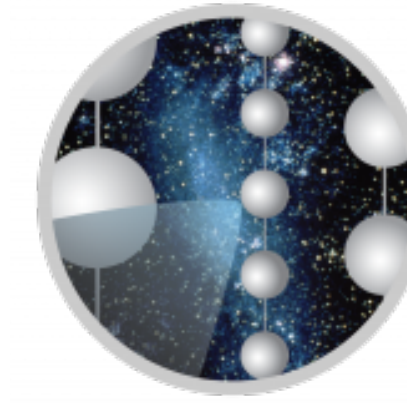




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REALTIME STUDIES OF EXTRAORDINARY EVENTS: THE GAMMA-RAY FOLLOW UP (GFU) PLATFORM FOR ICECUBE NEUTRINO OBSERVATORY

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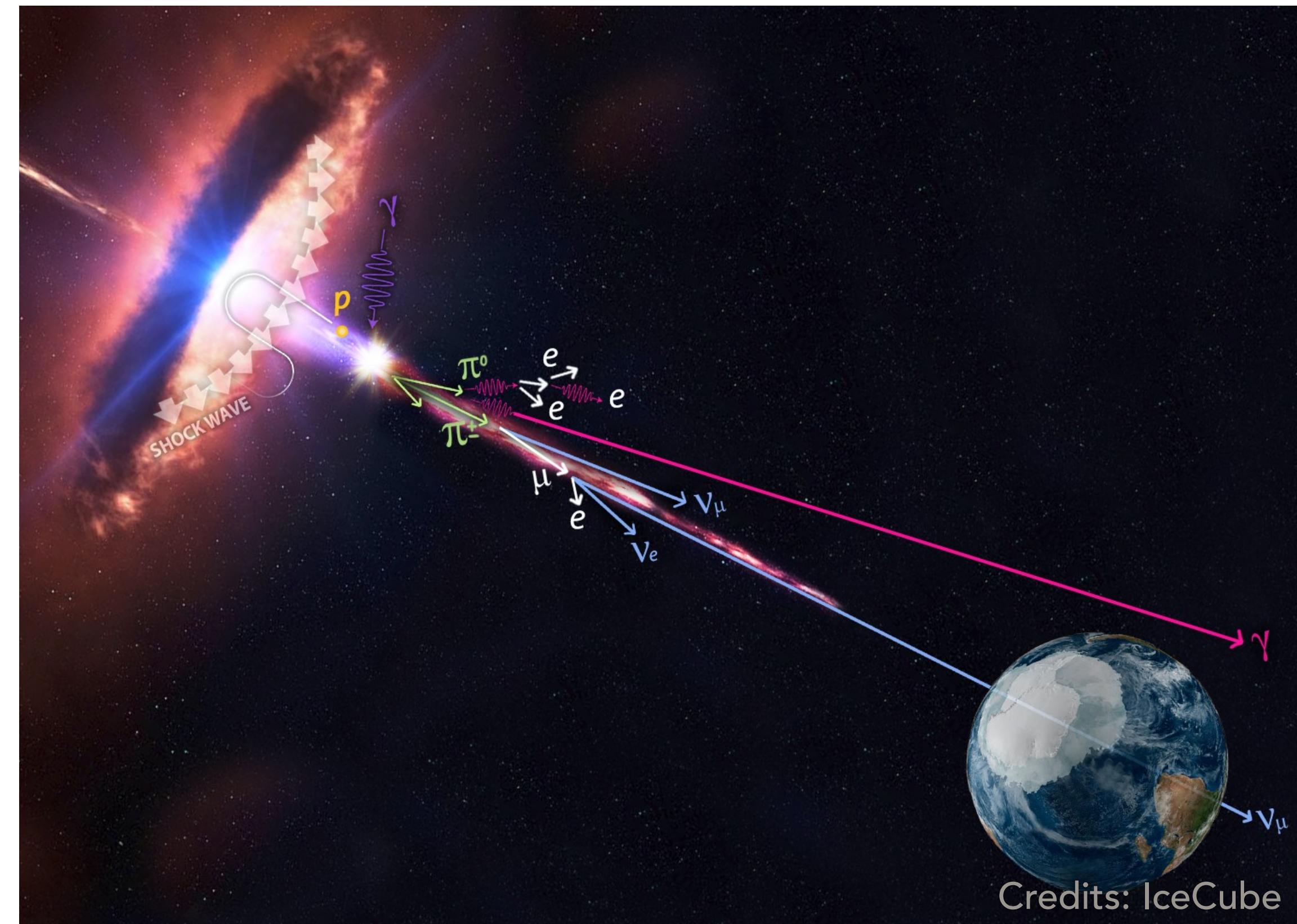
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NBIA PhD School – July 11-15, 2022 – Copenhagen

