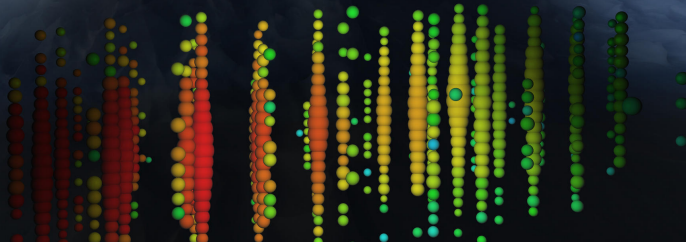


# Realtime and Multimessenger Programs using IceCube

Mike Richman

XVIII International Workshop on Neutrino Telescopes

March 19, 2019

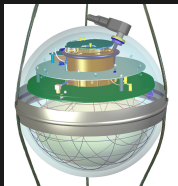


# The IceCube Neutrino Observatory

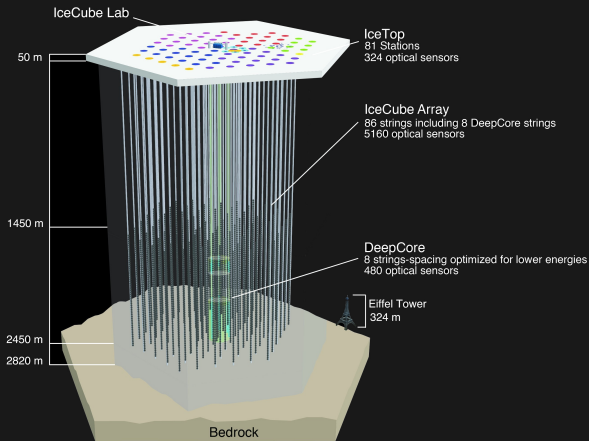
*1.5–2.5 km deep in the South Pole glacier*



Initial filtering on-site  
> 99% uptime



5160 light sensors  
All-sky visibility



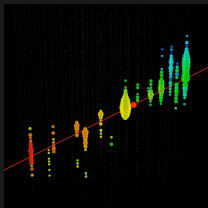
$1 \text{ km}^3$  instrumented volume

[JINST 12 P03012 (2017)]

# Neutrino Detection

*interactions and detector signatures*

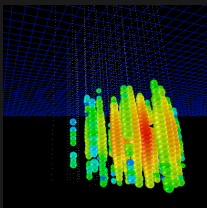
CC  $\nu_\mu$



$$\nu_\mu + N \rightarrow \mu + X$$

*track*

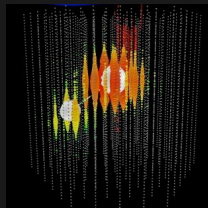
CC  $\nu_e$  / NC  $\nu_*$



$$\begin{aligned}\nu_e + N &\rightarrow e + X \\ \nu_* + N &\rightarrow \nu_* + X\end{aligned}$$

*cascade*

CC  $\nu_\tau$



$$\nu_\tau \rightarrow \tau + X$$

*cascade*  
*(or double-bang)*

Tracks are far better suited to rapid follow-up.

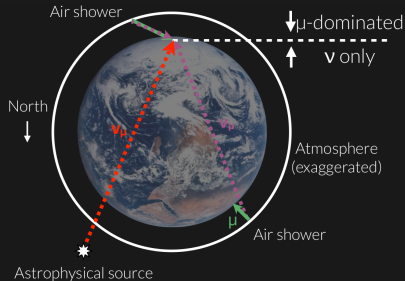
# Event Selection

*two approaches to neutrino selection*



Classic  $\nu_\mu$  strategy:

- Downgoing cosmic ray muon tracks outnumber neutrinos by  $> 10^5 \times$
- Earth acts as neutrino filter
- Well-reconstructed northern tracks must be neutrinos



→ North sky and  $\nu_\mu$  only

Both methods used to produce neutrino alerts.

