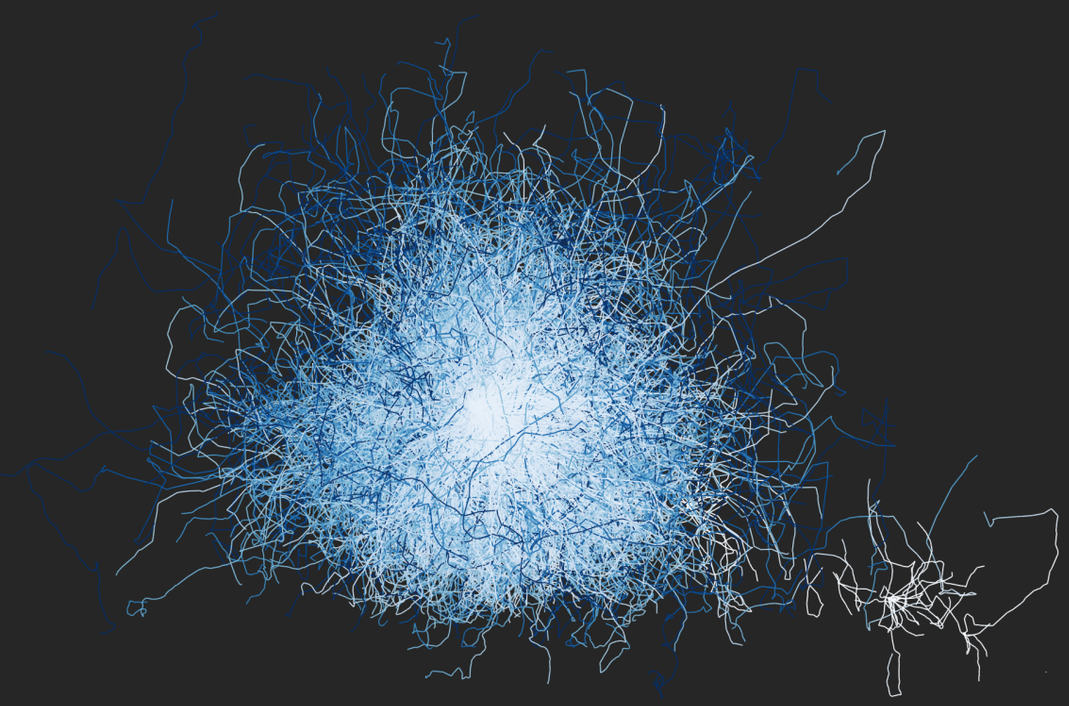


NEUTRINO ASTRONOMY AT THE VERY HIGH ENERGY SCALE

HILLAS SYMPOSIUM

Heidelberg | December 10 - 12, 2018

Elisa Resconi

Bundesministerium für Bildung und Forschung

DFG

SFB 1258 Neutrinos Dark Matter Messengers

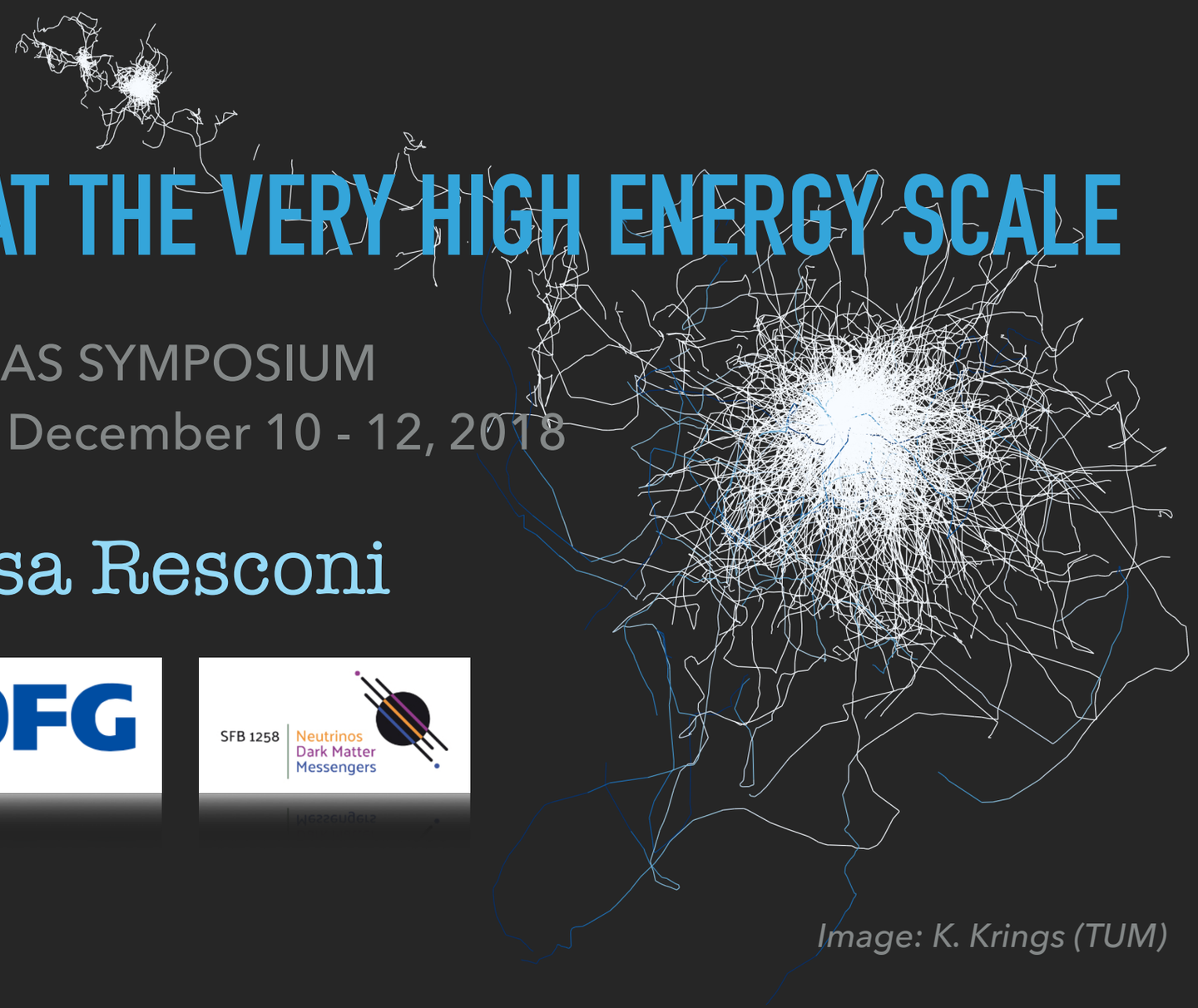
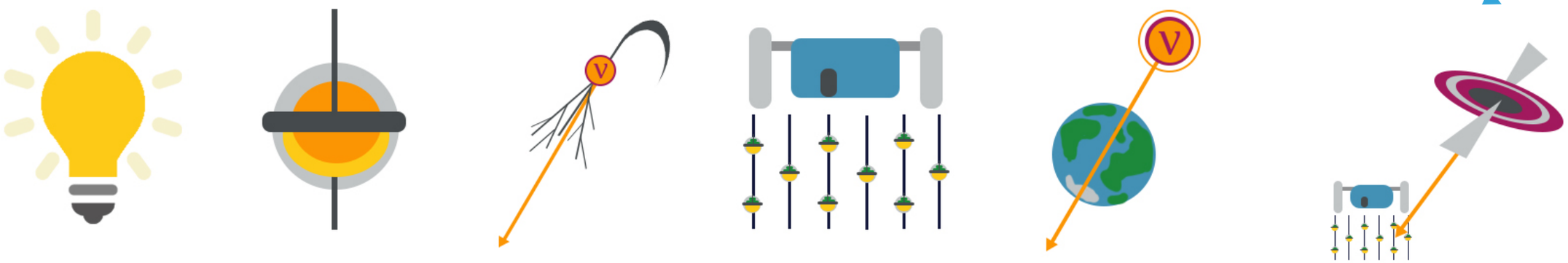


Image: K. Krings (TUM)

A History of Neutrino Astronomy in Antarctica

- 8 years, one (marginal) detection -



1960 Vision

1988 Telescope in the Ice Envisioned

2000 AMANDA Completed

2000-2001 Atmospheric Neutrinos Detected

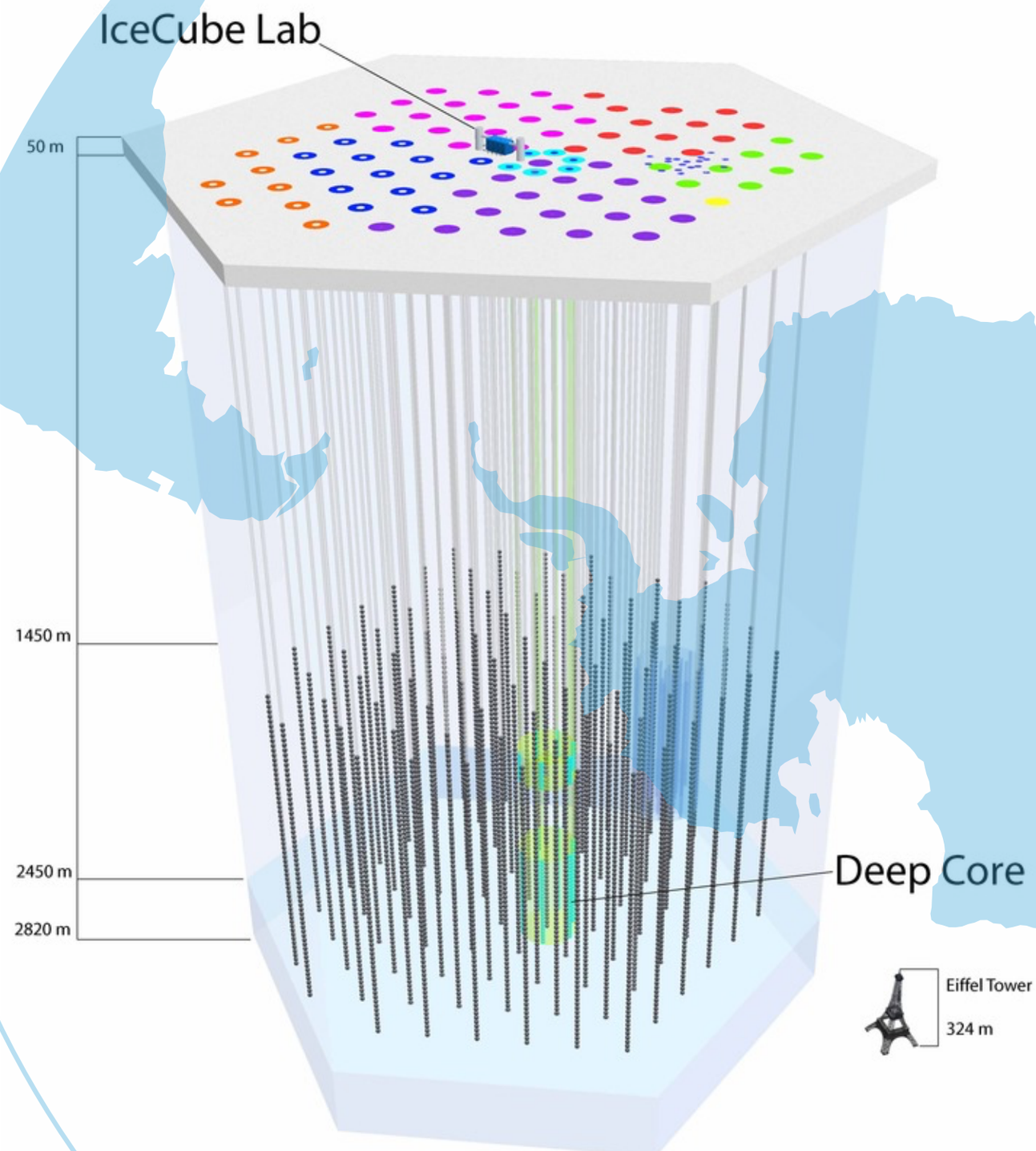
2011 IceCube Completed

2013 Astrophysical Neutrinos Discovered

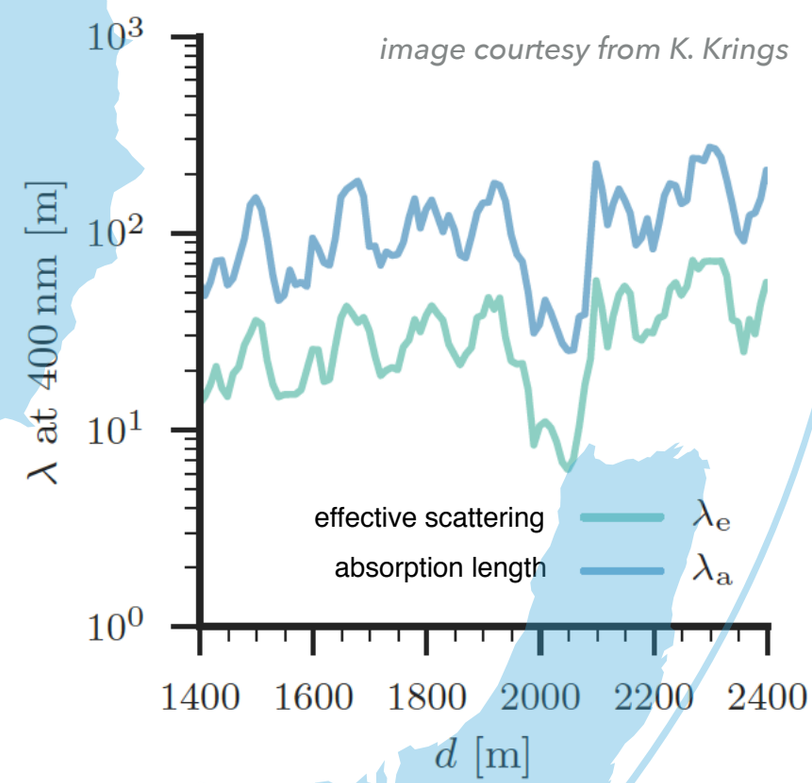
2018 First Source Identified

- Diffuse -

THE ICECUBE NEUTRINO OBSERVATORY

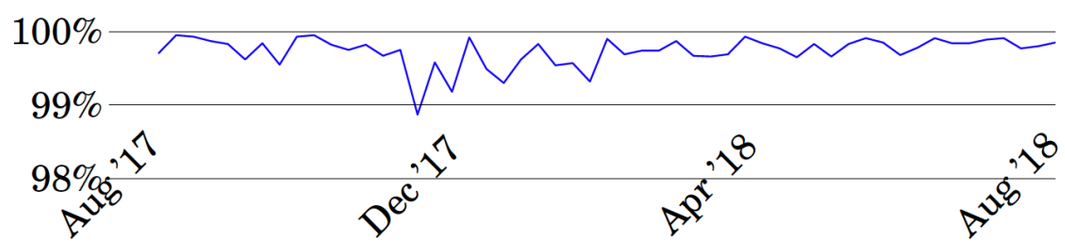


Digital Optical Modules



Martin Wolf

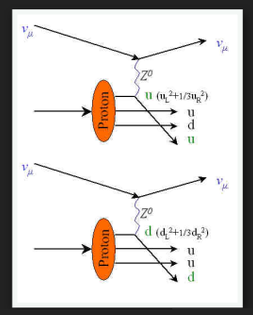
Uptime

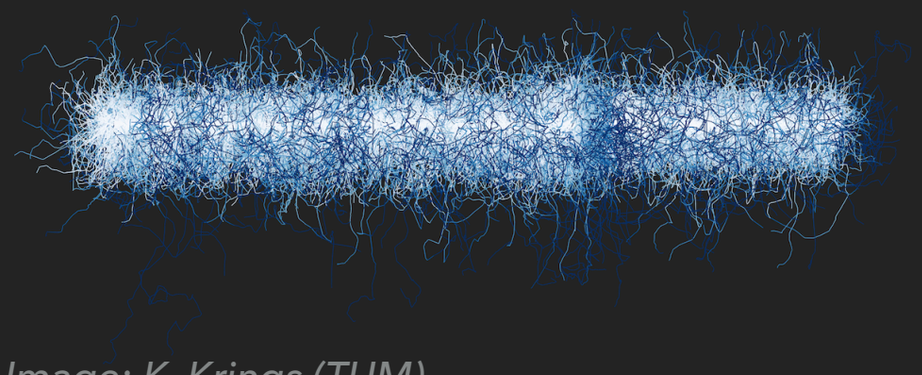


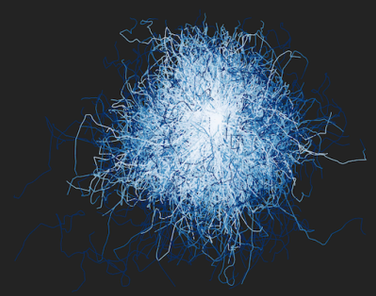
99.85%

NEUTRINO INTERACTION CHANNELS

Photon path induced by a ν_μ ν_e ν_τ







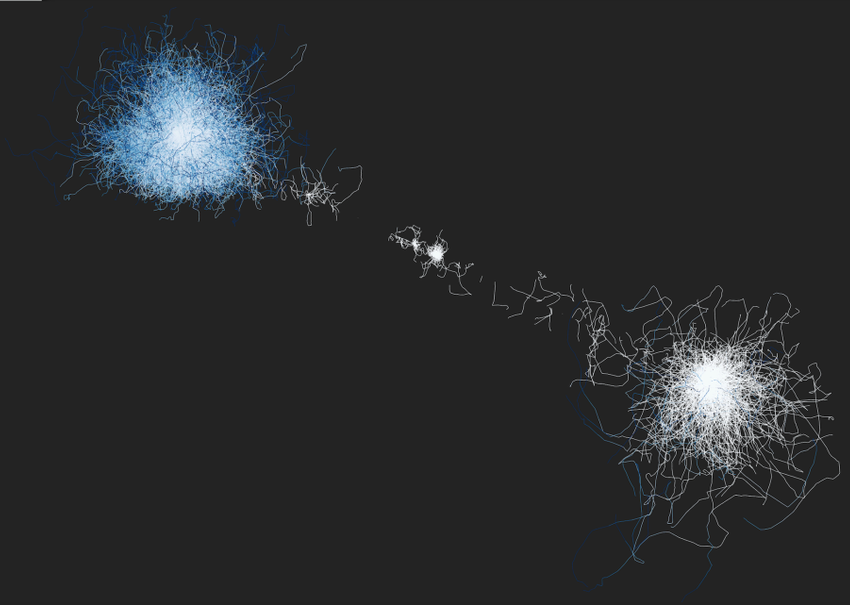
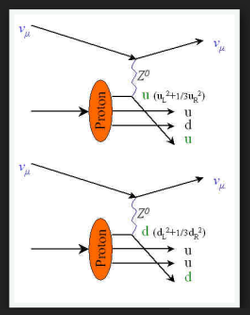
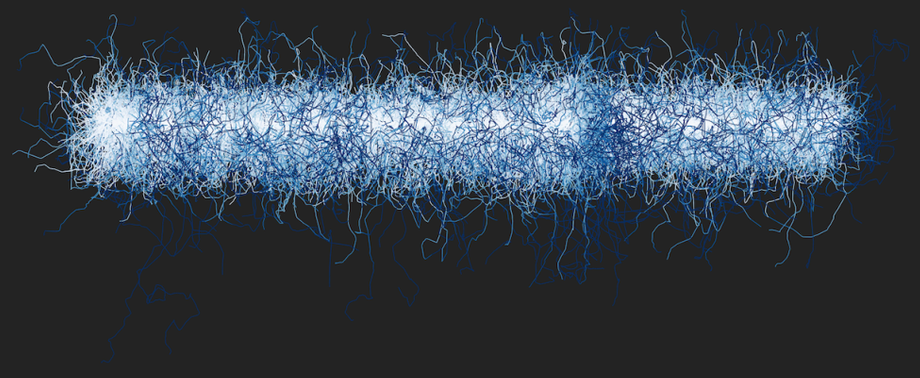


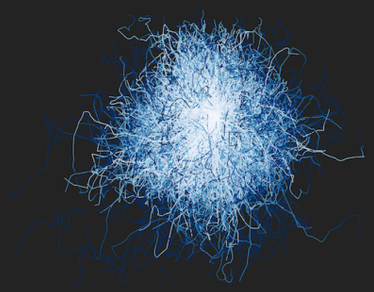
Image: K. Krings (TUM)

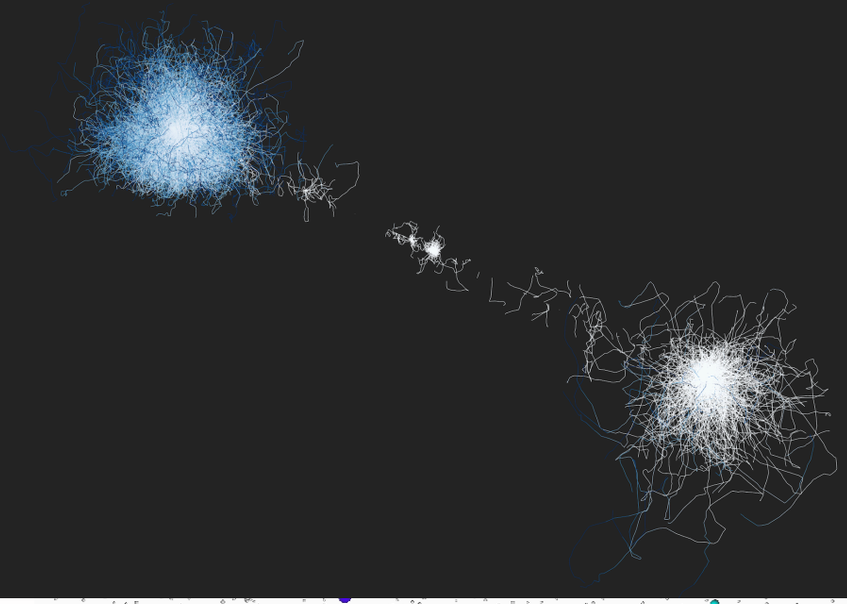
NEUTRINO INTERACTION CHANNELS

Photon path induced by a ν_μ ν_e ν_τ









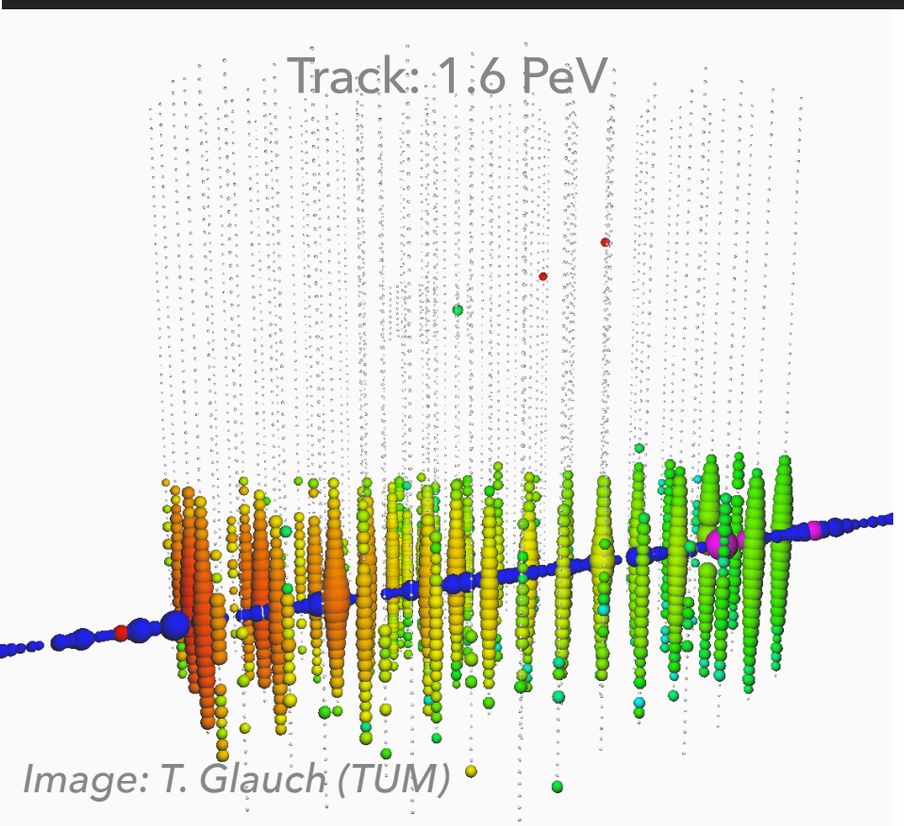
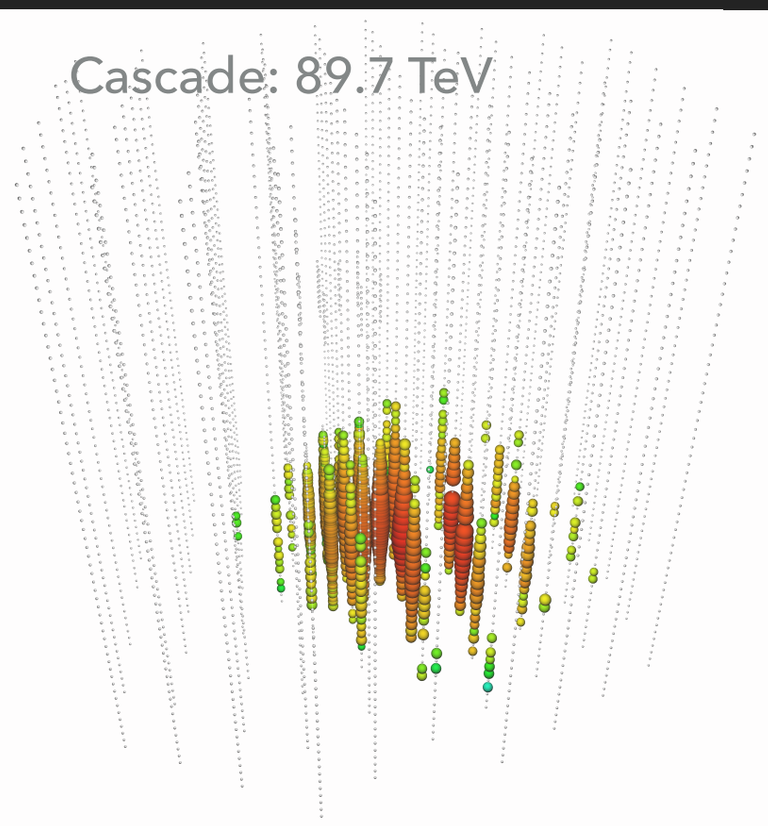
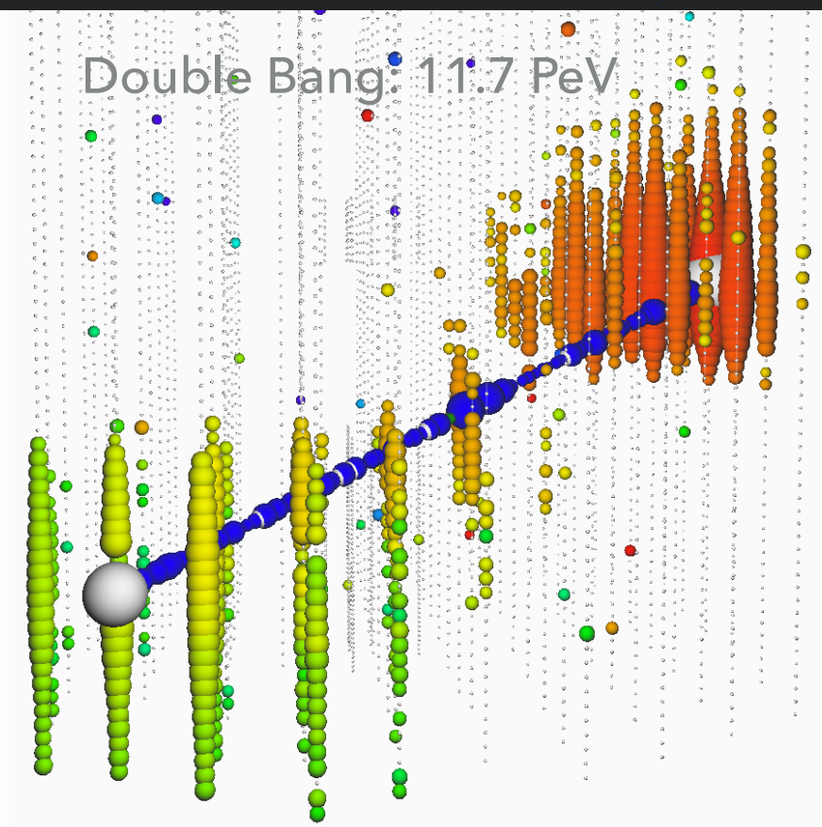


