# Radio Blazars:
# Sources of Neutrinos from TeV to PeV

Plavin, Kovalev, Kovalev, Troitsky
Jan 2020: *ApJ, 894, 101*
Sep 2020: arXiv:2009.08914

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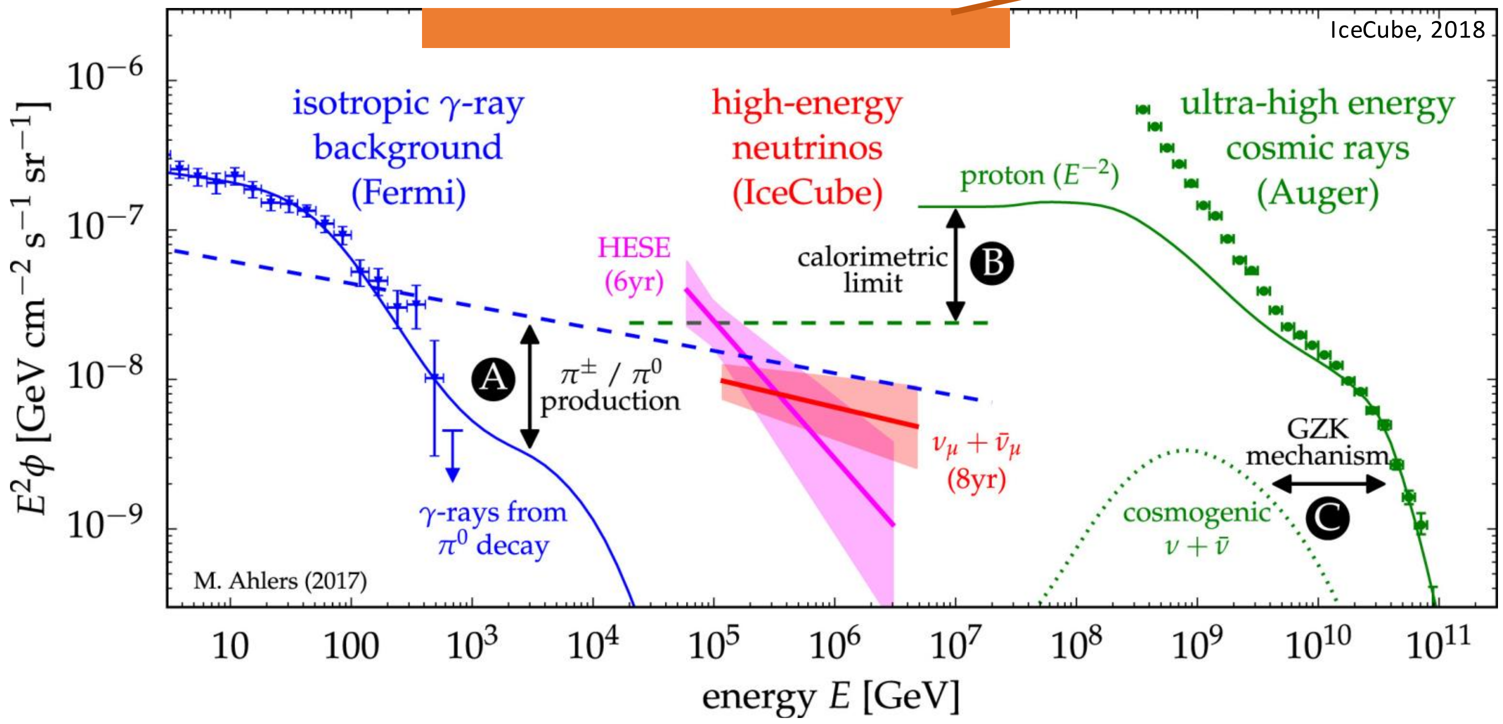
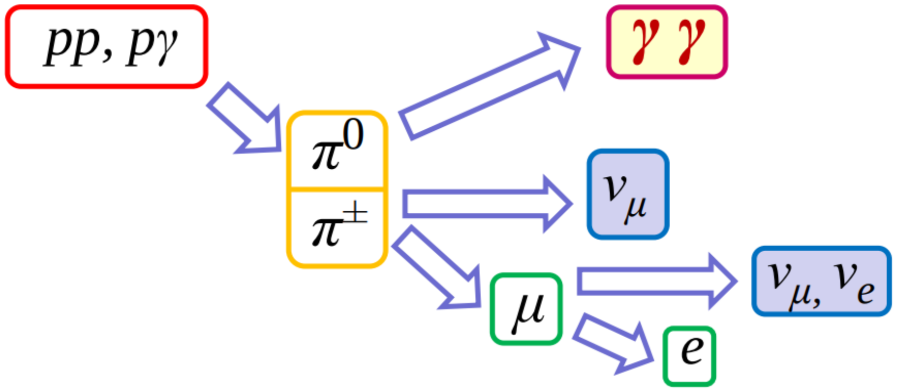
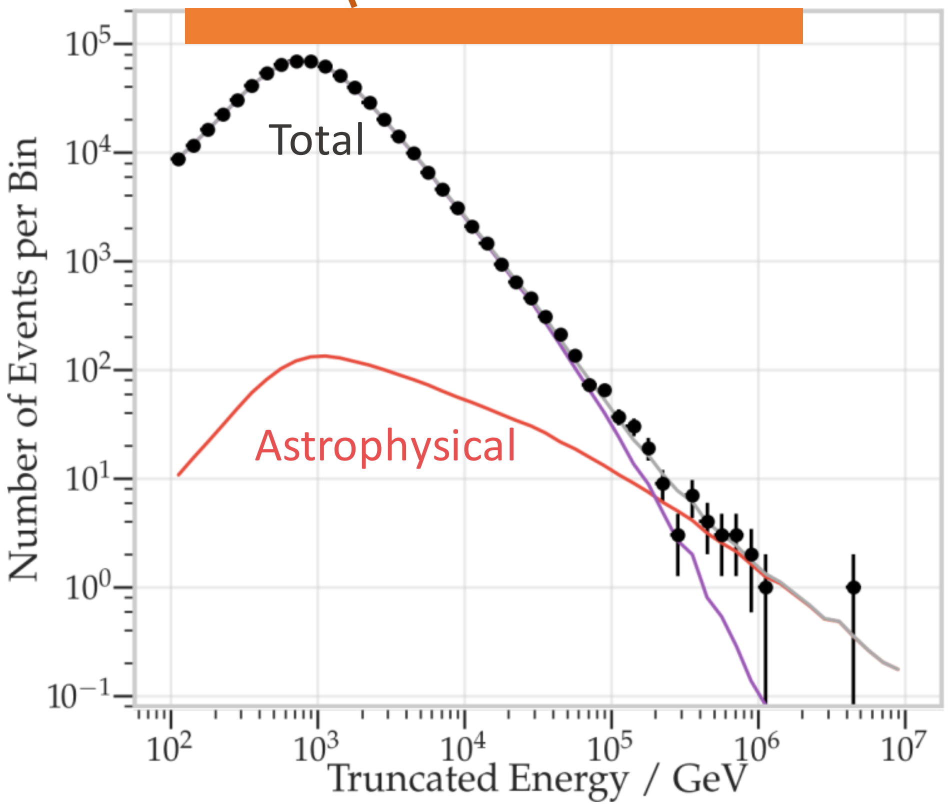
# HIgh-Energy Astrophysical Neutrinos

