



# Recent results from the VERITAS multi-messenger program

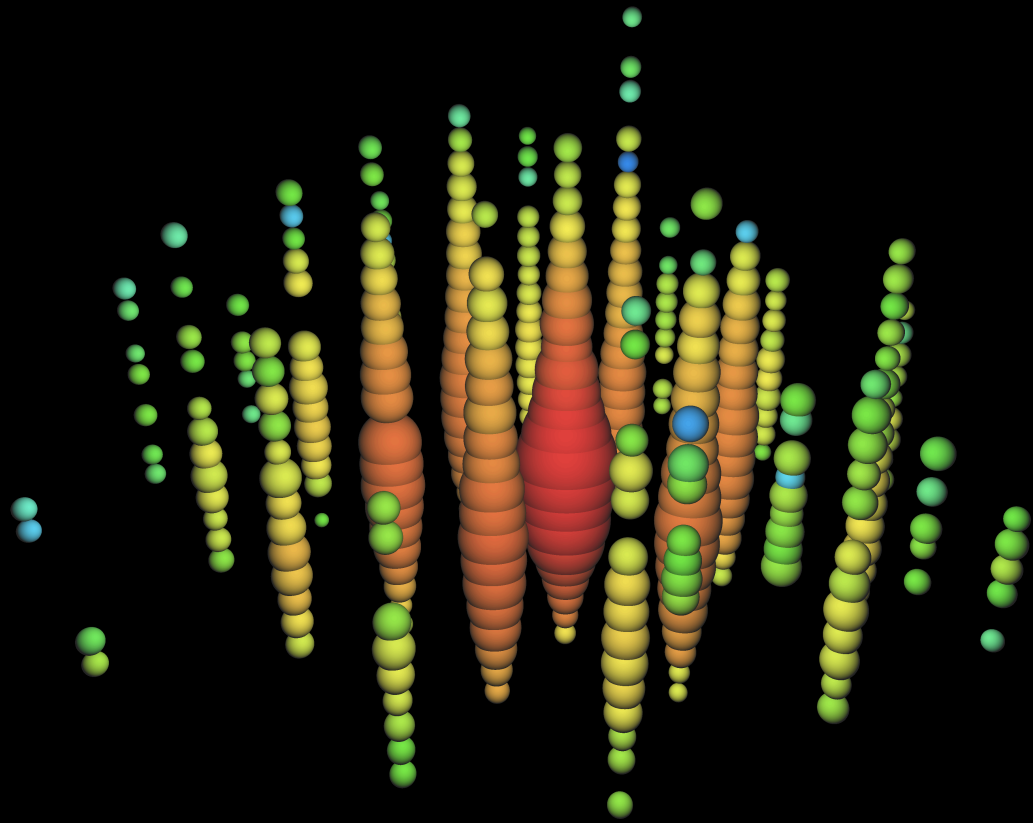
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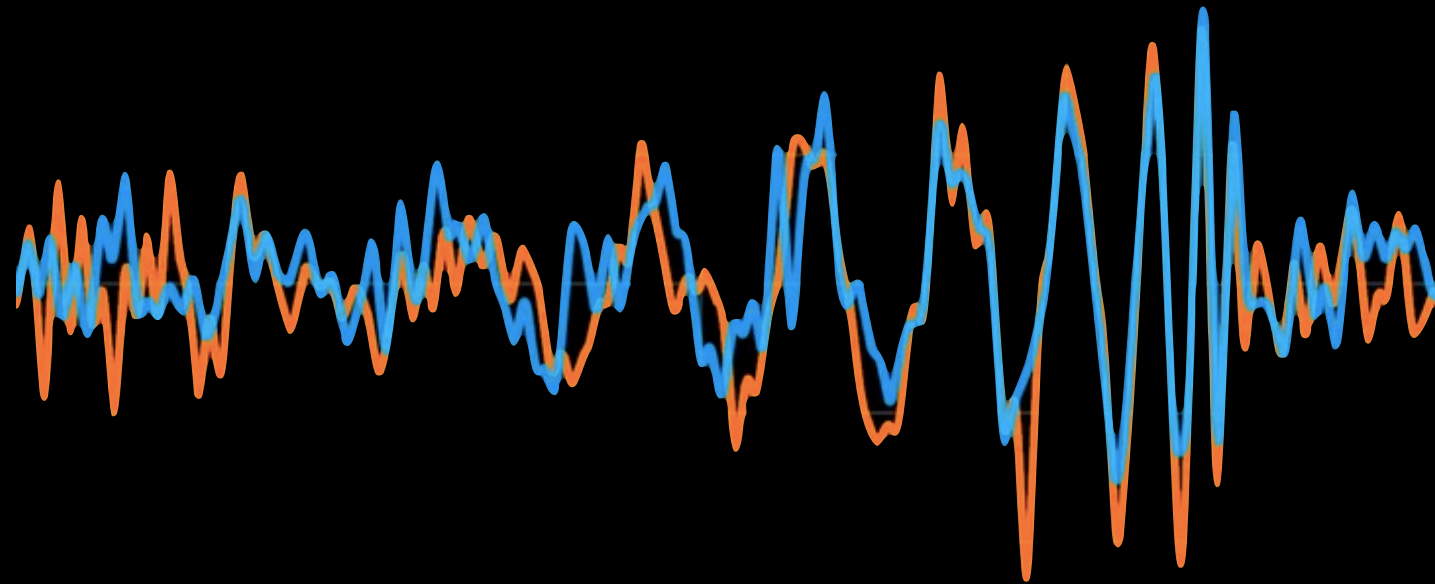
Marcos Santander  
University of Alabama

36th ICRC - Madison, WI (2019)

