Flaring Sources and the High-Energy Cosmic Neutrino Flux

Ali Kheirandish

In collaboration with Francis Halzen & Tom Weisgarber

8th Fermi Symposium
Baltimore, October 2018

WIPAC
Wisconsin IceCube Particle Astrophysics Center

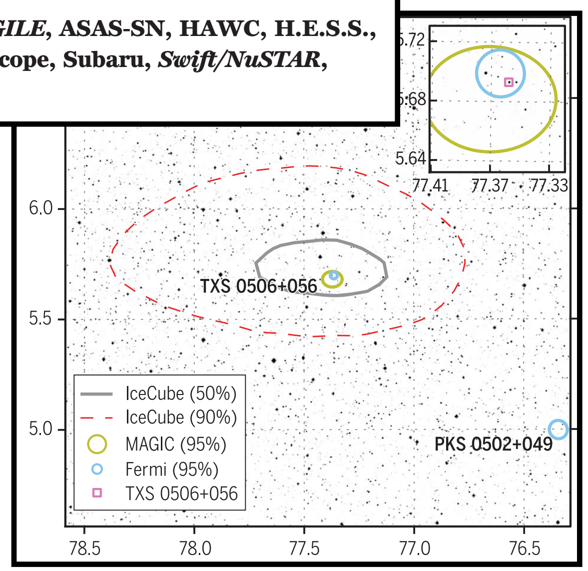
WISCONSIN
University of Wisconsin–Madison

Image Credit: DESY

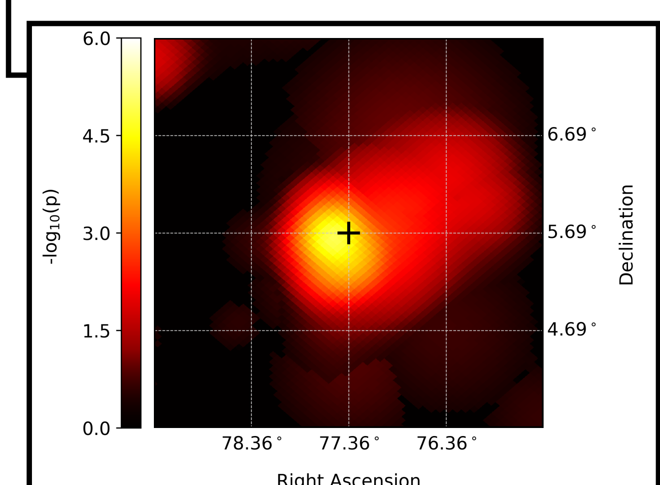
First Multimessenger Blazar: TXS 0506+056

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *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*†



Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert



TXS 0506+056

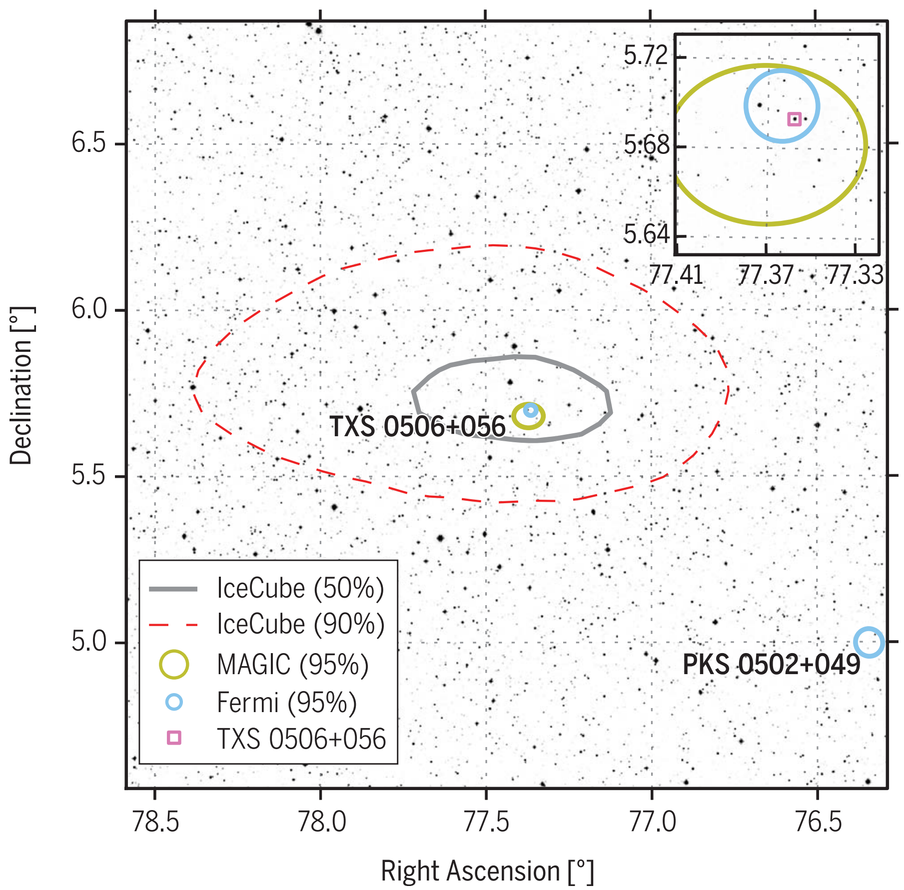
ISP BL Lac located at Redshift 0.3365 [Paiano+ 2018]

