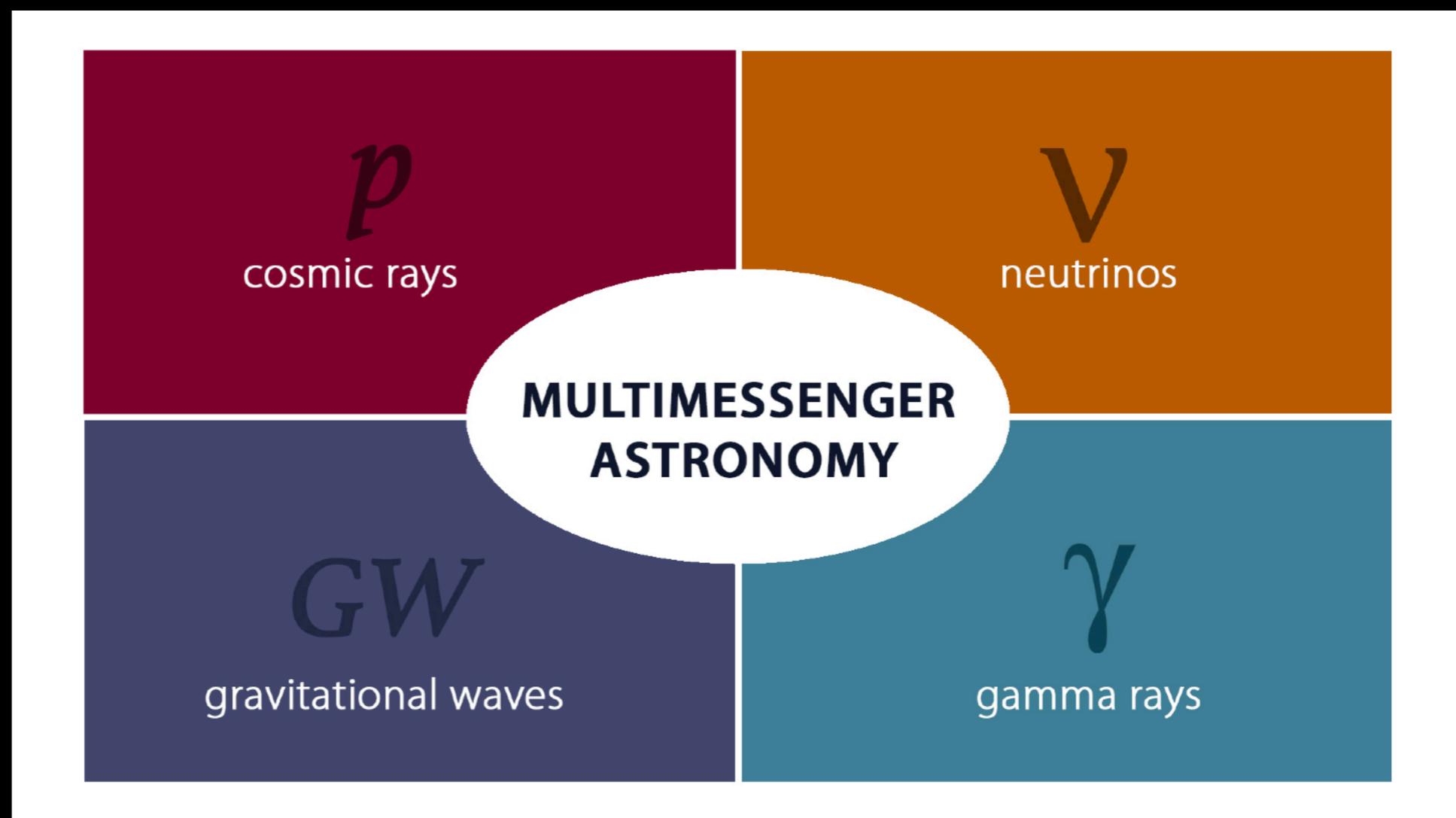


# Neutrino Telescope Alert Programs

Erik Blaufuss - U Maryland  
TMEX - Jan 5 -11 ,2020



or p, ...

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

$$\hookrightarrow \gamma + \gamma + p \quad \leftarrow \text{TeV gamma}$$

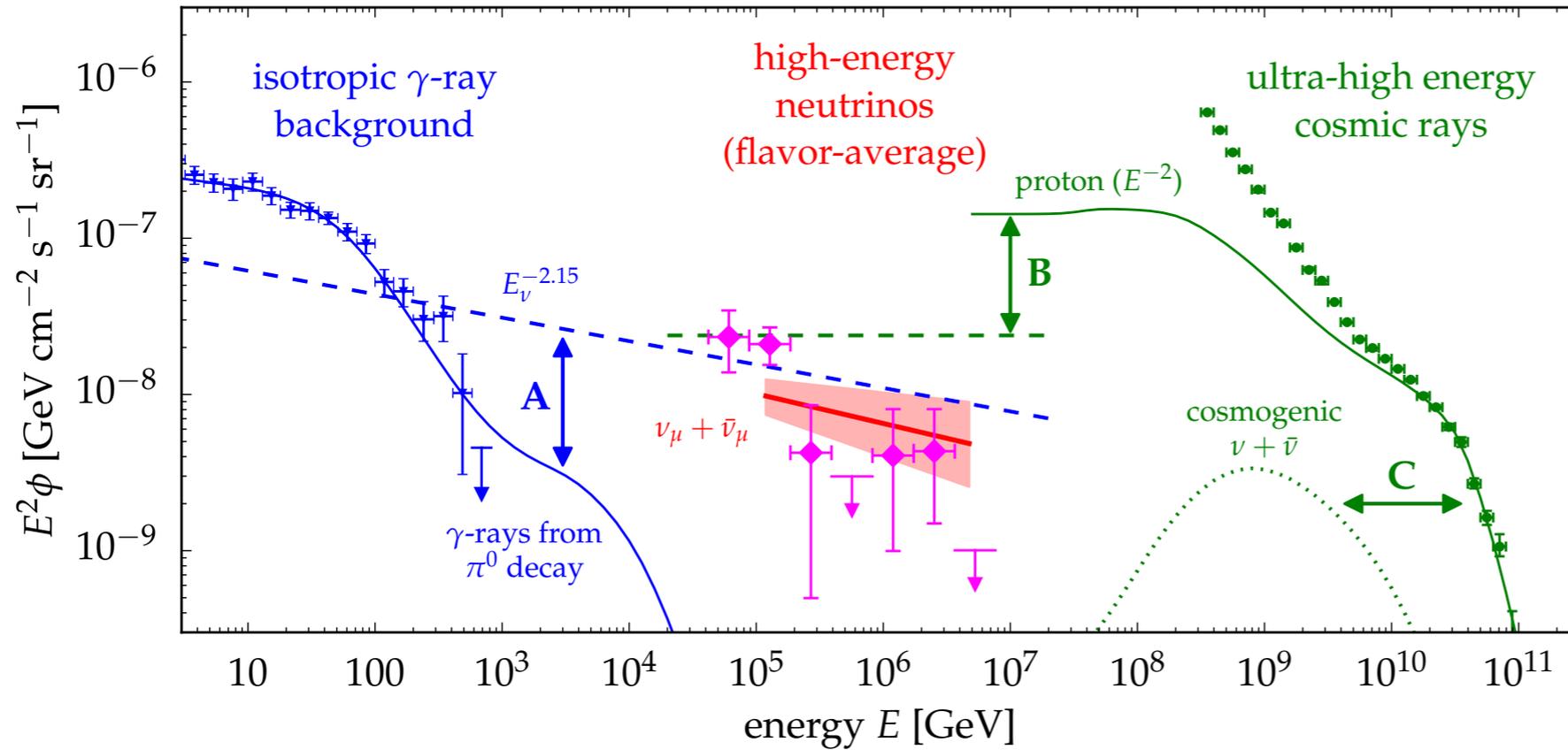
$$\rightarrow \pi^+ + n \quad \leftarrow \text{Cosmic rays?}$$

$$\hookrightarrow \mu^+ + \nu_\mu + n \quad \leftarrow \text{TeV neutrinos}$$

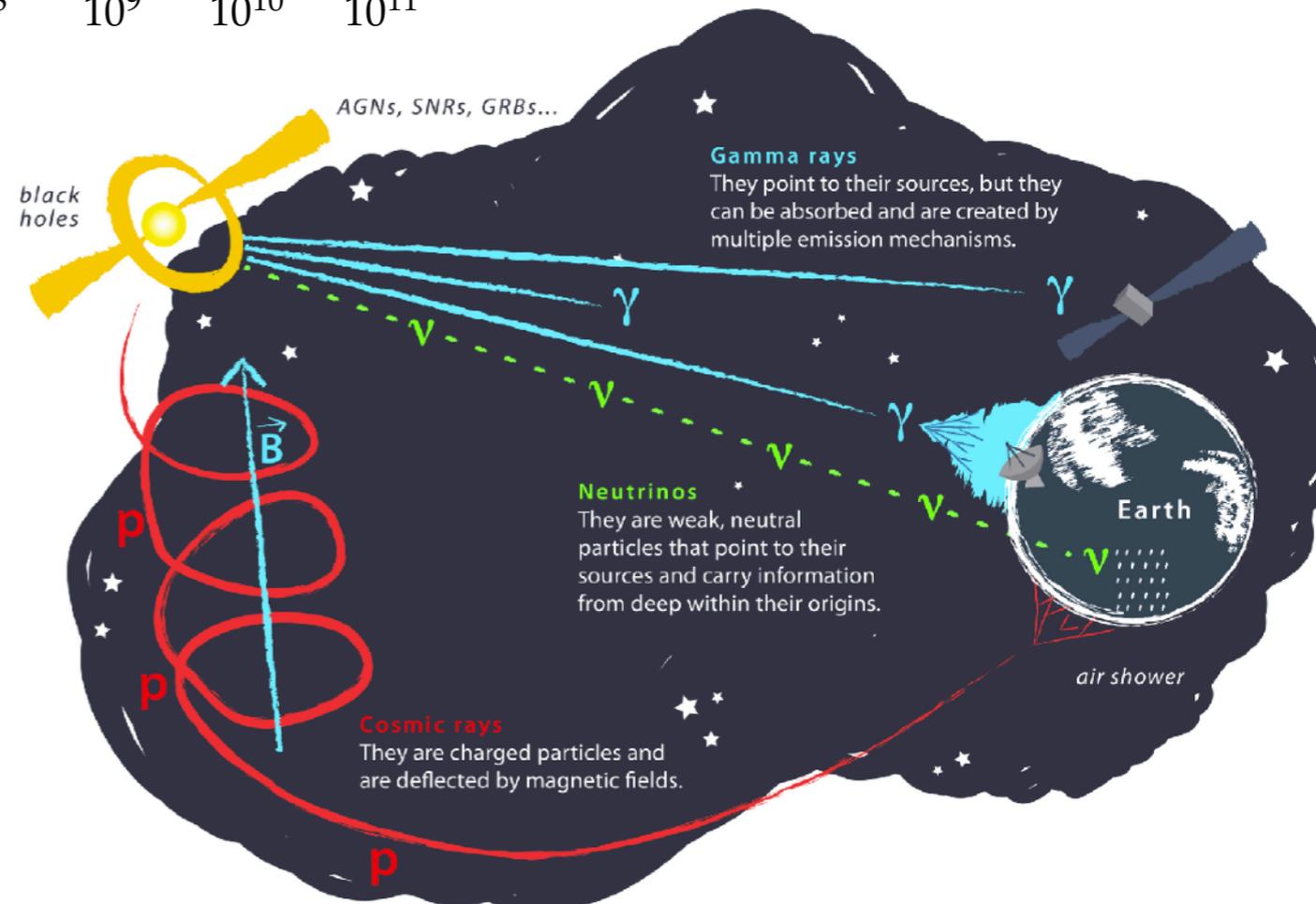
$$\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n \quad \leftarrow \text{TeV neutrinos}$$

# Multi-messenger astronomy

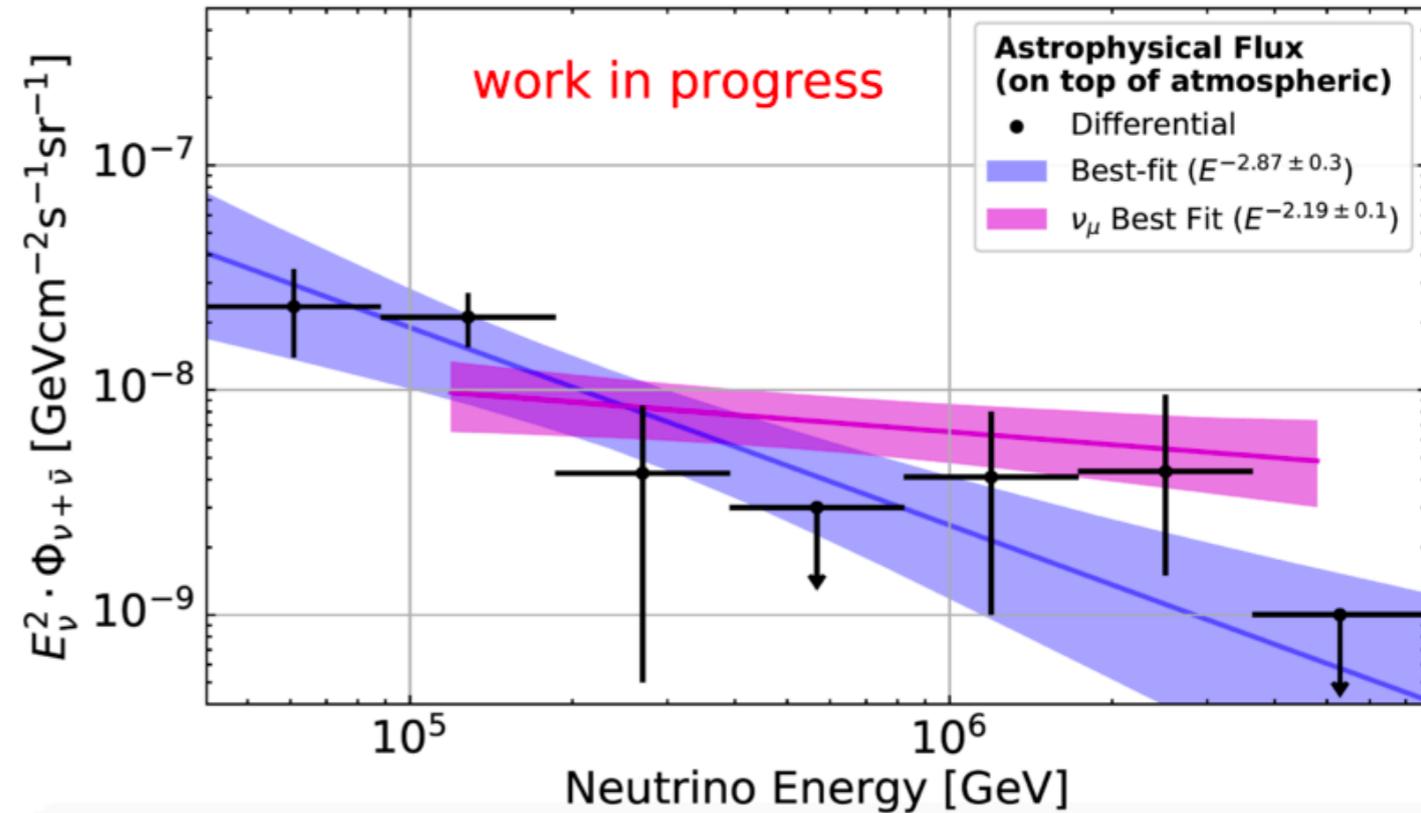
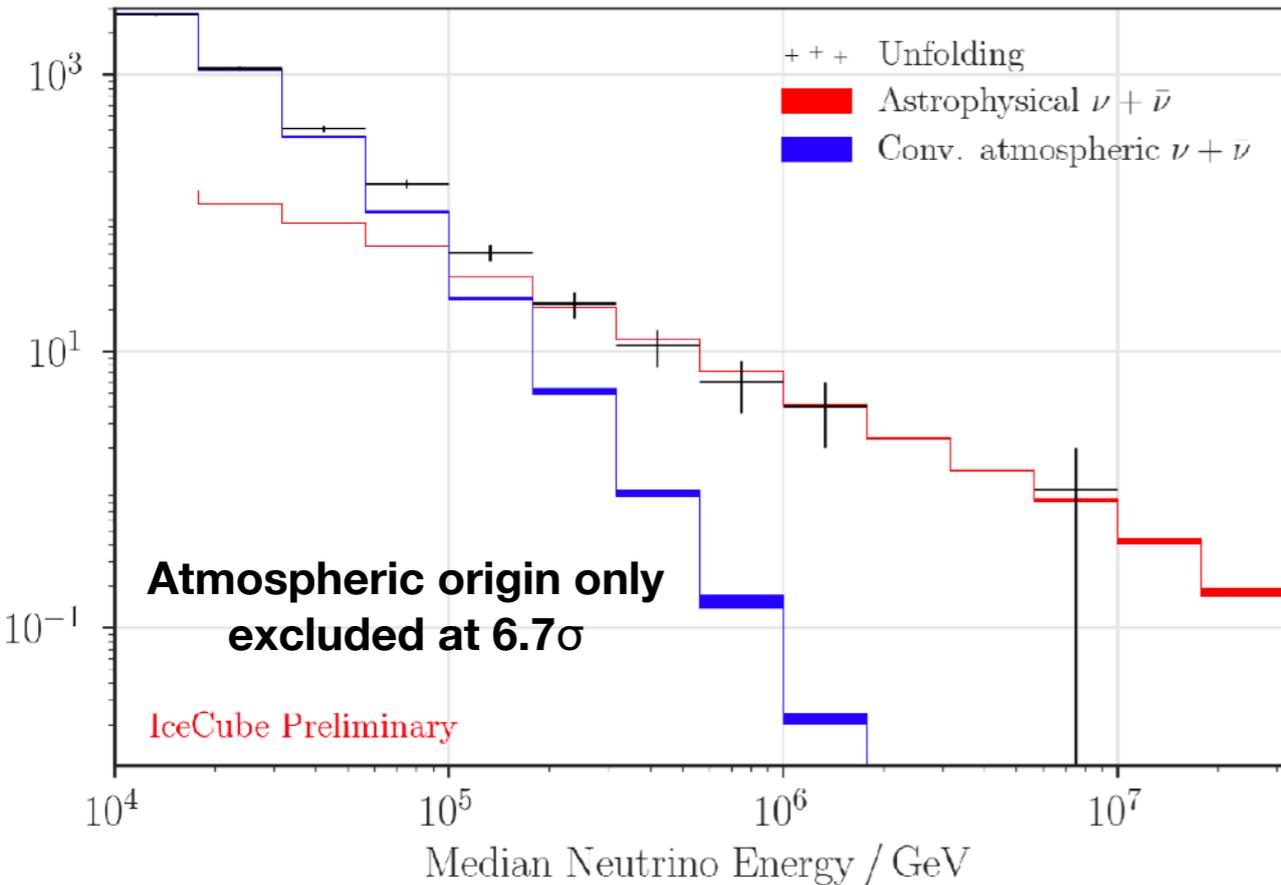
arxiv: 1903.04334



