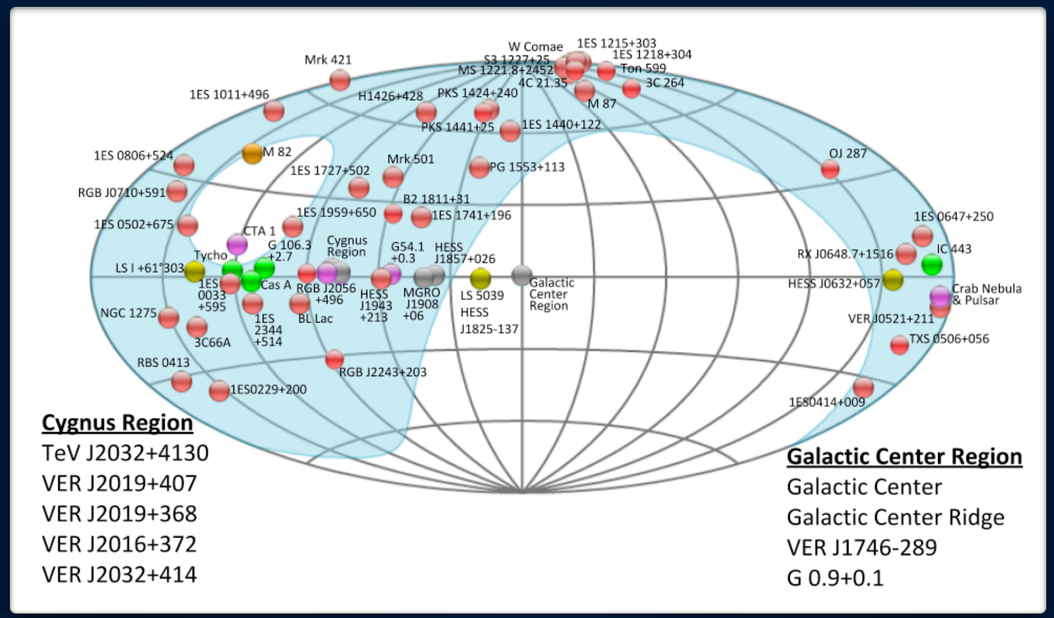
VERITAS


Point-source sensitivity of gamma-ray observatories
Fermi-LAT (10 yrs, (l,b)=(45,120))
CTA S. (50 hrs)
CTA N. (50 hrs)
MAGIC (50 hrs)
pSCT (50 hrs)
VERITAS (50 hrs)
LHAASO (1 yr)
HAWC (5 yrs)
Crab
0.1 Crab
0.01 Crab
0.001 Crab
$E^2 \frac{dN}{dE}$ (erg cm^{-2} s^{-1})
Energy (TeV)

VERITAS Observing Program

Typical Observing Plan

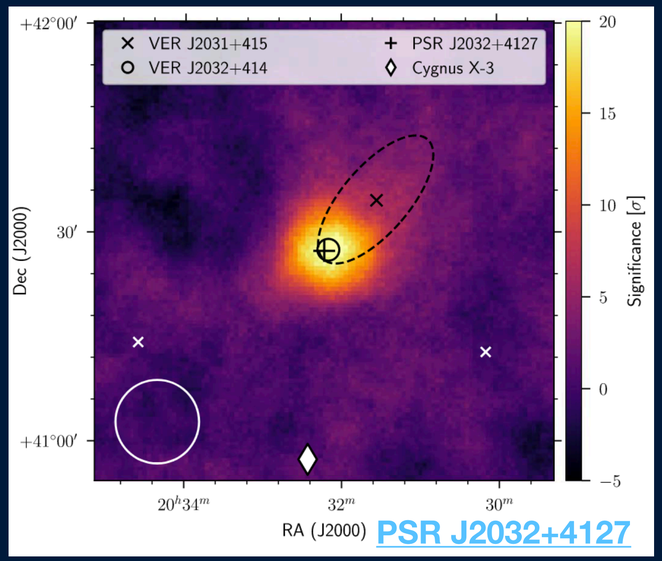




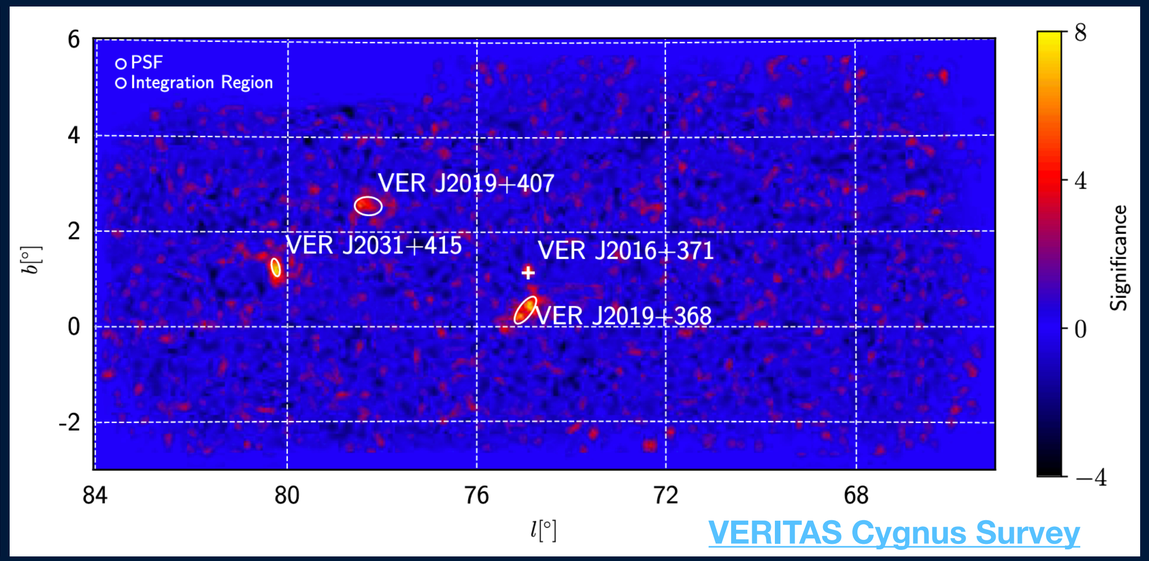
AGN
PWN
SNR
Starburst Galaxy
Binary/PSR
Unidentified

- Diverse observing program
- Nominal season operates from September to July (Monsoon season)
- Take ~950 hours of good-weather data (additional 250 hours bright moon)
- Dynamic observing program by design:
  - Long term science programs
  - Yearly TAC process
  - Dedicated ToO/DDT time
  - Moonshots - Risky, high-impact observations

Galactic Science

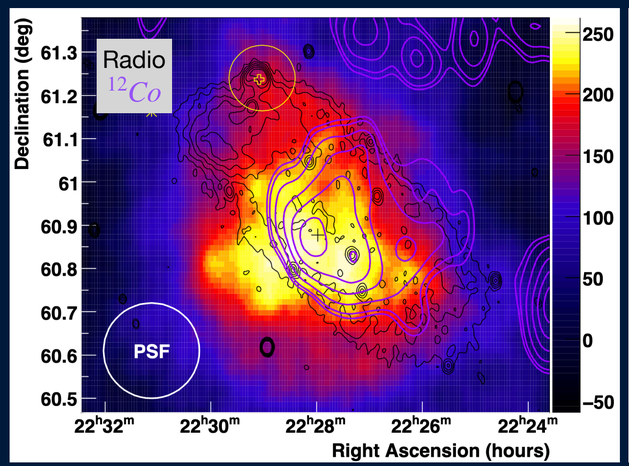


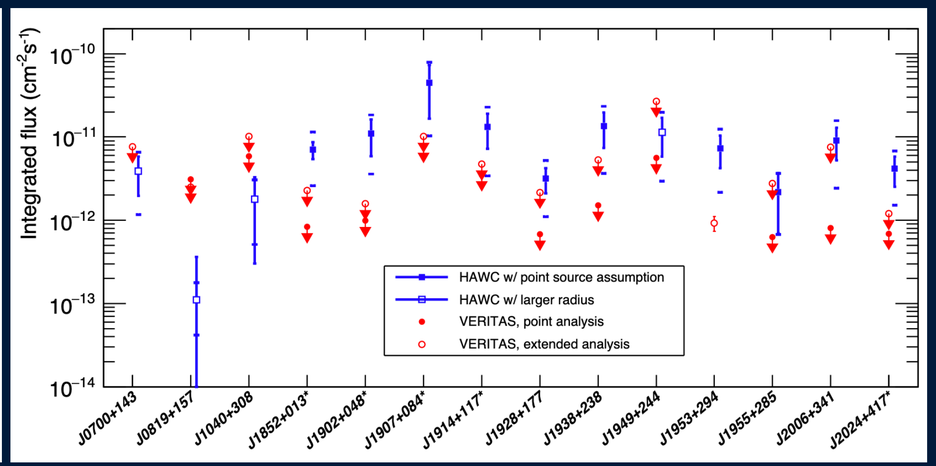
PSR J2032+4127



VERITAS Cygnus Survey

- Gamma-ray binaries
  - Resolving phase-wise spectra
  - Studying orbit-to-orbit variability
  - Identifying emission zones
- Searching for PeVatrons
  - Resolving emission regions
  - Studying energy dependant morphology
  - HAWC/LHAASO follow-up
- Galatic Cosmic Rays
  - Cosmic ray acceleration SNRs/PWNe
  - Cosmic ray diffusion
- Diffuse Gamma-ray emission
  - Galactic centre region





VERITAS observations of Boomerang/G106.3+27 VERITAS & Fermi-LAT follow-up HAWC sources

Galactic Centre

- 125 hours of data taken between 2010-2018
- Observations at large zenith angles -> boost high-energy sensitivity
- Spectral study of multiple sources within region:
  - Sgr A*
  - G0.9+0.1
  - HESS J1746-285
  - Galactic Diffuse
- Diffuse emission consistent with presence of a PeVatron.

