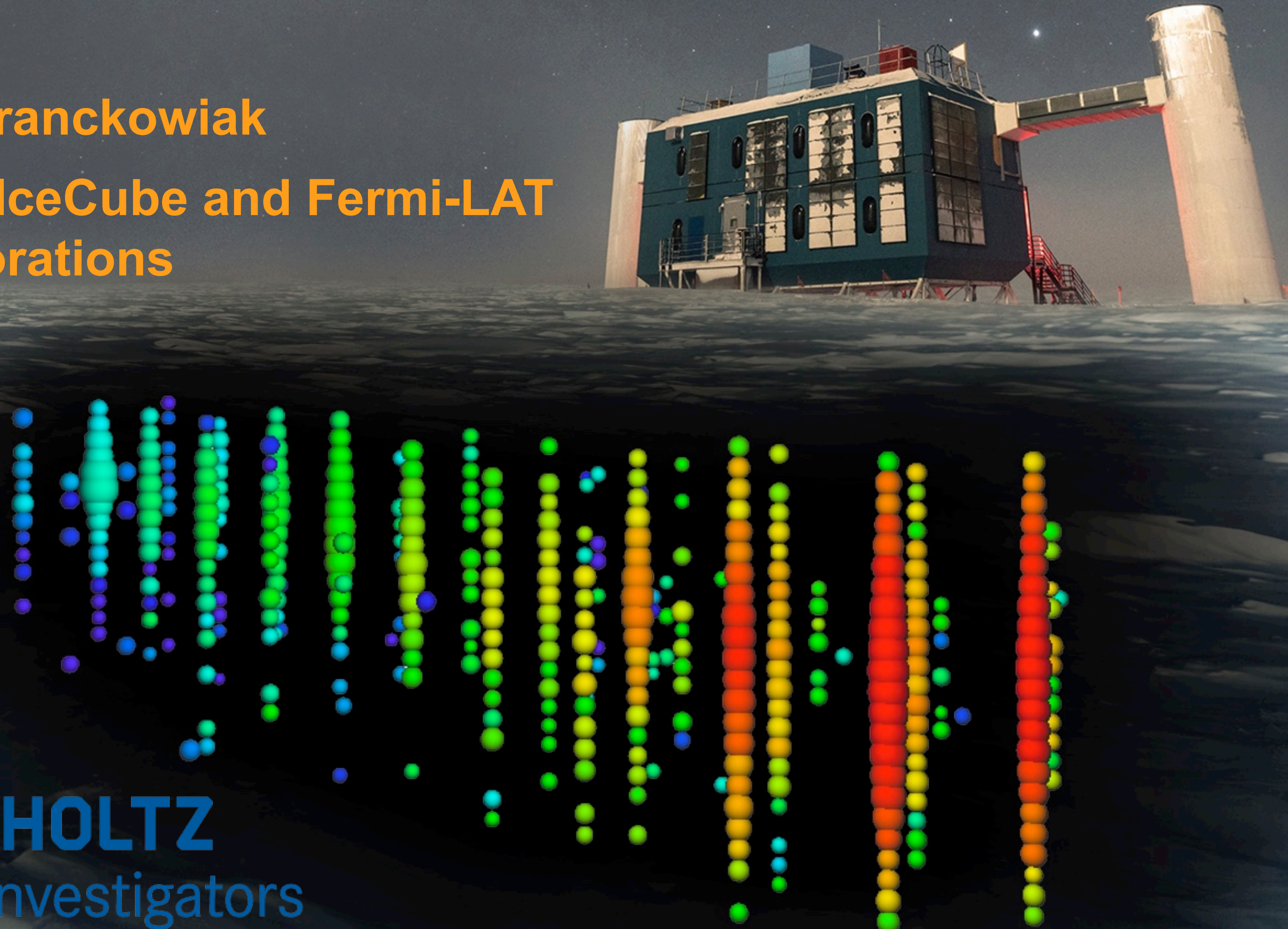
Multi-messenger Astronomy with high-energy Neutrinos: *IceCube-170922A and TXS 0506+056*

Anna Franckowiak

for the IceCube and Fermi-LAT Collaborations

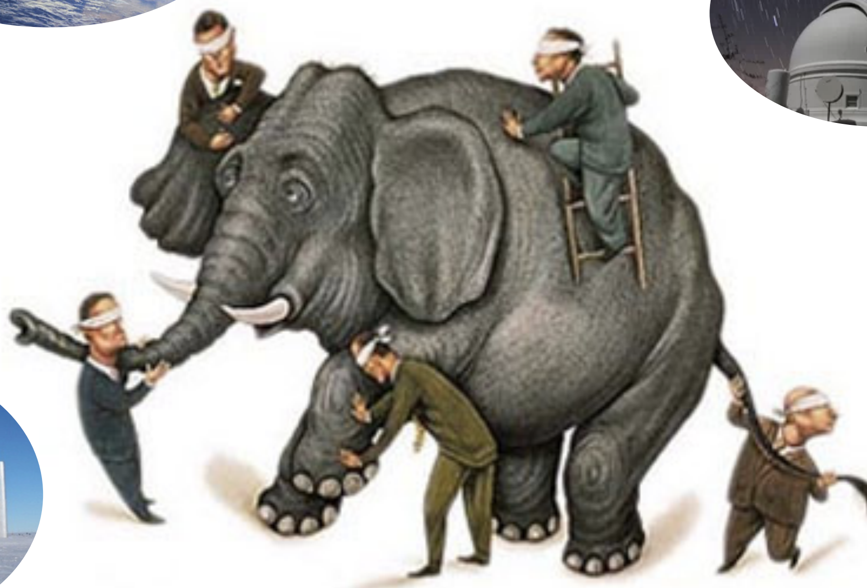


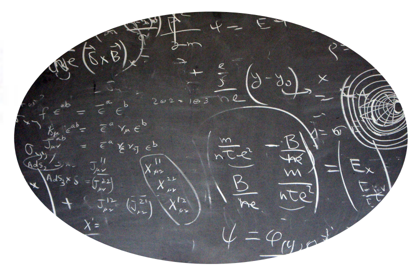
HELMHOLTZ
Young Investigators

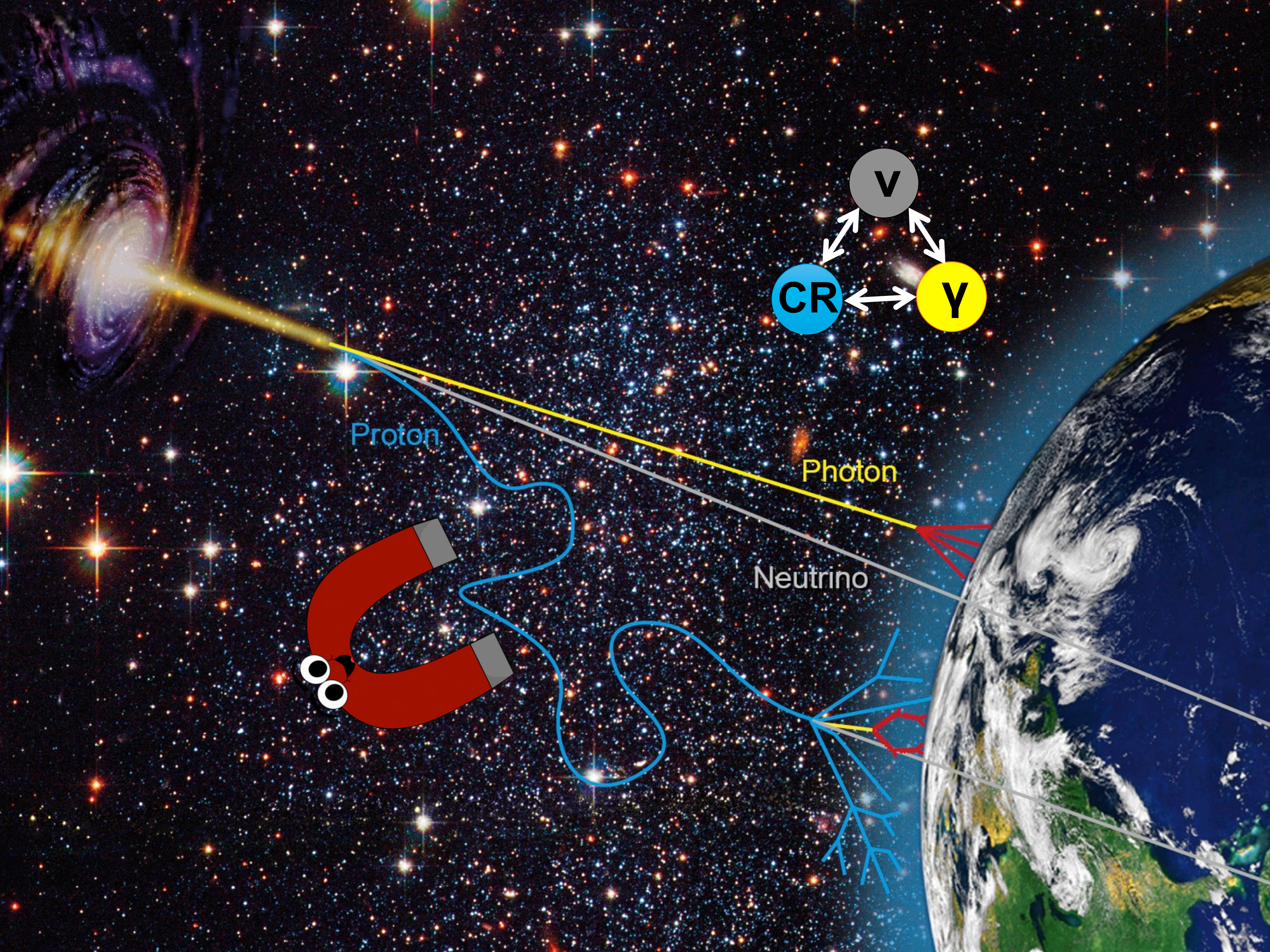
DESY.

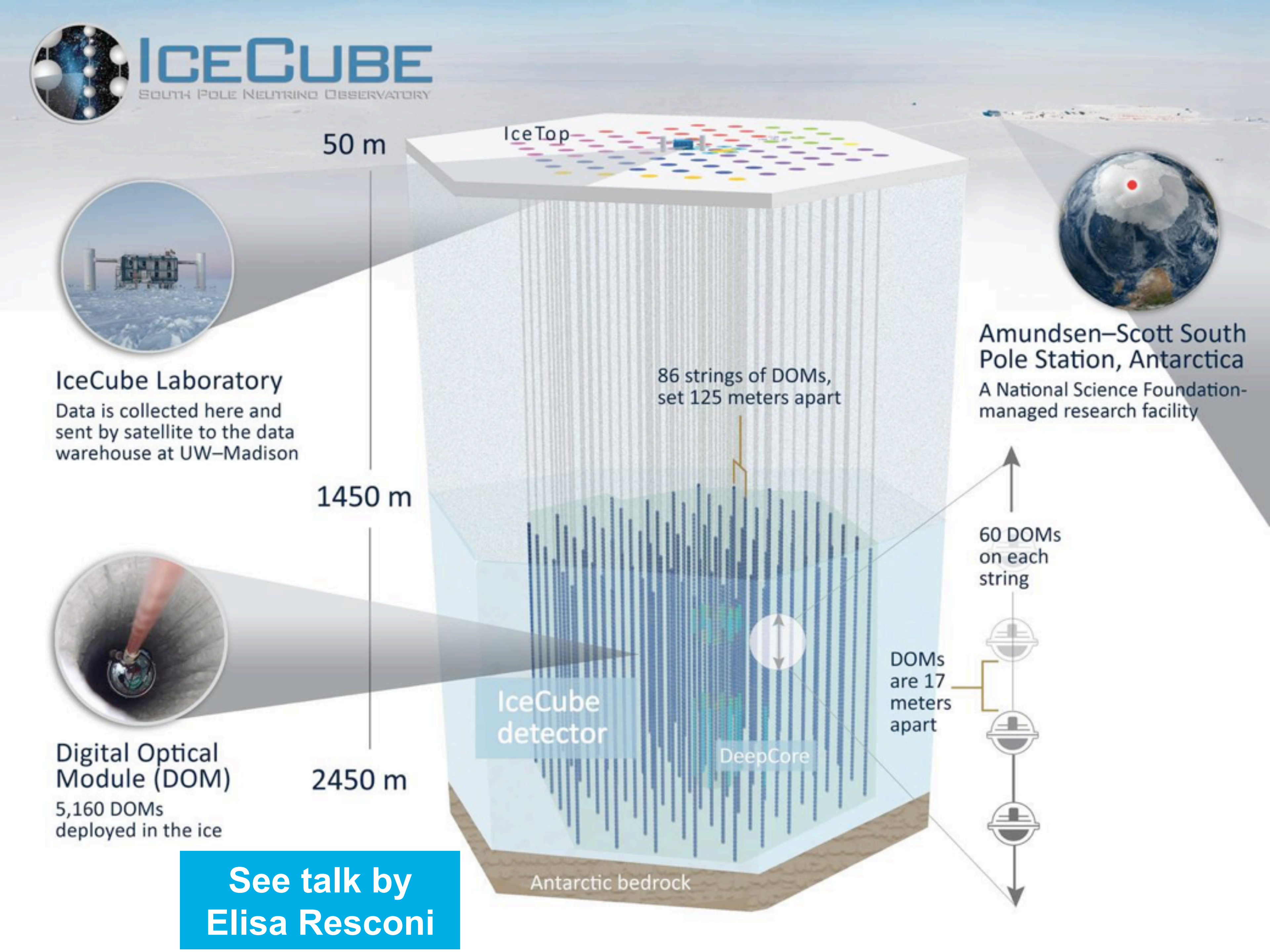
Astroparticle Physics in Germany, Mainz, September 18, 2018