Relevant energies: TeV to PeVs




IceCube muon neutrino spectrum

Stettner 2019

# HIgh-Energy Astrophysical Neutrinos

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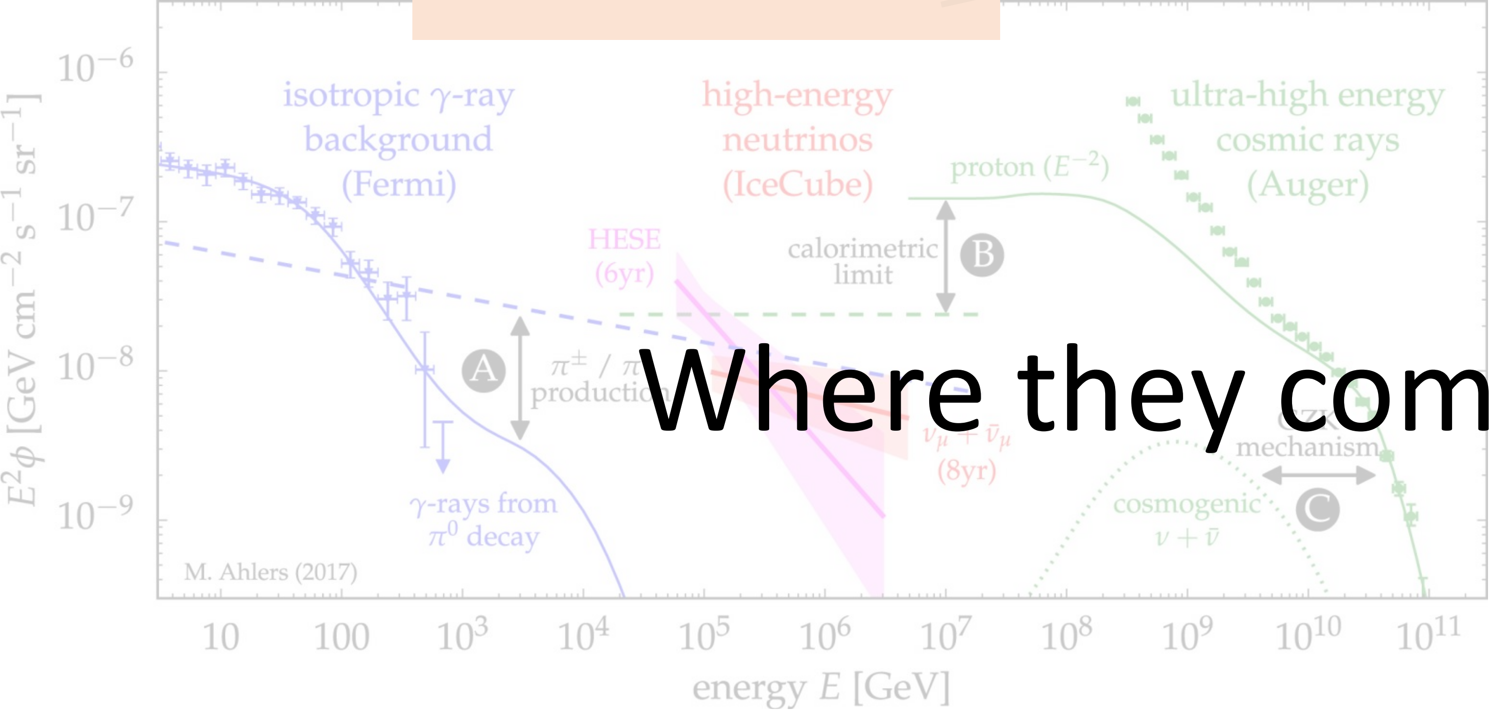
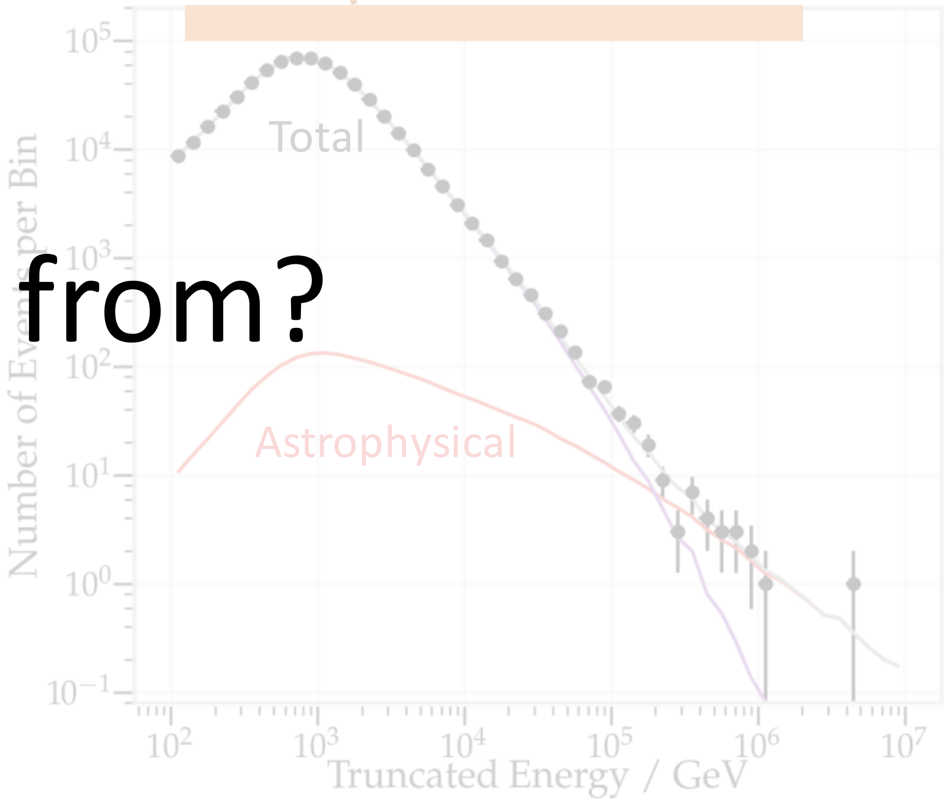


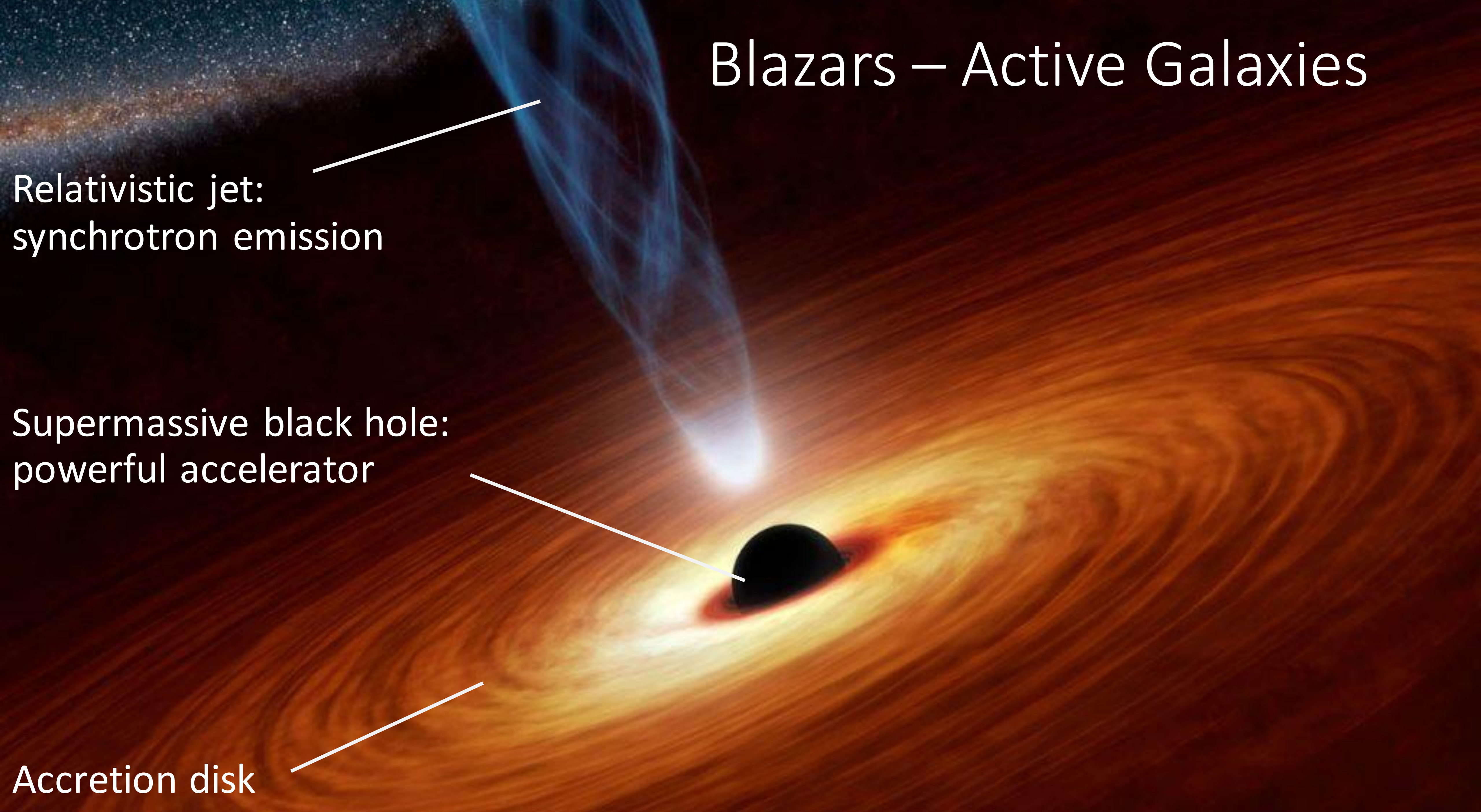

Where they come from?




