Growing evidence of the blazar-neutrino connection

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Early results:
Plavin, Kovalev, Kovalev, Troitsky
2020: ApJ, 894, 101
2021: ApJ, 908, 157

High energy astrophysical neutrinos: where do they come from?

What are these super-colliders accelerating protons?

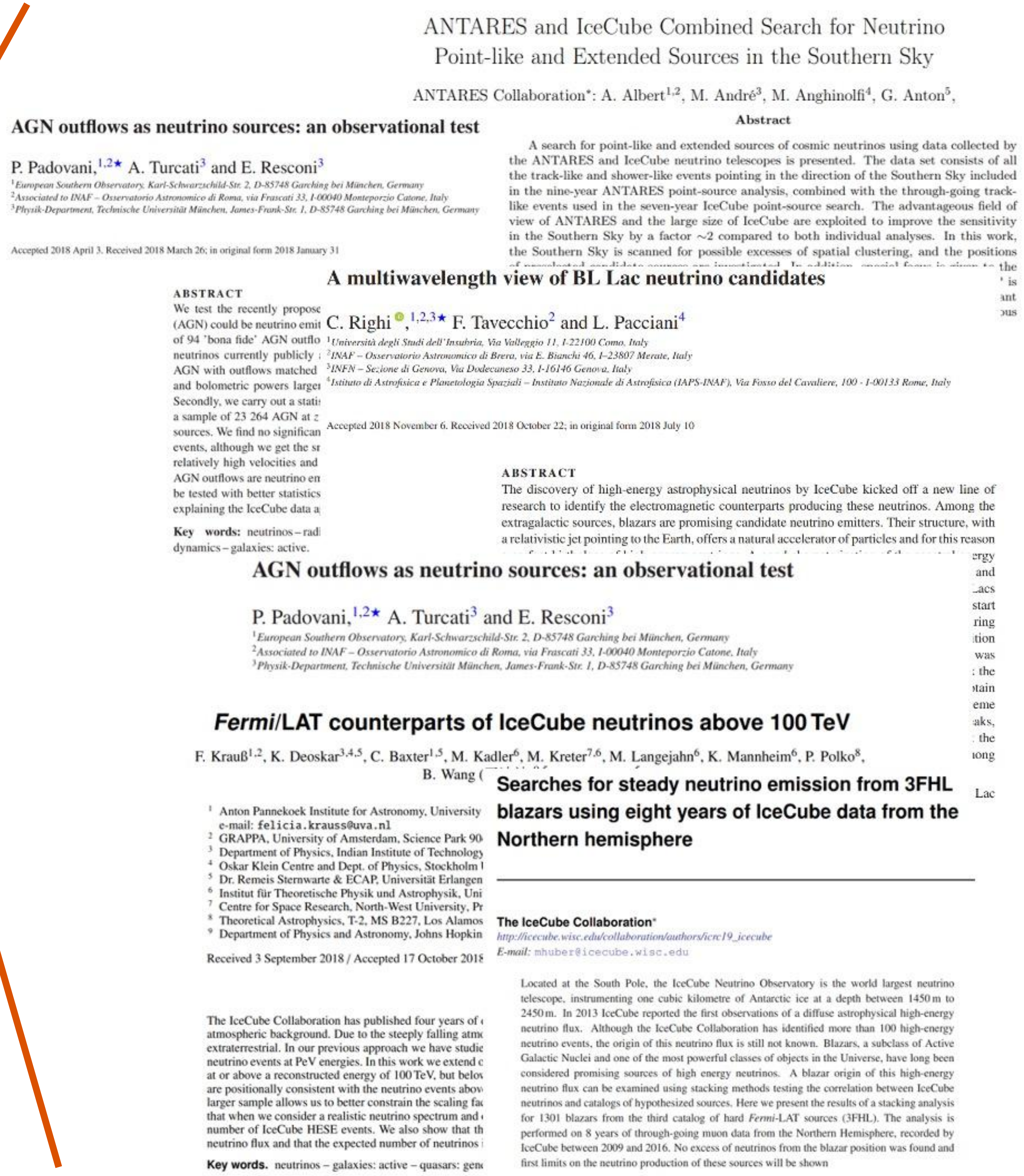
Could this be blazars? Lets check.