The Multi-Messenger Picture



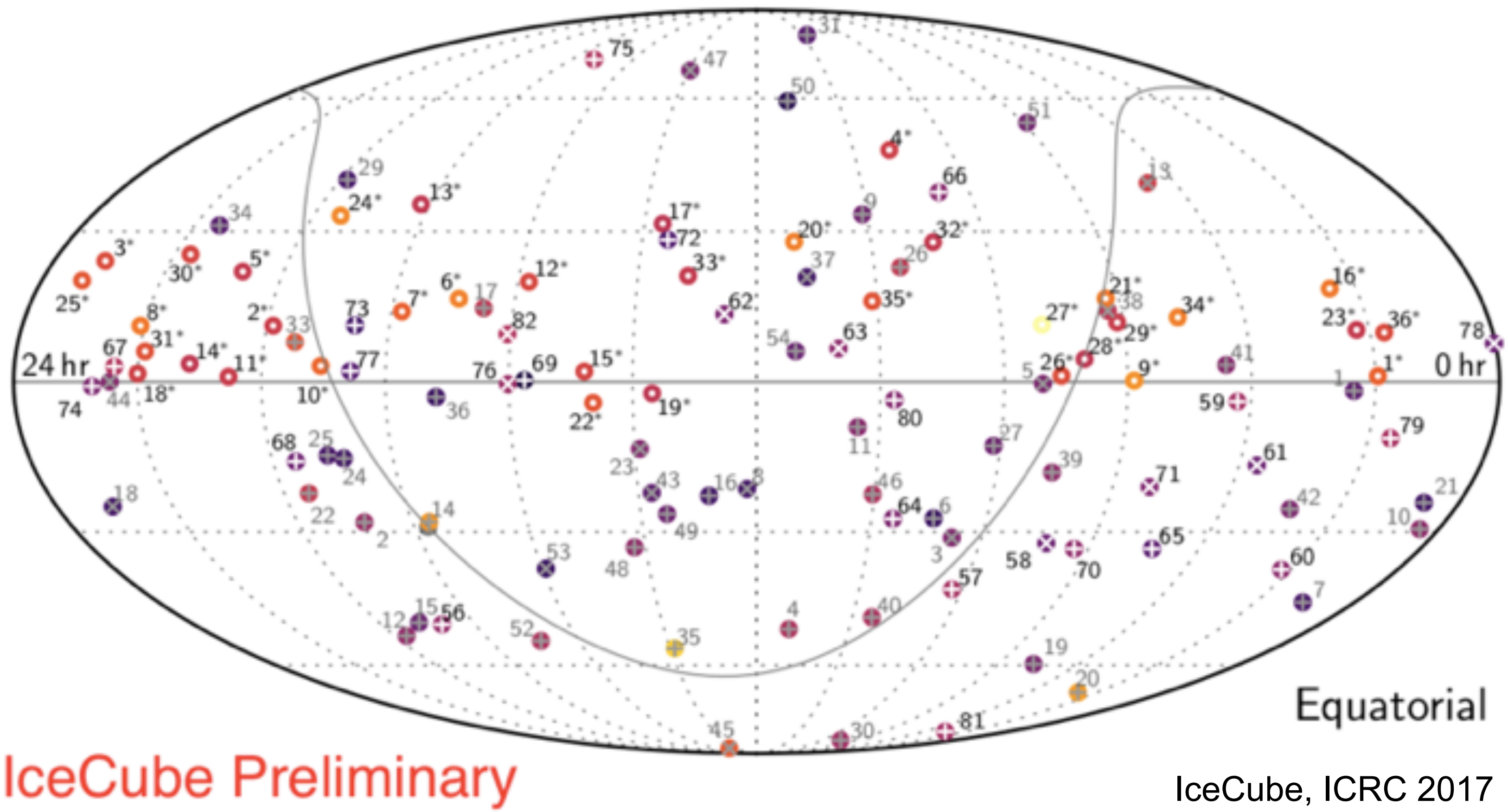



ν
CR
γ
Proton
Photon
Neutrino


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and
sent by satellite to the data
warehouse at UW–Madison
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
IceCube
detector
DeepCore
Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice
Antarctic bedrock
See talk by
Elisa Resconi

Diffuse Neutrino Flux detected, but where do the Neutrinos come from?

IceCube high-energy events > 30 TeV (2010 - 2016)



IceCube, ICRC 2017

Compatible with an isotropic distribution

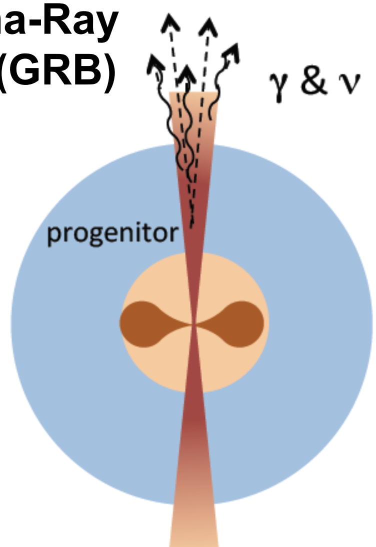
→ extragalactic origin of cosmic neutrinos

IceCube Target of Opportunity Program

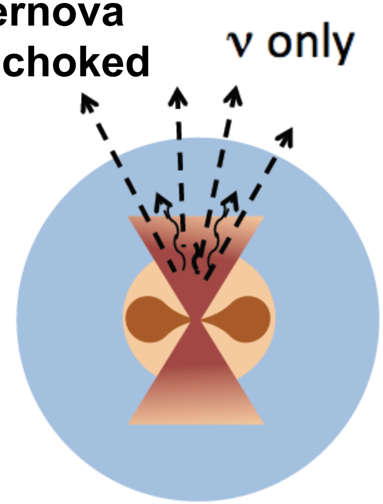
Public alerts since April 2016

- Single high-energy muon track events (> ~100TeV)
- 8 / yr, ~3 / yr of cosmic origin
- Median latency: 30 sec

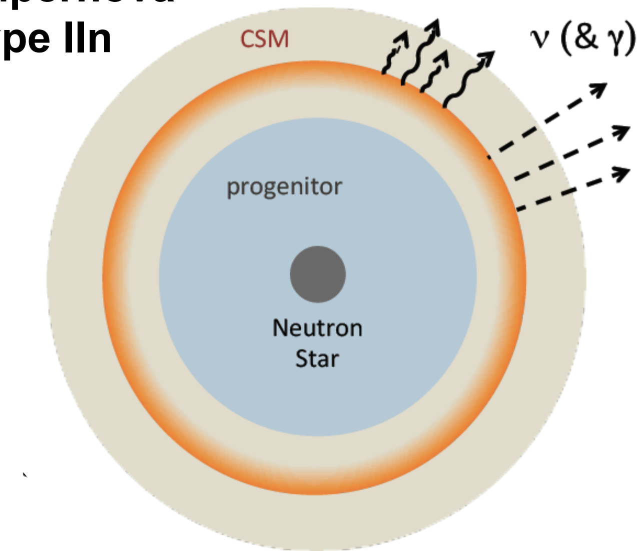
Gamma-Ray Burst (GRB)



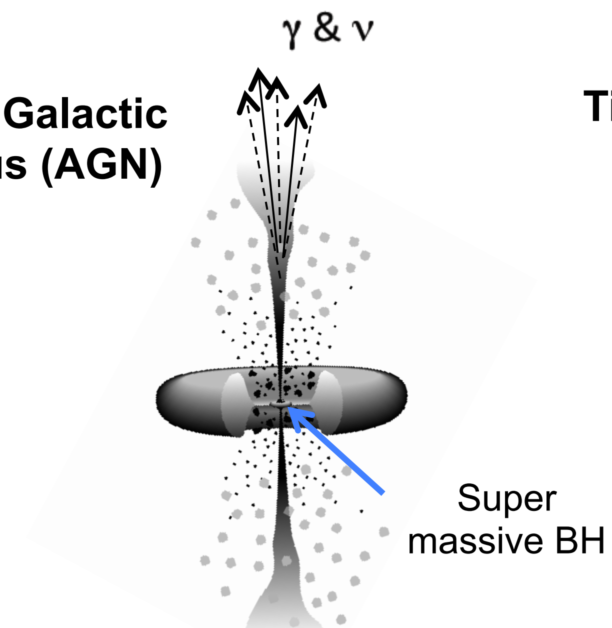
Supernova with choked jets



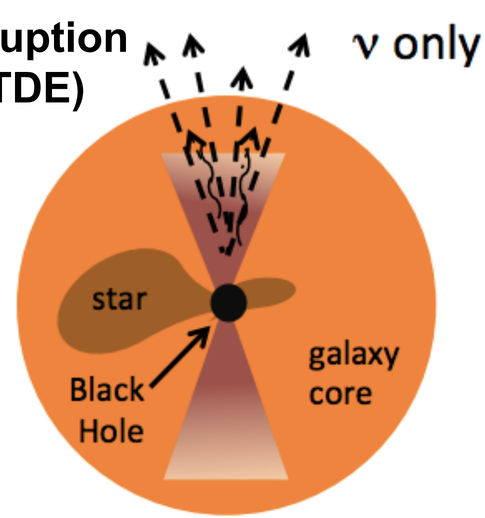
Supernova Type IIn



Active Galactic Nucleus (AGN)

