

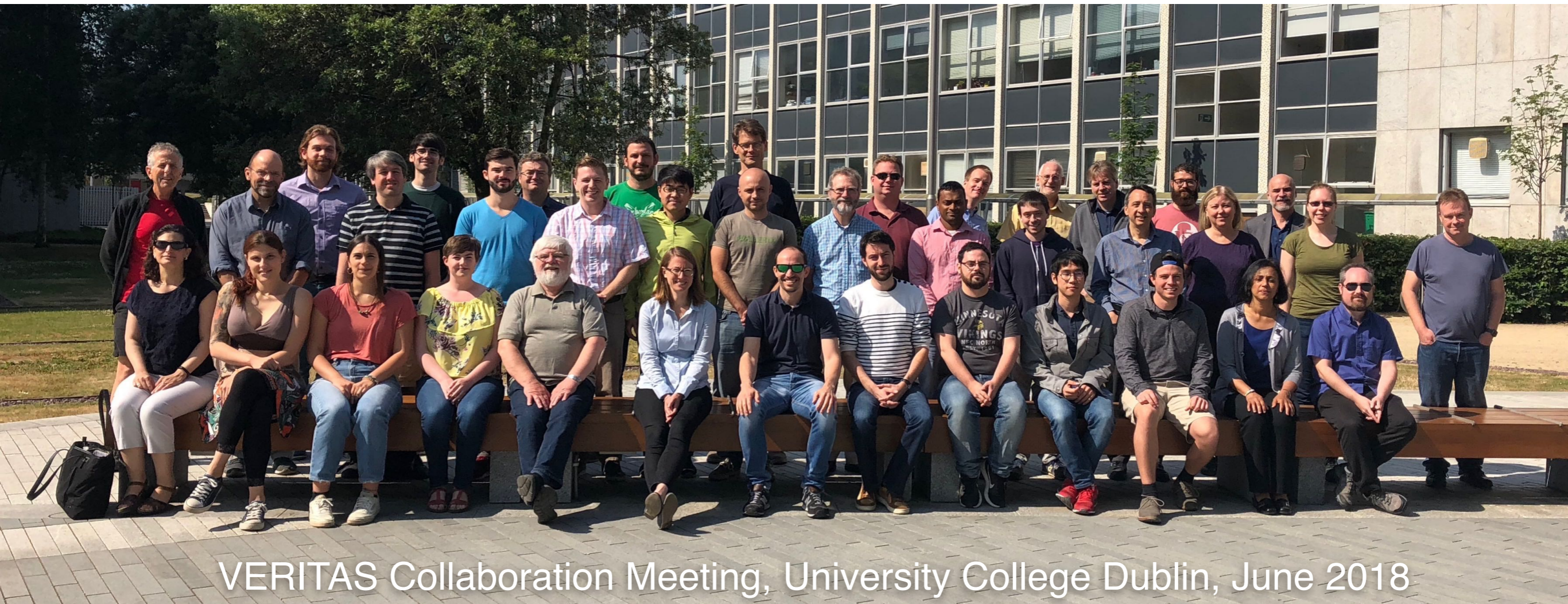


VERITAS: Status and Recent Results



John Quinn
(University College Dublin)
for the VERITAS Collaboration

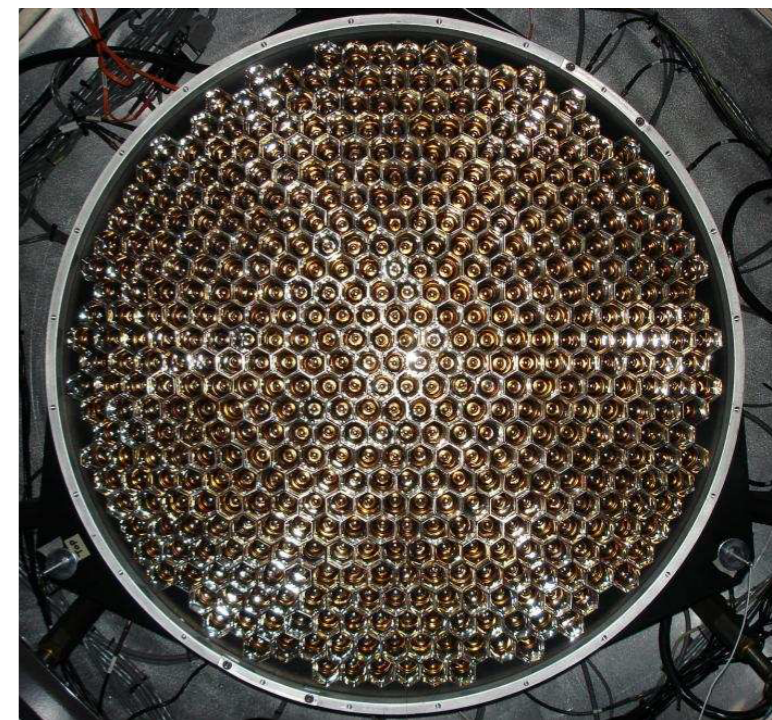


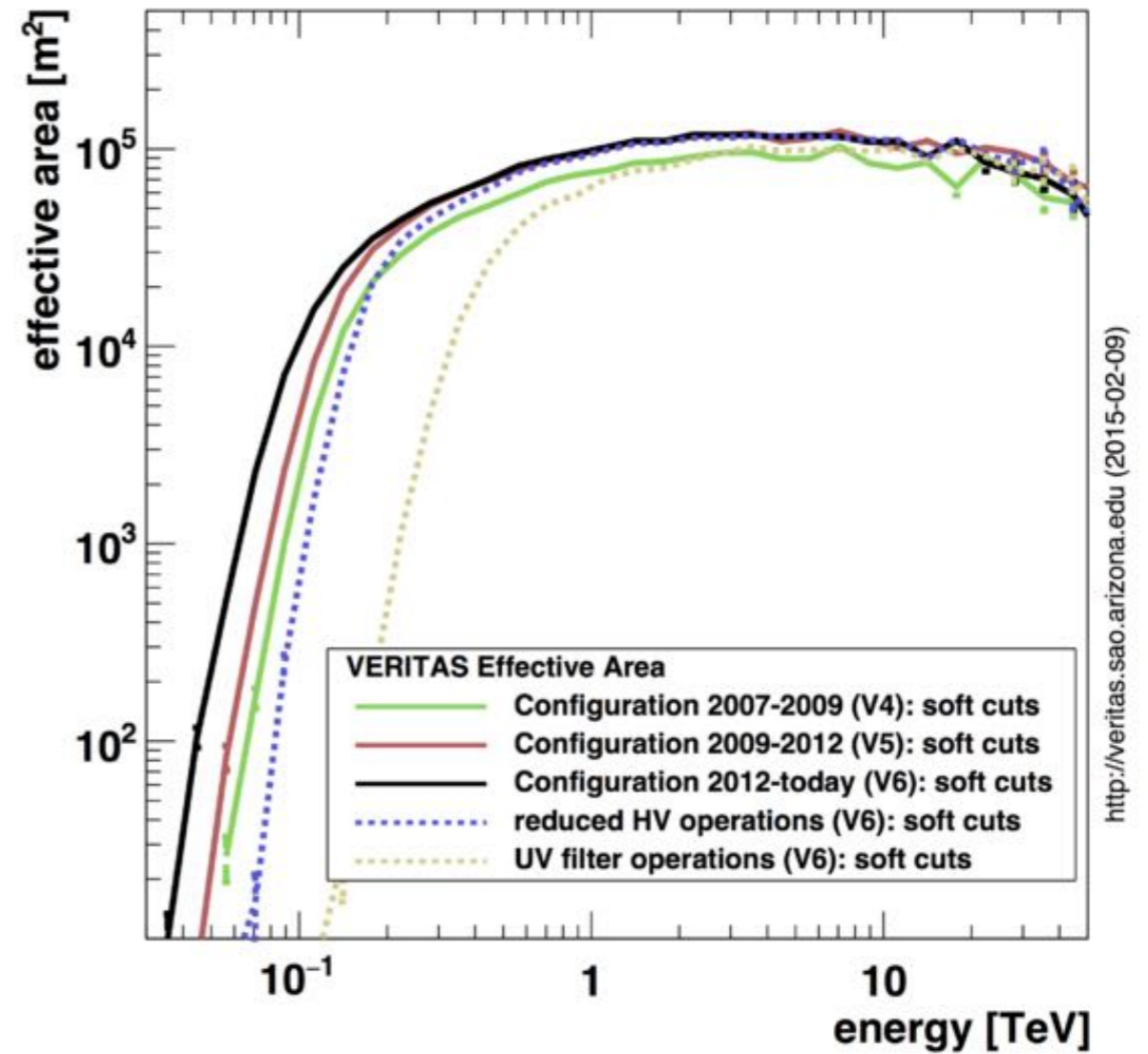
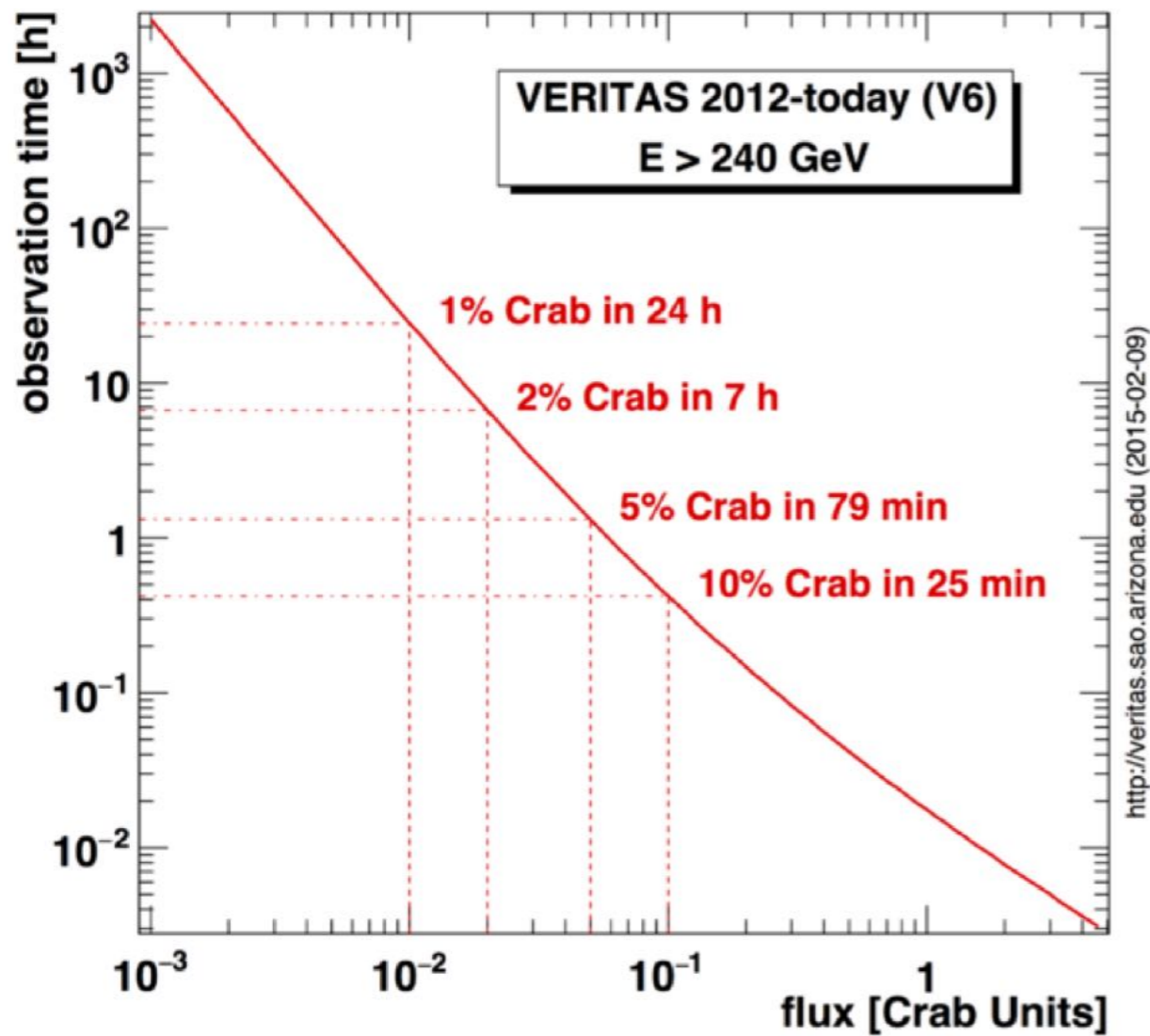


- * 84 Active participants (authors)
 - * 44% PhDs and Postdocs
- * 20 active Associate Members



- * VERITAS entered full 4-tel. scientific operation in 2007
- * It has since undergone several upgrades significantly improving its performance, the most significant of which were:
 - * Telescope 1 moved in summer 2009
 - * PMT camera pixels upgraded in summer 2012
- * Operations fully funded through 2019
- * Plan to apply for funding to extend operations through 2022





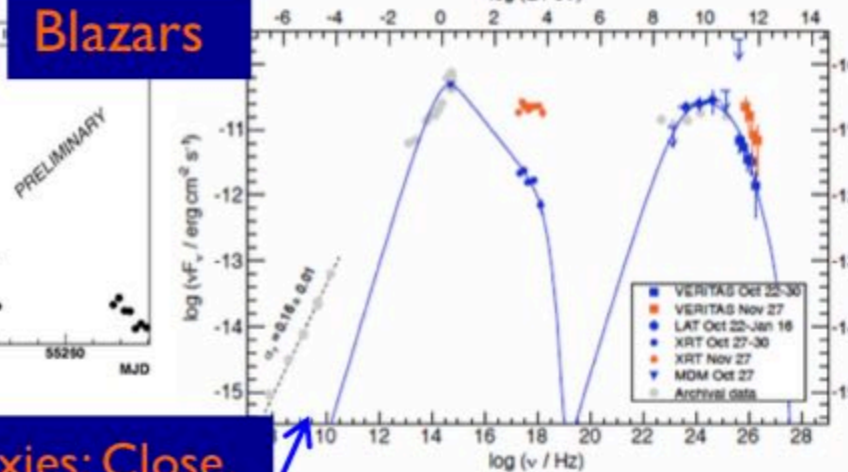
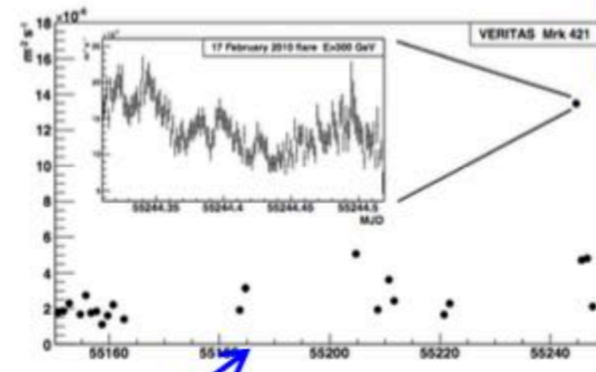
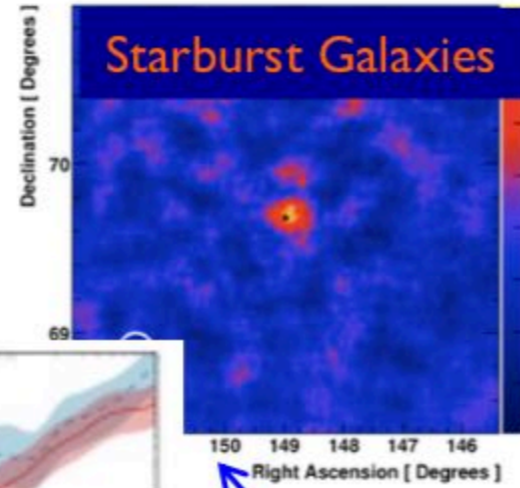
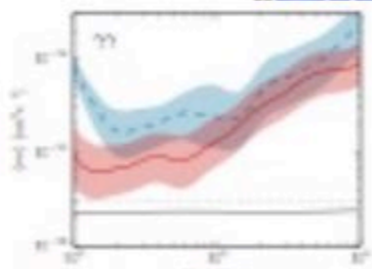
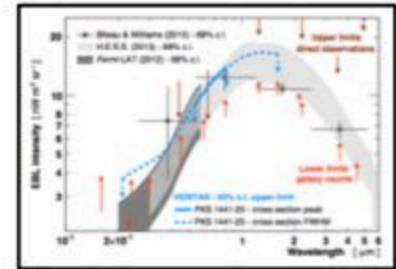
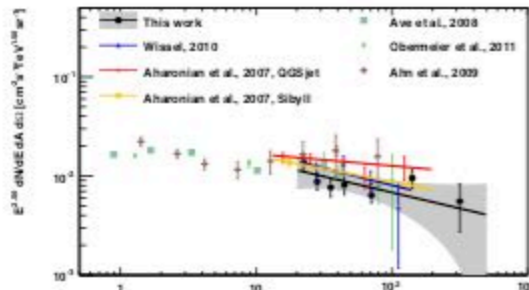
- * Energy range: ~85 GeV to ~30 TeV
- * Sensitivity: 1% Crab in <25 h
- * Angular Resolution: $r_{68} \sim 0.08^\circ$ @ 1 TeV
- * Energy resolution: ~17%
- * Systematic errors: Flux ~20%; $\Gamma \sim 0.1$

- * Good-weather data / yr:
 - * ~950 h in “dark time”
 - * ~250 h in “bright moon” (illum. >30%)
- * 4-Telescope efficiency: ~ 97%

A new occupant of T1's old site!

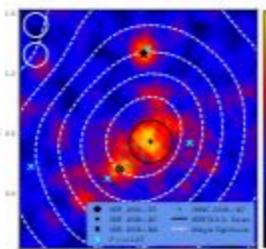
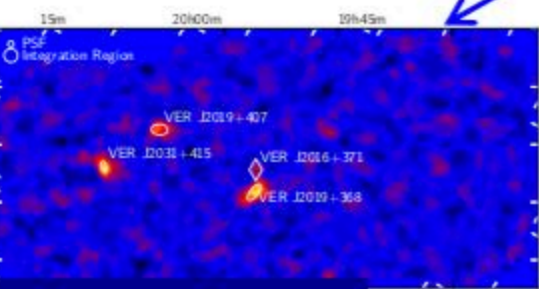
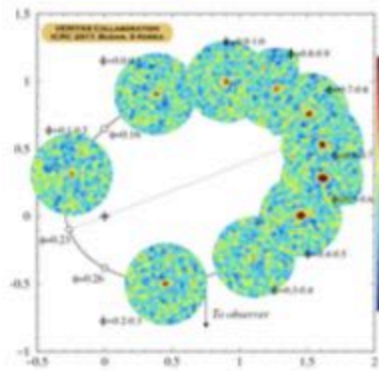


Fundamental Physics



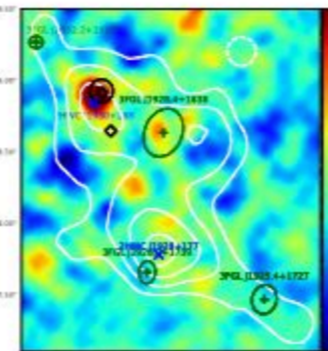
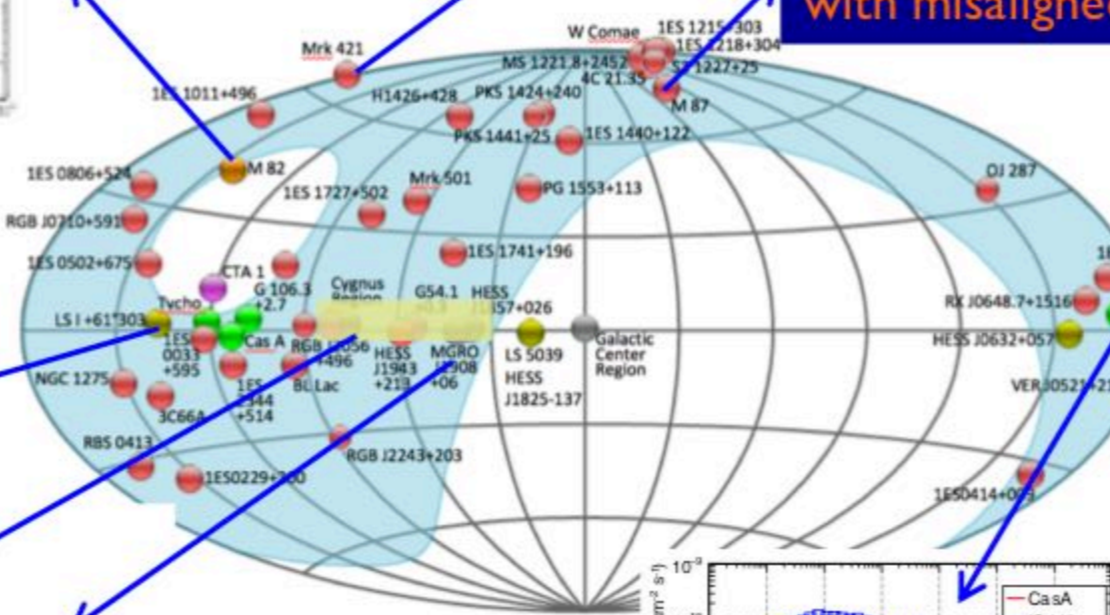
Radio Galaxies: Close, with misaligned jets