THE GAMMA-RAY FOLLOW UP (GFU) PLATFORM

MOTIVATION

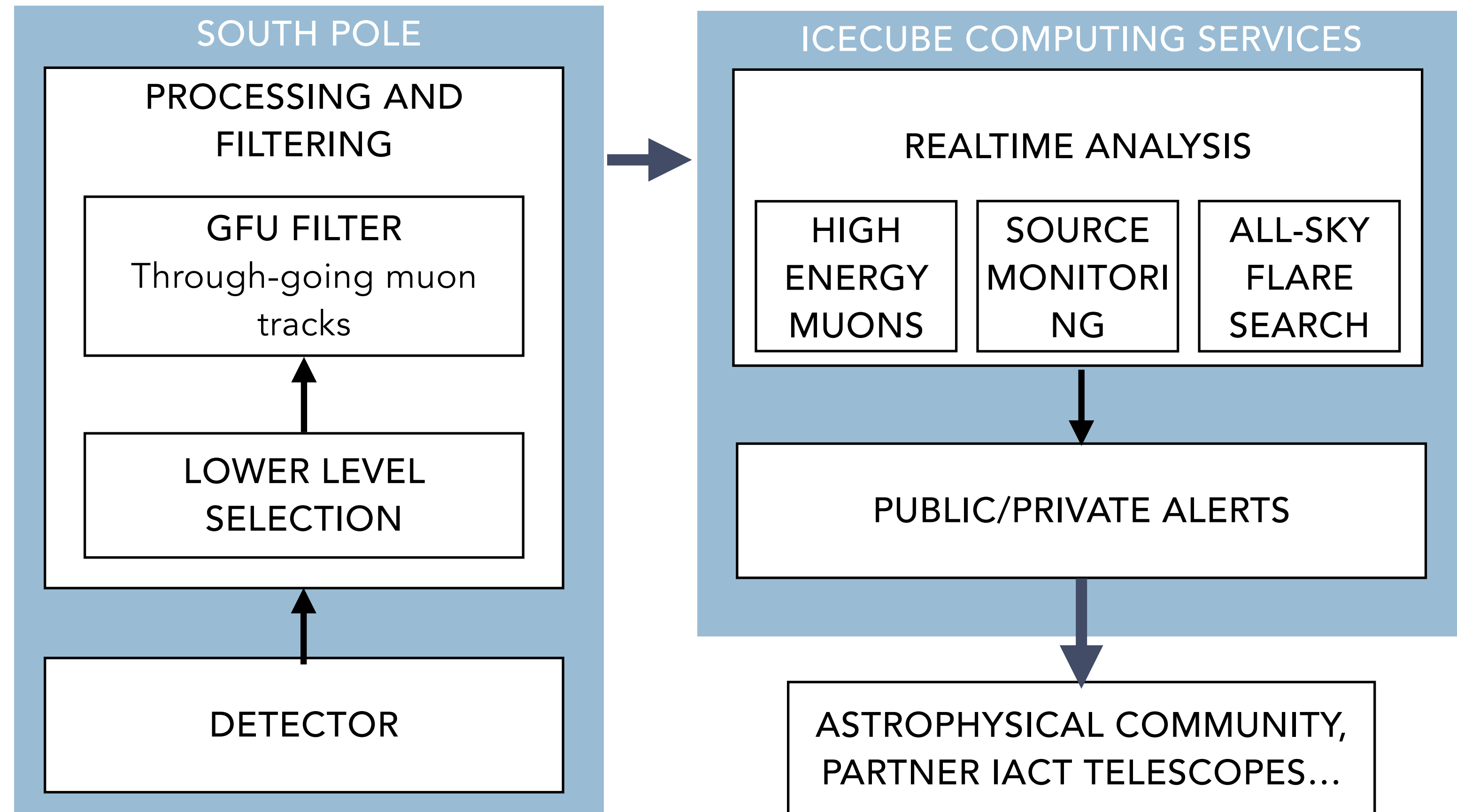
- Astrophysical ν flux discovered by IceCube in 2014^[1]
- privileged astrophysical messenger, signature of CR
- Time integrated search for neutrino sources failed so far



- Real time identification of transient neutrino sources
+ alerts to astrophysical community and partner IACTs
- **Multimessenger observations**

THE GAMMA-RAY FOLLOW UP (GFU) PLATFORM IN A NUTSHELL

- Selection of good muon neutrino candidates
 - GFU filter: ~6.5 mHz
- Realtime analysis
 - Single high energy neutrinos
 - Neutrino clusters (source-biased or all-sky)
- Alert generation



REAL-TIME ANALYSIS

SINGLE EVENTS VS NEUTRINO CLUSTERS

HIGH ENERGY SINGLE EVENT

- High astrophysical probability
- Aggressive energy cuts, mostly sensitive to the region around the horizon
- Public alerts:
 - Bronze (30/year):
astrophysical probability $> 30\%$
 - Gold (10/year):
astrophysical probability $> 50\%$