# Event Selection

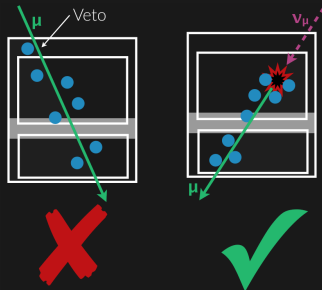
*two approaches to neutrino selection*

Classic  $\nu_\mu$  strategy:

- Downgoing cosmic ray muon tracks outnumber neutrinos by  $> 10^5 \times$
- Earth acts as neutrino filter
- Well-reconstructed northern tracks must be neutrinos

→ North sky and  $\nu_\mu$  only

Veto to select starting events:



→ Very low background

Both methods used to produce neutrino alerts.

# Data Flow Overview

*from IceCube to the community*

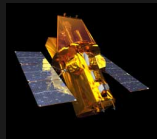


Alerts & data for improved reconstructions  
transferred via Iridium RUDICS

Gamma



X-ray



Iridium Data Transfer  
to "The North"



Real-time Processing



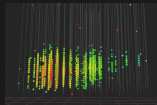
Optical



GW



IceCube  $\nu$



# Data Flow Overview

*from IceCube to the community*

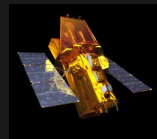


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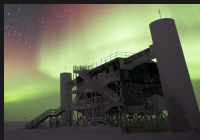
GW



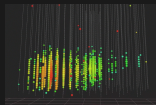
Iridium Data Transfer  
to "The North"



Real-time Processing



IceCube  $\nu$



- Private multiplet streams since 2008
- Public singlet streams since 2016  
[http://gcn.gsfc.nasa.gov/notices\\_amon/67093193\\_127853.amon](http://gcn.gsfc.nasa.gov/notices_amon/67093193_127853.amon)

# Realtime Detector Performance

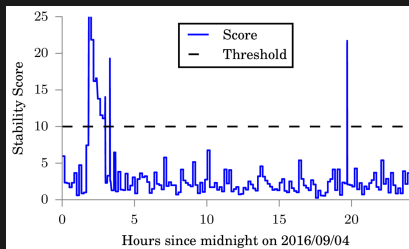
*low latency, high duty factor*



Goal: maximum info →  
minimum latency

Automated stability monitoring  
ensures data quality

Trigger and filter rates compared  
to exp.-weighted moving average  
for stability score



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



# Realtime Detector Performance

*low latency, high duty factor*

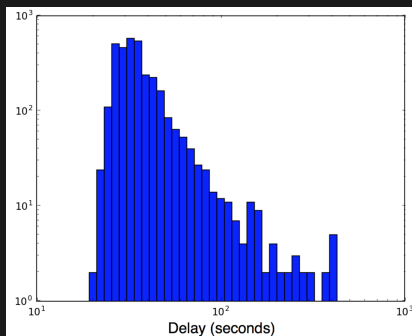


Goal: maximum info  $\rightarrow$   
minimum latency

Automated stability monitoring  
ensures data quality

Trigger and filter rates compared  
to exp.-weighted moving average  
for stability score

$\sim 33$  s median delay from  
detection to received alert



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

# Throughgoing Tracks

*classic muon neutrino strategy*

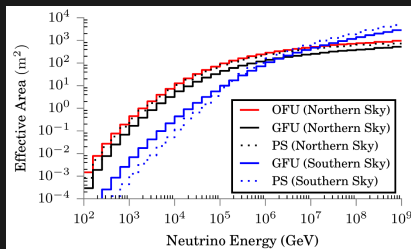


North: well-reconstructed tracks  
with  $\delta > -5^\circ$

South: high  $E$ , single muons  
(try to reject bundles)

Online system requires  $< 30$  s  
processing per event

Performance still comparable to  
offline analyses



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

# Throughgoing Tracks

*classic muon neutrino strategy*

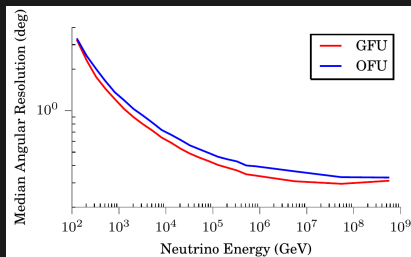


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[Astropart. Phys., 92, 30 (2017)]

