VERITAS

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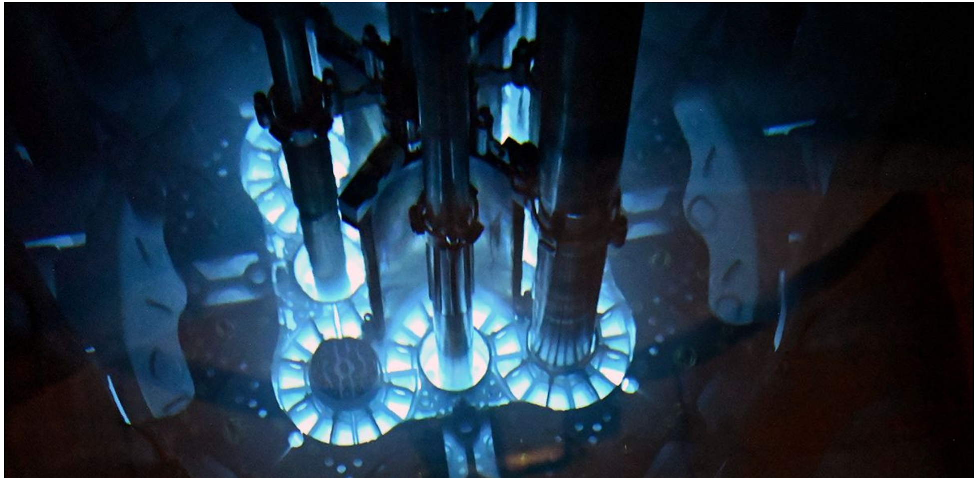
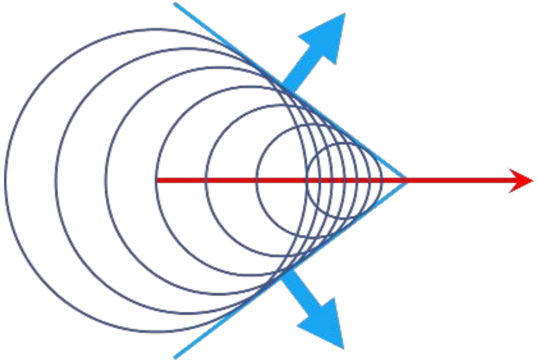
Cherenkov Radiation and Extensive Air Showers

Cherenkov Radiation

- Occurs when a particle travels faster than light in a given medium
  - Atmosphere in case of IACT
- Similar to sonic boom
  - Moving charged particle excites particles in medium
  - Particles return to ground-state - emit photons
  - Asymmetric polarisation - overlapping emitted waves - constructive interference - visible light

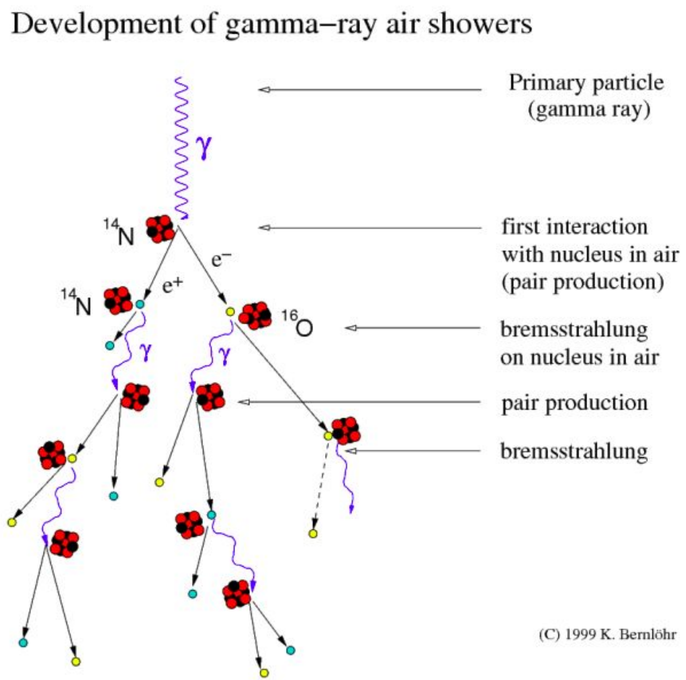




Gamma-ray Air Showers

- Occur when gamma ray enters the Earth's atmosphere.
  - Pair production -> bremsstrahlung -> pair production -> bremsstrahlung -> etc.