X-ray binaries

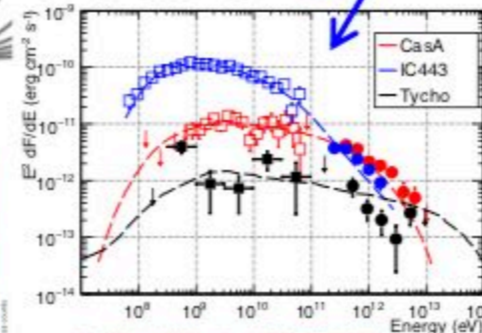


Unidentified

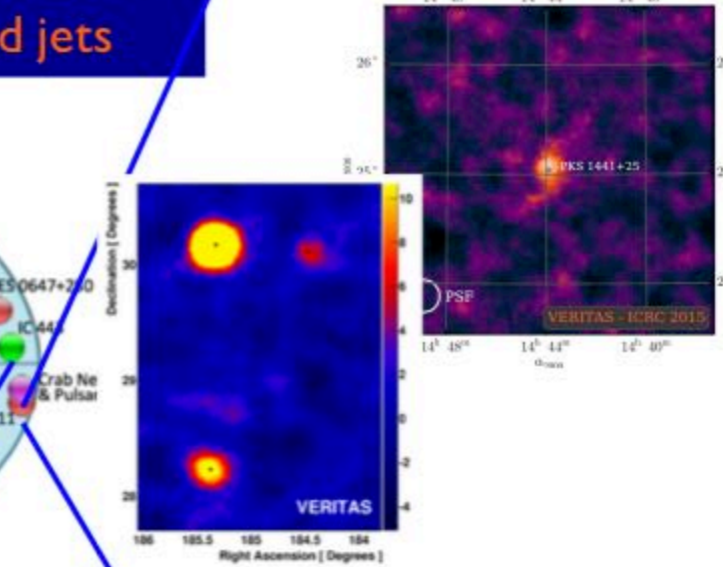
Galactic sources



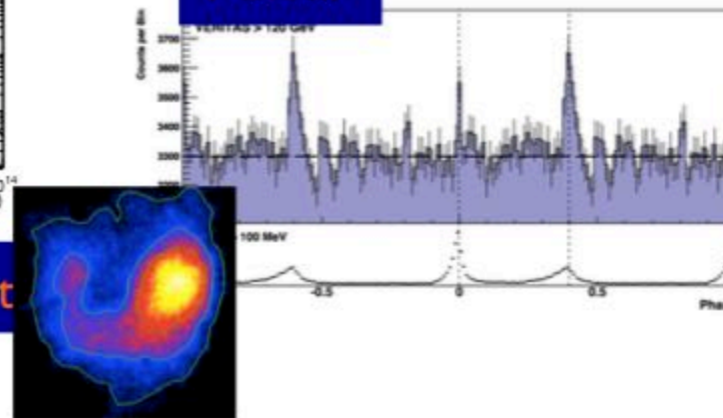
HAWC Follow-ups



Supernova Remnant

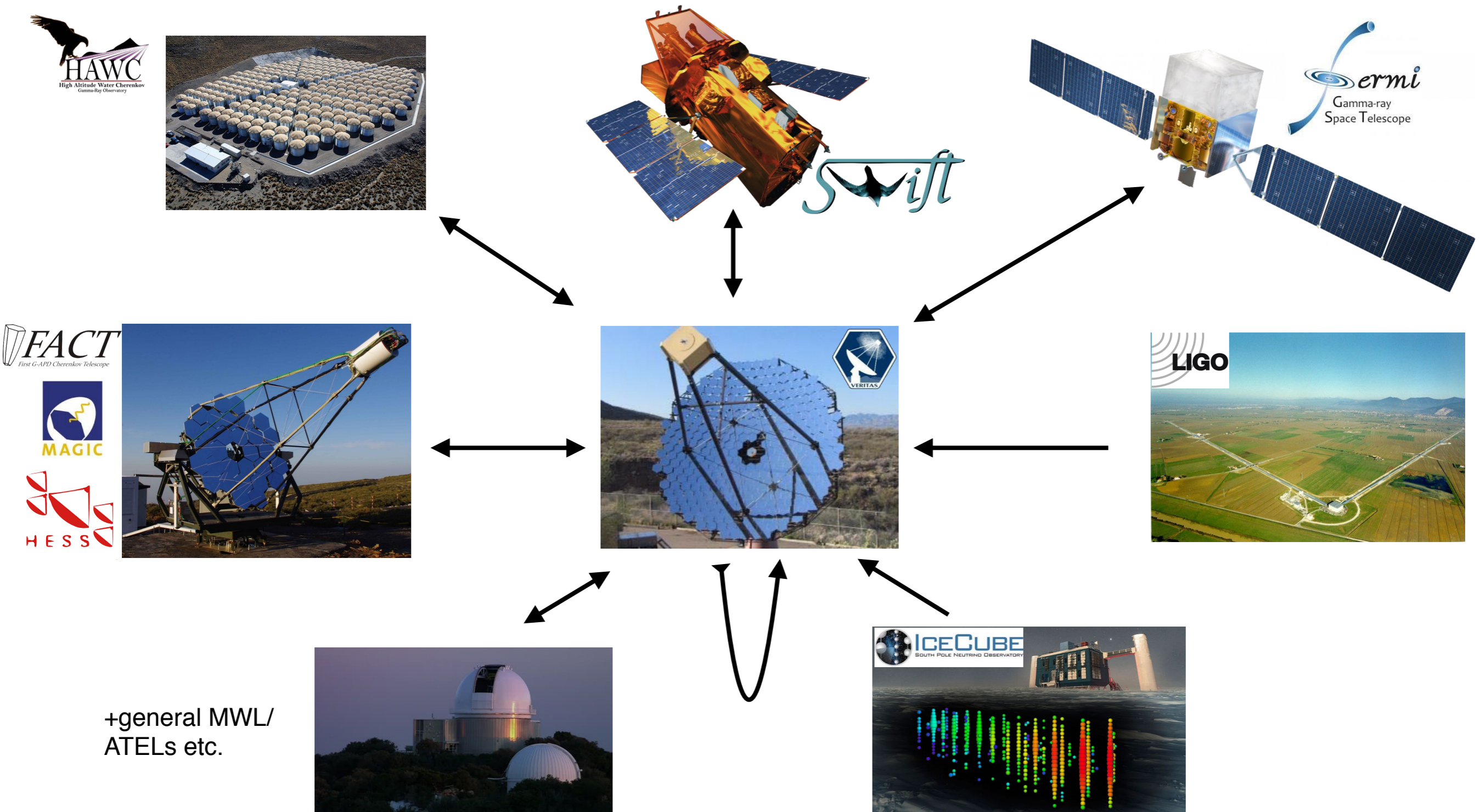


Pulsar

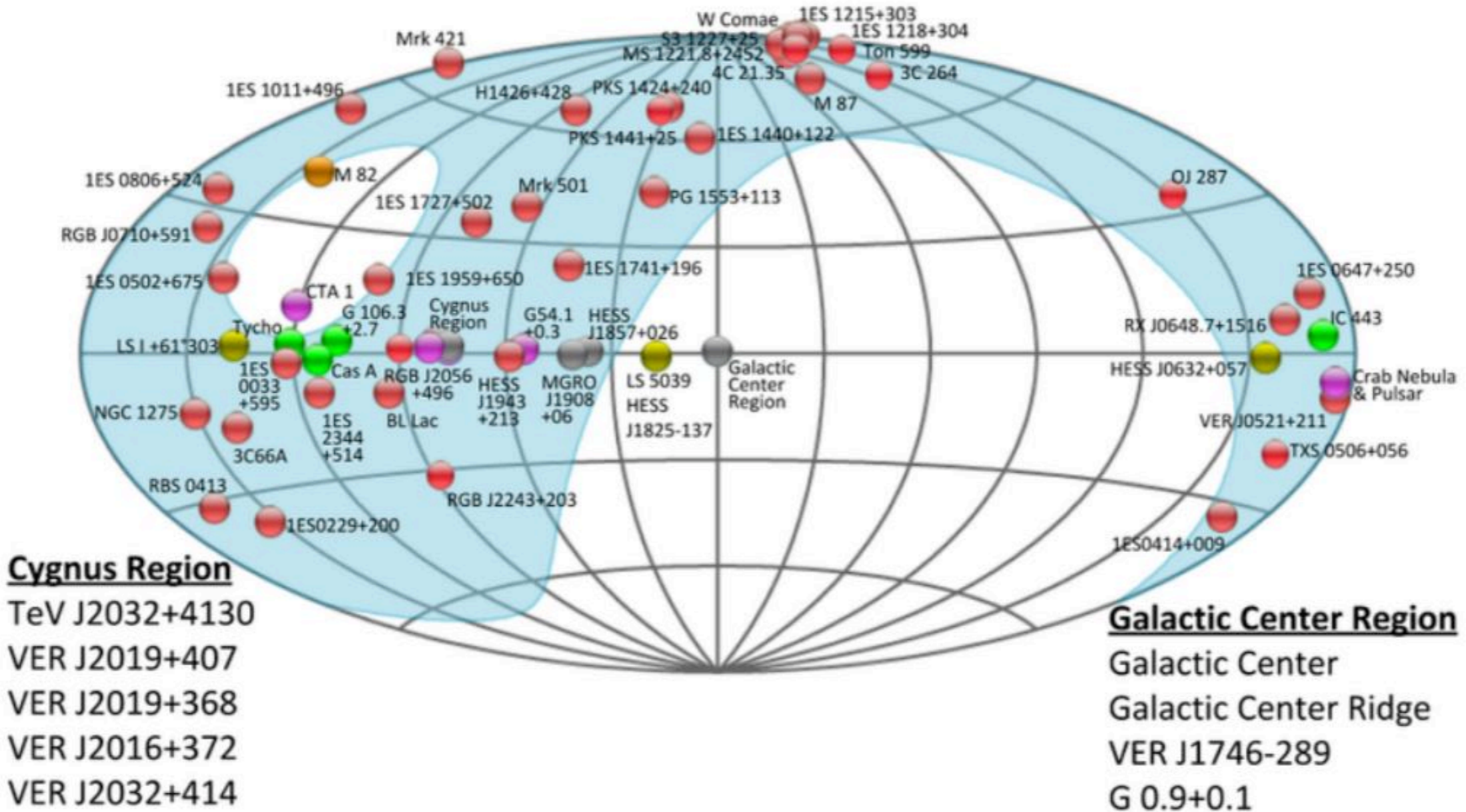


Multi-Messenger Astronomy

- * Responding to and providing multi-messenger alerts in a timely fashion has become increasingly important for VERITAS.



The VERITAS Source Catalogue



63 sources from 8 astrophysical classes

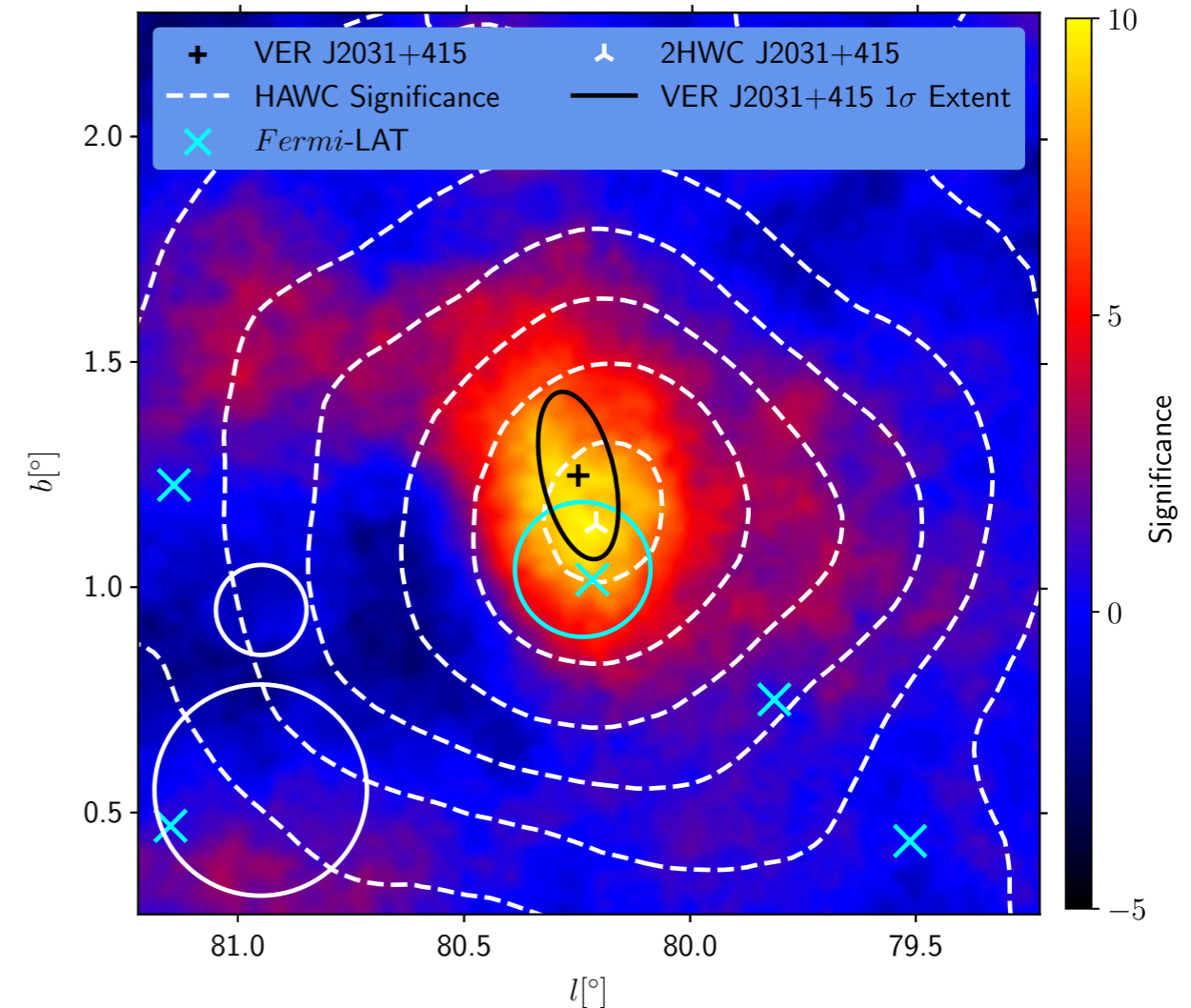
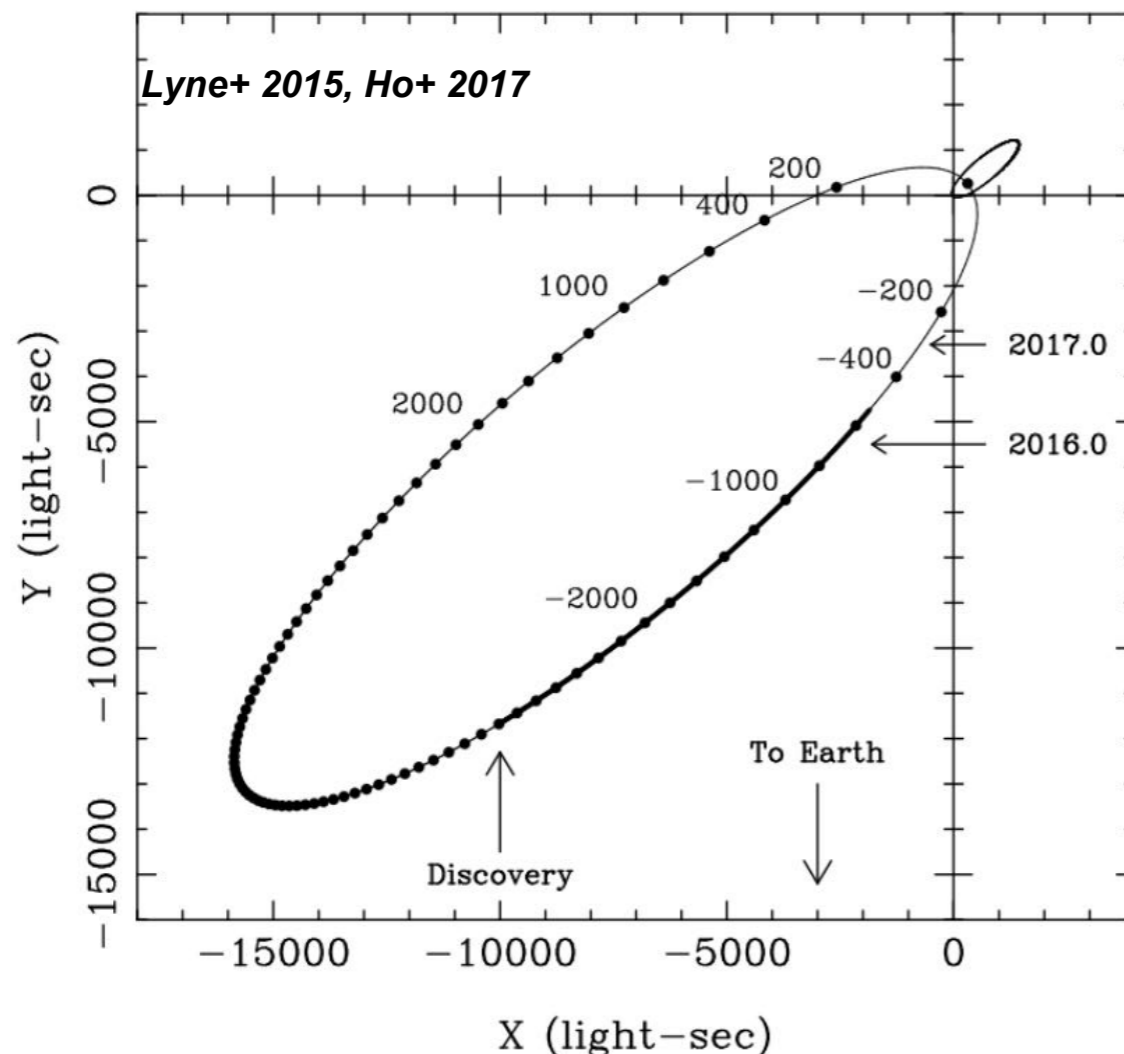
40 Extragalactic (63%) & 23 Galactic (37%) objects

Extragalactic: 39 AGN & a starburst galaxy (M82)

Detection of the TeV γ -ray binary PSR J2032+4127/ MT91 213

* TeV J2032+4130:

- * First unidentified TeV source (Aharonian et al. 2002)
- * Later found to be extended (Aliu et al., 2014)
- * PSR J2032+4127, a Fermi-LAT pulsar in southeast corner - is TeV J2032 a PWN?



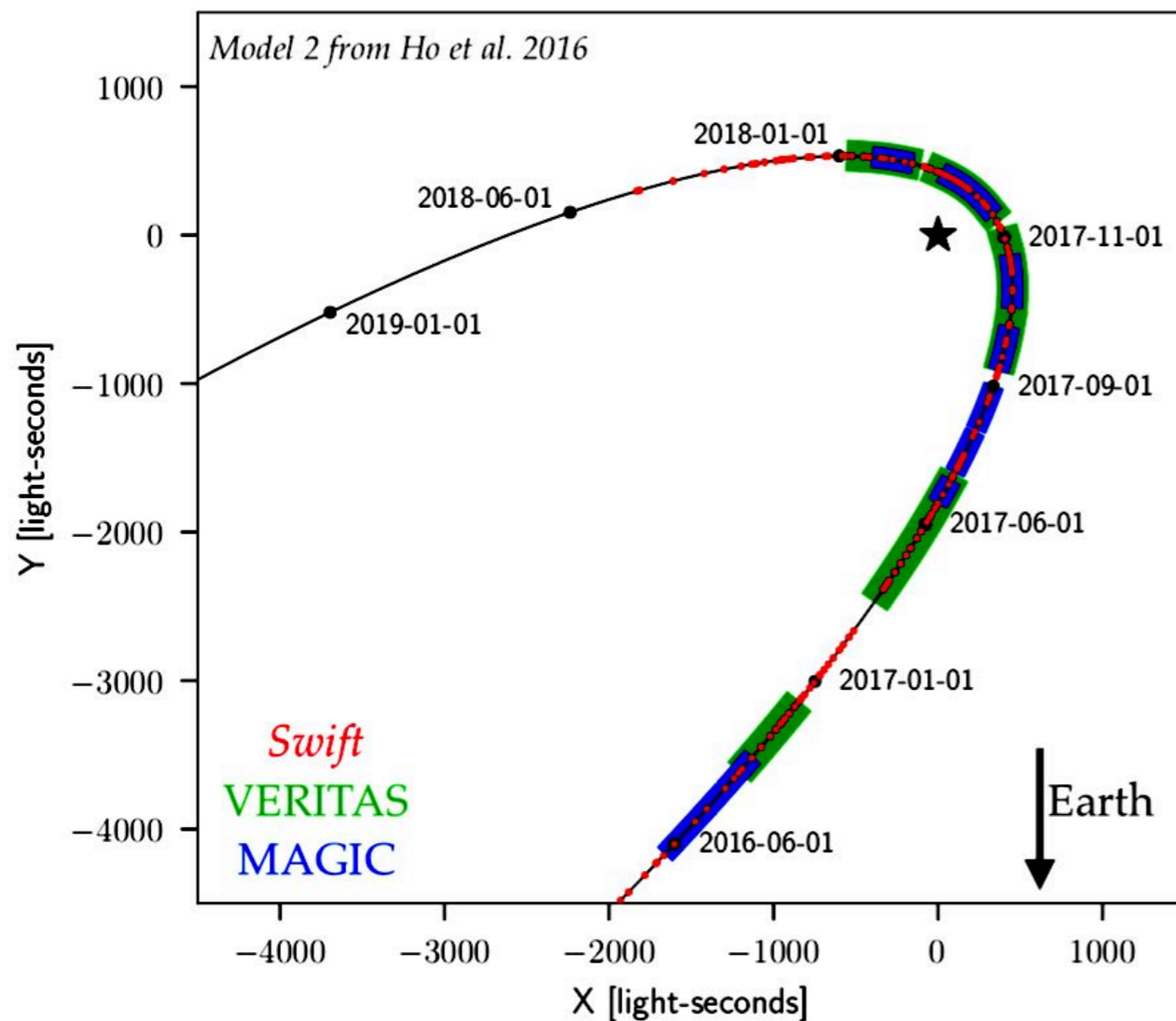
* PSR J2032+4127:

- * In 2015 identified as being in a binary with 15 M_{\odot} Be star MT91 213
- * ~ 50 year period orbit
- * Eccentricity ~ 0.95
- * Periastron 13 November 2017

Detection of the TeV γ -ray binary PSR J2032+4127/ MT91 213

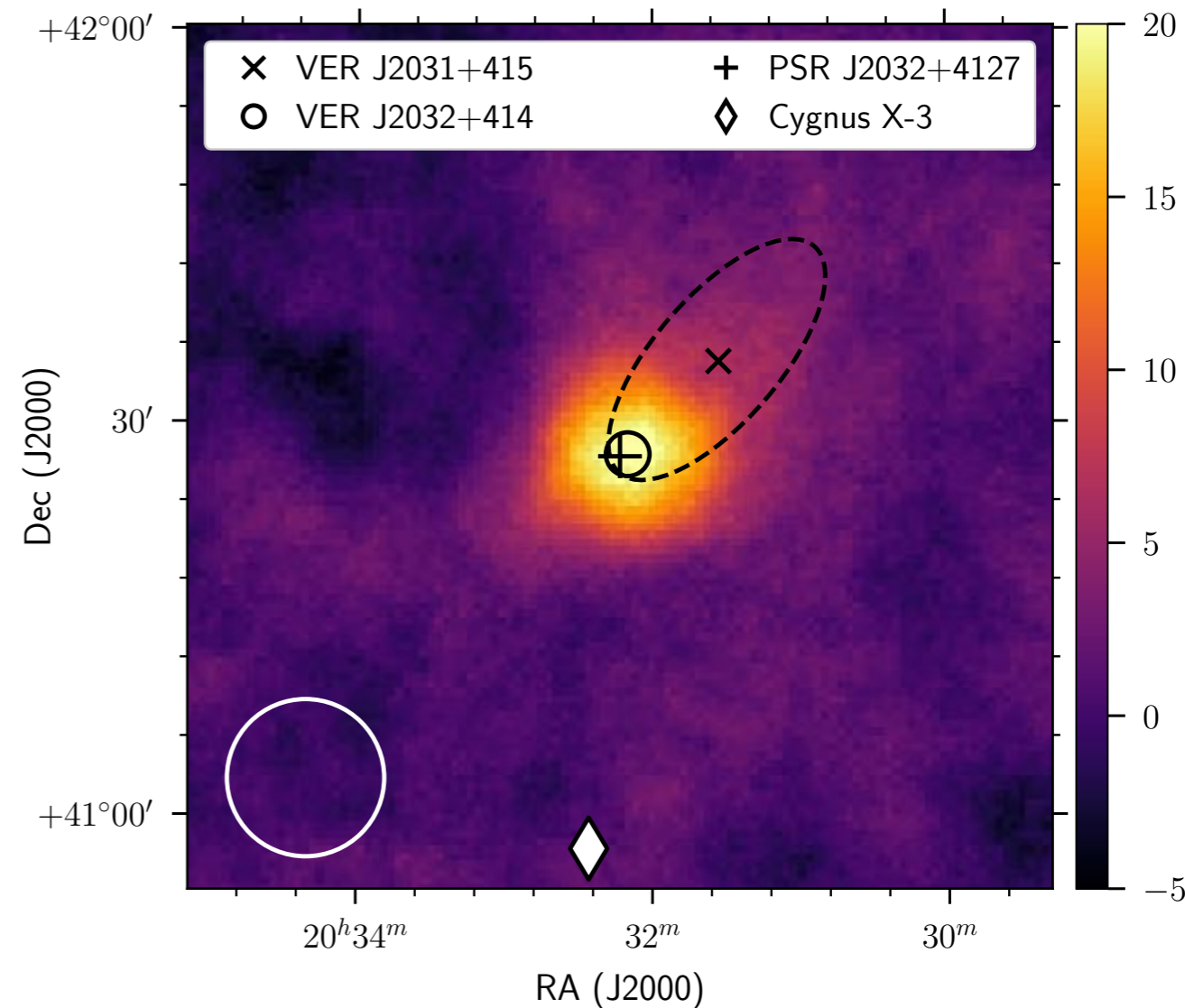
* Extensive MWL campaign with:

- * Swift (135 hrs)
- * VERITAS (181 hrs)
- * MAGIC (88h hrs)



* Detection!

