

Follow-up of neutrino alerts with IACTs



D. Dorner for FACT

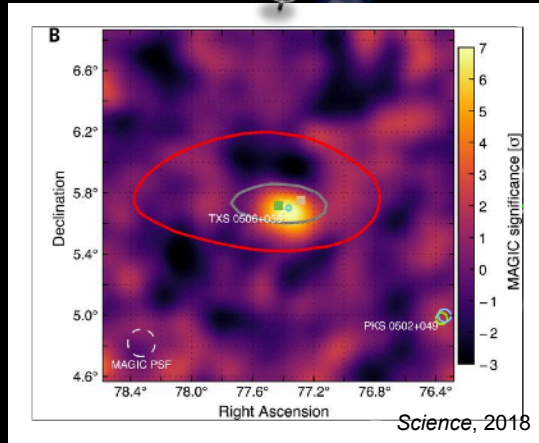
H. Ashkar, Y. Becherini, M. Cerruti, C. Hoischen, R. Konno, F. Schuessler, M. Senniappan for H.E.S.S.

E. Bernardini, E. Blaufuss, C. Boscolo-Meneguolo, T. Kintscher, M. Mallamaci for IceCube

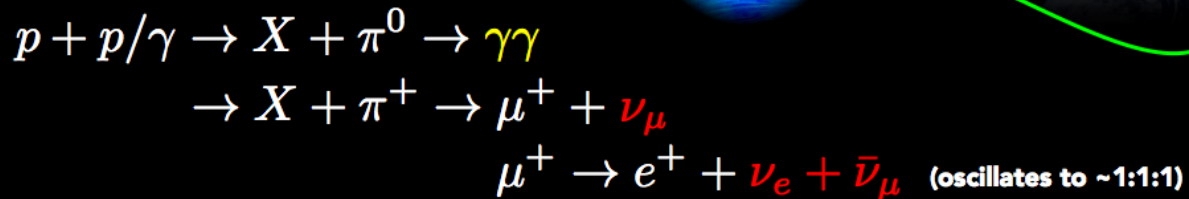
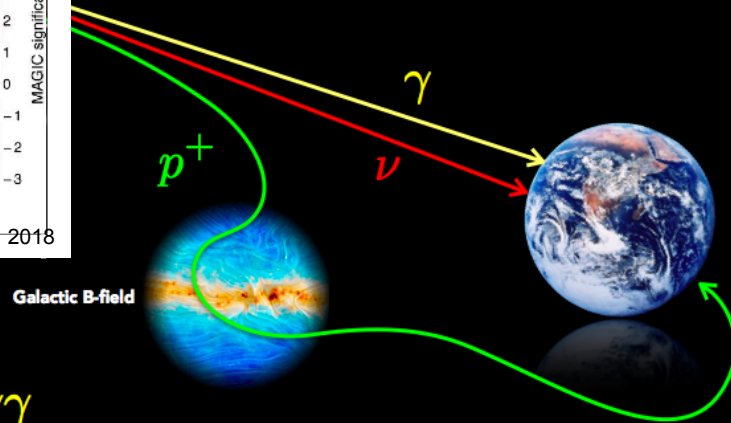
K. Satalecka, M. Artero, A. Berti, H. Boekenkamp, A. Fattorini, L. Heckmann, S. Mangano, H.A. Mondal, K. Noda, S. Sakurai, L. di Venere, I. Viale, S. Yoo for MAGIC

W. Jin, M. Santander, K. Farrell, J. Quinn, J. Christiansen, J.P. Caldwell, M. Lundy for VERITAS

Motivation



$\sim 3\sigma$ correlation of IC-170922A (~ 300 TeV) with the flaring **gamma-ray blazar** TXS 0506+056 (*Science*, 2018)



IACTs

Typical for all:

- Energy resolution:
~15-20%
- Angular resolution:
~0.06 deg
- Sensitivity:
~ 10^{-11} TeV cm⁻² s⁻¹
(> 100 GeV) in 30 min

FACT



- Camera FoV: 4.5°
- Energy range: 300 GeV - 10 TeV
- Repositioning speed: 180 deg/15 sec

H.E.S.S.



