Realtime Alerts and Archival Searches for Time-Evolving Neutrino Flares Using the IceCube Gamma-Ray Follow-Up (GFU) Platform

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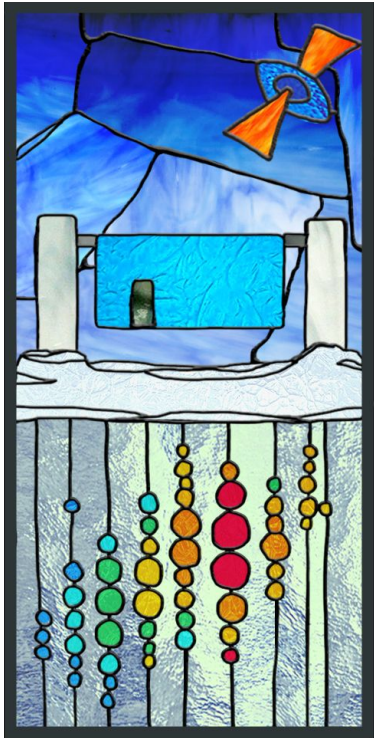


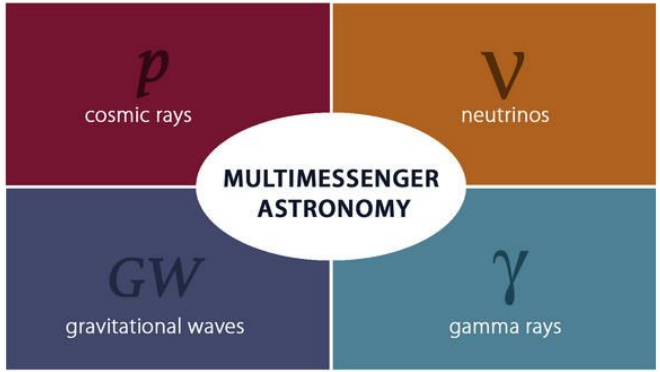
Università degli Studi di Padova
IceCube Neutrino Observatory

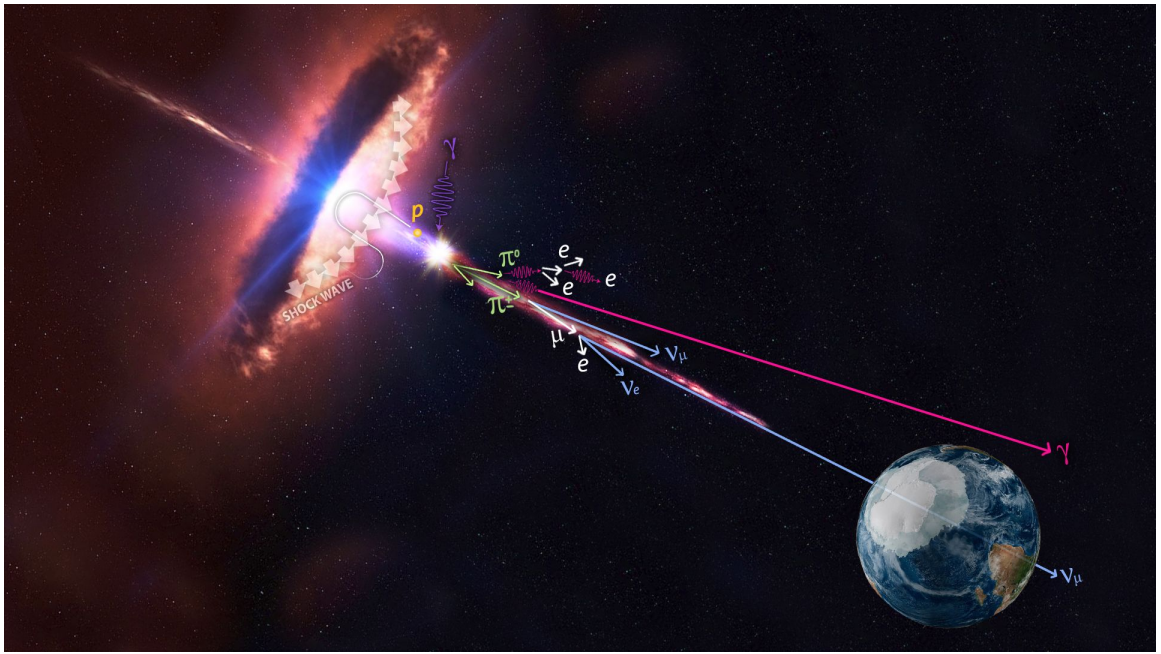
Neutrinos and multimessenger astrophysics