- * VERITAS and MAGIC both $>20\sigma$
- * variable point-like emission above TeV J2032 baseline

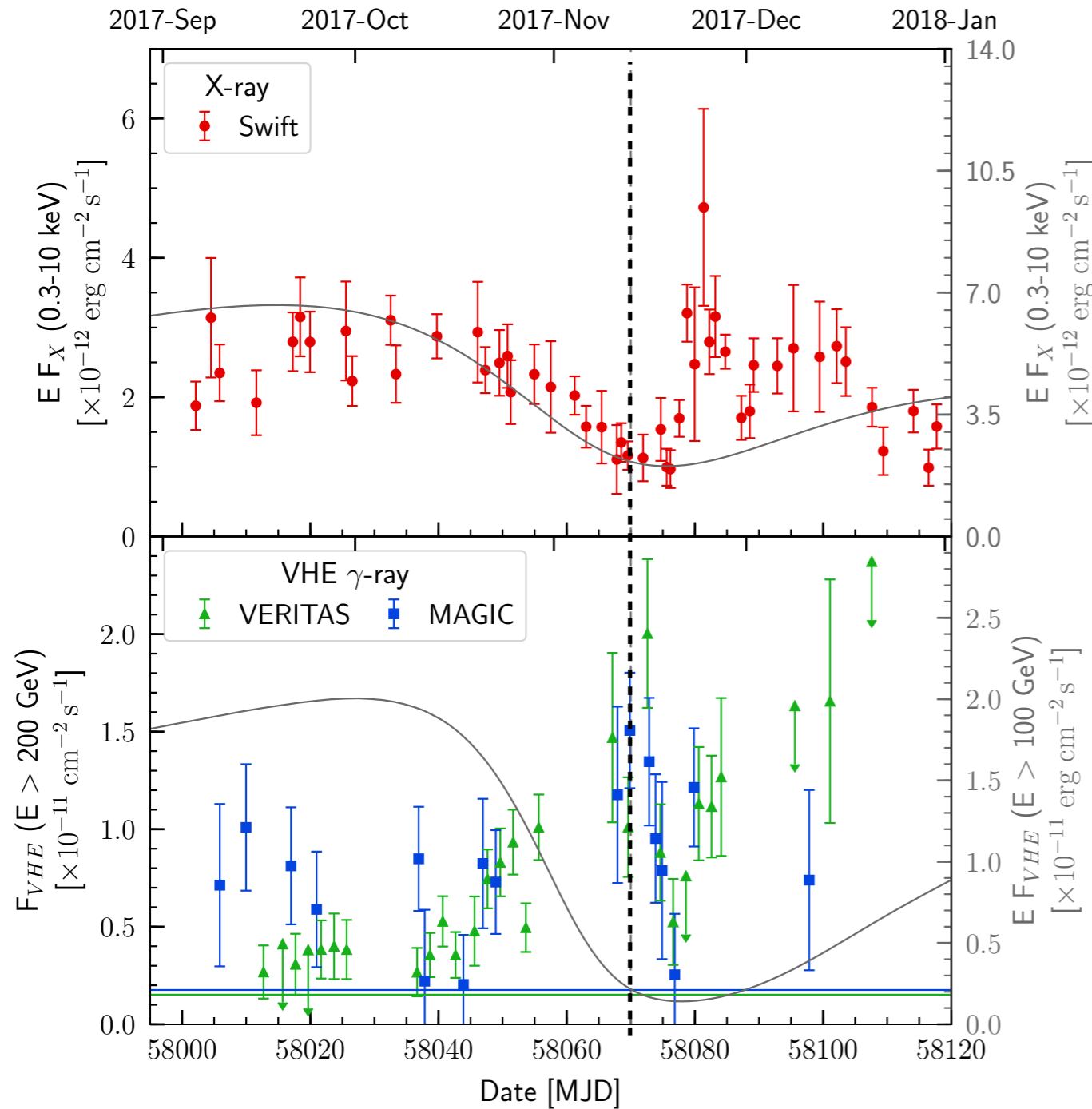


Abeysekara et al. (2018) ApJ submitted

Detection of the TeV γ -ray binary PSR J2032+4127/ MT91 213

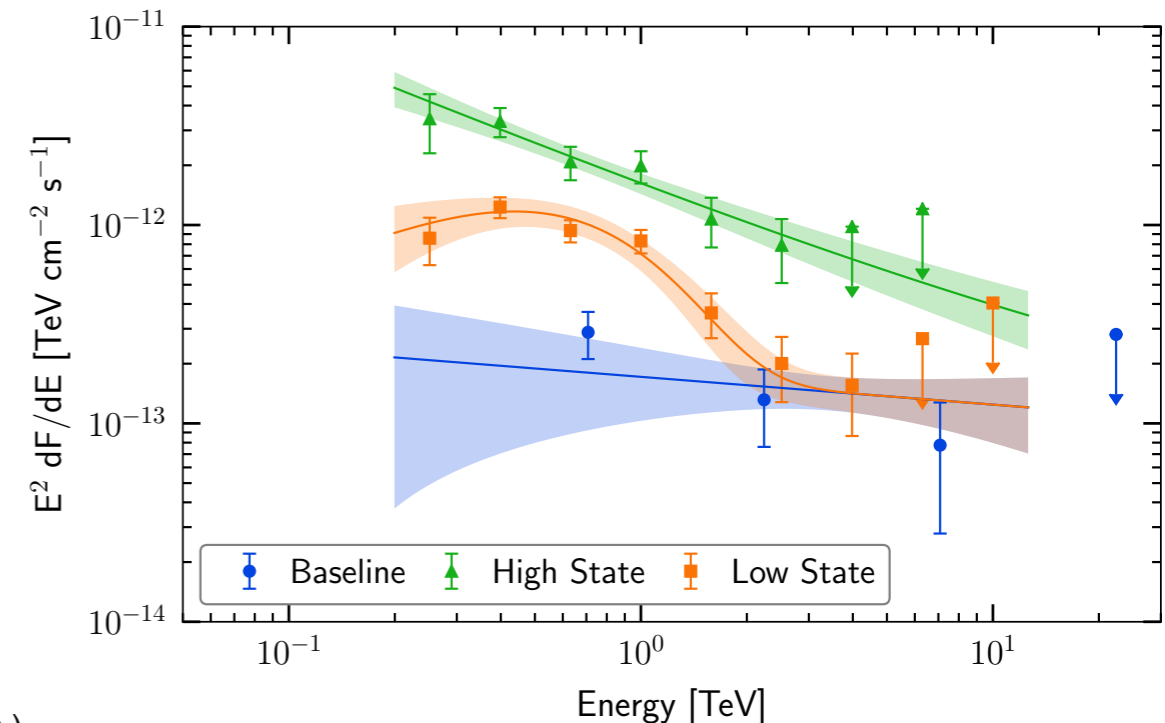
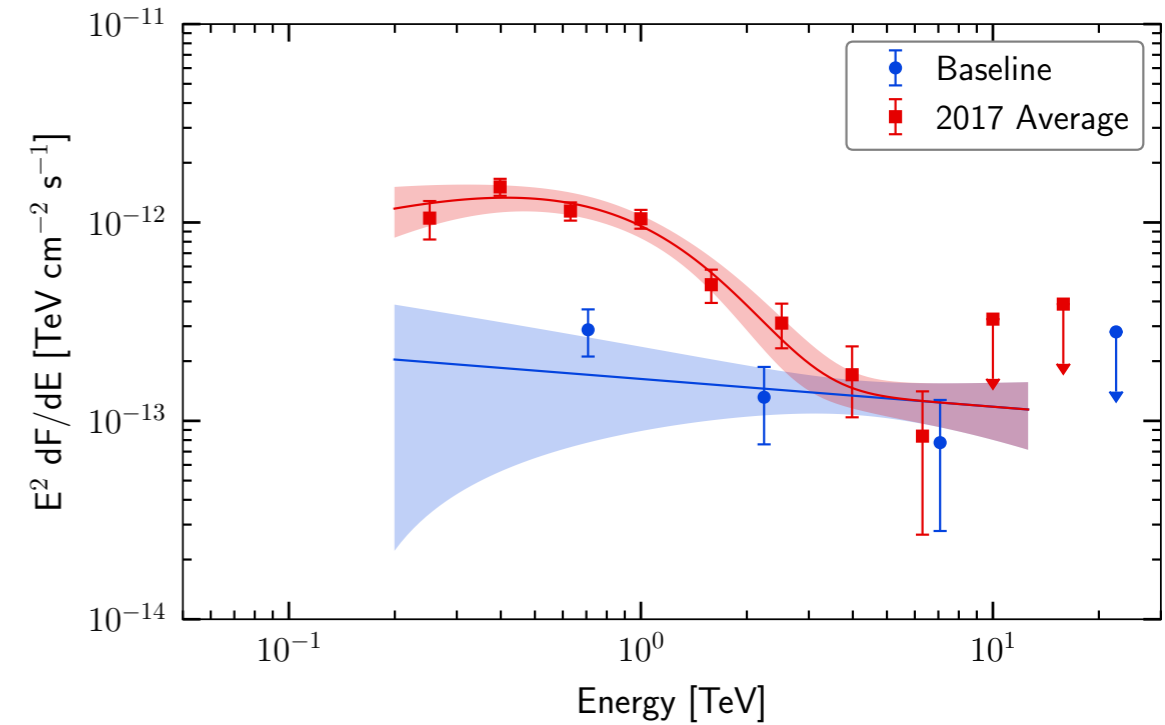
* Light curve around periastron:

* Spectra:



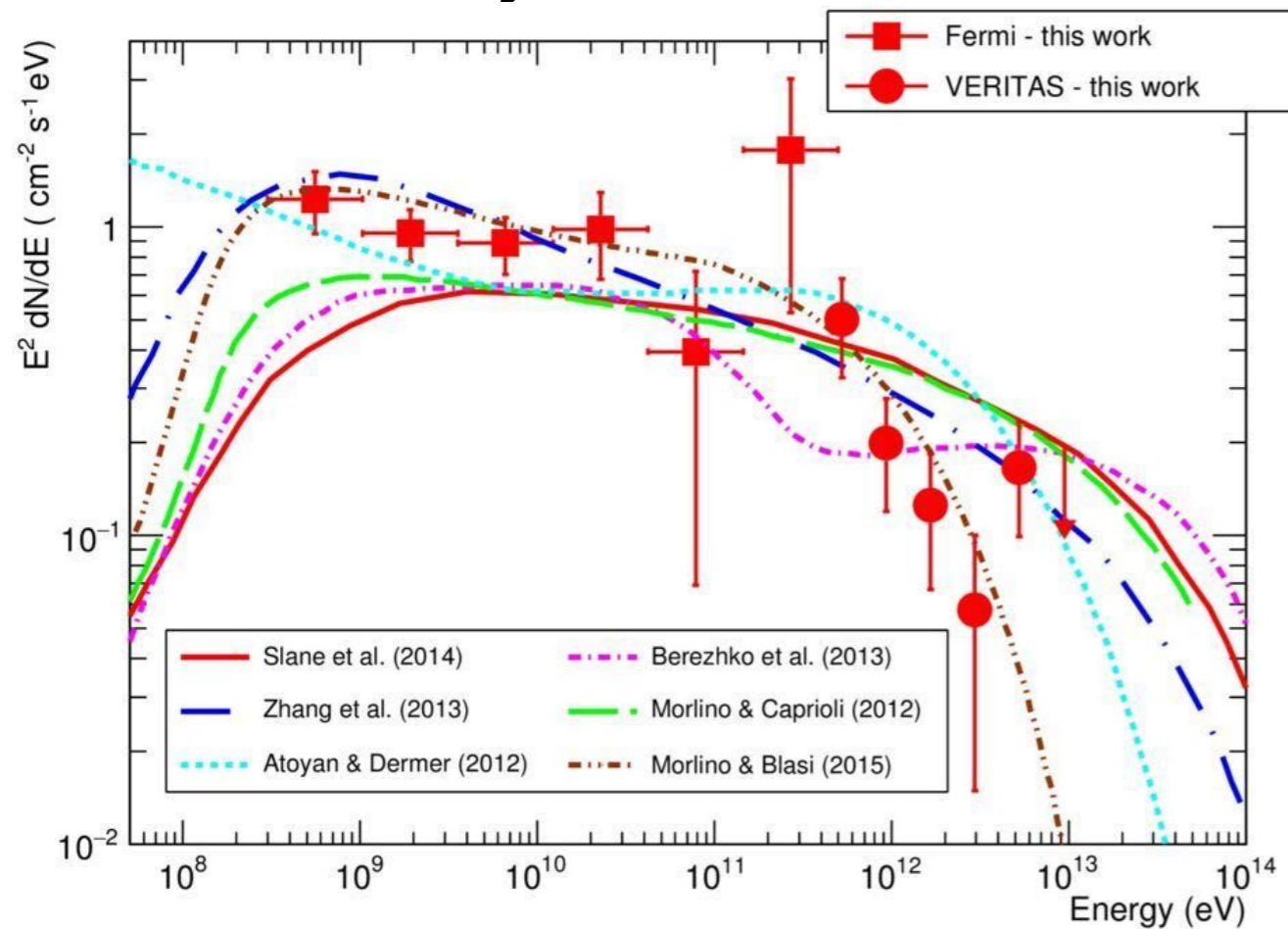
Grey lines:

- X-ray: model of predictions of Liu et al. (2018)
- VHE: model of Takata et al (2017) using parameters from Liu et al (2018) (Takata, private comm.)



Young SNR: Tycho & Cas A

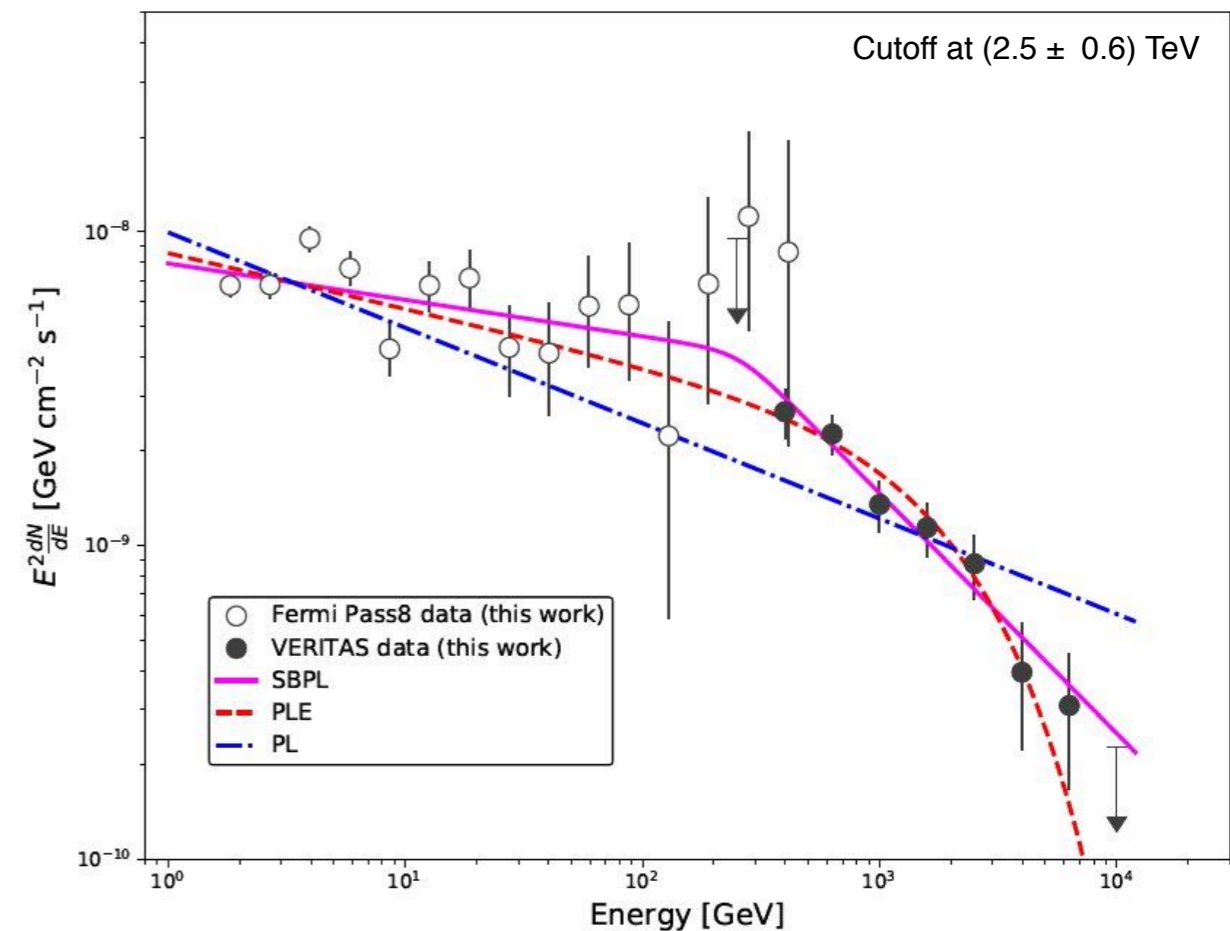
Tycho's SNR



147 hrs VERITAS 84 mo Fermi-LAT

Archambault et al. (2017)

Cassiopeia A



65 hrs VERITAS, 95 mo Fermi-LAT

Abeysekara et al. (2018) in prep.

- * Both Tycho's SNR (~450 yr) and Cas A (~350 yr) show spectral softening in the TeV range
- * These are not today's PeVatrons, but they are (almost certainly) hadronic accelerators.

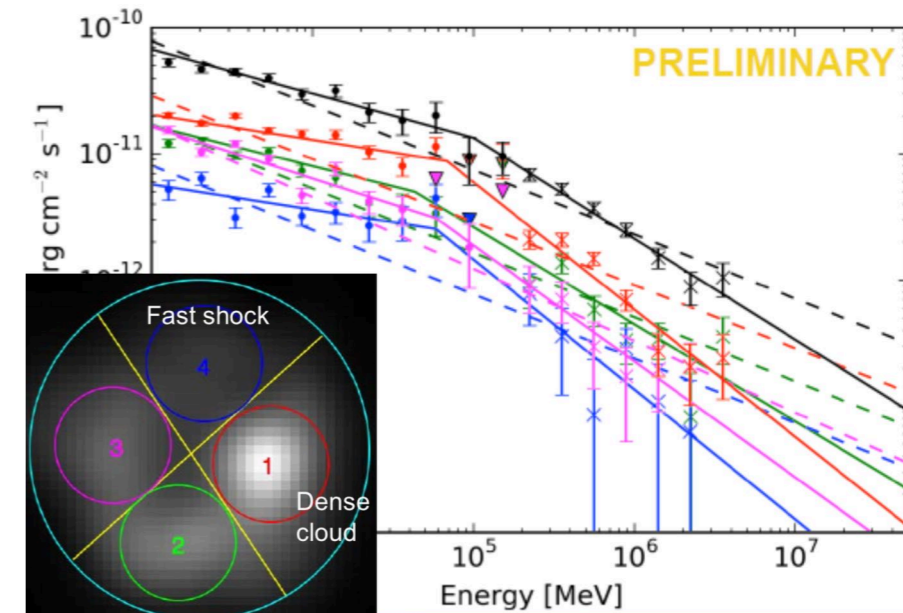
IC 443: an interacting SNR

Deconvolved 1–300 GeV events.
Pass 8 gives 2.4x statistics of
P7REP with cut on PSF68 < 0.4°

shocked HCO^+ contours

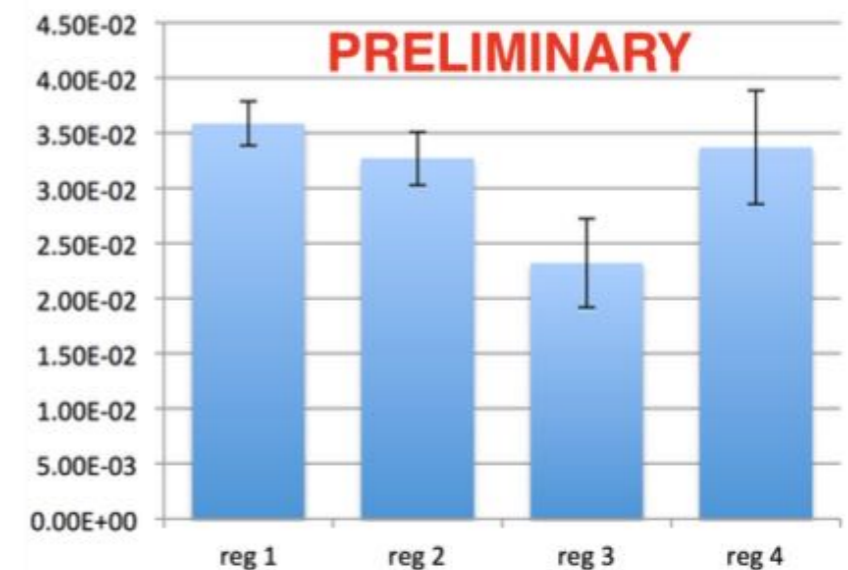
VERITAS Excess Map
 $E > 200$ GeV

Contours: 3, 6, 9 σ

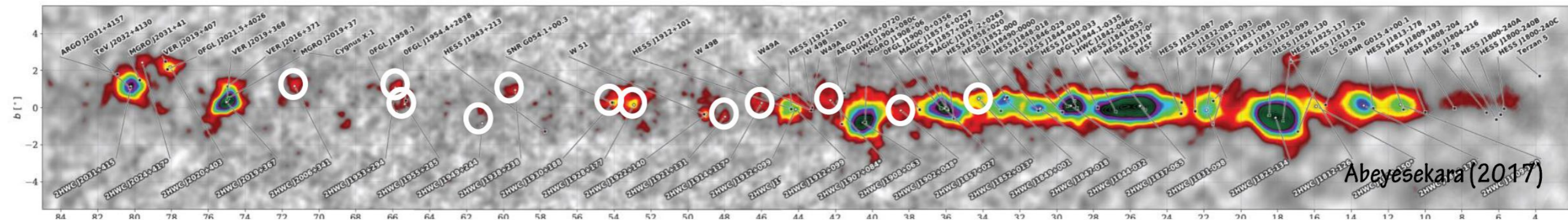


- * Resolved middle-aged shell, 0.7° across.
- * Strong differences in environment but no clear differences in spectral shape
- * Order of magnitude variation in intensity but **TeV/GeV integral flux ratios consistent within errors**
- * Common morphology from GeV to TeV argues for **single CR population**
- * Fermi-LAT now reports a second, hard-spectrum extended (1° radius) source encompassing IC 443 (FGES J0617.2+2235, Ackermann+ 1702.00476)
 - * CR escape signature?

