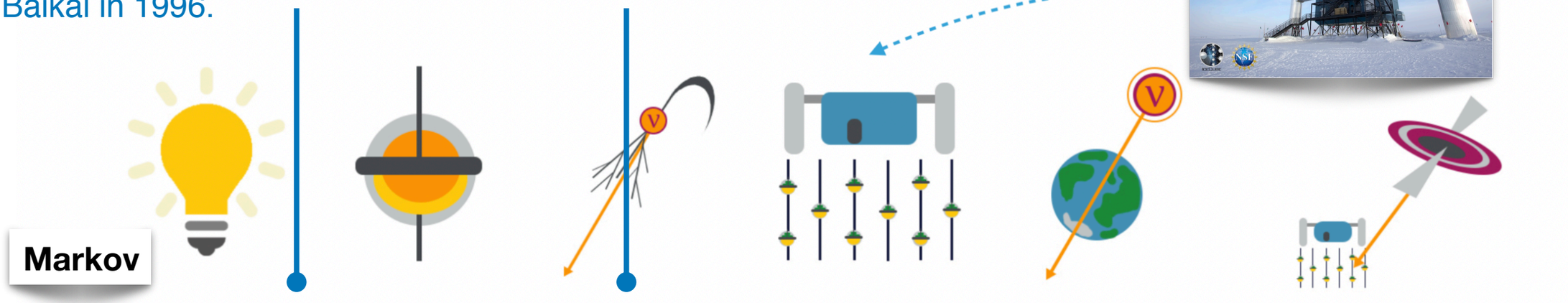
Multi-messenger Astrophysics and neutrinos

Elisa Bernardini, University of Padova (Italy)

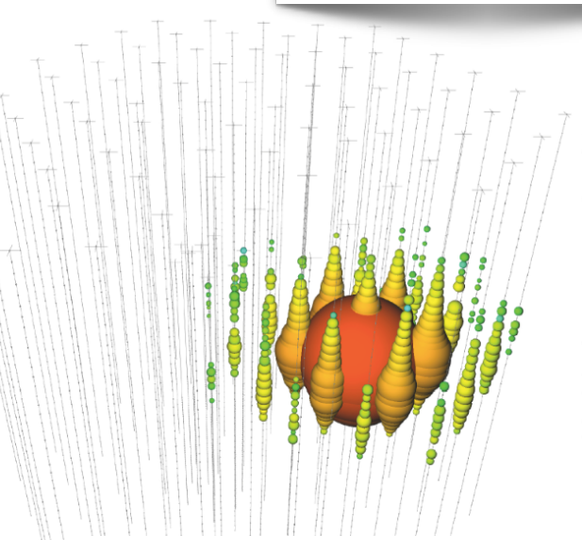
History of neutrino Astronomy in a nutshell

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

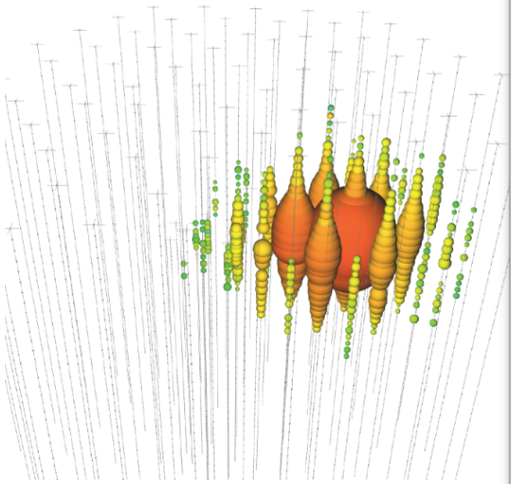
Construction of ANTARES in the Mediterranean Sea started in 2002



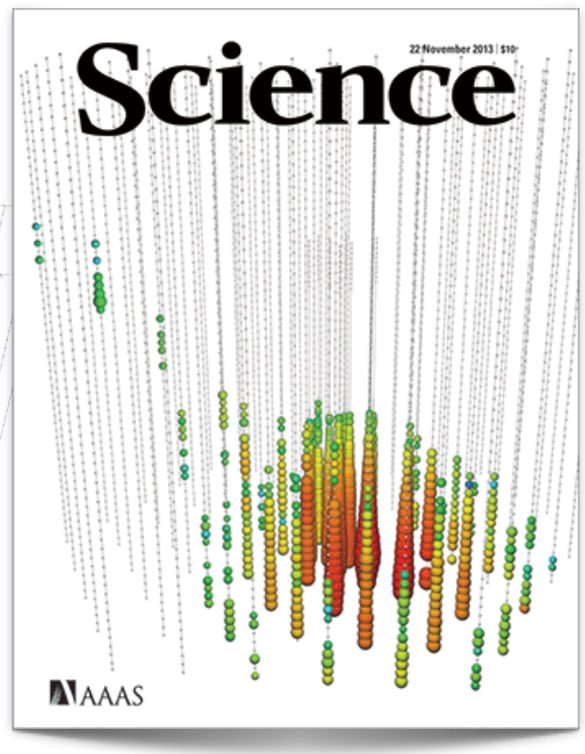
Halzen & Learned



1.1 ± 0.17 PeV



1.0 ± 0.15 PeV



IceCube

South Pole Neutrino Observatory

50 m

IceTop

IceCube Laboratory

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

1450 m

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

86 strings of DOMs, set 125 meters apart

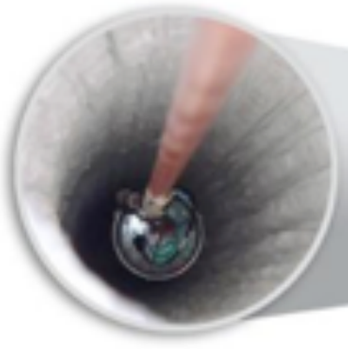
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

UPTIME >99%



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

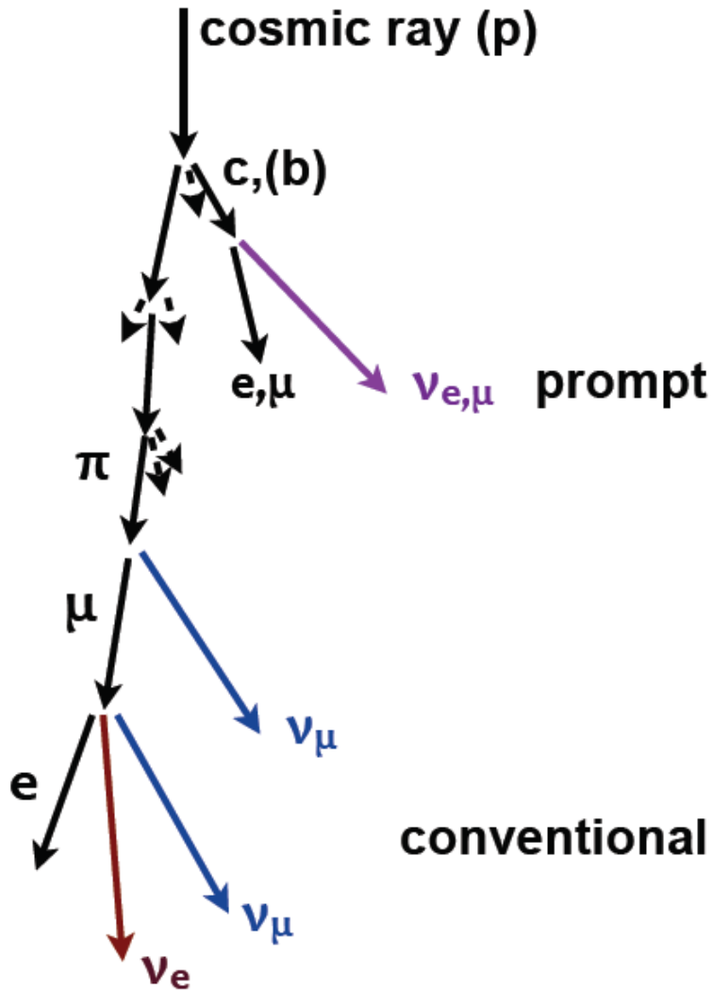
IceCube detector

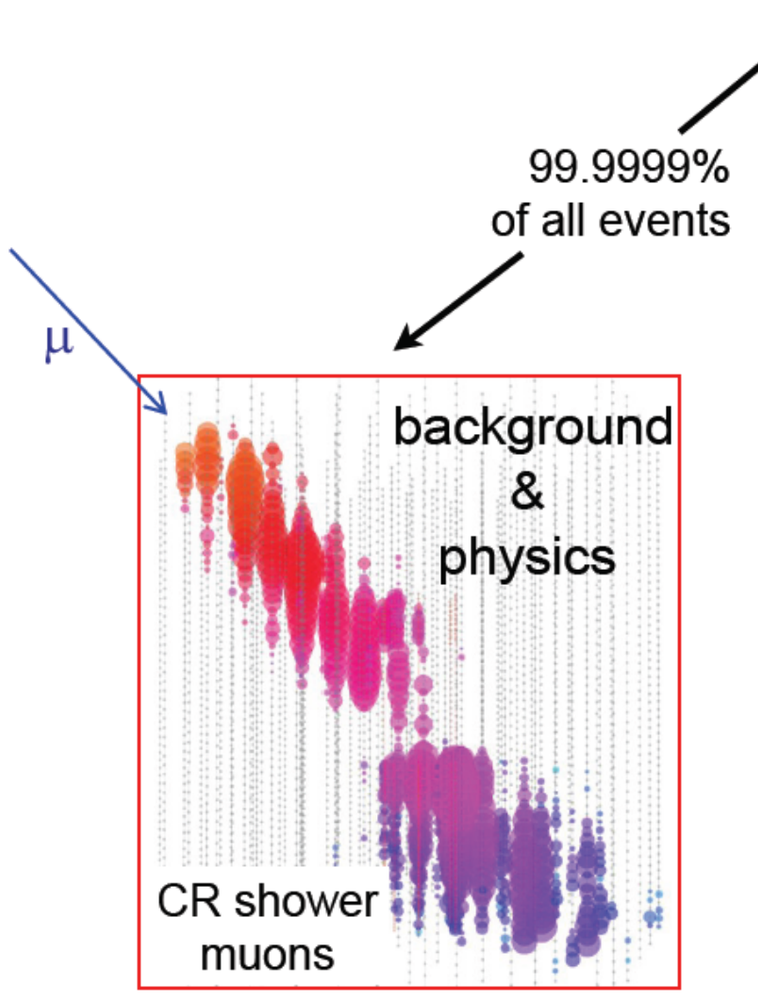
DeepCore

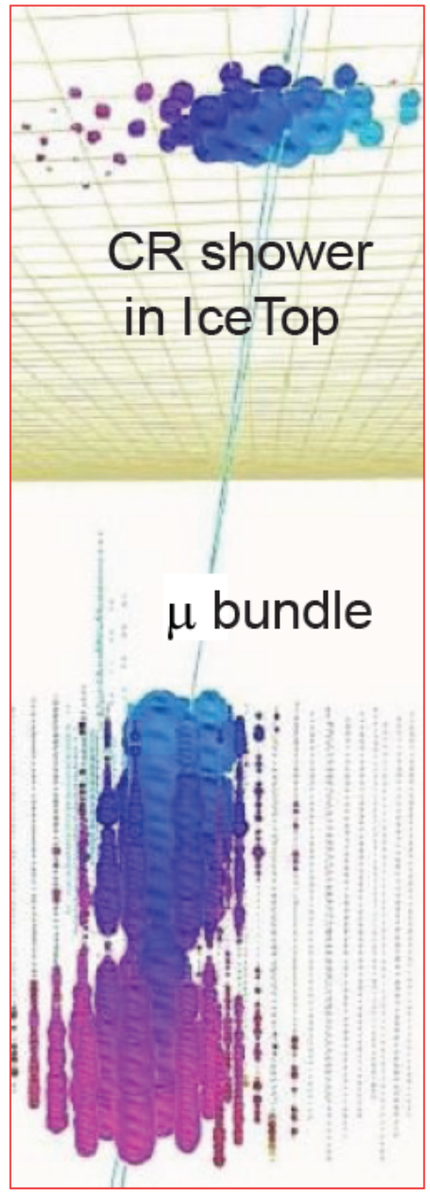
Antarctic bedrock

Challenge: Signal and backgrounds

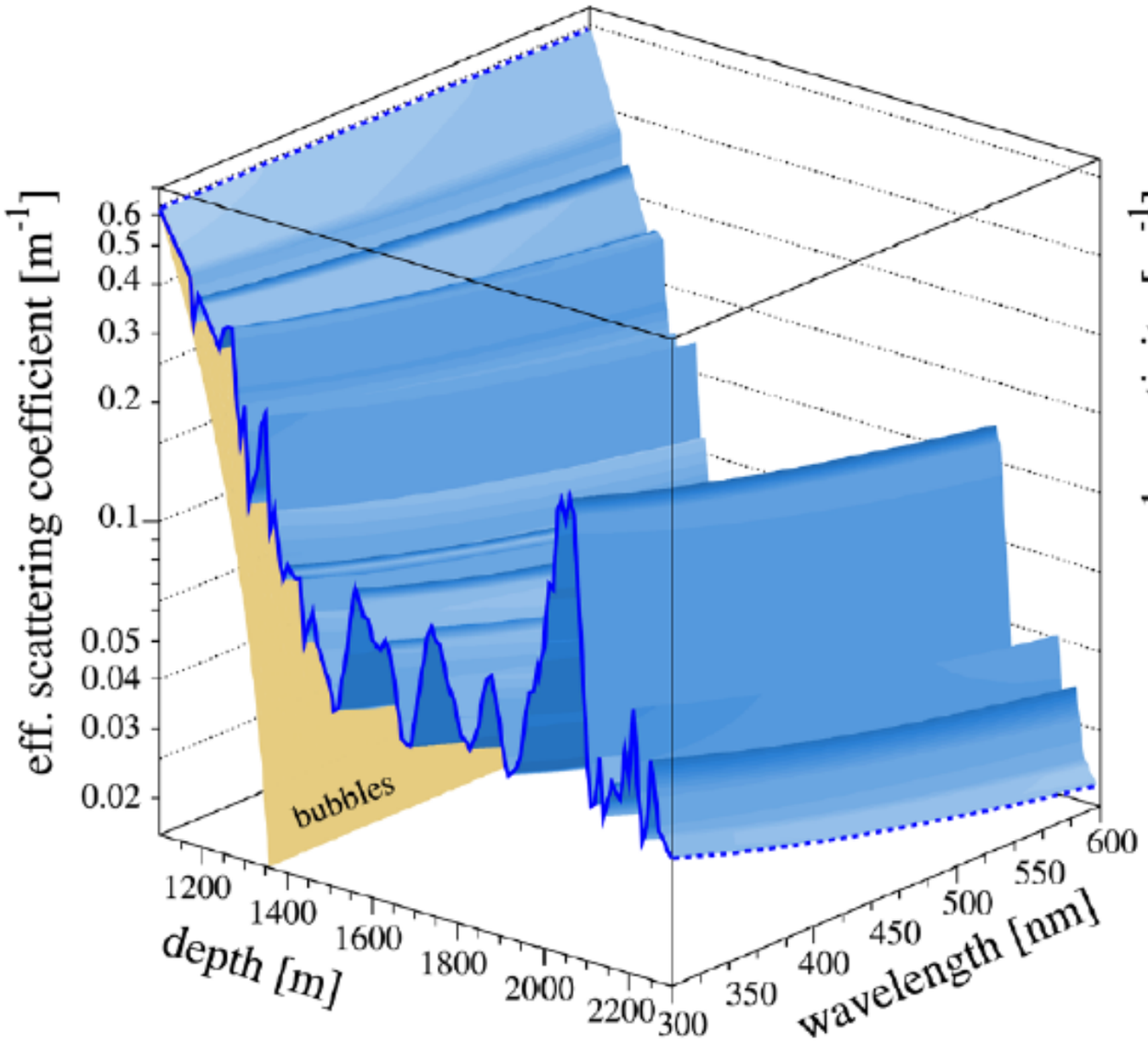
- Event rates in IceCube (year^{-1}):
  - atmospheric muons : 7 x 10^{10} (3000 per second)
  - atmospheric neutrinos : 8 x 10^{4} (1 every 6 minutes)
  - astrophysical : O(10)