Image by NASA

High energy neutrino sources

Observational Search

- ➢ Numerous attempts to find systematic associations, 2017-2019 and earlier
- ➢ TXS 0506+056 blazar: the only reliable identification after ~10 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 collected by the ANTARES and IceCube neutrino telescopes is presented. The data set consists of all the track-like and shower-like events pointing in the direction of the Southern Sky included in the nine-year ANTARES point-source analysis, combined with the through-going track-like events used in the seven-year IceCube point-source search. The advantageous field of view of ANTARES and the large size of IceCube are exploited to improve the sensitivity in the Southern Sky by a factor ~2 compared to both individual analyses. In this work, the Southern Sky is scanned for possible excesses of spatial clustering, and the positions

AGN outflows as neutrino sources: an observational test

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A multiwavelength view of BL Lac neutrino candidates

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ABSTRACT

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

Fermi/LAT counterparts of IceCube neutrinos above 100 TeV

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

The IceCube Collaboration*

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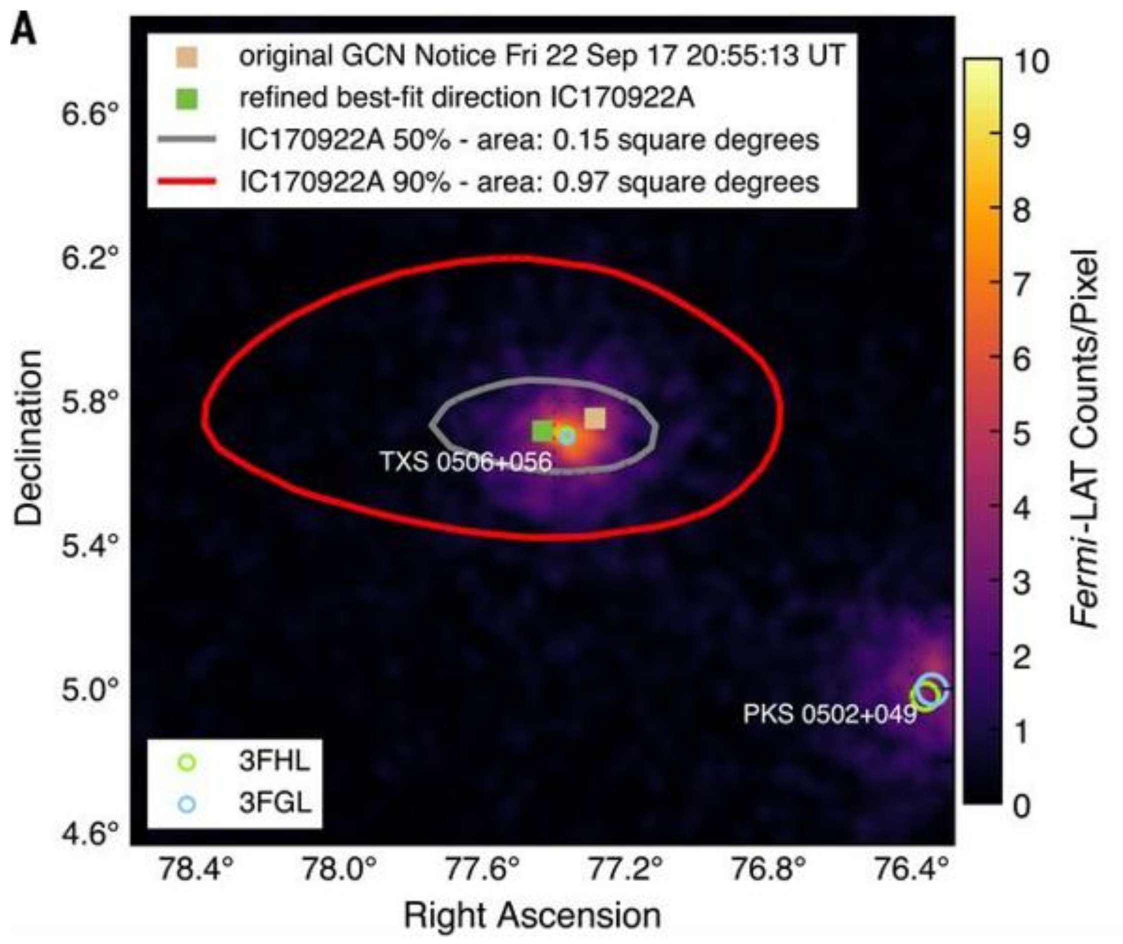
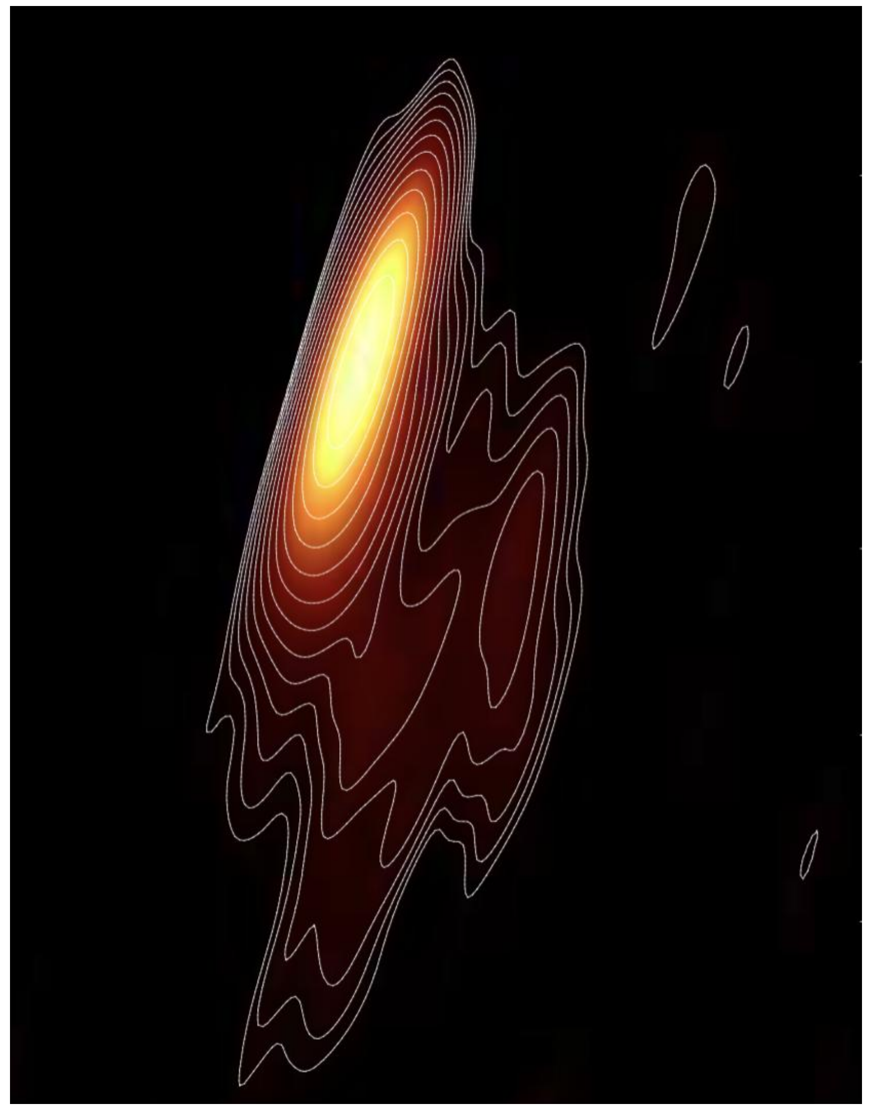
Located at the South Pole, the IceCube Neutrino Observatory is the world largest neutrino telescope, instrumenting one cubic kilometre of Antarctic ice at a depth between 1450 m to 2450 m. In 2013 IceCube reported the first observations of a diffuse astrophysical high-energy neutrino flux. Although the 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