High energy neutrinos produced as secondaries in astrophysical beams

Time correlation with other cosmic messengers can help identify neutrino sources

IceCube has developed various neutrino alert streams including **Gamma ray Follow-Up (GFU) Alerts**





Realtime neutrino alerts and the era of multimessenger astrophysics

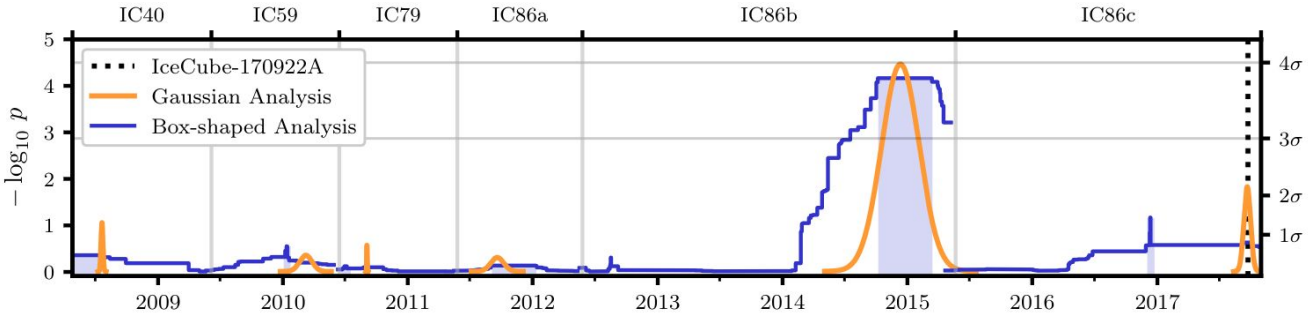
IceCube has ~100% duty cycle and view of full sky

Send prompt alerts to pointing telescopes

TXS 0506+056 example (2017):

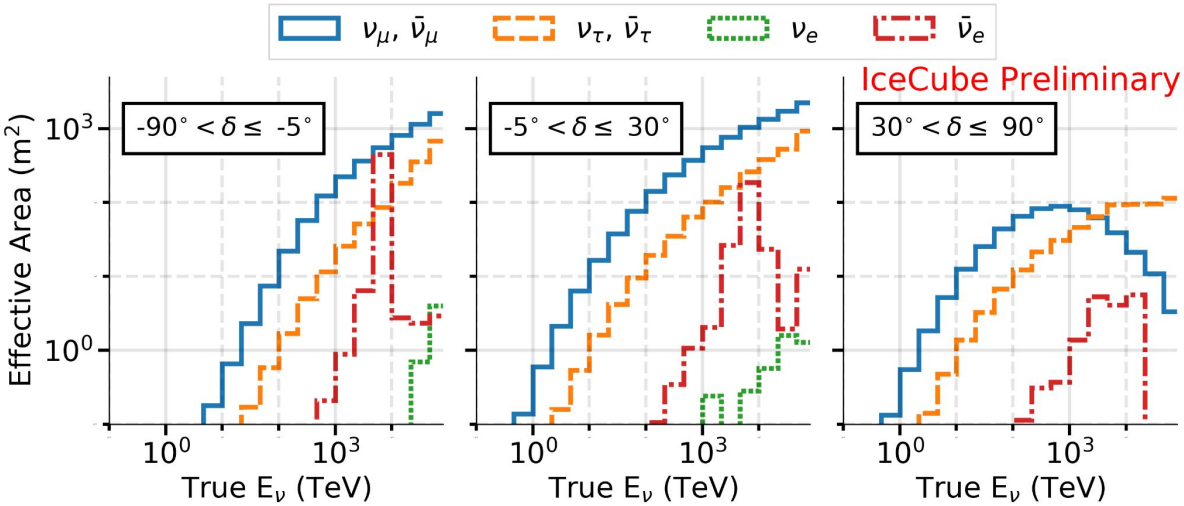
- Neutrino alert seen in coincidence with gamma ray flare from TXS 0506+056 (~3σ)
- Archival neutrino flare in 2014-15 from blazar (~3σ)

IceCube, NSF



Science 361, 147-151 (2018)

IceCube's GFU Event Selection: optimized for time-dependent realtime neutrino source searches