TeV/GeV ratio - 4 regions



HAWC: 507 days of observation, found 39 γ -ray sources

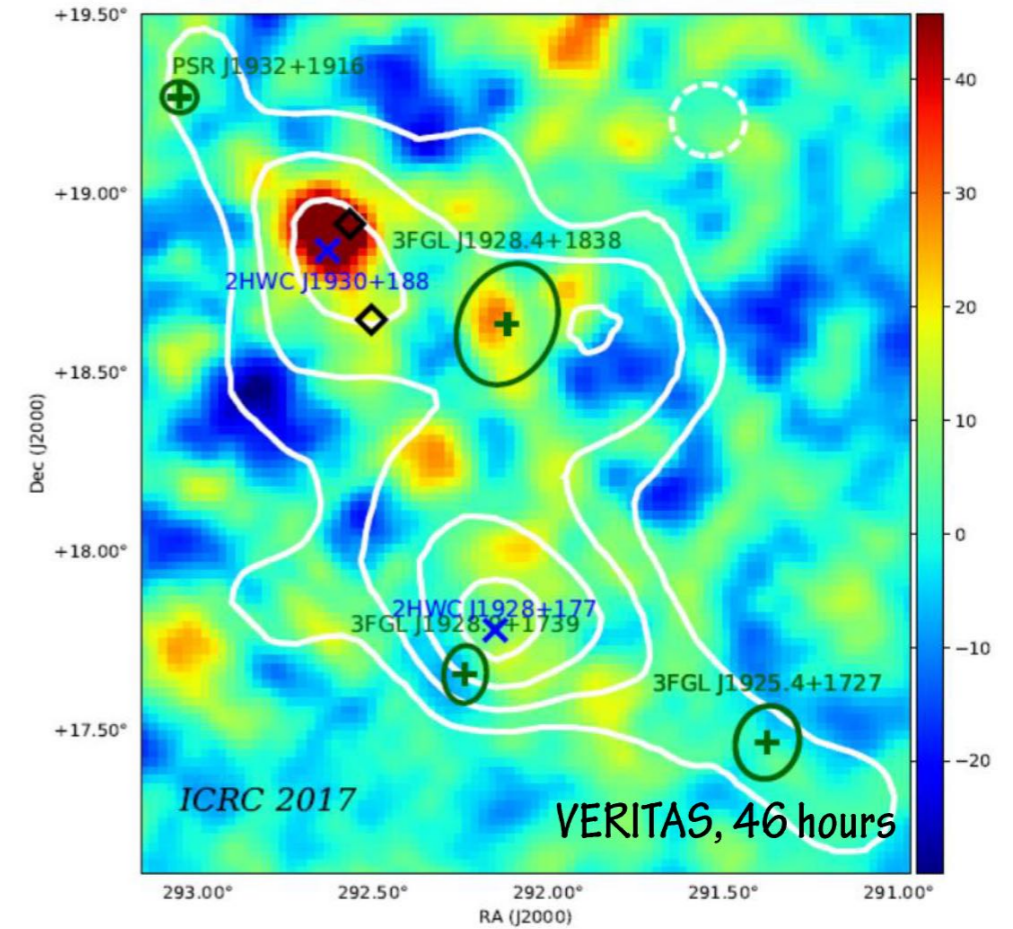
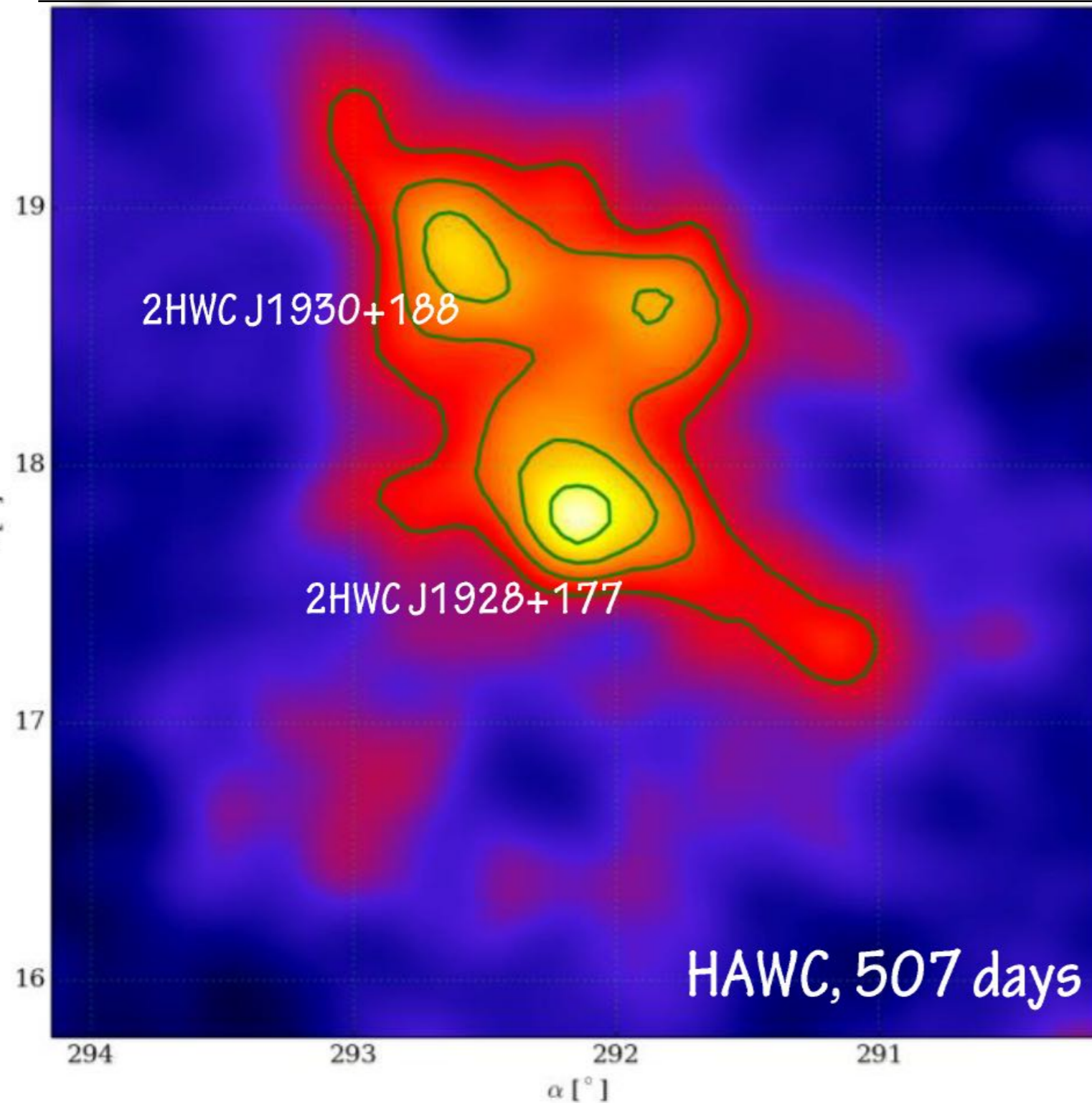


Abeysekara (2017)

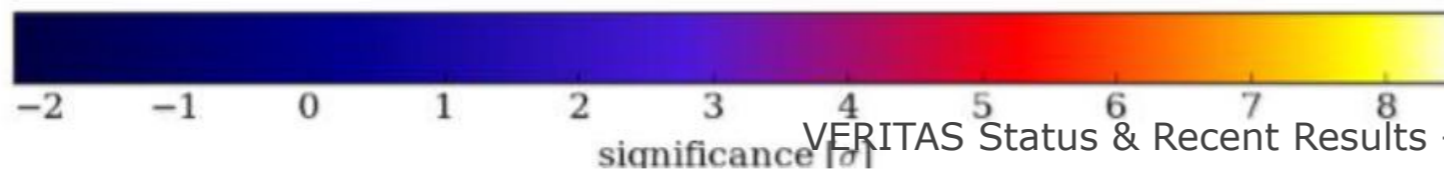
- * 16 sources $> 1^\circ$ from any known TeV γ -ray sources
- * VERITAS has 187 hrs exposure on 13 out of 16:
 - * Limits for 12 sources: rule out point source for 5 and require $> 0.23^\circ$ radius for 2
 - * New detection: **2HWC J1953+294 = VER J1952+294 = DA 495 PWN**
- * Fermi-LAT accumulated 8.5 years of exposure over all sky, improved sensitivity with Pass8 ($E > 10\text{GeV}$):
 - * Non-detection for 13 sources
 - * New detection of known TeV source SNR G54.1+0.3, PWN of PSR J1930+1852 (Acciari et al., ApJL, 719, L69 (2010))

Abeysekara et al (2018), ApJ accepted: <https://arxiv.org/abs/1808.10423>

SNR G54.1+0.3 and surroundings

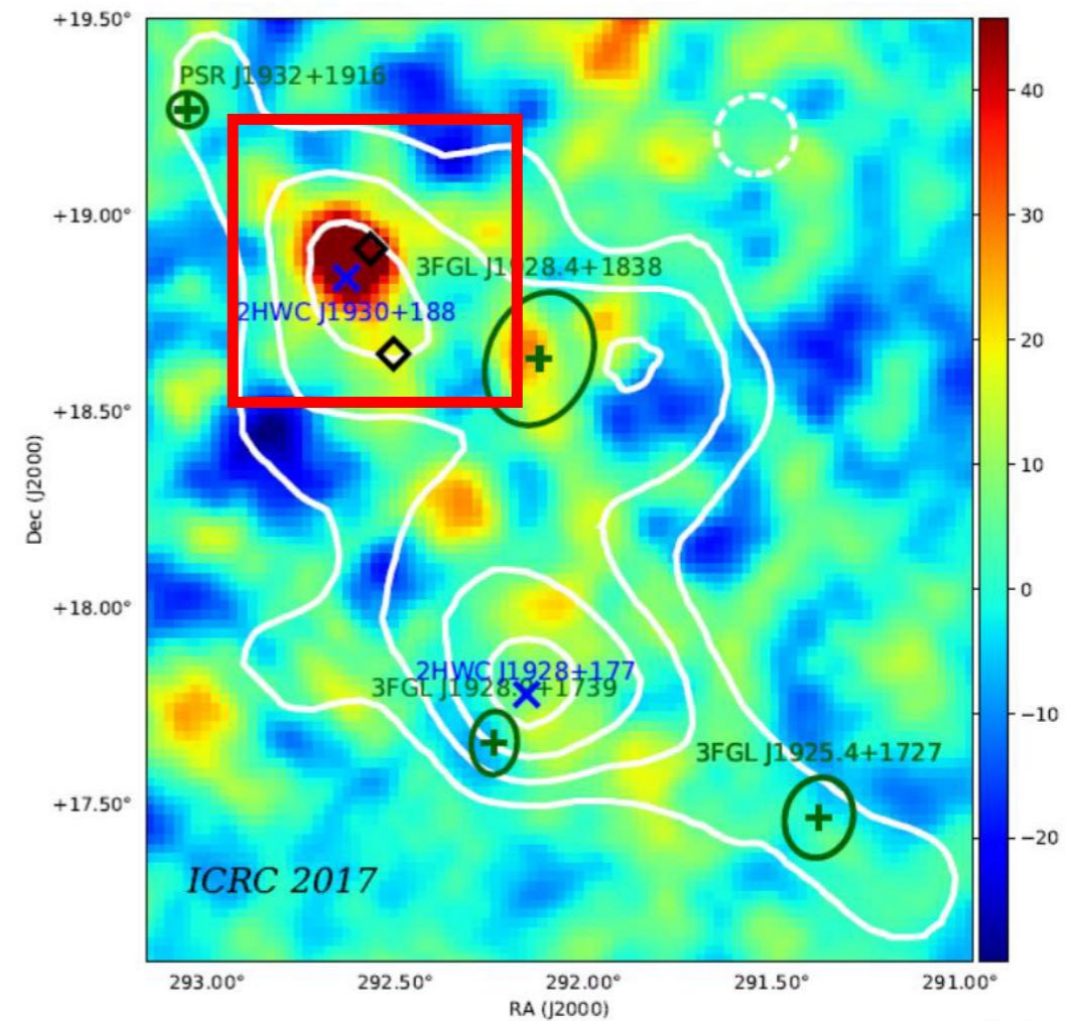
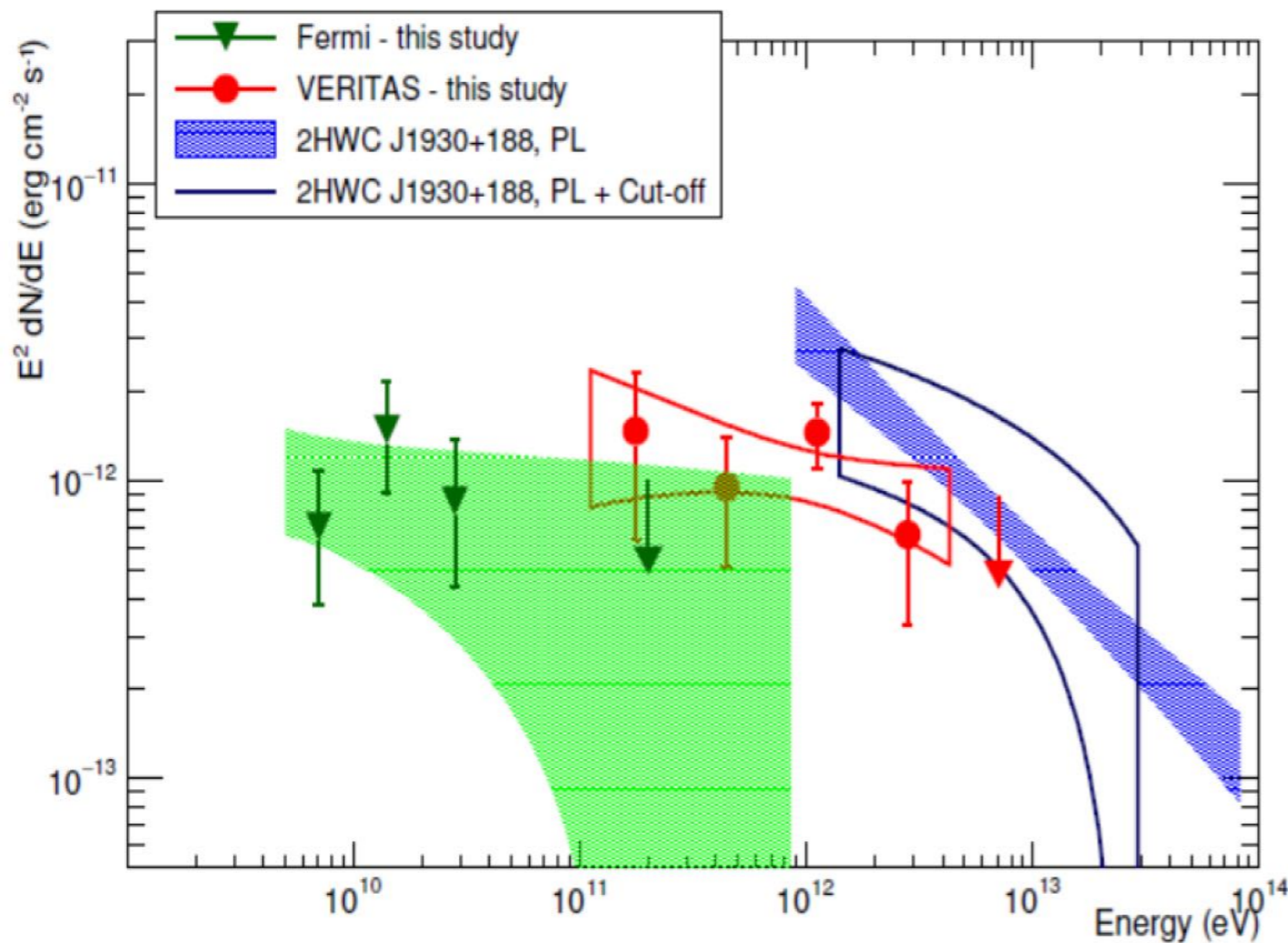


Abeysekara et al, (2018) ApJ accepted:
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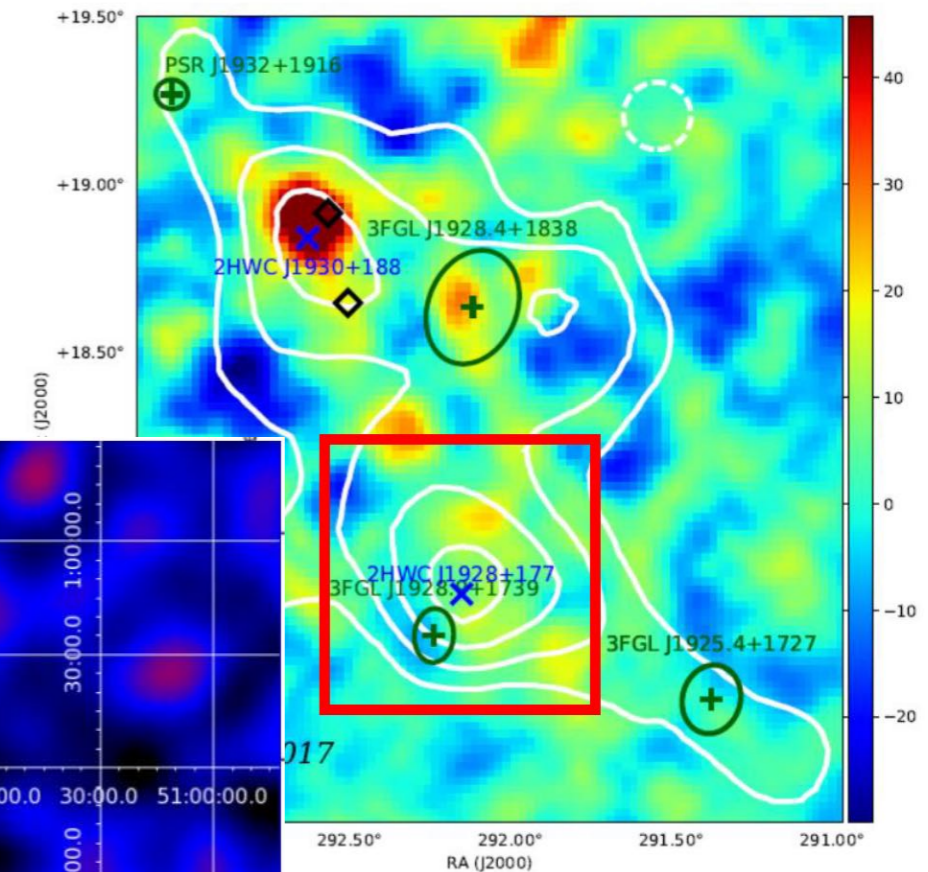
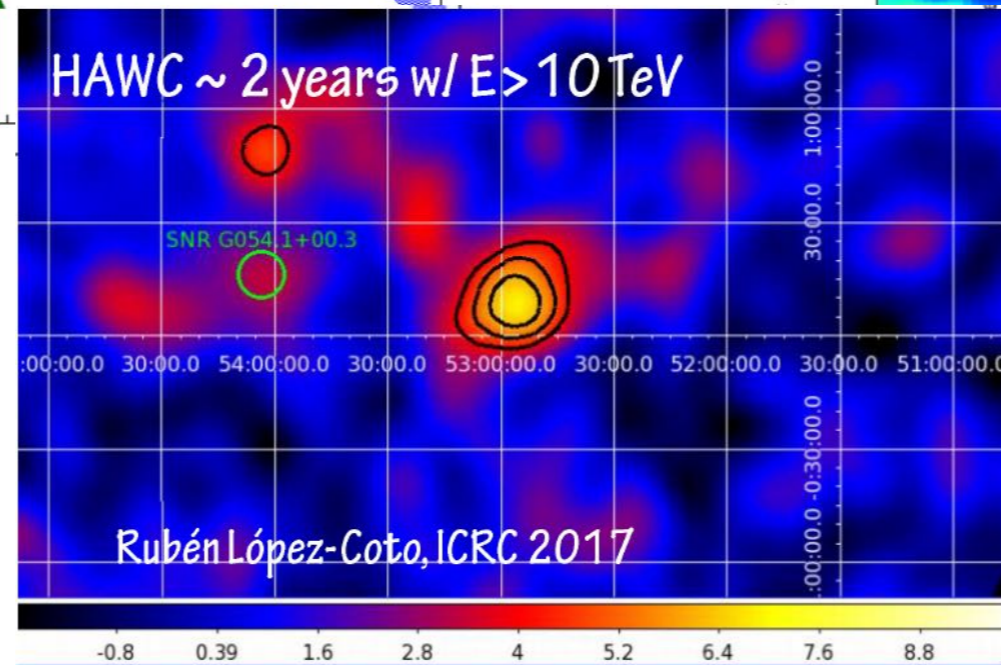
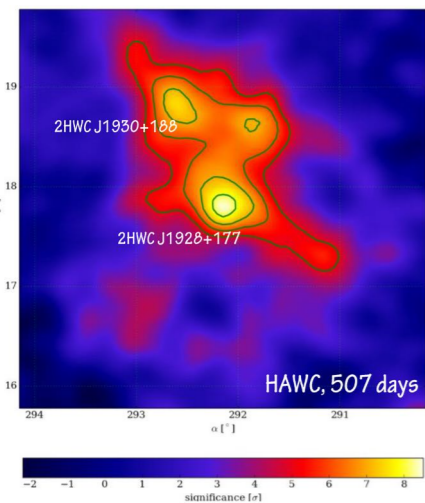
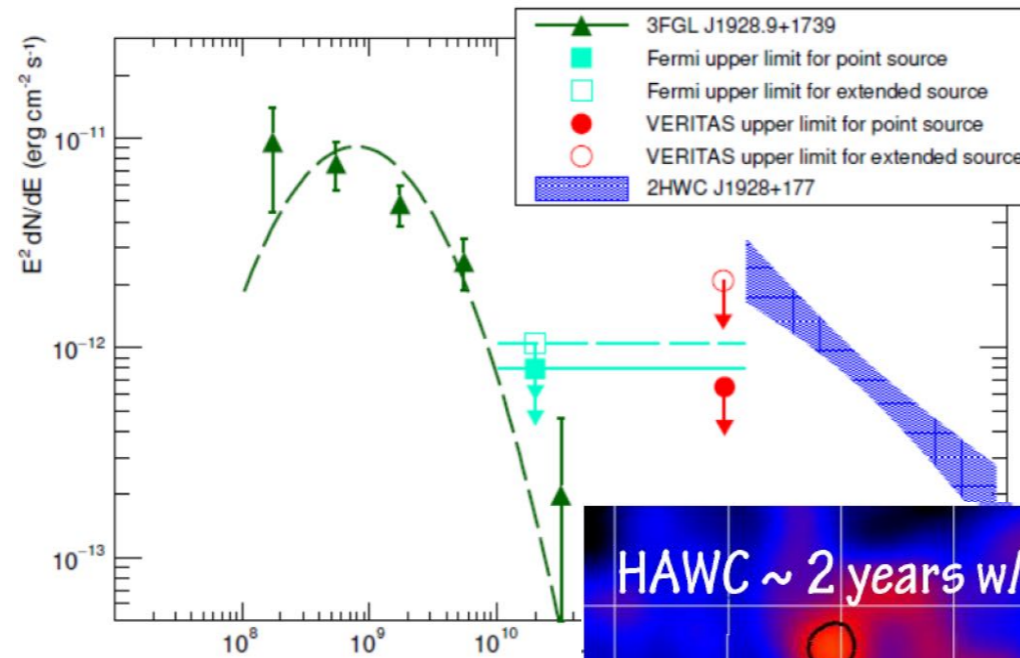
SNR G54.1+0.3 and surroundings

- * Fermi-LAT detection coincident with known TeV source, VER J1930+188, and 2HWC J1930+188
- * SNR G54.1+0.3 is likely the counterpart.
- * Fermi, VERITAS, & HAWC combined: the overall SED is more consistent with PL + cut-off hypothesis.