- Camera FoV: 5°
- Energy range: ~20 GeV - 100 TeV
- Repositioning speed: 200 deg/min

MAGIC



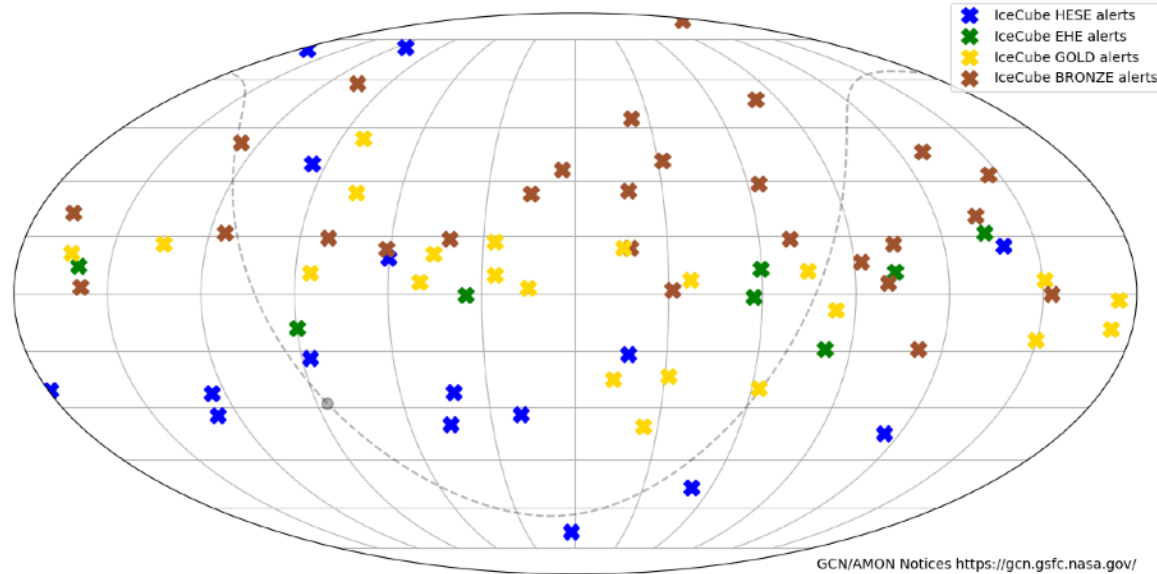
- Camera FoV: 3.5°
- Energy range: ~20 GeV - 100 TeV
- Repositioning speed: 180 deg/25 sec

VERITAS



- Camera FoV: 3.5°
- Energy range: ~100 GeV - >30 TeV
- Repositioning speed: ~1 deg/sec

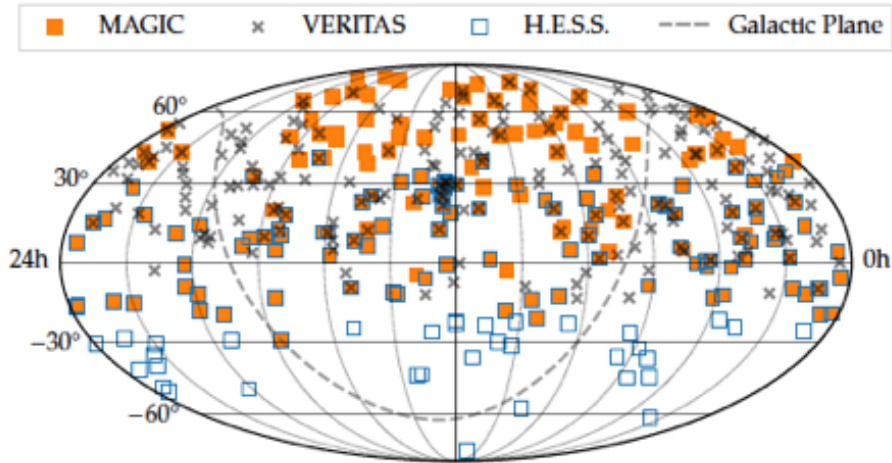
IceCube follow-up programs: single neutrino events