# Gamma-ray Followup

*targetting neutrino bursts from known source candidates*



Search for point-like, time-clustered emission from predefined subset of *Fermi*-LAT's 3FGL: mostly BL Lacs and FSRQs

Considers range of timescales up to 180 days

Northern sky operational since 2012; southern sky added 2015

Catalog favors variable sources visible to MAGIC, VERITAS, HESS

[JINST 11 (2016) no.11, P11009 ]

# Optical and X-ray Followup

*targetting short bursts of neutrinos*



Search for northern multiplets within  $3.5^\circ$  and 100 s

Signal candidates include GRBs or supernovae with choked jets

Operational since 2008, with partners PTF, MASTER, ASAS-SN, LCOGT, *Swift*-XRT

Doublets: per-telescope cut depending on angular+temporal separation and telescope FoV

Higher multiplicity: alerts forwarded immediately

# Partners through AMON

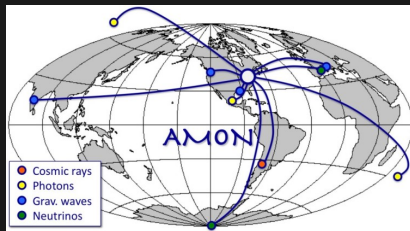
*Astrophysical Multimessenger Observatory Network*



Facilitates sharing as agreed upon by participants

Alerts from AMON coincidence analyses under development

Partners include FACT, VERITAS, MASTER, LMT, ASAS-SN, LCOGT



[Astropart.Phys. 45 (2013) 56-70]

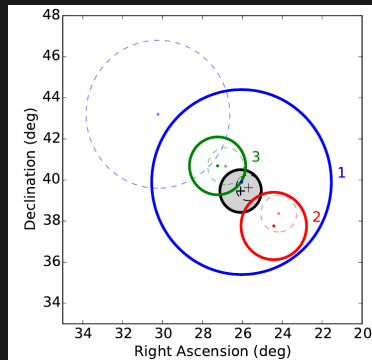
# A Rare IceCube Multiplet

*three neutrinos within 100 s*



Two doublets sharing an event  
on 2016-02-17

$$(\Delta T < 100 \text{ s}, \Delta \Psi = 3.6^\circ)$$



[A&A 607, A115 (2017)]

# A Rare IceCube Multiplet

*three neutrinos within 100 s*

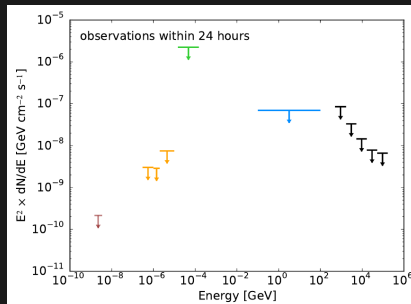


Two doublets sharing an event  
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$(\Delta T < 100 \text{ s}, \Delta \Psi = 3.6^\circ)$

Manual alert at +22 hrs  $\rightarrow$

- VERITAS, *Swift* XRT+BAT
- ASAS-SN, LCO, MASTER
- Later: *Fermi*-LAT, HAWC



[A&A 607, A115 (2017)]



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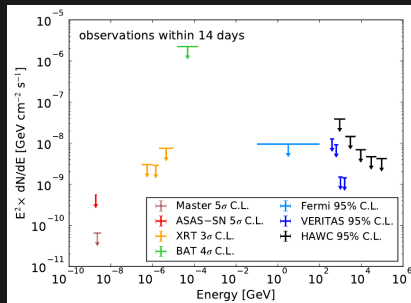


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[A&A 607, A115 (2017)]

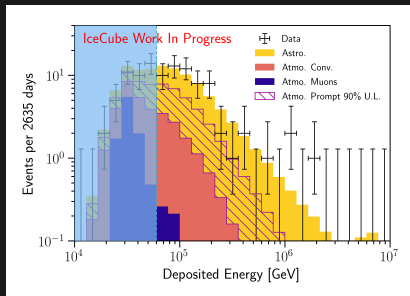
# Singlet Alerts

*individual astrophysical neutrino candidates*



High Energy Starting Events  
(HESE): first  $> 5\sigma$  astrophysical  
flux observation

Public alerts for EHE  
or high quality HESE tracks  
issued to GCN via AMON.