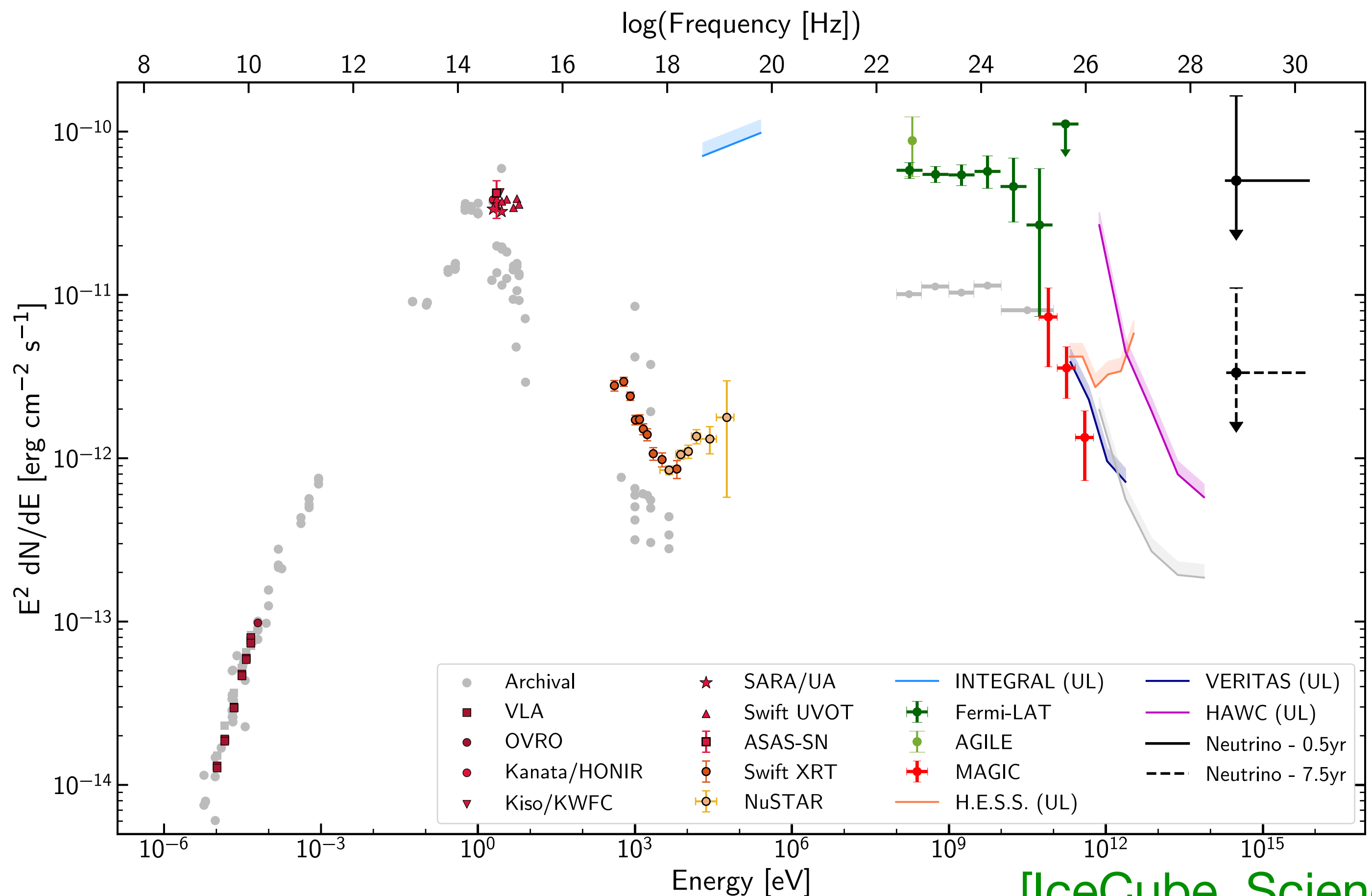
Among the 50 brightest Fermi blazars.

Outshines near by sources.

Highest energy gamma ray source in EGRET above 40 GeV [Dingus & Bertsch 2001]

Nu Signals from TXS 0506+056: IC-170922A



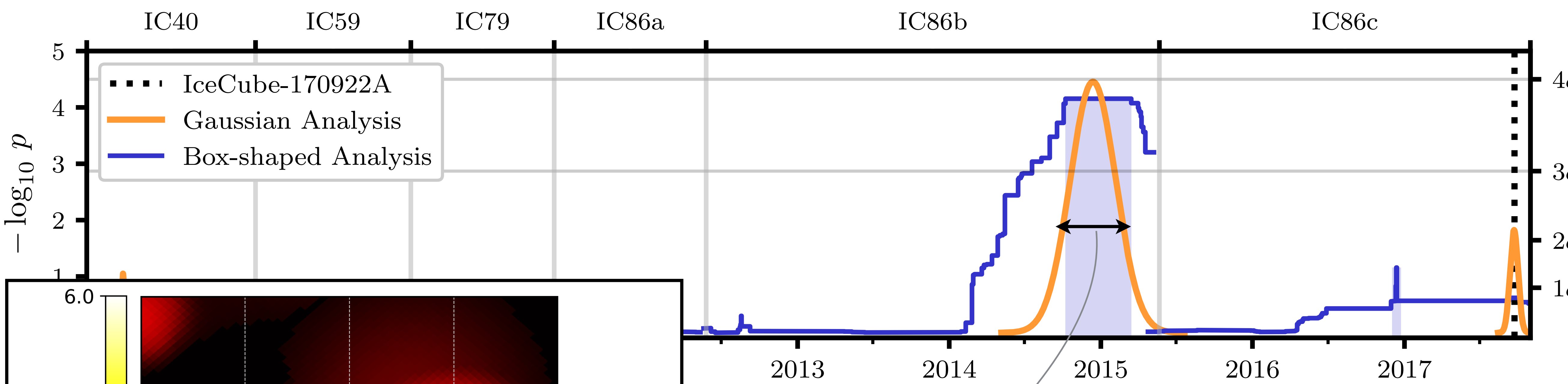


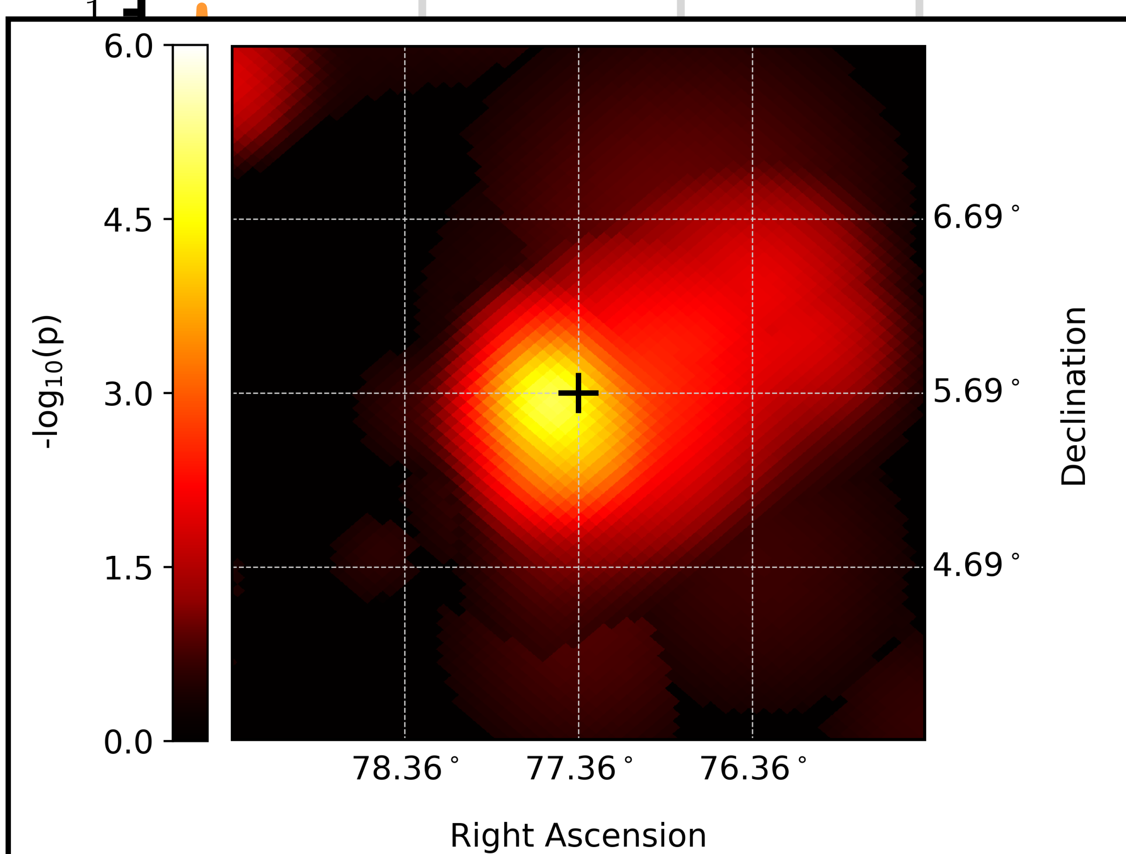
[IceCube, Science 2018]

- Up-going muon track observed on September 22, 2017 from 5.7° below horizon with best fit neutrino energy of ~300 TeV for E^{-2} Spectrum.
- Angular distance from TXS 0506+056: 0.1°.
- Coincidence with enhanced γ-ray activity, chance correlation rejected at the 3σ-level.
- Multi-wavelength observation available from multimessenger follow-up campaign.