THE ASTROPHYSICAL JOURNAL

VERITAS Observations of the Galactic Center Region at Multi-TeV Gamma-Ray Energies

C. B. Adams[1], W. Benbow[2], A. Brill[3], R. Brose[4], M. Buchovecky[5], M. Capasso[1], J. L. Christiansen[6], A. J. Chromey[7], M. K. Daniel[2], M. Errando[8] + Show full author list

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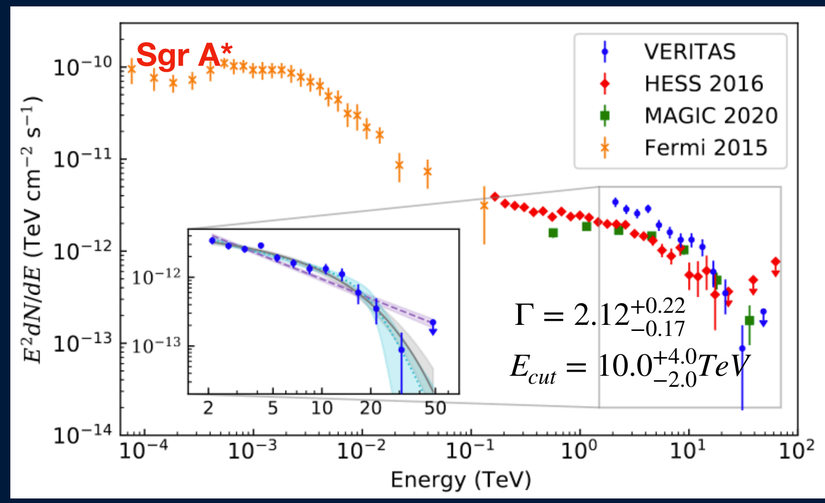
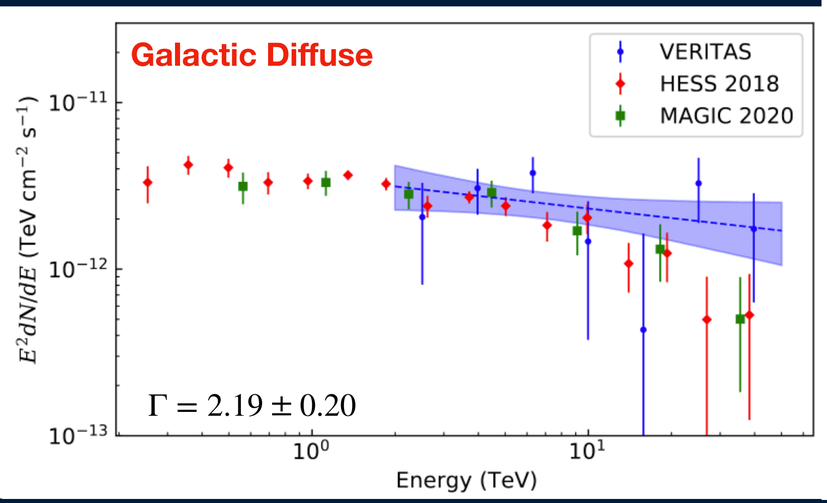
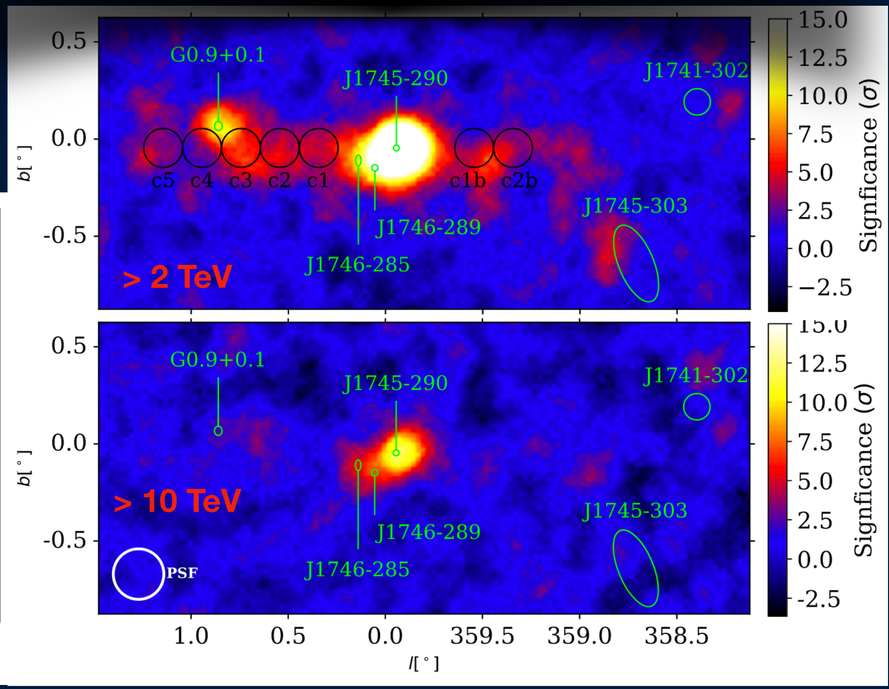
The Astrophysical Journal, Volume 913, Number 2

Citation C. B. Adams *et al* 2021 *ApJ* **913** 115





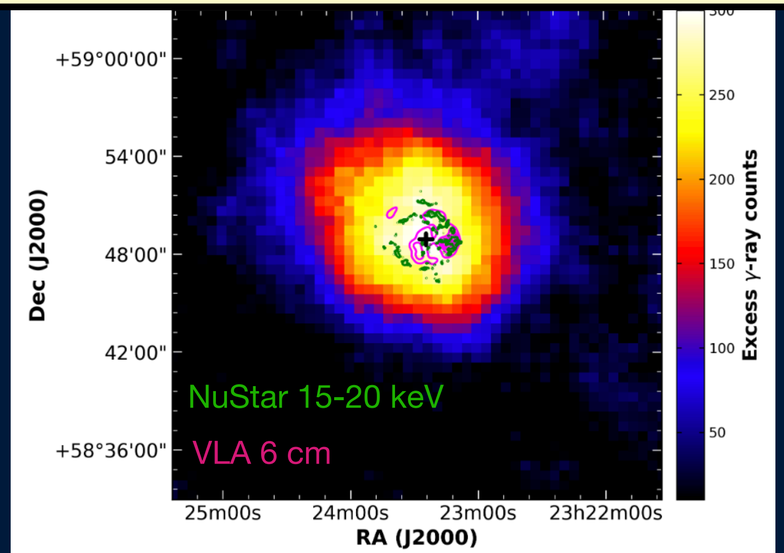


Cas A

- Cas A core collapse supernova remnant
- 65 hours of VERITAS data and 10.8 years Fermi-LAT data
- Energy Spectrum in the 0.1 GeV - 10 TeV range
  - Significant curvature at 1.3 ± 0.4 GeV (pion decay)
  - Spectrum above 1 GeV consistent with ECPL:

$$\Gamma = 2.17 \pm 0.02,\ E_{cut} = 2.31 \pm 0.51 \text{ TeV}$$

- Pure leptonic model ruled out
- Requirement of proton acceleration up to TeV energies



THE ASTROPHYSICAL JOURNAL

Evidence for Proton Acceleration up to TeV Energies Based on VERITAS and Fermi-LAT Observations of the Cas A SNR

A. U. Abeysekara[1], A. Archer[2], W. Benbow[3], R. Bird[4], R. Brose[5,6], M. Buchovecky[4], J. H. Buckley[7], A. J. Chromey[8], W. Cui[9,10], M. K. Daniel[3] + Show full author list

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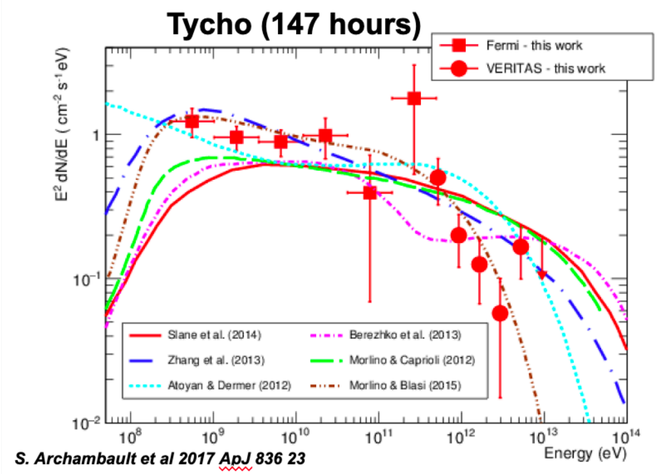
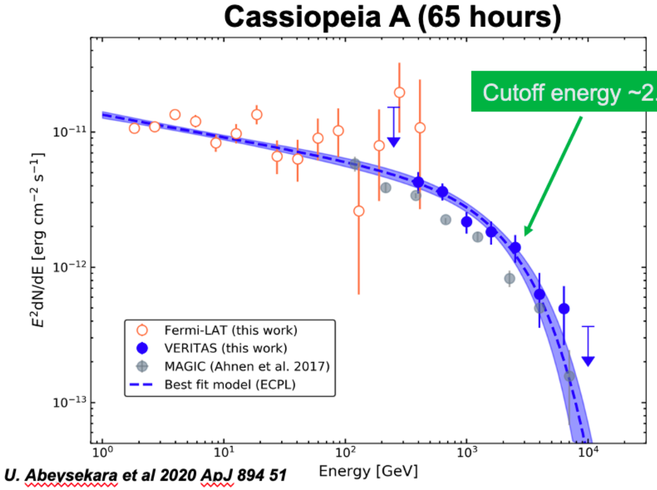
The Astrophysical Journal, Volume 894, Number 1

Citation A. U. Abeysekara *et al* 2020 *ApJ* **894** 51



S. Archambault et al 2017 ApJ 836 23



A. U. Abeysekara et al 2020 ApJ 894 51

- Both show spectral cutoffs in the TeV range
- Not today's PeVatrons, but (almost certainly) hadronic accelerators
- PeV particles have escaped – where can we find them?

