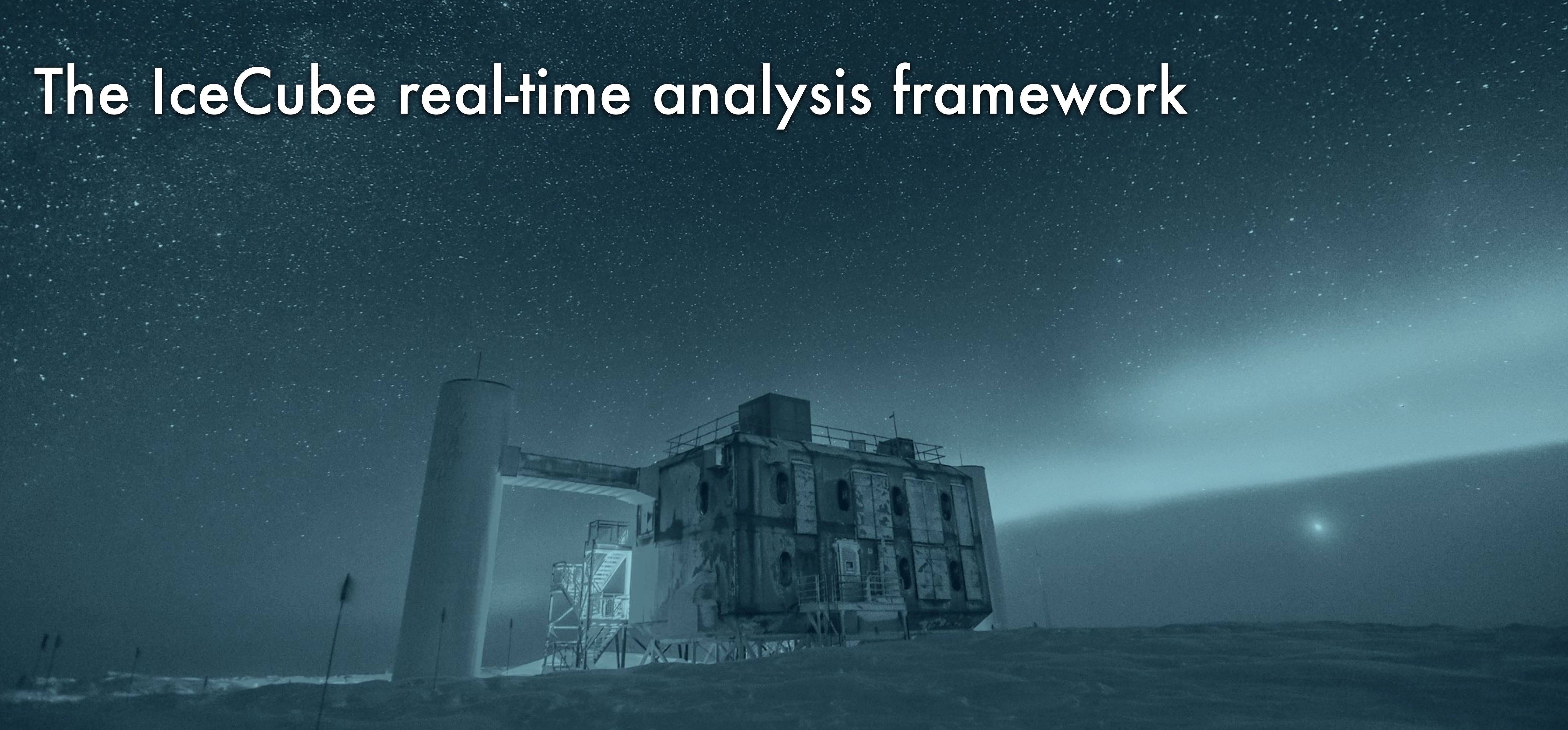


The IceCube real-time analysis framework

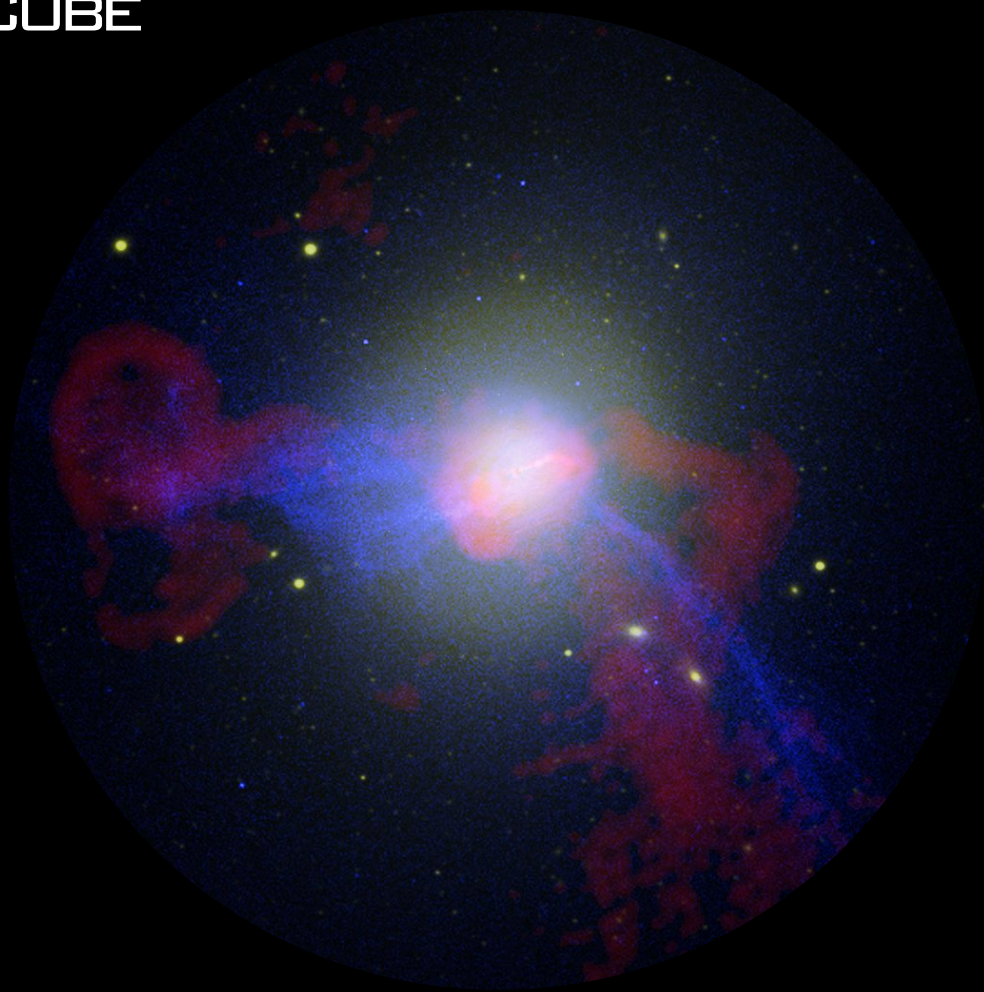


Marcos Santander
University of Alabama

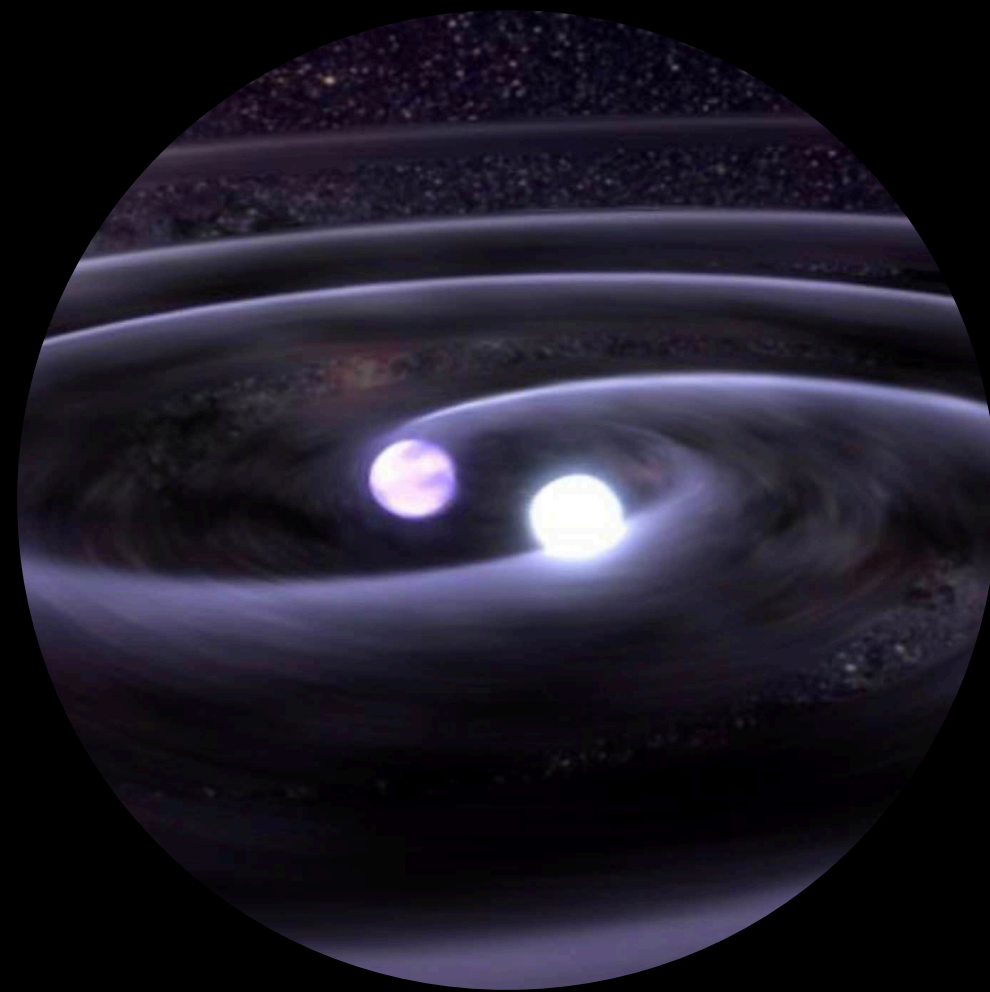
Town Hall KM3NeT meeting



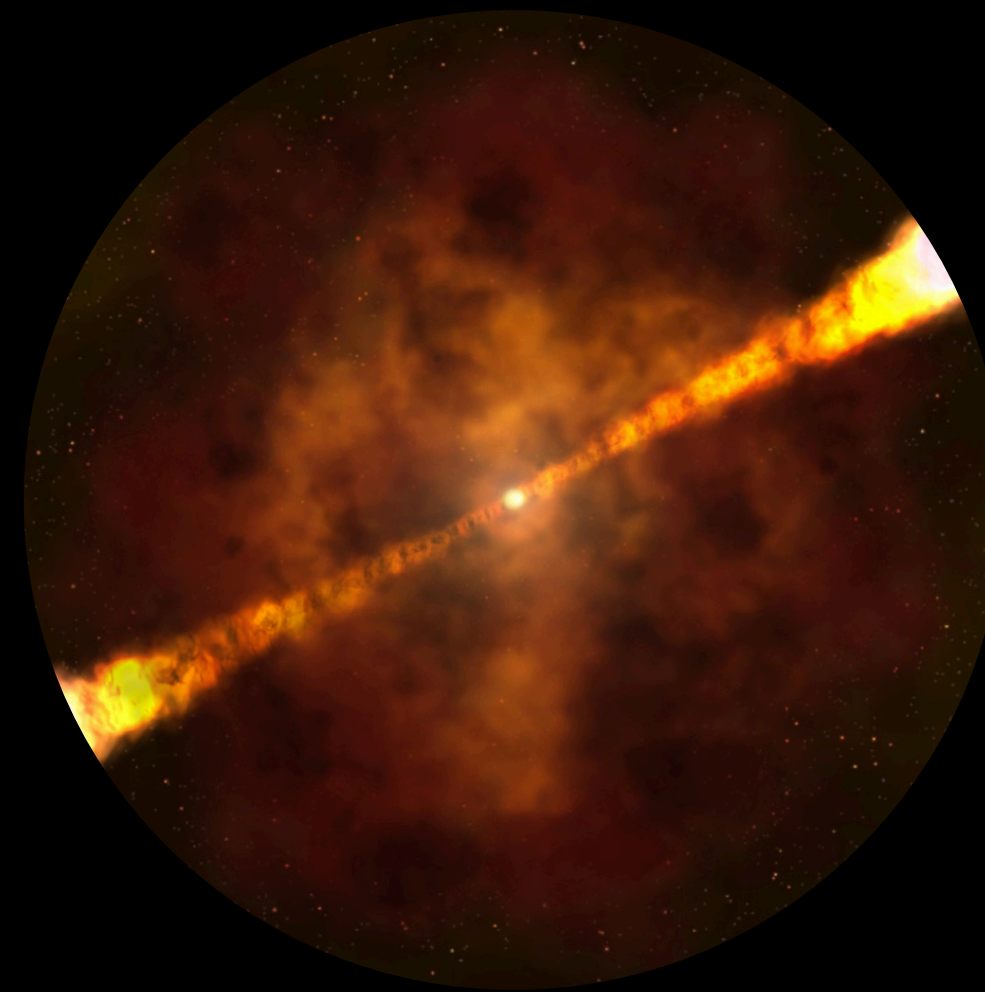
Neutrinos from transient astrophysical sources