Nu Signals from TXS 0506+056: Neutrino Flare in 2014

Time-dependent search in the direction of TXS 0506+056 revealed a **neutrino flare** in December 2014.





$$T_{\mathrm{W}} = 110^{+35}_{-24} \text{ days}$$

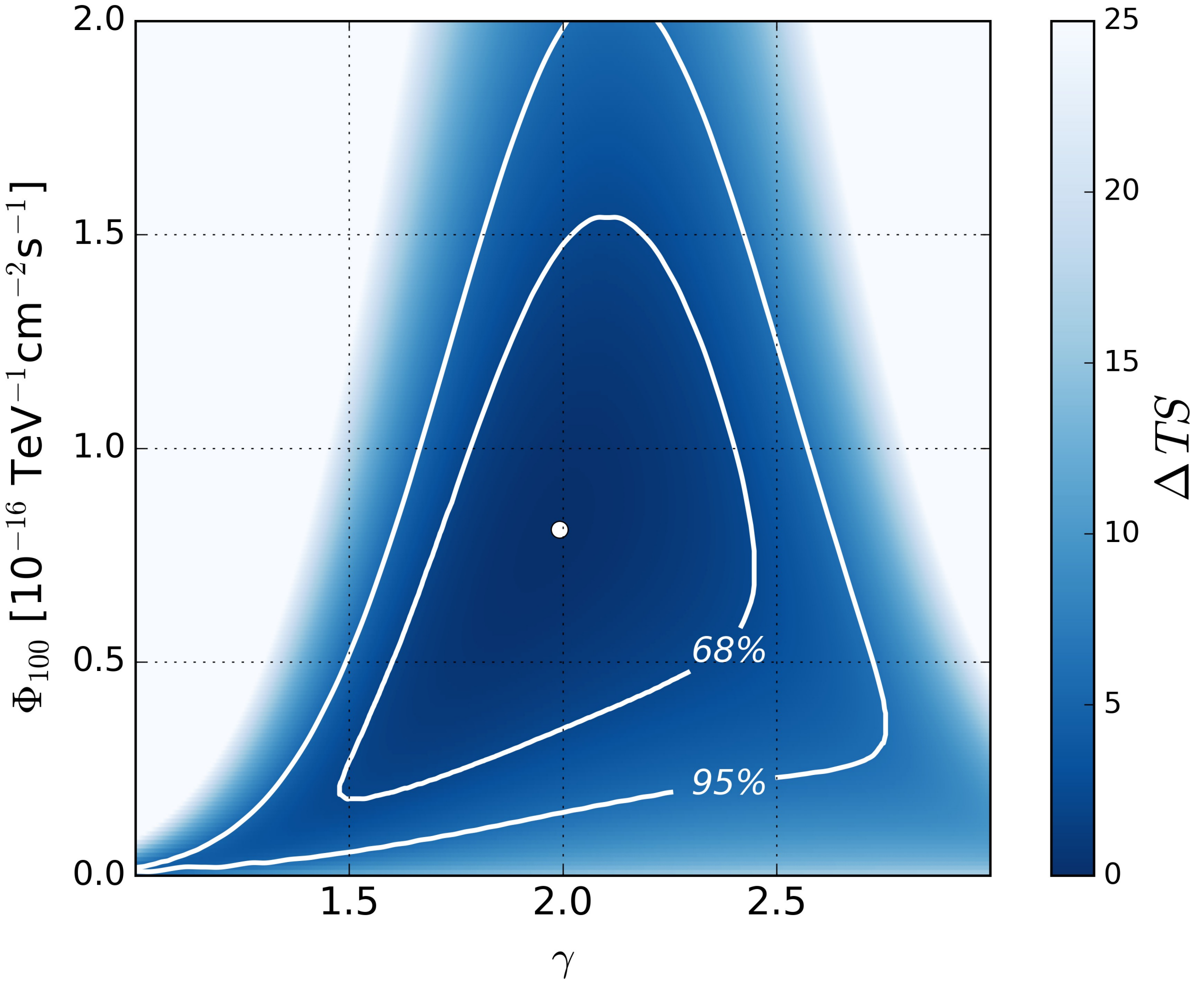
$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15} \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

13±5 signal events rejecting background hypothesis at 3.5σ

[IceCube, Science 2018]

Time-Integrated Neutrino Signal

Time-Integrated Search: looking for the signal from TXS 0506+056 in 9.5 years of IceCube data.



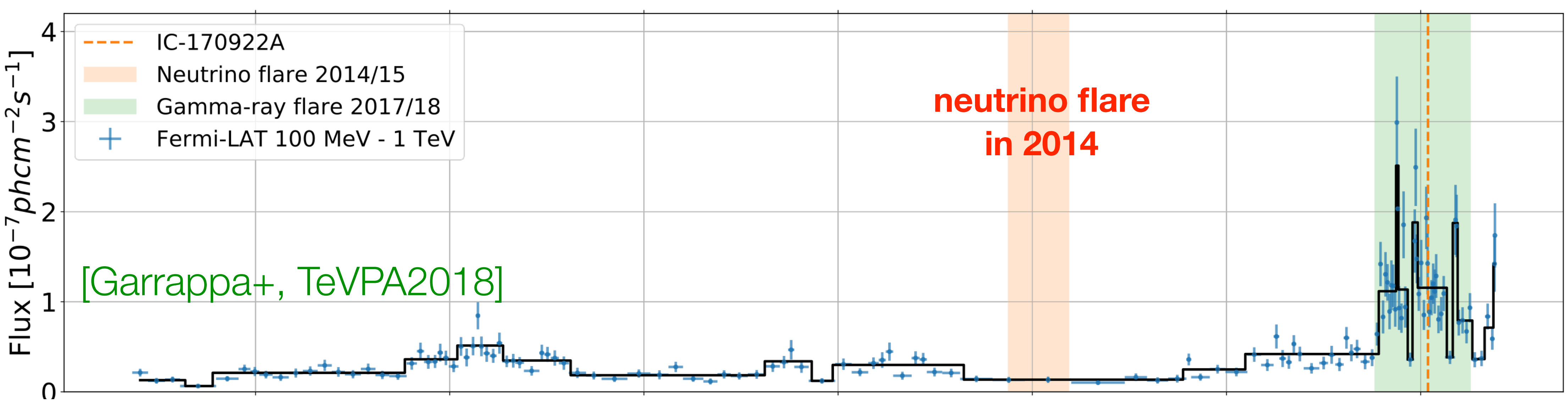
$$\Phi_{100} = (0.8^{+0.5}_{-0.4}) \times 10^{-16} \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

posterior significance (including IC-170922A)	4.1σ
significance after removing alert period	2.1σ

Neutrino emission from TXS 0506+056 is dominated by the 2014 flare!