HESS J0632+057

Astrophysics > High Energy Astrophysical Phenomena

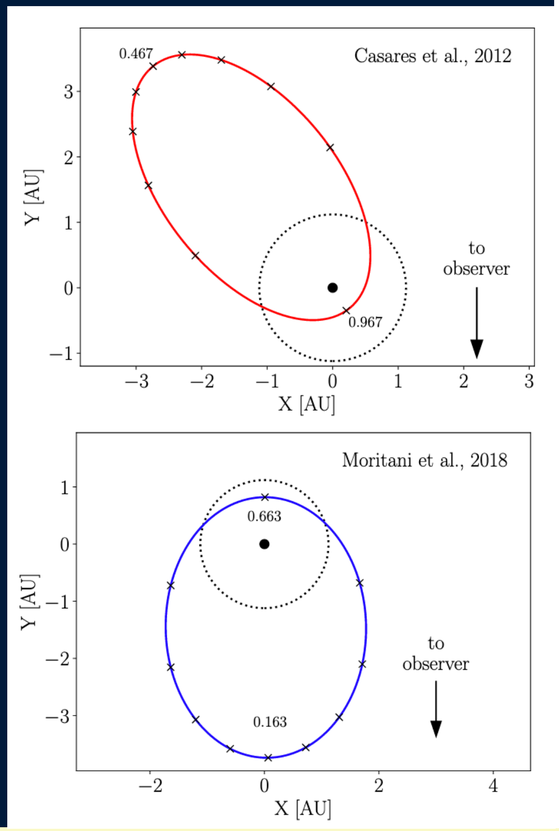
Accepted for publication in ApJ

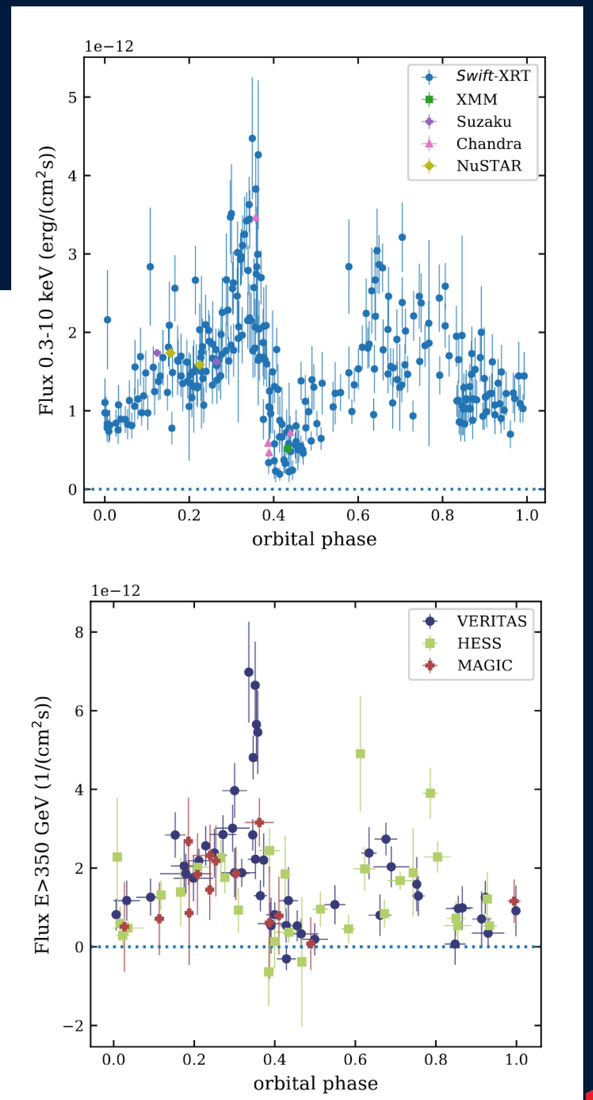
[Submitted on 24 Sep 2021]

Observation of the gamma-ray binary HESS J0632+057 with the H.E.S.S., MAGIC, and VERITAS telescopes

C. B. Adams, W. Benbow, A. Brill, J.H. Buckley, M. Capasso, A. J. Chromey, M. Errando, A. Falcone, K. A. Farrell, Q. Feng, J P. Finley, G. Foote, L. Fortson, A. Furniss, A. Gent, G. H. Gillanders, C. Giuri, O. Gueta, D. Hanna, T. Hassan, O. Hervet, J. Holder, B. Hona, T.B. Humensky, W. Jin, P. Kaaret, M.

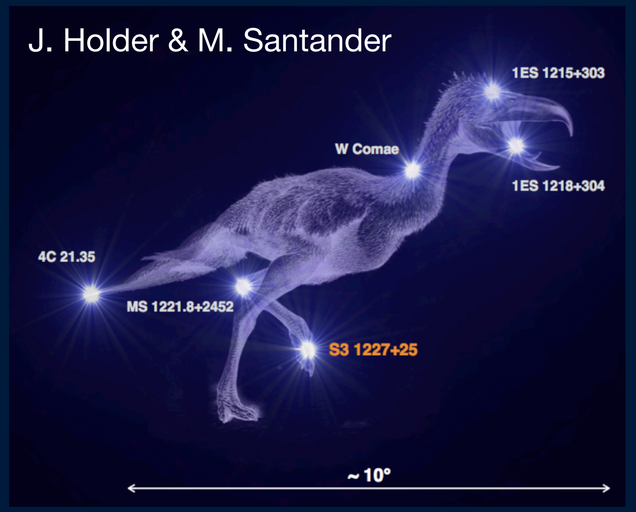
- Binary system with a Be Star and unknown compact companion.
- Multi-collaboration study (VERITAS, MAGIC, H.E.S.S.)
- 15 years of VHE observations combined with X-ray data (Swift-XRT, Chandra, XMM-Newton, NuSTAR and Suzaku)
- Independent measurement of period using gamma-ray data - 316.7 ± 4.4 days
- Dense orbital sampling
- Orbit-to-orbit variations observed





AGN Science

Blazar	Class	Redshift
Mrk 421	HBL	0.031
Mrk 501	HBL	0.034
1ES2344+514	HBL	0.044
1ES 1959+650	HBL	0.048
1ES 1727+502	HBL	0.055
BL Lac	IBL	0.0688
1ES 1741+196	HBL	0.084
W Comae	IBL	0.102
VER J0521+211	IBL	0.108
B2 1811+31	IBL	0.117
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
B2 1215+30	IBL	0.131
S3 1227+25	IBL	0.135
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.140
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.184
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
MS1221.8+2452	HBL	0.218
1ES 0414+009	HBL	0.287
OJ 287	LBL	0.306
TXS 0506+056	HBL	0.3365
1ES 0502+675	HBL	0.34
PKS 1222+216	FSRQ	0.432
PKS 1424+240	IBL	0.604
Ton 599	FSRQ	0.7247
PKS 1441+25	FSRQ	0.939



Blazar	Class	Redshift
HESS J1943+213	HBL	?
RGB J2056+496	Blazar	?
1ES 0647+250	HBL	>0.29
RGB J2243+203	HBL	>0.39
3C 66A	IBL	0.33 < z < 0.41
PG 1553+113	HBL	0.43 < z < 0.58
1ES 0033+595	HBL	0.467?

AGN	Class	Redshift
M 87	**FR I**	0.0044
NGC 1275	**FR I**	0.0176
3C264	**FR I**	0.0217

- Long term monitoring
  - Snapshot program
  - High cadence monitoring
- Dedicated ToO time
- Jet physics
  - Blazar variability
  - Particle acceleration
  - Flaring/Quiescent states
- Blazar Periodicity
  - Binary AGN Systems
  - Complexed Jet Morphology
- Radio galaxy
  - Discovery
  - Monitoring
- Cosmological Fields
  - EBL
  - IGMF

VHE Discovery of 3C 264

THE ASTROPHYSICAL JOURNAL

VERITAS Discovery of VHE Emission from the Radio Galaxy 3C 264: A Multiwavelength Study

A. Archer[1], W. Benbow[2], R. Bird[3], A. Brill[4], M. Buchovecky[3], J. H. Buckley[5], M. T. Carini[6], J. L. Christiansen[7], A. J. Chromey[8], M. K. Daniel[2] + Show full author list

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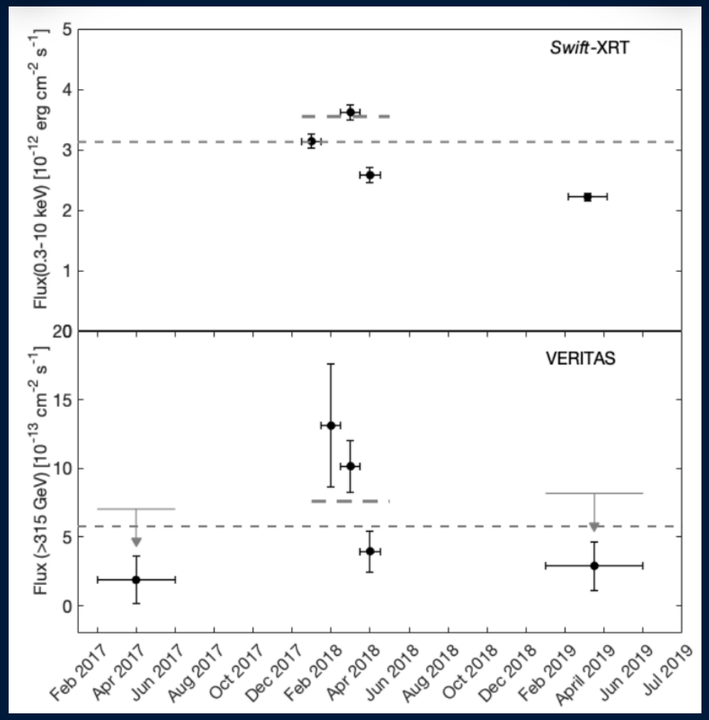
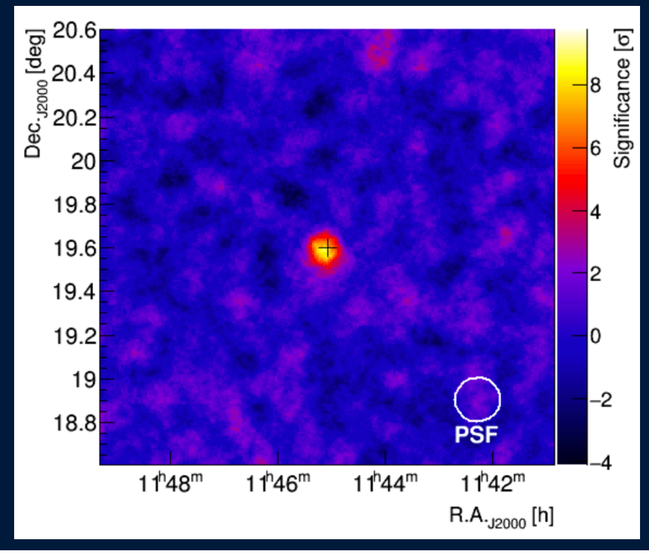
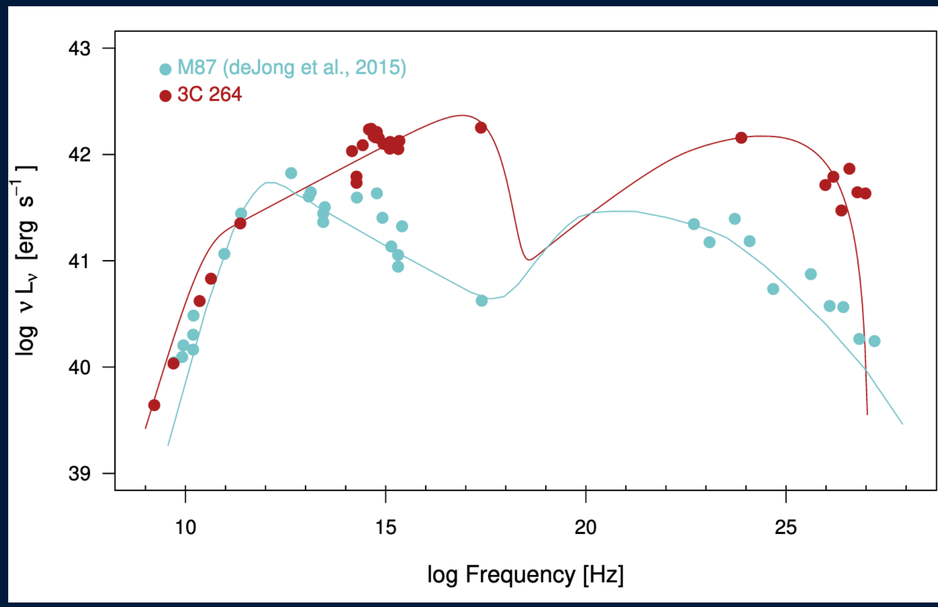
The Astrophysical Journal, Volume 896, Number 1
Citation A. Archer *et al* 2020 *ApJ* **896** 41