[Neutrino 2018]

# Singlet Alerts

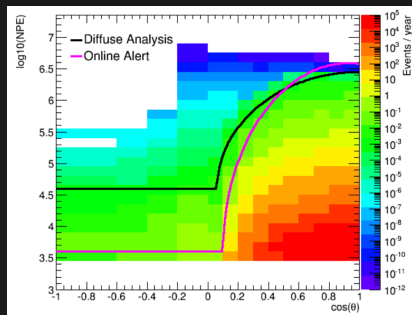
*individual astrophysical neutrino candidates*



High Energy Starting Events  
(HESE): first  $> 5\sigma$  astrophysical  
flux observation

Extremely High Energy (EHE):  
bright throughgoing tracks

Public alerts for EHE  
or high quality HESE tracks  
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(atmospheric backgrounds)  
[Astropart. Phys., 92, 30 (2017)]

# Singlet Alerts

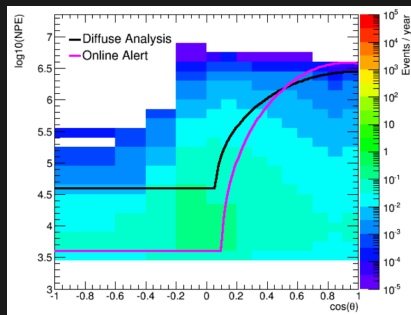
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( $E^{-2}$  neutrinos)

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

# Singlet Alerts — Upgrade

*improved performance, simplified alerts, coming very soon*



Unified track selection based on signalness  $S = N_{\text{sig}} / (N_{\text{sig}} + N_{\text{bg}})$

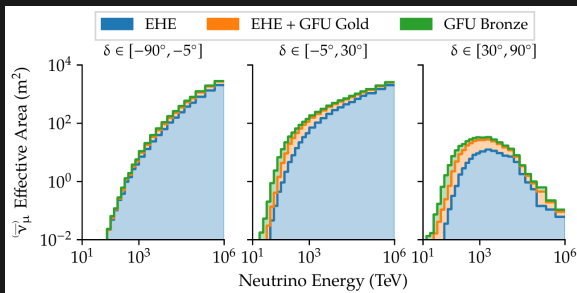
Two categories:

- Gold: EHE|GFU|HESE,  $S > 50\%$
- Bronze: GFU|HESE,  $S > 30\%$

Improved cuts  
reduce HESE 90%  
angular errors

counts per year

	Gold events	Bronze Events
Signal ( $E^{-2.19}$ )	6.6 (Total)	8.4 (Total)
	5.1 (GFU)	7.6 (GFU)
	0.5 (HESE)	0.8 (HESE)
	2.1 (EHE)	
Atmospheric Backgrounds	6.1 (Total)	19.8 (Total)
	4.7 (GFU)	18.5 (GFU)
	0.4 (HESE)	1.3 (HESE)
	1.9 (EHE)	
Observed historical rate	9.9 (Total)	28.2 (Total)
	7.8 (GFU)	26.2 (GFU)
	1.1 (HESE)	2.0 (HESE)
	4.3 (EHE)	



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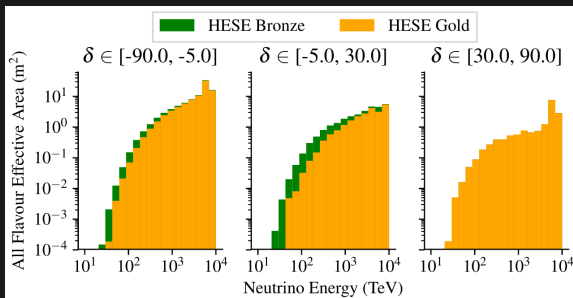
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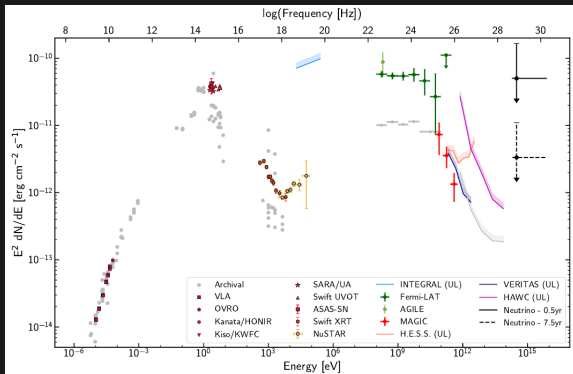
# Some Interesting Singlet Alerts