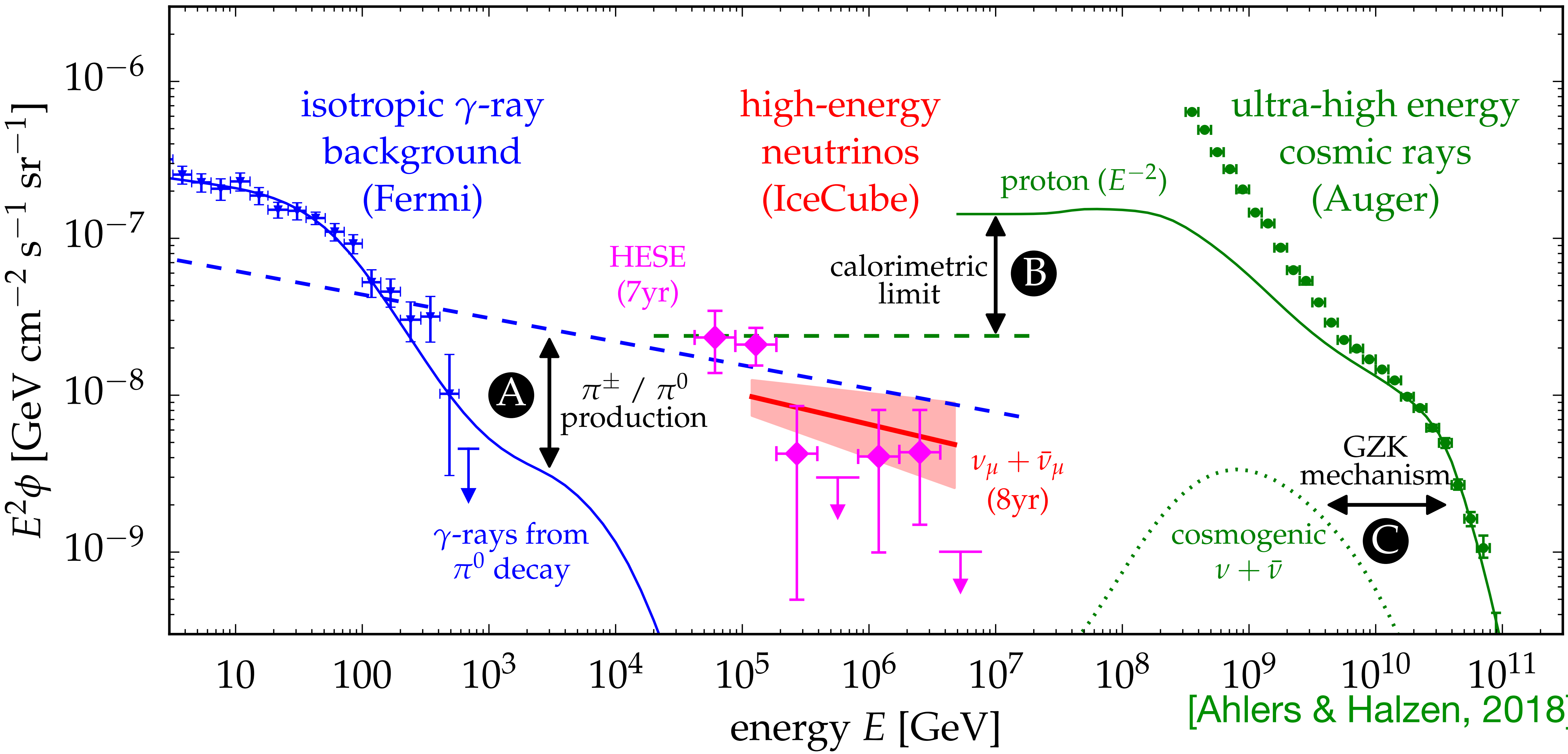
Observation of TXS 0506+056 in Neutrinos

- Two independent analyses provided **compelling evidence** for neutrino emission of TXS 0506+056.
- The 9.5 year averaged flux of neutrinos from TXS 0506+056 is **dominated** by the 2014 burst.
- **γ-ray enhancement** coincident with IC-170922A.
- **No enhanced γ-ray activity** for the neutrino burst in 2014. May be **hardening of the spectrum** [Padovani+, 2018] **although no significant slope change** [Garrappa+, TeVPA2018]



Where are the gamma rays? Why is not there enhanced γ-ray activity?

HE Cosmic Neutrinos & Multimessenger Interface



[Ahlers & Halzen, 2018]

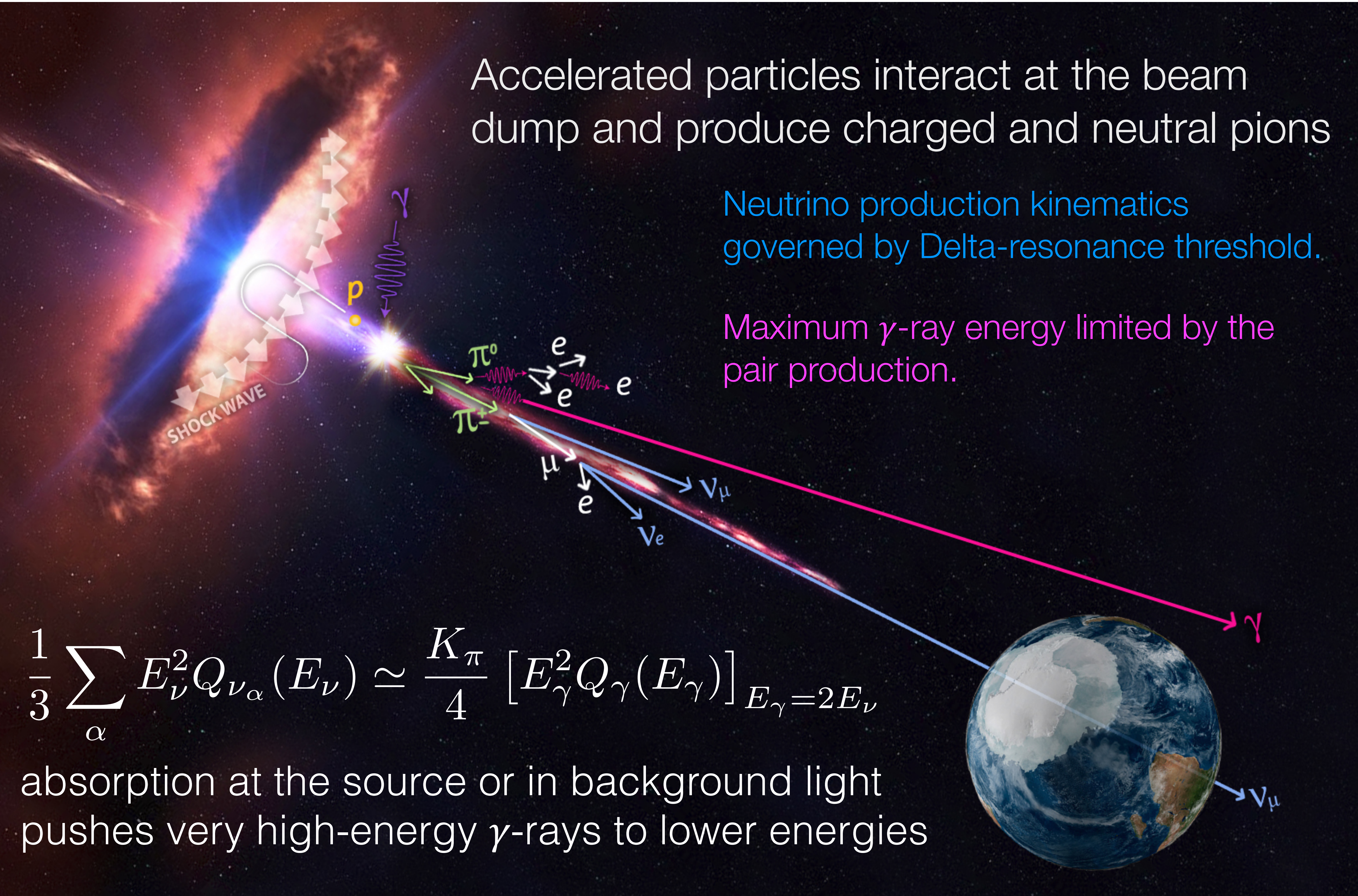
Similar energy in the Universe in γ-rays, neutrinos and cosmic rays
[Ahlers 2015, Murase+ 2014, Kowalski 2014]