- 3C 264 FR-I radio galaxy
- Detected by VERITAS between 2017-2019 (57 hours)
- Most distant radio galaxy detected at VHE (z = 0.0217)
- Hard energy spectrum ($\Gamma = 2.20 \pm 0.27_{stat} \pm 0.2_{sys}$)
- Low flux ~0.7% Crab
  - Evidence of variability on monthly timescales
- MWL campaign from radio to VHE
- No evidence of a significant change in the large scale jet
- Comparison of SED with M87:
  - Similar radio properties
  - 3C 264's jet may be more closely aligned





The Great Mrk 421 Flare

THE ASTROPHYSICAL JOURNAL

The Great Markarian 421 Flare of 2010 February: Multiwavelength Variability and Correlation Studies

A. U. Abeysekara[1], W. Benbow[2], R. Bird[3], A. Brill[4], R. Brose[5,6], M. Buchovecky[3], J. H. Buckley[7], J. L. Christiansen[8], A. J. Chromey[9], M. K. Daniel[2] + Show full author list

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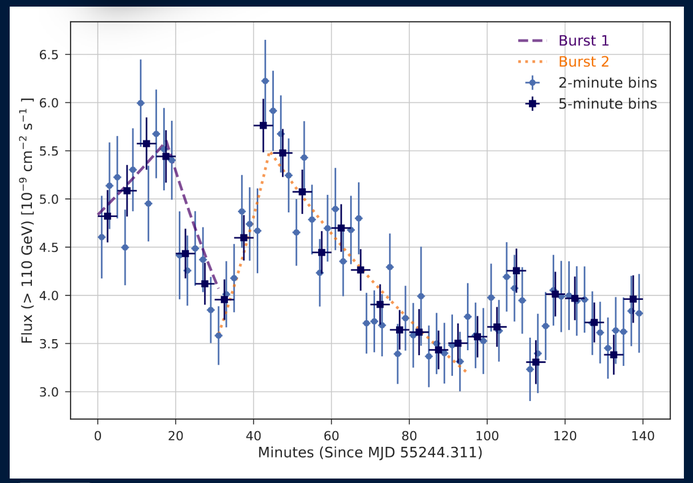
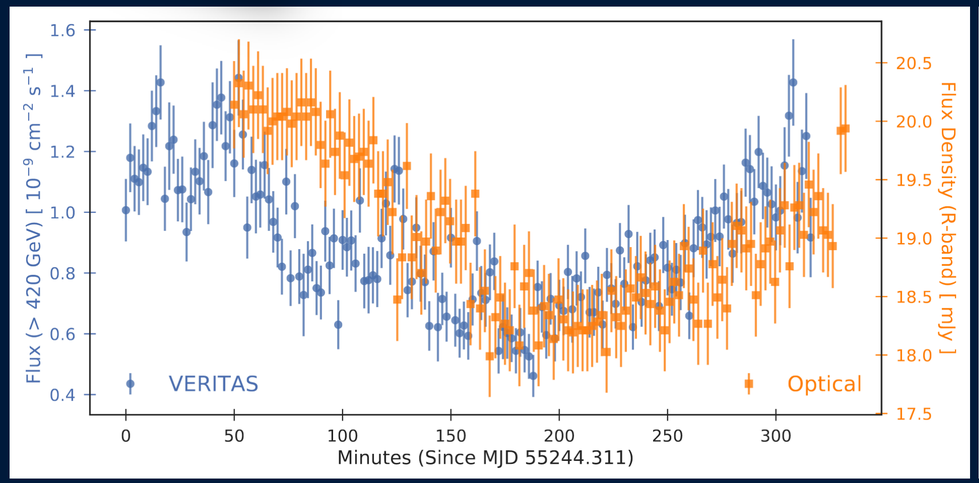
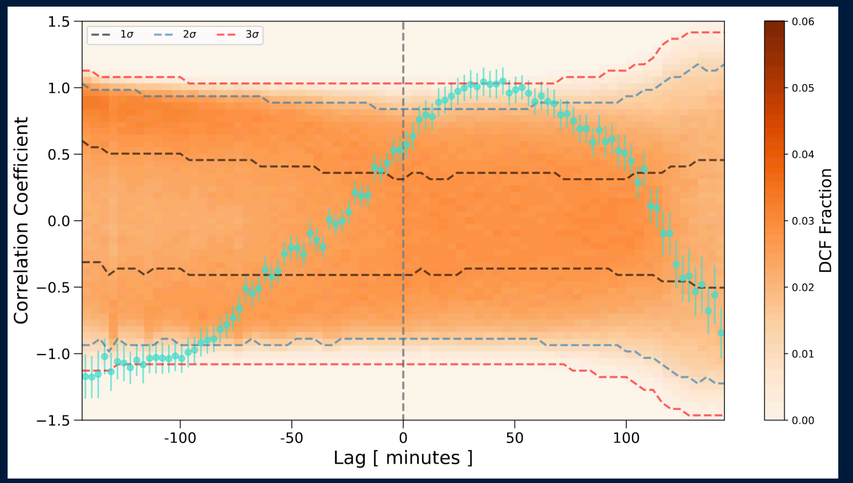
The Astrophysical Journal, Volume 890, Number 2

Citation A. U. Abeysekara *et al* 2020 *ApJ* **890** 97

- Historic VHE flare observed in 2010 during a large MWL campaign
- VHE flux reached ~27 Crab > 1 TeV
- Exponential rise/decay fit to two burst:
  - Doubling timescale 84/22 mins
  - Halving timescale 28/65 mins
- Significant VHE-Optical correlations (3σ), with a 25-55 minute time lag
- Complexed correlation (anti-correlation) observed during different epochs
- Difficult to explain in a single 1-zone SSC model







Decade multi-wavelength observations of 1ES 1215+303

- Decade of MWL observation on 1ES1215+303 (z=0.13)
- Focus on GeV-TeV emission on long time scales
- Long term change in baseline flux observed in HE and optical
- Strong long term correlation between HE-optical and VHE-HE bands
- Flare and quiescent states modelled using a two-zone SSC model
- Transition from LBL to HBL during flaring states

THE ASTROPHYSICAL JOURNAL

A Decade of Multiwavelength Observations of the TeV Blazar 1ES 1215+303: Extreme Shift of the Synchrotron Peak Frequency and Long-term Optical–Gamma-Ray Flux Increase

Janeth Valverde[1], Deirdre Horan[1], Denis Bernard[1], Stephen Fegan[1], (Fermi-LAT Collaboration), A. U. Abeysekara[2], A. Archer[3], W. Benbow[4], R. Bird[5], A. Brill[6] + Show full author list