- **Single neutrino events:**

- Since April 2016 (EHE/HESE event streams)
- Upgrade in 2019 to BRONZE/GOLD event streams with 30%/50% probability of being astrophysical
- Publicly distributed via AMON, all IACTs participate
- Goal: identify the EM counterpart to the neutrino event
- Here we concentrate on alerts sent since October 2017

IceCube follow-up programs: GFU*



*GFU stands both for Gamma-ray Follow-Up program and IC event selection used also in the single event alerts. Here used in the 1st sense.

- **Neutrino multiplets (*flares*)** from pre-defined source list:
 - Privately distributed under MoU
 - MAGIC & VERITAS (since 2012), H.E.S.S. (since 2019)
 - 339 sources from 3LAC/3FHL and TeVCAT catalogs (mostly AGN)
 - Sources selected according to variability, distance and potential visibility for IACTs
 - Looking for neutrino flares with duration from seconds to 180 days
 - Alert sent when pre-defined significance threshold passed
 - Goal: determine the changes to the state of the source (e.g. quiescence vs flaring or spectral changes)

- **All-sky flares:** same algorithm, but not restricted to pre-defined directions
- Goal: find the EM counterpart

○ Here we concentrate on alerts sent after the upgrade in 2019

Follow-up strategies

- **FACT:**

- Before May 2019: Follow-Up on a “best-effort” basis, i.e. if position is observable, observation not conflicting with core-monitoring, alert is not followed up by more-sensitive instruments
- Since May 2019: Automatic follow-up for 1h, extension depending on result of quick-look analysis and MWL info

- **H.E.S.S.:**

- Program part of H.E.S.S. Key Science; details updated every year during call for proposals
- Currently focussing on deep (~10h) observations of few (~5/yr) candidates
- Automatic repointing for GOLD alerts
- Extension of observations if on-line analysis shows hint of signal or interesting MWL info