Image: T. Glauch (TUM)

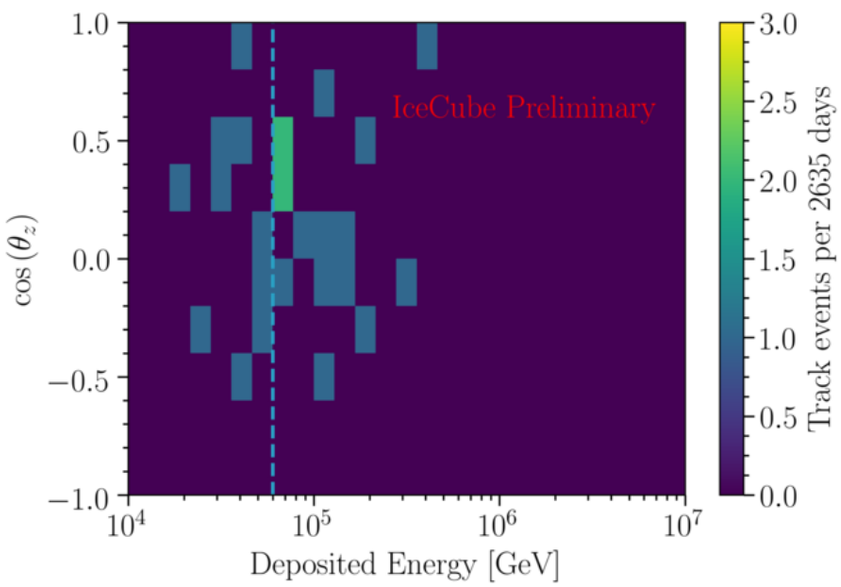




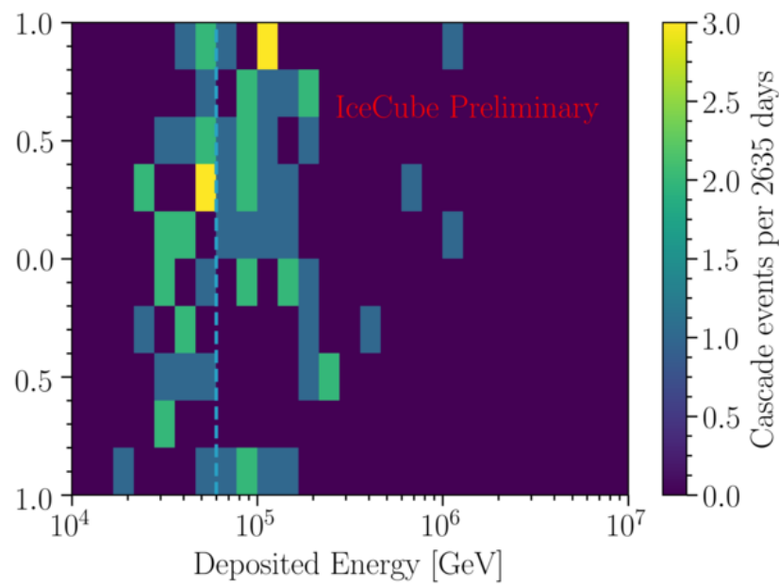
HIGH ENERGY, STARTING EVENTS, ALL FLAVOURS (2635 DAYS)

[IceCube Collaboration, Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector, Science(2013)]

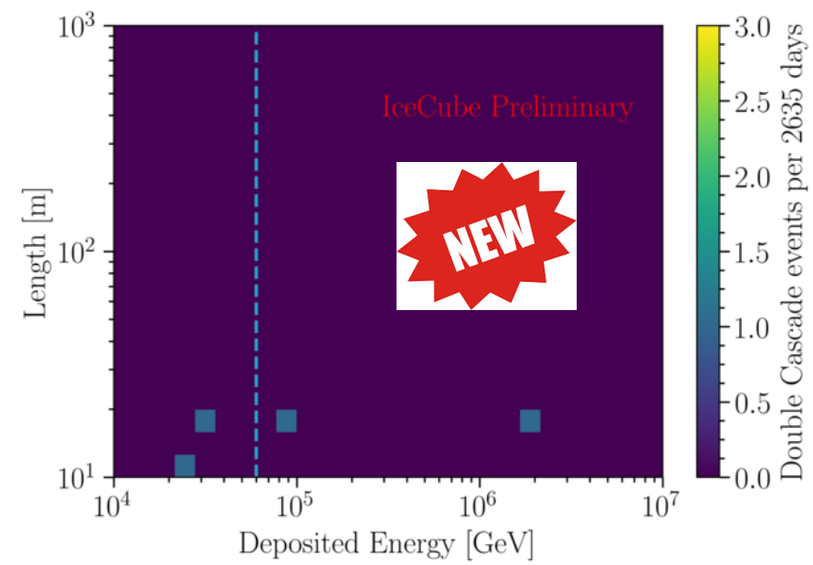
HE Starting Tracks
All energies: 26 events;
E > 60TeV: **16 events**

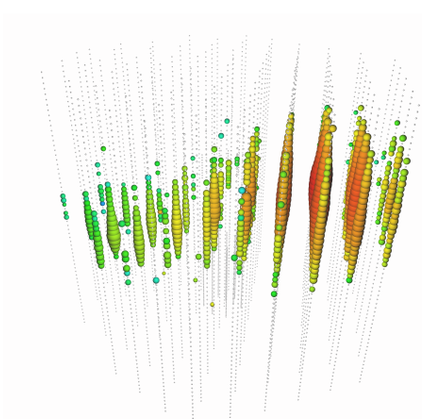


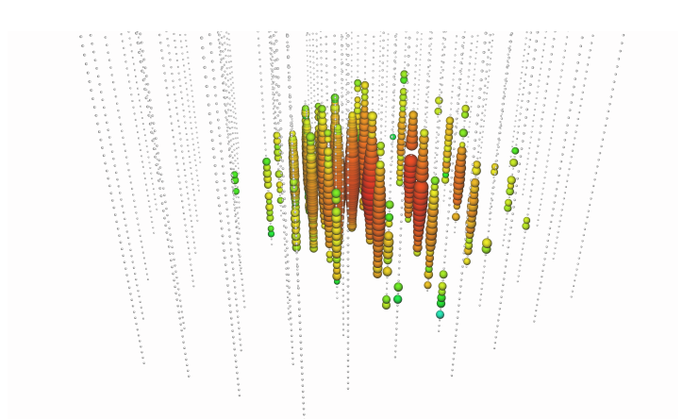
HE Starting Showers
All energies: 72 events;
E > 60TeV: **42 events**

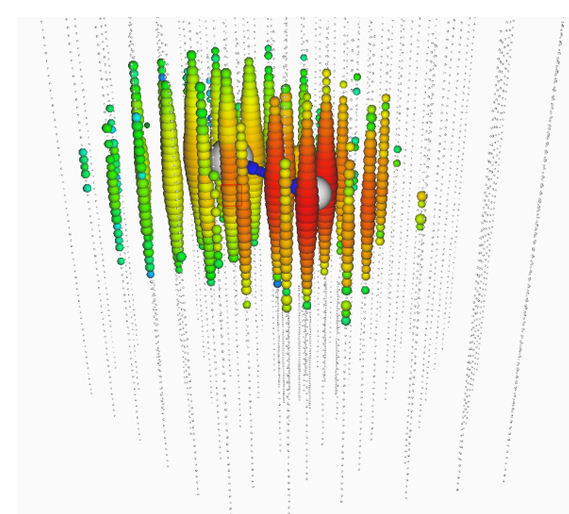


HE Starting Double Showers
All energies: 4 events;
E > 60TeV: **2 events**

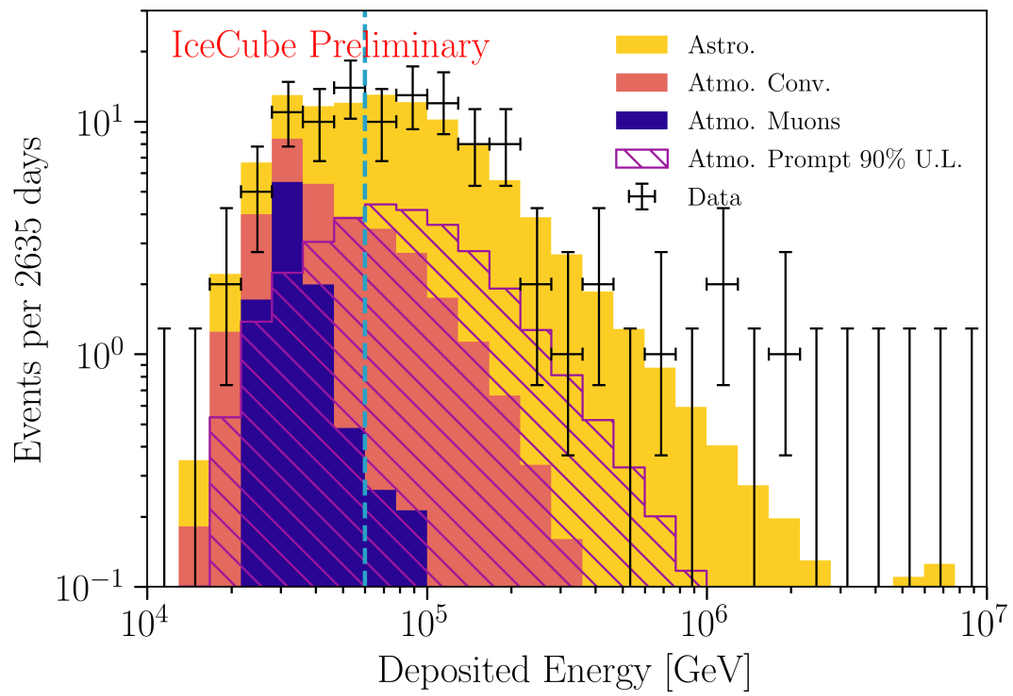


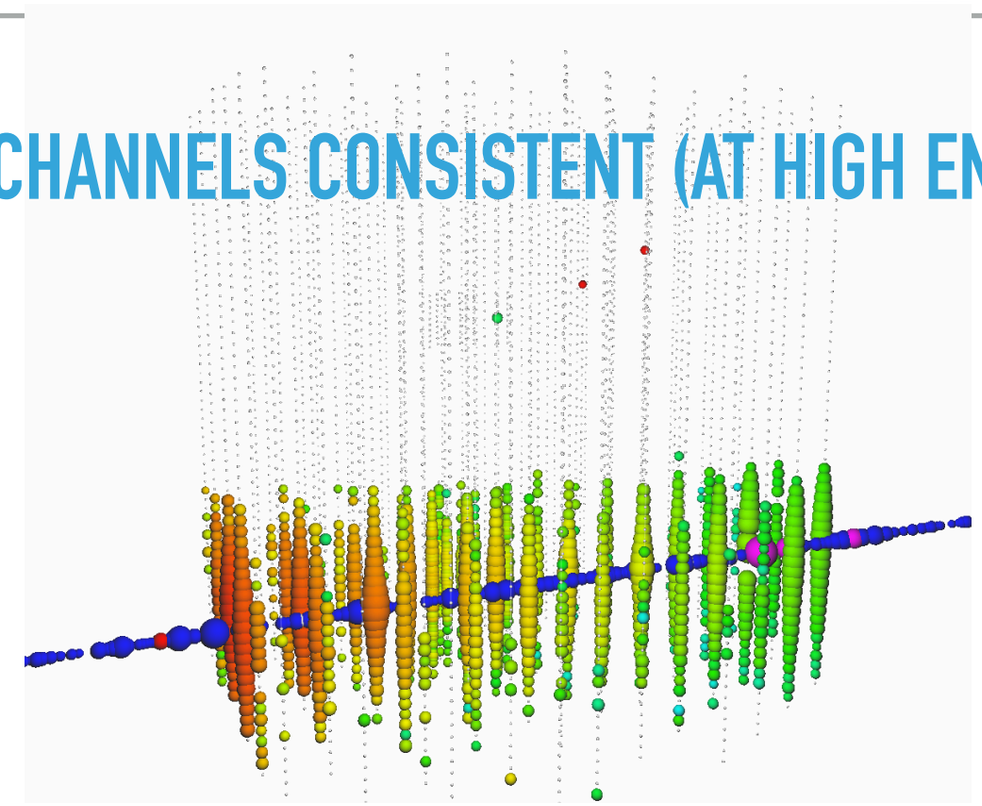


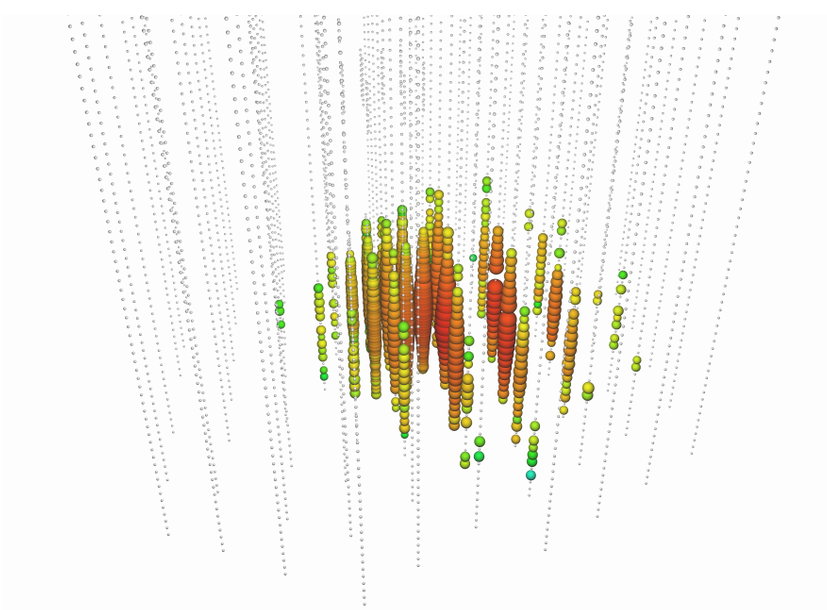


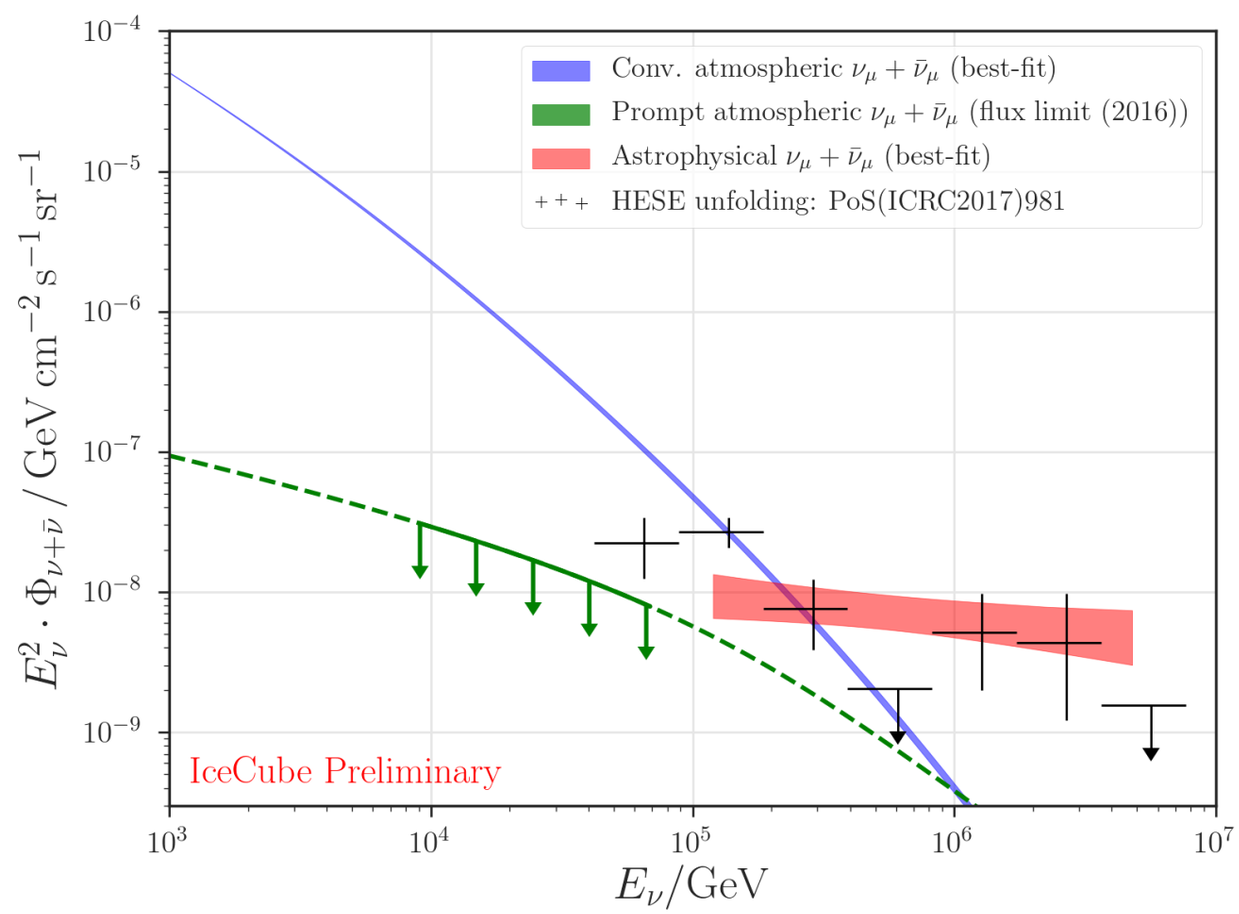


ASTROPHYSICAL DIFFUSE NEUTRINOS: ALL CHANNELS CONSISTENT (AT HIGH ENERGY)









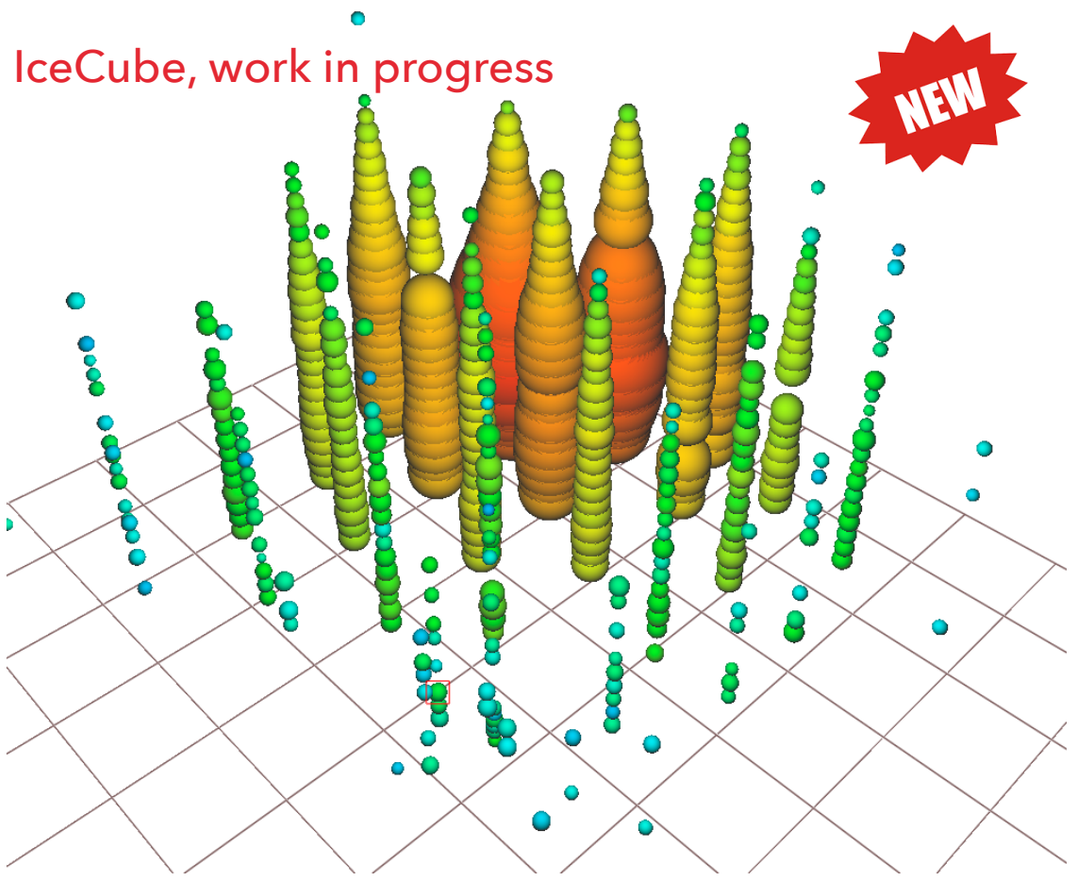
THE RECORD EVENT: HYDRANGEA -> GLASHOW RESONANCE EVENT CANDIDATE

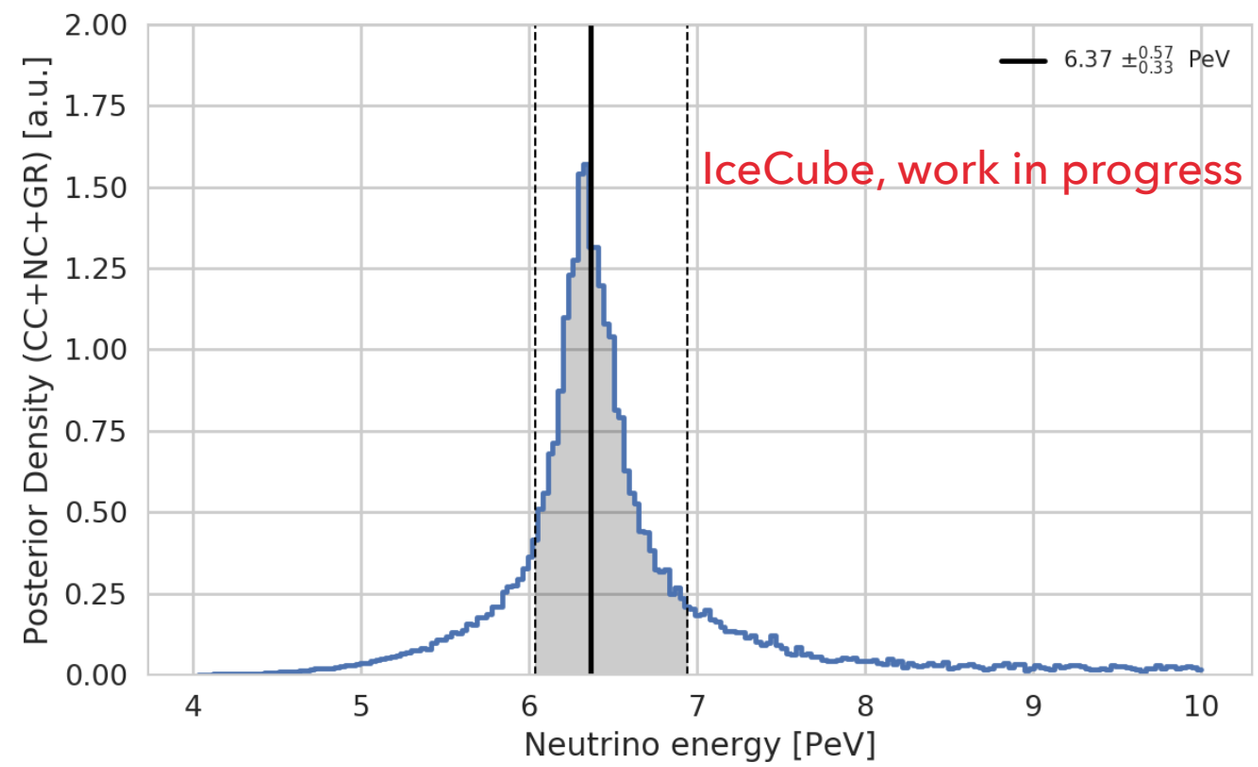
S.L. Glashow, Phys. Rev. 118B, 316 (1960)

$$\bar{\nu}_e e^- \to W^- \to \text{anything} \quad E_\nu \simeq 6.3 \text{ PeV}$$