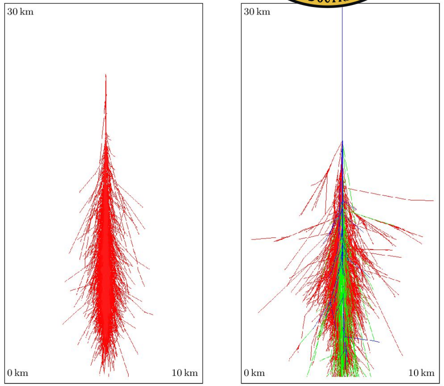
- Particle must undergo ~28 PP -> bremsstrahlung processes before reaching ground
  - Average distance for each process is known
  - Showers seen on ground produced by highly energetic particles



https://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html

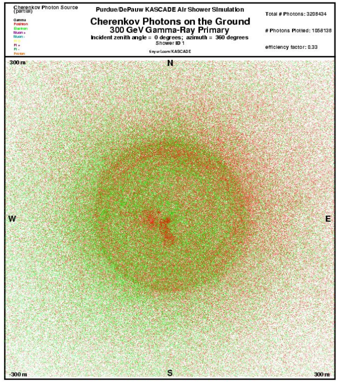
Hadronic Showers

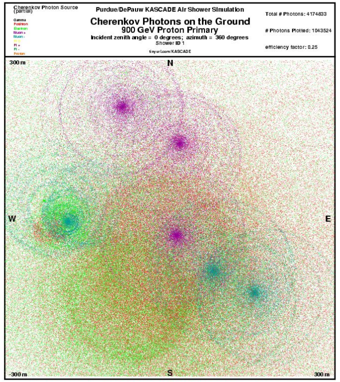
- Similar process as gamma ray
- Major source of background
- Pions most commonly produced upon entering atmosphere
  - π^0 quickly produce 2 gamma rays which undergo PP -> bremsstrahlung
  - Nearly indistinguishable from a shower produced by a single gamma ray
- Cosmic electrons and positrons can also induce an EAS
  - Further background