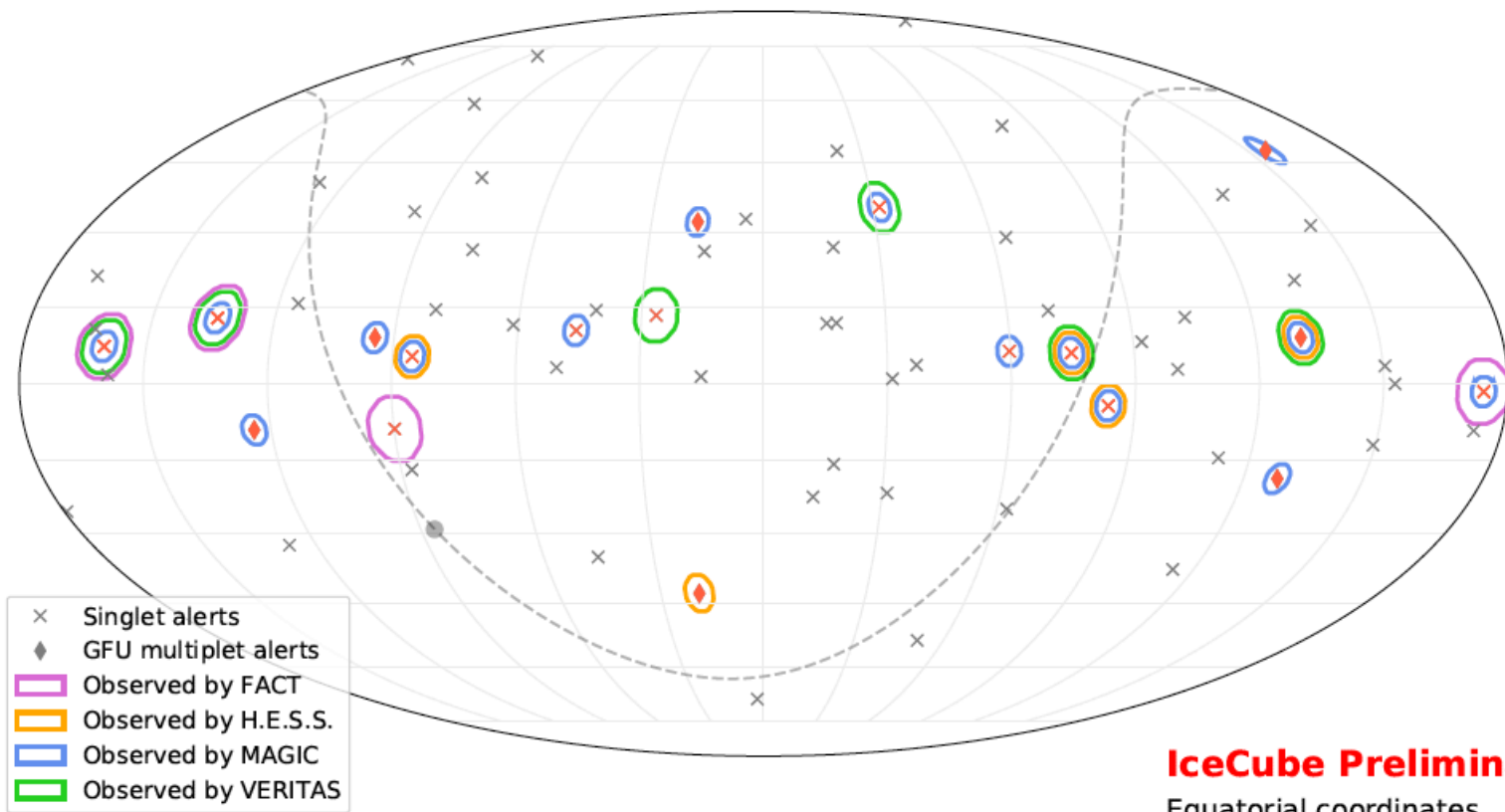
- **MAGIC:**

- 60 h/yr reserved for neutrino follow-up
- Automatic repointing for GOLD alerts with 0.5 deg loc. error at 50% CL, visibility estimate up to the end of nearest night; first observation for max. 2.5 h
- Extension of observations if on-line analysis shows hint of signal or interesting MWL info

- **VERITAS:**

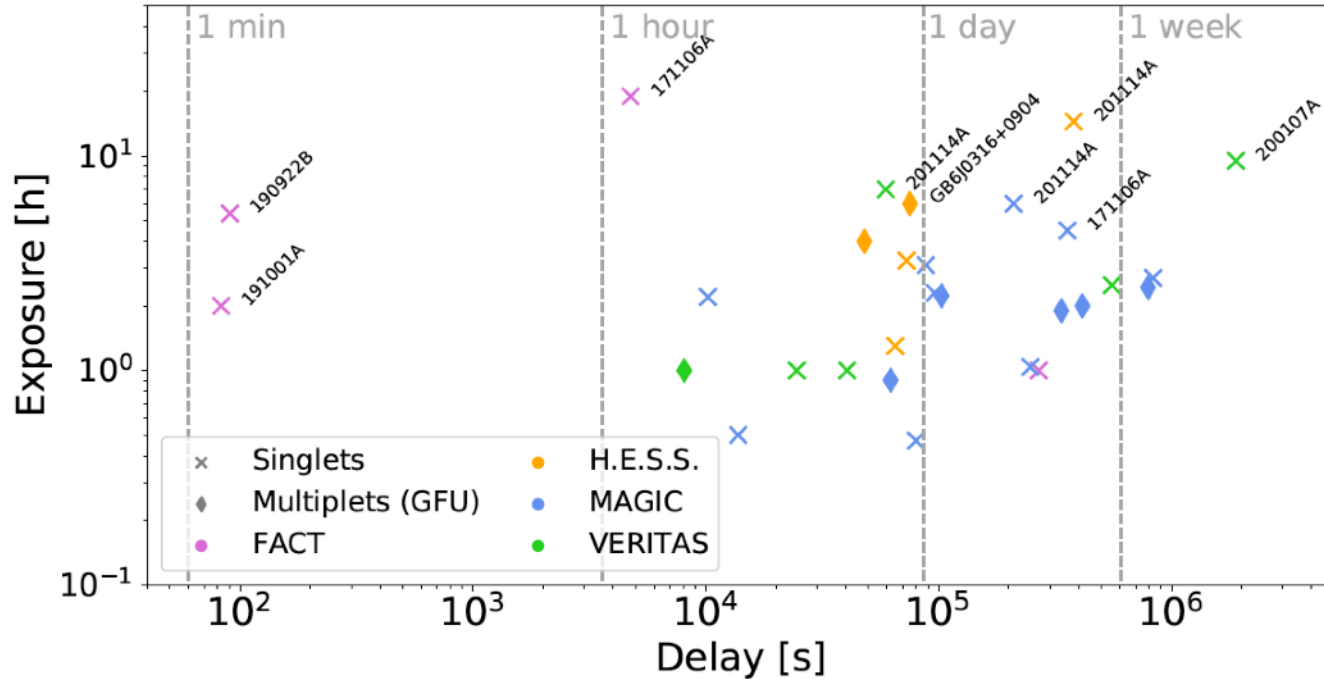
- 45 h/yr of pre-approved follow-up observations + 18 h on potential neutrino counterparts. Part of the VERITAS Long Term Science Plan.
- Automatic repointing for GOLD and BRONZE alerts. Exposures between 3-25 h depending on neutrino astrophysical probability, proximity of potential EM counterparts, online analysis results.