IceCube muon neutrino spectrum

Stettner 2019

# Blazars – Active Galaxies



# Search for Neutrino Sources

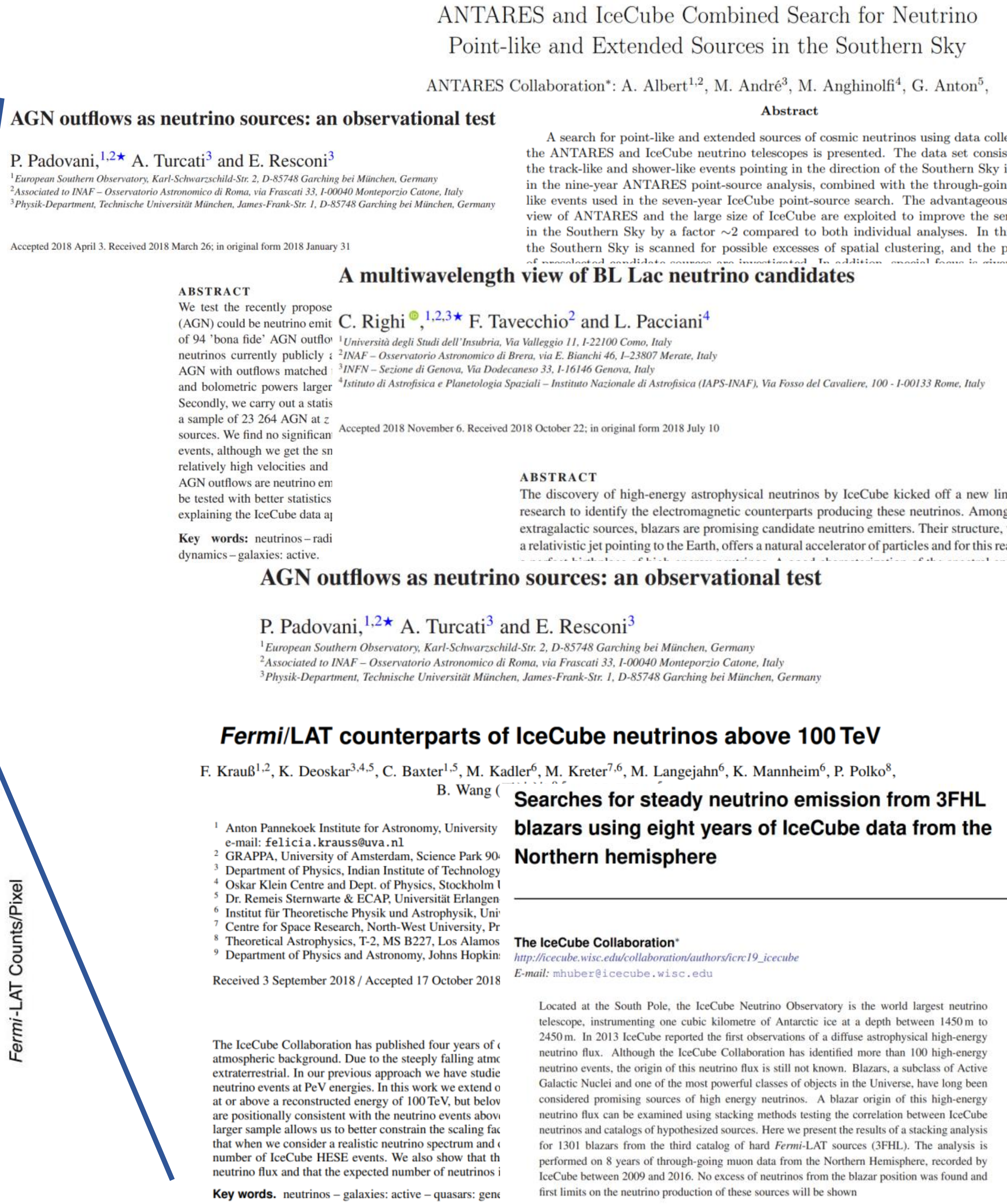
γ-ray photons:

- closest energies
- accompany neutrinos at birth

Should be detected simultaneously?..

Numerous searches for systematic associations, 2017-2019 and earlier

TXS 0506+056 blazar:
the only reliable source
after about ten years


ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky

ANTARES Collaboration*: A. Albert[1,2], M. André[3], M. Anghinolfi[4], G. Anton[5],

Abstract

A search for point-like and extended sources of cosmic neutrinos using data colle
the ANTARES and IceCube neutrino telescopes is presented. The data set consis
the track-like and shower-like events pointing in the direction of the Southern Sky i
in the nine-year ANTARES point-source analysis, combined with the through-goin
like events used in the seven-year IceCube point-source search. The advantageous
view of ANTARES and the large size of IceCube are exploited to improve the se
in the Southern Sky by a factor ~2 compared to both individual analyses. In th
the Southern Sky is scanned for possible excesses of spatial clustering, and the p

AGN outflows as neutrino sources: an observational test

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ABSTRACT
We test the recently propose
(AGN) could be neutrino emit
of 94 'bona fide' AGN outflo
neutrinos currently publicly
AGN with outflows matched
and bolometric powers larger
Secondly, we carry out a statis
a sample of 23 264 AGN at z
sources. We find no significan
events, although we get the sn
relatively high velocities and
AGN outflows are neutrino em
be tested with better statistics
explaining the IceCube data a

Key words: neutrinos – radi
dynamics – galaxies: active.

A multiwavelength view of BL Lac neutrino candidates

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Accepted 2018 November 6. Received 2018 October 22; in original form 2018 July 10

ABSTRACT
The discovery of high-energy astrophysical neutrinos by IceCube kicked off a new lin
research to identify the electromagnetic counterparts producing these neutrinos. Among
extragalactic sources, blazars are promising candidate neutrino emitters. Their structure,
a relativistic jet pointing to the Earth, offers a natural accelerator of particles and for this rea

AGN outflows as neutrino sources: an observational test

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*Fermi*/LAT counterparts of IceCube neutrinos above 100 TeV

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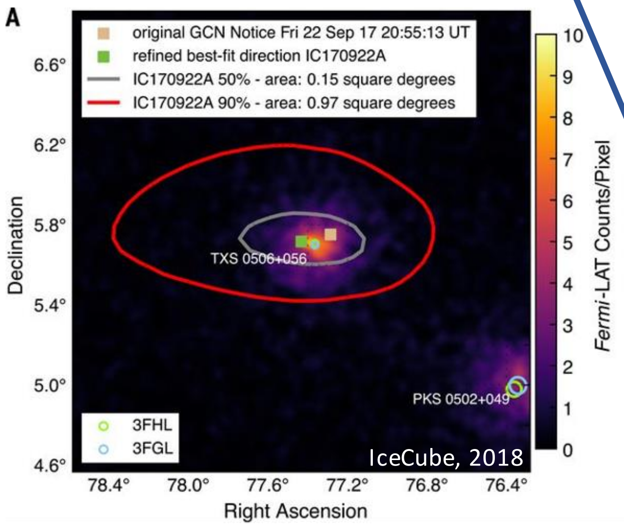
The IceCube Collaboration has published four years of
atmospheric background. Due to the steeply falling atm
extraterrestrial. In our previous approach we have studie
neutrino events at PeV energies. In this work we extend o
at or above a reconstructed energy of 100 TeV, but belov
are positionally consistent with the neutrino events abov
larger sample allows us to better constrain the scaling fac
that when we consider a realistic neutrino spectrum and
number of IceCube HESE events. We also show that th
neutrino flux and that the expected number of neutrinos i

Key words. neutrinos – galaxies: active – quasars: gen

Searches for steady neutrino emission from 3FHL blazars using eight years of IceCube data from the Northern hemisphere