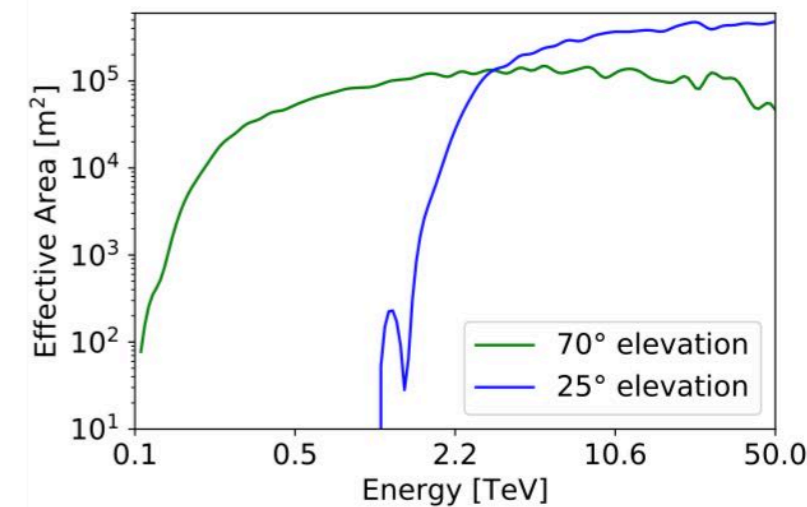
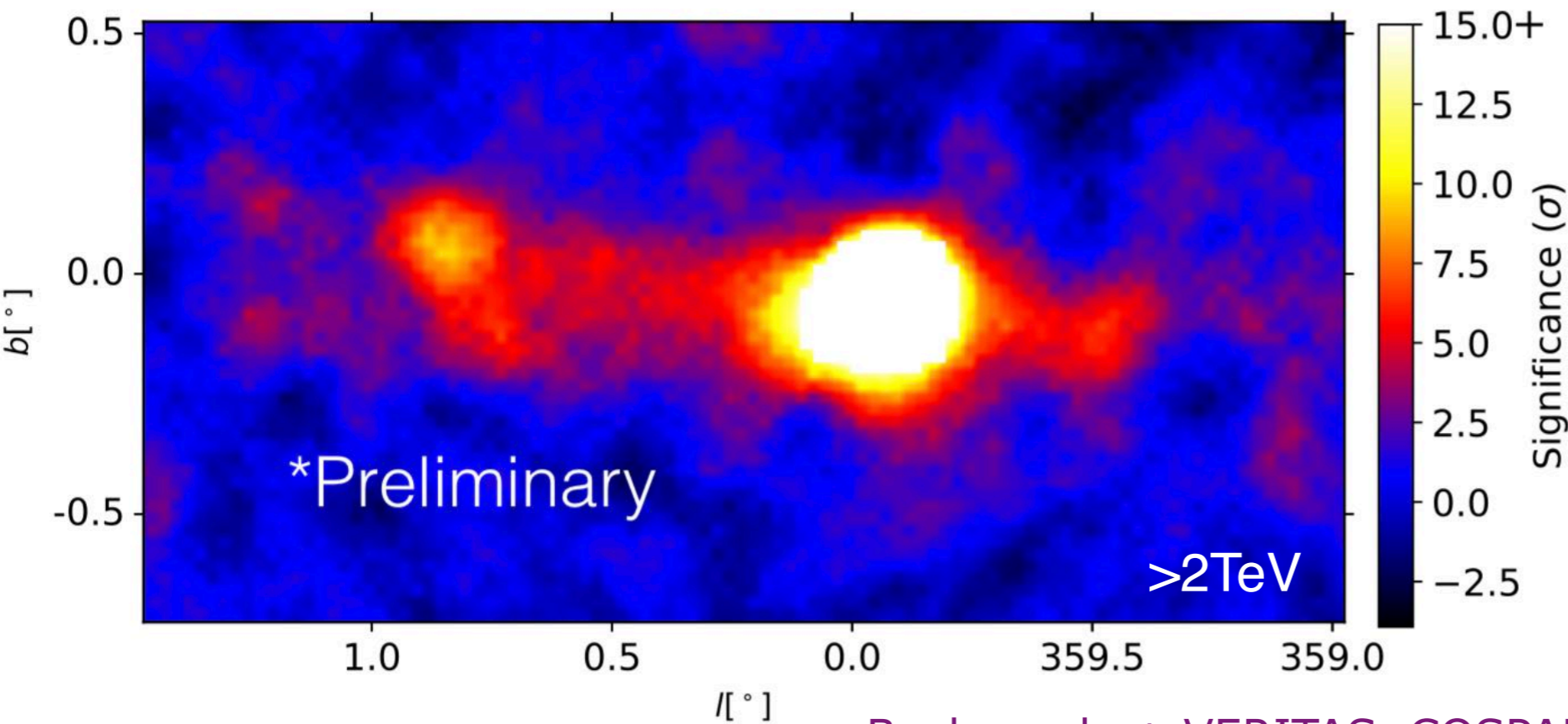
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SNR G54.1+0.3 and surroundings



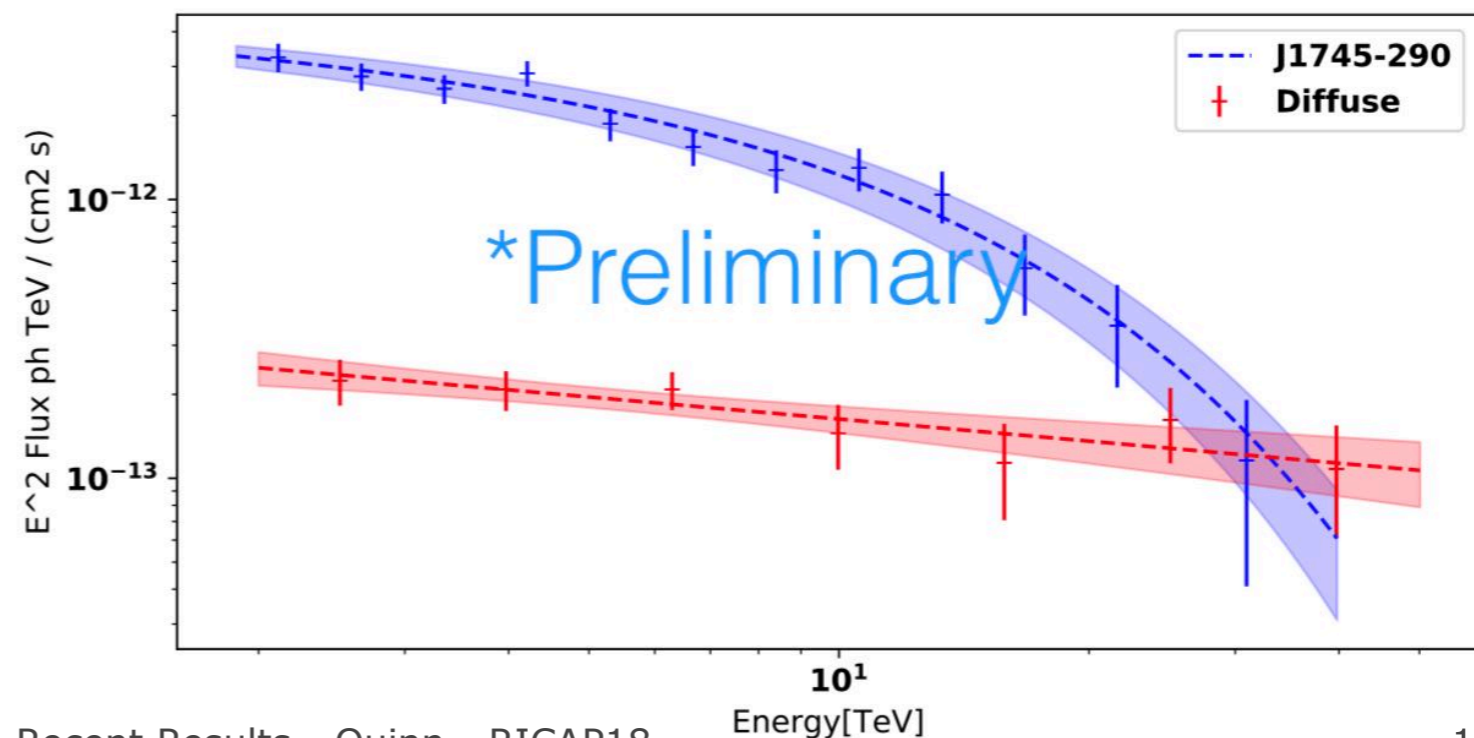
2HWC J1928+177:

- * Coincides with pulsar PSR J1928+1746
- * Equally strong source as 2HWC J1930+188 for HAWC
 - * Stronger than 2HWC J1930+188 for $E > 10$ TeV
 - * VERITAS limit excludes a point source assuming the same PL distribution

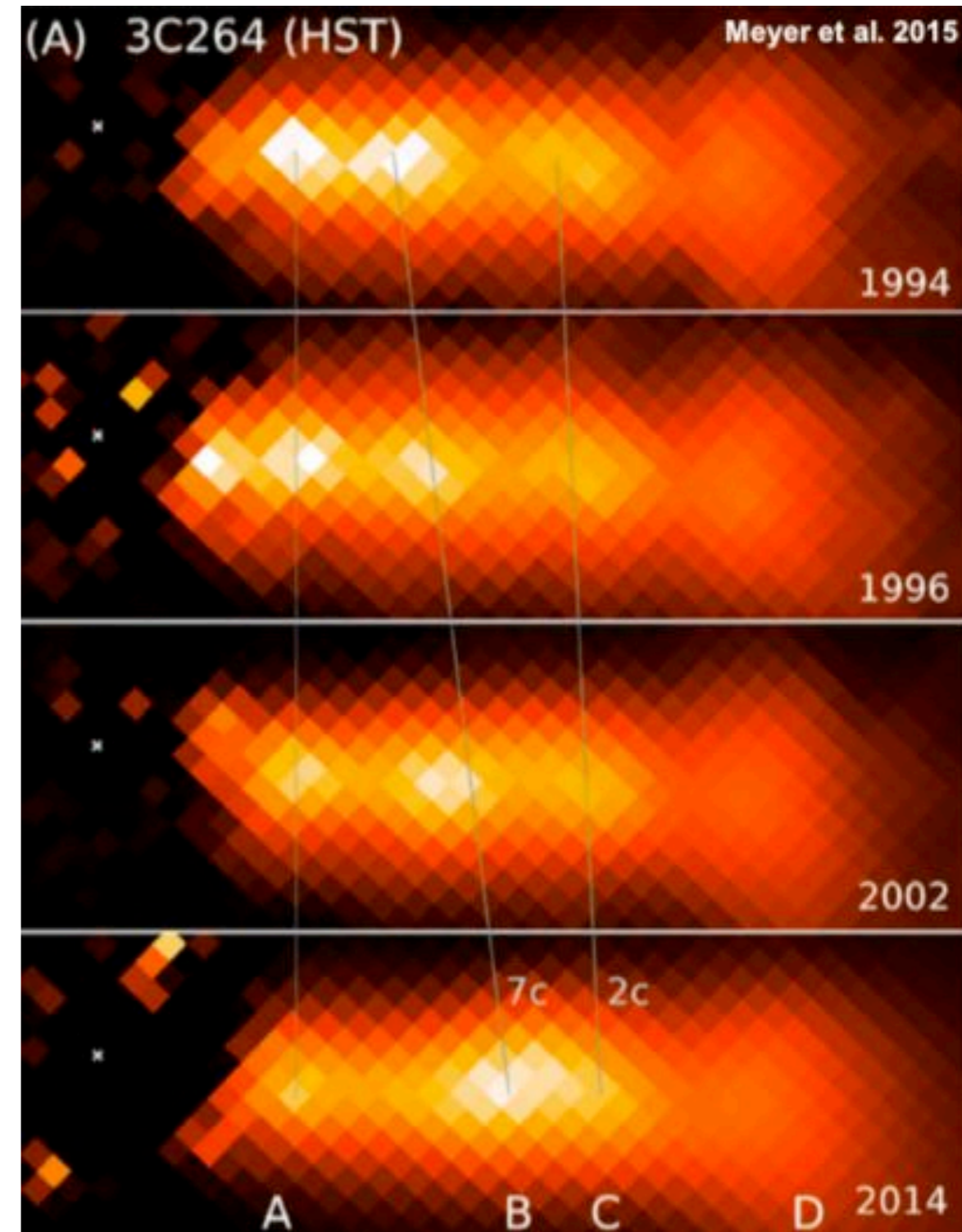
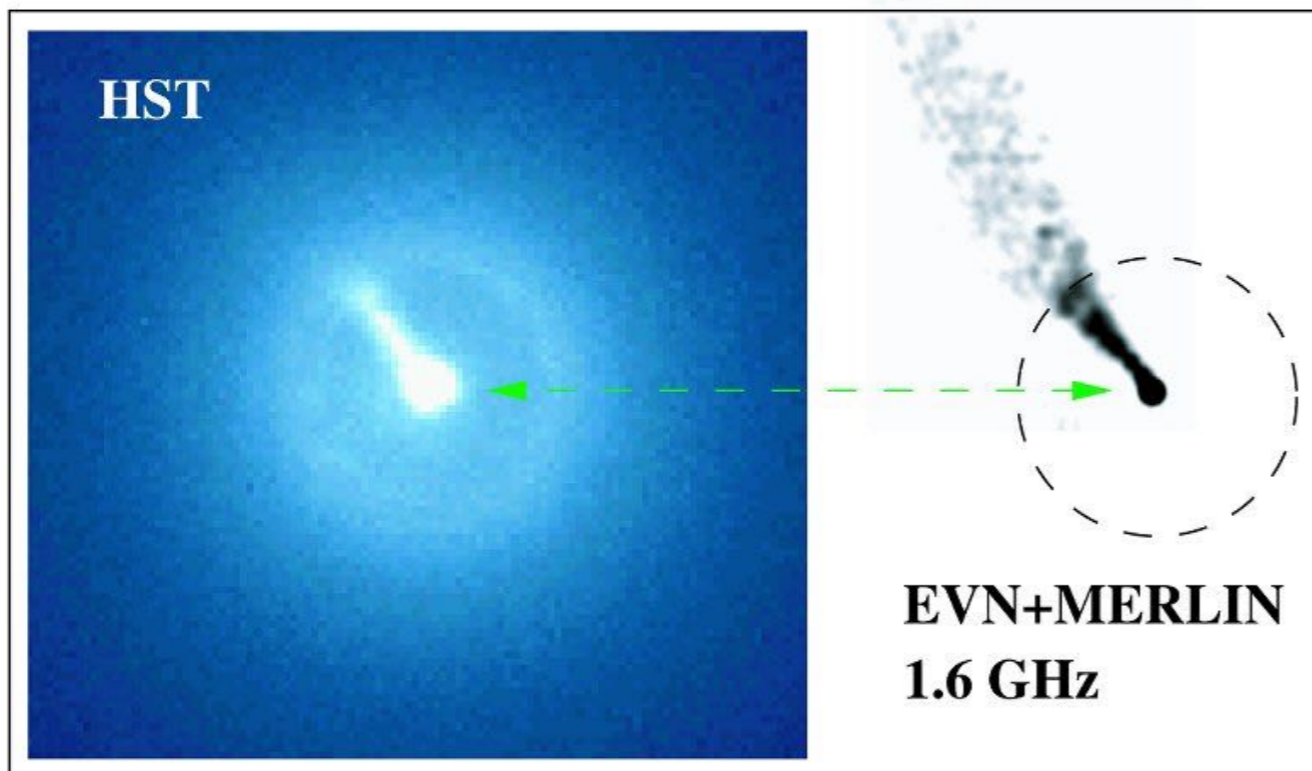


Buchovecky+ VERITAS, COSPAR (2018)

- * J1745-290 (Sgr A*):
 - * $>35\sigma$, consistent w/point source
 - * constant flux
 - * spectrum: PL w/exp. cutoff:
 - * $\Gamma = -2.16 \pm 0.18_{\text{stat}}$
 - * cutoff at 10.8 ± 3.0 TeV
- * Diffuse emission:
 - * regions as per H.E.S.S. (2016)
 - * PL with index -2.26 ± 0.13
 - * no cutoff observed up to 40 TeV

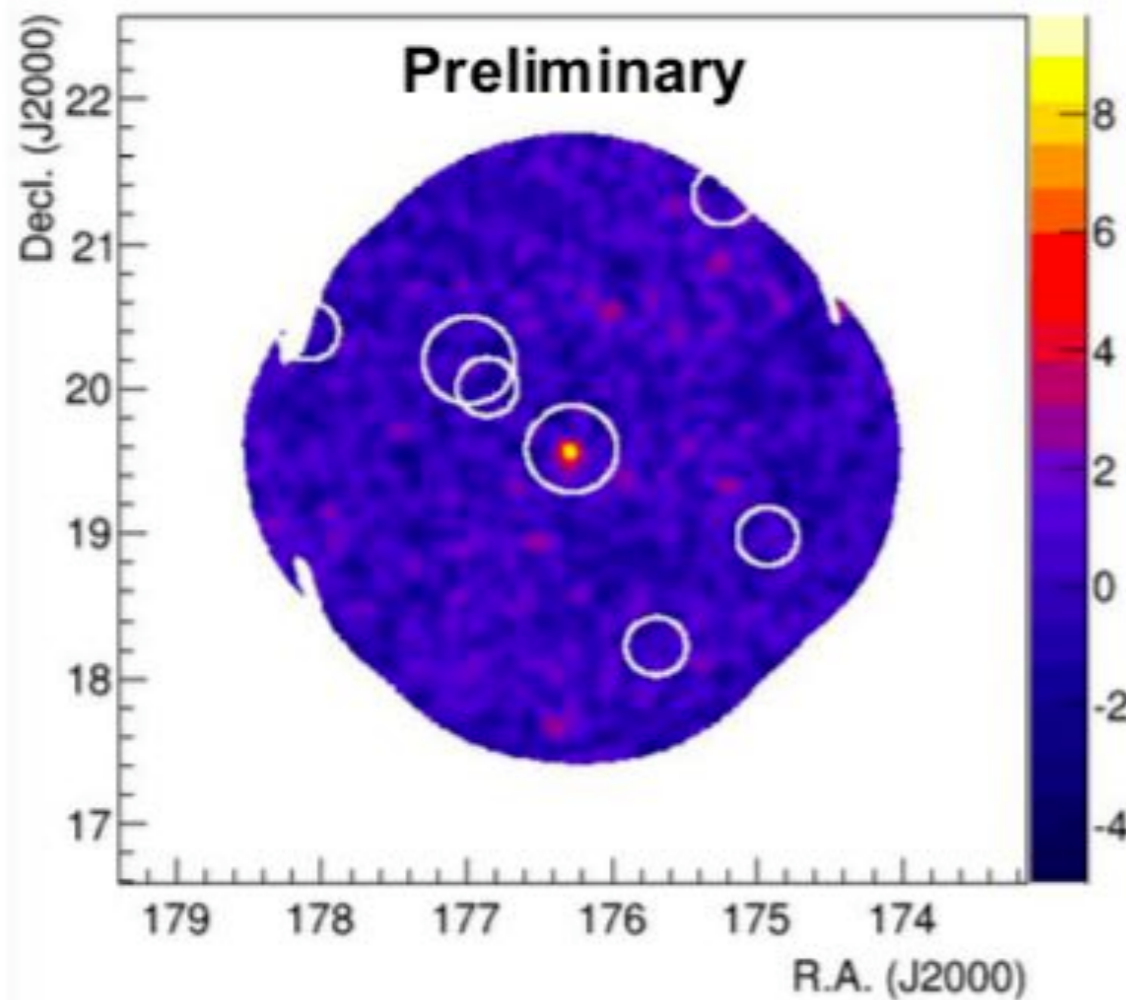


- * FR-I radio galaxy, $z = 0.0216$
 - * More distant ($\sim 6\times$) "M87" analog
- * Rapidly evolving knot-structure MeV-GeV source: 3FGL, 2FHL & 3FHL
 - * $\Gamma_{3\text{FHL}} \sim 1.65 \rightarrow F(>200 \text{ GeV}) \sim 1.6\% \text{ Crab}$
- * VERITAS $\sim 10 \text{ h}$ observation in 2017
 - * $\sim 2\sigma$ excess \rightarrow 2018 follow-up



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Significance map for 3C 264



VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

ATel #11436; **Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration**
on 17 Mar 2018; 00:25 UT

Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar

[Tweet](#) [Recommend 49](#)

We report the VERITAS discovery of very-high-energy emission (VHE; >100 GeV) from the FRI radio galaxy 3C 264, also known as NGC 3862. Nearly 12 hours of quality selected data, collected by VERITAS between 09 February 2018 and 16 March 2018 (UTC), were analyzed. Preliminary results yield an excess of 60 gamma-ray events above background at the position of the source, corresponding to a statistical significance of 5.4 standard deviations. Our preliminary flux estimate ($E > 300$ GeV) is $(1.3 \pm 0.2) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$, or approximately 1% of the Crab Nebula flux above the same threshold. The Fermi-LAT 3FHL catalog (Ackermann et al. 2017 ApJS 232, 18) lists a photon index of 1.65 ± 0.33 for 3C 264 which, when extrapolated to the VHE band, is consistent with the VERITAS detection. At a redshift of 0.0217, 3C 264 is a more distant analog to M87, with superluminal motion of $\sim 7c$ (Meyer et al. 2015, Nature 521, 495) detected in its kpc-scale optical jet. With this discovery, 3C 264 is the most distant radio galaxy detected at VHE so far. VERITAS will continue to observe 3C 264; multi-wavelength observations are encouraged. Questions regarding the VERITAS observations should be directed to Reshmi Mukherjee (rm34@columbia.edu). Contemporaneous target-of-opportunity observations with the Swift satellite have also been scheduled. VERITAS (Very Energetic Radiation Imaging Telescope Array System) is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA, and is most sensitive to gamma rays between 85 GeV and 30 TeV (<http://veritas.sao.arizona.edu>).