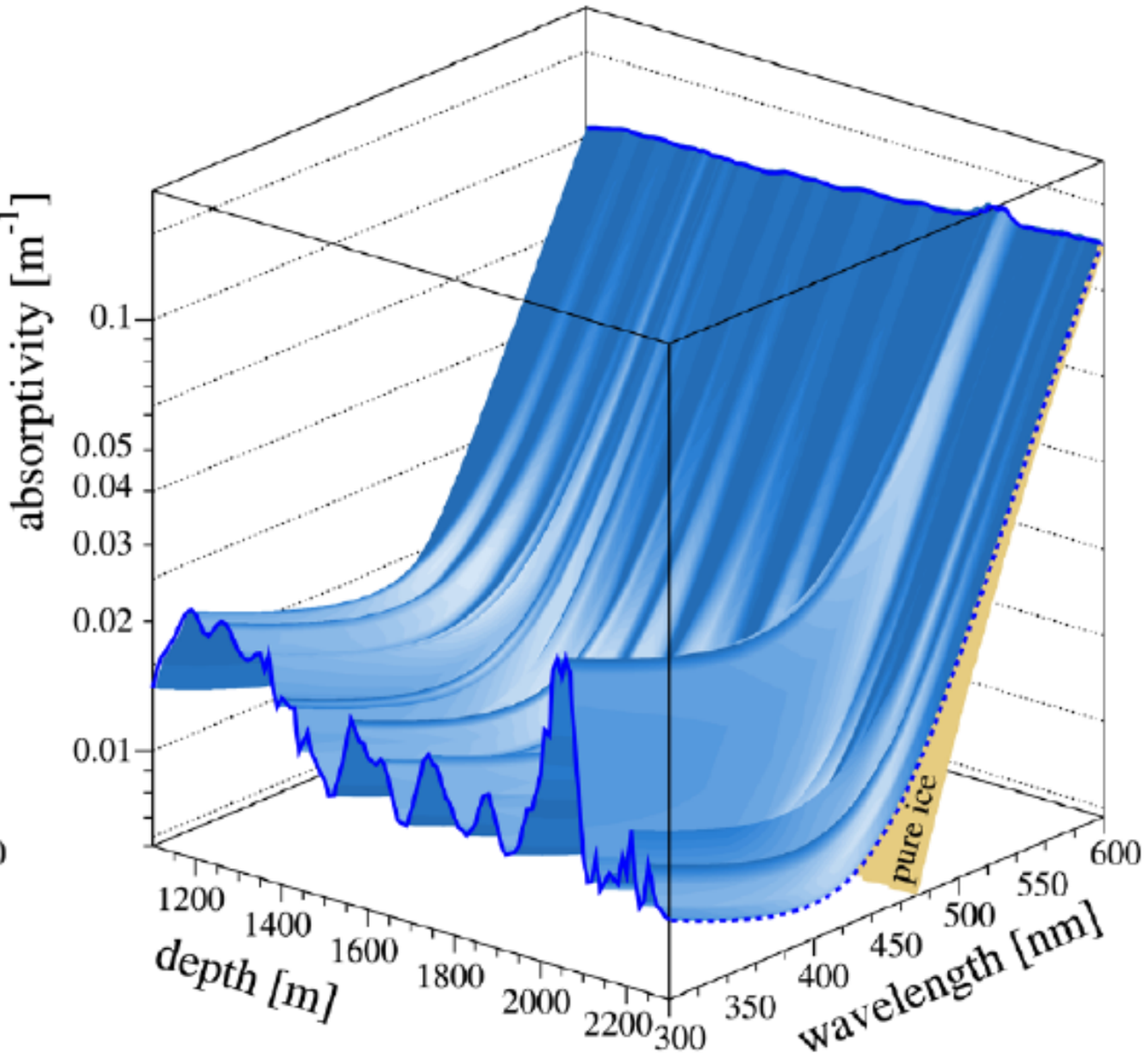






Challenge: Ice optical properties

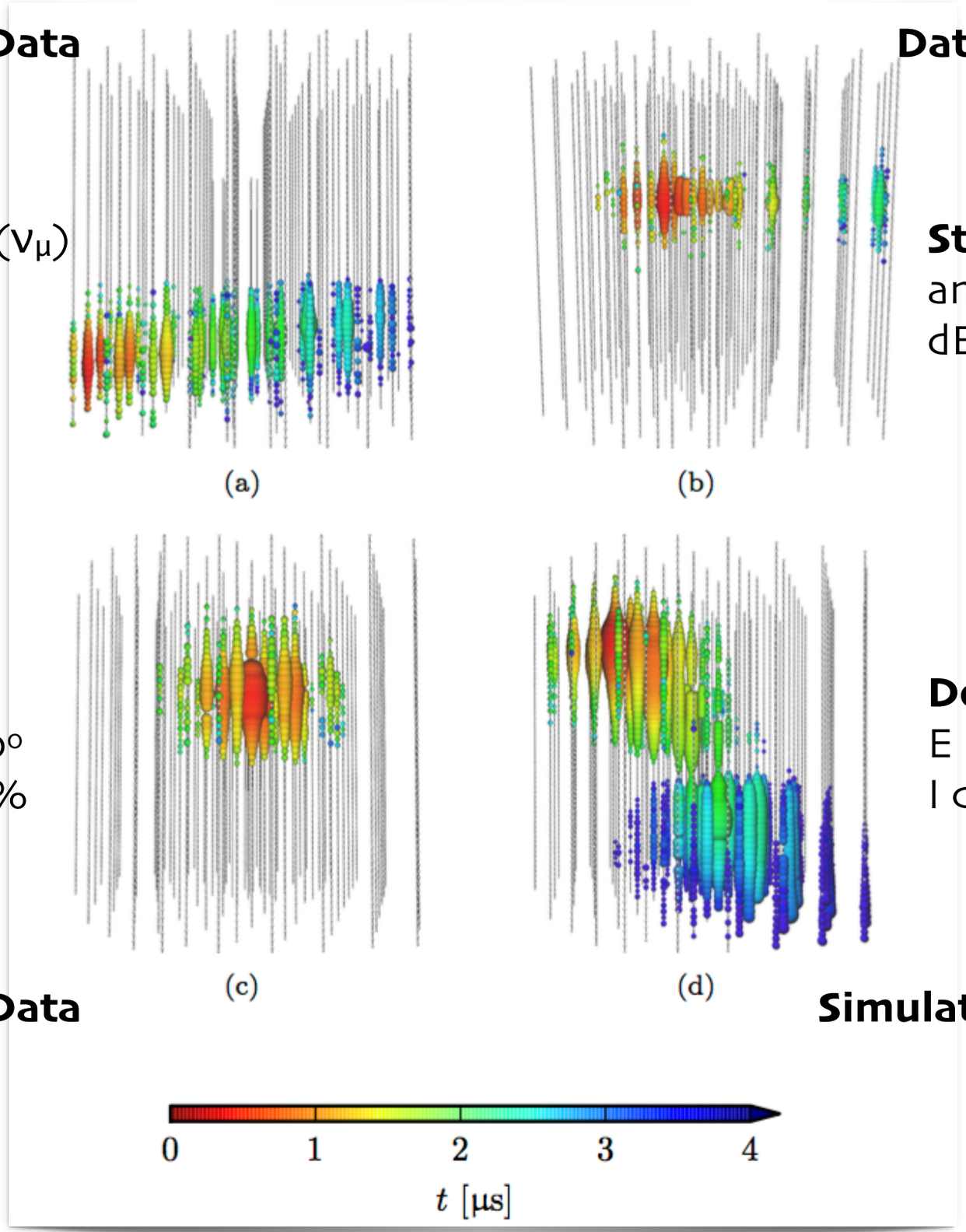




Neutrino signatures in IceCube

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

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



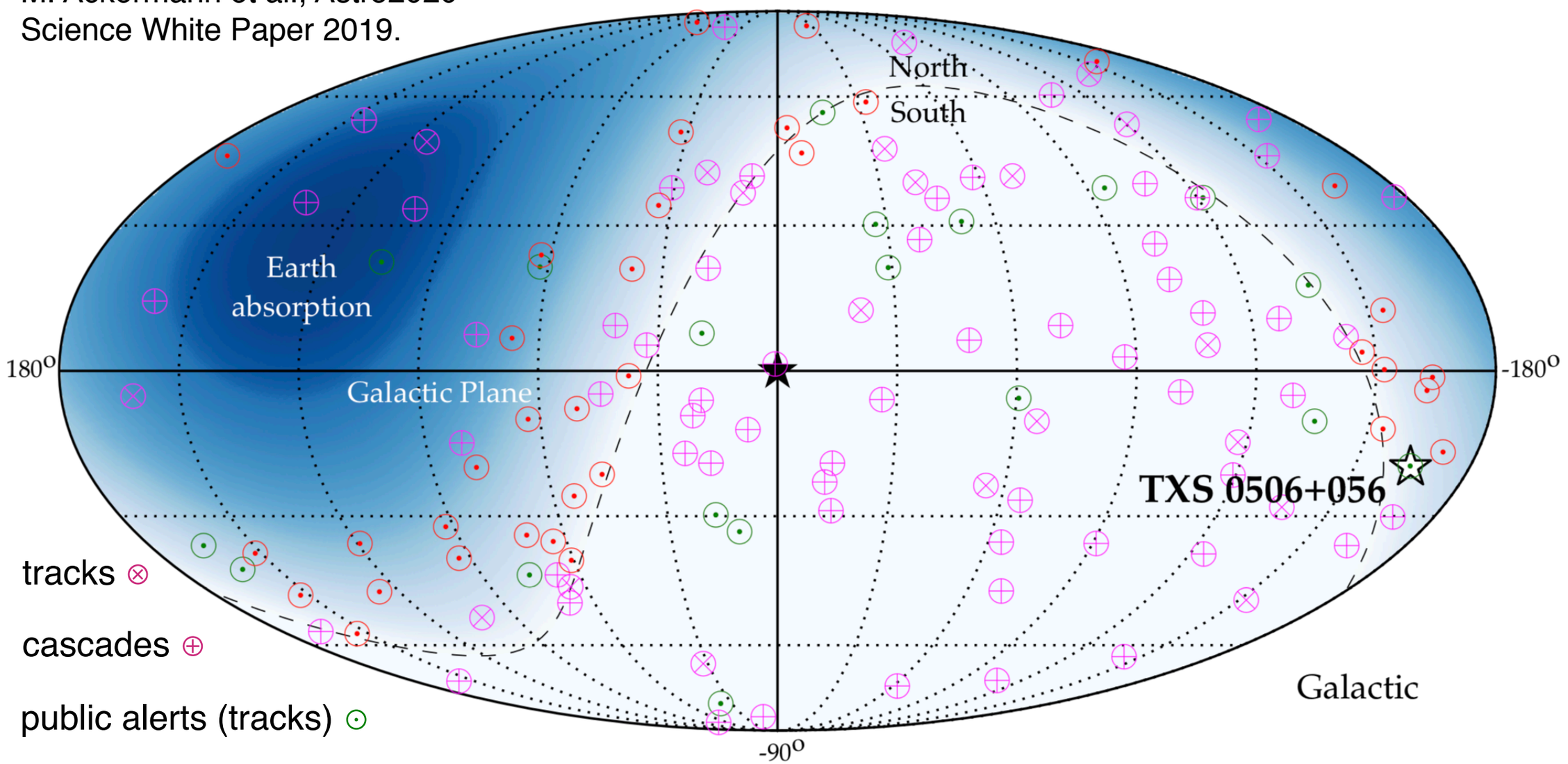
Starting track (ν_μ)
angular resolution < 1°
dE/dx + energy at vertex

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

IceCube Extragalactic Neutrinos

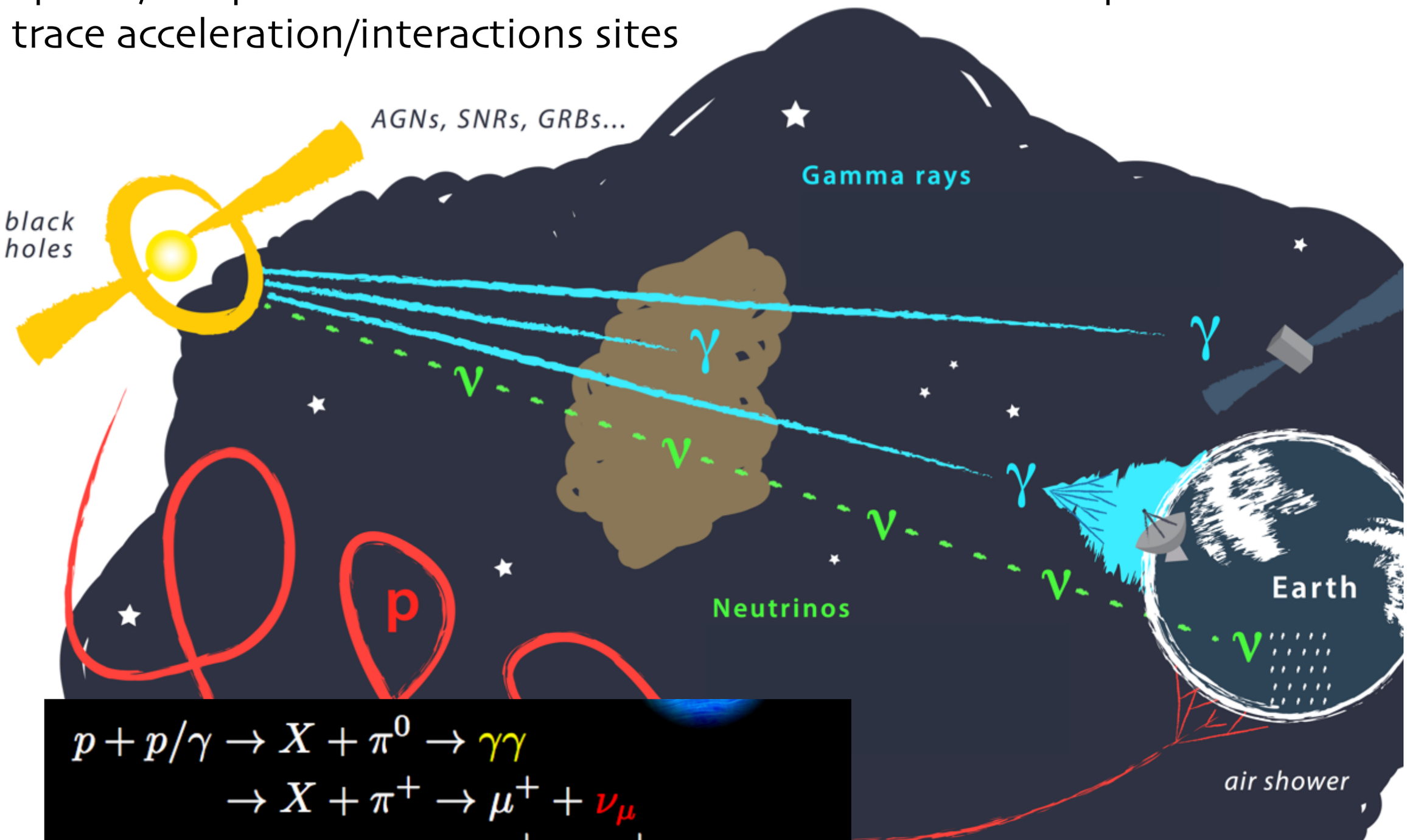
At high energies (few tens TeV) a clear excess of events is observed excluding an atmospheric-only origin. Directions show no obvious accumulation either around individual sources or the Galactic plane

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



Realtime Multi-Messenger

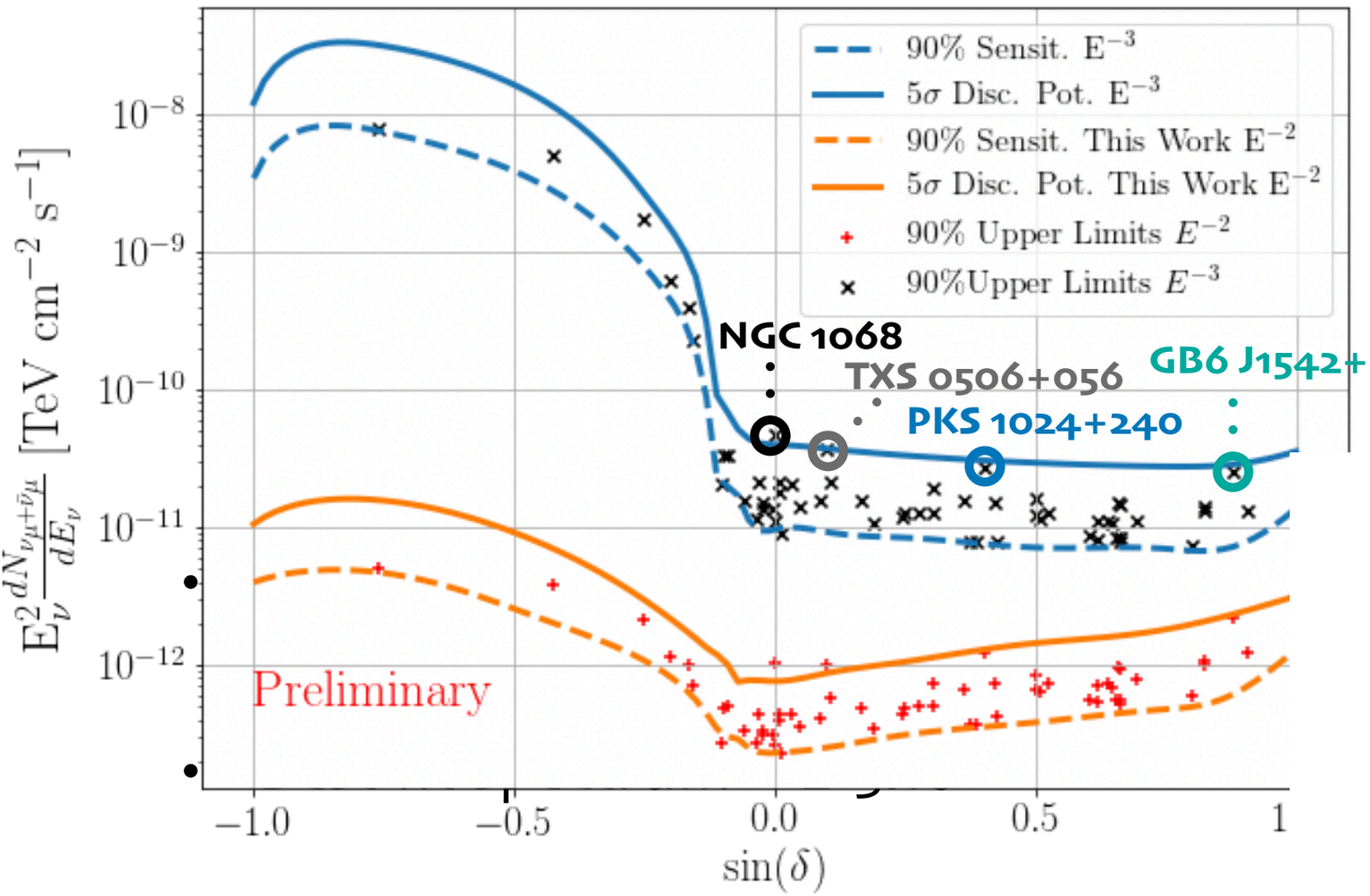
Spatial/temporal correlations between neutrinos and photons can trace acceleration/interactions sites

