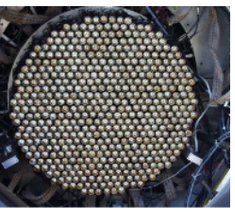
Very-High-Energy Emission from Extragalactic Cosmic Accelerators:

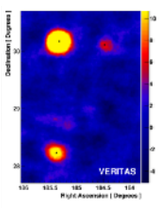
Highlights from Recent VERITAS AGN Observations

Qi Feng for the VERITAS Collaboration

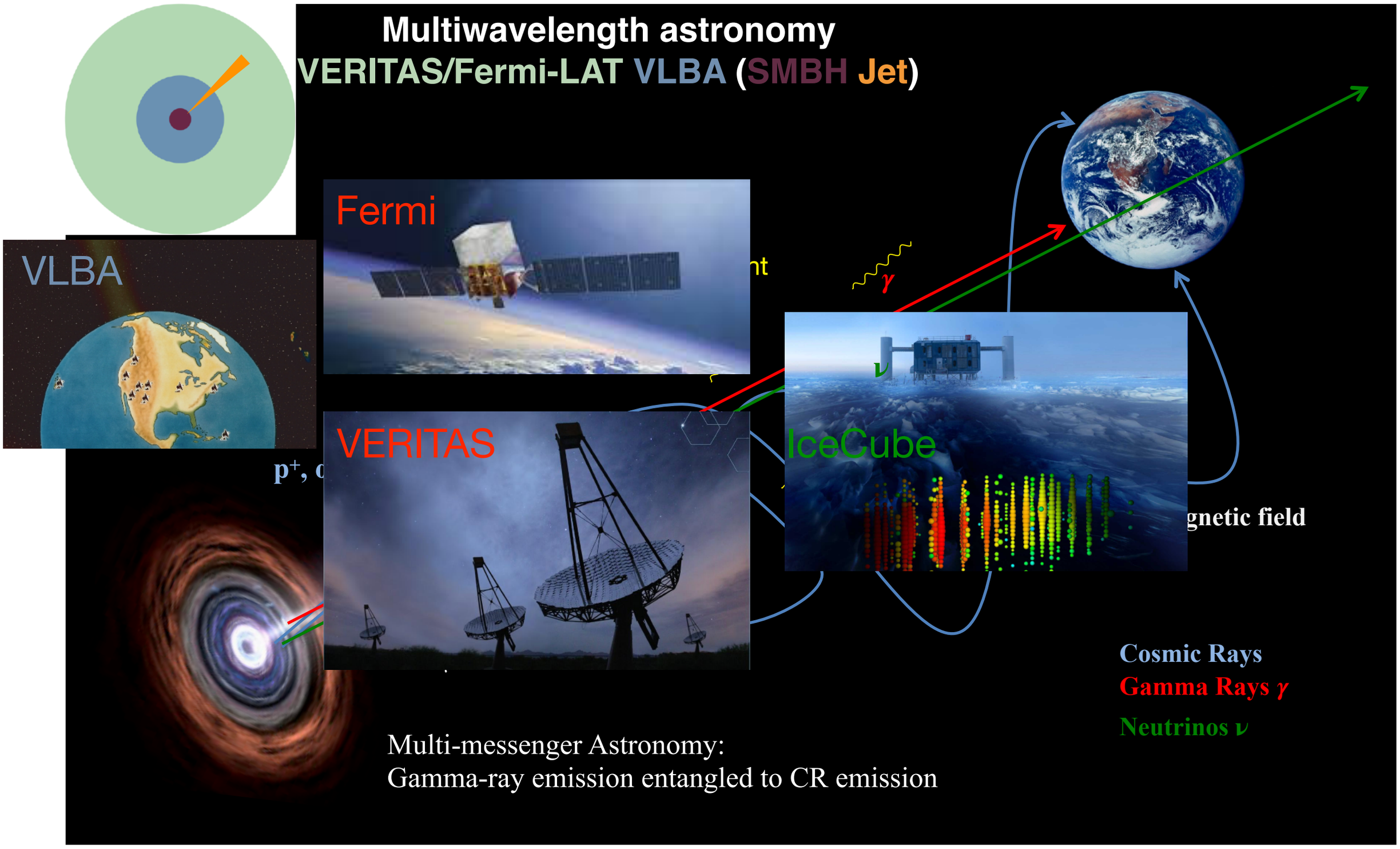
Columbia University
in the City of New York



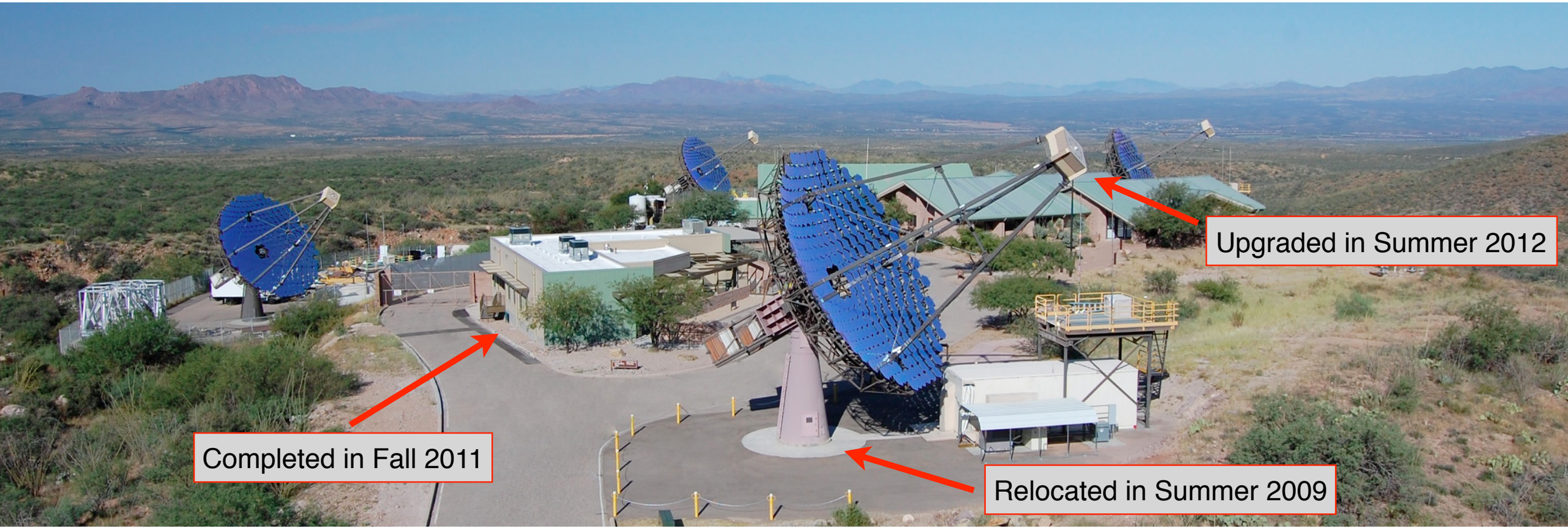



Extragalactic Cosmic Accelerators

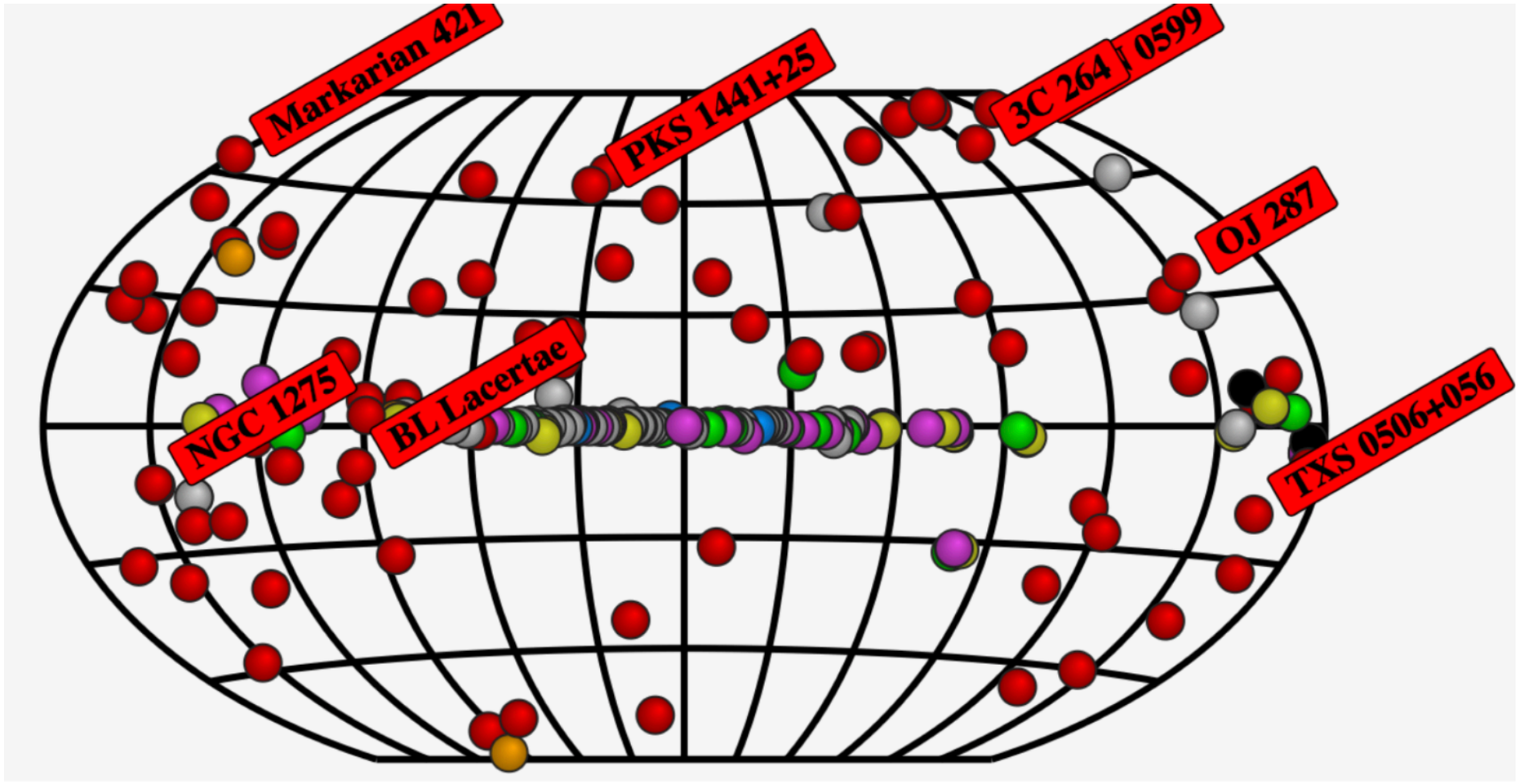


VERITAS Observatory Overview



- Study very-high-energy (~85 GeV to ~30 TeV) γ-rays from astrophysical sources
- Full-scale operations since 2007; Major upgrade completed in 2012
- Good-weather data / yr: ~950 h in “dark time” + ~250 h in “bright moon” (illum. >30%)
  - Sensitivity: 1% Crab in <25 h
  - Angular resolution: r_{68} ~ 0.08° @ 1 TeV
  - Energy resolution: ~17%
  - Energy Threshold: ~85 GeV
  - Spectral reconstruction > 100 GeV
  - Systematic errors: Flux ~20%; Γ ~ 0.1

Extragalactic Very-High-Energy Gamma-Ray Sky



The Extragalactic very-high-energy (VHE) sky (TeVCat as of Oct 2018):

- 10 LBL/IBL
- 50 HBL
- 4 Blazar Type Uncertain
- 7 FSRQ
- 4 FRI (RG)
- 2 Starburst

} 77 AGN - number comparable EGRET AGN catalogue
39 VERITAS AGN

VERITAS detections since June 2017:
TXS 0506+056, 3C 264, and Ton 599

TeV gamma-ray variability is amazing!