Alerts observed since October 2017



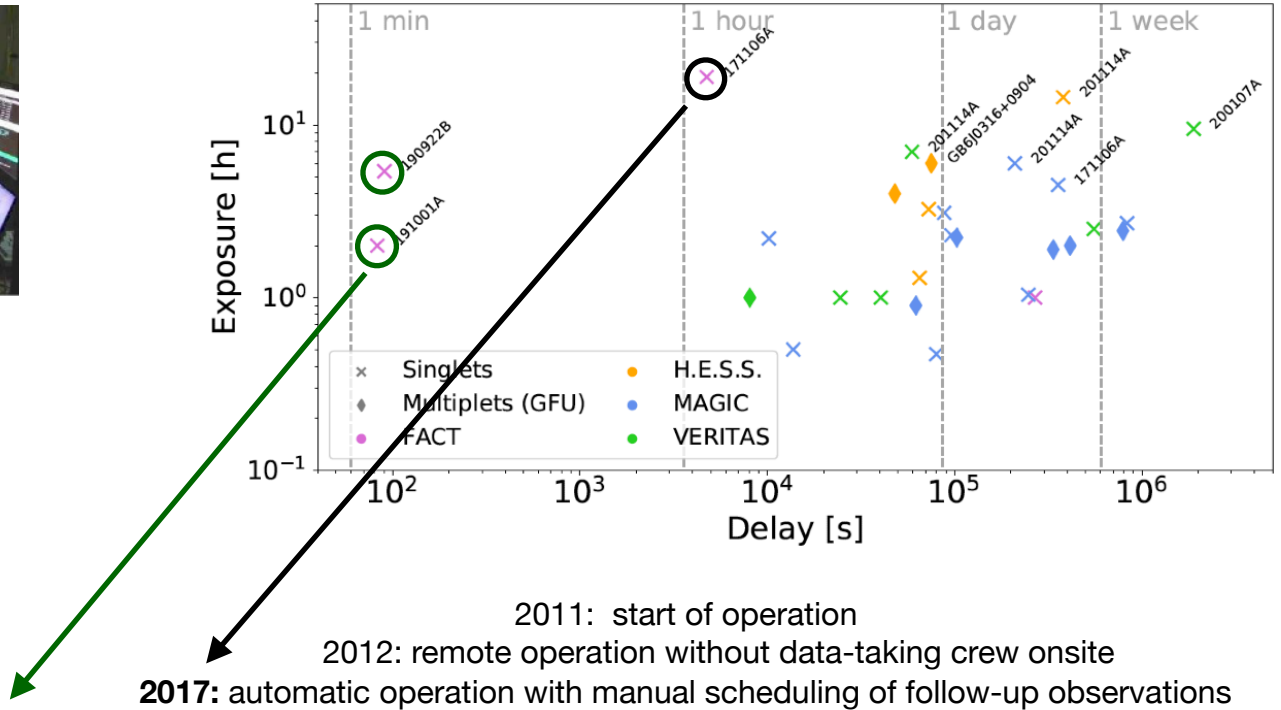
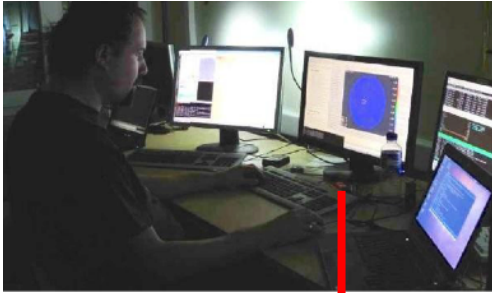
IceCube Preliminary
Equatorial coordinates