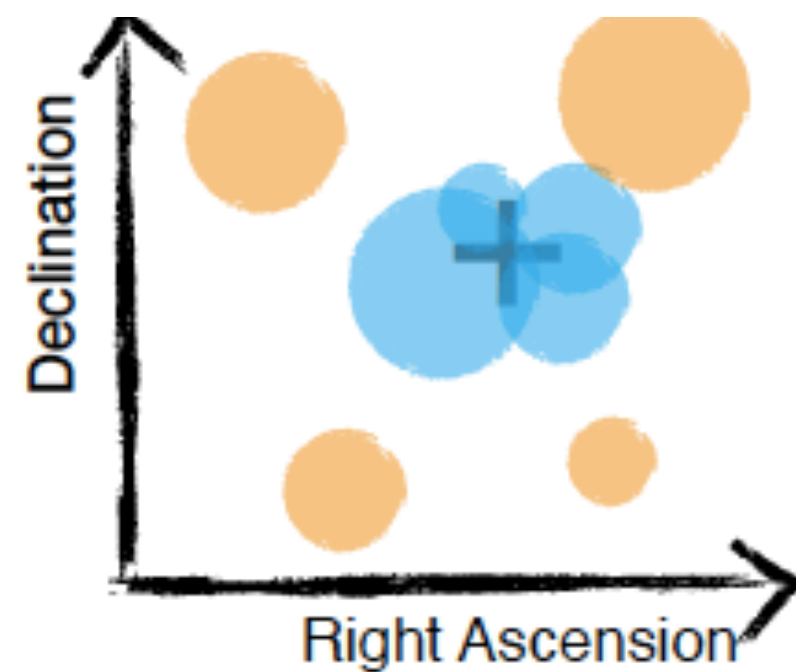
NEUTRINO CLUSTER SEARCH

- Unbinned maximum-likelihood method
- Looser cuts, sensitive to lower energy, and uniformly to the whole sky
- Private alerts:
 - Monitoring of catalogued gamma-ray sources (< 10 alerts/year)
 - Unbiased all-sky flare search (~ 1 alert/year)

NEUTRINO CLUSTER SEARCH

MAXIMUM-LIKELIHOOD METHOD

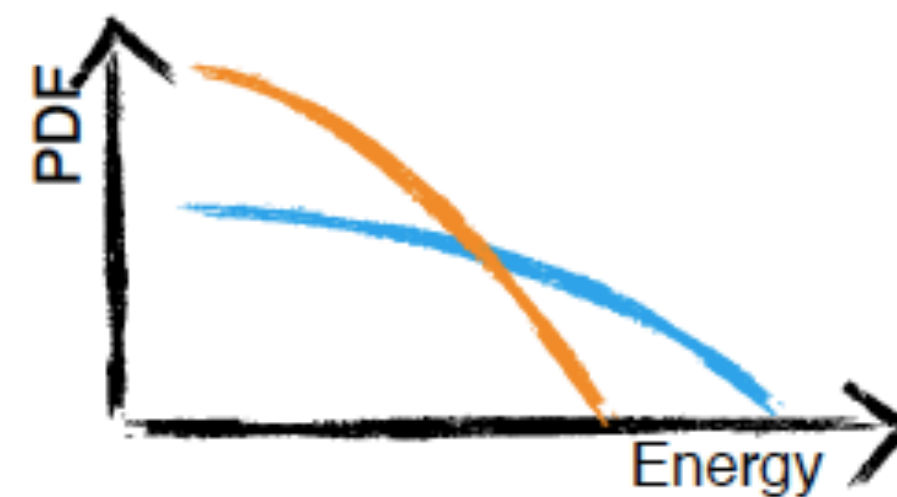
$$\mathcal{L} = \prod_i^{N \text{ events}} \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N} \right) B_i \right], \quad \text{TS} = 2 \log \left(\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(n_s = 0)} \right)$$



Spatial PDF

- ▶ Test compatibility with source location
- ▶ Use per-event angular uncertainty

×



Energy PDF

- ▶ Exploit different spectra of **signal** and **background**
- ▶ Use per-event energy estimate