TXS 0506+056: The "Neutrino Blazar"

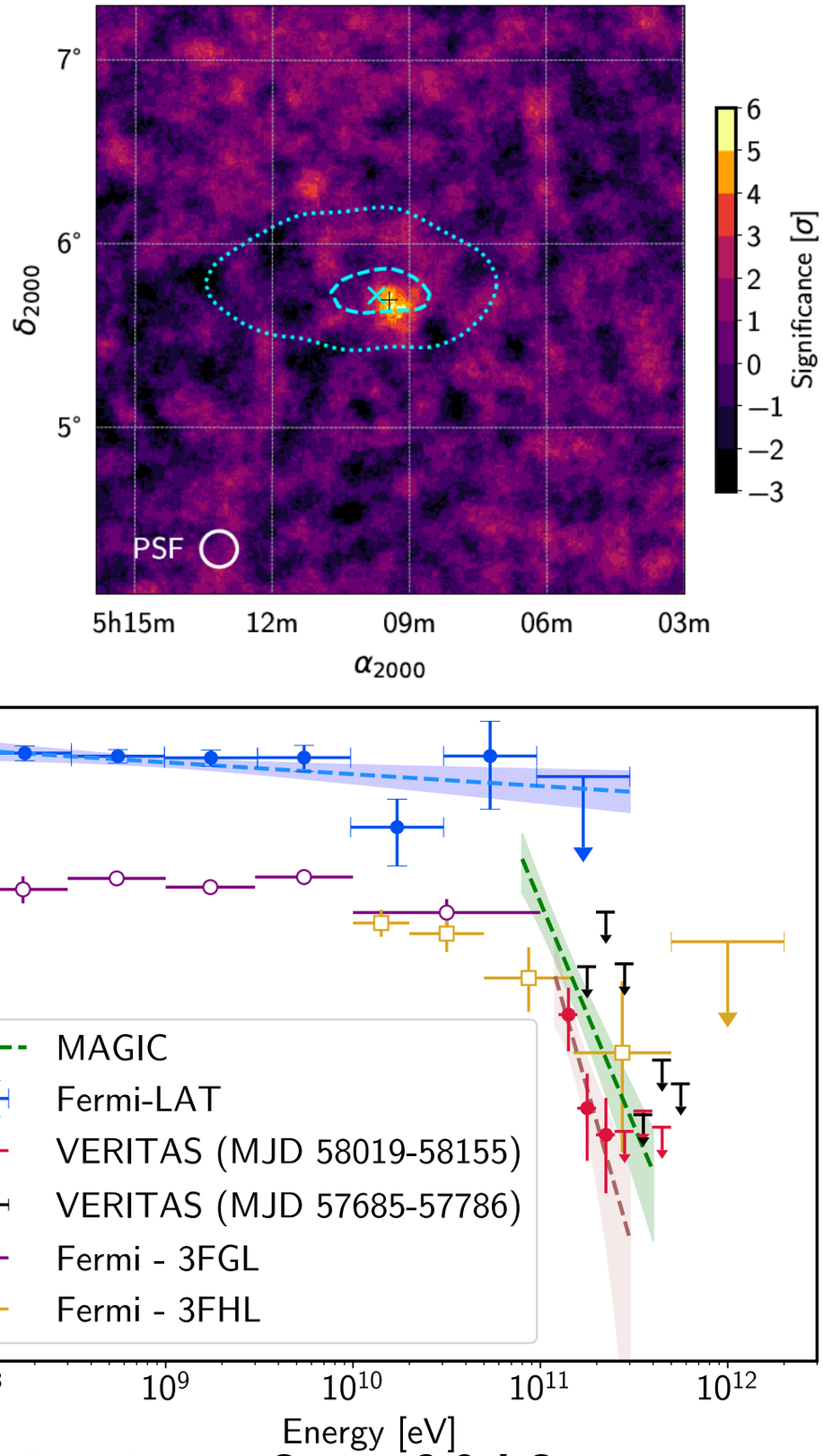
See Azadeh Keivani's talk

- BL Lac (IBL), z = 0.34
- Multi-messenger effort to search for cosmic hadron accelerators.
- Multiple alerts following the IceCube event IC170922A:

  +6 days *Fermi* ATel #10791: ~6x 3FGL flux

  +12 days MAGIC ATel #10817: VHE detected

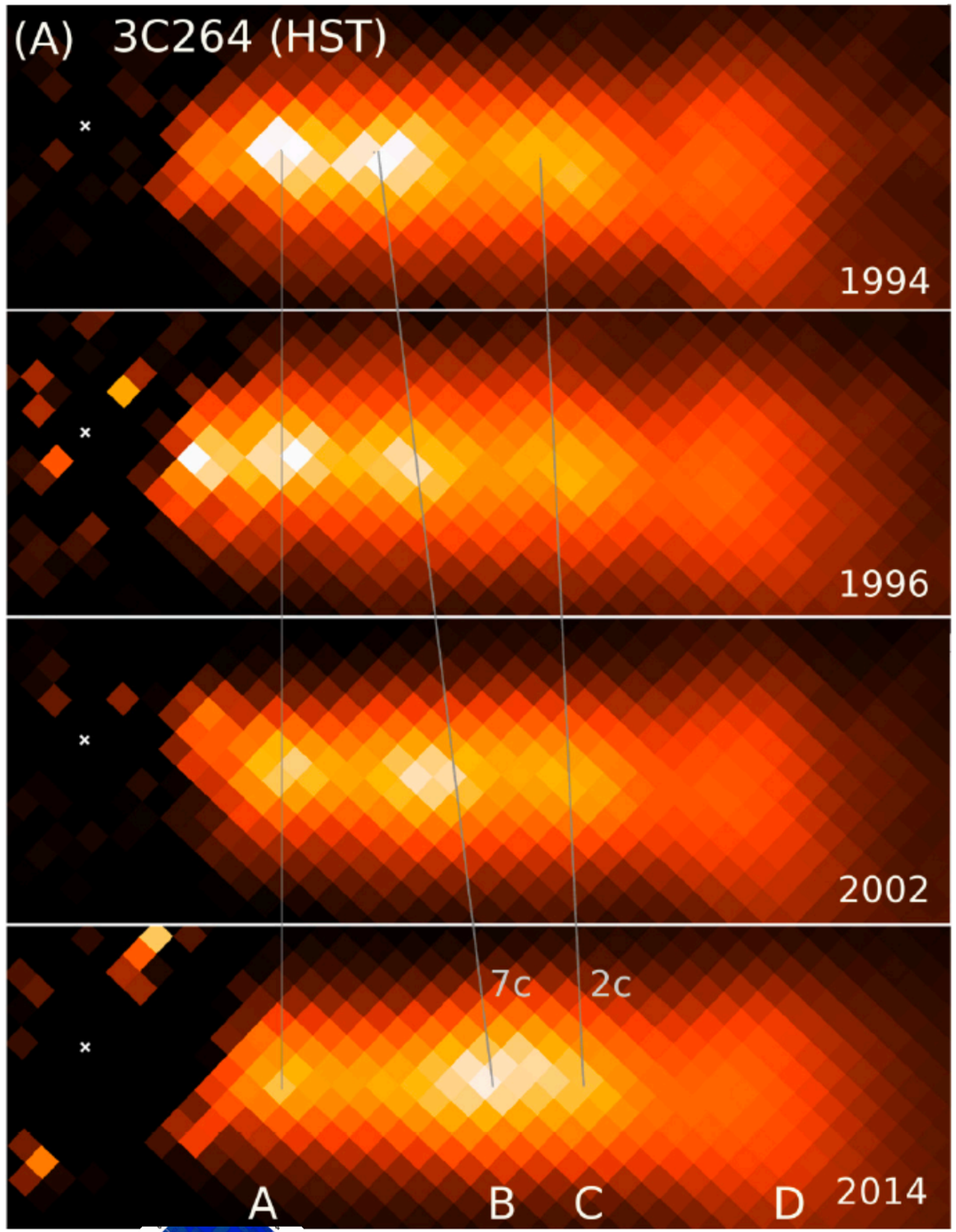
  +17 days VERITAS ATel #10833: 5.5-h of data in two weeks **starting 12.2 hours after** the event led to **no detection…**
- VERITAS kept observing until Feb 2018 (+5 months), 35-h data led to a detection of possibly the **base line flux**
- F(>110 GeV) ~ 1.6% Crab; Soft VHE spectrum: Γ = 4.8 ± 1.3; sharp spectral cutoff cannot be accounted for by EBL alone.

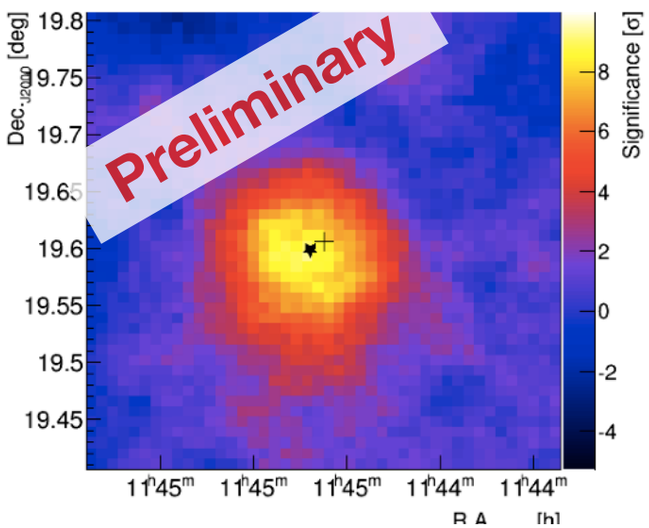


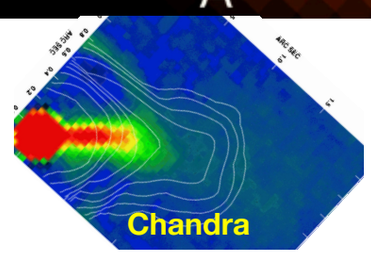
VERITAS Collaboration, 2018 ApJL, arXiv:1807.04607