(a) γ-ray induced air shower with 300 GeV and first interaction in 23 km height

(b) hadron induced air shower with 1 TeV and first interaction in 18 km height

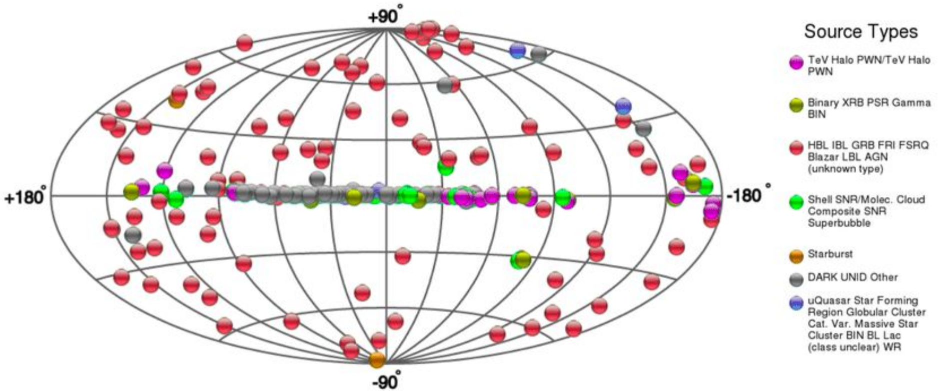




The Imaging Atmospheric Cherenkov Technique

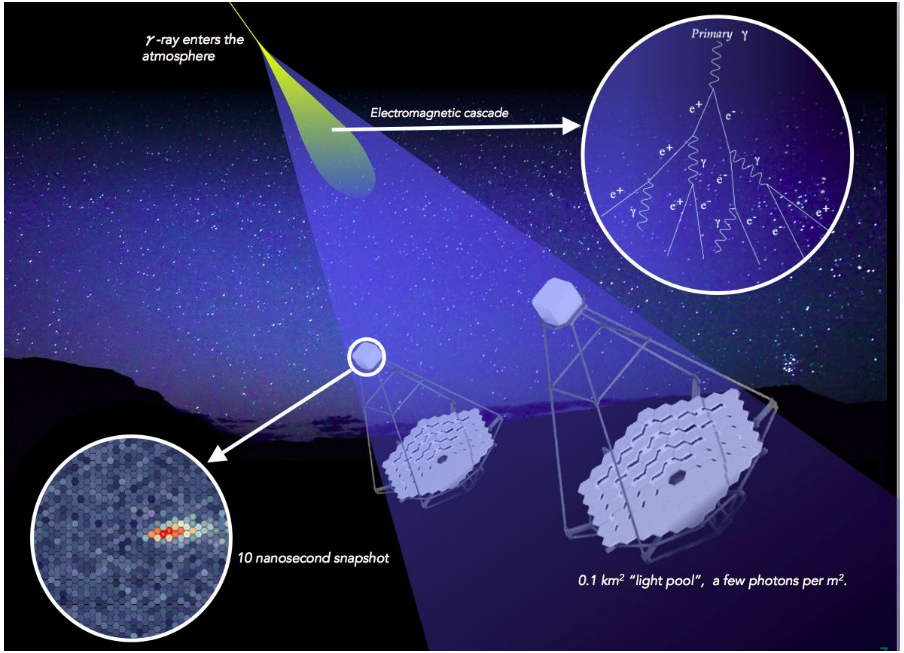
History of TeV Astronomy

- 1953 : Cherenkov emission from atmospheric showers of charged particles is discovered. (Jelly and Galbraith)
- 1961 : Successful imaging of Cherenkov light from a 10^{15} eV hadronic shower, using an image-intensifier with phosphor storage. (Hill and Porter)
- 1980-82 Weekes, Fegan, and Porter construct an imaging system for implementation on the 10m Whipple telescope
- 1989 : First significant detection (9σ) of TeV gamma rays by 10m at Whipple Observatory
- 1992 : Detection of first extragalactic source by Whipple: Markarian 421



Imaging Atmospheric Cherenkov Telescopes

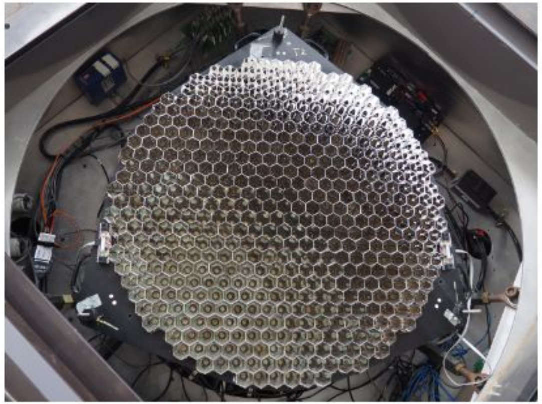
- Uses Earth's atmosphere as the detection medium
  - Or water/ice
- Observe Cherenkov radiation from gamma ray
- Reconstruct shower to estimate gamma-ray energy and point of origin
- Use image processing to discriminate against background cosmic-ray events
- Simulations required to derive instrument response

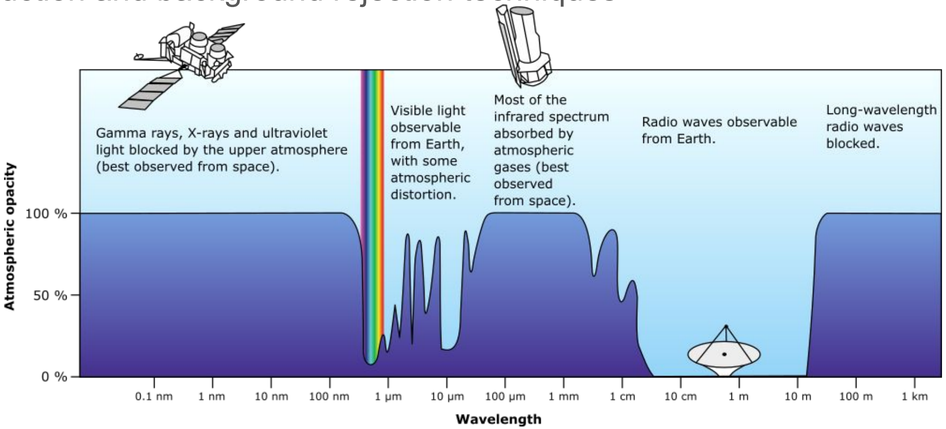


https://www.cta-observatory.org/astri-detects-crab-at-tev-energies/

Observing Cherenkov Showers

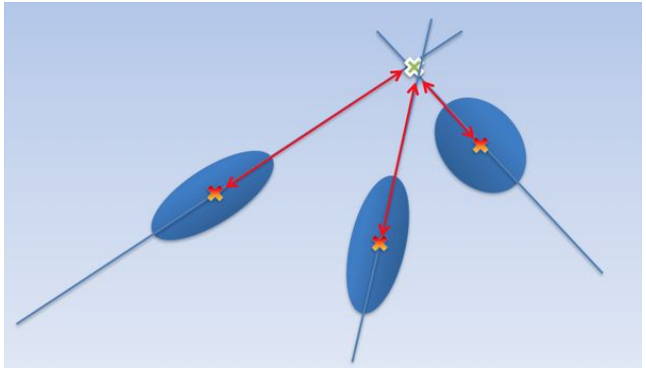
- Large light collection area
  - Complete shower must be seen for background discrimination and shower reconstruction
  - Large mirrors (~100 m^2) - reflectivity max at 300-350 nm (Cherenkov light peak intensity)
- Nanosecond cameras
  - Photomultiplier tubes
- Telescopes built in arrays
  - Array-level stereoscopic shower reconstruction and background rejection techniques