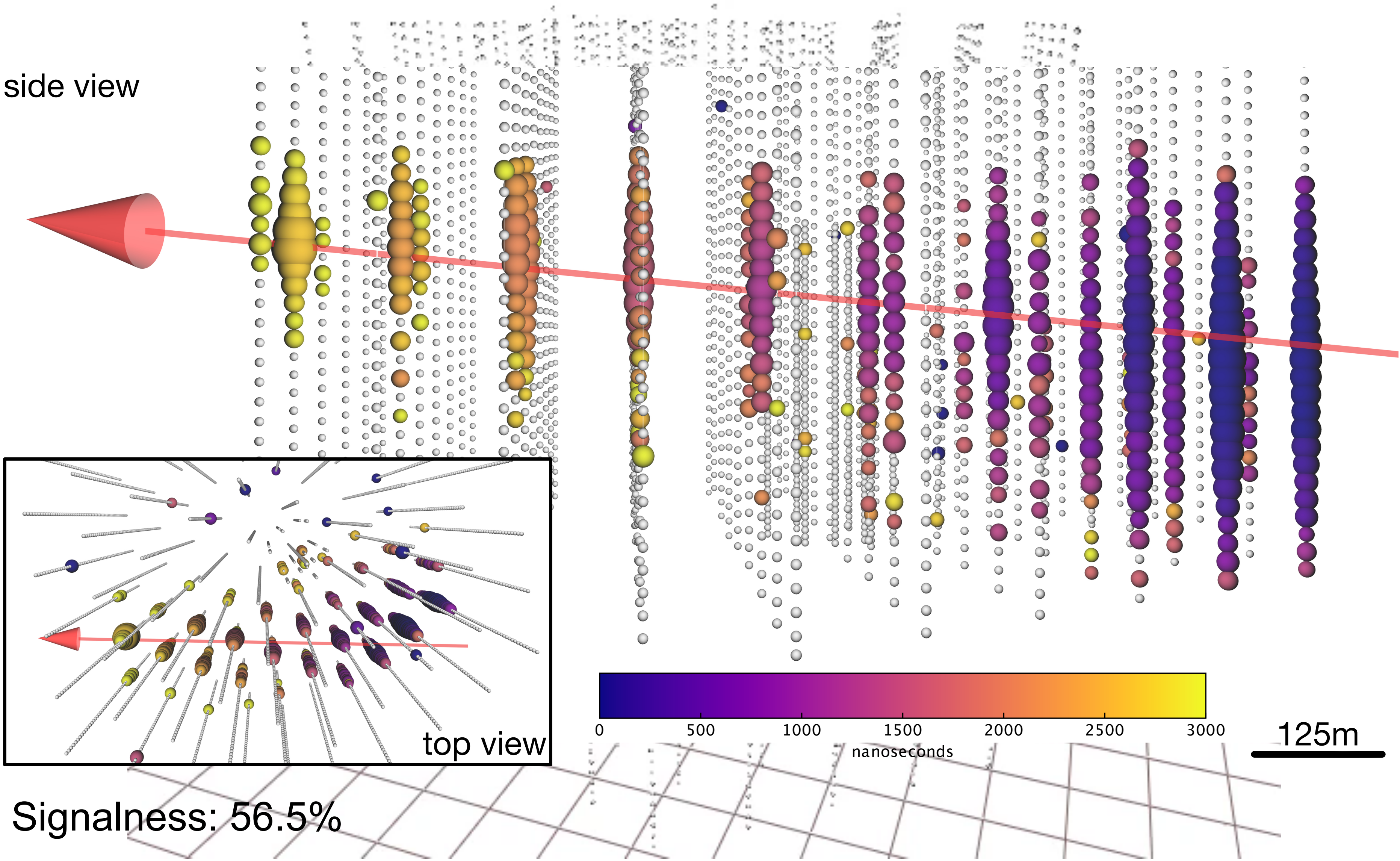


Tidal Disruption event (TDE)



All have distinct electro-magnetic counterparts

IC-170922A – a 290 TeV Neutrino



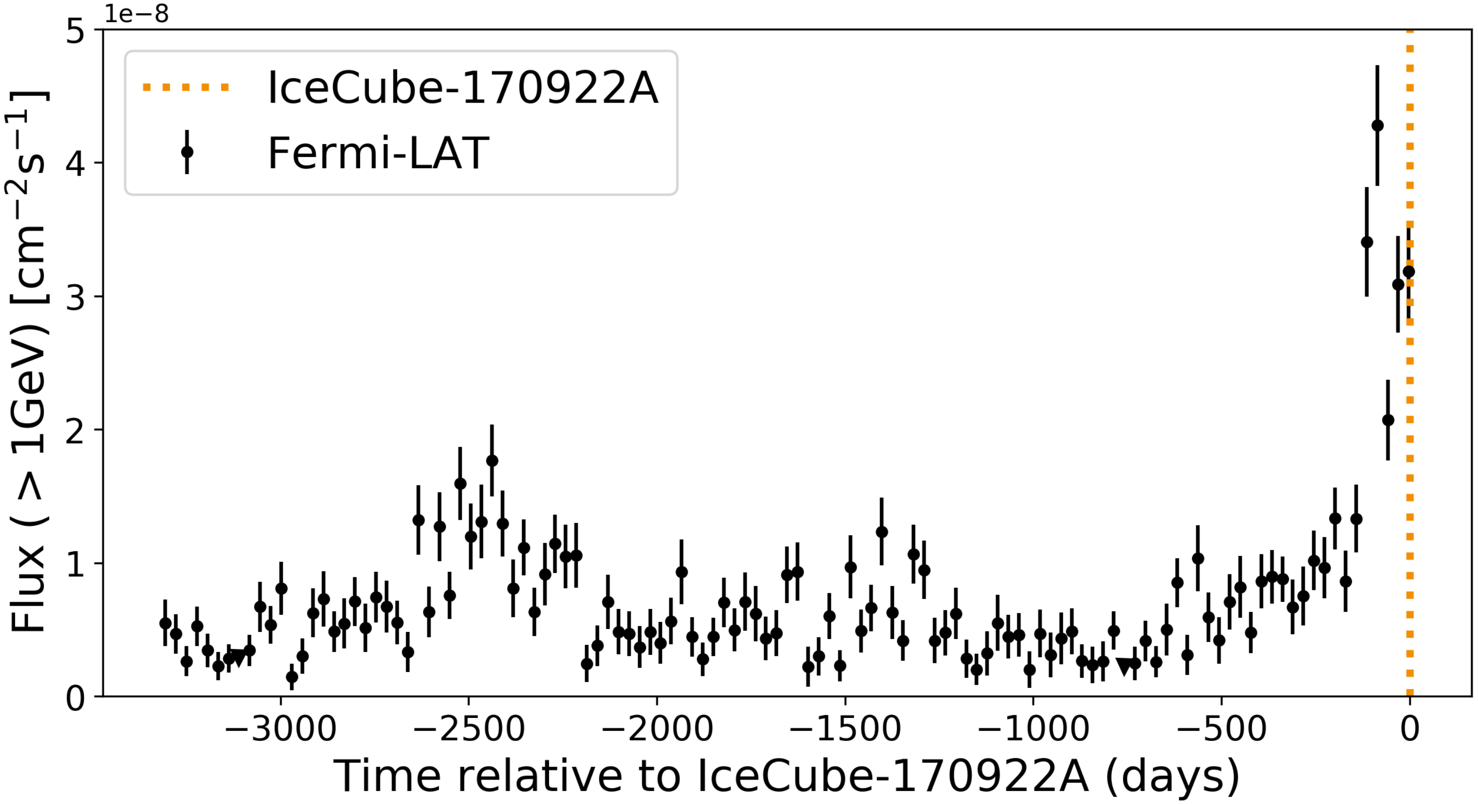
Signalness: 56.5%

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

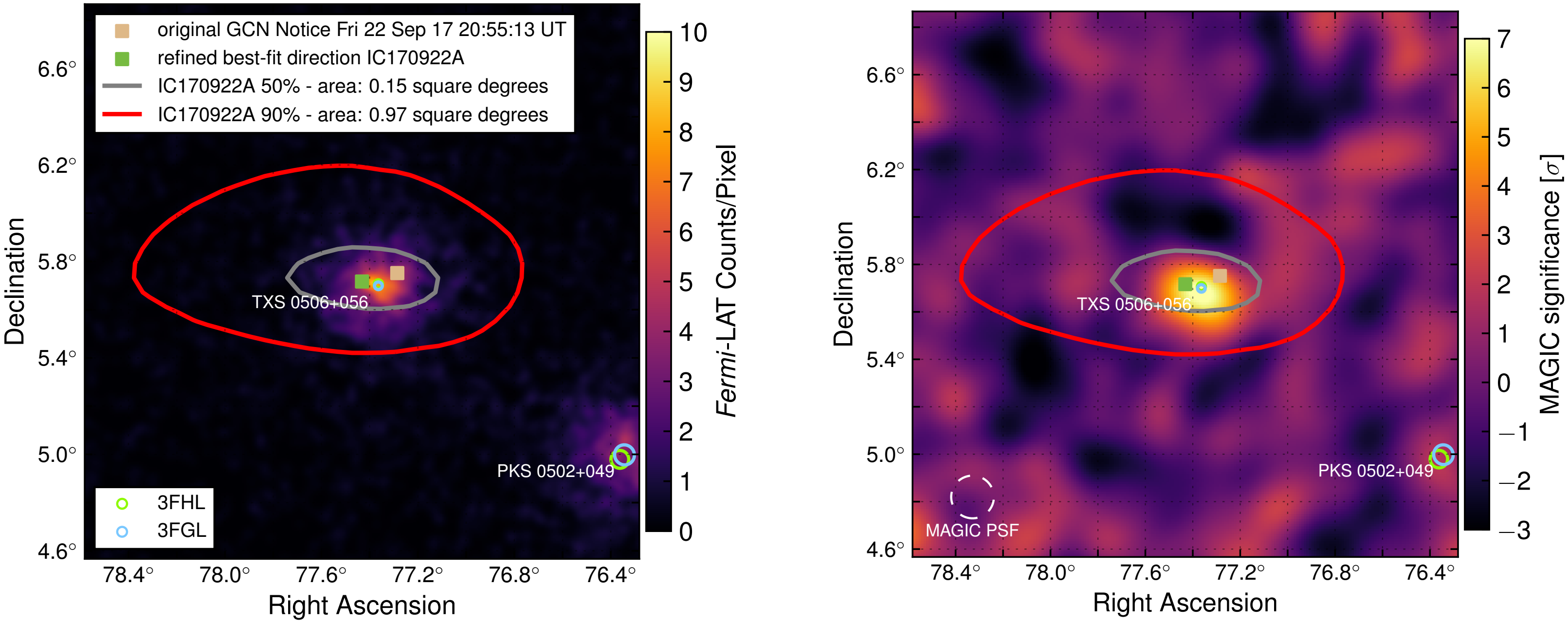
Fermi-LAT finds Flaring Blazar

Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Fermi-LAT finds Flaring Blazar: TXS 0506+056