The Neutrino γ-ray Connection

Accelerated particles interact at the beam dump and produce charged and neutral pions

Neutrino production kinematics governed by Delta-resonance threshold.

Maximum γ-ray energy limited by the pair production.



$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

absorption at the source or in background light pushes very high-energy γ-rays to lower energies

Flaring Sources and the IceCube Neutrino Flux

Neutrino flux from **episodic emission** from a **fraction** of a source class

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{c}{4\pi} \frac{\xi_z}{H_0} L_\nu \rho \, \mathcal{F} \, \frac{\Delta t}{T}$$

[Halzen, AK, Weisgarber, In prep.]

Flaring Sources and the IceCube Neutrino Flux

Neutrino flux from **episodic emission** from a **fraction** of a source class

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{c}{4\pi}\frac{\xi_z}{H_0} L_\nu \rho \, \mathcal{F} \, \frac{\Delta t}{T}$$

Adopting for the observation of 2014 neutrino burst for TXS:

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{\mathcal{F}}{4\pi}\left(\frac{R_H}{3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2\times10^{47}\,\mathrm{erg/s}}\right)\left(\frac{\rho}{1.5\times10^{-8}\,\mathrm{Mpc}^{-3}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\frac{10\,\mathrm{yr}}{T}\right)$$

$$= 3\times10^{-11}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}}$$

[Halzen, AK, Weisgarber, In prep.]

Flaring Sources and the IceCube Neutrino Flux

Neutrino flux from **episodic emission** from a **fraction** of a source class

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{c}{4\pi}\frac{\xi_z}{H_0} L_\nu \rho \mathcal{F} \frac{\Delta t}{T}$$

Adopting for the observation of 2014 neutrino burst for TXS:

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{\mathcal{F}}{4\pi}\left(\frac{R_H}{3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2\times10^{47}\,\mathrm{erg/s}}\right)\left(\frac{\rho}{1.5\times10^{-8}\,\mathrm{Mpc}^{-3}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\frac{10\,\mathrm{yr}}{T}\right)$$

$$= 3\times10^{-11}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}}$$

$$\longrightarrow \mathcal{F} \sim 5\%$$

A special class of blazars that undergo ~ 110-day duration flares like TXS 0506+056 once every 10 years accommodates the observed diffuse flux of high-energy cosmic neutrinos.

[Halzen, AK, Weisgarber, In prep.]

Relating to the Cosmic Rays

The equal energetics of cosmic rays and neutrinos dictates

$$\frac{1}{3}\sum_{\alpha} E_{\nu}^{2}\frac{dN_{\nu}}{dE_{\nu}} \simeq \frac{c}{8\pi}\left(1-e^{-f_{\pi}}\right)\frac{\xi_z}{H_0}\frac{dE}{dt}$$

The CRs energy injection rate: $\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

[Halzen, AK, Weisgarber, In prep.]

Relating to the Cosmic Rays

The equal energetics of cosmic rays and neutrinos dictates

$$\frac{1}{3}\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{8\pi}\left(1-e^{-f_\pi}\right)\frac{\xi_z}{H_0}\frac{dE}{dt}$$

The CRs energy injection rate: $\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

Finding the pion production efficiency of the neutrino source $\longrightarrow$ $f_\pi \gtrsim 0.4$

high opacity for p-γ interaction. Expected for an efficient neutrino emitter!

[Halzen, AK, Weisgarber, In prep.]

Relating to the Cosmic Rays

The equal energetics of cosmic rays and neutrinos dictates

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{8\pi}\left(1 - e^{-f_\pi}\right)\frac{\xi_z}{H_0}\frac{dE}{dt}$$

The CRs energy injection rate: $\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

Finding the pion production efficiency of the neutrino source $\longrightarrow$ $f_\pi \gtrsim 0.4$ *high opacity for p-γ interaction. Expected for an efficient neutrino emitter!*

γ-ray opacity is connected to pion efficiency

$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_\pi \longrightarrow \tau_{\gamma\gamma} \simeq 100$$

HE γ-rays will be absorbed at the source!

Is this compatible with the γ-ray observations?

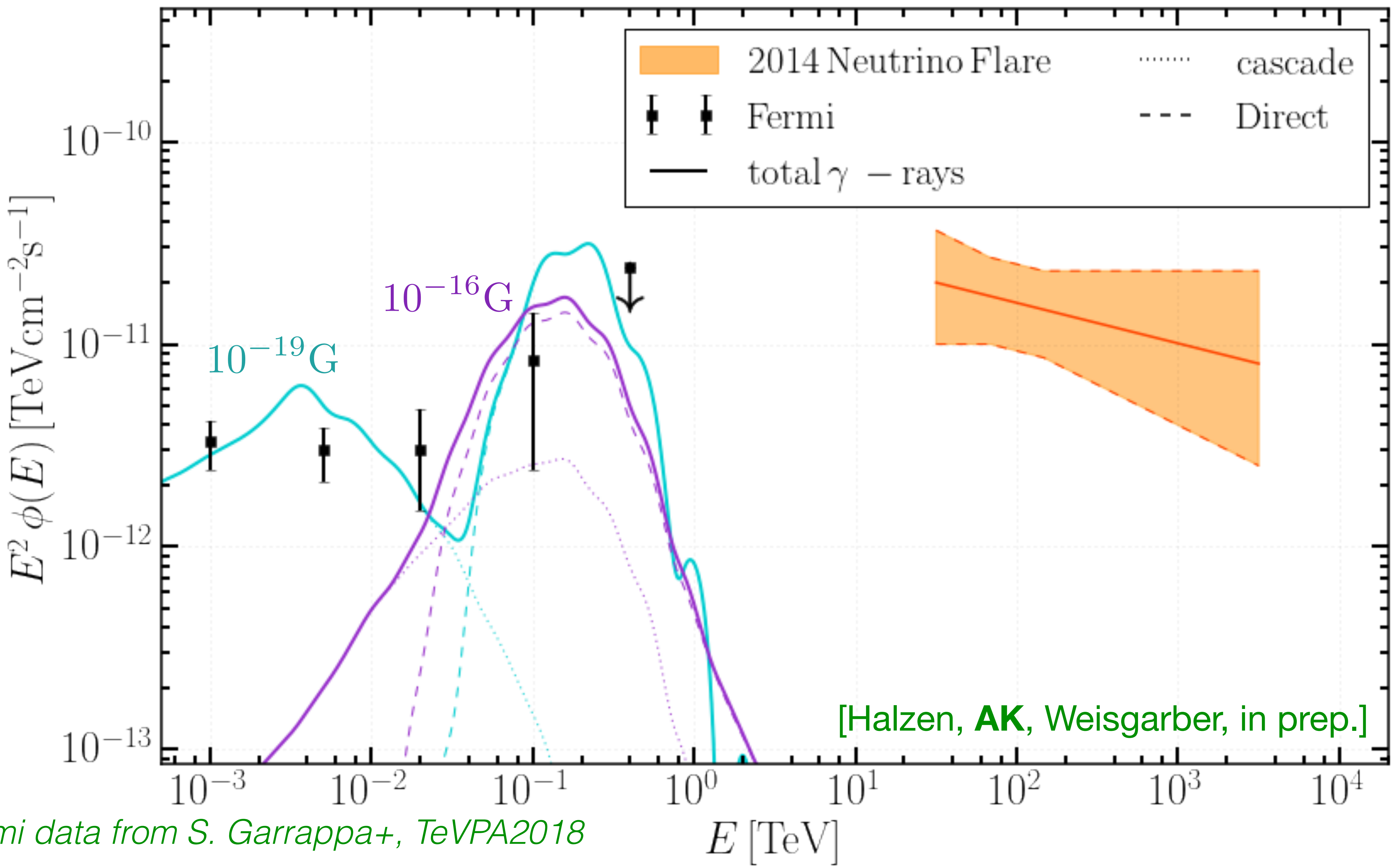
[Halzen, AK, Weisgarber, In prep.]