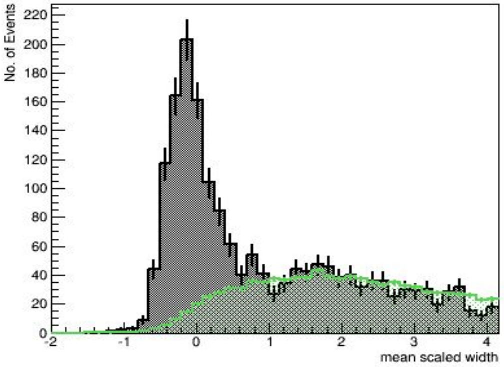


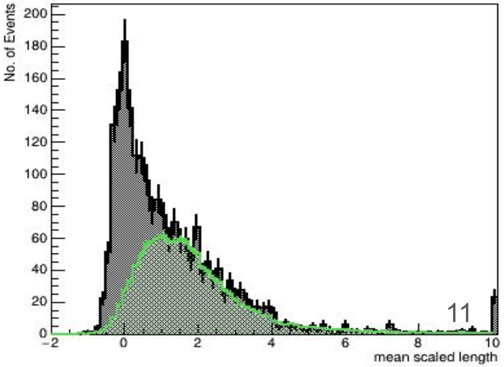


Reconstructing a Gamma-Ray

- Gamma-ray showers will appear as narrow ellipses
  - Major axis gives vertical extension and direction of source
  - Height estimated from the distance of the shower location to telescope on ground plane (Impact Parameter)
- Energy estimated from brightness of shower image and impact parameter
  - Brighter image - more energetic
  - Monte Carlo lookup tables used for estimation
- Hadron rejection
  - Cuts applied to shape of showers
  - Gamma-ray showers : longer and more narrow - not an exact science

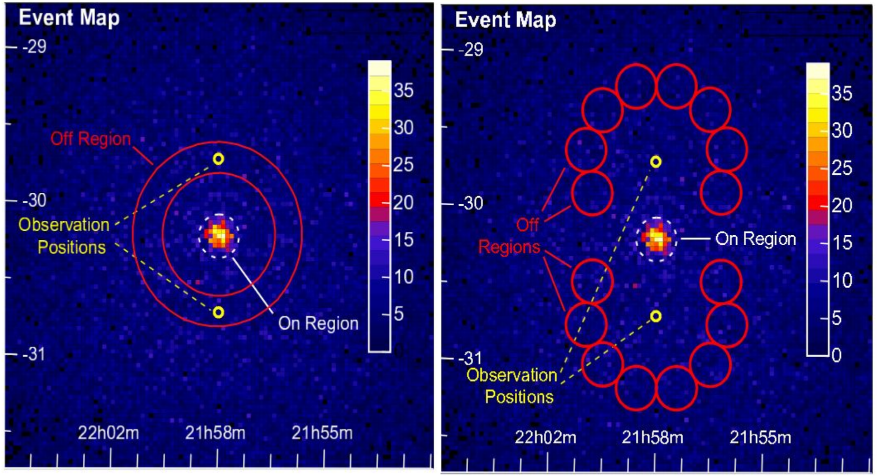






Background Estimation

- Data still not background free
  - Remainder must be estimated
- Determine statistical significance of observation with Li & Ma equation 17 (Li and Ma 1983)
  - 5σ required for a statistically significant detection of target over the background



$$S = \sqrt{2}\left\{N_{on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right] + N_{off}\ln\left[(1+\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{\frac{1}{2}}$$

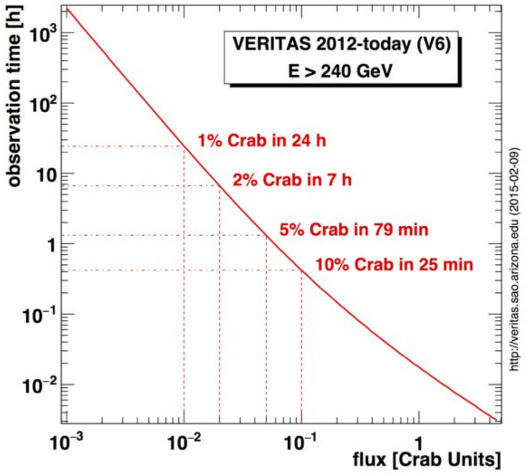
The VERITAS Instrument and Collaboration

