Le osservazioni di IceCube nel contesto multi-messaggero

Neutrini, fotoni e onde gravitazionali:
nuove prospettive per l'astrofisica di alte energie

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IceCube

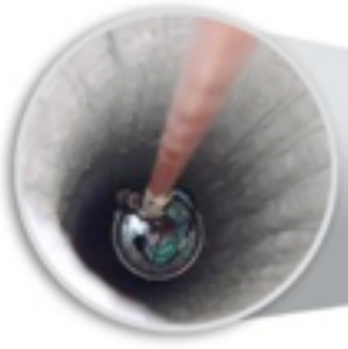
South Pole Neutrino Observatory

50 m

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

IceCube **1 km³** 5160 OMs completed in **2010**

86 strings of DOMs, set 125 meters apart

IceCube detector

DeepCore

Antarctic bedrock

Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs on each string

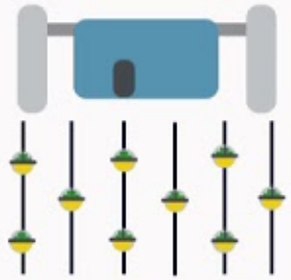
DOMs are 17 meters apart

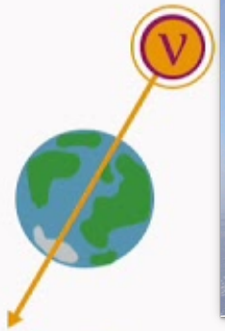
UPTIME >99%

History of neutrino Astronomy in a nutshell

First high energy atmospheric neutrinos were detected underwater at Lake Baikal in 1996.

Construction of ANTARES in the Mediterranean Sea started in 2002





1988
Telescope in the Ice Envisioned

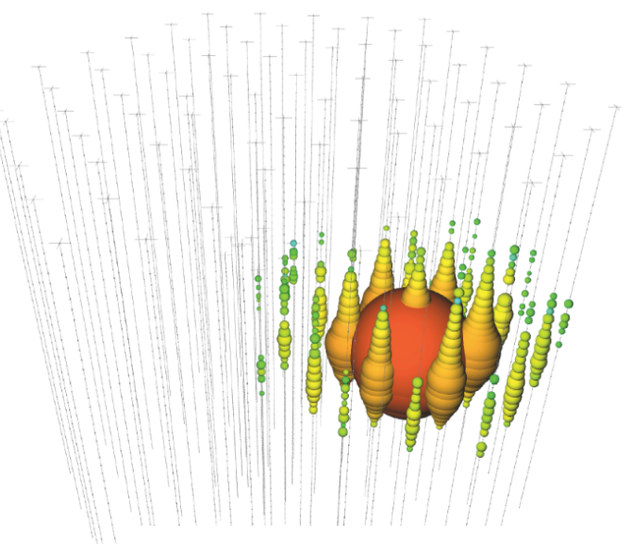
2000
AMANDA Completed

2001
Atmospheric Neutrinos Detected

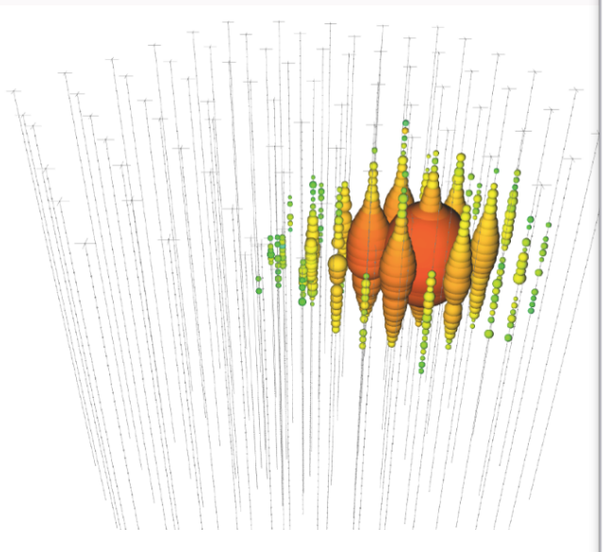
2011
IceCube Completed

2013
Astrophysical Neutrinos Discovered

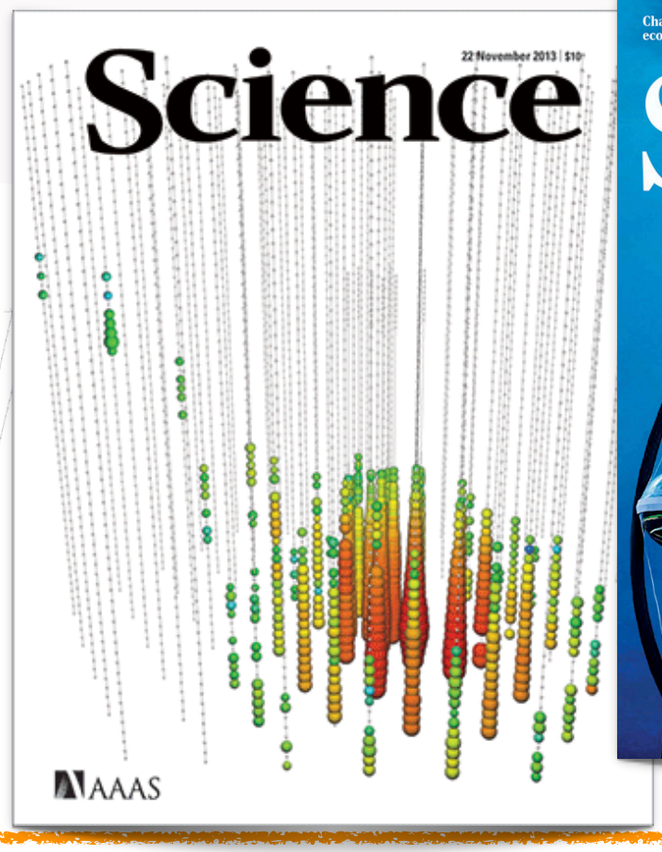
2017
First Neutrino Source



1.1 ± 0.17 PeV

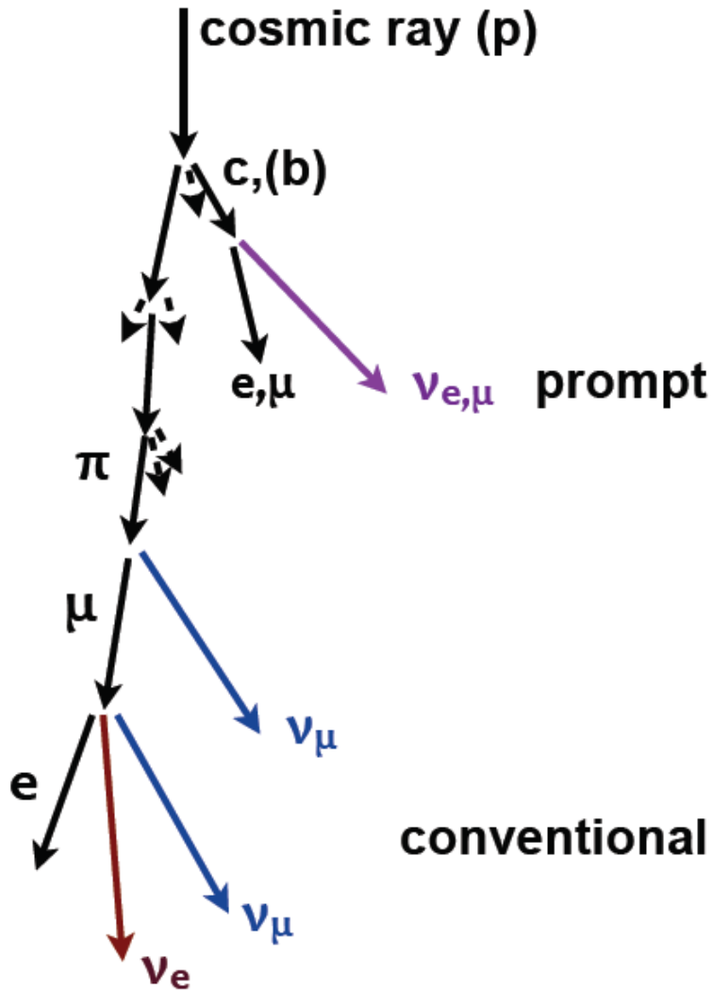


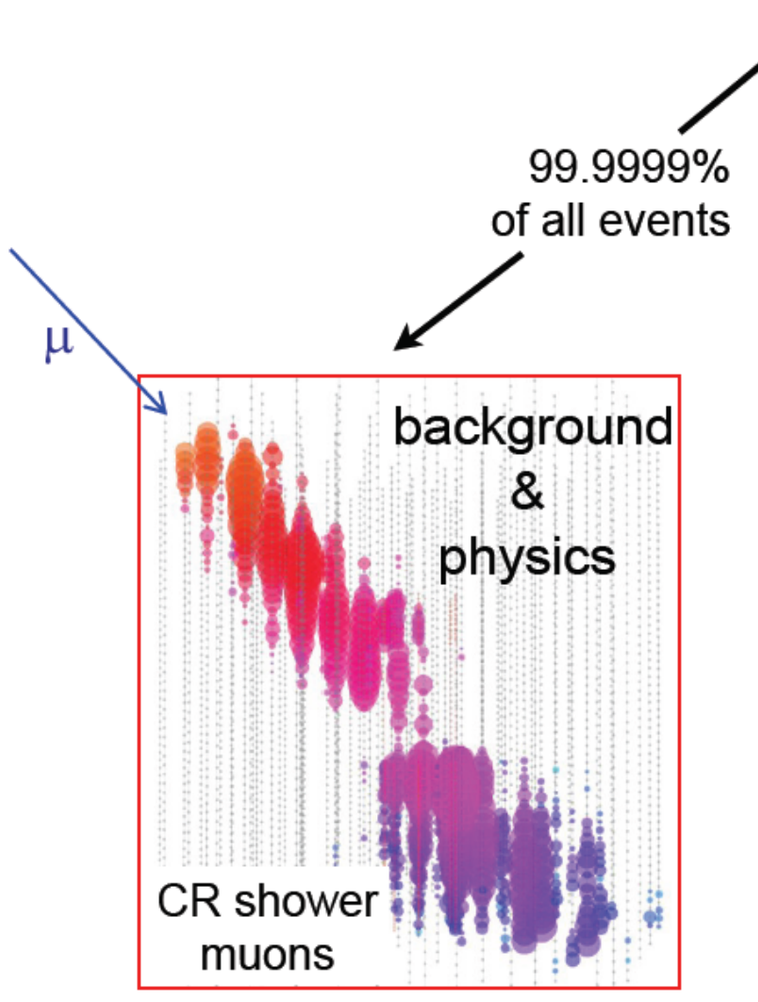
1.0 ± 0.15 PeV

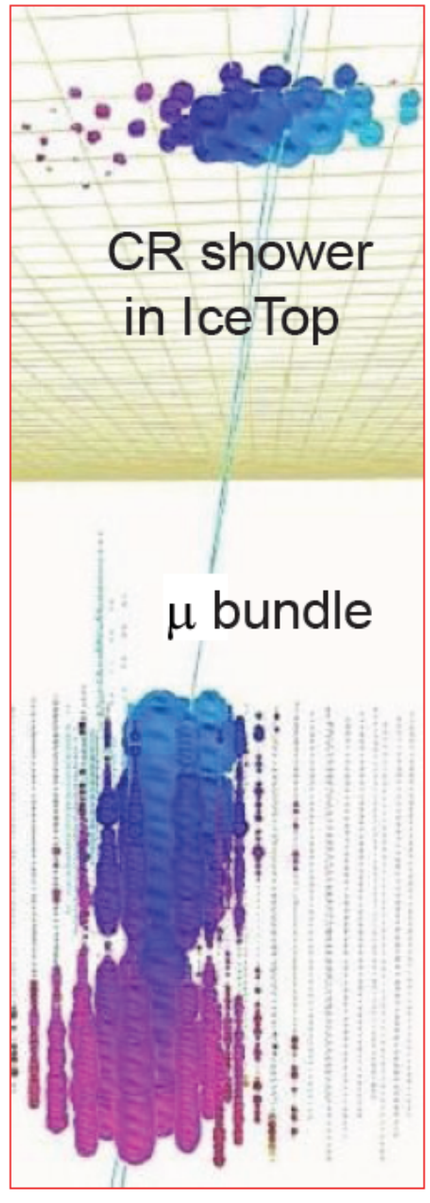


Signal and backgrounds

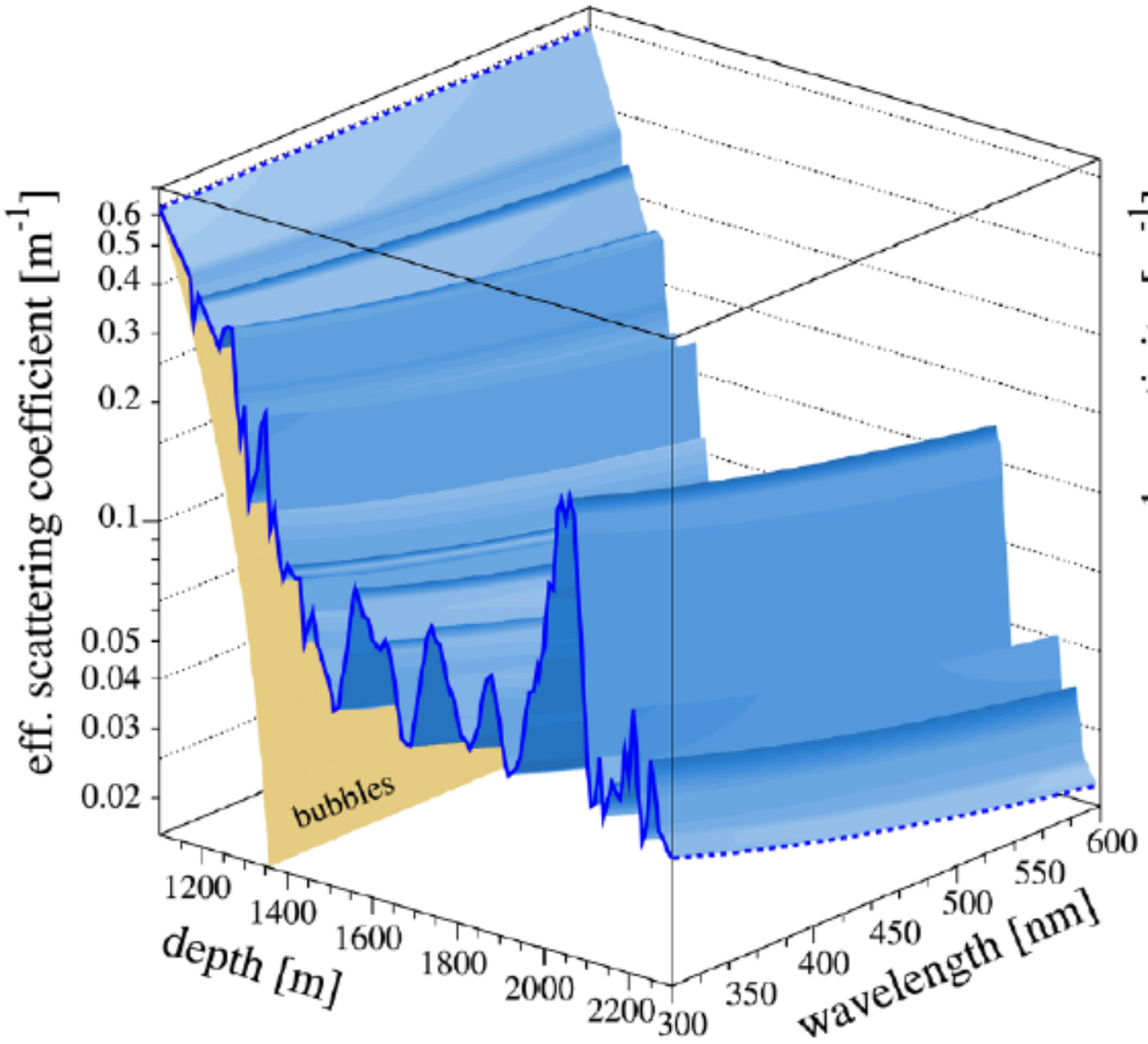
- Event rates in IceCube (year^{-1}):
  - atmospheric muons : 7 x 10^{10} (3000 per second)
  - atmospheric neutrinos : 8 x 10^{4} (1 every 6 minutes)
  - astrophysical : O(10)

