

# *Multi-messenger observations of the high-energy transient sky*



# Transient astrophysical sources @ high-energies

Flaring stars

CVs / Novae

Supernovae

Gamma-ray Bursts

Gravitational Waves

Gamma-ray Binaries

Microquasars

Unknowns

Neutrinos

Active Galactic nuclei

Tidal Disruption Events

Fast Radio Bursts

Soft Gamma-ray Repeaters

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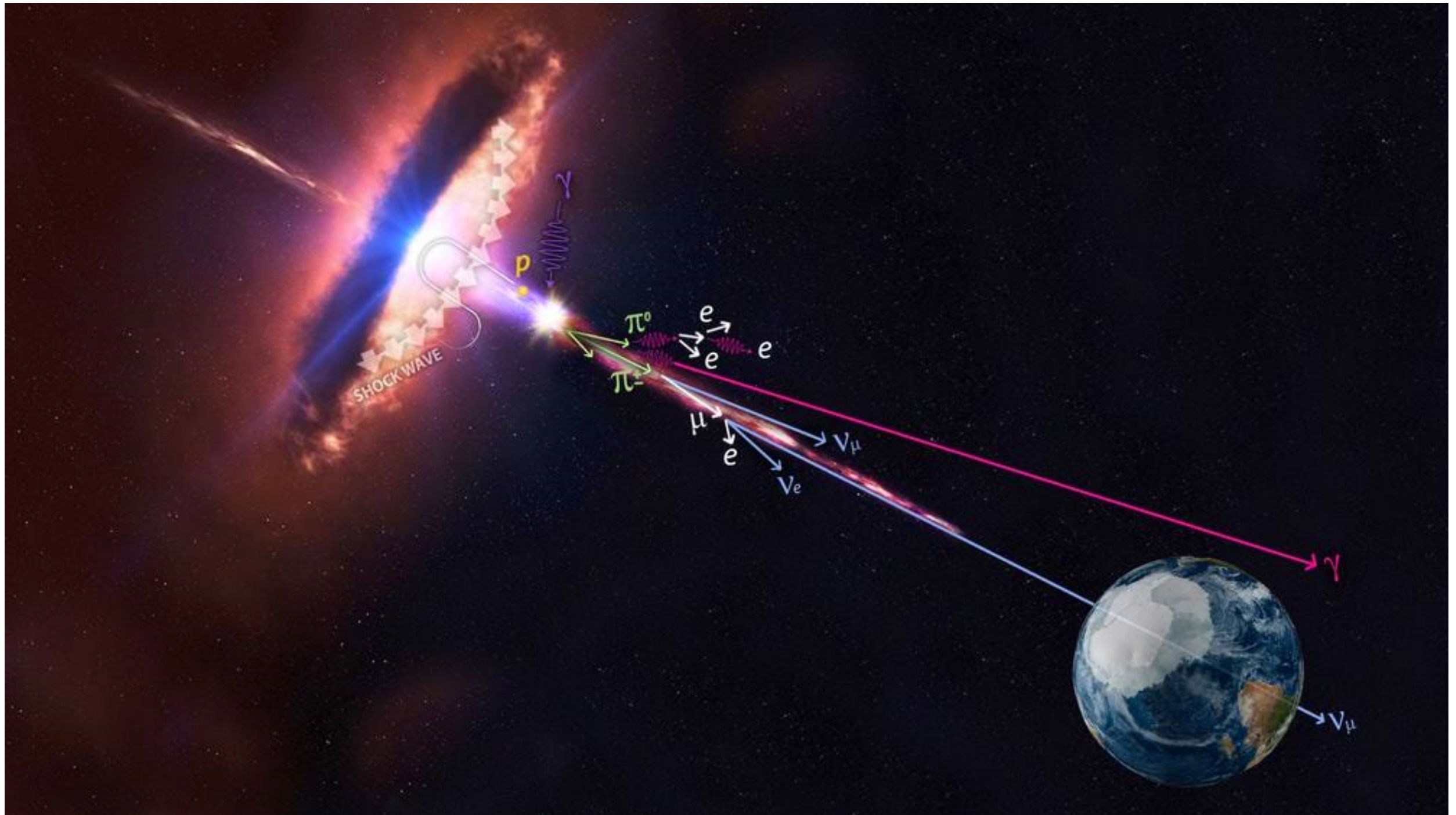
Tidal Disruption Events

Fast Radio Bursts

Soft Gamma-ray Repeaters

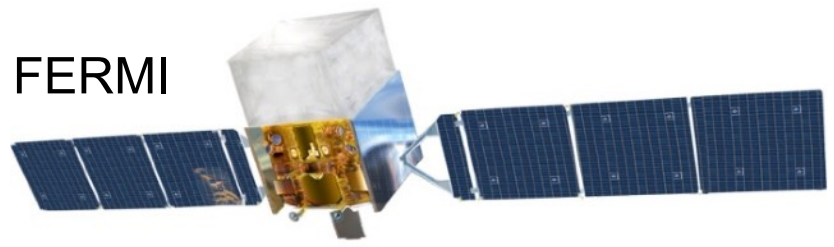
# Multi-messenger astrophysics in a nutshell

- **Space (and time !!) correlations** would provide "smoking gun" signal for joint emission processes => CR interaction/acceleration

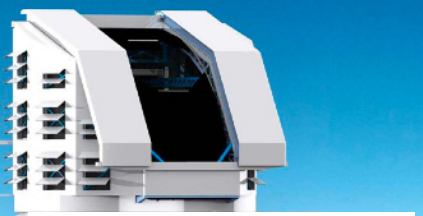




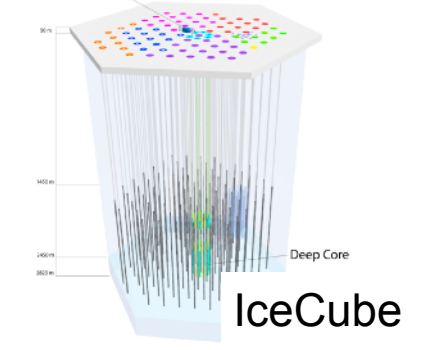
# Monitoring vs follow-up observatories



HAWC



LSST / Vera Rubin



IceCube



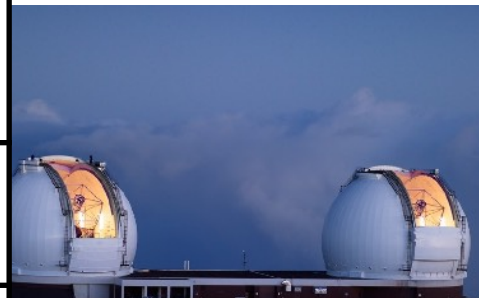
CHIME



ASKAP



H.E.S.S.



Keck



VLA

	Large FoV	Small FoV
Monitoring (+ duty cycle)	✓	✗
Sensitivity	✗	✓
Resolution	✗	✓
Energy threshold	High	Low



# Neutrino telescopes: monitoring the neutrino sky

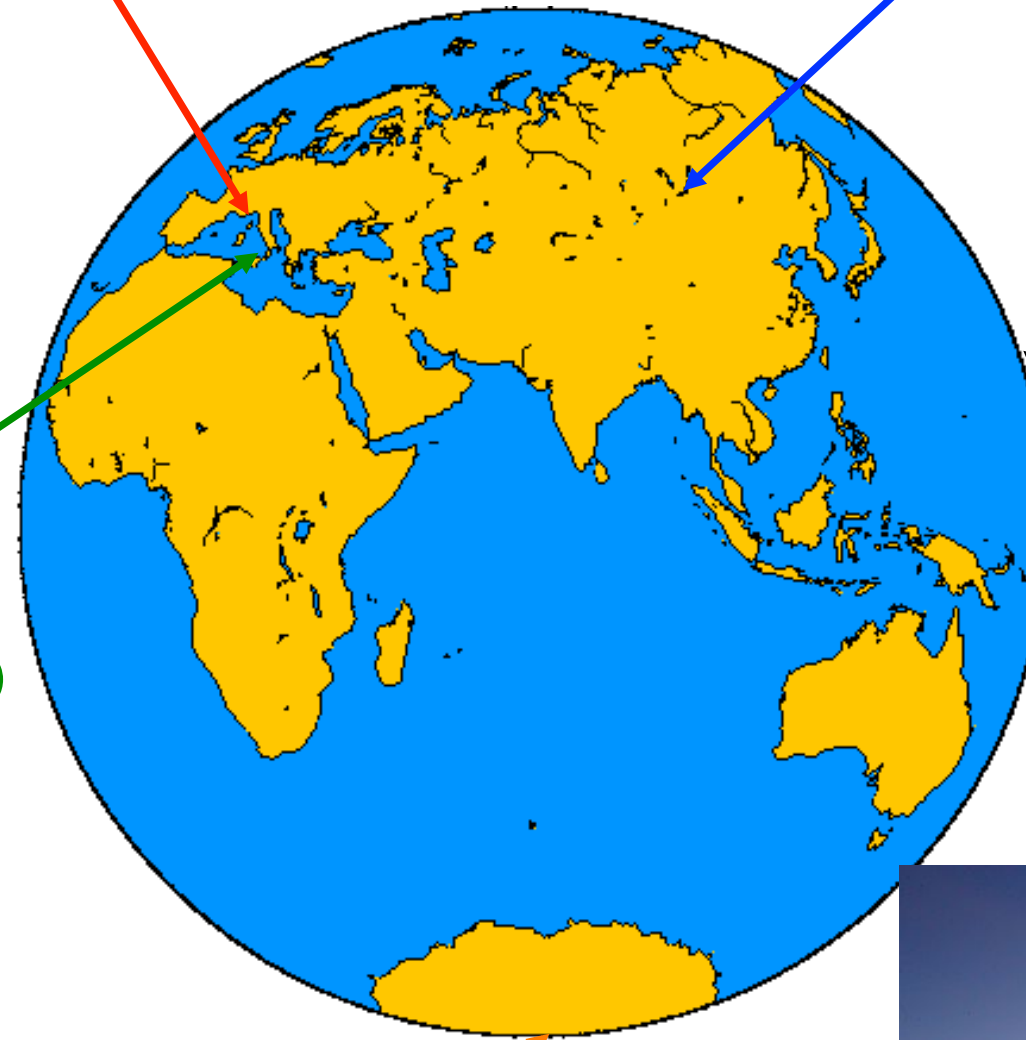
**ANTARES:** La-Seyne-sur-Mer, France

**BAIKAL:** Lake Baikal, Siberia



**KM3NeT** (Catania, Italy)

DUMAND, Hawaii  
(cancelled 1995)