- Similar energy densities observed for extra-galactic components
  - Diffuse gamma-rays
  - Extra-galactic cosmic rays
  - Astrophysical neutrinos
- All potentially arising from a common source class



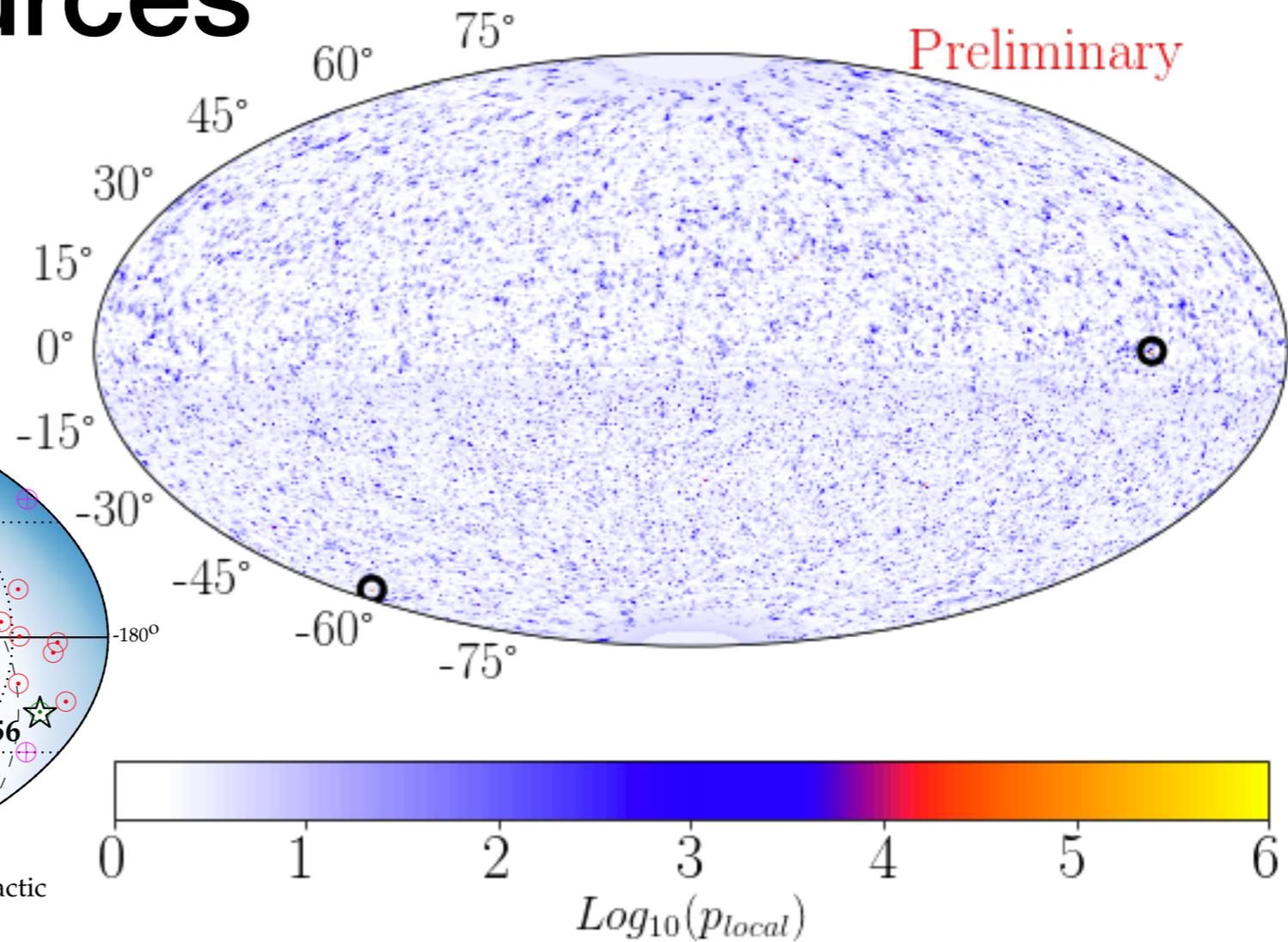
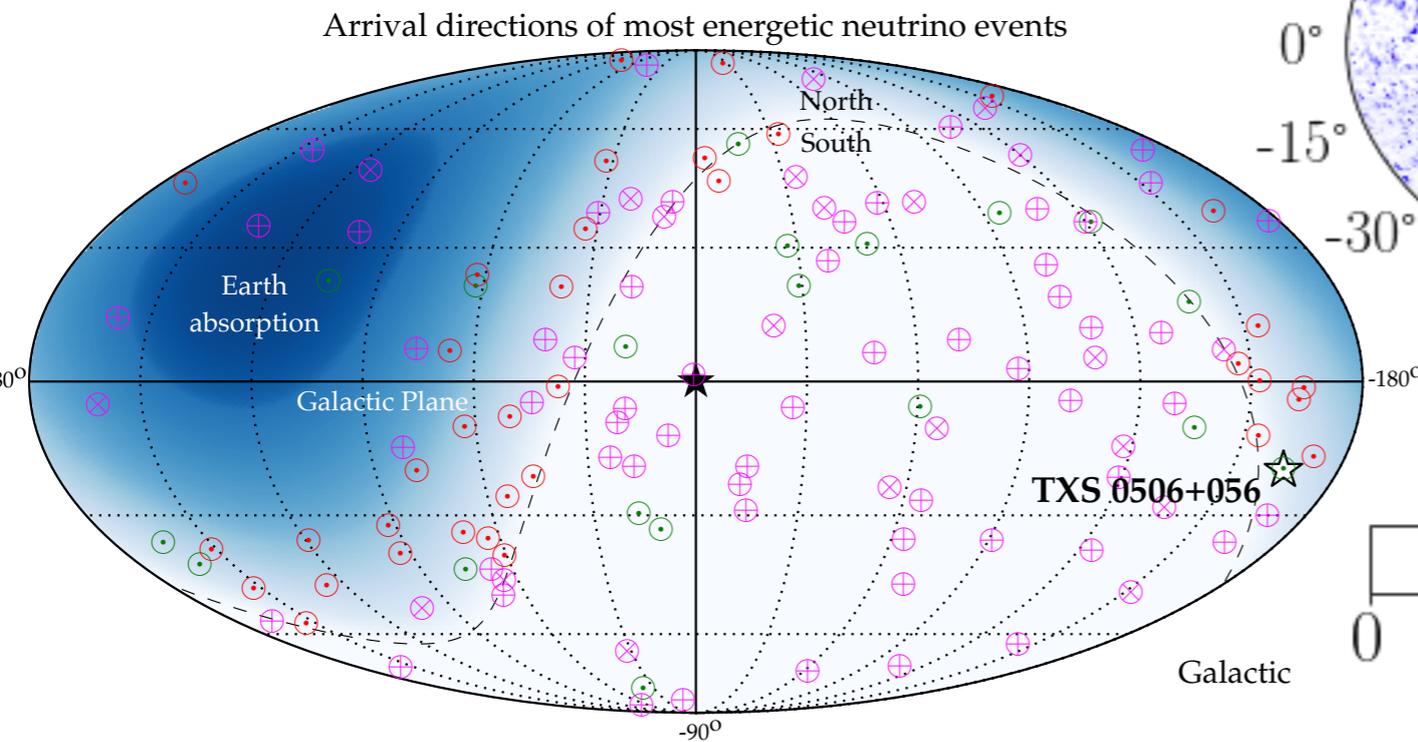
# Astrophysical neutrinos



- Up-going neutrino tracks from 8 yr of IceCube data
- Excess of events above atmospheric backgrounds
  - No evidence for prompt flux (best fit 0)

- Starting neutrino events from 7.5 yr of IceCube data
  - 103 events, with 60 events >60 TeV

# Searches for sources



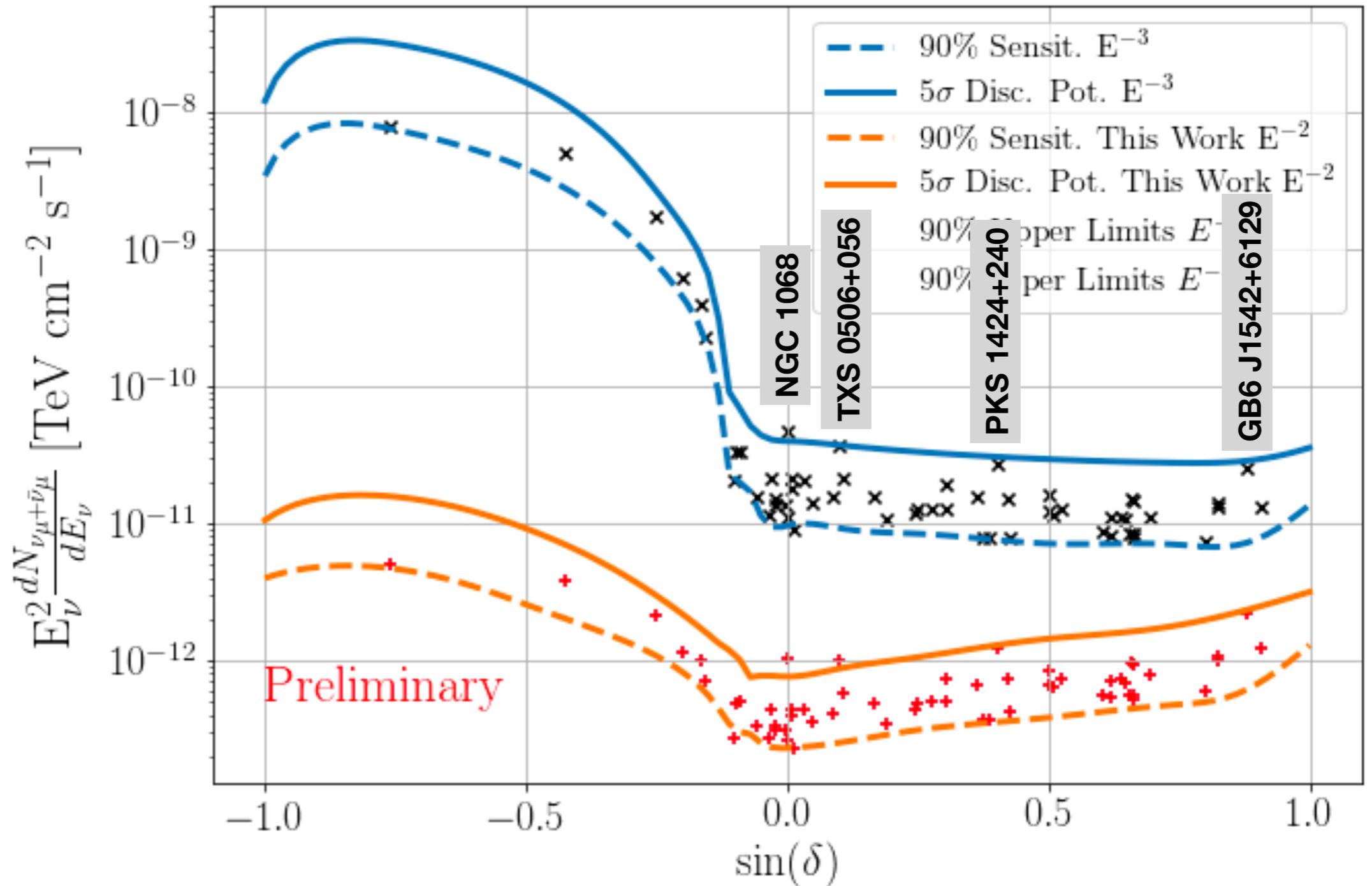
Measured astrophysical neutrino flux appears to be mostly isotropic in nature, with no obvious sources seen

- \* No correlation with galactic plane (<10%)
- \* No correlation with known catalogs of high-energy gamma ray sources

~80k northern hemisphere evt/yr (atm  $\nu$ )  
 ~35k southern hemisphere evt/yr (atm  $\mu$ )  
 ~200 starting tracks from southern sky

IceCube all-sky source search (10 yr data):  
 -No significant source found (N/S p-values: 0.10/0.75)  
 -No correlation with list of 74 known HE gamma-ray sources in both hemispheres (Galactic & Extragalactic)

# Searches for sources



4 “warm” spots observed in catalog-based search.

- \* Inconsistent with background at  $3.3 \sigma$

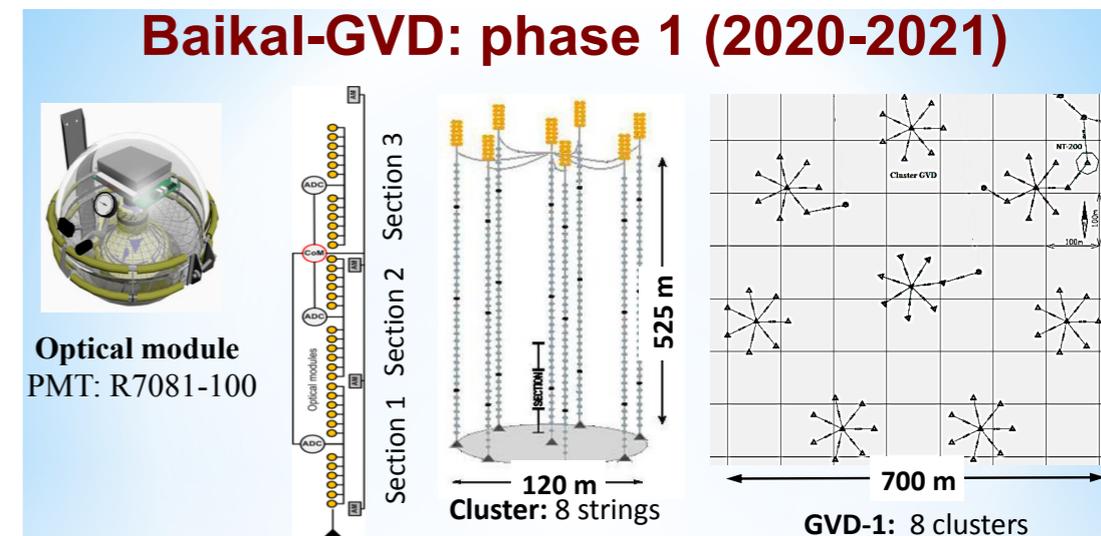
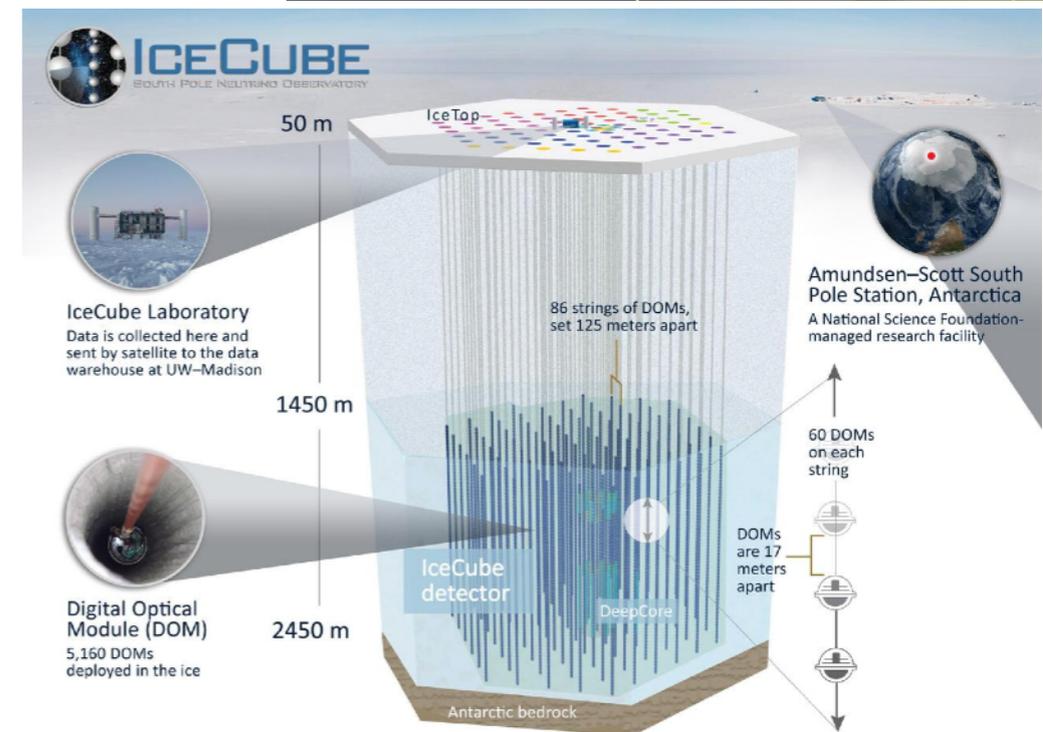
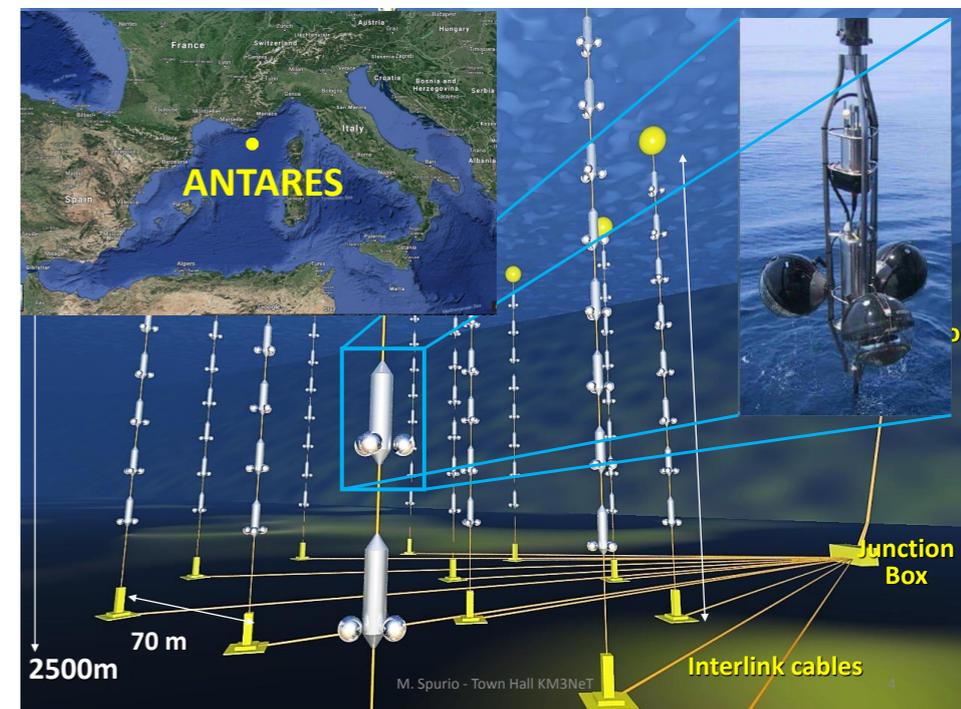
- \* Hints of a class of active galaxies that produce neutrinos?