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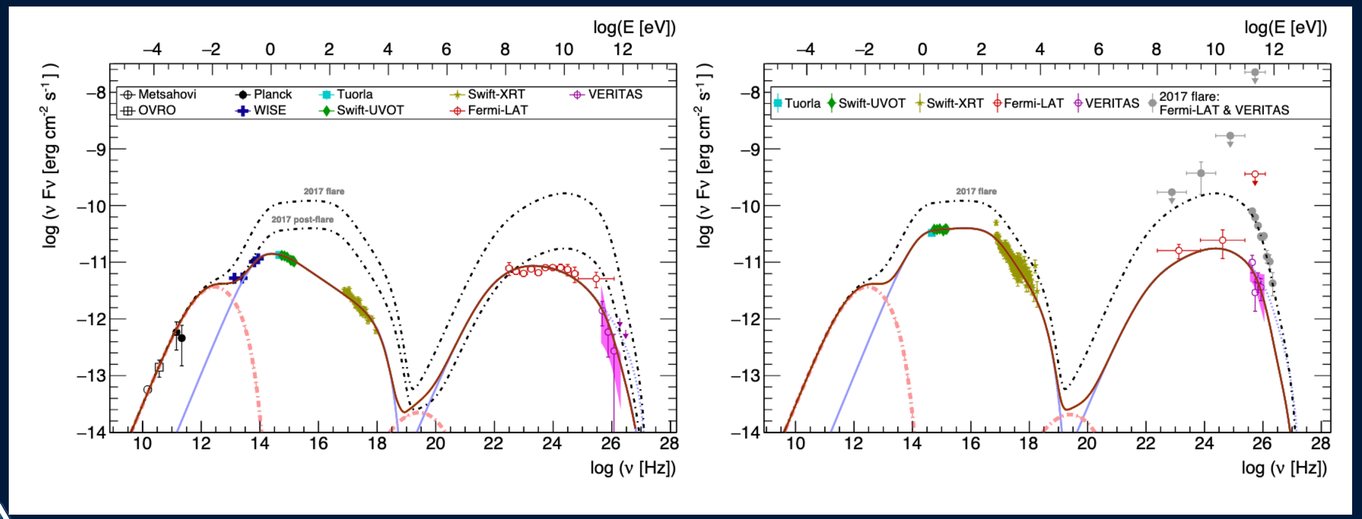
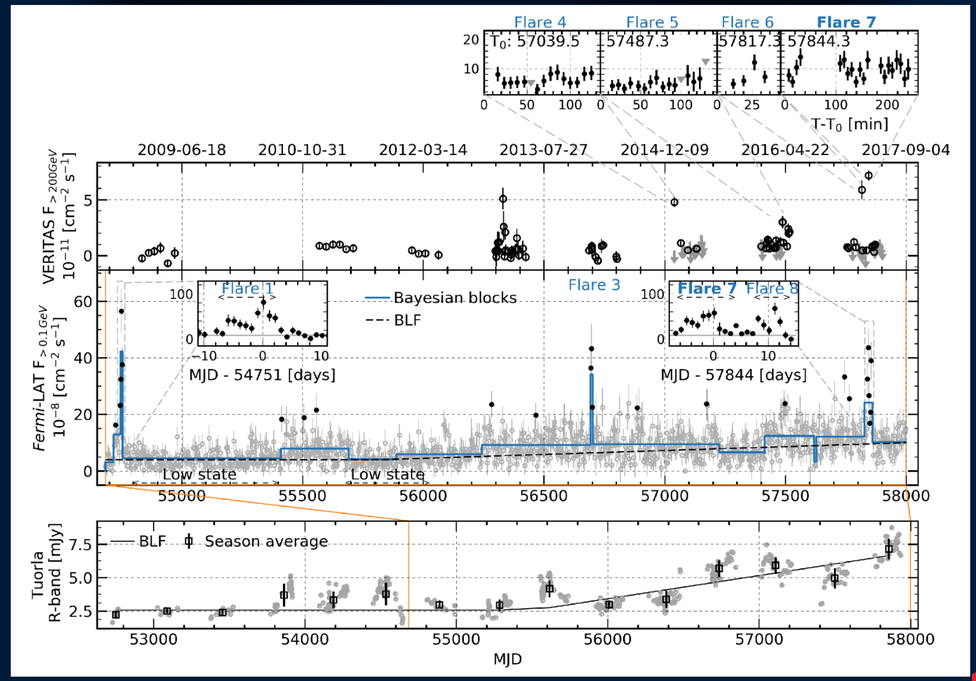
The Astrophysical Journal, Volume 891, Number 2

Citation Janeth Valverde *et al* 2020 *ApJ* **891** 170

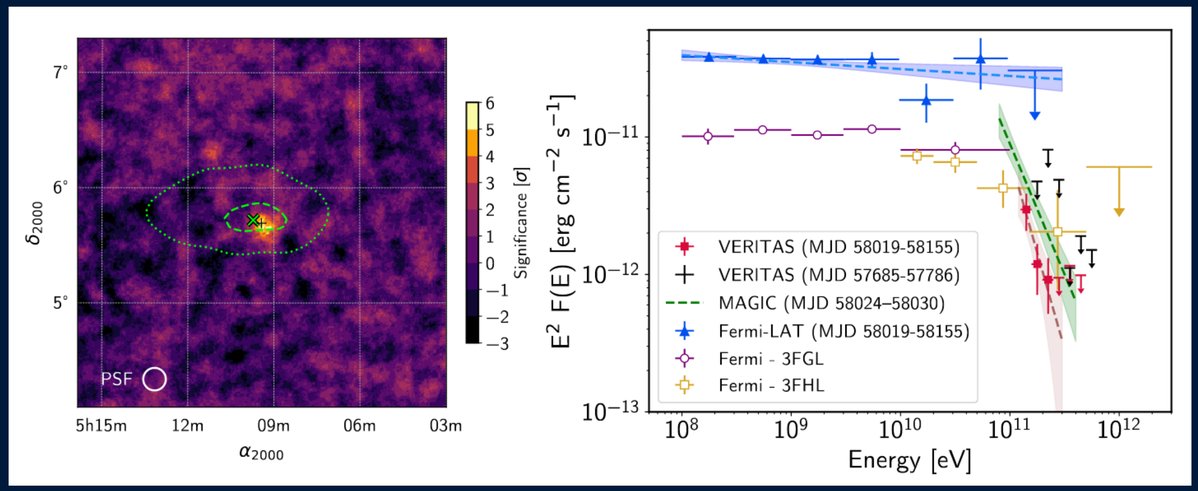


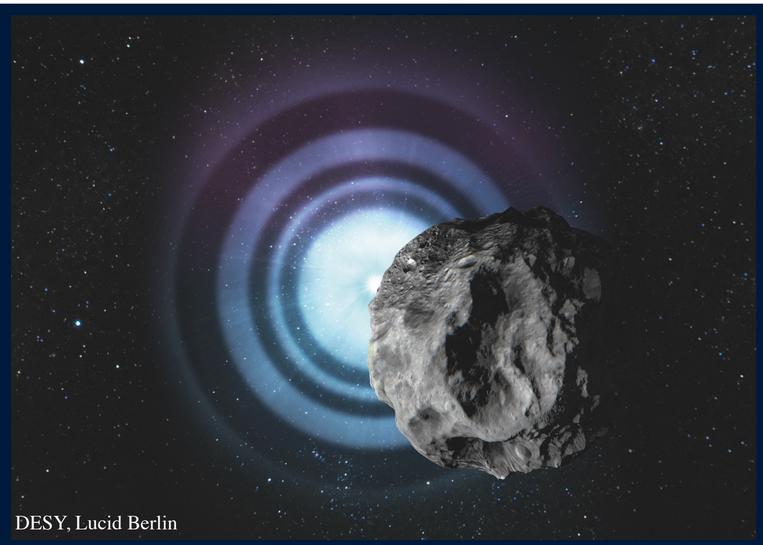


ATOMM

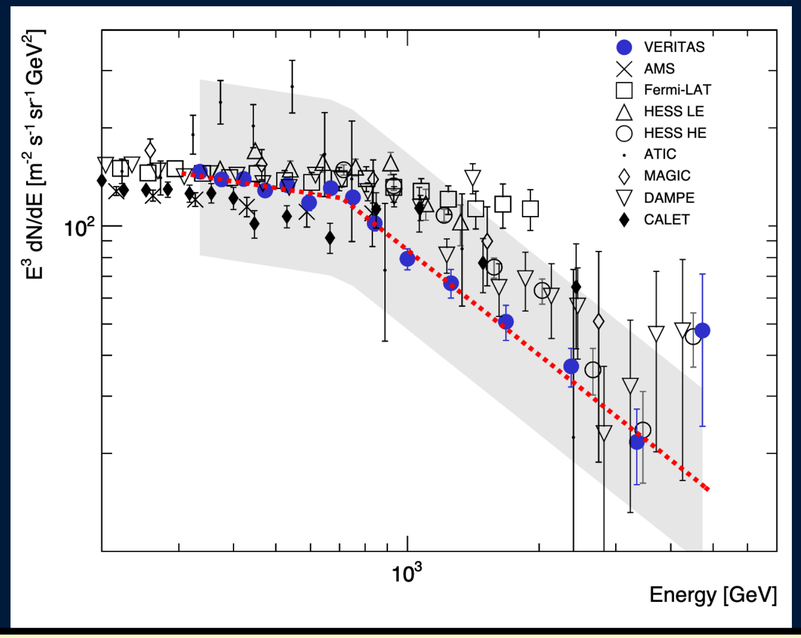
- Astropartical
  - Cosmic-ray physics
  - Dark Matter
  - Non-standard model physics (LIV, ALPs, etc)
- Transients
  - GRBs
  - FRBs
- Optical
  - Optical transients
  - Stellar Intensity Interferometry
- Multi-Messanger
  - Neutrino and Gravitational Wave Followup

VERITAS OBSERVATIONS OF THE BL LAC OBJECT TXS 0506+056





Measurement of Cosmic-ray Electrons



PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Highlights Recent Accepted Collections Authors Referees Search Press About

Measurement of cosmic-ray electrons at TeV energies by VERITAS

A. Archer *et al.* (The VERITAS Collaboration)
Phys. Rev. D **98**, 062004 – Published 20 September 2018

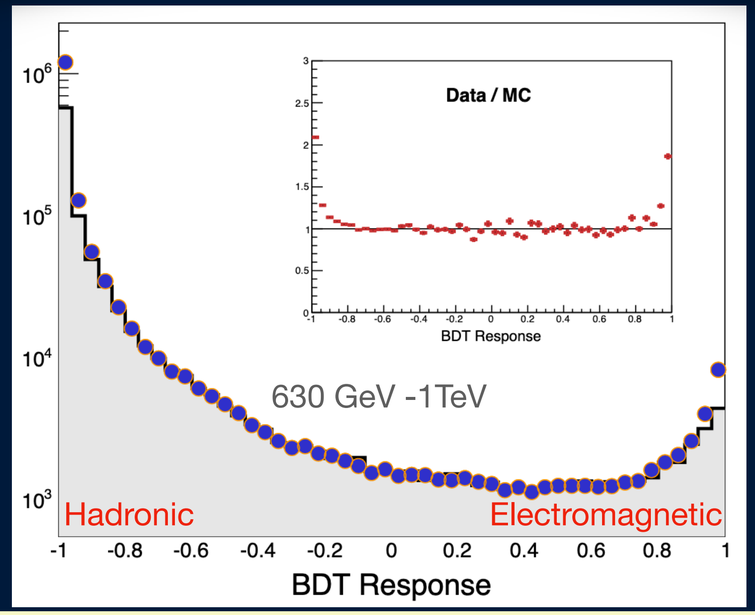
- 300 hours of data taken between 2009 and 2012
- Boosted decision trees used to classify electrons and hadrons
- Broken Power Law:

$$\Gamma_1 = 3.2 \pm 0.1$$

$$\Gamma_2 = 4.1 \pm 0.1$$

$$E_{break} = 710 \pm 40 \text{ GeV}$$

- Consistent with MAGIC and H.E.S.S. results
- Reanalysis using >1000 hours of archival data is currently underway