Active galaxies



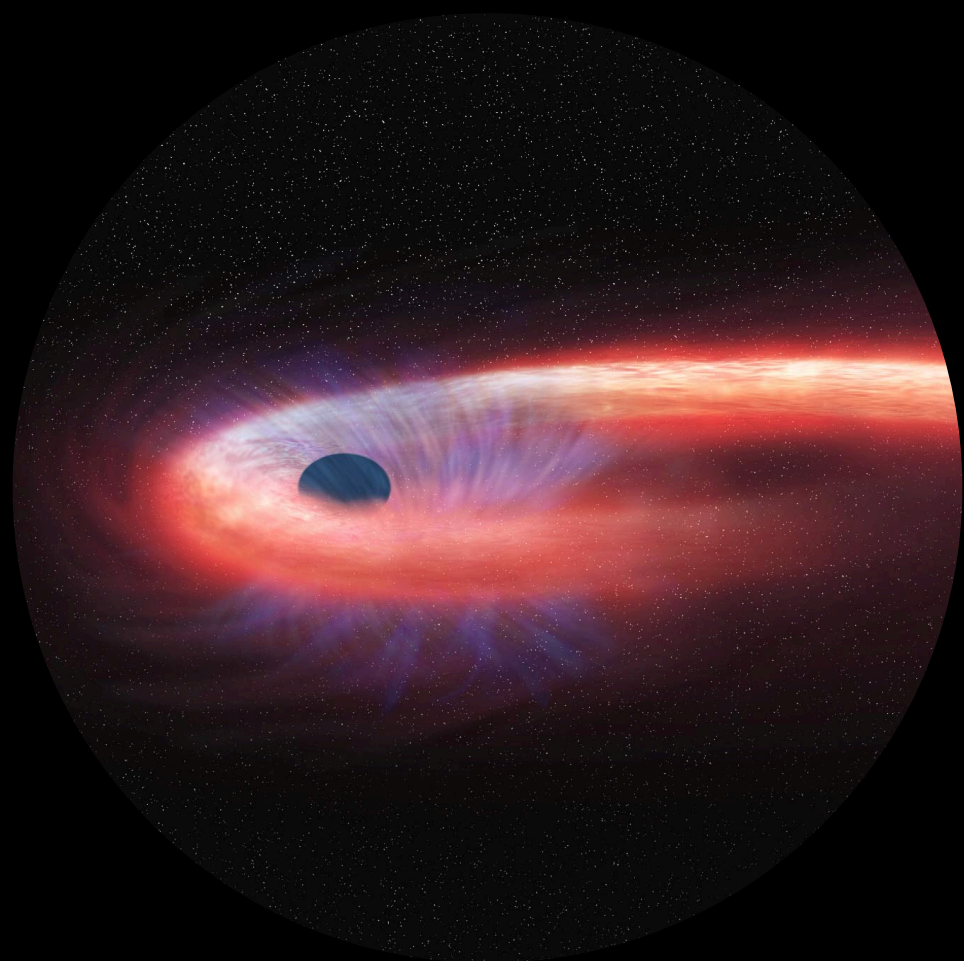
Compact object mergers



Gamma-ray bursts

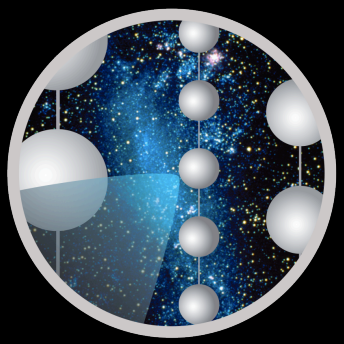


Core-collapse supernovae



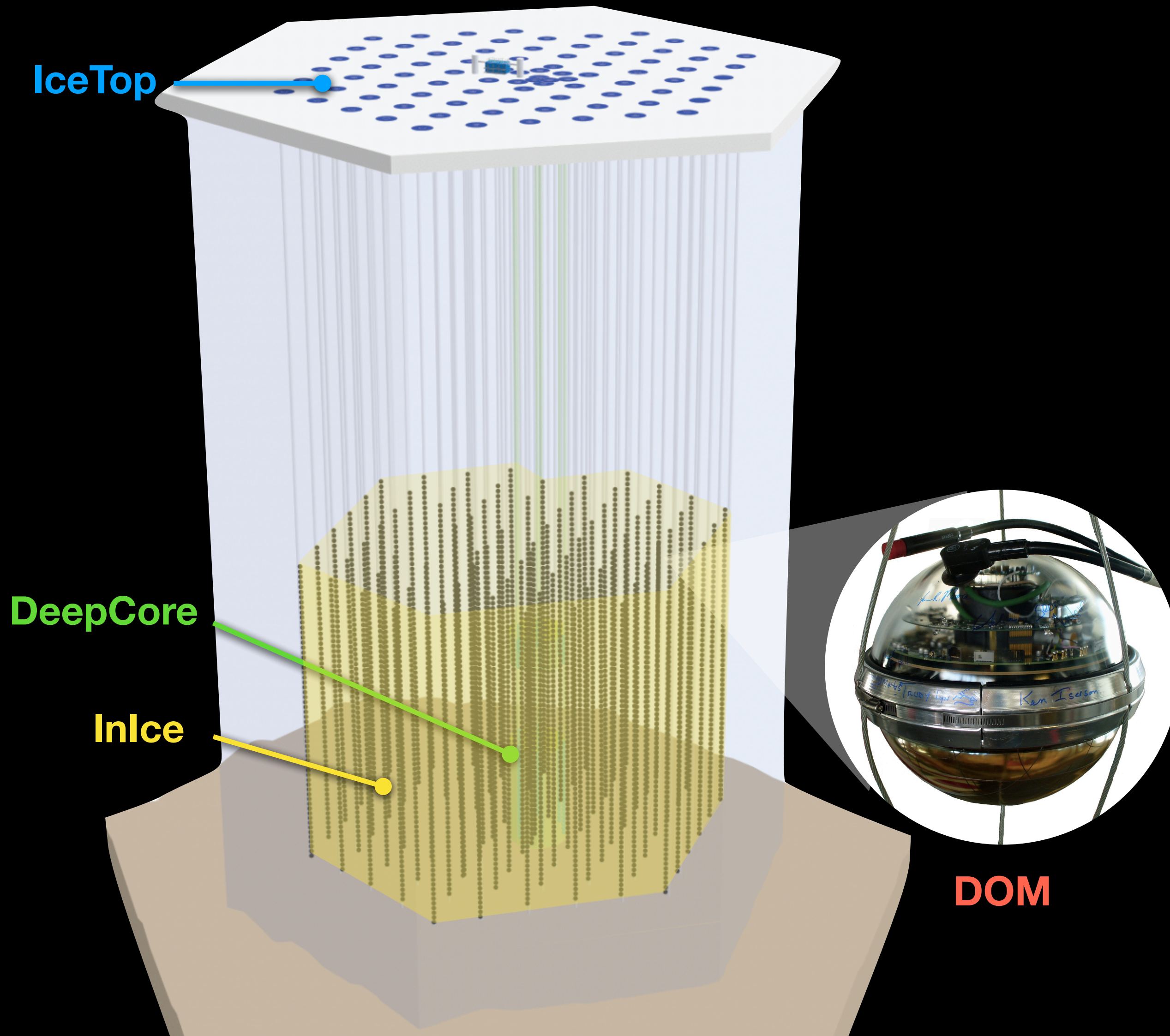
Tidal disruption events

- Transient and highly-variable persistent astrophysical sources display high-energy non-thermal emission potentially from hadronic processes.
- Searching for neutrinos correlated with known MM signals provides direct insights into particle acceleration processes in these sources.



ICECUBE

The IceCube Neutrino Observatory



- First km³-scale neutrino detector
- 4π sensitivity
- High uptime (>99%)
- Realtime program:
 - HE neutrino alerts
 - Follow-up of astrophysical events. Realtime correlations.

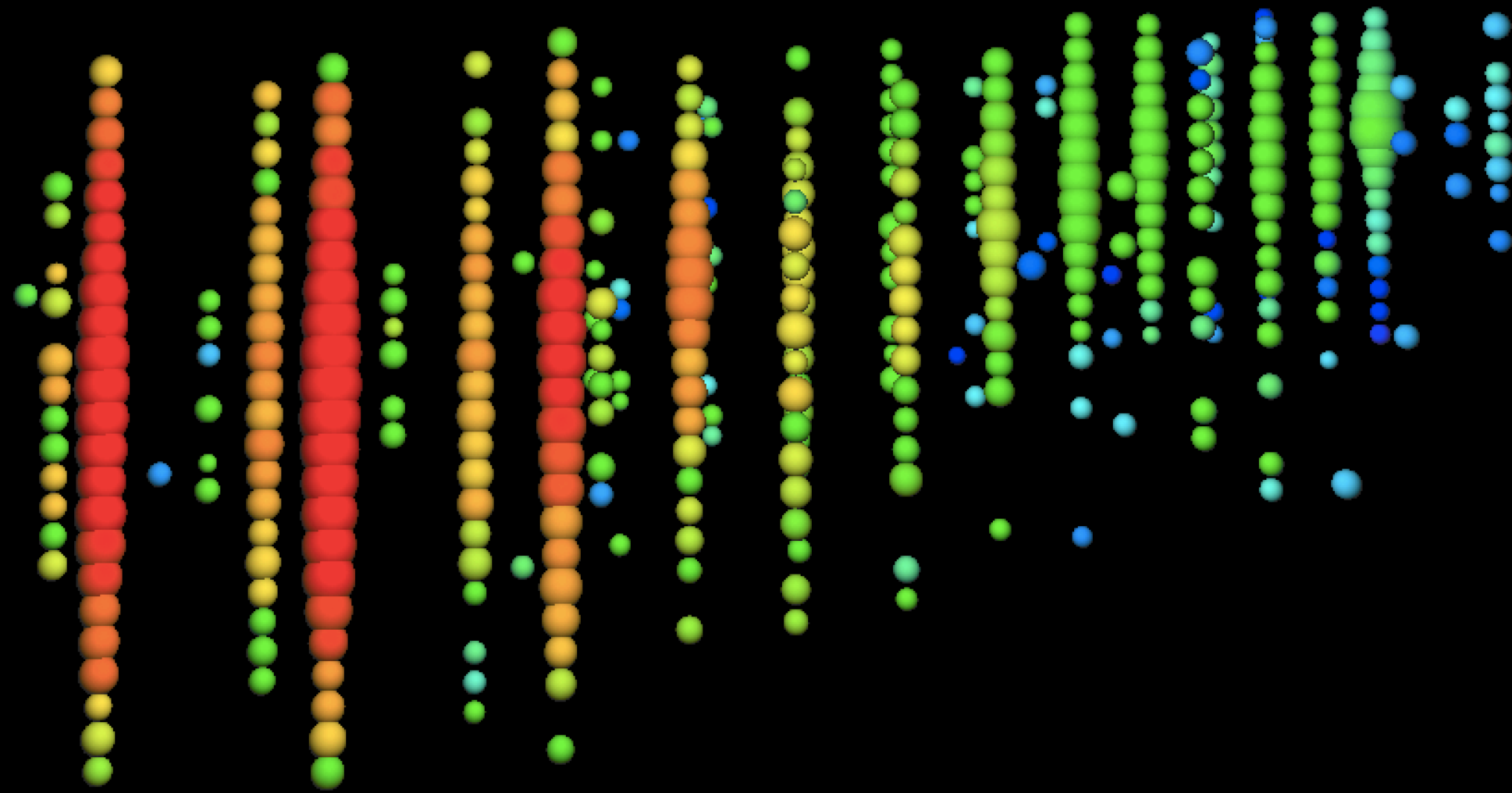
[Astropart. Phys., 92, 30, 2017]



Event topologies

Muon tracks

CC ν_μ interactions

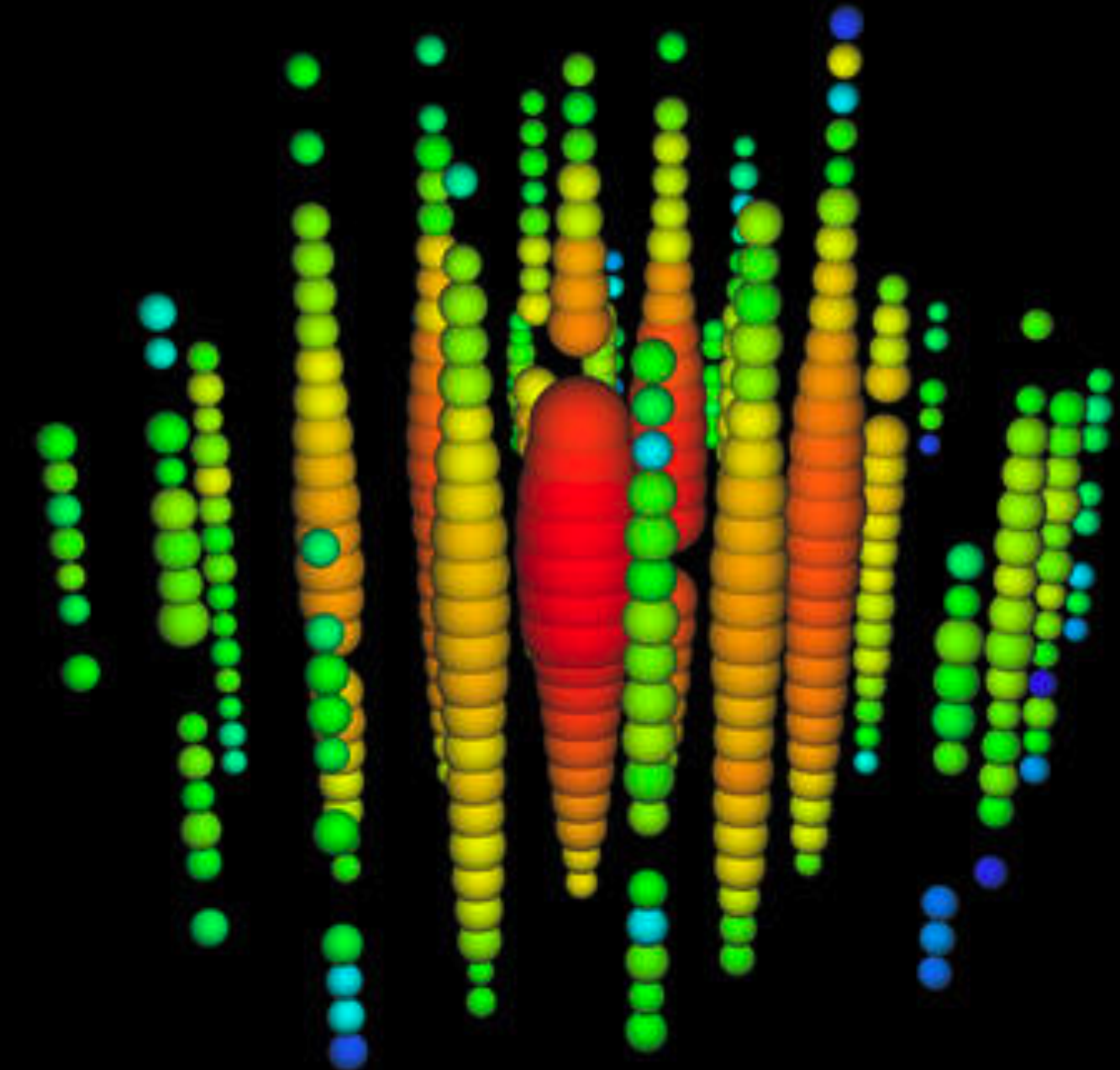


Factor of ~ 2 energy resolution on neutrino energy
($\sim 15\%$ on deposited visible muon energy)
Angular resolution 0.5° @ 10 TeV, 0.3° @ 100 TeV



Cascades

NC / CC ν_e , most ν_τ



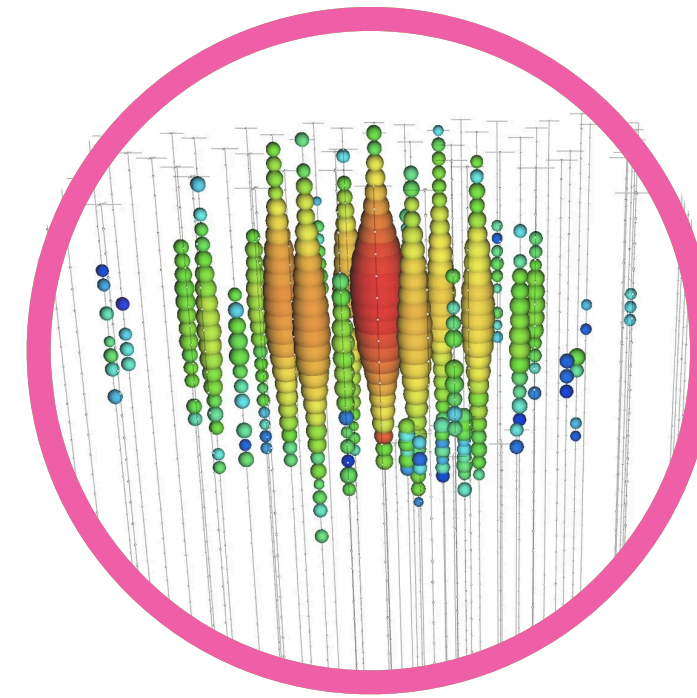
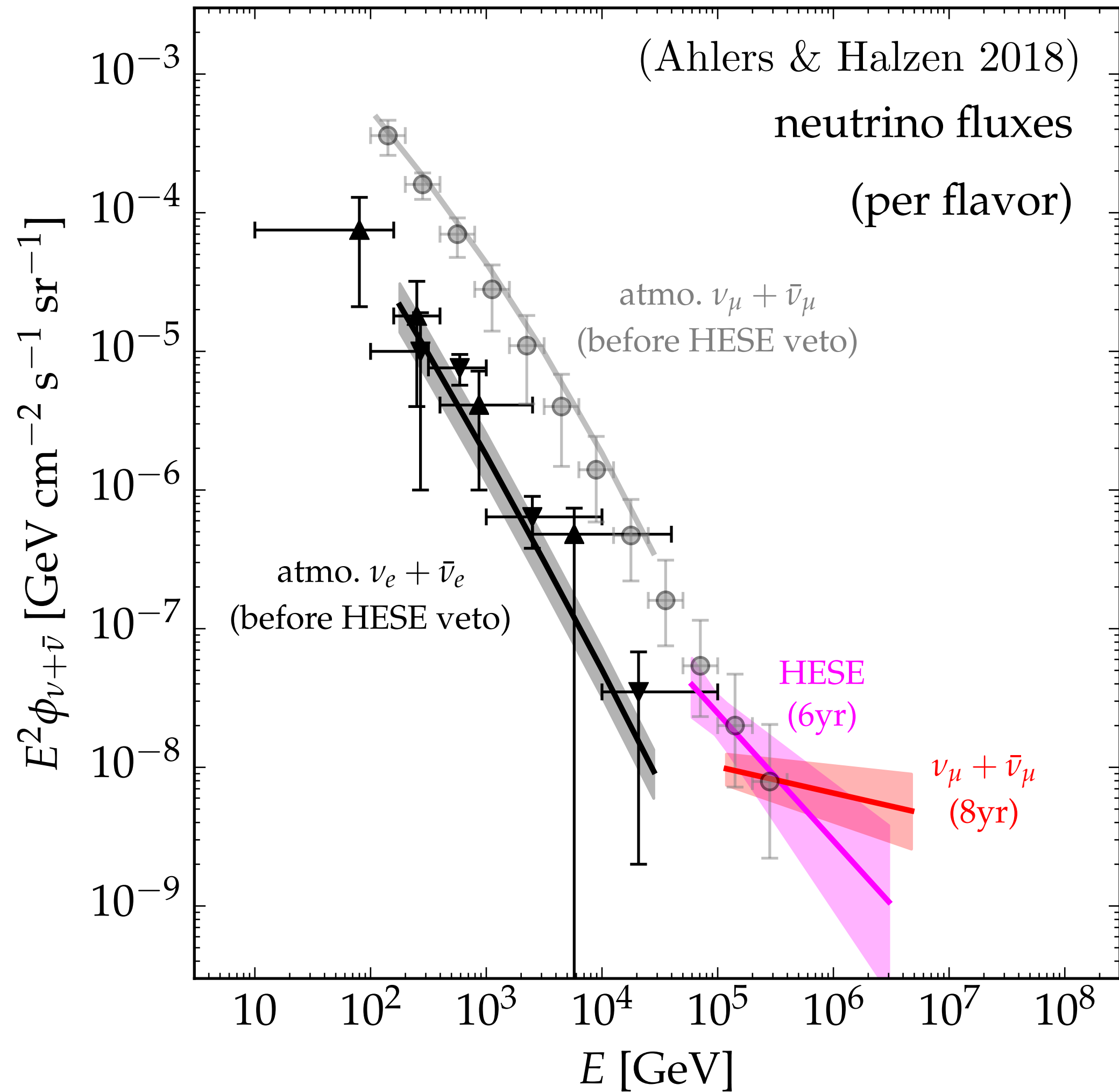
15% deposited energy resolution
 $\sim 15^\circ$ median angular resolution @ 10 TeV (8° @ 100 TeV)