×



Time PDF

- ▶ Clustering of **signal** over flat **background**
- ▶ Generic box shape

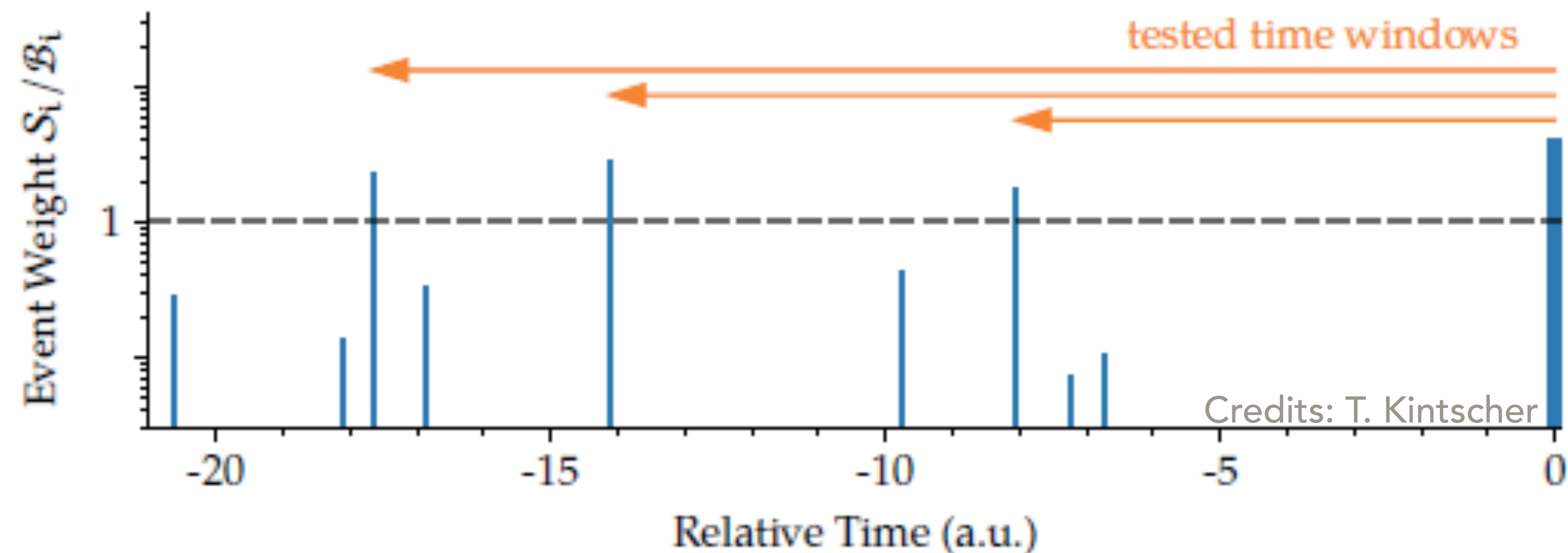
Credits: T. Kintscher

- Fit parameters: number of signal events n_s , spectral index γ , time window.

NEUTRINO CLUSTER SEARCH

TIME SCAN ALGORITHM

- Events with $S/B \geq 1$ trigger the analysis
- Likelihood analysis is performed scanning back in time to all possible event combinations