*TXS 0506+056 and SN PS16cgx*



IC-170922A →  
TXS 0506+056

Detailed spectral  
measurements  
within 14 days



[Science 361, eaat1378 (2018)]

# Some Interesting Singlet Alerts

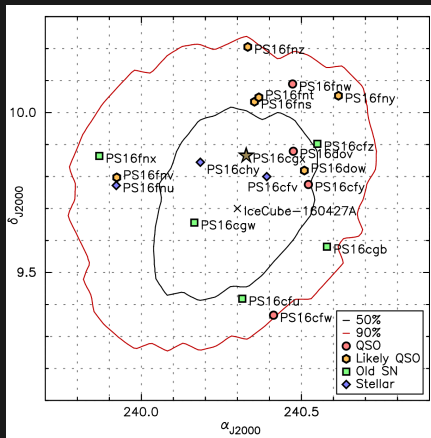
*TXS 0506+056 and SN PS16cgx*



IC-170922A →  
TXS 0506+056

Detailed spectral  
measurements  
within 14 days

Pan-STARRS1  
found SN PS16cgx  
near IC-160427A  
(likely Type Ia)



[arXiv:1901.11080 (sub. to A&A)]

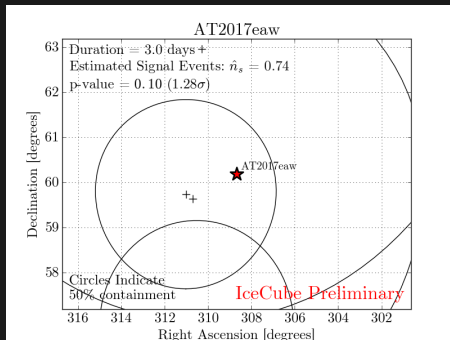


# Fast Response Analysis

... what did IceCube see?



## Pre-set transient analysis



[followup of ATel 10372]

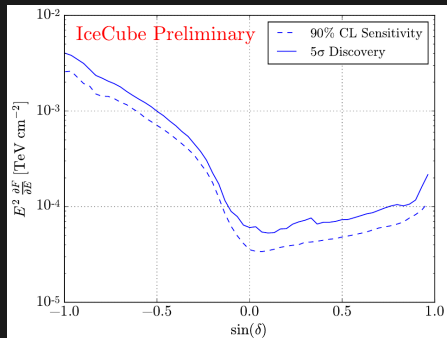
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Pre-set transient analysis

Search for neutrinos given direction, duration, and angular extent of “something interesting”



[PoS(ICRC2017)1007]

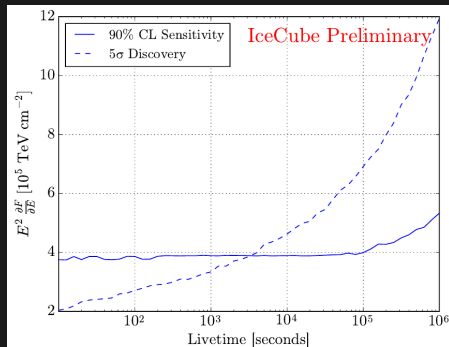
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[PoS(ICRC2017)1007]

# Fast Response Analysis

... what did IceCube see?