The Multimessenger Picture

Neutrino flux $\xrightarrow{\text{energetics}}$ γ-ray flux outside the source shifted to lower energies by internal cascade/absorption $\xrightarrow{\text{EBL Absorption}}$ Observed flux @ Fermi

The Multimessenger Picture

Neutrino flux $\xrightarrow{\text{energetics}}$ γ-ray flux outside the source shifted to lower energies by internal cascade/absorption $\xrightarrow{\text{EBL Absorption}}$ Observed flux @ Fermi



Fermi data from S. Garrappa+, TeVPA2018

Summary

There is a difference in γ-ray activity for neutrinos from TXS 0506+056 between 2017 alert and the neutrino flare in 2014. Different scenario? site of production? or more powerful emission?

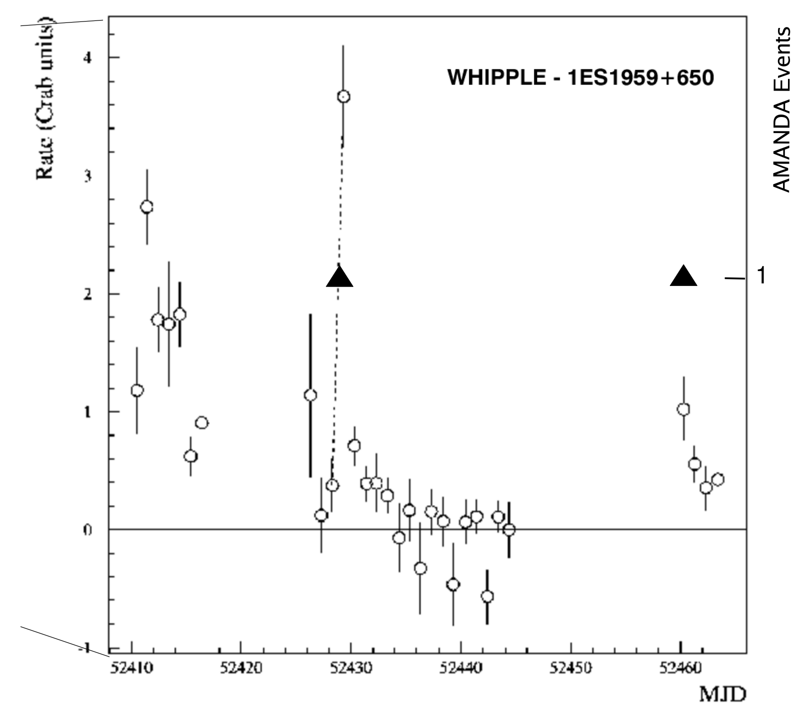
Multimessenger interface could help obtaining a better understanding of the dominant emission from TXS 0506+056.

Absorption at the source could explain why no enhanced γ-ray activity is seen for 2014 neutrino flare.

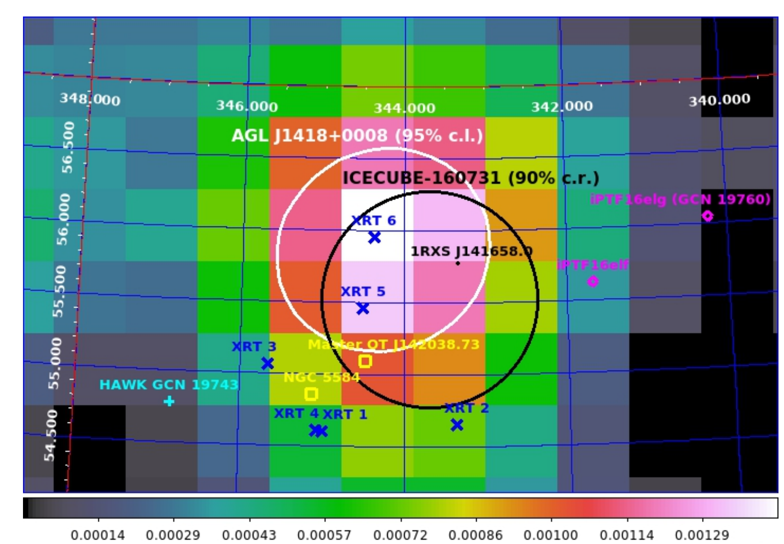
Understanding the emission process and establishing blazars as neutrino emitters require more observations.

Need More Neutrino Sources! But let's not forget the previous hints: AGL J1418+0008 & IC 16073A [Lucareli+ 2017], PKS 0723-008 & HESE-5 [Kun+ 2016], 1ES 1959+650 in AMANDA.

Getting all the elements of this puzzle to fit together is not easy, but they suggest that the blazar may contain important clues on the origin of cosmic neutrinos and cosmic rays.