- Max time window: 180 days
- For each trigger, the fit result is the time window with best Test Statistic
- If significance crosses alert threshold: alert is sent



MONITORING OF KNOWN GAMMA-RAY SOURCES

RESULTS FROM ARCHIVAL DATA

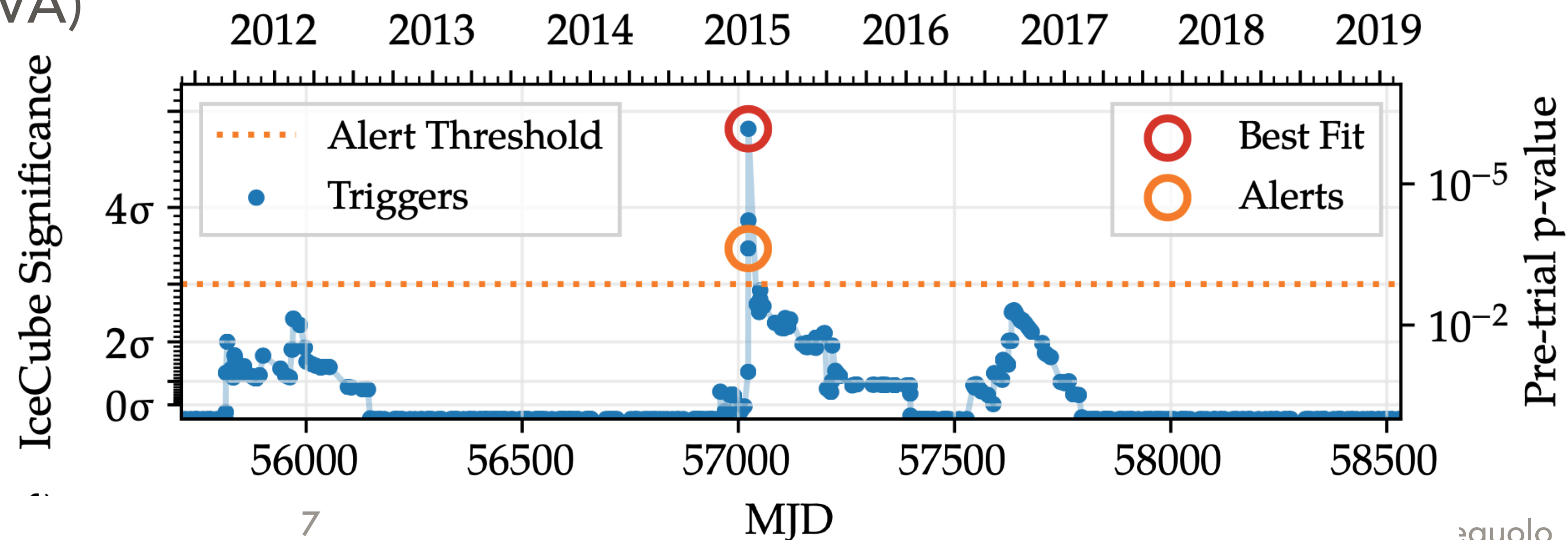
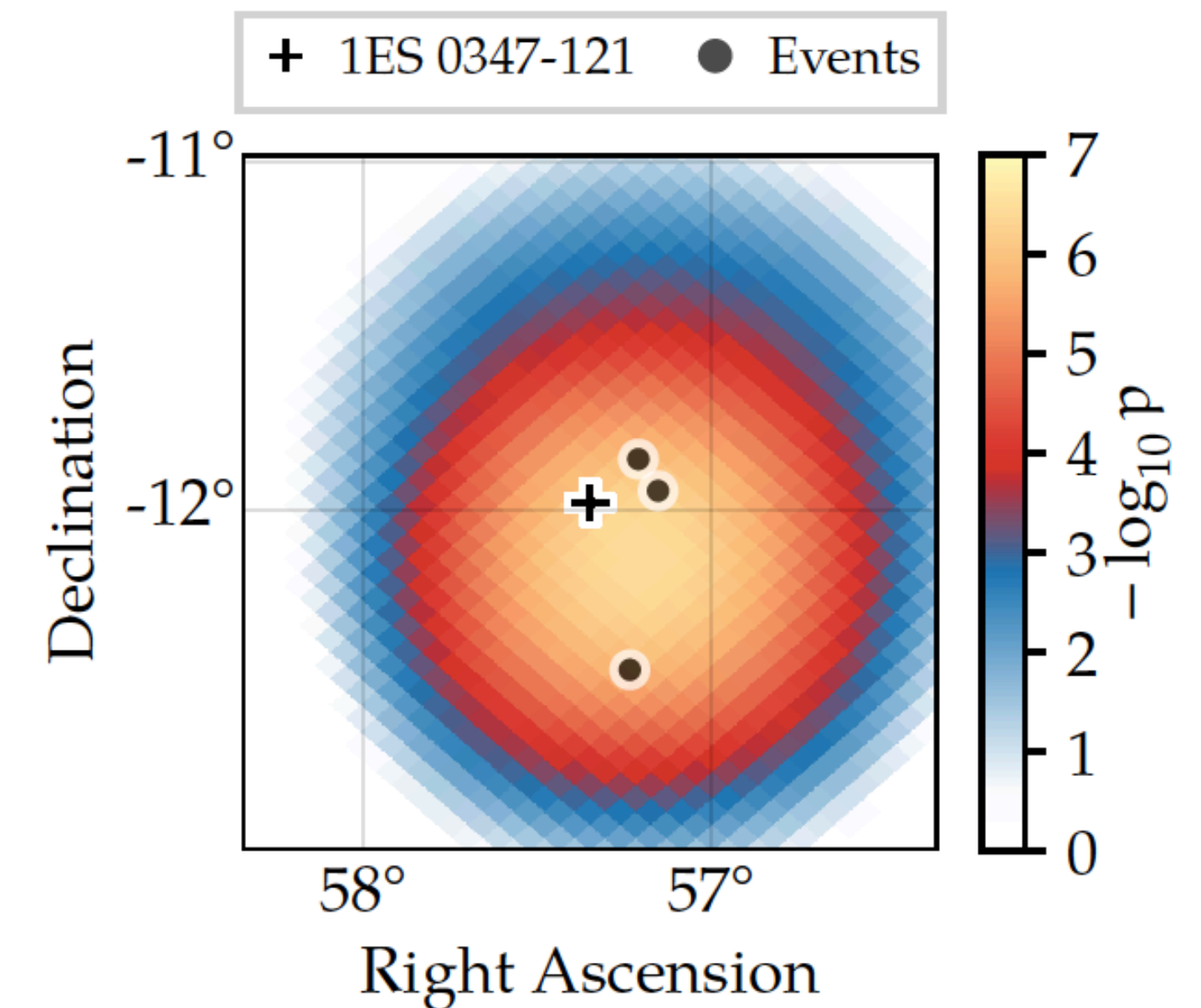
- predefined list of 339 sources, monitored by IACTs (MAGIC, VERITAS, H.E.S.S.)