VERITAS

- VERITAS: Very Energetic Radiation Imaging Telescope Array System
- Prototype SCT telescope for CTA on site
- Located in Southern Arizona, USA
- Full array operations begin: 2007 - 17 years of operation
- Currently ~100 members in total
- Funded to operate through 2025

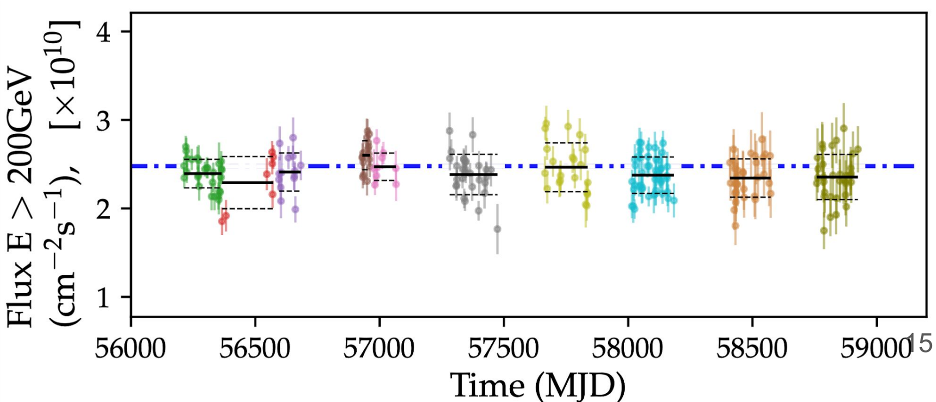
VERITAS Performance + Observations

- FOV 3.5 deg (diameter)
- Energy range: ~85 GeV to ~30 TeV
- Effective Area: 10^5 m^2 @ 1TeV
- Ang. resolution: 0.08° resolution @ 1 TeV
- Sensitivity: 1% Crab in 25 hours
- Energy resolution: ~17%



- Runs September - July
- ~950 hrs dark time, ~250 hrs bright moon (30-65% illum.).
- Optical stellar intensity interferometry during full moon (> 65%)
- Remote observing capabilities introduced during lockdowns - now a long term option

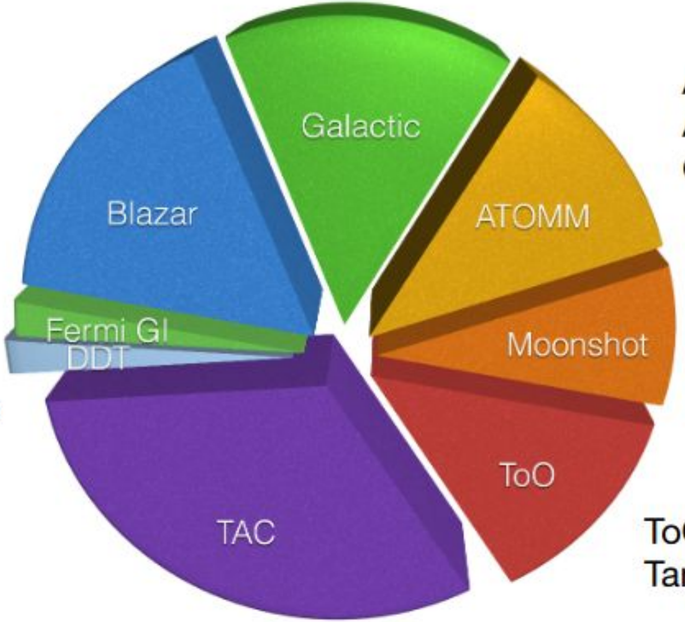
Long-term instrument response well understood: (Adams et al., A&A 658, A83 (2022)):



Gamma Ray Science Programme

Fermi GI:
Fermi Guest
Investigator Program

DDT:
Director's Discretionary Time



ATOMM:
Astroparticle, Transient,
Optical, Multi-Messenger

ToO:
Target of Opportunity

TAC:
Time Allocation Committee

The Science of VERITAS

Gamma-ray Science

- Blazars and Radio Galaxies
  - 37 Blazars and 4 Radio Galaxies detected
  - ~200 hrs/year (Long term monitoring and ToO)
  - Multiwavelength collaboration (Swift, Fermi, IXPE, IceCube)
- Binaries
  - 3 systems detected: HESS J0632+057, LS I +61 303 and PSR J2032+4127
- HBLs
  - Ongoing study to derive the luminosity function of HBLs
  - Search using > 2000 hrs of data - extracted unbiased data