# New astrophysical messengers

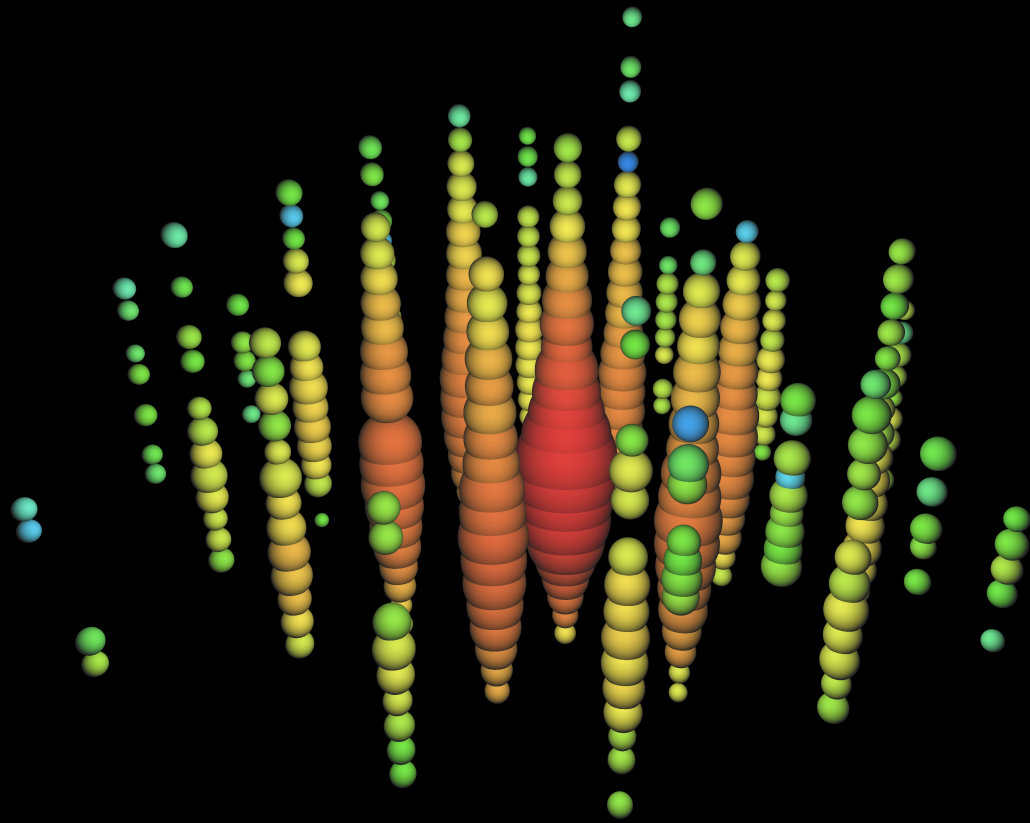


**High-energy neutrinos**

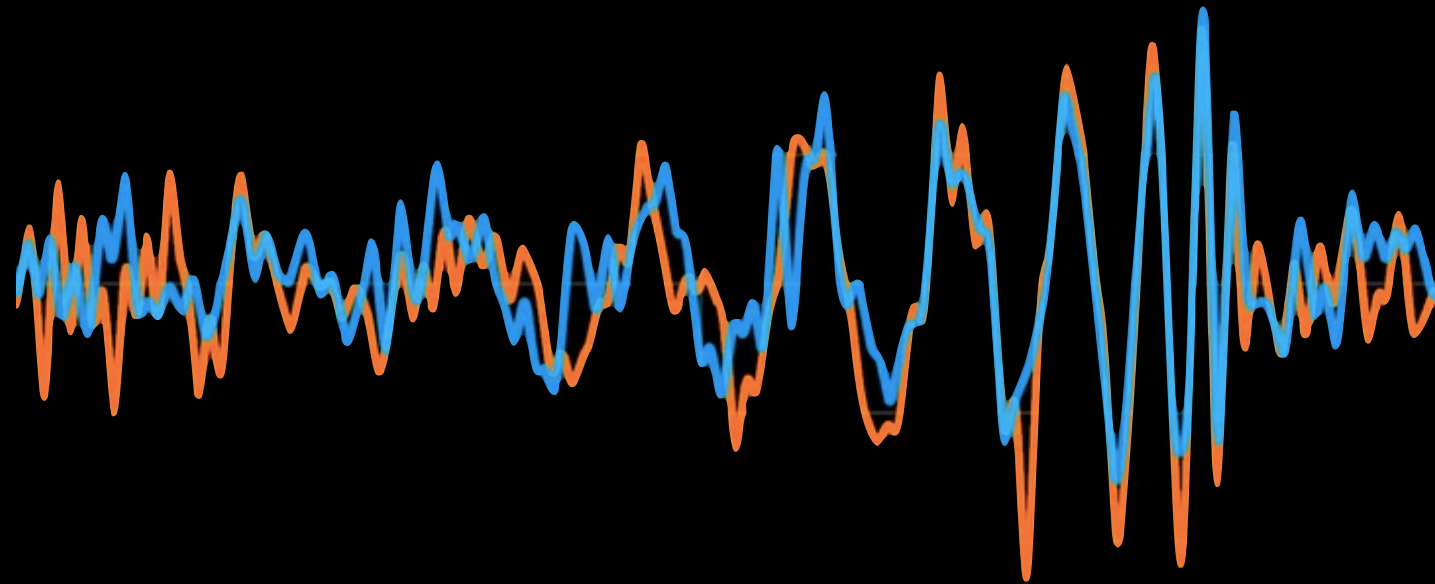


**Gravitational waves**

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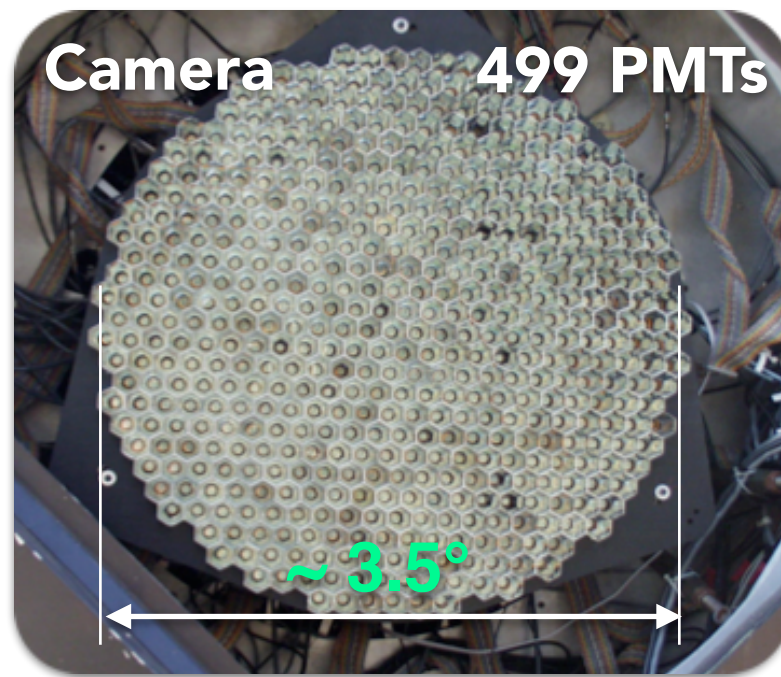
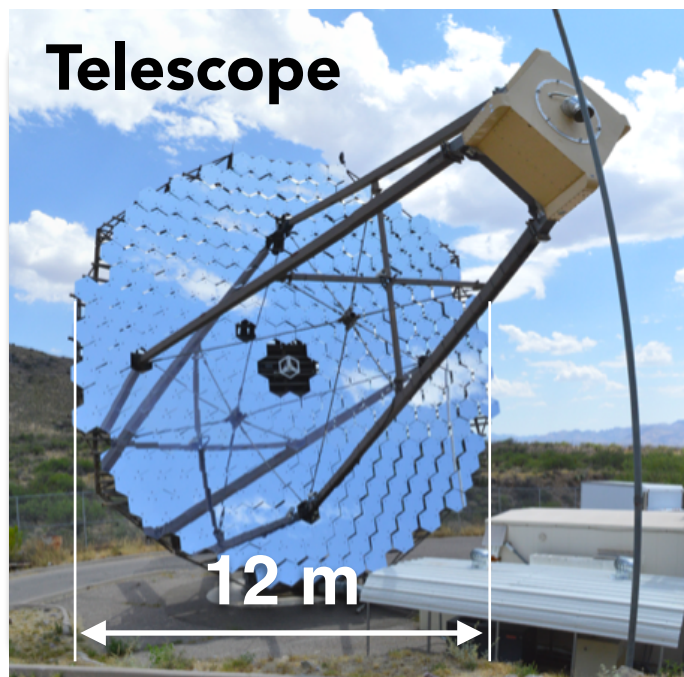


**Gravitational waves**

- The discovery of HE astrophysical neutrinos and gravitational waves opens new windows into extreme events and processes.
- VHE emission potentially associated with the sources of HE neutrinos (hadronic accelerators) and gravitational waves (compact object mergers as GRB progenitors).
- Localization of electromagnetic counterparts.



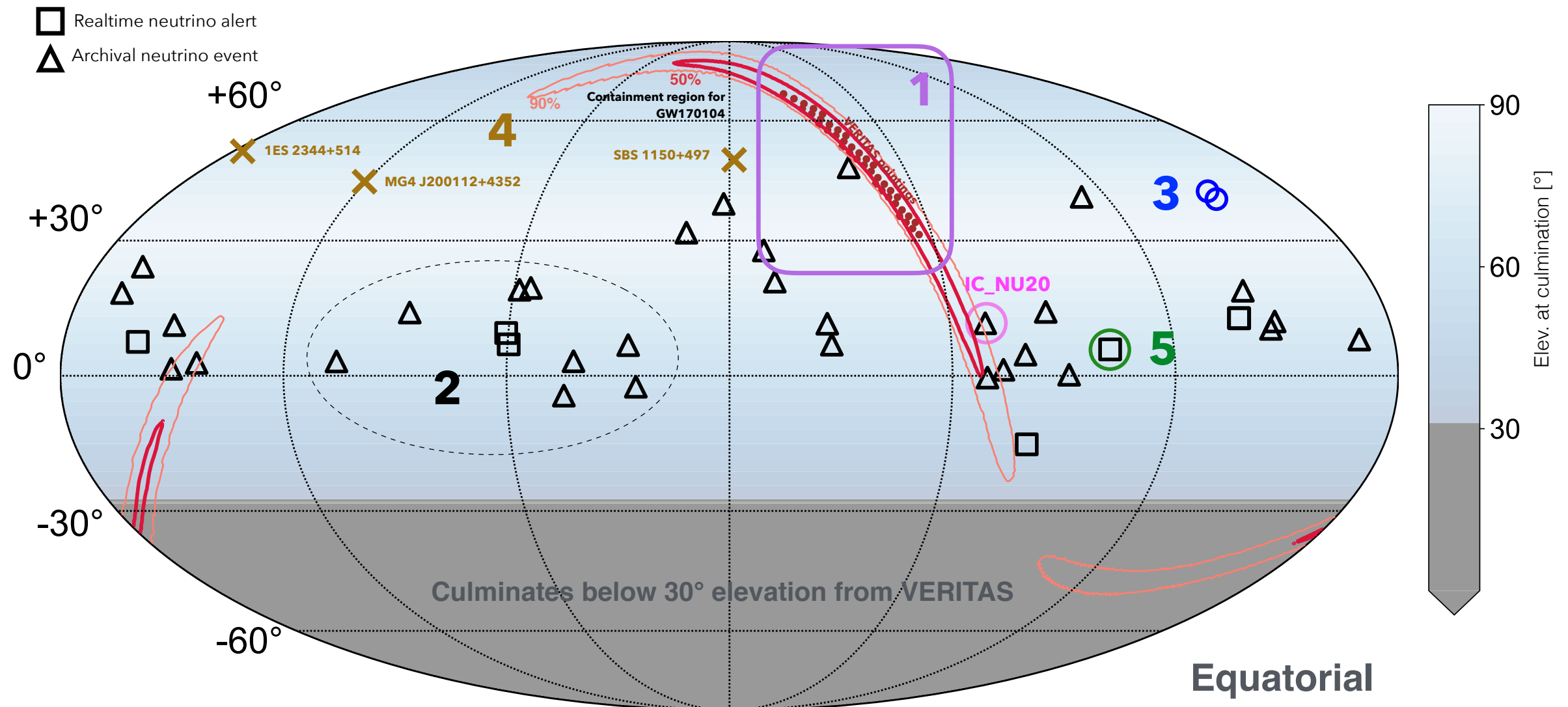
# VERITAS telescopes



- First light in 2007
- *Energy range:* ~ 80 GeV - 30 TeV
- *Obs. time:* ~1300 hrs / year
- *Ang. resolution:* 0.1° resolution @ 1 TeV
- *Sensitivity:*
  - 1 Crab in 2 mins.
  - 1% Crab in 25 hrs.