Measurements of Cosmic-ray Iron

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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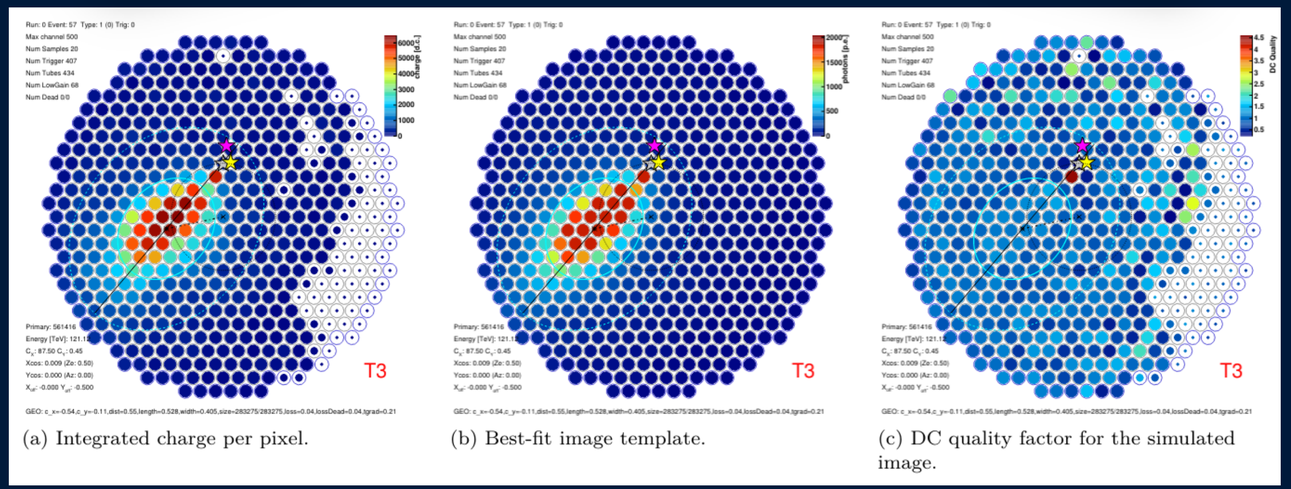
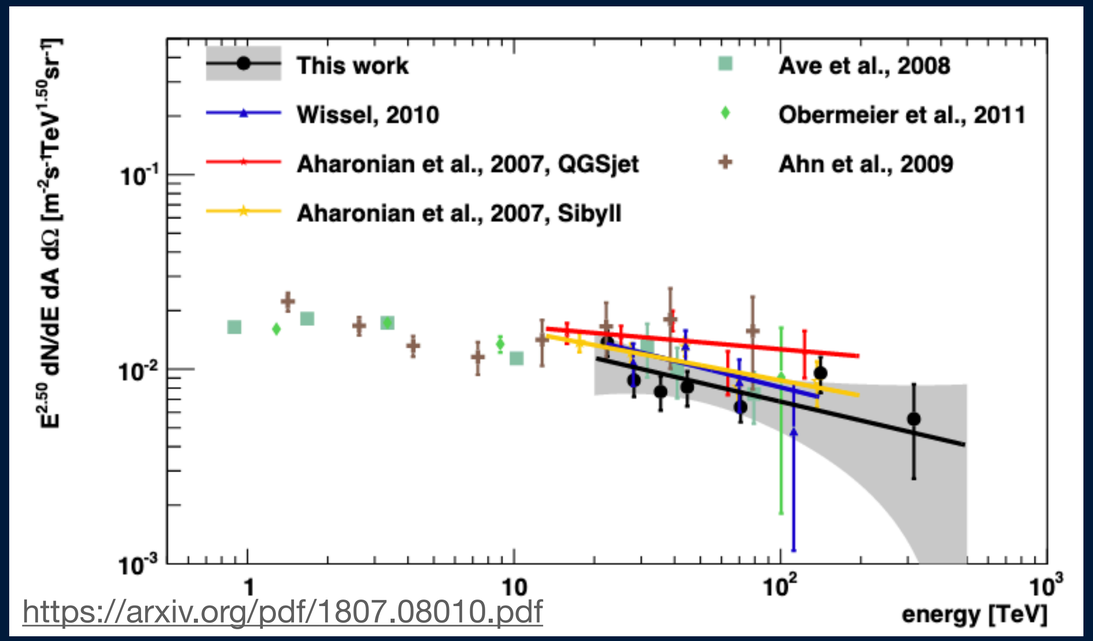
Measurement of the iron spectrum in cosmic rays by VERITAS

A. Archer *et al.* (VERITAS Collaboration)
Phys. Rev. D **98**, 022009 – Published 25 July 2018



(a) Integrated charge per pixel. (b) Best-fit image template. (c) DC quality factor for the simulated image.



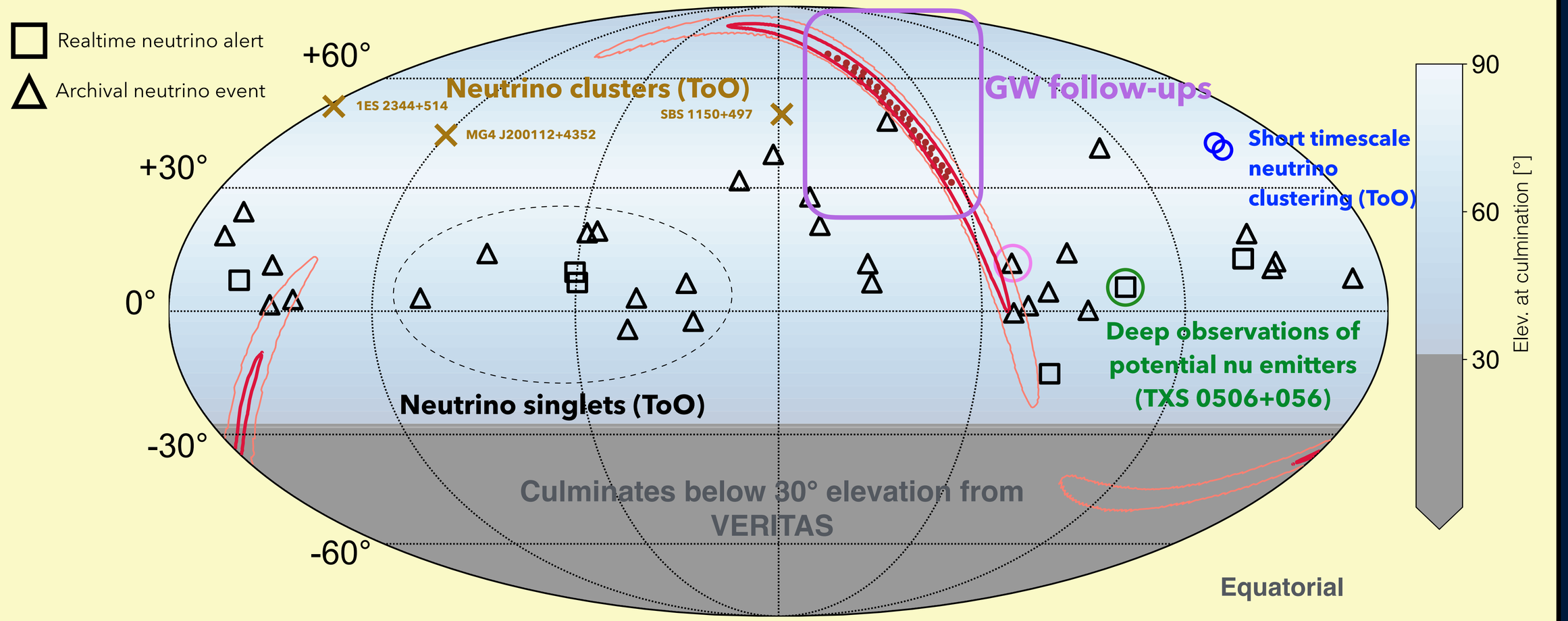
https://arxiv.org/pdf/1807.08010.pdf

- 71 hours of data taken between 2009-2012
- Measurement of direct Cherenkov emission from Iron particles
- Image template-based analysis method
- Consistent with a single power law between 20-500 TeV:

$$\Gamma = 2.82 \pm 0.3$$

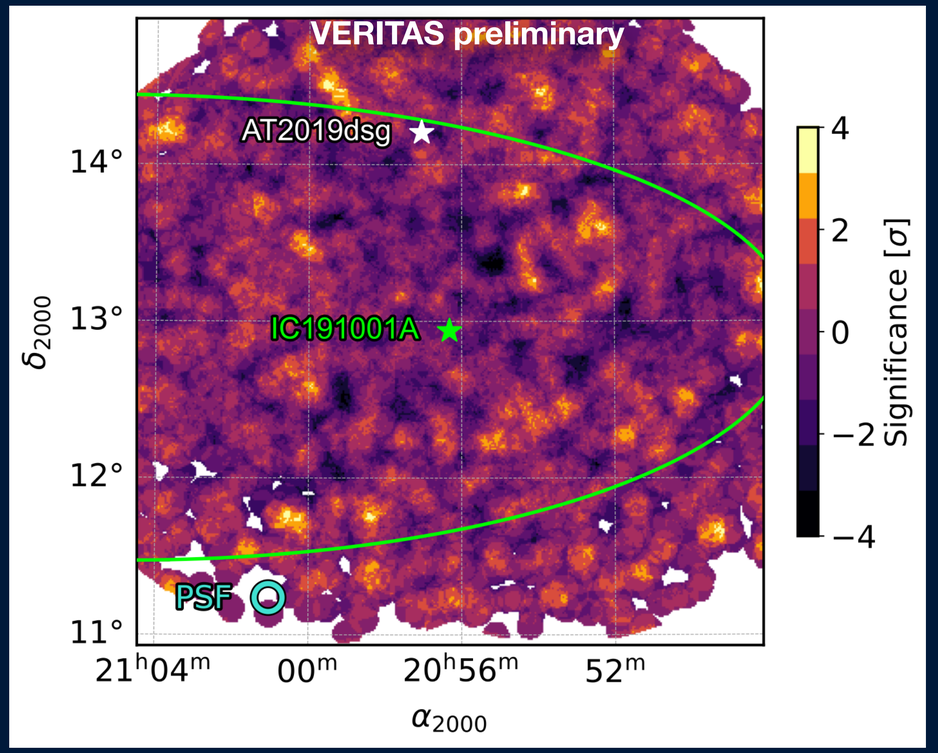
- No evidence of a spectral break

Multi-Messenger Follow Up



IceCube-191001A Follow Up

- IceCube GOLD neutrino event observed on Oct 1st 2019 (GCN 25913)
- VERITAS observations began ~3 hours after refined source position
- Neutrino event potentially associated with a tidal disruption event AT2019dsg (Stein et al. Nat. Ast. 2021)
- No significant excess observed in 1 hour of observations
- Joint VERITAS, MAGIC, HESS, FACT and IceCube publication on ToO program is in preparation