3C 264 - The Newest VHE Radio Galaxy

- Radio galaxy (FR I), z = 0.0217
- VERITAS detection in 2018 (ATel #11436)
- Strong, hard-spectrum detection:
  ~8σ in ~44 h; Γ ~ 2.3
- Low, weakly variable VHE flux:
  ~0.5% Crab; ~Month-scale variations
- The misaligned jets in radio galaxies are unique laboratory for understanding their structures.
- Jet <1 kpc, multiple superluminal knots
- Major VERITAS + MWL effort: Radio (e.g. VLA), Optical (HST, ground-based), X-ray (Chandra + Swift), Fermi-LAT =>
  No major activity in knots or core







See Eileen Meyer's talk

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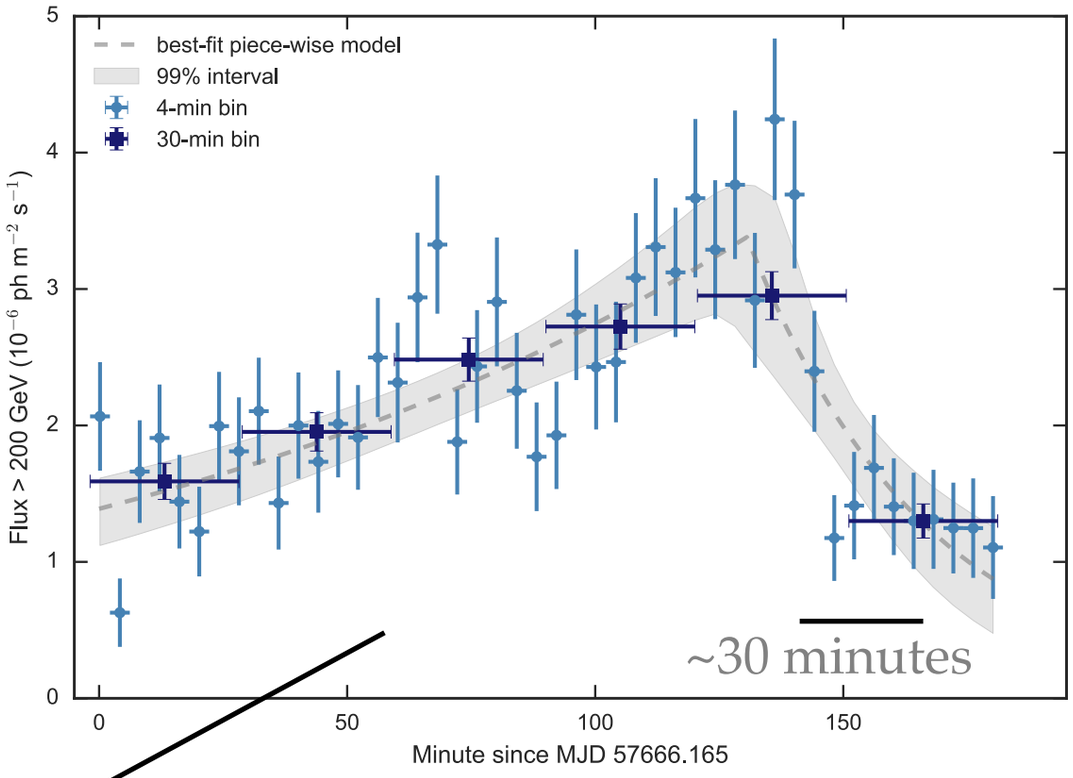
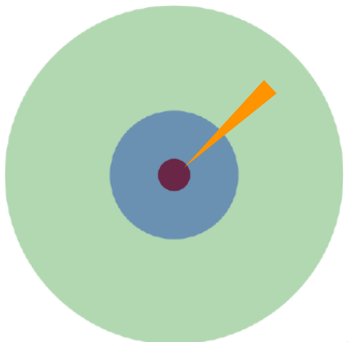
BL Lacertae
Fast TeV Flares Coincident With Emergence of a Radio Knot

- IBL, z = 0.069
- Fast flares constrain the size of the emitting region
- Brief flare in 2011: Arlen et al., ApJ 762, 92 (2013)
  - Peak: ~125% Crab; Exp. decay: τ_d = **13±4 min**
  - Associated w/ birth of superluminal radio knot
- Two, single-night flares in 2015 (16% & 9% Crab)

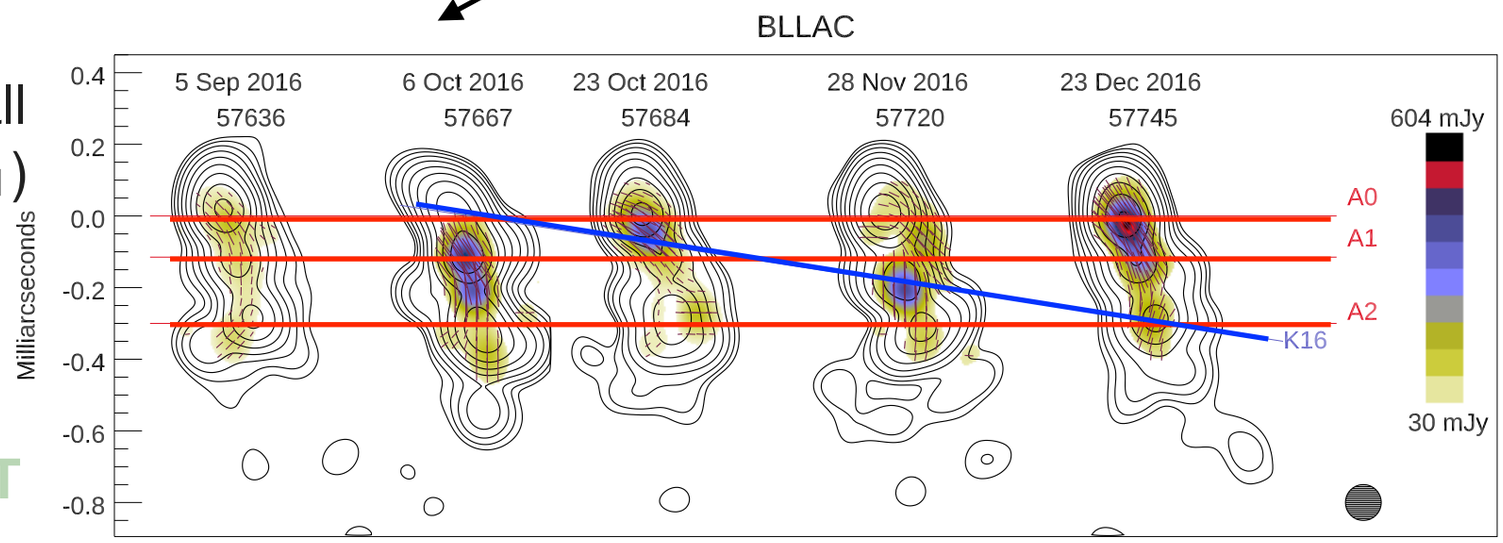
VERITAS Collaboration, 2018, ApJ, 856, 95



- Major flare on Oct. 5, 2016
  - Peak flux ~180% Crab
  - Slow rise (t_{rise}~140 min) & rapid fall (**t_{decay}~36 min** => <12 $R_{Schwarzschild}$)
  - Another candidate superluminal knot appears



VERITAS/Fermi-LAT
VLBA SMBH Jet



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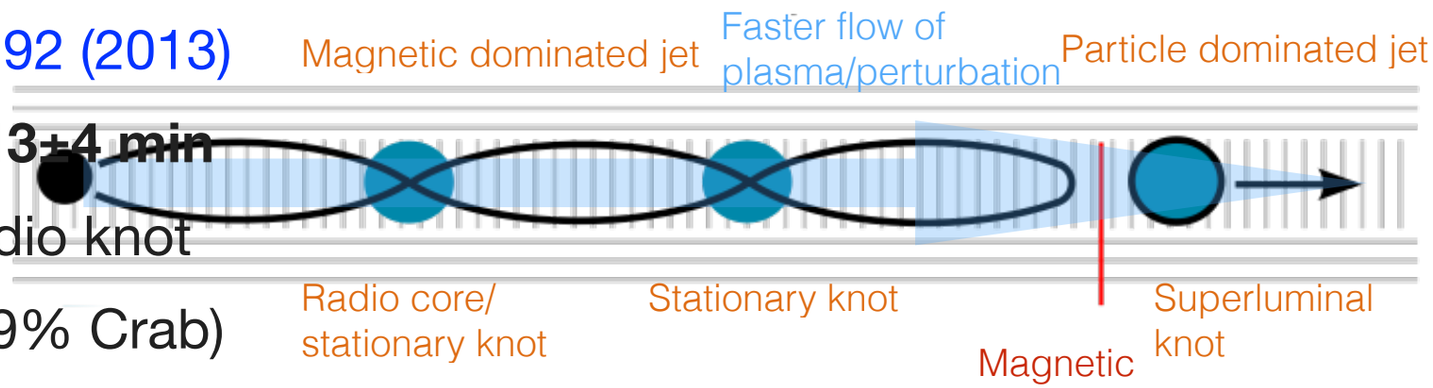