# Multi-messenger astronomy

- Given the current statistics-limited samples of astrophysical neutrinos, prioritizing multi-messenger observations is key:
  - Alerts to community upon detection of likely astrophysical neutrinos for rapid followups
  - Rapid searches for neutrino signals in response to transient events observed in other messengers
    - Most high-energy sources are known to have time dependent behavior
- These observations can:
  - Strengthen or refine detections made in single messenger
  - Probe source dynamics and populations, even in the absence of a signal
  - Identify the sources of the observed high-energy astrophysical neutrinos

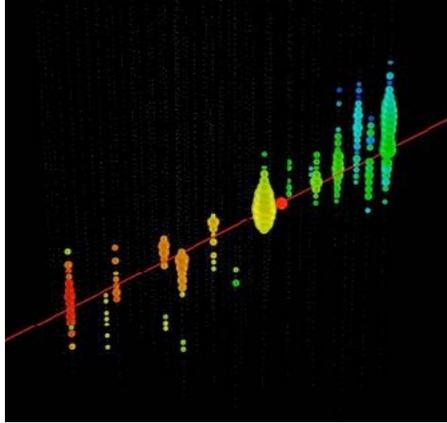
# Alerts from neutrino detectors

- A rapid growing network of large high-energy neutrino detectors are now providing alerts to the astronomy community
  - High-duty factor (>95% observing)
  - Half/Full sky coverage
    - Ideal for alerts
  - Rapid neutrino event identification
    - Performed onsite with rapid communication to community (< 30 s)
  - Neutrino searches in response to community alerts
    - Good angular resolution:  $\sim 0.5^\circ$  (tracks)
  - Neutrino alerts for potential astrophysical signals

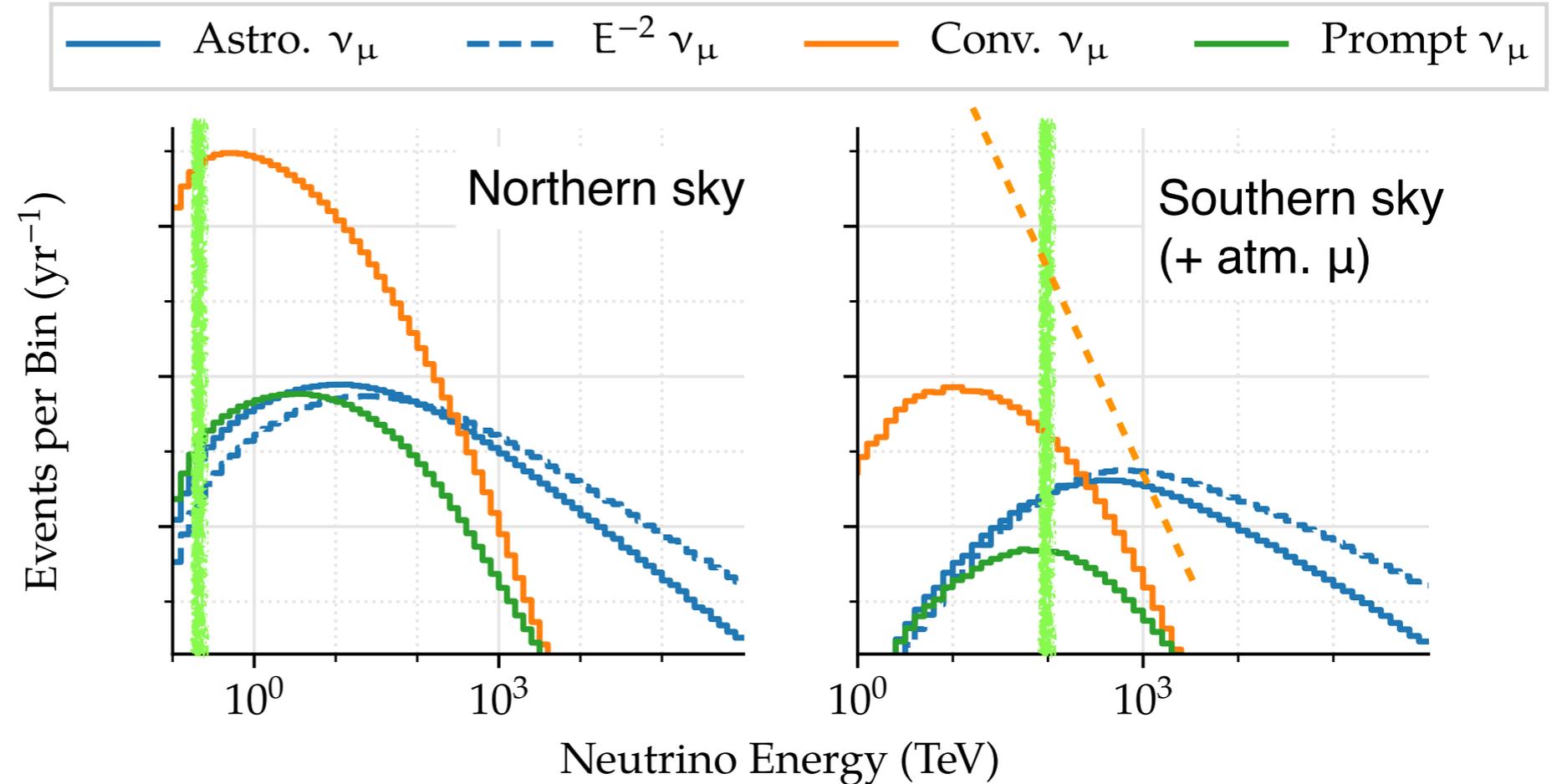


# Neutrino event selections

## IceCube online neutrino track selection



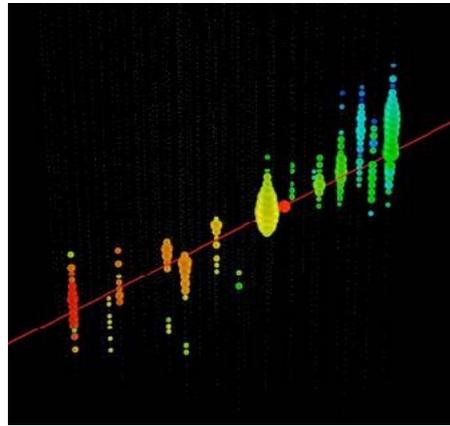
Angular resolution:  $\sim 0.5^\circ$



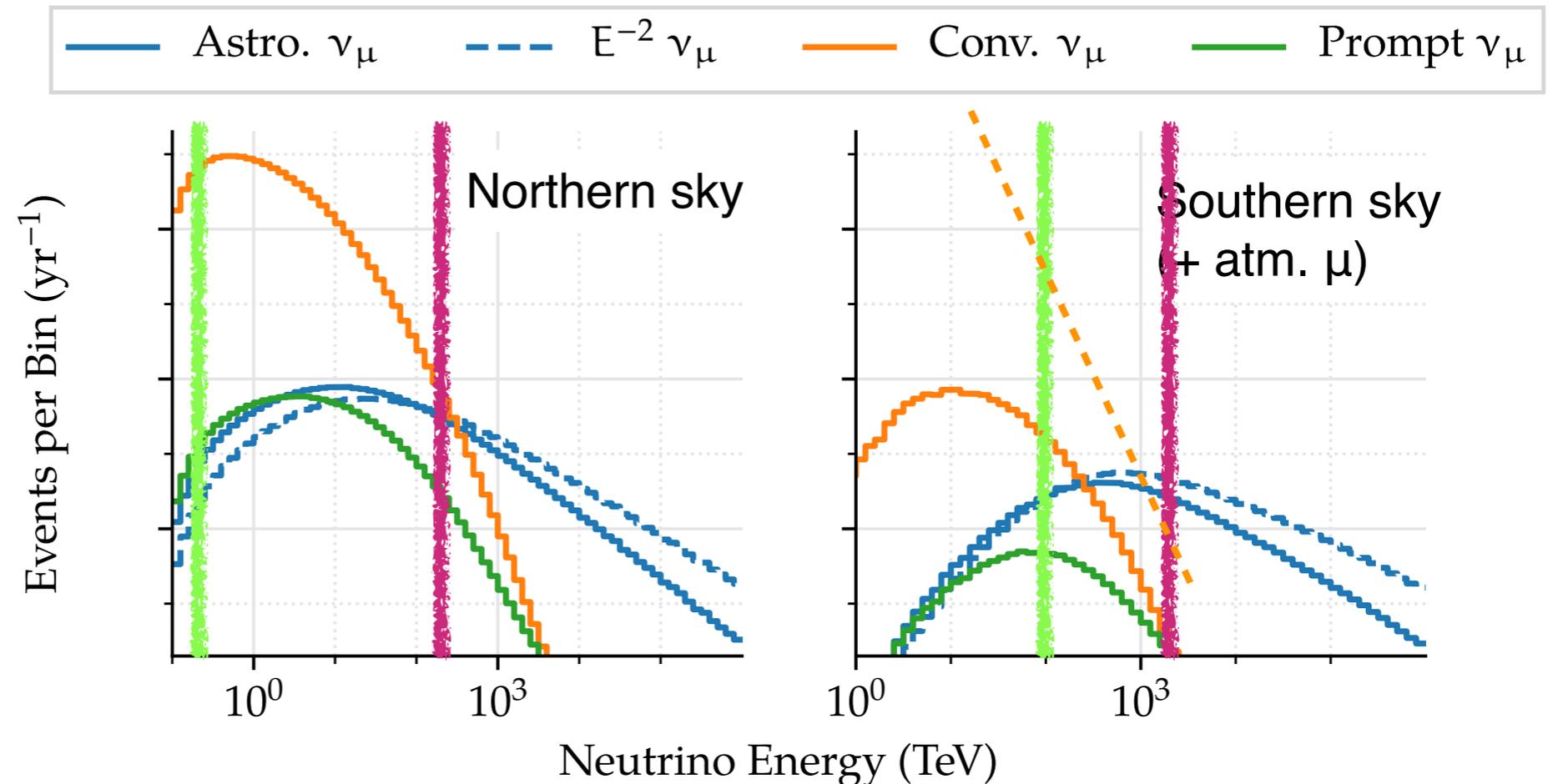
- Neutrino telescopes swamped in atmospheric backgrounds
  - IceCube: 2.5 kHz triggers,  $\sim 5$  mHz neutrino candidate (atmospheric dominated)
    - 10's/yr of identifiable astrophysical neutrinos
- Online selection
  - Look for good quality tracks (upgoing), select energetic tracks above atmospheric muons (downgoing)
    - Sample for rapid searches for neutrinos
  - Alerts: select the highest energy events (least consistent with backgrounds)

# Neutrino event selections

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# ANTARES neutrino alert selection

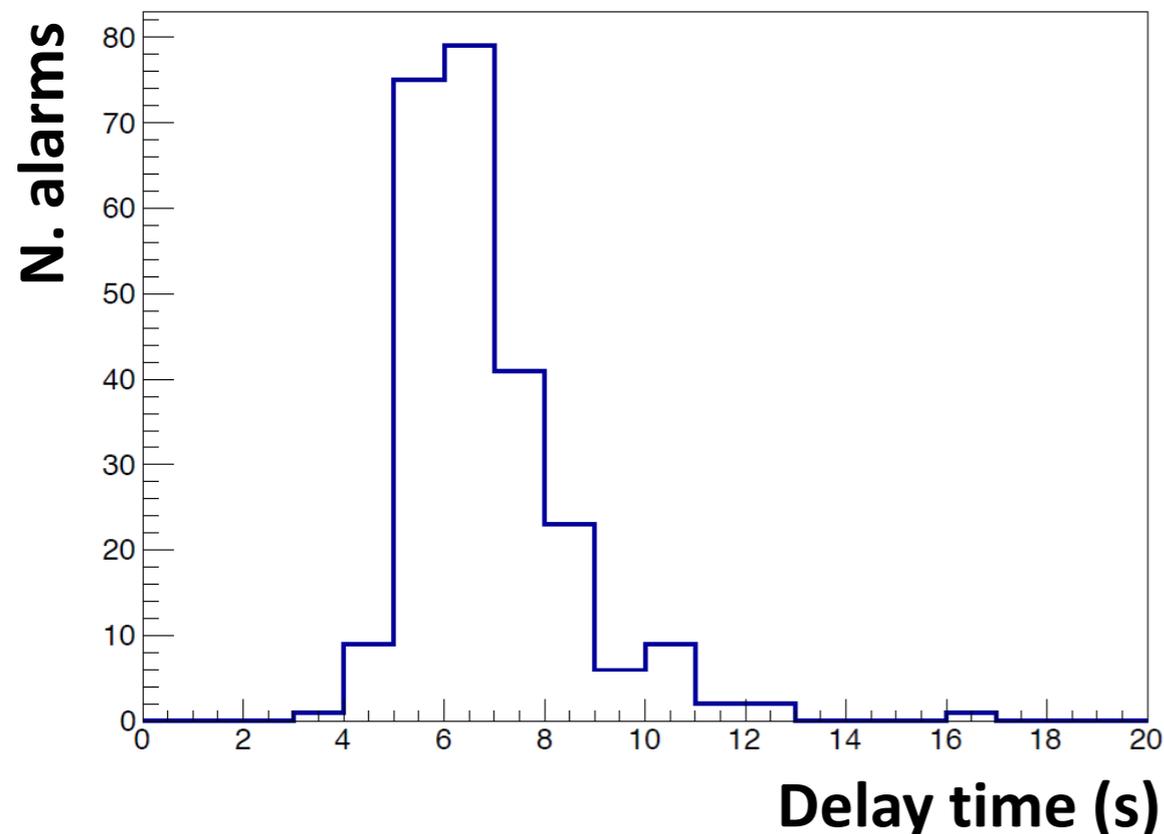
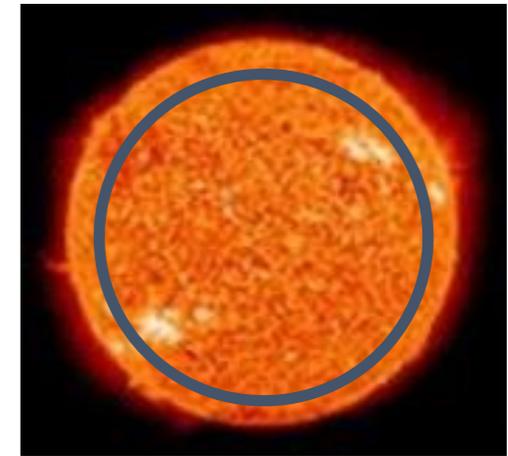


## Triggers (upgoing tracks):

- Doublet of neutrinos:  $\sim 0.04$  evt / yr.
- Single neutrino with direction close to local galaxies (1 TeV):  $\sim 10$  evt / yr.
- Single HE neutrinos (7 TeV):  $\sim 15$  evt/yr
  - VHE neutrinos (30 TeV):  $\sim 3-4$  evt/yr.