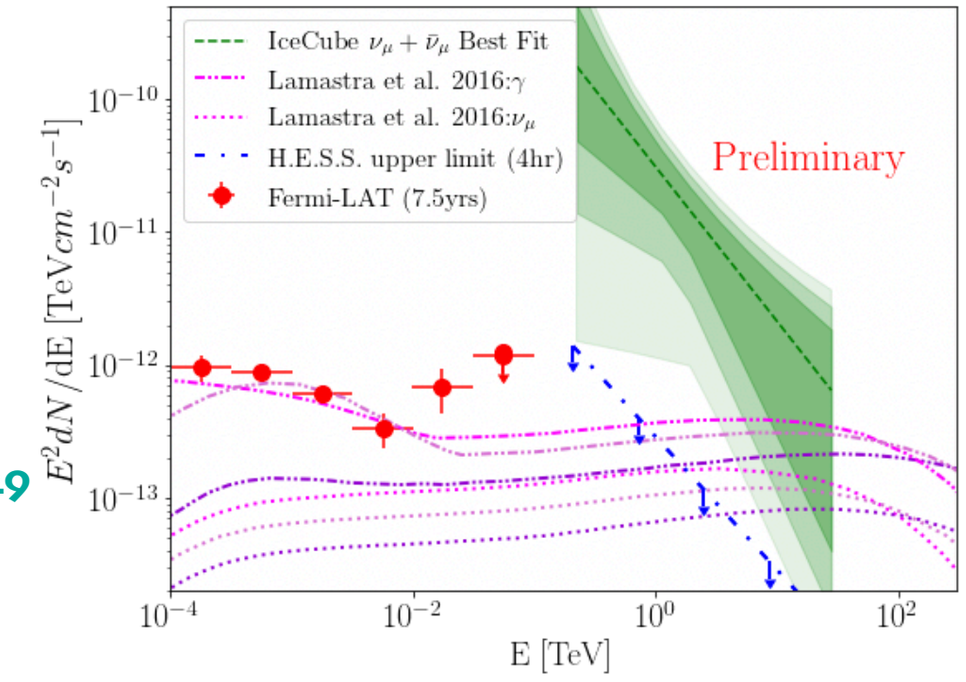


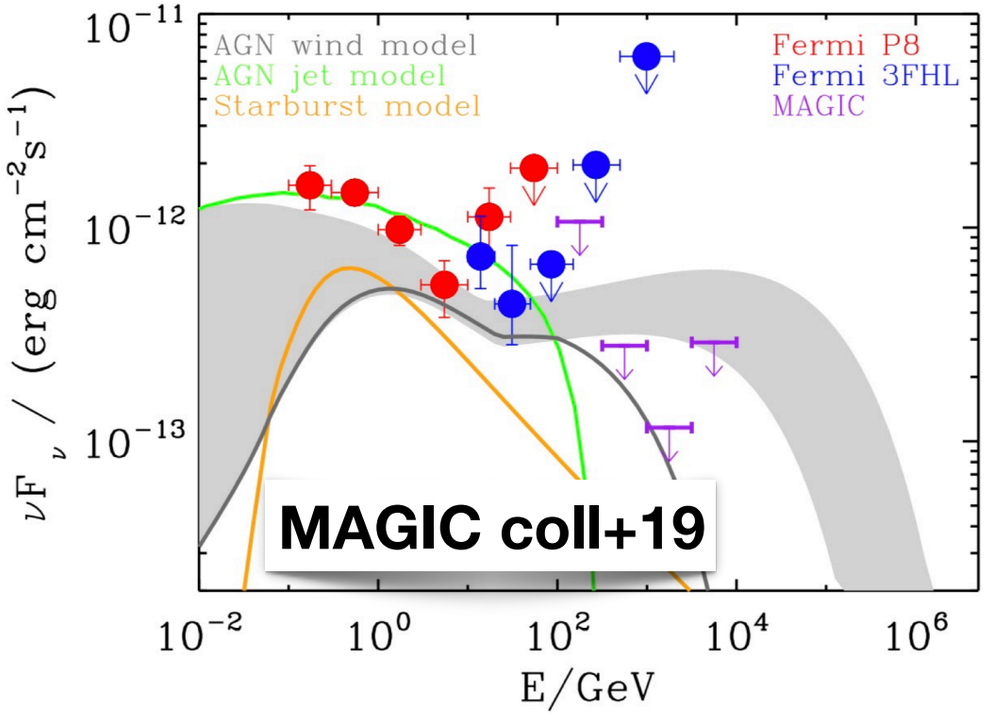
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Searches for point sources (10 yr)

Tessa Cerver for IceCube 2019 Neutrino Telescopes, Venice





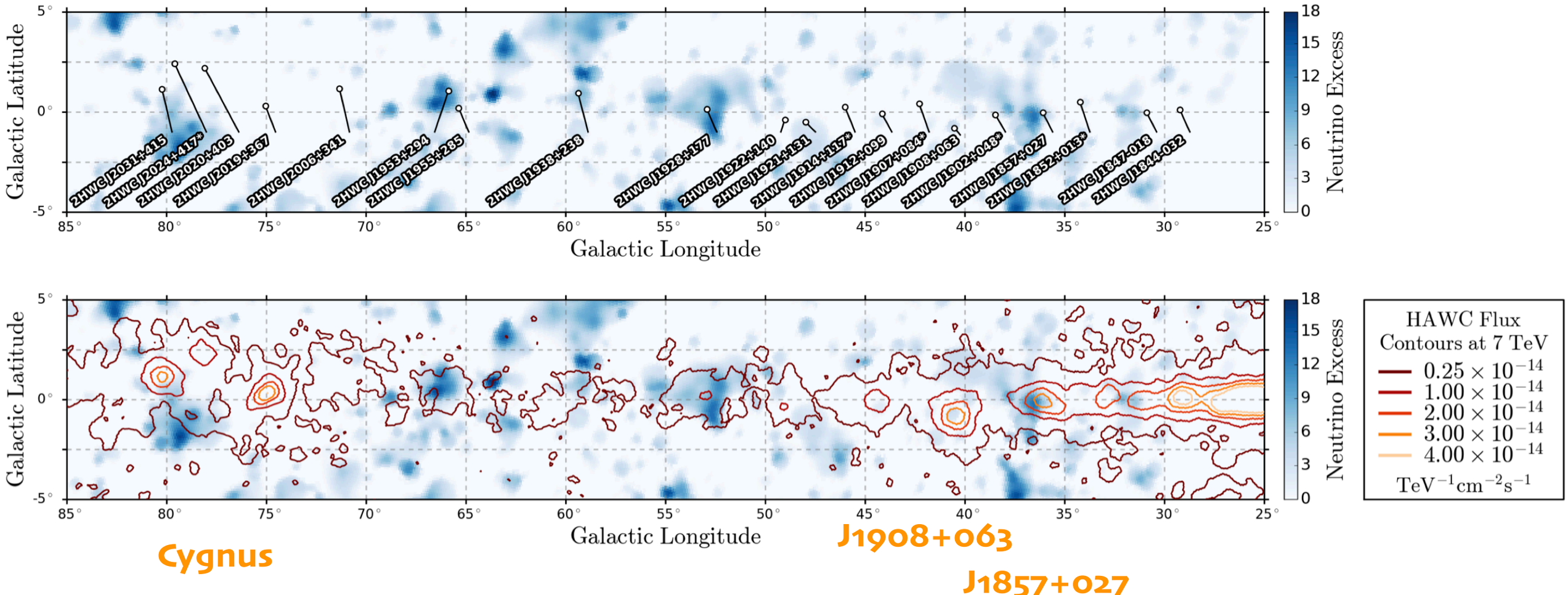


- Best fit normalisation for largest hot-spot is greater than current Gamma-ray limits.
- Best fit spectrum ∝ E-3.16

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



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)

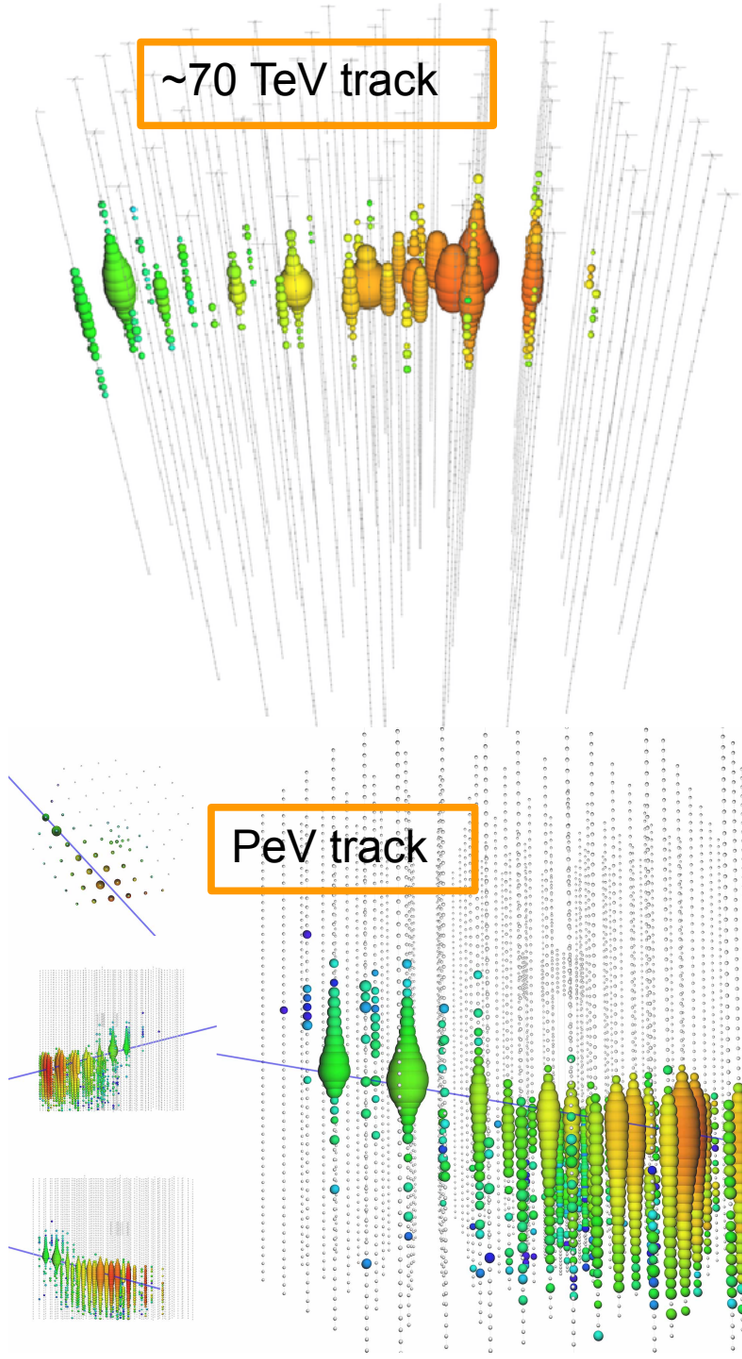
- Event multiplets (**PRIVATE**):
  - γ-ray follow-up (**GFU**) timescales up to three weeks, 2 (background) alerts/yr [also @ M. G. Aartsen, et al., JINST 11 (2016), arXiv: 1610.01814]
  - optical and X-ray follow-up (**OFU**) timescales up to 100 s, 7 (background) alerts/yr [also @ M. G. Aartsen, et 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

IceCube public alerts

- **HESE** = High Energy Starting Event (since Apr 2016):
  - Muon track starting inside the detector
  - Eth ~ 60 TeV
  - median angular resolution 0.4-0.6 deg
  - expected rate: 4/yr all-sky (50% signal probability)

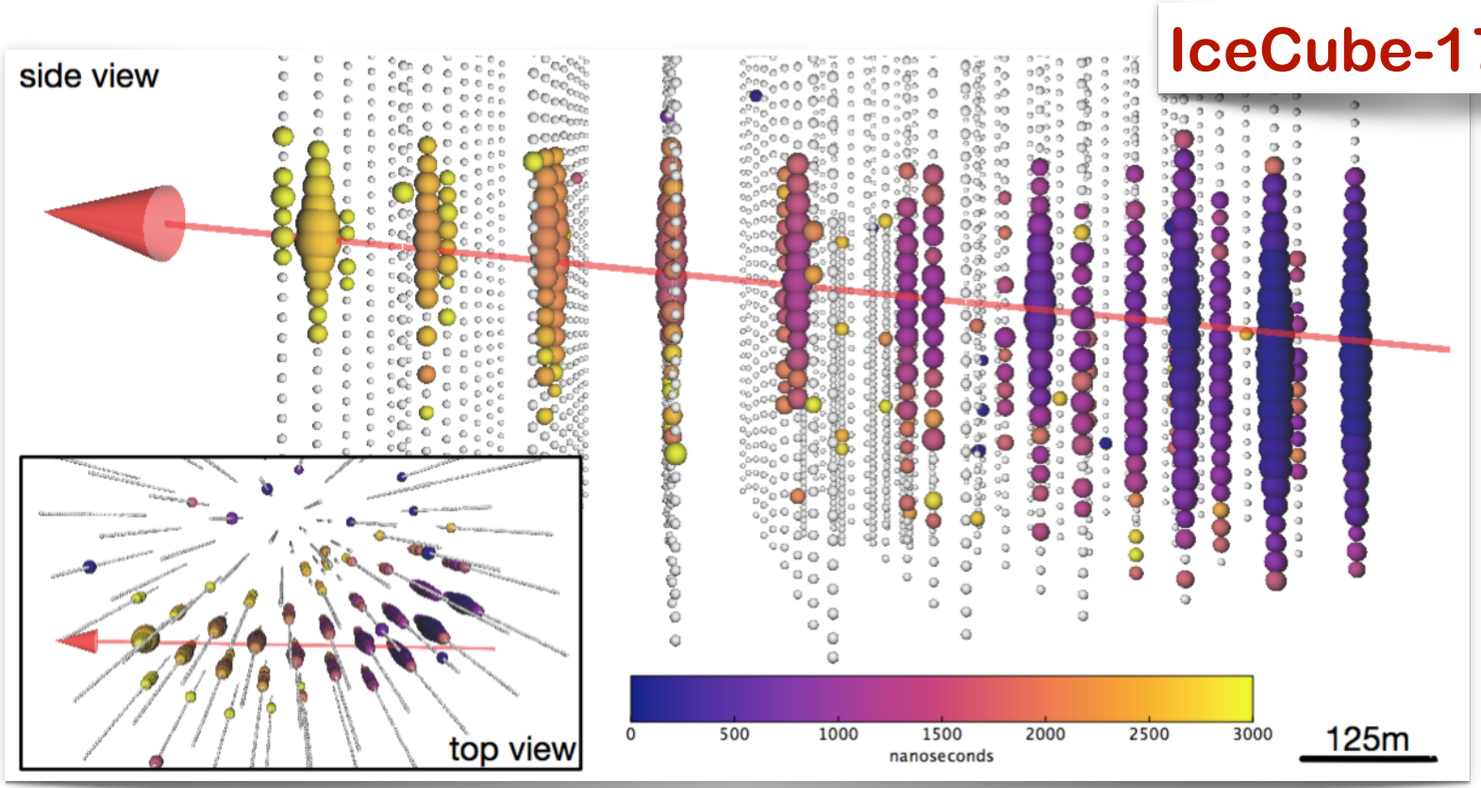
- **EHE** = Extremely High Energy (since Jun 2016):
  - Muon track going through the detector
  - Eth ~ 100 TeV
  - median angular resolution 0.22 deg
  - expected rate: 4/yr all-sky (75% signal probability)

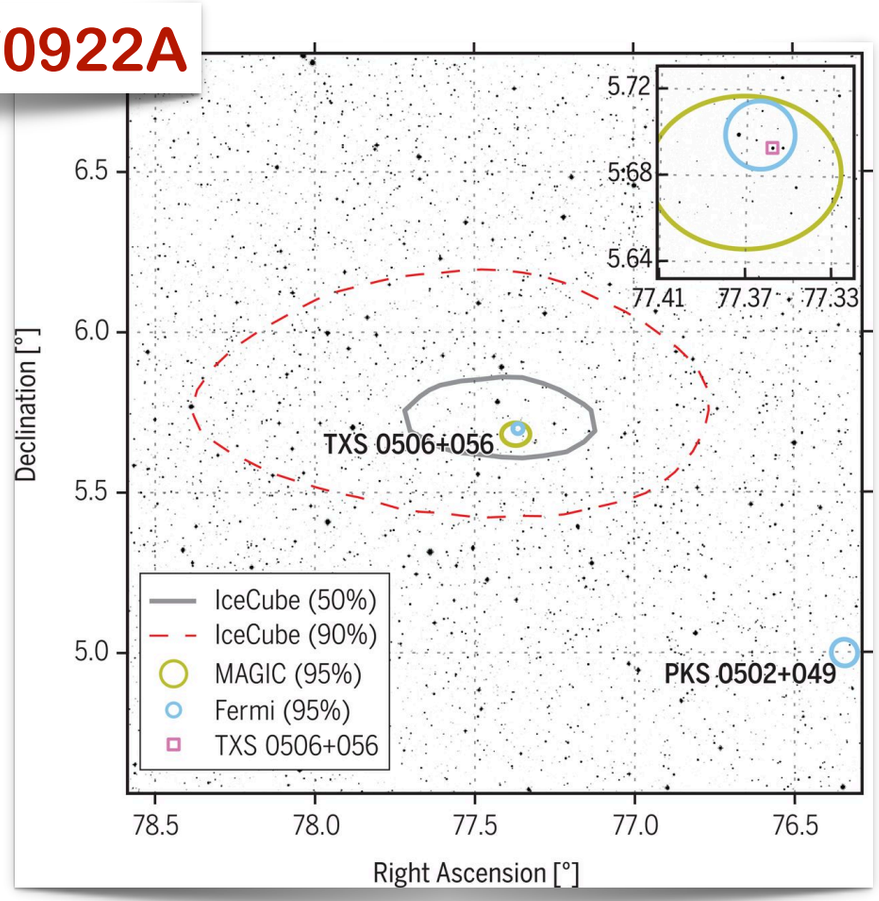
- Planned extensions: all-sky nu event clusters,
- lower E threshold single events