- Most significant flare (May 2011 – March 2019):

1ES 0347-121 ($\alpha = 57.35^\circ, \delta = -11.98^\circ$)

- Neutrino cluster in ~ 7 h
- Post-trial significance: 2σ
- No activity reported by Fermi

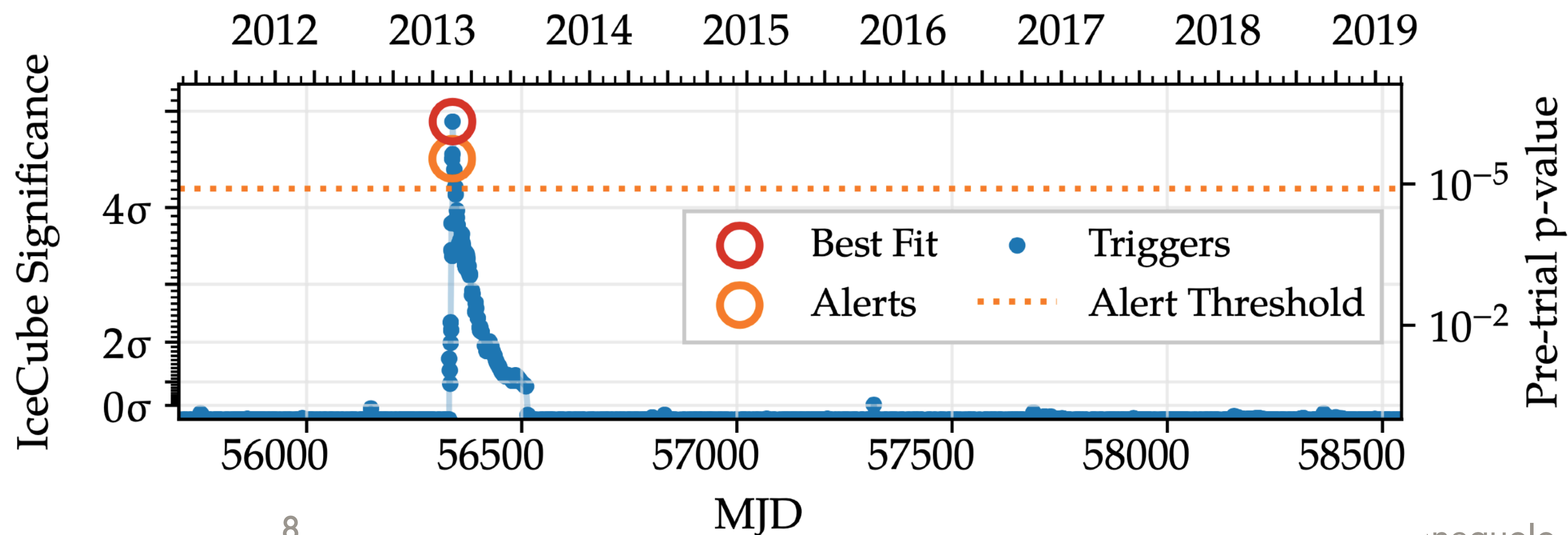
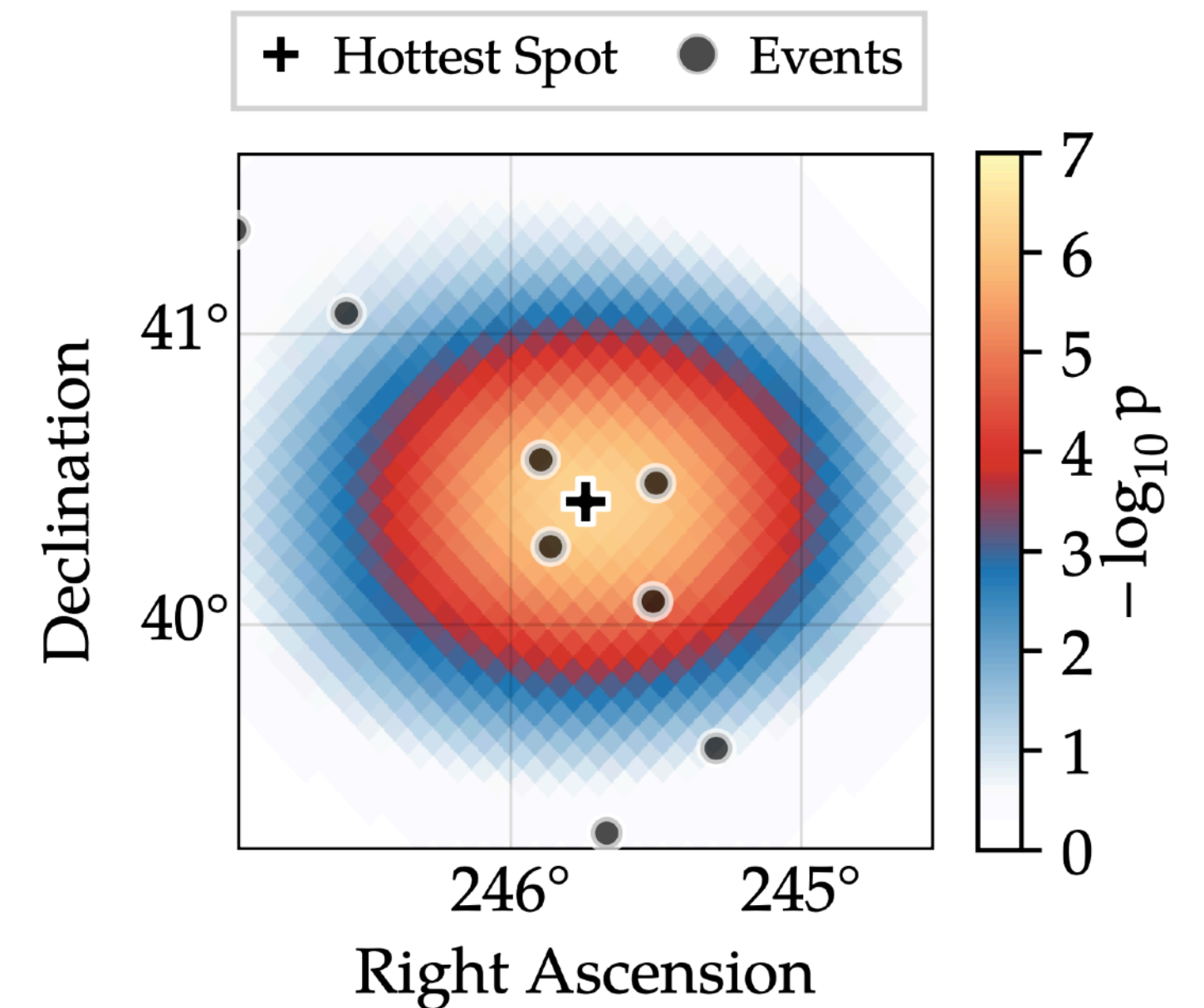
All-sky Variability Analysis (FAVA)



ALL-SKY FLARE SEARCH

RESULTS FROM ARCHIVAL DATA

- Unbiased rolling analysis on the entire sky
- Hottest spot (May 2011 – March 2019):
($\alpha = 245.7^\circ$, $\delta = 40.4^\circ$)
 - Neutrino cluster in 9.4 d
 - Post-trial significance: 0.5σ
 - No conclusive results from FAVA analysis



IACTS FOLLOW-UP TO GFU ALERTS


A PROMISING PARTNERSHIP

- After 2019:
 - 76 single track GFU bronze/gold public alerts
 - 55 neutrino multiplets private alerts to IACTs
- ➔ Partner IACTs have follow-up programs^[4].
Aim: identify VHE counterparts (for tracks)
and determine changes in state of sources (for multiplets)
 - IACTs decide whether to observe
 - Observation within a few days. Automatic repointing in specific cases



CONCLUSION & FUTURE PERSPECTIVES

WHAT AM I WORKING ON?