# Current multimessenger efforts

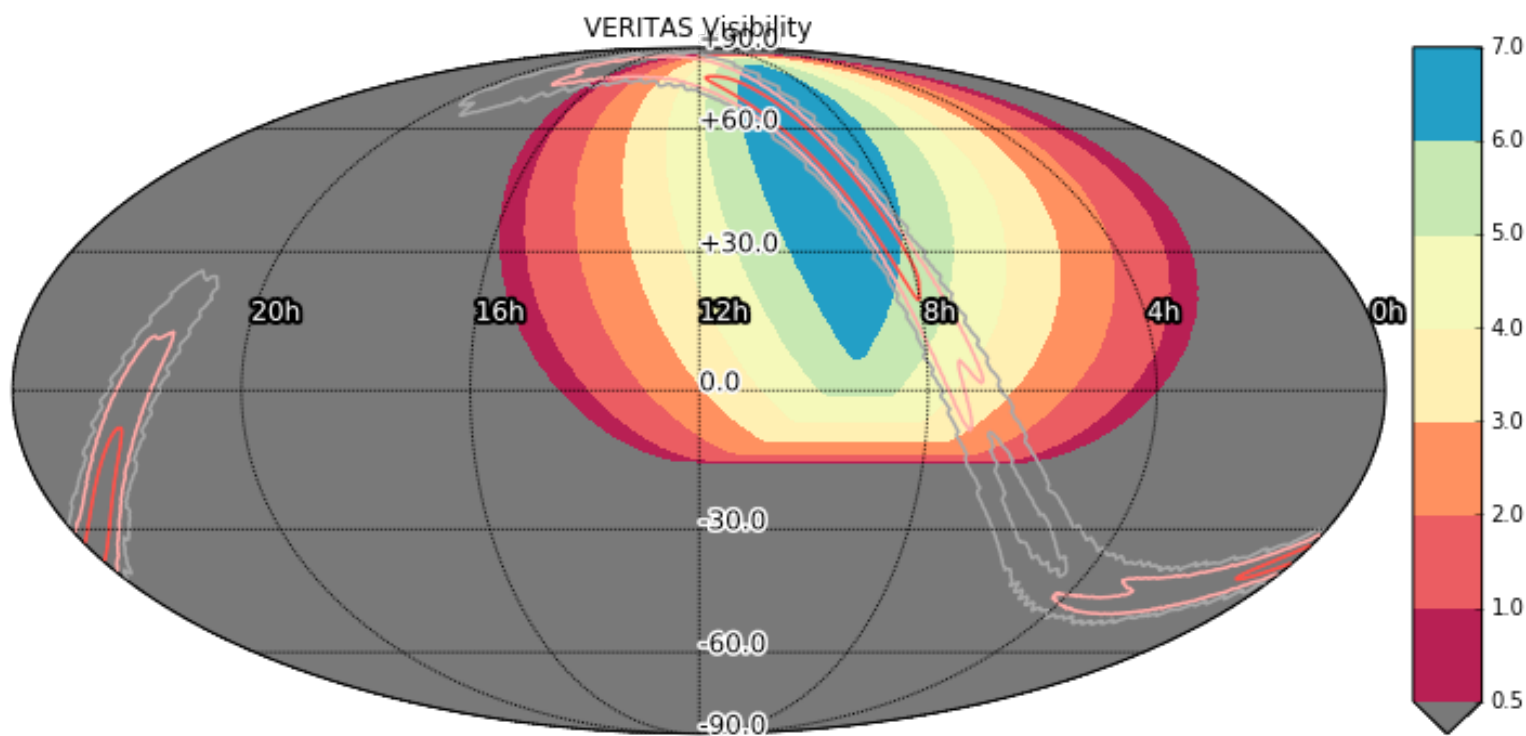


1. Gravitational-wave VHE counterpart searches
2. Realtime and archival neutrino event follow-ups
3. Follow-up of IceCube neutrino event multiplets
4. Follow-up of neutrino clusters near known VHE sources
5. Long-term monitoring of the candidate neutrino blazar TXS 0506+056



# 1) Gravitational-wave follow ups

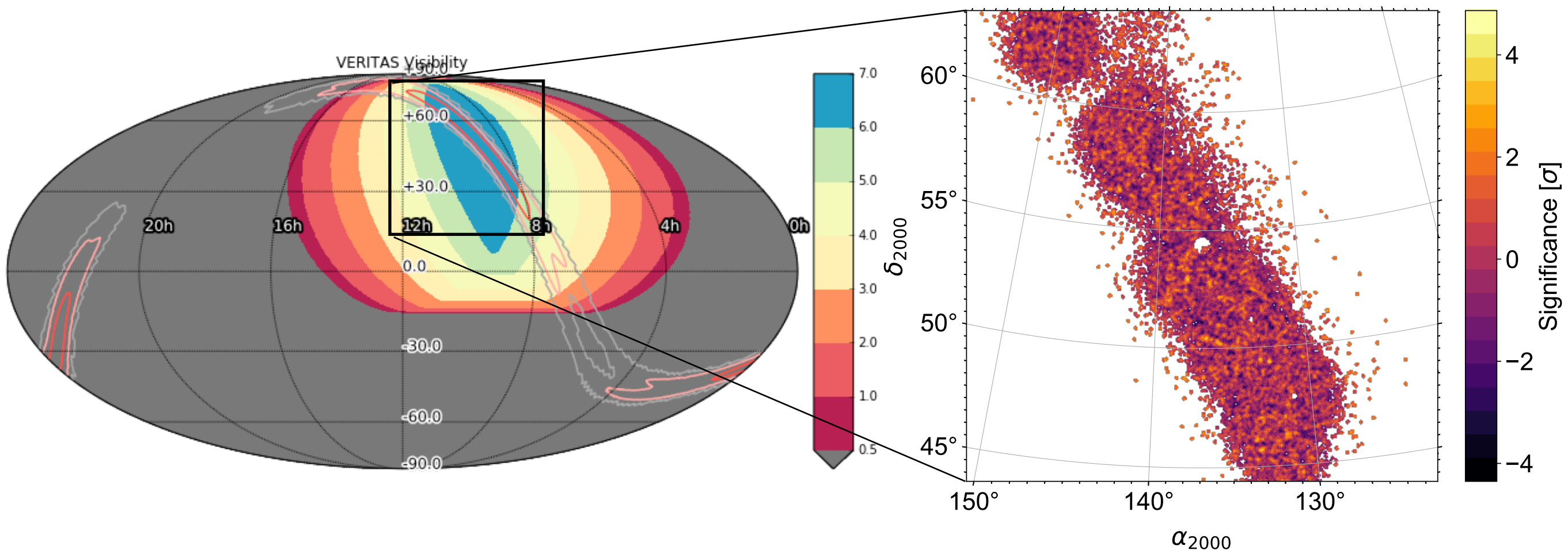
- **GW170104**: 50- $M_{\text{sun}}$  BBH merger at  $z = 0.2$  detected by LIGO during its O2 run.
- Alert was 6.5 hours old when received. Good visibility of the core region of the event.
- About 4.5 hours of data taken, 39 pointings with  $\sim 5$  min / pointing.
- **No detection**. Observations affected by bad weather. Preliminary results circulated as GCN circular #21153





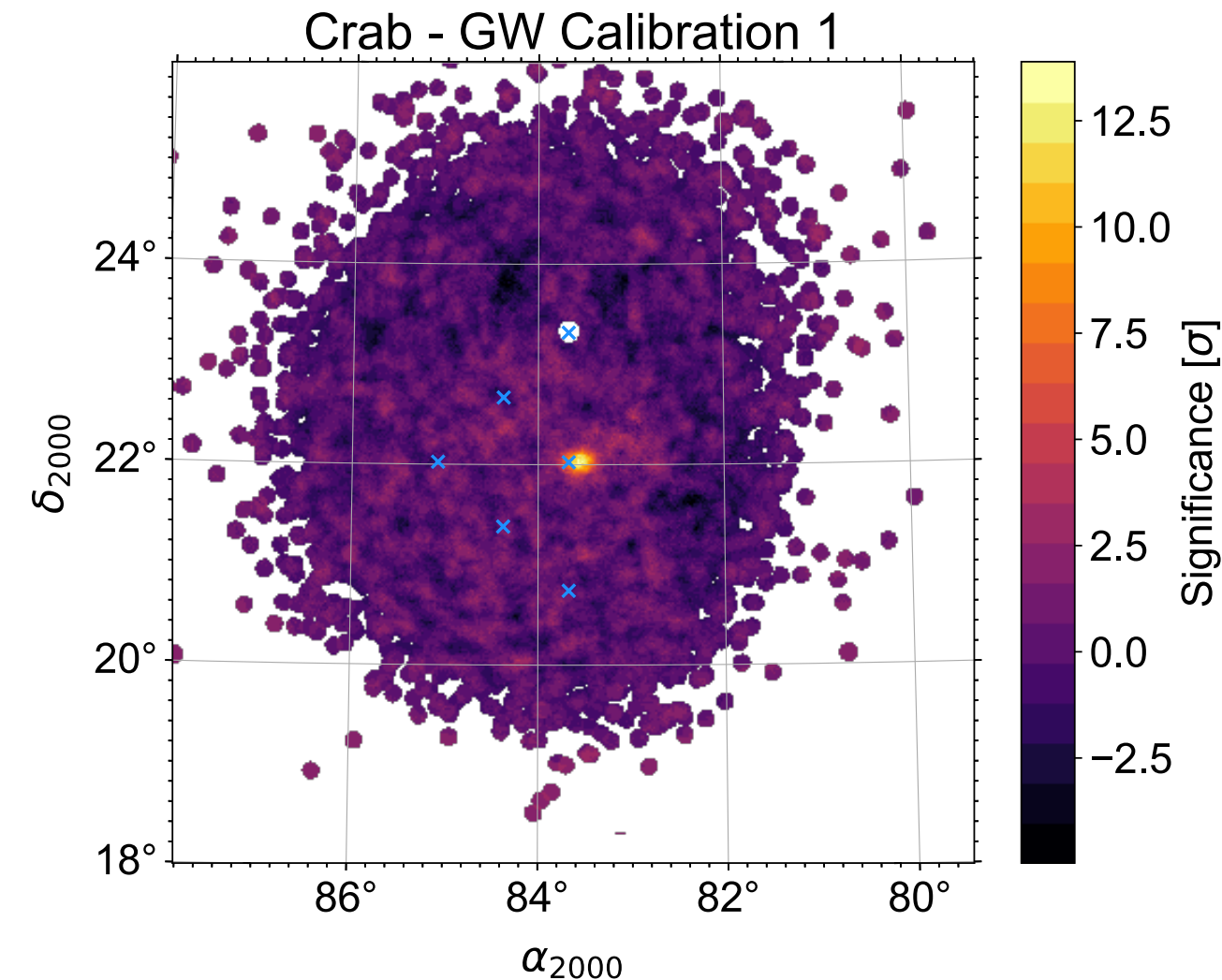
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# 1) Gravitational-wave follow ups



**Strategy validation:** tiling around the Crab nebula. 6 pointings with 5 mins / pointing.

## O3 LIGO/Virgo run:

- Higher GW rate. Notice delay reduced to ~minutes.
- 4 follow-ups out of 18 alerts issued
- Tiling calculated using a Greedy Traveling Salesman algorithm that maximizes probability coverage and minimizes slewing time.