Gravitational Wave Follow-up

THE ASTROPHYSICAL JOURNAL

An Archival Search for Neutron-star Mergers in Gravitational Waves and Very-high-energy Gamma Rays

C. B. Adams[1], W. Benbow[2], A. Brill[1], J. H. Buckley[3], M. Capasso[4], J. L. Christiansen[5], A. J. Chromey[6], M. K. Daniel[2], M. Errando[3], A. Falcone[7] + Show full author list

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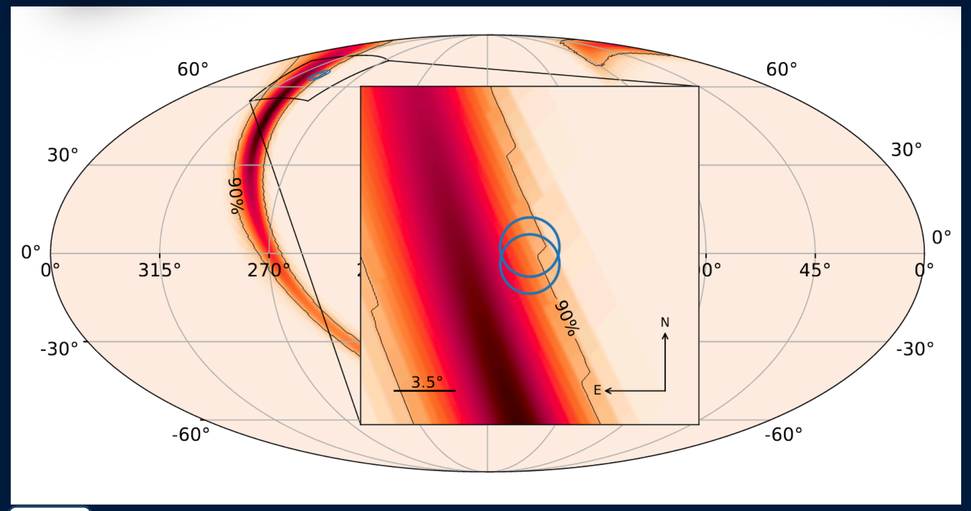
The Astrophysical Journal, Volume 918, Number 2

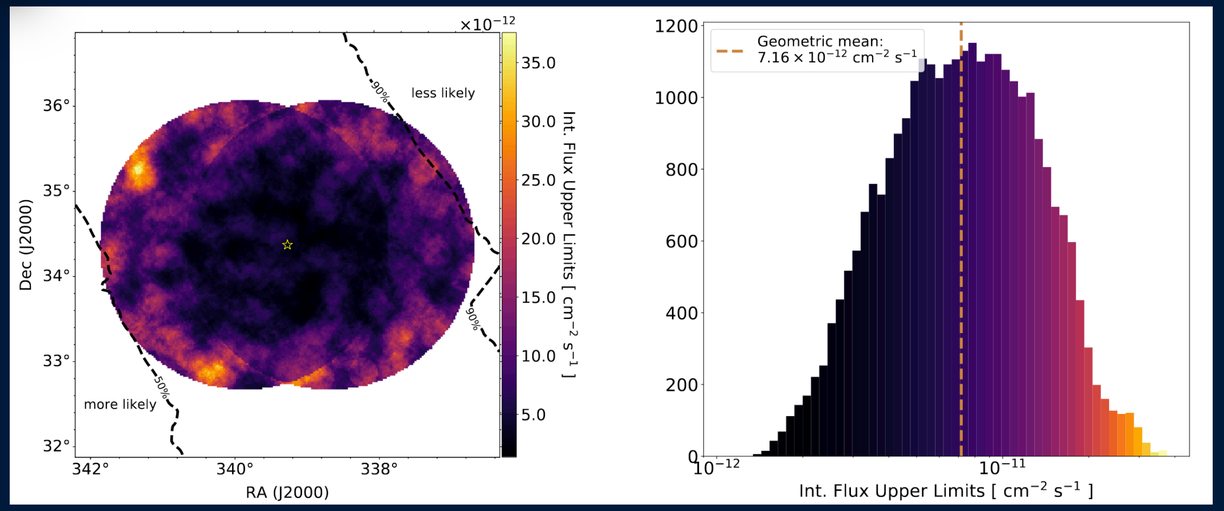
Citation C. B. Adams *et al* 2021 *ApJ* **918** 66

- Search for VHE counterparts to BNS candidates
- Sub-threshold O1 BNS candidate events
- Archival data with serendipitous exposure for 7 events
- No significant excesses observed
- Upper limits placed on integral flux across the FoV

Event ID: 2015Oct12T02:40:22.39



Event ID: 2015Dec04T01:53:39.14



Fast Radio Bursts

- Close geographic location allows for simultaneous observations of FRBs with CHIME
- Models of FRBs predict optical and/or gamma-ray emission
- Extensive monitoring of known FRB repeaters
  - Search for persistent Gamma-ray emission
  - Search for pulsed emission coincident with FRB detection
- Optical and gamma-ray data streams in operation
- Ready to monitor VOEvents

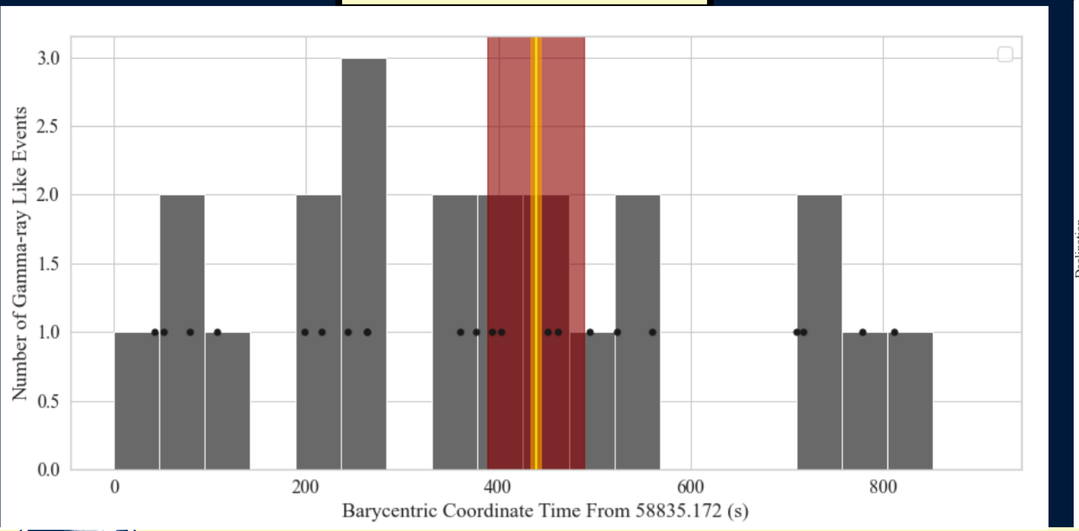
PROCEEDINGS OF SCIENCE

Volume 395 - 37th International Cosmic Ray Conference (ICRC2021) - GAI - Gamma Ray Indirect

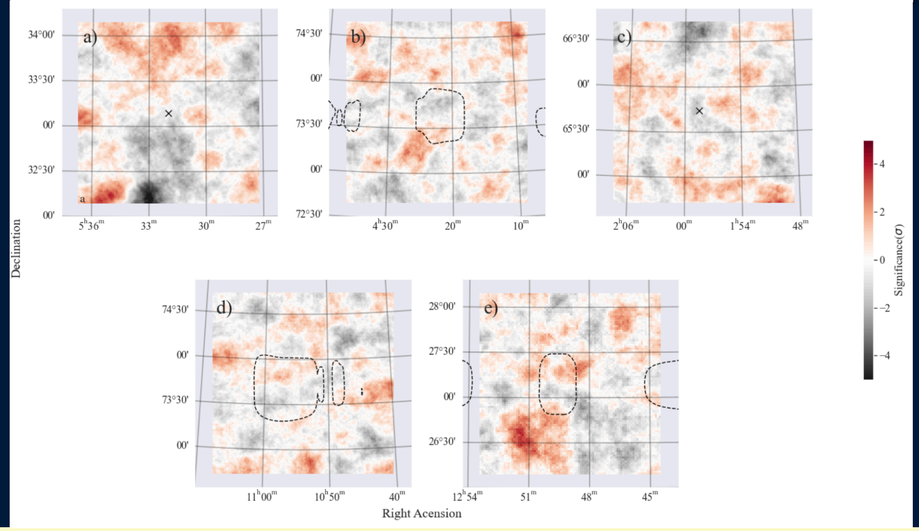
Gamma-ray and Optical Observations of Repeating Fast Radio Bursts with VERITAS

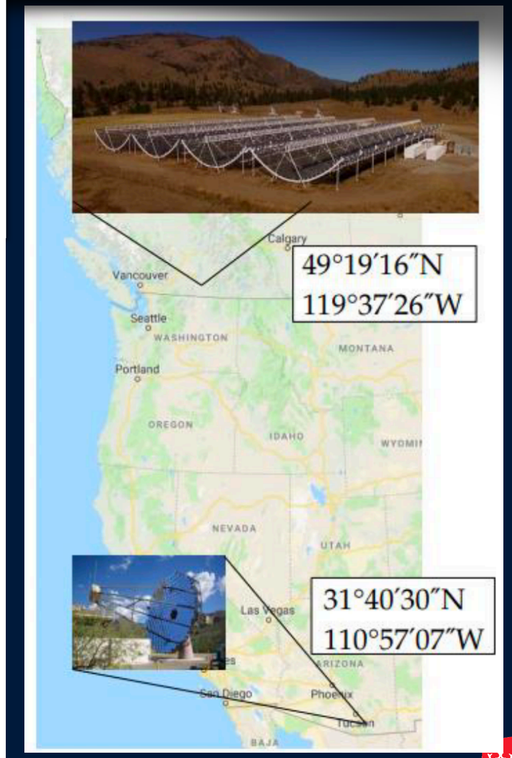
Veritas, M. Capasso, R. Ong, I. Sadeh, P. Kaaret, W. Jin, et al. (click to show)