Pre-set transient analysis

Search for neutrinos given direction, duration, and angular extent of “something interesting”

Since mid-2018, issuing ATels, GCN circulars more frequently

```
TITLE: GCN CIRCULAR
NUMBER: 23926
SUBJECT: Search for additional neutrino events from the direction of IceCube-190221A with IceCube
DATE: 19/02/22 20:57:41 GMT
FROM: Alex Pizzuto at ICECUBE/U of Wisconsin <pizzuto@wisc.edu>
```

The IceCube Collaboration (<http://icecube.wisc.edu/>) reports:

IceCube has performed a search for additional track-like muon neutrino events arriving from the direction of IceCube-190221A (<https://gcn.gsfc.nasa.gov/gcn3/23918.gcn3>) in a time range of 2 days centered on the alert event time (2019-02-20 08:25:40.00 UTC to 2019-02-22 08:25:40.00 UTC) during which IceCube was collecting good quality data. Excluding the event that prompted the alert, 2 additional track-like events are found in spatial coincidence with the 90% PSF containment of IceCube-190221A. We find that these 2 additional events are well described by atmospheric background expectations, with a p-value of 0.08. Accordingly, these data would represent a time-integrated muon-neutrino flux upper limit assuming an  $E^{-2}$  spectrum ( $E^2$  dN/dE) at the 90% CL of  $2.71 \times 10^{-4}$   $\text{TeV cm}^{-2}$  for this observation period.

A subsequent search was performed to include the previous month of data (2019-01-21 08:25:40.00 UTC to 2019-02-22 08:25:40.00 UTC). In this case, we report a p-value of 1.0, consistent with no significant excess of track events, and a corresponding time-integrated muon-neutrino flux upper limit assuming an  $E^{-2}$  spectrum ( $E^2$  dN/dE) at the 90% CL of  $3.5 \times 10^{-4}$   $\text{TeV cm}^{-2}$ .

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at [roc@icecube.wisc.edu](mailto:roc@icecube.wisc.edu) <<mailto:roc@icecube.wisc.edu>>

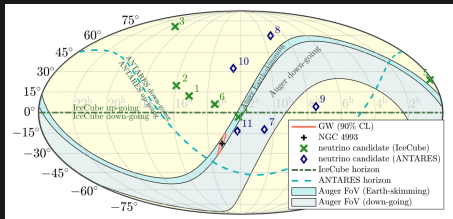
[GCN Circular 23926]

# Gravitational Waves

*working up to LIGO+Virgo O3 run*



So far, simple all-sky  $\pm 500$  s  
search upon GW observations



[ApJL 850 (2017) no.2, L35]

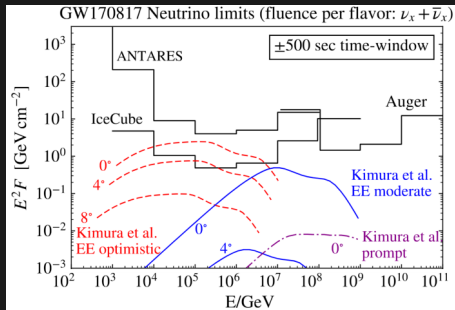
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New, more sensitive “GW as spatial prior” analysis ready for O3 rapid followup



[ApJL 850 (2017) no.2, L35]

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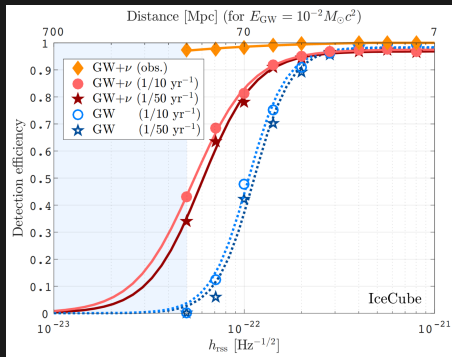
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New, more sensitive “GW as spatial prior” analysis ready for O3 rapid followup

Related method for lowering GW threshold also under development



[ApJ 870 (2019) no.2, 134]

# Summary

“Multimessenger studies are essential for identification of [neutrino] sources” — A. Kheirandish, last session

IceCube is working closely with EM and GW partners to maximize opportunities for detailed time-dependent studies

Ongoing work seeks to improve alert and followup systems in response to community needs — talk to us!