First evidence for a neutrino source

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

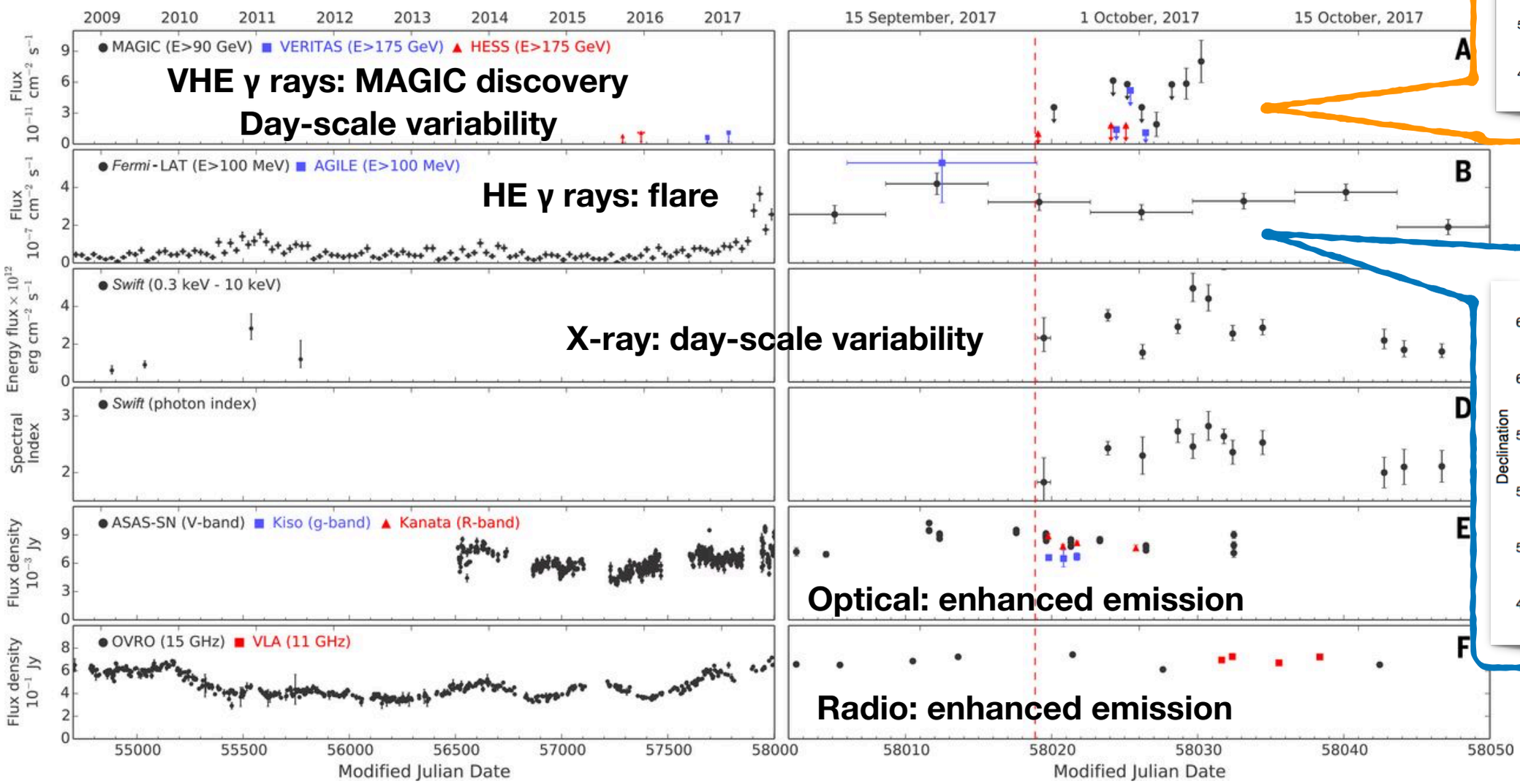
Kanata, NuSTAR
October 12

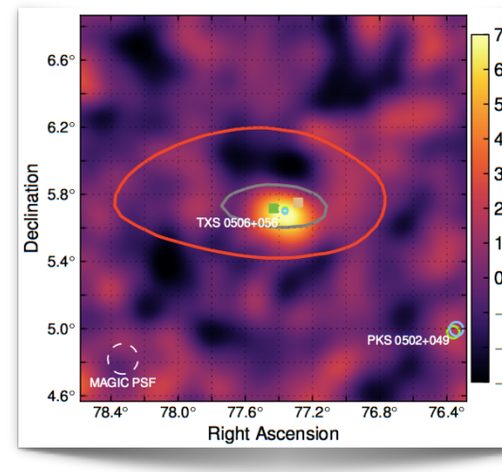
VLA
October 17

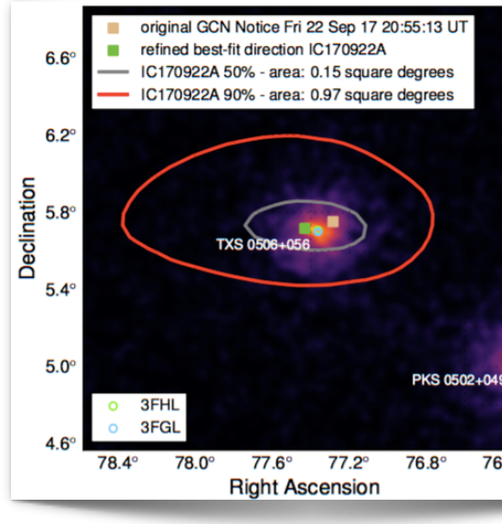
Subaru
October 25

The Blazar TXS 0506+056

IceCube-170922A

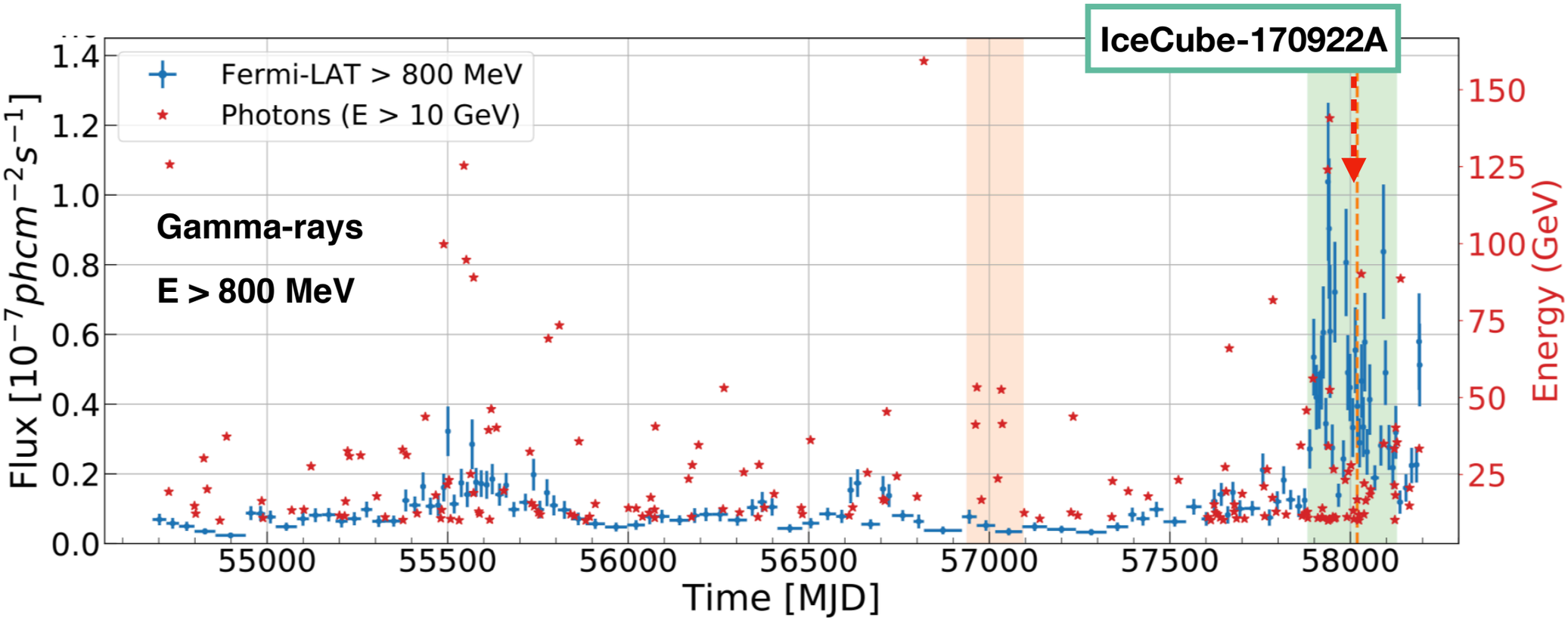






The Blazar TXS 0506+056

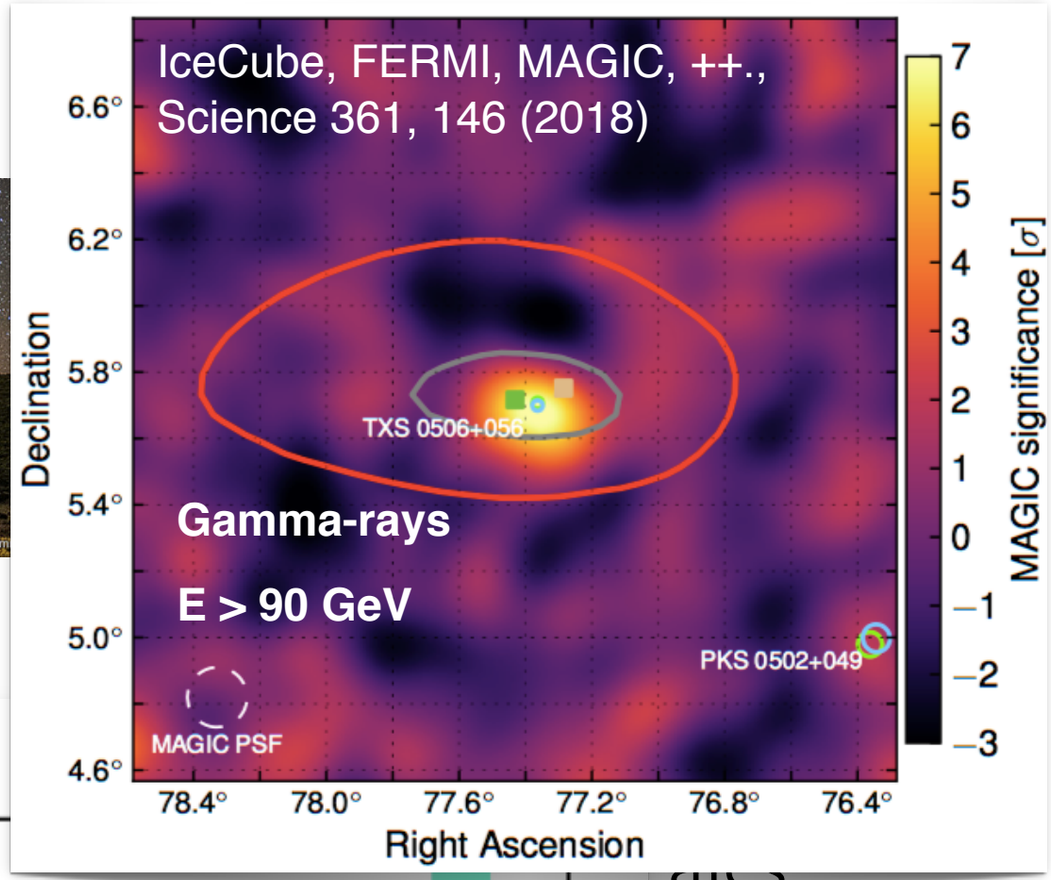
Compelling evidence for neutrino emission from the Blazar TXS 0506+056. Identification of a cosmic hadron accelerator with >PeV energies!

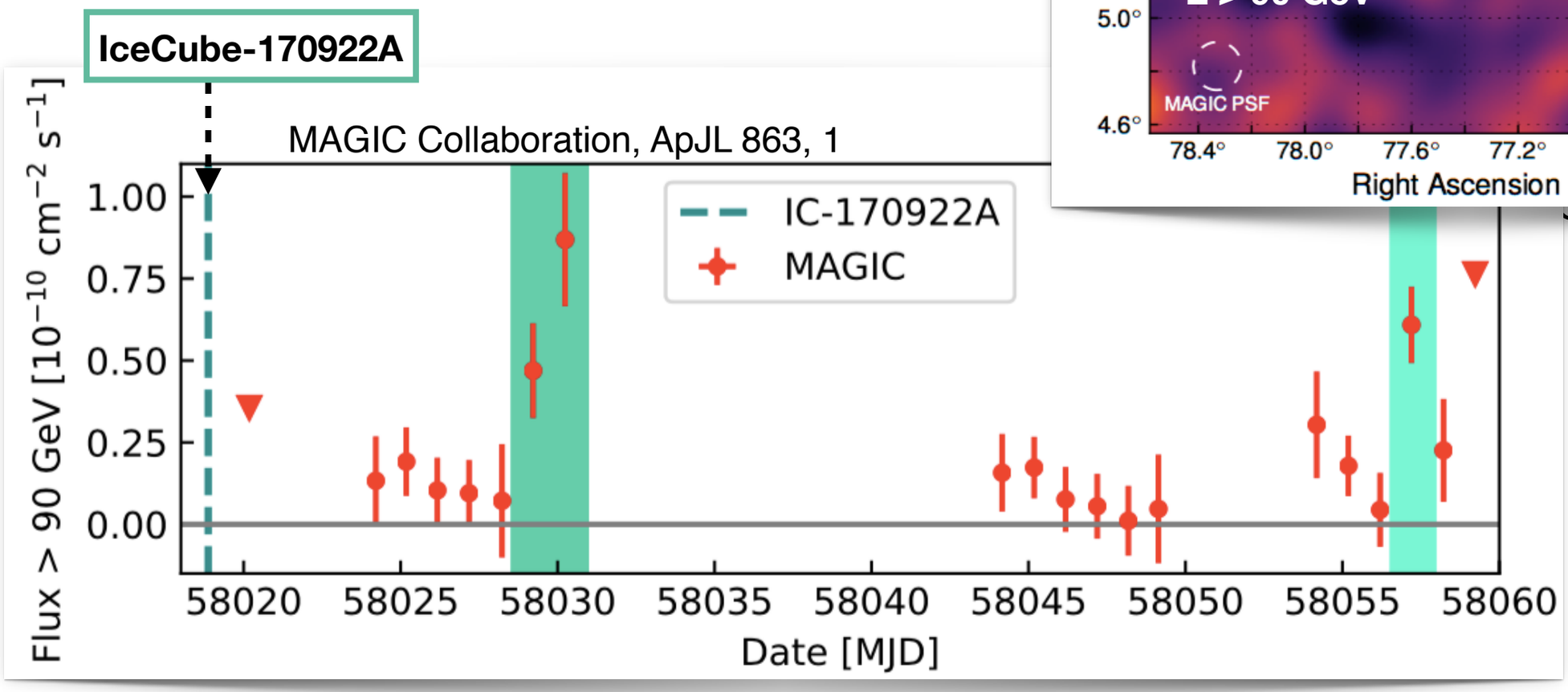


- The source was found in a state of enhanced gamma-ray activity lasting several months
- Coincidence probability after trials (10 public alerts and 40 archival events): 3 σ