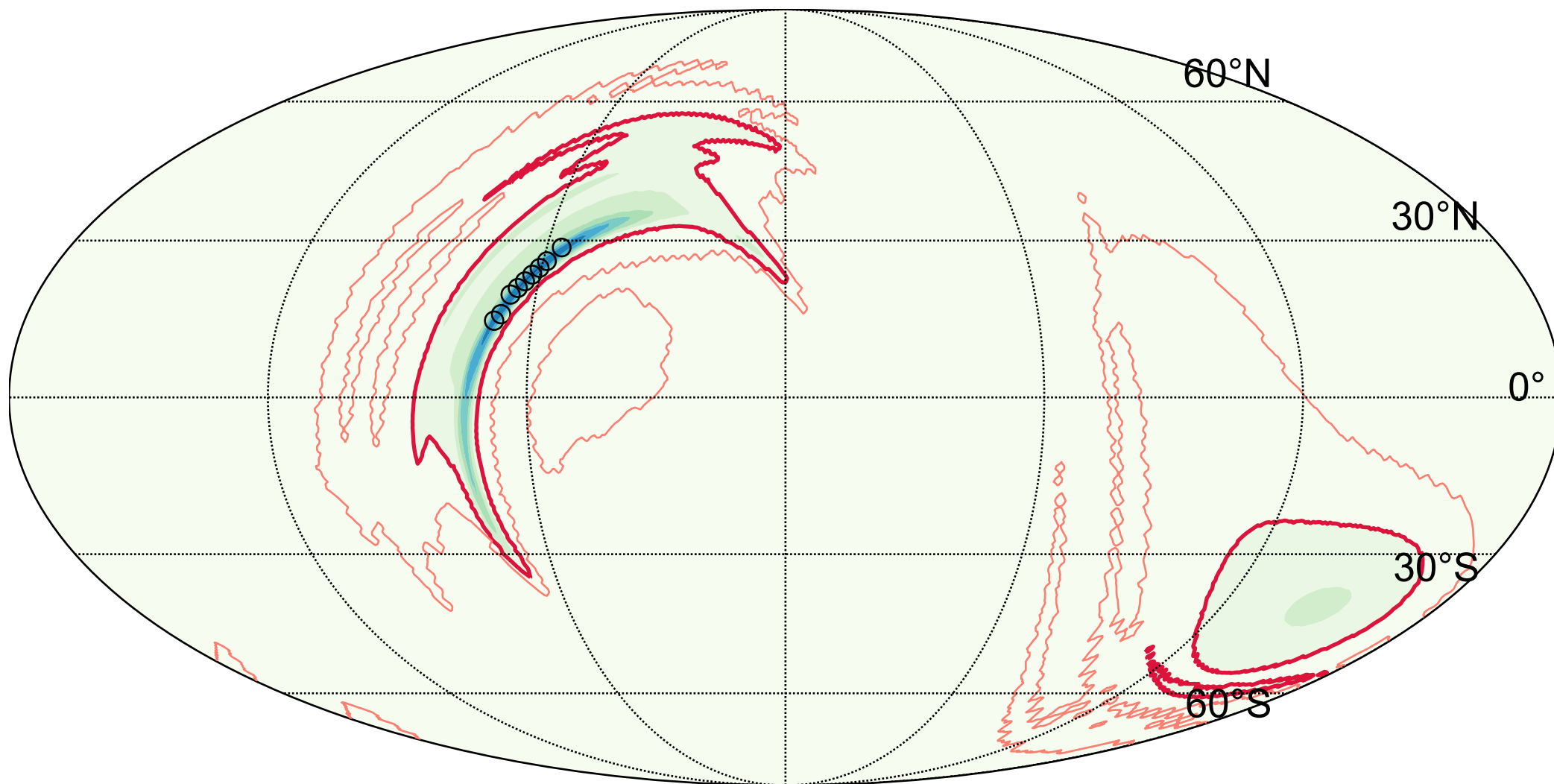
## O3 Follow-up observations

GW ID	Delay [hrs]	Compact binary coalescence type	Prob. covered	VERITAS obs. [hrs]
S190412m	24.1	BBH:> 99%	~ 50%	3.1
S190425z	1.3	BNS:> 99%	~ 2%	0.9
S190426c	17.6	NSBH:60%, MG: 25%, BNS:15%	~ 20%	2.5
S190707q	20.3	BBH:> 99%	~ 30%	3.0



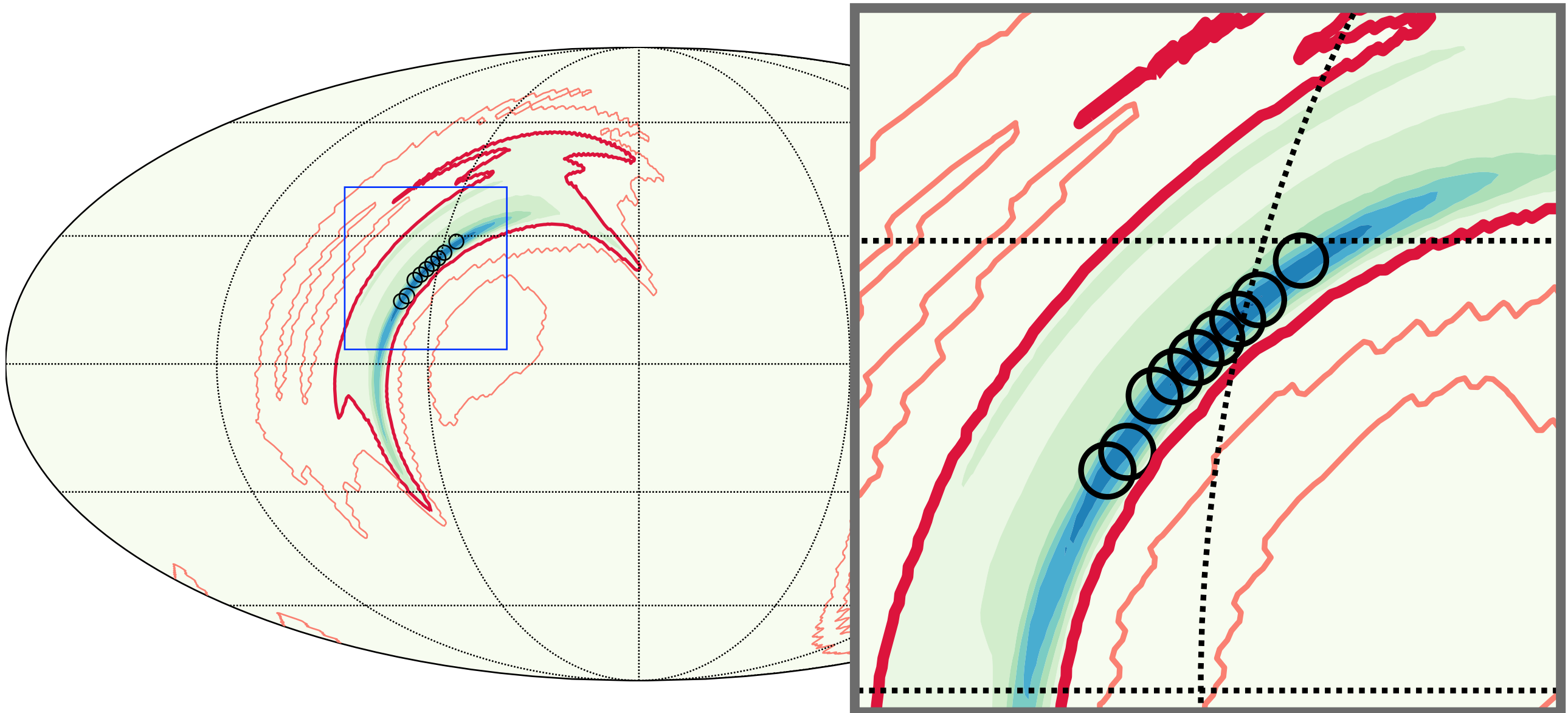
# 1) Gravitational-wave follow ups - S190425z

- Only high-probability BNS merger so far in O3 (>99%). Only Livingston + Virgo.
- First localization region had 50% area with  $\sim 2800 \text{ deg}^2$ .
- First observation started 35 mins after the initial skymap was circulated. 10 x 6 min exposures (reduced high voltage). Analysis ongoing.