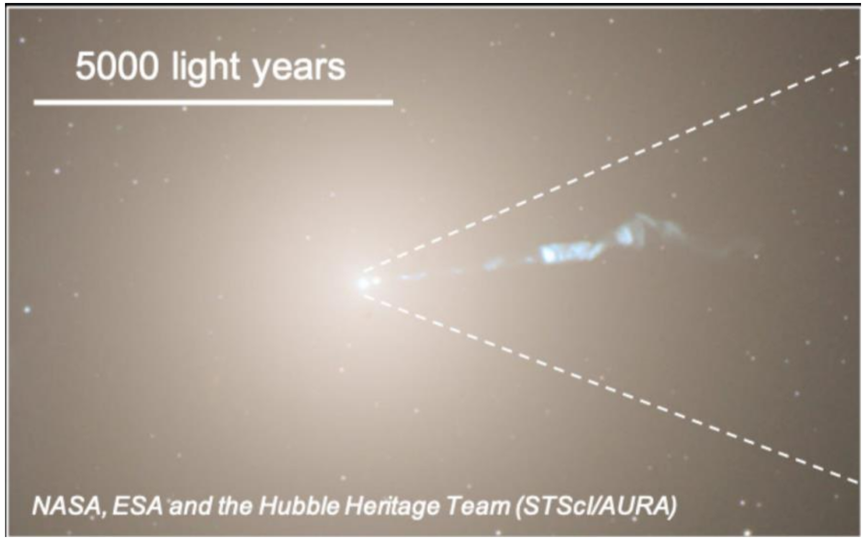
The IceCube Collaboration*
http://icecube.wisc.edu/collaboration/authors/icrc19_icecube
E-mail: mhuber@icecube.wisc.edu

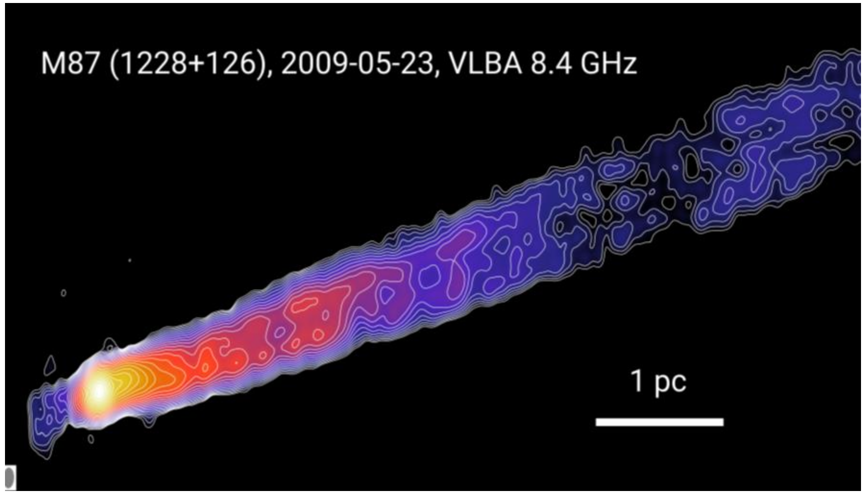
Located at the South Pole, the IceCube Neutrino Observatory is the world largest neutrino telescope, instrumenting one cubic kilometre of Antarctic ice at a depth between 1450 m to 2450 m. In 2013 IceCube reported the first observations of a diffuse astrophysical high-energy neutrino flux. Although the IceCube Collaboration has identified more than 100 high-energy neutrino events, the origin of this neutrino flux is still not known. Blazars, a subclass of Active Galactic Nuclei and one of the most powerful classes of objects in the Universe, have long been considered promising sources of high energy neutrinos. A blazar origin of this high-energy neutrino flux can be examined using stacking methods testing the correlation between IceCube neutrinos and catalogs of hypothesized sources. Here we present the results of a stacking analysis for 1301 blazars from the third catalog of hard *Fermi*-LAT sources (3FHL). The analysis is performed on 8 years of through-going muon data from the Northern Hemisphere, recorded by IceCube between 2009 and 2016. No excess of neutrinos from the blazar position was found and first limits on the neutrino production of these sources will be shown



# Our Approach: Neutrino-VLBI Comparison

- Radio interferometry, VLBI —
  the only way to directly resolve central parsecs in active galaxies




- VLBI-flux — reliable indicator of bright compact structure
- Selects blazars: jets pointed towards us

# Radio & Neutrino: Data

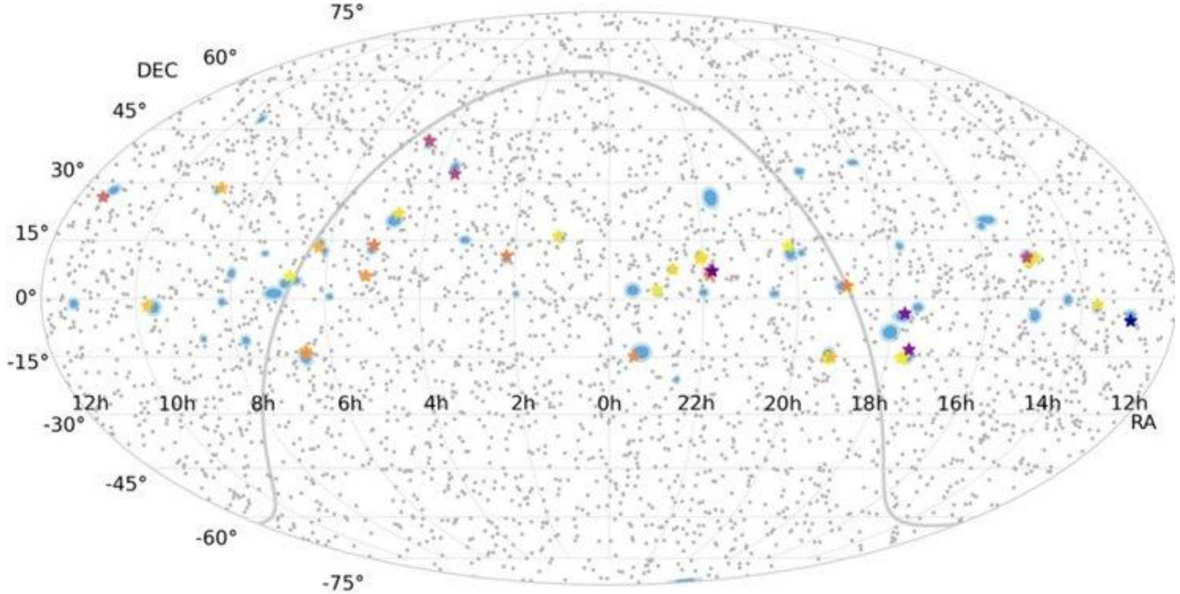
## Blazars: flux density-complete VLBI sample, 3411 objects

≈30 years of observations, $S_{8\ GHz} \geq 150$ mJy http://astrogeo.org/rfc/

## Neutrinos — IceCube tracks, public data

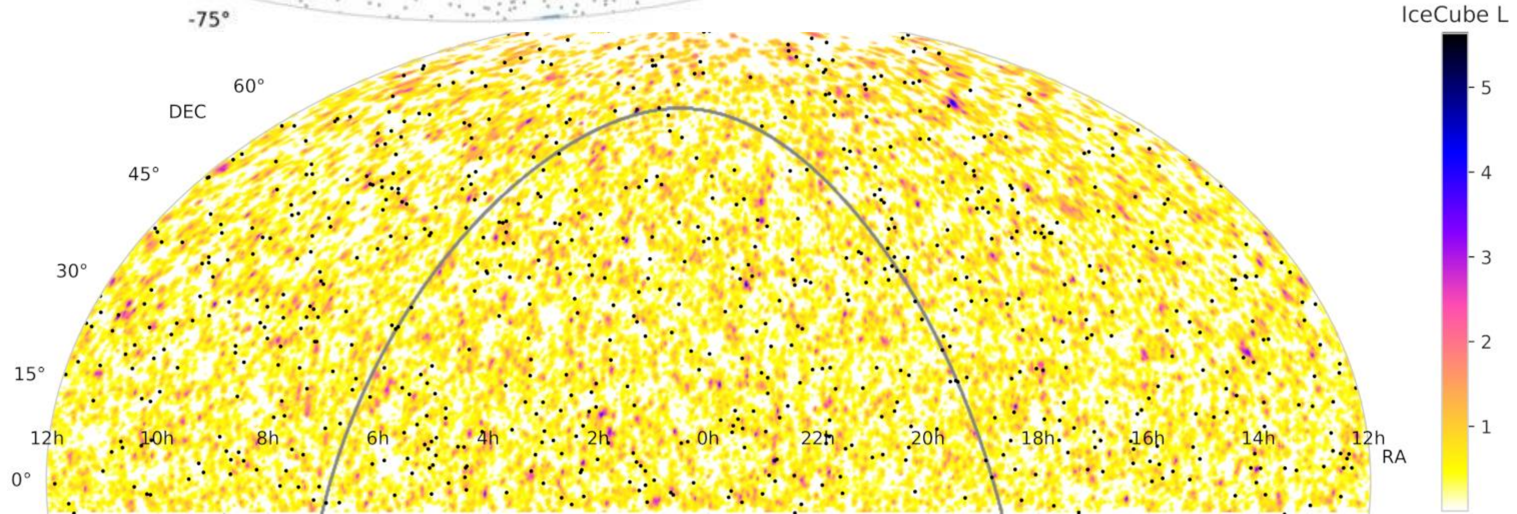
- 200 TeV and above:

  alerts & alert-like events
  *57 events, 2009-2019*
  around 30 are astrophysical




- All energies:

  point-source likelihood for each direction
  *712830 events, 2008-2015*
  *around* 2000 are astrophysical
  ***Events ~10 TeV dominate***



# Neutrino – Blazar Association

Testing hypothesis:

- Bright blazars commonly coincide with neutrino arrival directions?
- Neutrinos commonly arrive from directions of bright blazars?