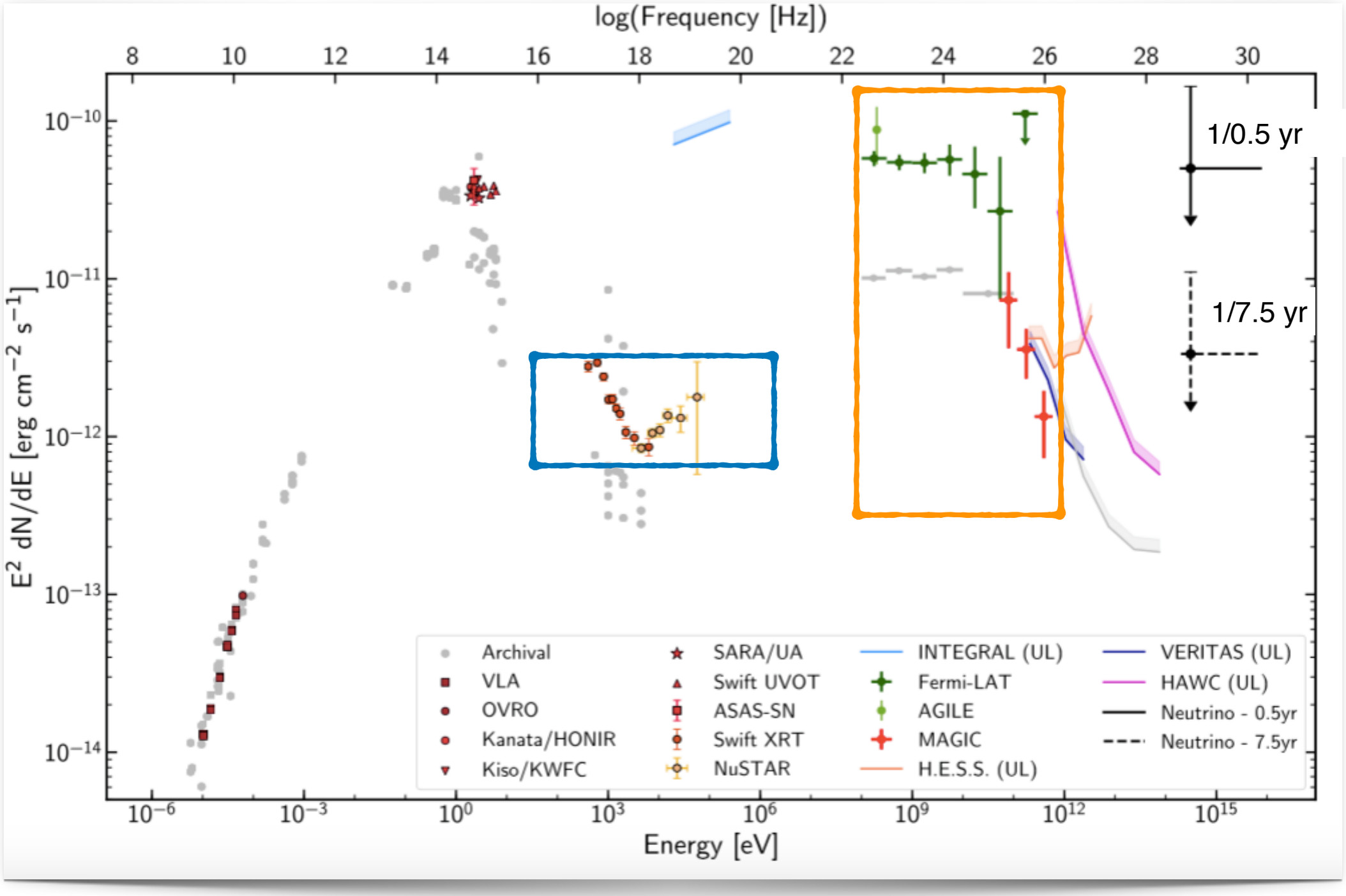
Very high energy gamma-rays from TXS 0506+056

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





Does it all fit together?



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.

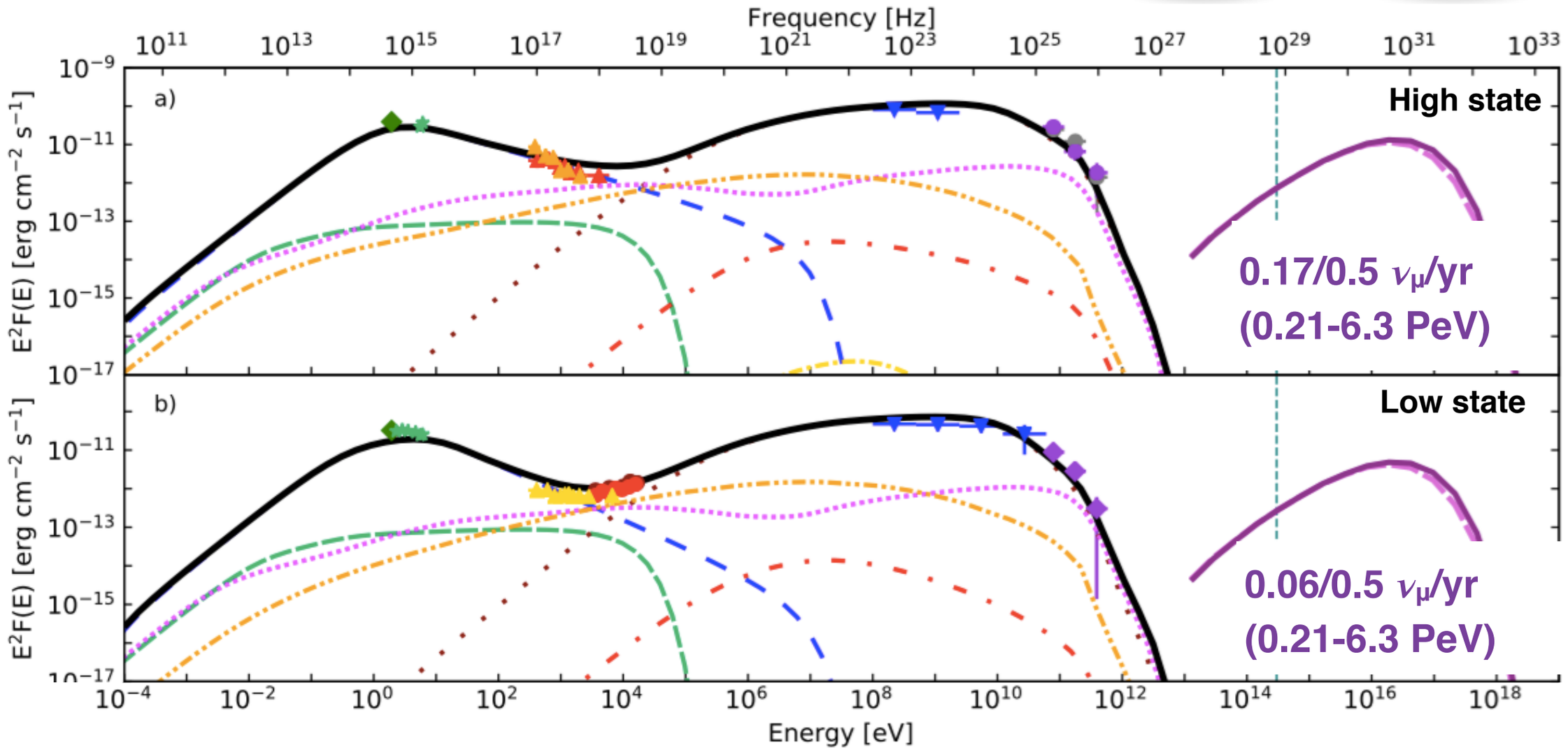
Ruo-Yu Liu, Kai Wang, Rui Xue, Andrew M. Taylor, Xiang-Yu Wang, Zhuo Li, and Huirong Yan. Hadronuclear interpretation of a high-energy neutrino event coincident with a blazar flare. *Phys. Rev.*, D99(6):063008,

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.

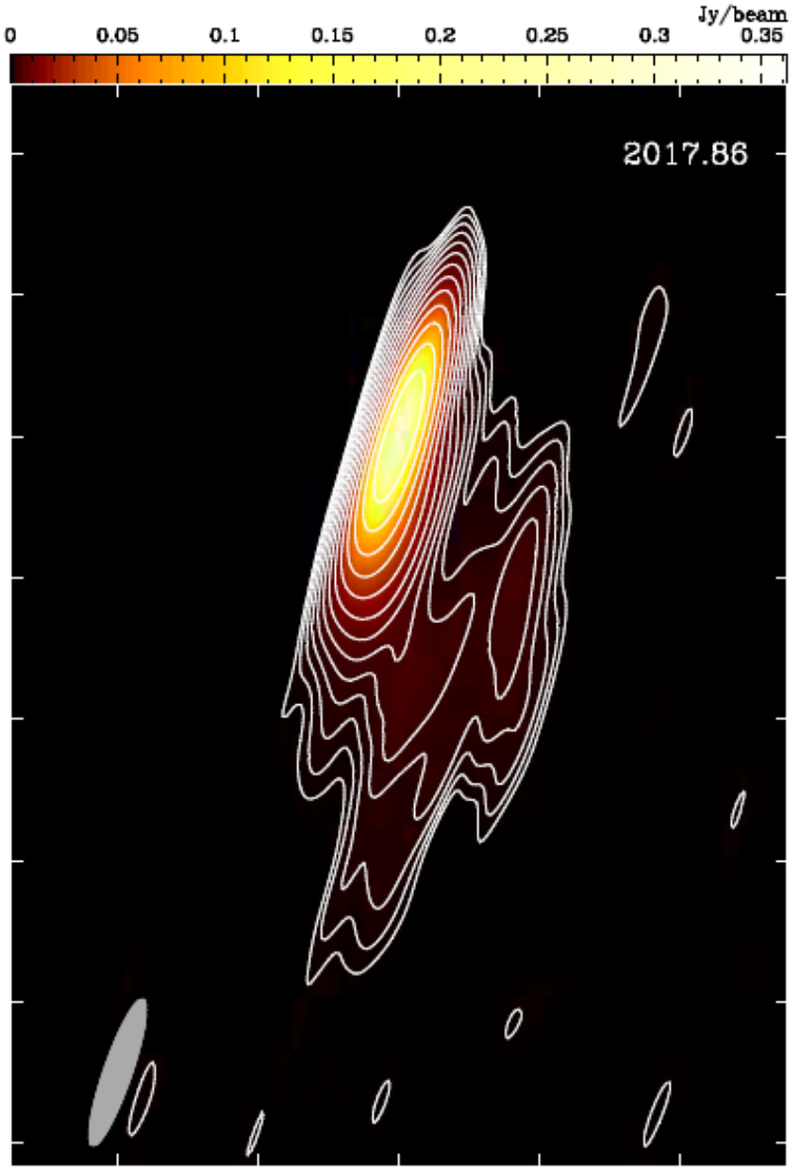
One option: structured jets?

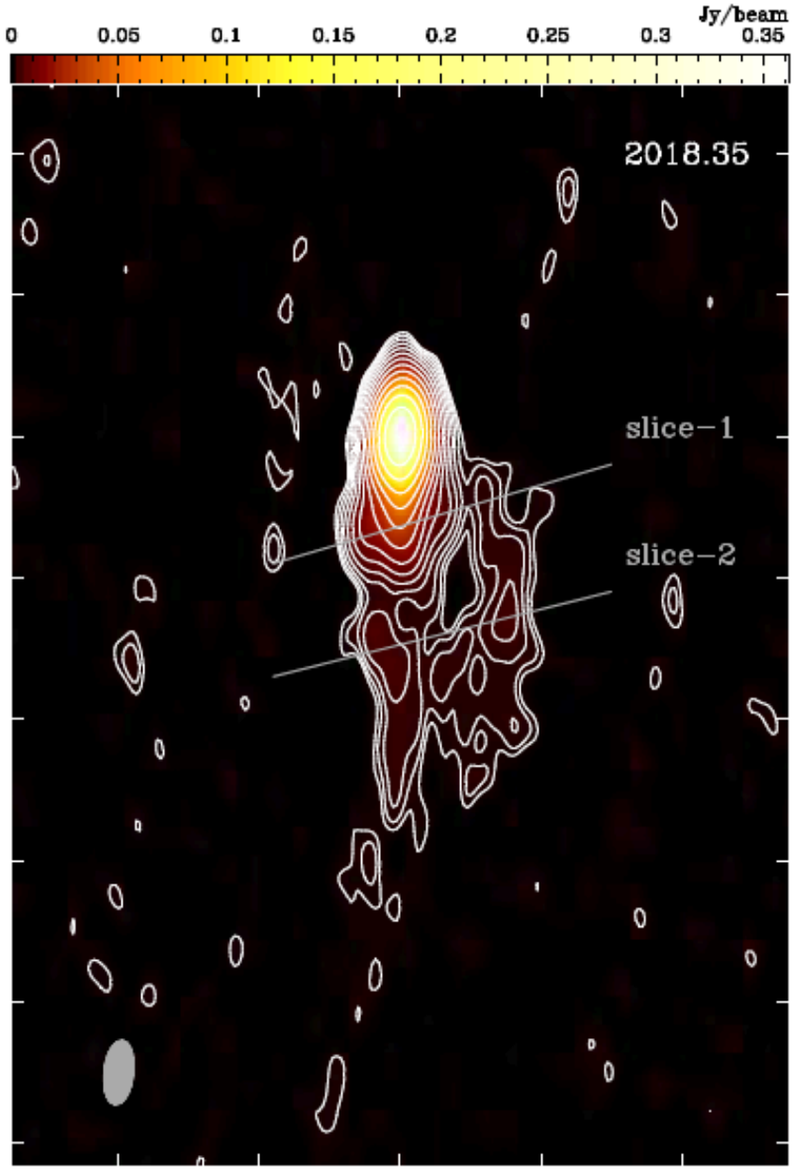
- Photopion efficiency $f_{p\gamma}(E_p \sim 6\ \mathrm{PeV}) \sim O(10^{-4})$
- $\tau_{\gamma\gamma}(E_\gamma \sim 12\ \mathrm{GeV}) \sim 0.1 \Longrightarrow \tau_{\gamma\gamma}(E_\gamma \sim 100\ \mathrm{GeV}) \sim 1$
  Consistent with observed GeV-TeV break

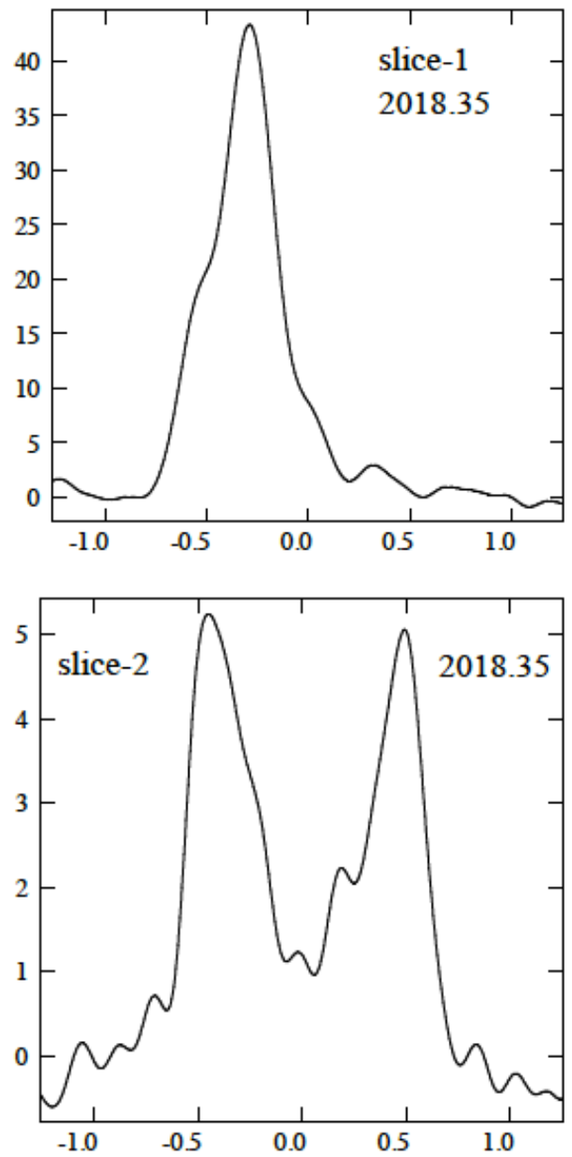


News from radio

Radio measurements (VLBI) confirm the structured jet layer proposed in Ansoldi et al., 2018!