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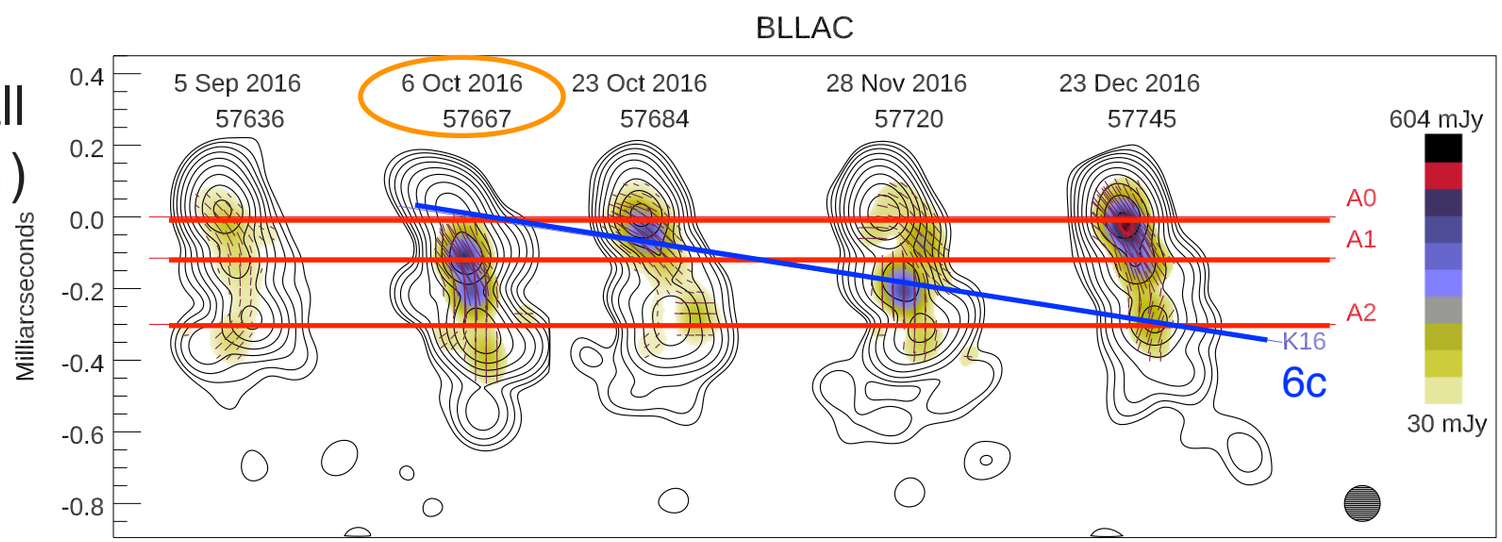
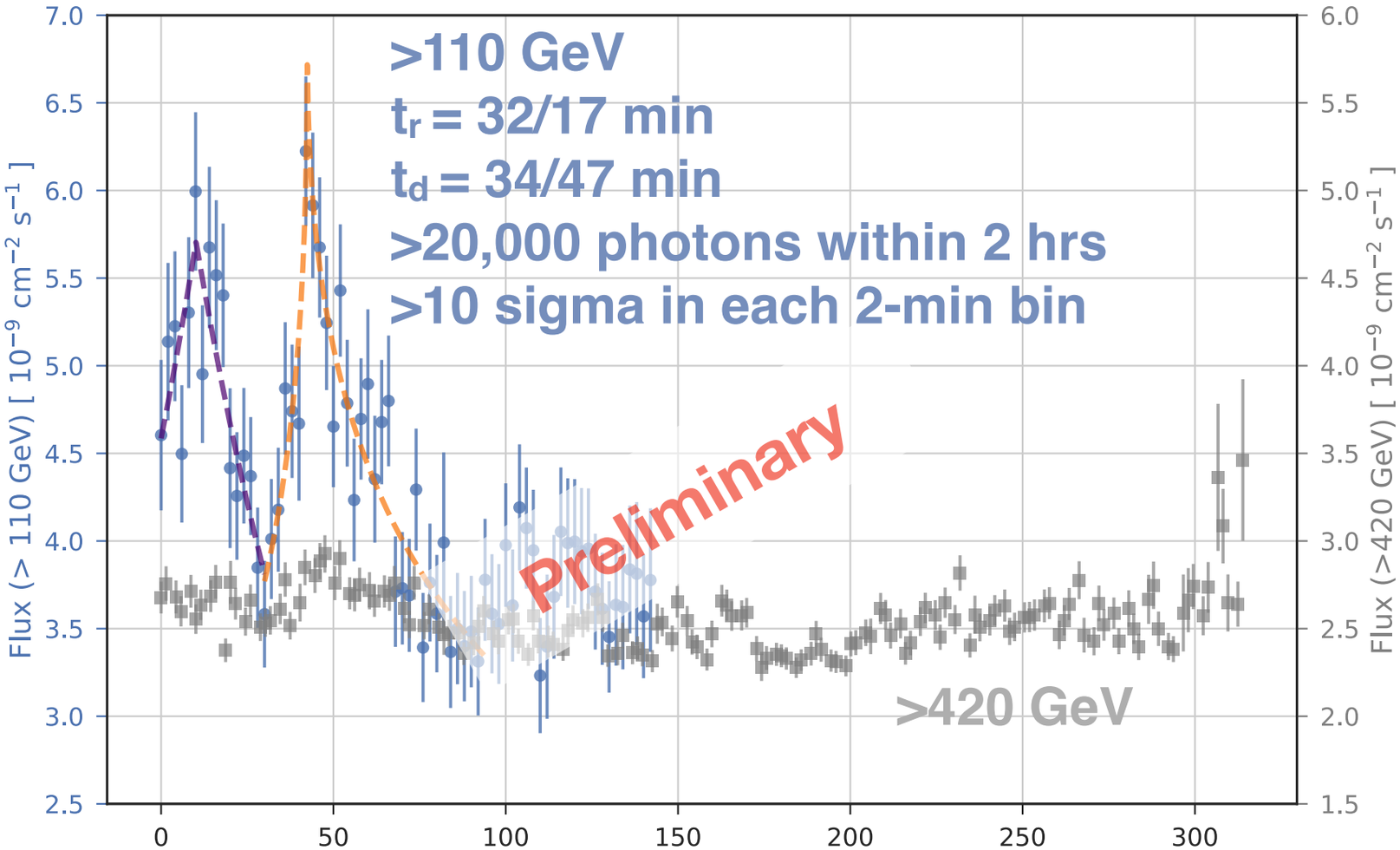


Mrk 421: Fast Flares during a Major Outburst

- HBL, z = 0.031
- Iconic TeV blazar with many flares at all wavelengths
- A major flare in 2010 with multiple sub-hour TeV gamma-ray flares (peak >10 Crab)
- Fast variability on timescales of ~17 min => emitting size < a few Schwarzschild radii
- TeV gamma-ray and X-ray spectral variability compared



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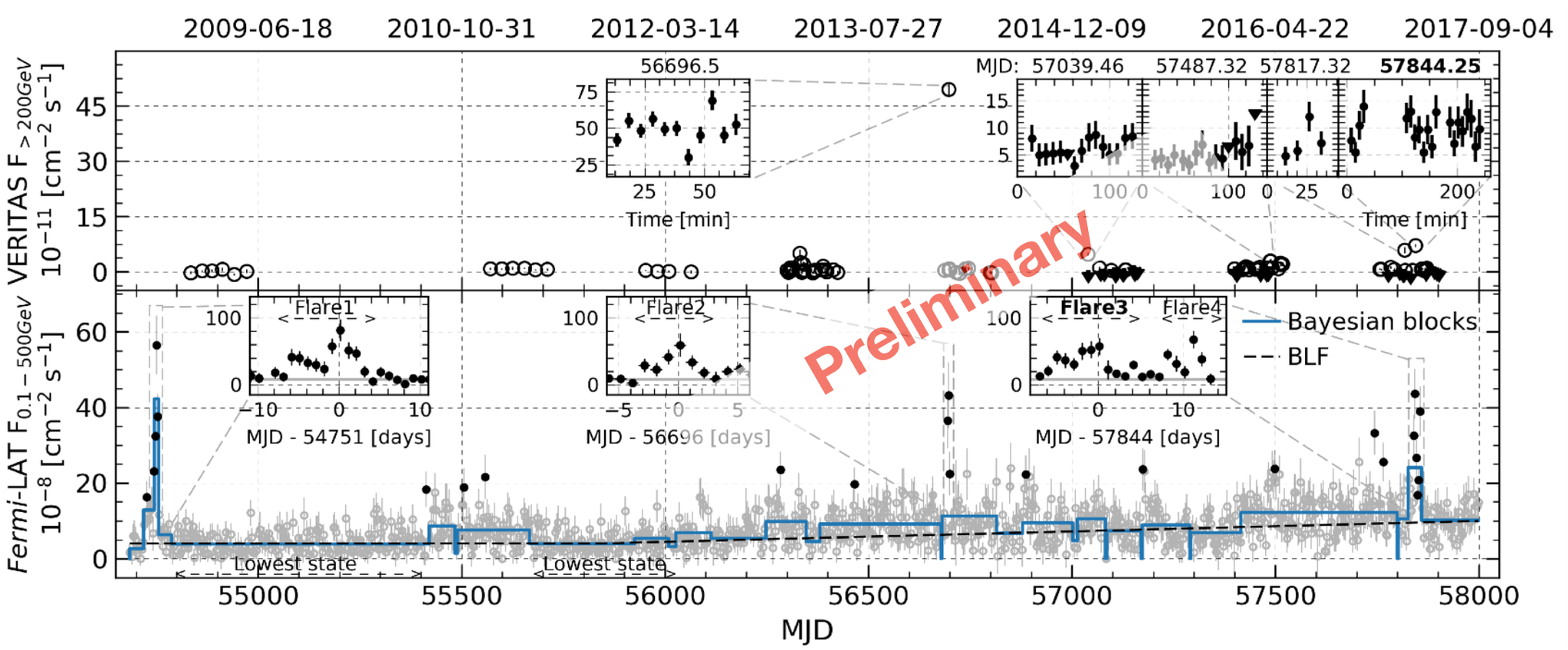
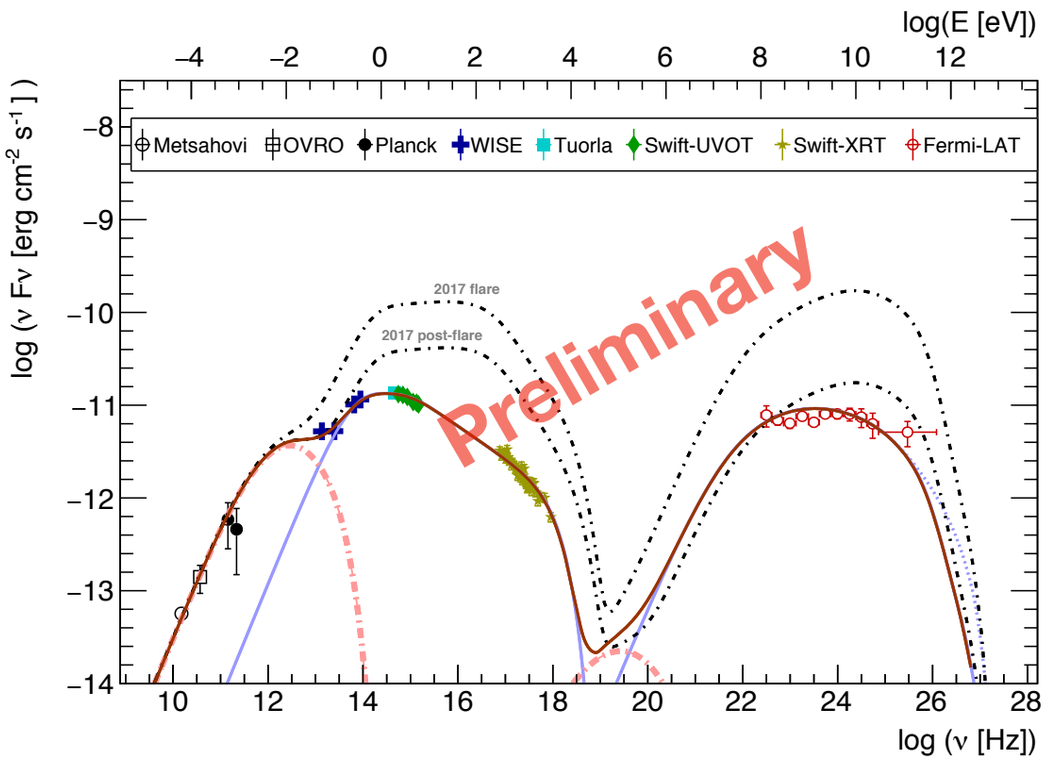
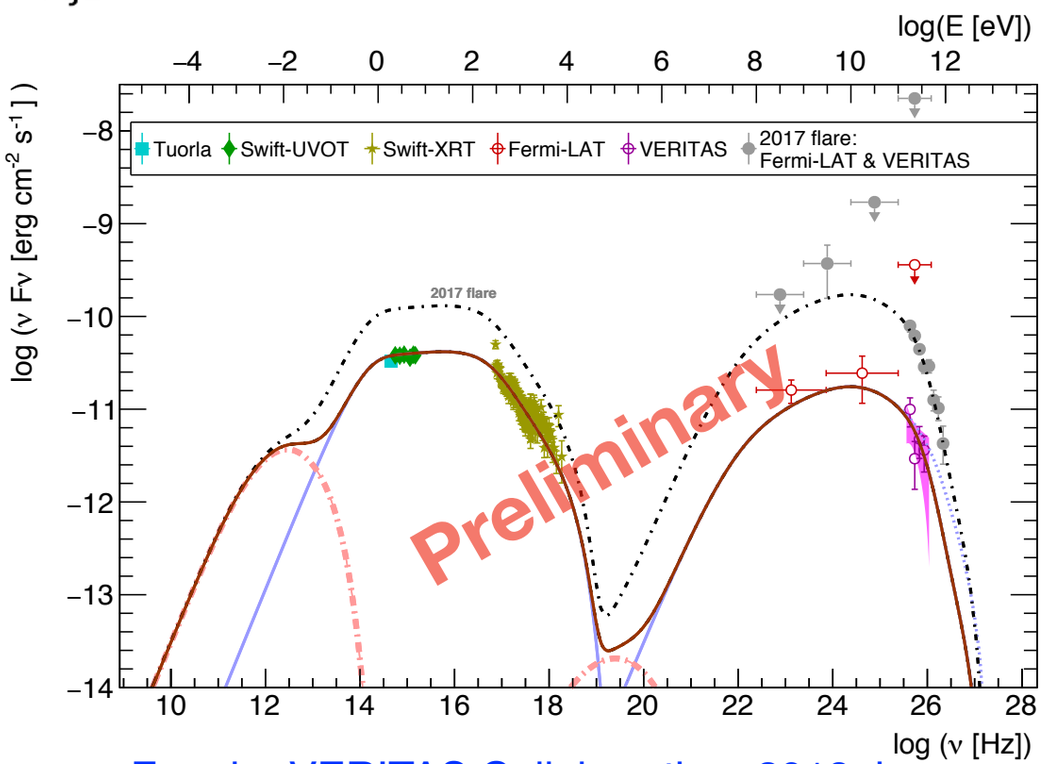
1ES 1215+303: 10 Years of Fermi and VERITAS Data