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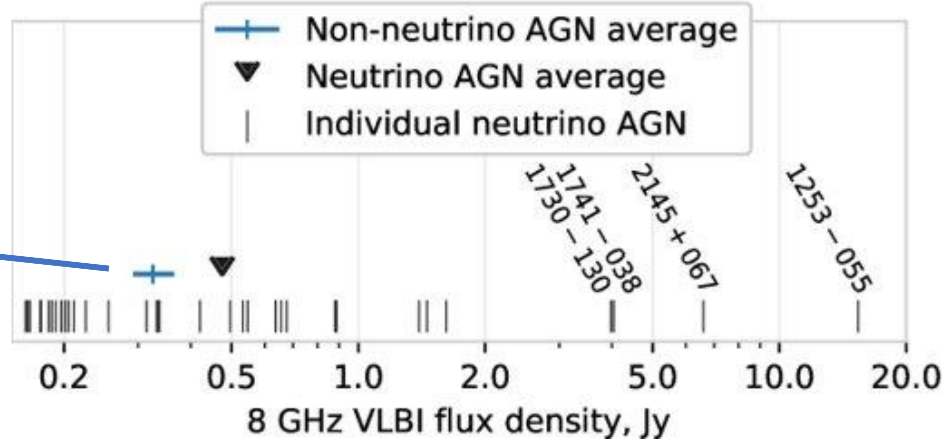
Testing hypothesis:

- Bright blazars commonly coincide with neutrino arrival directions?
- Neutrinos commonly arrive from directions of bright blazars?

(Plavin+2020)

**Result:** yes, this correlation is present! ⇒ Neutrinos are emitted by blazars!

Events ≥ 200 TeV: p-value = 0.2%
Test: blazars within neutrino error regions are brighter than average.




Lower energies, likelihood map: p-value = 0.3%
Test: higher than average IceCube likelihoods in the directions of blazars

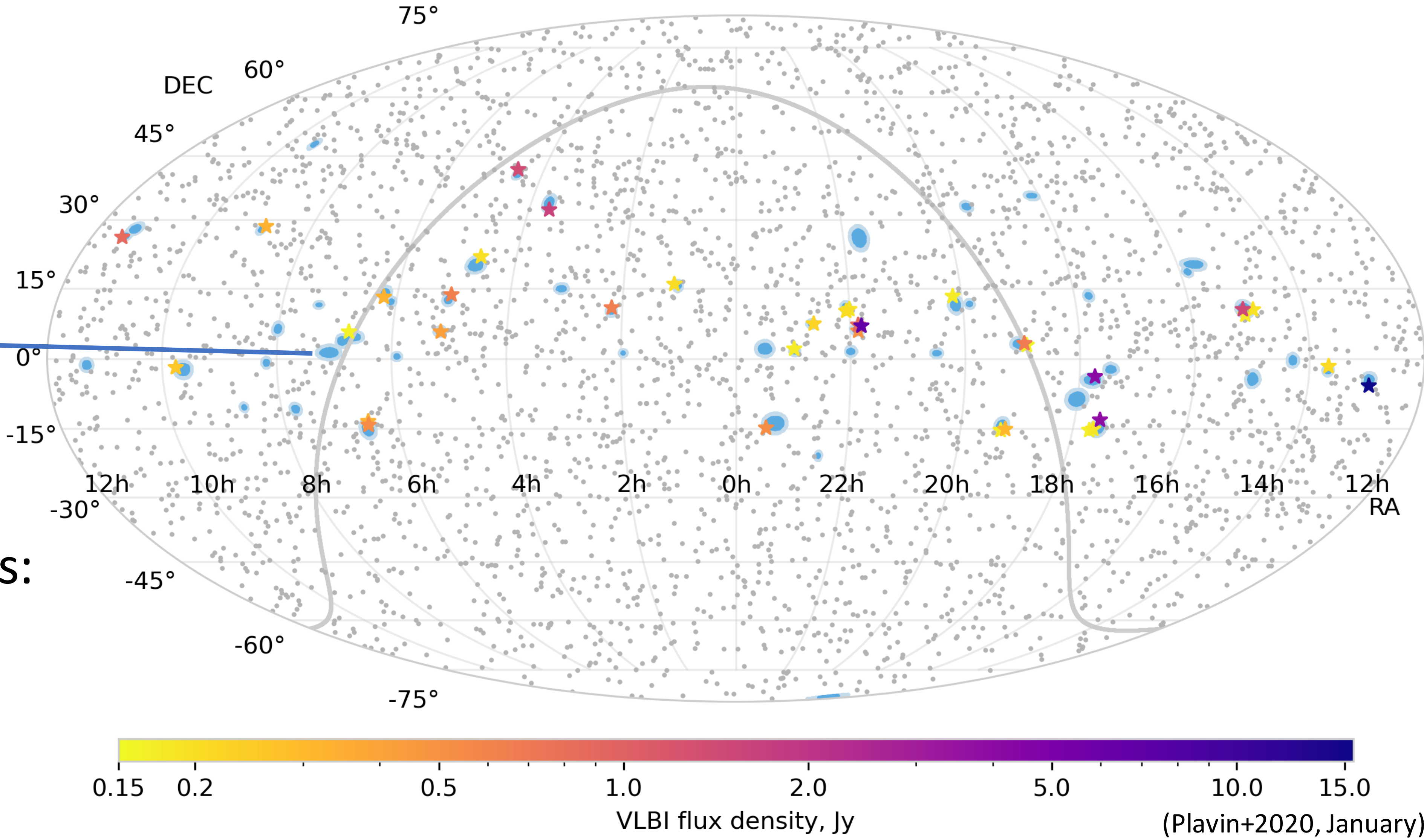
Combined: p-value = $4\times10^{-5}$, $4.1\sigma$