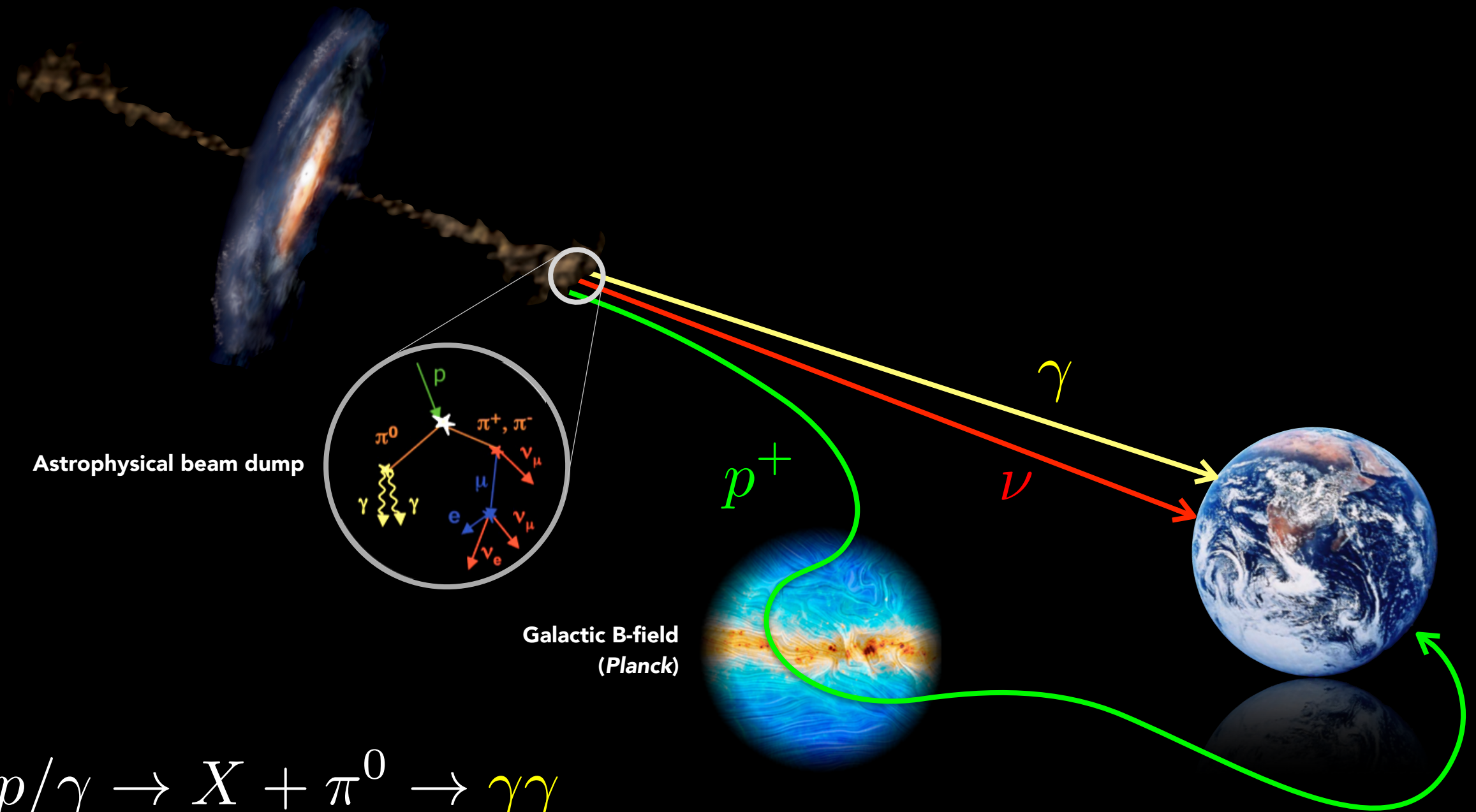
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# Neutrinos and gamma rays



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (\text{oscillates to } \sim 1:1:1)$$

# IceCube follow-up programs

**Goal:** Searching for hadronic VHE emission at the location of single (or clusters of) high-energy muon neutrinos ( $\sim 1^\circ$  ang. resolution).

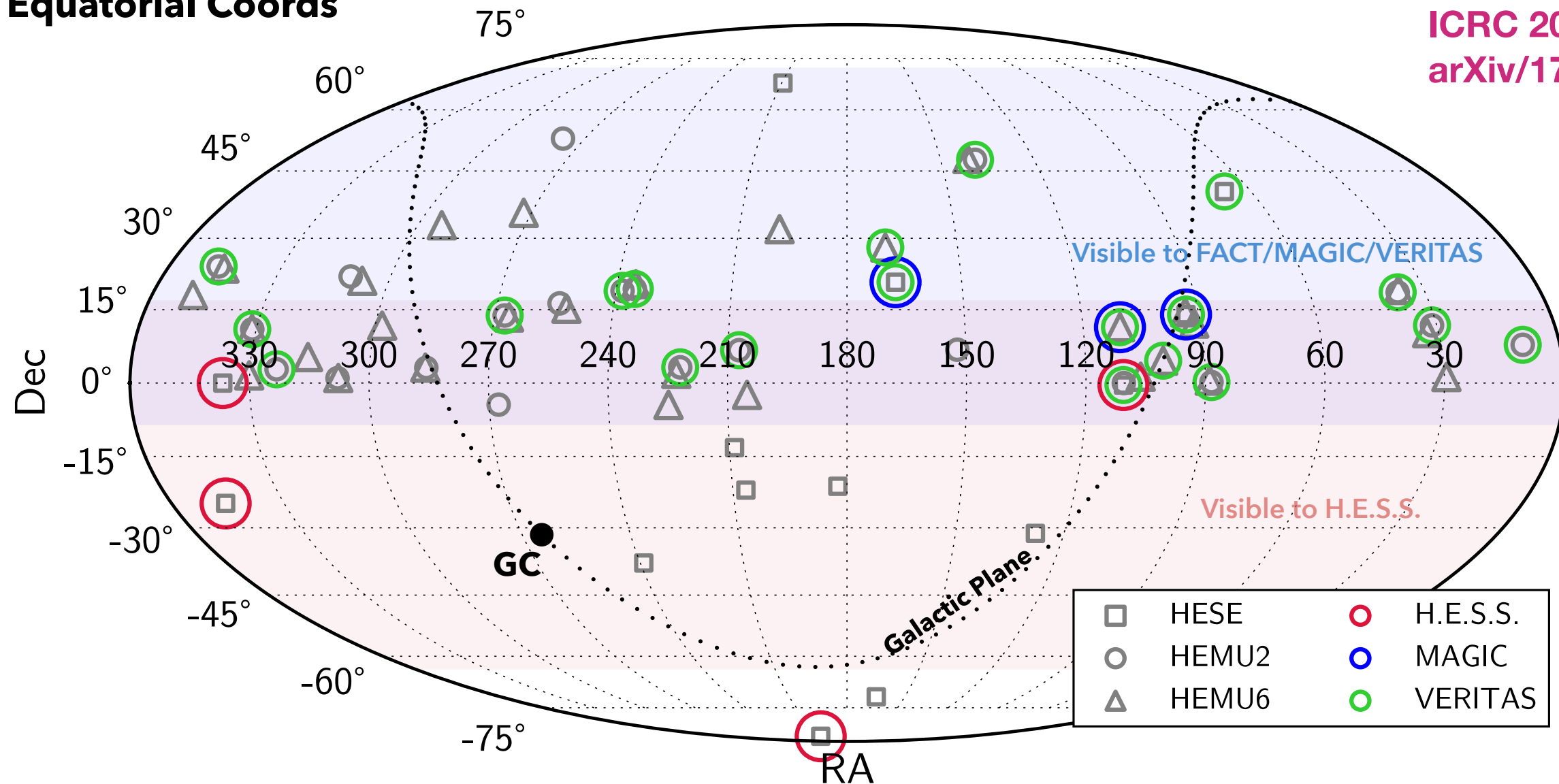
## Variety of follow-up approaches:

- 
- The diagram illustrates various follow-up approaches for IceCube, categorized by time scale and follow-up latency. On the left, three orange curly braces group the approaches by time scale: 'months-years' for archival searches and correlation studies, 'days/weeks' for neutrino flares and multiplets, and 'seconds/minutes' for prompt alerts. On the right, a vertical pink arrow points upwards, labeled 'Follow-up latency', indicating that the latency decreases as the time scale for observation becomes shorter.
- Searches for VHE emission at “archival” muon neutrino positions that are likely astrophysical ( $E_\nu \gtrsim 100$  TeV)
  - Correlation studies of neutrino and gamma-ray emission from VHE sources.
  - Observation of neutrino “flares” from known VHE sources.
  - Observation of neutrino multiplets.
  - Observation of prompt online HESE alerts.
  - Observation of prompt EHE alerts.



## 2) “Archival” IceCube neutrino events

Equatorial Coords

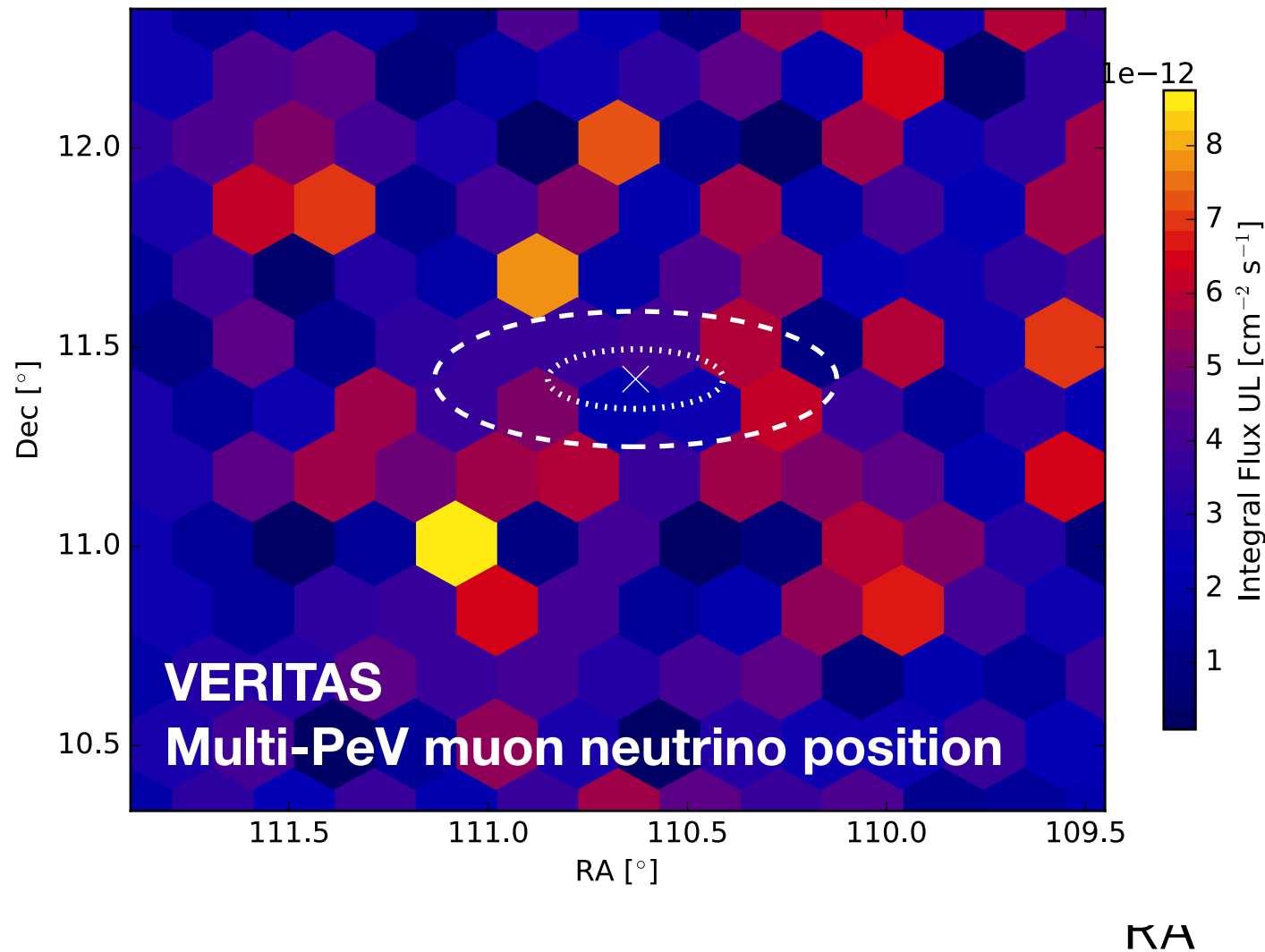


- Selection of high-energy neutrino events from IceCube publications + shared through MoU that are potentially astrophysical ( $p_{\text{astro}} > 50\%$ ) and have good localizations ( $\sim 1^\circ$ ).
- **~40 hours of VERITAS** exposure so far. Publication plans being discussed with other IACTs.