Public IceCube alerts

… optical follow-up

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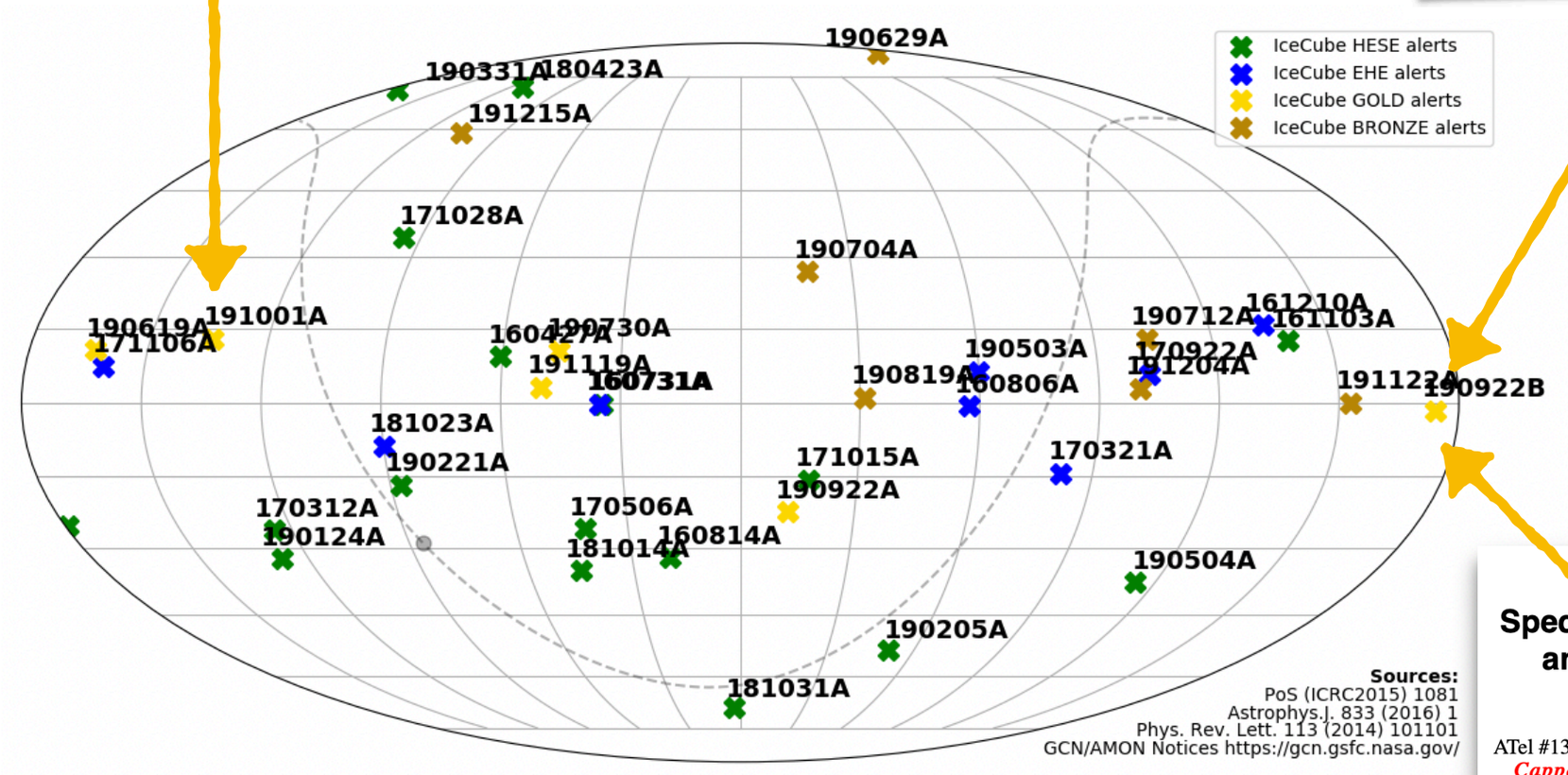
Candidate Counterparts to IceCube-191001A with ZTF

ATel #13160; *Robert Stein (DESY), Anna Franckowiak (DESY), Jannis Necker (DESY), Suvi Gezari (UMd), Sjoert van Velzen (UMd/NYU)*
on 2 Oct 2019; 22:00 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

Subjects: Radio, Optical, X-ray, Neutrinos, Supernovae, Transient, Tidal Disruption Event

ZTF found a coincident Tidal Disruption Event



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A candidate supernova coincident with IceCube-190922B from ZTF

ATel #13125; *Robert Stein (DESY), Anna Franckowiak (DESY), Marek Kowalski (DESY), Mansi Kasliwal (Caltech)*
on 23 Sep 2019; 20:34 UT
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

Subjects: Optical, Neutrinos, Request for Observations, Supernovae, Transient

ZTF found SN 2019pqh

Type investigated by NUTS2, strong interaction between ejecta and circumstellar medium disfavoured

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Spectroscopic classification of SN 2019pqh by NUTS2, and implications for the claimed association with IceCube-190922B

ATel #13133; *A. Reguitti (Univ. Andres Bello), A. Pastorello, S. Benetti, Y.-Z. Cai, E. Cappellaro, A. Fiore, N. Elias-Rosa, L. Tomasella (INAF-OAPd), G. Valerin, P. Ochner (Padova University), A. Morales-Garoffolo (UCA), M. Stritzinger, S. Holmbo (Univ. of Aarhus), S. Moran (NOT), S. Brennan, E. Callis, M. Fraser (UCD), E. Kankare, R. Kotak, H. Kuncarayakti, T. Heikkila, S. Mattila, T. Reynolds (Univ. of Turku), P. Lundqvist (Stockholm Univ.), S. Dong, P. Chen, S. Bose (KIAA-PKU)*
on 26 Sep 2019; 13:51 UT
Distributed as an Instant Email Notice Supernovae
Credential Certification: Andrea Pastorello (andrea.pastorello@oapd.inaf.it)

Subjects: Optical, Neutrinos, Supernovae, Transient

Public IceCube alerts

… high-energy gamma-ray follow-up

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IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

ATel #12967; *Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen)*
on 30 Jul 2019; 23:58 UT
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)

Subjects: Neutrinos, AGN

Referred to by ATel #: 12971, 12981, 12983, 12985, 12996

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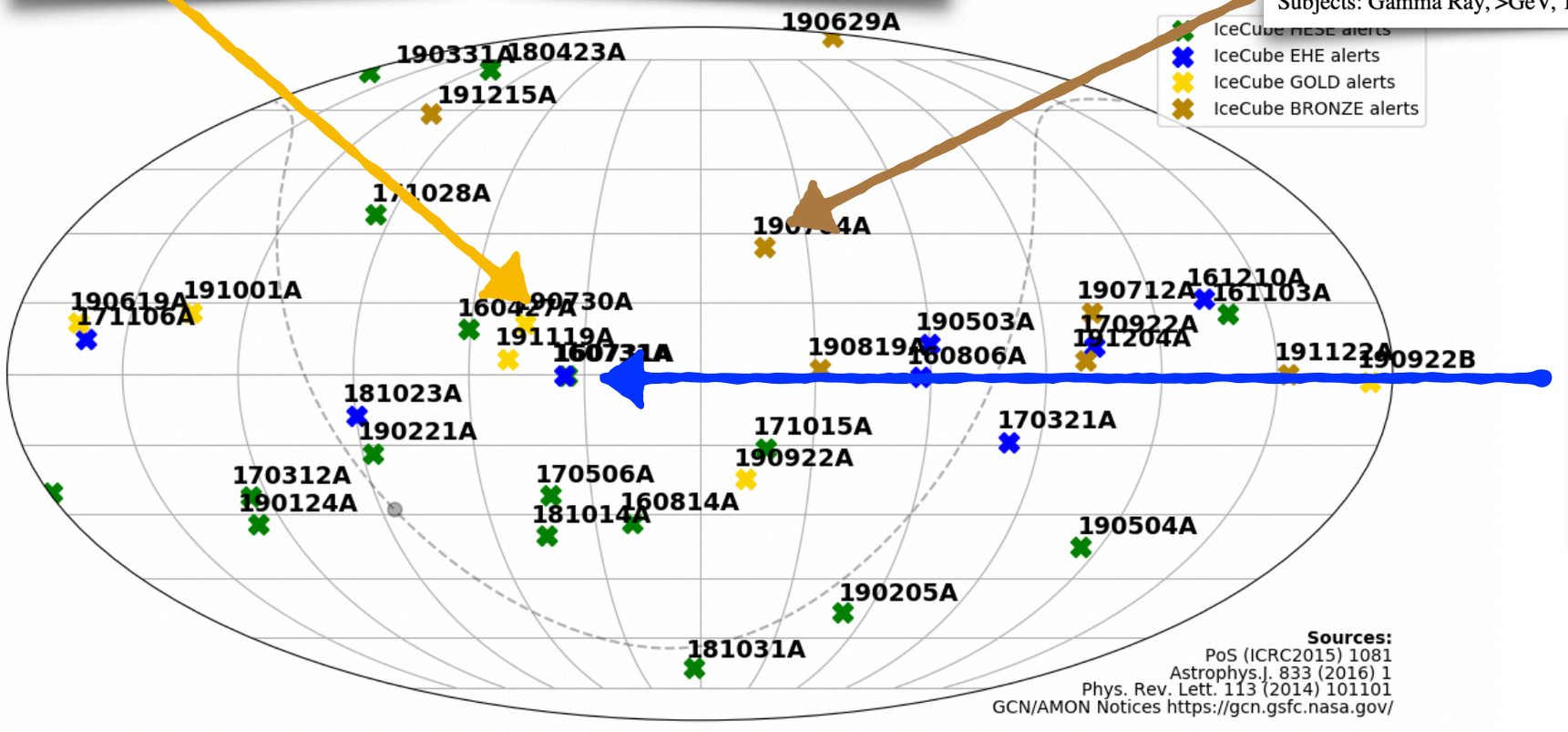
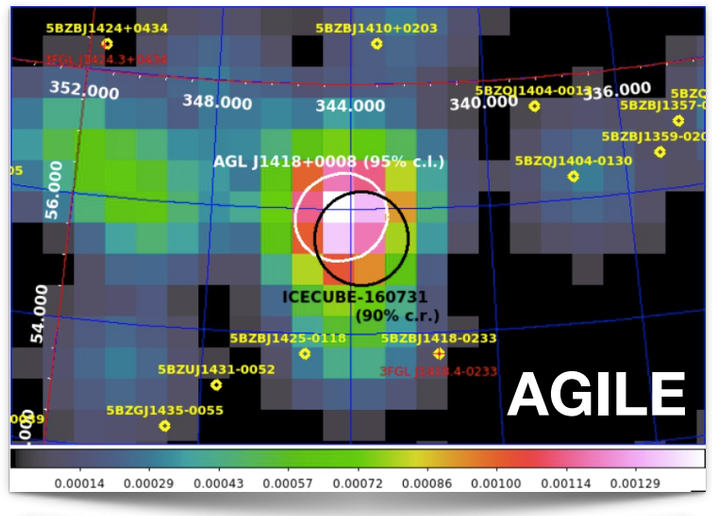
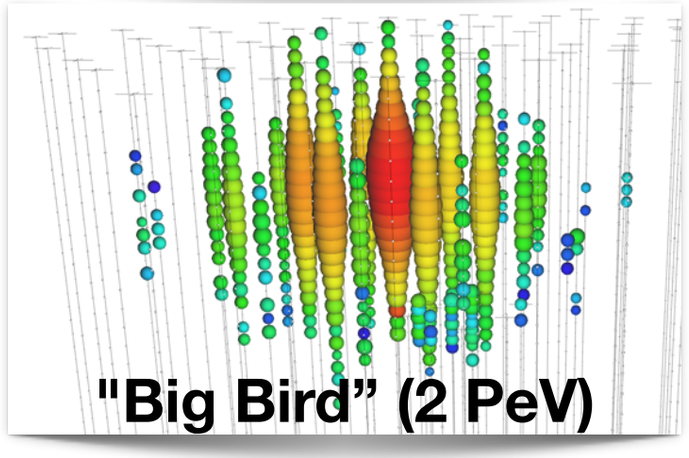
Fermi-LAT Gamma-ray Observations of IceCube-190704A and detection of the new gamma-ray source 1WHSP J104516.2+275133

ATel #12906; *S. Garrappa (DESY-Zeuthen, DE), S. Buson (Univ. of Wuerzburg, DE; UMBC, USA) and T. Venters (NASA-GSFC, USA) on behalf of the Fermi-LAT collaboration*
on 5 Jul 2019; 23:57 UT
Credential Certification: Sara Buson (sara.buson@gmail.com)

Subjects: Gamma Ray, >GeV, TeV, VHE, Neutrinos, Request for Observations, AGN, Blazar







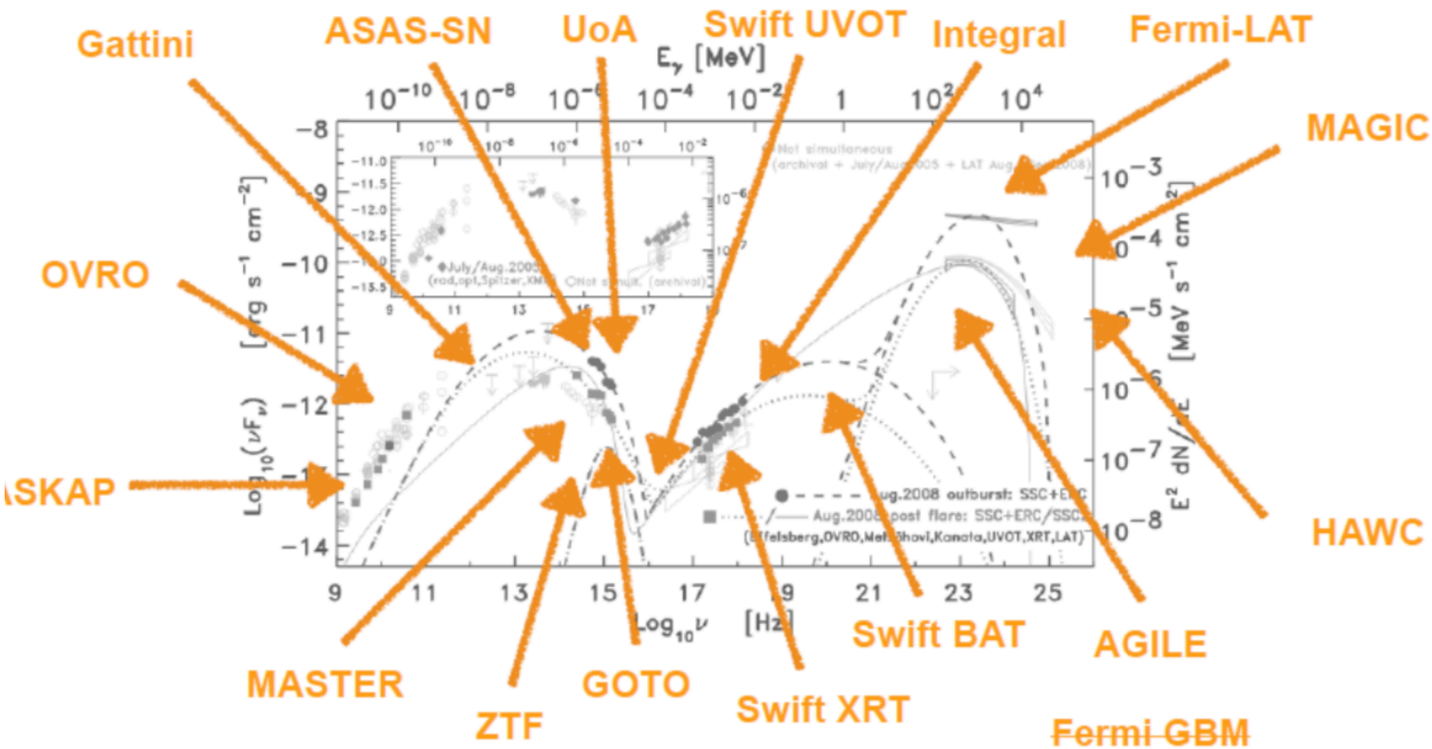
A possible γ-ray precursor flare (1 to 2 days) at ~ 4σ in coincidence with an EHE neutrino of 85% signalness, no clear MWL counterpart [F. Lucarelli et al. ApJ 846, Vol. 2, p. 121 (2017), arXiv:1707.08599]

PKS 1502+106

PKS 1502+106

Extensive MWL camapaign

Credit: R.Stein, TEXAS 2019



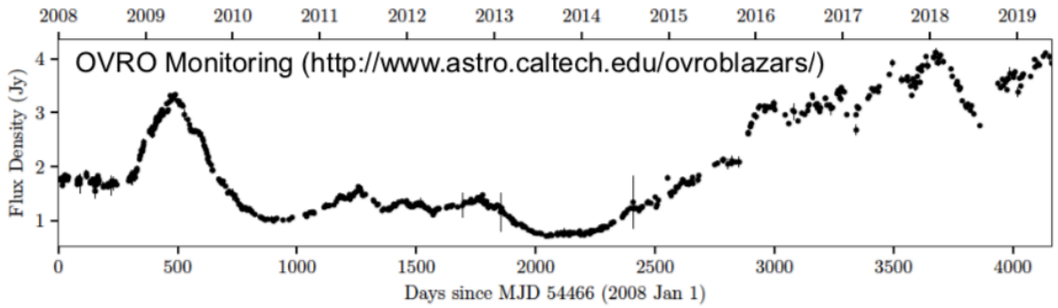
Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.



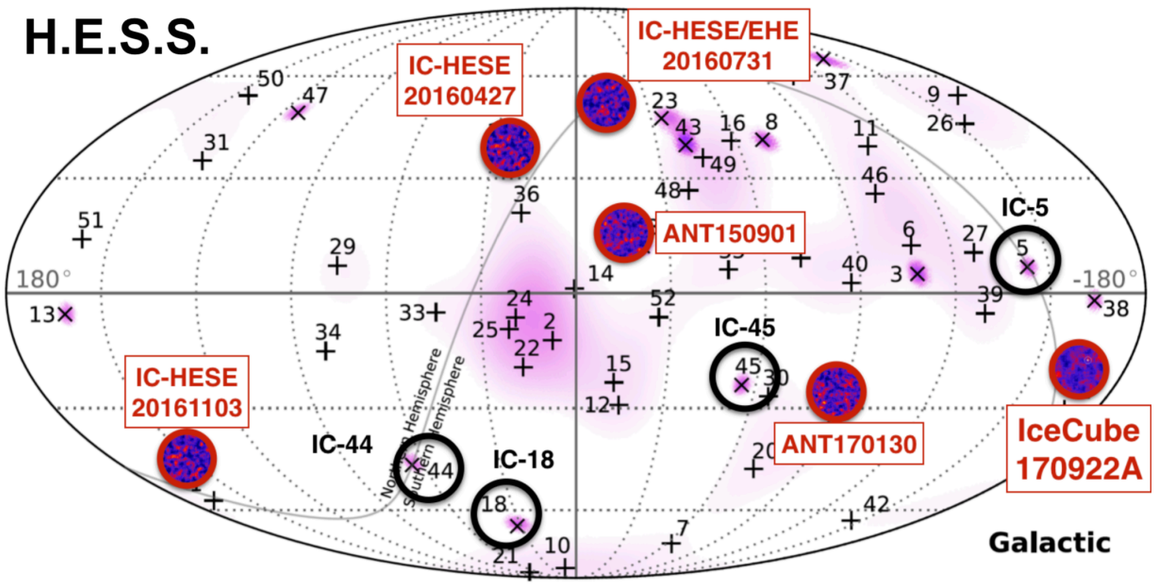
No evidence of short-term flaring activity in any wavelength…

Long-term radio flare reported by OVRO, similar to TXS 0506+056…
Trend? Coincidence?