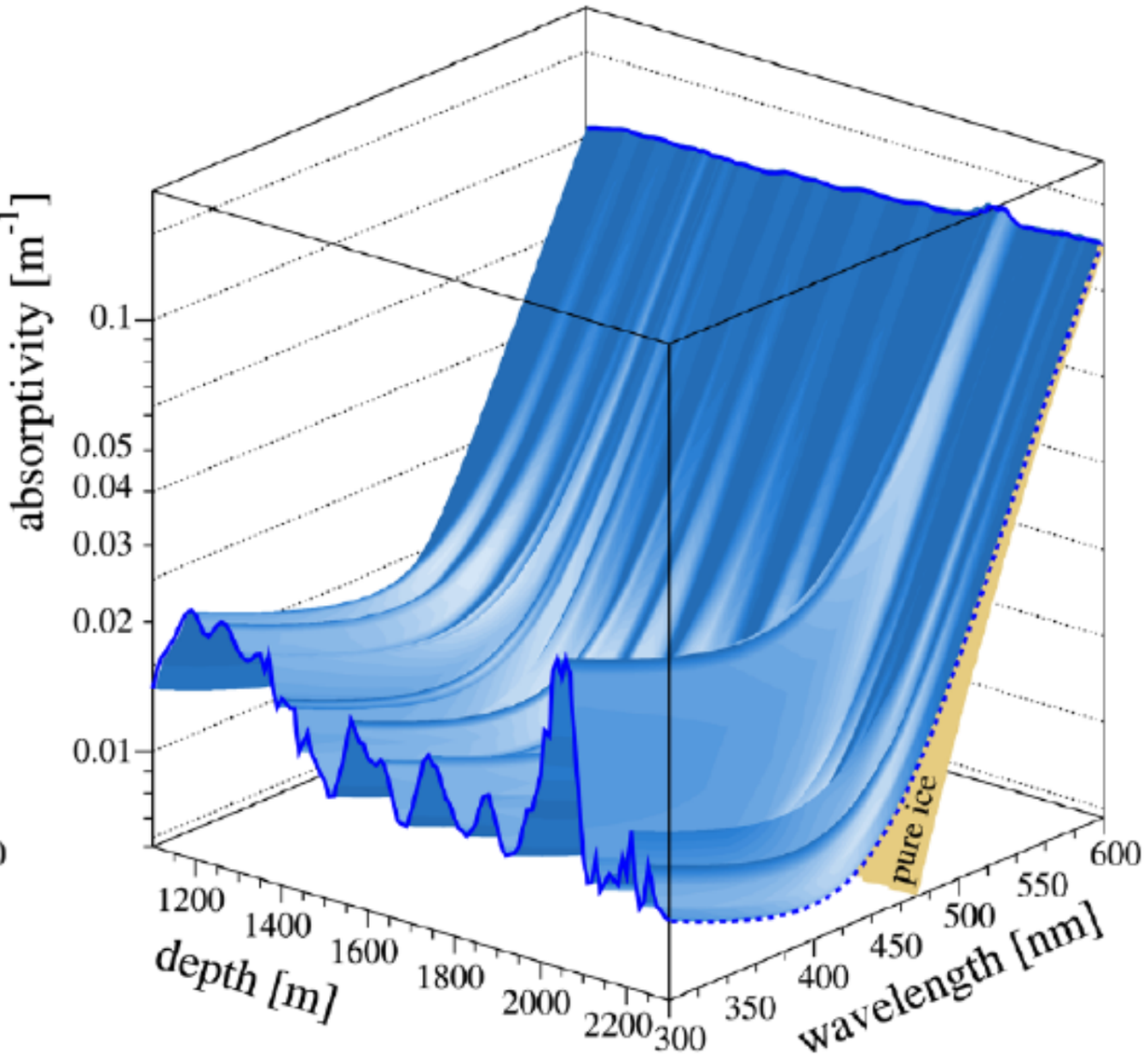






Challenge: Ice optical properties

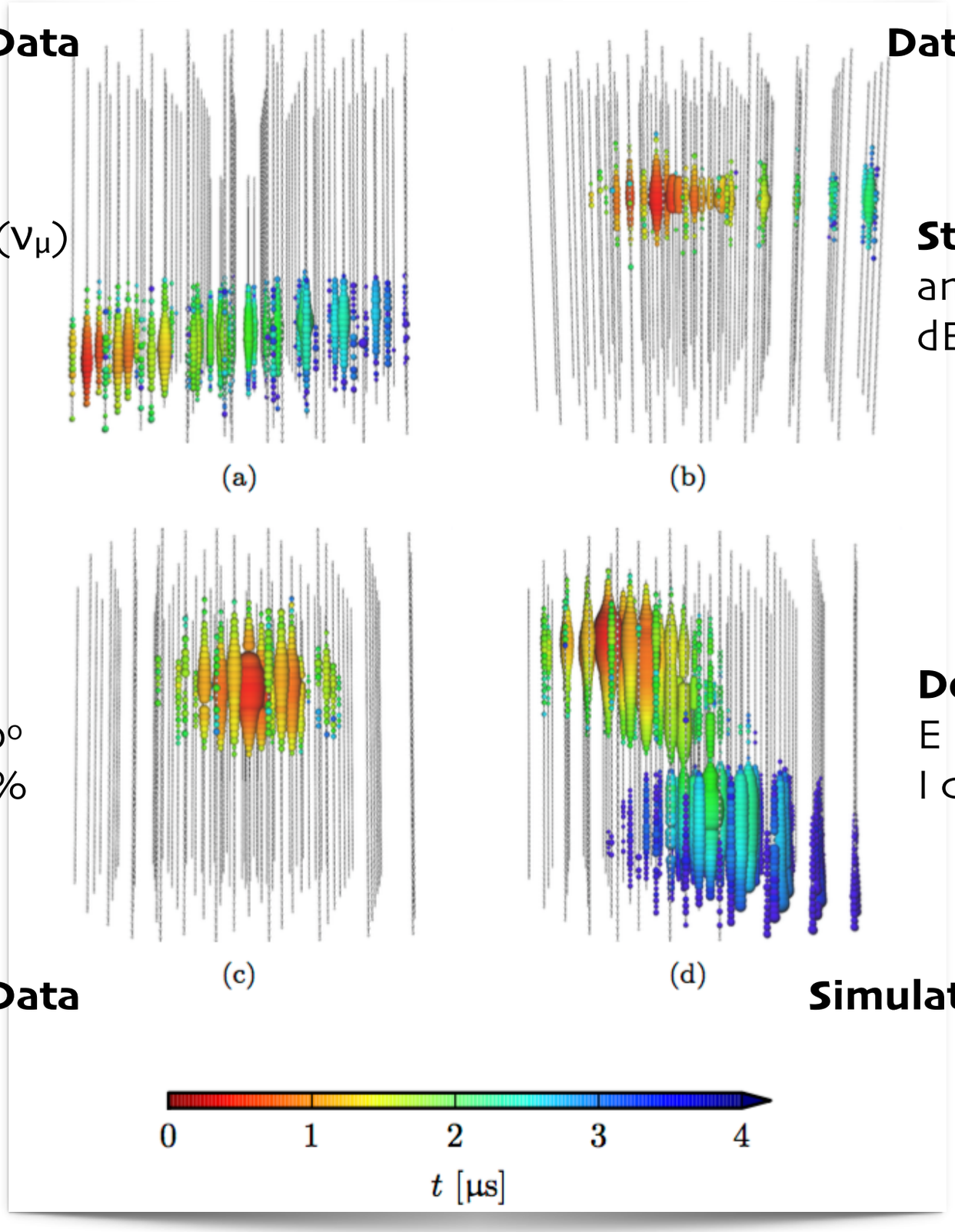




Neutrino signatures in ice

Through-going track (ν_μ)
angular resolution < 1°
only dE/dx

Cascade (ν_e, ν_μ, ν_τ)
angular resolution > 10°
energy resolution ~ 15%

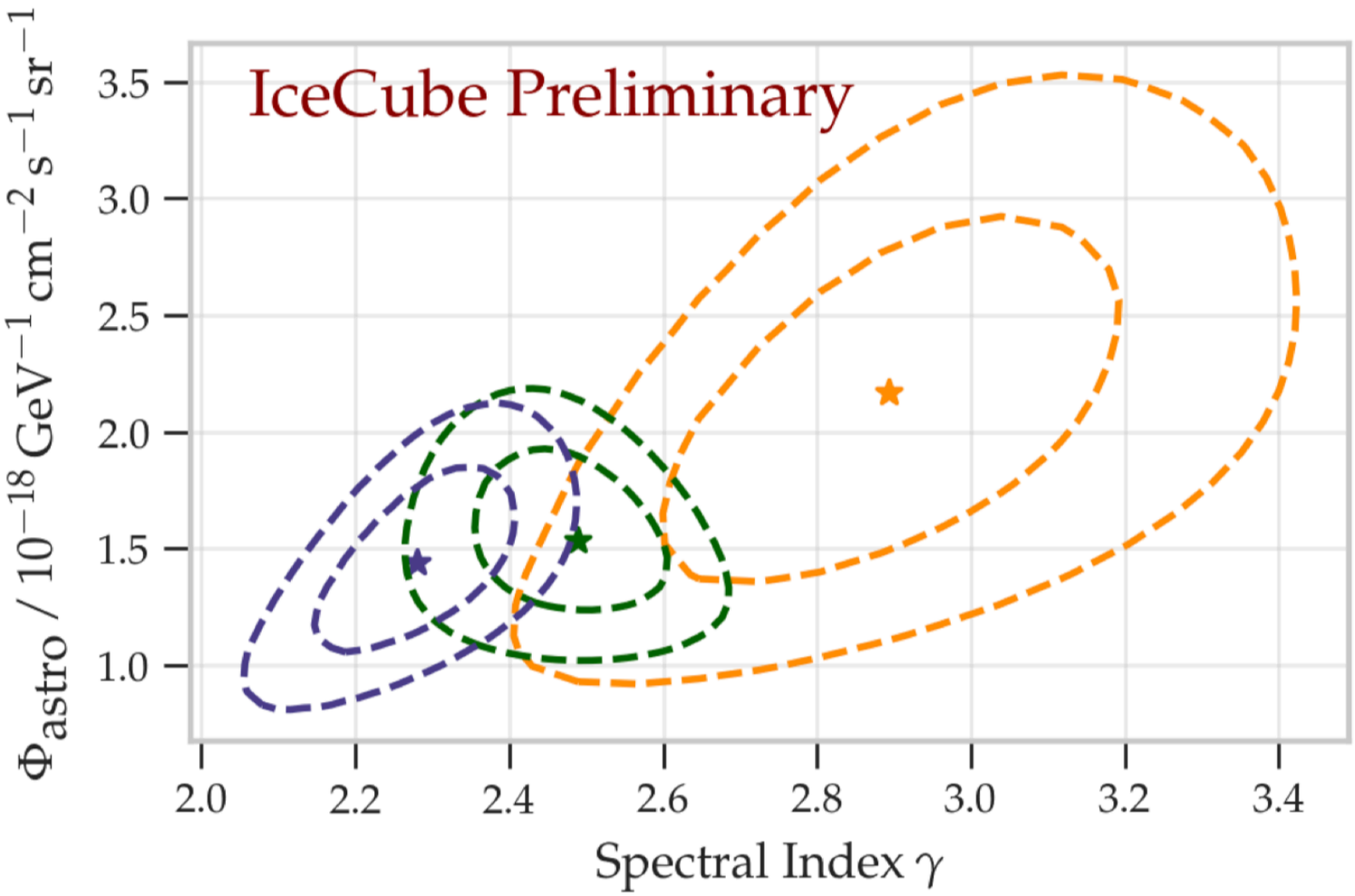


Starting track (ν_μ)
angular resolution < 1°
dE/dx + energy at vertex

Double-Bang (ν_τ)
E > O(PeV)
I candidate found!!

A few results

Diffuse neutrinos



HESE (7.5y Full-sky)
PoS(ICRC2019)1004

Cascades (4y Full-sky)
PoS(ICRC2017)968

Through-going Muon-Neutrinos
(9.5y Northern-hemisphere)
This Work

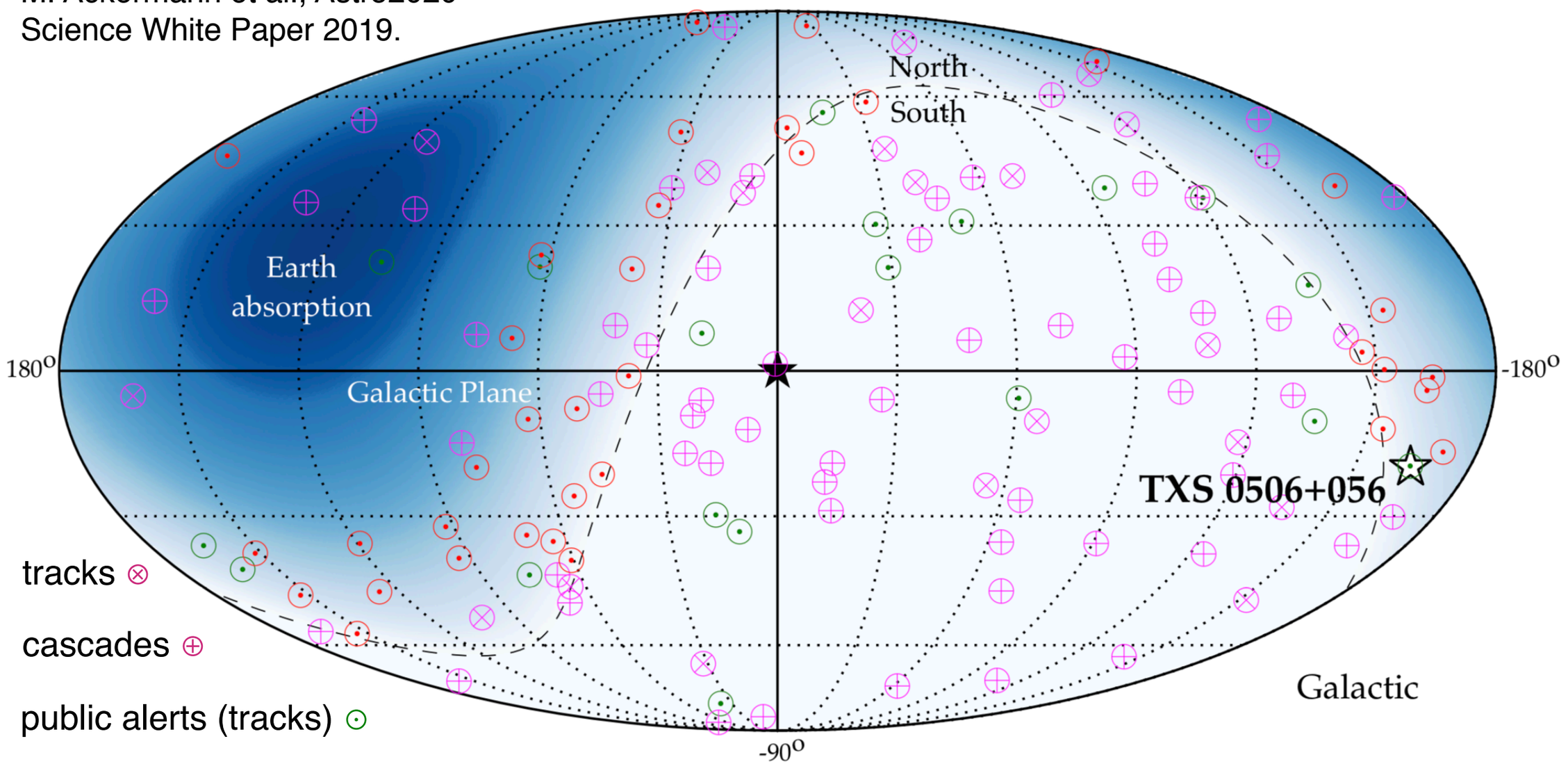
J. Stettner PoS(ICRC2019) 1017
+ Starting tracks only: Phys. Rev. D99, 032004 (2019)

Icecube paper on 6yr cascade (nue+nu_tau) flux
will be submitted for publication very soon

Extragalactic neutrinos

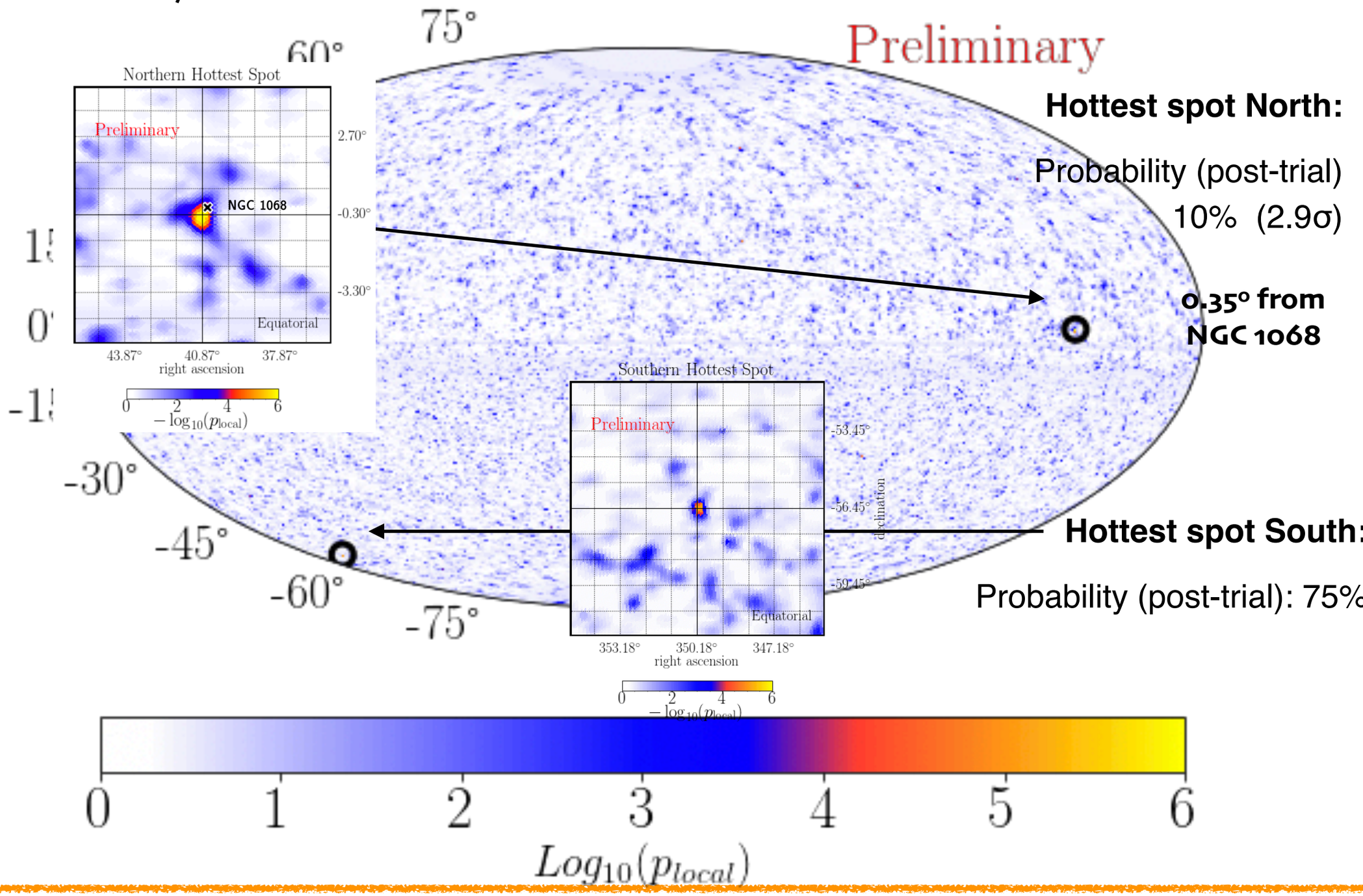
At high energies (few tens TeV) a clear excess of events is observed excluding an atmospheric-only origin. Directions show no obvious accumulation either around individual sources or the Galactic plane

M. Ackermann et al., Astro2020 Science White Paper 2019.



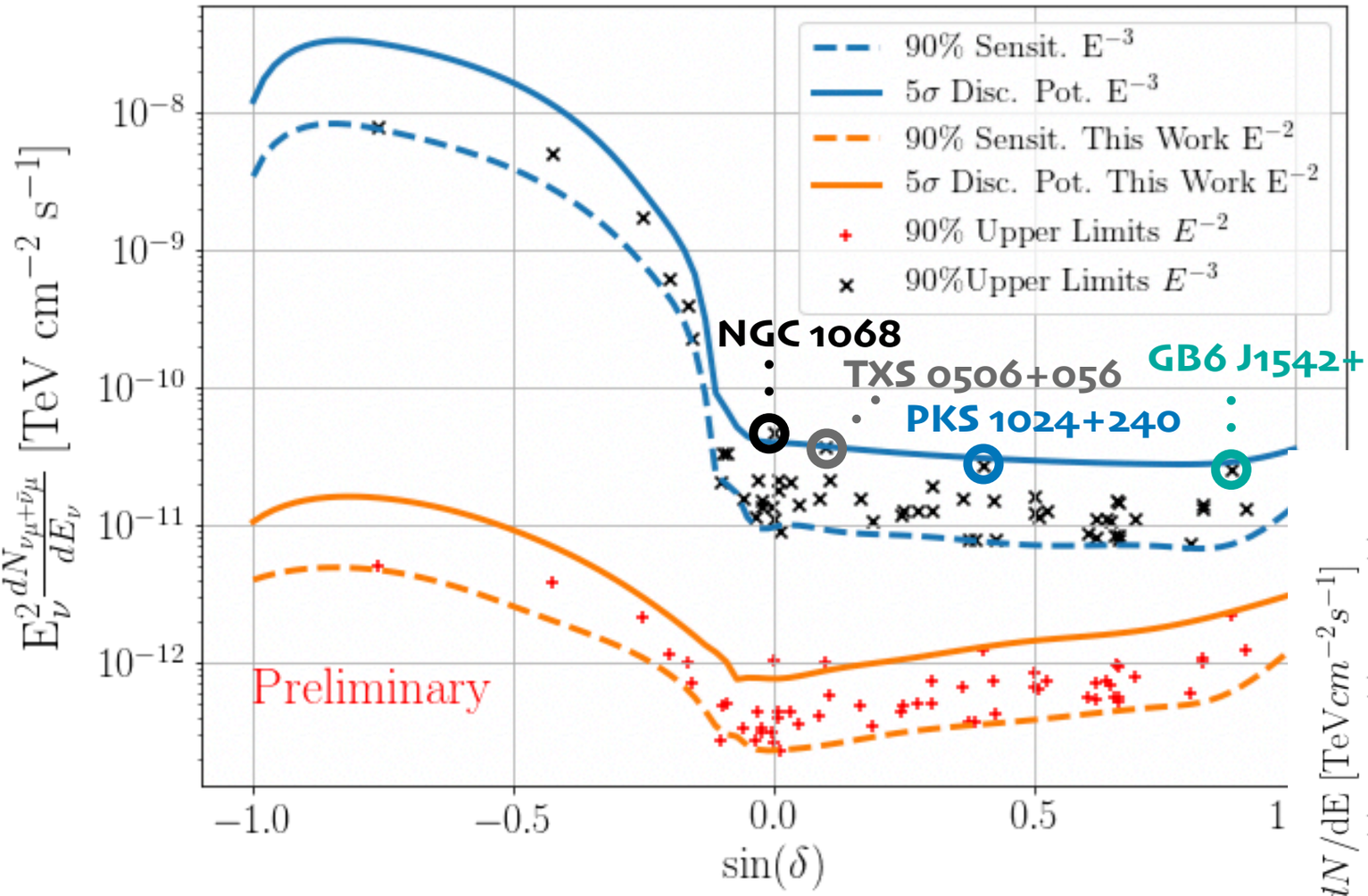
The IceCube neutrino Sky

A sample of ~1x10⁶ neutrinos recorded by IceCube in 10 years provides no evidence for neutrino sources in the full sky and in locations motivated by gamma-ray observations

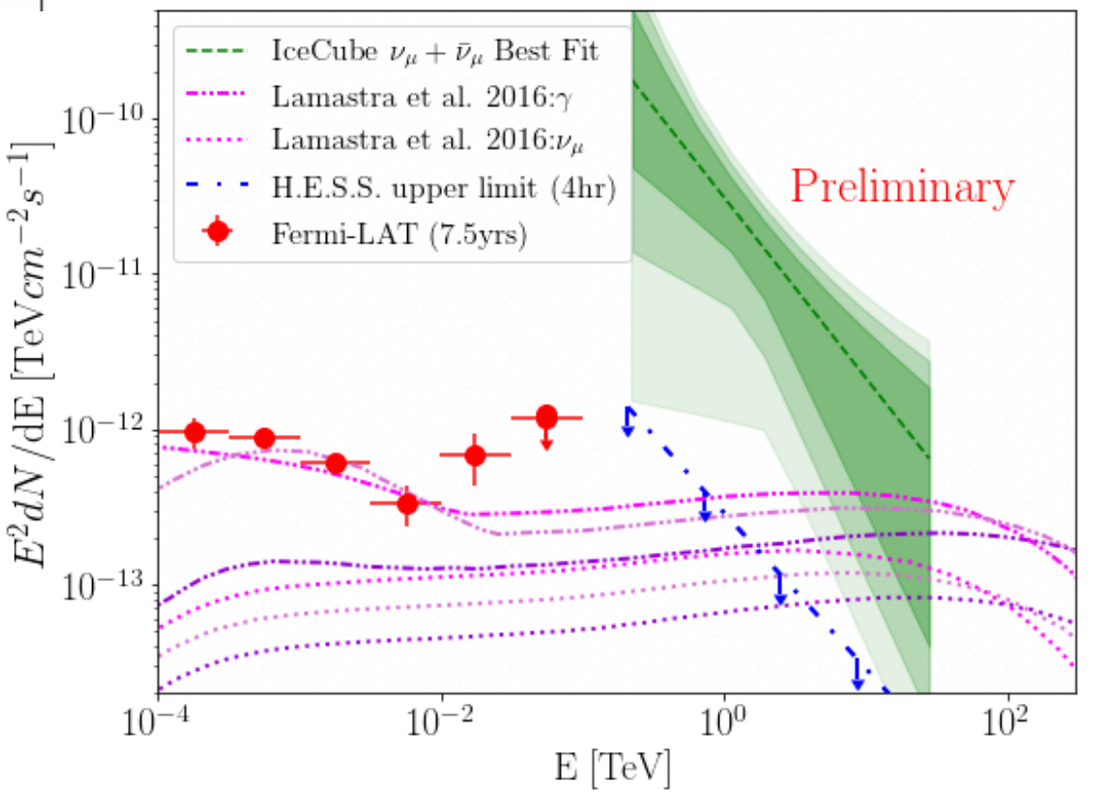


Searches for point sources (10 yr)