Angular resolution better suited for correlating with pointing instruments

Added statistics at high energies

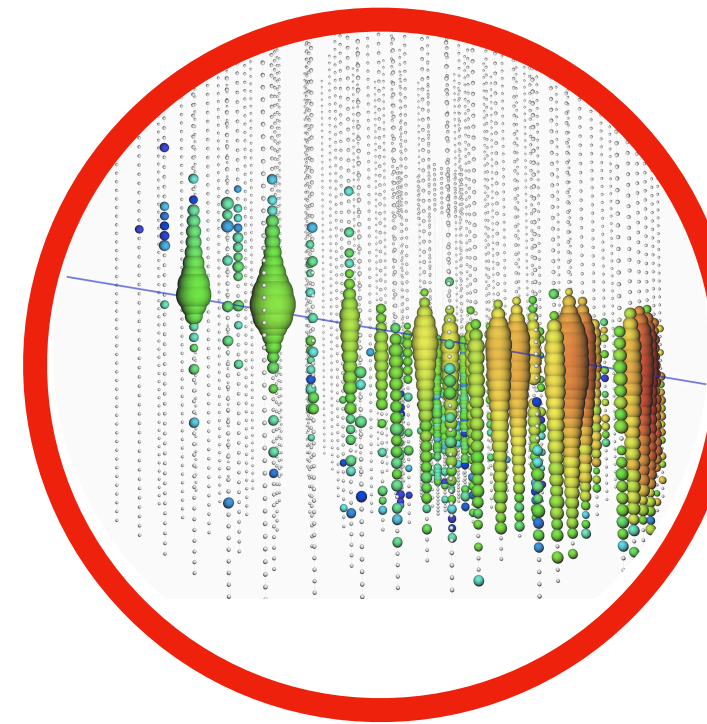


Astrophysical neutrino flux

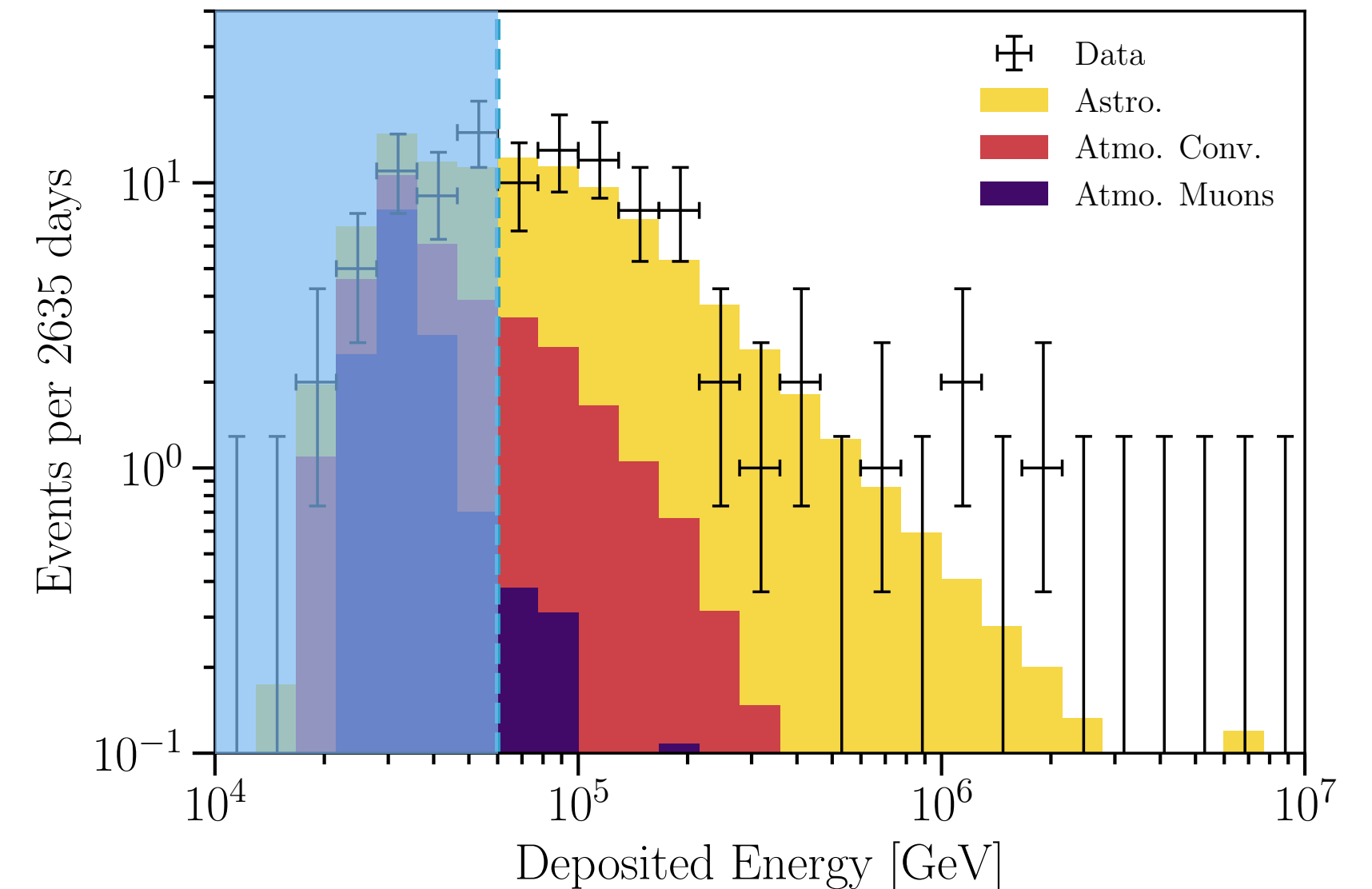


High-energy starting events (HESE)
Interaction vertex within the detector
All flavor, all sky

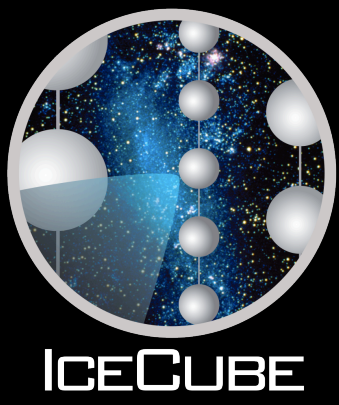
R. Abbasi et al. (IceCube)
arXiv/2011.03545



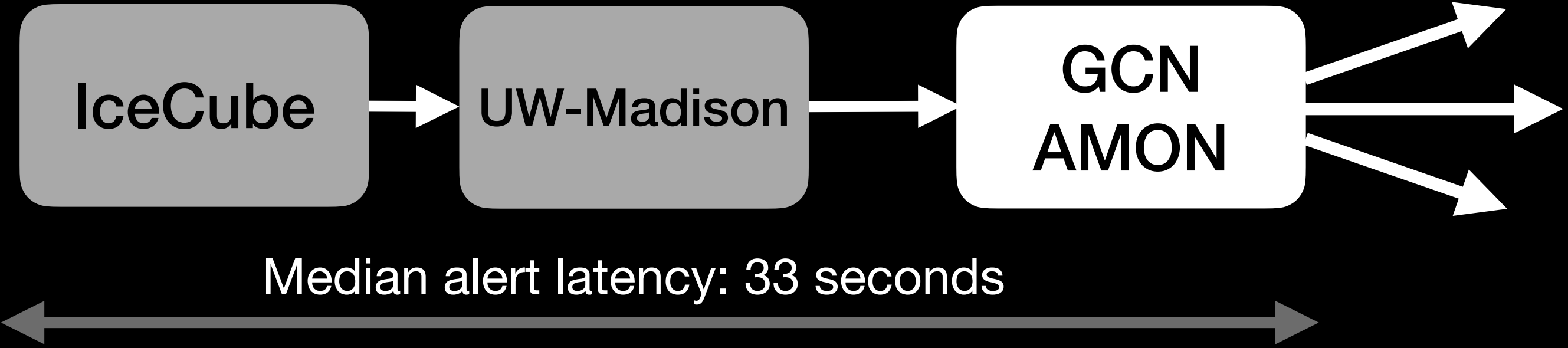
Up-going tracks
Muon-dominated
Northern sky



- Astrophysical flux in the 20 TeV - 9PeV range, **dominant over atmospheric background at $\gtrsim 100$ TeV**
- Detected in multiple analyses.



Realtime alerts



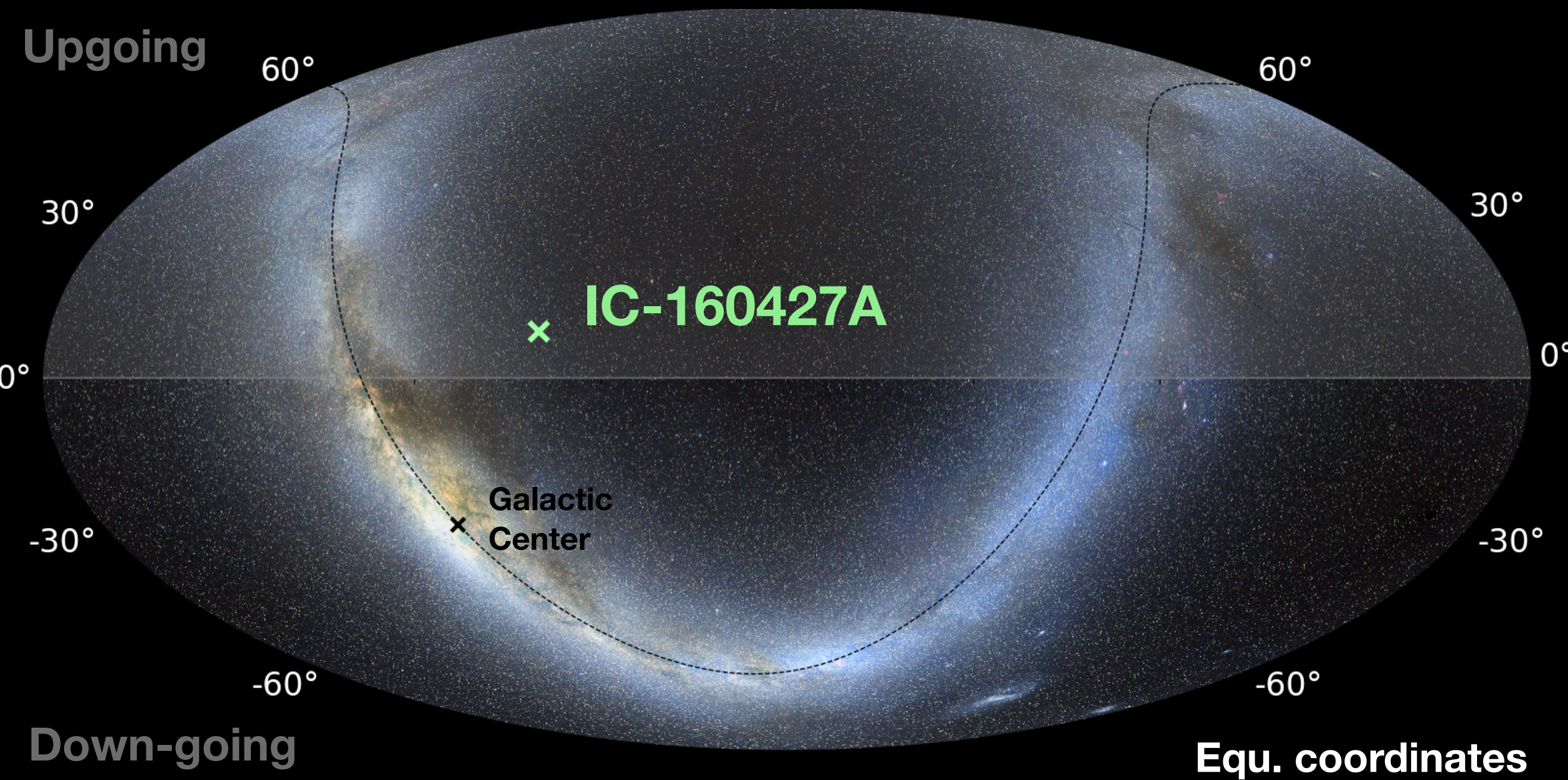
<https://gcn.gsfc.nasa.gov/amon.html>

• Original alert streams (2016-2019)

- **HESE**: HE starting muon events. Median ang. resolution $\sim 1.5^\circ$. 3-4 / year. $\sim 25\%$ astrophysical fraction.
- **EHE**: HE through-going muons. Median angular resolution $< 0.5^\circ$. 4-6 / year. $\sim 50\%$ astrophysical fraction.

• First alert on April 2016.

• Alerts issued via GCN: 18 HESE, 9 EHE.

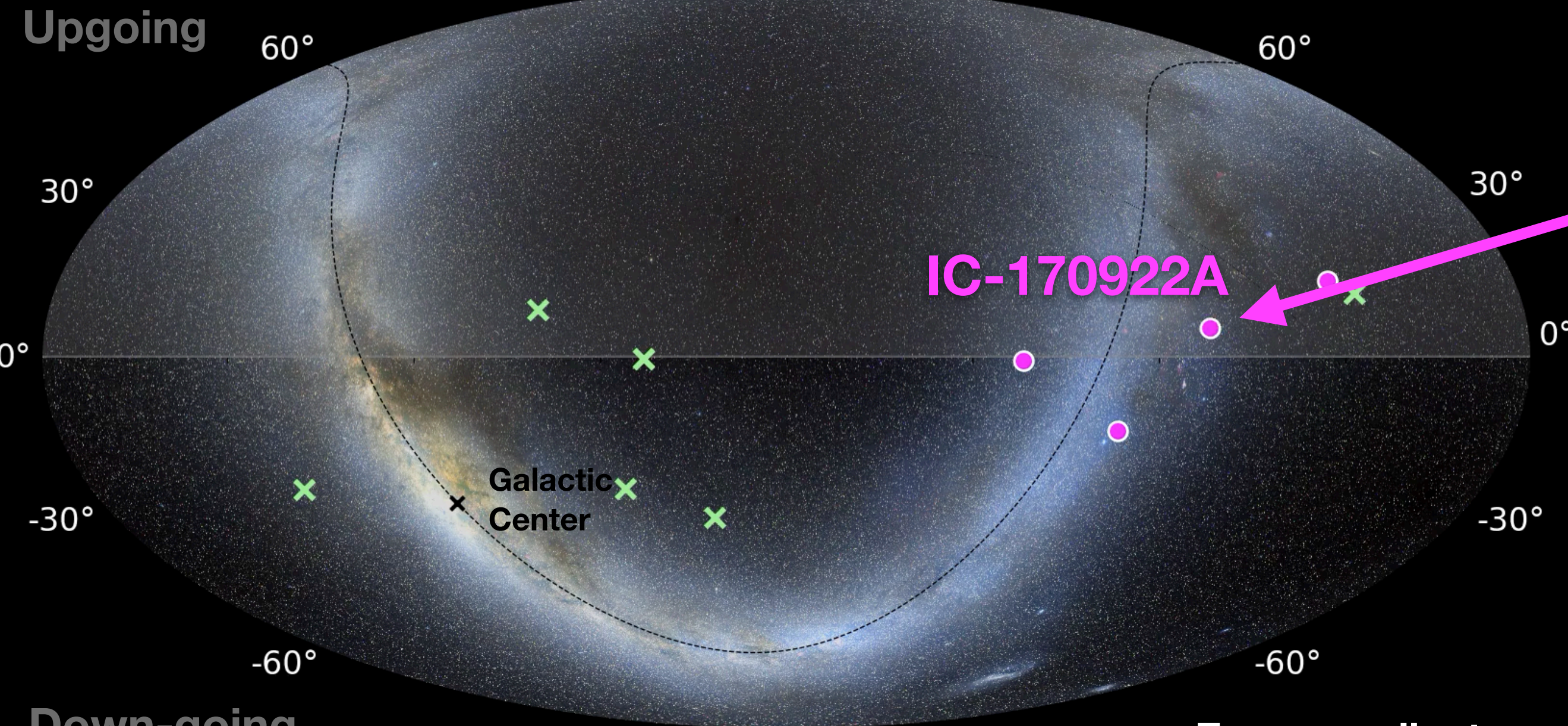


- | | | |
|-----------------------------------|--------|---------------|
| Extremely-high energy (EHE) | Bronze | Neutrino + EM |
| High-energy starting event (HESE) | Gold | Cascades |