Resonant scattering

IceCube, work in progress

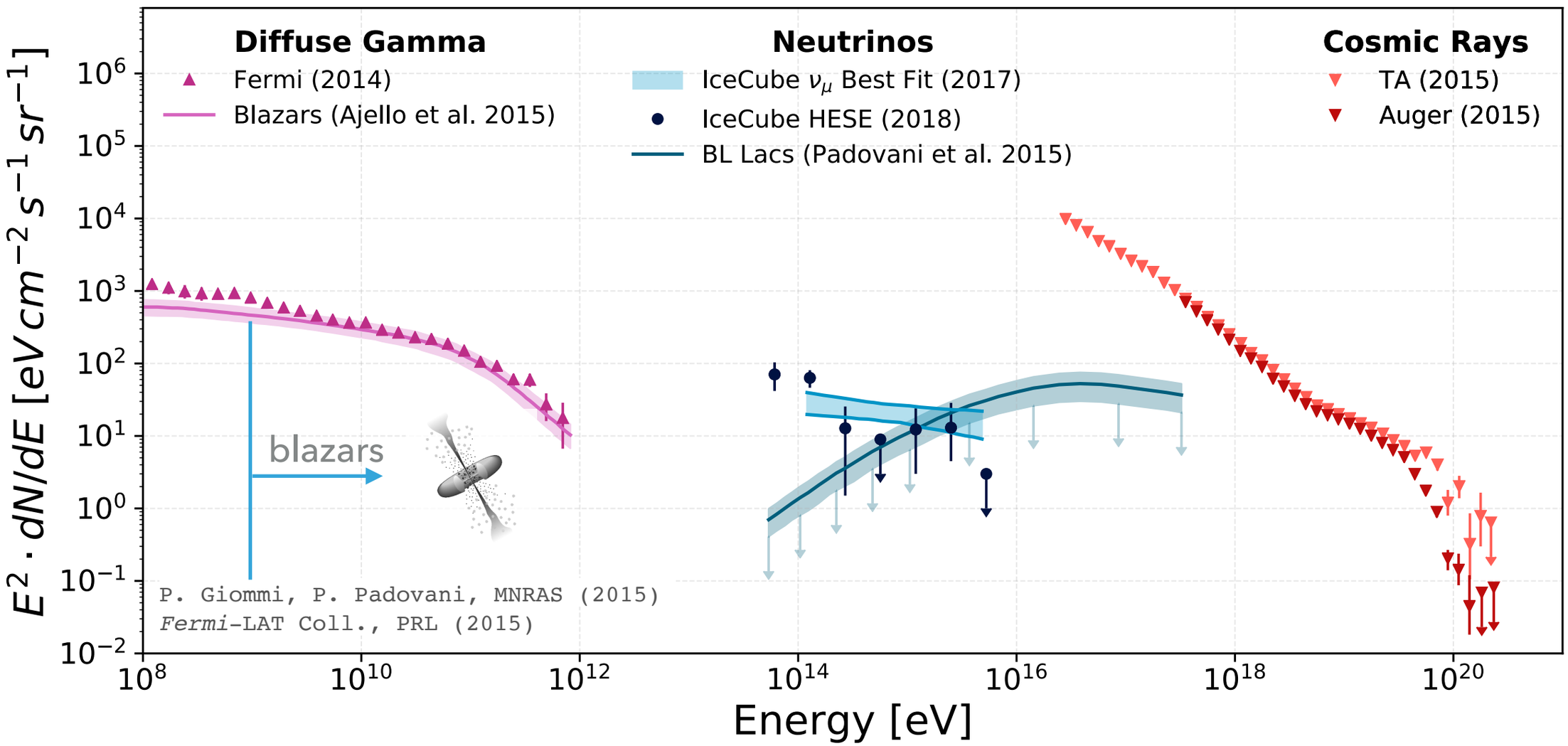




ν_e candidate, cosmic ray origin excluded at the > 5 sigma level

THE MULTI-MESSENGER OBSERVATIONS

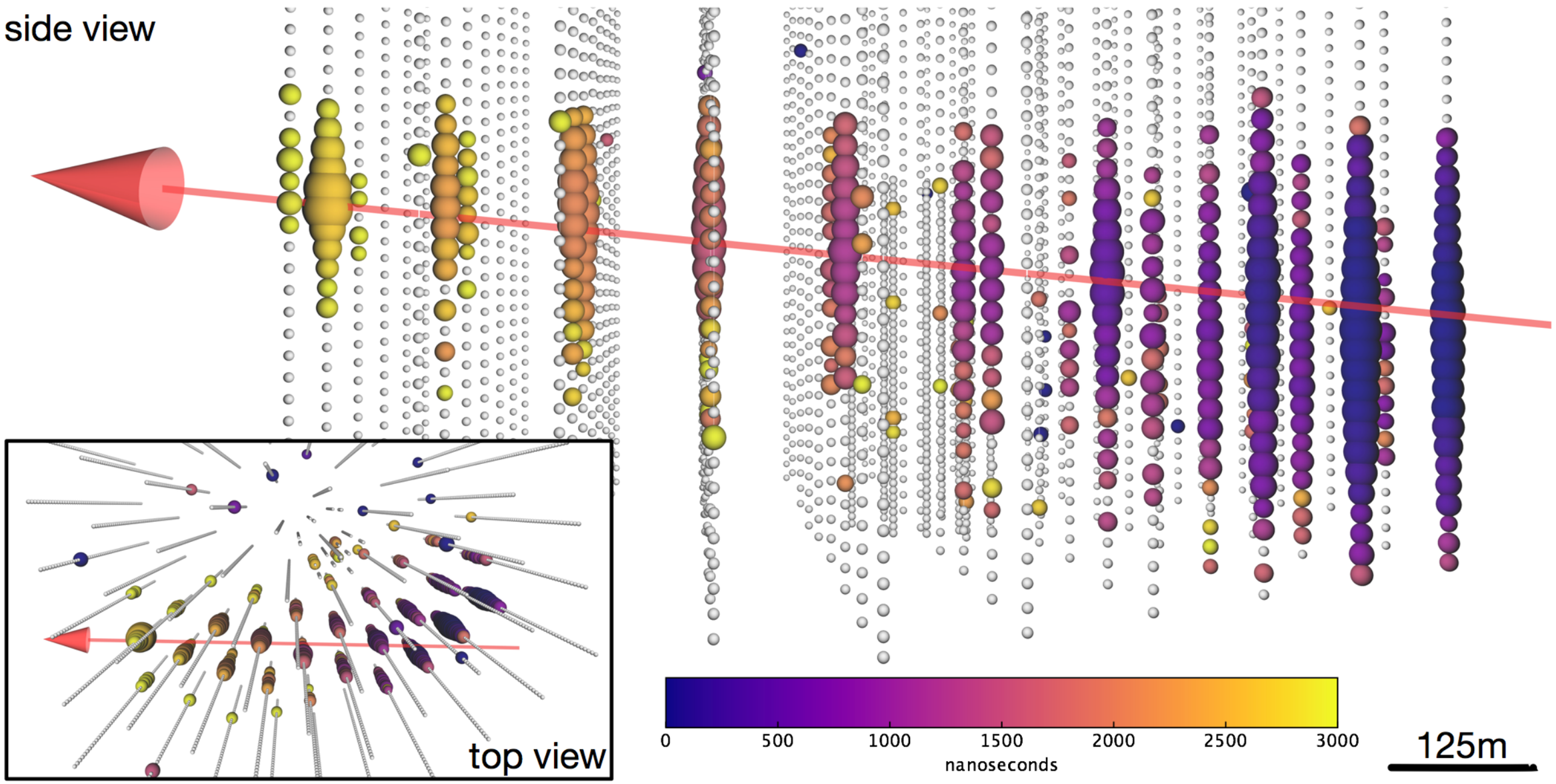
P. Padovani, E.R., MNRAS (2014)
M. Petropoulou, S. Dimitrakoudis, P. Padovani, A. Mastichiadis, E.R., MNRAS (2015)
P. Padovani, M. Petropoulou, P. Giommi, E.R., MNRAS (2015)
P. Padovani, E.R., P. Giommi, B. Arsioli, Y. L. Chang, MNRAS (2016)



E.R., S. Coenders, P. Padovani, P. Giommi, L. Caccianiga, MNRAS (2017)

ICECUBE-170922A: THE NEUTRINO ALERT

"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018



ICECUBE-170922A: THERE IS A COUNTERPART – A BLAZAR

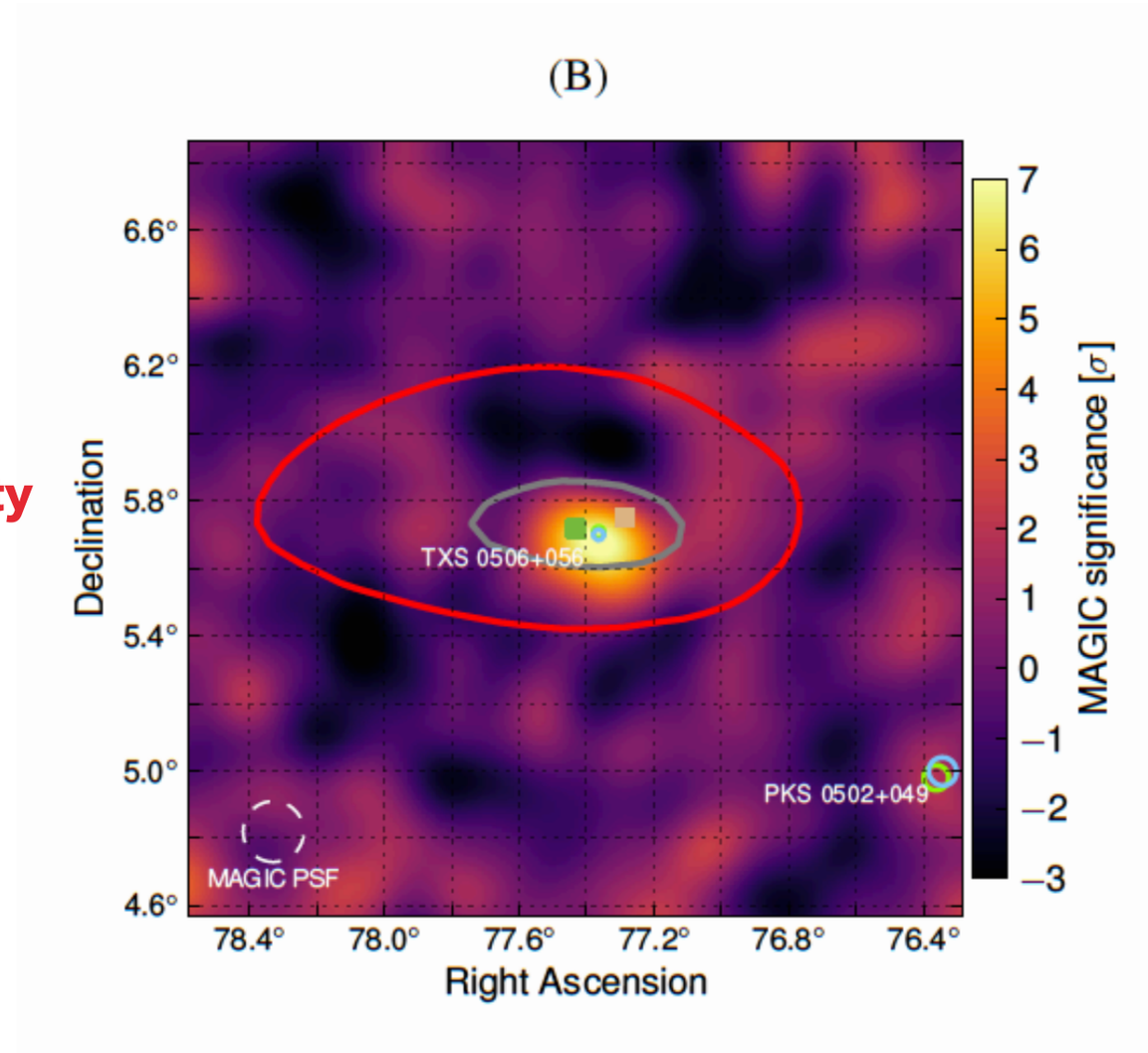
"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

Event occurred on the 22nd Sept 2017, 20:54:30 UTC
First notice sent **43s later**!

Revised coordinates sent 4 hours later

- Follow-up responses
  GCN 21917 - Integral - No detection [...]
- ATel 10791 - **Fermi - increased gamma-ray activity of TXS 0506+056** (RA 77.36 deg, Dec +5.69 deg)
- ATel 10817 – The First-time **detection of VHE gamma rays by MAGIC**

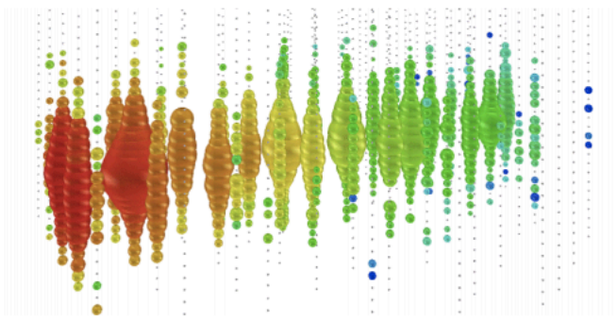
....and observations and reports by many more telescopes: AGILE, ASAS-SN, Kapteyn, Kanata, Kiso, Liverpool, Subaru, VERITAS, VLT



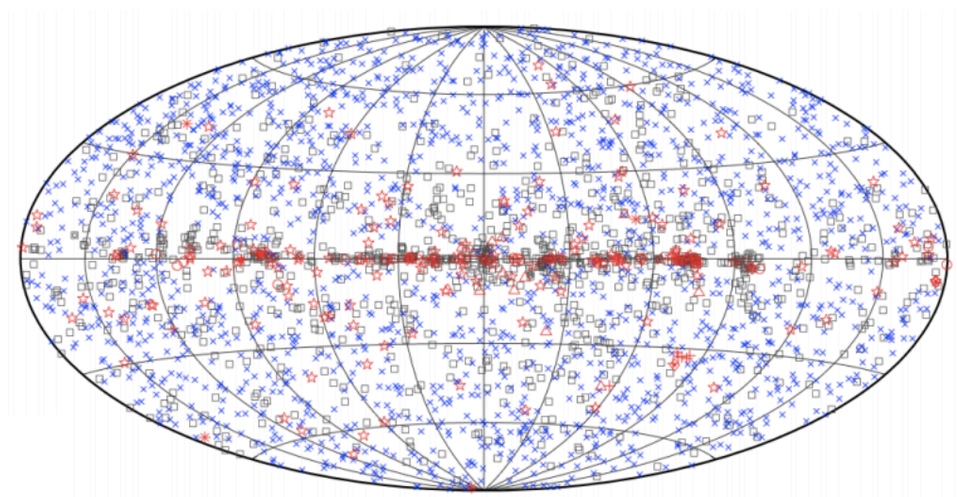
ICECUBE-170922A VS TXS 0506+056: RANDOM COINCIDENCE?

"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

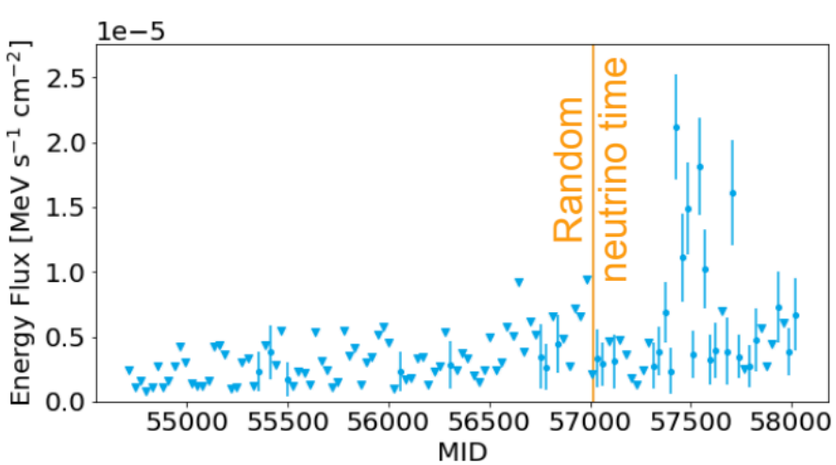
Excluded with 99.73%CL



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



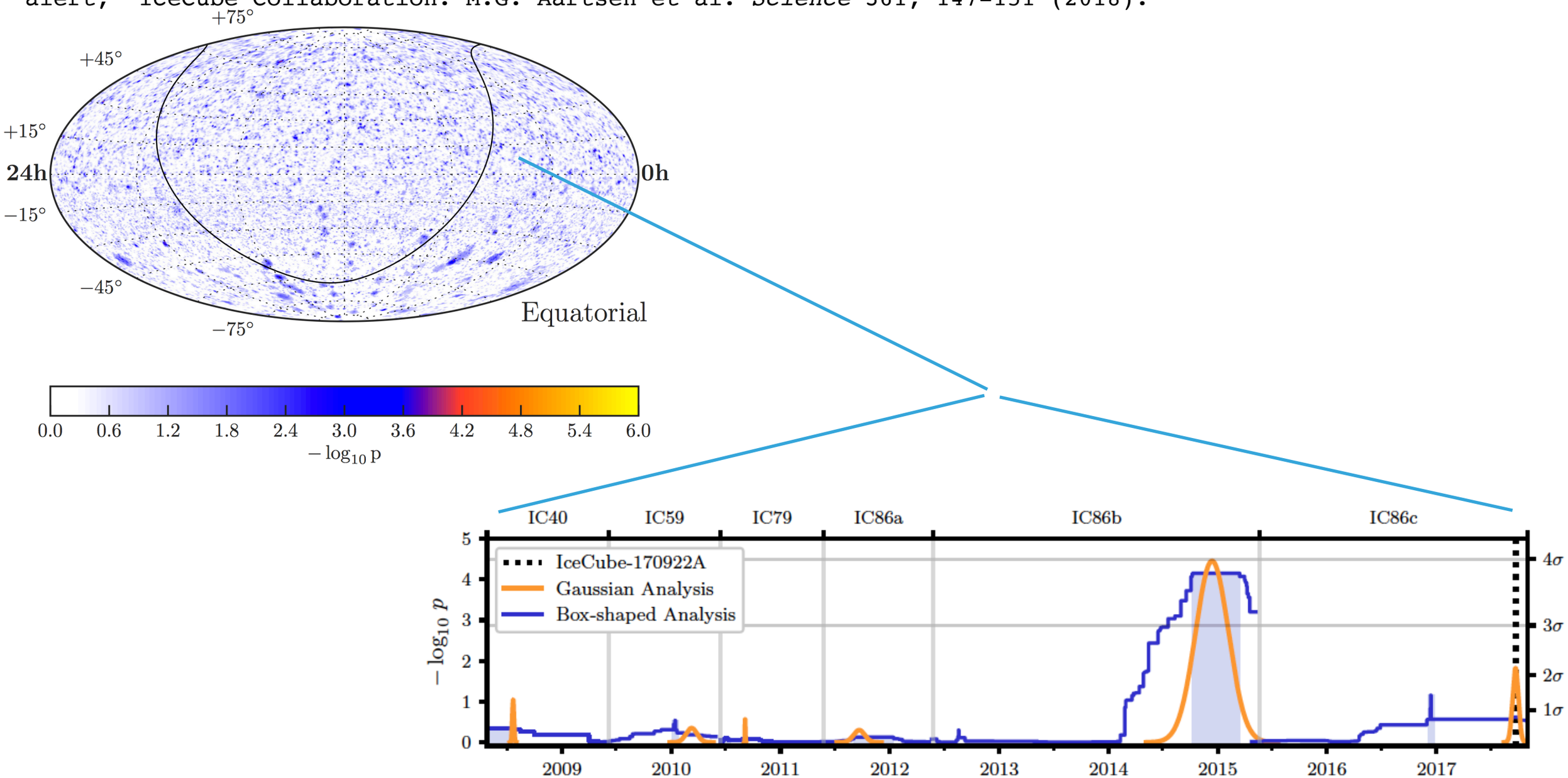
Step II: Are there any extra-galactic Fermi source close in space to the neutrinos?



Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

THE ICECUBE FOLLOWUP: THERE ARE MORE NEUTRINOS!!

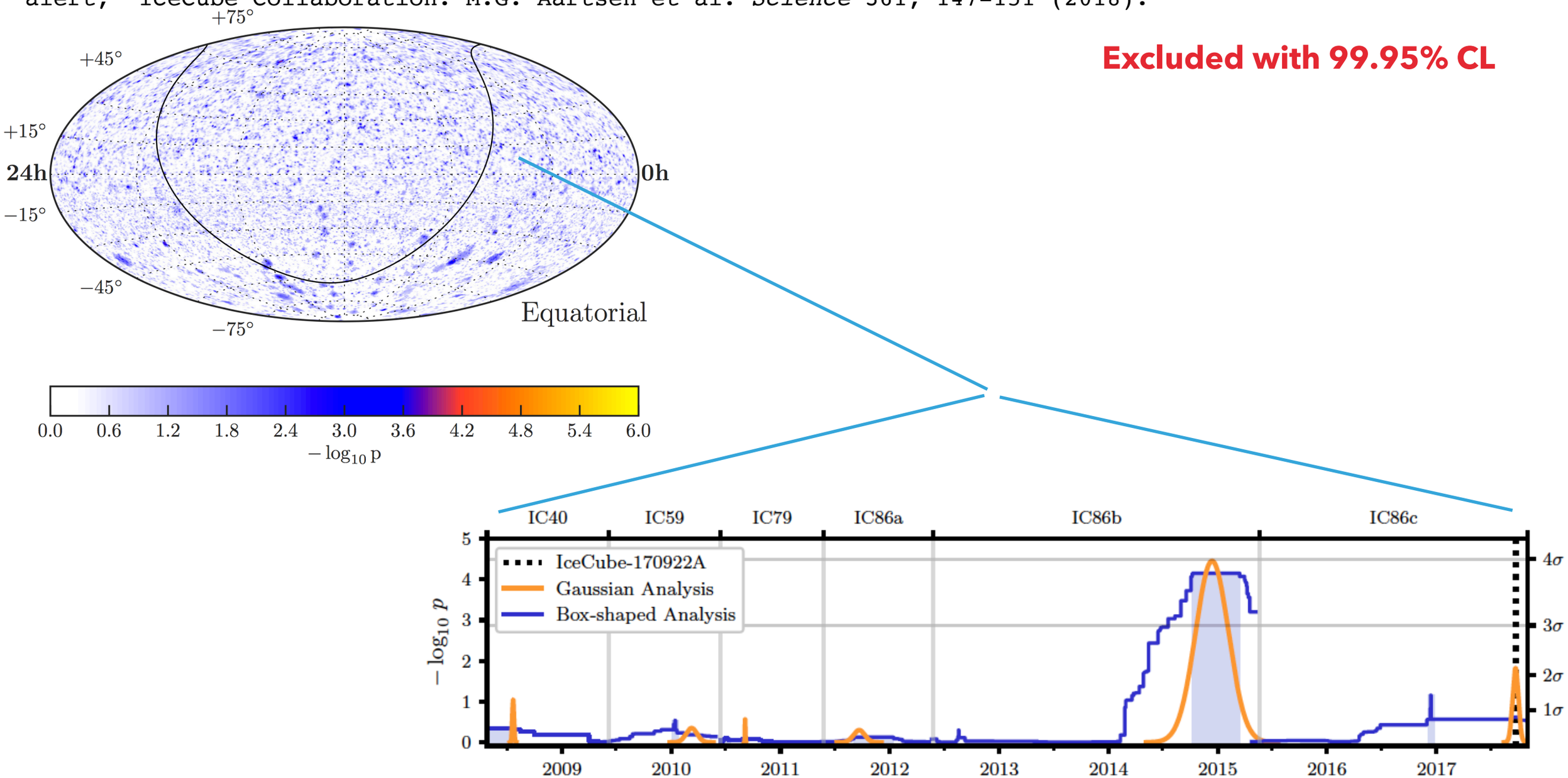
"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert," IceCube Collaboration: M.G. Aartsen et al. *Science* 361, 147-151 (2018).



THE ICECUBE FOLLOWUP: BACKGROUND FLUCTUATION?

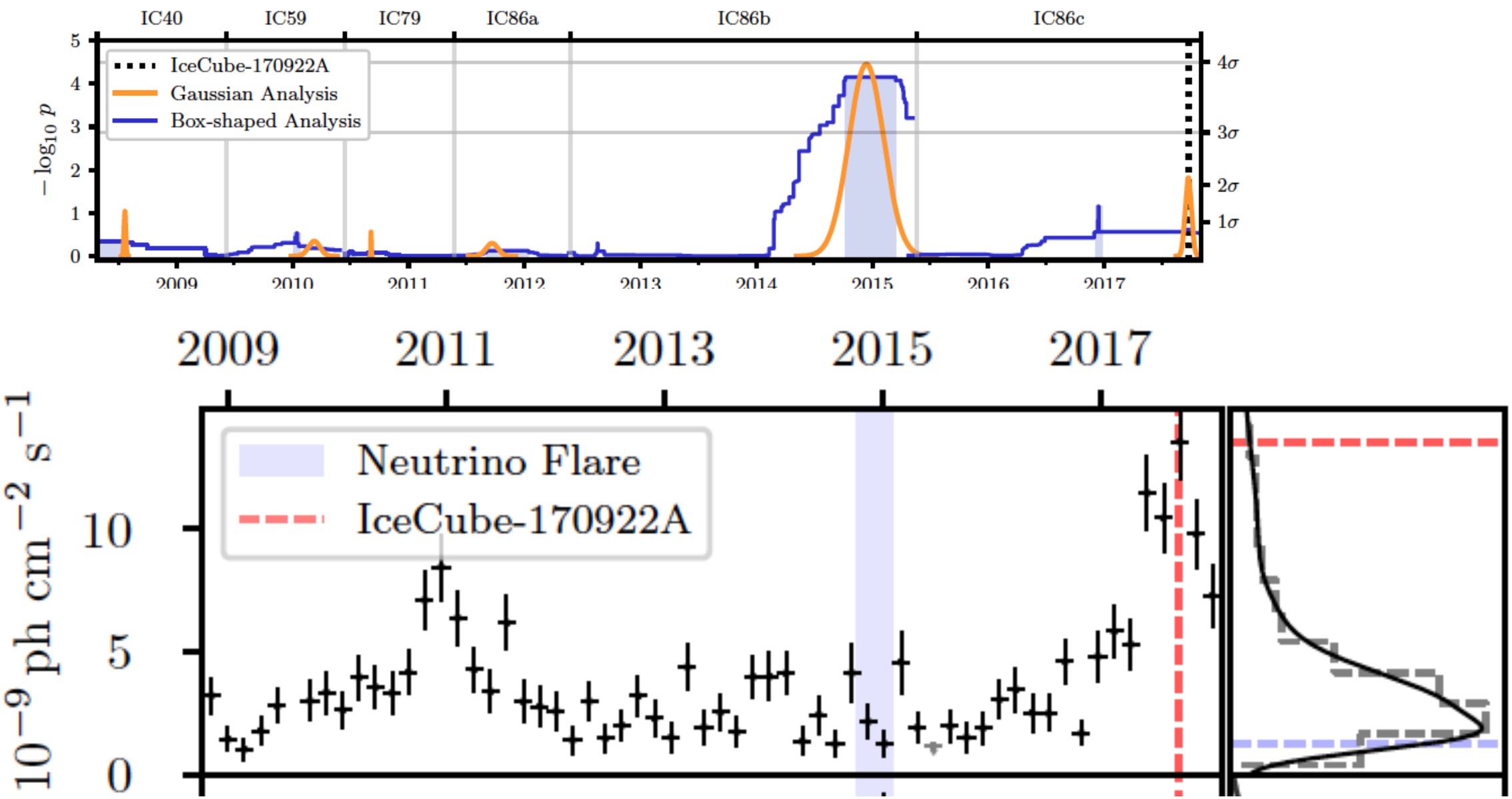
"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert," IceCube Collaboration: M.G. Aartsen et al. *Science* 361, 147-151 (2018).

Excluded with 99.95% CL



THE ICECUBE FOLLOWUP: WHAT ABOUT THE GAMMA-RAY?

"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert," IceCube Collaboration: M.G. Aartsen et al. *Science* 361, 147-151 (2018).