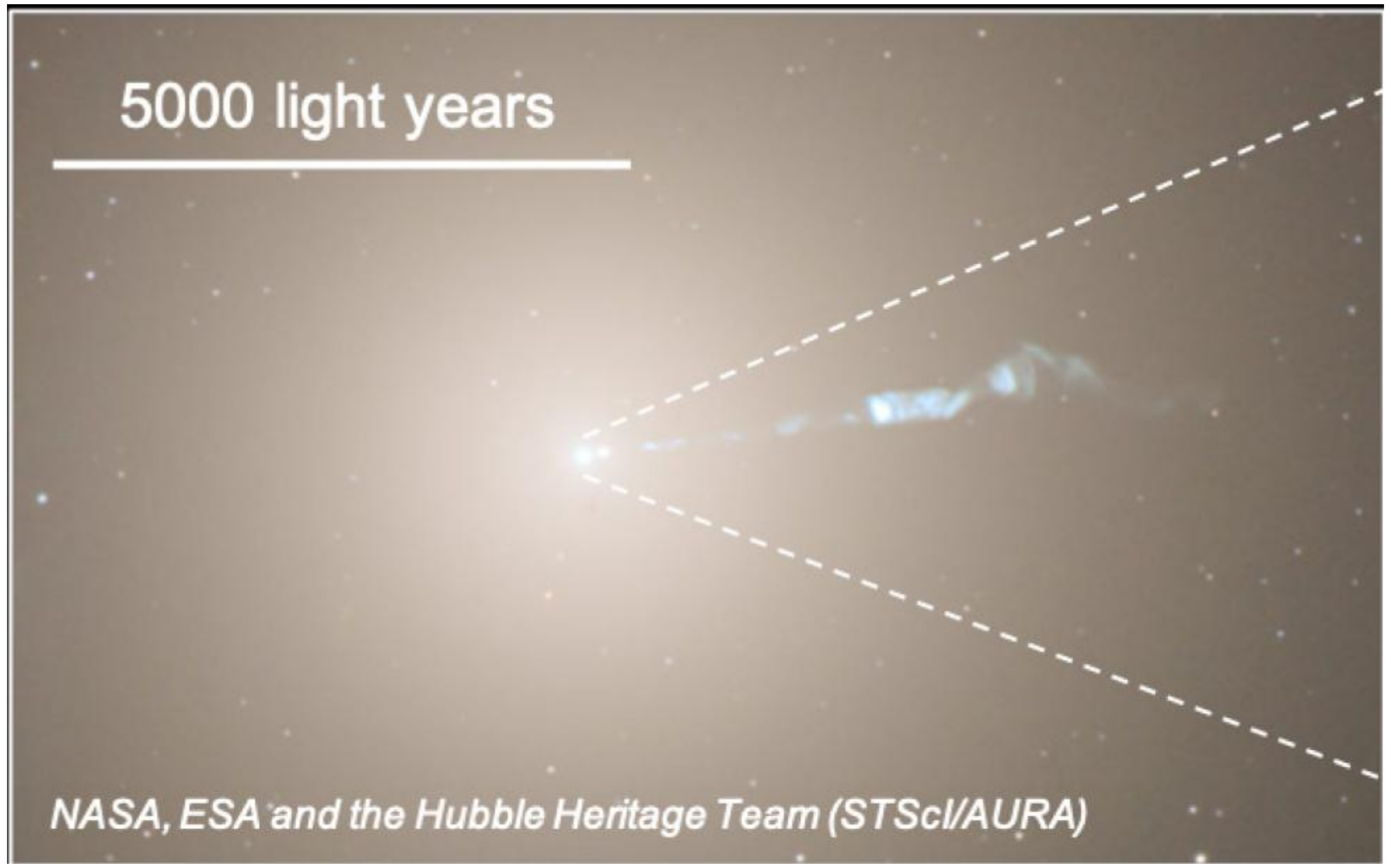


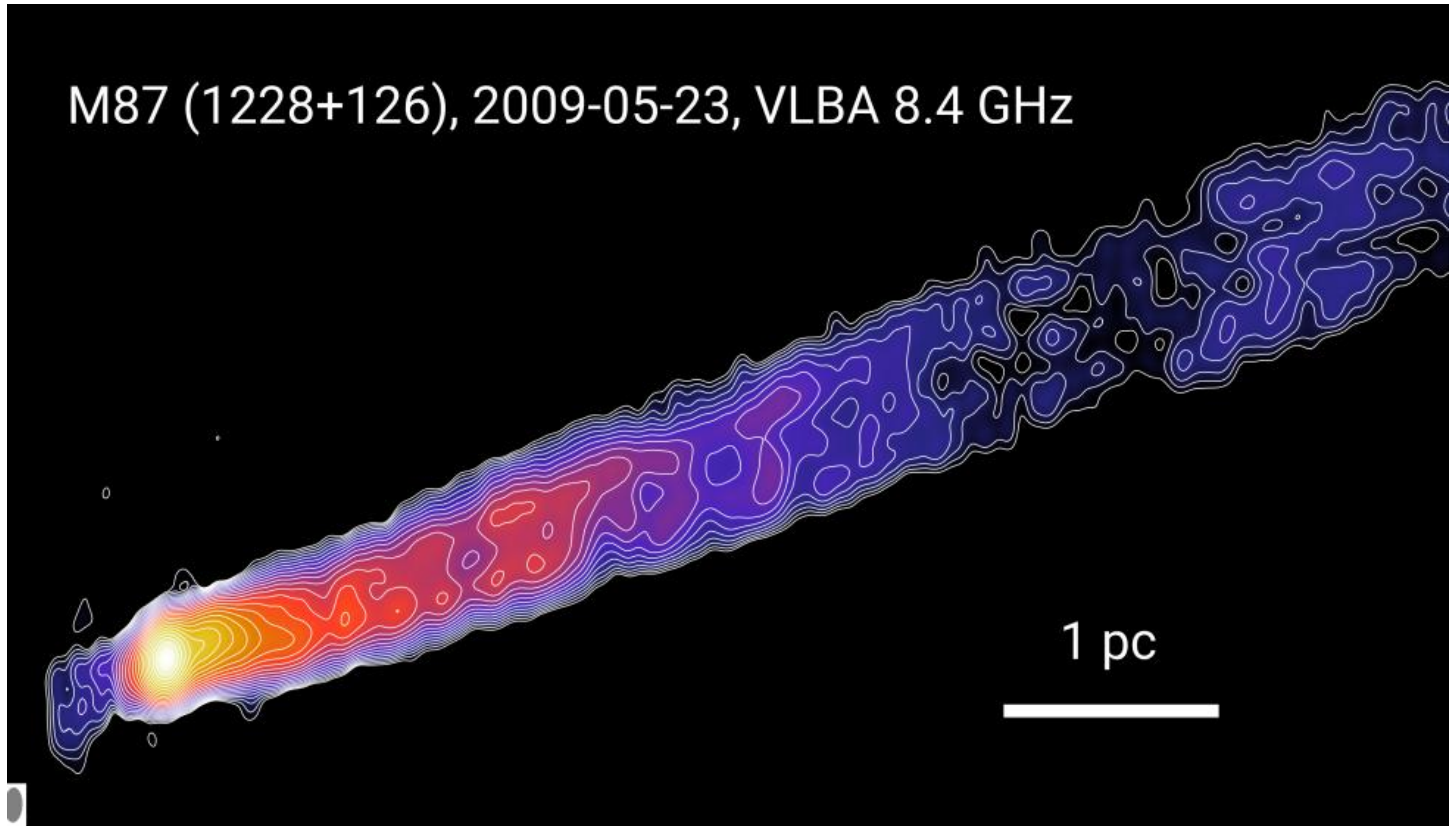
IceCube/Fermi (IC collaboration)



VLBI image (Ros+2020)

Our idea: check possible connection using VLBI data





Talk by Nikonov.