Tessa Cerver for IceCube 2019 Neutrino Telescopes, Venice



Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events (improved sensitivity in the Southern sky) Aartsen, M. G., et al. 2019, ApJ, 886, 1

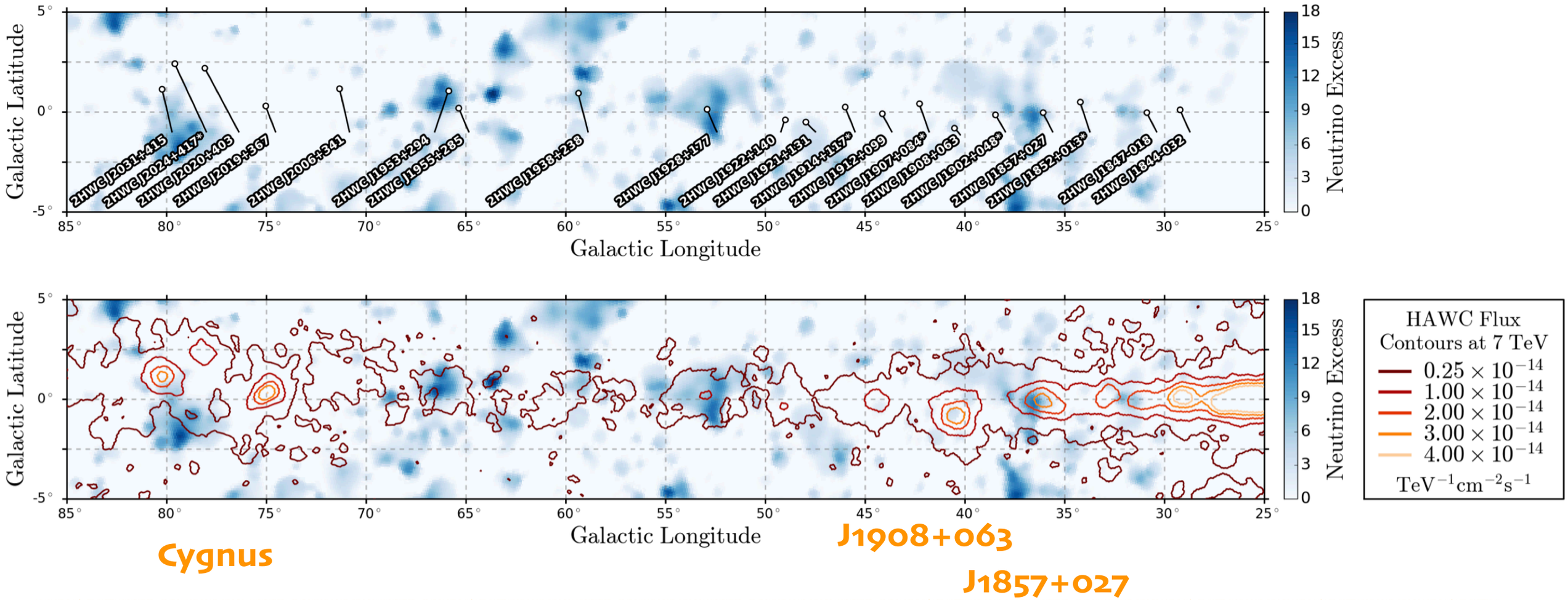


- Best fit normalisation for largest hot-spot is greater than current Gamma-ray limits.
- Best fit spectrum ∝ E-3.16

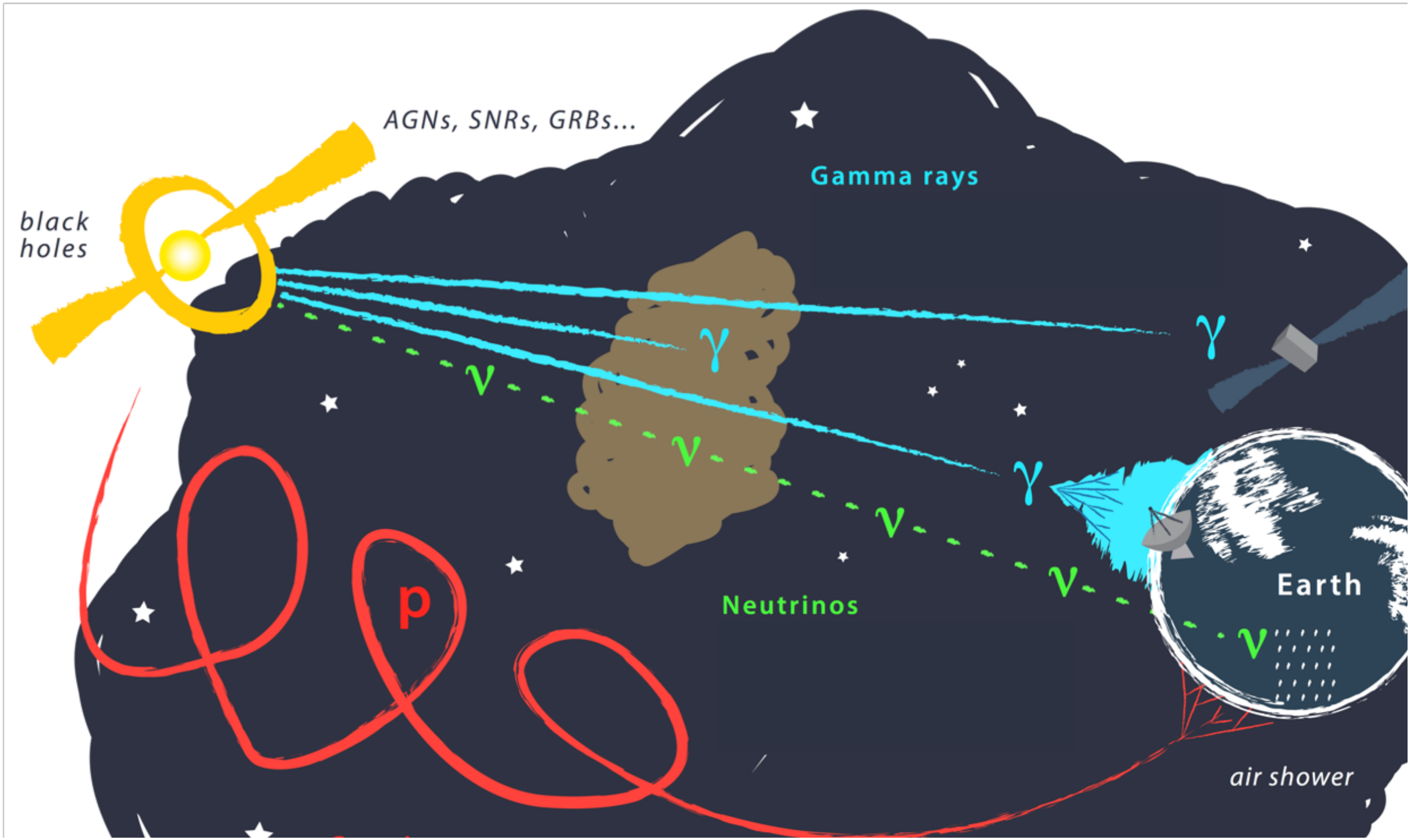
IceCube (8 yr) + HAWC (1100 days)

- Stacked analysis of 20 HAWC non PWN sources
- 4 Template searches:
  - Northern galactic plane
  - Cygnus region, J1908+063 region, J1857+027 region

A. Kheirandish et al. PoS(ICRC2019)932



Realtime Multi-Messenger



The IceCube Target of Opportunity Program

If neutrinos and photons are produced in correlation, observing neutrinos and electromagnetic flares would greatly increase the chances of identifying the sources of cosmic neutrinos (multi-messenger).

Since **2016** IceCube issues **public** alerts on single events: EHE, HESE since **2012 private** alerts for gamma-ray follow-up **GFU** and X-ray follow-up (**OFU**).

E.B "Multi-messenger approaches to search for point sources of high energy neutrinos with AMANDA/IceCube"@ The Multi-Messenger Approach to High-Energy Gamma-Ray Sources, Barcelona (**2005**)

M. Ackermann, E.B., et al., Neutrino Triggered Target of Opportunity (NToO) test run with **AMANDA-II and MAGIC**, arXiv:0709.2640 (**2007**)

M. G. Aartsen, et al., Very High-Energy Gamma-Ray Follow-Up Program Using Neutrino Triggers from IceCube, JINST 11 (**2016**), arXiv:1610.01814

M. G. Aartsen, et al., Detection of a Type IIn Supernova in Optical Follow-up Observations of IceCube Neutrino Events, Astrophysical Journal (ApJ), 811, 52 (**2015**), arXiv:1506.03115

Trigger types before 2019

IceCube Coll., The IceCube Realtime Alert System, Astropart. Phys., 92, 30 (2017)

- Event multiplets (**PRIVATE**):
  - γ-ray follow-up (**GFU**) timescales up to three weeks, 2 (background) alerts/yr [also @ M. G. Aartsen, et al., JINST 11 (2016), arXiv: 1610.01814]
  - optical and X-ray follow-up (**OFU**) timescales up to 100 s, 7 (background) alerts/yr [also @ M. G. Aartsen, et al., Astrophys. J. 811 52 (2015), arXiv:1506.03115]
- Single events (**PUBLIC, since 2016**)
  - Track-like high-energy starting events (**HESE**): single events, 4 alerts/yr, 1/yr signal expected
  - Extremely high-energy through- going tracks (**EHE**): single events, 4 alerts/yr, 2/yr signal expected

Public alerts before June 2019

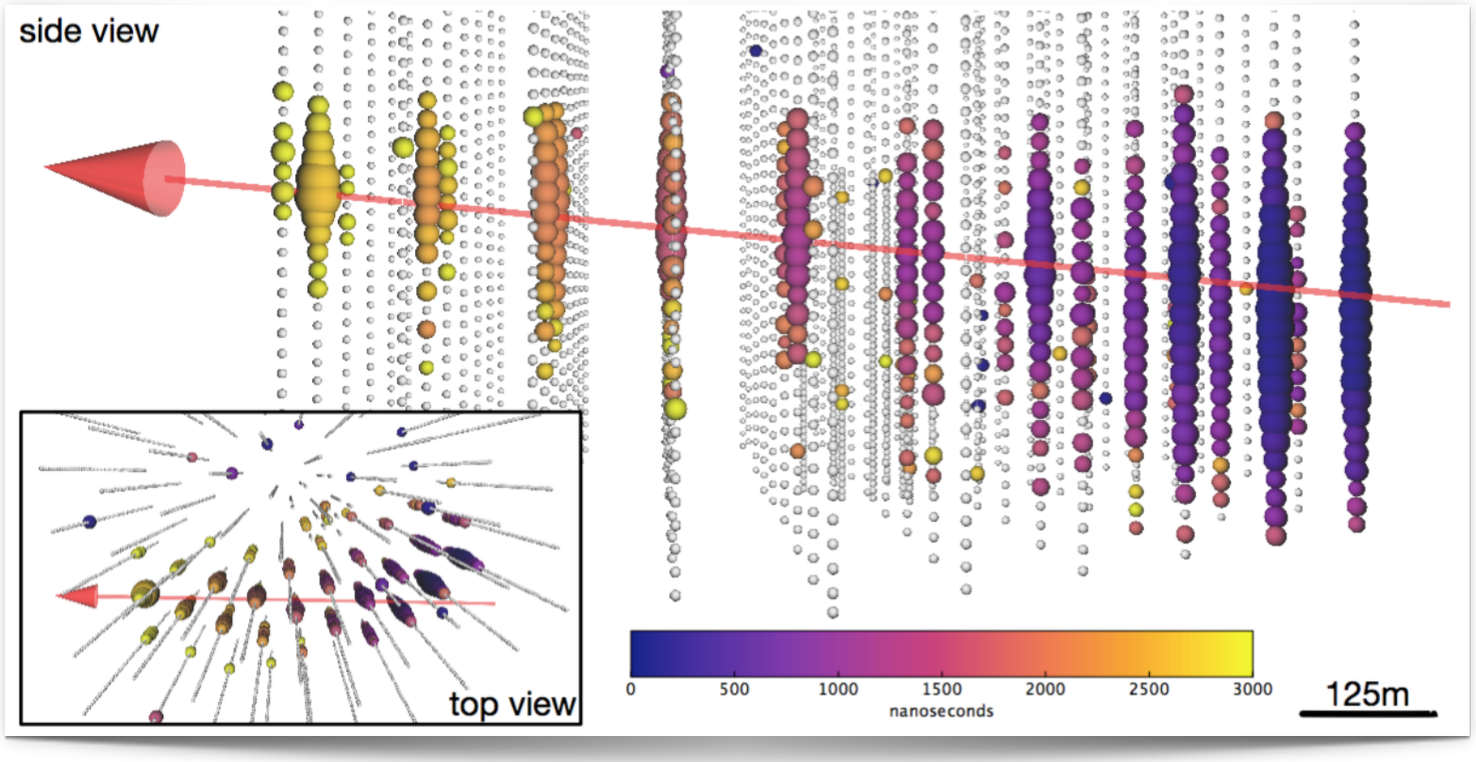
EVENT			OBSERVATION		
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec
41485283_132628	19/05/29	01:55:22.21	HESE	287.3190	+78.1432
766165_132518	19/05/04	18:25:18.39	HESE	65.7866	
15947448_132379	19/03/31	06:55:43.44	HESE	355.6349	
66688965_132229	19/02/21	08:25:39.71	HESE	267.3650	
36142391_132143	19/02/05	21:21:10.50	HESE	128.6959	
9759013_132077	19/01/24	03:43:54.79	HESE	307.1920	
68269692_131999	19/01/04	08:34:38.23	HESE	359.3299	
66412090_131680	18/10/31	02:02:51.41	HESE	182.7920	
12296708_131624	18/10/14	11:52:19.07	HESE	225.1839	
71165249_130949	18/04/23	02:28:40.98	HESE	294.8820	
34032434_130171	17/10/28	08:28:14.81	HESE	275.0760	
56068624_130126	17/10/15	01:34:30.06	HESE	162.5790	
32674593_129474	17/05/06	12:36:55.80	HESE	221.6750	
65274589_129281	17/03/12	13:49:39.83	HESE	304.7300	
38561326_128672	16/11/03	09:07:31.12	HESE	40.8252	
38561326_128672	16/11/03	09:07:31.12	HESE	40.8740	
58537957_128340	16/08/14	21:45:54.00	HESE	199.3100	
6888376_128290	16/07/31	01:55:04.00	HESE	215.1090	
6888376_128290	16/07/31	01:55:04.00	HESE	214.5440	
67093193_127853	16/04/27	05:52:32.00	HESE	240.5683	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	
67093193_127853	16/04/27	05:52:32.00	HESE	239.6639	+6.8528

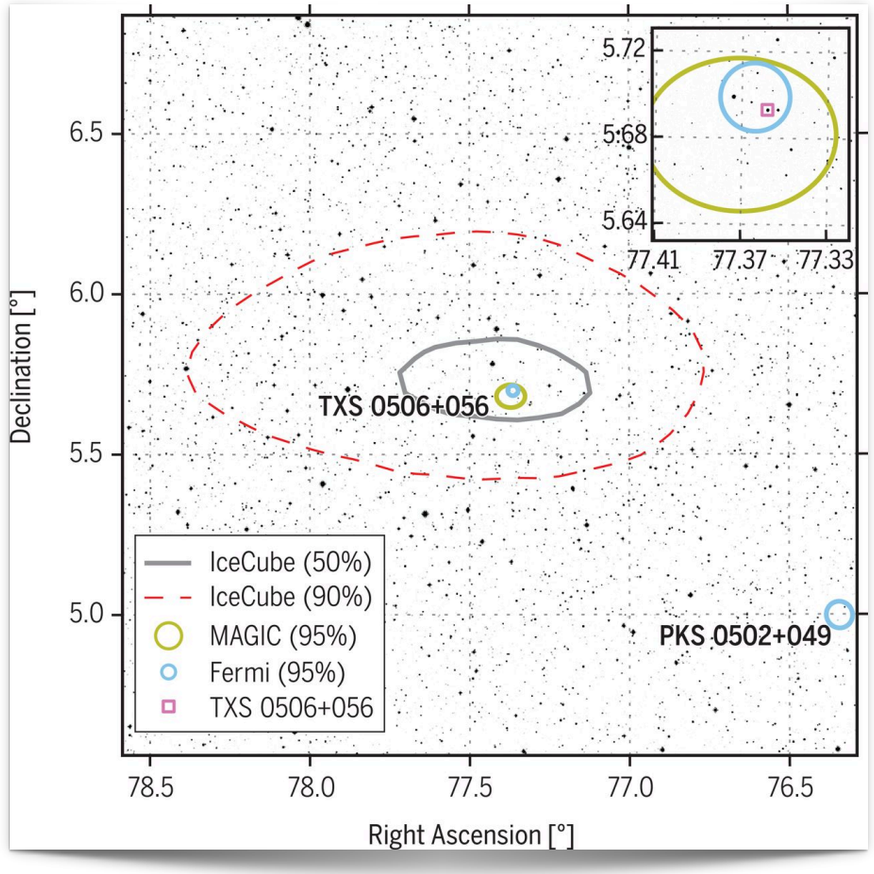
IceCube-170922A

EVENT			OBSERVATION		
EventNum_RunNum	Date	Time UT	NoticeType	RA	Dec
42419327_132508	19/05/03	17:23:08.72	EHE	120.3040	+6.3568
53411354_131653	18/10/23	16:37:32.65	EHE	269.8360	-8.8863
34507973_131475	18/09/08	19:59:31.84	EHE	145.7729	-2.5178
17569642_130214	17/11/06	18:39:39.21	EHE	340.2500	+7.3140
50579430_130033	17/09/22	20:54:30.43	EHE	77.2853	+5.7517
80305071_129307	17/03/21	07:32:20.69	EHE	98.3268	-14.4861
80127519_128906	16/12/10	20:06:40.31	EHE	46.5799	+14.9800
80127519_128906	16/12/10	20:06:40.31	EHE	45.8549	+15.7851
26552458_128311	16/08/06	12:21:33.00	EHE	122.7980	-0.7331
6888376_128290	16/07/31	01:55:04.00	EHE	214.5440	-0.3347
6888376_128290	16/07/31	01:55:04.00	EHE	215.0929	-0.4191

IceCube-170922A

Compelling evidence for neutrino emission from the **Blazar TXS 0506+056.**
Identification of a cosmic hadron accelerator with >PeV energies!





- Publicly distributed 43 seconds after trigger, refined direction 4 hr later
- At 6 arc-minutes from the direction of TXS 0506+056
- Most probable energy between 250 and 300 TeV and probability of astrophysical origin 56.6%

Follow-up detections of IC170922 based on public telegrams

IceCube
September 22

Swift
September 26

Fermi, ASAS-SN
September 28

SALT, Kapteyn
October 7

MAGIC
October 4

Liverpool, AGILE
September 29

Kanata, NuSTAR
October 12

VLA
October 17

Subaru
October 25

~1000 astronomers / 18 observatories!
(~3000 astronomers / 70 observatories was for GW170817)

A neutrino emitter?

For $E_\nu \sim 300$ TeV, **interacting protons shall have energies $E_p \geq 6$ PeV** and must interact with photons with energies in the UV to soft X-ray range. Getting all the elements of this puzzle to fit together is not easy. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.

C. Righi, F. Tavecchio, and S. Inoue. Neutrino emission from BL Lac objects: the role of radiatively inefficient accretion flow

S. Ansoldi et al. The Blazar TXS 0506+056 Associated with a High-energy Neutrino: Insights into Extragalactic Jets and Cosmic

M. Cerruti, A. Zech, C. Boisson, G. Emery, S. Inoue, and J. P. Lenain. Leptohadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056. *Mon.*

Shan Gao, Anatoli Fedynitch, Walter Winter, and Martin Pohl. Modelling the coincident observation of a high-energy neutrino and a bright blazar flare. *Nature Astronomy*, 3:88–92, 2019.

A. Keivani et al. A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implica- tions for High-energy Neutrino

A. Gokus, S. Richter, F. Spanier, M. Kreter, M. Kadler, K. Mannheim, and J. Wilms. Decom- posing blazar spectra into lepto-hadronic emission components. *Astron. Nachr.*, 339:331, 2018.

Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys. Rev.*, D99(6):063008,

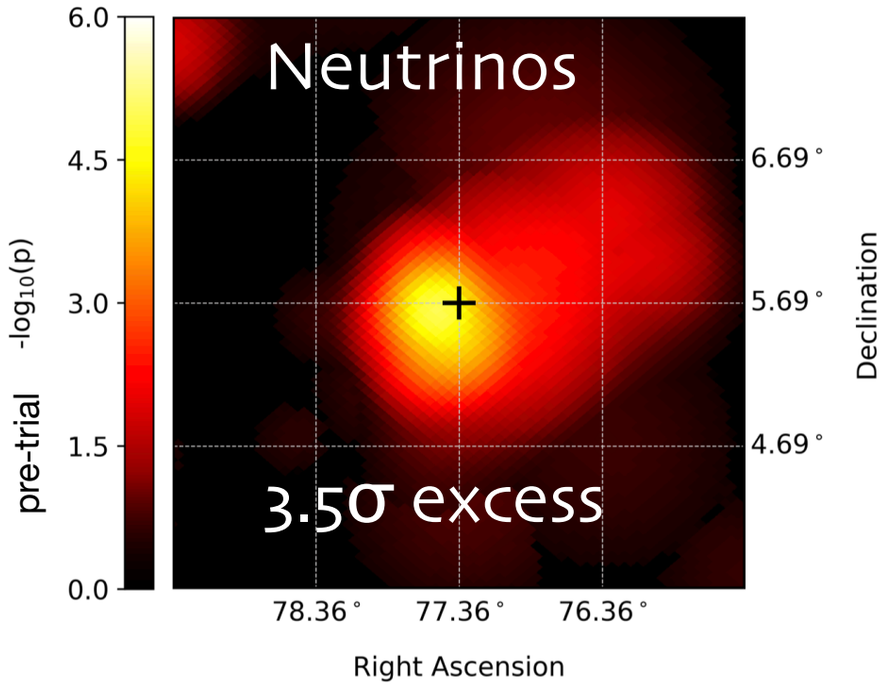
S. Britzen, et al, A&A 630, A103 (2019) (radio images)

N. Sahakyan. Lepto-hadronic γ-ray and neutrino emission from the jet of TXS 0506+056. *Astrophys. J.*, 866(2):109, 2018.

An improved realtime pipeline (and the full GFU story)

IceCube archival data on TXS 0506+056

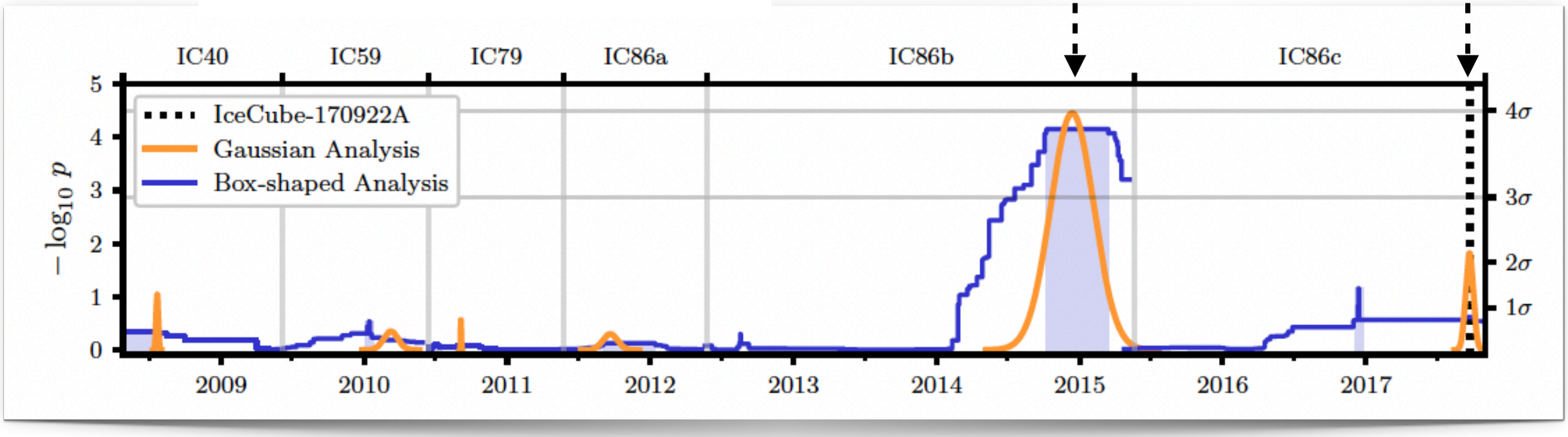
The observation of an excess of neutrino events in ~5 months (2014-2015) of 9.5 yr of data, together with IceCube-170922A in coincidence with a flaring state provides a strong evidence against the background hypothesis



~110-150 days ~20 days

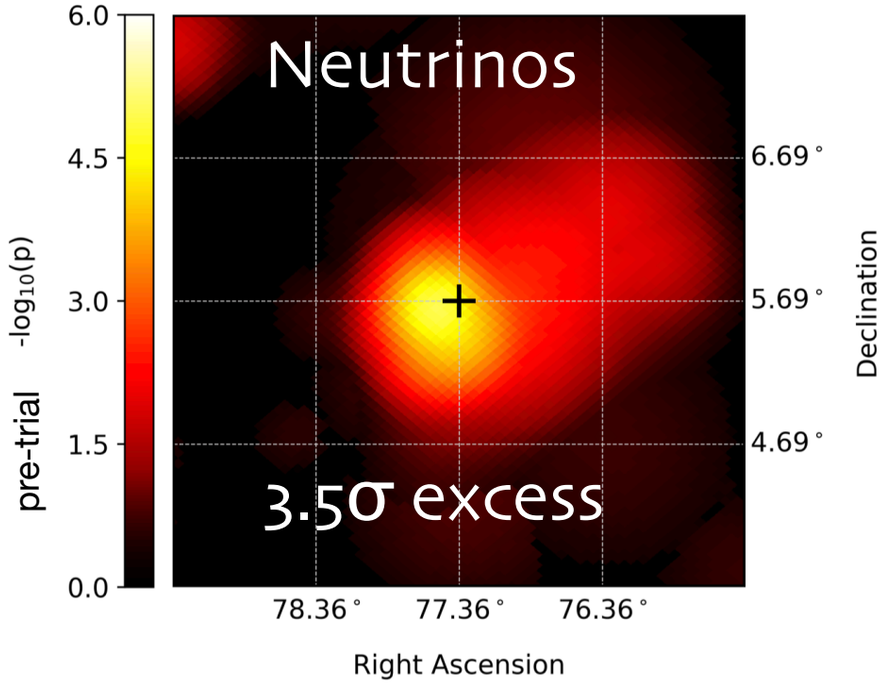
IceCube Coll. Science 361, eaat1378 (2018)

Spectral index ~2 Spectral index ~1.7



IceCube archival data on TXS 0506+056

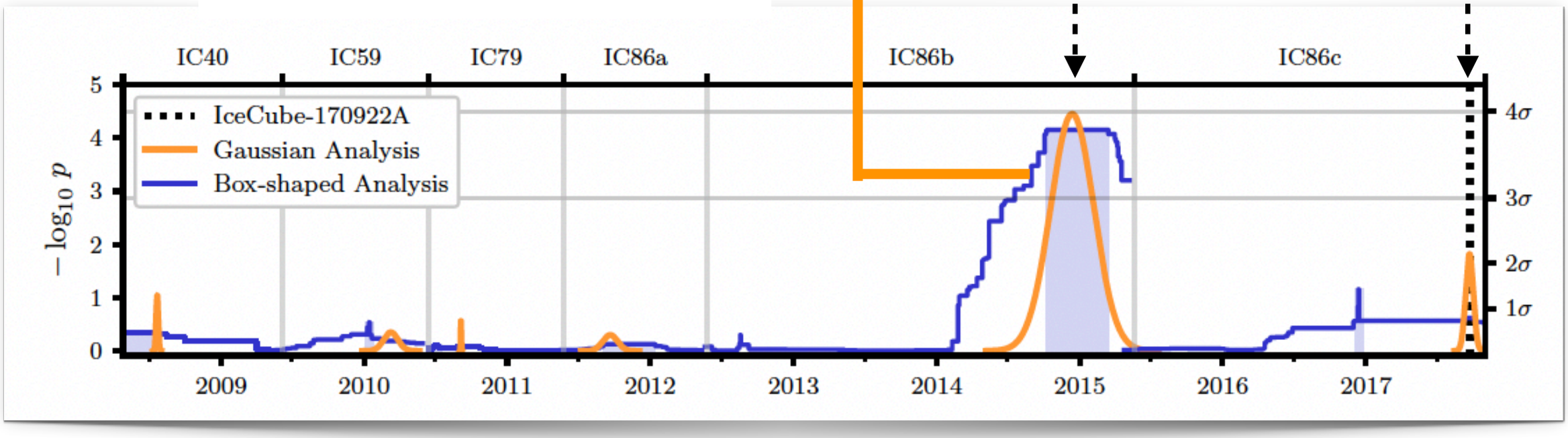
It would have issued a GFU (PRIVATE) alert, but TXS 0506+056 was not on GFU catalogues of monitored sources because of unknown redshift ….



~110-150 days
Spectral index ~2

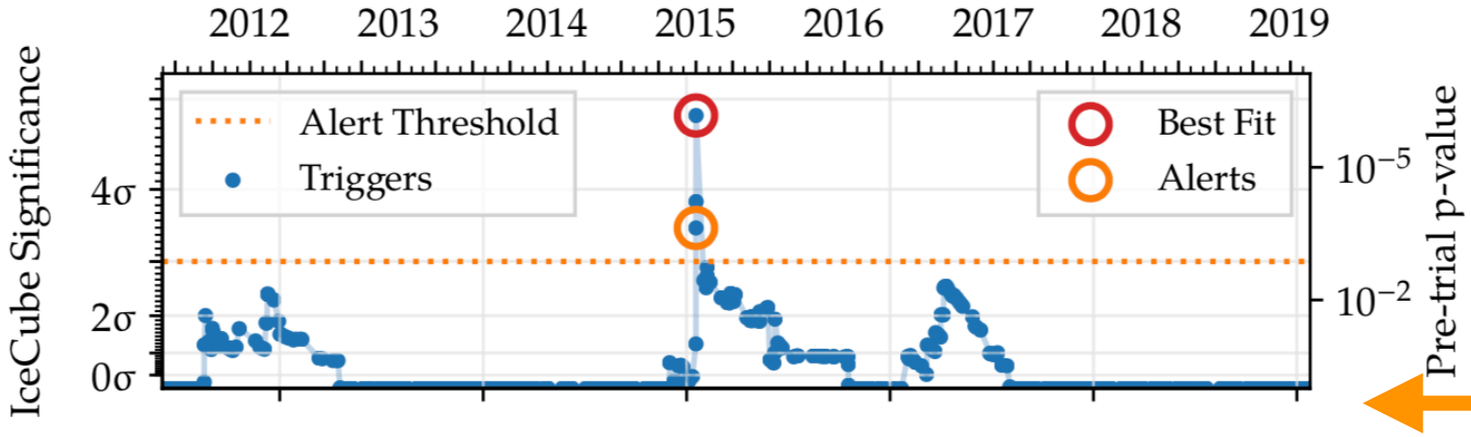
~20 days
Spectral index ~1.7

IceCube Coll. Science 361, eaat1378 (2018)

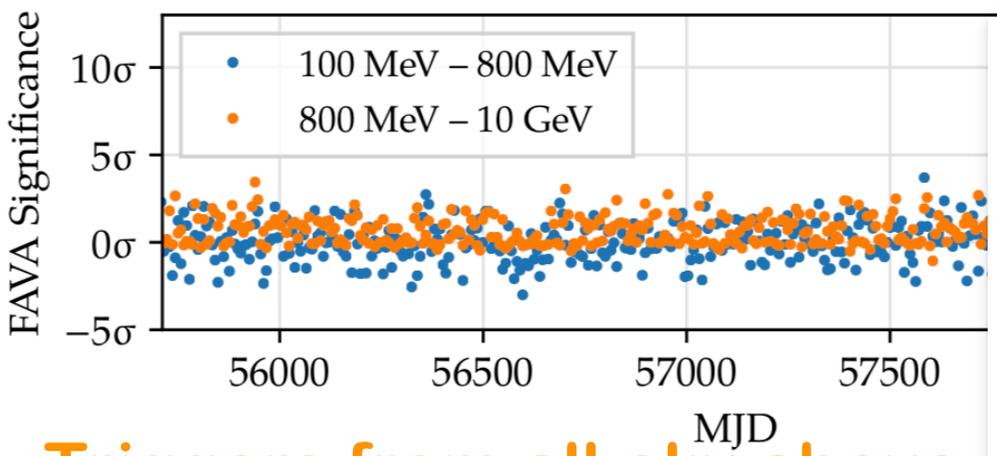


Gamma-ray follow-up (GFU) alerts

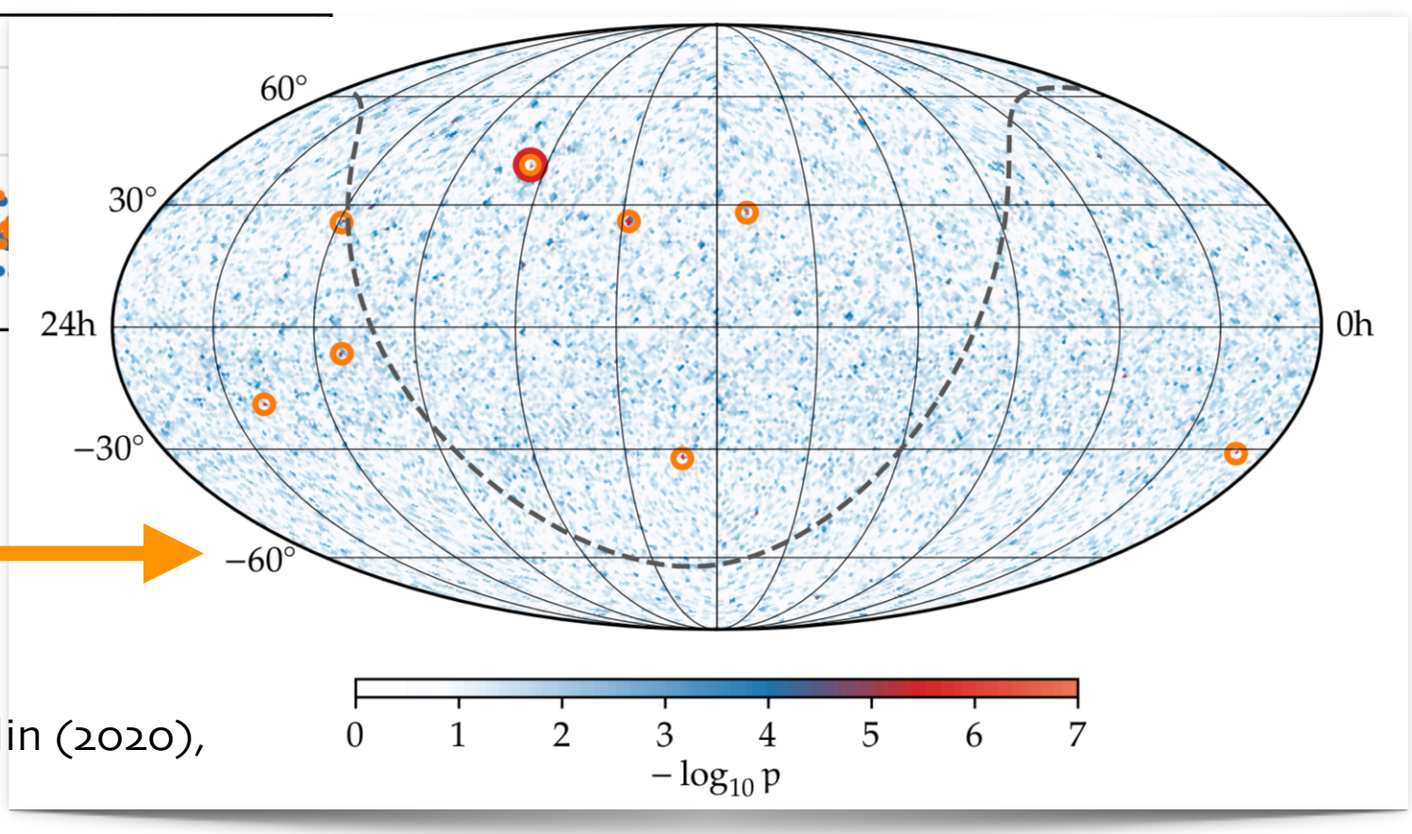
Alerts are being sent to Imaging Air Cherenkov telescopes H.E.S.S., MAGIC and VERITAS through **PRIVATE** channels regulated under dedicated MoUs



Triggers for a list of pre-selected sources (promising for TeV detections) above 3 sigma (pre-trial)

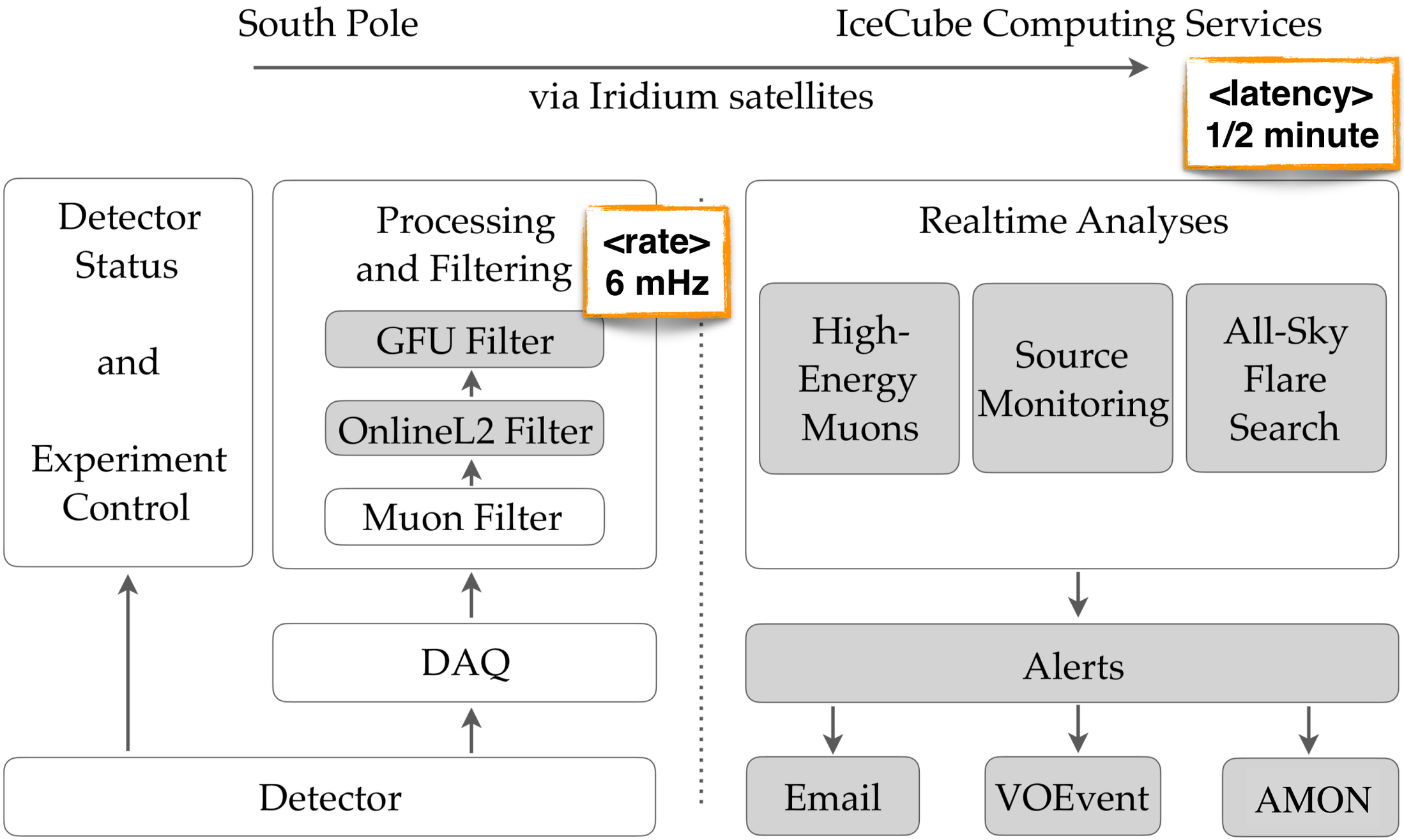


Triggers from all-sky above 4.2 sigma (pre-trial, 6.8 needed for discovery)



Thomas Kintscher, Humboldt University of Berlin (2020), supervisor E.B. paper in preparation