* 44 hrs taken in 2018 \rightarrow 8σ detection

* Spectrum:

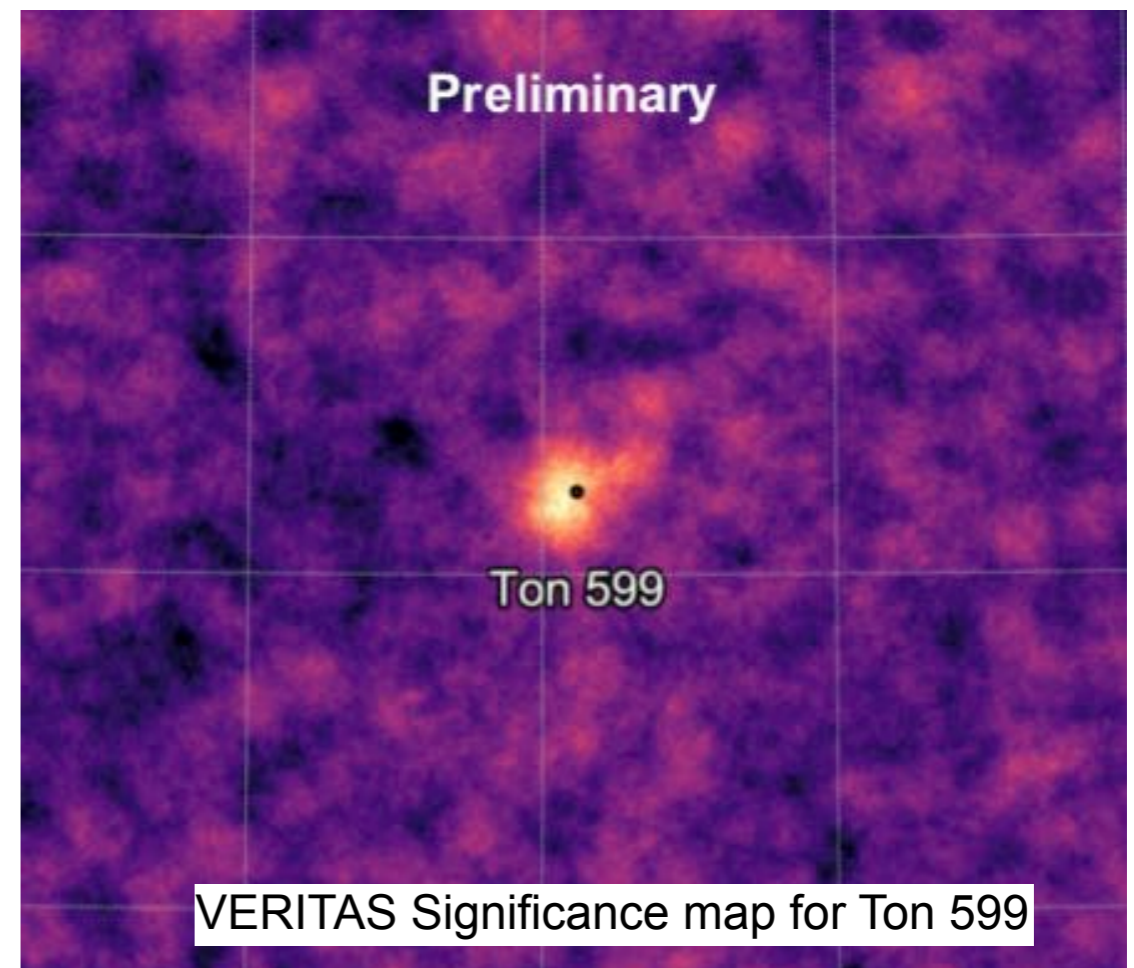
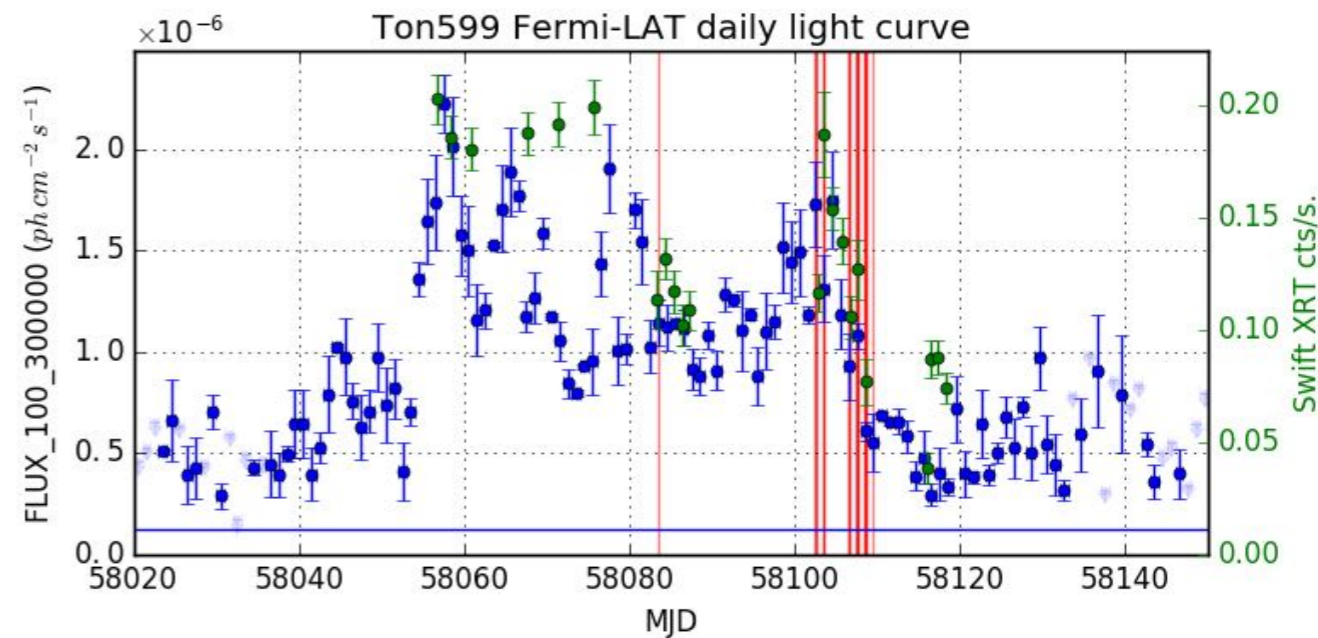
* hard with index $\Gamma \sim 2.3$

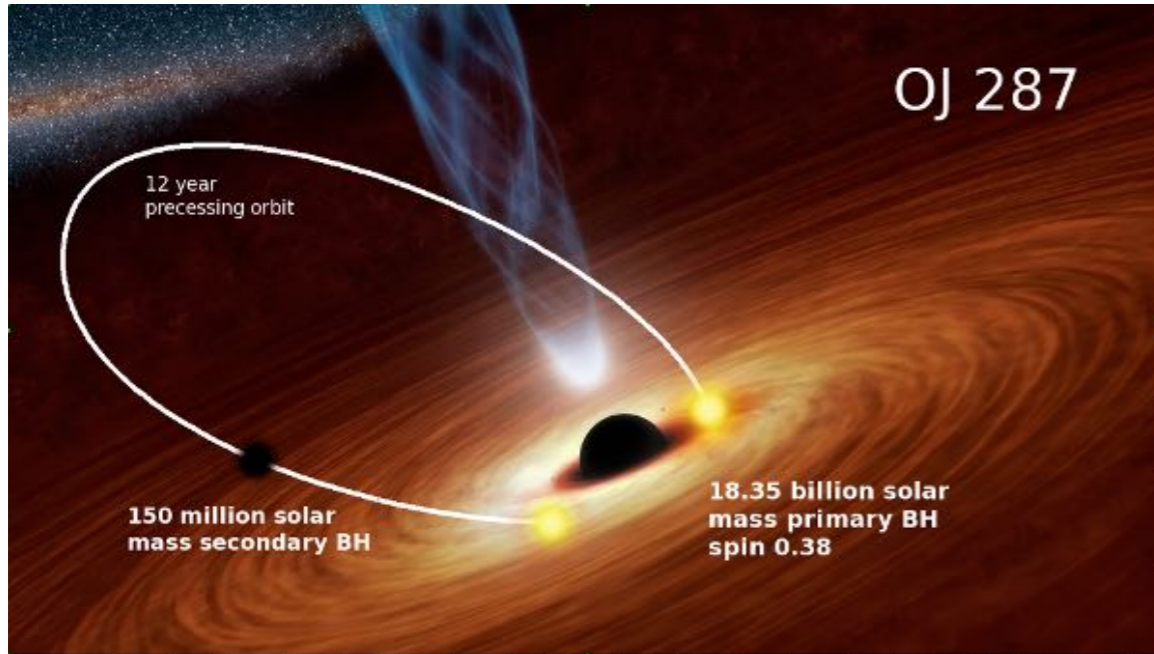
* low $\sim 0.5\%$ Crab, weakly variable flux (timescale \sim months)

* VERITAS triggered major MWL effort: Radio (e.g. VLBA), Optical (HST, ground-based), X-ray (Chandra + Swift), Fermi-LAT \rightarrow No major activity in knot sub-structure.

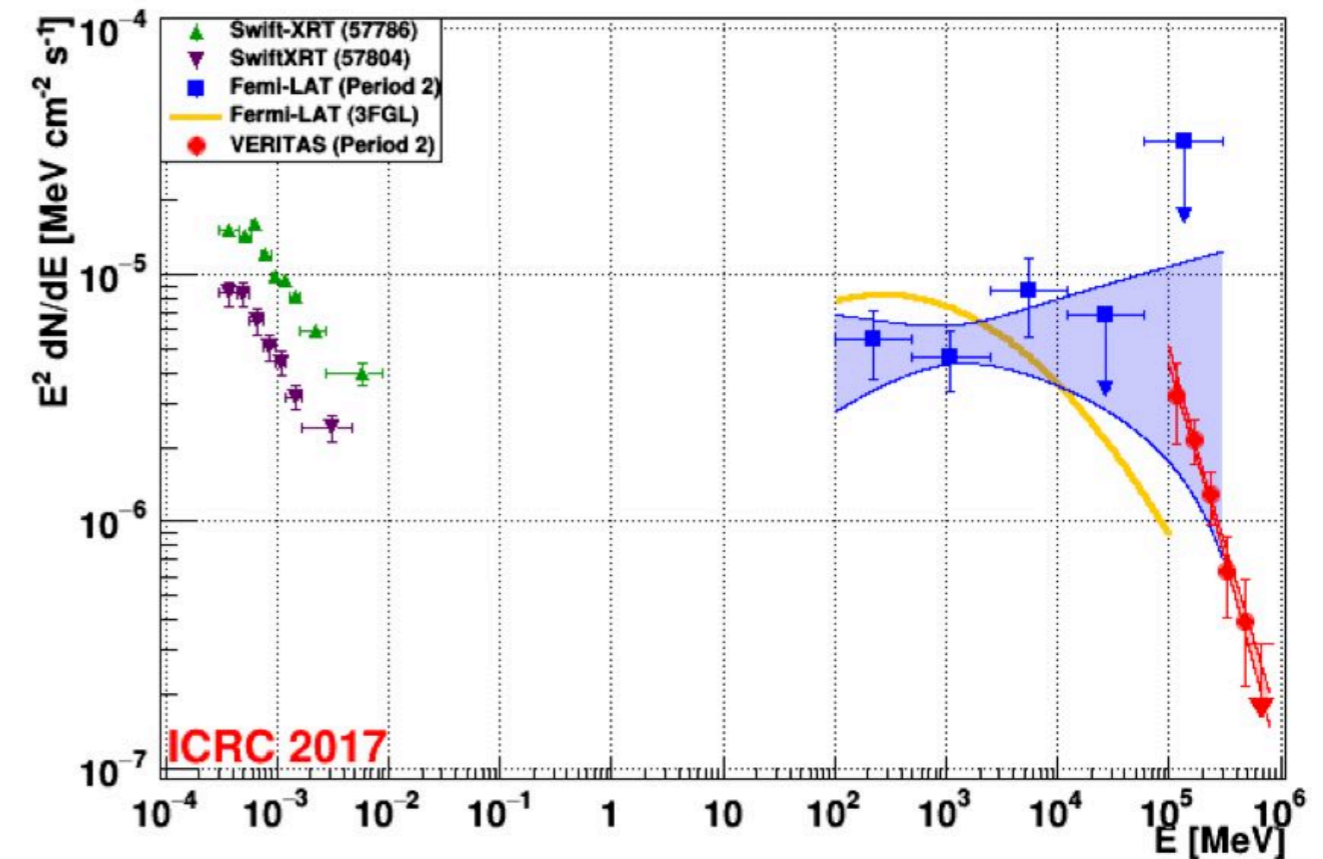
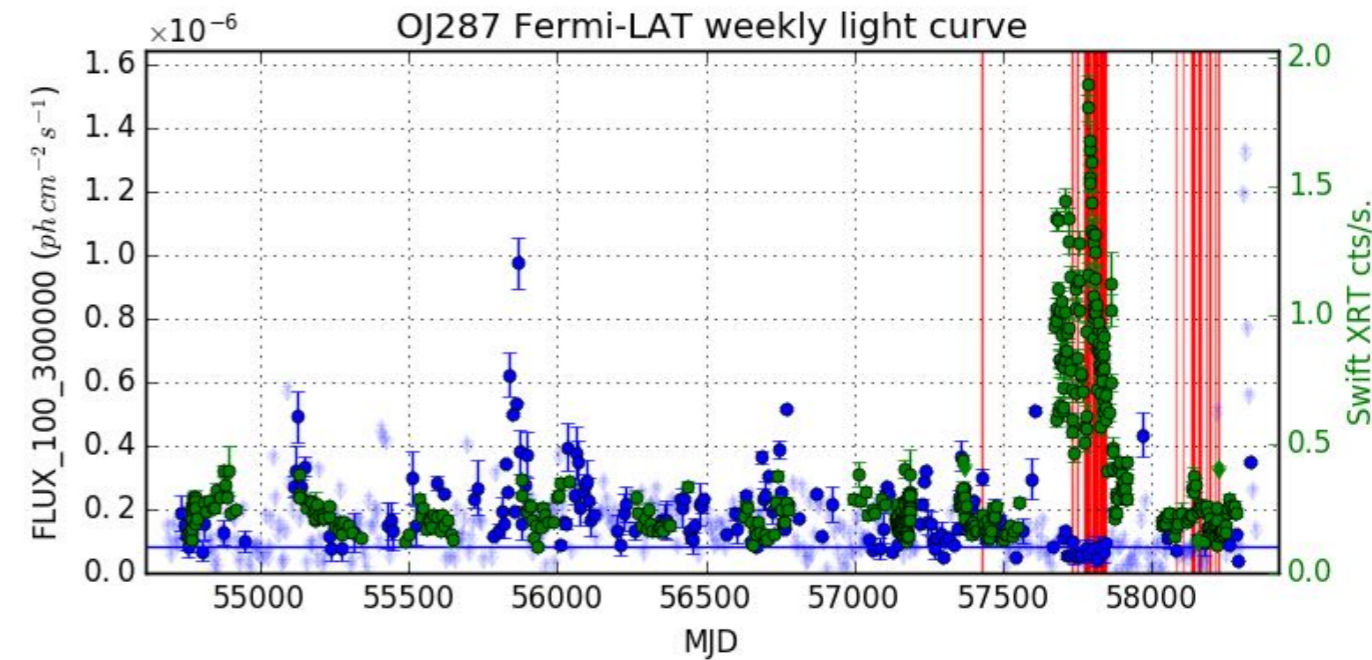
TON 599: 3rd most-distant VHE source

- * FSRQ @ $z=0.72$
- * November 2017: exceptional flaring:
 - * FERMI-LAT in early Nov. 2017 (ATel #10931: 20 x 3FGL flux)
 - * NIR flares in Nov. 2017 (ATel #10949)
 - * Too low in sky for VERITAS....
- * VERITAS waits and observes on December 15-16
 - * detection (ATel #11075):
 - $\sim 8\sigma$ in $\sim 2h$; $\Gamma \sim 5$
 - $F(>100 \text{ GeV}) \sim 12\%$ Crab
- * MAGIC also detects on December 15: ATel #11061
- * Most-distant VERITAS-detected object: PKS 1441+25 @ $z=0.939$

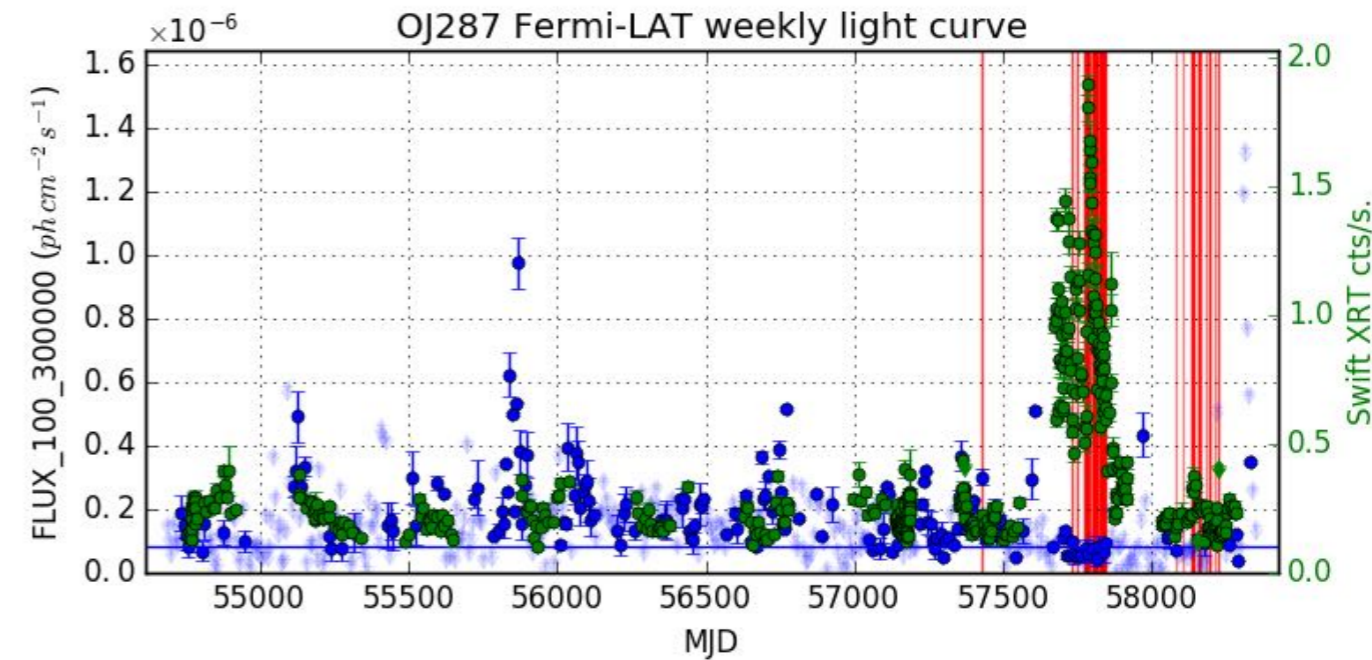
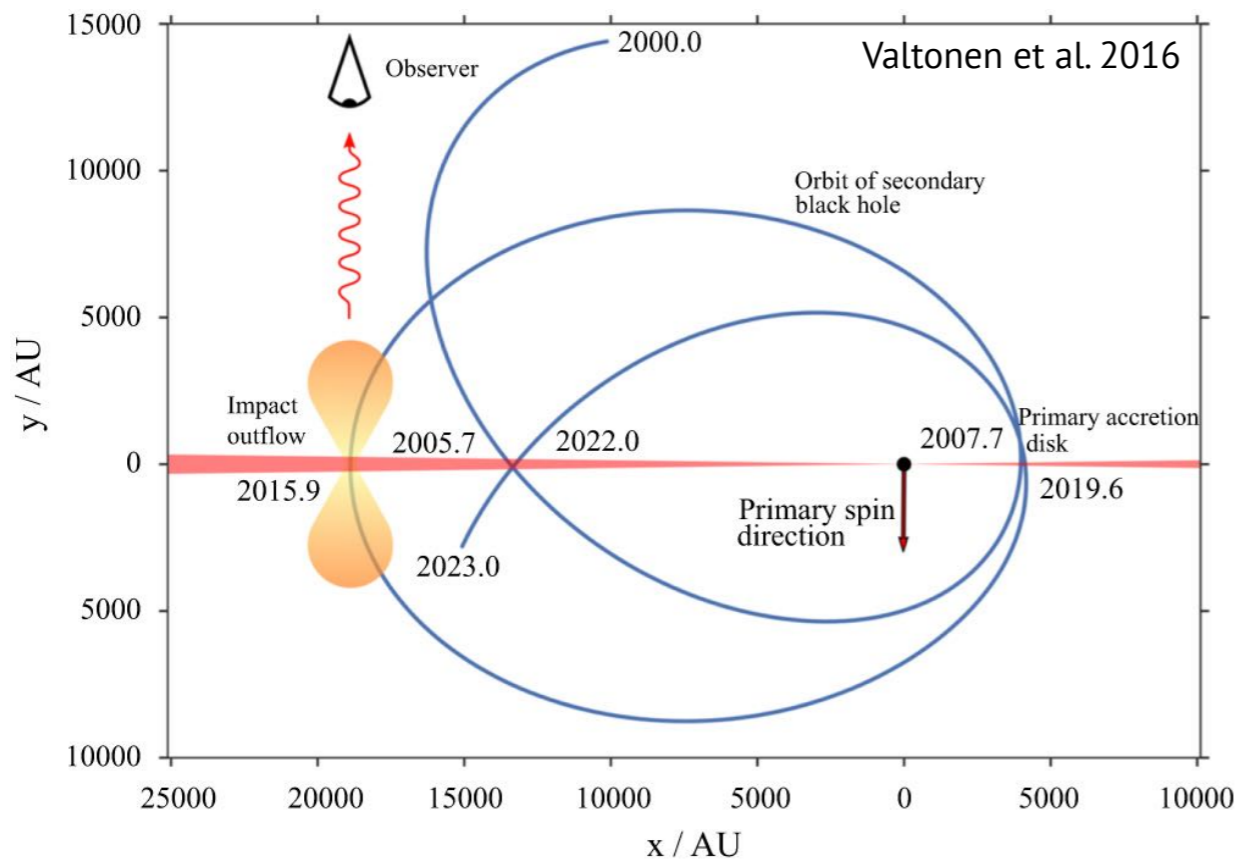




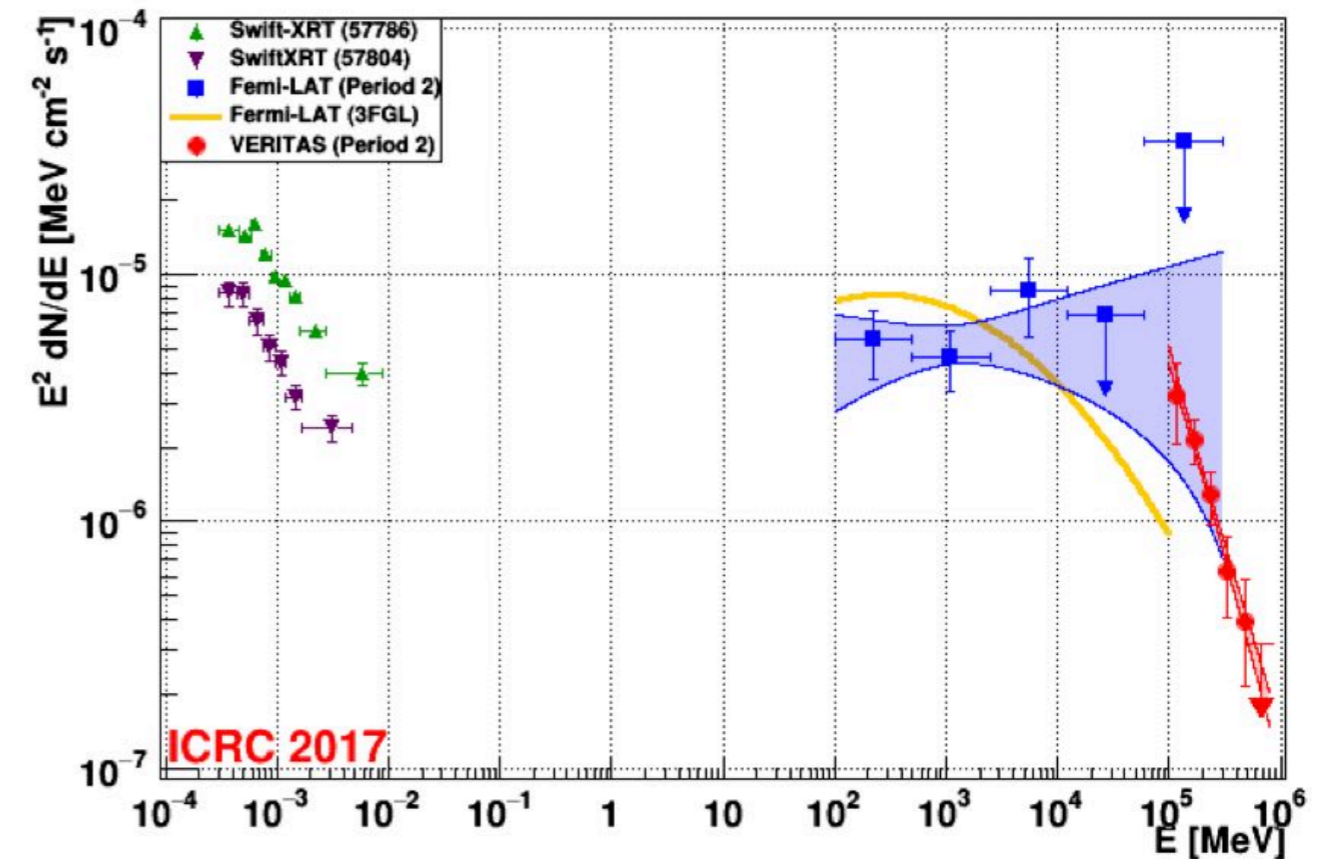
- * VERITAS limit in 2007: 10 h, <2.6% Crab
- * Swift XRT flaring => 2016-17 ToO
- * VERITAS VHE discovery in Feb. '17: ATel #10051
- * 2016-17:
 - * ~50 h, 9.7σ ,
 - * $F(>150 \text{ GeV}) \sim 1.3\% \text{ Crab}$
 - * $\Gamma = 3.49 \pm 0.28$
- * Copious MWL data:
 - * SED shifts
 - * Possible contemporaneous birth of radio knot near BH
- * Paper in preparation....