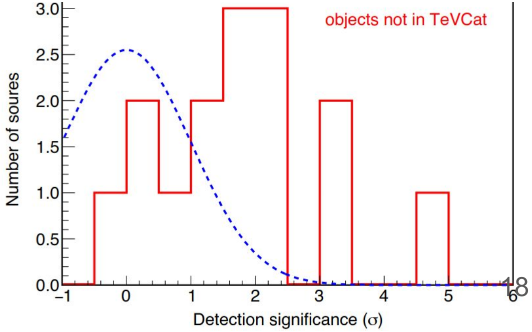
VHE detected Radio Galaxies

VERITAS detected so far

3C 264 discovery
Archer el al. (2020)

Name	Cross-ID	Type	Distance	BH mass [10^8 Msun]
Cen A	NGC 5128	FR 1	3.7 Mpc	(0.5-1)
M87	NGC 4486, Virgo A	FR 1	16 Mpc	(20-60)
NGC 1275	3C84, Perseus A	FR 1	70 Mpc	3-4
IC 310	B0313+411	FR I/BL Lac	80 Mpc	3 [0.3?]
3C 264	NGC 3862	FR I	95 Mpc	4-5
PKS 0625-35	OH 342	FR I/BL Lac	220 Mpc	~10

Rieger & Levinson 2018



VERITAS Blazars

Science Drivers

- Jet physics, EBL, Intergalactic Magnetic Field, Particle processes and acceleration mechanisms, neutrino/cosmic ray origin.

Observations

- ~ 200 hrs/year
    - Monitoring & ToO (self-triggering)
- Multiwavelength coverage
- Simultaneous observations with IXPE (2022-2025)

Multi-year projects

- HBL luminosity function
- Nightly Mrk 421 snapshots
    - Looking for a repeating flaring pattern

Flaring

- OJ 287 - 2017 flare
- Mrk 421 giant 2010 flare (*Abeysekara at al., ApJ, 890, 97 (2020)*)
- FSRQs (3C 279, PKS 1222+216, and Ton 599) (*Adams et al., ApJ, 924, 95 (2022)*)
- Radio Galaxies

Blazars with uncertain redshift: 7

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

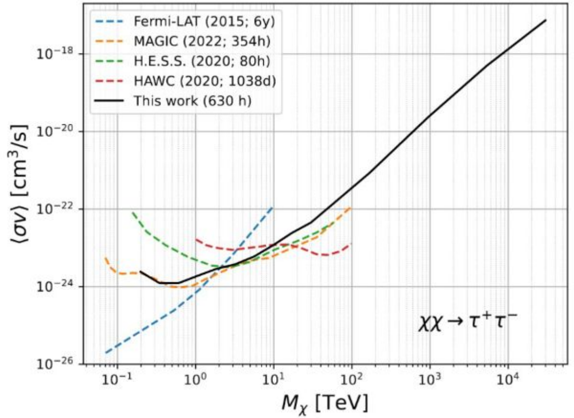
AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
IC 310	FR I/HBL	0.019
3C 264	FR I	0.026

Blazars with well measured redshift: 30

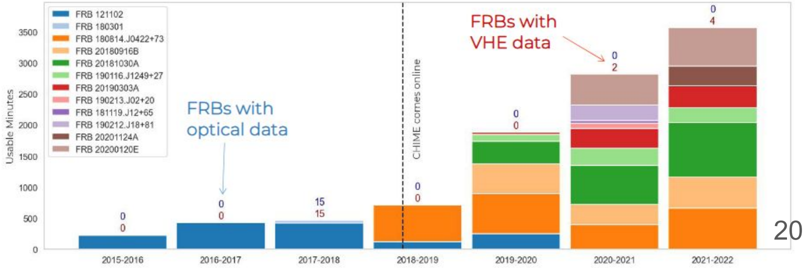
Blazar	Type	z
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	IBL	0.069
1ES 1741+196	HBL	0.084
W Comae	IBL	0.102
VER J0521+211	IBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
B2 1215+30	HBL	0.131
S3 1227+25	IBL	0.135
1ES 0806+524	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
MS 1221.8+2452	HBL	0.218
RBS 1366	HBL	0.237
1ES 0414+009	HBL	0.287
OJ 287	LBL	0.306
TXS 0506+056	HBL	0.337
1ES 0502+675	HBL	0.341
PKS 1222+216	FSRQ	0.432
PKS 1424+240	IBL	0.601
Ton 599	FSRQ	0.720
PKS 1441+25	FSRQ	0.939