# Neutrino – Blazar Associations

IceCube alerts typically include stochastic uncertainties only

We try to account for systematics: expand error regions by some value

The best value is fit as part of our analysis: turns out to be 0.5°

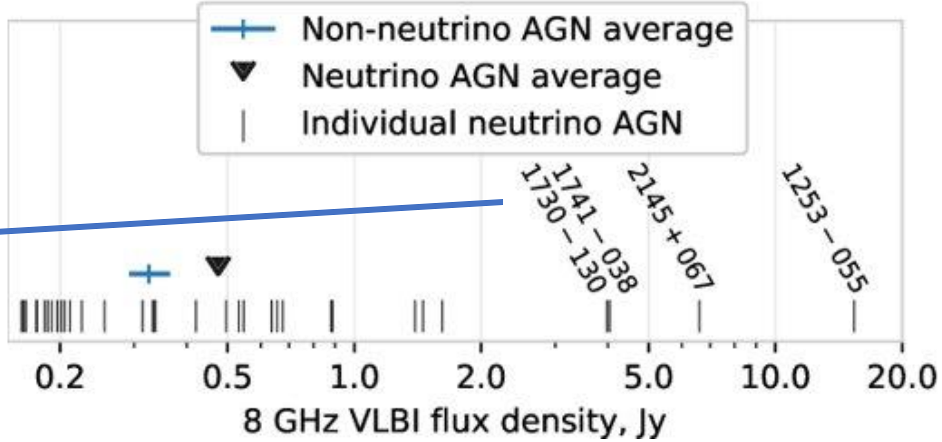


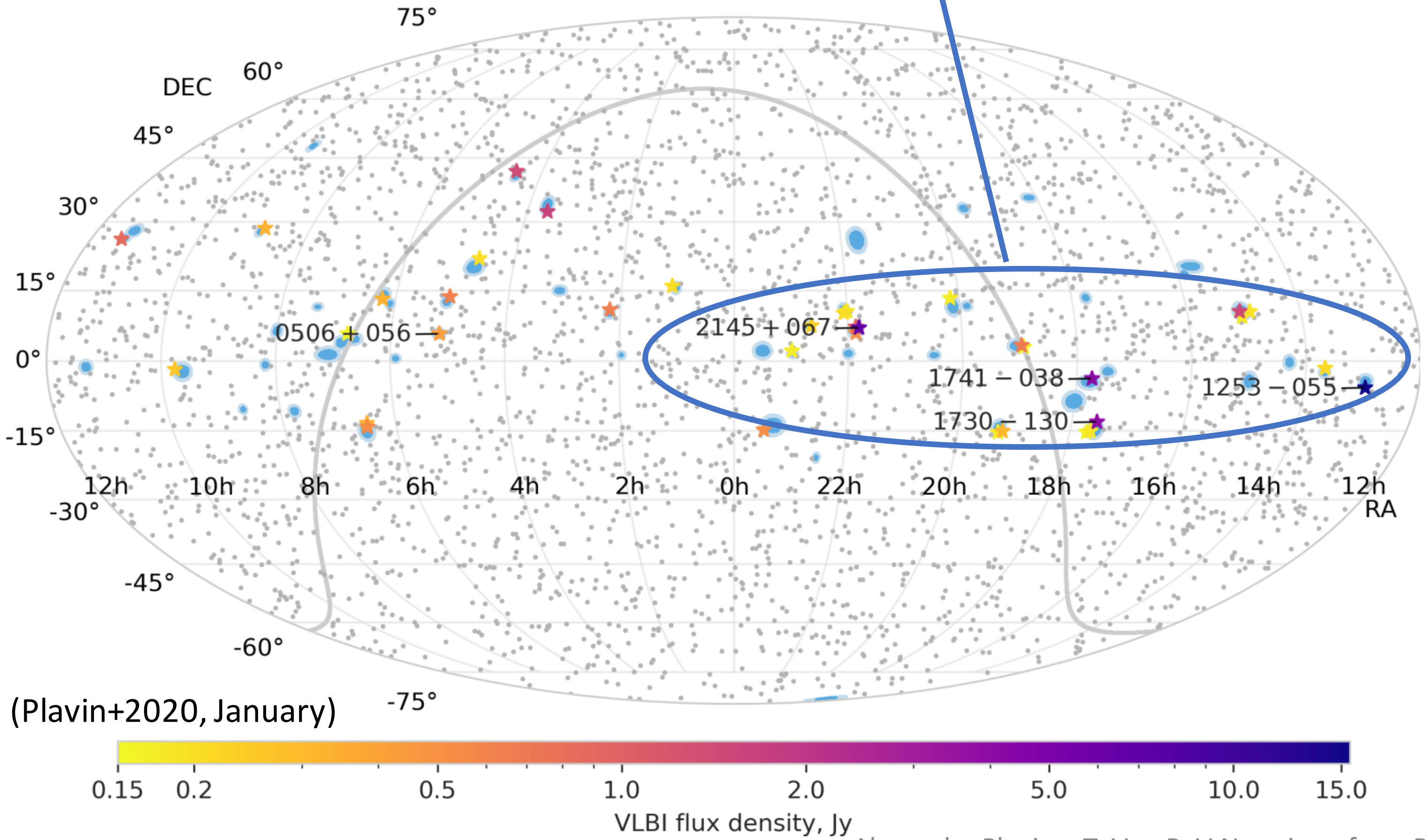

(Plavin+2020, January)

# Number of Neutrino – Blazar Associations

How many blazars emit neutrinos?

Events ≥ 200 TeV:
effect is dominated by four brightest blazars




(Plavin+2020, January)

Lower energies:
at least ~70 blazars associated with neutrino tracks

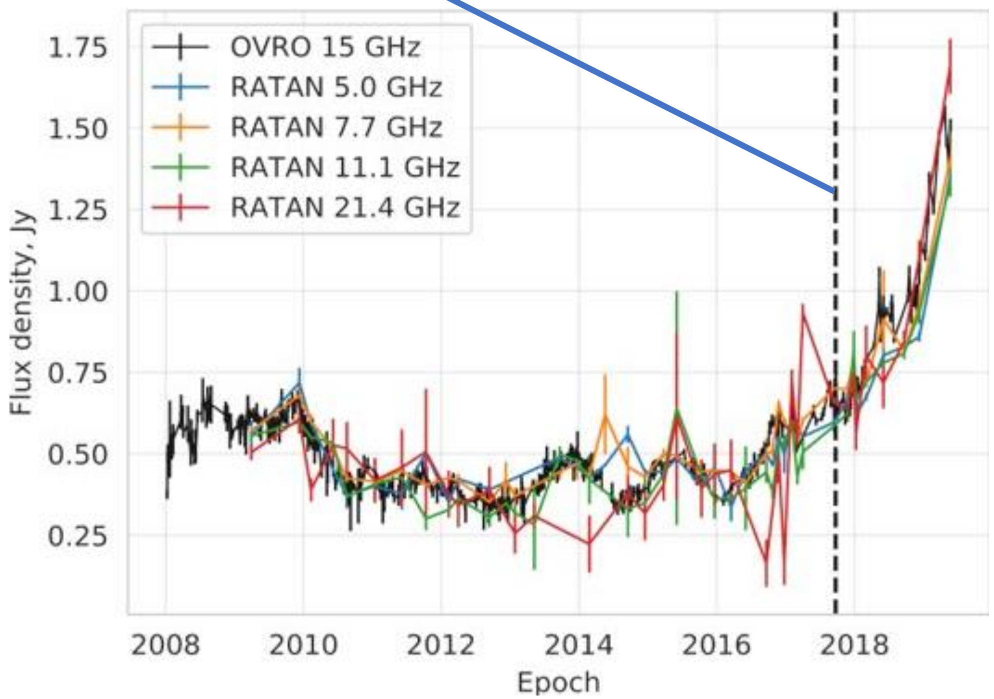
There are enough bright blazars to explain the whole astrophysical neutrino flux!

# Neutrinos and Blazar Flares

Flares close to the SMBH were predicted to produce neutrinos (e.g., Murase 17)

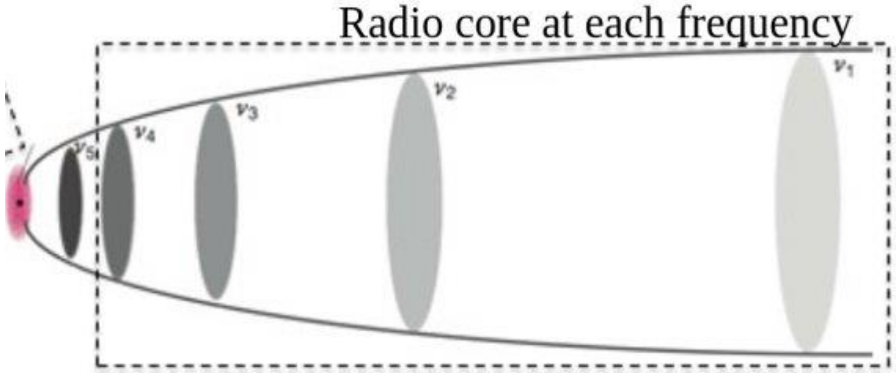
Neutrino from TXS 0506+056 arrived at the start of a major flare:

Flare as seen in radio:

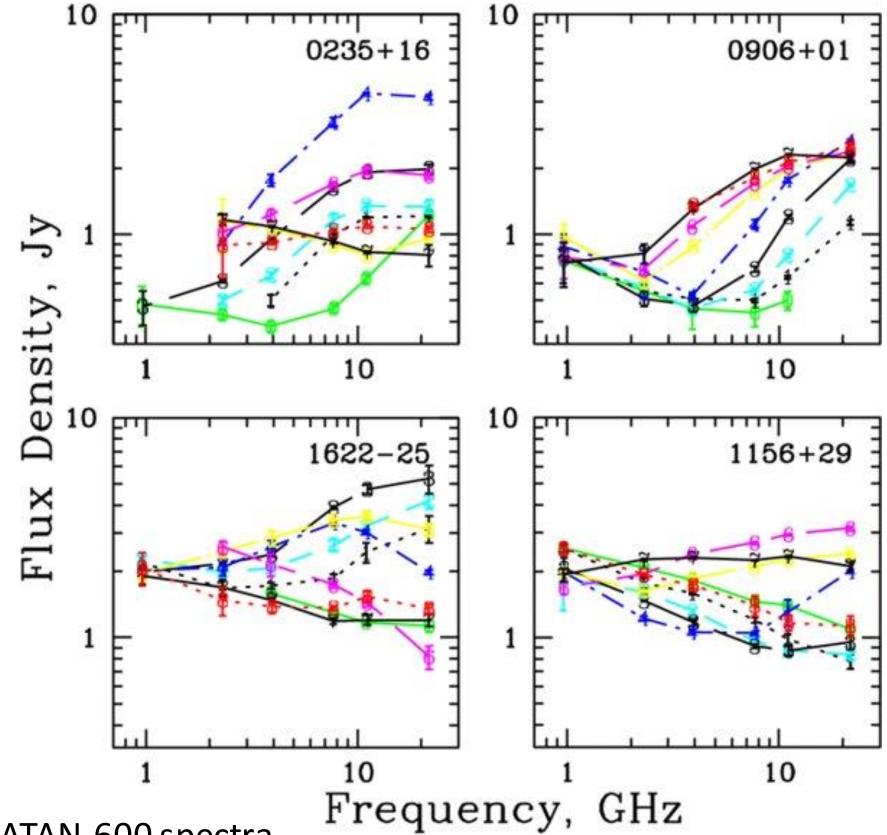



⇒ We correlate radio flux with neutrino detection dates

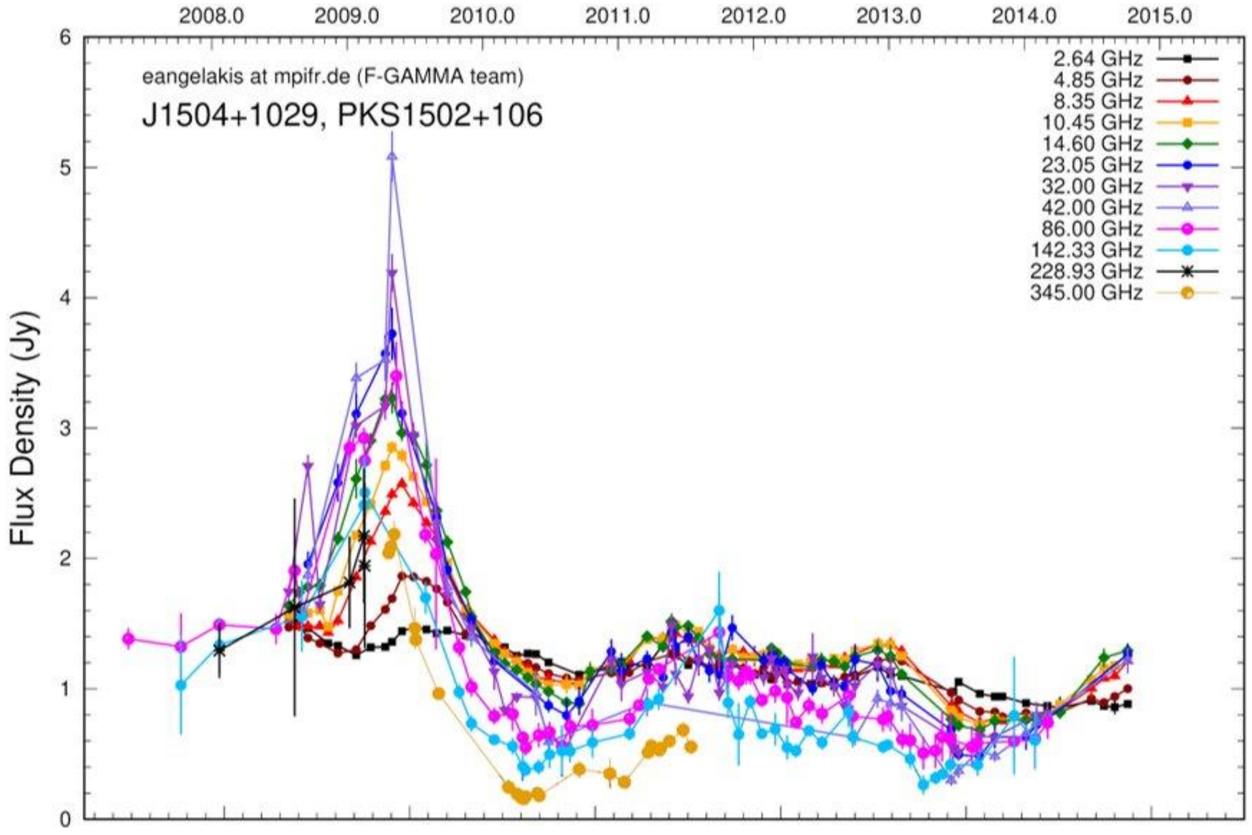
# Blazar Flares as Seen in Radio




At higher frequencies flux changes are stronger and occur earlier: emission from regions closer to SMBH

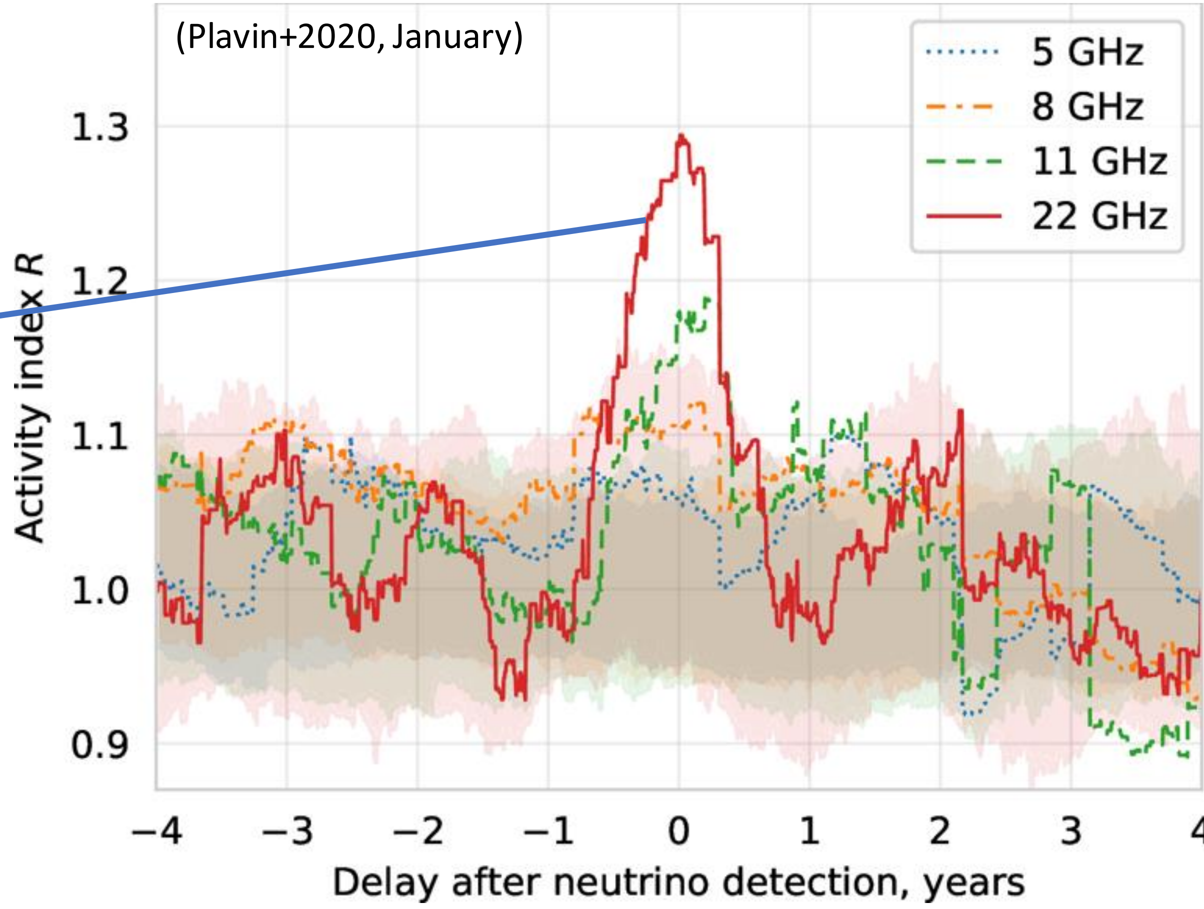



RATAN-600 spectra



# Neutrinos and Blazar Flares

- We compare the average radio flux within ± ΔT/2 of neutrino detection to the average flux outside of this window
  *Activity index* R = ratio of these fluxes




- **Result:**
  AGN are brighter around neutrino events!
  Effect is weaker at lower frequencies