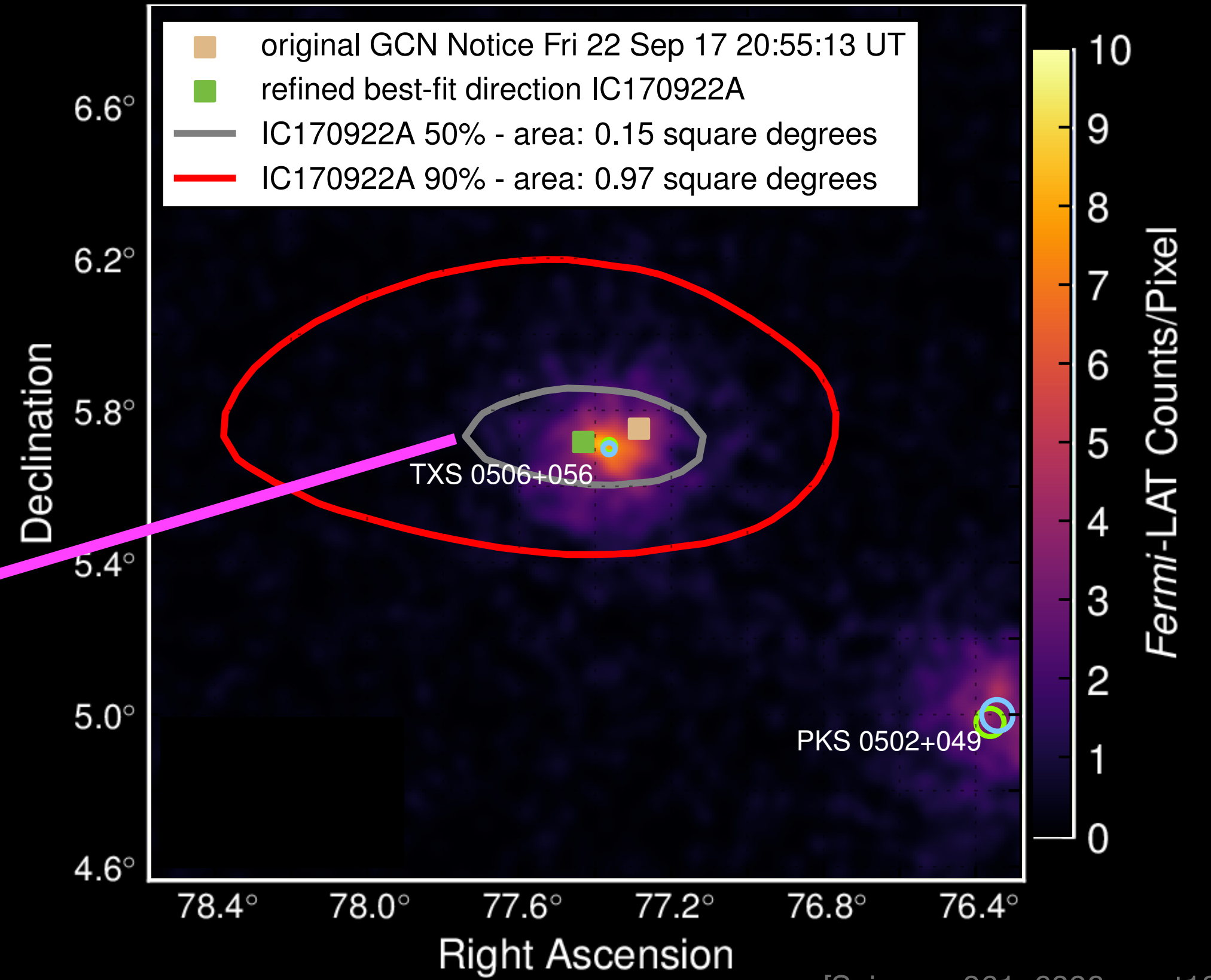


Realtime alerts

Sep 29, 2017



Fermi-LAT 0.1 - 300 GeV



[Science, 361, 6398, eaat1378, 2018]
 [Science, 361, 6398, 147-151, 2018]

- Equ. coordinates
- Extremely-high energy (EHE)
 - ▲ Bronze
 - + Neutrino + EM
 - × High-energy starting event (HESE)
 - Gold
 - ★ Cascades

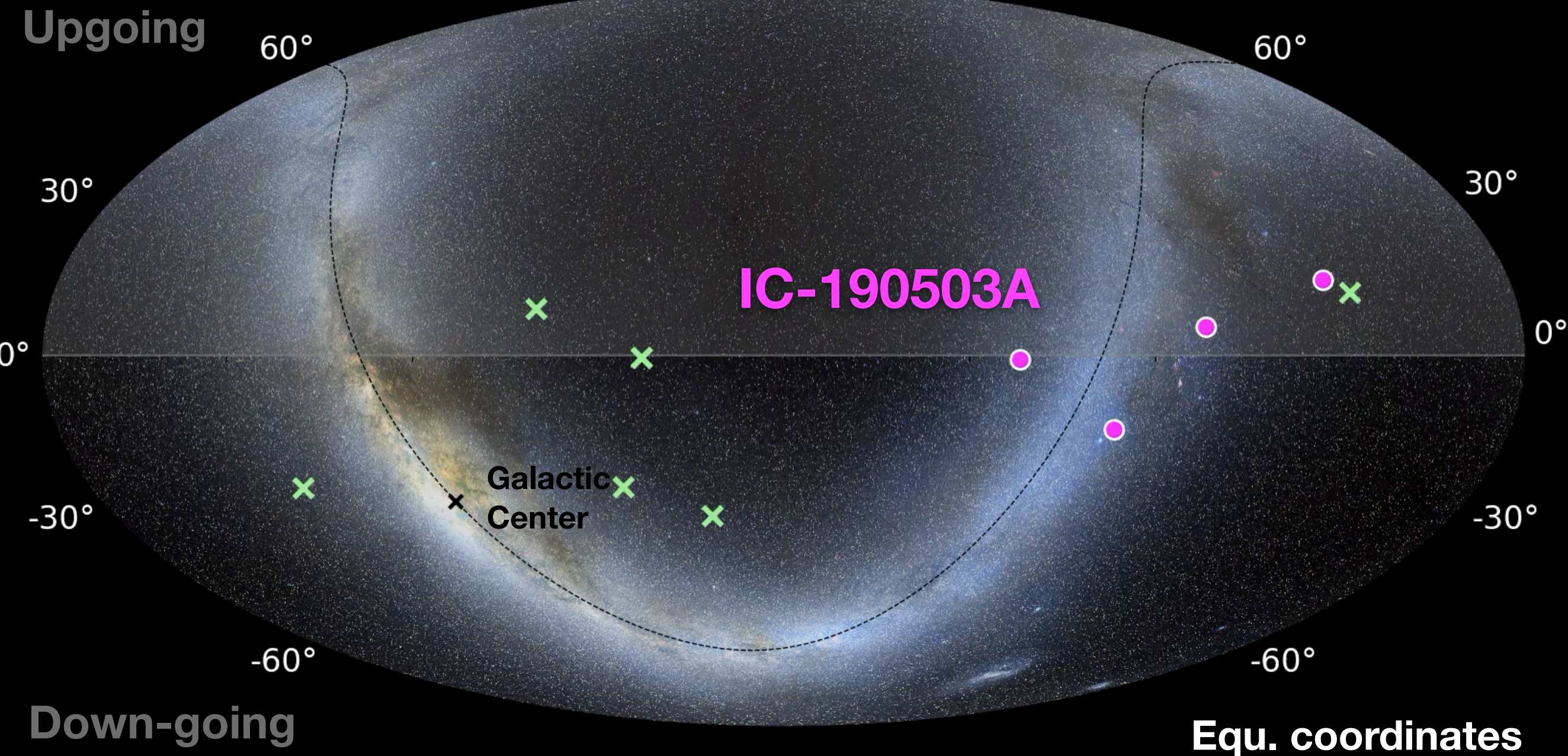
- IceCube-170922A: 290 TeV neutrino energy
- Correlated with flaring, hard-spectrum gamma-ray blazar **TXS 0506+056** (3σ). Additional neutrino emission in 2014-2015.
- Detected in VHE gamma-rays.



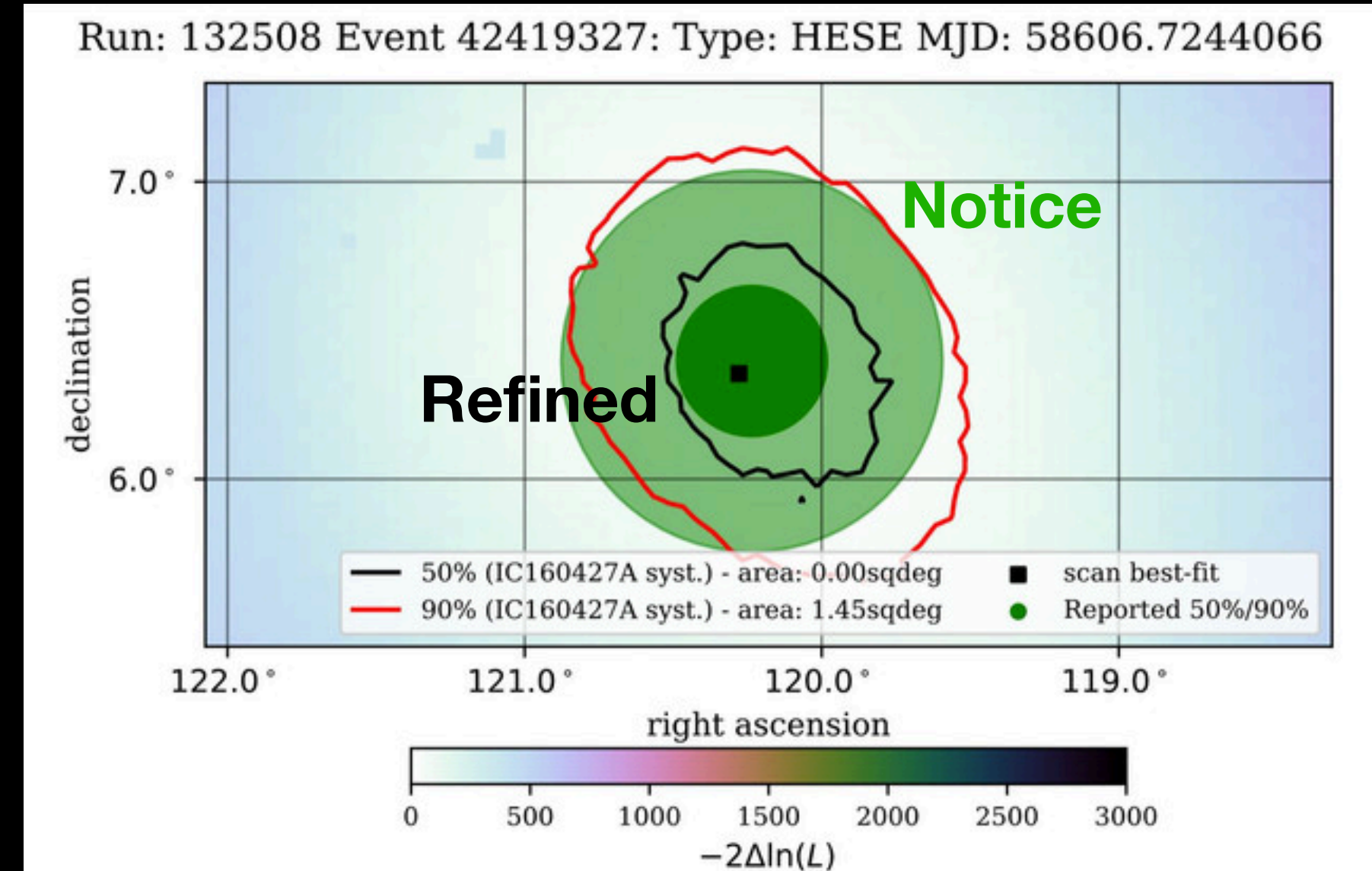
Realtime alerts

- Initial GCN Notice followed by GCN circular with refined position and error estimates (within couple of hours)

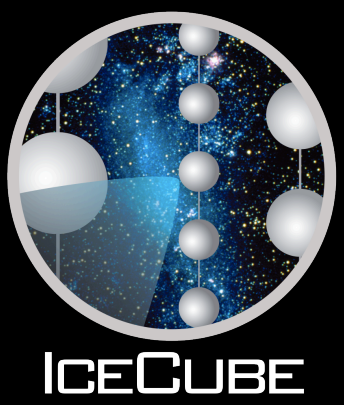
Sep 25, 2017



- | | | |
|-----------------------------------|--------|---------------|
| Extremely-high energy (EHE) | Bronze | Neutrino + EM |
| High-energy starting event (HESE) | Gold | Cascades |

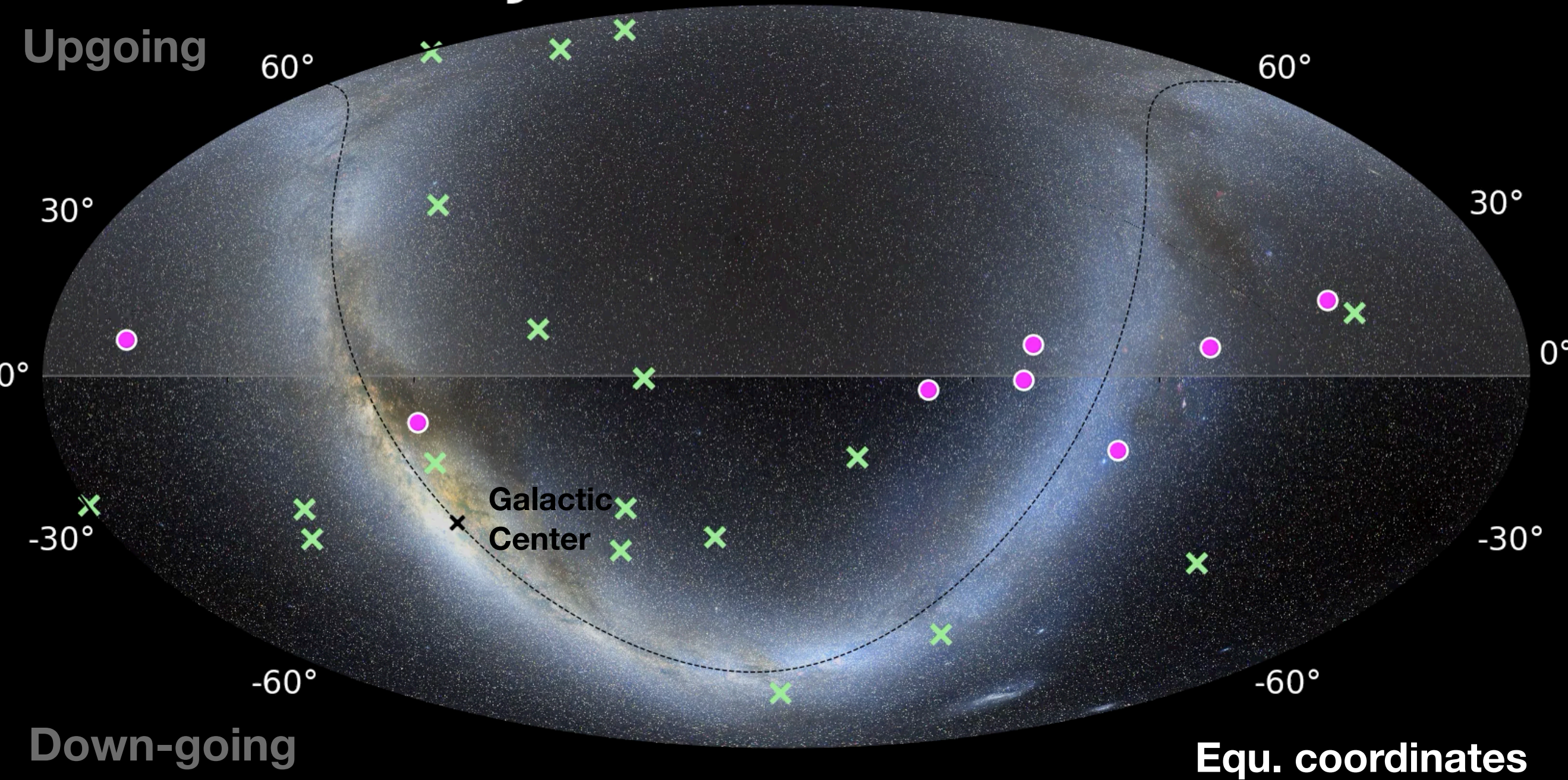


- Typically followed up by multiple multimessenger/multiwavelength facilities.
- Example: IC-190503A event**
 - ~145 TeV EHE event
 - Follows up by ZTF, ASAS-SN, Kanata, INTEGRAL, IceCube, Fermi-GBM, ANTARES, Fermi-LAT, Lick/KAIT, Swift-XRT, Insight-HXMT (9 GCNs, 3 ATels)



Realtime alerts

Jun 15, 2019



- Extremely-high energy (EHE)
- ▲ Bronze
- + Neutrino + EM
- × High-energy starting event (HESE)
- Gold
- ★ Cascades

Unified track alert streams

- Signalness = $N_{\text{signal}} / (N_{\text{signal}} + N_{\text{background}})$
- Improved selection based on signalness combines through-going and starting tracks.
- Doubled effective area at 0.1 - 1 PeV
- **Gold** stream: ~50% signalness (16 issued)
- **Bronze** stream: ~30% signalness (26 issued)

	Gold Events	Bronze Events
Signal ($E^{-2.19}$)	6.6 (Total) 5.1 (GFU) 0.5 (HESE) 2.1 (EHE)	2.8 (Total) 2.5 (GFU) 0.3 (HESE)
Atmospheric Backgrounds	6.1 (Total) 4.7 (GFU) 0.4 (HESE) 1.9 (EHE)	14.7 (Total) 13.8 (GFU) 0.9 (HESE)
Observed historical rate	9.9 (Total) 7.8 (GFU) 1.1 (HESE) 4.3 (EHE)	19.5 (Total) 18.4 (GFU) 0.9 (HESE)