O'Brien+ VERITAS, ICRC (2017)

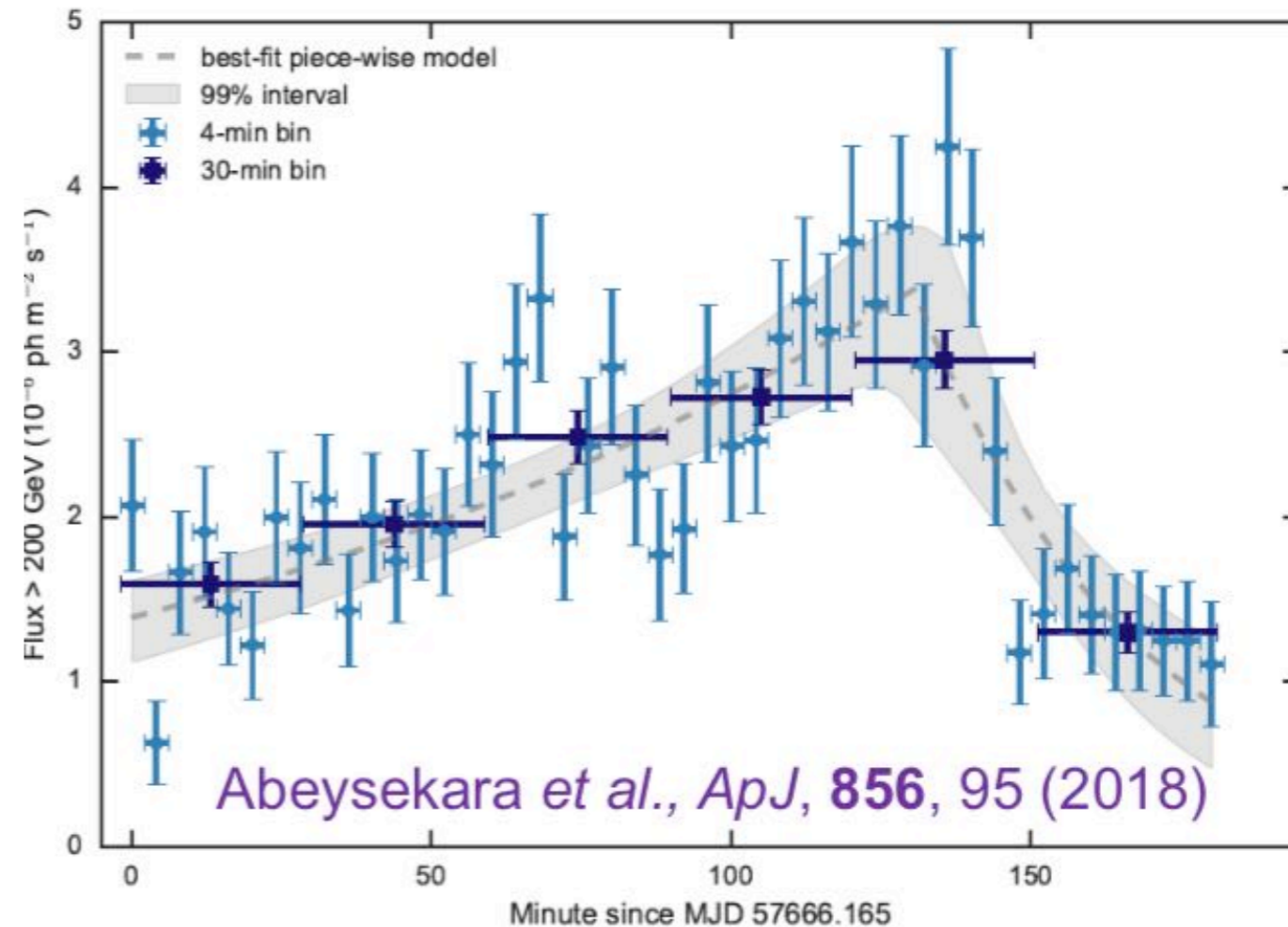


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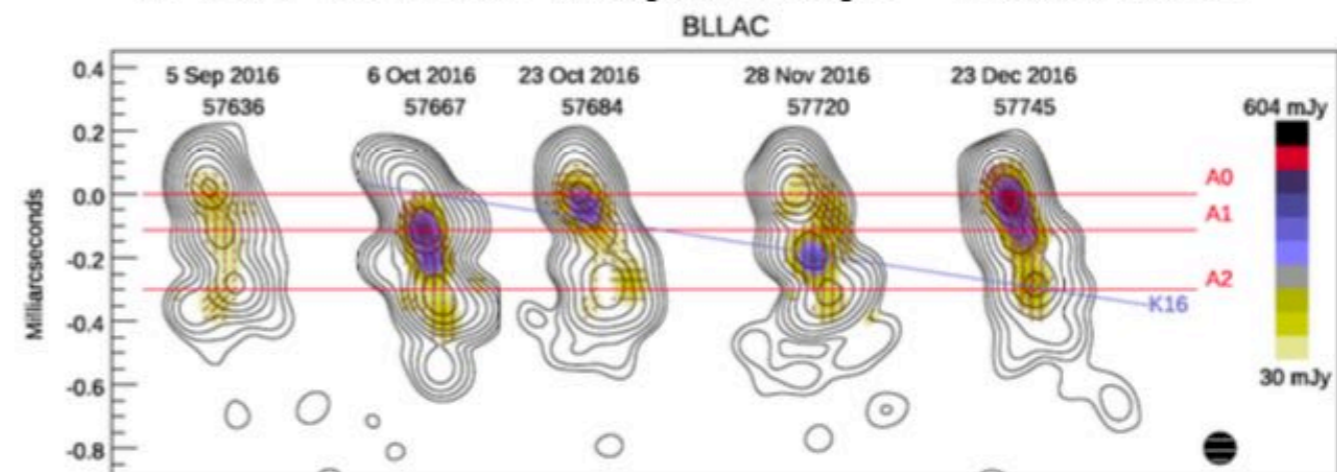


O'Brien+ VERITAS, ICRC (2017)

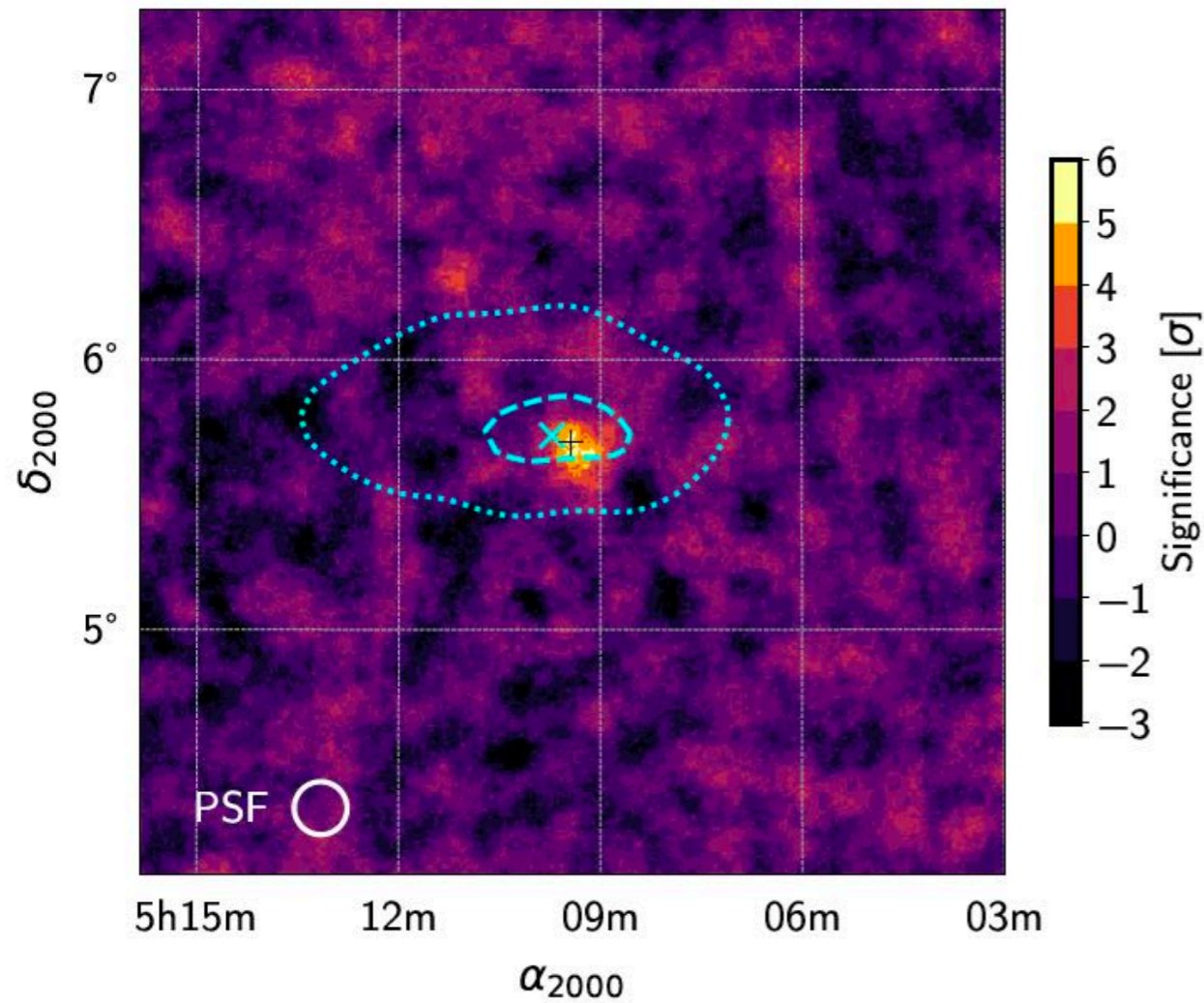
- * Major flare on Oct. 5, 2016:
 - * monitoring \rightarrow 2.6 h, 71σ , Peak \sim 180% Crab
 - * slow rise ($t_{\text{rise}} \sim 140$ min) & rapid fall ($t_{\text{fall}} \sim 36$ min)
 - * Another candidate superluminal knot appears
- * VERITAS: 70 h of data since 2010:
 - * not usually detected at VHE
 - * 3 other flares:
 - * Brief flare in 2011: Arlen et al., ApJ, 762, 92 (2013)
 - * Peak: \sim 125% Crab
 - * Exp. decay: $\tau = 134$ min
 - * Associated w/ birth of superluminal radio knot
 - * Two, single-night flares in 2015:
 - * 16% Crab on June 21
 - * 9% Crab on November 30
- * MAGIC flare in 2005 (3% Crab)



VLBA 43 GHz Maps: Sept - Dec 2016

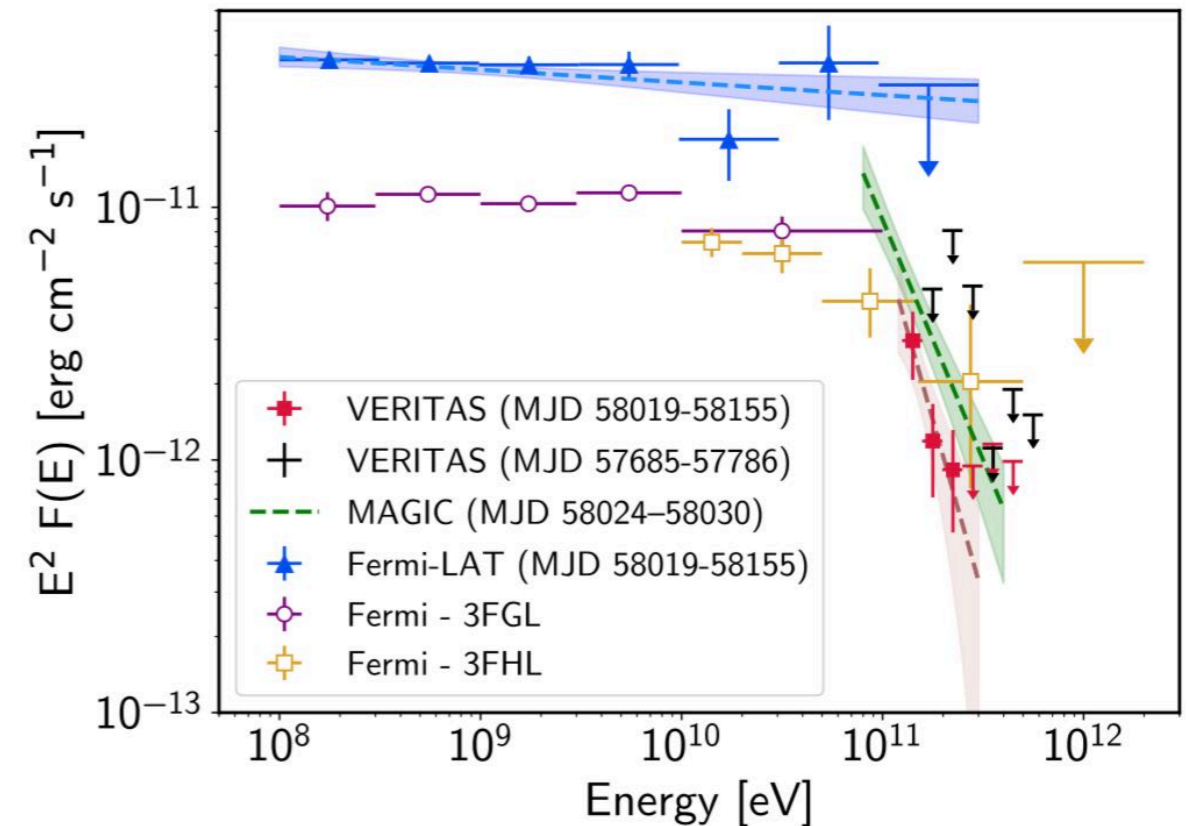


VERITAS confirms TXS 0506+056 as a TeV gamma-ray blazar



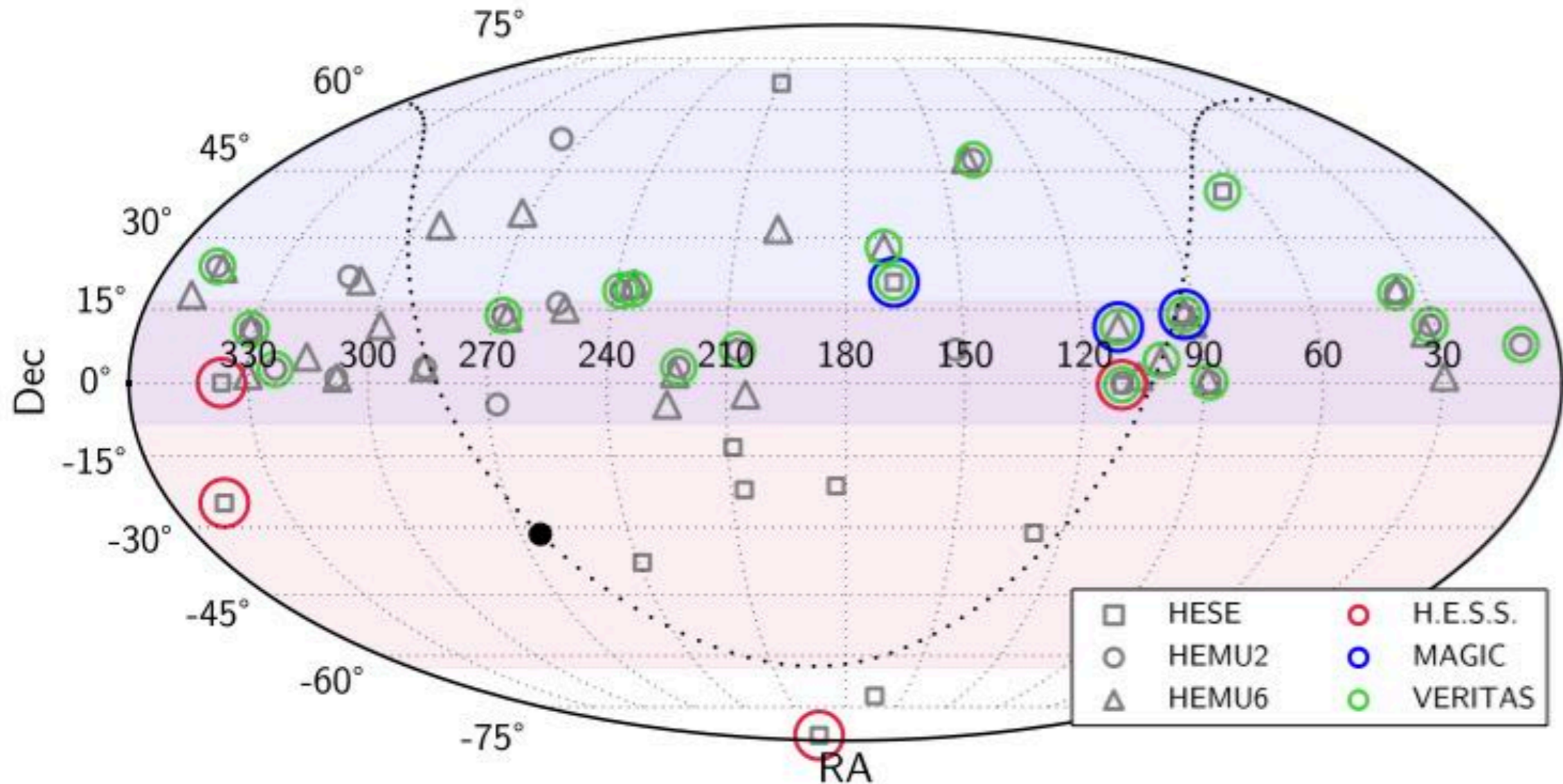
* VERITAS:

- * 35 hrs: 5.8σ
- * Weak flux: $F(>110 \text{ GeV}) \sim 1.6\% \text{ Crab}$;
- * Soft VHE spectrum: $\Gamma = 4.8 \pm 1.3$