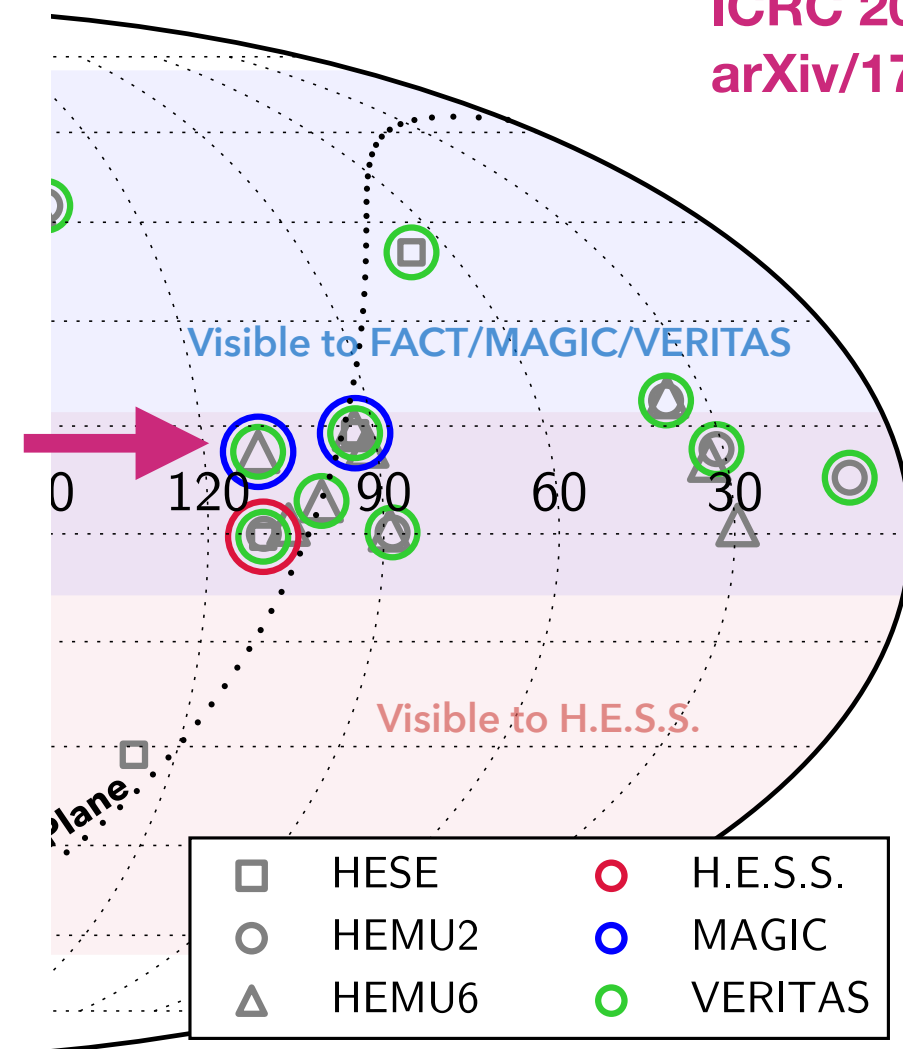
**No VHE gamma-ray excess found in the region of interest of the archival neutrino events**

## 2) “Archival” IceCube neutrino events

Integral flux upper limit map for event #27 in ApJ 833, 2016, 3



ICRC 2017 Proc  
arXiv/1708.08945



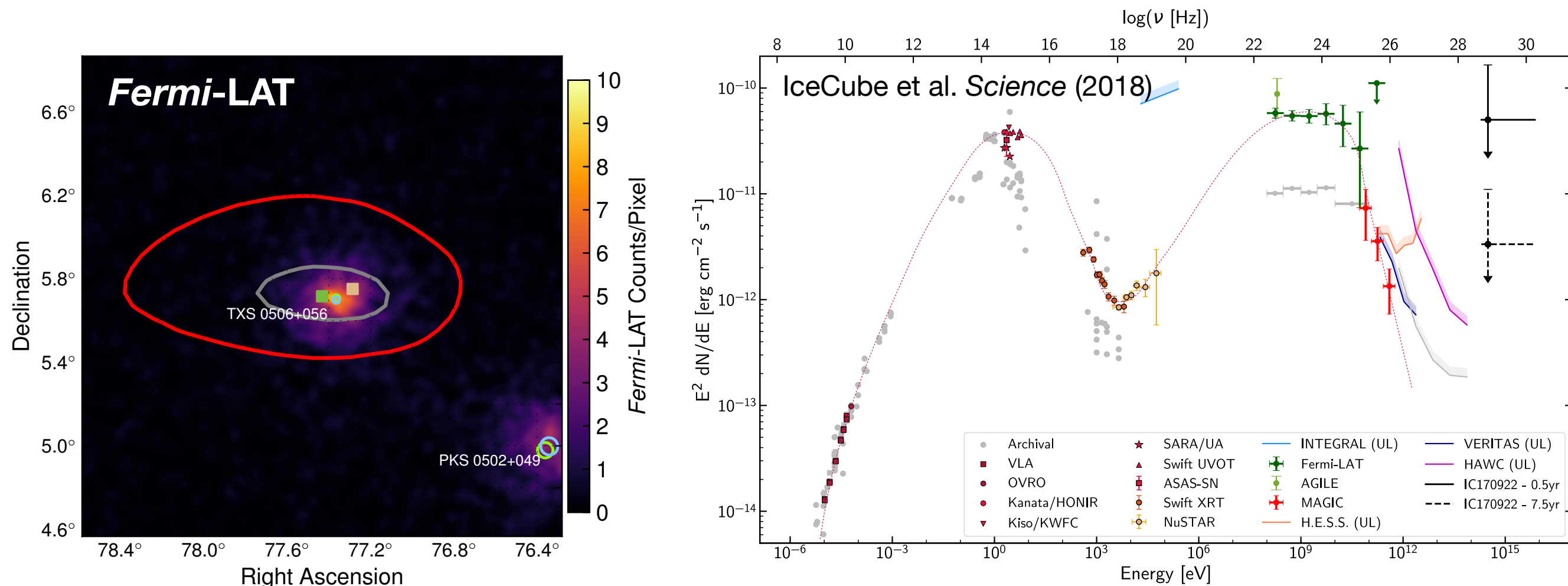
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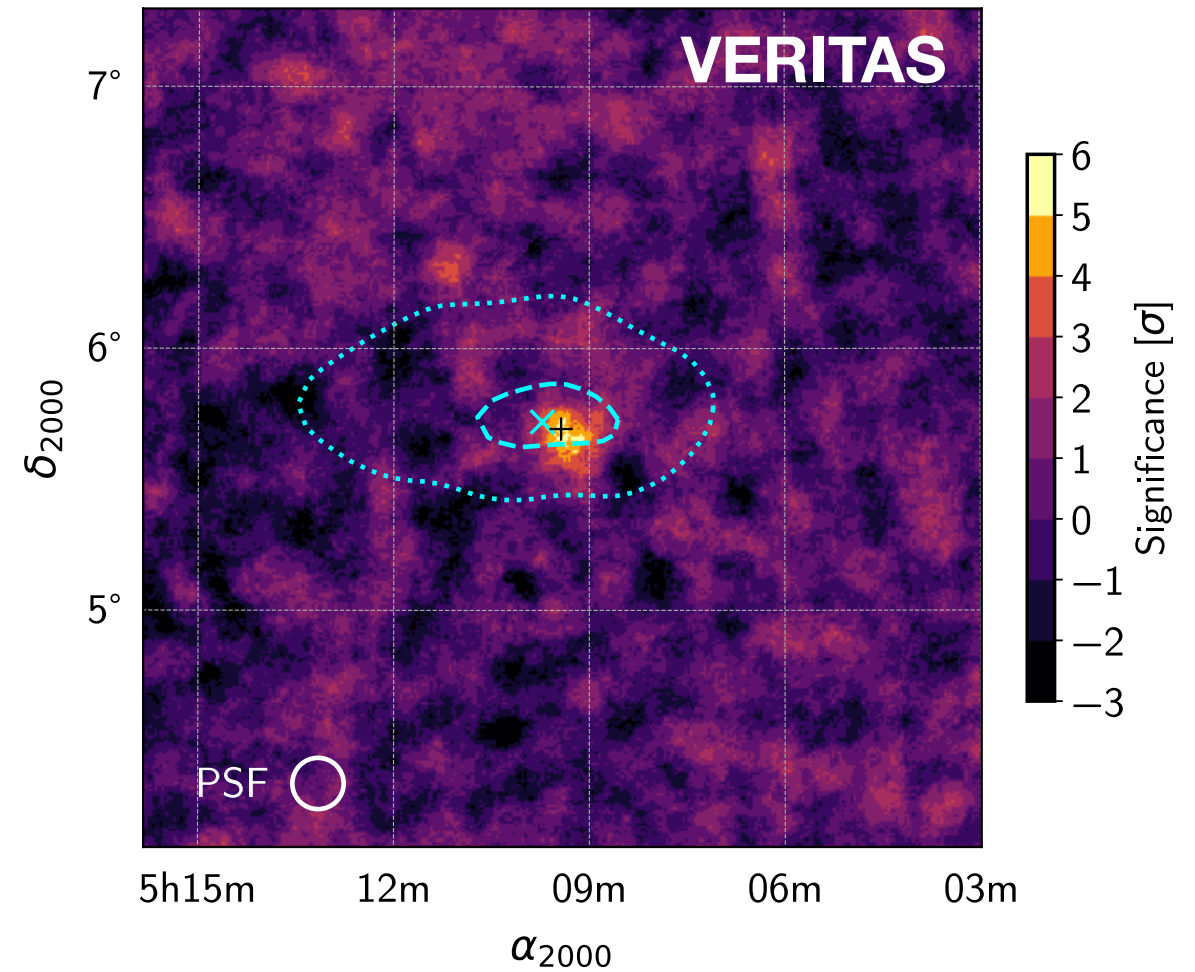
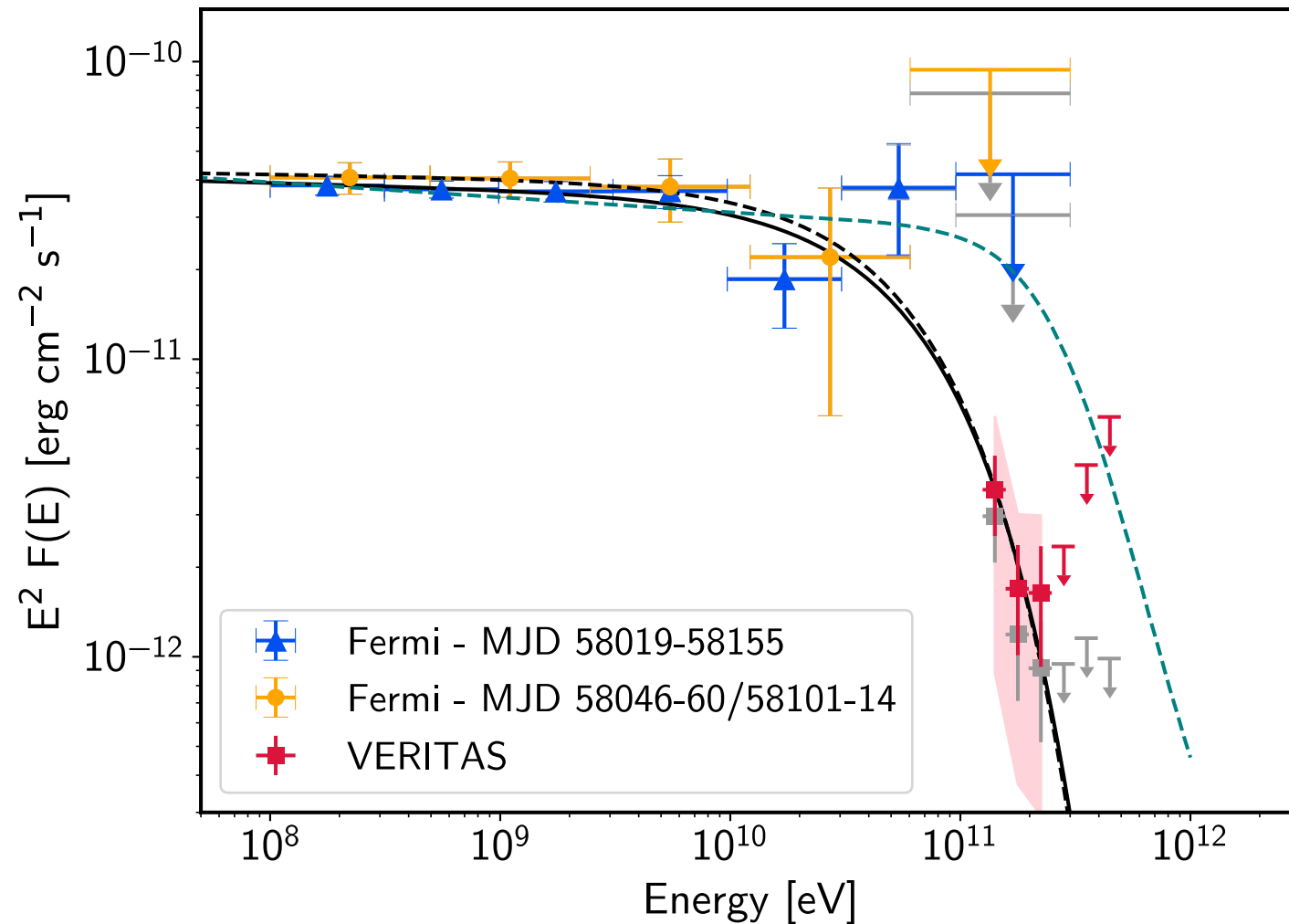
## 2) Realtime IceCube neutrino alerts