**AMANDA/IceCube:** Antarctica



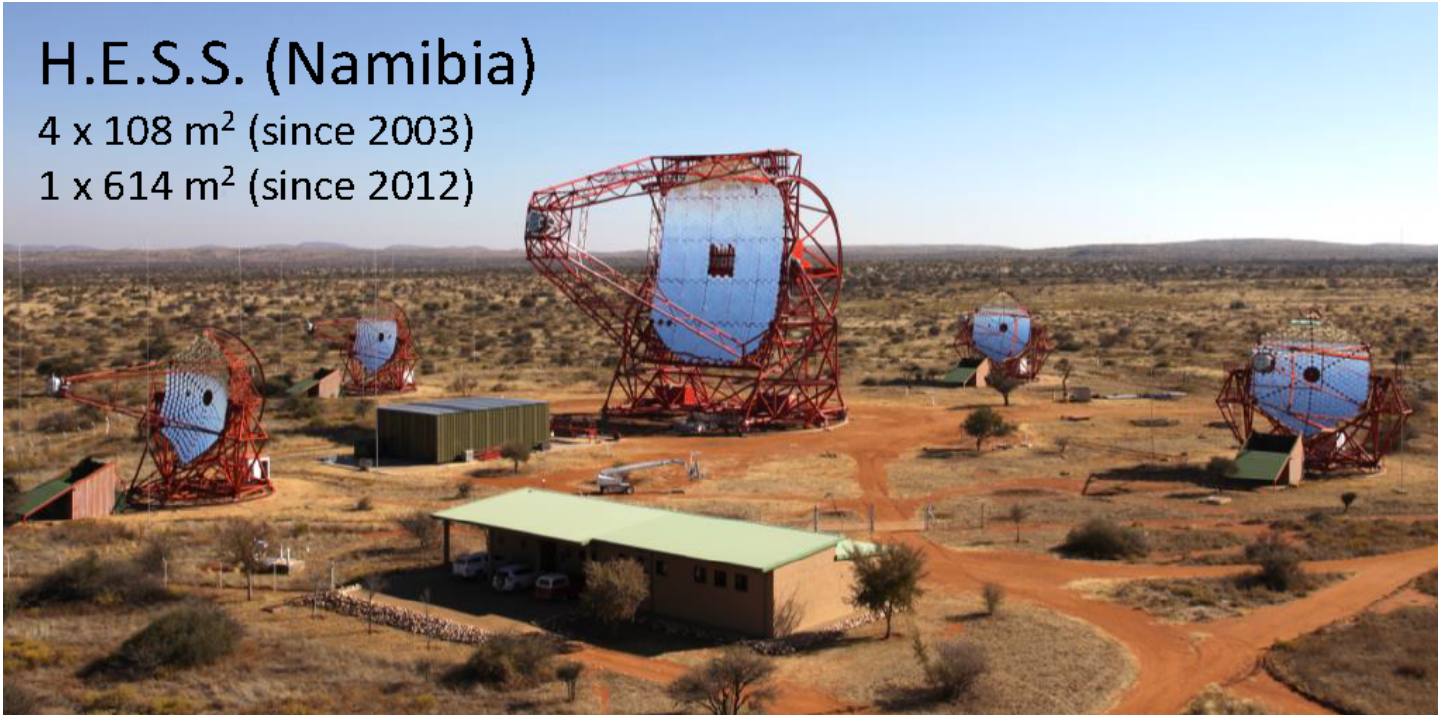


# IACTs: high resolution follow-up observatories

## H.E.S.S. (Namibia)

4 x 108 m<sup>2</sup> (since 2003)

1 x 614 m<sup>2</sup> (since 2012)



## MAGIC (La Palma)

2 x 236 m<sup>2</sup> (since 2003 / 2009)



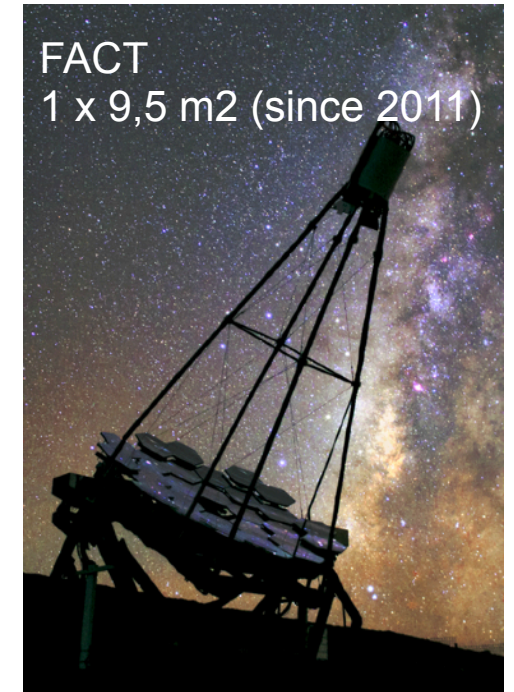
## VERITAS (Arizona)

4 x 110 m<sup>2</sup> (since 2007)



## FACT

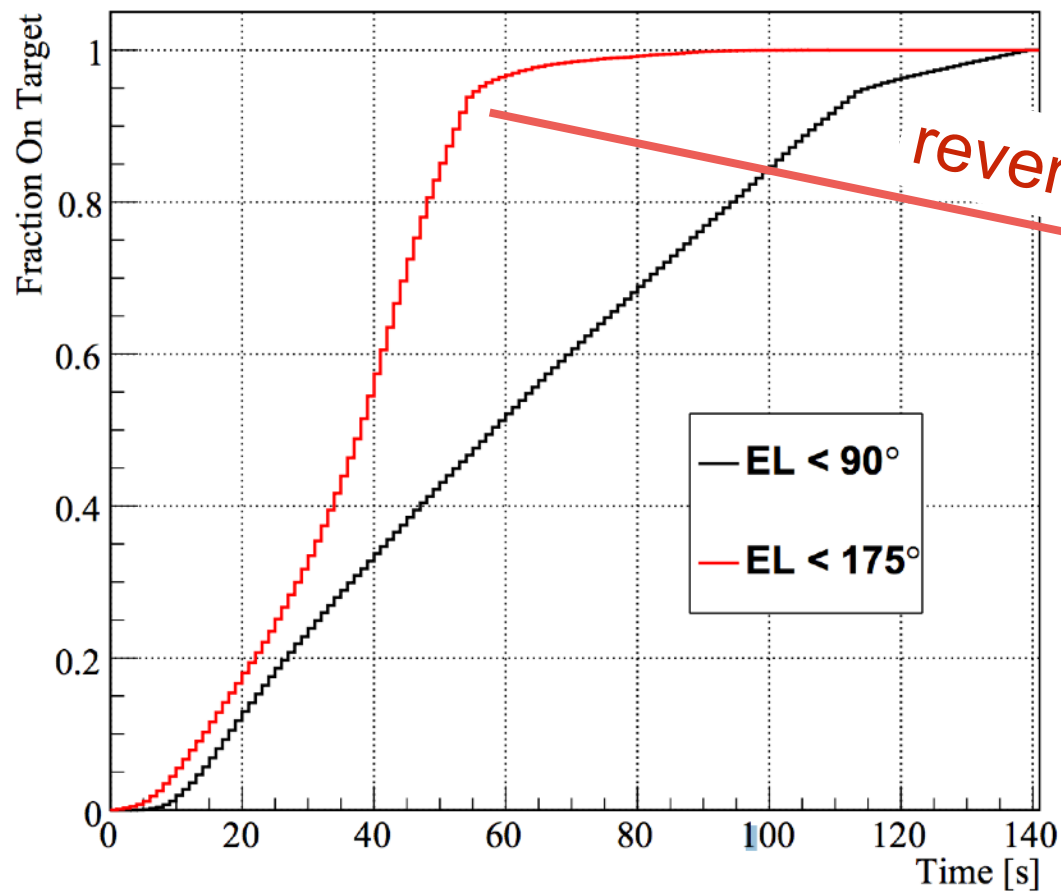
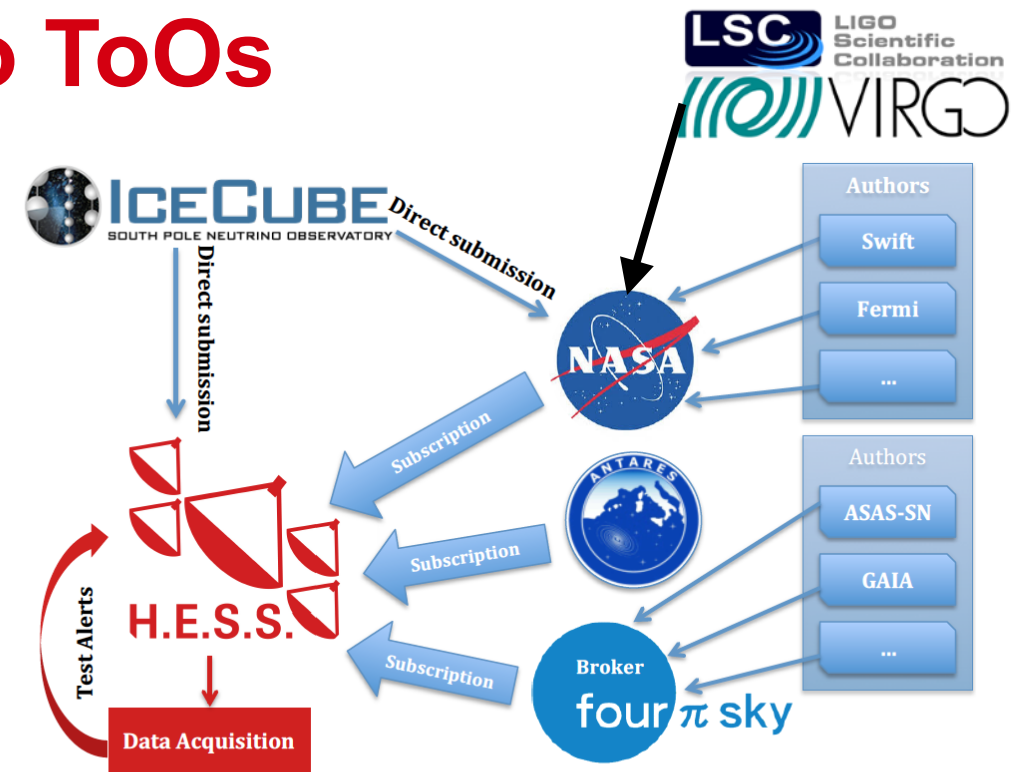
1 x 9,5 m<sup>2</sup> (since 2011)