Public and private IceCube alerts

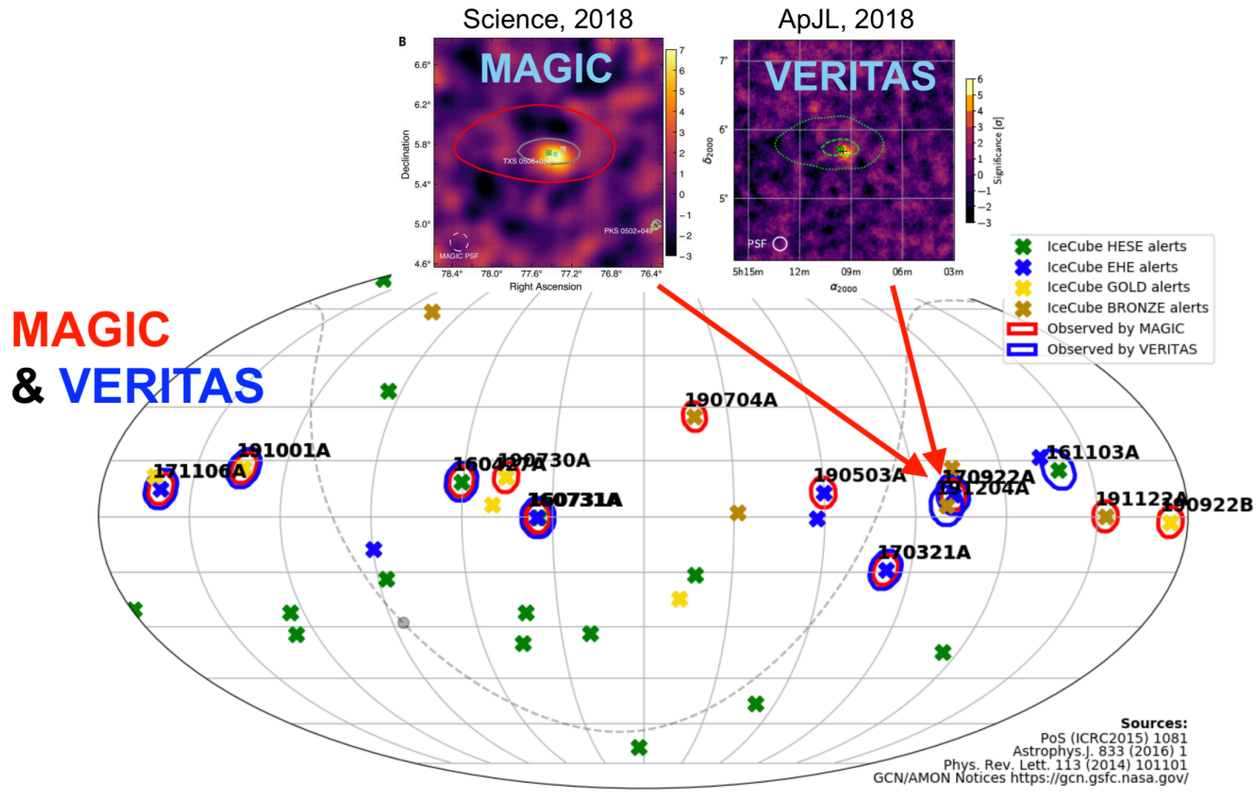
… very high-energy gamma-ray follow-up

PoS(ICRC2019)787



Science, 2018 ApJL, 2018

MAGIC & VERITAS



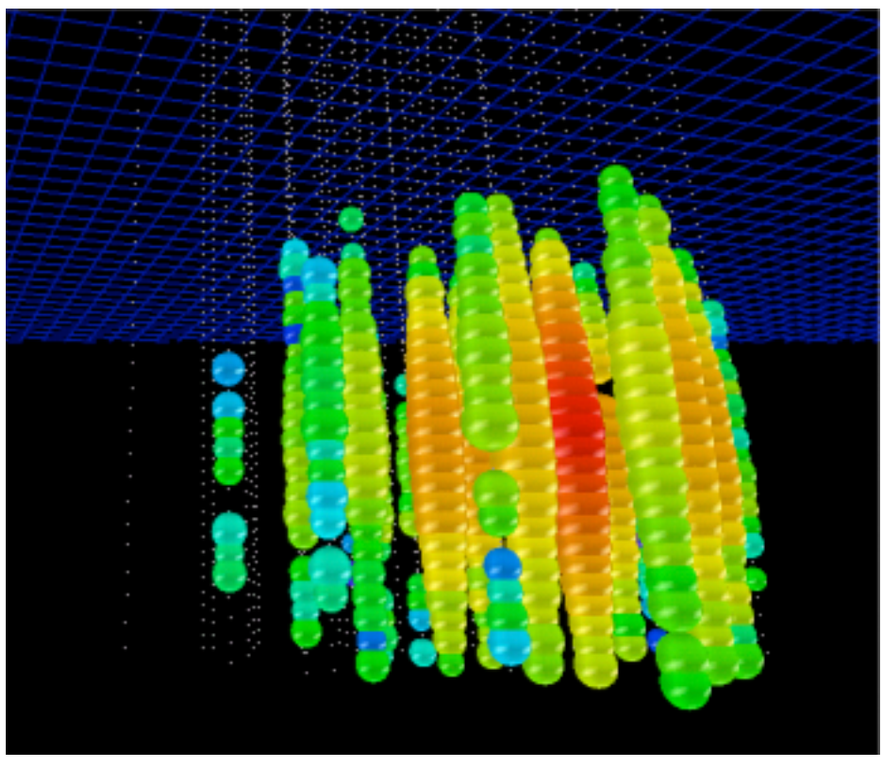
H.E.S.S, MAGIC, VERITAS (>50 GeV) - up to 15% of their time spent on neutrino alerts follow-up

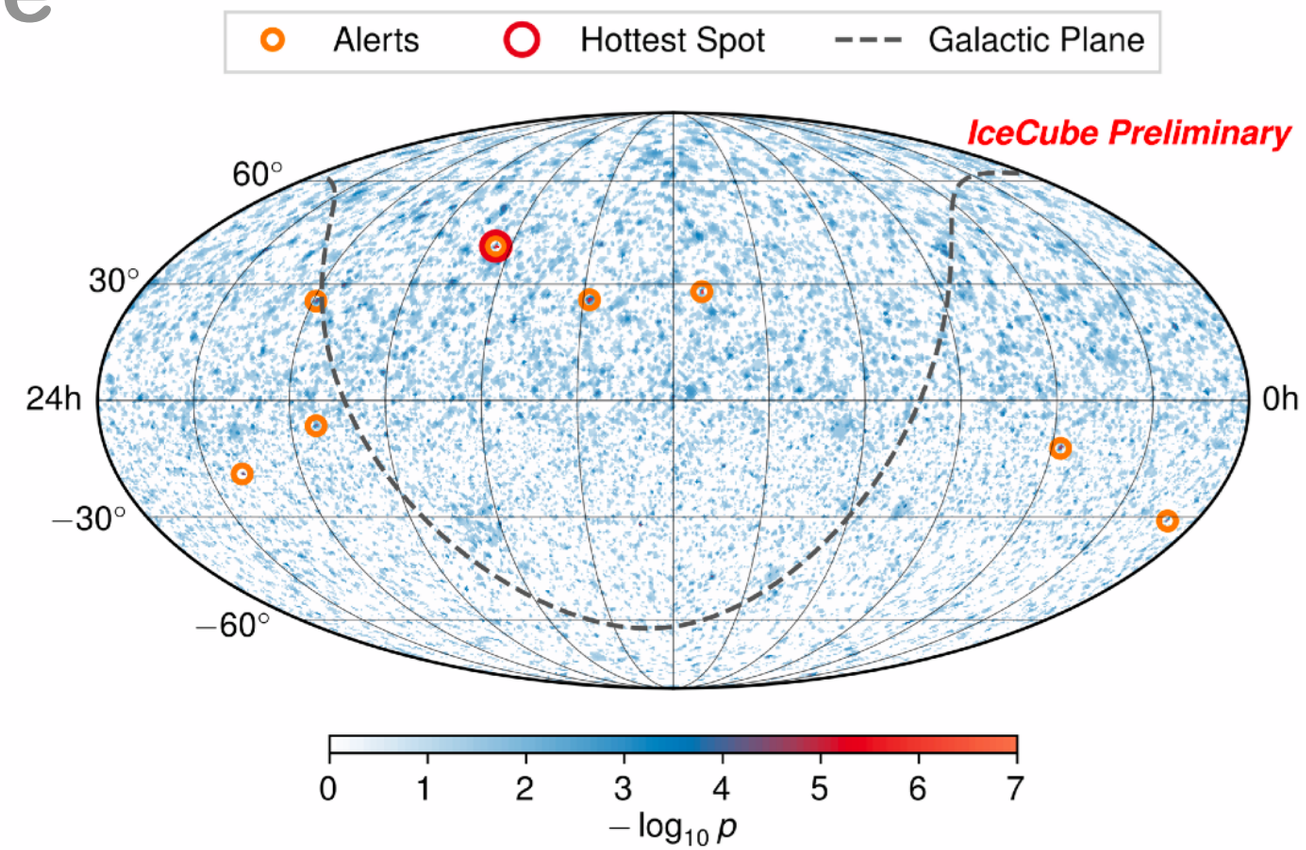
So far the only VHE g-ray source detected in coincidence with neutrino alert is TXS 0506+056 (Science, 2018)

see K. Satalecka @ TMEX 2020

Neutrino alerts: what next?

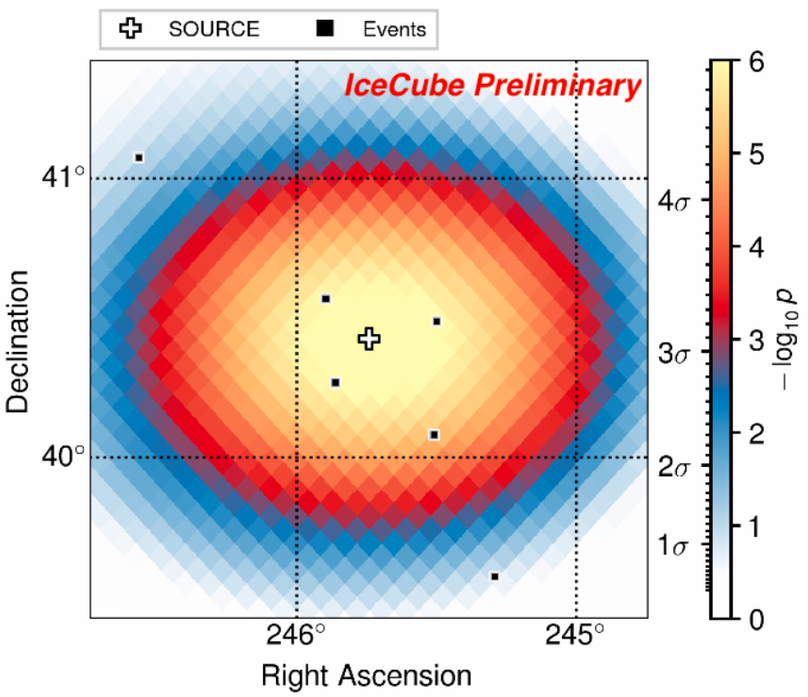
… on the neutrino side





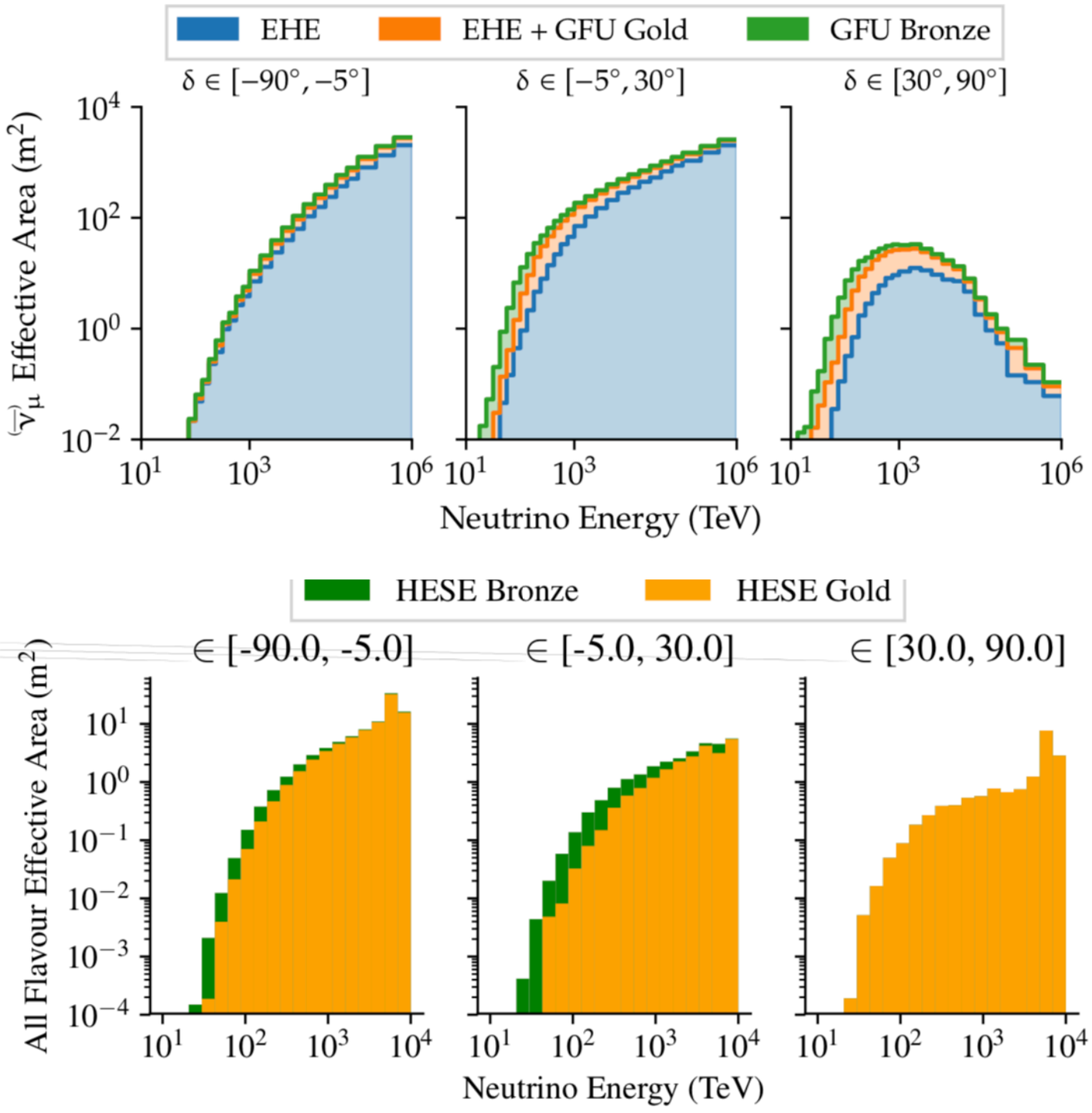
- Next steps for IceCube alerts:
  - Alerts from cascade events (~6/yr)
  - Alerts for all-sky time dependent flaring searches (~1/yr)

Hottest spot in 8 yr of data: consistent with background after trials corrections (PhD Thomas Kintscher, Humboldt Univ.)