- Started in 2016 by IceCube. Fully-automated in VERITAS. First follow-up in April 2016, **112s delay** between detection and the South Pole and start of on-target observations by VERITAS.
- Five alerts follow-ups to date. Most important has been IC170922A.
  - Fermi*-LAT detection of flaring from TXS 0506+056. VHE detection by MAGIC.
  - No VERITAS detection in first two weeks after IC170922A.



# VERITAS detection of TXS 0506+056

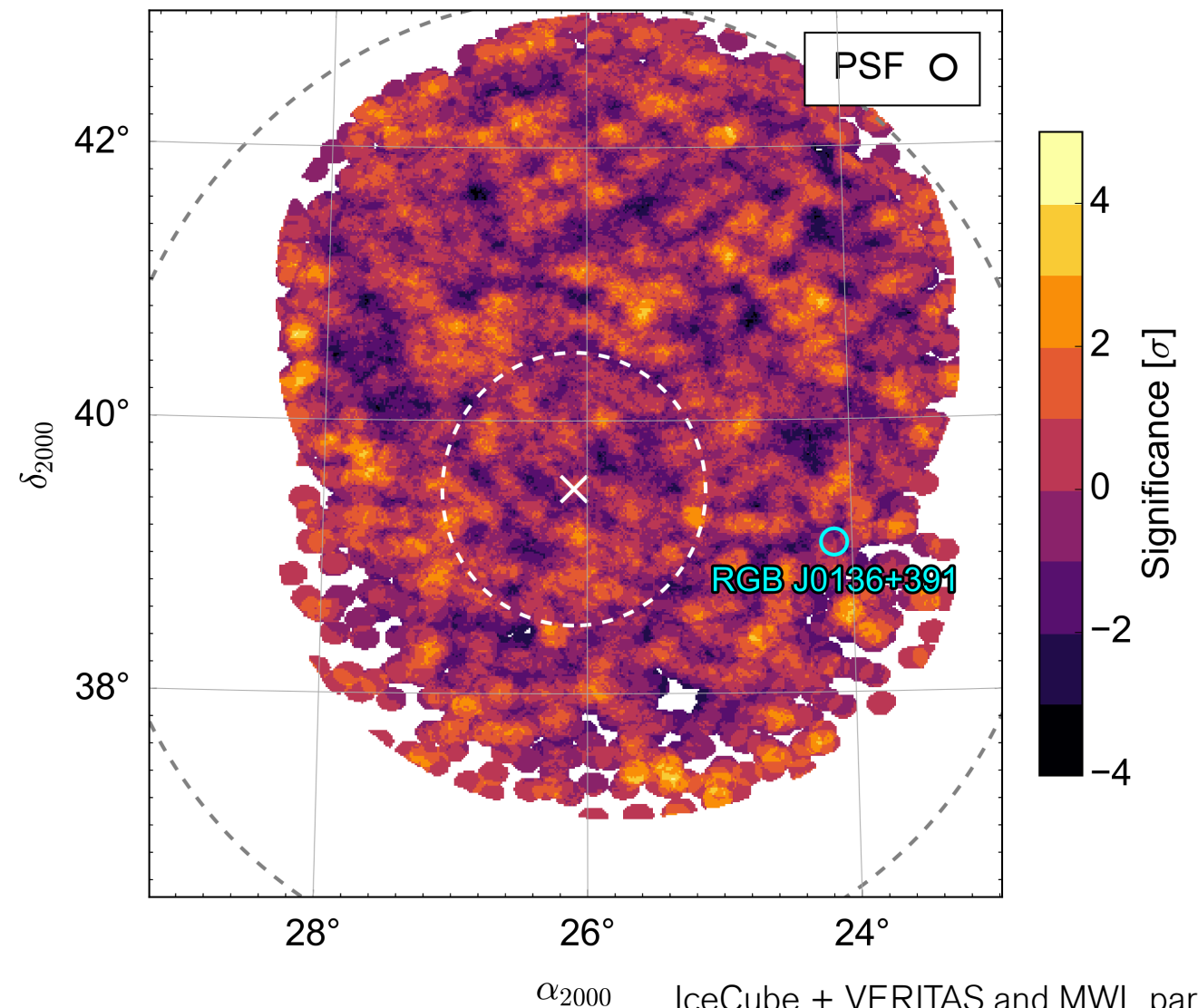
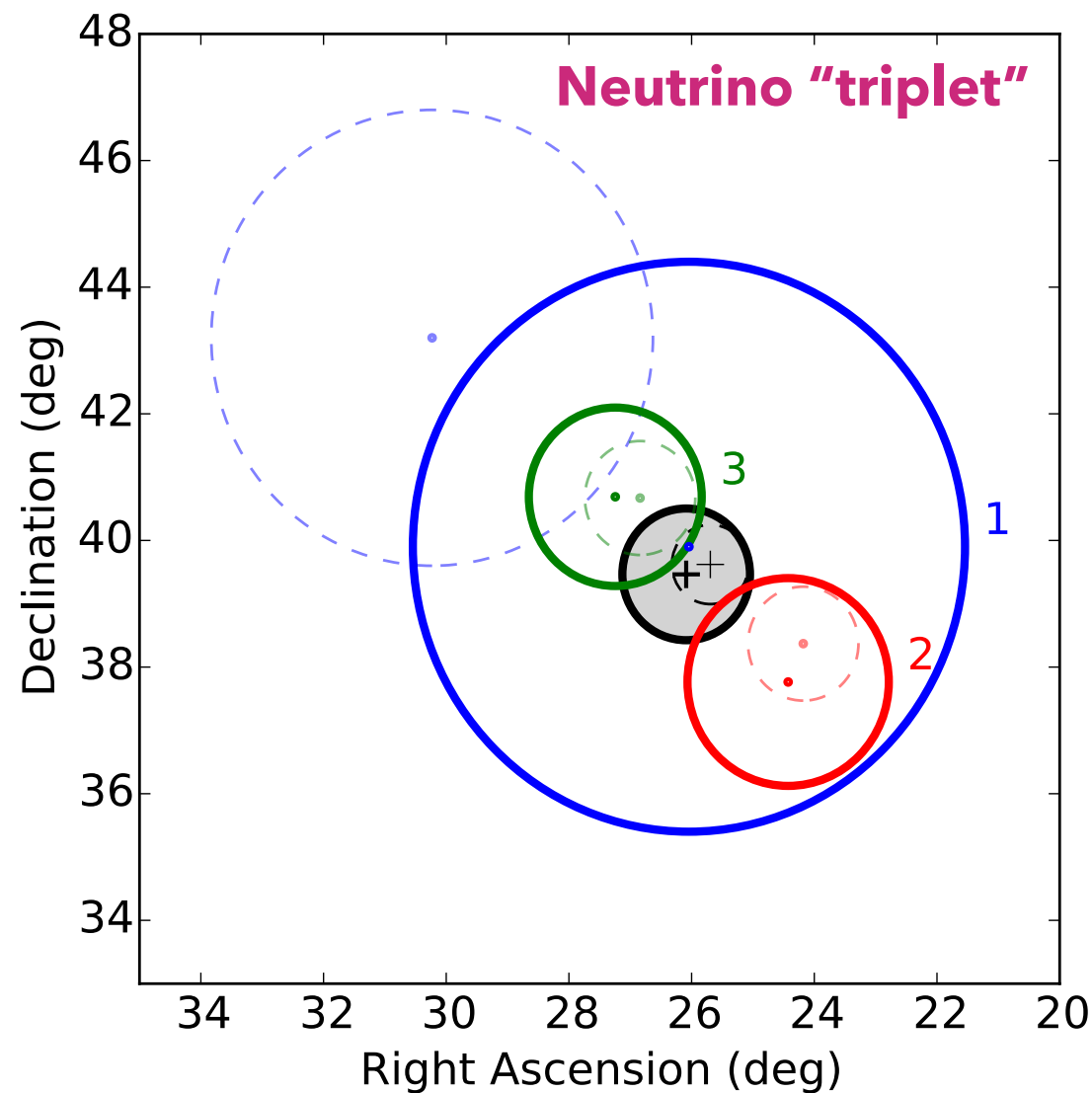
Abeysekara et al. (VERITAS) *ApJL*, 2018