- VLBI: the only tool to resolve central parsecs of AGN
- VLBI flux density: a good indicator of compact jet structure
- This approach selects blazars with jets looking at us.

Our approach: AGN VLBI ↔ neutrino

Check hypothesis: VLBI-bright AGN prefer high energy neutrino arrival directions

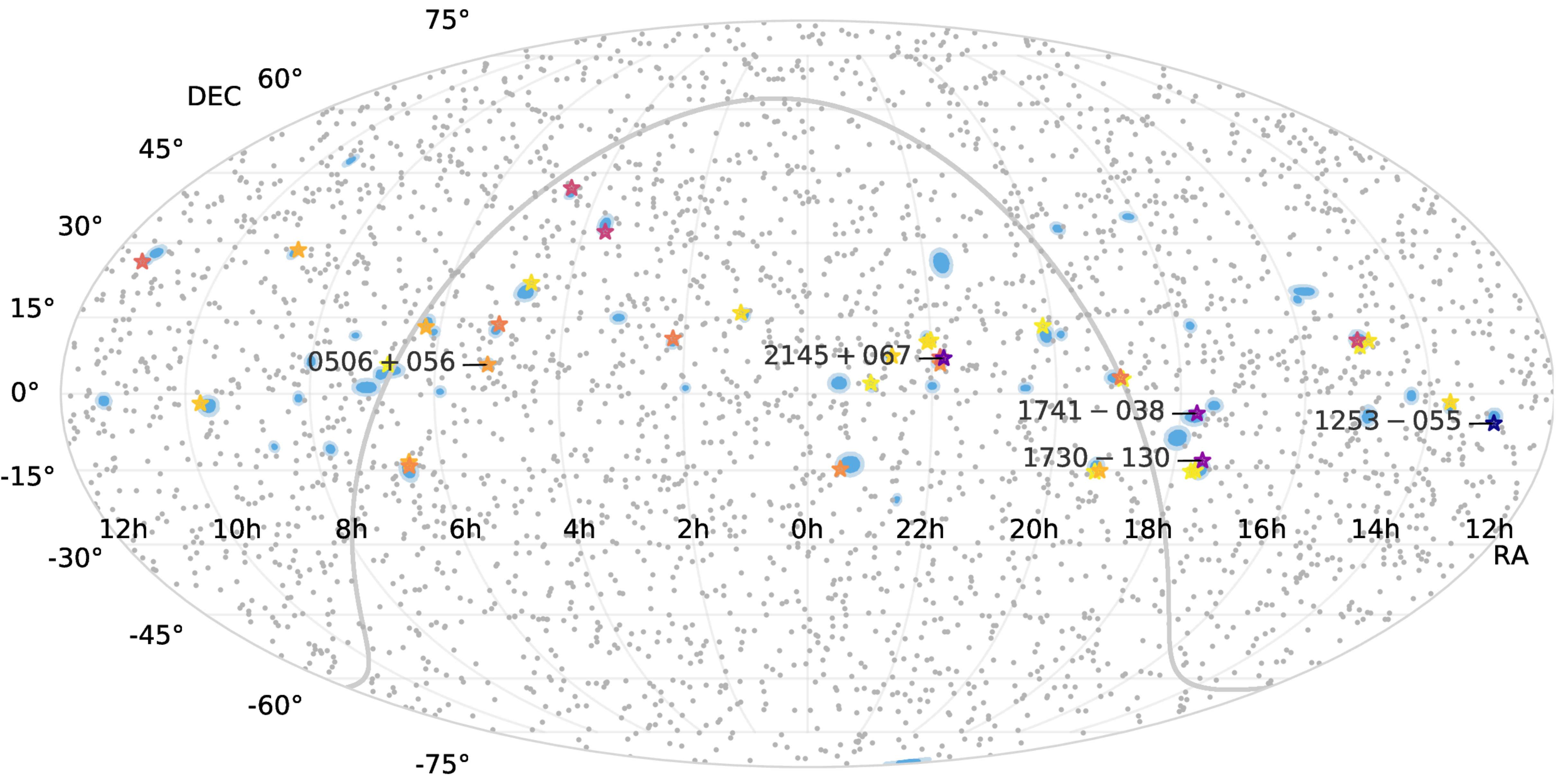
<u>VLBI (RFC)</u>: 3411 bright blazars (dots) with S>0.15 Jy, 30 yr of observations; resolve central parsecs