[Ackermann+, ICRC 2005]



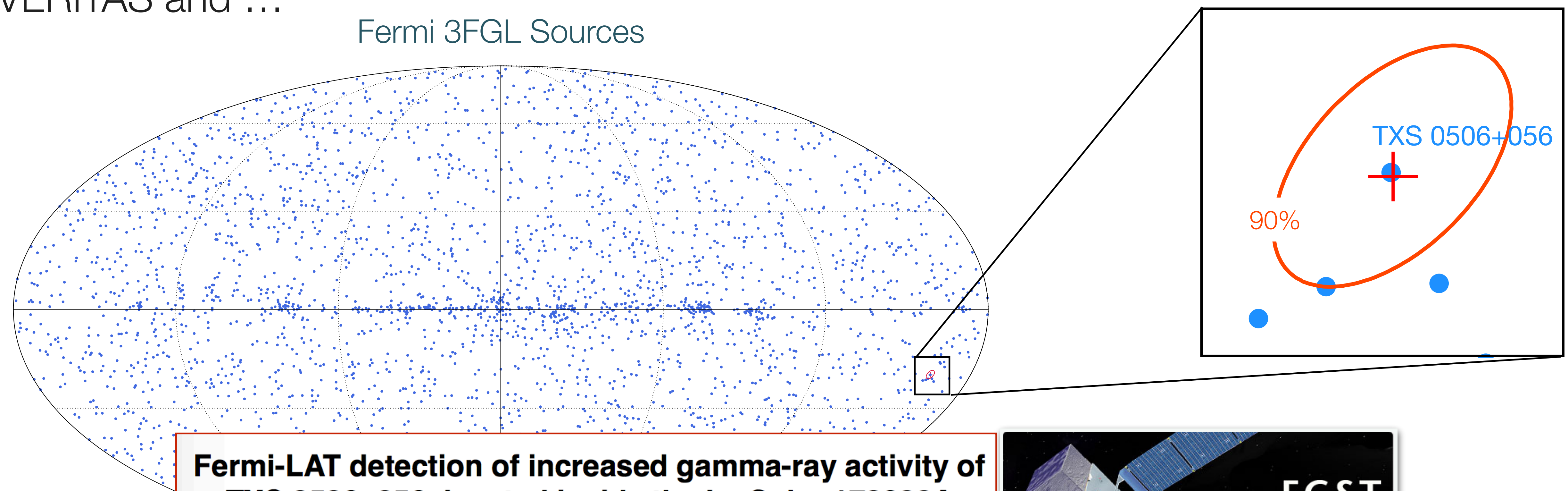
[Lucareli+ 2017]

Thanks!

Back up Slides

IC 170922A Gamma ray counterpart

- IceCube issued an alert on September 22, 2017.
- Follow up observations by ANTARES, H.E.S.S. , **Fermi-LAT**, **Swift**, AGILE, **MAGIC**, HAWC, VERITAS and …

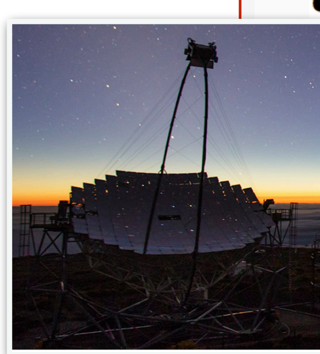


Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

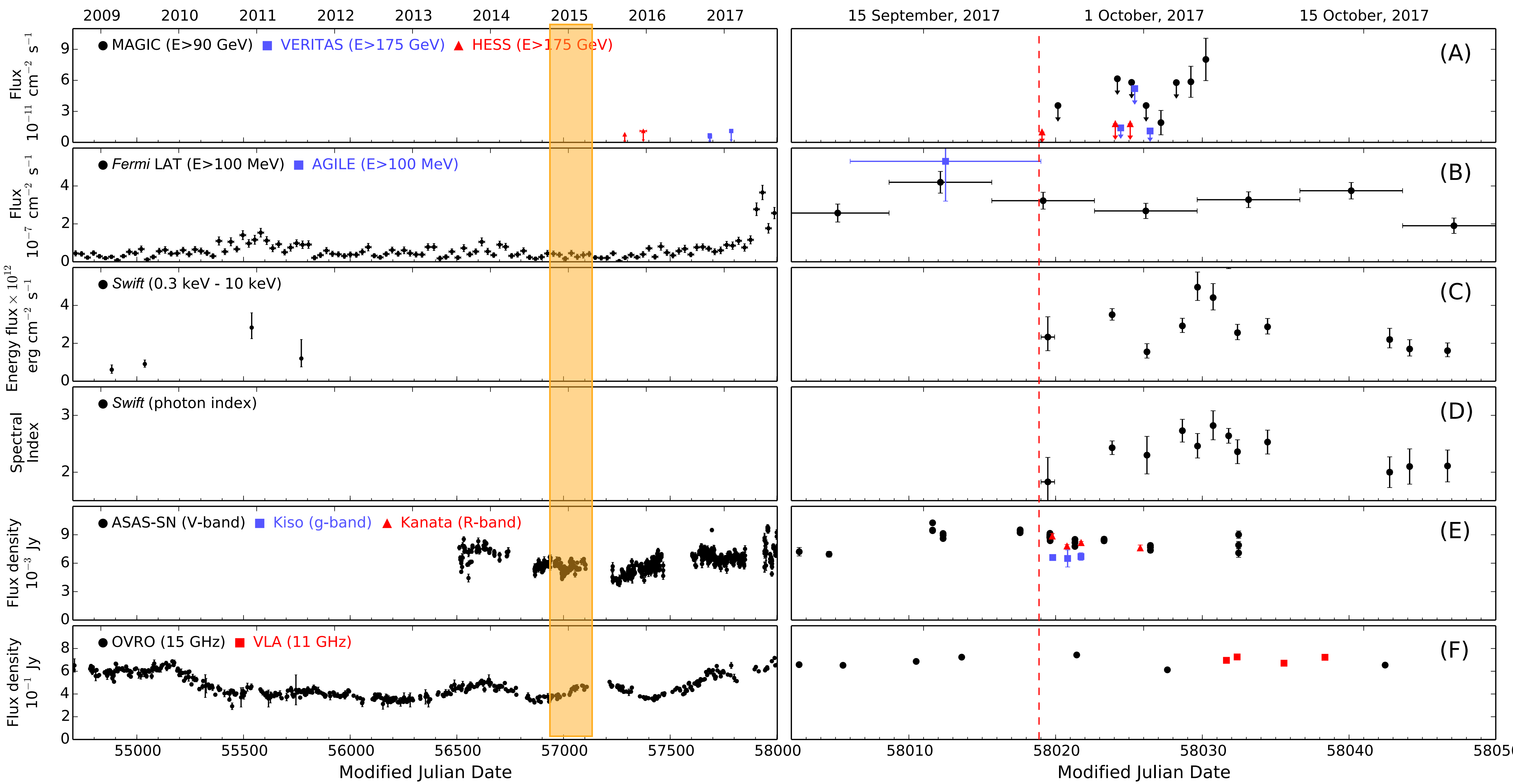
ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2
Credential Certification: David J. Th