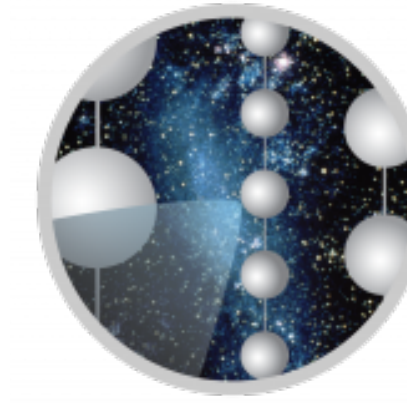
- Realtime alerts and partner telescope follow-up: non-conclusive yet
- Results from offline analysis of flare significance evolution:
No excess found yet...
- Improvements of event selection/reconstruction
- Improvements on algorithm efficiency
- Automatic self follow-up for significance evolution following alerts
- Extension of source selection for other follow-up instruments (now IACTs bias)
- Make multiplet alerts public



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THANK YOU

References:

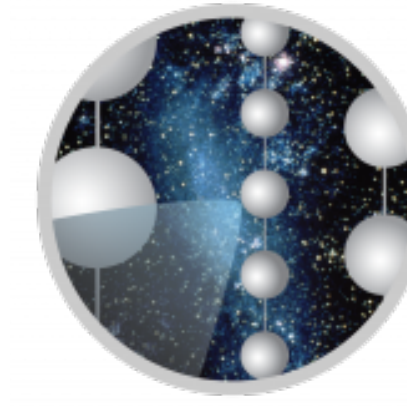
- (1) IceCube Collaboration, M.G. Aartsen et al. (Nov 27, 2013), Phys.Rev.D 89 (2014) 6, 062007, doi.org/10.1103/PhysRevD.89.062007
- (2) T. Kintscher for the IceCube Collaboration, at KM3Net Town Hall Meeting 2019, Marseille, FR indico.cern.ch/event/848390/contributions/3614228/attachments/1964044/3265348/2019_12_18_Marseille_IC2.pdf
- (3) T. Kintscher, Humboldt-Universität zu Berlin dx.doi.org/10.18452/21948
- (4) I. Viale at Neutrino2022, Zenodo. doi.org/10.5281/zenodo.6769386



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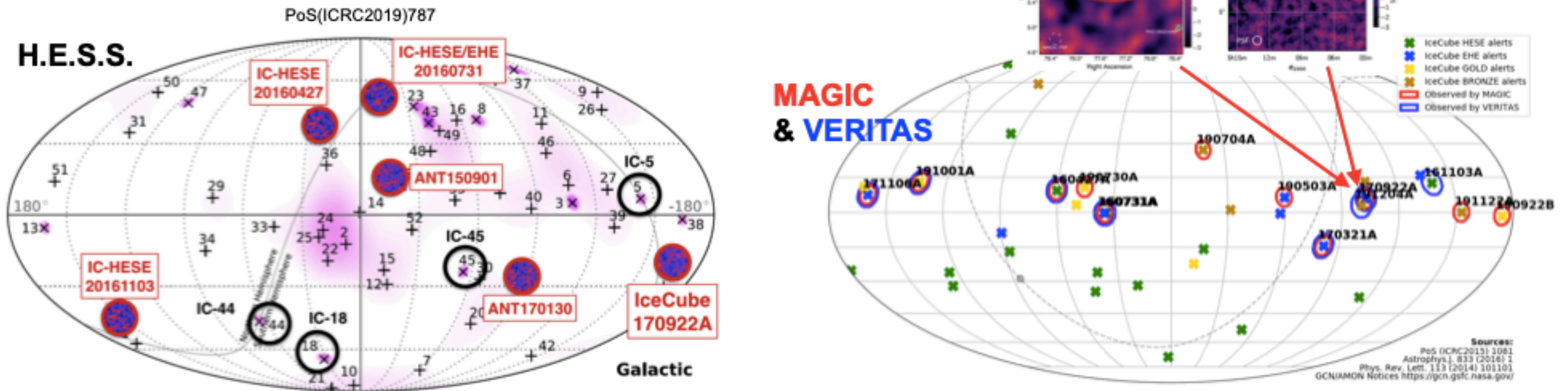
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BACKUP