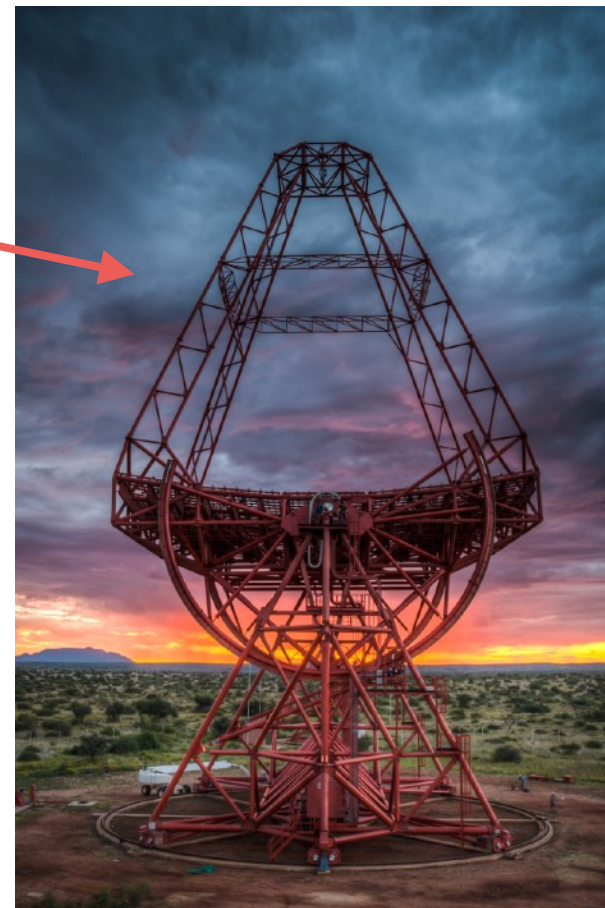


# Example: the H.E.S.S.-II response to ToOs

- main design principles of the H.E.S.S. 28m telescope
  - large photon collection area (614 m<sup>2</sup> mirror area; largest IACT worldwide)
  - rapid response time
  - flexible + fully automatized alert system



Hofverberg et al., ICRC 2013

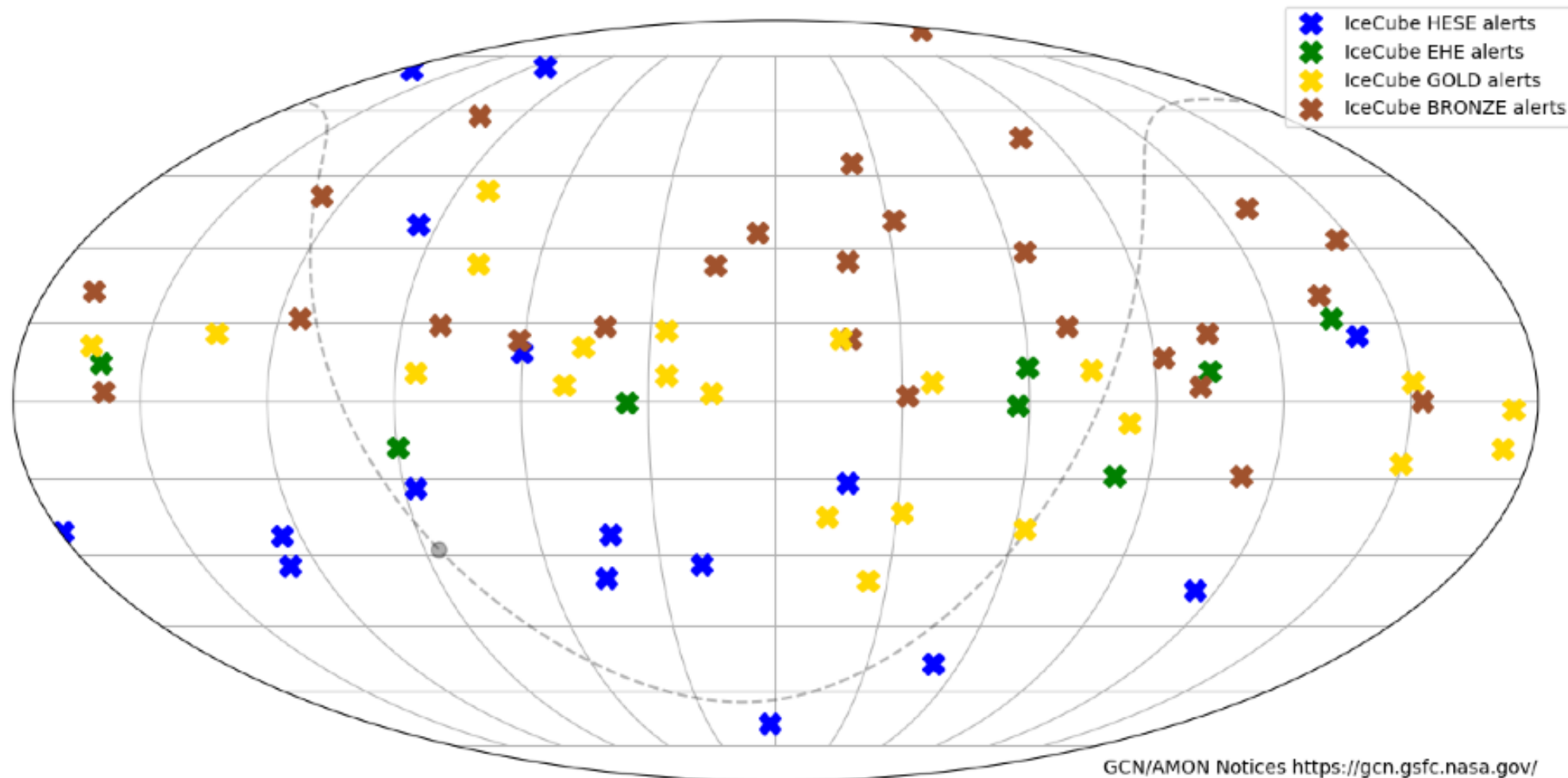


Hoischen et al.  
A&A 666, A119 (2022)



# IceCube alert streams (I): single neutrino events

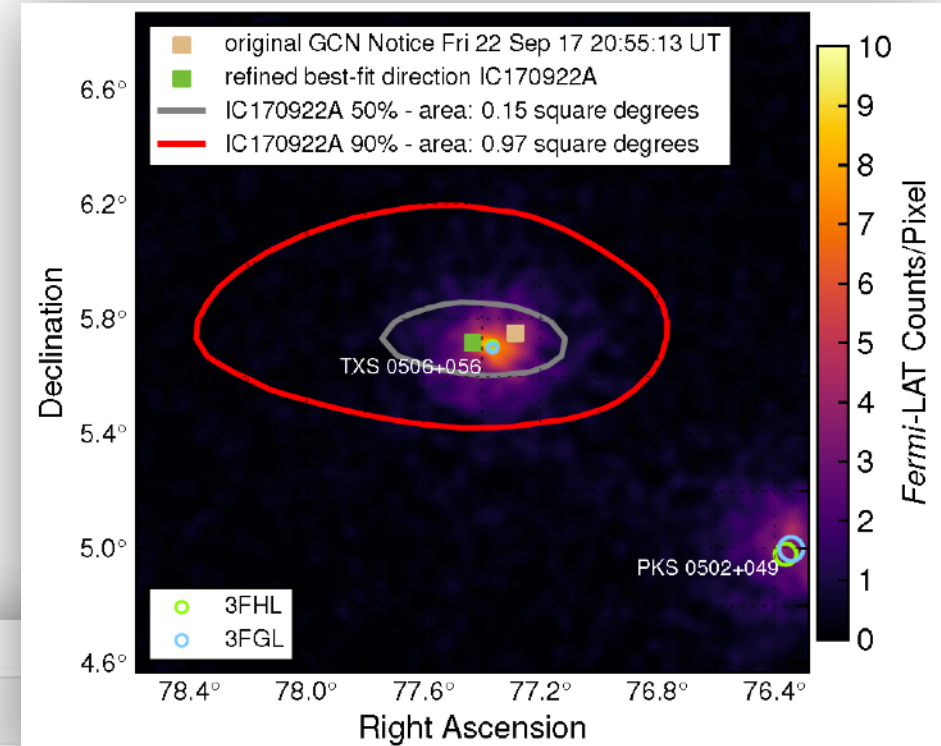
- Since April 2016: EHE + HESE event selections
- Upgrade in 2019: Bronze/Gold alert streams (30%/50% astrophysical probability)
- Publicly distributed via AMON/GCN => follow-up observations by all IACTs
- Aim: identify a plausible EM counterpart to the neutrino event



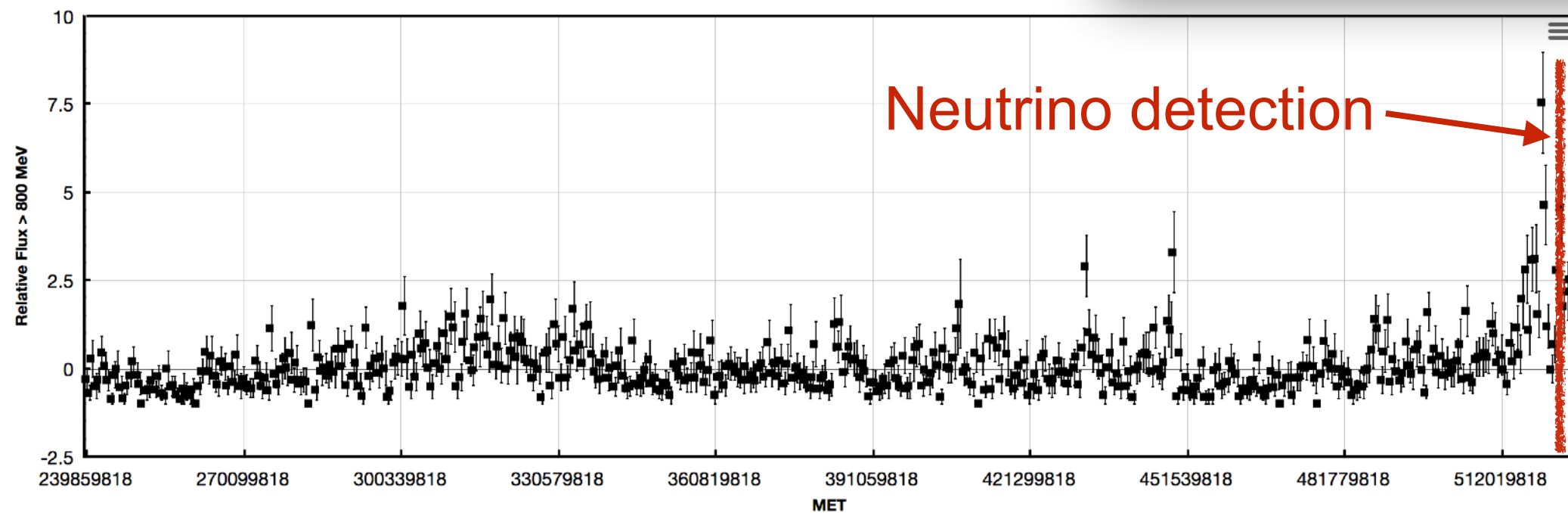
# IceCube-170922A and TXS 0506+056

Science, 2018

- 28/09/2017 Fermi-LAT: Detection of an active blazar within the neutrino uncertainty region  
ATEL #10791 + MAGIC/VERITAS TeV detection + MWL campaign ...