## ANTARES PSF :

$\sim 0.4^\circ$  (median)



## Alert delay:

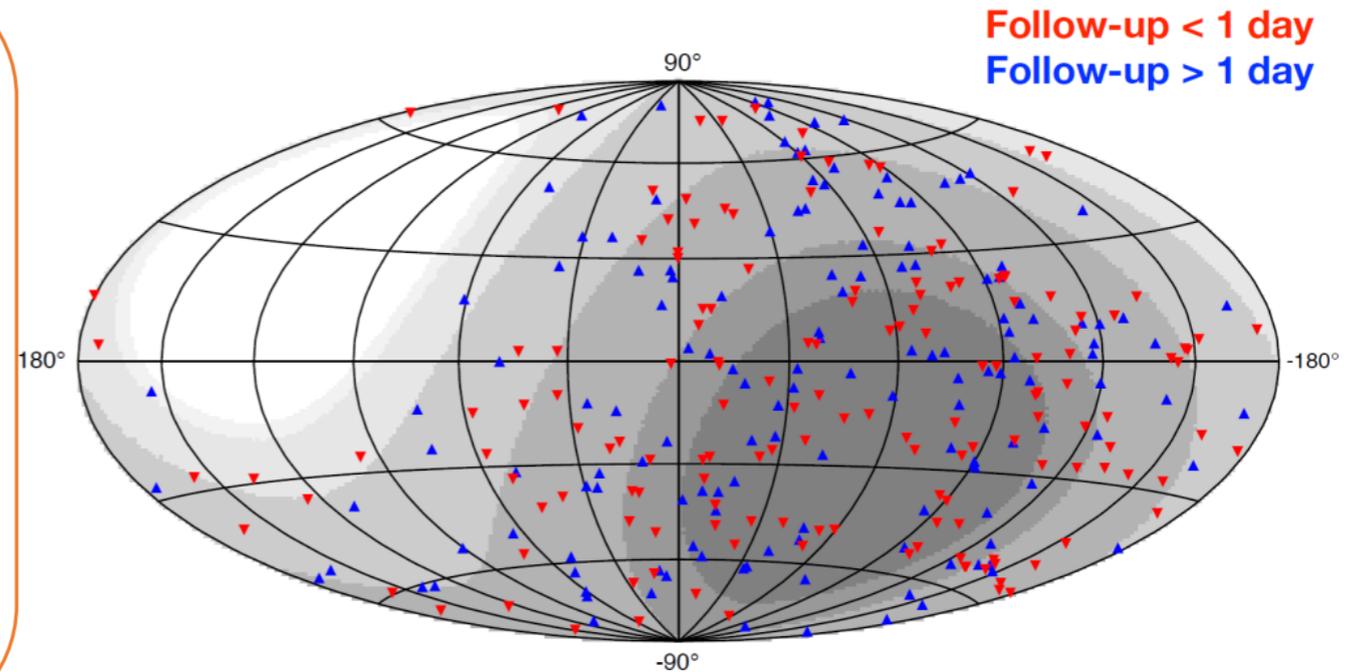
- Alert message sent via GCN using GCN socket/VO Event (XML file)
- Average delay:  $\sim 6-7$  s (filtering, online reco, neutrino selection, alert message)

# ANTARES neutrino alert selection: follow-ups

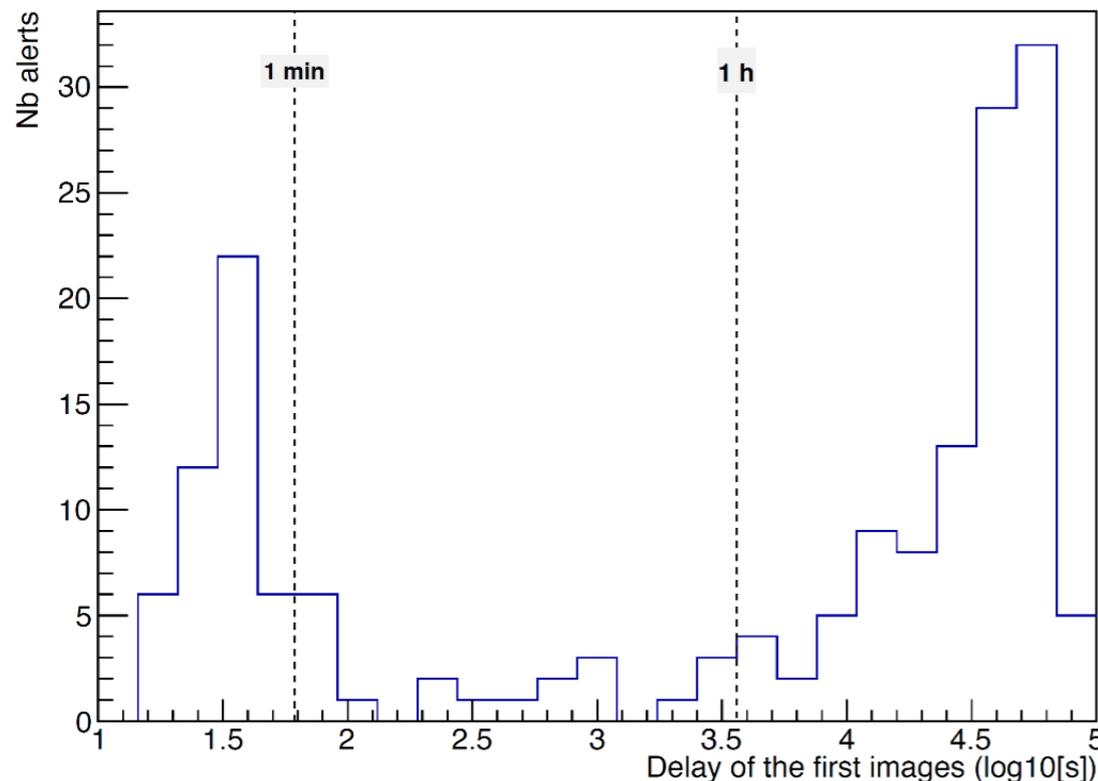


## Status ANTARES alerts (Oct 2009 - July 2019):

- 311 robotic **optical** telescopes
- 18/25 followed by **Swift-XRT**
- 4 followed by Integral
- 4 followed by MWA
- 2 followed by H.E.S.S.



JCAP02(2016)062



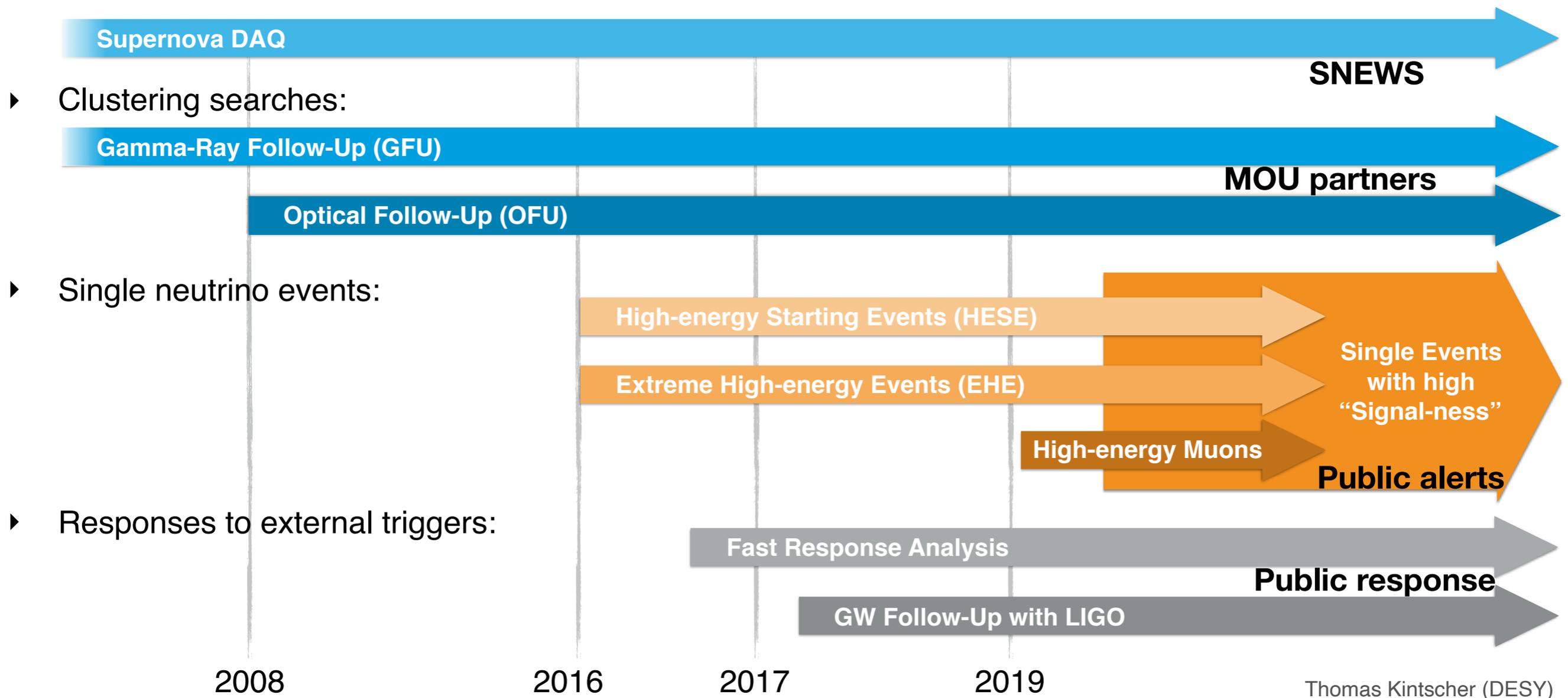
## Follow-up delay (optical):

- $\Delta t$  between 1st image/trigger:
    - **55 alerts < 1 min**
    - **208 alerts < 1 day**
- (wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)

To date: no significant association found

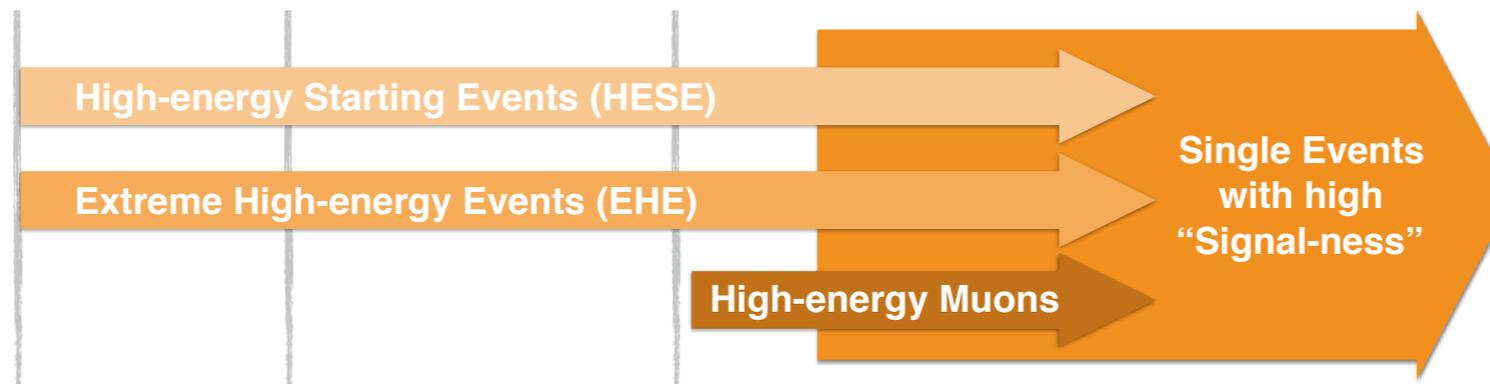
M. Spurio - KM3Net Town Hall (Dec 2019)

# IceCube realtime analyses



- Broad alert and response program.
- Focus on rapid notification for alerts and responses to external triggers

# Single neutrino alerts



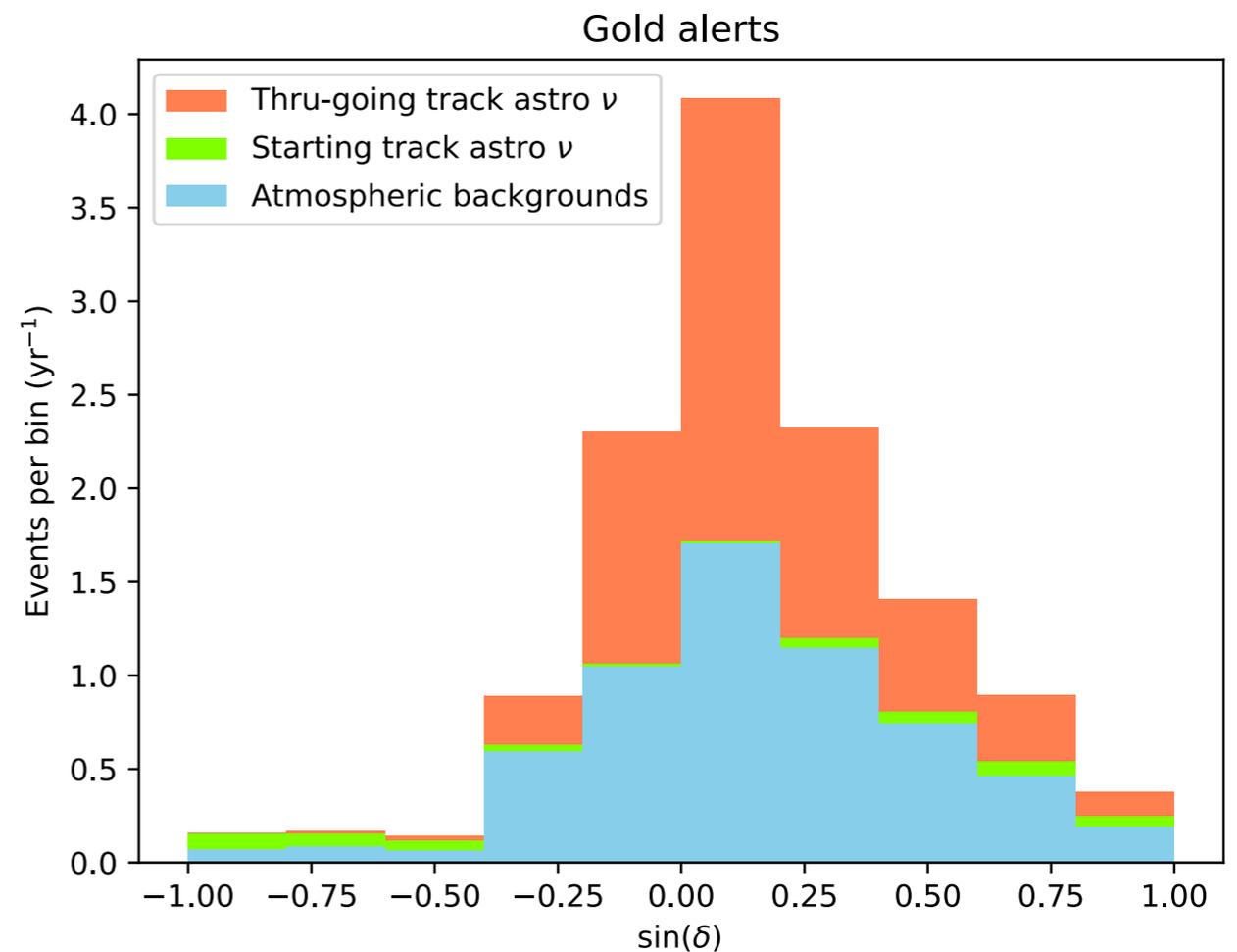
**V2: Updated in June 2019**

- Alerts focusing on single events that are likely astrophysical in origin
- 2019: upgraded event selection
  - Improved background rejections
  - Added through-going track selections
  - “Signalness” =  $N_{\text{Signal}} / (N_{\text{Signal}} + N_{\text{Background}})$
  - 2 classifications:
    - Gold : > 50% signalness
    - Bronze >30% signalness

# Single neutrino alerts

- Alerts issued as **public** GCN Notices
- Report:
  - Direction and uncertainty
  - Signalness and expected yearly rate
  - Most likely neutrino energy
- Updated GCN circular follows
  - Detailed direction likelihood scan results (~3-4 hr later)
- Encourage community followup!