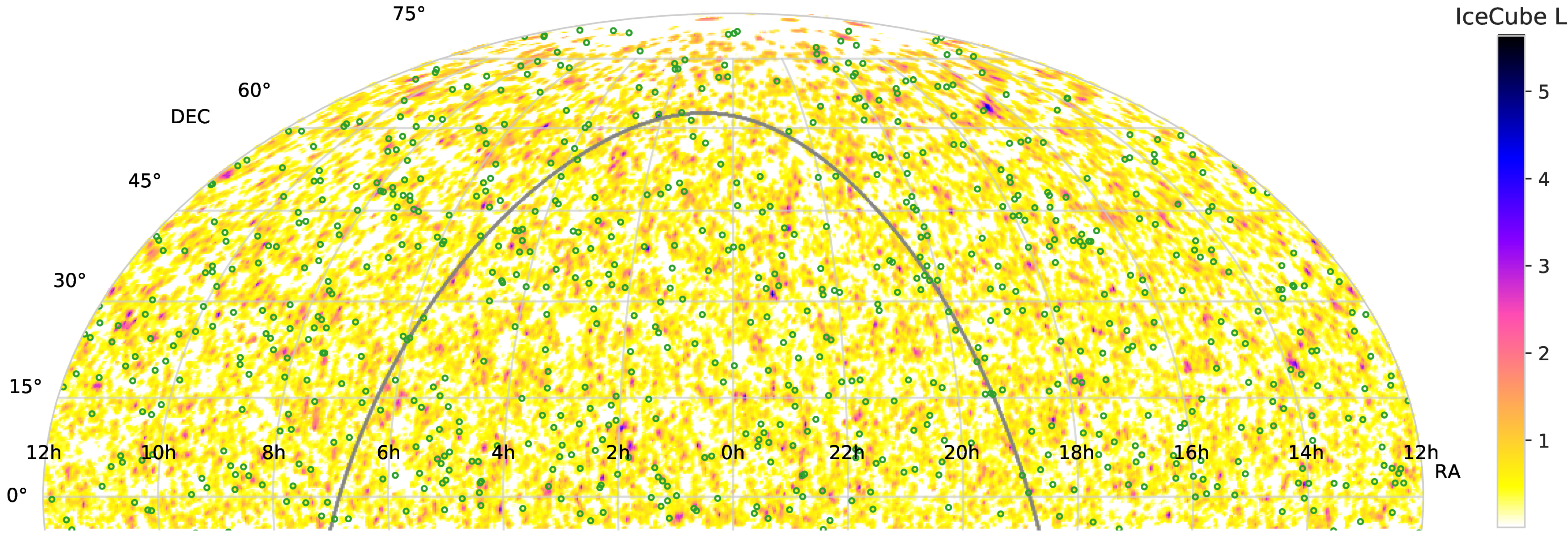
<u>Neutrino (Ice Cube):</u>

57 events (2009-2019) ≥ 200 TeV,
30 astrophysical
Systematics IceCube error: 0.5°
AGN-neutrino p-value = 0.2%

Probability map for all energies
Dominated by energies ~10 TeV
712830 events in 2008-2015, ~2000 astrophysical
AGN-neutrino p-value = 0.3%