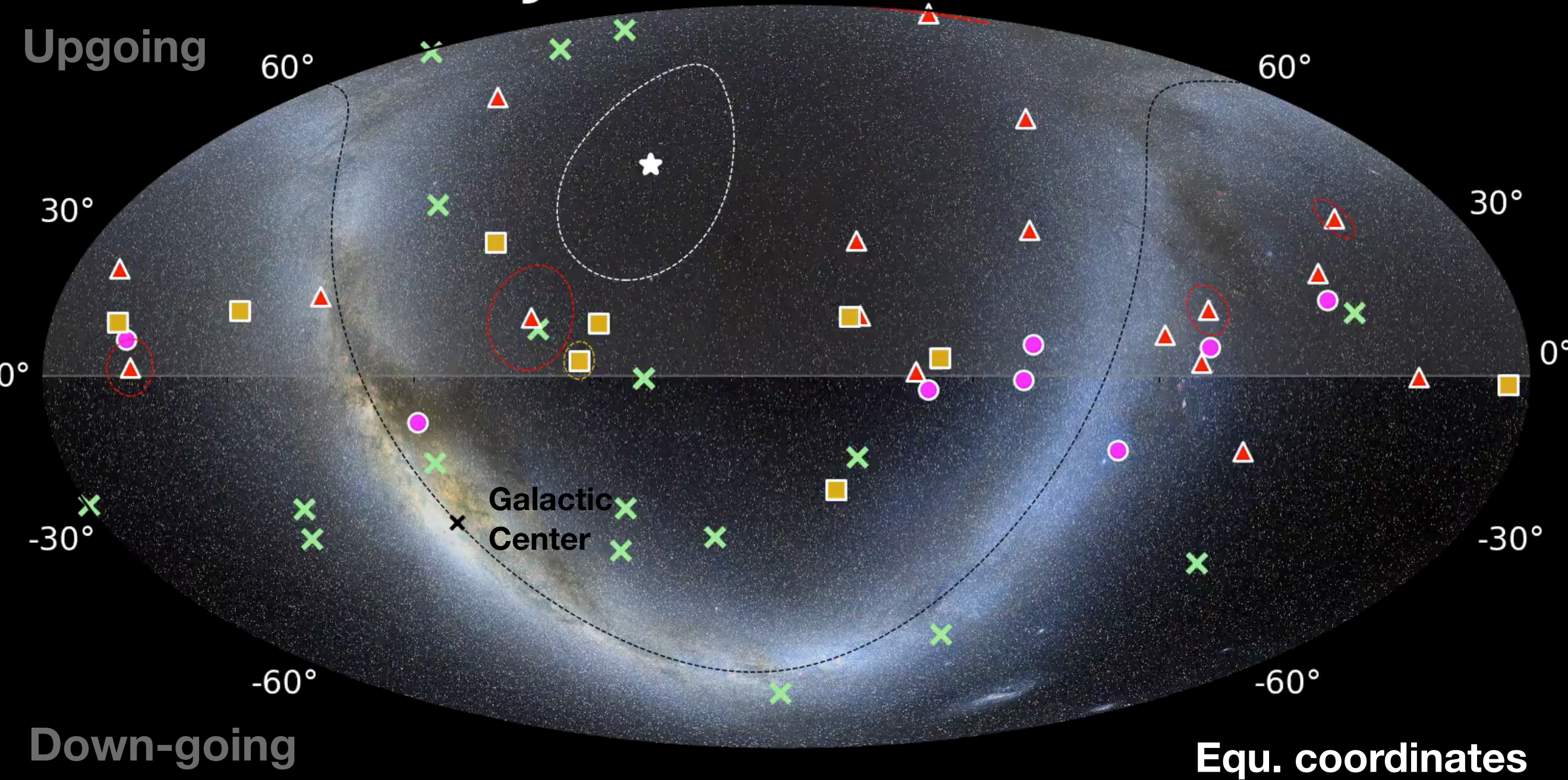
- As of Dec 2nd, 2020: 16 gold and 26 bronze alerts issued
https://gcn.gsfc.nasa.gov/amon_icecube_gold_bronze_events.html

[PoS-ICRC2019-1021]



Realtime alerts

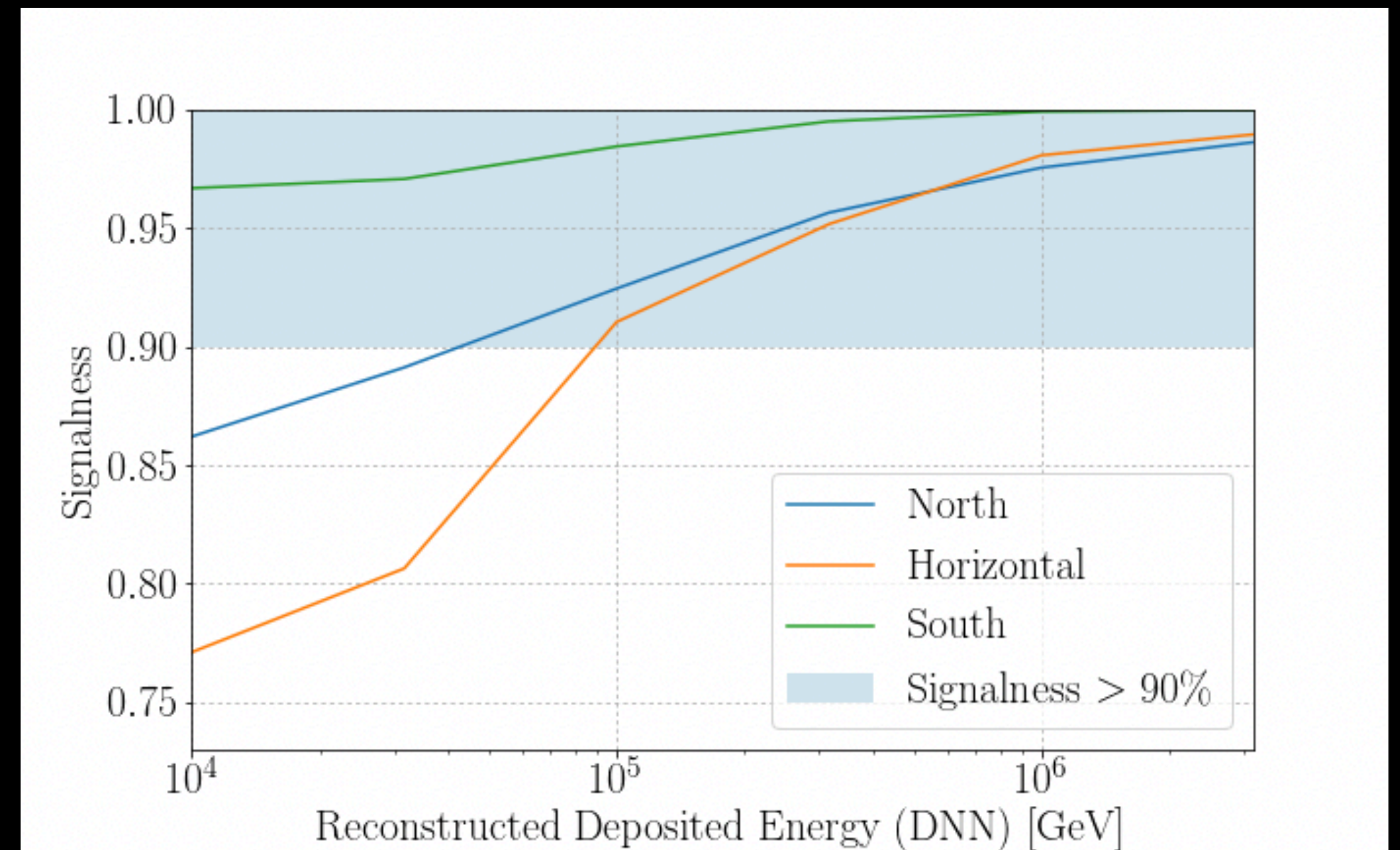
Jul 03, 2020



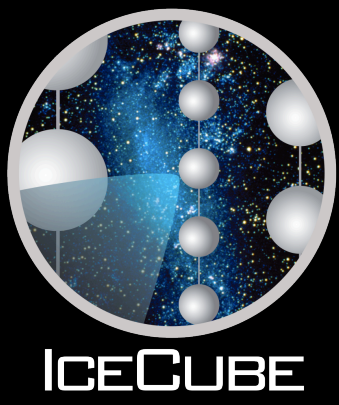
- Extremely-high energy (EHE)
- ▲ Bronze
- + Neutrino + EM
- × High-energy starting event (HESE)
- Gold
- ★ Cascades

Cascade alerts

- HESE events are selected using a deep neural network (DNN) classifier.
- 50% have an uncertainty $< 7^\circ$, 68% is $< 9^\circ$.
- Signalness > 0.9 at energies above 100 TeV
- Online July 2020, two alerts as of Dec 2020.

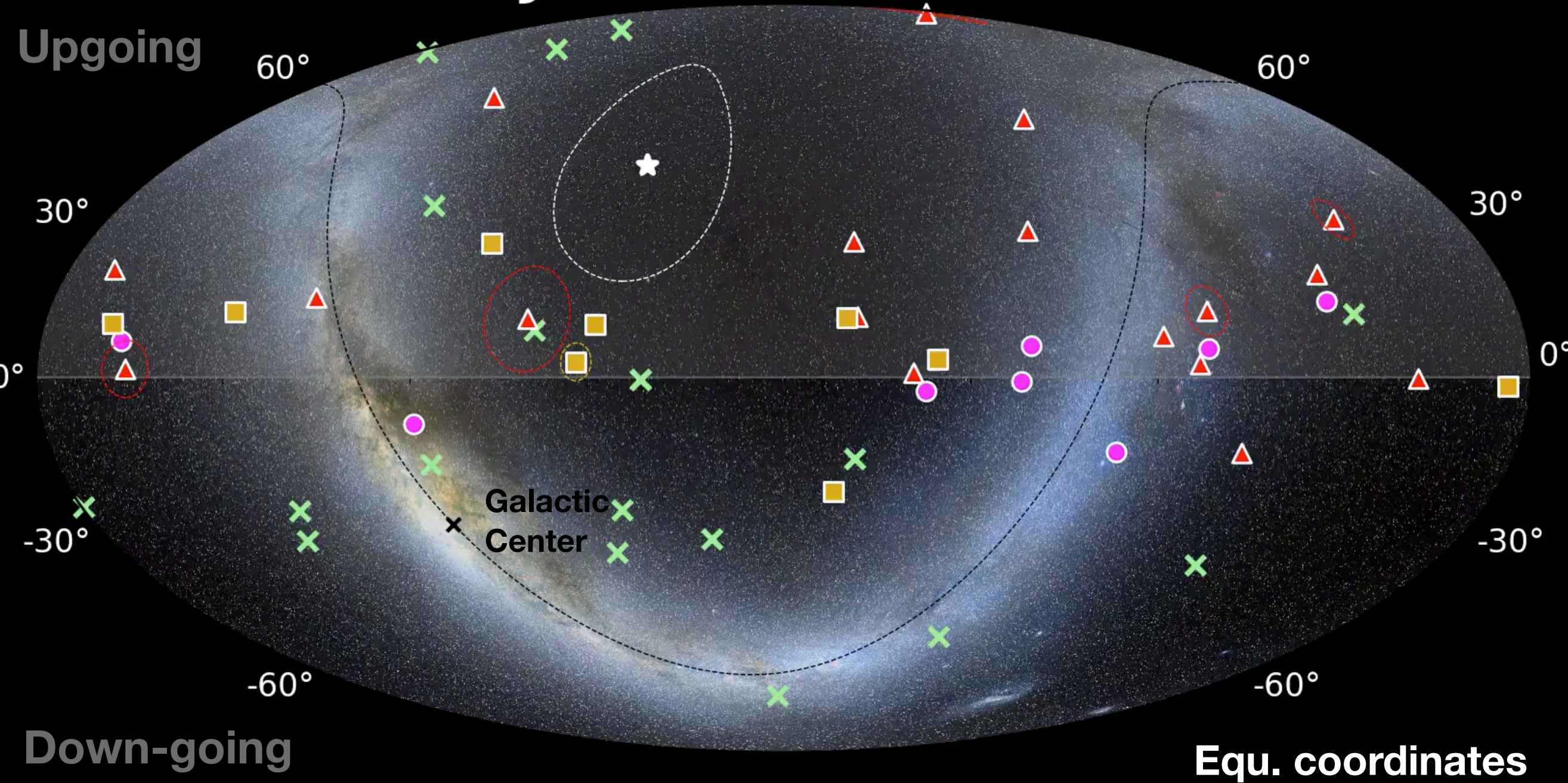


https://gcn.gsfc.nasa.gov/amon_icecube_cascade_events.html



Realtime alerts

Jul 03, 2020



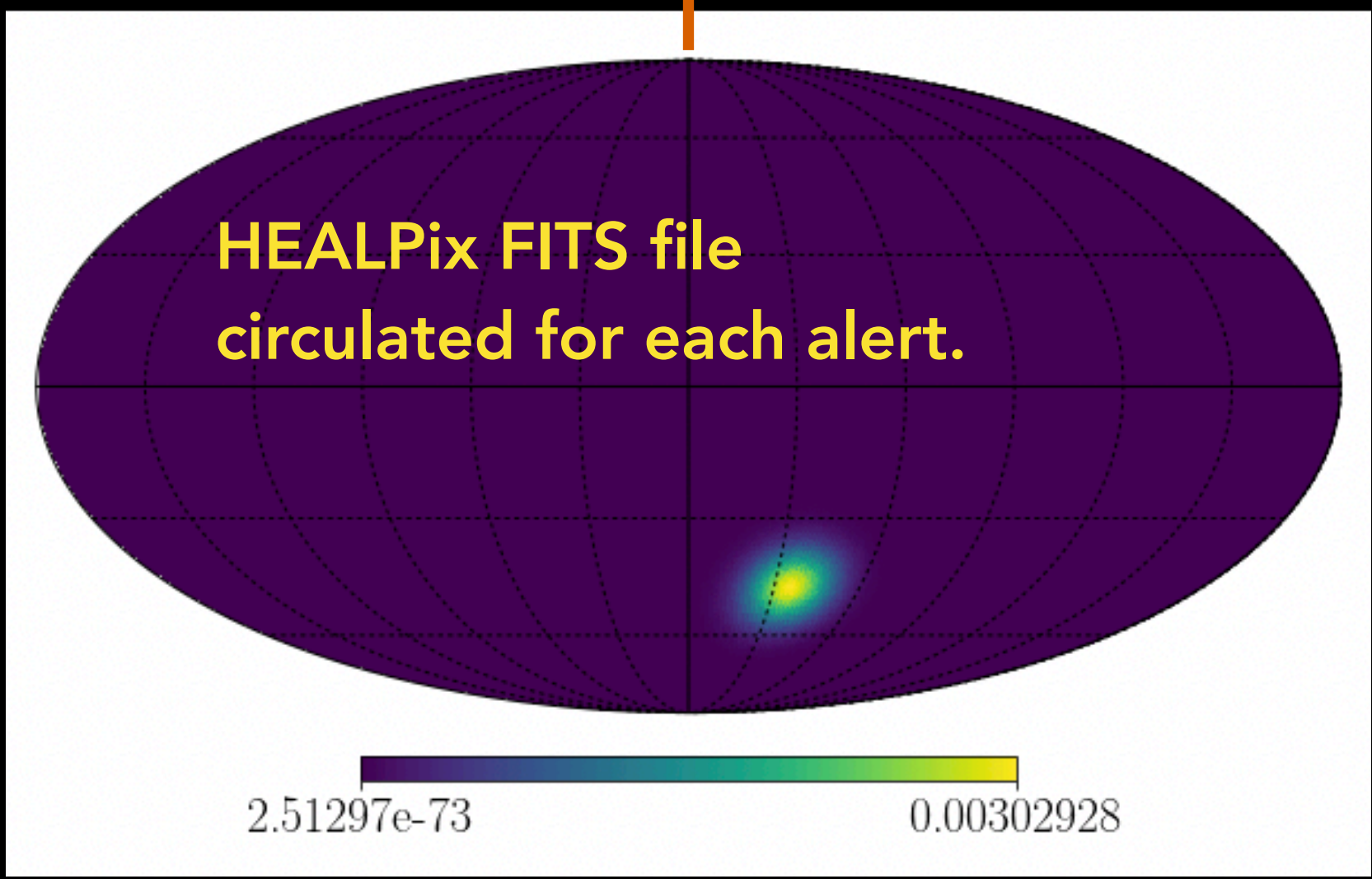
- Extremely-high energy (EHE)
- ▲ Bronze
- + Neutrino + EM
- × High-energy starting event (HESE)
- Gold
- ★ Cascades

Cascade alerts

```

////////////////////////////////////
TITLE:                GCN/AMON NOTICE
NOTICE_DATE:          Wed 29 Jul 20 21:58:55 UT
NOTICE_TYPE:          ICECUBE Cascade
EVENT_NAME:           IceCubeCascade-200707b
STREAM:               26
RUN_NUM:              134262
EVENT_NUM:            14361443
SRC_RA:               273.9880d {+18h 15m 57s} (J2000),
                     274.2275d {+18h 16m 55s} (current),
                     273.4044d {+18h 13m 37s} (1950)
SRC_DEC:              +11.5828d {+11d 34' 58"} (J2000),
                     +11.5910d {+11d 35' 28"} (current),
                     +11.5649d {+11d 33' 53"} (1950)
SRC_ERROR:            28.42 [deg radius, stat+systematic, 90% containment]
SRC_ERROR50:          15.59 [deg radius, stat+systematic, 50% containment]
DISCOVERY_DATE:       19037 TJD; 189 DOY; 20/07/07 (yy/mm/dd)
DISCOVERY_TIME:       33610 SOD {09:20:10.40} UT
REVISION:              0
ENERGY:               11.93 [TeV]
SIGNALNESS:           9.0012e-01 [dn]
FAR:                  0.3110 [yr^-1]
SUN_POSTN:            129.63d {+08h 38m 30s} +18.46d {+18d 27' 48"}
SUN_DIST:             133.93 [deg] Sun_angle=-9.6 [hr] (East of Sun)
MOON_POSTN:           246.97d {+16h 27m 53s} -19.95d {-19d 57' 01"}
MOON_DIST:            41.41 [deg]
GAL_COORDS:           39.40, 13.06 [deg] galactic lon,lat of the event
ECL_COORDS:           274.77, 34.96 [deg] ecliptic lon,lat of the event
SKYMAP_FITS_URL:      https://roc.icecube.wisc.edu/public/hese_cascades/hese_59037_run00134262.evt000014361443.fits
SKYMAP_PNG_URL:       https://roc.icecube.wisc.edu/public/hese_cascade/hese_59037_run00134262.evt000014361443.png
COMMENTS:              IceCube Cascade event.
COMMENTS:              The position error is the combined statistical and the systematic.
    
```