See Janeth Valverde's poster







Fermi + VERITAS Collaboration, 2018, in prep

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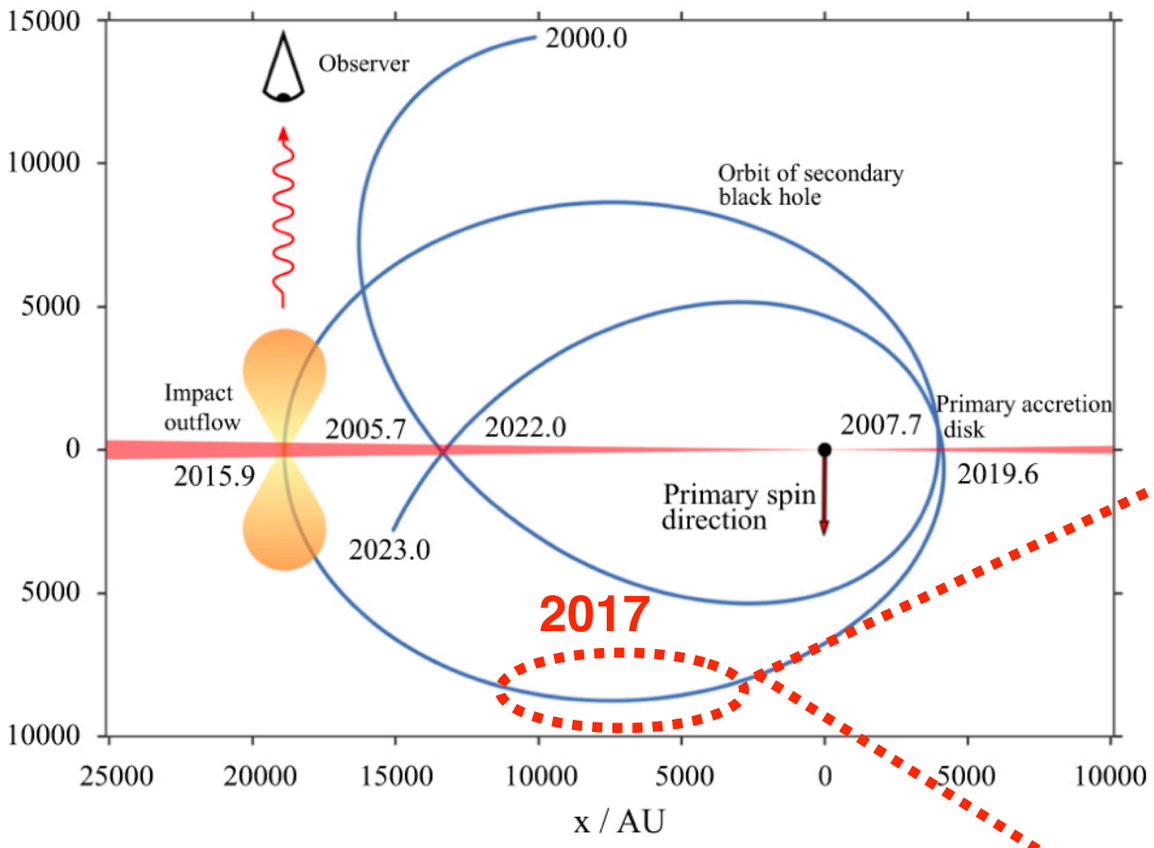
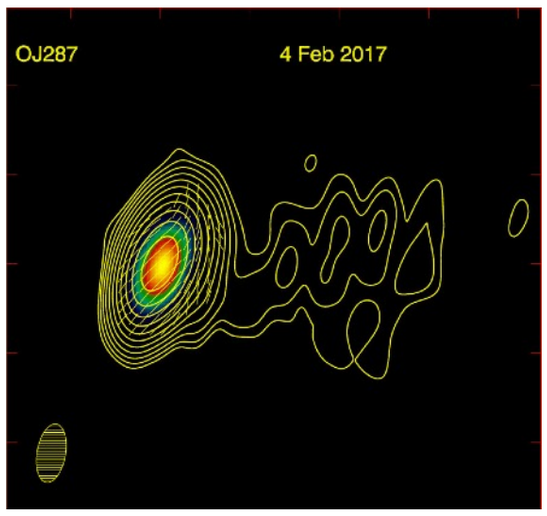
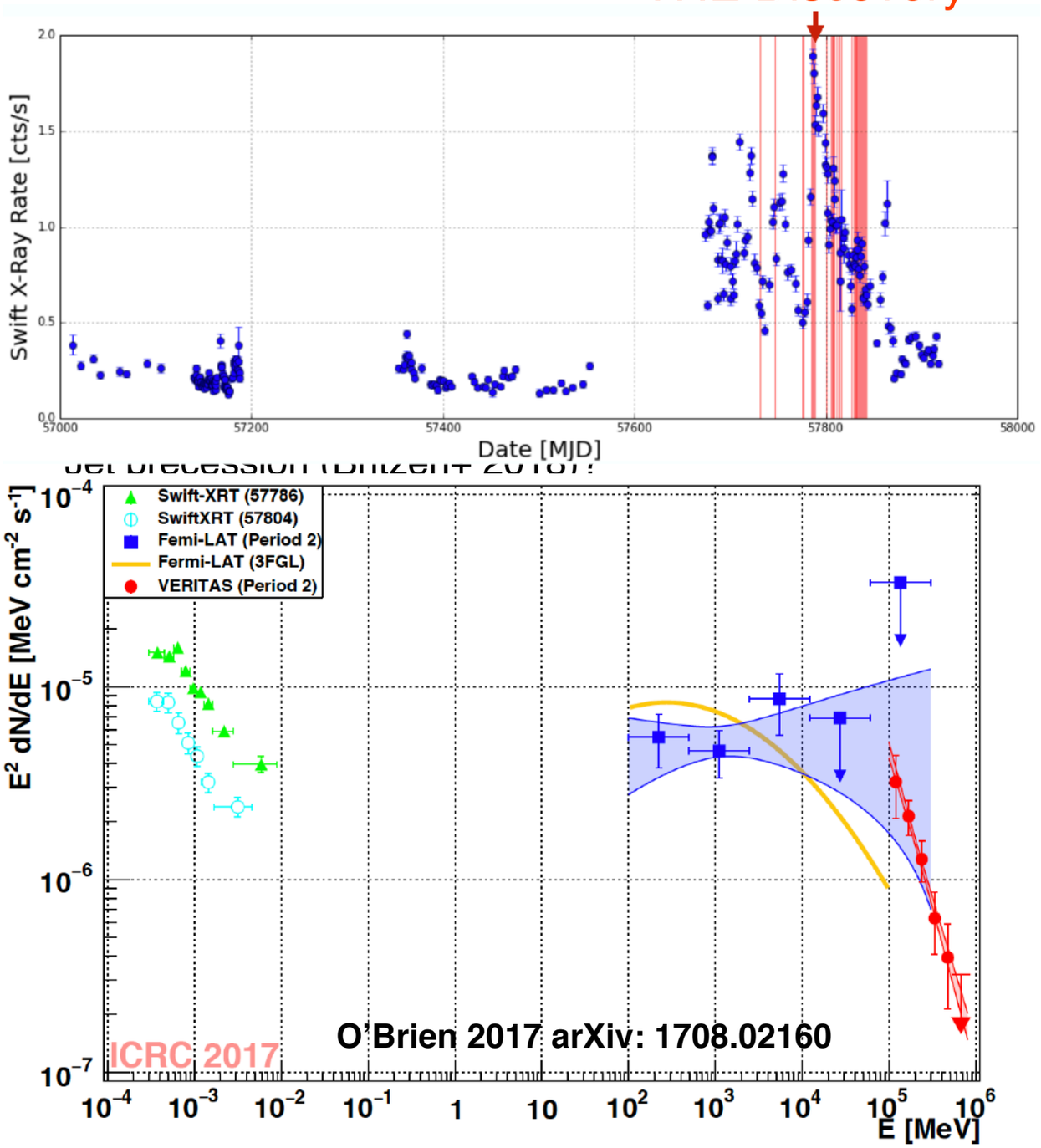
OJ 287: a VERITAS VHE Discovery