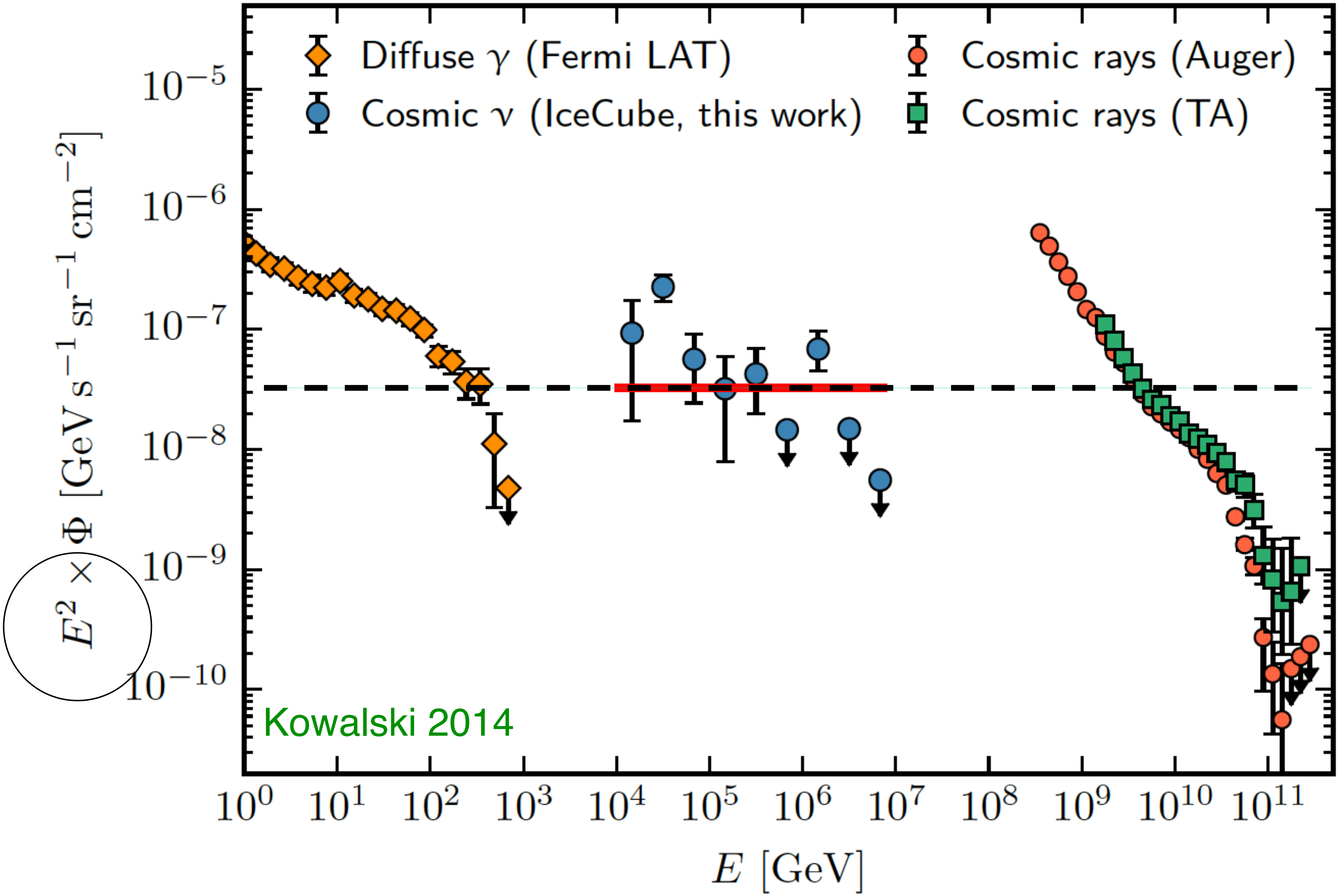
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

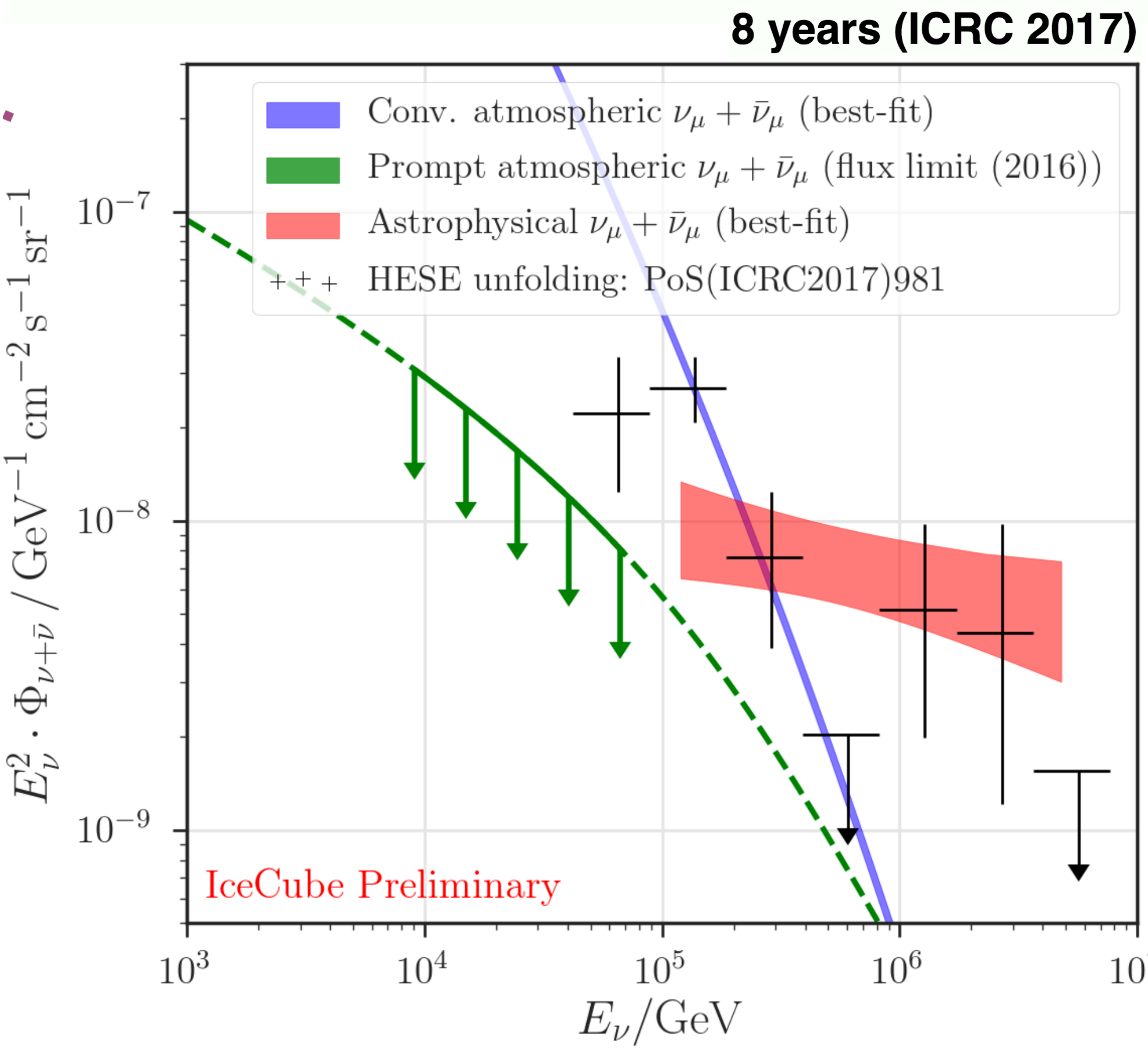


Multiwavelength Observation





energy in the Universe in gamma rays, neutrinos and cosmic rays


8 years (ICRC 2017)
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
Prompt atmospheric $\nu_\mu + \bar{\nu}_\mu$ (flux limit (2016))
Astrophysical $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
HESE unfolding: PoS(ICRC2017)981
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ / GeV^{-1} cm^{-2} s^{-1} sr^{-1}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
E_ν/GeV