	Event Rate (1/yr)	
	Gold	Bronze
<b>Astro. Signal (<math>E^{-2.19}</math>)</b>	6.6	9.4
<b>Atm. Backgrounds</b>	6.1	20.8
<b>Data</b>	9.9	29.4



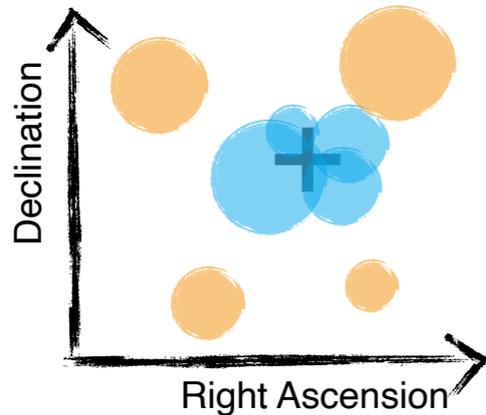
# Fast response analyses

## \* Time dependent source search

- ▶ Unbinned maximum-likelihood method:

$$\mathcal{L} = \prod_i^{\text{events}} \left[ \frac{n}{N} S_i + \left( 1 - \frac{n}{N} \right) B_i \right]$$

$$\text{TS} = -2 \log \left( \frac{\mathcal{L}(\hat{n}, \hat{\gamma})}{\mathcal{L}(n=0)} \right)$$



×



×



### 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

## • Followup several classes of events

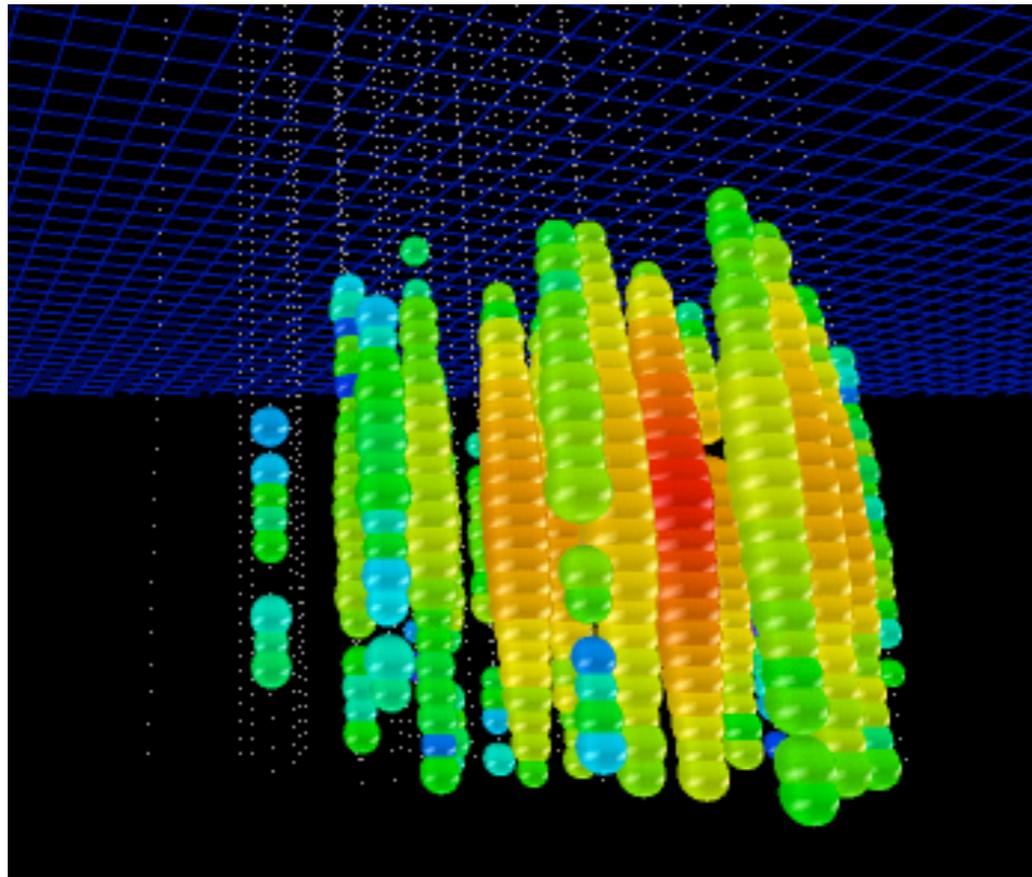
### • IceCube alerts

- Search for additional neutrinos associated with alert (+/- 1 day, +1/-30 day)

### • External alerts (GCN, ATels...)

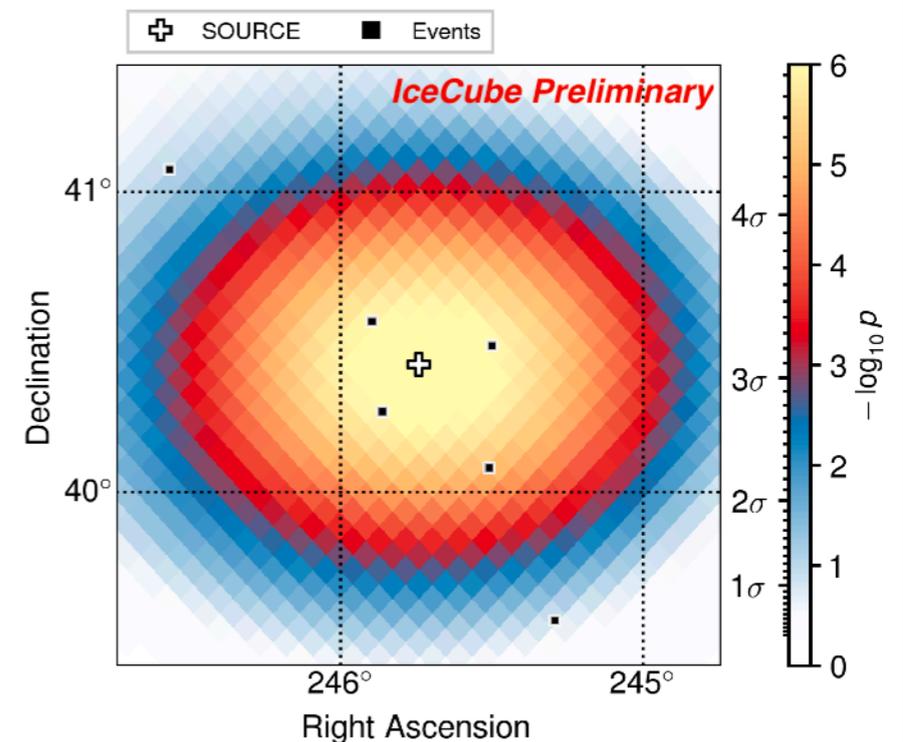
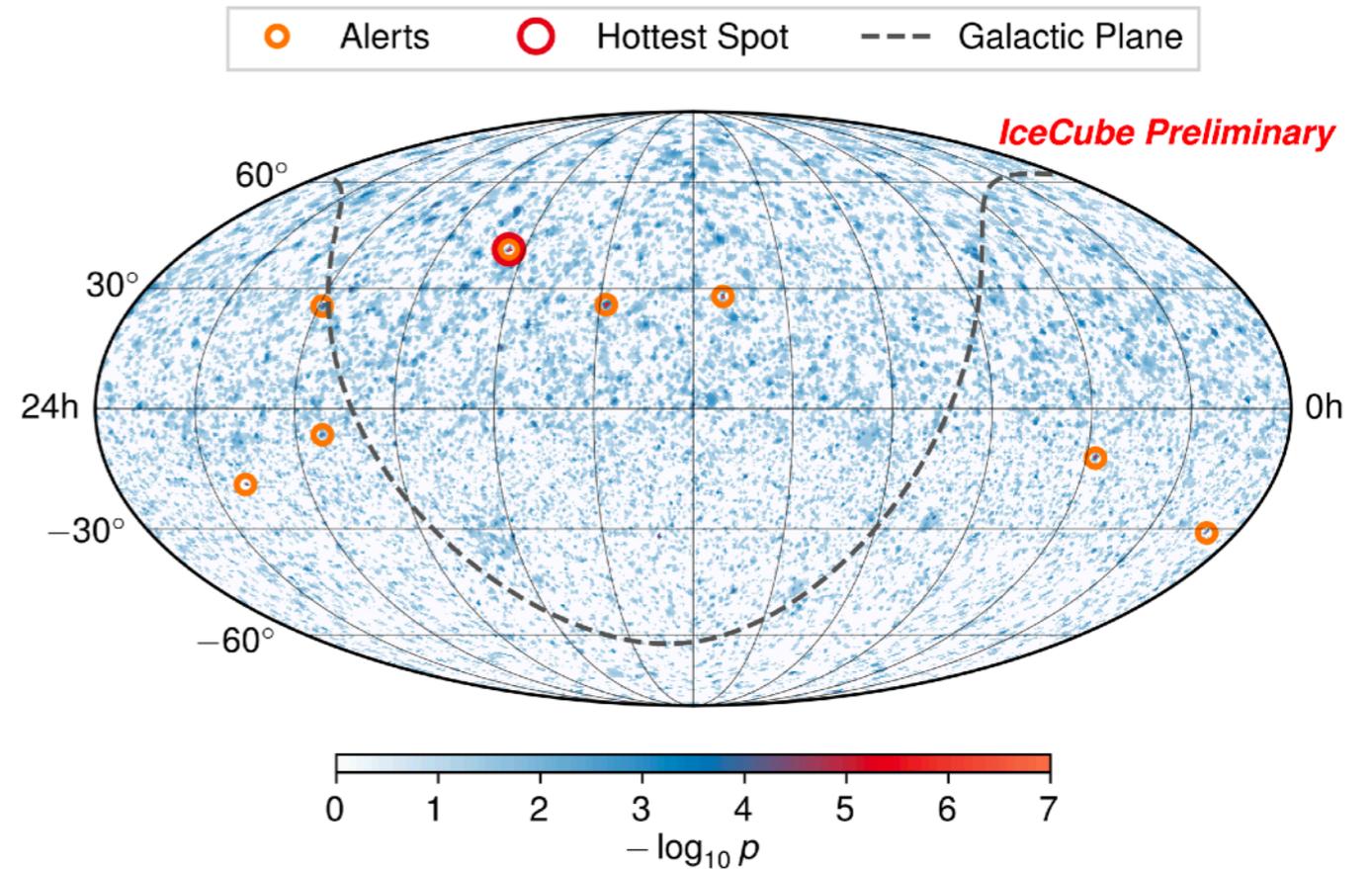
- Selecting likely neutrino candidates or extraordinary sources

# IceCube alerts - upcoming



$O(10^\circ)$  angular uncertainty)

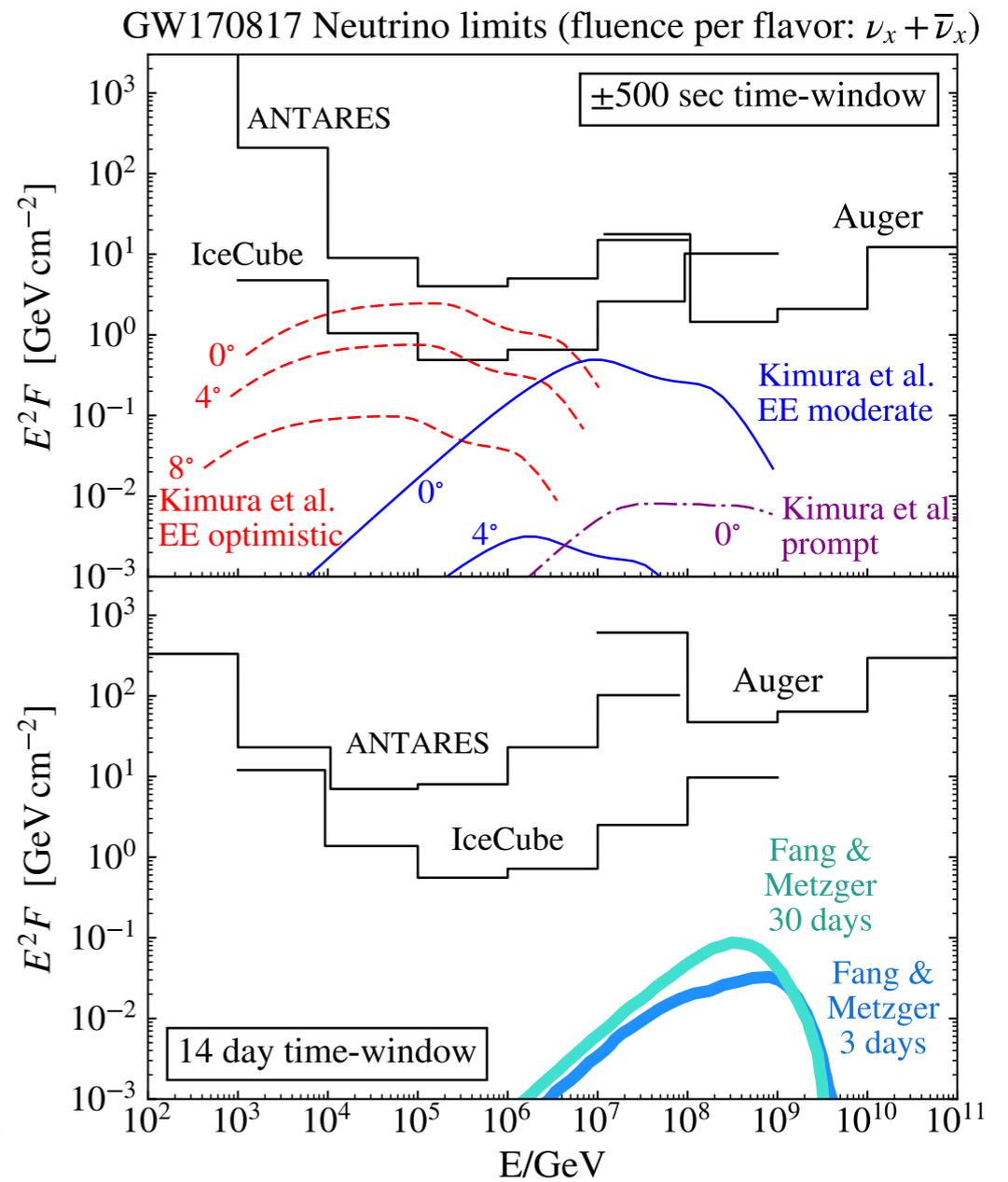
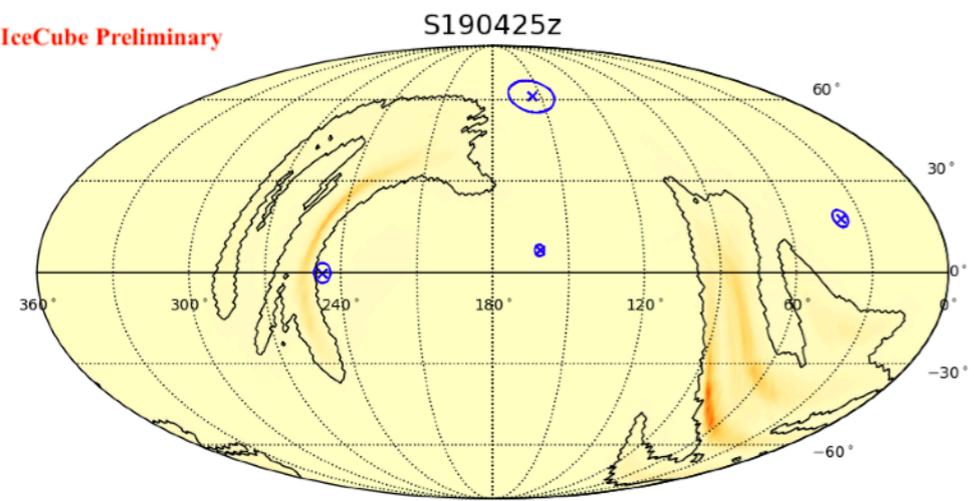
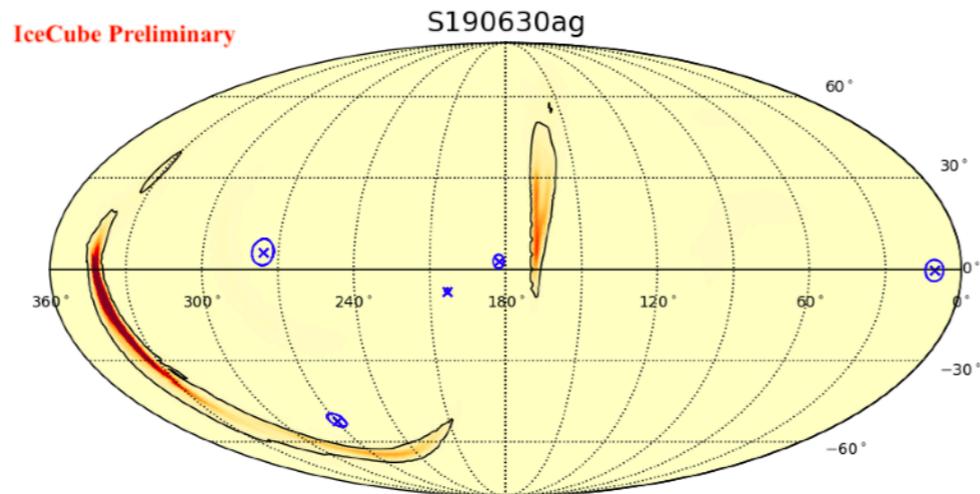
- Next steps for IceCube alerts:
  - Alerts from cascade events ( $\sim 6/\text{yr}$ )
  - Alerts for all-sky time dependent flaring searches ( $\sim 1/\text{yr}$ )



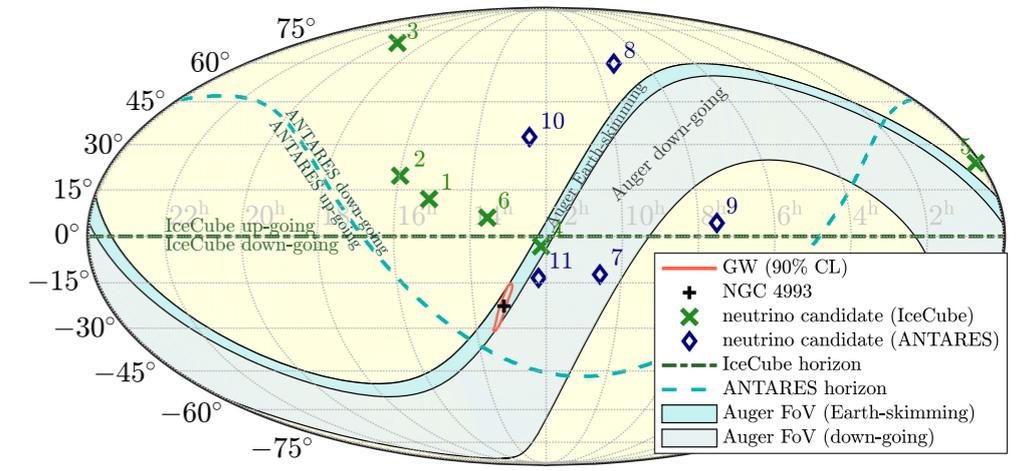
Hottest spot in 8 yr of data  
Consistent with background after trials correction

# GW-Neutrino event searches

- High-energy neutrinos can provide important information:
  - Coincident neutrino detection could reduce localization uncertainty and aid followup observations
  - Provide understanding of particle acceleration and high-energy emission from compact objects
- Now searching in realtime for neutrinos in Run O3!