Neutrino alerts follow up in VHE g-rays

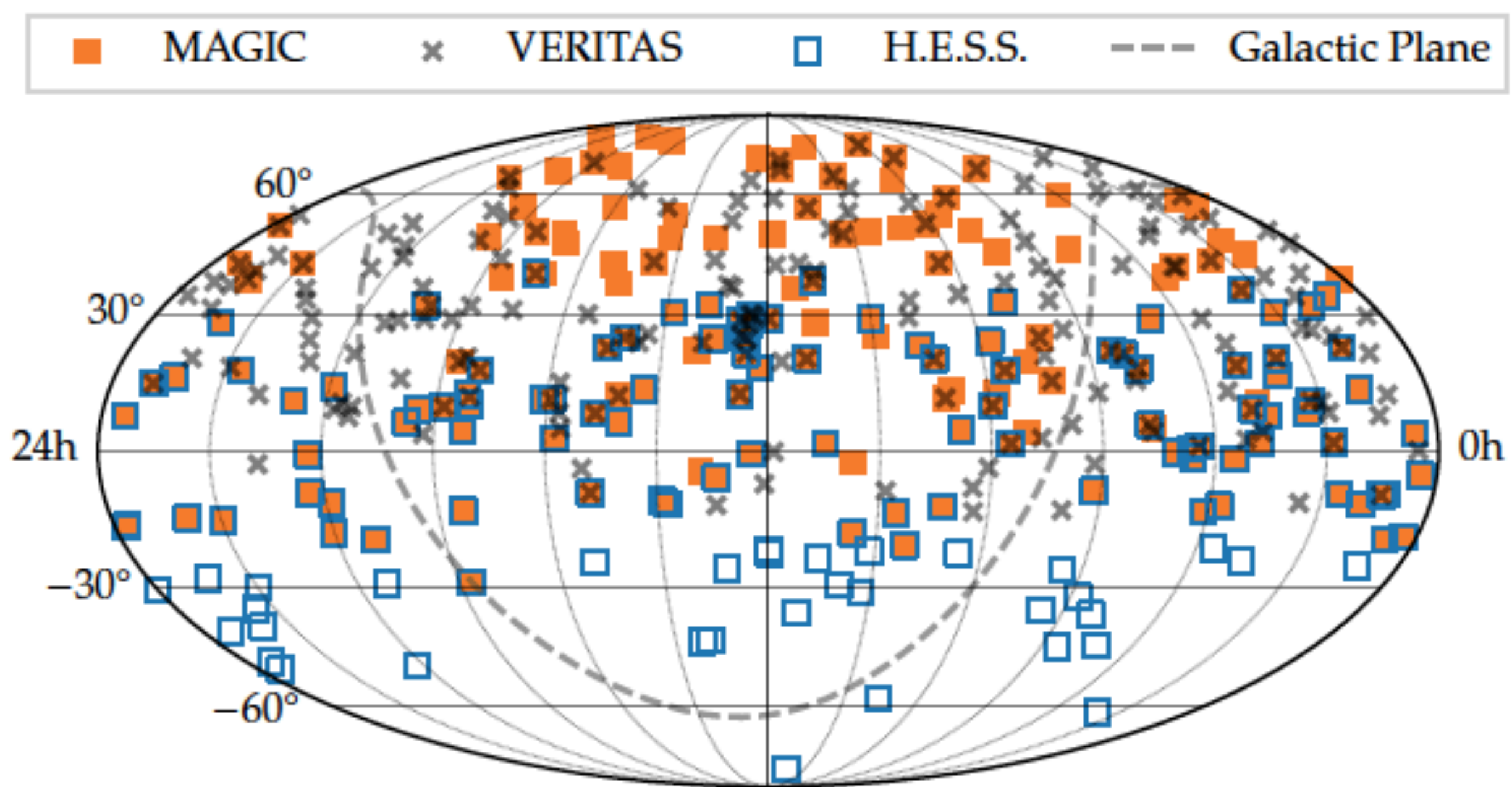


- H.E.S.S, MAGIC, VERITAS (>50 GeV) - up to 15% of their time spent on neutrino alerts follow-up
- **So far the only VHE g-ray source detected in coincidence with neutrino alert is TXS 0506+056**
- Challenges:
 - IACTs have small FoV → Need repointing (automatic for H.E.S.S. and MAGIC for GOLD alerts)
 - Limited by EBL (redshift up to ~1)
 - Dependence on source visibility, Moon, weather...
 - Large IC event localization error → how to interpret the non-detection?

SOURCE SELECTION CRITERIA

- Based on the 3FGL and 3FHL catalogs, the following selection steps are applied:

1. Extragalactic source with known redshift and $z \leq 1.0$
2. 3FGL: variability index > 77.2 ; 3FHL: variability based on Bayesian blocks > 1
3. Culmination at the IACT site within a chosen zenith angle limit (usually $< 45^\circ$)
4. Extrapolated flux above 100GeV has to exceed the IACT 5σ sensitivity for observation times between 2.5 h to 5 h



TXS 0506+056

- Sept. 22nd, 2017: EHE alert
 - Neutrino energy: 290 TeV: 56% probability for astrophysical origin
- 3FHL source in the error circle: the blazar TXS 0506+056
 - Fermi-LAT report of gamma-ray flare → plenty of follow-up observations (~1K astronomers / 70 observatories)
 - MAGIC: VHE gamma-ray detection at 6.2σ
 - Chance coincidence? Disfavored at 3σ
- TXS would have triggered 2 alerts prior to 2017