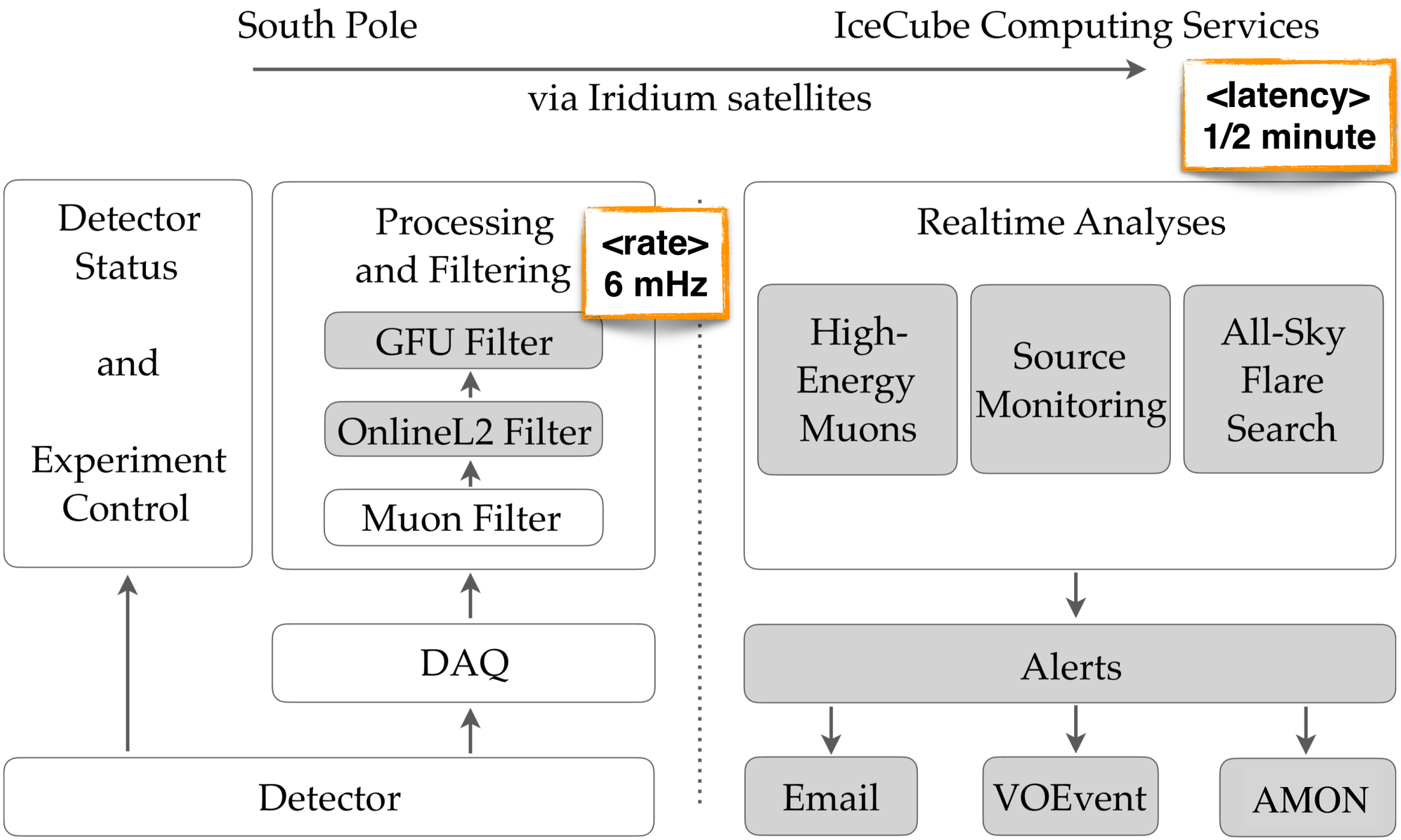


Above threshold GOLD/BRONZE alerts since June 2019

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



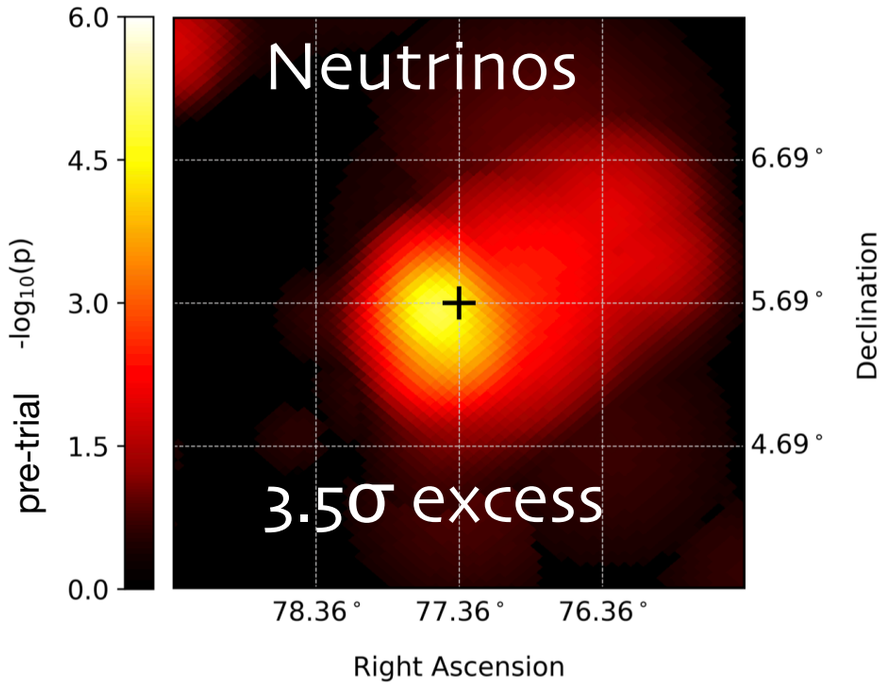
Realtime IceCube pipeline: GFU



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

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



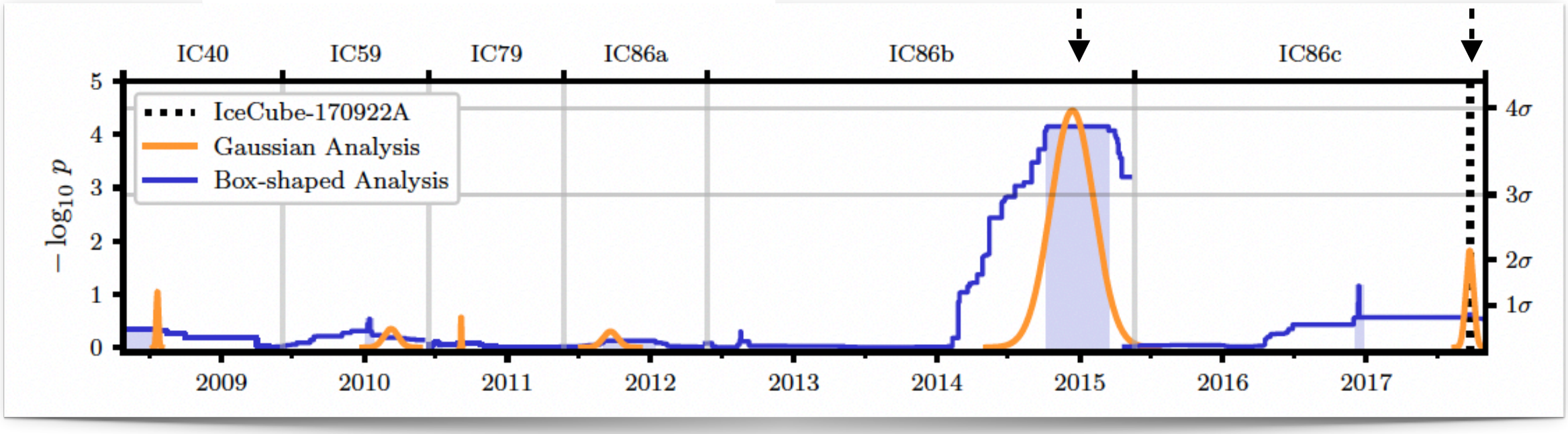
~110-150 days

~20 days

Spectral index ~2

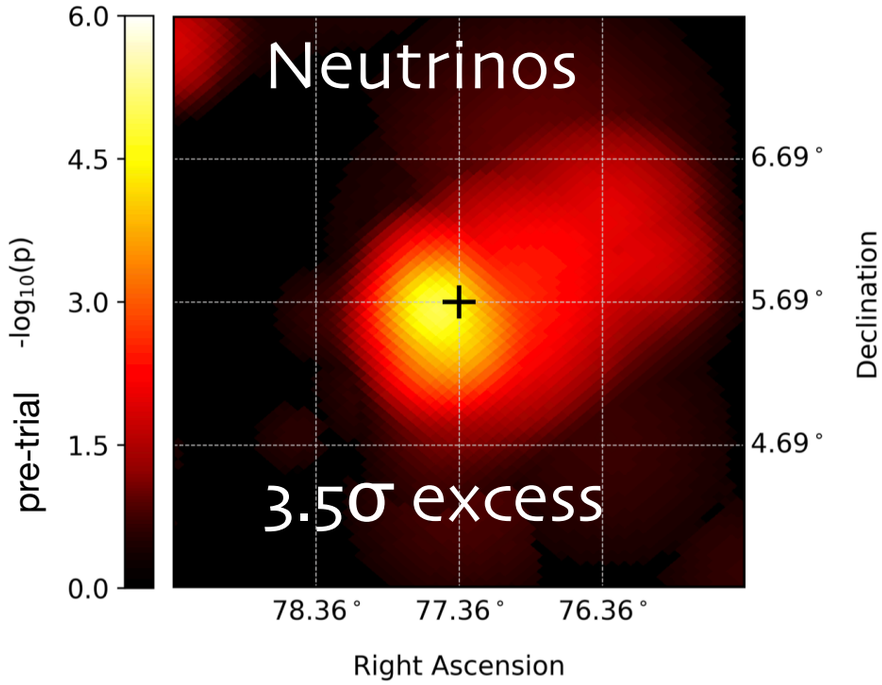
Spectral index ~1.7

IceCube Coll. Science 361, eaat1378 (2018)



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
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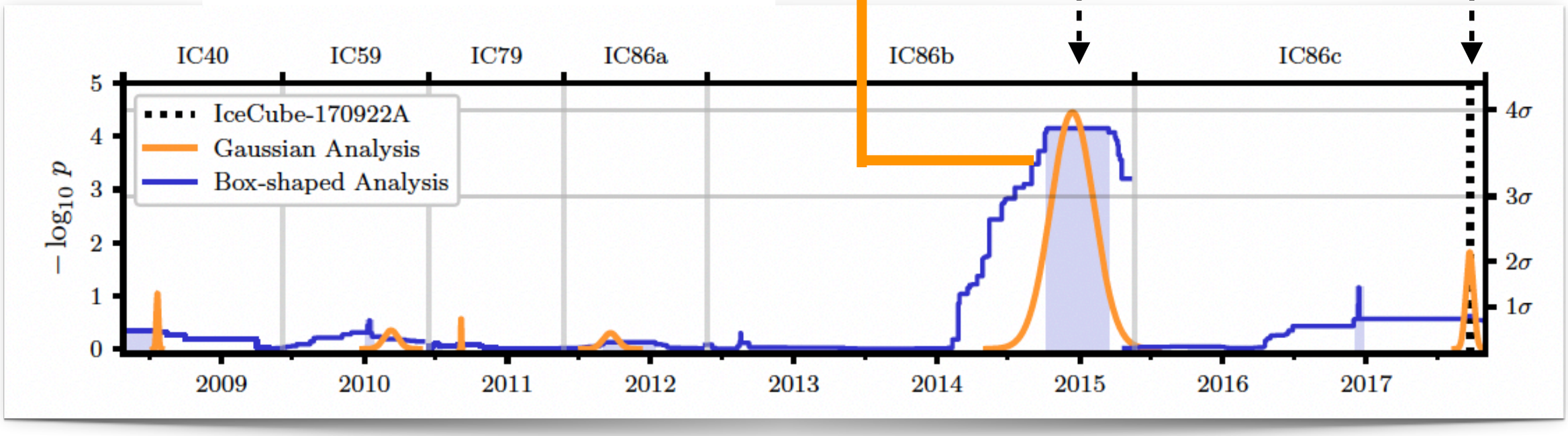
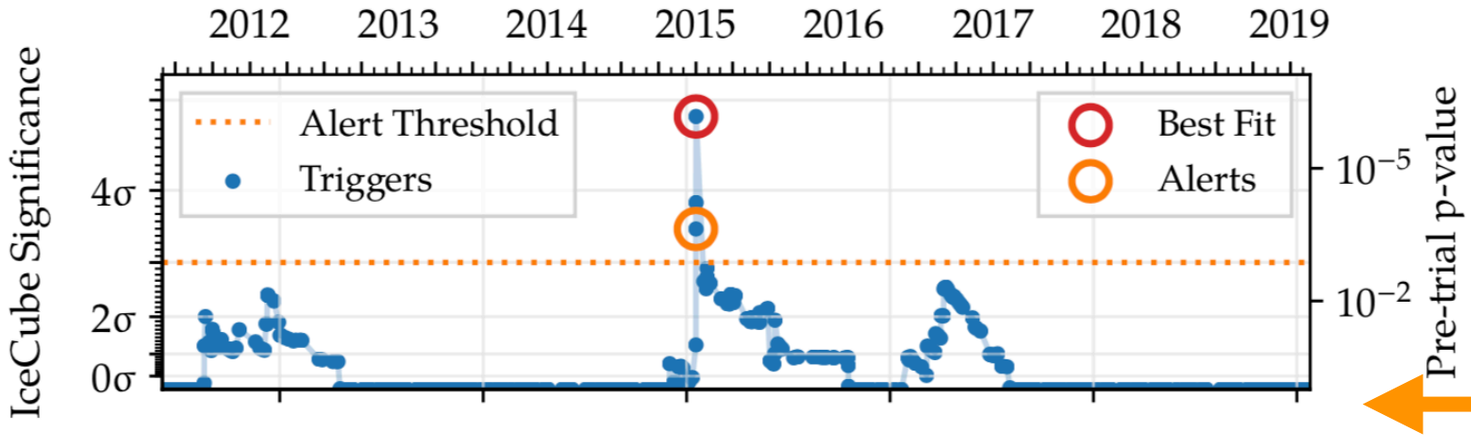
IceCube Coll. Science 361, eaat1378 (2018)

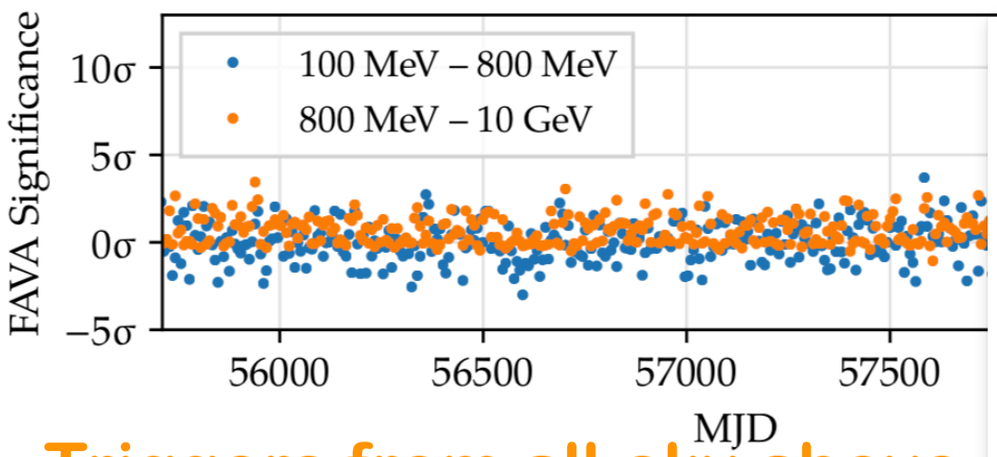


Gamma-ray follow-up (GFU) alerts

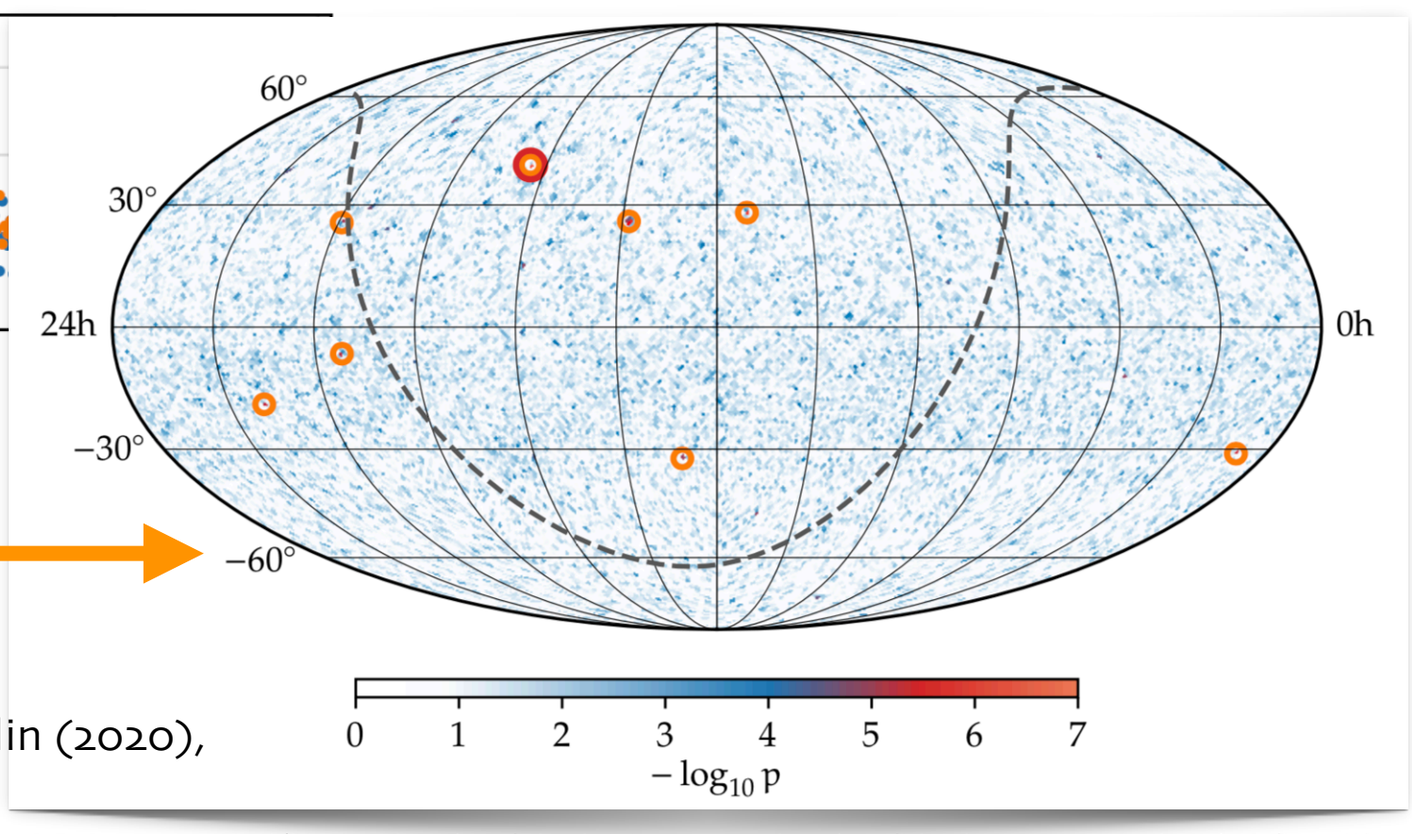
Alerts are being sent to Imaging Air Cherenkov telescopes H.E.S.S., MAGIC and VERITAS through **PRIVATE** channels regulated under dedicated MoUs



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

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, compatib with background

J. Vanderbroucke et al.
PoS(ICRC2019)1026