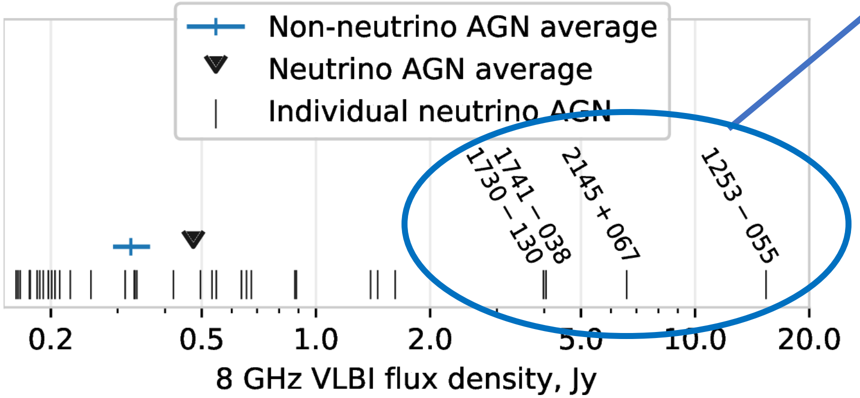
  At 22 GHz: p-value = 5% (post-trial), 1% (pre-trial)

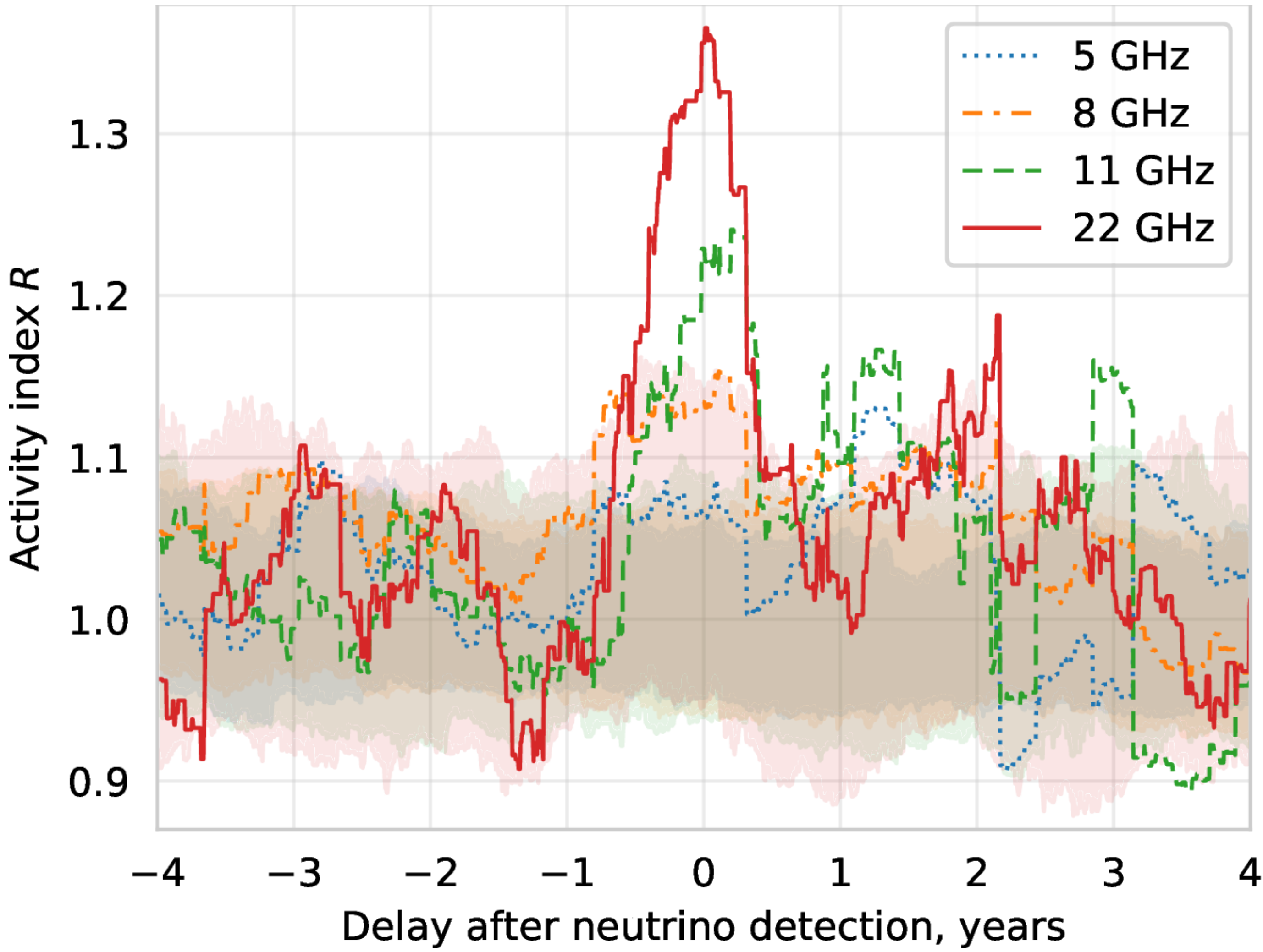
  Fitted value of additional directional error: 0.7°

Already got independent confirmation: Hovatta et al., arXiv:2009.10523 (22 September 2020)

# Neutrinos and Blazar Flares

Correlation is present even without the four brightest-on-average AGN:




Maximal correlation for PKS 1502+106, but it's not the only one causing this effect.

# Physical Interpretation

Neutrinos are produced in central parsecs of bright blazars via p+ɣ process

They get emitted predominantly along the jet direction (Stecker+91, Neronov+02, Kalashev+15, Cerruti 19, Bottcher+19)

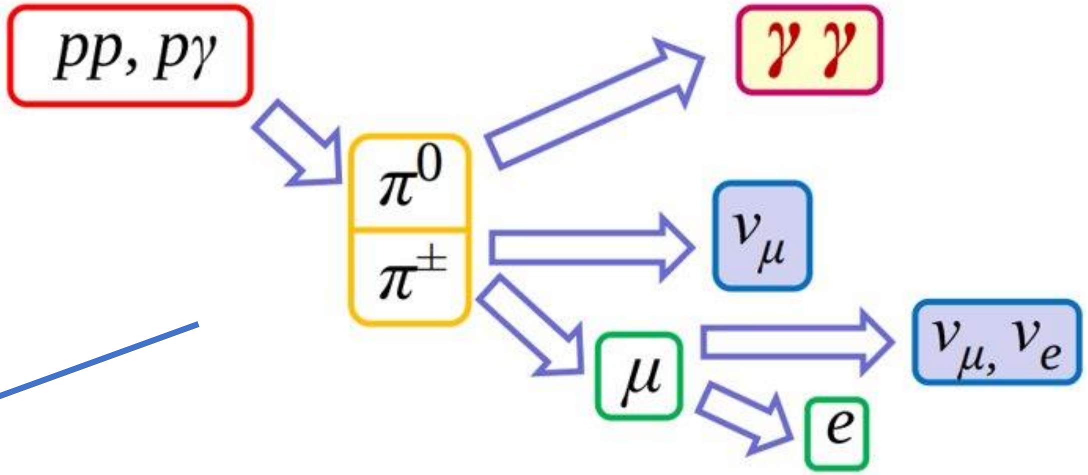
(predicted in Neronov+02)

Require photons from 100 eV to 200 keV...

- SSC-photons in the jet?

... and protons to $10^{16}$ eV

- Acceleration in shocks?
  (Bykov et al. 2012; Lemoine & Waxman 2009)




Neutrinos accompanied by ɣ-rays, but no correlation found yet – why?
Secondary photons lose energy to pair production fast.

Note: despite observed correlations, neutrinos, radio and gamma photons can be produced in different processes.

# Summary

Plavin, Kovalev, Kovalev, Troitsky
Jan 2020: *ApJ, 894, 101*
Sep 2020: https://arxiv.org/abs/2009.08914

**Neutrinos from TeV to PeV are produced in central parsecs of bright blazars**

Significance 4.1σ, $p = 4\times10^{-5}$

- At least 70 blazars are associated with IceCube neutrino tracks
- VLBI is key to this association
- Essential to account for systematic positional errors: our estimate is $\simeq 0.5°$

- Radio blazars can explain all astrophysical neutrinos of these energies
- They emit neutrinos along the jet direction
- Strong constrains on the astrophysical conditions: photons to 100 keV, protons to $10^{16}$ eV

Ongoing and future studies:

- Independent confirmations: temporal correlation with flares detected in *Hovatta et al., 2020*
- More neutrino detections with better precision: IceCube, Baikal, ANTARES, ...
- Observing blazars specifically focused on those coinciding with neutrinos. 2 Dec 2020: triggered VLBA follow-up on IC 201130A