Other Astroparticle Physics

- Indirect dark matter searches
  - Galactic centre, dwarf spheroidal galaxies
  - Largest mass range by an IACT
  - Combined analysis with Fermi-LAT, HAWC, H.E.S.S. and MAGIC

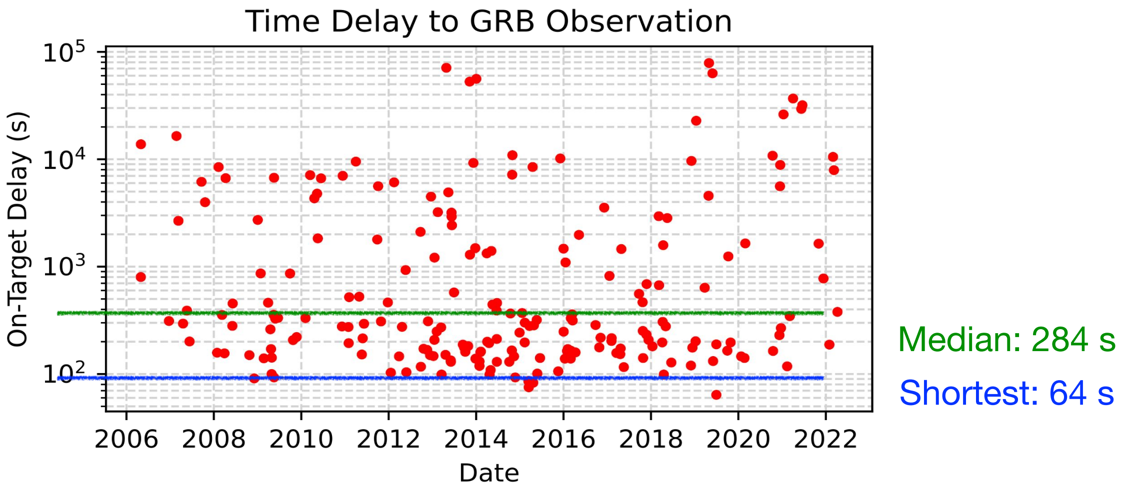


- Fast Radio Bursts
  - Simultaneous gamma-ray and rapid (ms) optical observations (2-4 pixels)
  - Observations are taken simultaneously with CHIME - a radio instrument that has detected > 500 FRBs



Gamma-Ray Bursts

- High priority observations - Interrupt other observations
- 211 observed to date - 127 with a position < VERITAS PSF
  - 16 published in ApJ 743, 62 (2011)
  - 1 in ApJL 795, L3 (2014); 1 in ApJ 857, 33 (2018)
- No detections to date - stacked analysis always underway
- ~25 hours taken on GRB 221009A (BOAT)



Neutrino Follow-up Program

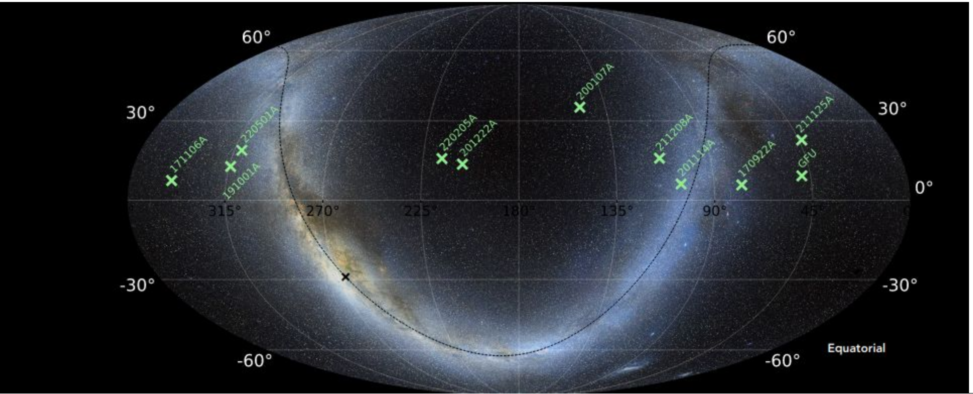
- Automatic repointing for IceCube alerts - 45 hrs/yr on potential neutrino counterparts
- 9 follow ups on real-time neutrino alerts since TXS 0506+056 detection - No detections

TXS 0506+056

- VERITAS detection following IceCube
- Monitoring since detection in 2018
- >100 hrs collected
- MWL with Swift and NuSTAR

PKS 0735+178 (IceCube-211208A)

- VERITAS, HESS, Fermi-LAT, NuSTAR, Swift-XRT
- ~20 hours of VTS data, taken hours after IceCube alert
- https://arxiv.org/abs/2306.17819