High Energy Light Curve (800 MeV - 300 GeV)



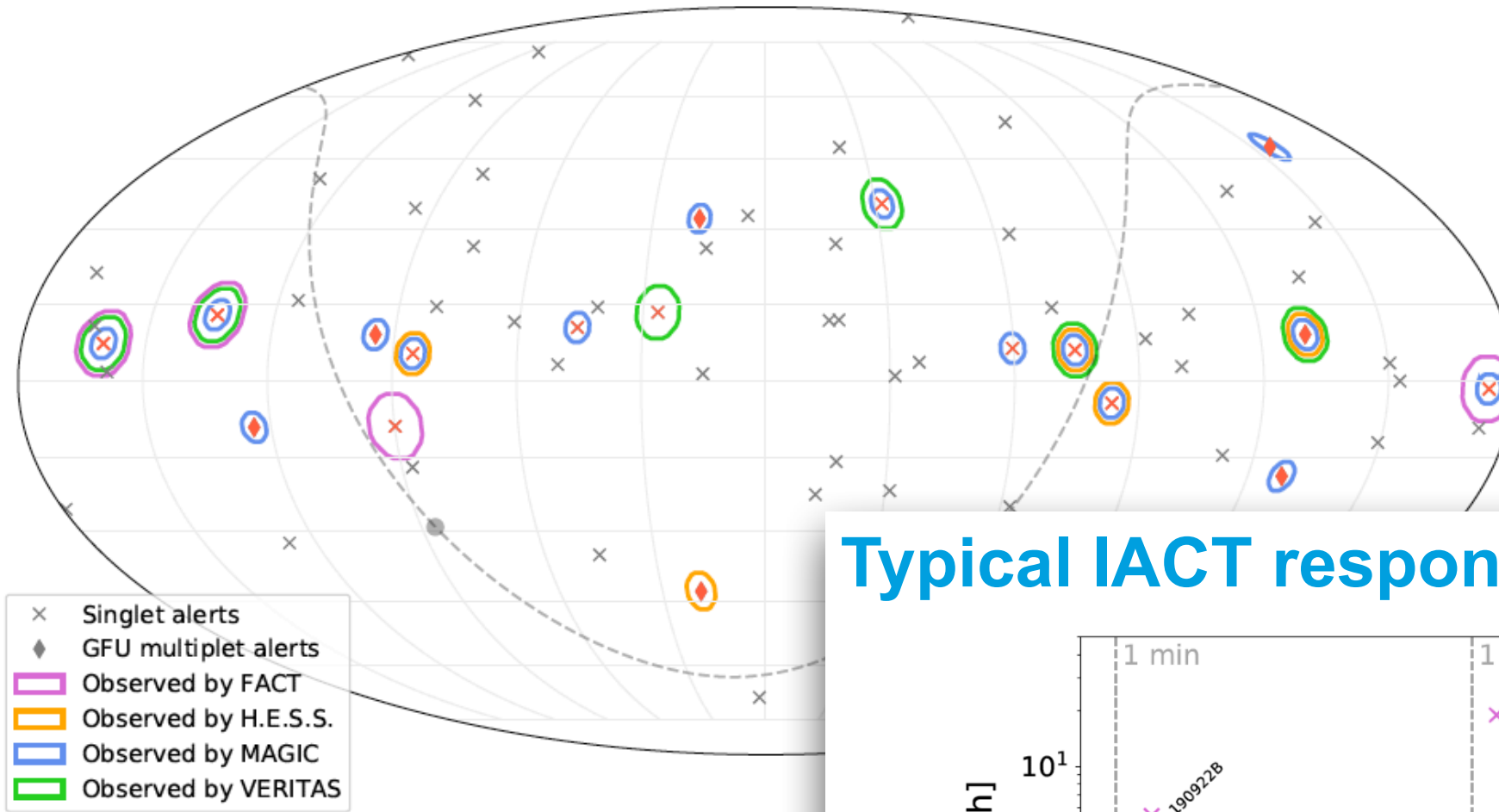


# Continued searches for additional correlations

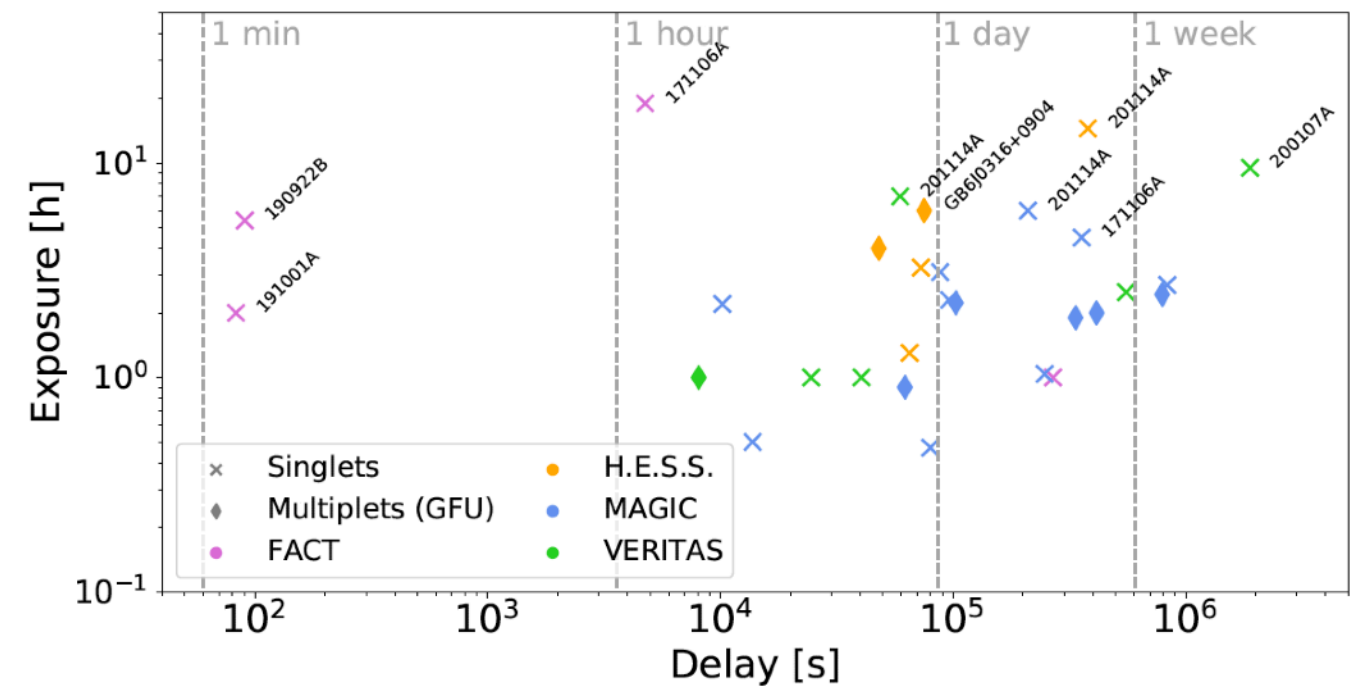
## Alerts observed since October 2017

Alerts (Oct 2017 - Dec 2020):  
62 singlets,  
27 GFUs from 17 sources

Observed:  
11 singlets,  
GFUs from 7 sources



## Typical IACT response

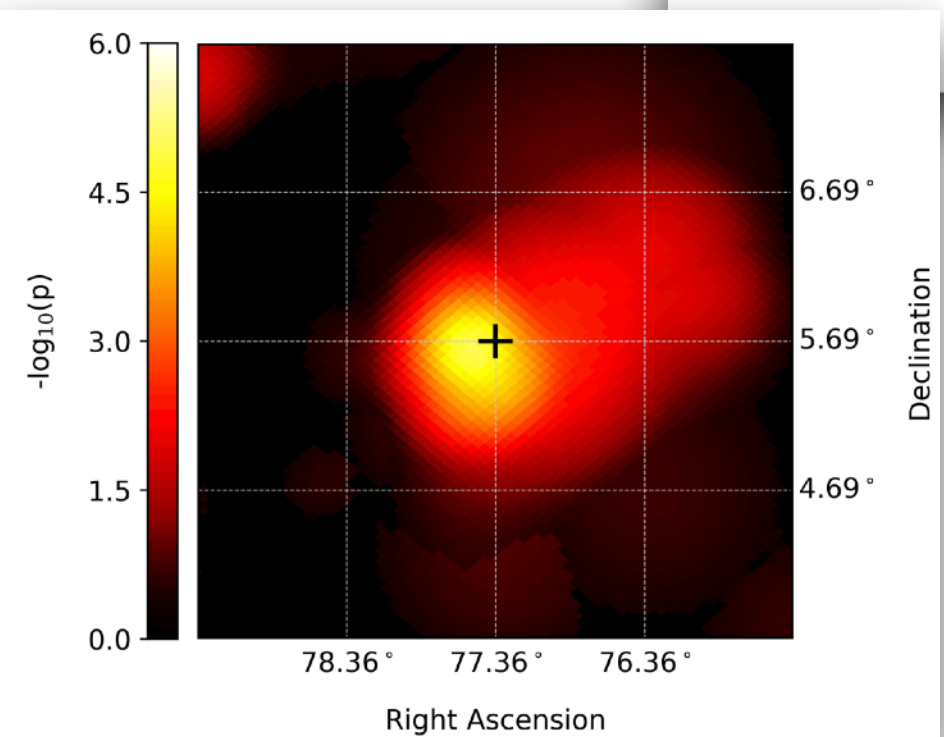
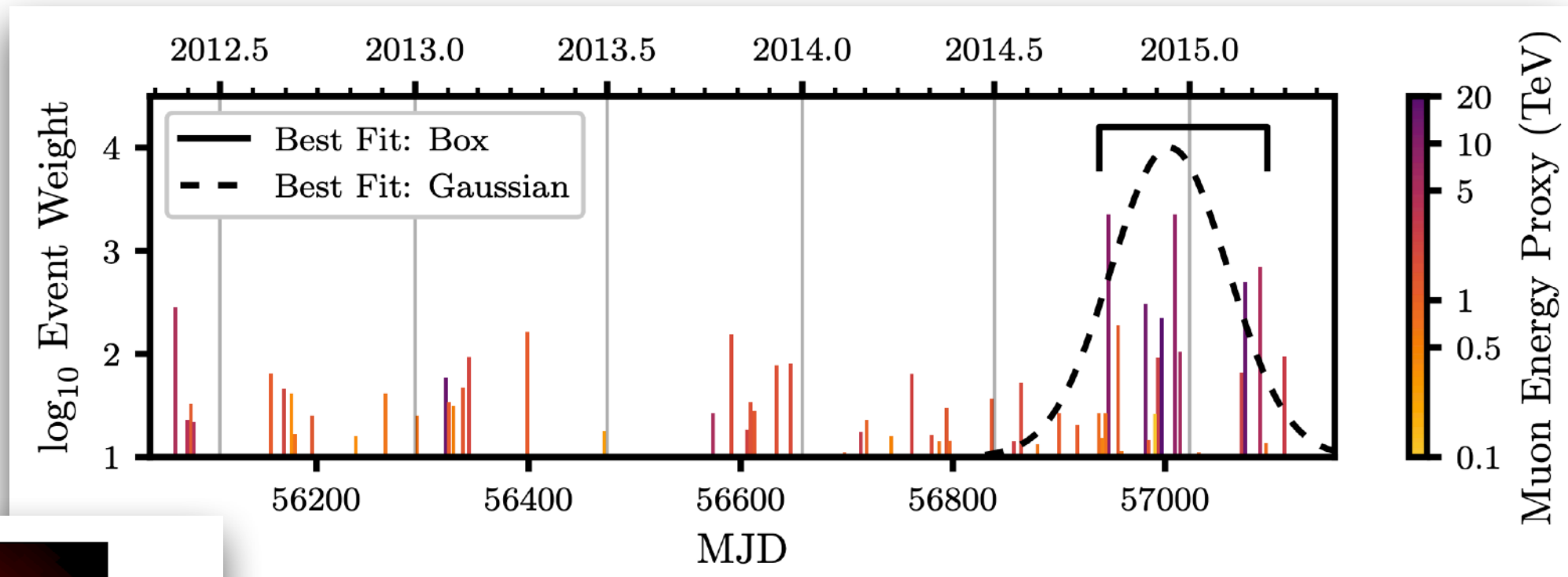


### Joint effort by all IACTs

Santander et al. ICRC 2017  
Satalecka et al., ICRC 2021

# IceCube alert streams (II): Gamma-ray follow-up (“GFU”)

- Searches for neutrino multiplets (“flares”) in the IC online data stream
  - Time periods ranging from seconds to 180days