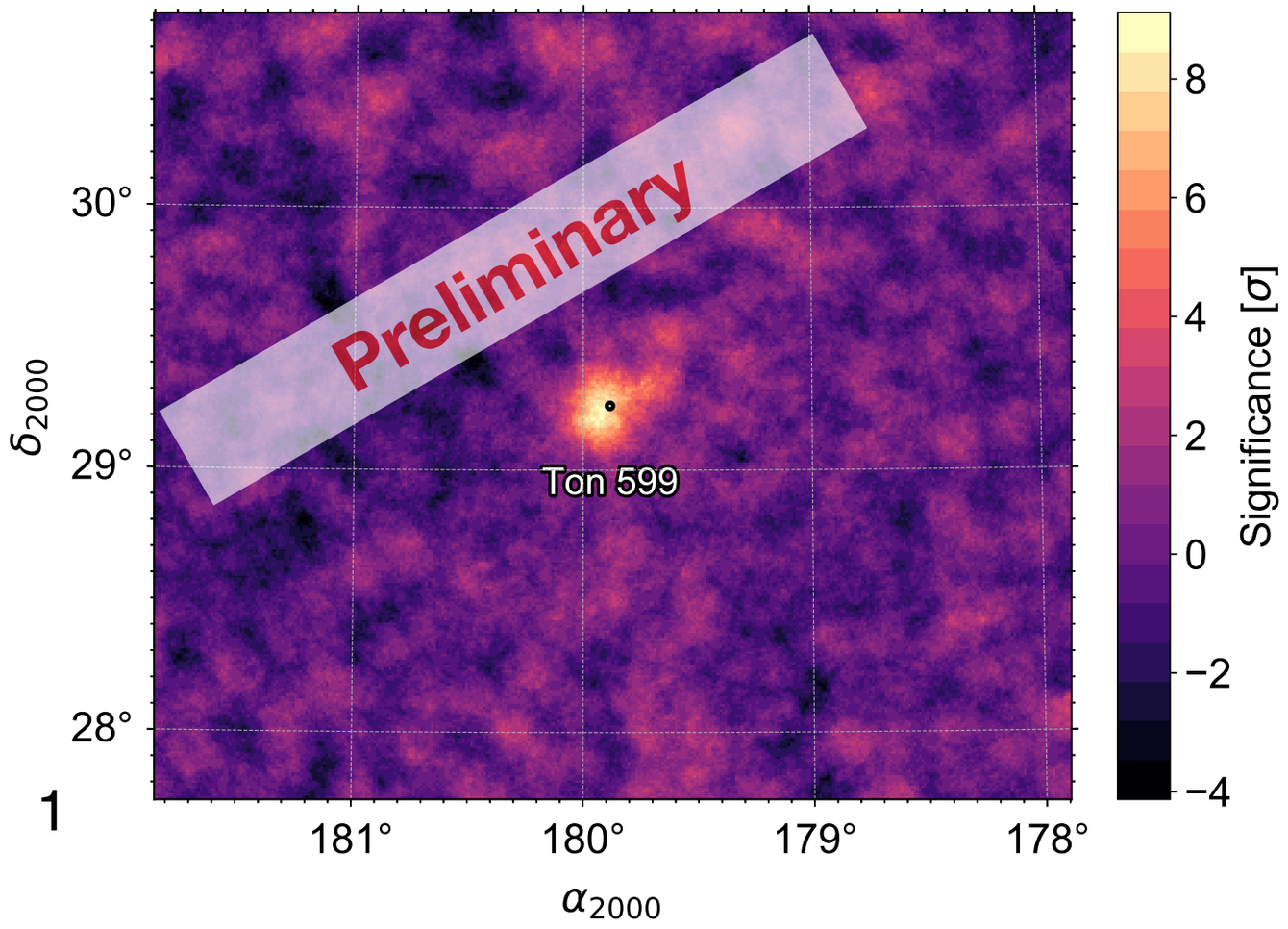
Project VLBA-BU-BLAZAR (Marscher, Jorstad)

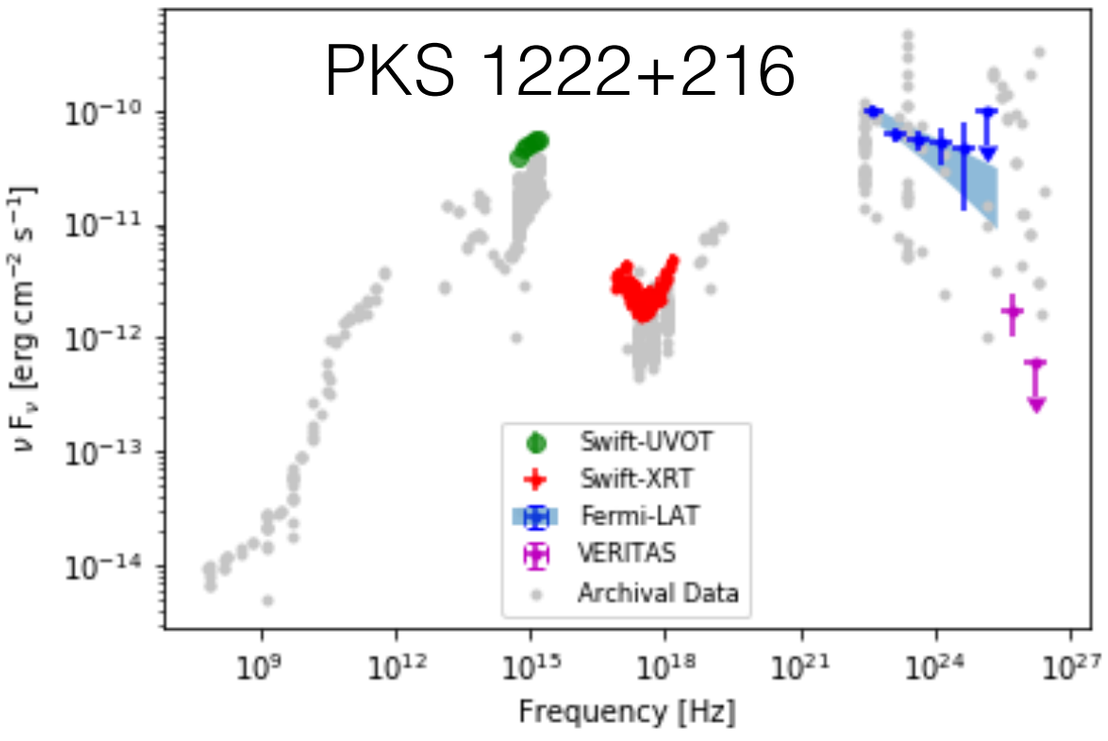


Ton 599: The Third Highest *z* VHE Source

See Ari Brill's poster

- **FSRQ**, z = 0.72
- Fermi-LAT flare in early Nov. 2017
- ATel #10931: ~20x 3FGL flux
- Exceptional NIR flares in Nov. 2017
- ATel #10949: 0.5 mag. after 10x flux





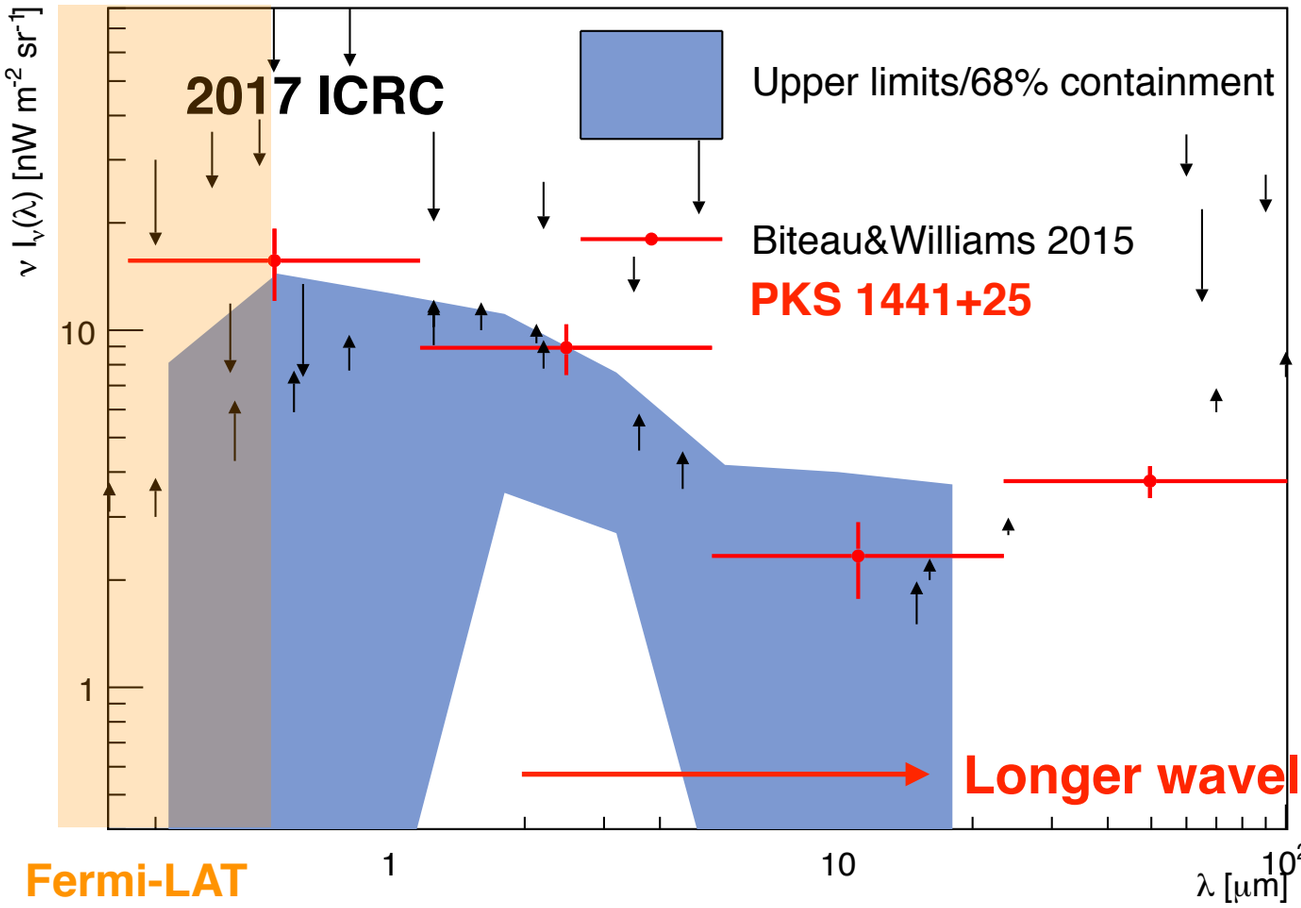
VERITAS' 3rd FSRQ & 7th in VHE

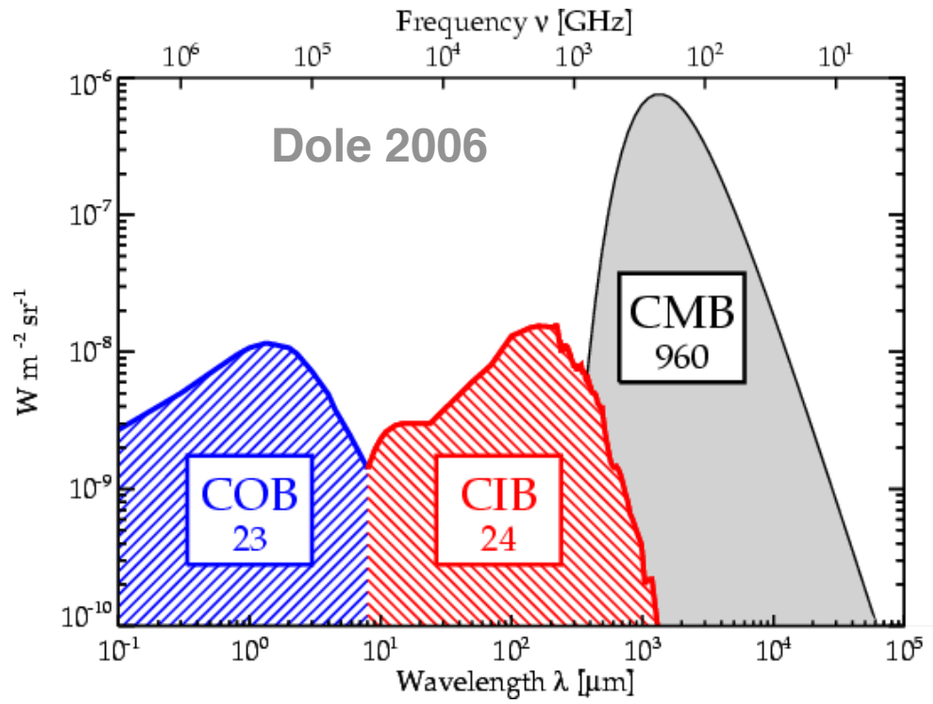
PKS 1441+25 (z ~ 0.94) & 4C +21.35 (z ~0.43)

TeV photons provide cosmological constraints!