LET'S DISSECT THE REGION AROUND ICECUBE-170922A

(1) first association neutrino alert and a BL Lac in a flaring state;

→ *The IceCube Coll. & partners, "Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", Science 2018*

(2) the evidence of a neutrino flaring activity during 2014 - 2015 from the same direction;

→ *The IceCube Coll., "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert", Science 2018*

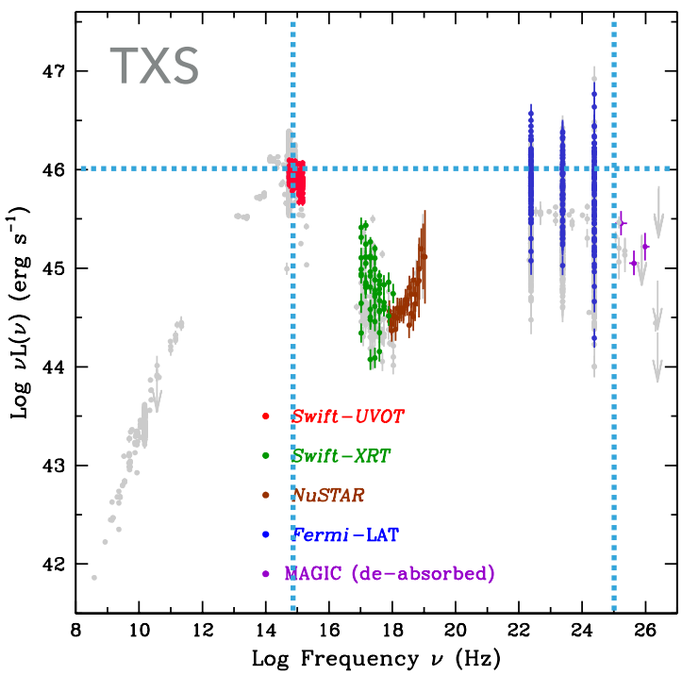
(3) the lack of an accompanying simultaneous gamma-ray enhancement;

(4) the contrasting flaring activity of a neighbouring bright gamma-ray source during 2014-2015.

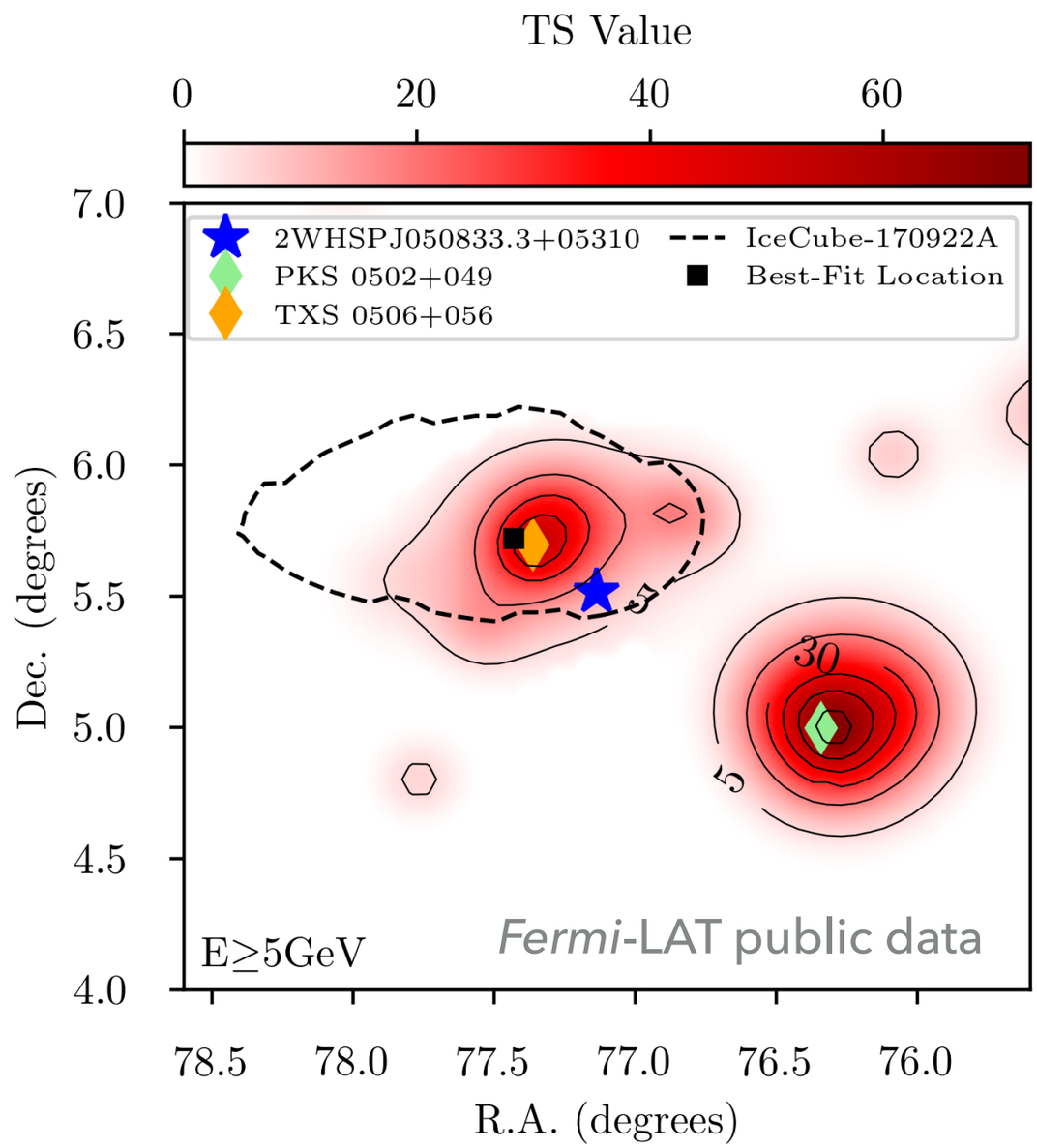
→ *P. Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, N. Sahakyan, M. Huber, "Dissecting the region around IceCube-170922A: TXS 0506+056 as the first cosmic neutrino source", MNRAS 2018*

GAMMA-RAY EMISSION NEAR ICECUBE-170922A: TXS AND PKS

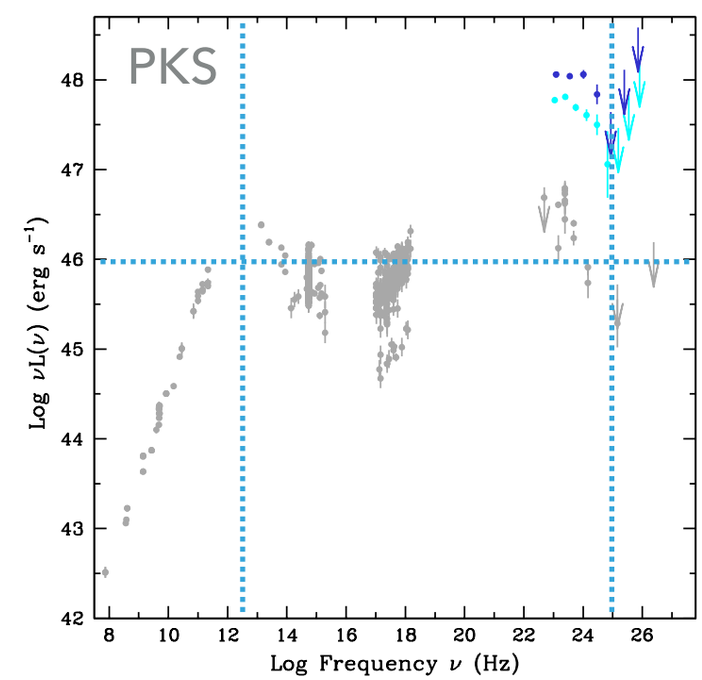
P. Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, N. Sahakyan, M. Huber, "Dissecting the region around IceCube-170922A: TXS 0506+056 as the first cosmic neutrino source", MNRAS 2018



ISP/HSP BL Lac



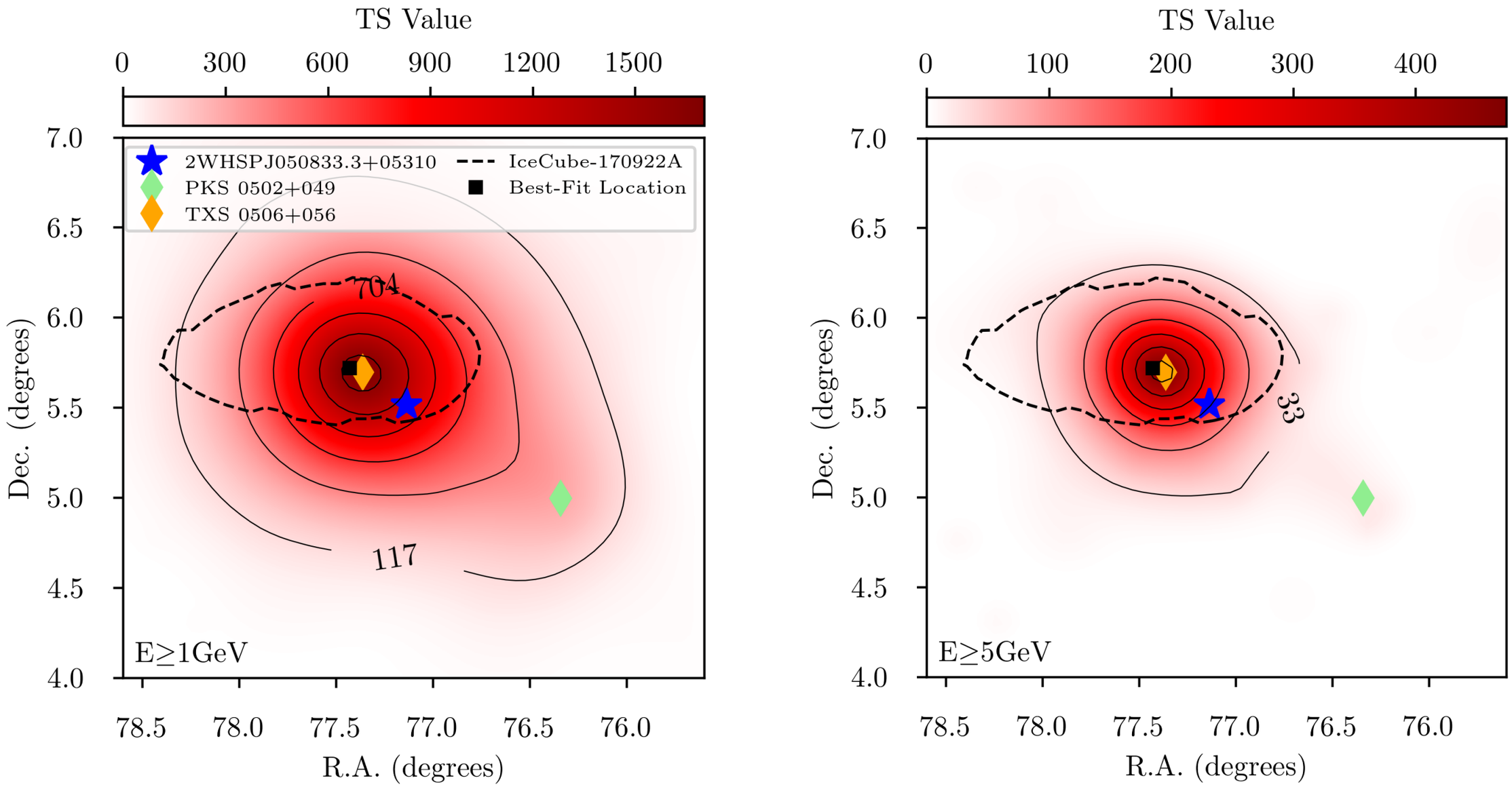
FSRQ



MJD 55762 - 55842 (July 20 - October 8, 2011)

GAMMA-RAY EMISSION NEAR ICECUBE-170922A: TXS AND PKS

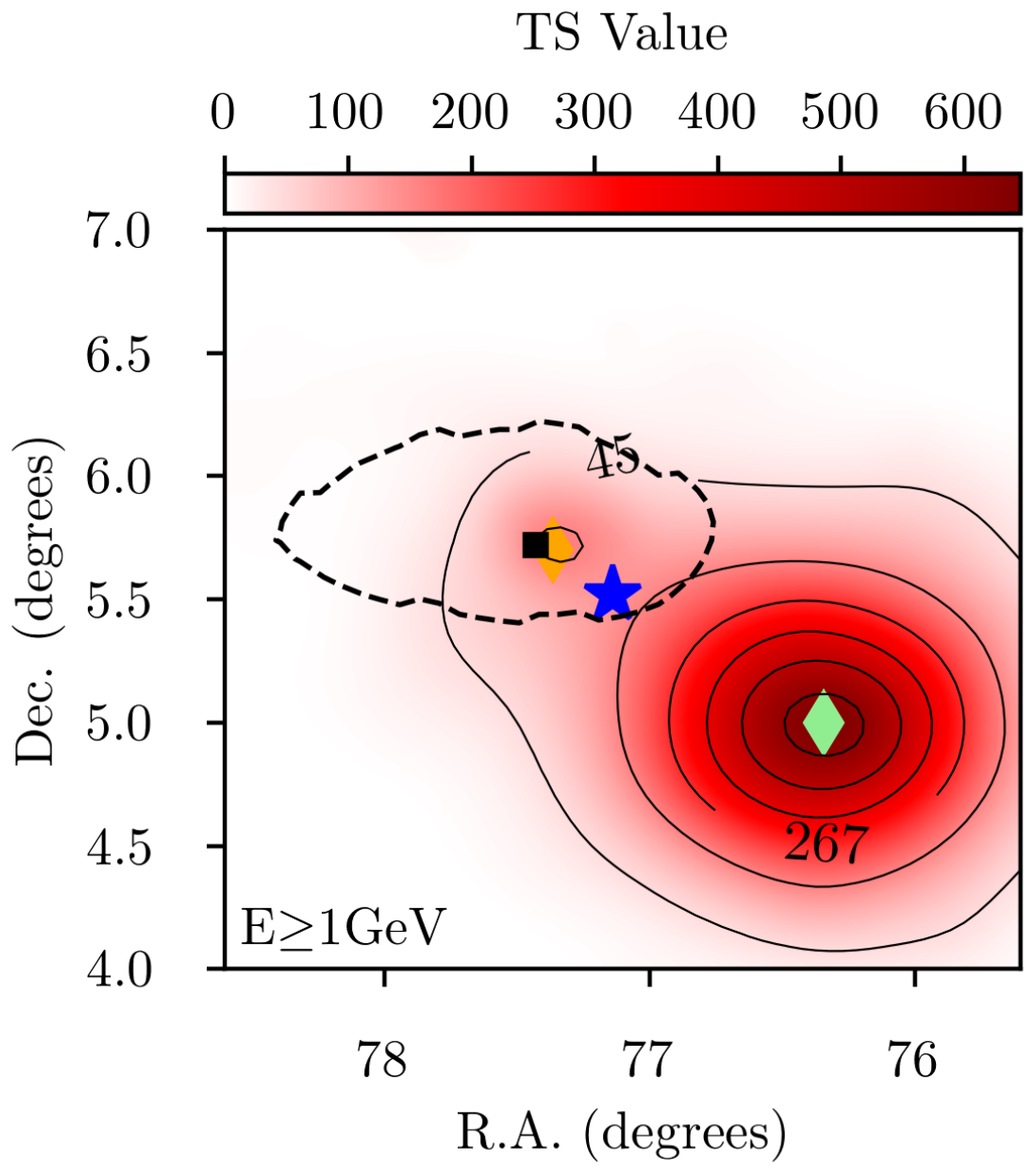
P. Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, N. Sahakyan, M. Huber, "Dissecting the region around IceCube-170922A: TXS 0506+056 as the first cosmic neutrino source", MNRAS 2018



Neutrino alert time: MJD 57908 - 58018 (June 4 - September 22, 2017)

GAMMA-RAY EMISSION NEAR ICECUBE-170922A: TXS AND PKS

P. Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, N. Sahakyan, M. Huber, "Dissecting the region around IceCube-170922A: TXS 0506+056 as the first cosmic neutrino source", MNRAS 2018



Neutrino flare time: MJD 56949 - 57059 (October 19, 2014 - February 6, 2015)

GAMMA-RAY EMISSION NEAR ICECUBE-170922A: TXS AND PKS

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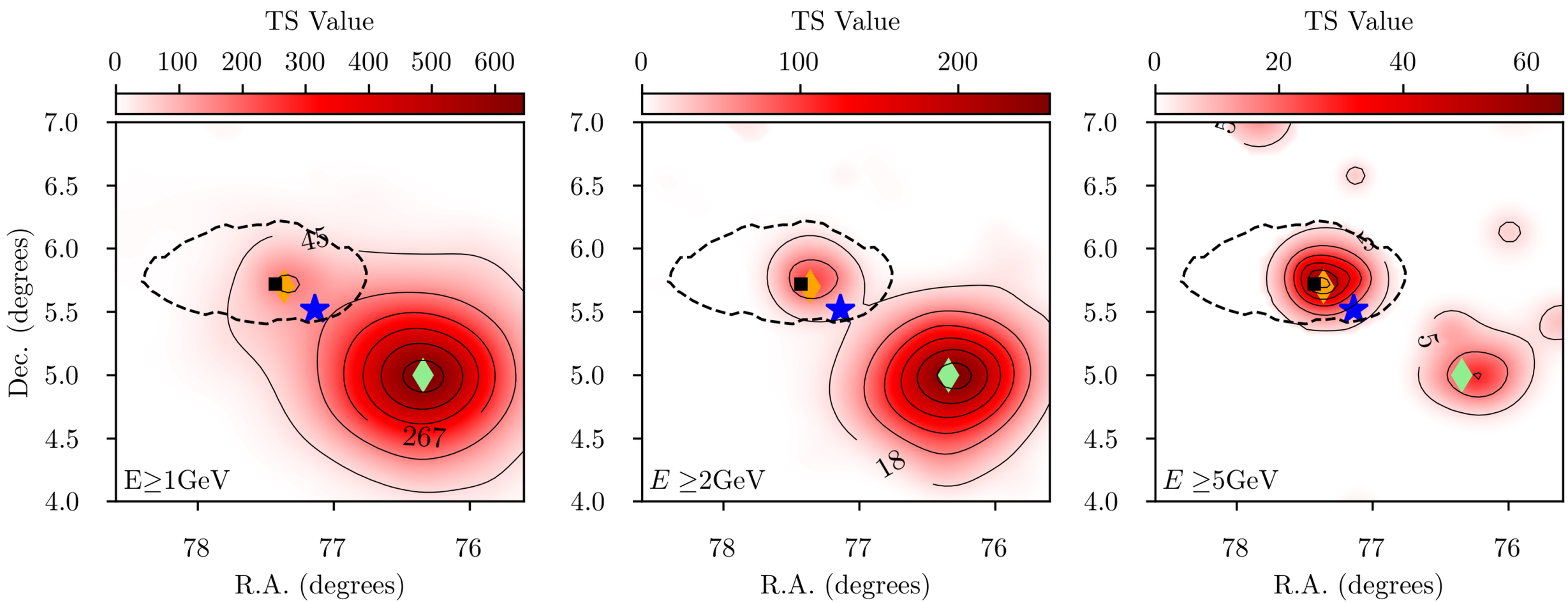
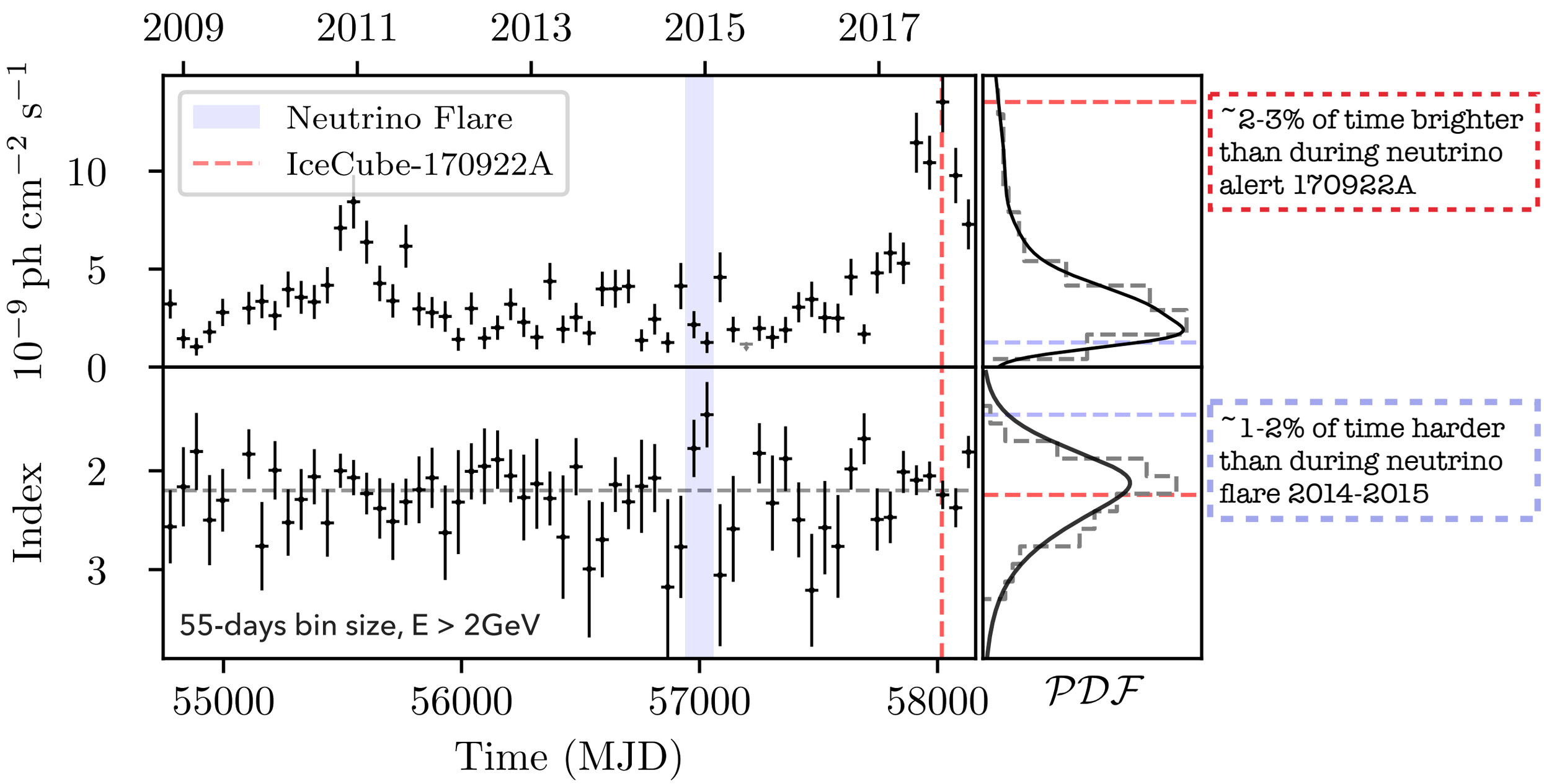


Neutrino flare time: MJD 56949 - 57059 (October 19, 2014 - February 6, 2015)

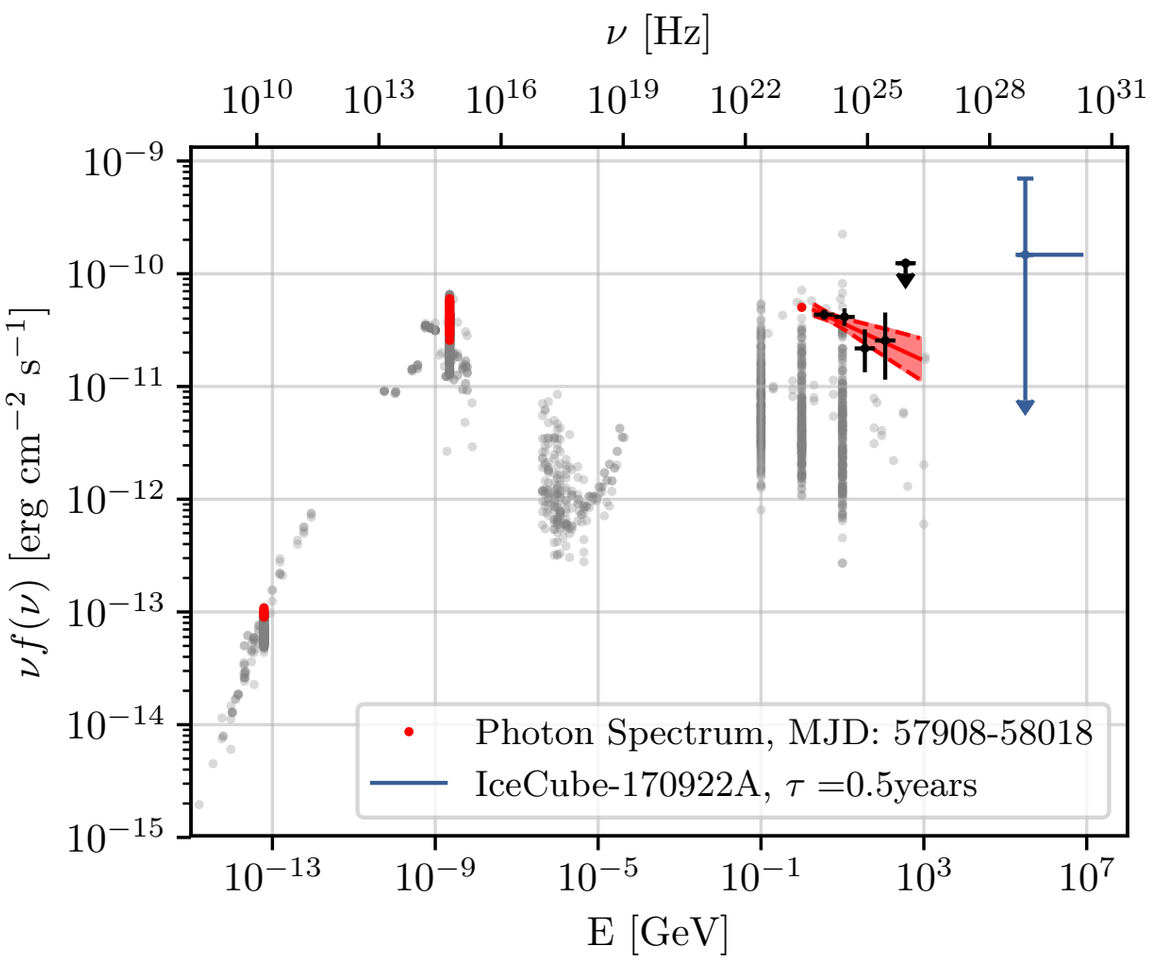
GAMMA-RAY LIGHT CURVES: TXS 0506+056



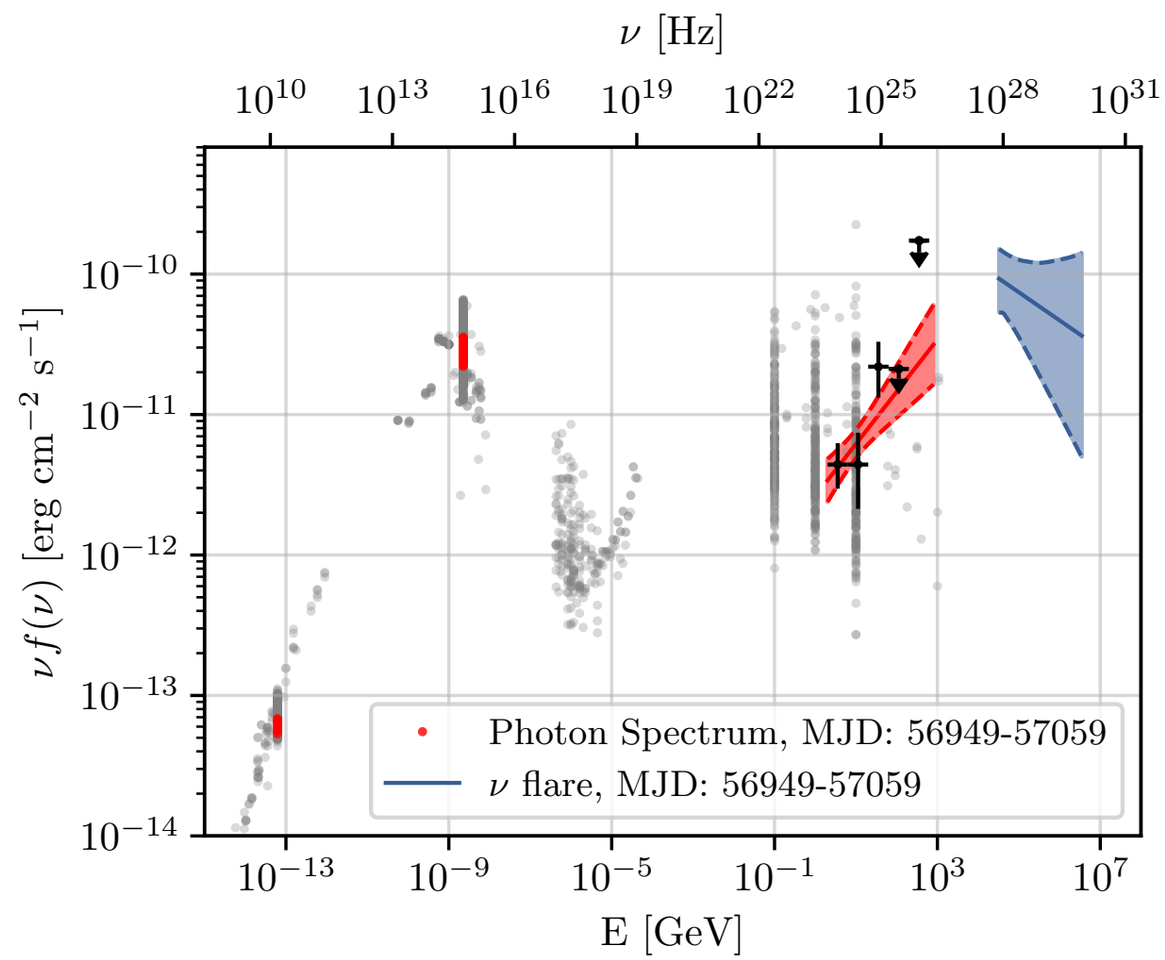
THE PHOTON – NEUTRINO SPECTRAL ENERGY DISTRIBUTION OF TXS 0506+056

P. Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, N. Sahakyan, M. Huber, "Dissecting the region around IceCube-170922A: TXS 0506+056 as the first cosmic neutrino source", MNRAS 2018