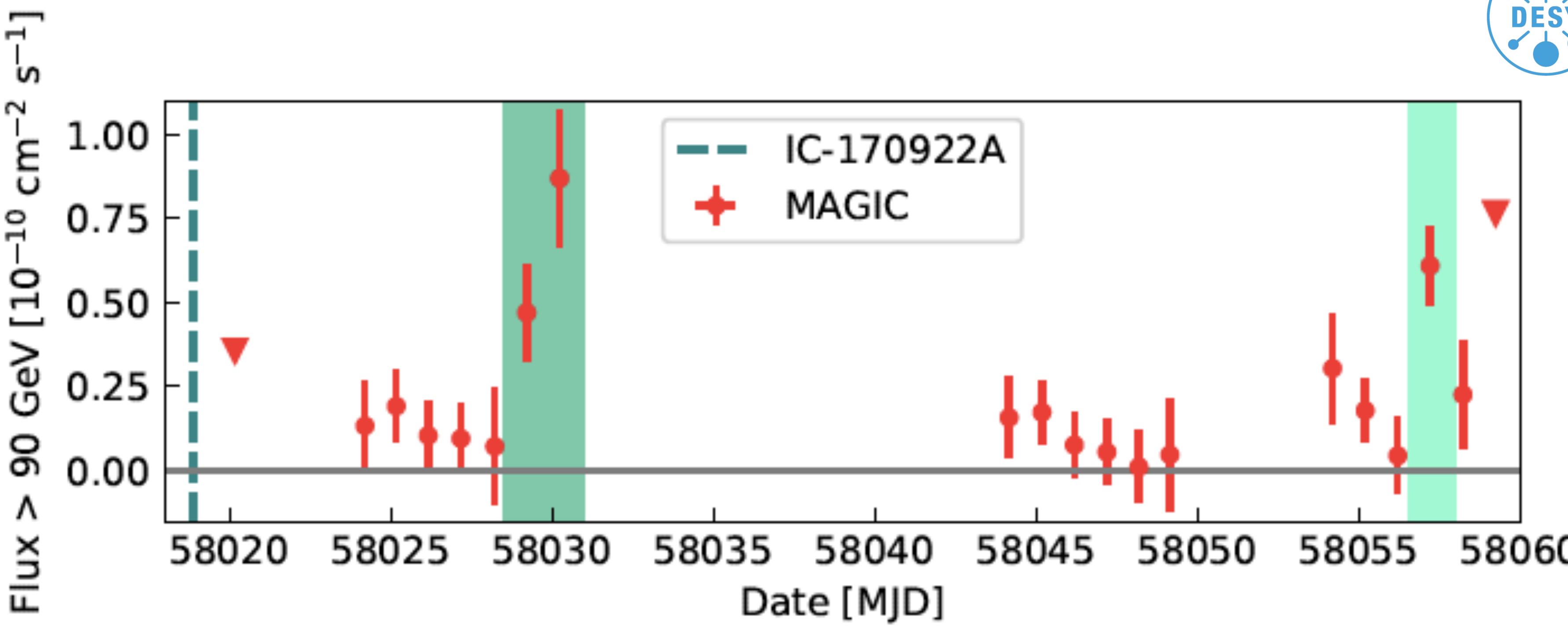


MAGIC observes >100 GeV gamma rays



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

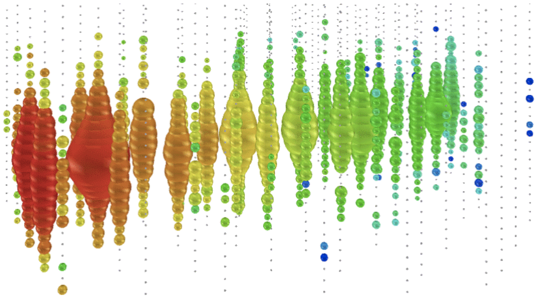
MAGIC finds variability on 1-day scale



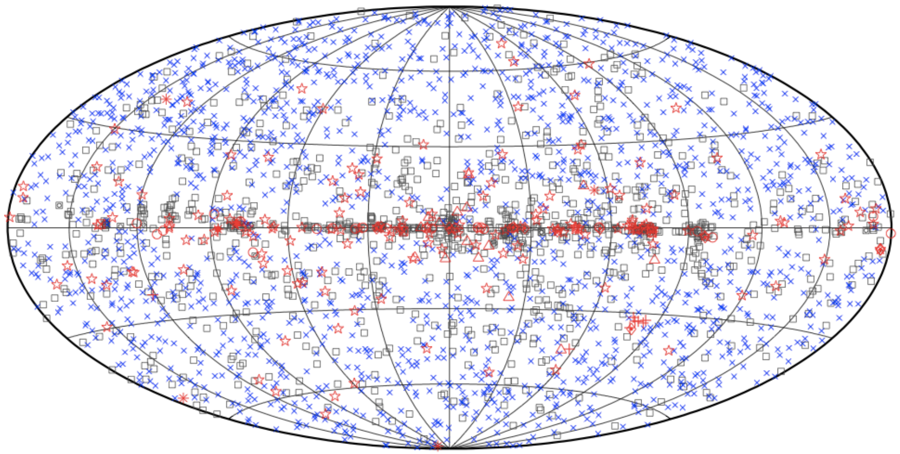
Compact emission region

MAGIC Coll. ApJL, 2018

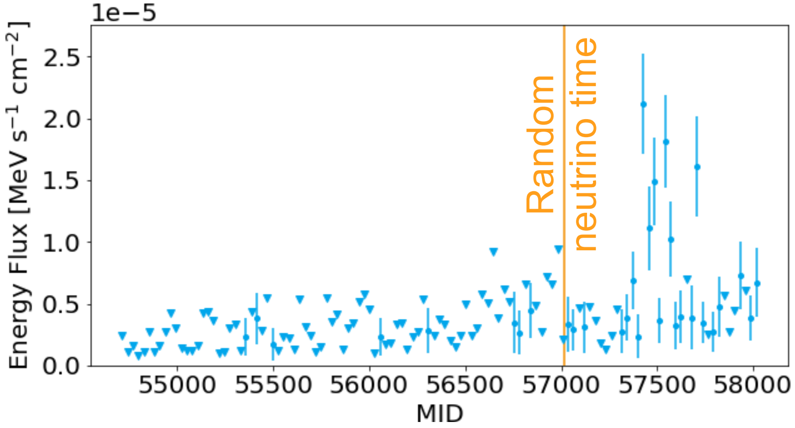
How Likely is it a Chance Probability?



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



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



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

How Likely is it a Chance Probability?

$$TS = 2\log\frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}$$

$$\mathcal{B}(\vec{x}) = \frac{\mathcal{P}_{BG}(\sin\theta)}{2\pi}$$

$$\mathcal{S}(\vec{x}, t) = \sum_s \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)}\, w_s(t)\, w_{\mathrm{acc}}(\theta_s)$$

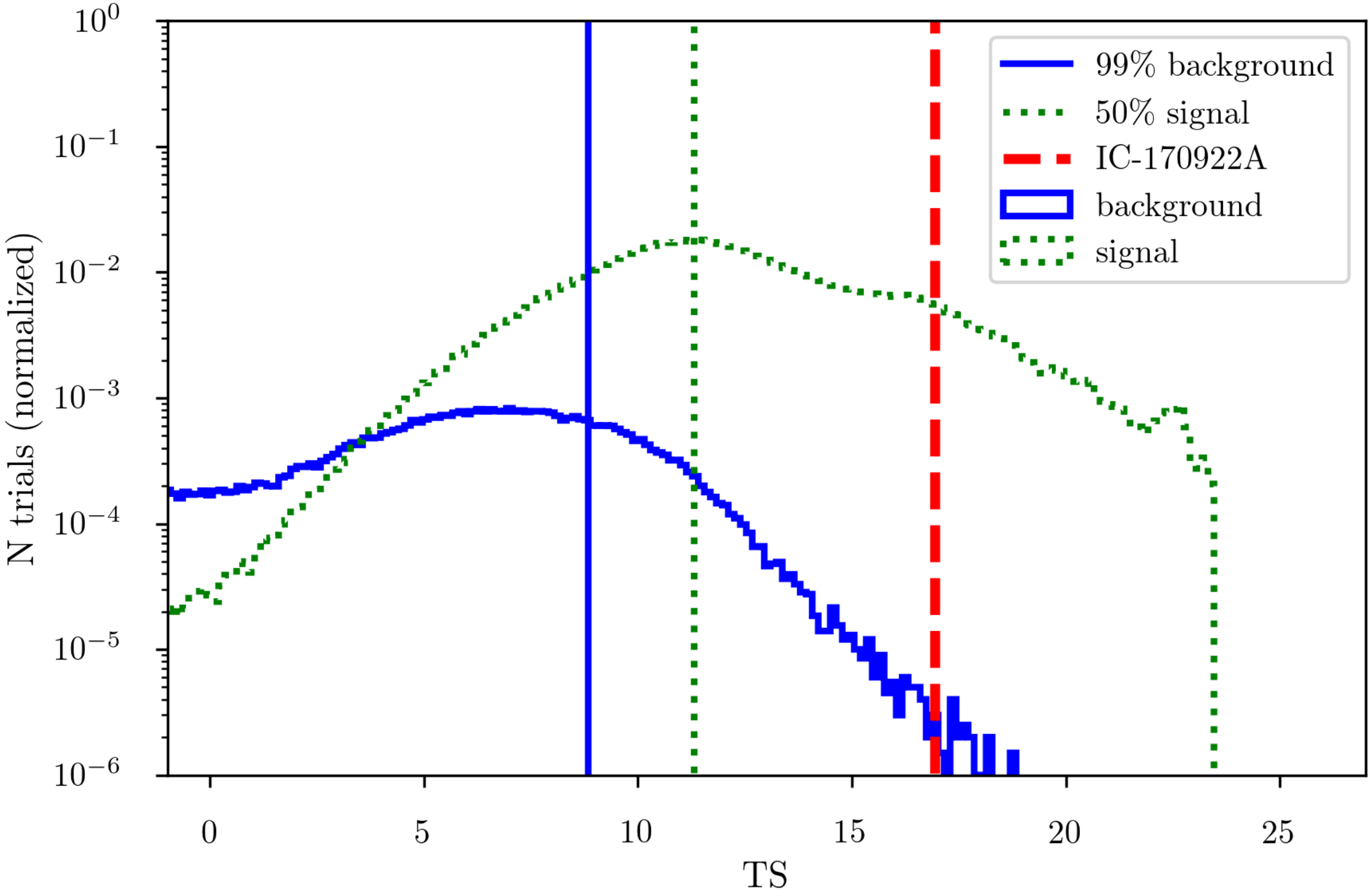
Spatial term

gamma-ray energy flux at time t

acceptance

How Likely is it a Chance Probability?

$$TS = 2 \log \frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2 \log \frac{\mathcal{S}}{\mathcal{B}}$$