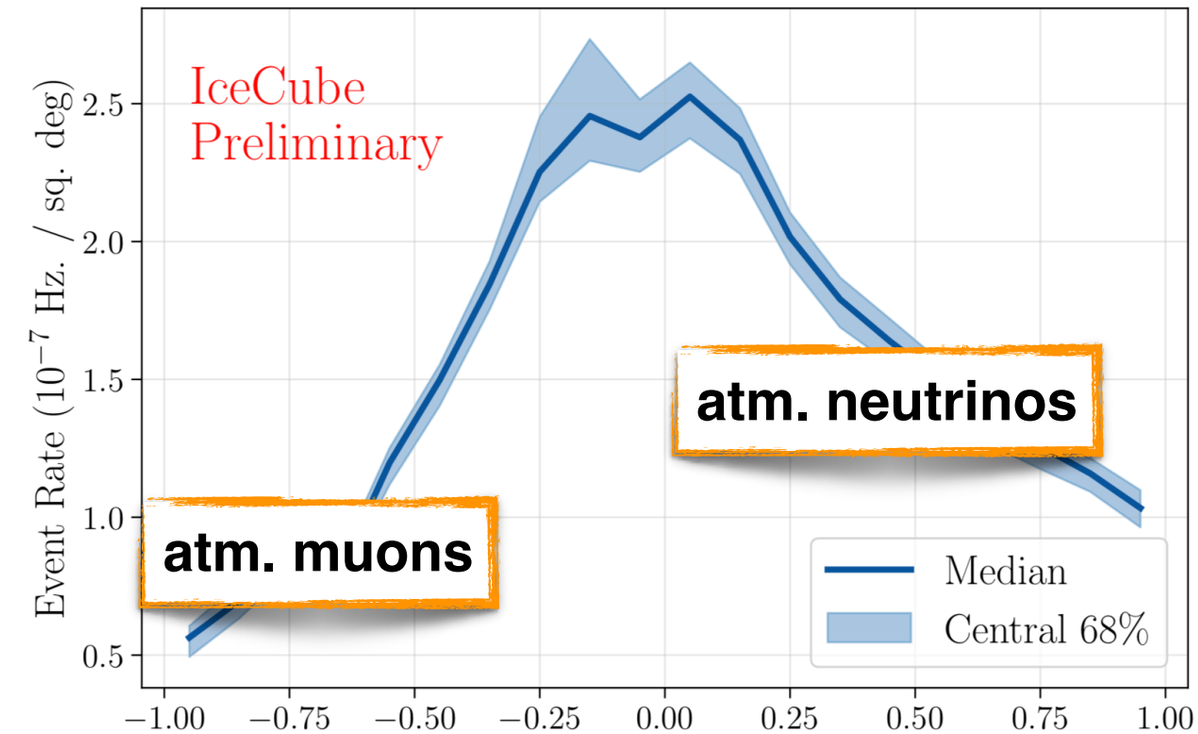
Realtime IceCube pipeline: GFU

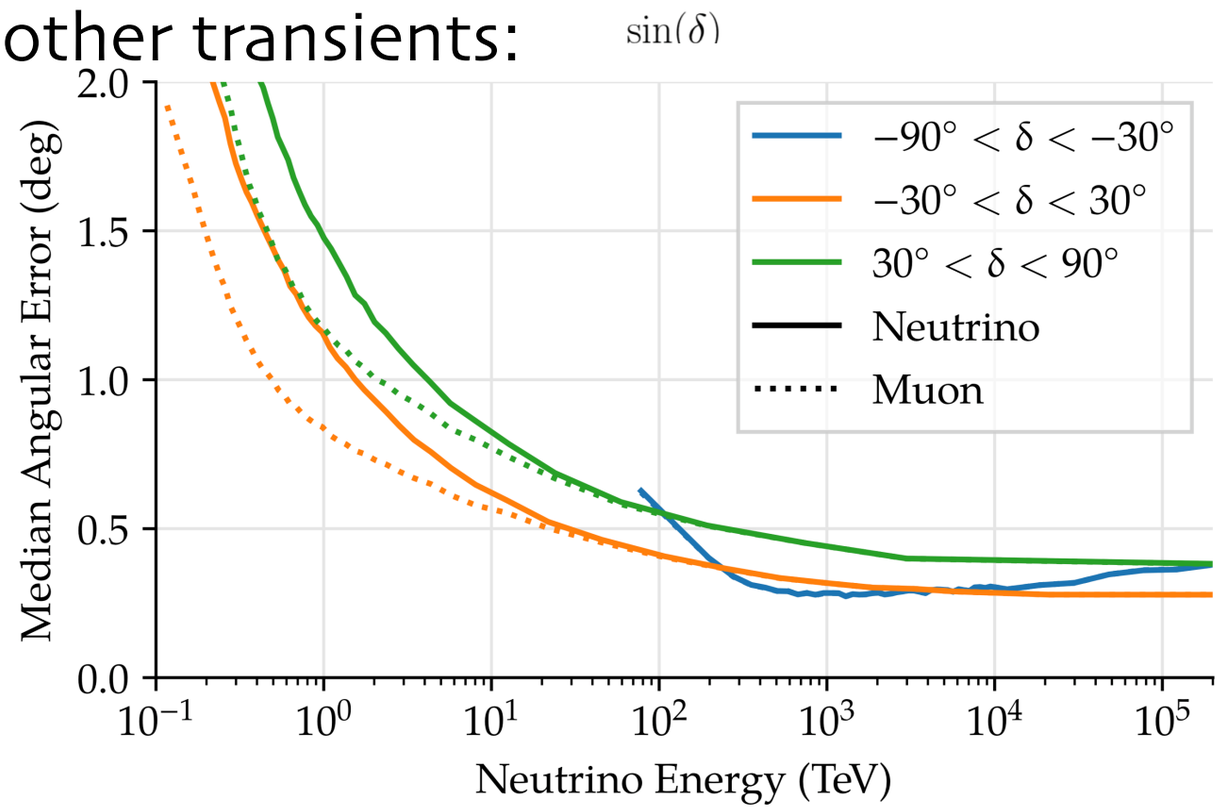


Thomas Kintscher, Humboldt University of Berlin (2020), supervisor E.B. paper in preparation

Realtime IceCube pipeline: GFU

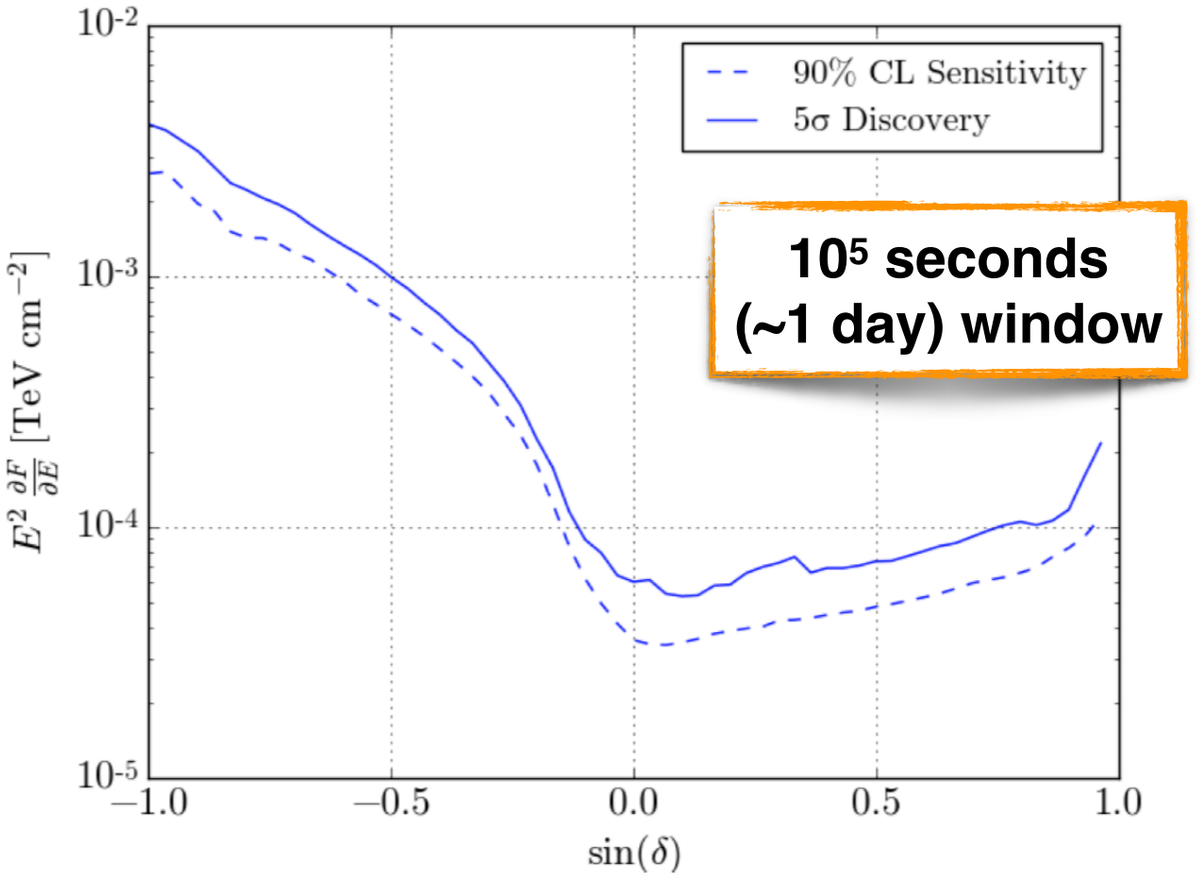
- The pipeline can search for:
  - Extended sources
  - Point-like sources
- Many applications for analysis of other transients:
  - ANITA neutrino candidates
  - Gravitational Waves
  - AMON sub threshold analyses
  - ….

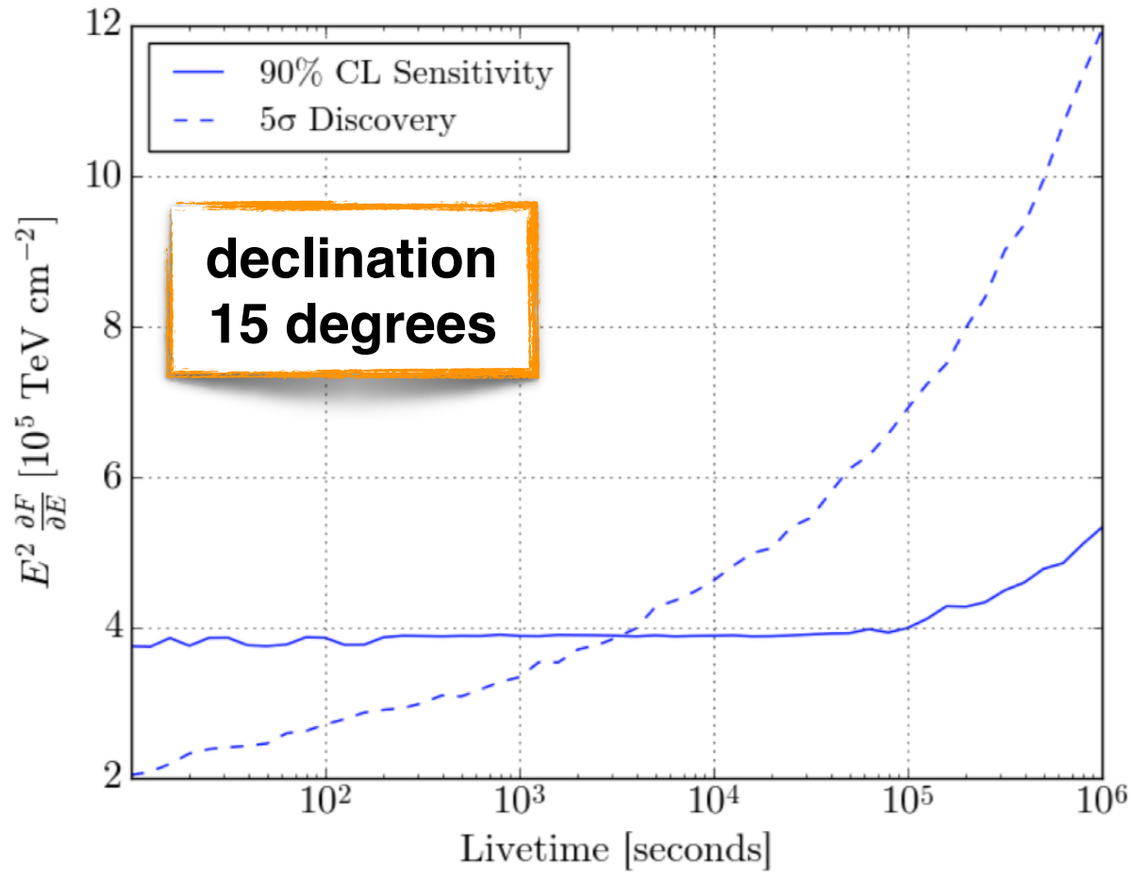




Realtime IceCube pipeline: GFU

- IceCube self-follow-up analysis, allows a Fast Response Analysis
  - (-1;+1) day window
  - (-30;+1) day window
  - or customised time window (Realtime Oversight Committee, ROC)





Fast response analysis: TXS 0506+056

[Previous | Next | ADS]

MAGIC detects enhanced flux of VHE gamma rays from TXS 0506+056

ATel #12260; *Razmik Mirzoyan (Max-Planck-Institute for*
MAGIC Collaboration
on 3 Dec 2018; 22:22 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mir

Subjects: Gamma Ray, >GeV, TeV, VHE, AGN, Blazar

Referred to by ATel #: 12267, 12274

Tweet

We report an enhanced emission of VHE gamma-rays from the direction of the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the estimated direction of the high energy IceCube neutrino event IceCube-170922A (ATel #10791). On Dec 3rd 2018 the MAGIC telescopes observed this source for about 2 hours under good weather conditions. The source was detected at VHE gamma-rays above 90 GeV with a significance larger than 5 sigma. The preliminary analysis yields an estimate of the VHE gamma-ray flux above 90 GeV of ~10-15% of the flux from the Crab Nebula above the same energy threshold, and a spectral index of ~4. This flux is consistent with the emission level integrated between September 28th 2017 to October 3rd 2017, when the source was discovered at VHE gamma-rays (ATel #10817). The MAGIC telescopes will continue monitoring the VHE gamma-ray emission of TXS 0506+056. Soft-X-rays and ultraviolet ToO observations with the Neil Gehrels Swift Observatory have been approved for the next three nights (PI: Cerruti, on behalf of MAGIC), to occur within the time-window 00:00 to 04:00 UTC. NuSTAR ToO observations have also been approved (PI: Satalecka). Multi-wavelength observations (quasi)-simultaneous with MAGIC in this time-window are strongly encouraged.

The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de), E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de).

MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Table 1: MAGIC measurements of TXS 0506+056

Data set	Duration [h]	Significance	VHE activity
MJD 58453	2.5	3.8σ	High
MJD 58455	1.8	5.4σ	Very high
Rest	74.4	4.0σ	Low

K. Satalecka, E. B. et al.
PoS(ICRC2019)783

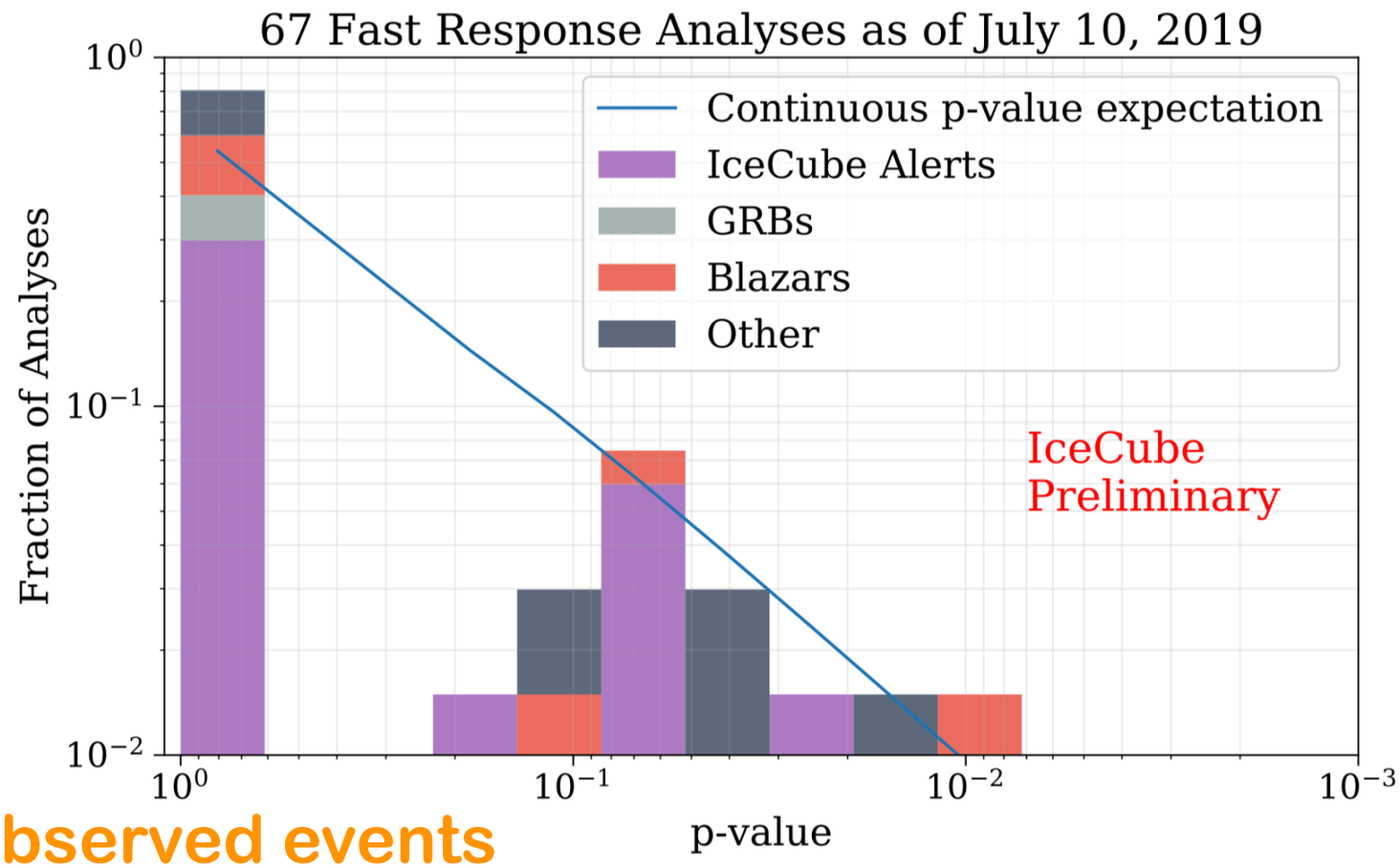
- IceCube follow-up analysis:
  - one week time window
  - one event found, compatible with background

J. Vanderbroucke et al.
PoS(ICRC2019)1026

Fast response analysis: best cases

More than 70 analyses performed so far searching for associations between IceCube neutrinos and astrophysical transients reported by radio, optical, X-ray, and gamma-ray instruments in addition to searching for lower energy neutrino signals in association with IceCube's own high-energy alerts.

J. Vandenbroucke et al. PoS(ICRC2019)1026



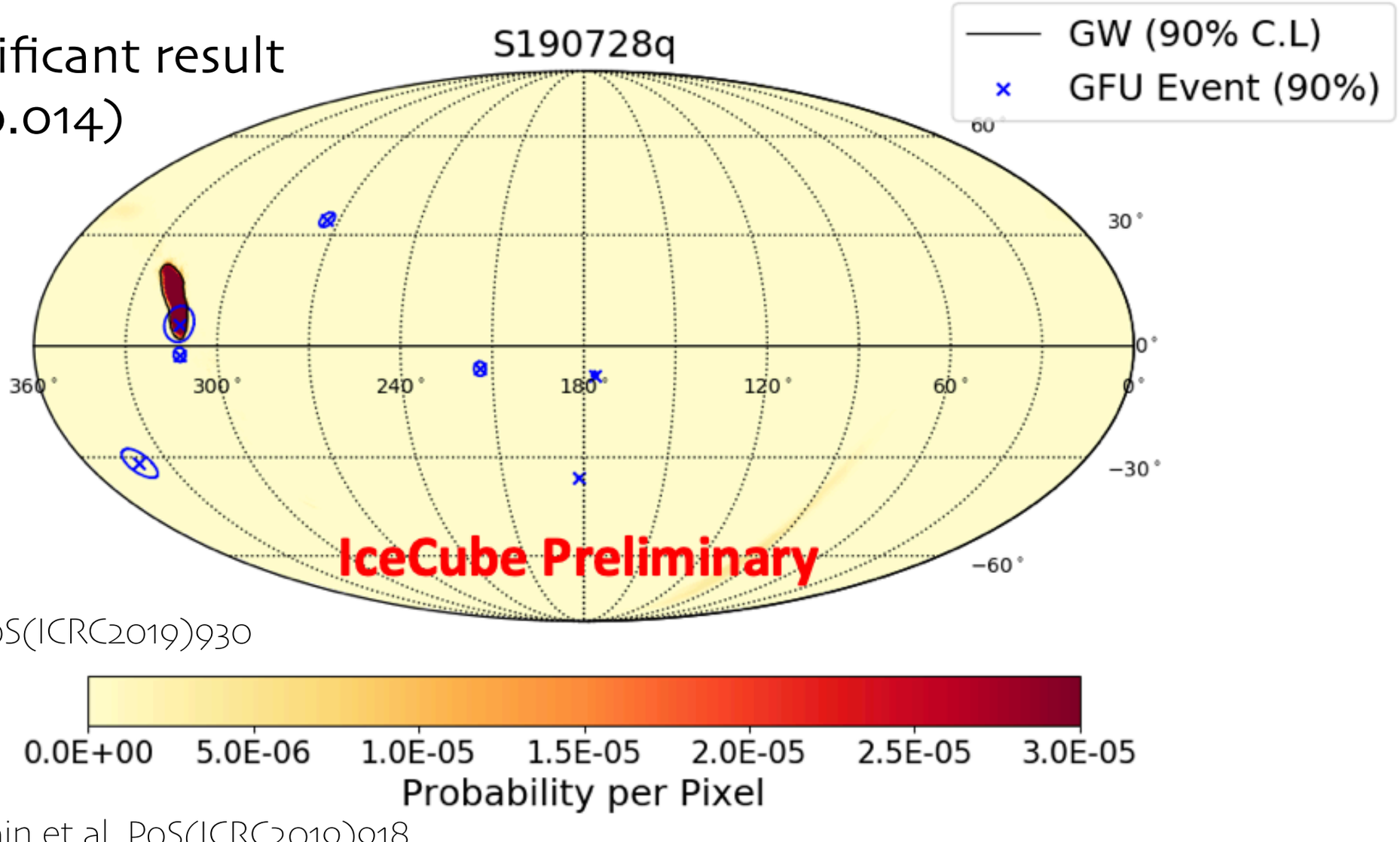
0 observed events

1 observed event

Neutrinos from Gravitational Waves

33 GW from O1, O2 and O3 LIGO Virgo runs looked for coincident neutrinos (within +/- 500 s) using GFU data based upon an unbinned maximum likelihood which uses the LVC skymap as a spatial prior.