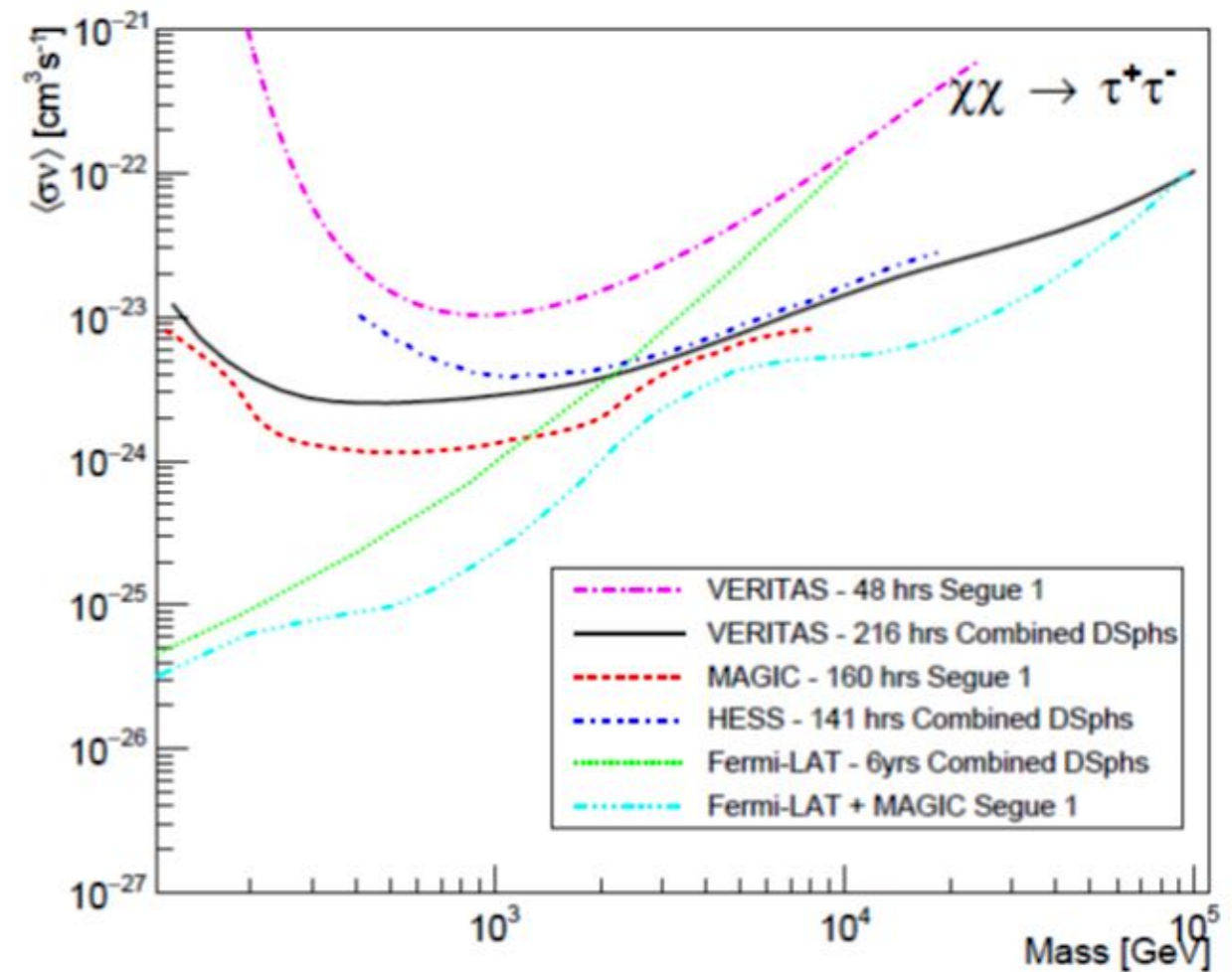
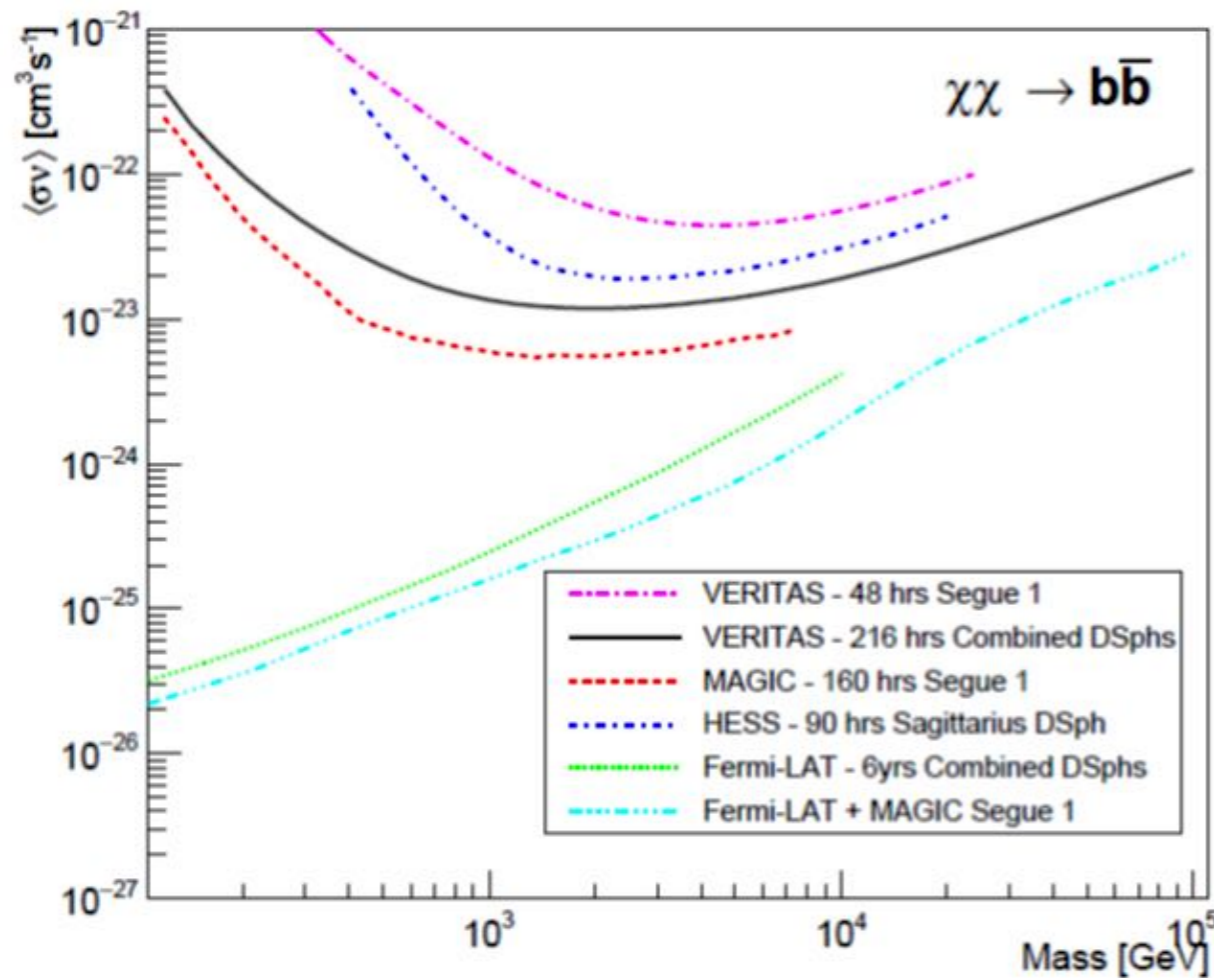


| | |
|------------------------|--|
| 22nd September 2017 | IceCube-170922A spatially coincident with TXS 0506+056, a BL Lac at $z=0.3365$ |
| 23rd September | VERITAS observes for 1 hr (+12 hrs) - no signal (poor weather) |
| 28th September | Fermi-LAT ATEL#10791 - TXS 0506+056 6x 3FGL flux in period Sept. 15th-27th |
| 28th - 30th Sept. | VERITAS 5hrs: no detection. (ATEL#10833 9th Oct.) |
| 28th Sept. - 4th Oct. | MAGIC 12 hrs: detects (ATEL #10817 4th Oct.), variable |
| Sept. 2017 - Feb. 2018 | VERITAS 35hrs: 5.8σ detection - implications for follow-up strategy! |

Archival IceCube Neutrino Events



- * Selection of high-energy neutrino events from IceCube publications + shared through MoU that are potentially astrophysical ($p_{\text{astro}} > 50\%$) and have good localizations ($\sim 1^\circ$)
- * ~ 40 hours of VERITAS exposure so far; publication in the works with other IACTs
- * No VHE gamma-ray excess found in the regions of interest.



Archambault *et al.*, *PRD*, 95, 082001 (2017)

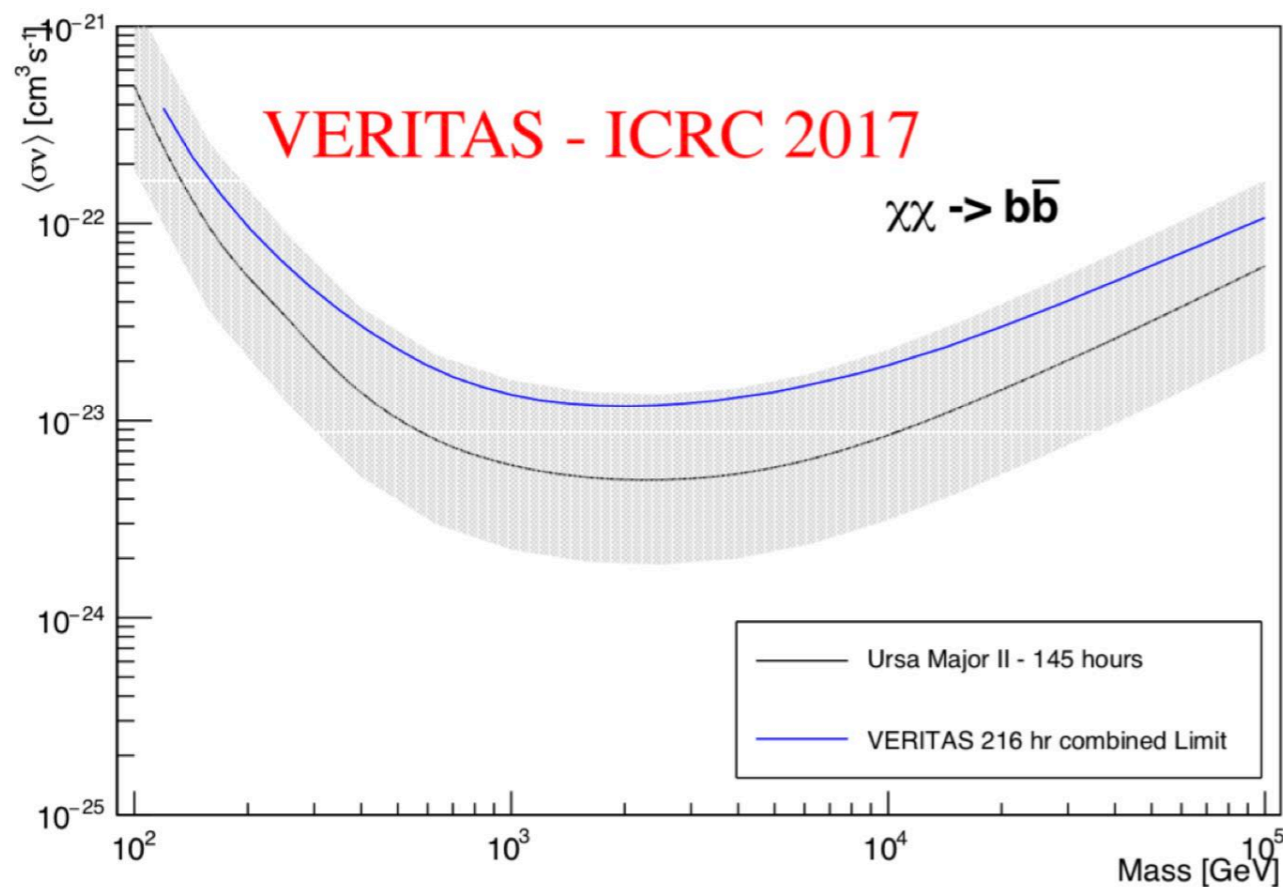
* Combined result from four dwarf galaxies:

* Segue1, Ursa Minor, Draco, Boötes

* IACT dwarf results similar

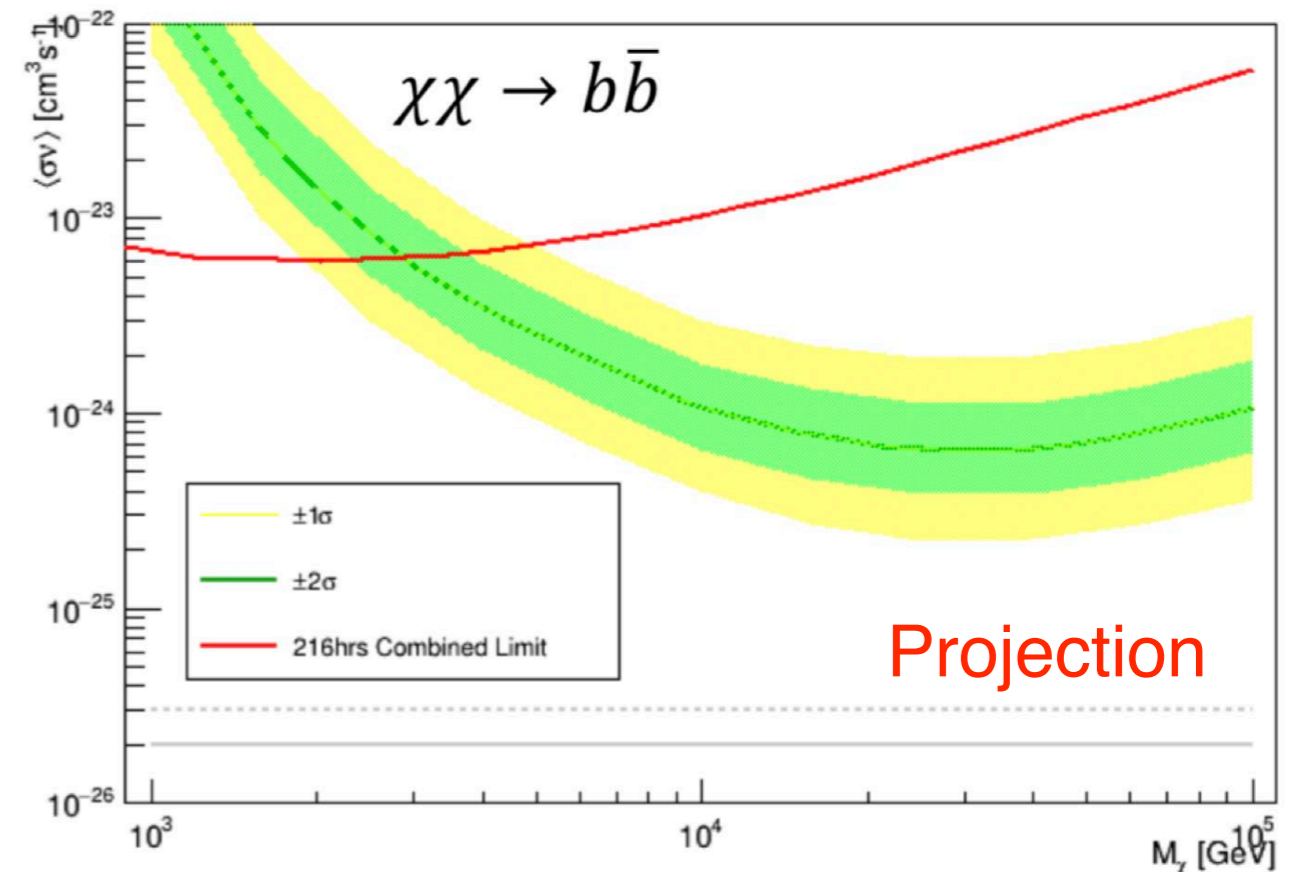
* Fermi-LAT dominates for low-mass WIMPs

- * Preliminary limit from 145 hours observing Ursa Major II:

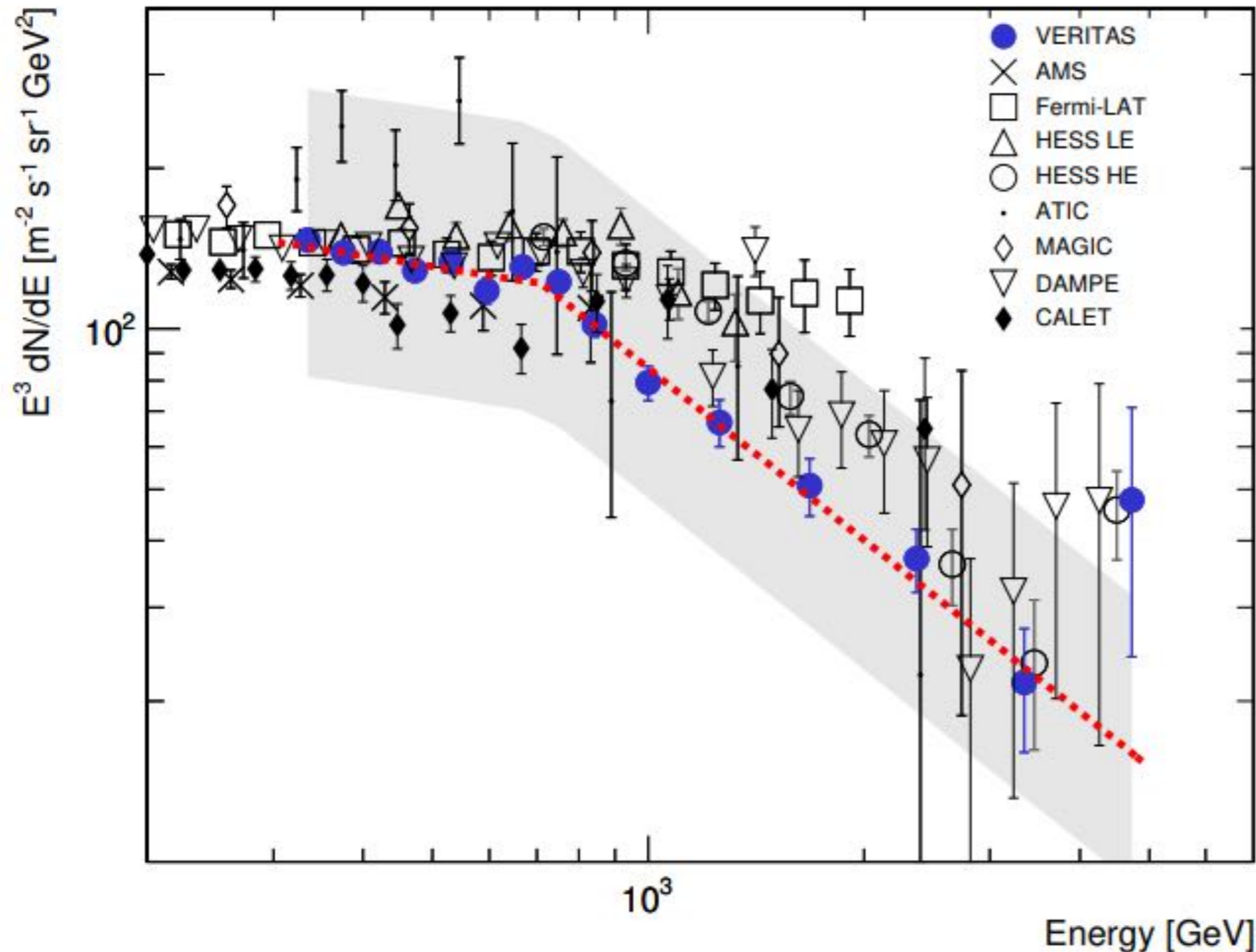


Zitzer (VERITAS), arXiv:1708.07441

- * Projected sensitivity of Galactic Centre observations through mid 2018:



- * 296 hours of post-T1 move, pre-camera upgrade data
- * Energy range: 300 GeV to 5 TeV

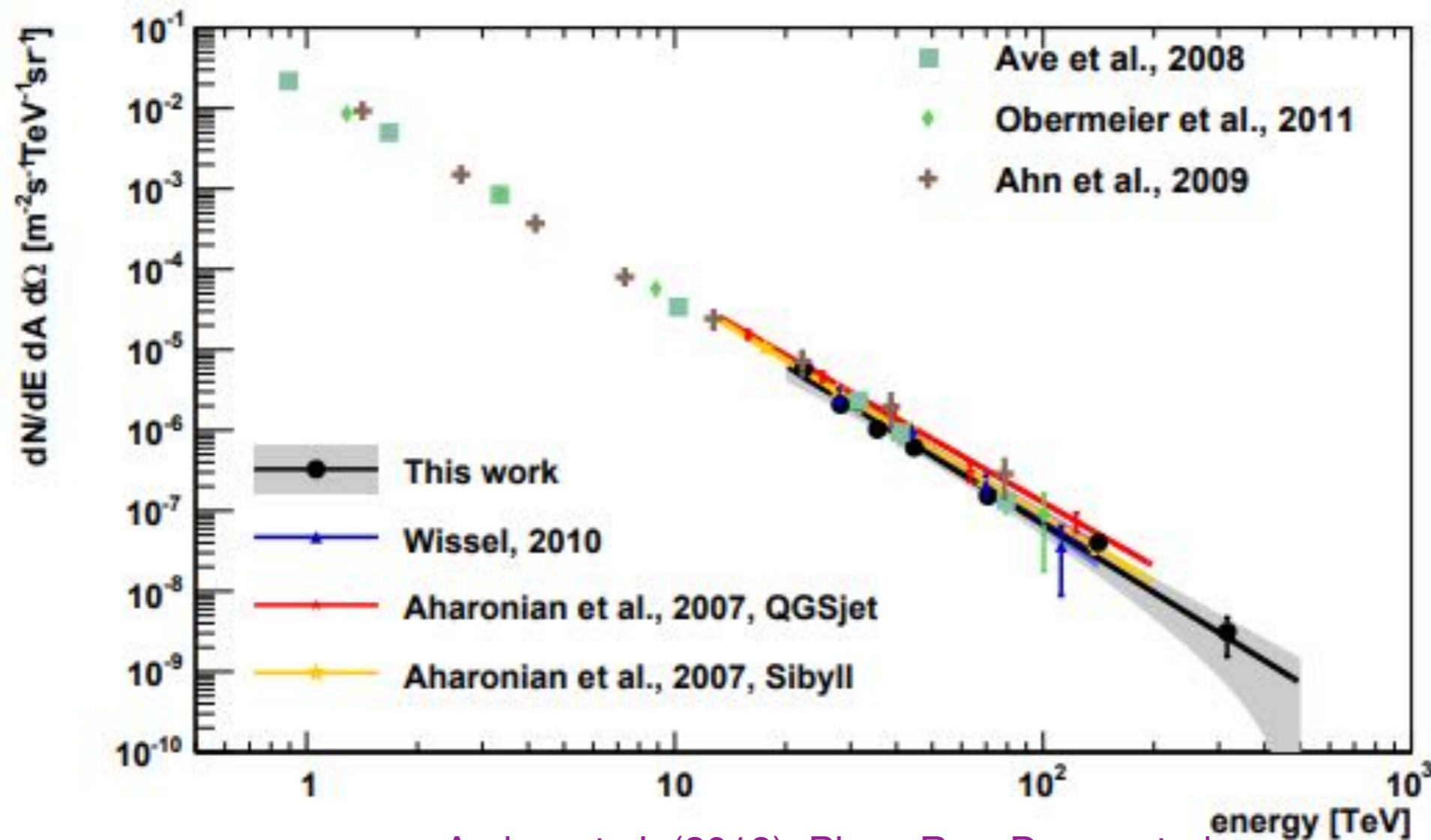


Archer et al. (2018) Phys. Rev. D accepted.

- * Broken power law with a break at
 $710 \pm 40_{\text{stat}}$ GeV
- * Index transitions from
 $3.2 \pm 0.1_{\text{stat}}$
below to
 $4.1 \pm 0.1_{\text{stat}}$
above the break
- * Consistent with previous measurements
- * Second ground-based high-statistics measurement of a break at $\sim 1\text{TeV}$

Cosmic Ray Iron Spectrum

- * Direct Cherenkov technique used to identify showers from Cosmic Ray primaries
- * 71 hours of post-T1 move, pre-camera upgrade high-quality data
- * Energy Range: 20 TeV – 500 TeV



Archer et al, (2018) Phys. Rev. D accepted.

- * Power law with index $2.82 \pm 0.3_{\text{stat}}$.
- * Extends the spectrum to higher energies

- * After more than 10 years of continued operations, VERITAS is still going strong:
 - * ~1200 hrs. of good-weather observations per year
 - * 4-Tel. efficiency of 97%
- * VERITAS has a strong and productive science program covering Galactic, Extragalactic, Dark Matter, Cosmic Rays and Fundamental Physics.
- * VERITAS is a critical player in multi-messenger astronomy.
- * VERITAS is fully funded through 2019
- * Later this year VERITAS will apply for funding to extend operations until at least 2022.

Backup

GC Diffuse Regions

H.E.S.S. GC map (Abramowski et al. 2016)