Larger effective area = greater signal acceptance

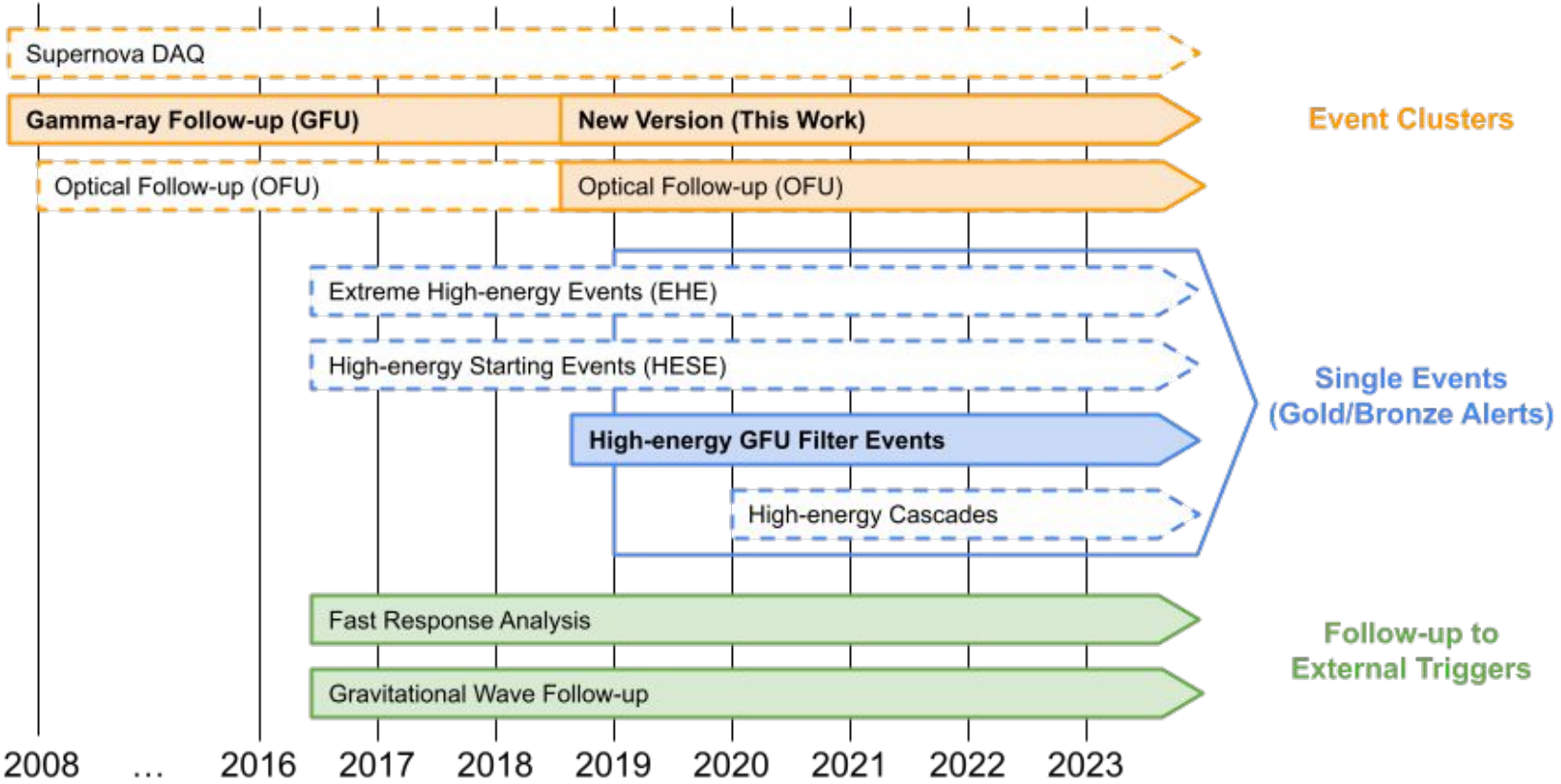
Goal: Select astrophysical muon neutrino events for rapid transfer north