Most significant result
(p-value 0.014)

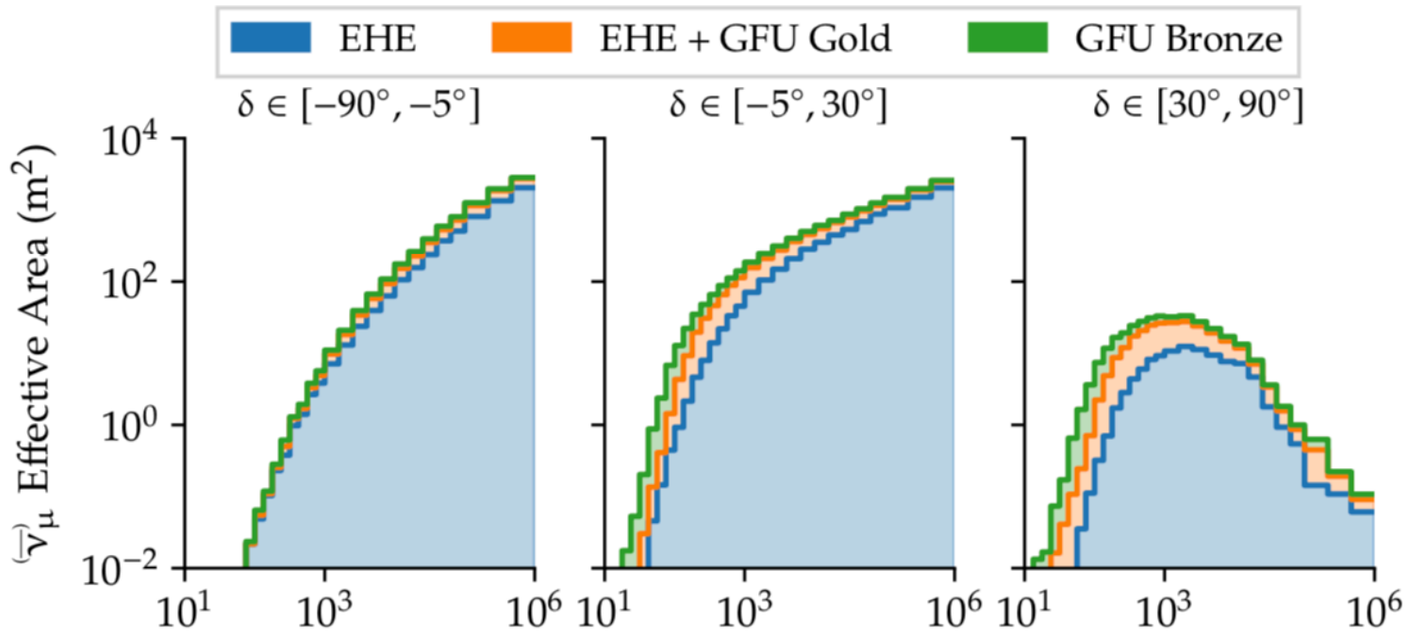


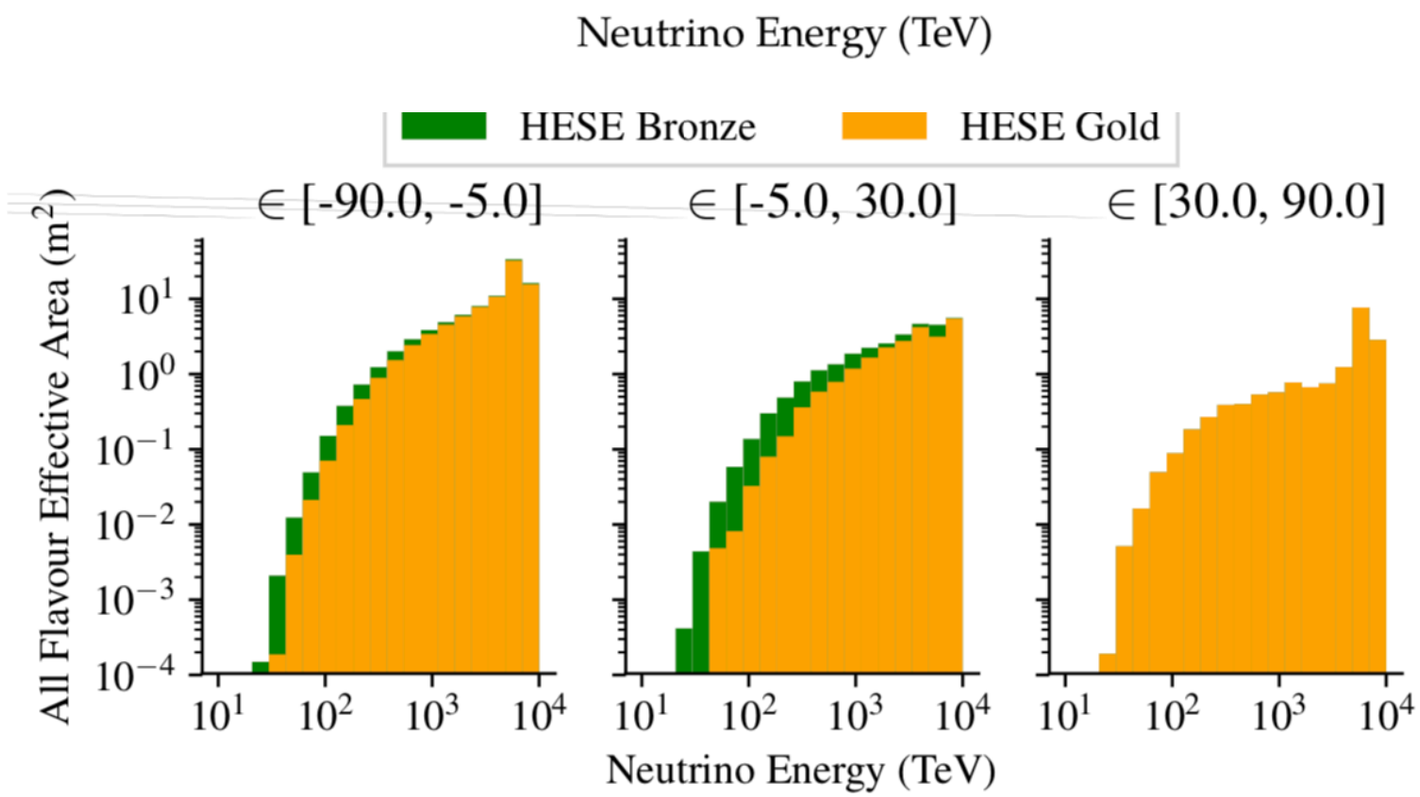
Keivani et al. PoS(ICRC2019)930

see also R. Hussain et al. PoS(ICRC2019)918

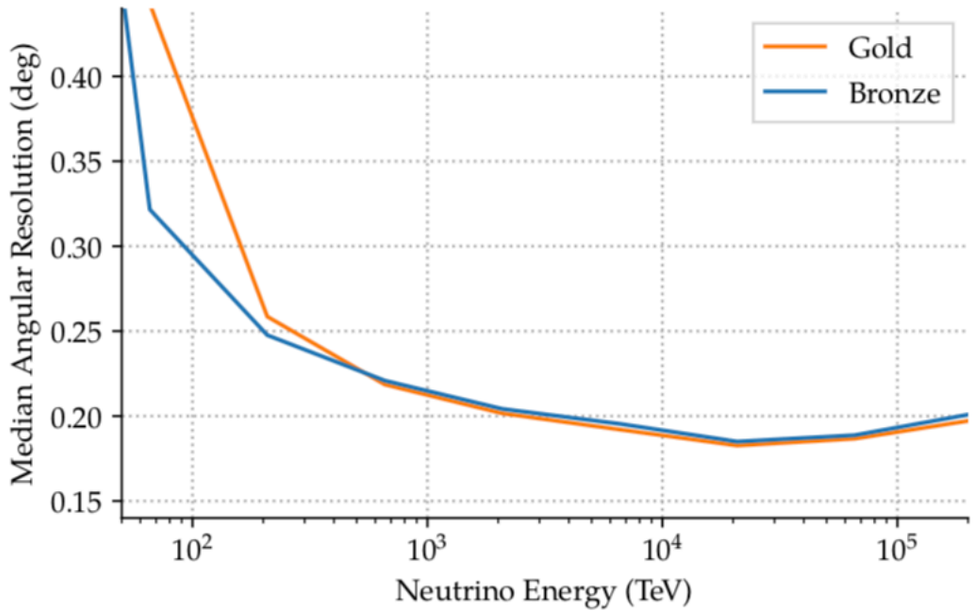
Above threshold GOLD/BRONZE alerts since June 2019

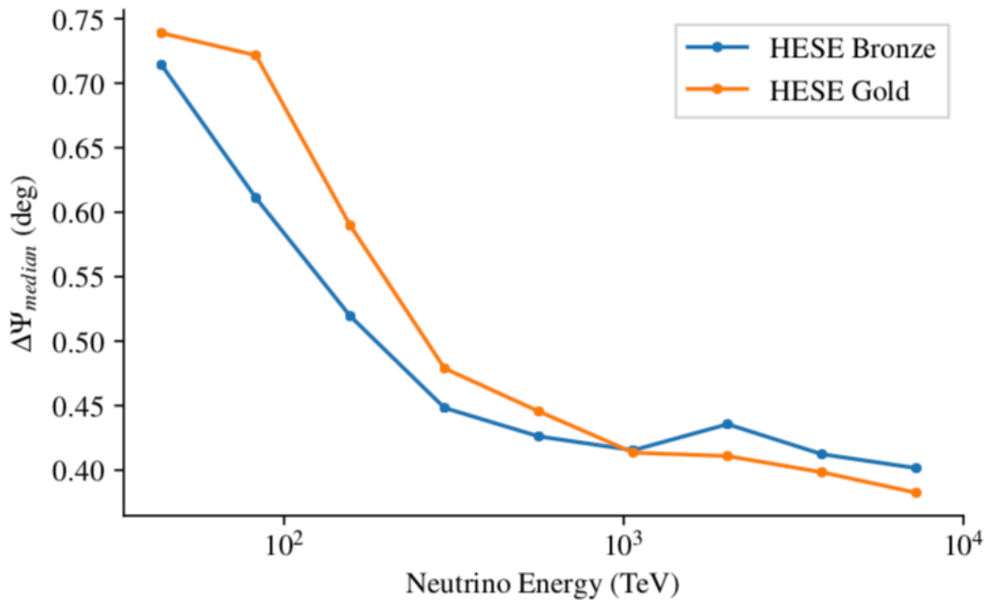
- GFU: improved energy proxy and multivariate event s3election (BDT)
- EHE: high charge + track quality
- HESE: high charge + veto





Above threshold GOLD/BRONZE alerts since June 2019





$$\text{Signalness} = \frac{N_{signal}}{N_{signal} + N_{background}}$$

Gold selection: 50% signalness

Bronze selection: 30% signalness

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

Full list of alerts: https://gcn.gsfc.nasa.gov/amon_icecube_gold_bronze_events.html

In Summary

- High Energy Neutrinos are opening a new window into the cosmos:
  - Diffuse cosmic neutrinos well established (more than 8 sigma) by two channels
  - Compelling evidence for the first non-stellar neutrino source: a blazar
- State of the art is limited by too few photons and too few neutrinos
- Multimessenger studies are essential for identification of sources
- Better understanding of the potential sources and relevant data can help the way to new breakthroughs
- Not covered in this talk: supernova neutrinos

Extras

p
Cosmic rays

ν
Neutrinos

Multi-messenger astrophysics

SN 1987 A

TXS 0506+056 & IC-170922A

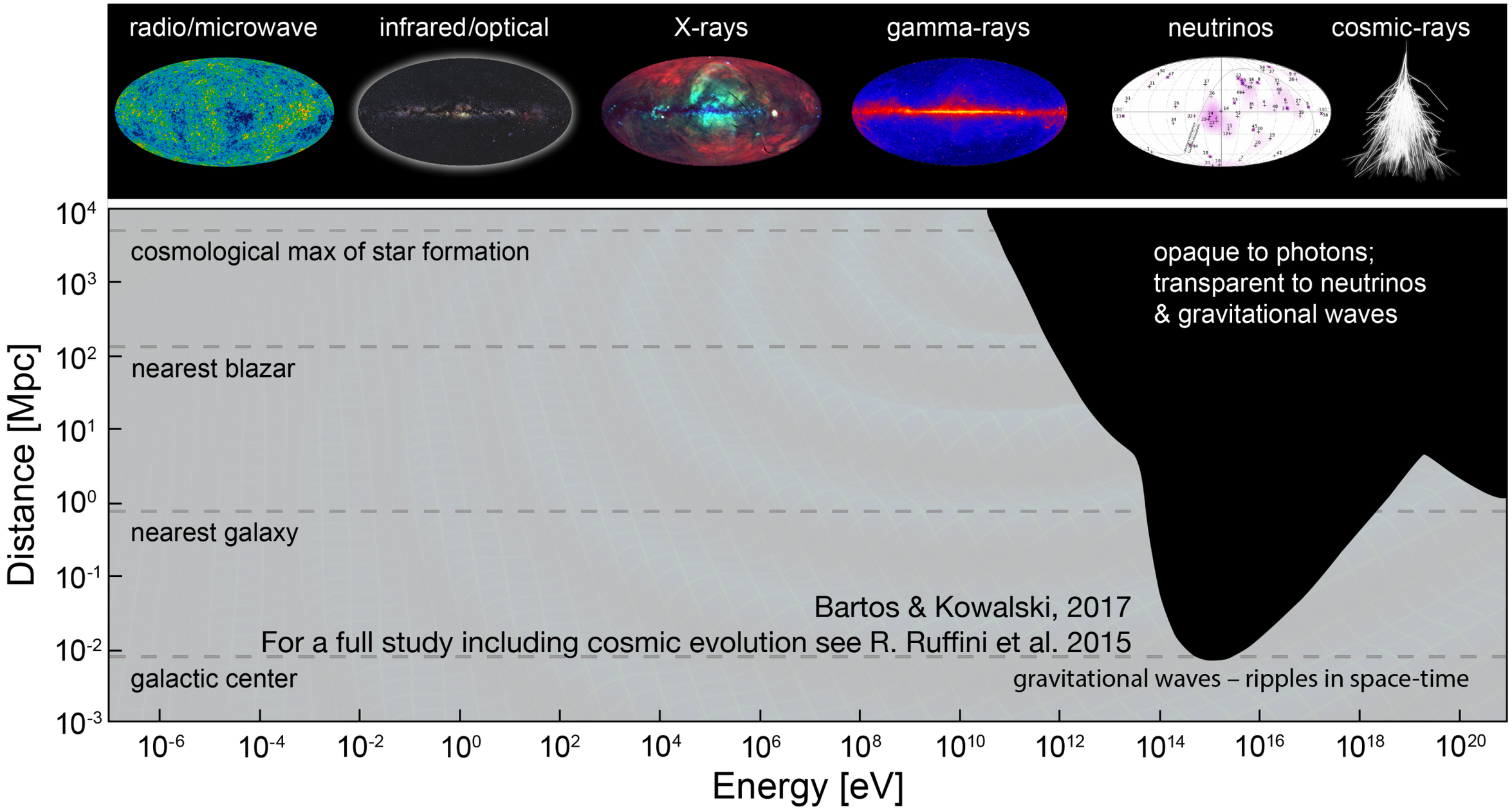
GW170817

GW
Gravitational Waves

γ
Gamma rays

Observable Universe

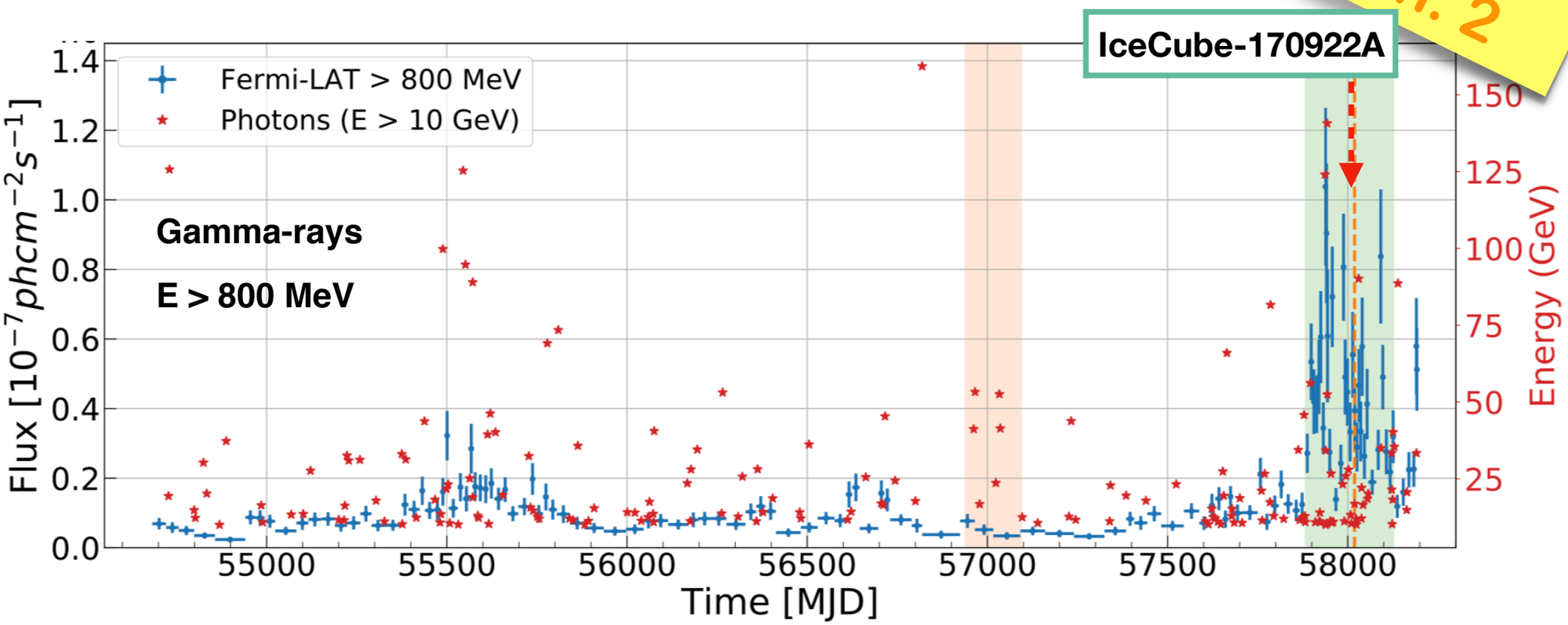
Photons are absorbed in the Extragalactic Background Light (EBL)
Protons ($E > 10^{20}$ eV) interact with the Cosmic Microwave Background (CMB)



IceCube-170922A

Multi-messenger Highlight n. 2

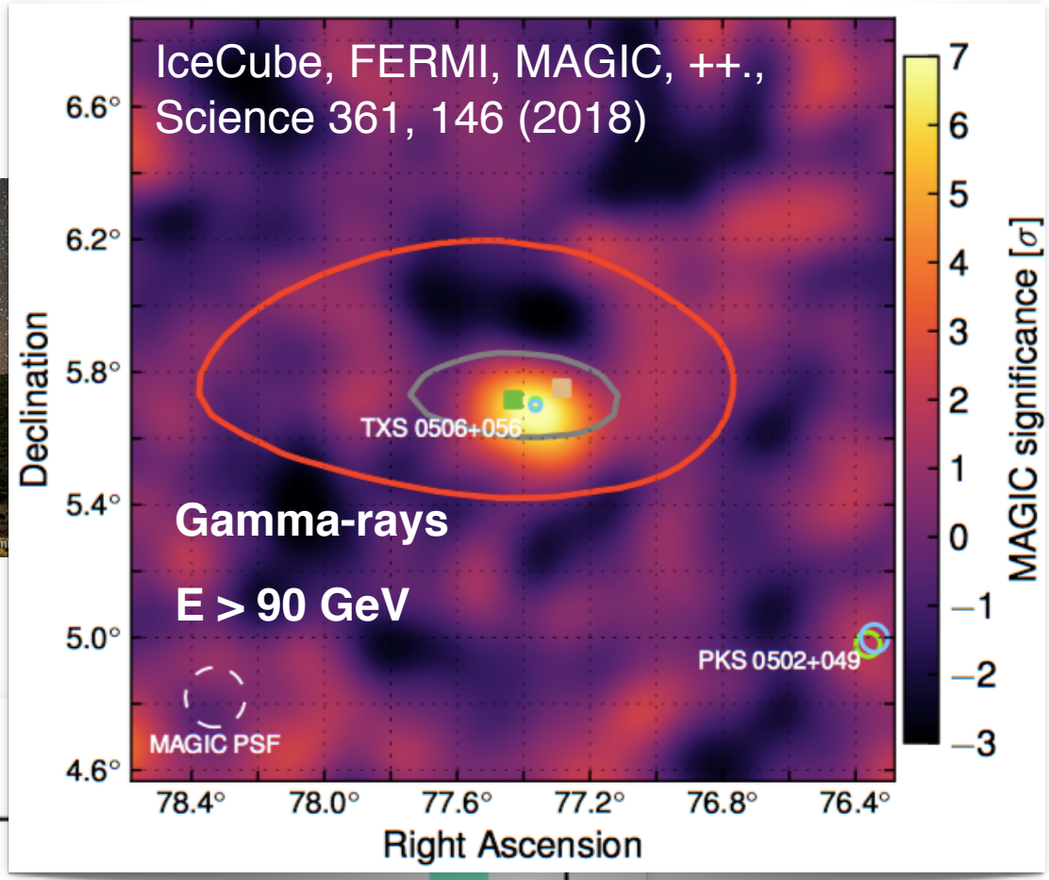
Compelling evidence for neutrino emission from the B[illegible]6+056.
Identification of a cosmic hadron accelerator with >PeV ene[illegible]