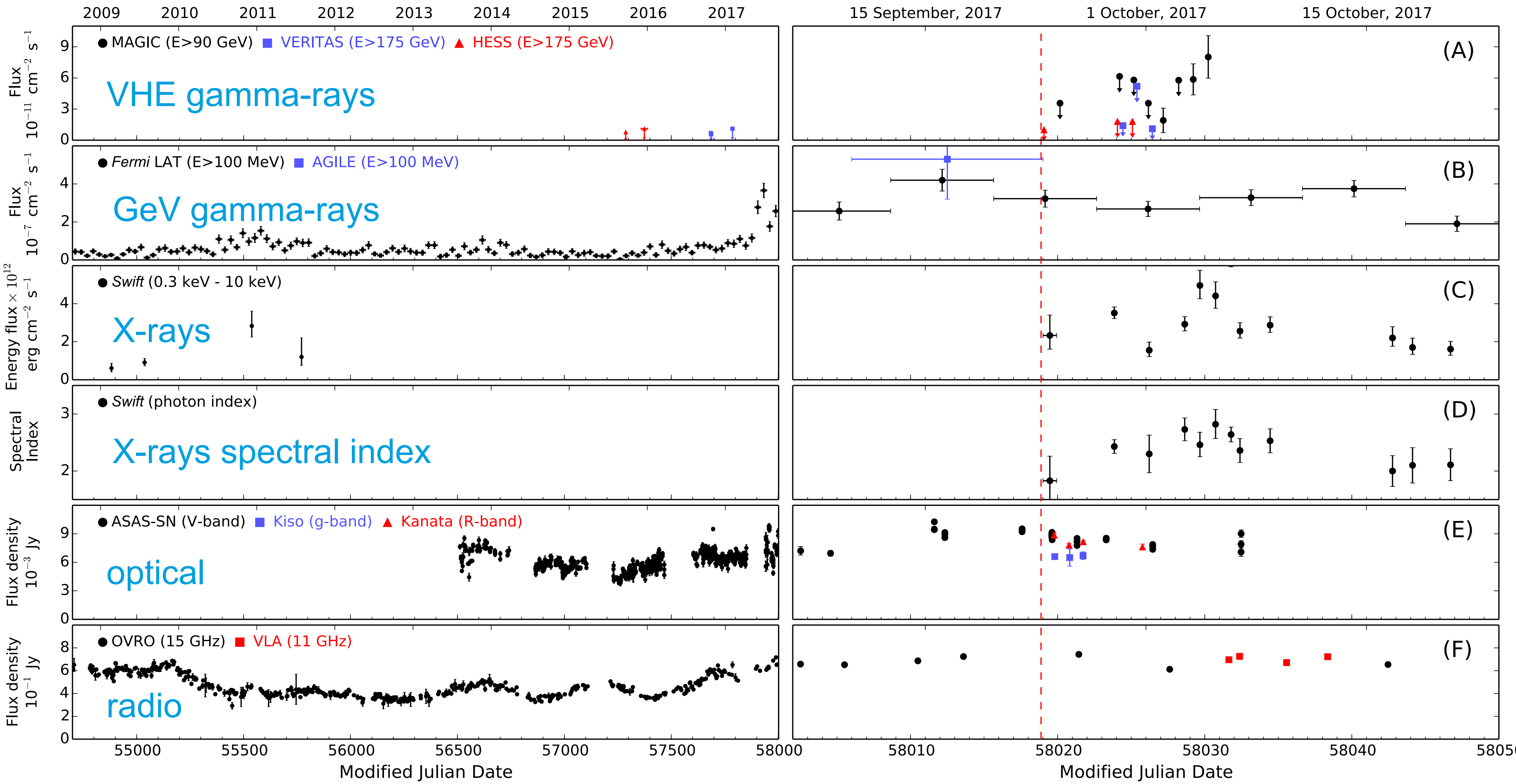
Pre-trials p-value: 4.1σ

10 public alerts and 41 archival events → Post-trials p-value: 3.0σ

Three tested models yield similar p-values

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

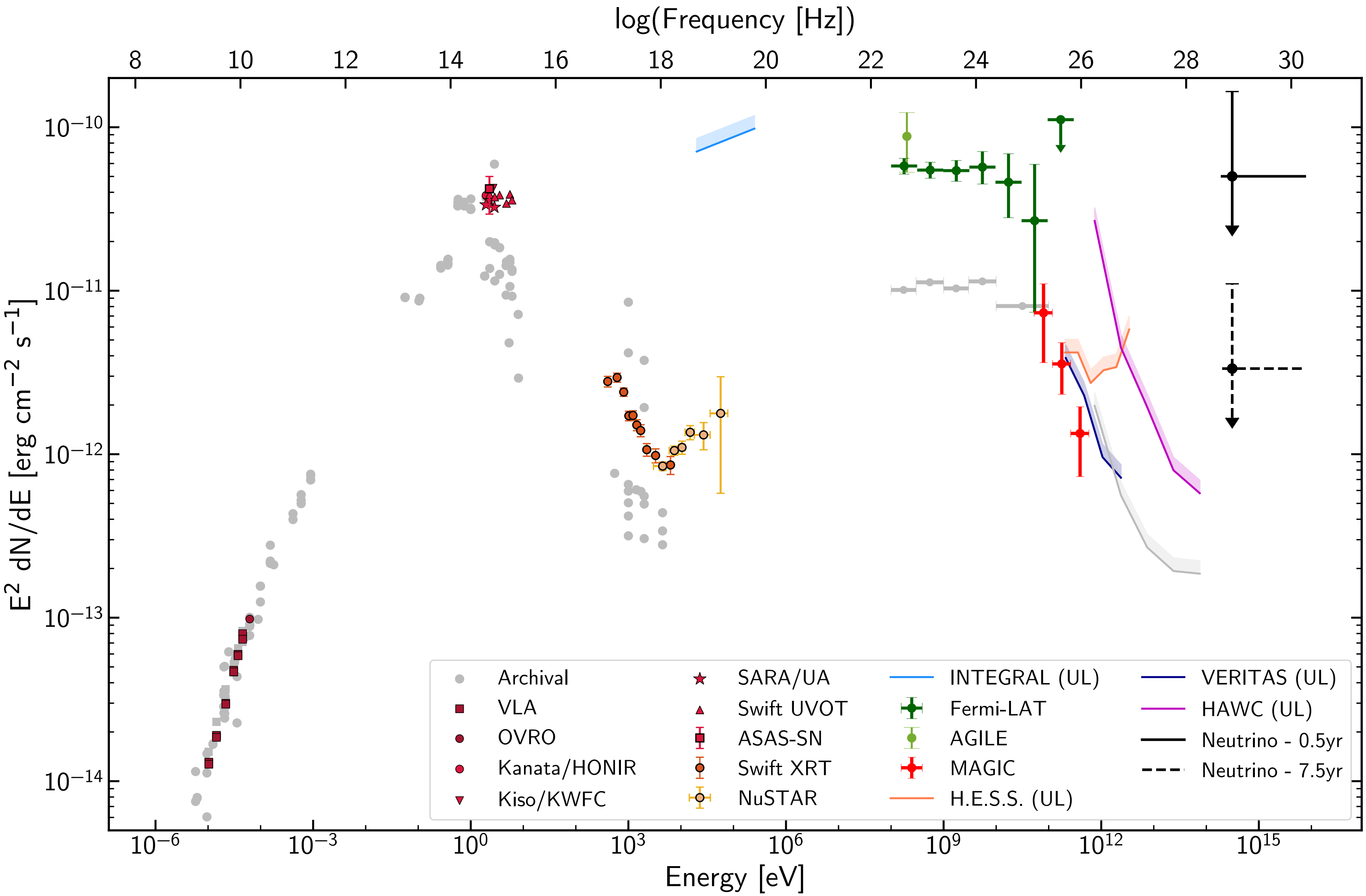
The Multi-Messenger Light Curve



DESY. IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

The Multi-Messenger SED

Redshift: z=0.337
S. Paiano et al. 2018



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

The Source: TXS 0506+056

- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

Are there more Neutrinos from this Source?

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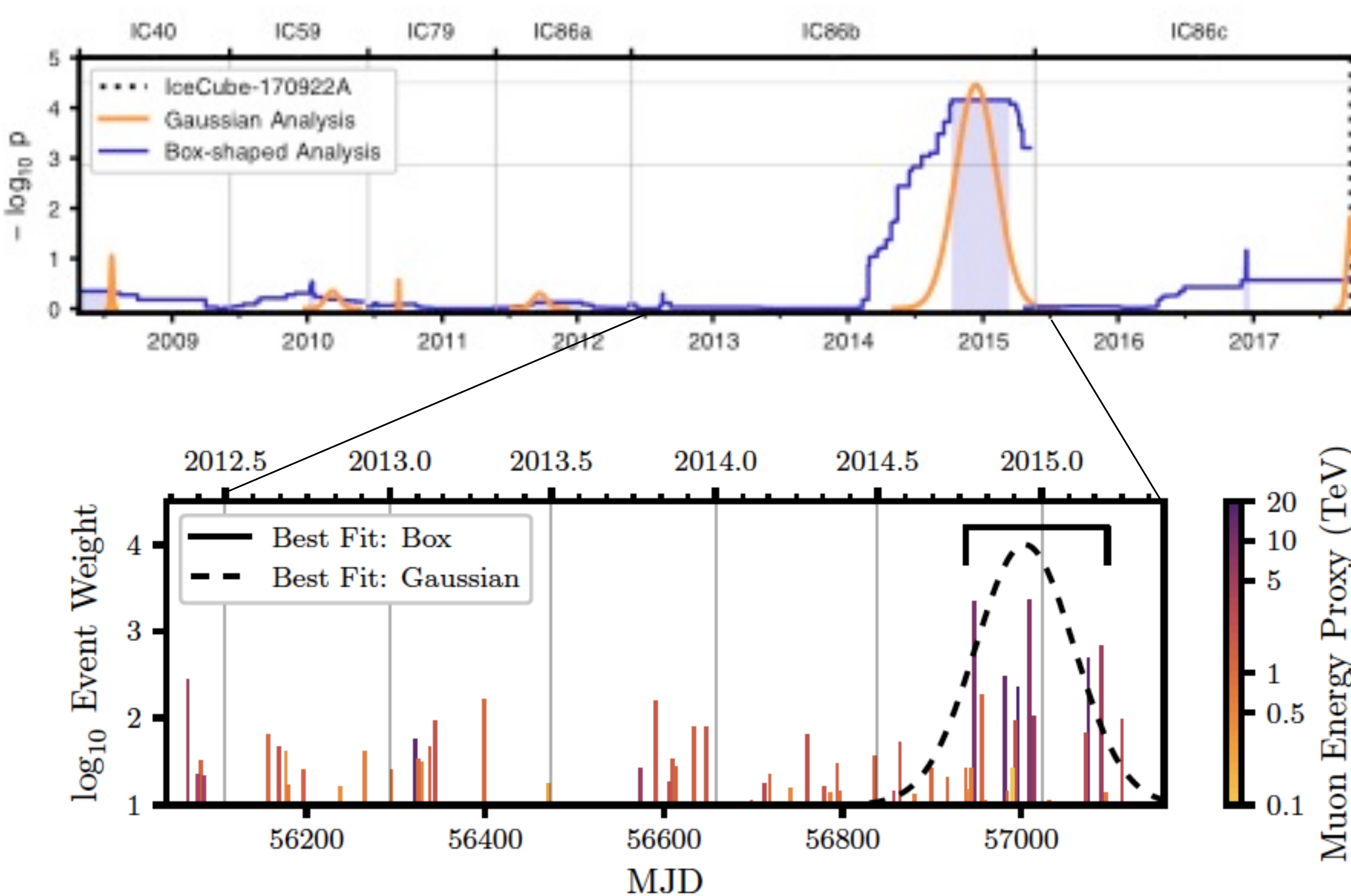
13±5 above the background of atmospheric neutrinos, 3.5σ



IceCube Coll.,Science 2018

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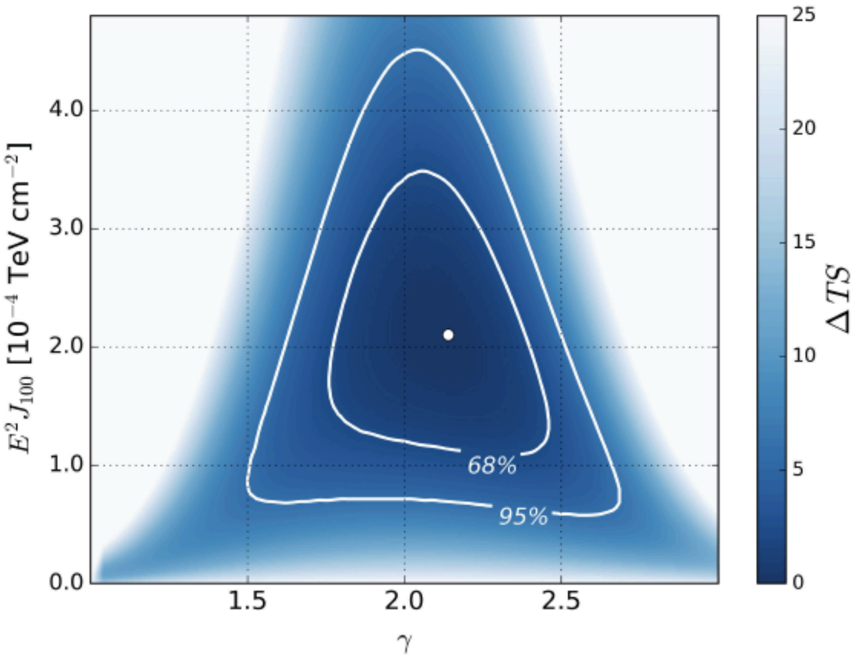
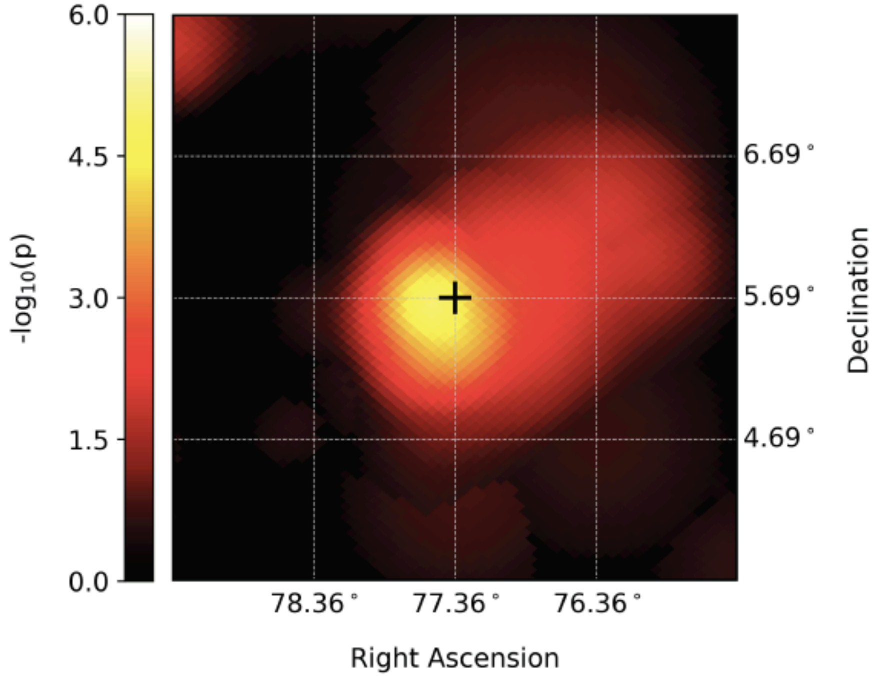