Neutrino alert 179022A



Neutrino 'flare, 2014-2015



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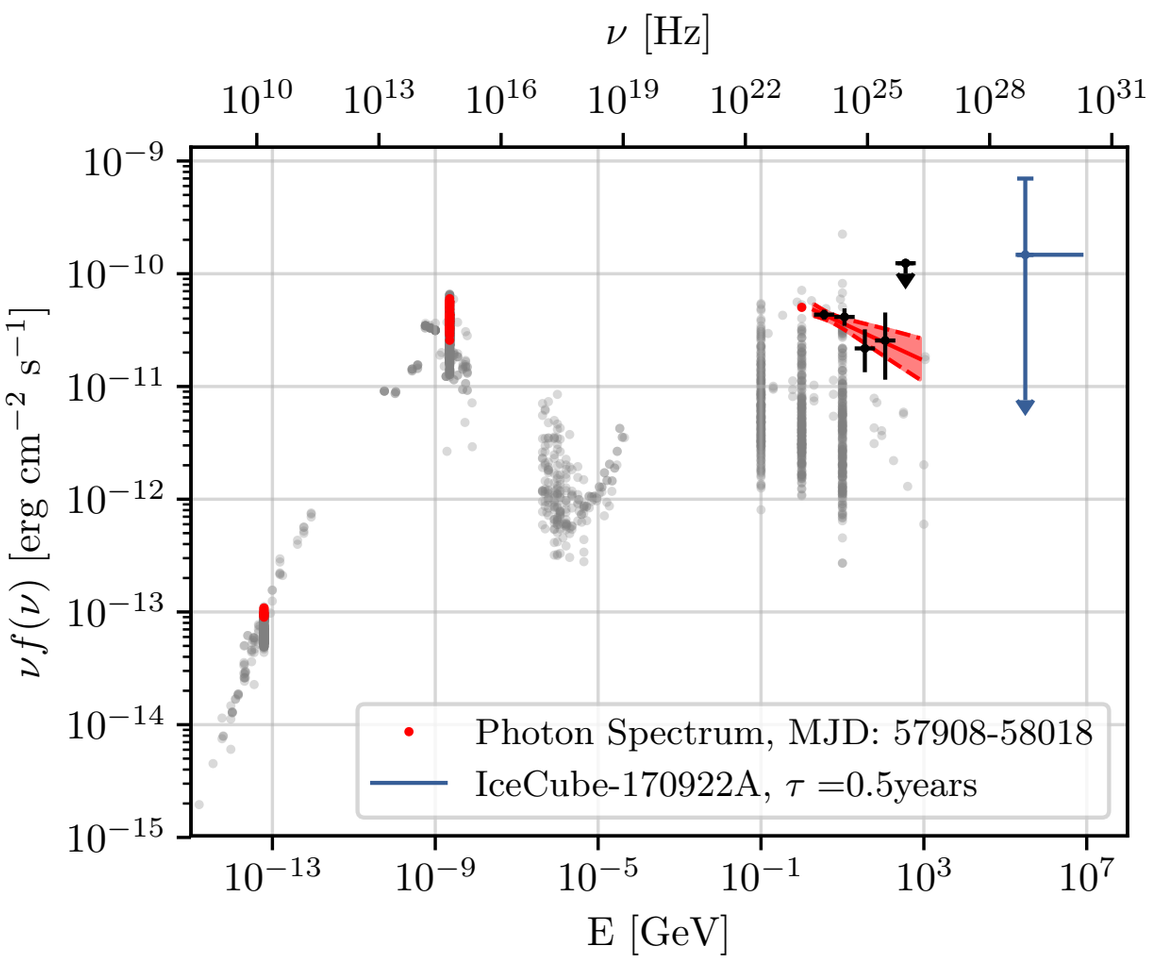

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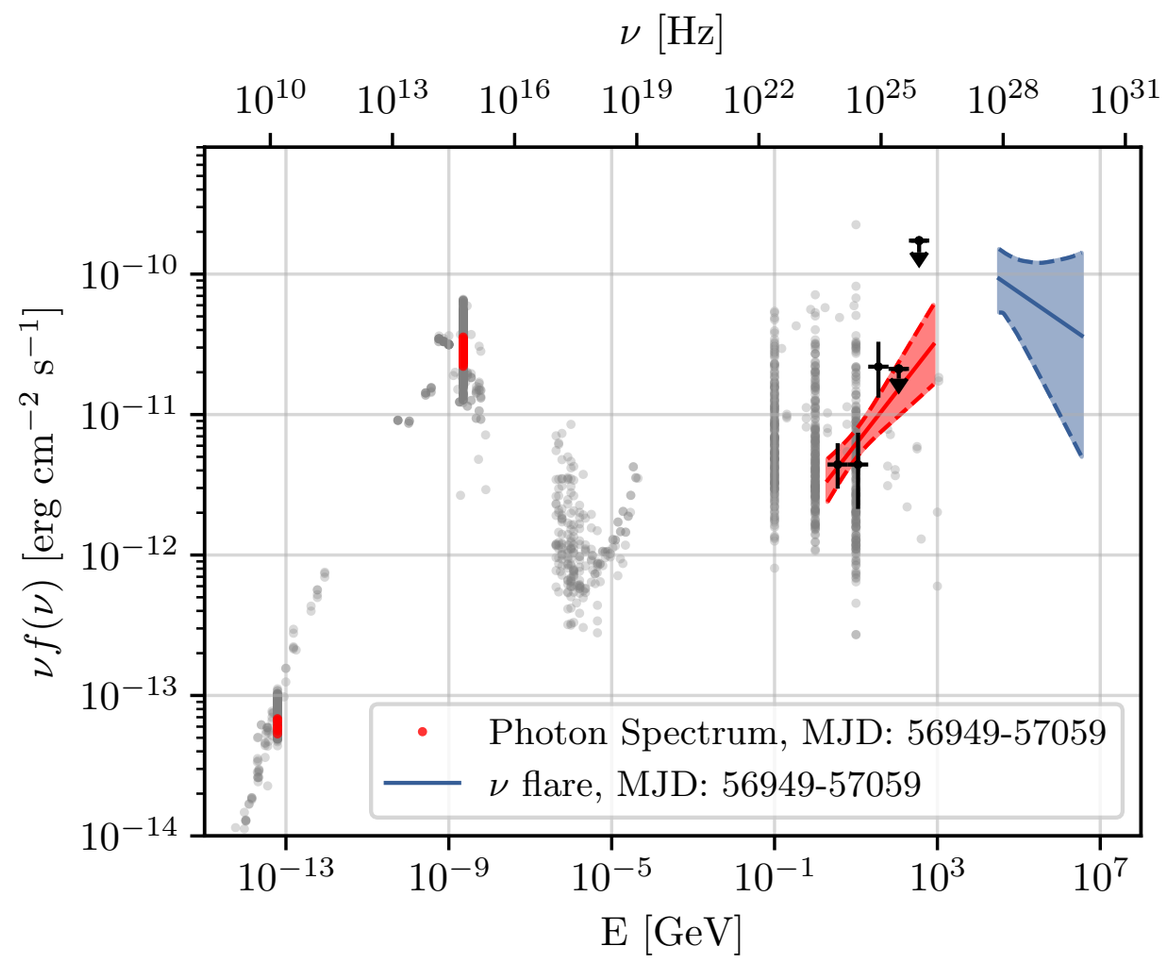

Compelling evidence of first HE neutrino sources

... limited by too few photons and too few neutrinos

IN SUMMARY

Neutrinos in IceCube are opening a new window into the cosmos:

- Diffuse cosmic neutrinos - two independent channels
- First double shower events
- First Glashow resonance candidate event
- Compelling evidence for the first non-stellar neutrino source: a blazar

IN SUMMARY

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Why the TXS0506+056?

WHY THE TXS0506+056?

- γ-ray: top 4% in *Fermi* 3LAC; average flux (> 100 MeV) 7.1 x 10^{-8} ph cm^{-2} s^{-1}; it also belongs to the 2FHL (>50GeV);
- Radio: top 0.3% of the NRAO VLA Sky Survey, ~1 Jy at 6 cm and ~537 mJy at 20 cm;
- Redshift 0.3365 [Paiano et al., 2018];
- Among the most powerful BL Lacs known:
  - peak luminosities ~2 x 10^{46} erg s^{-1} in the synchrotron peak / 10^{47} erg s^{-1} at 10 GeV;
  - maximum luminosities ever observed in MKN 421 and PKS2155-304 are a factor of 5-50 lower than TXS0506+056 (Giommi et al., in preparation).

+ It is at the horizon where the IceCube sensitivity maximal and no neutrino absorption in the Earth.

IN SUMMARY

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... the case has been made and it is convincing.

Looking forward to the next source!

some extra in case

IN SUMMARY

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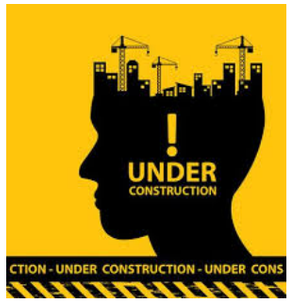
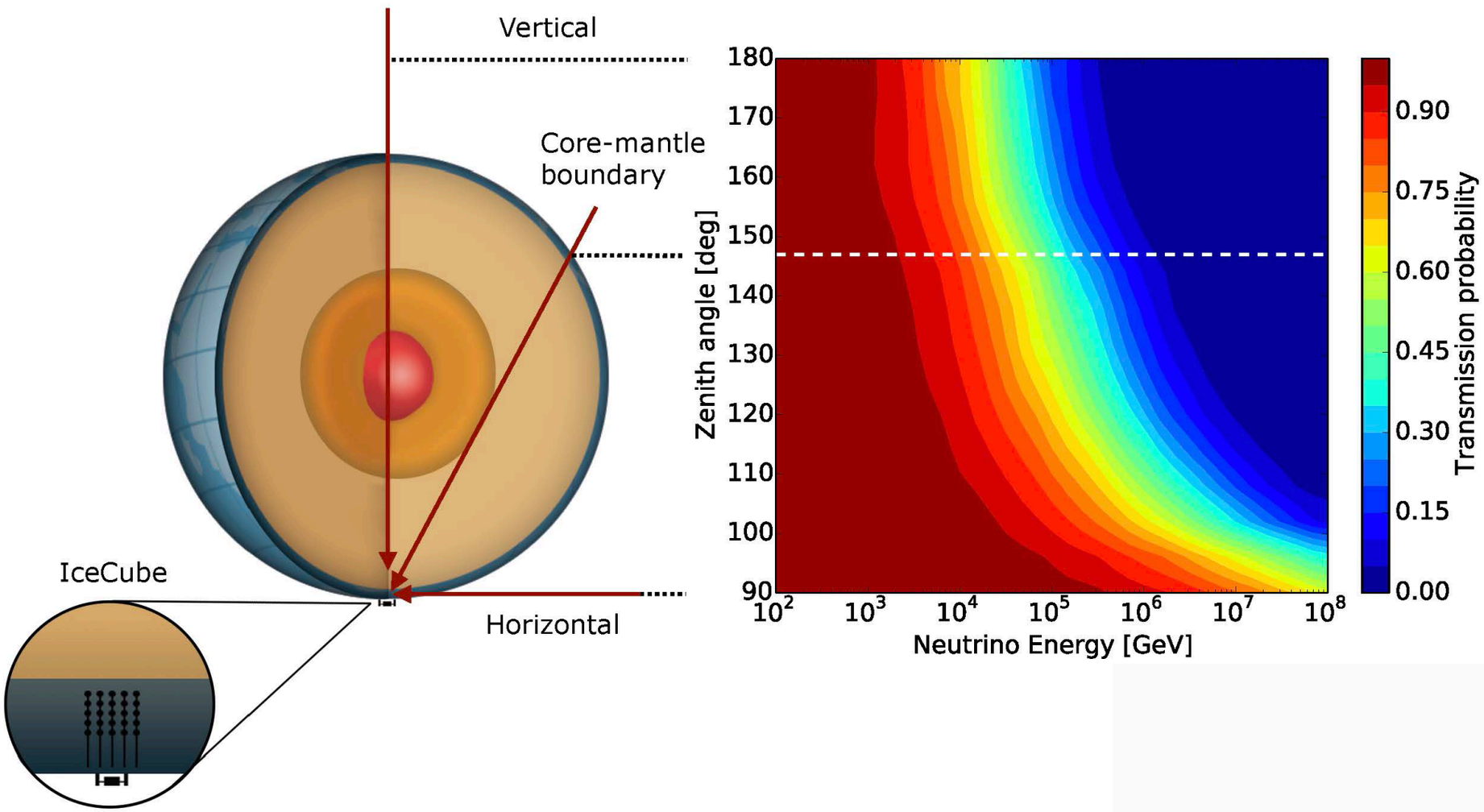
THE FRONTIER: A PLANETARY NEUTRINO TELESCOPE



AT HIGH ENERGY THE EARTH IS OPAQUE TO NEUTRINOS



IceCube Collaboration, "Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption," *Nature 551 (2017) 596-600.*

THE FRONTIER: A PLANETARY NEUTRINO TELESCOPE

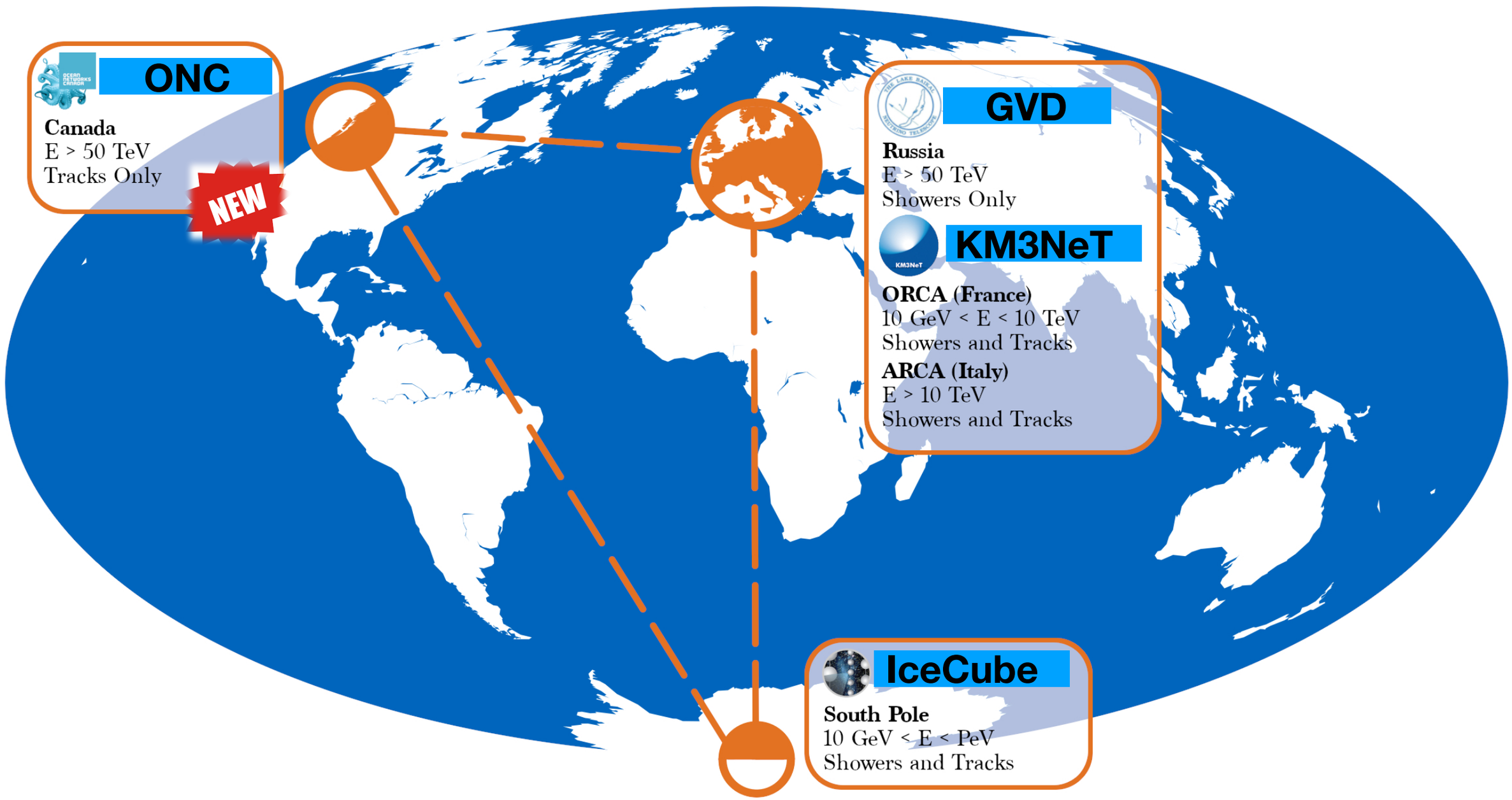
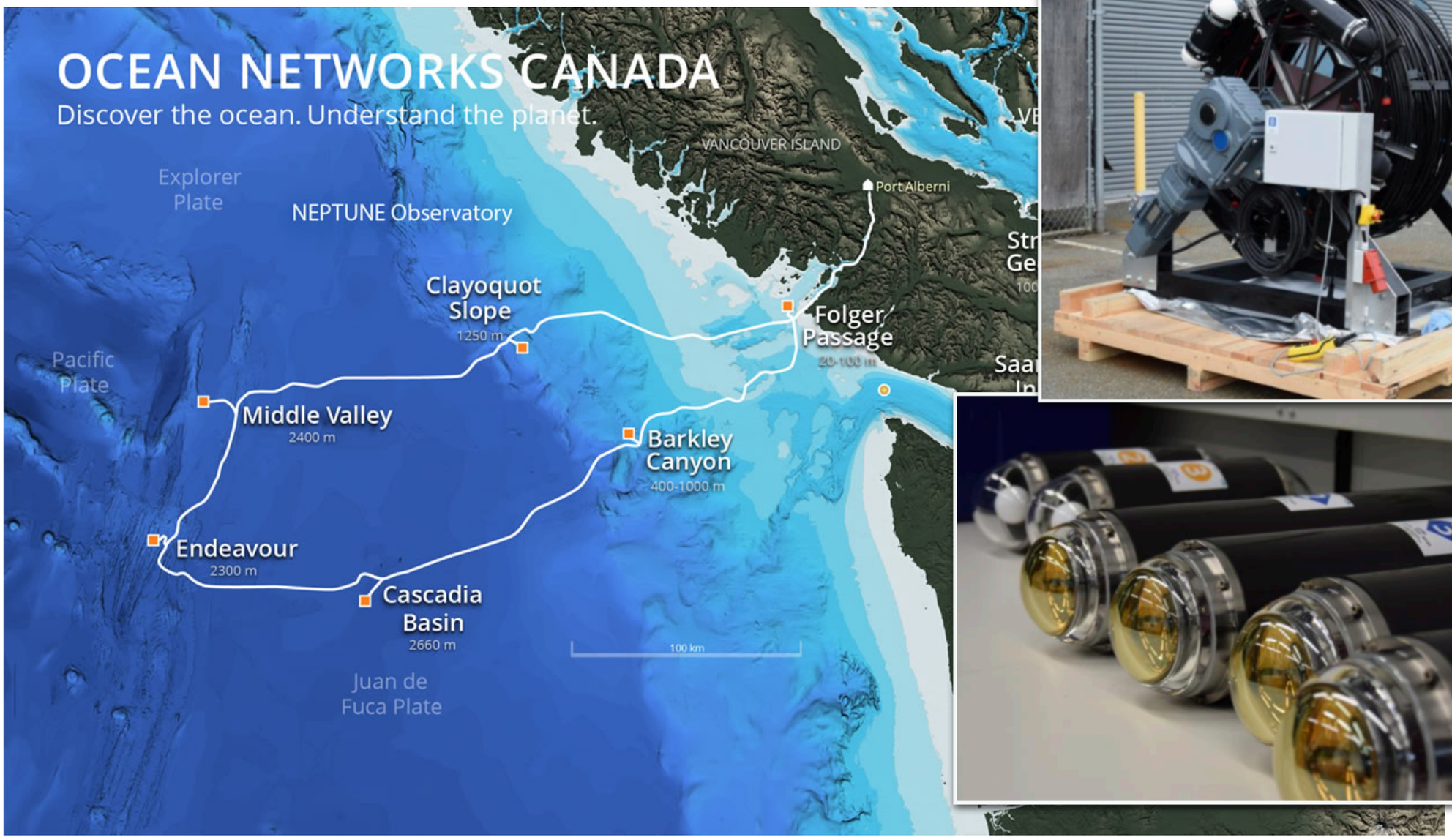


Image: A. Turcati (TUM)