Typical IACT response



- **Typical delays:** immediate - 10 days (depends on visibility, weather, moonlight, MWL info...)
- **Typical observation time:** 0.5 - 10s of hours (same dependencies as above)

FACT automatic scheduling



2020: no operation (problem in DAQ electronics, repair delayed due to SARS-CoV-2)
June 2021: back to operation, waiting for alerts

Observed alerts: single events

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

Highlight

- From October 2017 until December 2020, IceCube sent 62 single event public alerts
- 11 were observed by at least one IACT
- In total, each collaboration spent 20 h of its observations time on public IceCube alerts follow-up
- FACT, H.E.S.S. and VERITAS observed 3-5 alerts each but concentrated longer exposures on a few of them
- MAGIC performed the highest number of follow-ups (nine) but with typically shorter exposure

Observed alerts: neutrino multiplets

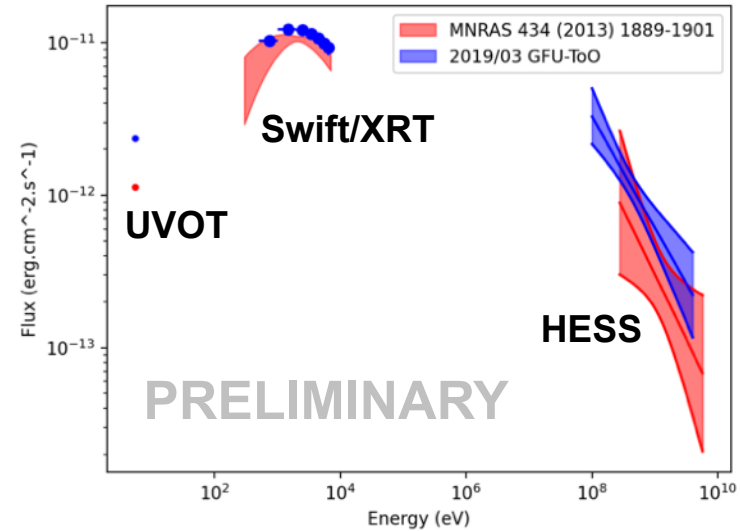
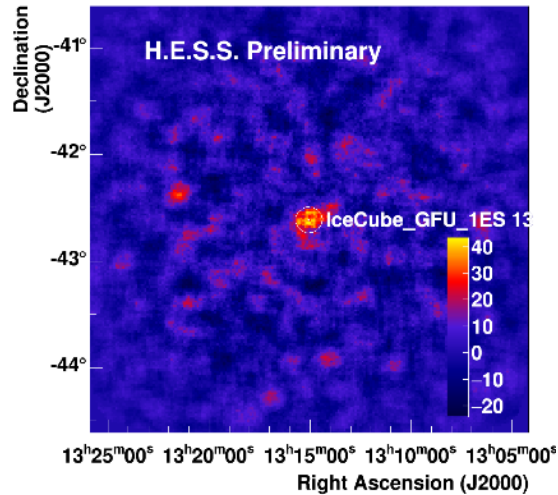
Source	Duration [days]	Pre-trial significance	H.E.S.S.	MAGIC	VERITAS
MG1 J181841+0903	Multiple alerts	$> 3.3 \sigma$	—	1.6 h	—
1ES 1312-423	0.26	3.4σ	2.6 h	—	—
PMN J2016-09	0.01	3.6σ	—	0.9 h	—
OP 313	Multiple alerts	$> 3.0 \sigma$	—	3.2 h	—
OC 457	0.30	3.3σ	—	2.5 h	—
GB6 J0316+0904	2.25	3.1σ	6 h	1.9 h	1.0 h
All-sky alert (PMN J0325-1843)	3.67	5.1σ	—	2.0 h	—