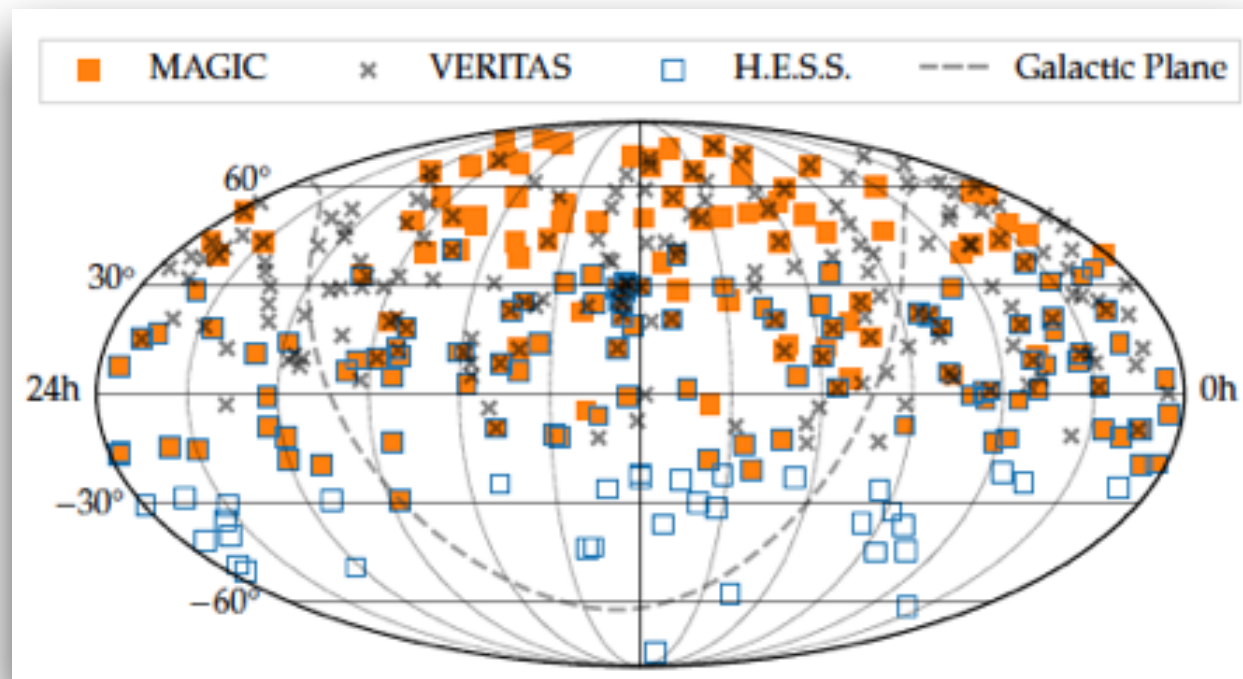


IceCube collaboration, Science 361 (2018) 147-151



# IceCube alert streams (II): Gamma-ray follow-up (“GFU”)

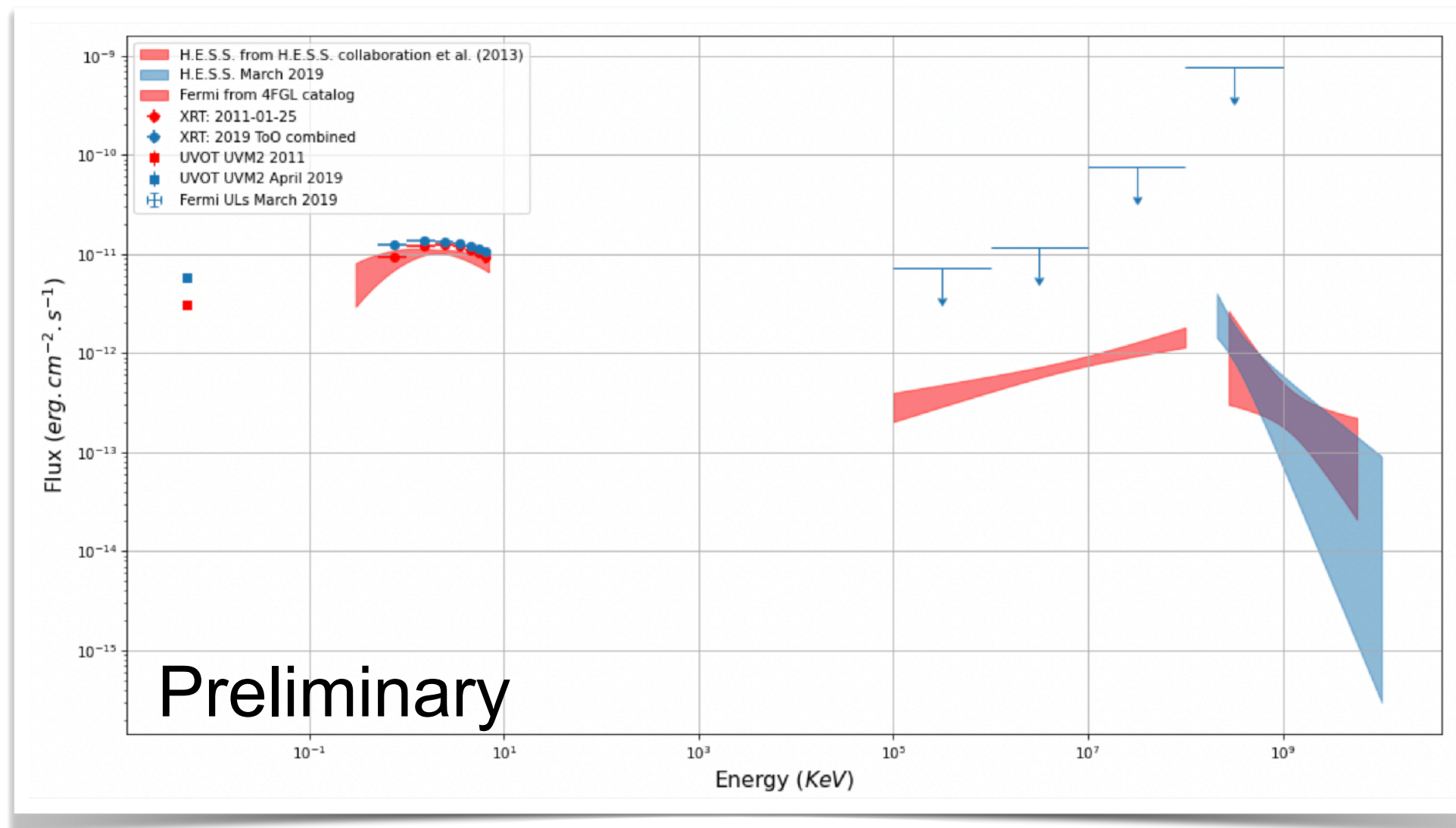
- Searches for neutrino multiplets (“flares”) in the IC online data stream
  - Time periods ranging from seconds to 180days
- Predefined targets + all-sky search (in preparation)
- Alerts distributed privately under MoU
  - Northern Sky: MAGIC & VERITAS since 2012
  - Southern Sky: H.E.S.S. since 2019
  - CTA/LST-1 since 2023
- Source selection based on 3LAC/3FHL/TeVCat; variability; distance; visibility
- Aim: determine the state of the source (quiescence vs flaring state; spectral changes)



Discussion of improvements  
Koji Noda (yesterday)