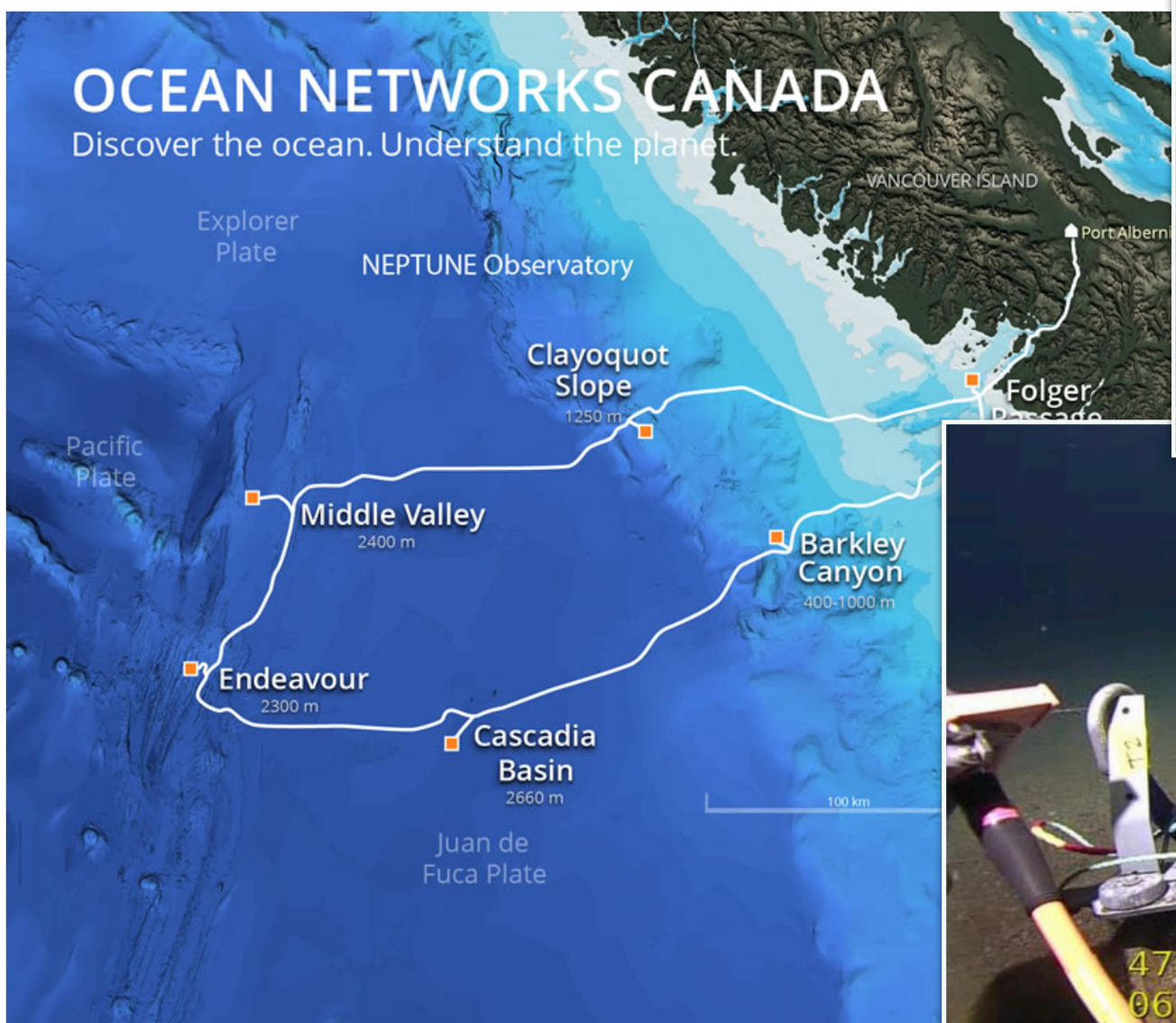
IceCube Upgrade 2022-24

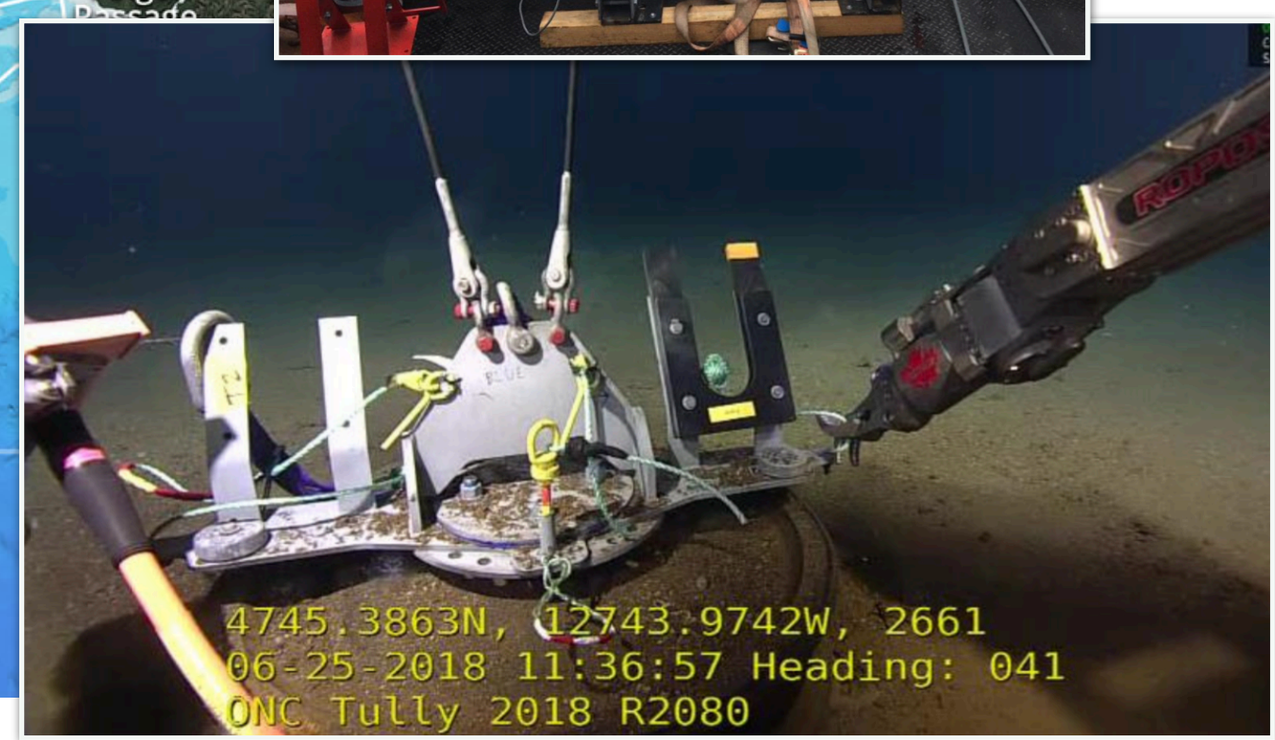
THE FRONTIER: NEW ENTRY ON THE NEUTRINO MAP
OCEAN NETWORK CANADA



STRAW Instrumentation (submitted to JINST), https://arxiv.org/abs/1810.13265

THE FRONTIER: NEW ENTRY ON THE NEUTRINO MAP
OCEAN NETWORK CANAD





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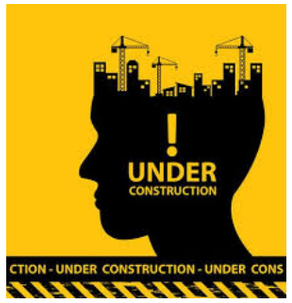


THE FRONTIER: A PLANETARY NEUTRINO TELESCOPE COVER THE HIGH ENERGIES AT THE HORIZON

Field of view at the horizon at a specific moment in time!

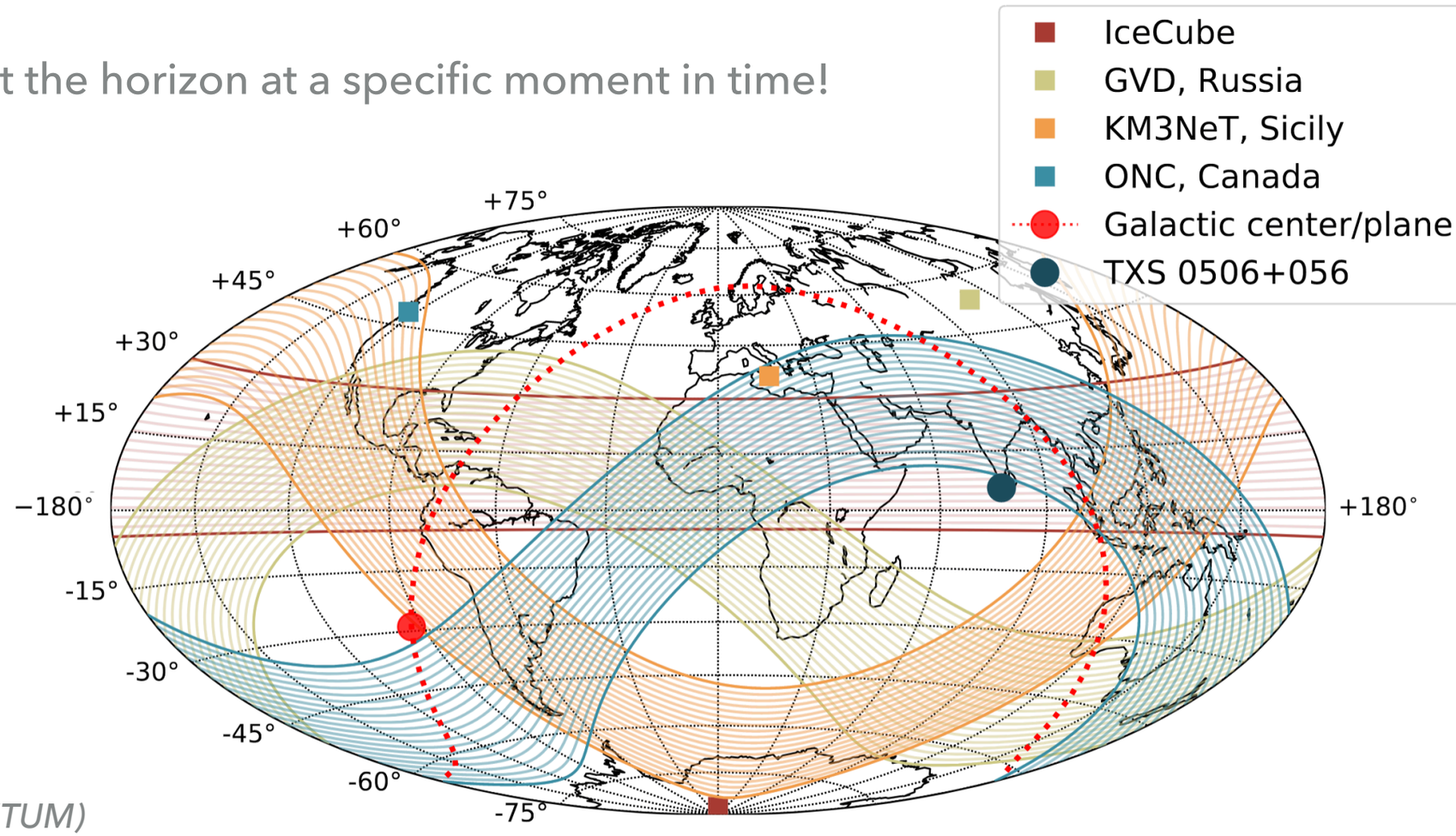
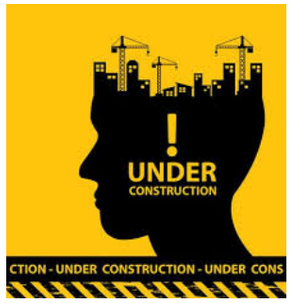


Image: M. Huber (TUM)

COMBINING MORE NEUTRINO TELESCOPES ....

THE FRONTIER: A PLANETARY NEUTRINO TELESCOPE

COVER THE HIGH ENERGIES AT THE HORIZON



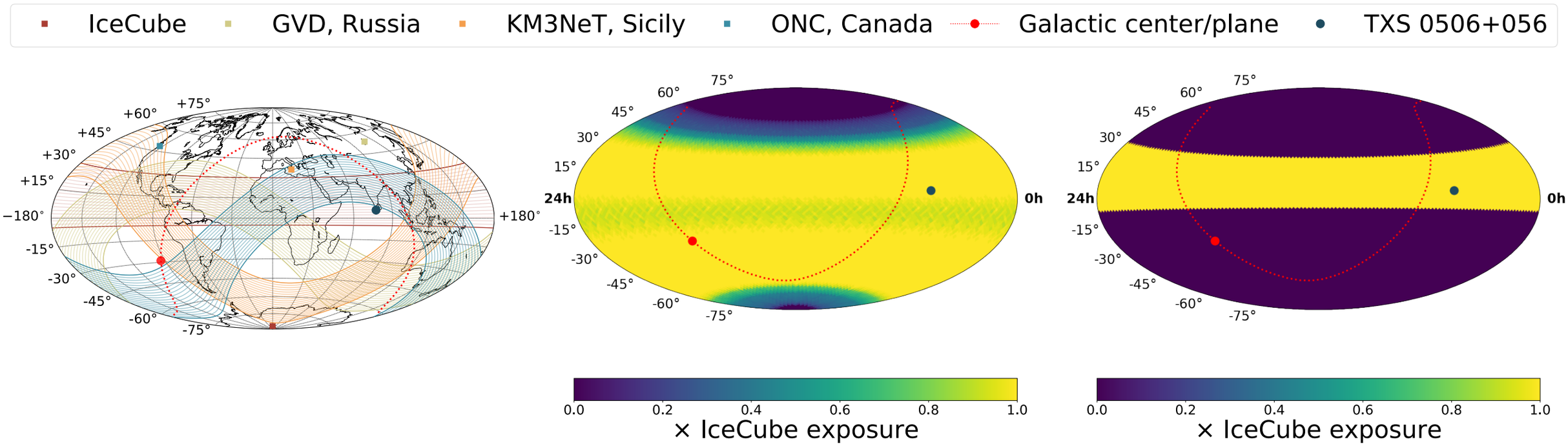


Image: M. Huber (TUM)

Field of view at the horizon combining three neutrino telescopes in the North

Field of view at the horizon of IceCube

THE HYBRID PHOTON – NEUTRINO SED OF TXS 0506+056

Neutrino luminosity:

$$L_\nu = 3 \times L_{\nu_\mu} \sim 1.4^{+0.6}_{-0.5} \times 10^{47} \text{ erg s}^{-1}$$

[32 TeV - 3.6 PeV]

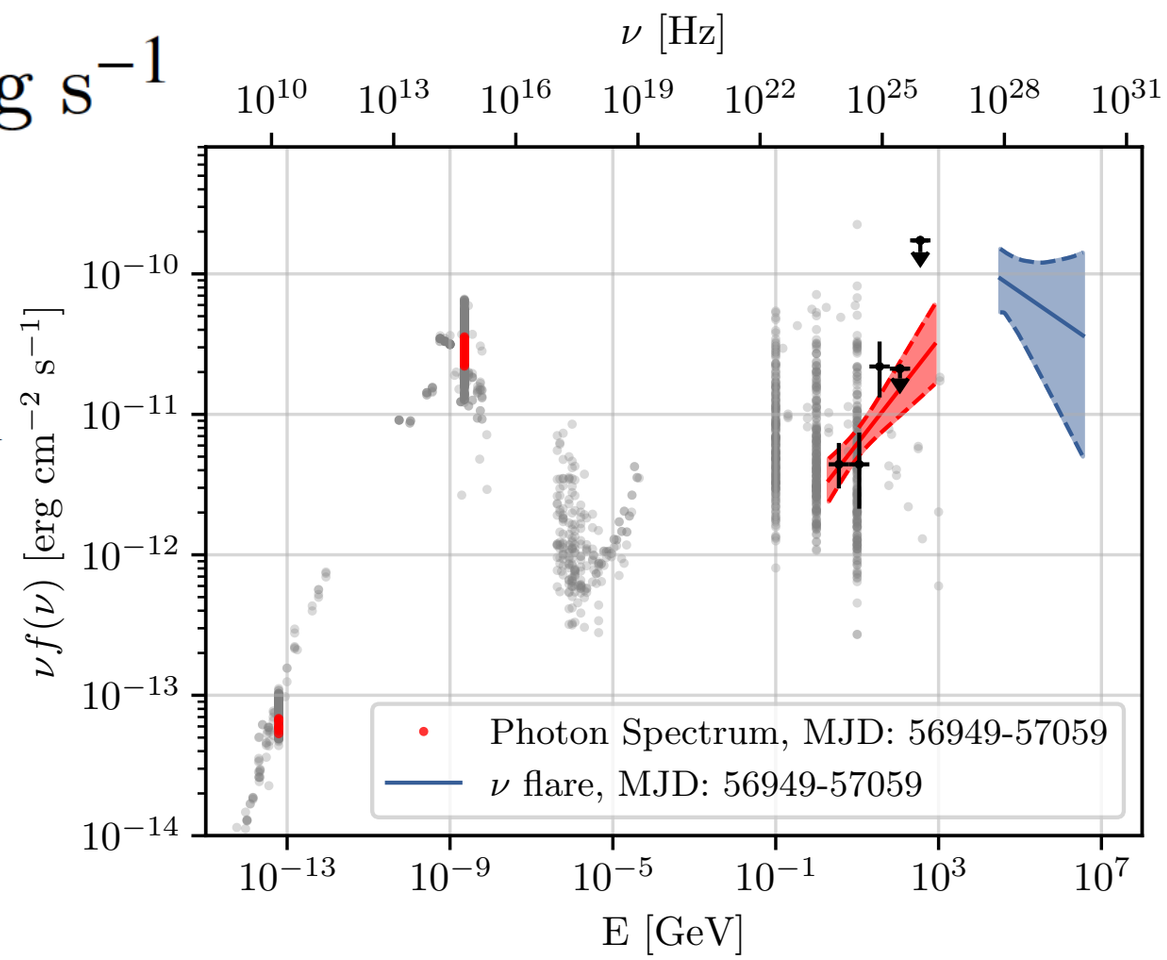
Simultaneous gamma-ray luminosity:

$$L_\gamma \ (2\,\text{GeV} - 1\,\text{TeV}) \sim 3 \times 10^{46} \text{ erg s}^{-1}$$

$$L_\gamma \ (2\,\text{GeV} - 100\,\text{GeV}) \sim 10^{46} \text{ erg s}^{-1}$$

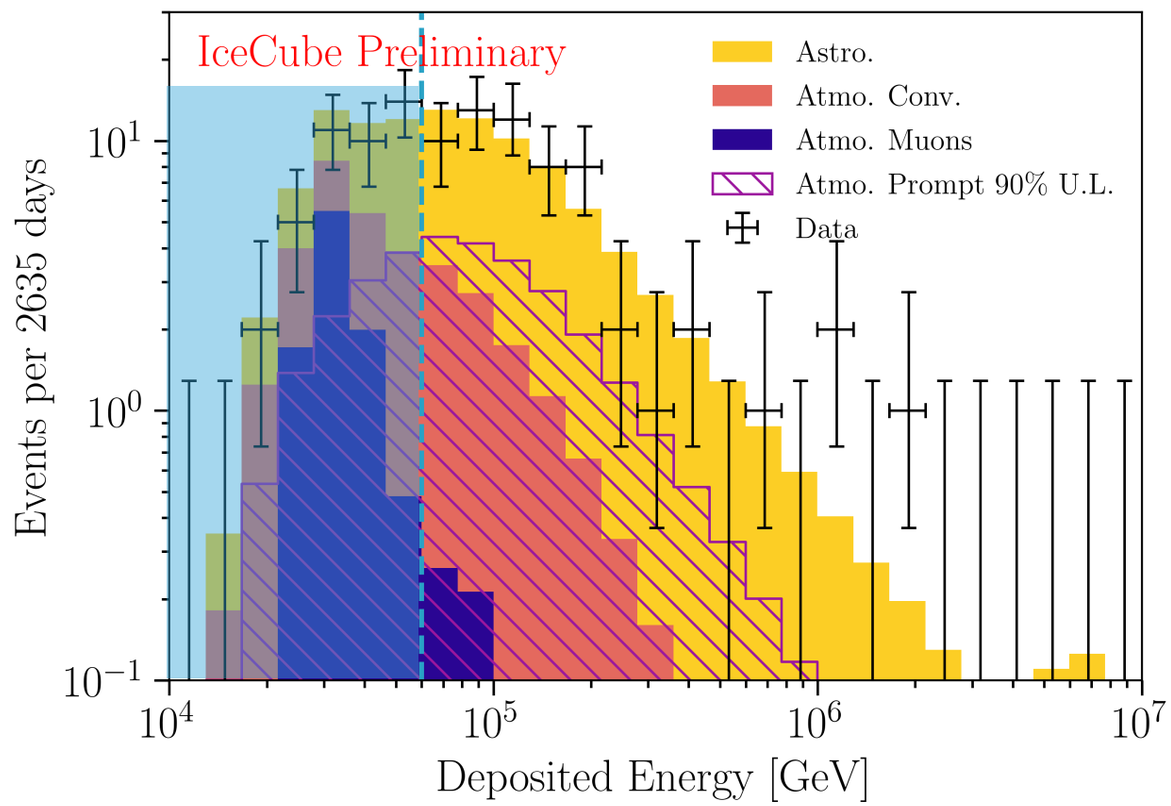
existence of a hadronic component strong enough to explain the bulk of the gamma-ray emission.

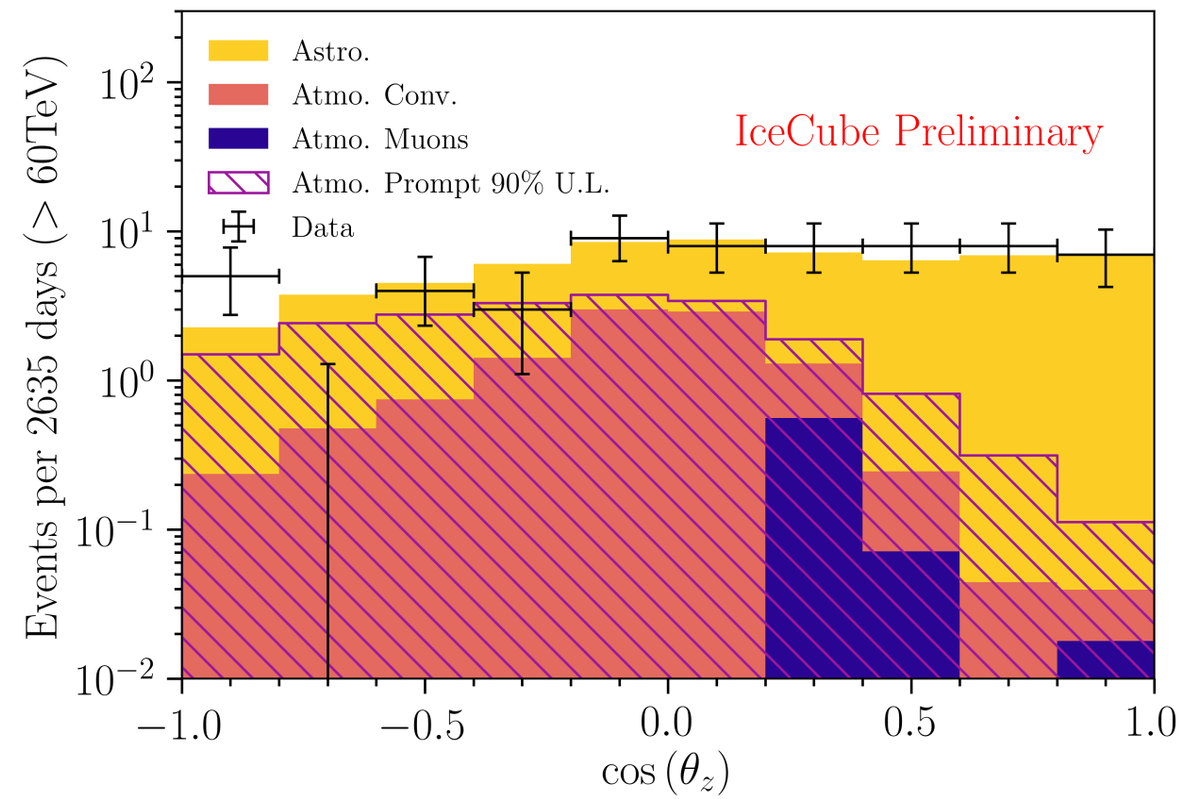
Neutrino 'flare, 2014-2015



HIGH ENERGY, STARTING EVENTS, ALL FLAVOURS (2635 DAYS)

All energies: 102 events; E > 60TeV: 60 events

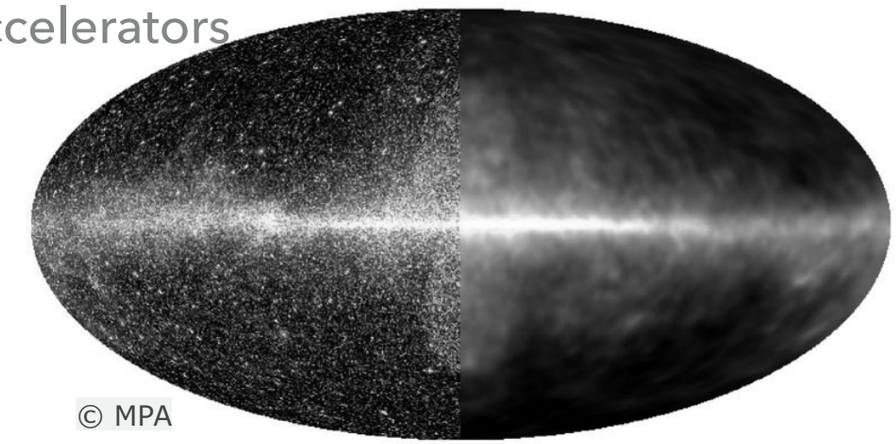




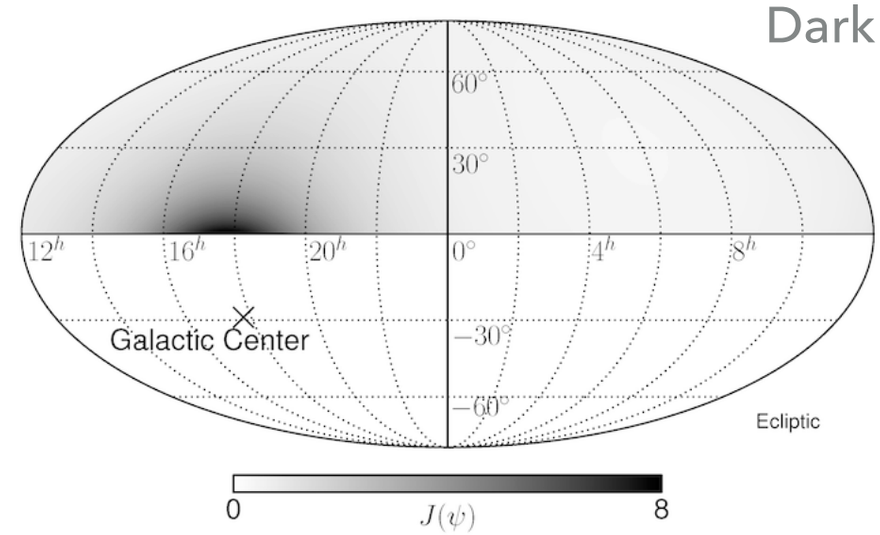
$2.19(+1.10,-0.55)\times E^{-2.91(+0.33,-0.22)}$

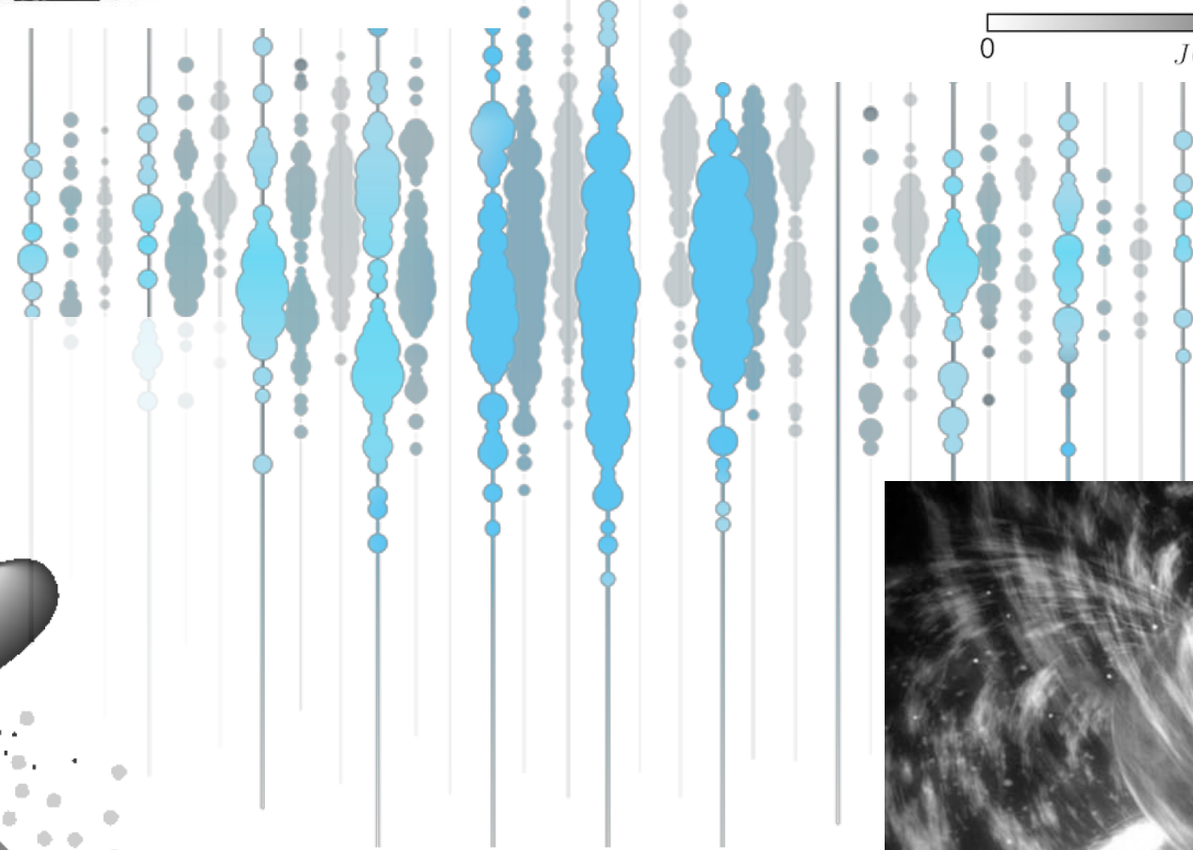
ORIGIN OF HIGH ENERGY COSMIC NEUTRINOS?