Constraints on Extragalactic Background Light with VERITAS Blazar Observations

Puschel 2017 ICRC POS 1107

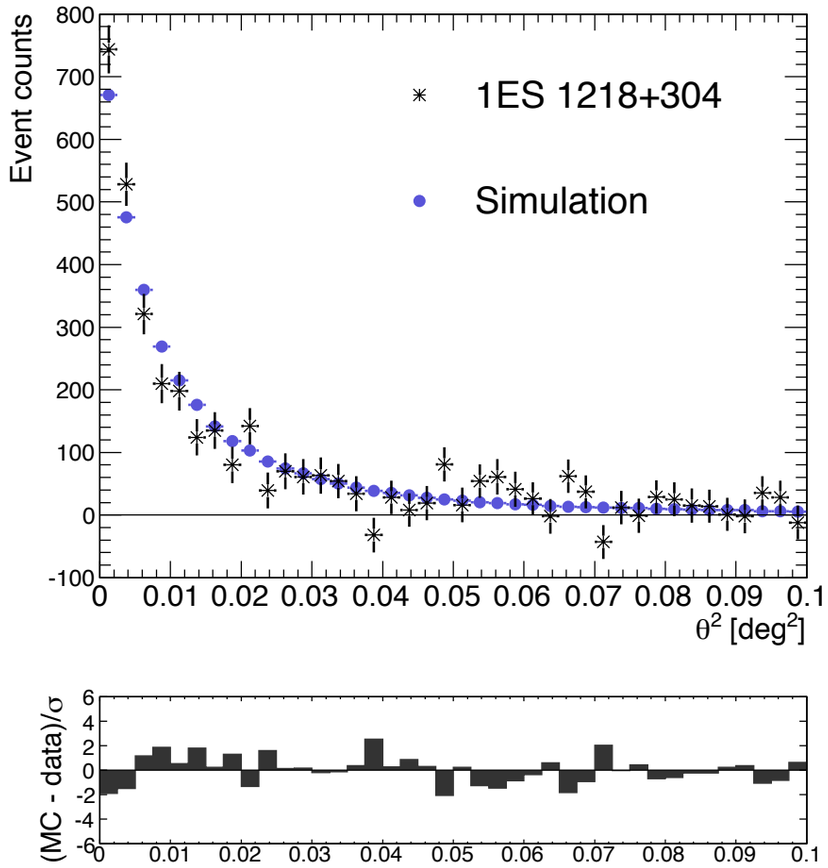


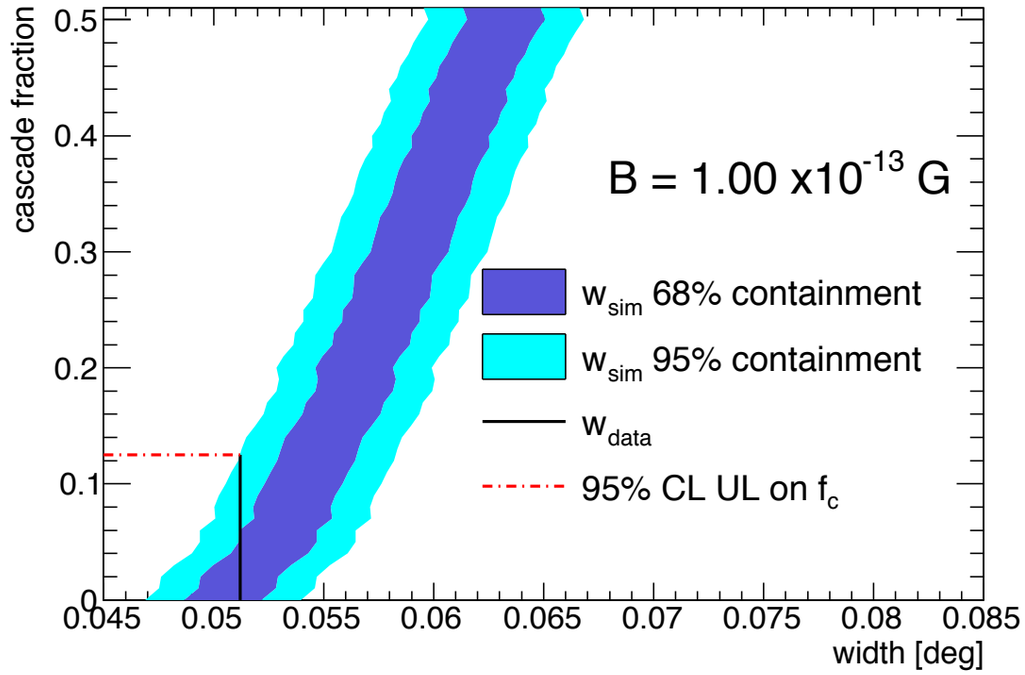


- Interaction of EBL-VHE photons results in attenuation above 100 GeV
- VERITAS long term program on extreme blazars exhibiting high-energy spectrum with no evidence of a cutoff up to a few TeV
- Model-independent upper limits on EBL spectrum from 8 VERITAS blazars => galaxy surveys have resolved most of the sources of the EBL at these wavelengths
- VERITAS fills a unique niche with observations of extreme blazars at nearby to moderate redshift ($0 < z < 0.3$), great for probing the longer wavelength EBL, complimentary to Fermi-LAT, with better sensitivity than HAWC

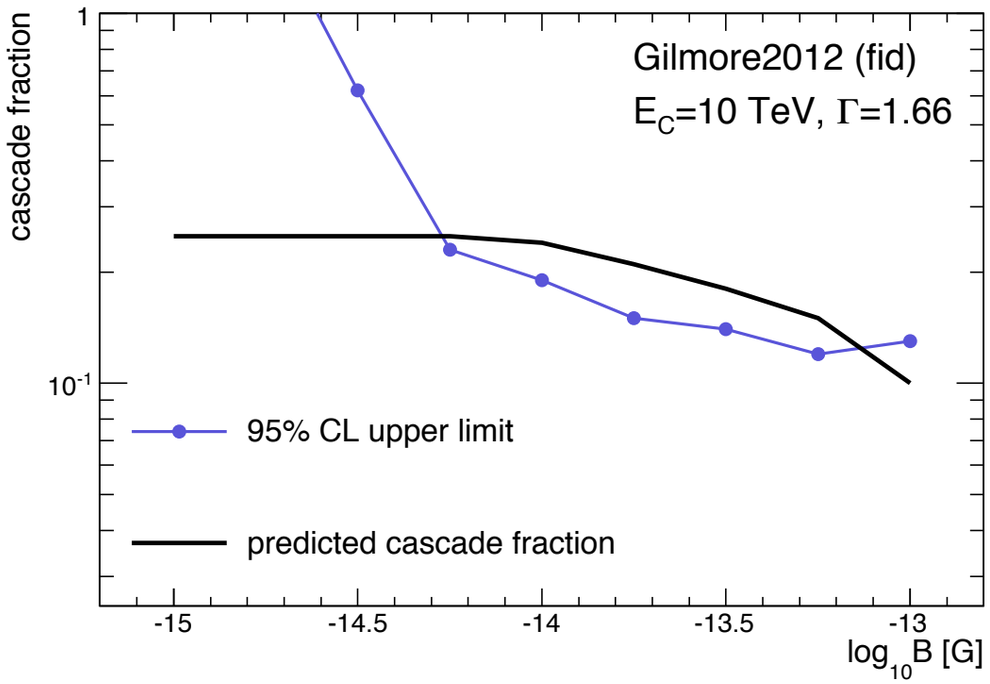
Constraints on Intergalactic Magnetic Field with VERITAS Blazar Observations

VERITAS Collaboration 2017 ApJ: arXiv:1701.00372





- For IGMF 10^{-16} G — 10^{-12} G, pair halos for blazars (z: 0.1 – 0.2) are detectable by current IACTs
- Tested for extended emission around 7 hard-spectrum blazars
- No deviation from simulated instrument PSF
- Exclude IGMF strengths around ~10^{-14} G at 95% confidence level

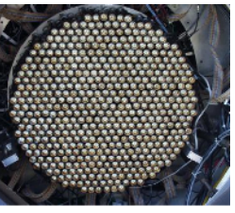
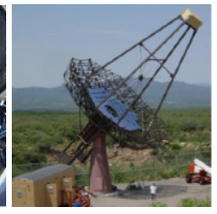


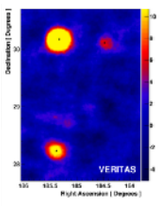
TeV gamma-ray variability is amazing!

- VERITAS observations are revealing the processes of cosmic-ray acceleration and transport
- Multi-messenger programs are opening new windows into extreme environments
  - VERITAS detection of TXS 0506+056 following IceCube HE neutrino alert: more deep campaigns coming
- Probe the location & mechanism of gamma-ray emission & connection with radio activity:
    - Radio galaxy flares (3C 264, NGC 1275, MWL observations)
    - Fast variability: IBL/LBL (BL Lac, VLBA; Mrk 421)
    - SMBBH OJ 287 detection (not disk crossing, but jet activity)
- MWL observation of flares allow broadband SED modelling, VERITAS data constrain the highest-energy particles.
- Indirect measurement of EBL and IGMF with gamma-ray observations continue to provide new constraints on the gamma-ray propagation in cosmology context

- We are always looking to collaborate! https://veritas.sao.arizona.edu/
  - External proposals are welcome!