Highlight

Highlight

- Since the upgrade in 2019, IceCube sent 27 multiplet alerts from 17 sources and one all-sky alert
- 7 sources were observed by at least one IACT
- GB6 J0316+0904 was observed by all participating IACTs
- H.E.S.S. took the longest exposures
- MAGIC performed the highest number of follow-ups (six)

Neutrino multiplet from 1ES 1312-423: H.E.S.S.



- Observation triggered on neutrino events from vicinity of **known TeV emitter 1ES 1312-423**
- Neutrino alert duration of 0.26 days
- **H.E.S.S.** re-observed the source for 2.6h => **~4 σ significance**
- Cross-checked by independent analysis chain
- Contemporaneous **multiwavelength observations with Swift** (UVOT, XRT)
- **No significant change** in the non-thermal emission of the source during the ToO

All-sky alert (PMN J035-1843): MAGIC

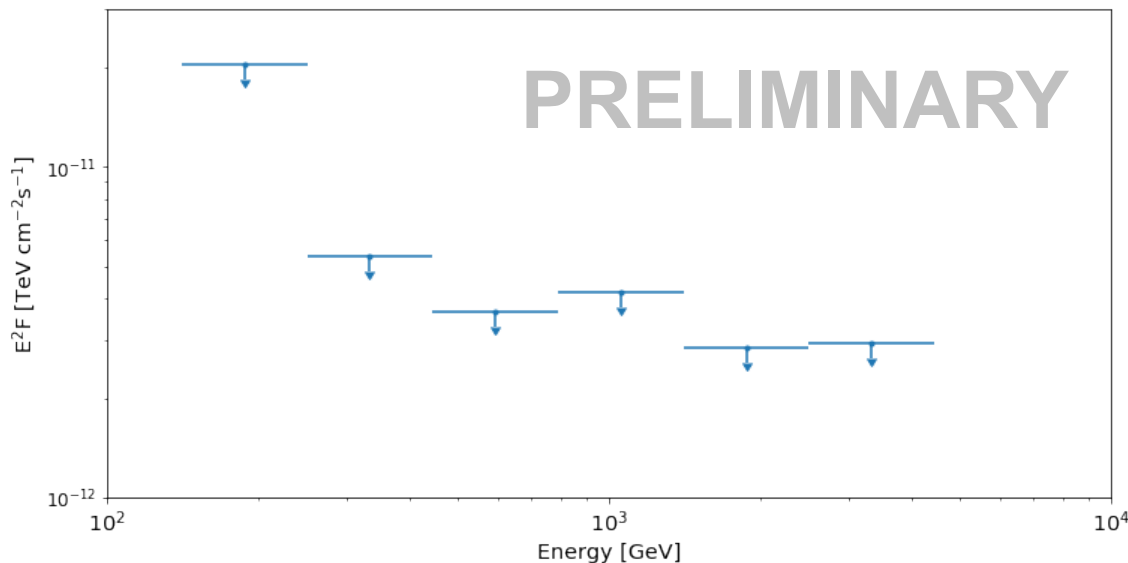


- **Neutrino flare:**

- Found using the **all-sky multiplet** search algorithm
- FAR for this alert channel $< 1/\text{yr}$
- Duration: ~ 3.7 days
- **Significance: 5.1σ (pre-trial)**
- Alert issued with delay of 1 day, channel was in test phase