Time-dependency reduces background, prioritize signal acceptance

Events must be high energy in southern sky to reduce atmospheric muon background

Classes of IceCube realtime alerts

Several alert streams many of which use the GFU event selection



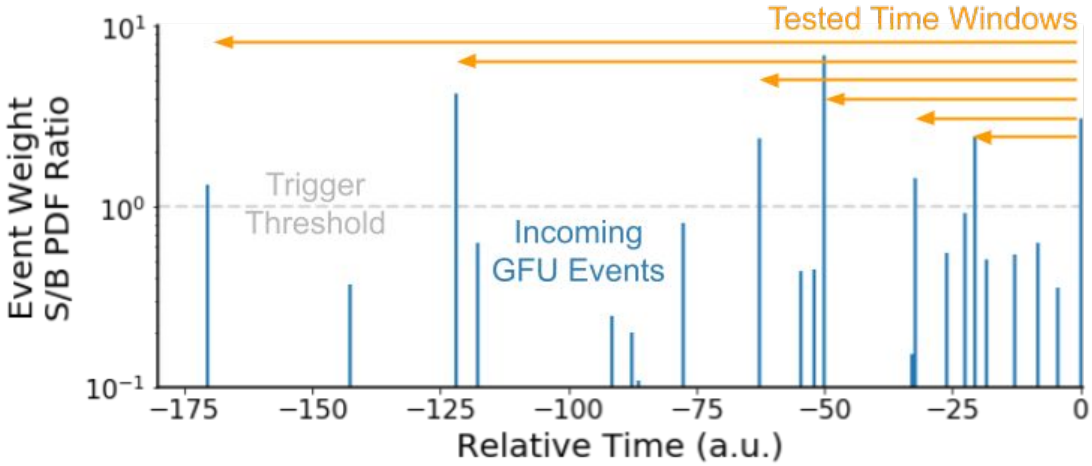
Neutrino flare alerts algorithm (GFU alerts)

Event clustering alert

Goal: Look for coincident neutrino and gamma-ray emission

Identify neutrino flares as they begin to evolve

Send alerts to imaging air cherenkov telescopes (IACTs) for follow-up



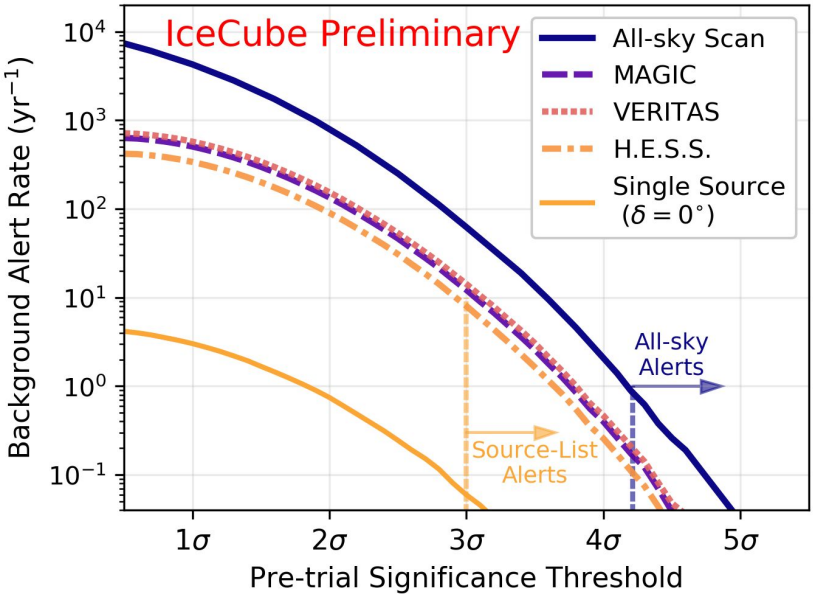
Alert method:

1. Evaluate if signal over background likelihood > trigger threshold
2. Build time windows with previous trigger events
3. Select time window that results in max test statistic (TS)
4. Calculate local p-value with max TS
5. Send alert if local p-value > defined threshold