GCN Notice

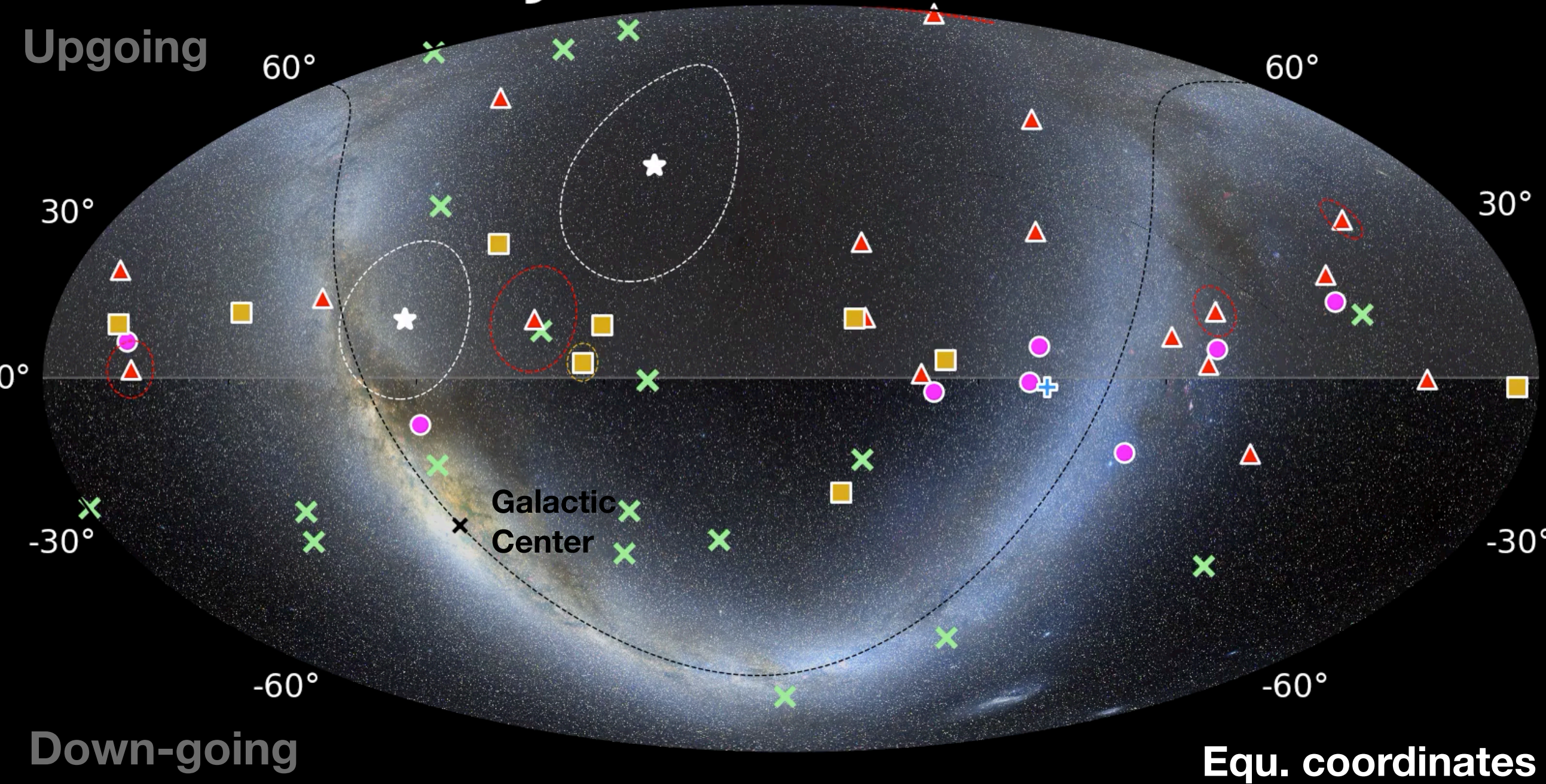


https://gcn.gsfc.nasa.gov/amon_icecube_cascade_events.html



Realtime alerts

Jul 20, 2020

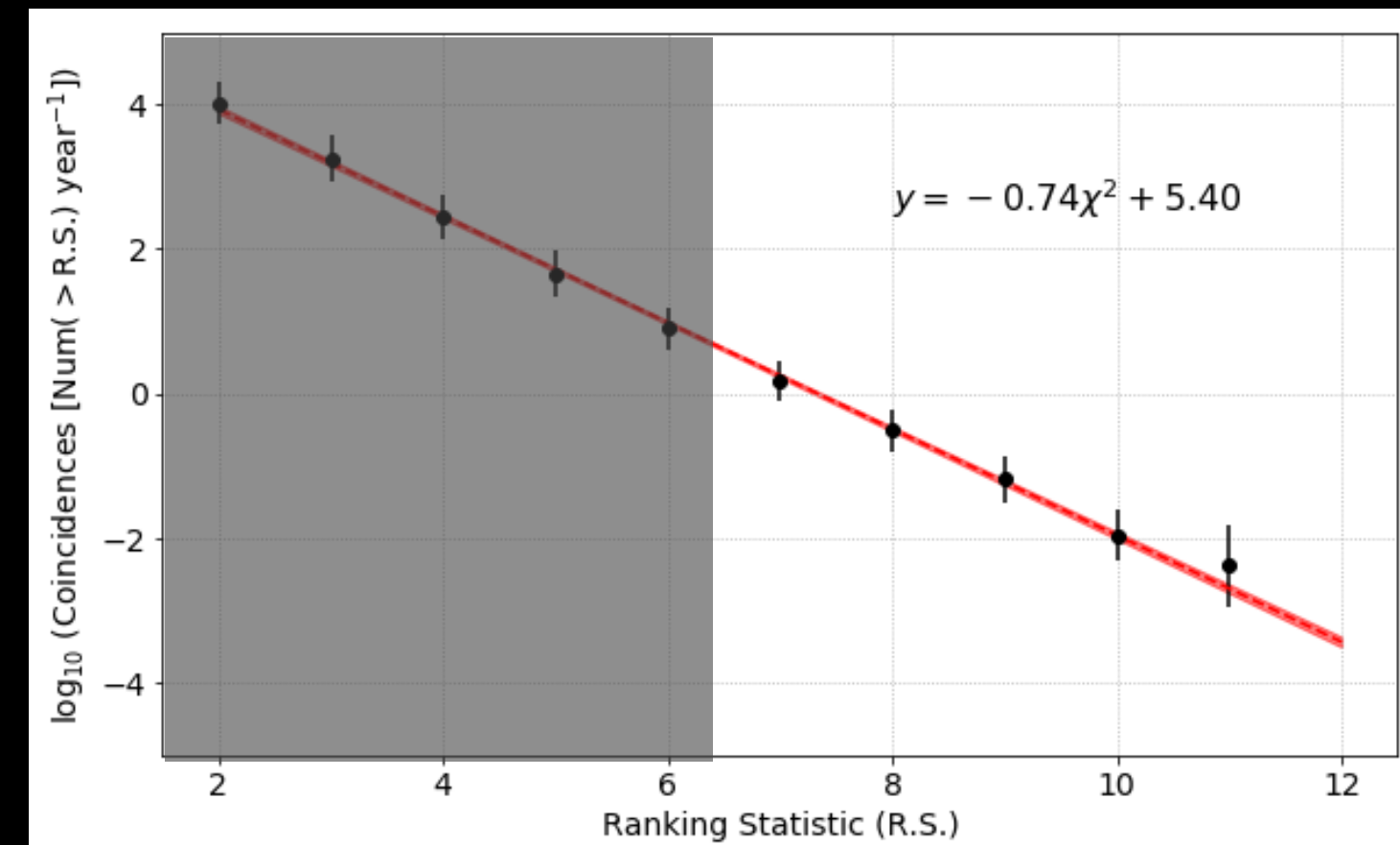


- Extremely-high energy (EHE)
- ▲ Bronze
- + Neutrino + EM
- × High-energy starting event (HESE)
- Gold
- ★ Cascades

Neutrino-gamma coincidences

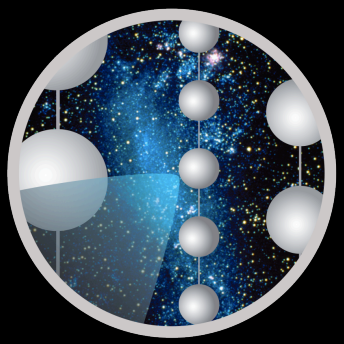
- HAWC + IceCube: HAWC daily transit hotspot correlated by AMON with IceCube neutrinos within 3.5°.
- Ranking statistic (RS) distribution derived from 2 years of scrambled data. Cuts on RS defined to send 4 alerts per year to GCN.
- Started April 2020, **3 alerts sent so far**

$$\chi^2_{6+2n_\nu} = -2 \ln [p_\lambda p_{HAWC} p_{cluster} \prod_i^{\nu} p_{IC,i}],$$



[PoS-ICRC2019-841]

https://gcn.gsfc.nasa.gov/amon_nu_em_coinc_events.html



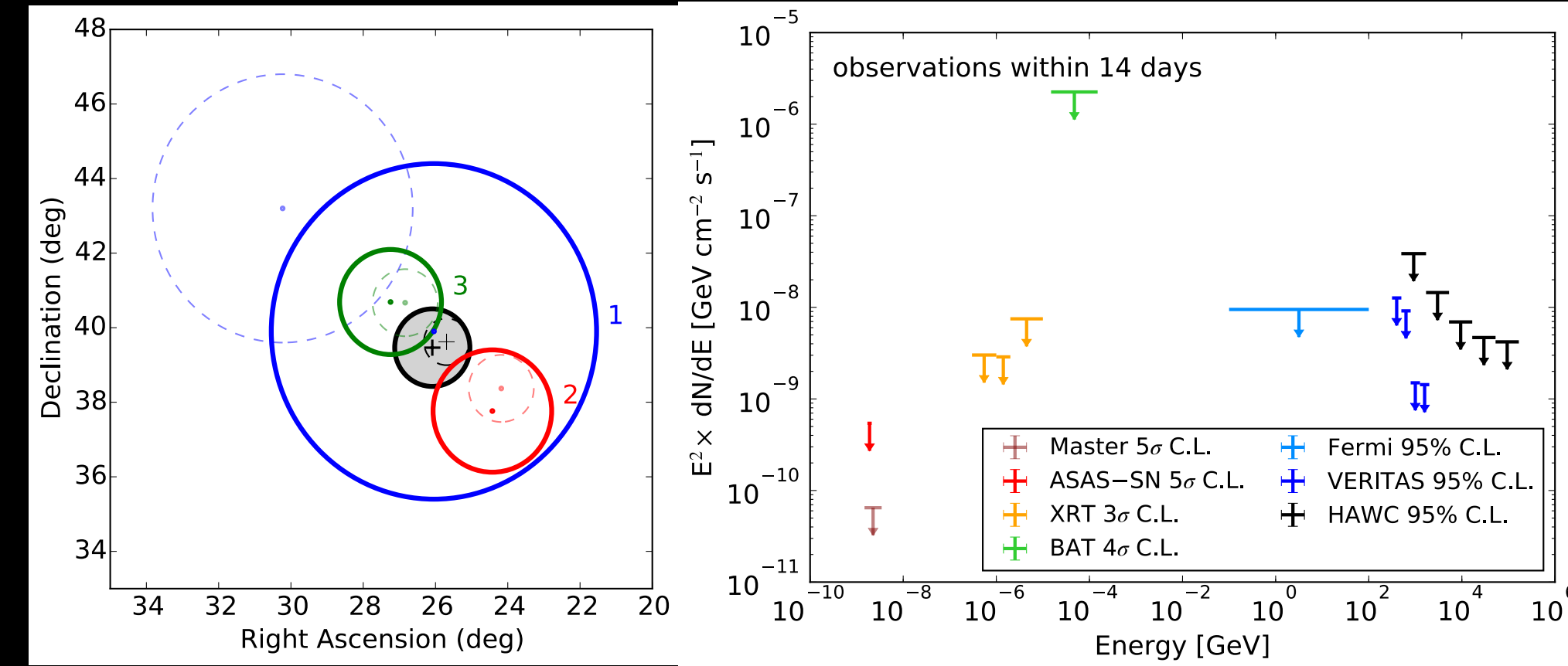
ICECUBE

Clustering searches

- Spatial correlations can reveal an astrophysical signal buried in the atmospheric neutrino background.
- **Optical follow-up (OFU):** GRB/SN
 - 2+ events in 100 s, within 3.5°
 - Private alerts to ZTF and Swift
- **Gamma-ray follow-up (GFU):** Blazar flares
 - Likelihood analysis on variable time-scales correlated with known or likely VHE gamma emitters.
 - Private alerts to MAGIC, VERITAS, H.E.S.S.
 - Online event selection / reconstruction
 - Similar sensitivity to previous offline searches

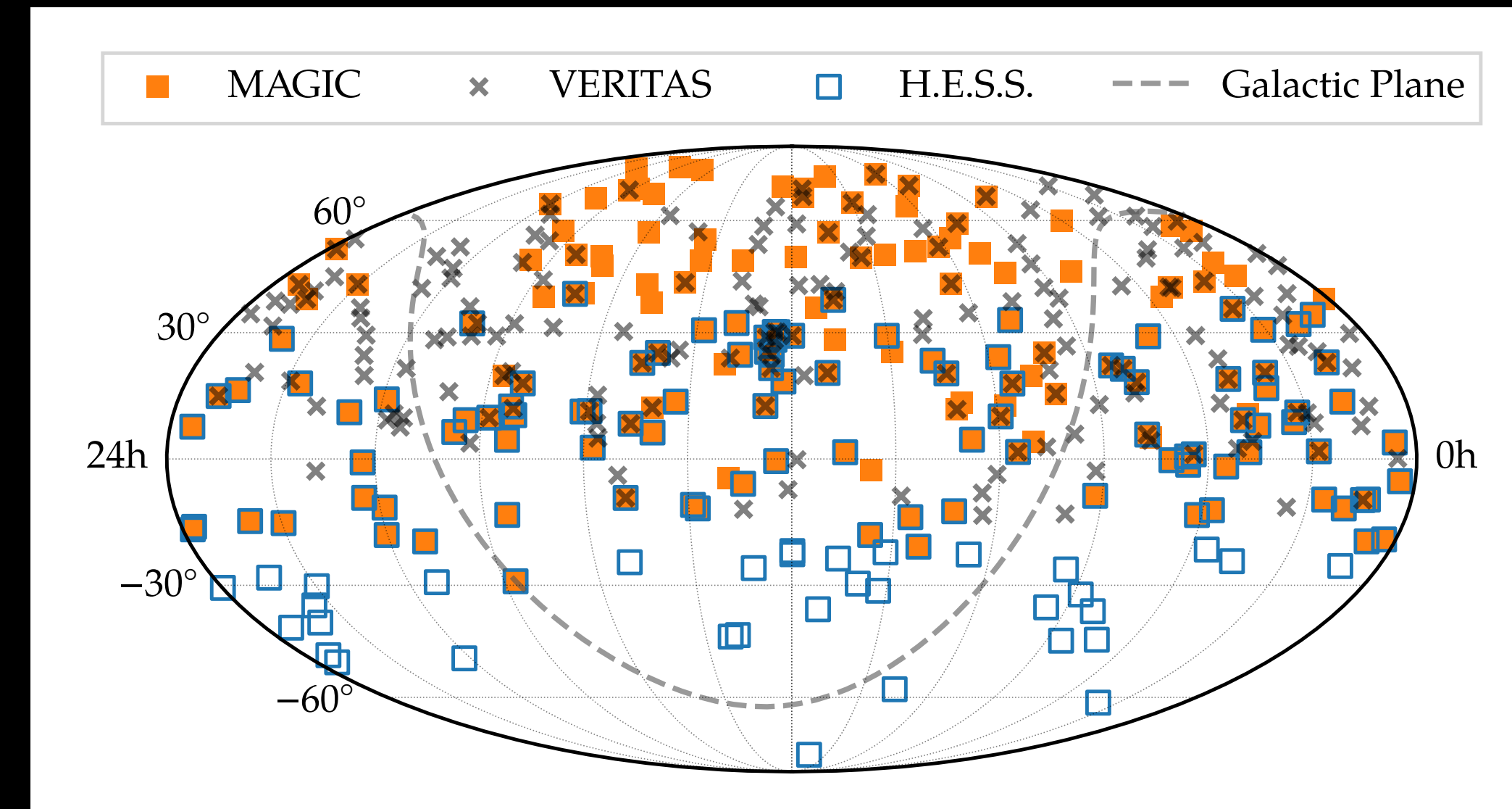
Neutrino triplet (2016)

[A&A 607, A115 (2017)]



Sources from IACTs

[2016 JINST 11 P11009]