Galactic accelerators

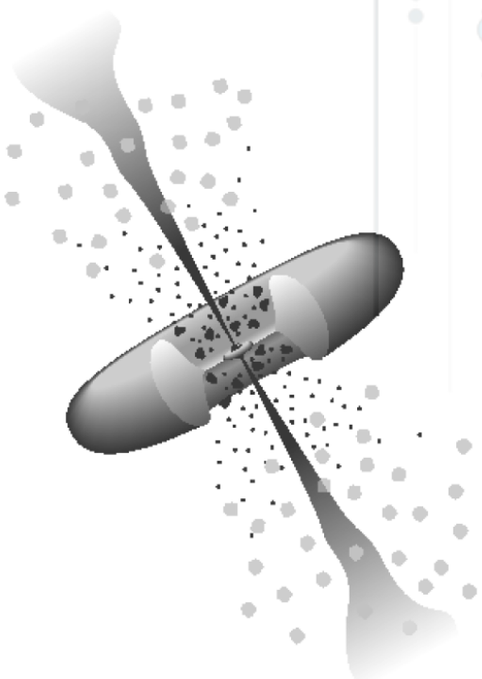


Dark Matter

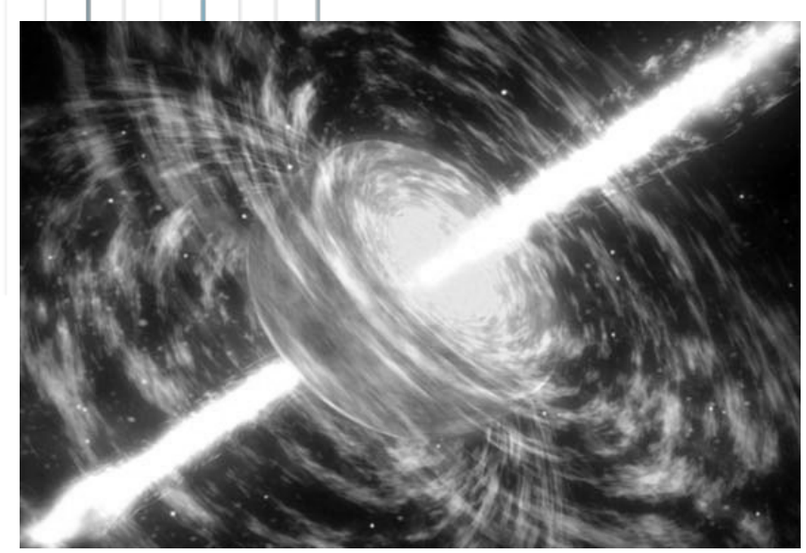




AGN, Blazars



Gamma Ray Bursts



THE DISSECTION BASED ON THE OPEN UNIVERSE TOOL

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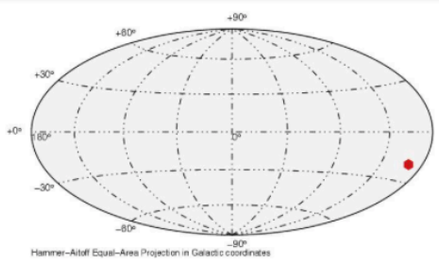


Aitoff coordinates type: **Galactic** - *Equatorial*

Source Name(s) : **5BZBJ0509+0541**

R.A.(J2000) = **05 09 25.96 (77.358167 deg)**

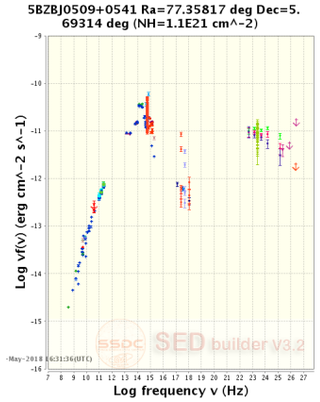
Dec.(J2000) = **+05 41 35.3 (5.693139 deg)**

Version 1.1

Object name or coordinates: 5BZBJ0509+0541 (SSDC)

5BZBJ0509+0541

ESASky | SKY-MAP.ORG | Google Sky | SDSS SkyServer | Aladin Lite | Legacy Surveys | MAST Archive | SuperCOSMOS
Radio Surveys | SSDC Catalogs | Astronomical Catalogs | SkyMapper | CADC Archive | ESO Archive | NOAO Survey Data | NRAO Archive
ALMA Archive | ISDC - HEAVENS | SSDC Archive | Radio Telescope DC | INAF IA2 | Multi-freq. Explorer | VOU SED | SED builder
SED movie | Bibliographic Search



THE ICECUBE REALTIME ALERT SYSTEM

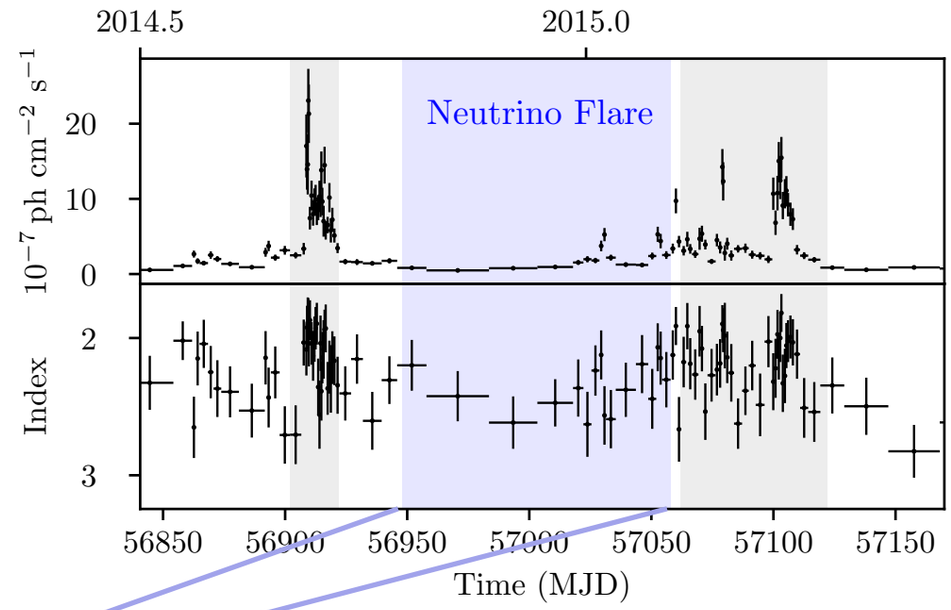
[The IceCube Coll., AstroParticle Phys (2017)]

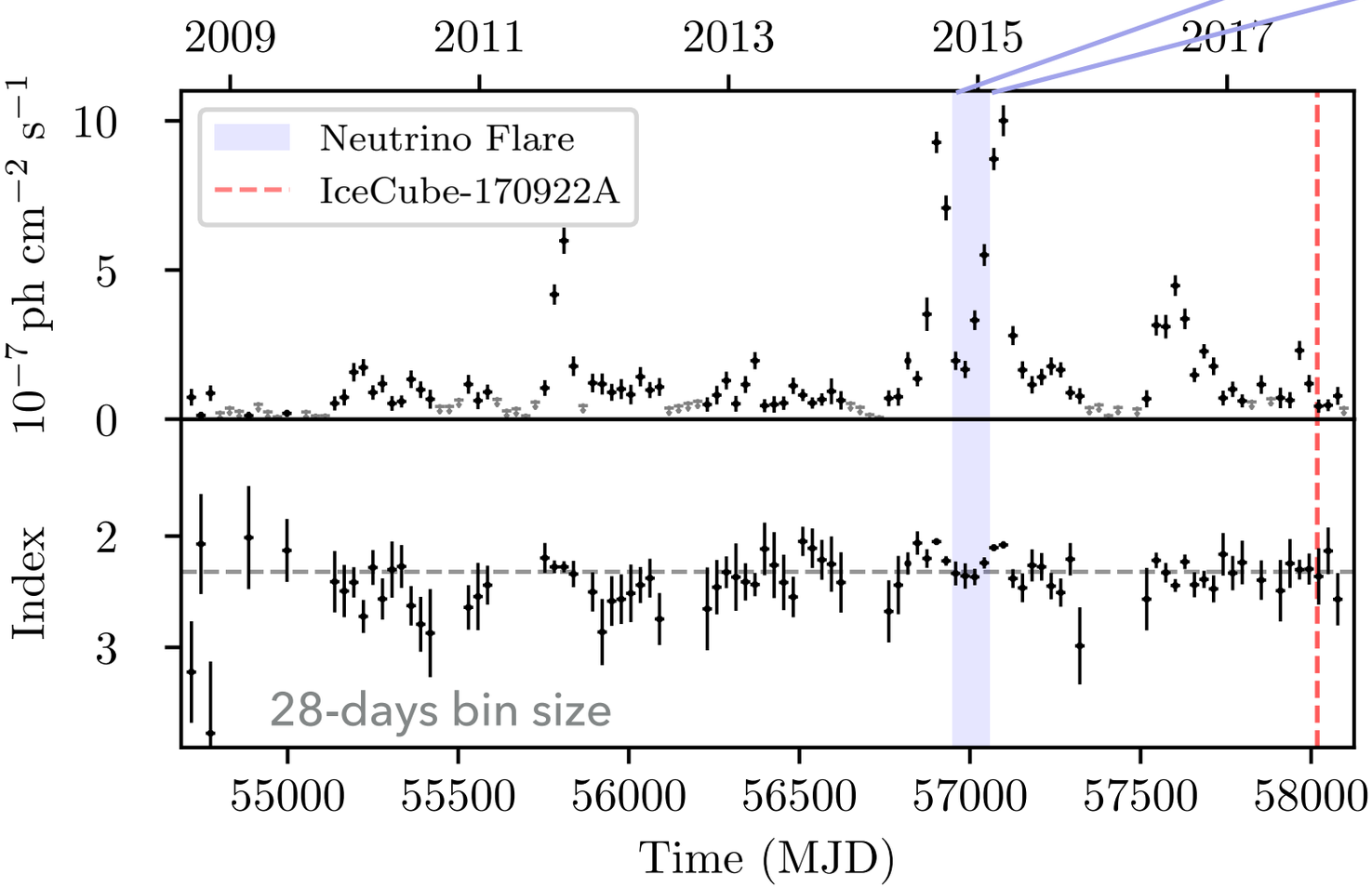
AMON ICECUBE_EHE EVENTS – Since June 2016 archiv		
EventNum_RunNum	Date	Time UT
17569642_130214	17/11/06	20:54:30.43
50579430_130033	17/09/22	18:39:39.21
80305071_129307	17/03/21	07:32:20.69
80127519_128906	16/12/10	20:06:40.31
26552458_128311	16/08/06	12:21:33.00
6888376_128290	16/07/31	01:55:04.00

same event

AMON ICECUBE_HESE EVENTS – Since April 2016 archived at ht		
EventNum_RunNum	Date	Time UT
34032434_130171	17/10/28	08:28:14.81
56068624_130126	17/10/15	1:34:30.06
32674593_129474	17/05/06	12:36:55.80
65274589_129281	17/03/12	13:49:39.83
38561326_128672	16/11/03	09:07:31.12
58537957_128340	16/08/14	21:45:54.00
6888376_128290	16/07/31	01:55:04.00
67093193_127853	16/04/27	05:52:32.00

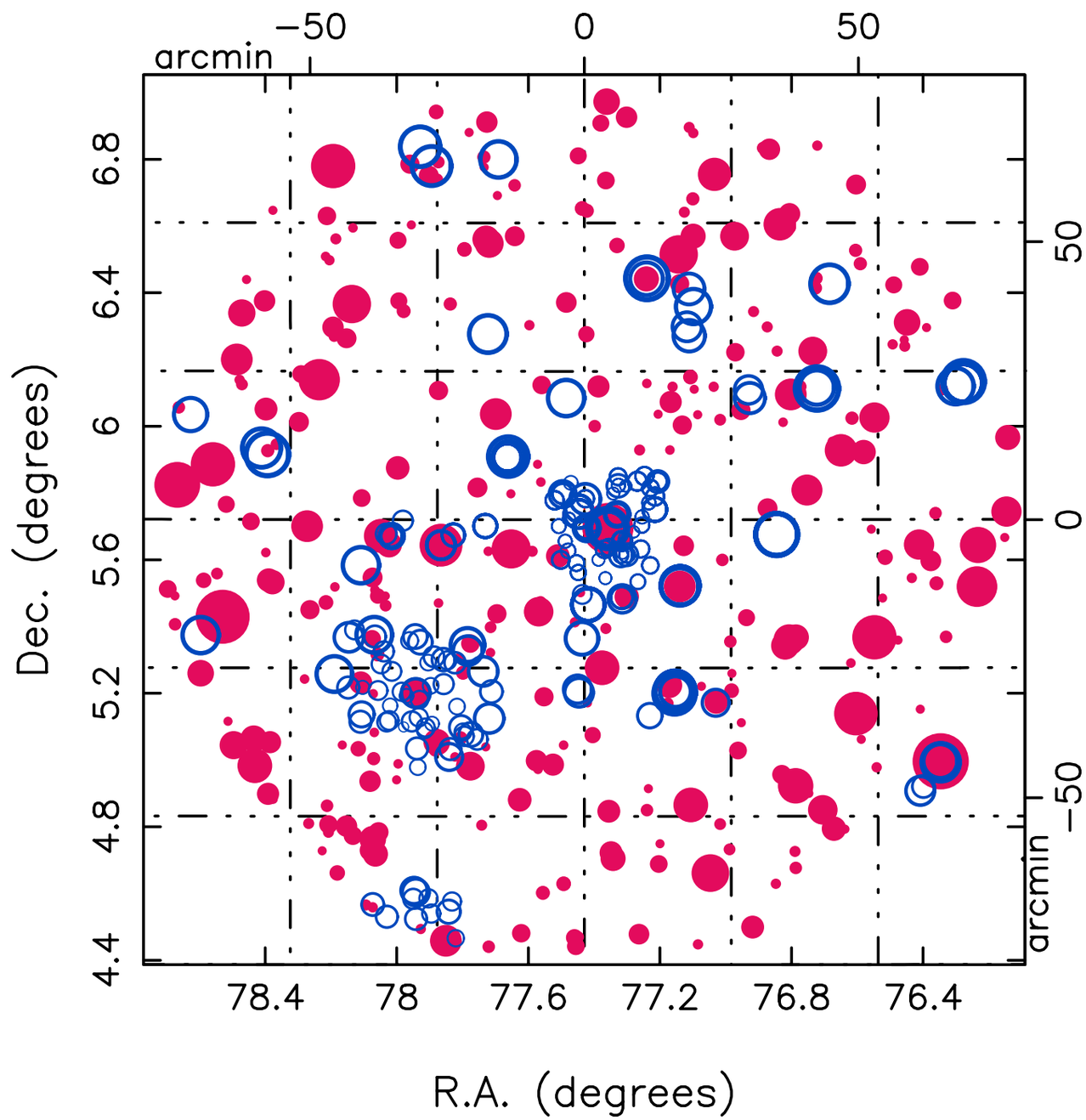
GAMMA-RAY LIGHT CURVES: PKS





ICECUBE-170922A; THE REGION (R = 80 ARCMIN) AROUND

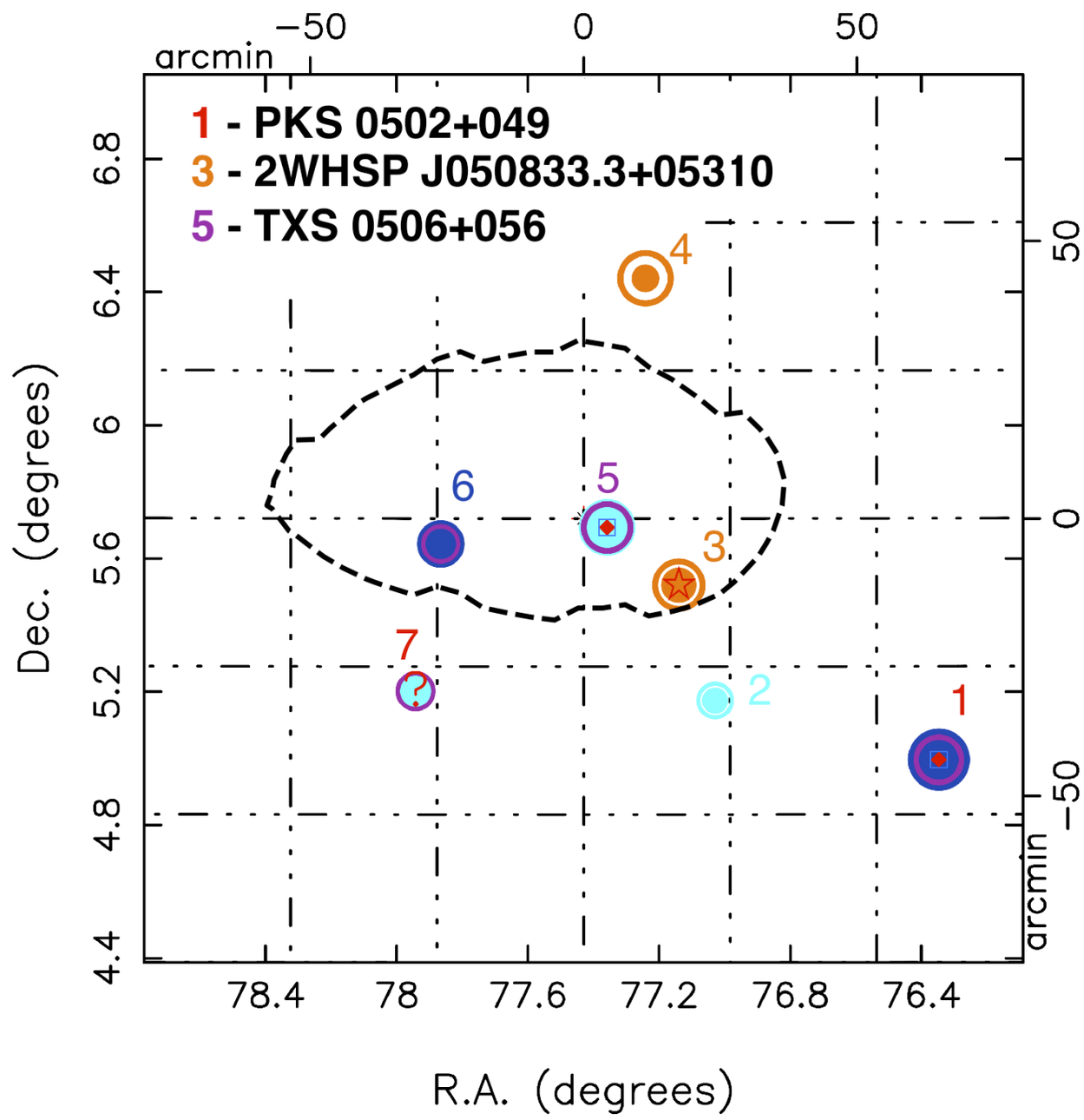
- 637 radio (red) and/or X-ray (blue) sources;
- 7 radio AND X-ray sources;
- all 7 show X-ray to-radio flux ratio blazar-like.



ICECUBE-170922A; THE REGION (R = 80 ARCMIN) AROUND

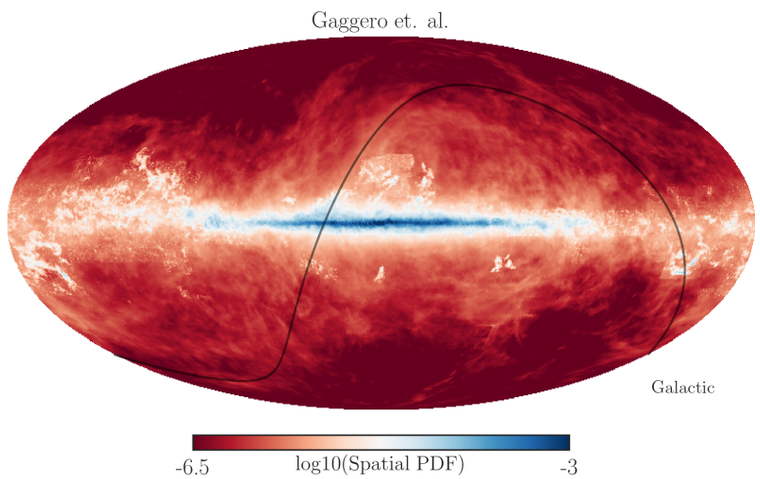
From detailed investigations of the SED:

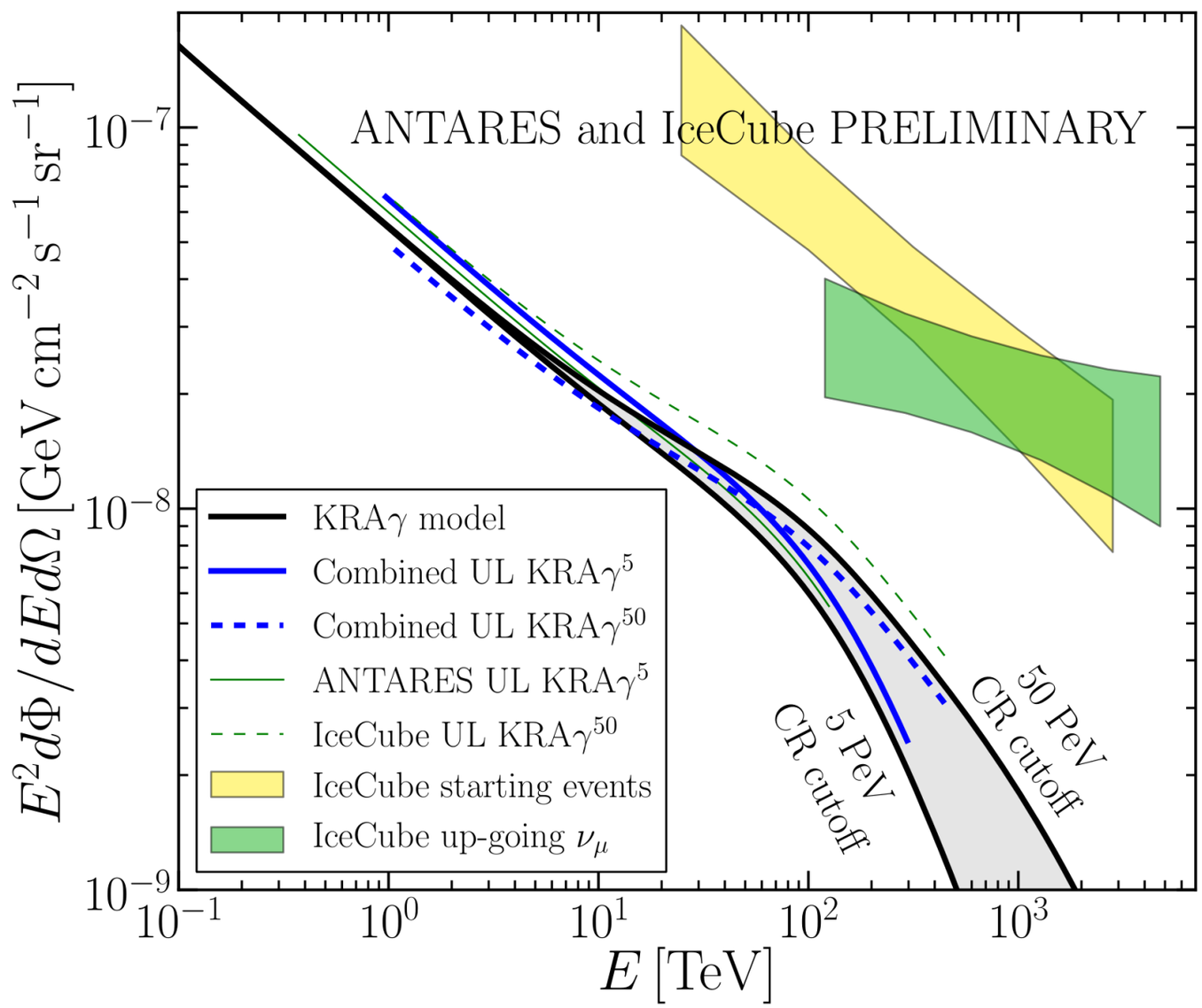
- 3 known objects:
  - (5) TXS 0506+056 (an IBL/HBL at z=0.3365, *Paiano et al. 2018*)
  - (1) PKS 0502+049 (an LBL/FSRQ at z=0.954)
  - (3) 2WHSPJ050833.3+05310 (an HBL)
- (4) HBL candidate
- (7) likely a cluster of galaxies
- (6) steep radio spectrum object
- (2) nearby (z = 0,03677) elliptical galaxy



CONSTRAINTS ON THE FROM THE GALACTIC PLANE NEUTRINO COMPONENT

NEW





https://arxiv.org/abs/1808.03531
Submitted to APJL

TWO SLIDES ABOUT ICECUBE IN THE PRECISION ERA

IN SUMMARY

(1) first association neutrino alert and a blazar in a flaring state;

(2) the evidence of a neutrino flaring activity during 2014 - 2015 from the same direction;

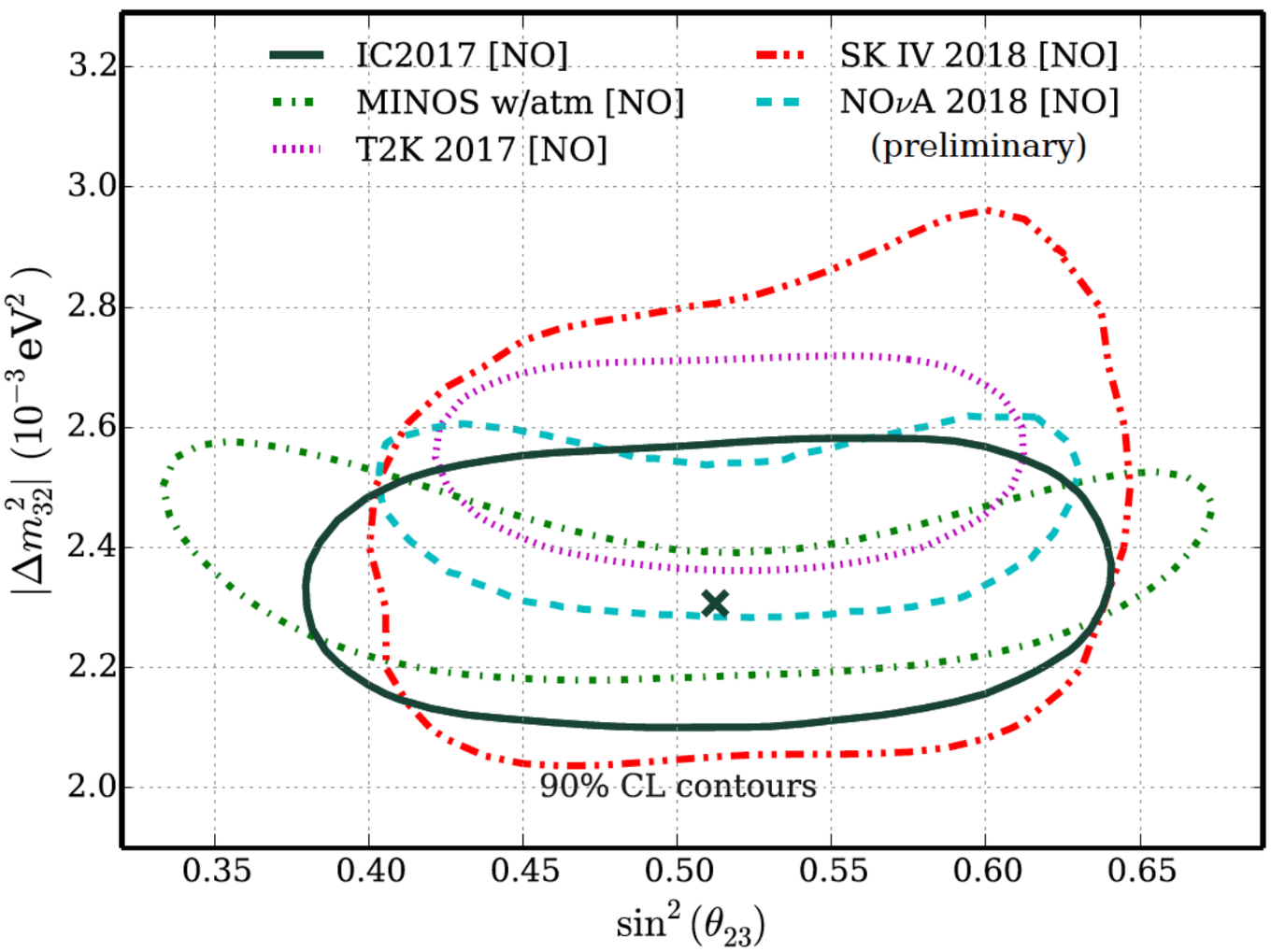
(3) around the period of the neutrino excess in 2014, the TXS is (> few GeV) the protagonist of the gamma-ray sky.