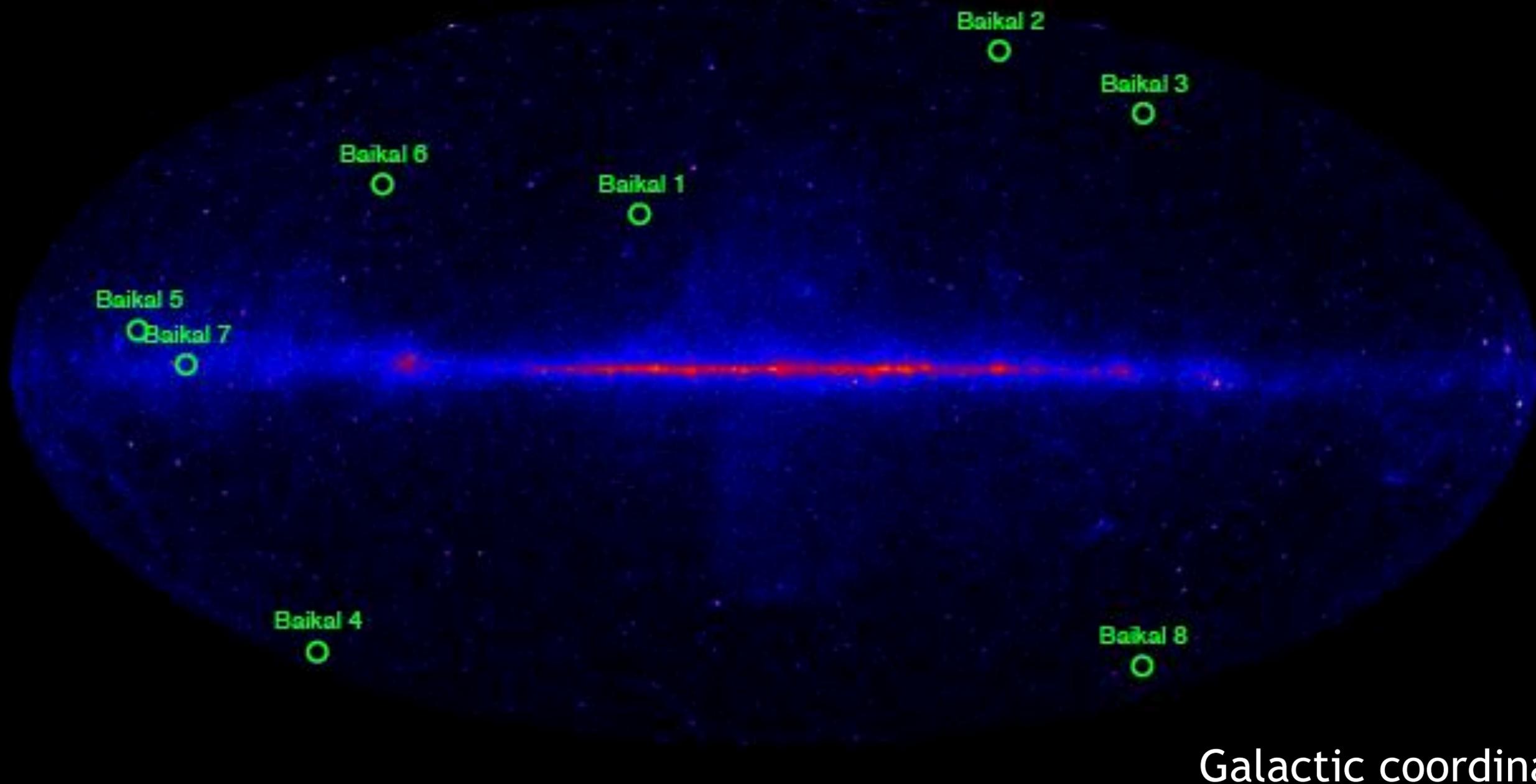


Astrophys.J. 850 (2017)



# GVD alert base of 8 cascades : 2015-2016, 2018-2019

*(Preliminary)*



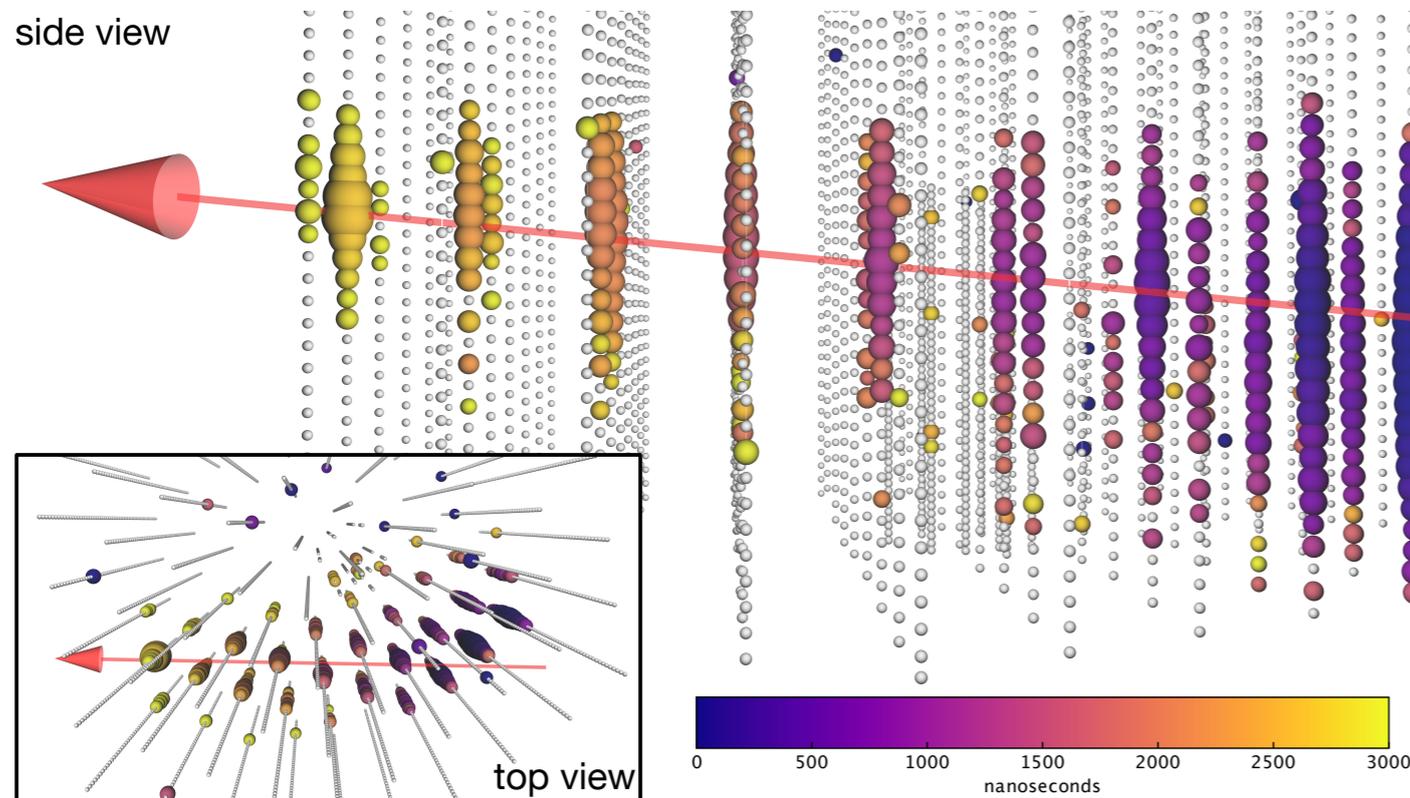
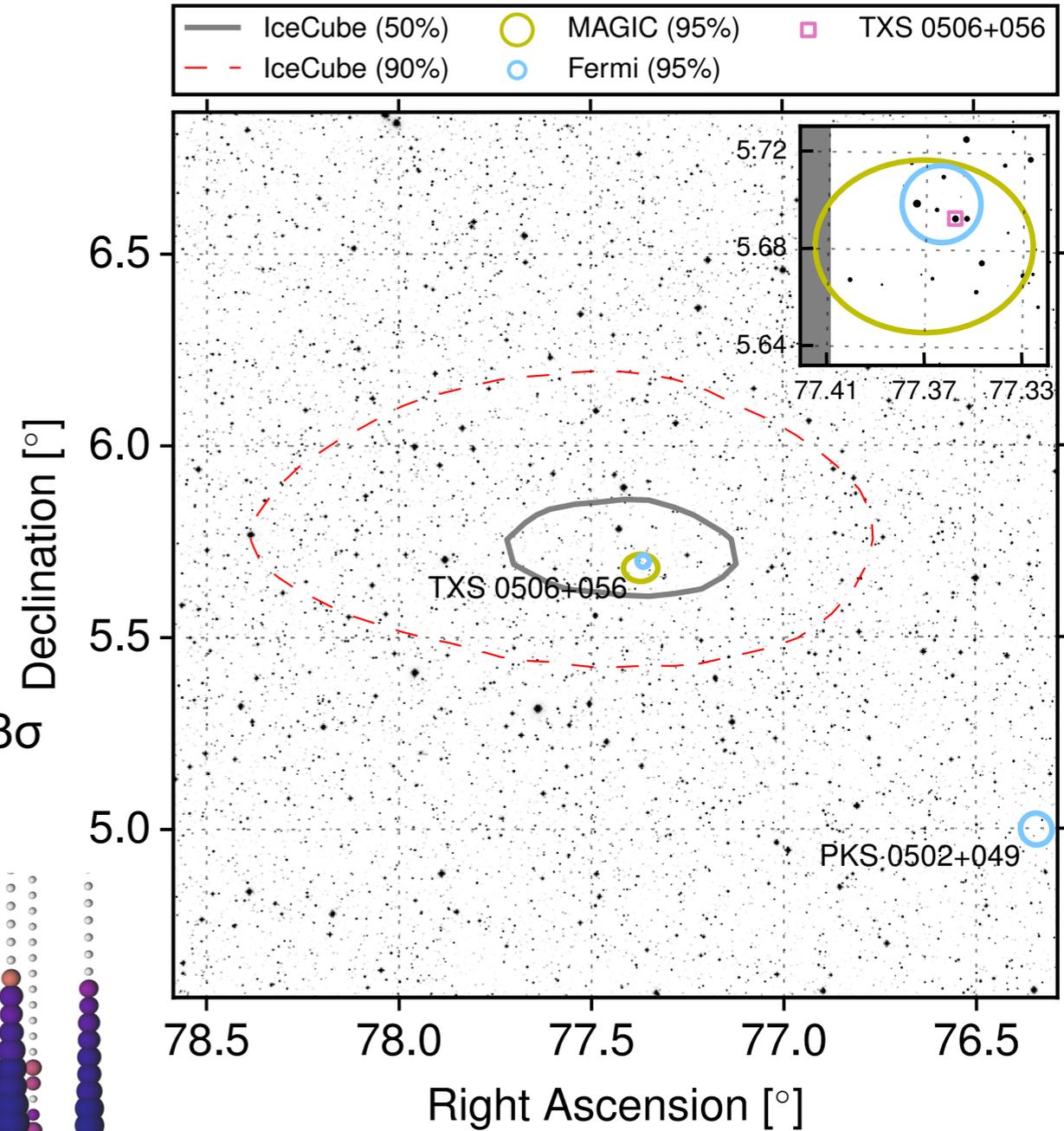
Galactic coordinates

GVD approaching  $\sim 0.4 \text{ km}^3$  volume in next year  
7 events  $> 100 \text{ TeV}$  - online, public alerts in preparation

O. Suvorova - KM3Net Town Hall (Dec 2019)

# IceCube-170922A: Alert

- Neutrino alert: 22 September 2017
  - Neutrino energy: 290 TeV (56% likely astrophysical)
  - 3FHL source found in error box: TXS 0506+056
    - Fermi-LAT reported active flaring at time of alert
  - MAGIC VHE detection at  $> 80$  TeV
  - Large multi-wavelength followup campaign
- Chance coincidence for correlated emission reject at  $3\sigma$



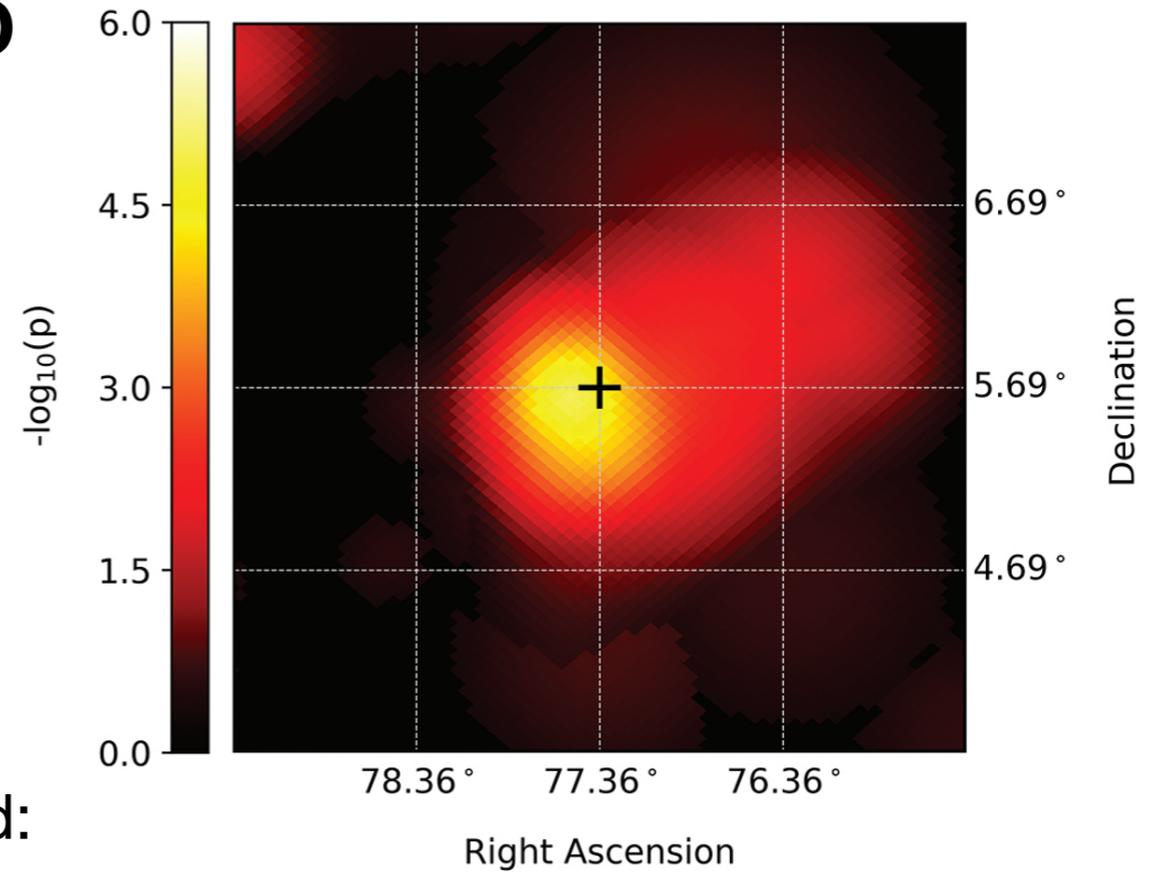
Published: Science 361 (2018)



# IceCube-170922A: Followup

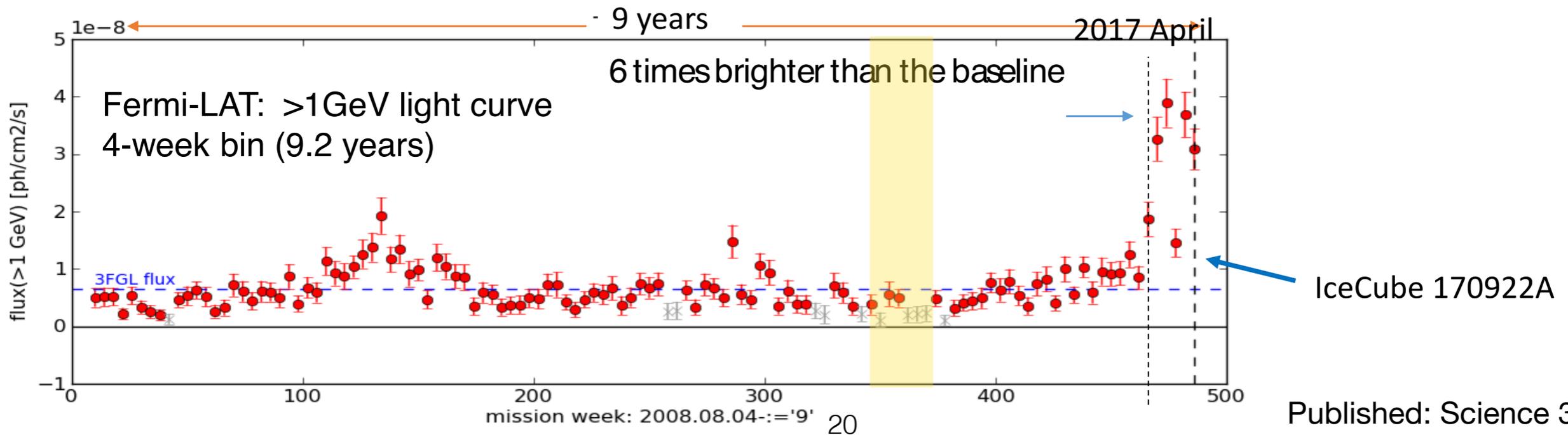
Based on the neutrino alert - flaring blazar correlation, IceCube performed a search for evidence of a neutrino flux from TXS 0506+056 in archival point source data samples

- Is it a constant neutrino source?
- Does it exhibit time dependent emission?
- Apply standard point source likelihood analysis



Evidence of time-dependent emissions is observed:

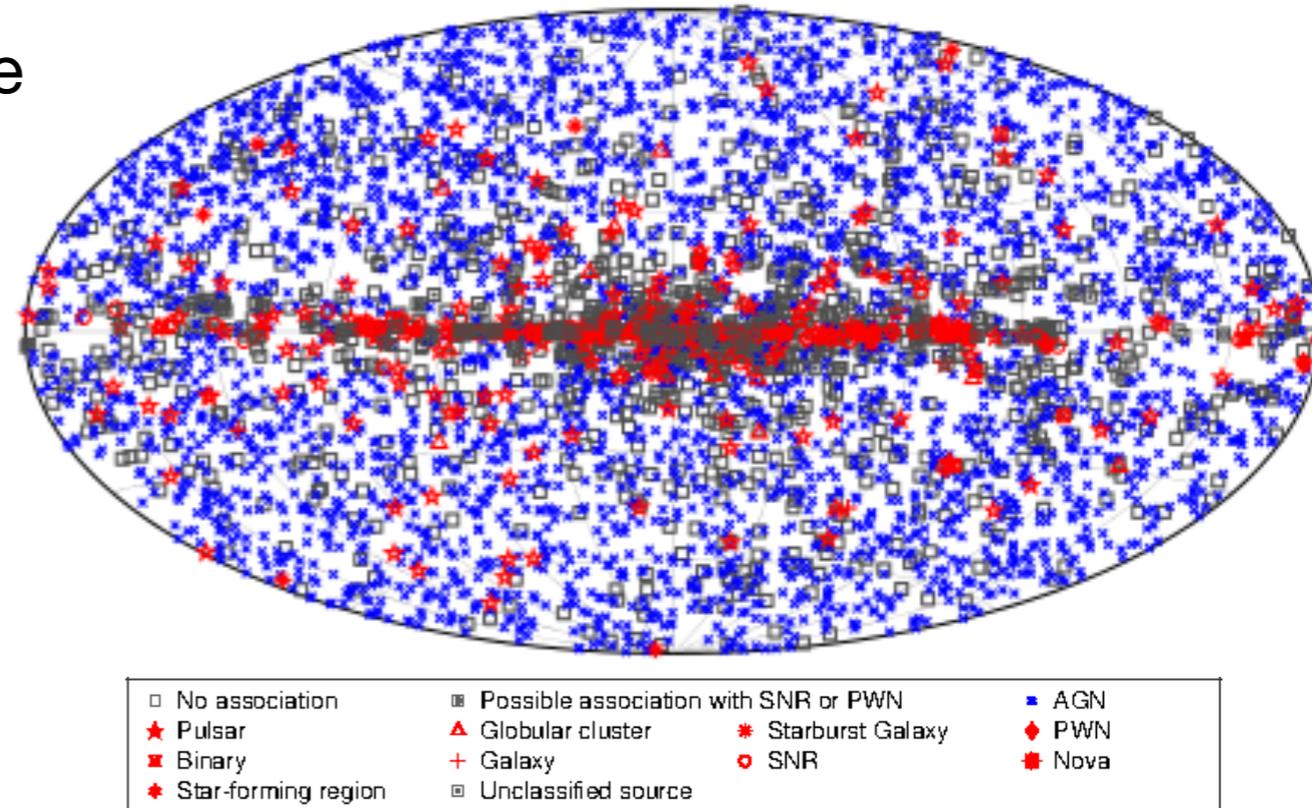
- September 2014 - March 2015
  - Independent of, and prior to neutrino alert
- $3.5\sigma$  excess over expected background
  - $13 \pm 5$  events over background



# Challenges for neutrino alerts

- Source confusion
  - Even at  $\sim 0.2^\circ$  direction uncertainty, there are many potential sources
    - 4FGL has more than 3000 AGN
  - Observing a rapid timescale transient does help
  - Deep observations in unknown region
- Neutrino horizon
  - Some fraction of neutrino events likely arising from distances too far to be resolved in photons.
- Rapidly growing number of transient alerts.
  - Need for better coordination of multi-messenger efforts

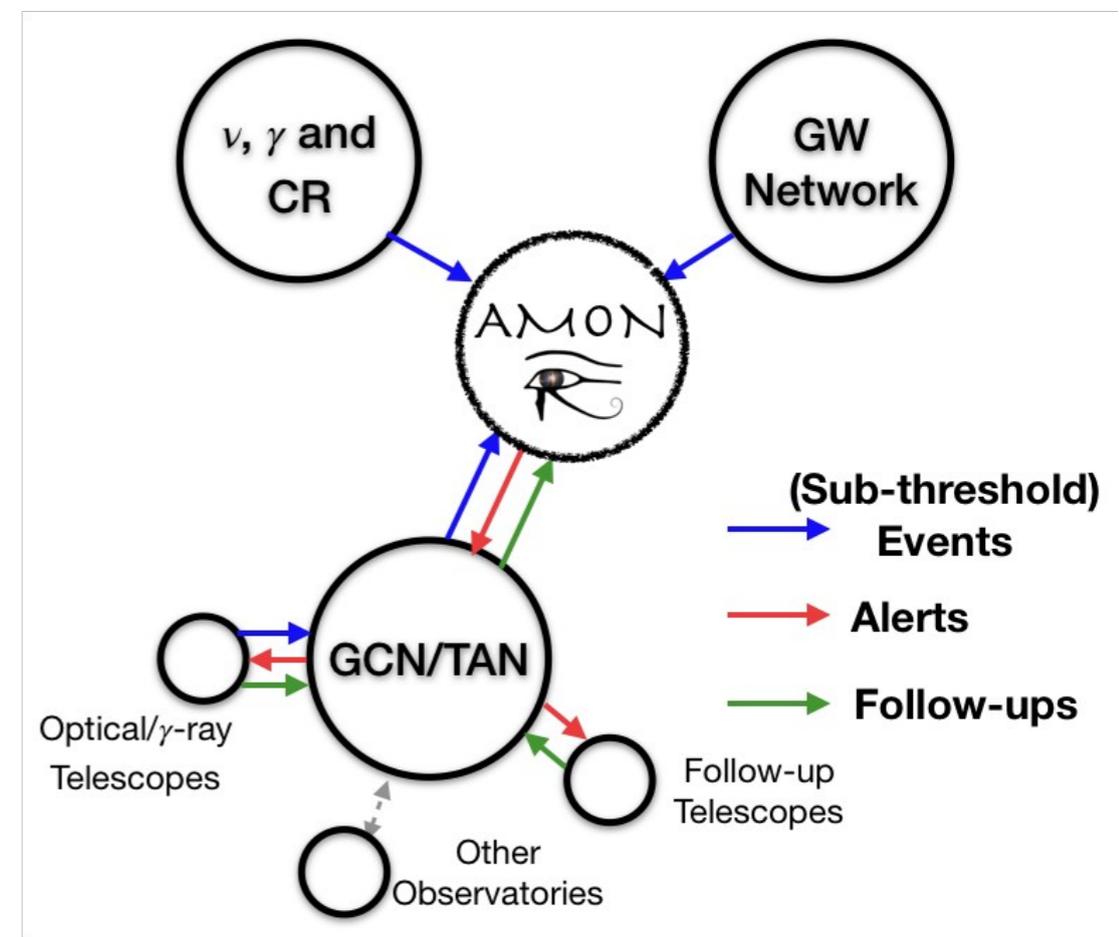
FERMI LAT FOURTH CATALOG



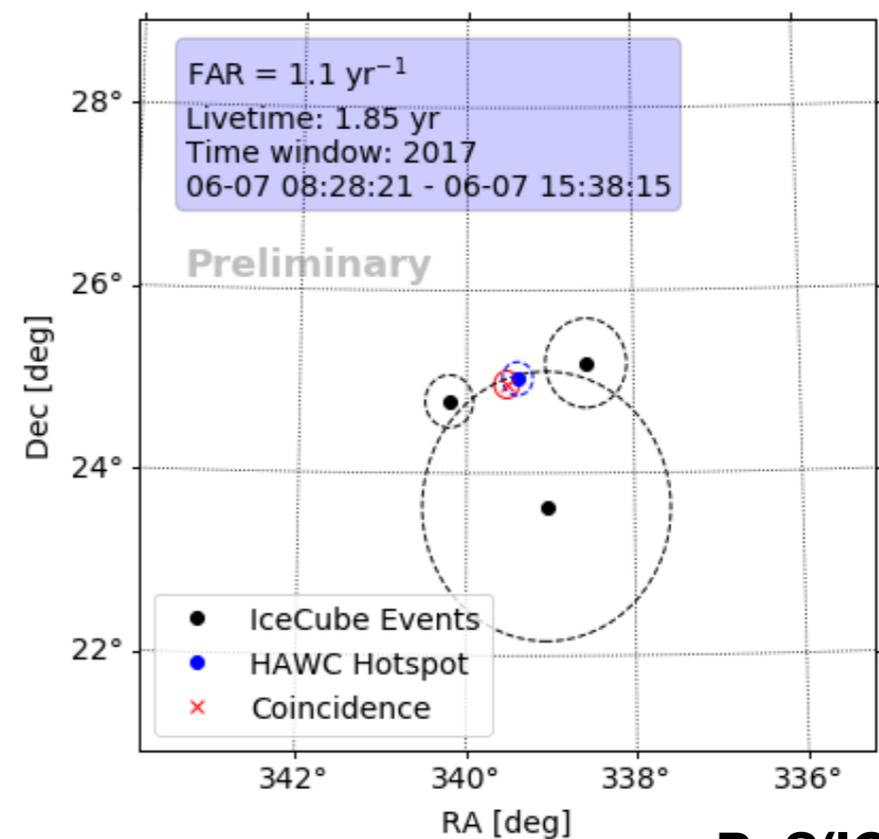
**Prompt, multi-wavelength coverage will likely be needed to understand source dynamics.**

# AMON

- Astrophysical Multi-messenger Observatory Network (AMON) established to explore sub-threshold coincidences between messengers
  - Trigger followup observations
- First searches coming to maturity
  - Search for IceCube neutrinos coincident with HAWC gamma-ray hotspots
    - Public alerts expected to start soon
- ANTARES - Fermi-LAT coincidences

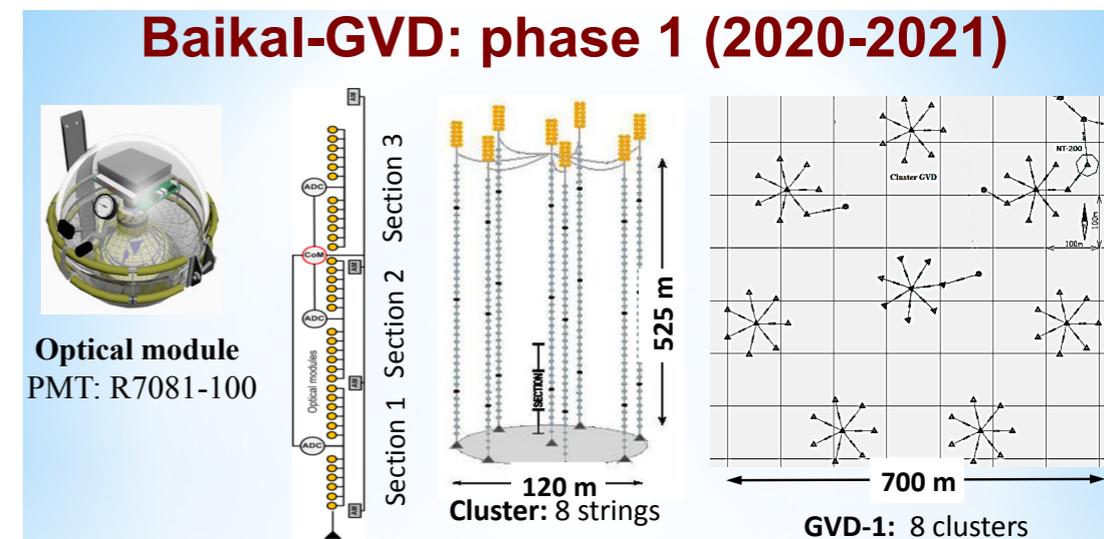
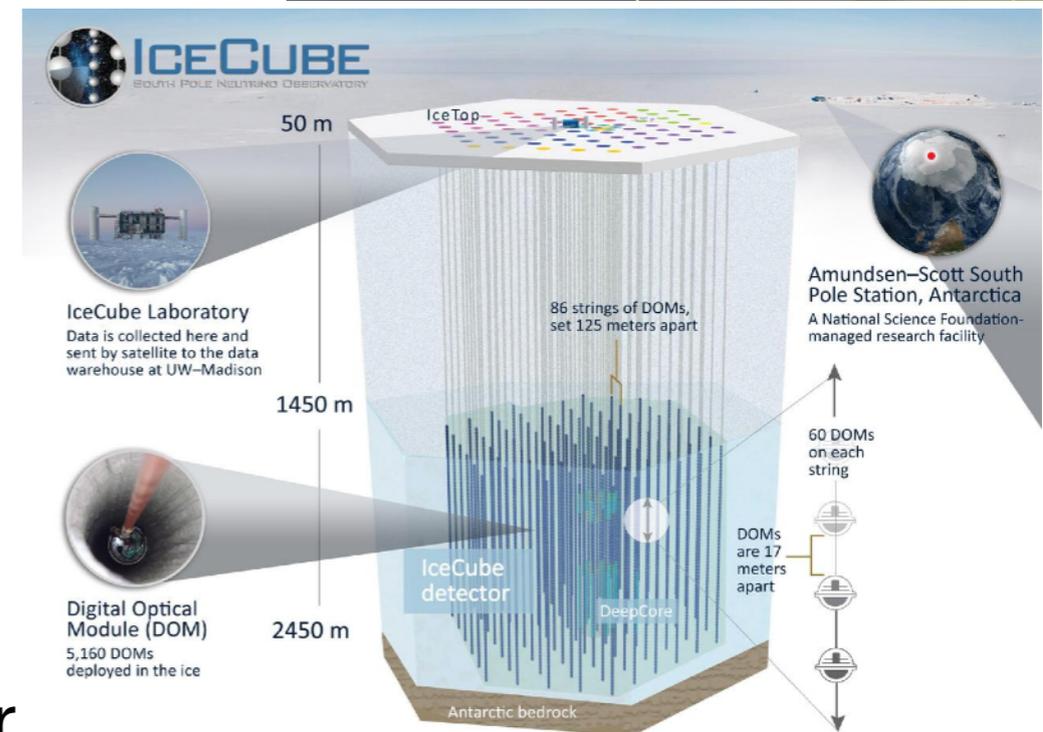
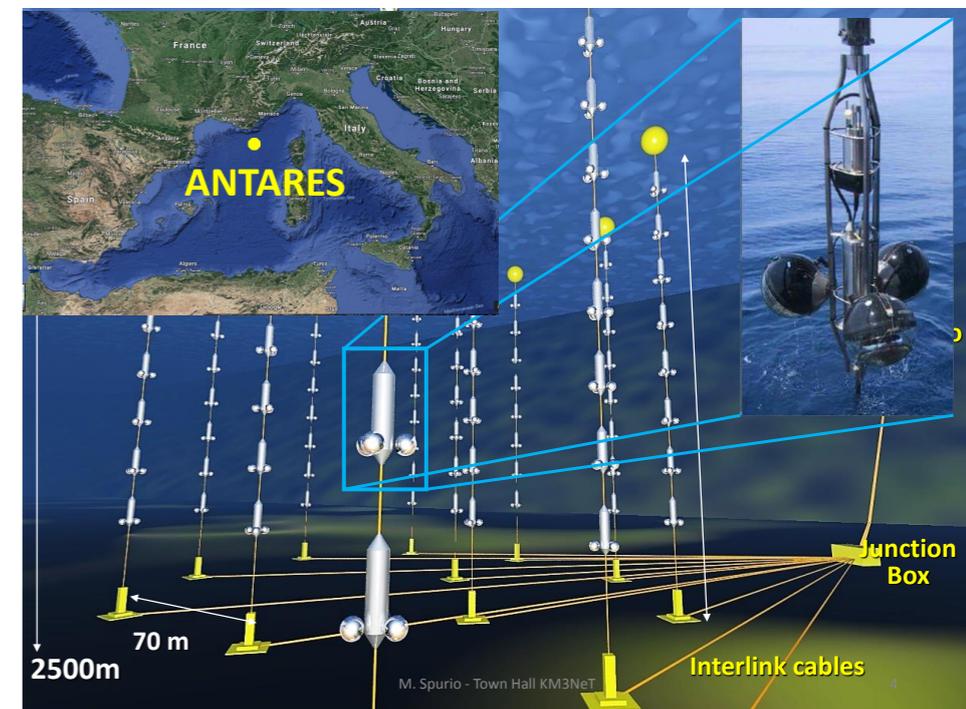