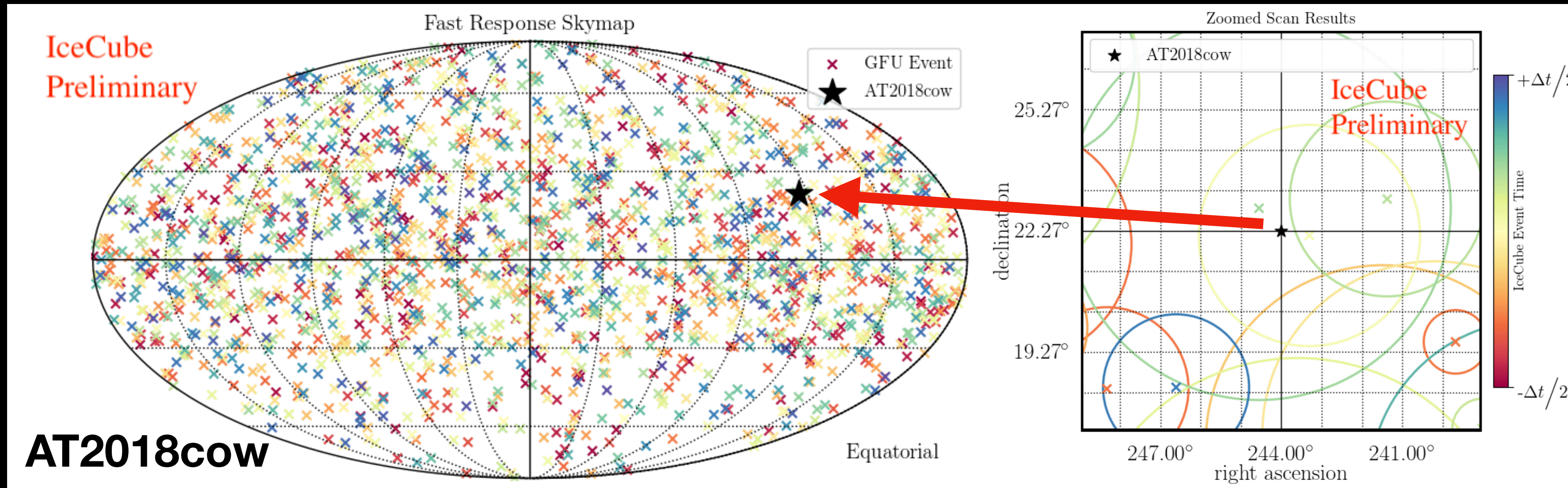
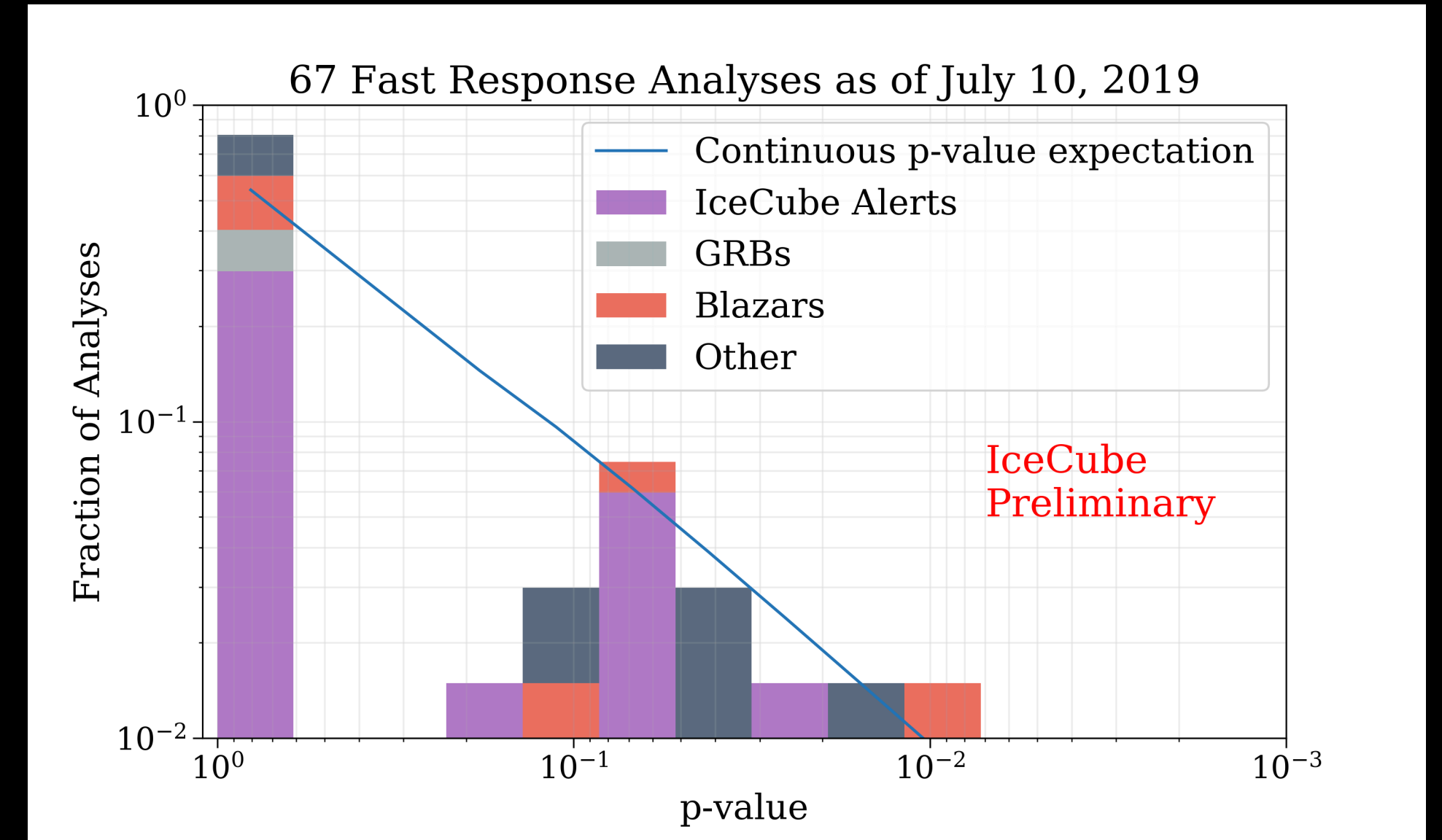




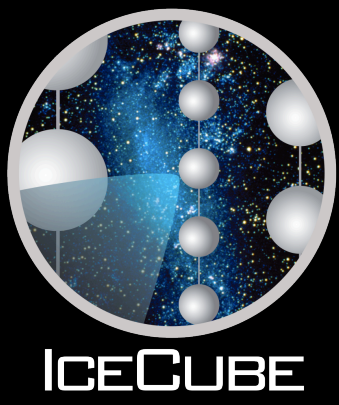
Fast response analysis

- Fast response analysis following:
 - IceCube HE alerts (search for additional, LE nus). 102 up to Dec 2020.
 - HE astrophysical events with potential neutrino emission: ATels, GCN, etc. 60 up to Dec 2020.

Did IceCube see something?



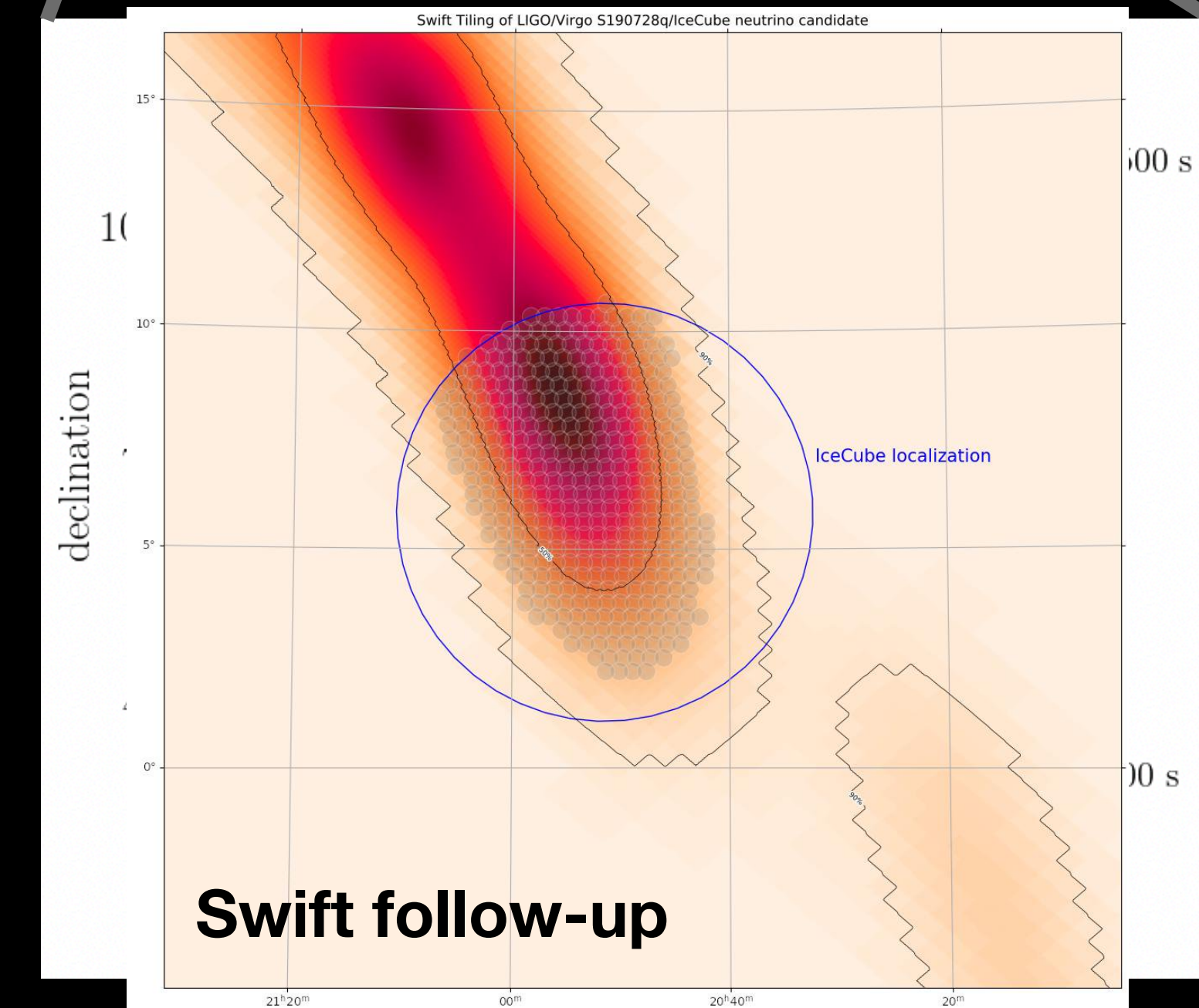
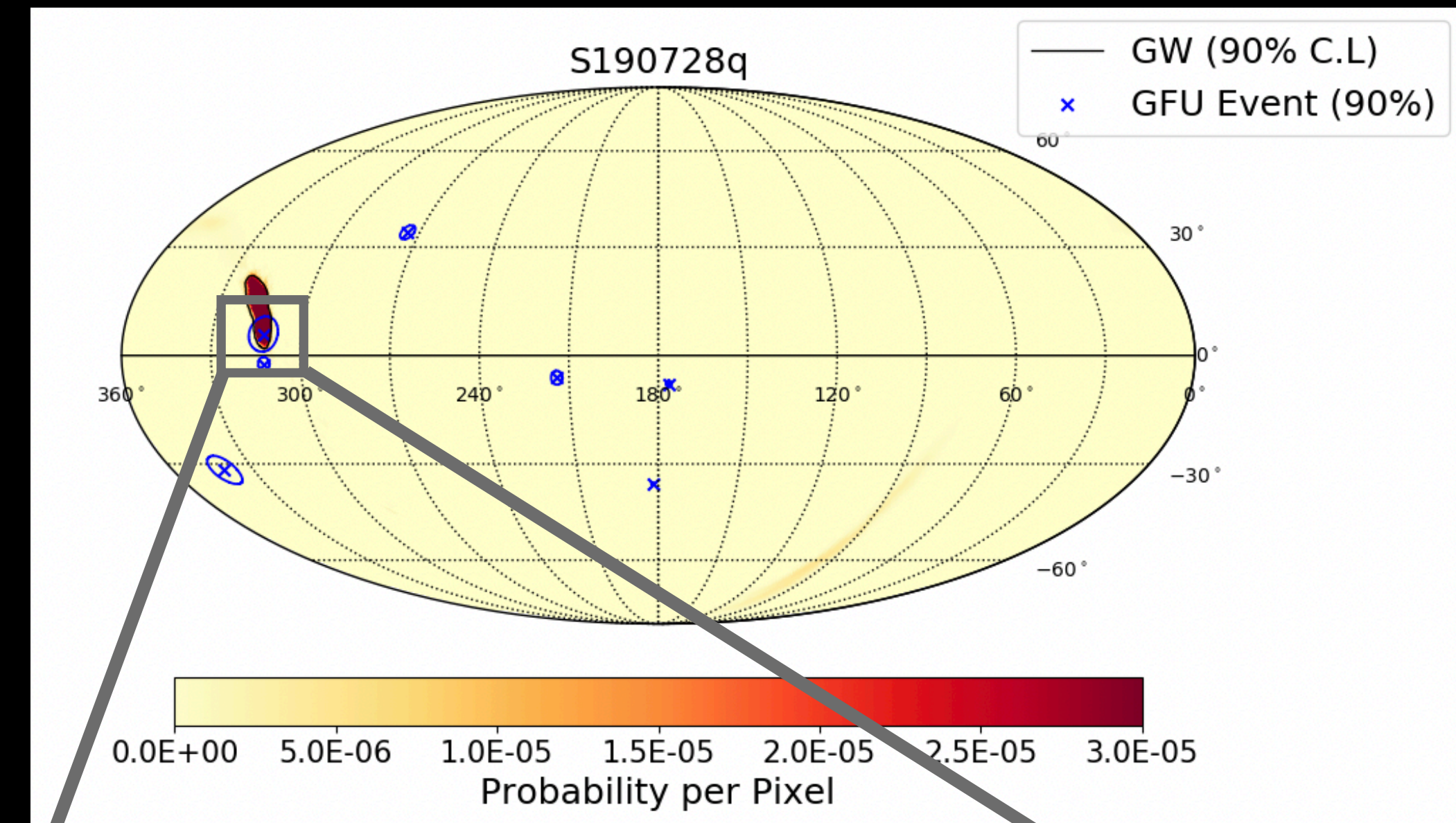
[PoS-ICRC2019-1026]



Gravitational waves

- Two independent analysis of neutrino candidates within 500 s of the GW trigger.
 - Unbinned maximum likelihood search: test for point source consistent with GW localization.
 - Bayesian approach: probability of a joint GW+nu joint signal with astrophysical priors
- Results are reported in GCN circulars. 56 GW follow-ups during O3 run of LIGO/Virgo.
- **Example: GW190728, BBH merger**
 - p-value ~ 0.01 in both analyses, triggered MWL follow-up
 - <https://gcn.gsfc.nasa.gov/gcn3/25210.gcn3>

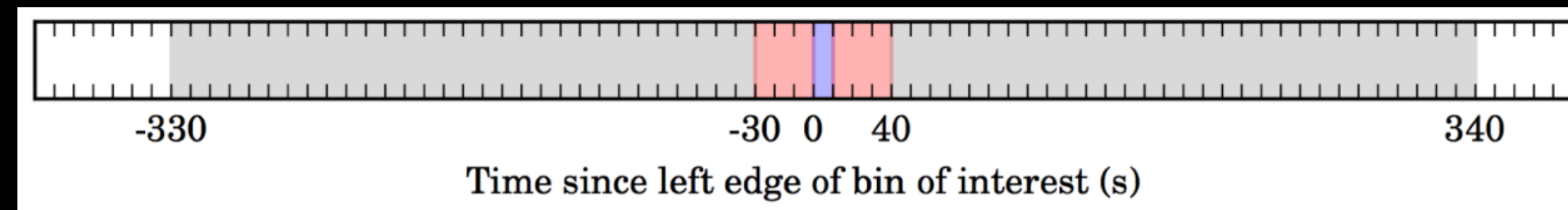
[Astrophys. J. Lett. 898 (2020) L10]