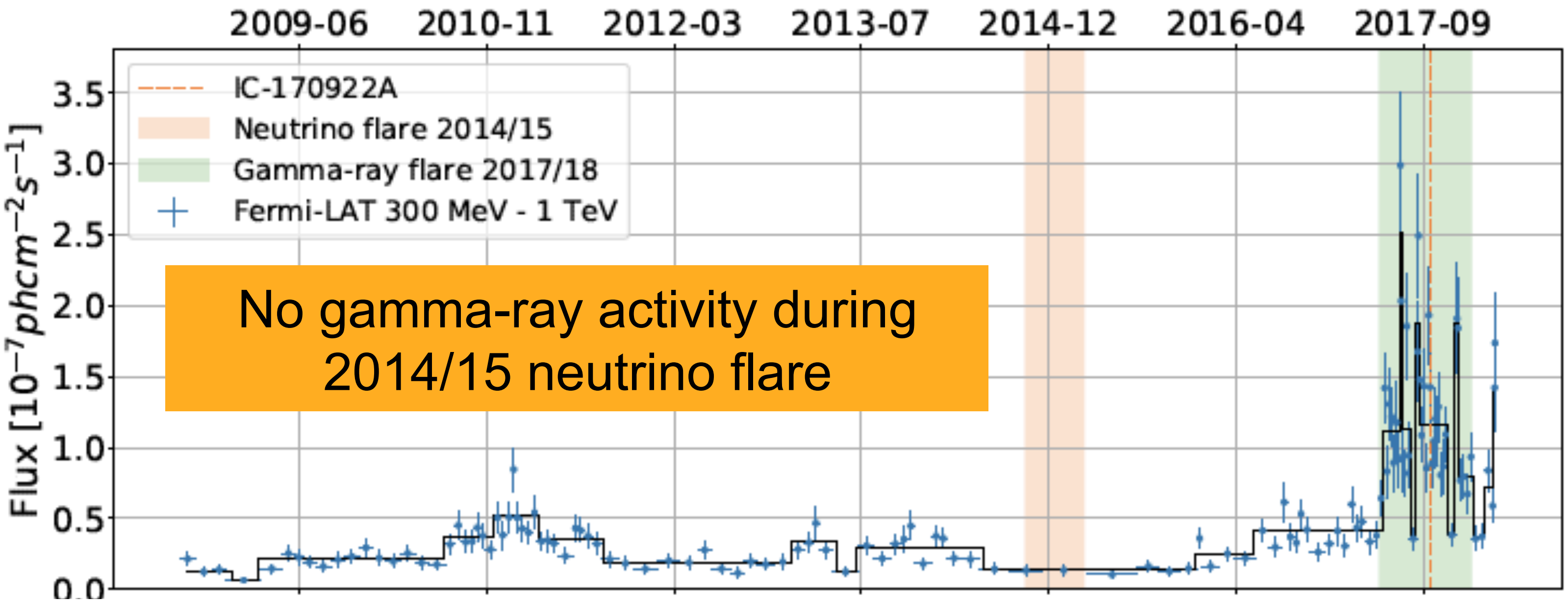


Neutrino luminosity (averaged over 158 days): $(1.2^{+0.6}_{-0.4}) \times 10^{47}$ erg s^{-1}

4 times larger than average gamma-ray luminosity!

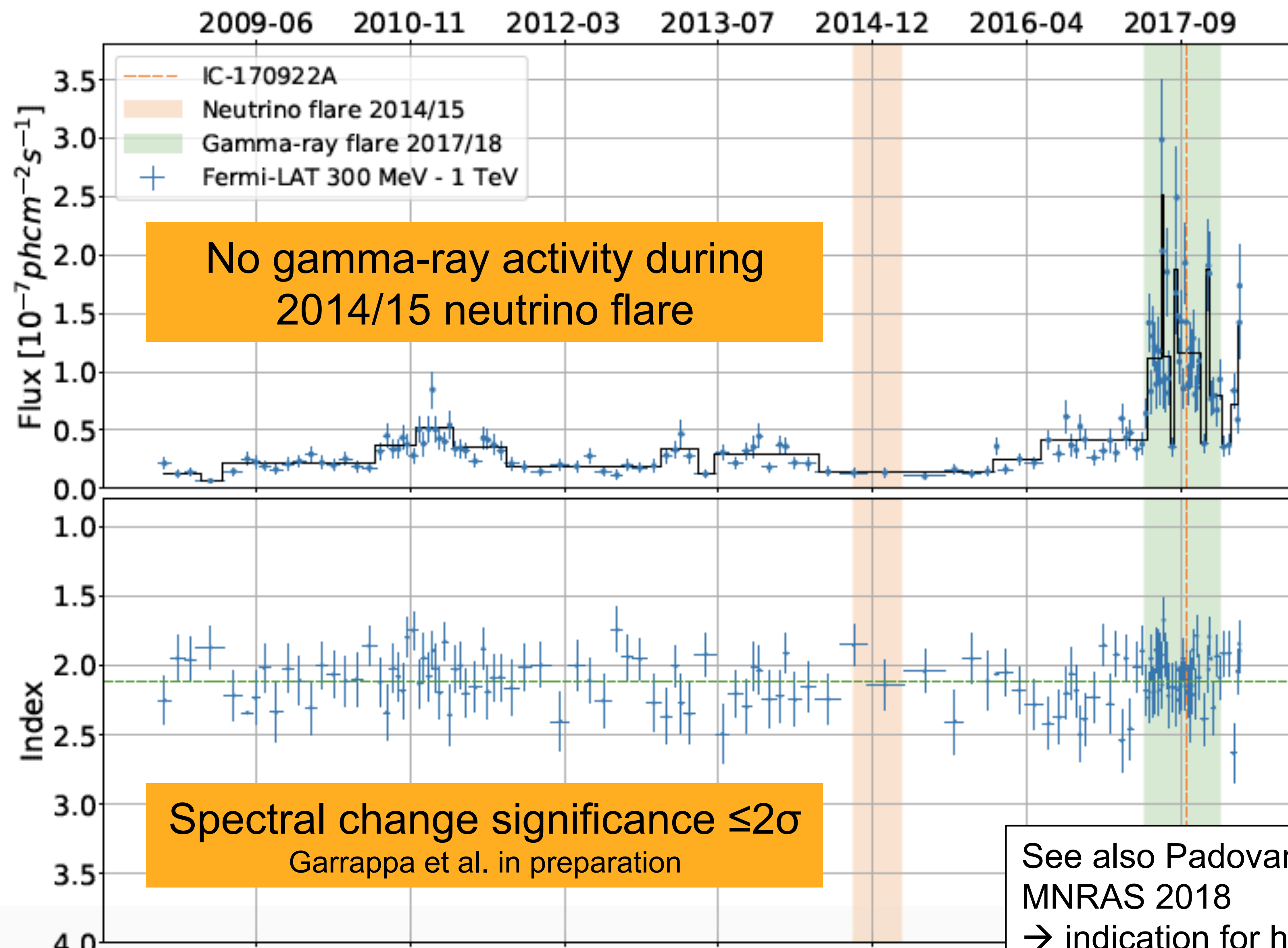
IceCube Coll.,Science 2018

Is there also a Gamma-ray Flare?



No gamma-ray activity during 2014/15 neutrino flare

Is there also a Gamma-ray Flare?



No gamma-ray activity during 2014/15 neutrino flare

Spectral change significance ≤2σ

Garrappa et al. in preparation

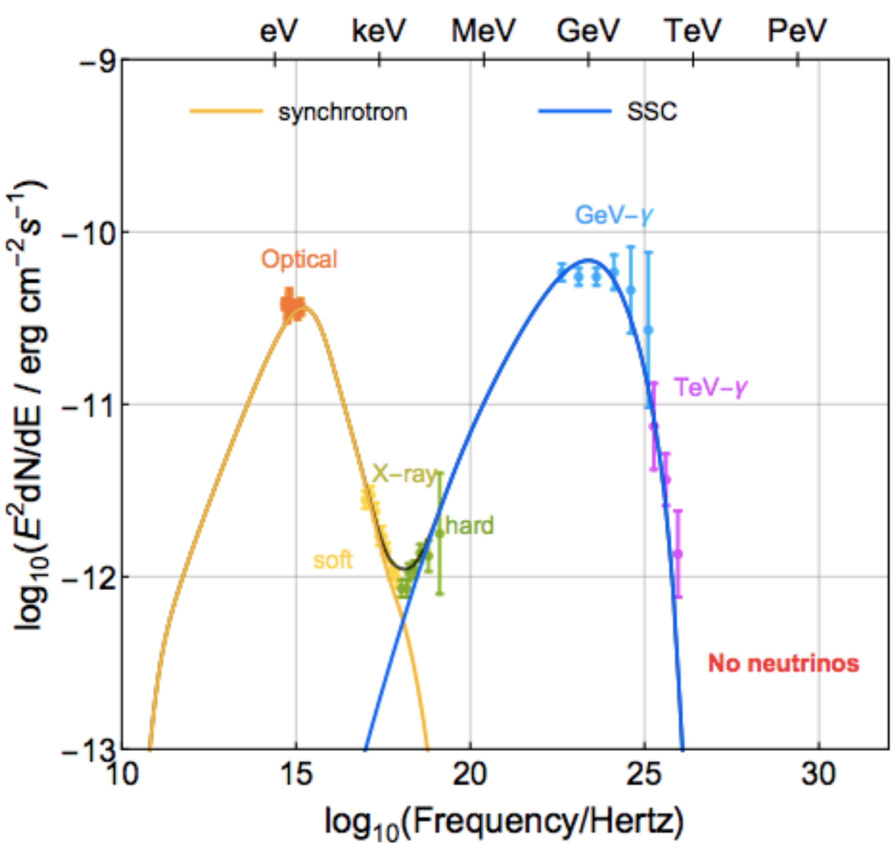
See also Padovani et al. MNRAS 2018
→ indication for hardening with 2% p-value

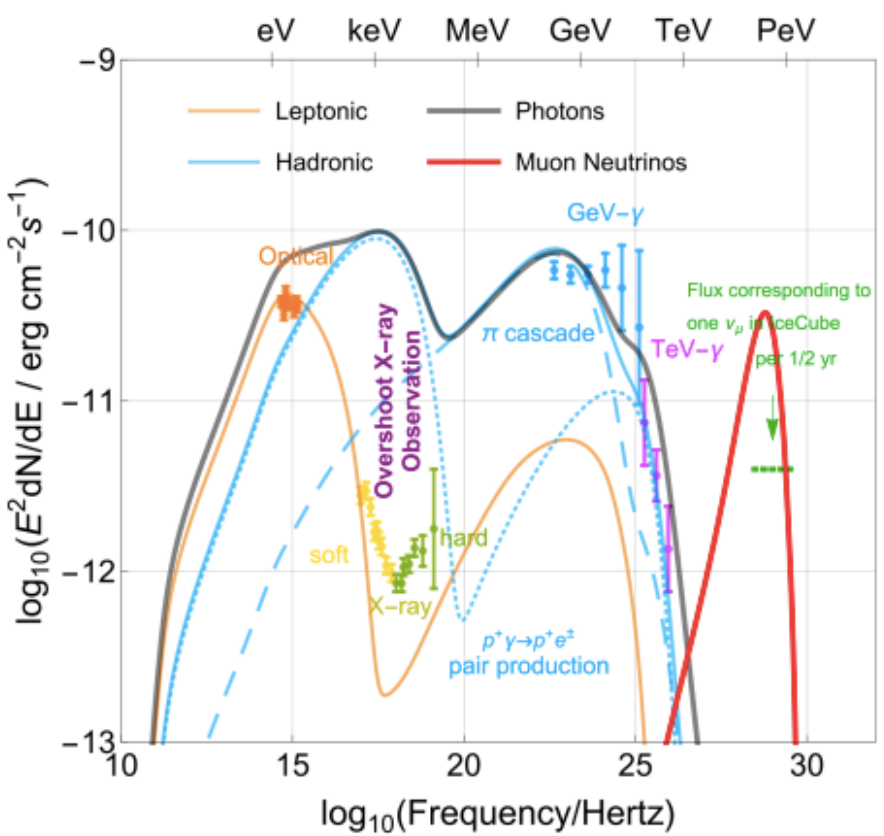
Modeling Papers on the arXiv on July 12

- “Interpretation of the coincident observation of a high energy neutrino and a bright flare”, Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275
- “A multiwavelength view of BL Lacs neutrino candidates”, Righi, Tavecchio, Pacciani, arXiv::1807.04299
- “The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration”, MAGIC Collaboration, arXiv: 1807.04300
- “Lepto-hadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056”, Cerruti, Zech, Boisson, Emery, Inoue, Lenain, arXiv:1807.04335
- “A Multimessenger Picture of the Flaring Blazar TXS 0506+056: implications for High-Energy Neutrino Emission and Cosmic Ray Acceleration”, Keivani, Murase, Petropoulou et al., arXiv:1807.04537
- “Blazar Flares as an Origin of High-Energy Cosmic Neutrinos?” Murase, Oikonomou, Petropoulou, arXiv:1807.04748