- **MAGIC observations:**

- Delay: ~ 5 days after passing the alert threshold
- Exposure of 2h, with zenith angle 47-52 deg
- Pointed to the **nearest (~ 0.35 deg away) source PMN J035-1843**, a blazar with unknown redshift
- **No detection**, integral flux upper limit: $F_{\text{UL}} (> 250 \text{ GeV}) = 5.16 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$
- Differential flux ULs calculated using the Rolke method at 95% C.L. and assuming a spectral index of 2.5

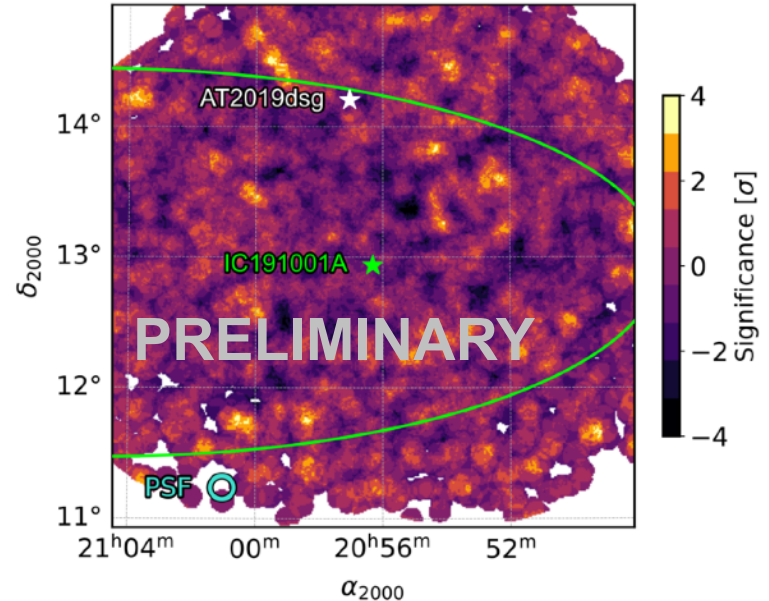


IceCube-191001A - VERITAS observation



- IceCube GOLD neutrino event detected on Oct 1st, 2019 at 20:09 UT (GCN Circular 25913). Large 90% uncertainty region ($\sim 26 \text{ deg}^2$ due to event topology); 59% signalness.
- Neutrino event **potentially associated with tidal disruption event AT2019dsg** (Stein et al. Nat. Ast. 2021). Neutrino detected ~ 175 days after the TDE discovery

- VERITAS took a 1 hr exposure centered at the refined neutrino position as it became visible, ~ 3 hr after the refined position was circulated.
- **No significant excess in the FoV** including the best-fit neutrino position (0.5σ) and the TDE (-0.4σ). Energy threshold: 140 GeV.



Summary

- IACTs are actively involved in IC neutrino follow-up programs:
 - Neutrino multiplets (flares), since 2012 for catalogued sources, since 2019 including all-sky alerts:
 - Goal: determine the changes to the state of the source
 - One source detected (1ES 1323-423, H.E.S.S), but flux at the same level as previously observed
 - Since 2016, single high energy neutrino events with high probability of being astrophysical
 - Goal: find the EM counterpart
 - No other detections since IC-170922A/TXS 0506+056 (MAGIC and VERITAS)
- Observation strategies developed and updated as more channels become available
- Current trends:
 - Fast reaction (typical delay < 1day)
 - Few deep exposures (FACT, H.E.S.S., VERITAS) vs follow-up of as many alerts as possible (MAGIC)
- **Publication with detailed results from Oct 2017 - Dec 2020 coming soon!**
 - Upper limits to integral VHE gamma-ray flux and differential SED ULs, with data from more IACTs combined where possible (also for interesting counterparts)
 - Sky-maps with flux ULs for the entire IC error region for each event
 - Including MWL data if available