Ayala Solares et al. 2019,  
Astropart. Phys. 114, 68



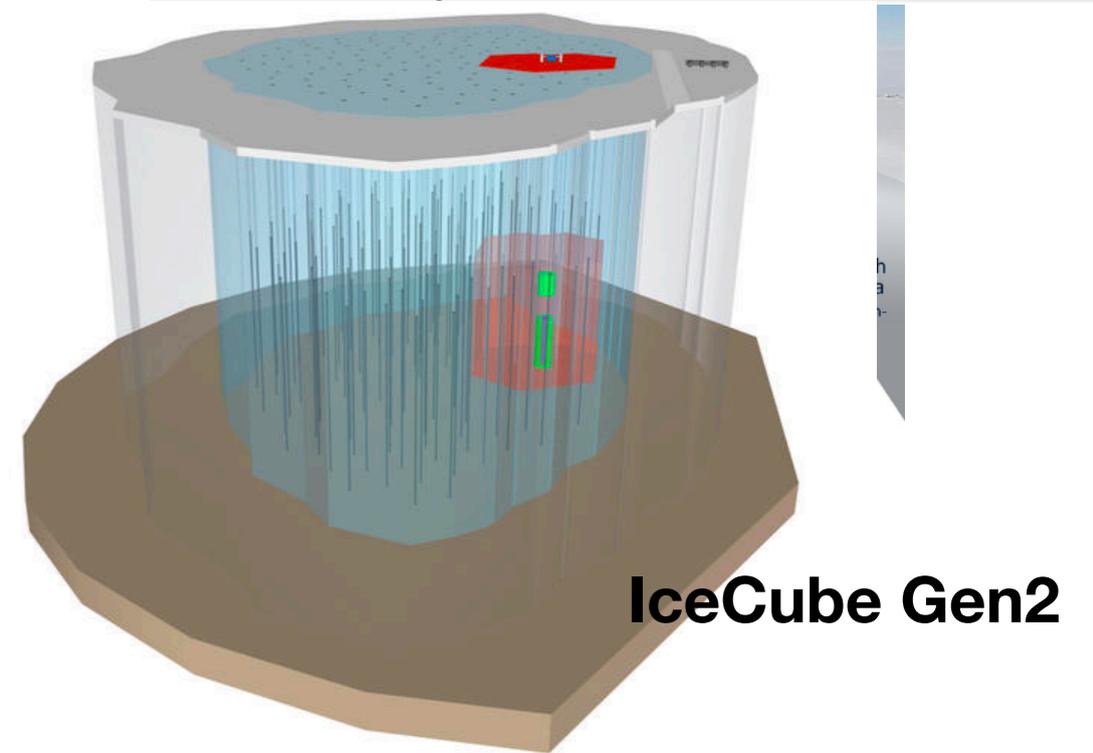
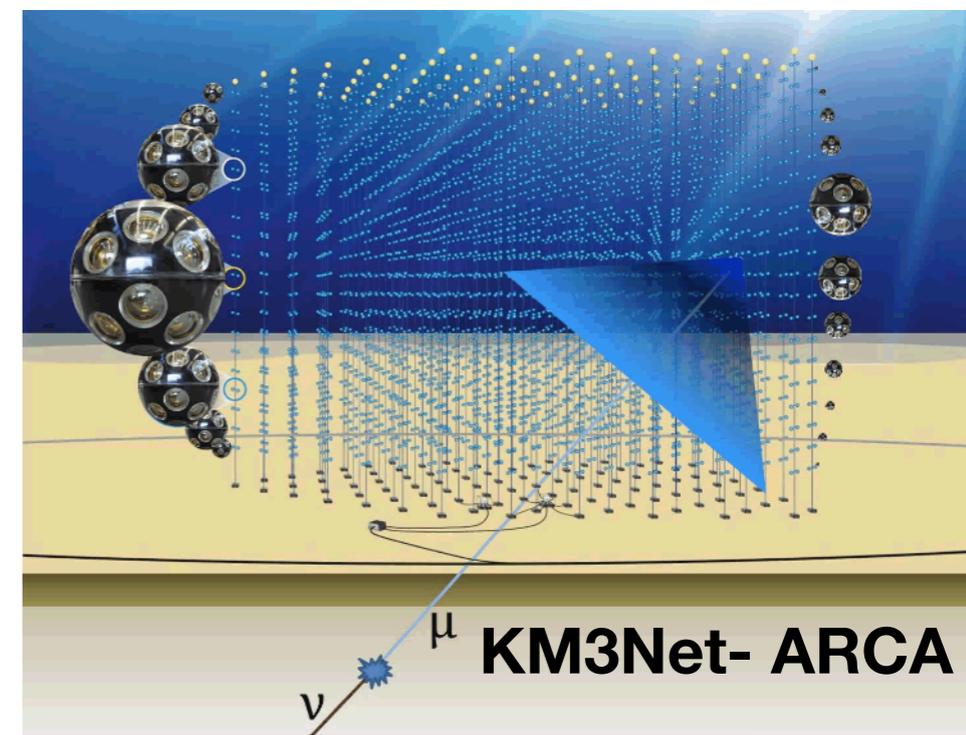
# Future alerts in neutrinos

- With several new neutrino telescopes under active construction or expansion, the landscape is going to change over the coming years.
- ANTARES -> KM3Net
  - KM3Net realtime alert framework in development now, expected to start operation in the next year.
    - See M. Taiuti's talk later today.
- Baikal-GVD growing to complete phase 1
  - Expecting first public alerts in the next year from observation of cascade events
  - Track selection and alerts under development
- IceCube Upgrade and Gen2

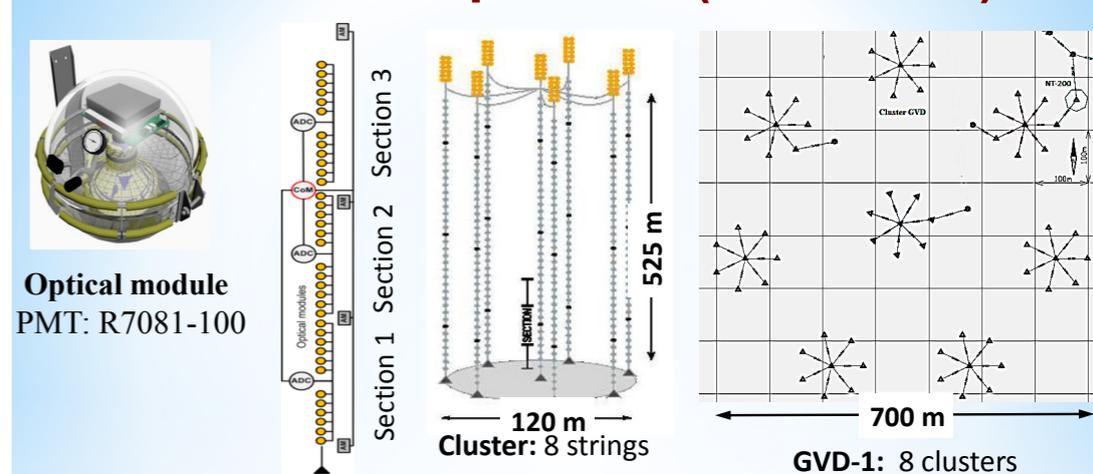


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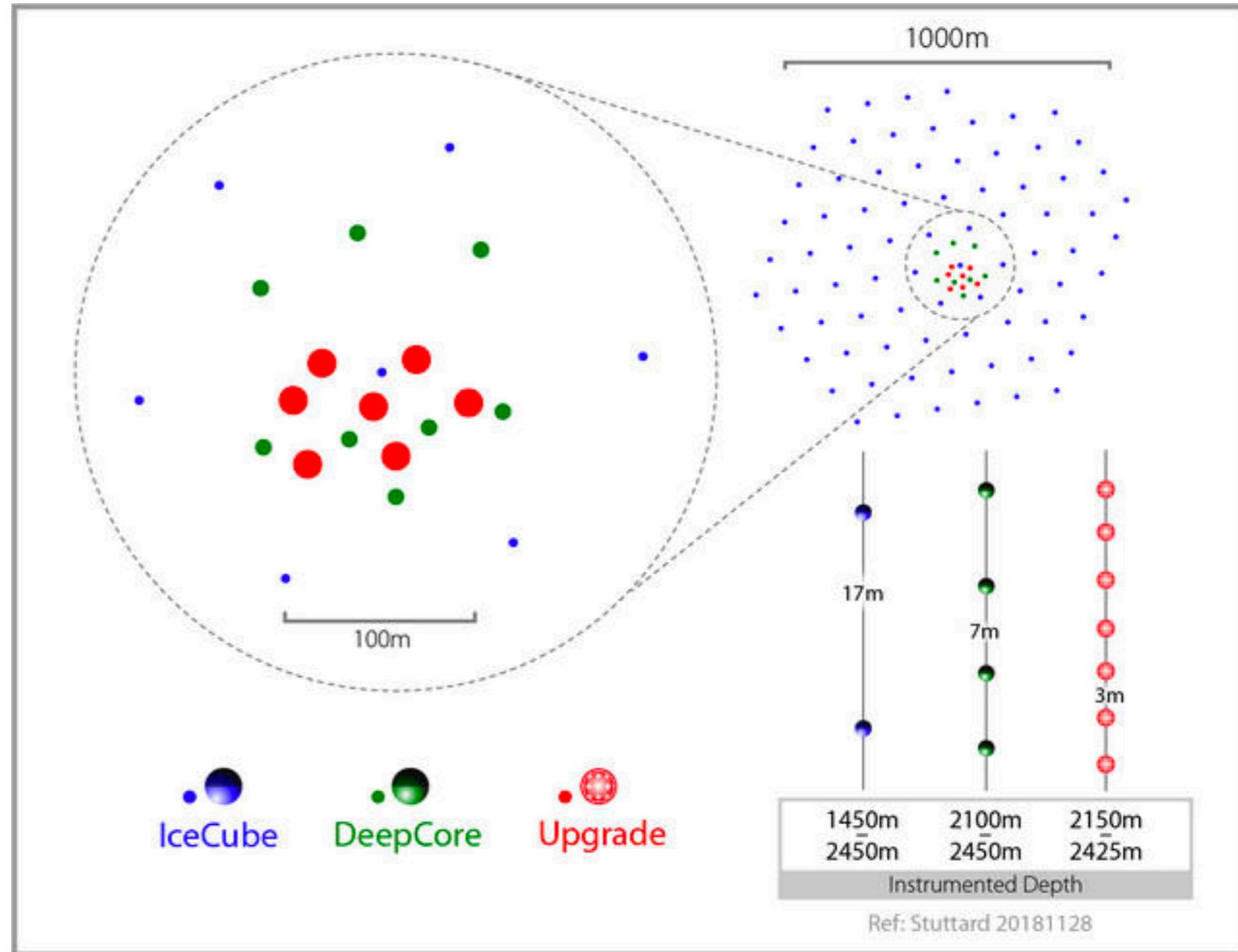


## Baikal-GVD: phase 1 (2020-2021)



# IceCube plans for Upgrades

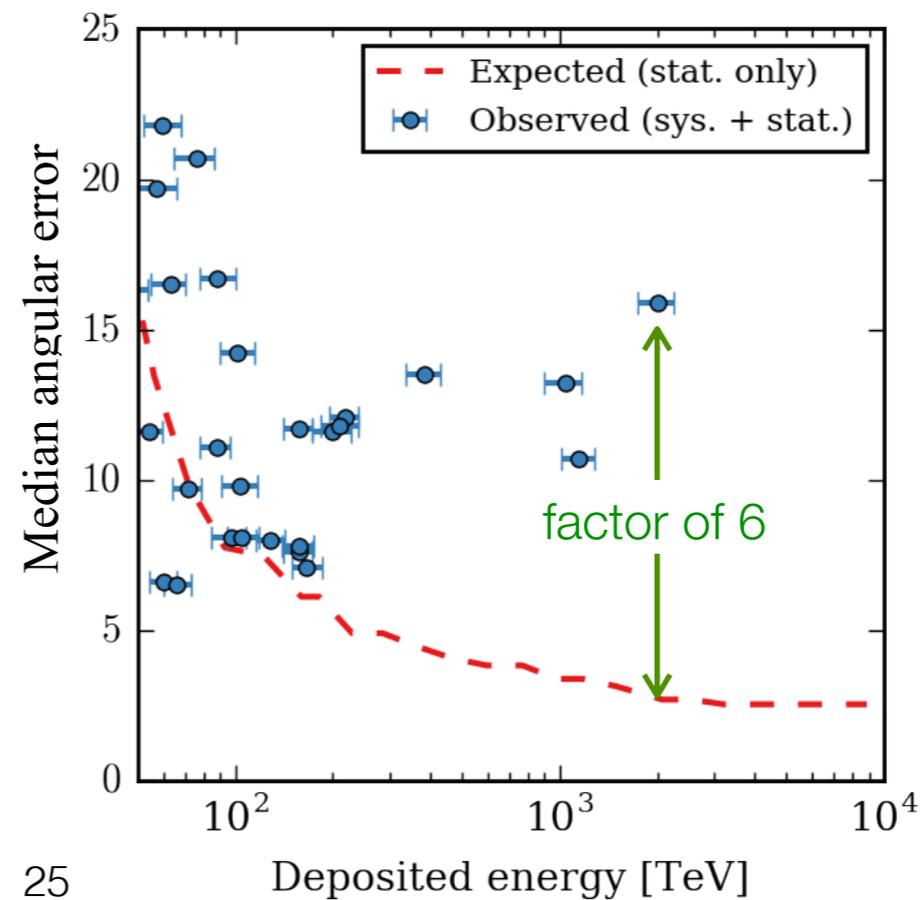
- Two-tier effort
  - IceCube Upgrade - *funded*
    - Focus on improved calibration and low energy neutrino physics
    - Test new technologies
    - Deploying 2022/23
  - IceCube Gen2
    - Larger samples of astrophysical neutrinos
    - Wide energy coverage



## IceCube Upgrade

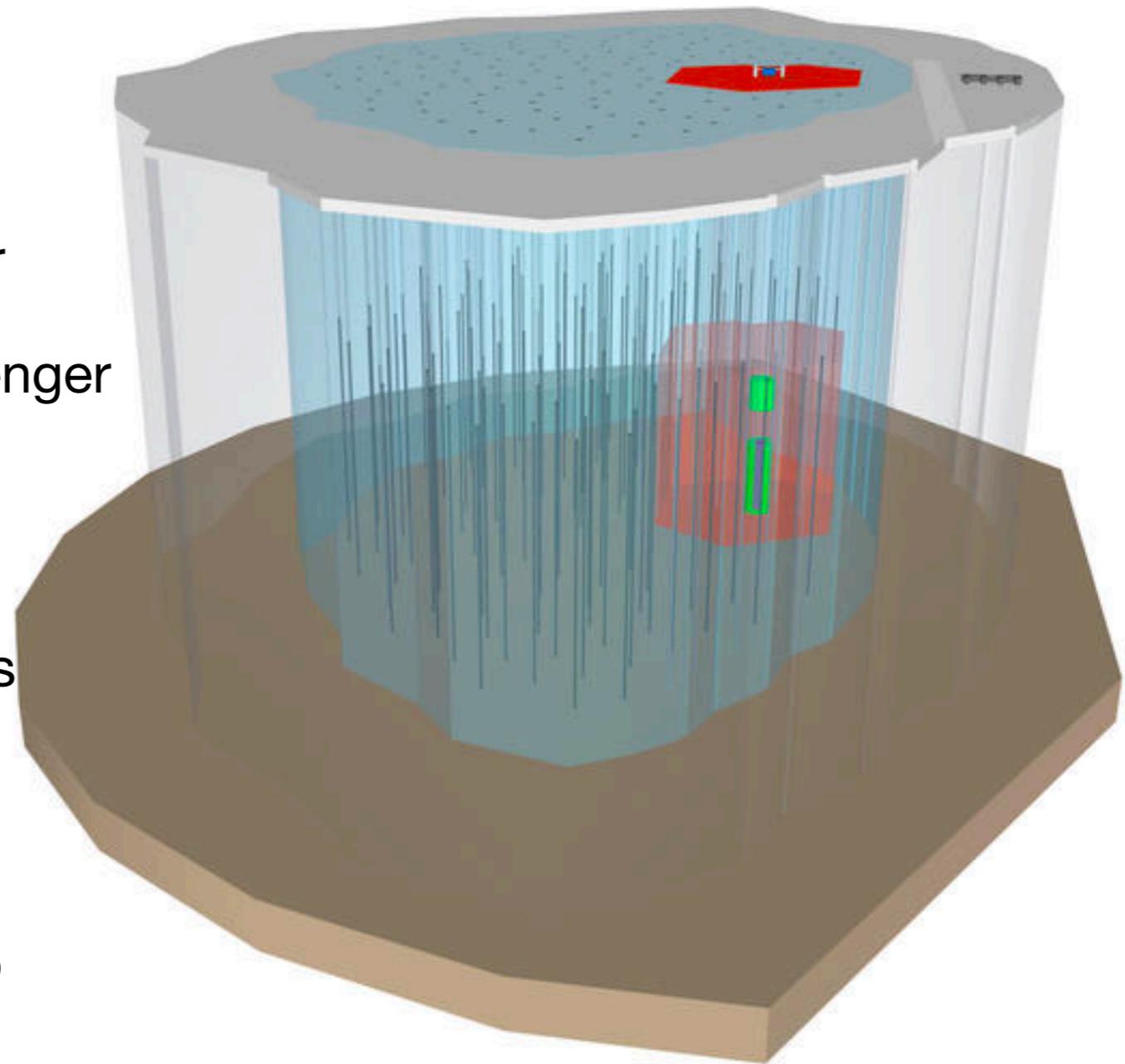
# IceCube Upgrade Instrumentation

- Several new optical sensors planned for Upgrade
  - mDOM - 24 x 3" PMTs
  - DEgg - 2 x 8" PMTs
- New Calibration devices
- Improved understanding of glacial optical properties
  - Far from statistical limits on angular resolution at high energies
    - O(0.1) deg for tracks and O(3) deg for showers
  - Cleaner identification of Tau events
- Ice is stable: Able to reprocess decade of neutrinos with better understanding



# IceCube Gen2

- Looking forward, to get larger and better samples of astrophysical neutrinos, a larger detector is needed
- Envision a wide-band neutrino observatory
  - 8-10 x larger optical Cherenkov detector
    - Neutrino astronomy and multi-messenger astrophysics
  - Askaryan radio detector array
    - Probe neutrinos beyond EeV energies
  - Surface particle detector
    - Detailed cosmic ray spectrum and composition measurements and veto capabilities



***Full design work is underway***

# Summary

- Very rich neutrino alert and followup searches in operation in the neutrino telescope community
  - Generation of alerts based on neutrino observations
  - Quick response to transient events observed in other messengers.
- Future looks bright
  - More (public) alerts planned from growing northern hemisphere neutrino telescopes
  - Upgrade and expansion plans for IceCube
- Highly optimistic for next neutrino-source association.
  - Path toward understanding cosmic ray acceleration mechanisms and sources of astrophysical neutrinos



**Thanks!**