# Example: Neutrino multiplet from 1ES 1312-423

- Neutrino ‘flare’ detected by IceCube (duration 6.5 hours)
- H.E.S.S. ToO observations => re-detection of the source (~4sigma)
- Contemporaneous MWL observations ATOM + Swift (UVOT + XRT)
- No significant change in the non-thermal emission during the ToO



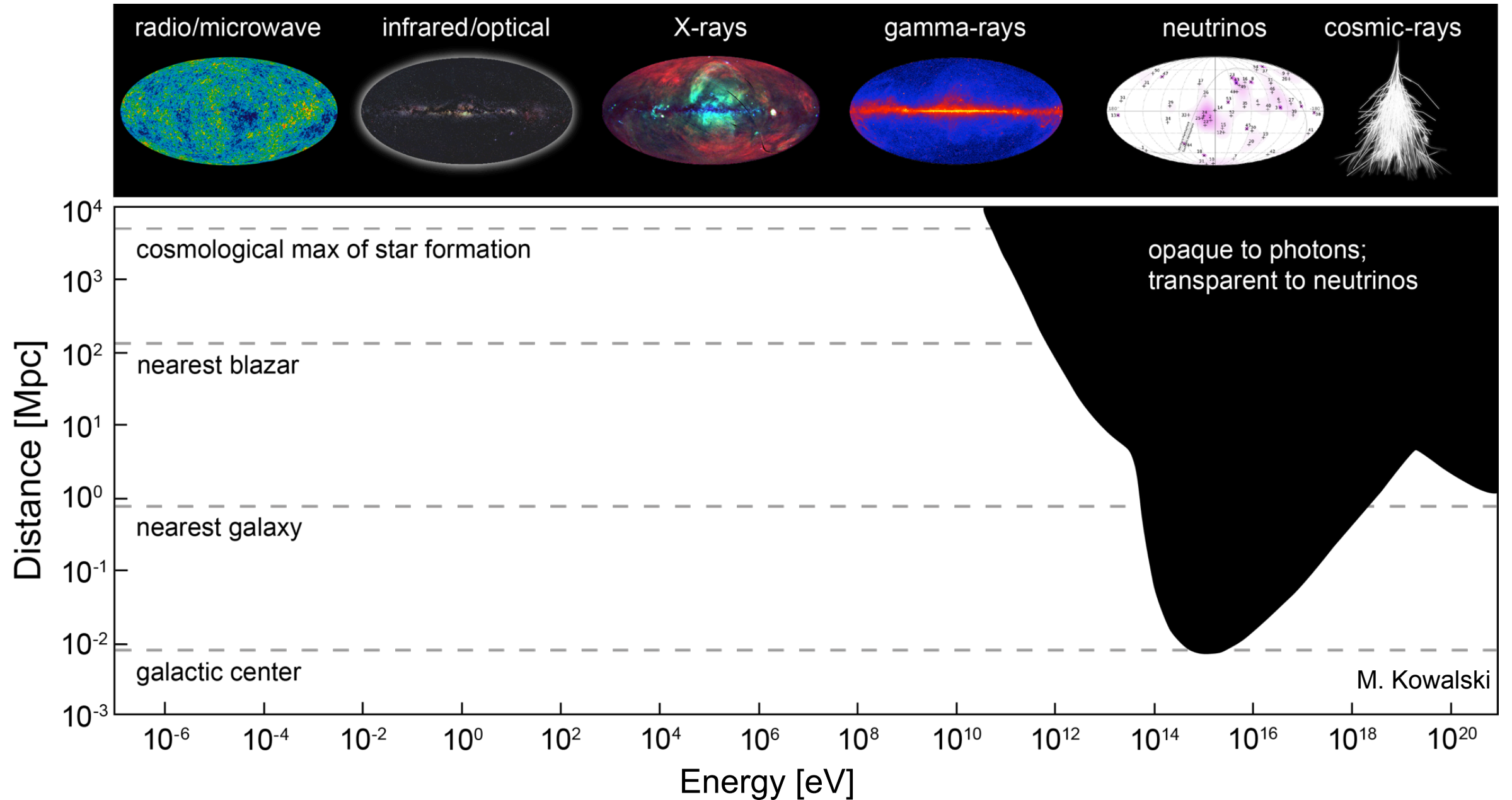


# High-energy multi-messenger astrophysics in real-time

- **Several years of preparation coming to fruition**
  - automatic alert systems + dedicated data analysis tools + MoUs + ...
- **Sources of high-energy neutrinos**
  - diffuse astrophysical flux detected
  - transient sources promising (reduced background)
  - IceCube-170922A and TXS 0506+056: a first hint
- **VHE gamma-ray follow-ups with all IACTs**
  - Important part of the multi-messenger and transients programs
  - Different + complementary approaches
  - Joint analyses in progress

# Caveats to VHE neutrino - gamma-ray correlations

- Neutrino backgrounds are important → Can't expect to find TeV gamma-ray emission to all neutrino events
  - Atmospheric neutrinos
  - No cosmic horizon



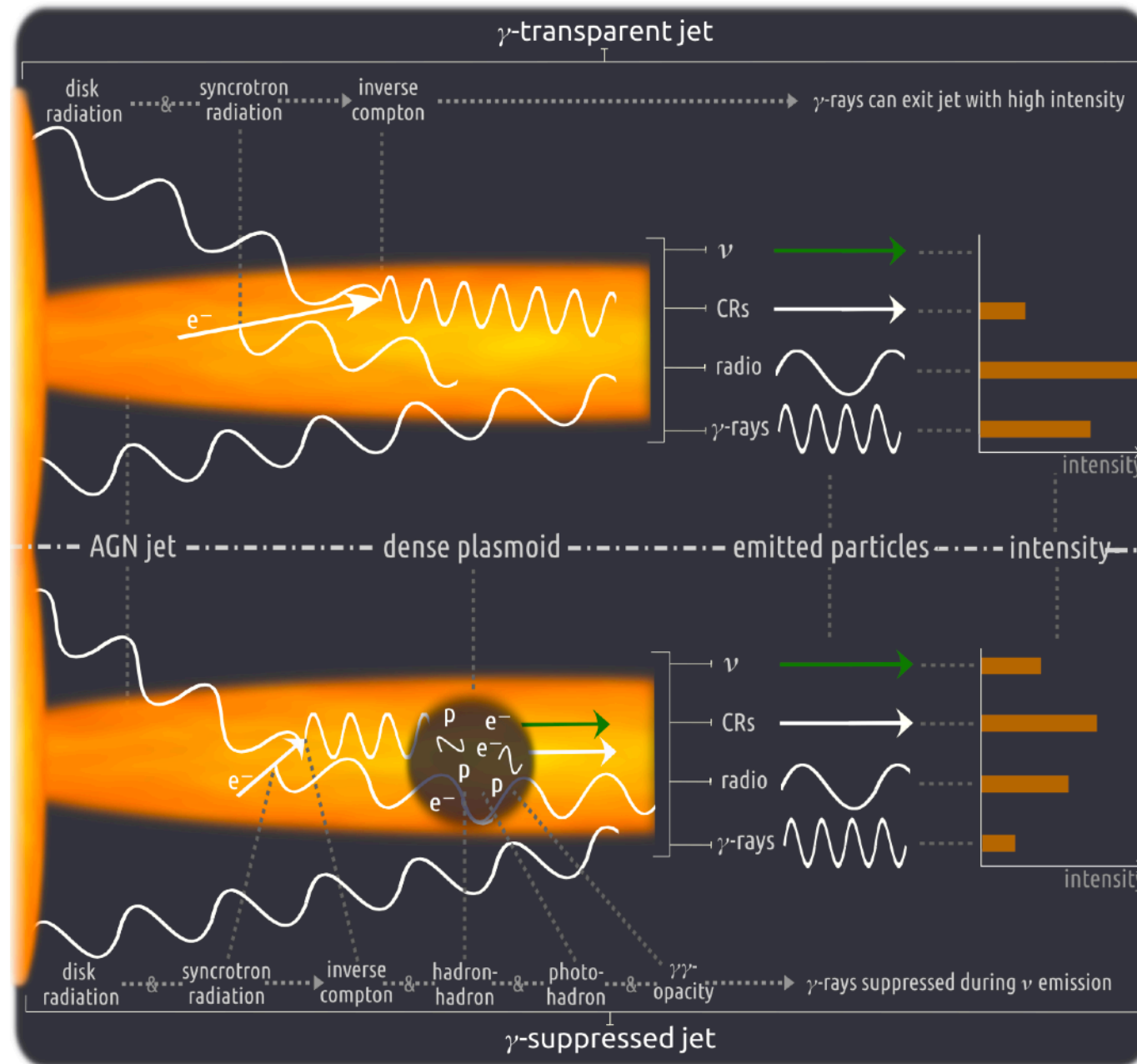


# Caveats to VHE neutrino - gamma-ray correlations

- Neutrino backgrounds are important
  - Atmospheric neutrinos
  - No cosmic horizon

- Neutrino emission requires hadrons + sizable target densities
  - High densities cause gamma-ray absorption