See talk by Walter Winter

Modeling – leptonic, hadronic, Gin & Tonic



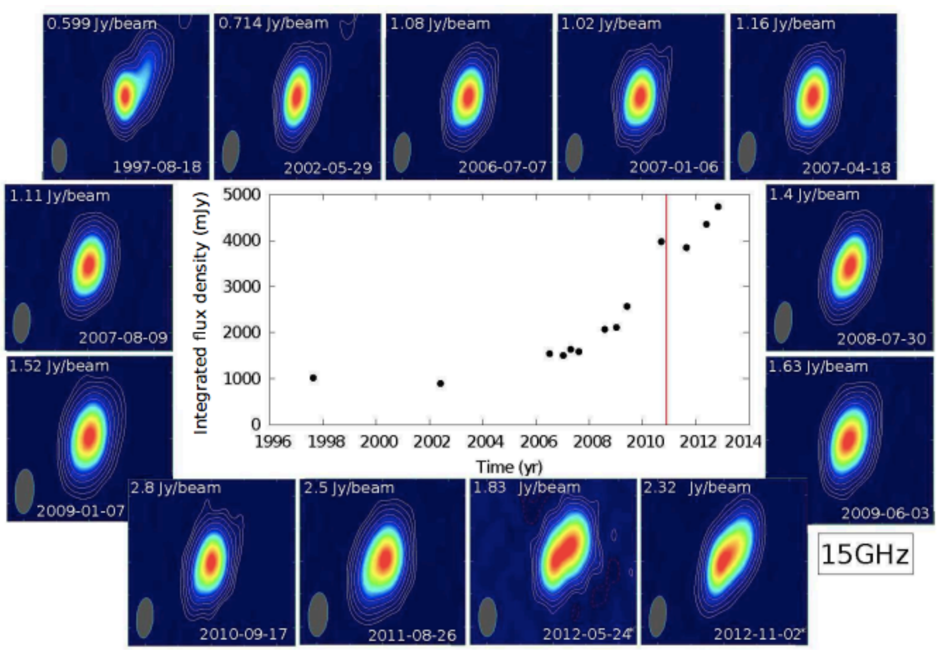


Pure one-zone hadronic models violate X-ray constraints
→ More complex models needed

Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

Other interesting candidates

PKS 0723-008 + track event,
Barely outside 90% error circle,
dim gamma-ray source



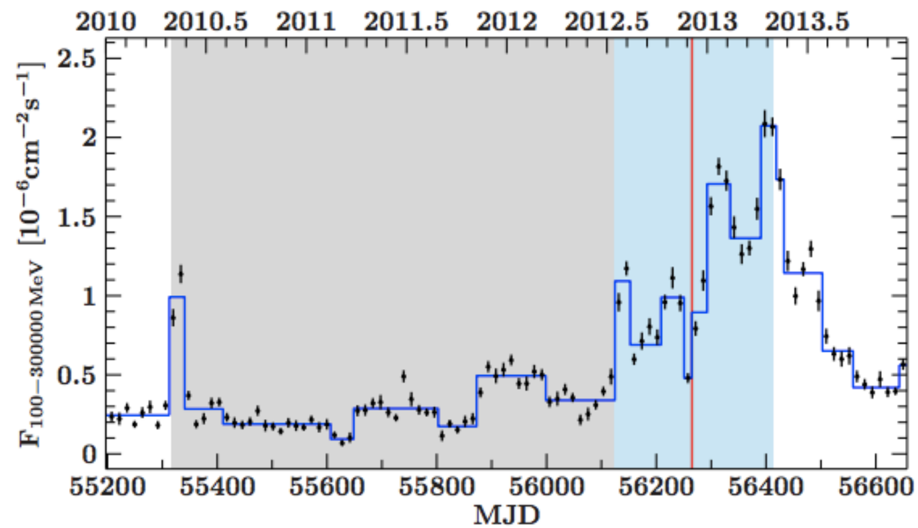
Kun et al. 2017

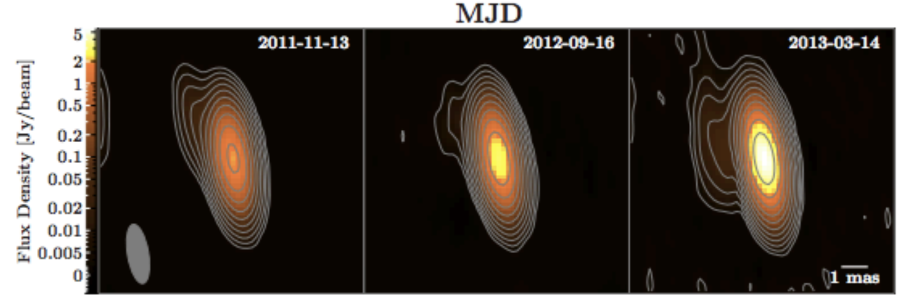
Max-Planck-Institut
für
Radioastronomie

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

PKS B1424−418 + cascade event
5% chance coincidence





Kadler et al. 2016

Another interesting candidate?

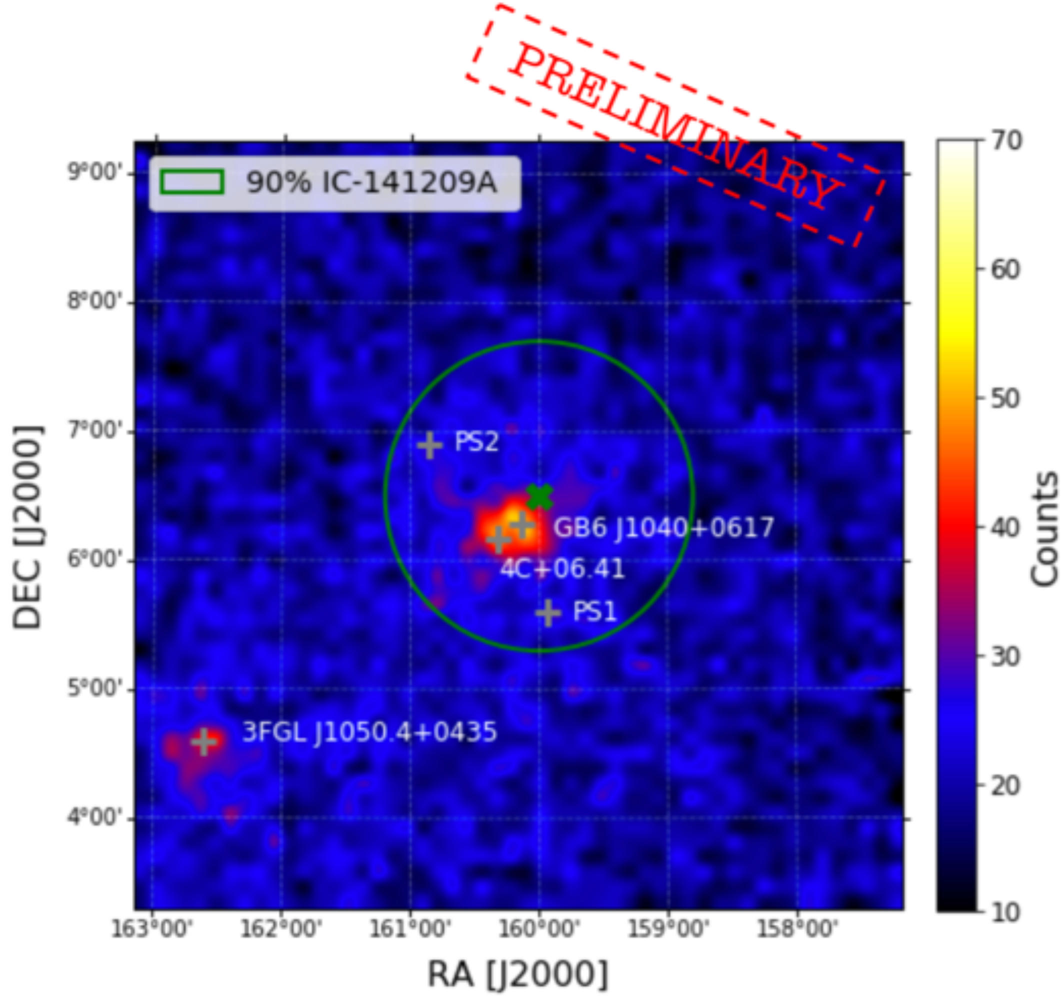
Possible counterpart of another well-reconstructed high-energy neutrino

IC-141209A

- MJD 57000.14
- (Ra , Dec) = (160.0°, 6.5°)
- Ang. Err. (90%) : 1.2°

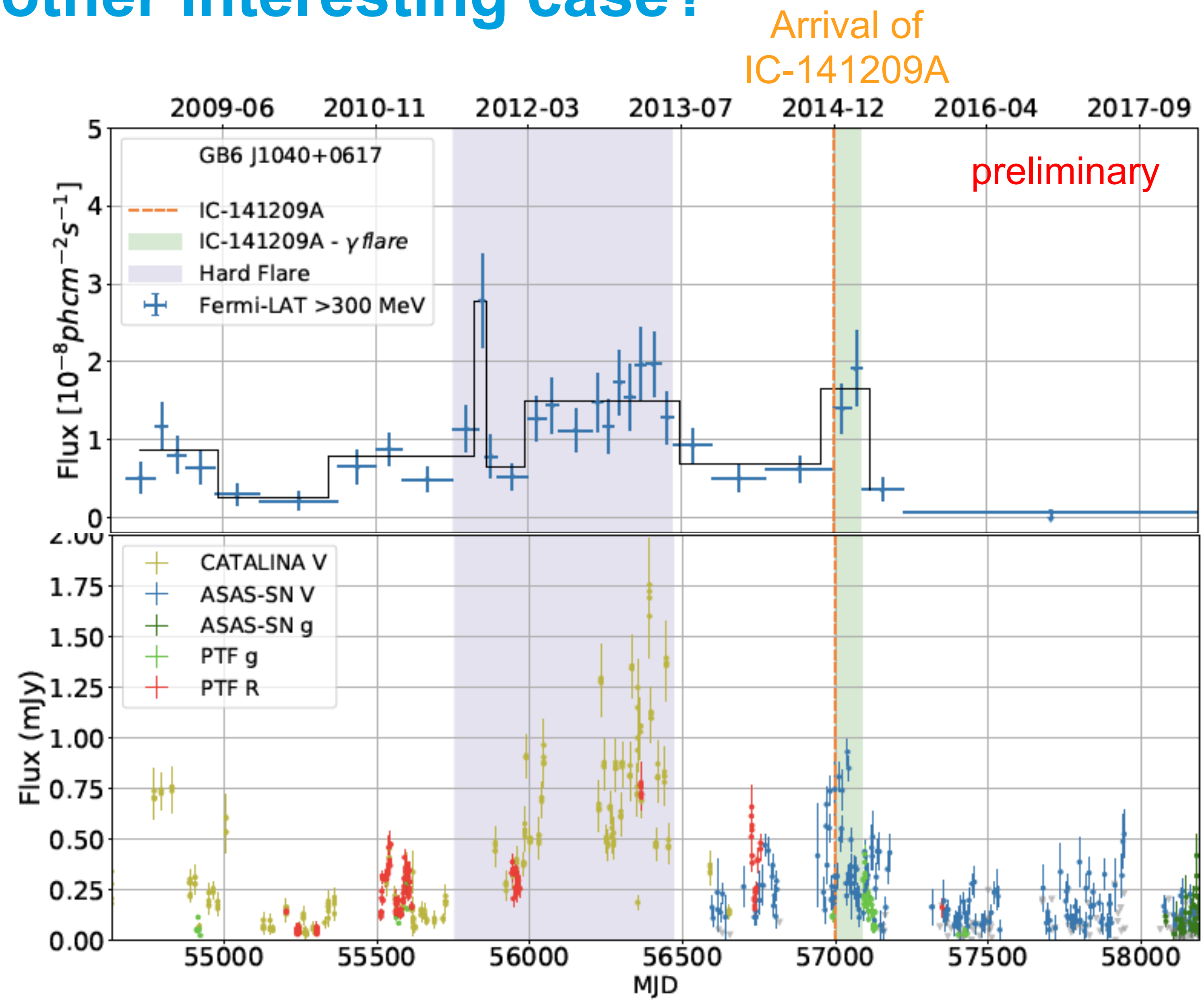
GB6 J1040+0617

- BL Lac, LSP
- 3FGL J1040.4+0615
- z = 0.7351± 0.0045 *
- Dist. from IC-141209A: 0.27°