- The neighbour source (PKS) is flaring before and after the neutrino flare in 2014 -2015. It still contaminates at lower energies the TXS spectra.
- The TXS shows very hard states during the observation of the neutrino excess which indicates a shift of the second hump to higher energies / a second component.
- SED shows that energetically 2014-2015 can be reconnected to the neutrino flux.

- **All spatial, timing, and energetic multi-messenger diagnostics point to TXS as the best and only candidate for the neutrino alert & the neutrino excess in 2014-2015.**

ICECUBE DEEPCORE: OSCILLATION, MUON NEUTRINO DISAPPEARANCE

Most precise atmospheric measurement, highest energy range
(constraints primarily from 15-50 GeV neutrinos)



41,599 events (full-sky), all flavour low energy sample

[15,138 track, 26,461 cascade events]

Best fit values:

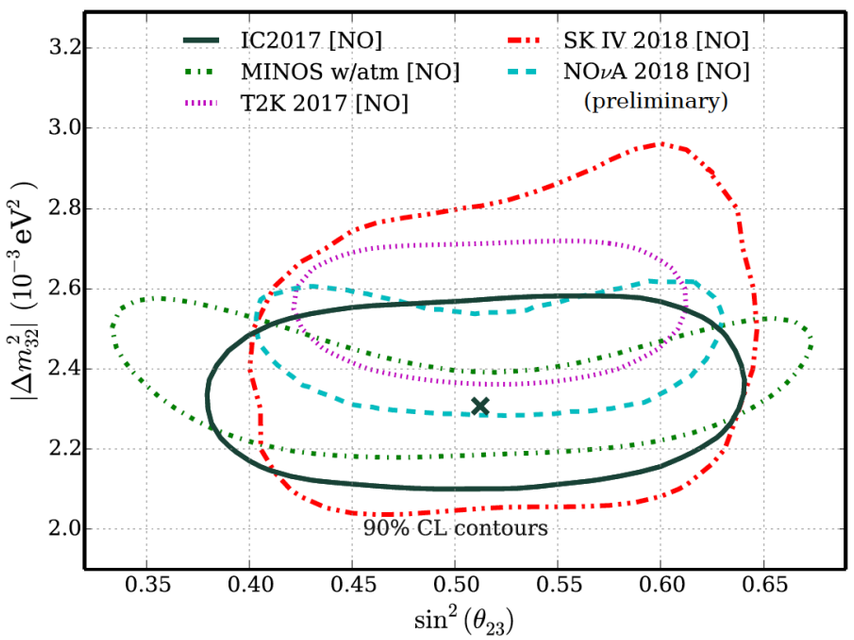
$\sin^2\theta_{23} = 0.51(+0.07-0.09)$

$\Delta m^2_{32} = 2.31(+0.11-0.13) \times 10^{-3}\ \mathrm{eV}^2$

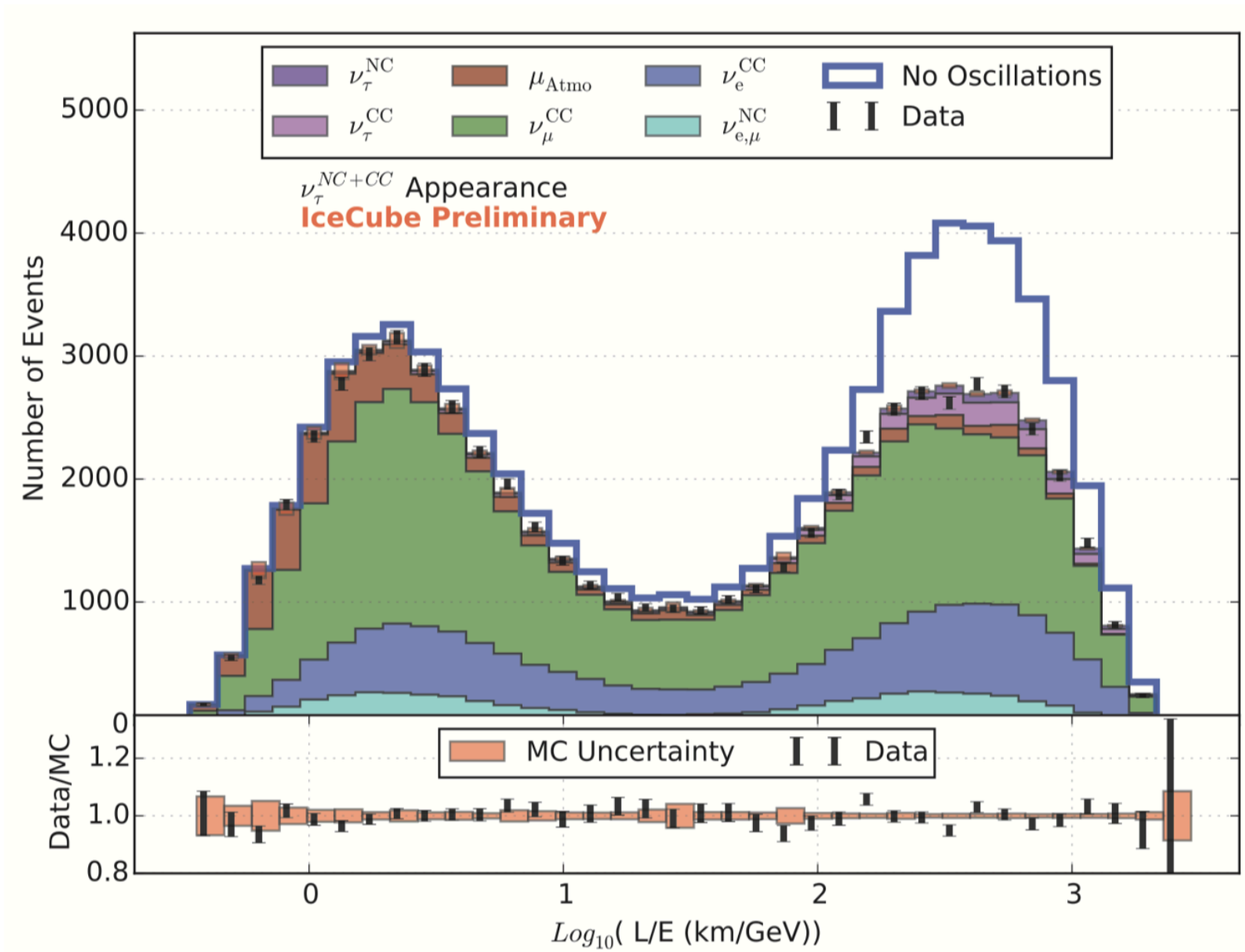
[M. Aartsen et al. (IceCube), Phys. Rev. Lett. 120, 071801 (2018)]

ICECUBE DEEPCORE: OSCILLATION, TAU NEUTRINO APPEARANCE

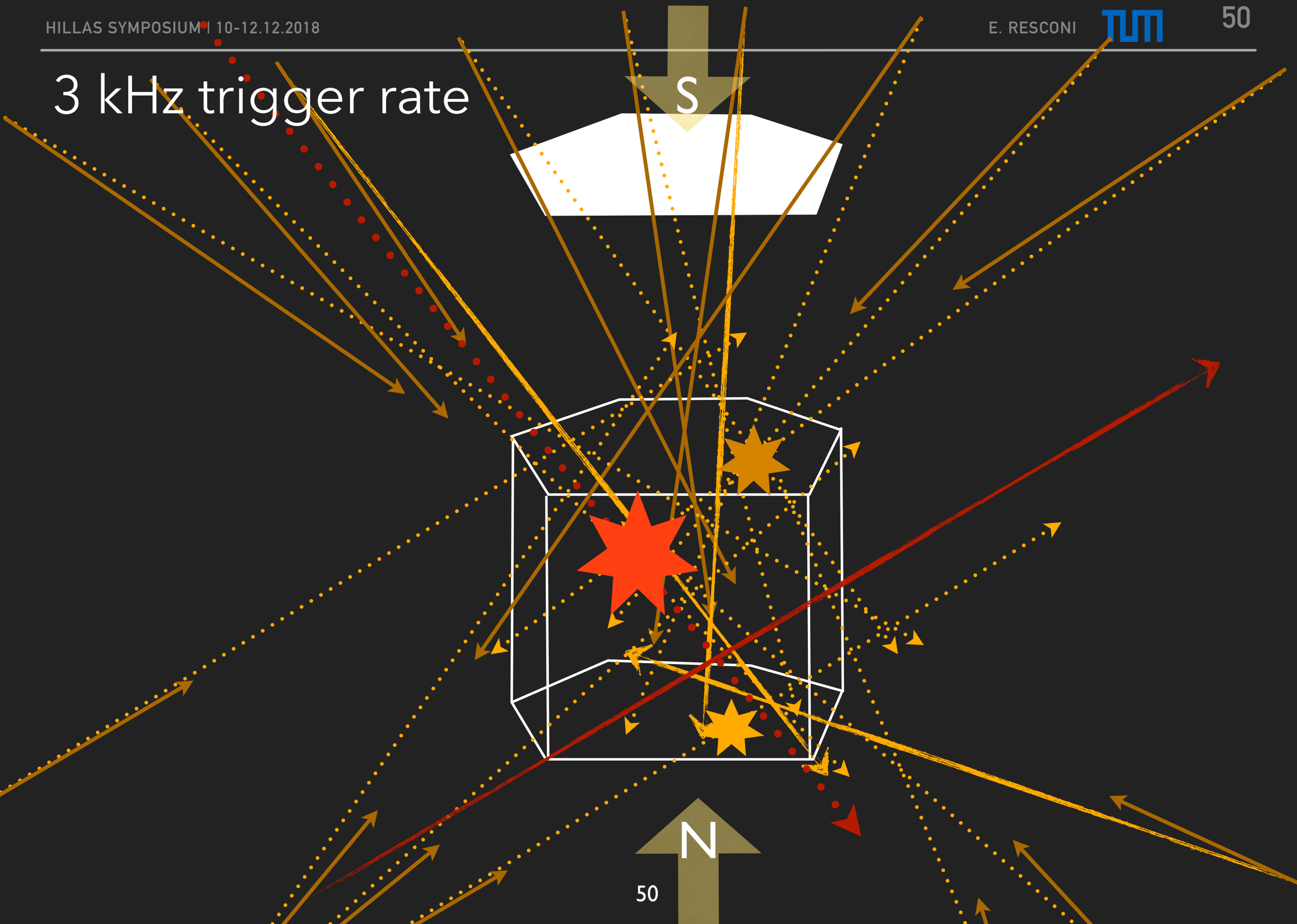
NEW



Similar precision on tau neutrino appearance as SK and Opera

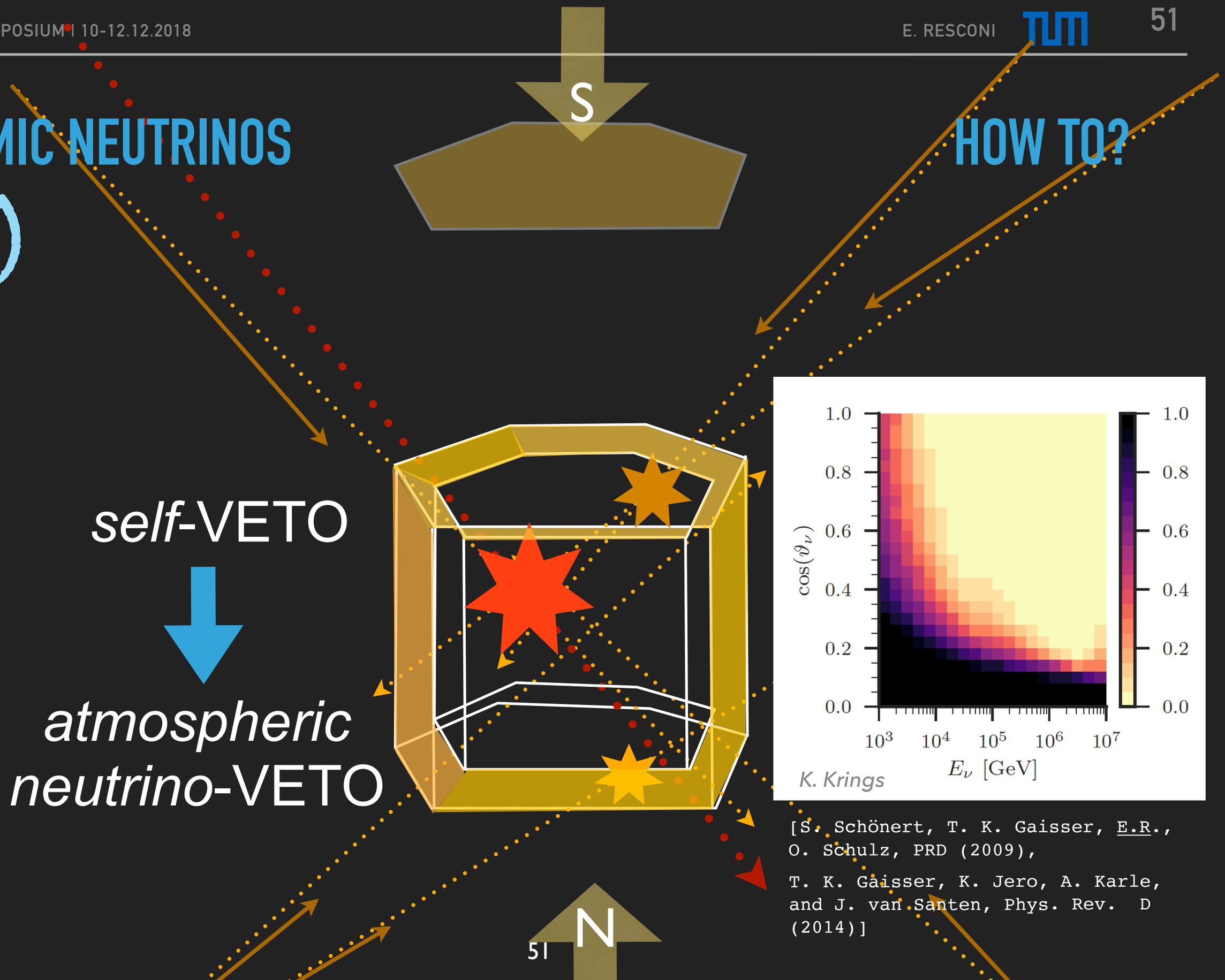


3 kHz trigger rate



COSMIC NEUTRINOS (1)

HOW TO?



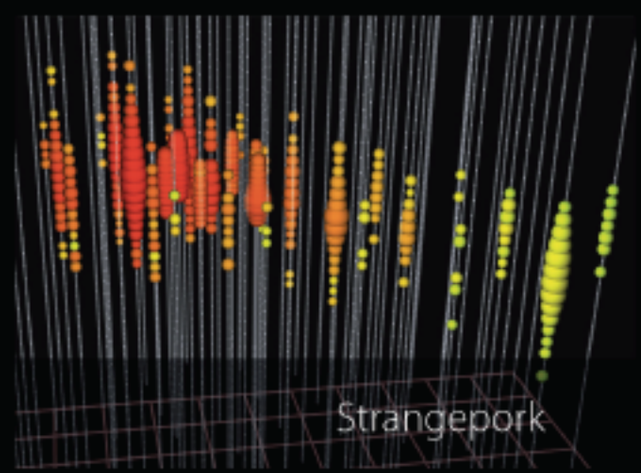
[S. Schönert, T. K. Gaisser, E.R., O. Schulz, PRD (2009),

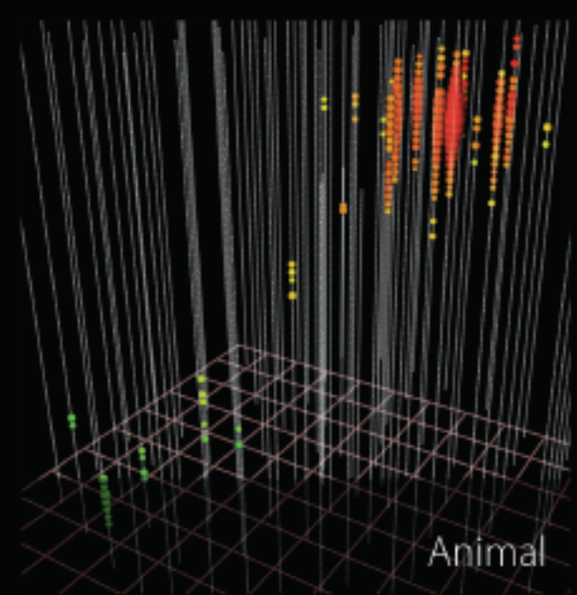
T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, Phys. Rev. D (2014)]

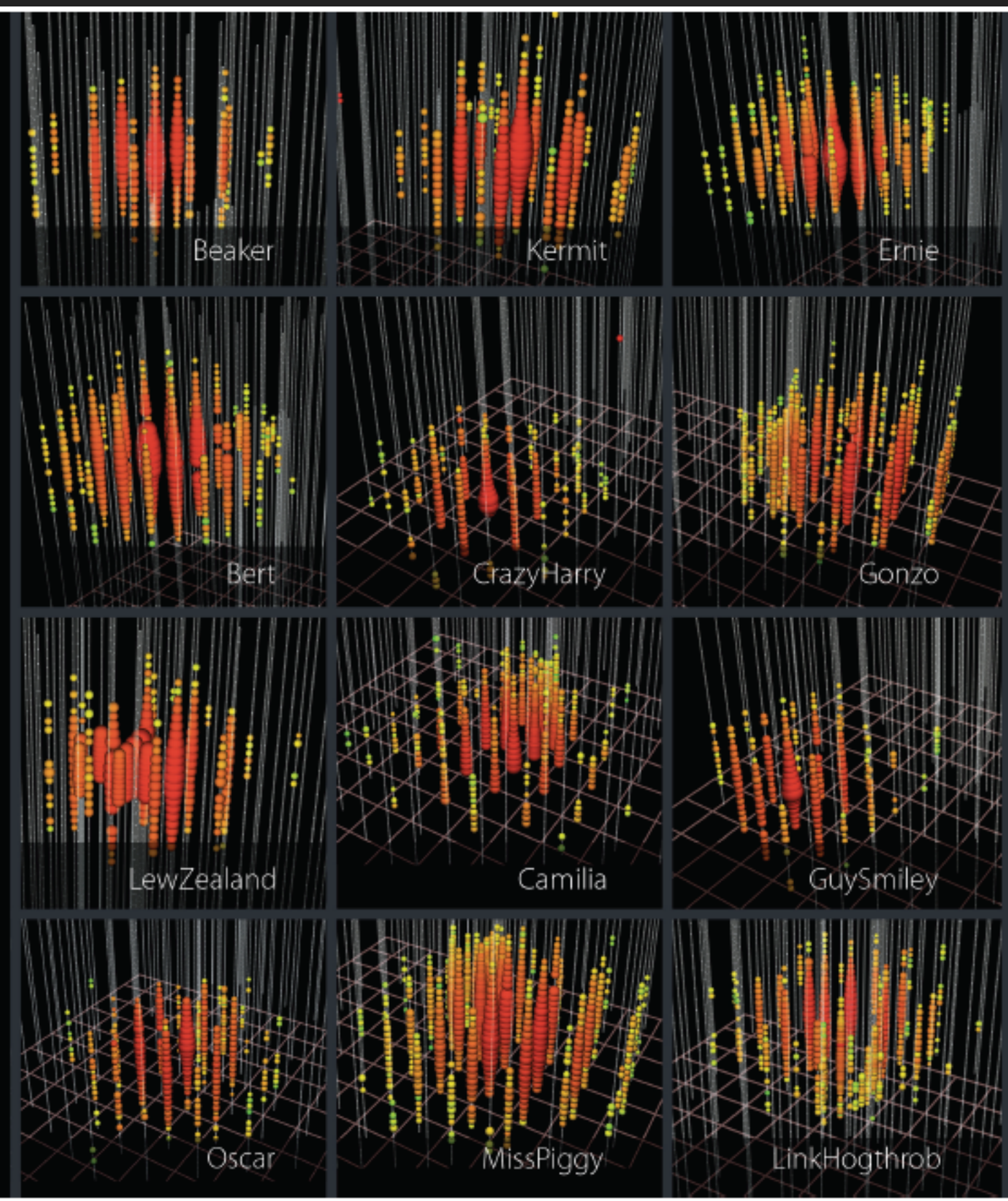
Examples of events:

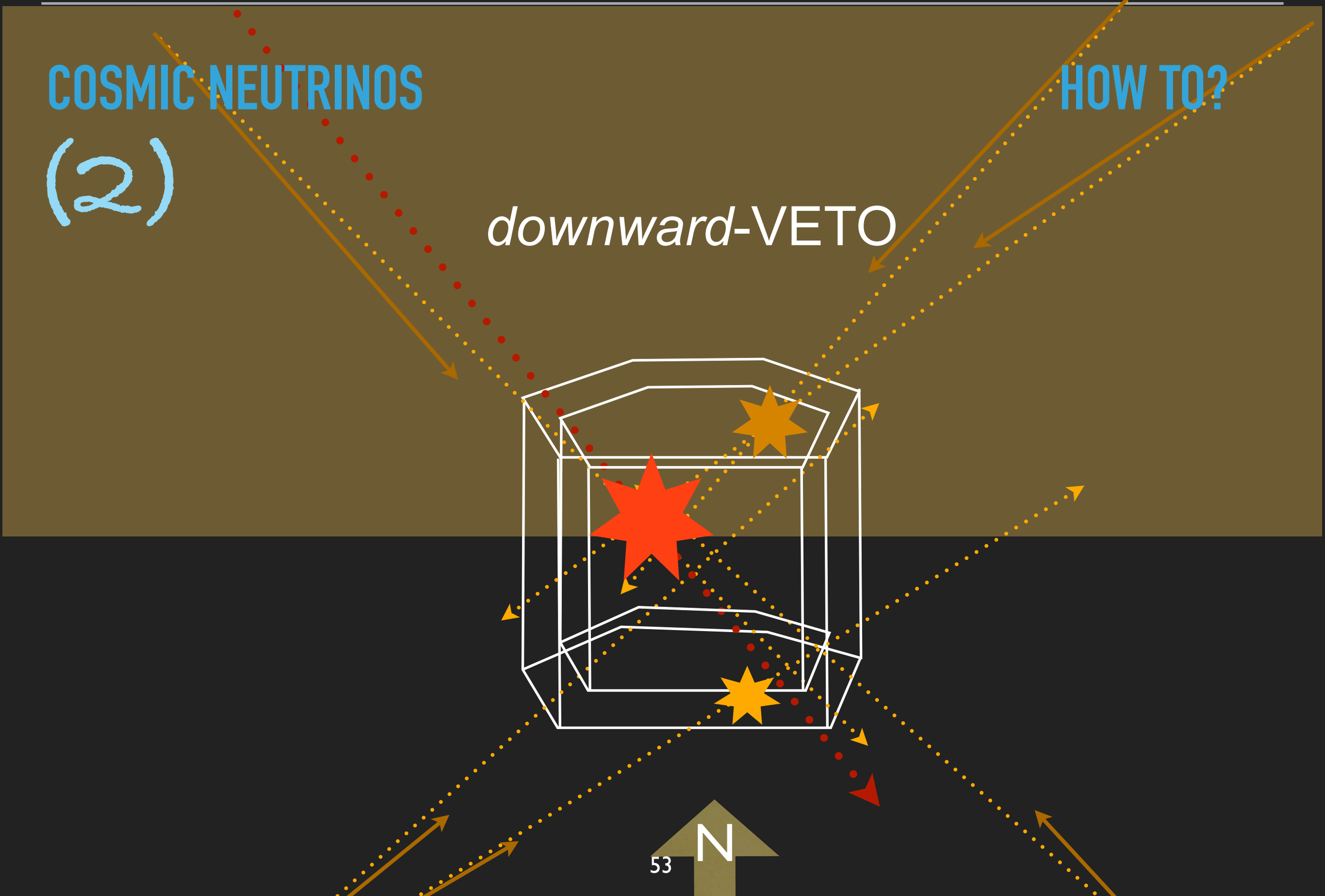
charge threshold > 6000 p.e.
& < 3 p.e. in veto region

2078-day sample: 82 events







COSMIC NEUTRINOS (2)

HOW TO?