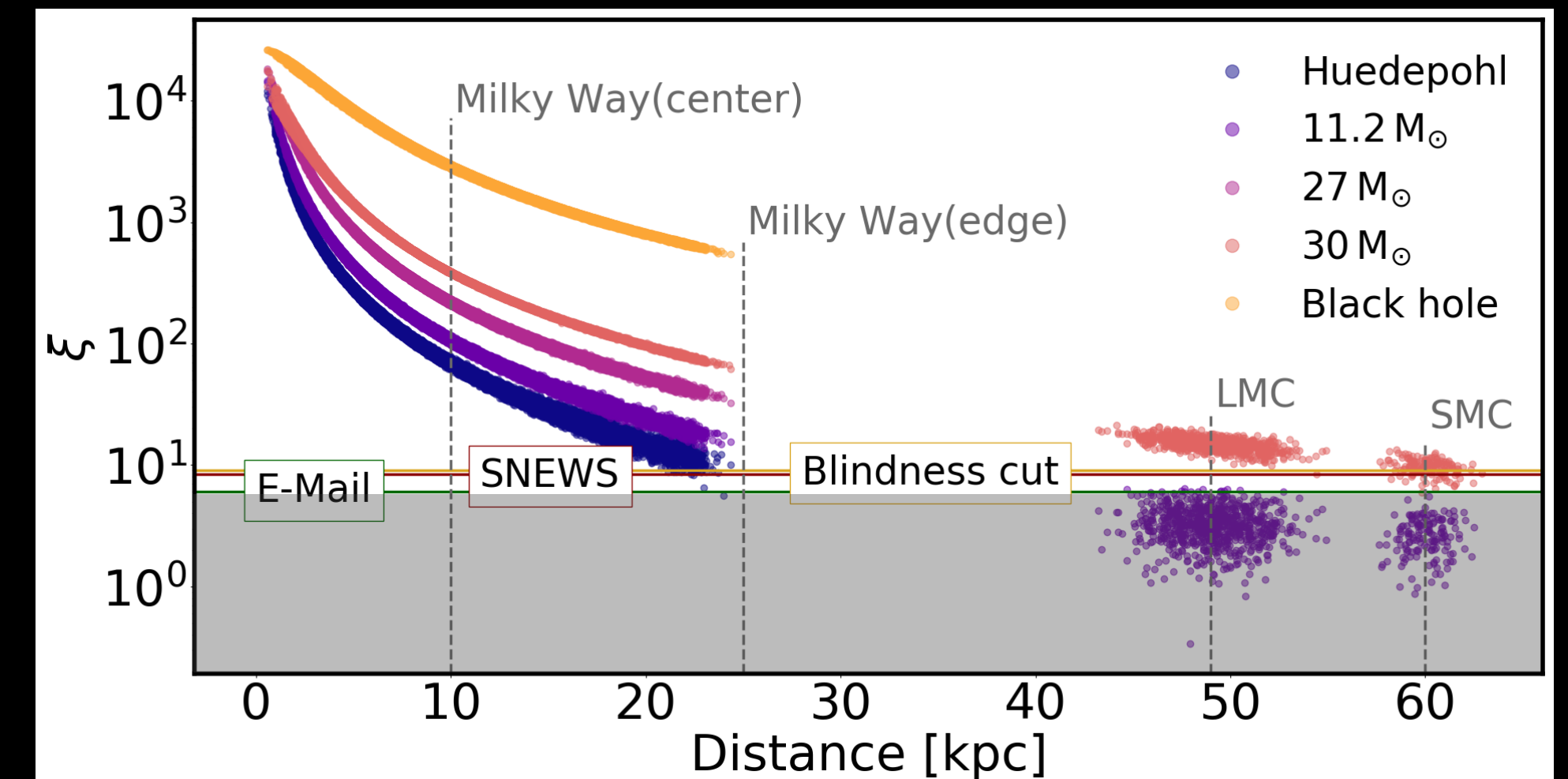
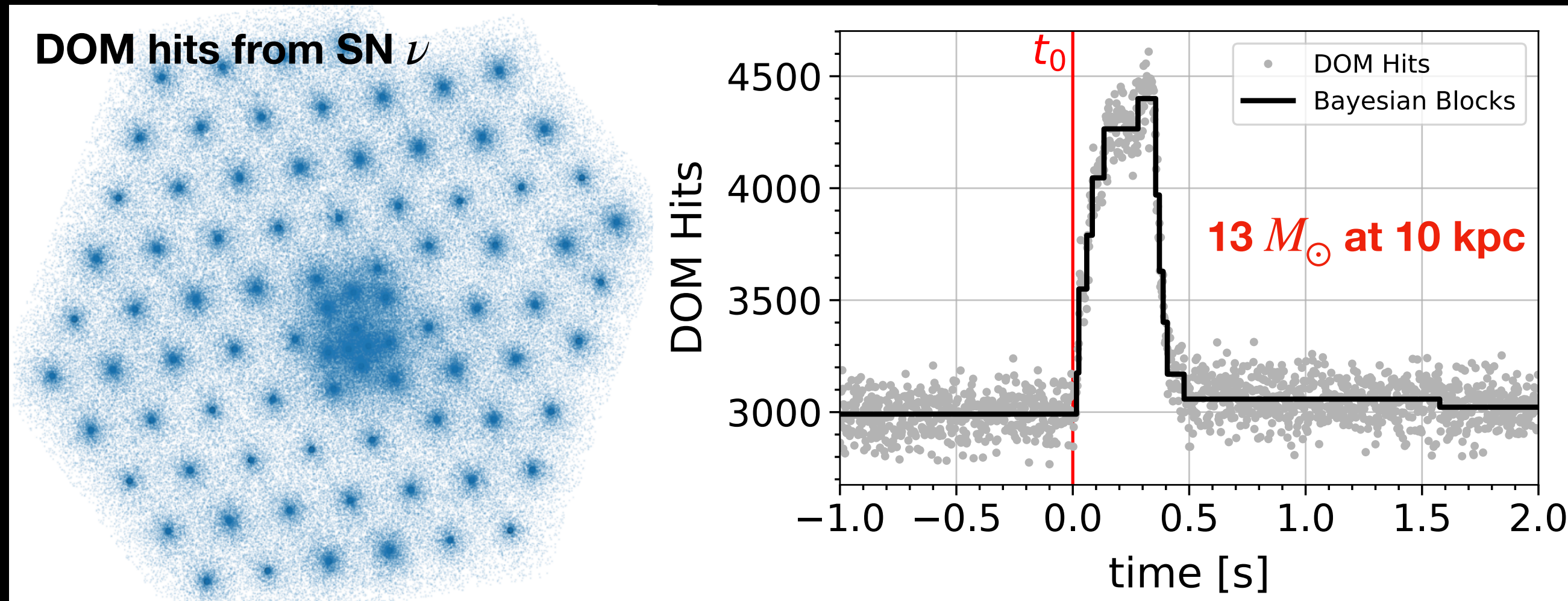
Galactic supernovae

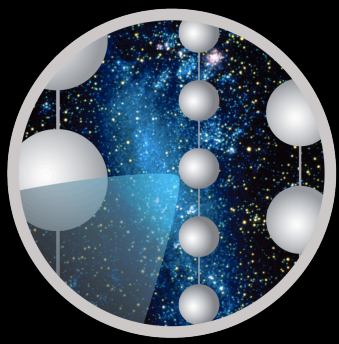
- A Galactic core-collapse supernova would be seen by IceCube as an overall increase in the DOM noise rate produced by Cherenkov photons from 10 MeV neutrino interactions.
- SNDAQ searches for correlated noise rate increases in a 0.5 s time bin with respect to a moving average calculated over a ± 5 min window. Can be triggered by SNEWS and LIGO GW alerts. SNDAQ retrieves waveforms from HitSpool buffers.



- Alerts over significance threshold sent to SNEWS.

[A&A 535, 2011, A109]
[PoS-ICRC2019-889]





ICECUBE

Future directions

[PoS-ICRC2019-1177]

The screenshot shows the website interface for the IceCube Catalogue of Astrophysical Neutrino Candidates. At the top, there is the IceCube logo and the text 'SOUTH POLE NEUTRINO OBSERVATORY'. Below the logo, there are navigation links for 'Home' and 'About', and the URL 'https://neutrino-catalog.icecube.aq/main'. The main heading is 'IceCube Catalogue of Astrophysical Neutrino Candidates'. A welcome message states: 'Welcome to this curated online catalogue of astrophysical neutrino candidates. Information on high-energy neutrinos is often published multiple times using various analyses. This catalog records all these publications and highlights the information recommended to use in further studies.' Below this, it specifies '(RA & Dec): J2000'. There is a section for 'Events' with a list of checkboxes: 'Show Name', 'Show RA (deg)', 'Show Dec (deg)', 'Show RA 90%', 'Show Dec 90%', 'Show Time (UTC)', and 'Show Type'. There are also input fields for 'RA Min', 'RA Max', 'Dec Min', and 'Dec Max', and a 'Filter Events' button. Below the filter section, there are two links: 'Download All Data as CSV' and 'Download Selected Data as CSV'. To the right of the filter section is a 'Sky map of neutrino events (Celestial Coordinates)' showing a grid of celestial coordinates with several blue stars representing neutrino events. At the bottom of the screenshot is a table with the following data:

Names	RA (deg)	Dec (deg)	RA 90%	Dec 90%	Time (UTC)	Type
IceCube-190504A	65.79	-37.44	+1.23 -1.23	+1.23 -1.23	2019-05-04 18:25:18.39	HESE
IceCube-190503A	120.28	6.35	+0.57 -0.77	+0.76 -0.70	2019-05-03 17:23:08.72	EHE
IceCube-190331A	337.68	-20.70	+0.23 -0.34	+0.30 -0.48	2019-03-31 06:55:43.44	HESE

- Catalog of astrophysical neutrino events (both archival and realtime) in preparation.
- Angular error estimation improvements for realtime alerts.
- Questions? Requests? Contact the IceCube Realtime Oversight Committee (ROC) at roc@icecube.wisc.edu

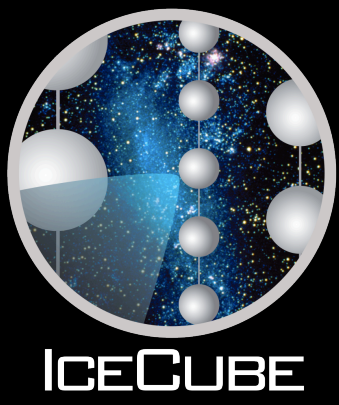


Conclusions

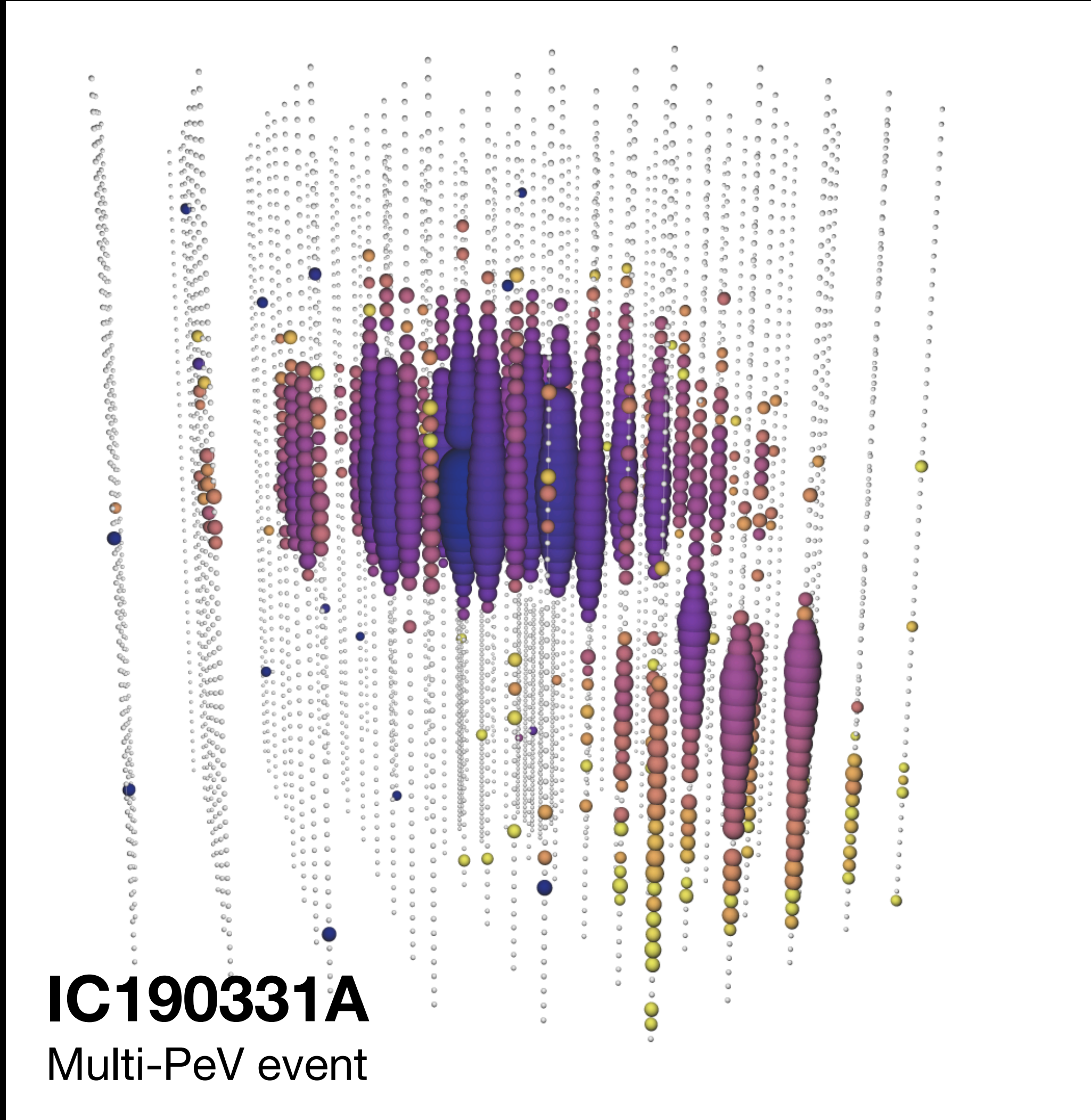
- **IceCube operates a realtime alert program from MeV to PeV energies**
 - Realtime **high-energy neutrino events** of potential astrophysical origin
 - Monitoring of known **gamma-ray emitters**
 - All-sky monitoring for **neutrino clusters**
 - Fast-response analysis to **external triggers**
 - Sensitivity to **Galactic supernovae**
- **A lot of interest in collaborating and coordinating with KM3NeT on realtime activities!**

Thank you

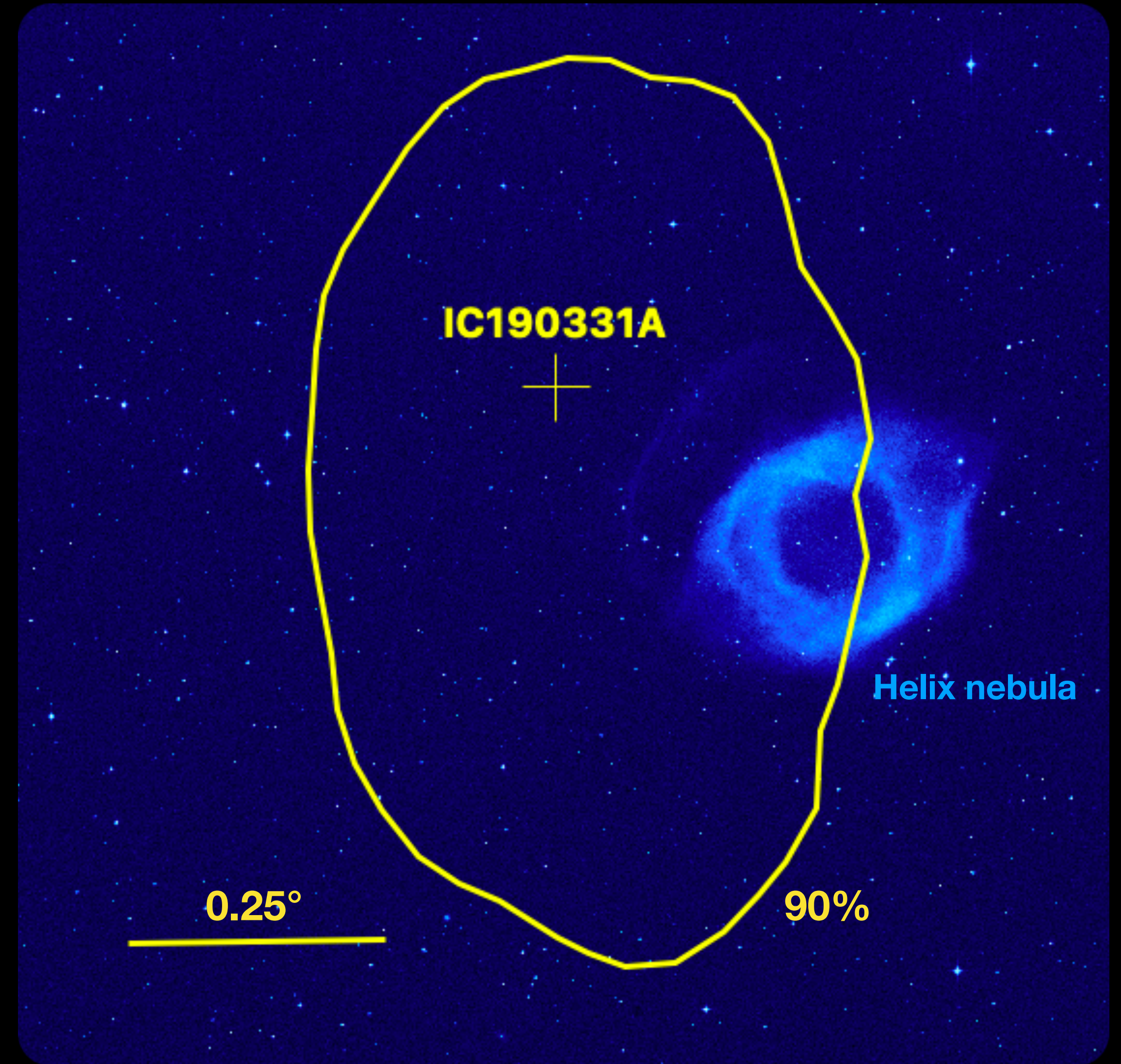




More recent alerts



Digitized Sky Survey (optical)



No obvious high-energy EM counterparts