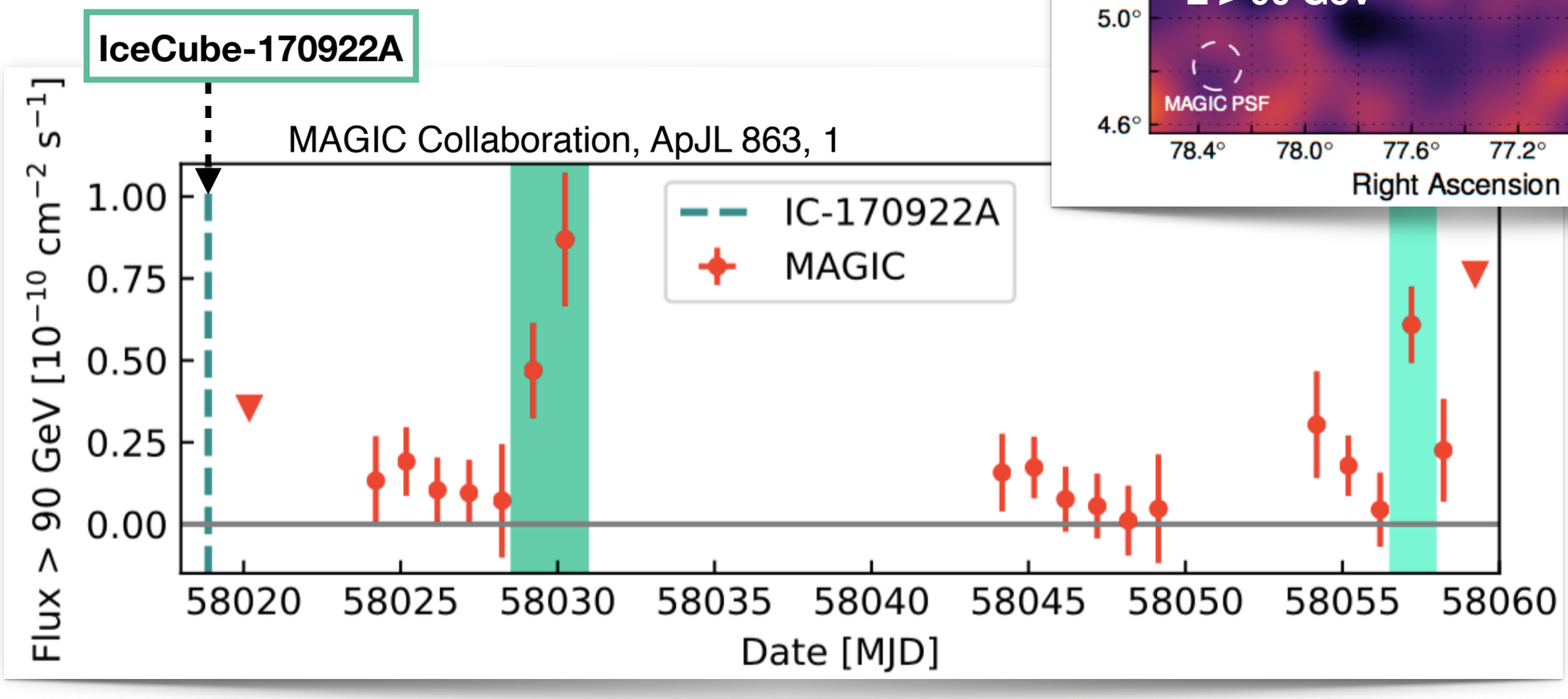


- Consistent with the direction of IceCube-170922A there is the Blazar TXS 0506+056
- The source was found in a state of enhanced gamma-ray activity lasting several months
- Coincidence probability after trials (10 public alerts and 40 archival events): 3 σ

Very high energy gamma-rays from TXS 0506+056

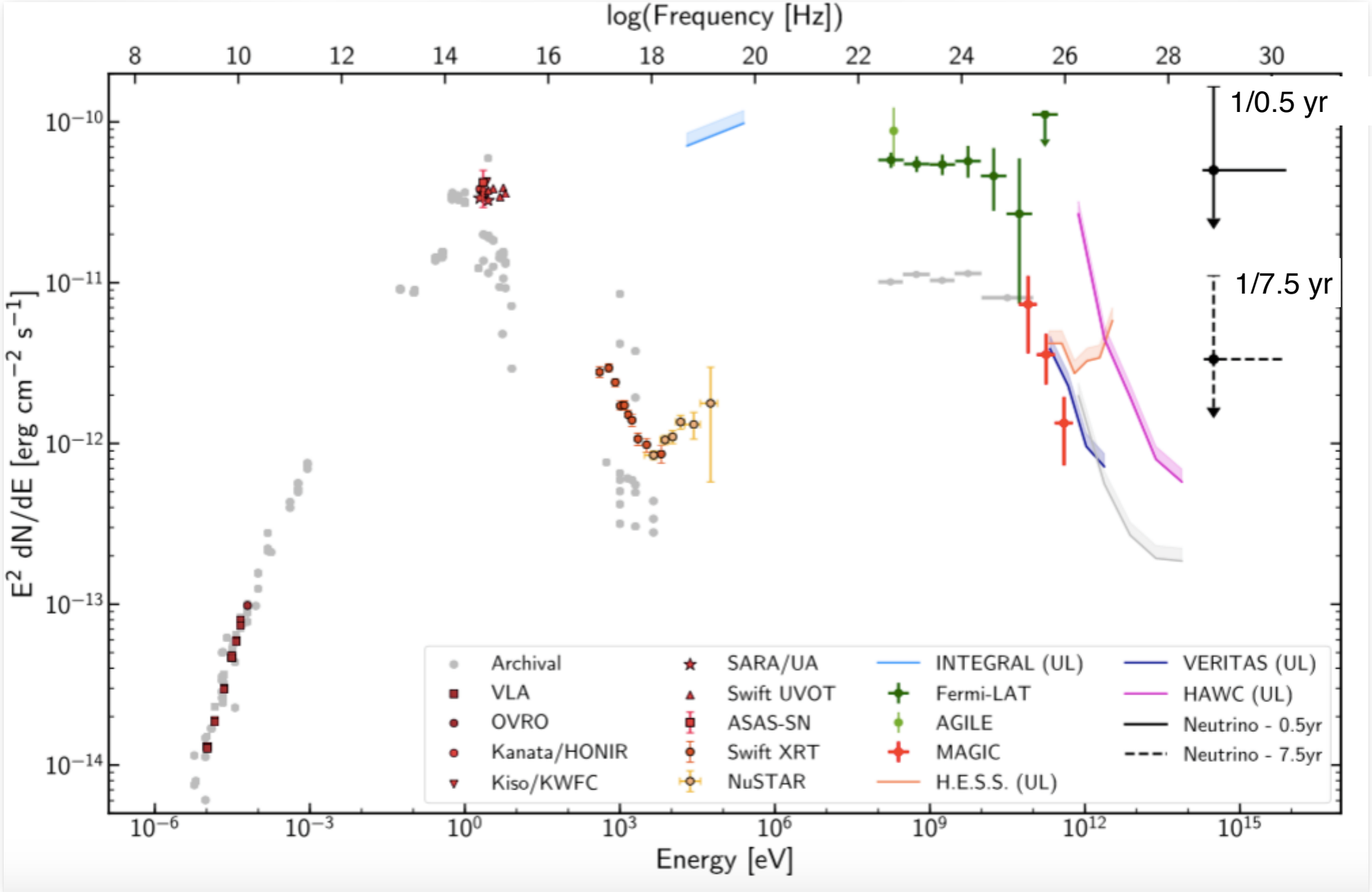
MAGIC detected γ-rays with energies up to about 400 GeV with strong day-to-day variations





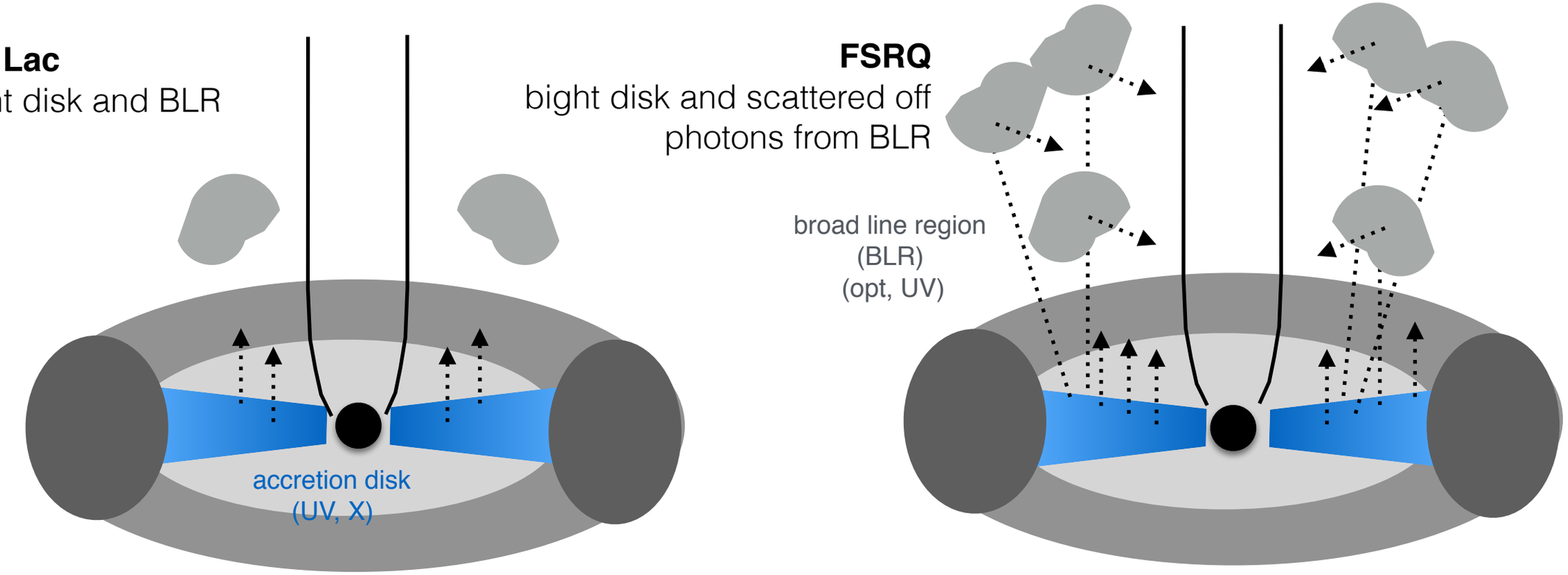
Does it all fit together?

IceCube, FERMI, MAGIC, ++., Science 361, 146 (2018)



Interpreting the multi-messenger data in a nutshell

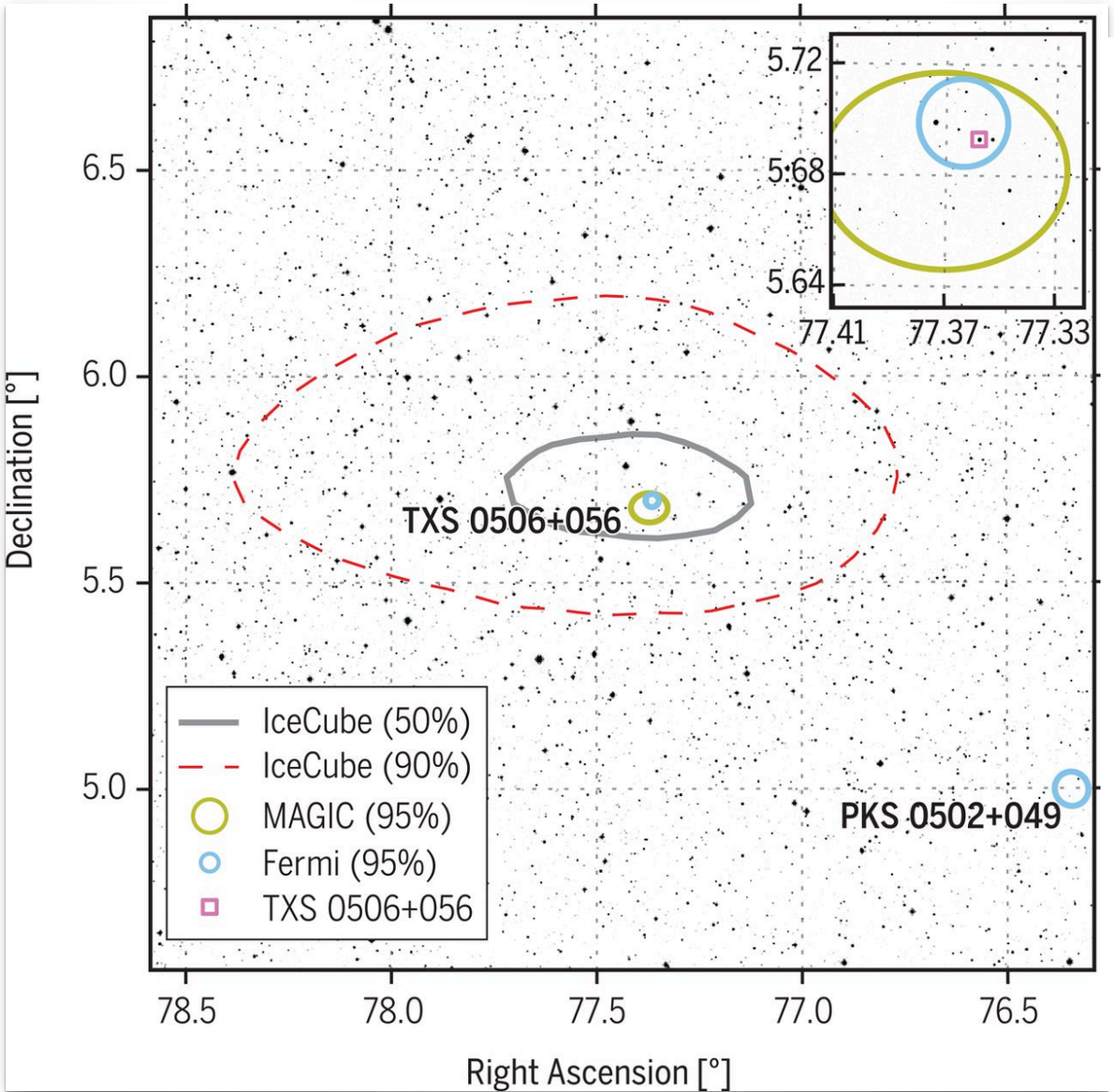
Most Blazar emission models assume that high-energy particles (electrons, protons, nuclei) are injected into the jet where they encounter target radiation (non-thermal emission by the high-energy particles, or external photons from the accretion disk, clouds or dust torus.

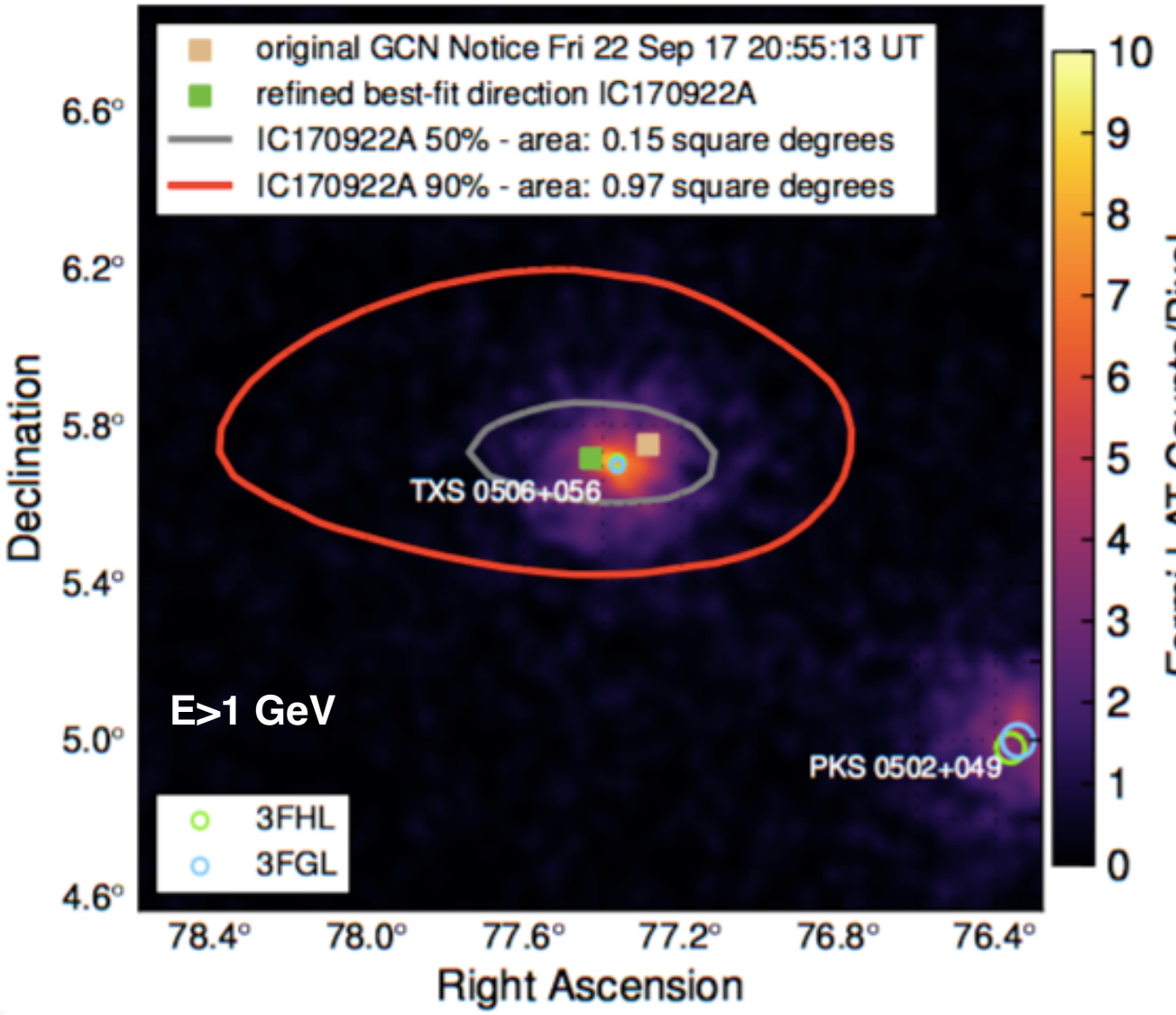


The Blazar TXS 0506+056

Probability to observe by chance a flaring Fermi-LAT Blazar in the error circle of a high energy neutrino after trials (10 public alerts and 40 archival events): 3 σ

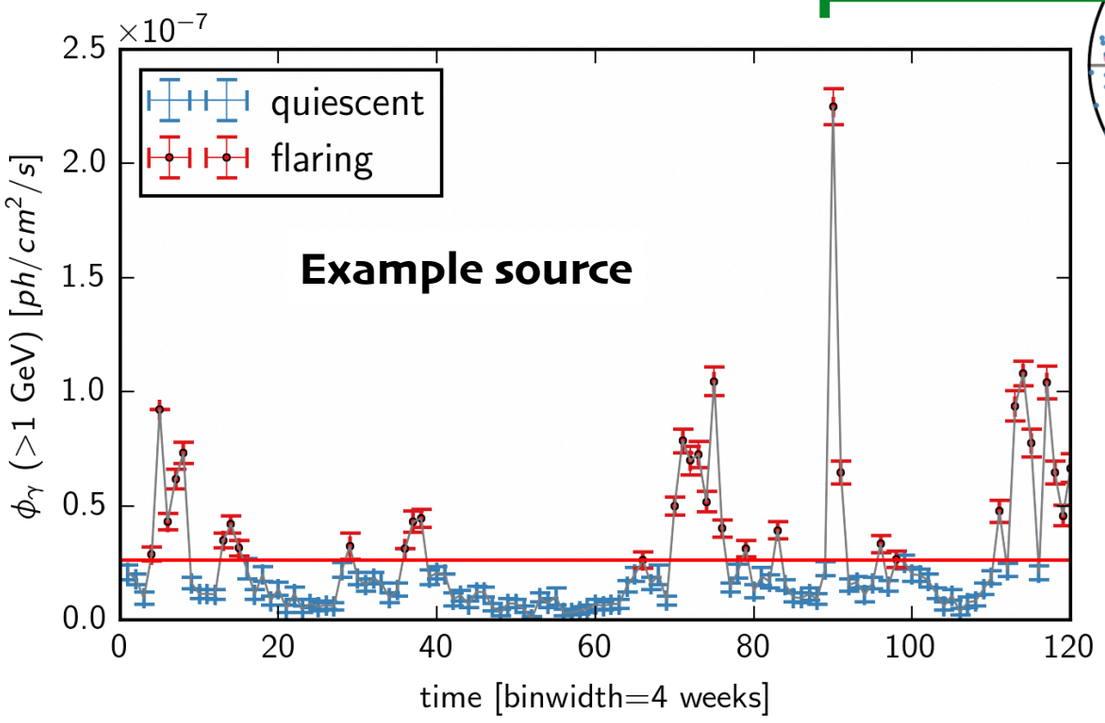
IC+Fermi+MAGIC++., Science 361, 146 (2018), arXiv:1807.08816