GFU Source list vs. Allsky alerts

GFU alert stream has two different modes: Source list and Allsky

Send out alerts for both with different p-value thresholds



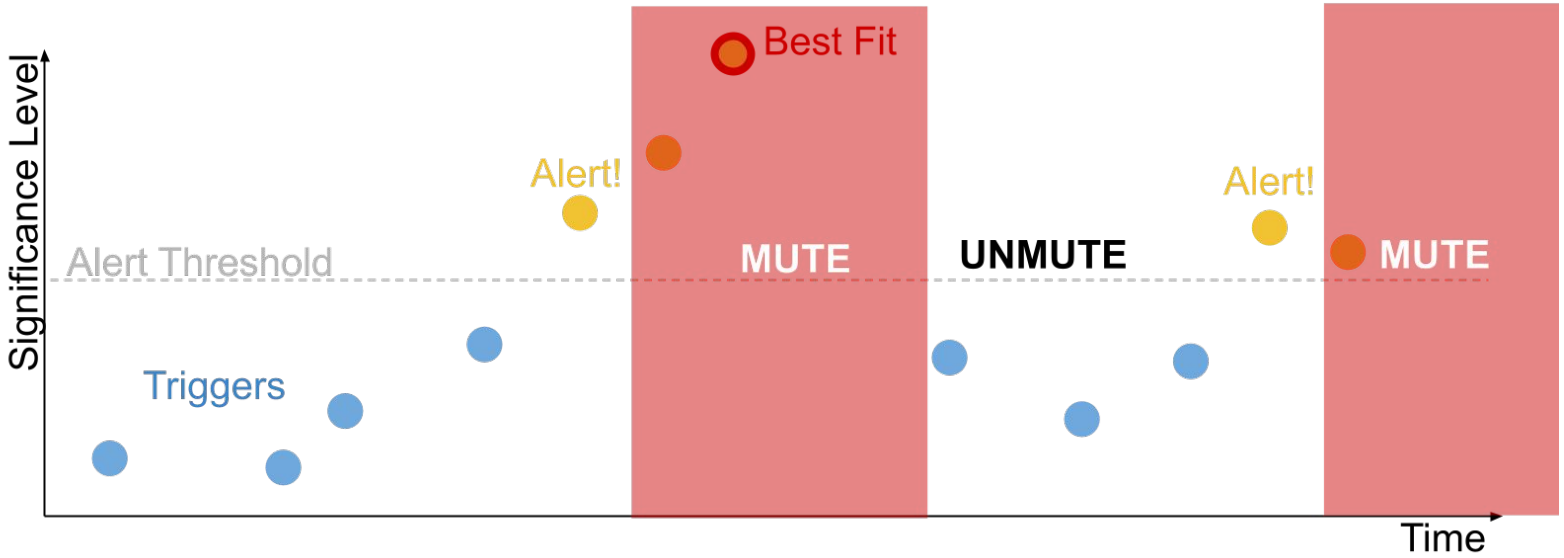
Source list alerts (model dependent)

- Test location of nearby AGN that are highly variable in gamma-rays
- Pro: reduces trials factor
- Con: relies on model assumptions
- Con: $z \leq 1$ bias

Allsky alerts (model independent)

- Test pixels around incoming events
- Pro: can identify previously unknown/unexpected sources
- Con: large number of trials

Muting system to prevent alert spamming

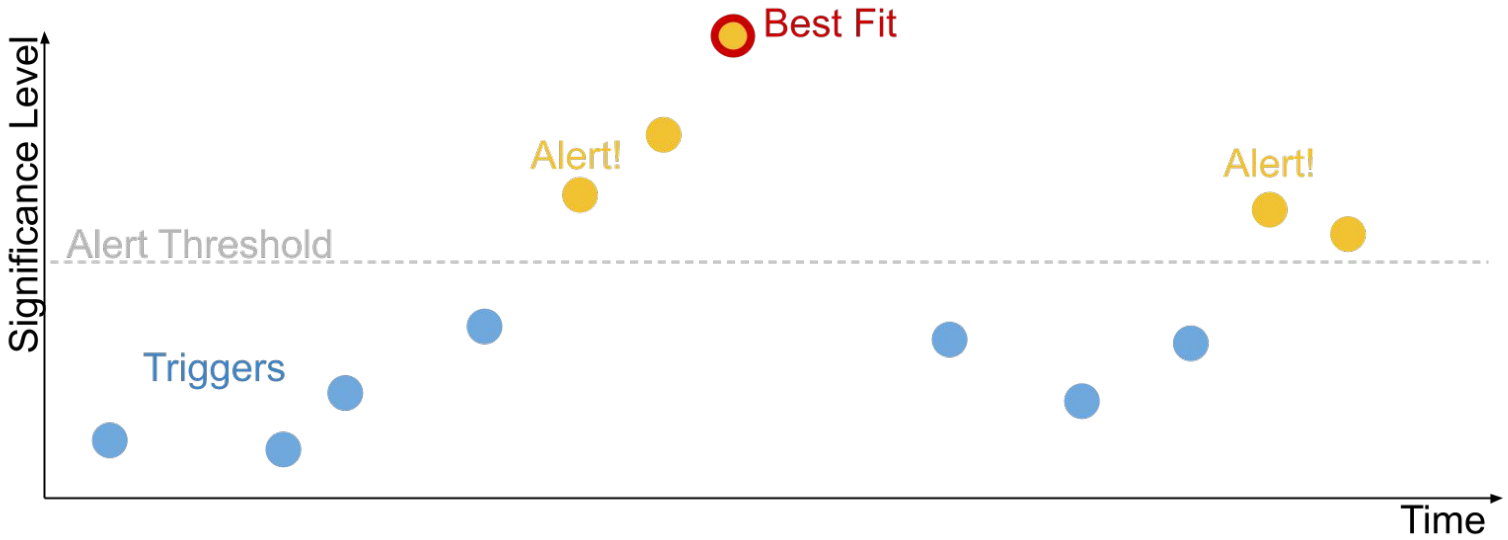


To prevent spamming of alerts:

- MUTE: after first alert level trigger
- UNMUTE: after first sub-alert level trigger

Con: obscures behavior of source after first alert

Offline analysis of GFU alerts



Run source list and allsky analyses on 11.5 years of archival data

Goals:

- study evolution of flares after alert muting
- check for flares which occurred before alert stream activation (2019)

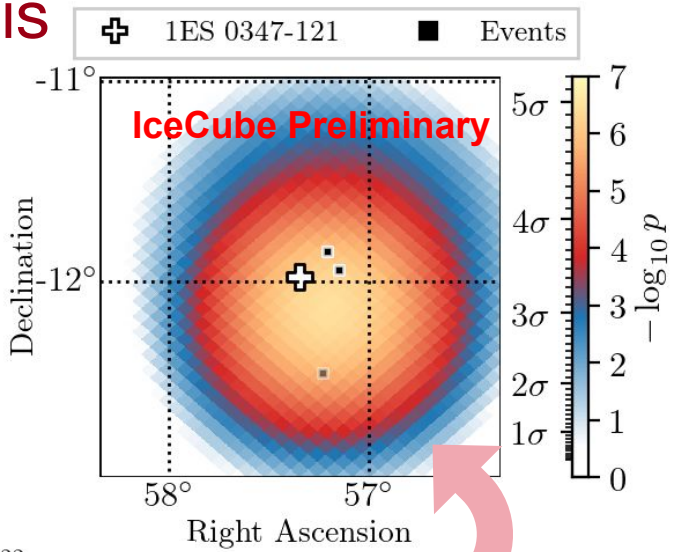
Source list results from the offline analysis

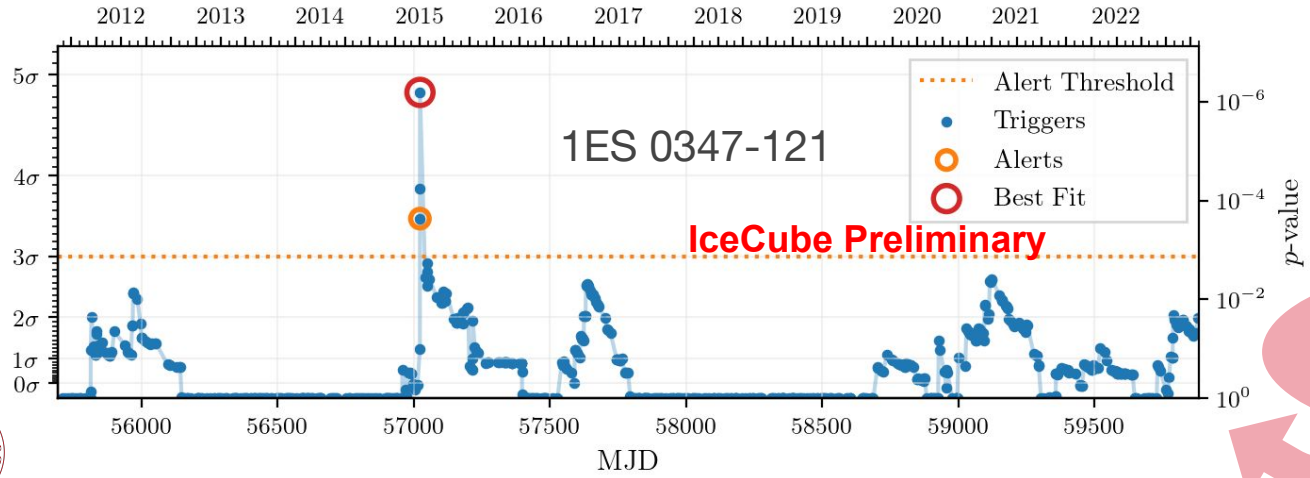
Best fit source: 1ES 0347-121 (δ=-11.98°)

4.84σ local → 1.81σ post-trial significance after correcting for all trials from all triggers for all sources