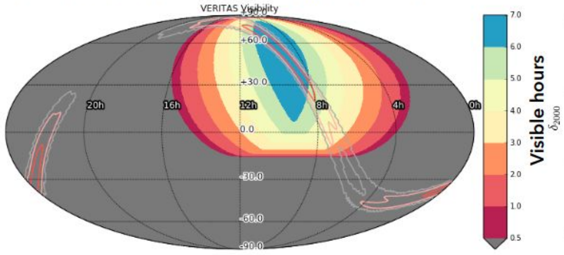
MAGIC, IceCube, FACT, H.E.S.S. and VERITAS collaborations PoS ICRC2021 960

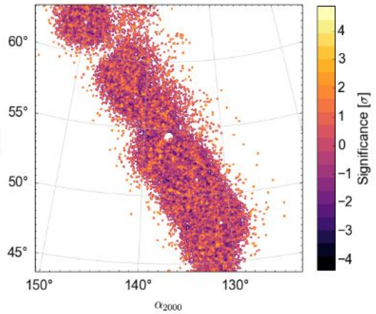
Name	Energy [TeV]	Signalness	FACT	H.E.S.S.	MAGIC	VERITAS
IceCube-171106A	230	0.75	19 h	—	4.5 h	2.5 h
IceCube-181023A	120	0.28	1 h	—	—	—
IceCube-190503A	100	0.36	—	—	0.5 h	—
IceCube-190730A	299	0.67	—	—	3.1 h	—
IceCube-190922B	187	0.50	5.4 h	—	2.2 h	—
IceCube-191001A	217	0.59	2.0	—	2.3 h	1.0 h
IceCube-200107A	—	—	—	—	2.7 h	9.5 h
IceCube-200926A	670	0.44	—	1.3 h	1.0 h	
IceCube-201007A	683	0.88	—	3.25 h	0.5 h	—
IceCube-201114A	214	0.56	—	14.5 h	6 h	7 h
IceCube-201222A	186	0.53	—	—	—	1.0 h

Gravitational Wave Follow Ups

On Jan 5, 2017 VERITAS follow-up of a GW event GW170104 (GCN #21153). First systematic follow-up of a GW event by an IACT.

GW170104: 50-$M_\odot$ BBH merger @ z = 0.2.





- *An Archival Search for Neutron-Star Mergers in Gravitational Waves and Very-High-Energy Gamma Rays*, Adams et al., ApJ 918, 66 (2021)

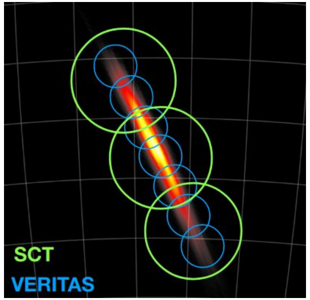
Candidate Label	LIGO BNS Candidate Event ID	LIGO FAR (yr^{-1})	LIGO S/N	LIGO p-astro (10^{-3})	LIGO Area (deg^2)	VERITAS t_{first}	VERITAS t_{coinc}	VERITAS Coverage Probability
C1	2015Oct12T02:40:22.39	142.27	8.42	3.82	2321	-0:11:17	0:18:53	0.22%
C2^L	2015Oct24T09:03:52.00	7.52	9.69	79.6	24218	1:33:08	1:11:08	0.06%
C3^H	2015Nov17T06:34:02.07	7.52	8.84	181	24221	-0:08:02	2:37:43	0.18%
C4	2015Dec04T01:53:39.14	225.02	9.09	2.5	2909	0:16:20	1:00:00	0.19%
C5^L	2015Dec06T06:50:38.17	77.45	7.72	6.64	24264	-0:09:02	2:10:18	0.15%
C6	2015Dec09T07:25:24.68	141.65	7.85	3.84	2606	1:36:25	0:15:00	0.03%
C7	2016Jan02T02:47:29.35	356.13	7.51	1.63	3487	1:44:55	0:30:00	0.18%

O3 LIGO/Virgo run (2019-2020)

- Development of automated tiling algorithm for GW error regions
- 12 GWs followed up

Plans

- Synergise with SCT



Summary

- Ground-based gamma-ray physics is statistics and background dominated
  - Background rejection optimisation methods key
- Telescopes require fast optics, large collection areas and complex image reconstruction methods
- No calibrated source so Monte Carlo simulations required for calibrations.
- VERITAS is on it's 17th year and still going strong
  - 8 papers in last year, more in works
    - Dark Matter
    - Blazars
    - OSETI
    - Superluminous Supernova + more