e.g. NGC 1068



P. Reichherzer

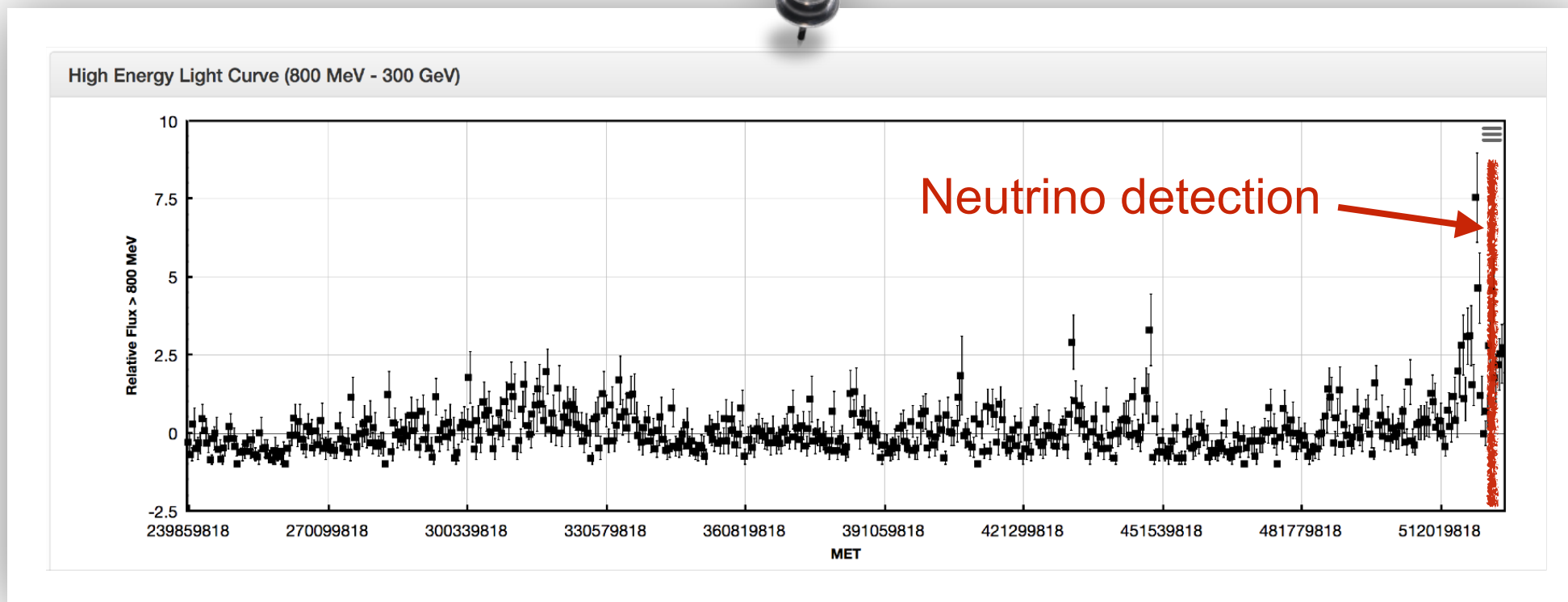
# IceCube-170922A and TXS 0506+056

- 22/09/2017 IceCube: Detection of a high-energy neutrino
- 28/09/2017 Fermi-LAT: Detection of an active blazar within the neutrino uncertainty region [ATEL #10791](#)

**It took us ~1 week to realize that!**

All data and tools were publicly available.

Missing: connections between different platforms/tools + modern interfaces





# Astro-COLIBRI

- Alerts from a large variety of transient phenomena (smartphone notifications)
- Modern interfaces allowing for efficient and informed decision making
- Direct links to a many dedicated services

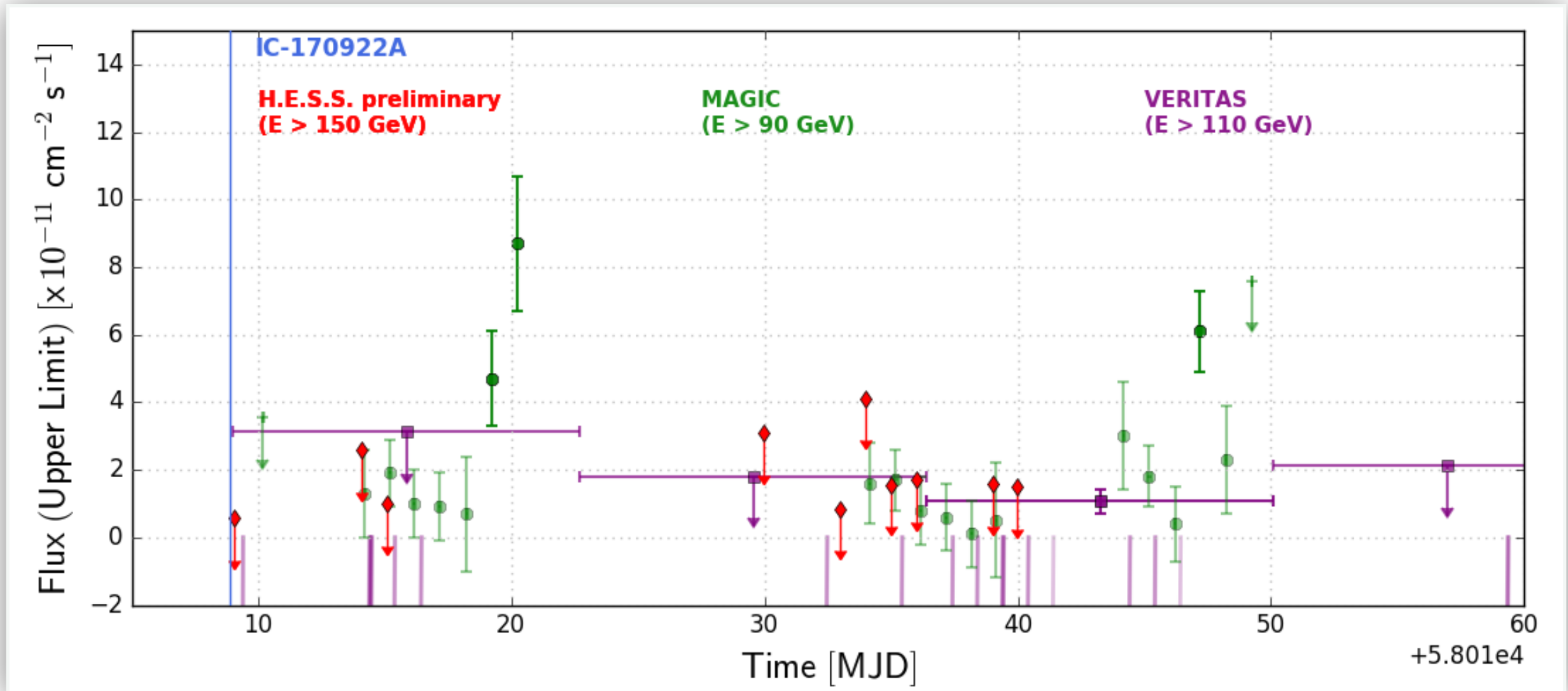
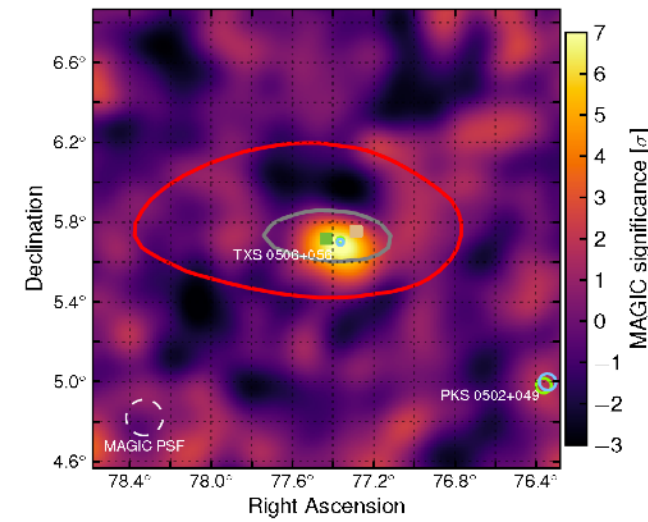


<https://astro-colibri.com>



# Observational challenges

- Time scales unclear
  - $\Delta T$  between neutrino(s) and gamma-rays (TXS 0506+056:  $>10$ days)
  - Variability timescale (TXS 0506+056:  $\lesssim 1$ day)
- $\Rightarrow$  Long and deep follow-up campaigns



FS et al, TeVPA 2018



# The era of the Cherenkov Telescope Array

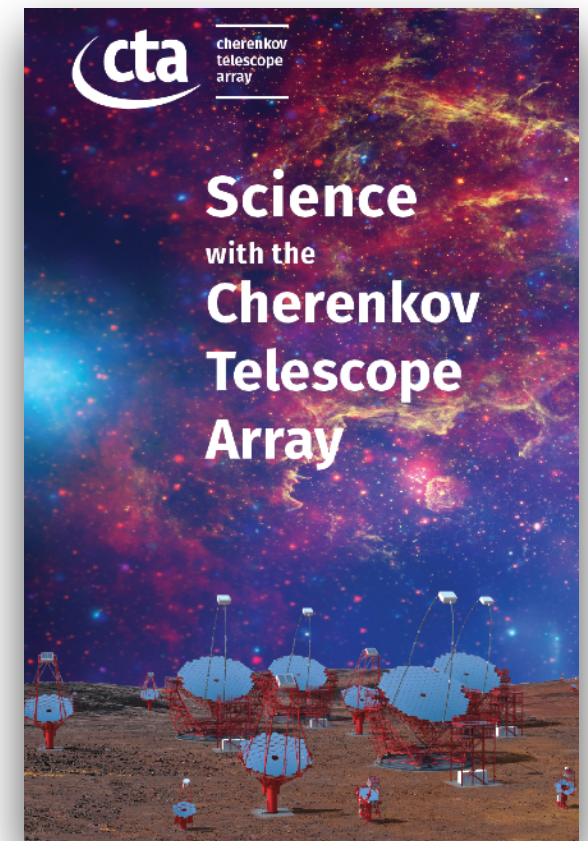
- Multi-messenger observations are integral part of the CTA Key Science
- Both hemispheres (CTA-North + CTA-South)
- Improved sensitivity



# The era of the Cherenkov Telescope Array

- Multi-messenger observations are integral part of the CTA Key Science
- Both hemispheres (CTA-North + CTA-South)
- Improved sensitivity

- 
- Limited duty-cycle + limited longitude range
  - Significant oversubscription
    - Approval of long monitoring campaigns will be challenging