Garrappa et al. in preparation

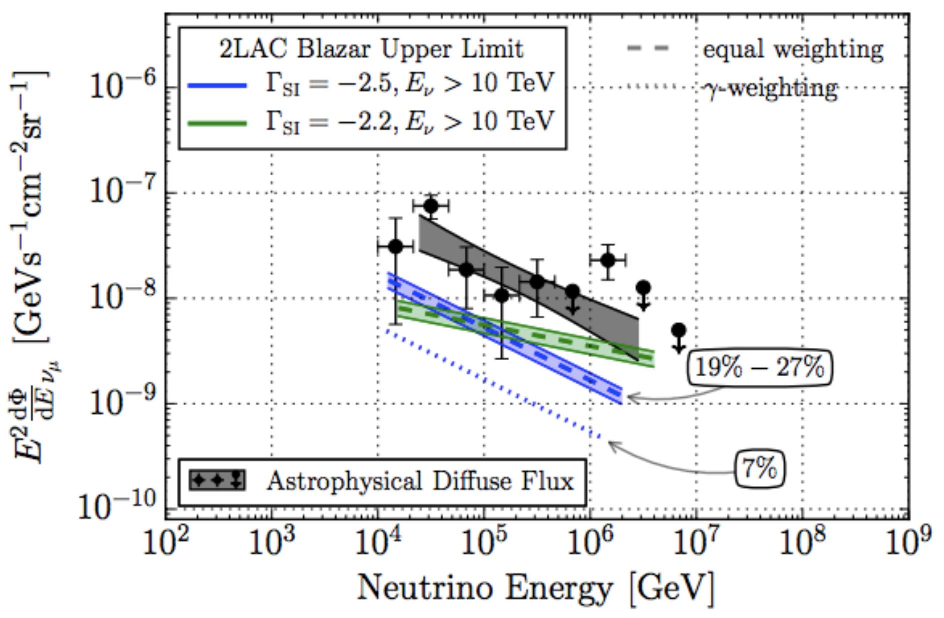
Another interesting case?



Garrappa et al. in preparation

Do gamma-ray blazars produce all diffuse neutrinos?

- 40 high-energy neutrinos, 20 signal neutrinos, 1-2 neutrino blazar coincidences → 10% blazar contribution
- Averaged over 9.5 years, the neutrino flux of TXS 0506+056 by itself corresponds to 1% of the astrophysical diffuse flux
- *2LAC Blazar Stacking:*
  - Upper limit of 27% of the diffuse flux fit between 10 TeV and 100 TeV with a soft $E^{-2.5}$ spectrum
  - Upper limit of 40% and 80% for an E^{-2} spectrum (compatible with the diffuse flux fit > 200TeV)

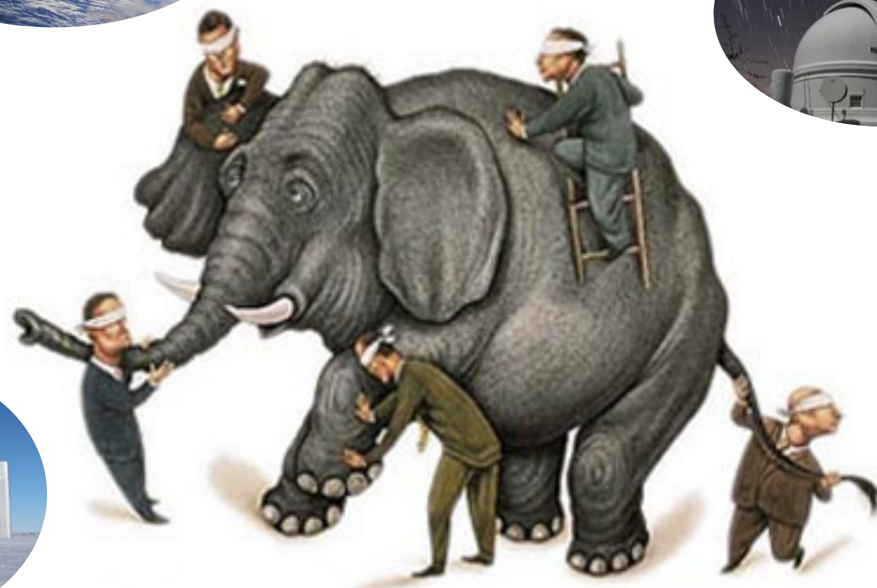


Fully compatible with blazar catalog stacking results

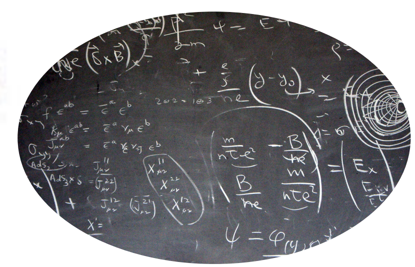
Summary

gamma-rays

visible light



theory

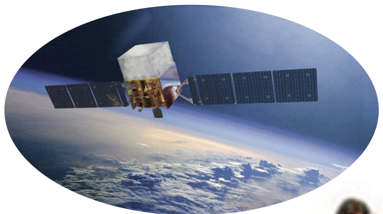


neutrinos

cosmic rays

Summary

gamma-rays



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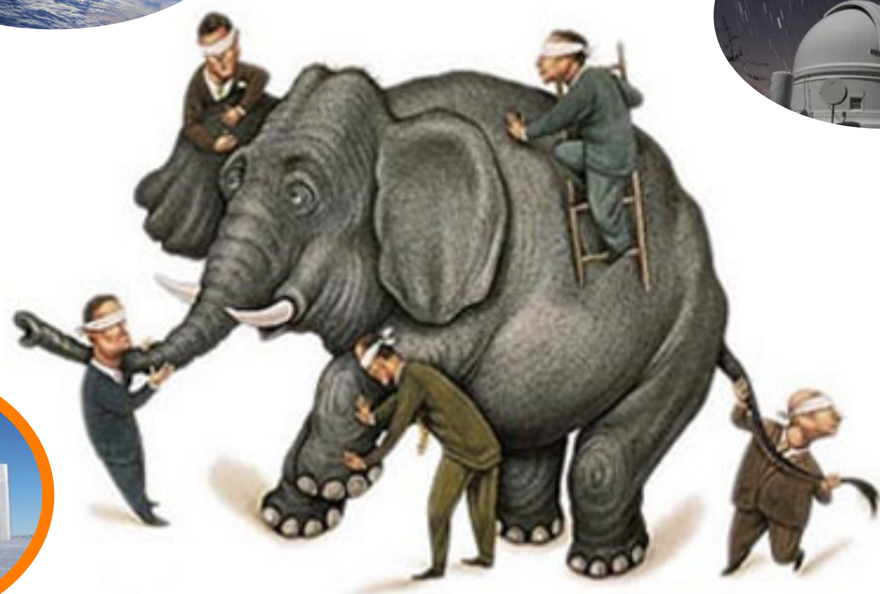

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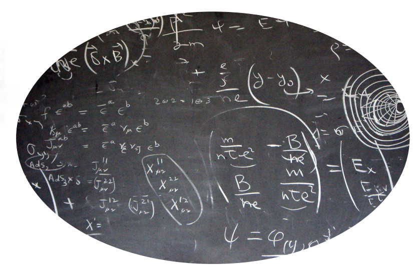


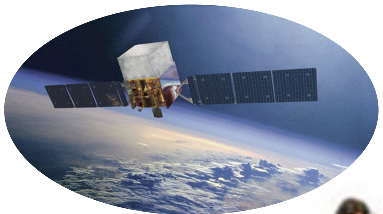
neutrinos

unique messengers from the high-energy Universe

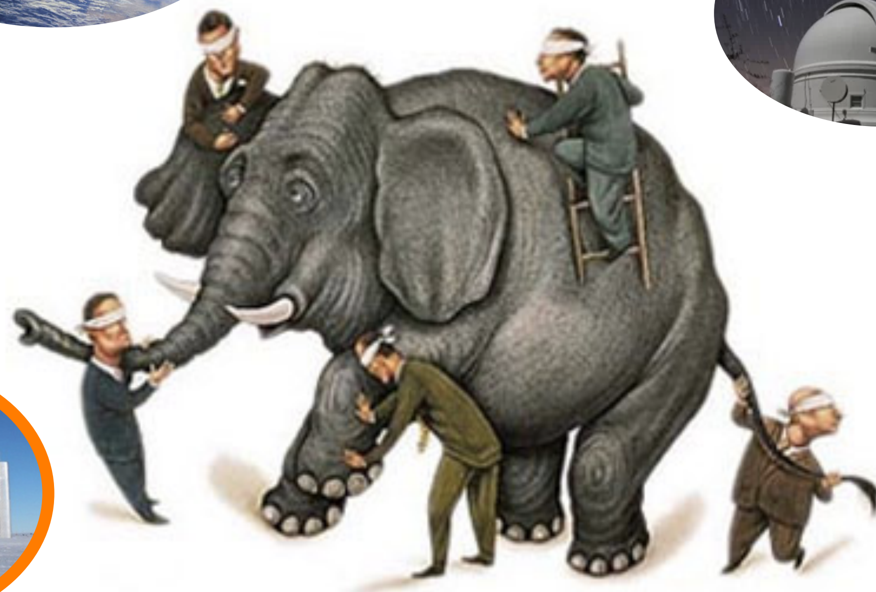
cosmic rays

Summary

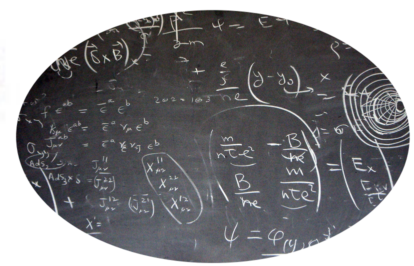
gamma-rays



visible light



theory



neutrinos

Neutrinos can reveal the sources of high-energy cosmic rays

cosmic rays

Summary

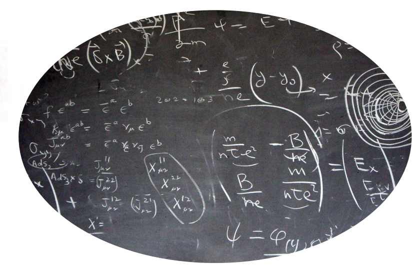
Electro-magnetic counterparts are crucial to identify the sources.

First compelling candidate found!
IC170922A + TXS flare: 3σ
2014/15 neutrino flare (13 events): 3.5σ

gamma-rays

visible light

theory



neutrinos

cosmic rays

Summary

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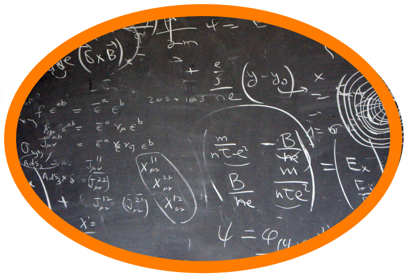

neutrinos

cosmic rays

How does this all fit together?

Stay tuned!

Back-up