Best fit flare parameters: 6.9 hours and 3.93 events

Archival alert - occurred before current alert stream





Localization around best fit flare time

Time evolution of GFU p-value around source

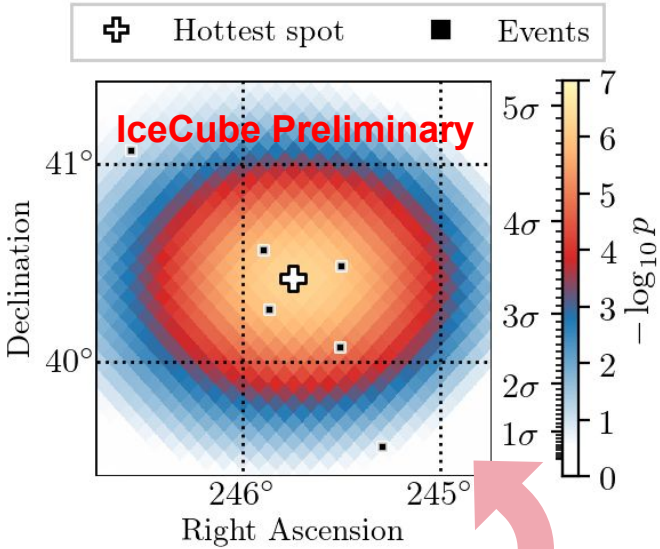
Allsky results from the offline analysis

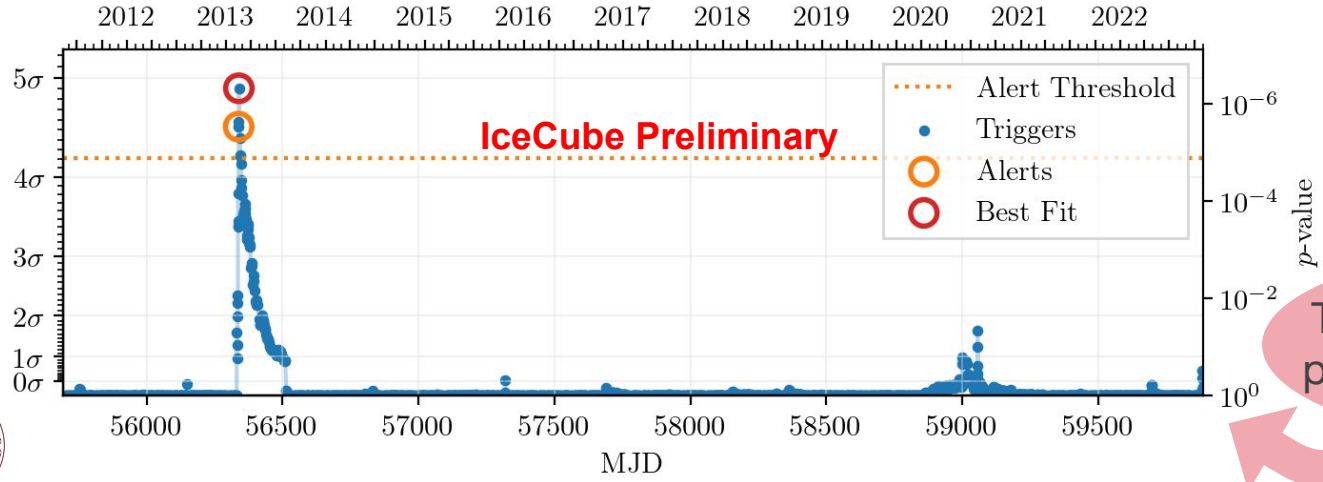
Most significant flare (hotspot) in allsky found in the northern sky (δ=-40.42°)

4.90σ local → 0.482σ post-trial significance after correcting for all trials from all triggers across whole sky

Best fit flare parameters: 9.4 days and 10.7 events

Archival alert - occurred before current alert stream



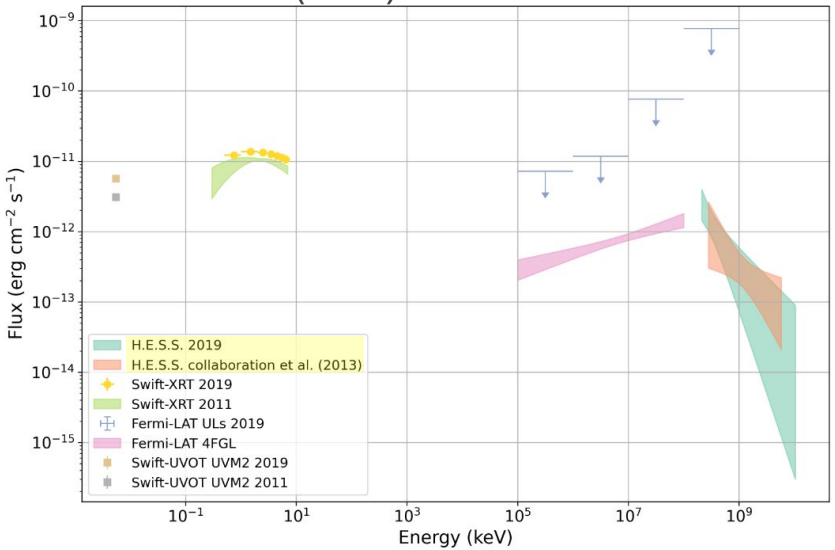


Localization around best fit flare time

Time evolution of GFU p-value around hotspot

Conclusions and future improvements to the GFU alerts

Source: 1ES 1312-423
Multiwavelength spectral energy distribution (SED) around GFU alert time