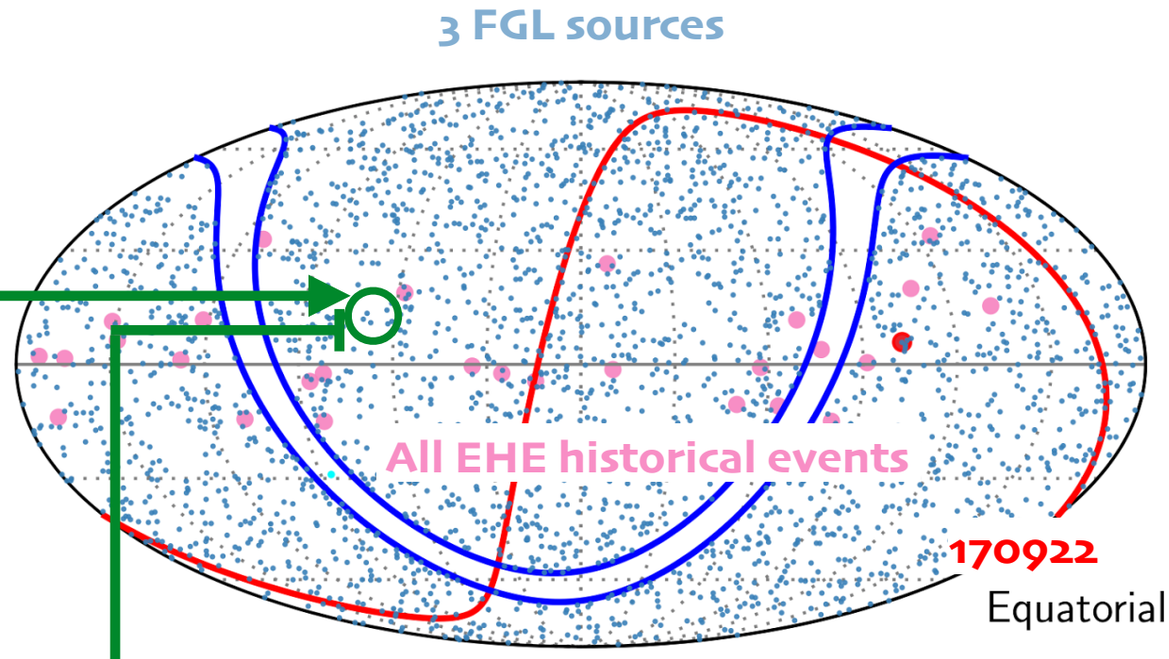




Spatial + temporal coincidence

Step 1: Draw many times a random neutrino from a representative sample of high-energy muon-track events





Step 2: Check for existence of a F Blazar in neutrino error circle and **Step 3:** check its GeV γ-ray flux at the same time bin

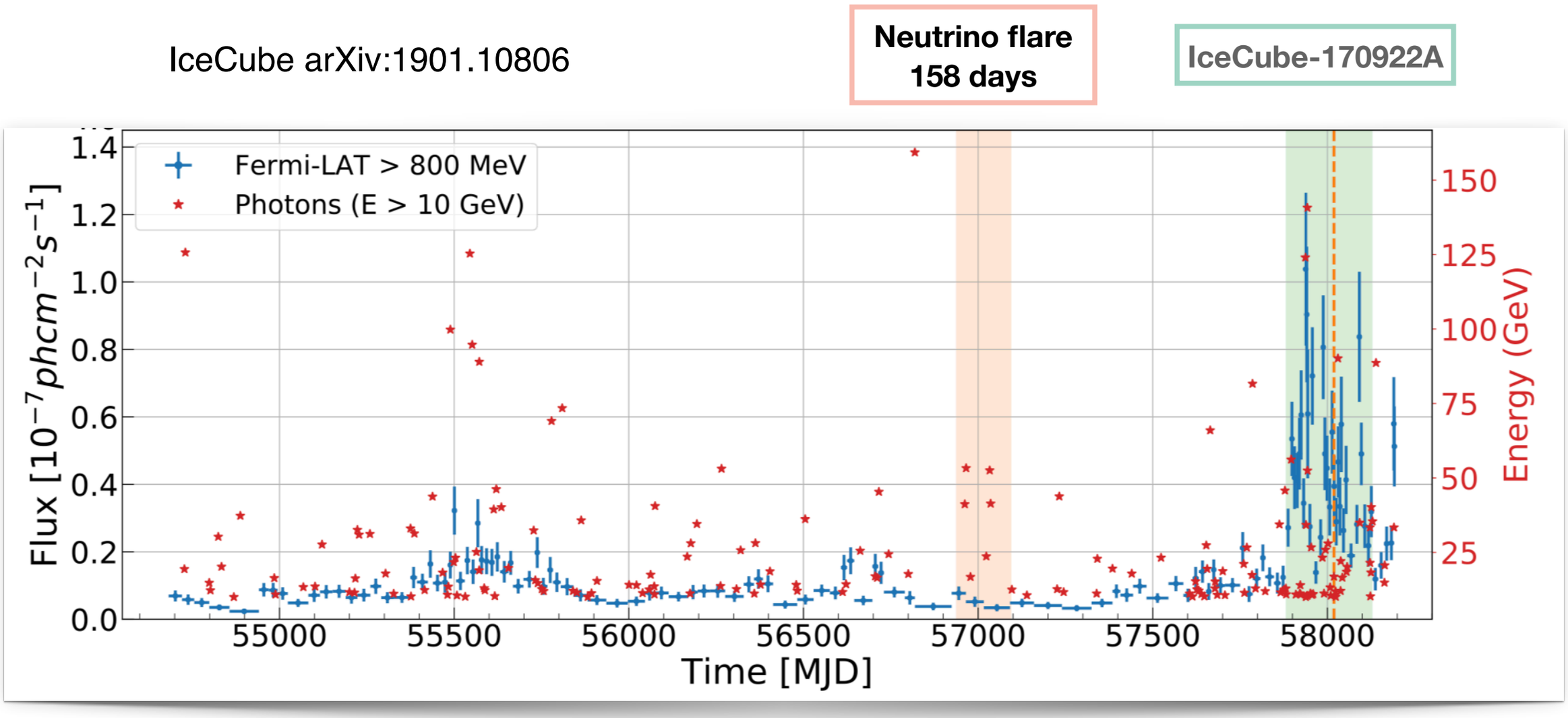
Probability to observe by chance a flaring Fermi-LAT Blazar in the error circle of a high energy neutrino:

Pre-trials p-value: 4.1 σ

Post-trials p-value (10 public alerts and 40 archival events): **3 σ**

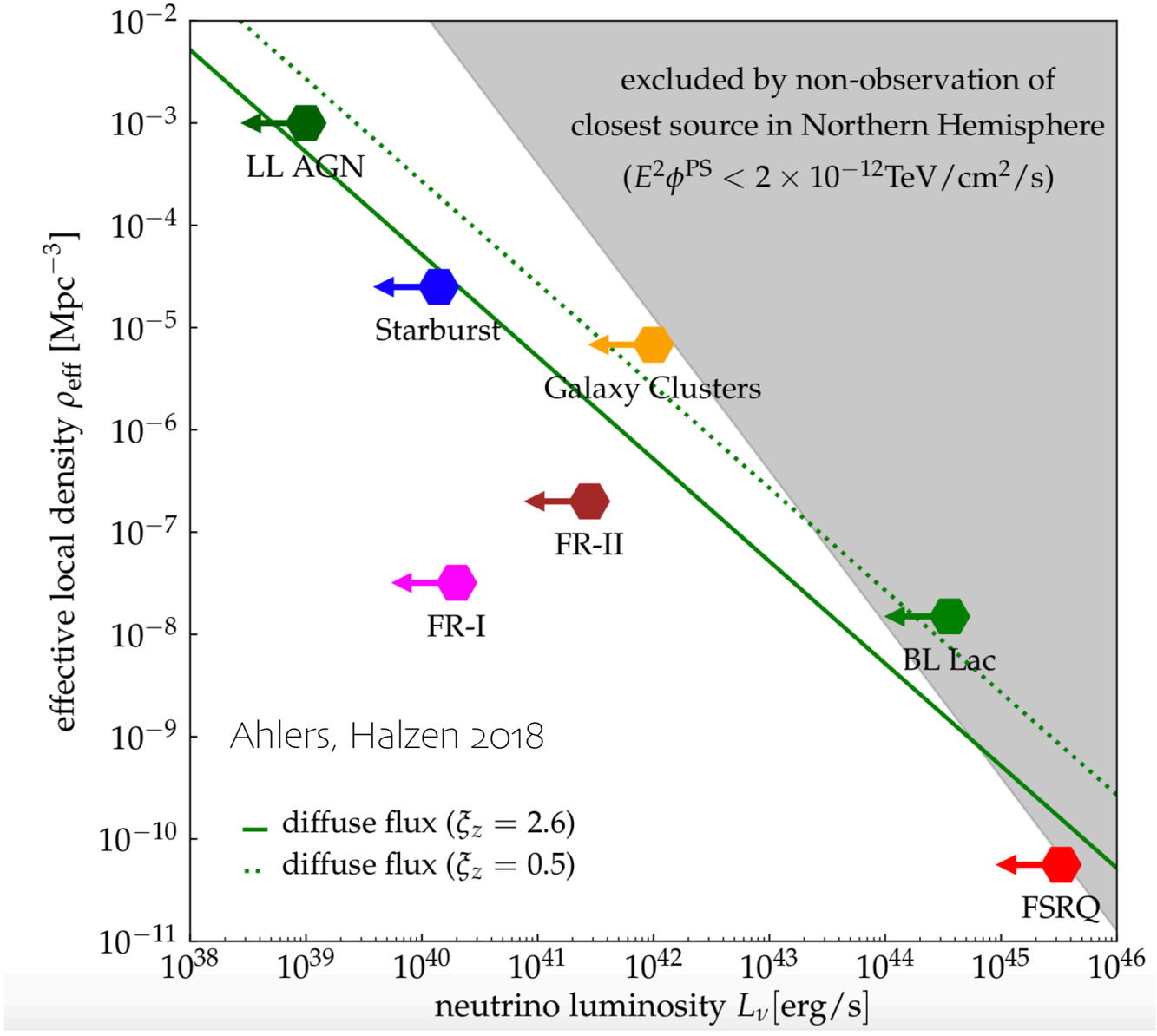
and FERMI archival data on TXS 0506+056

During the earlier (2014/15) neutrino flare no significant gamma-ray flaring activity or spectral change have been observed, few authors report a possible hint of hardening (P. Padovani, et al. MNRAS 2018)



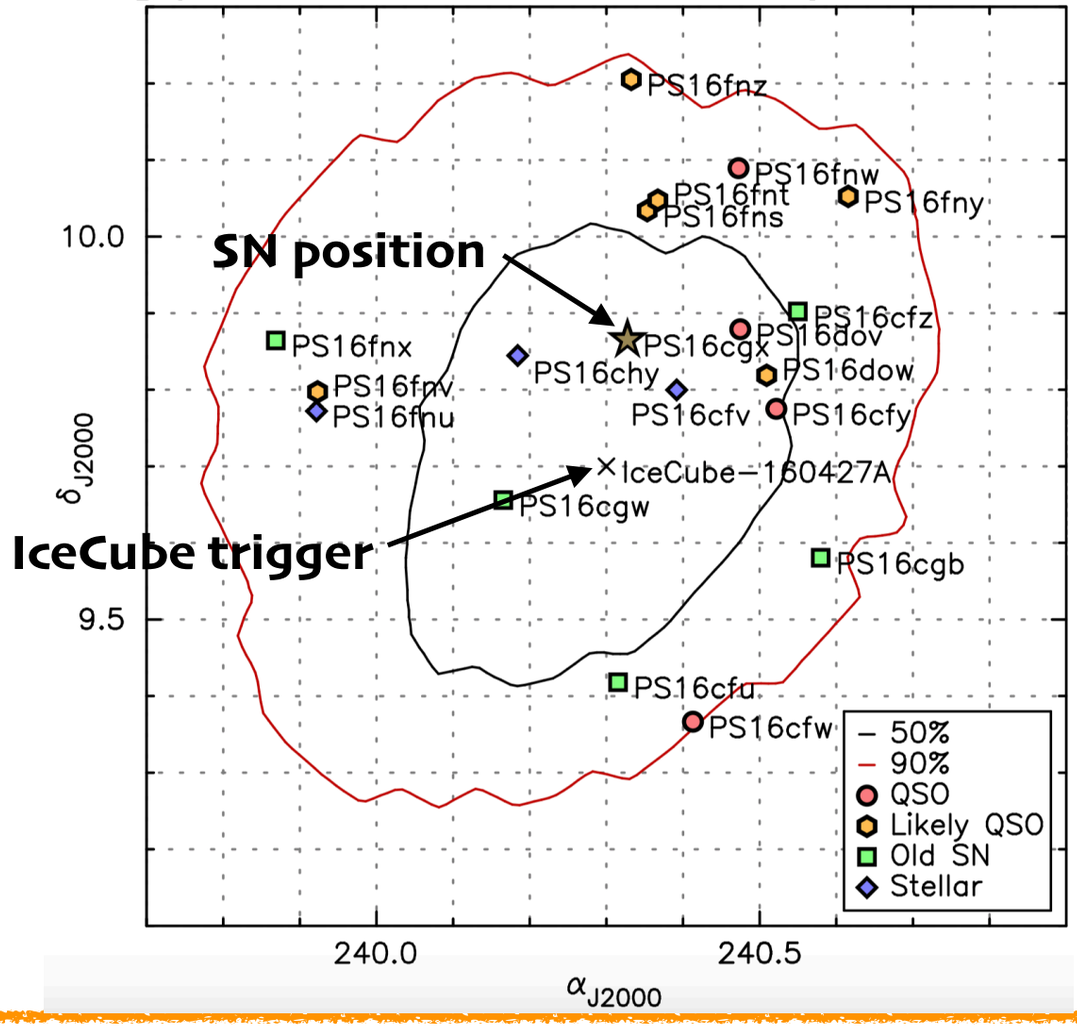
Implications of point source limits

- The absence of localised excesses suggests that the sources are distributed across the sky and that even the brightest individual objects contribute only a small fraction of the total observed flux.



Supernovae

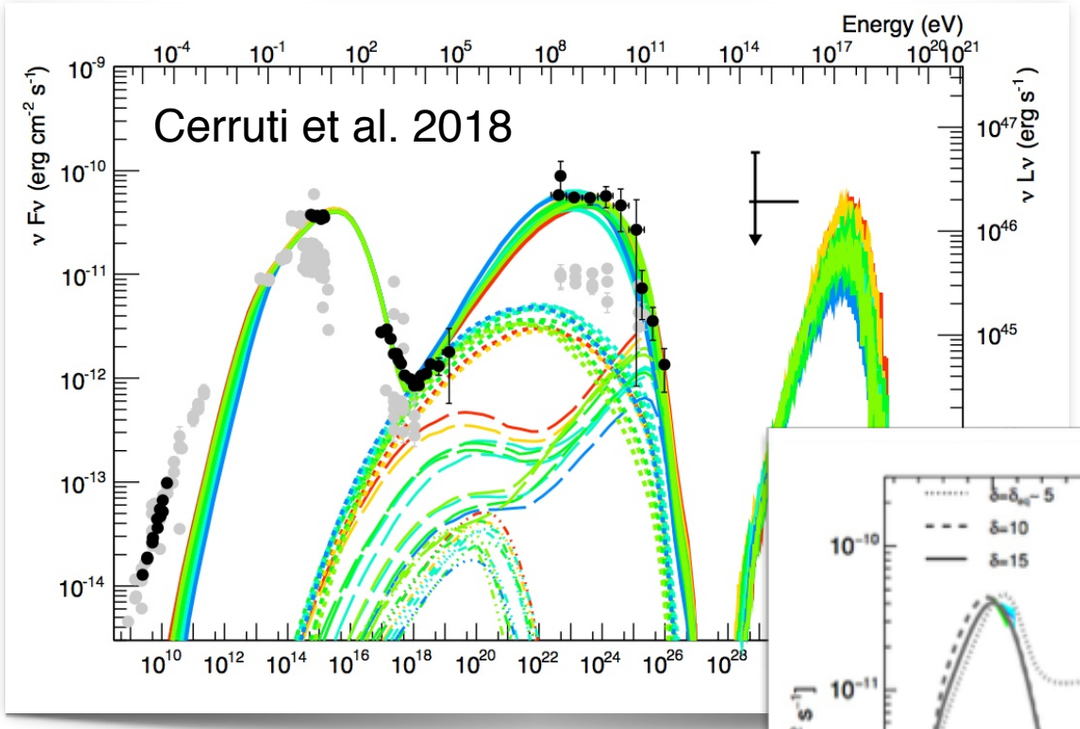
- Pan-STARRS1 used to follow-up 5 alerts in 2016–2017 to search for any optical transients that may be related to the neutrinos
- A SN (PS16cgx) found at 10.0′ from the direction of one alert (50% atrophy. probability): IceCube-160427A, likely a Type Ia SN, chance detection ~7%.
- No high-energy neutrino emission predicted from Type Ia SNe

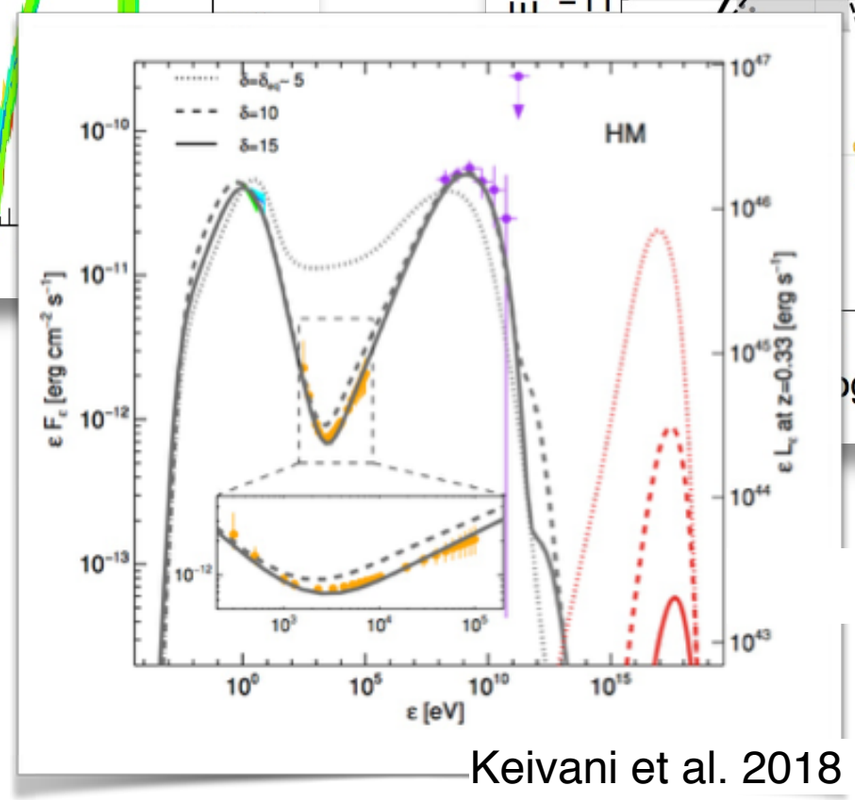


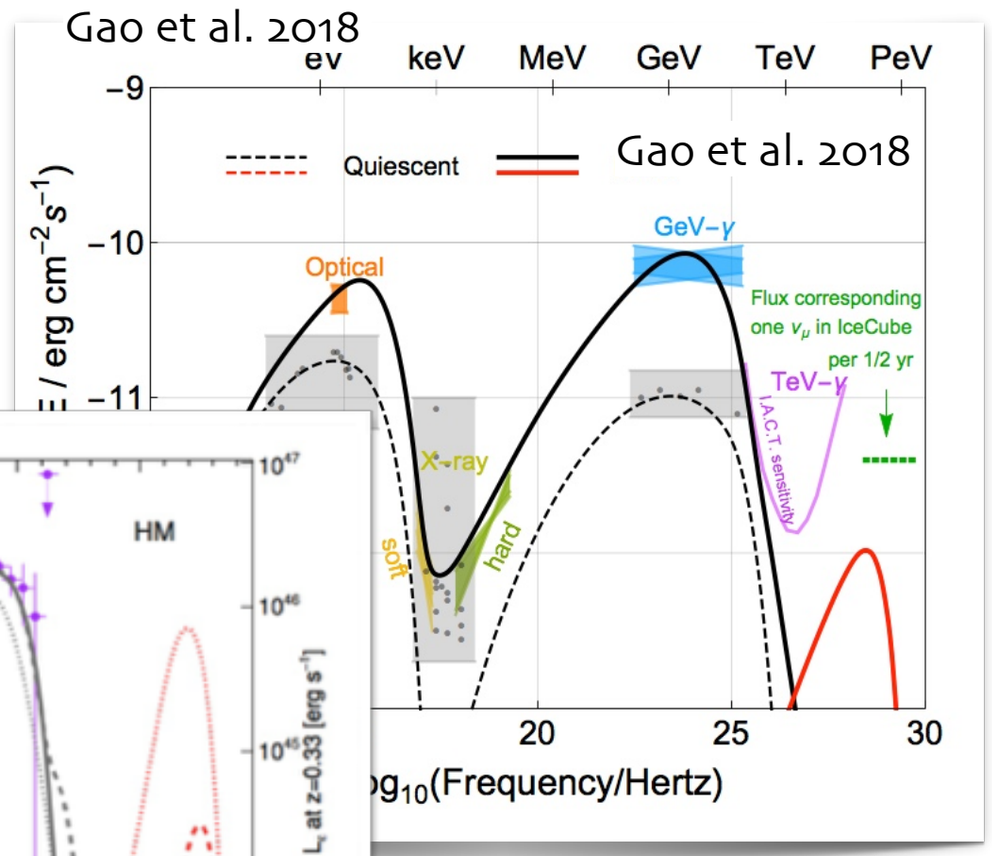
IceCube, arXiv: 1901.11080

Interpretation

Getting all the elements of this puzzle to fit together is not easy. Blazars seem to contain important clues on the origin of cosmic neutrinos and cosmic rays.







Also Reimer at al. 2018