FRB J180916.J0158+65

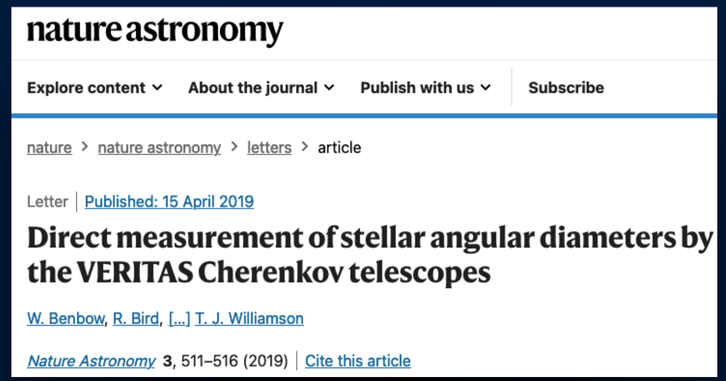


	FRB Name	Exposure (min)	On Counts	Off Counts	Significance(σ)
a)	FRB 121102	1216.64	1681	14134	-0.61
b)	FRB 180814.J0422+73	1013.22	966	8955	-0.62
c)	FRB 180916.J0158+65	397.45	522	4907	-0.06
d)	FRB 181030.J1054+73	226.26	277	2650	-0.33
e)	FRB 190116.J1249+27	45.00	111	768	0.83





Optical Capabilities of VERITAS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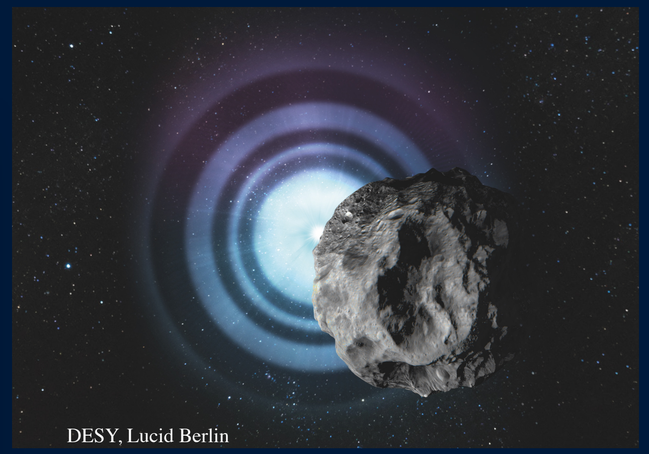
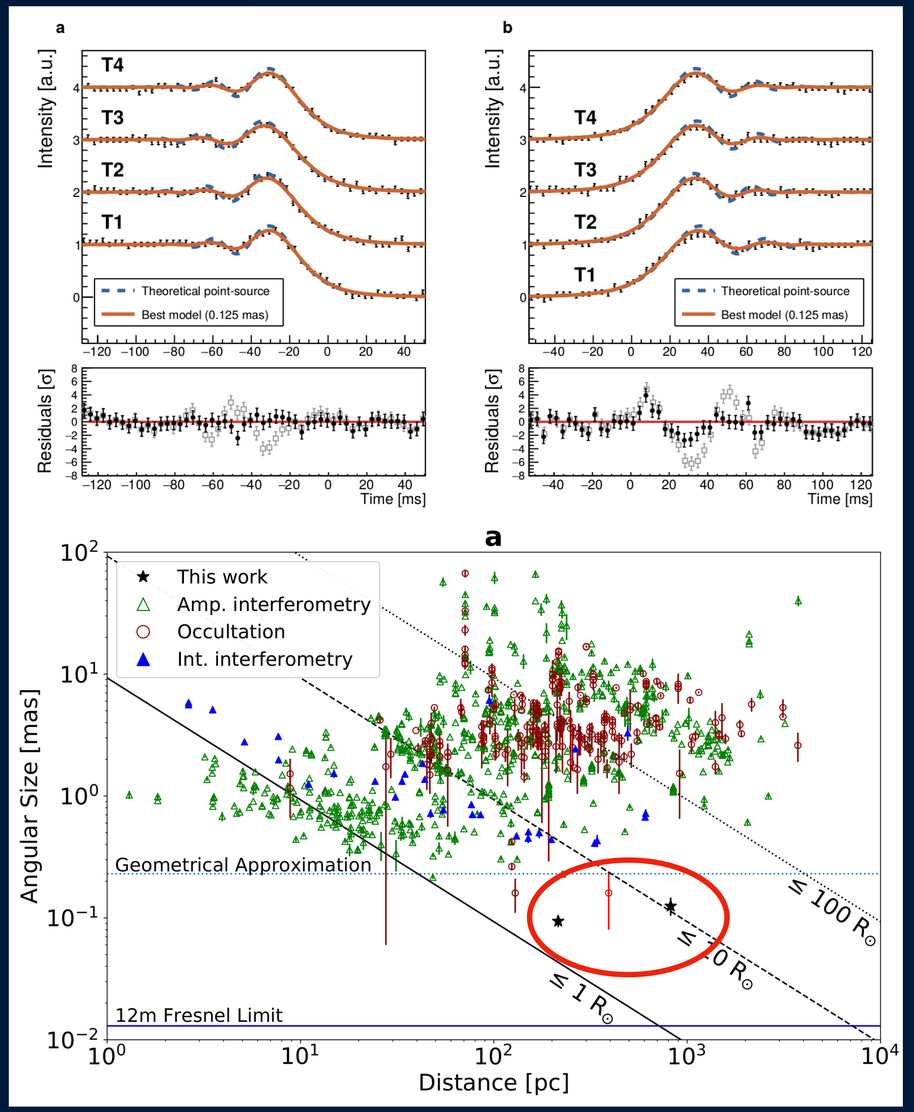
Letter | Published: 15 April 2019

Direct measurement of stellar angular diameters by the VERITAS Cherenkov telescopes

W. Benbow, R. Bird, [...] T. J. Williamson

Nature Astronomy **3**, 511–516 (2019) | Cite this article

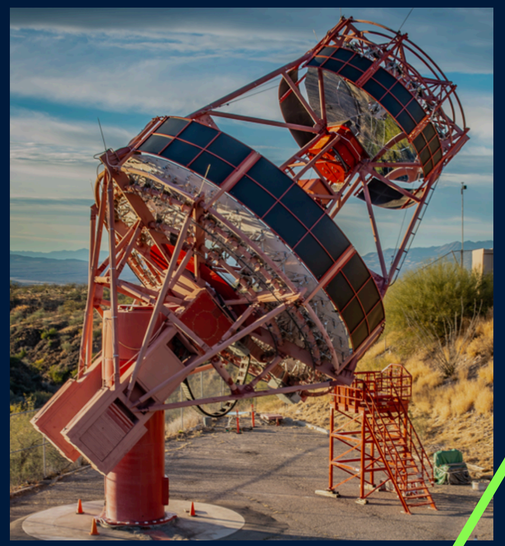


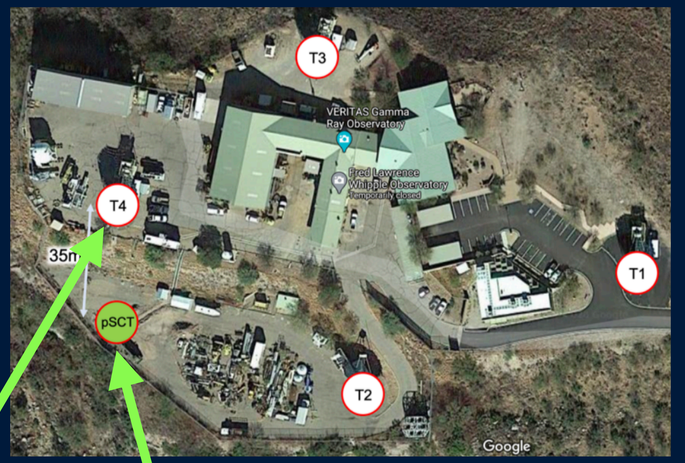


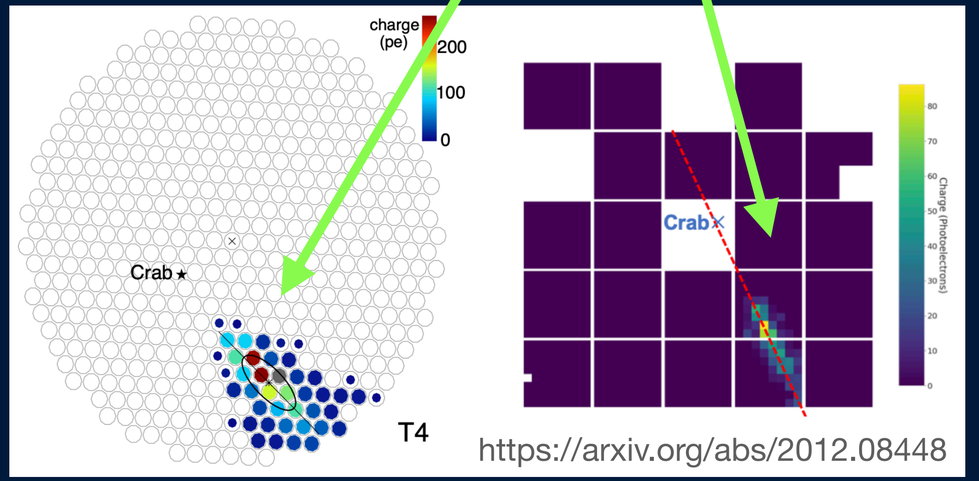
- Measurement of diffraction pattern in the shadow cast by an asteroid occulting a star
- Enabled by ms sampling of the central pixel current
- VERITAS measurement probe ≤ 0.1 milliarcsecond scale
- Probing largely un-probed parameter space

Future of VERITAS

- VERITAS continues to operate with a strong science output
- Difficult times for observing (Covid-19)
  - VERITAS has adapted to remote observing
- Exciting times in VHE astrophysics
  - LHAASO producing first results
  - CTA ramping up
- Development of pSCT telescope at FLWO
  - Joint observations and analyses
  - Benefit from larger FoV
  - Improve off-axis response
  - Transient follow-up
  - Higher energy response
- VERITAS intends to continue operations until completion of CTA North (~2025)
- Proposed upgrades and advanced analysis methods continue to improve VERITAS sensitivity







Thank you for your attention!
Questions?