Example of GFU follow-up by IACT from [F. Schüssler, PoS (ICRC 2023) 1501]

Gamma-ray Follow-Up (GFU) alerts aim to identify potential neutrino flares

Send GFU alerts to high energy gamma-ray imaging air cherenkov telescopes (IACT)

Flares of interest from archival search cannot reject null hypothesis after trials corrections

Plans to expand and update the operation of GFU in the future:

- Use more modern event selection, reconstruction, and analysis techniques
- Update source list with increasing knowledge of neutrino sources
- Share alerts with other observatories beyond IACTs

Backup Slides

Archival Allsky analysis skymap

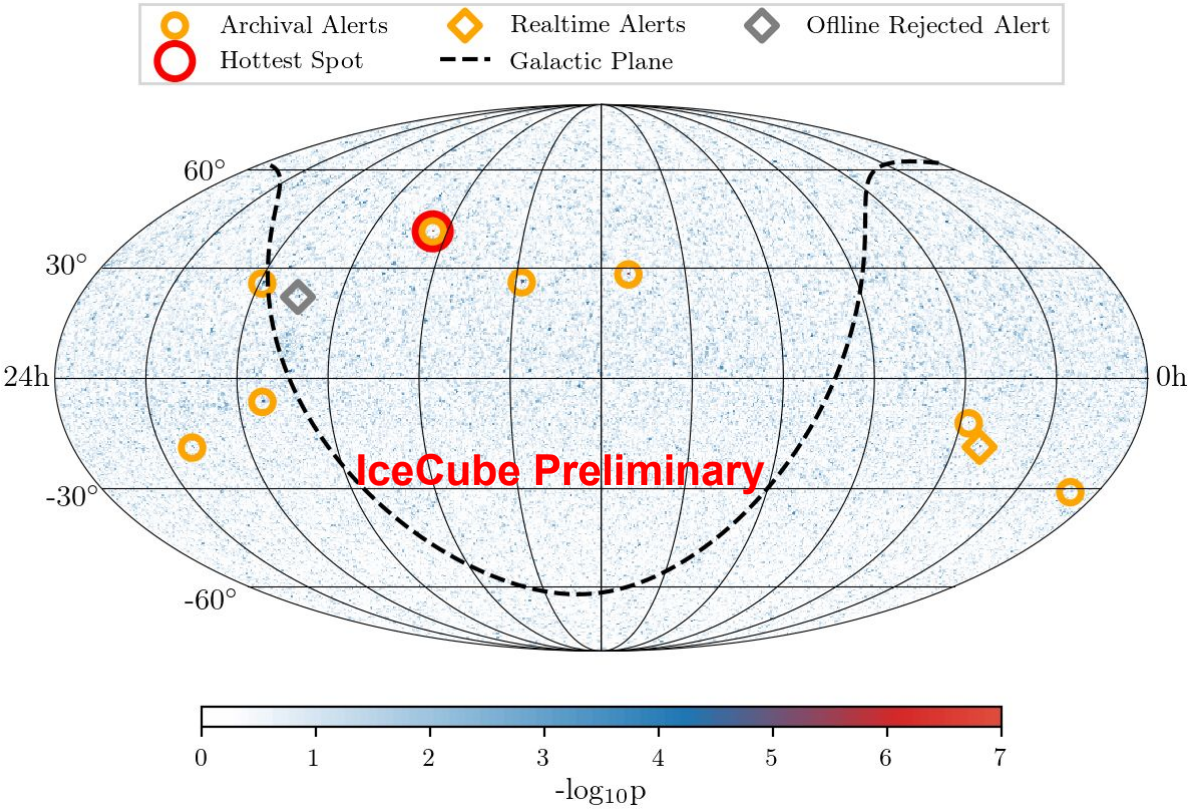


Figure: local p-value for most significant flare at each pixel

Find 9 point in archival allsky data where local p-value > threshold

At the moment only two realtime alerts have been issued

One online alert not found in archival analysis

⇒ Contributing events located in detector data later flagged as low quality