Neutrino ToOs: 5–10 h/yr/site



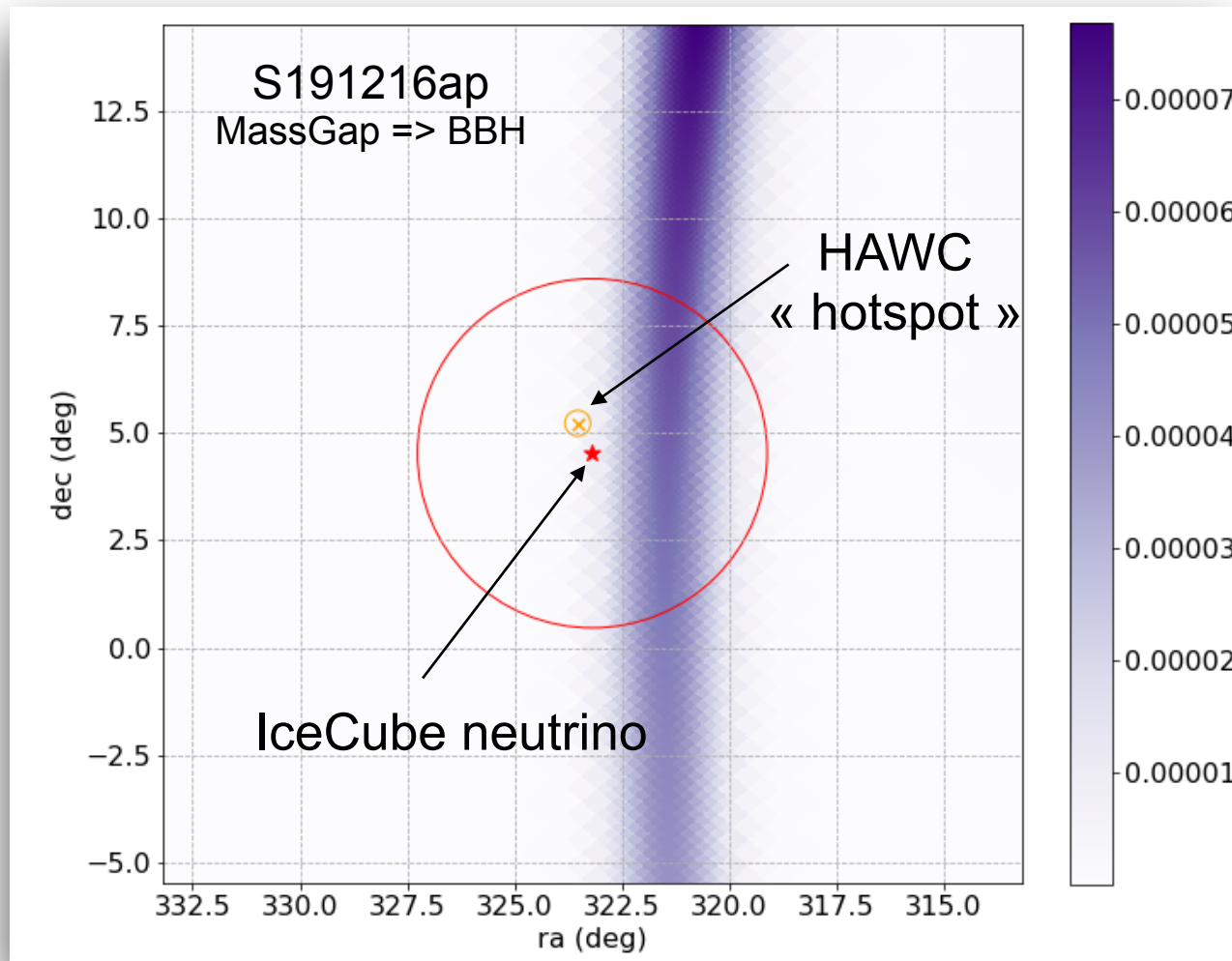
- Air shower arrays (HAWC, LHAASO, SWGO?)
- **Continued operations of current IACTs ?**





# Searches with air shower arrays

- HAWC + LHAASO (+ SWGO, ALPACA, etc.)
- Large FoV + high duty-cycle
  - **Smaller instantaneous sensitivity + higher  $E_{\text{threshold}}$**
- HAWC: automatized searches for excess at several timescales (0.3s - 100s)



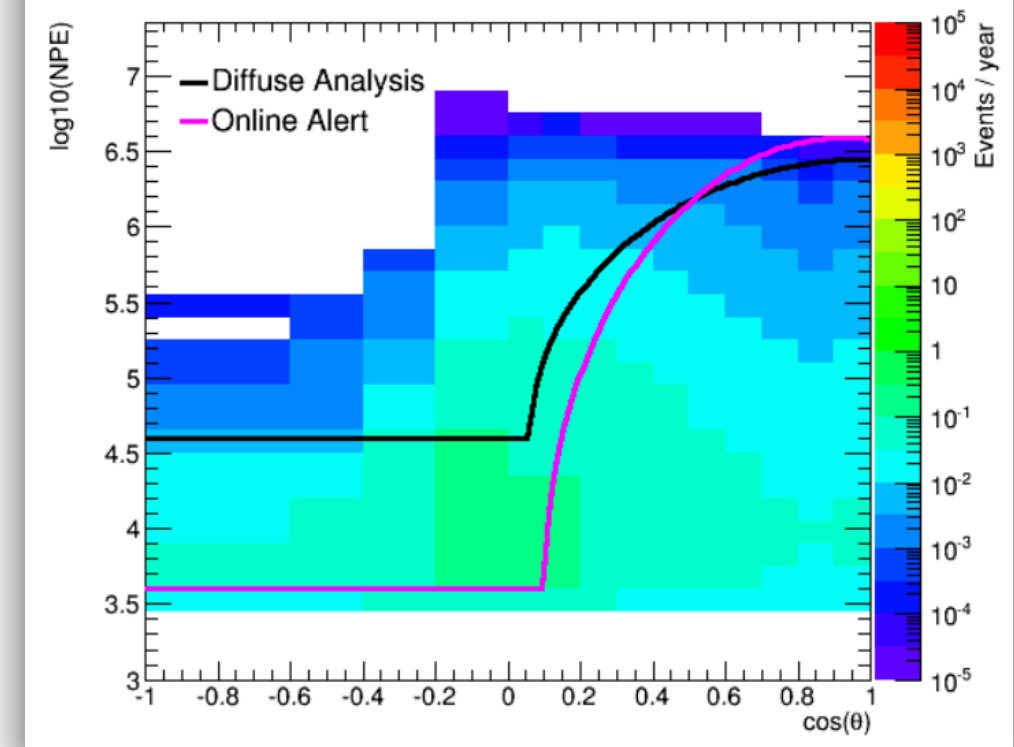
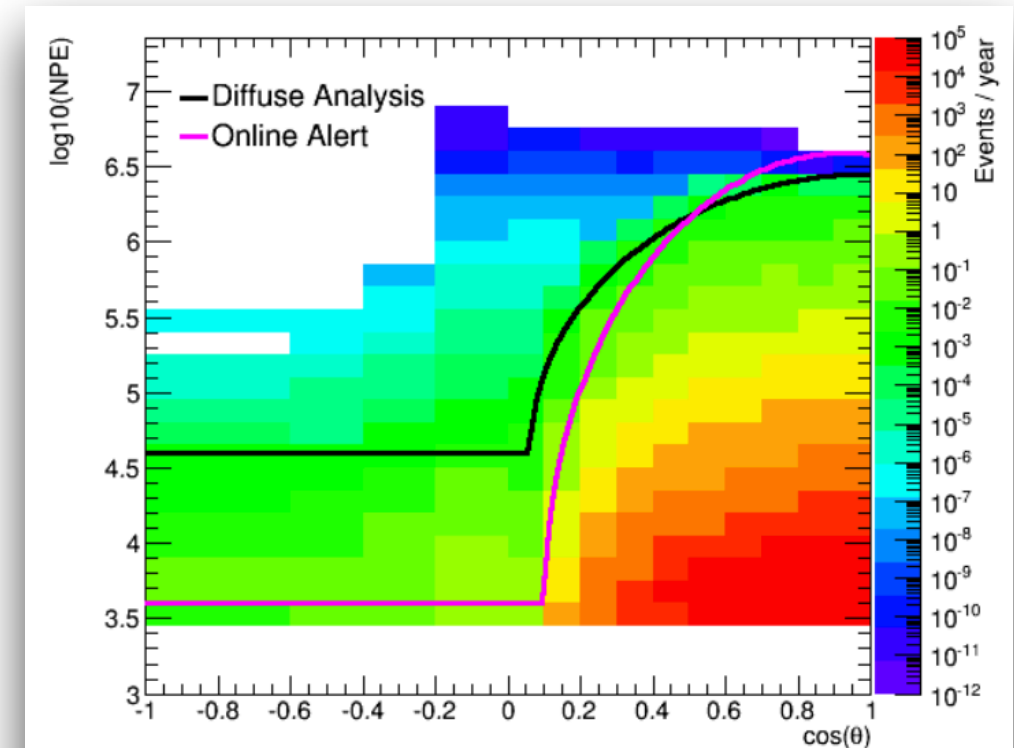
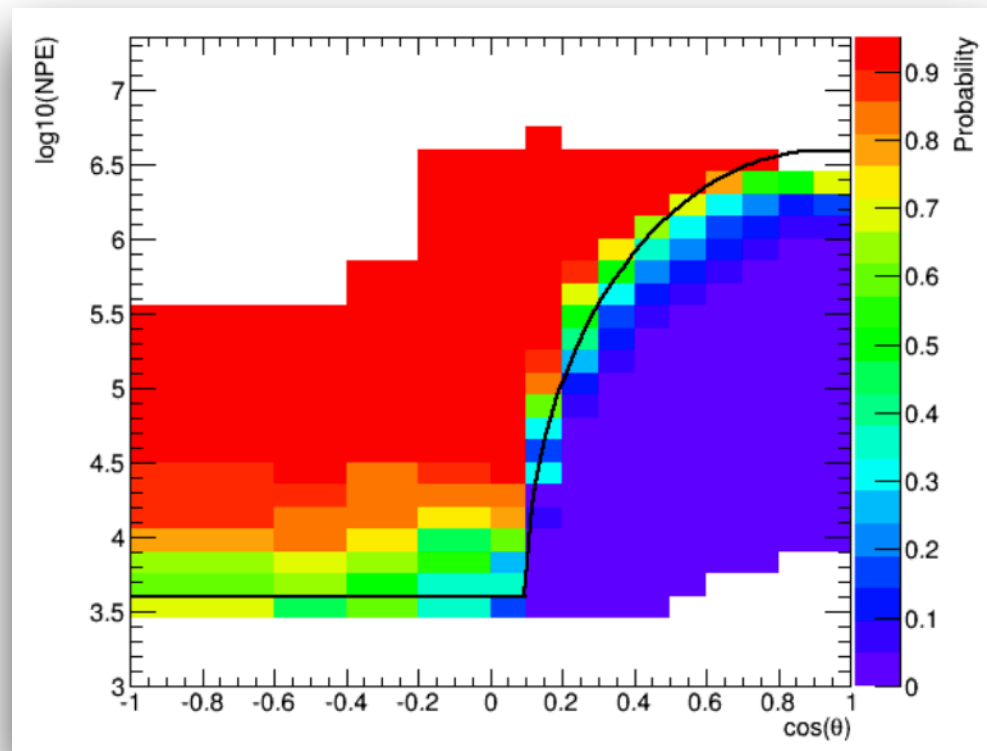
GCN #26455  
GCN #26463  
**GCN #26472**  
...

I. Martinez + H. Schoorlemmer et al. (HAWC)



# Neutrino alert emission

- Data recorded by neutrino telescopes is dominated by atmospheric background
- Multi-dimensional cuts to increase the SNR
- Event-by-event estimation of  $P_{\text{astro}}$
- Reconstruction + filtering + alert emission fully automatic => delays < 10s



IceCube collaboration, Astroparticle Physics 92 (2017) 30-41