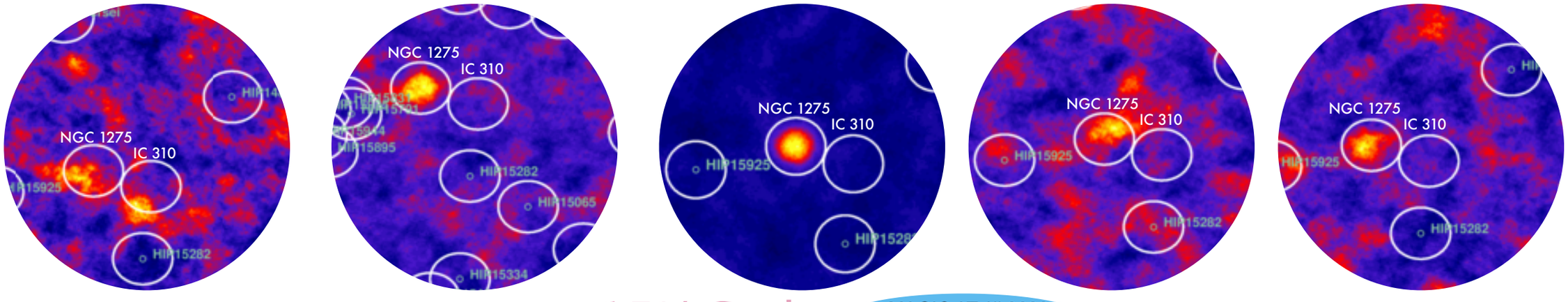
Backup slides

NGC 1275: The Brightest VHE Flaring Radio Galaxy

Oct 30 2016



~15% Crab

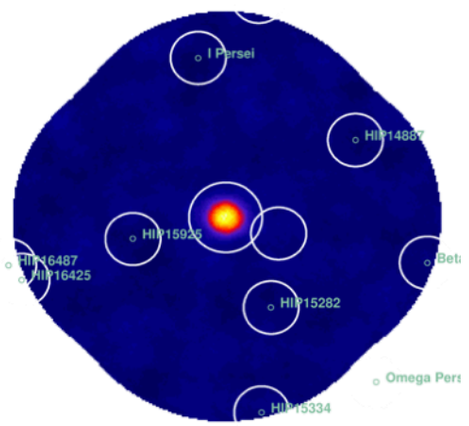
MAGIC ATel# 9689
VERITAS ATel# 9690

MJD57687 → MJD57690 → MJD57691 → MJD57692 → MJD57694

MJD57687	MJD57690	MJD57691	MJD57692	MJD57694
Significance = 1.7σ Exp. = 25 min Rate = 0.6 γ / min	Significance = 4.0σ Exp. = 26 min Rate = 1.8 γ / min	Significance = 18.1σ Exp. = 286 min Rate = 1.8 γ / min	Significance = 3.0σ Exp. = 51 min Rate = 0.6 γ / min	Significance = 4.1σ Exp. = 26 min Rate = 1.3 γ / min

- Radio galaxy (FR I) in the center of Perseus Cluster, z = 0.0176
- Multiple flares in 2016 and 2017
- Brightest-ever VHE radio galaxy detection in 2017. (flux ~50% Crab), but no intra-night variation
- Significant spectral hardening: Γ ~ 2.75; c.f. Γ ~ 4.1 prior to 2016-17

Jan 2 2017

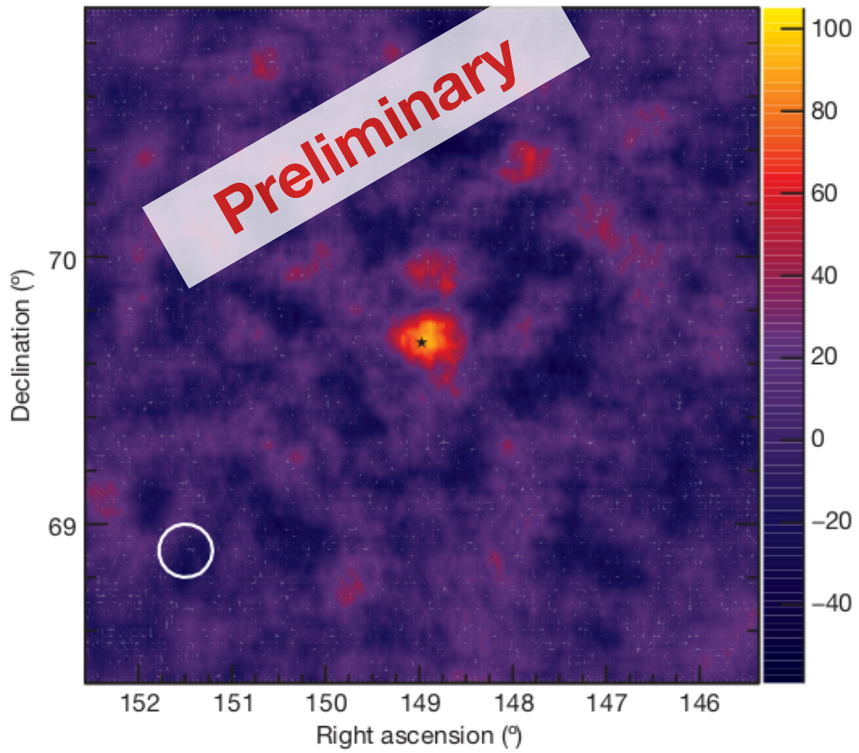


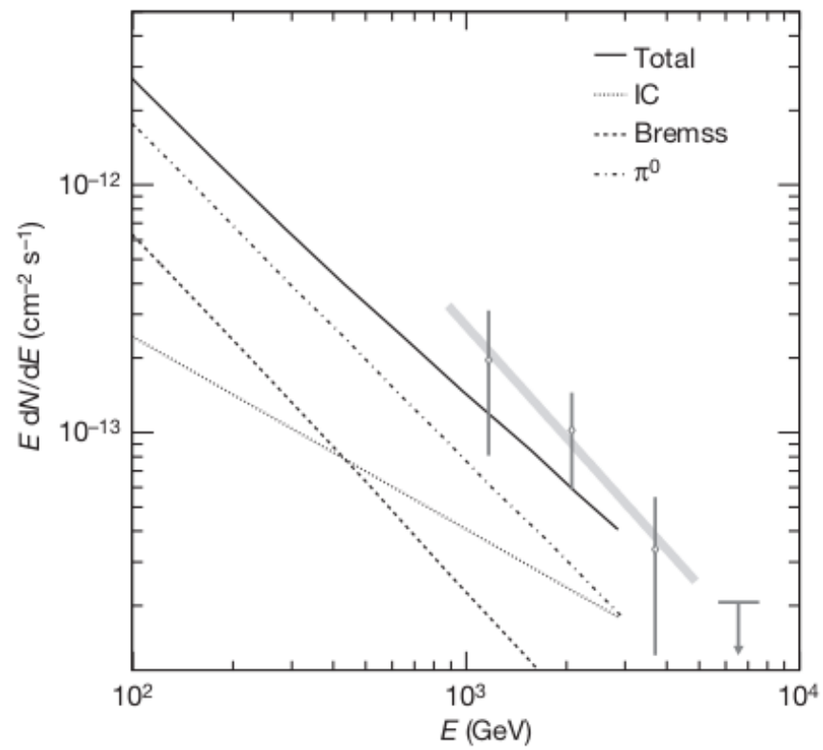
Significance = 34σ
Exp. = 130 min
Rate = 6 γ / min

M 82

See Andriy Petrashyk's poster

- VERITAS detected M82 in 2009
- Among weakest-ever VHE sources, 0.9% Crab
- No clear determination of the origin of the VHE emission

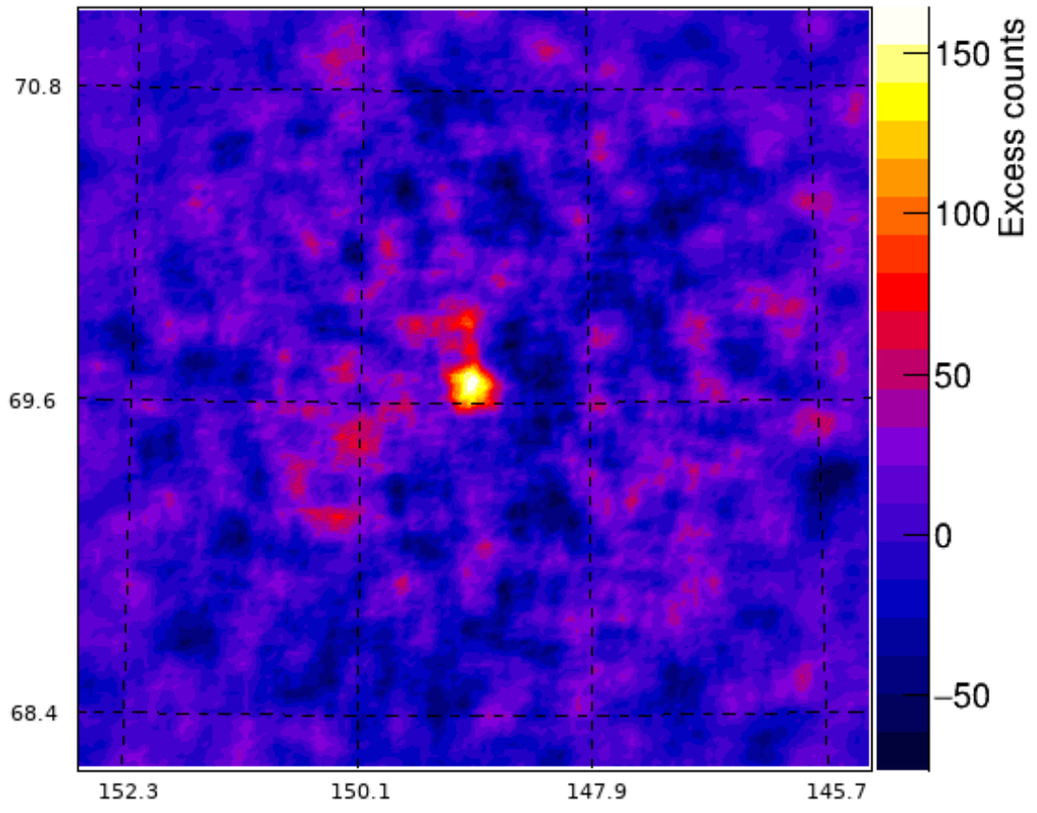




- VERITAS has since undergone two upgrades
- The exposure on M82 has increased: ~137 hours → ~240 hours
- We have deployed new analysis methods

An update on M82

- Post-camera upgrade data allow lowering the energy threshold
- Image template method and boosted decision trees offer a remarkable improvement over standard analysis
- Much tighter θ^2 cut of 0.006 deg^2 vs 0.01 for standard analysis



- New results consistent with the published ones within errors
- Total flux at the lower end of the published value – even weaker than initially estimated
- Analysis ongoing

GRB 150323A

"A strong limit on the very-high-energy emission from GRB 150323A"
Abeysekara et al., ApJ, 857, 33 (2018)