- VERITAS detected the blazar in 35 hours of observation ( $5.8\sigma$ ) between Sept 2017 and Feb 2018.
- Very soft spectrum. Best fit power-law fit in the 110-300 GeV yields  $\Gamma = 4.8 \pm 1.3$ . ( $\Gamma_{\text{MAGIC}} = 3.9 \pm 0.4$ )
- Integral flux above 110 GeV is  $\sim 60\%$  of that reported by MAGIC in first detection.
- Continued monitoring of the source over the next years to characterize variability and low-state spectrum.



### 3) Search for neutrino “burst” counterparts

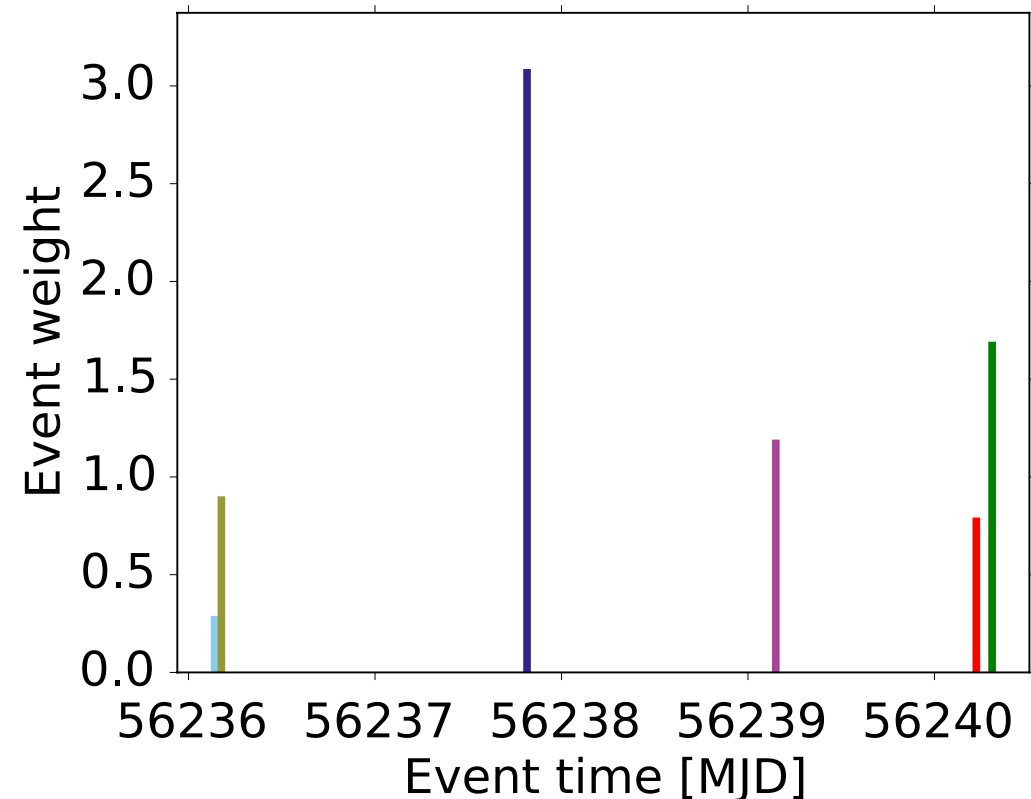
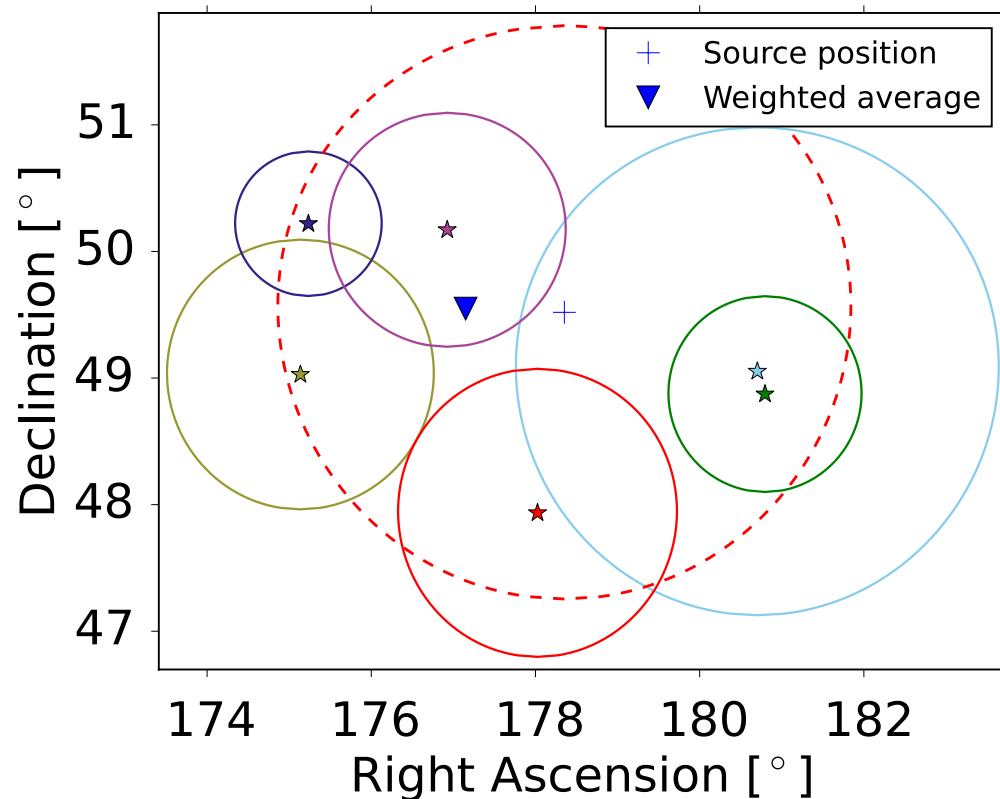


$\alpha_{2000}$  IceCube + VERITAS and MWL partners.  
**A&A** 607, A115 (2017)

- Two or more neutrinos in spatial coincidence within 100 s.
- Most significant: event triplet detected in Feb 17, 2016.
- No counterpart detection in VERITAS observations on Feb 25 & 26 (63 min exposure).
- No activity from the known VHE blazar RGB J0136+391.

## 4) Search for a time-dependent neutrino emission from known VHE sources

- Neutrino candidates are identified around a predefined list of gamma-ray sources. Number, energy, and position of the events are considered and an alert is sent by IceCube once a trigger condition is satisfied.



- Four alerts followed-up to date with VERITAS (2016 JInst 11 P11009 (IceCube, MAGIC, VERITAS))
- Gamma-ray sources list has been recently updated to include newer catalogs (*Fermi* 3FHL, 4FGL) and optimize for sky regions with maximal IceCube sensitivity.



# Conclusions

- **Active multimessenger program involving GW and neutrino follow-up studies with VERITAS**
- **Close connection with other programs within VERITAS (in particular GRBs and blazars).**
- **Continued observations over the next three years.**