Joint p-value = 4×10^{-5}, 4.1σ

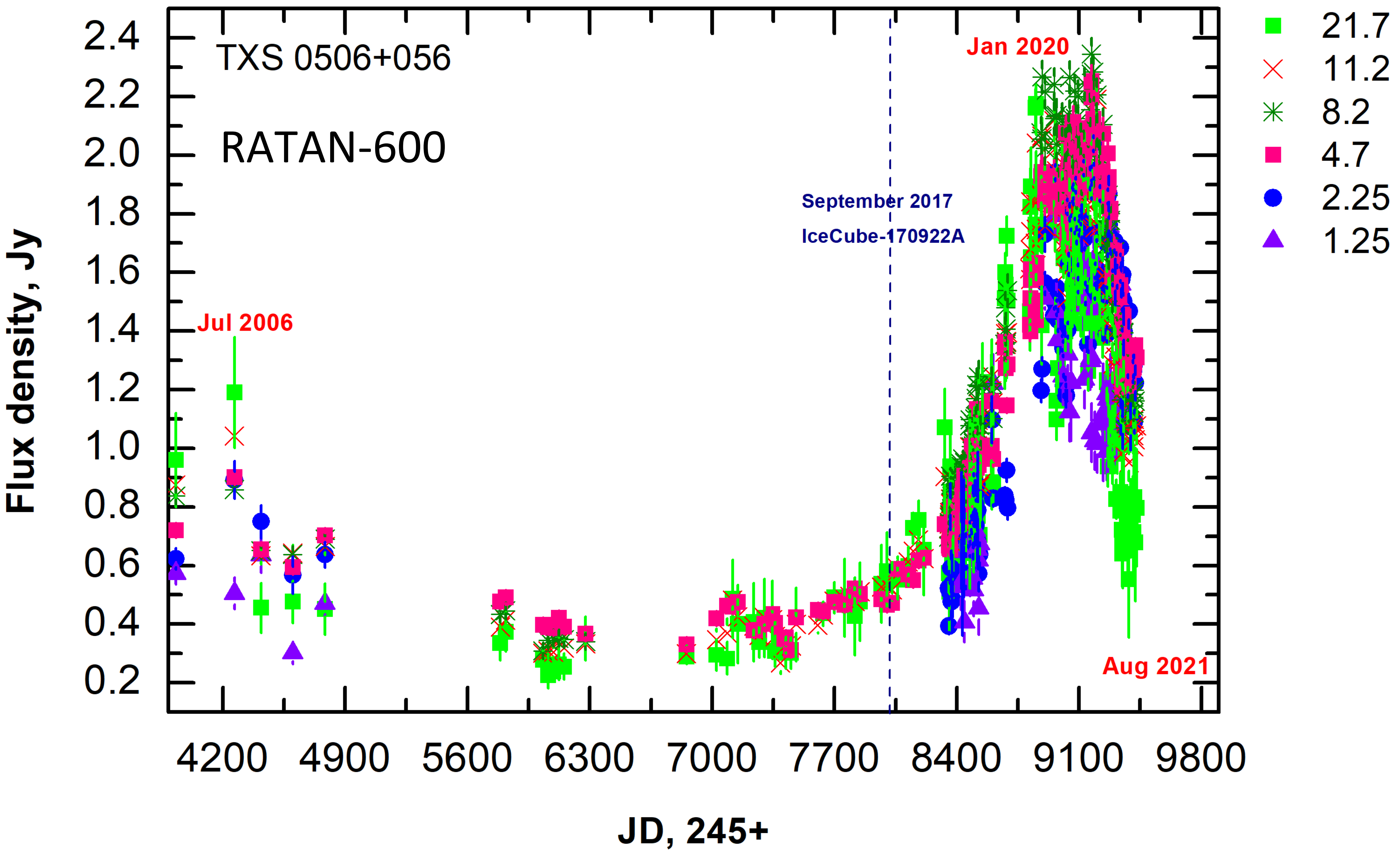




Plavin+ (2020,2021)

When Blazars Produce Neutrinos?

TXS 0506+056:
neutrino arrival = start of a major radio flare



Theoretical predictions also exist: e.g. Murase 17

Are neutrinos generally related to jet flares?

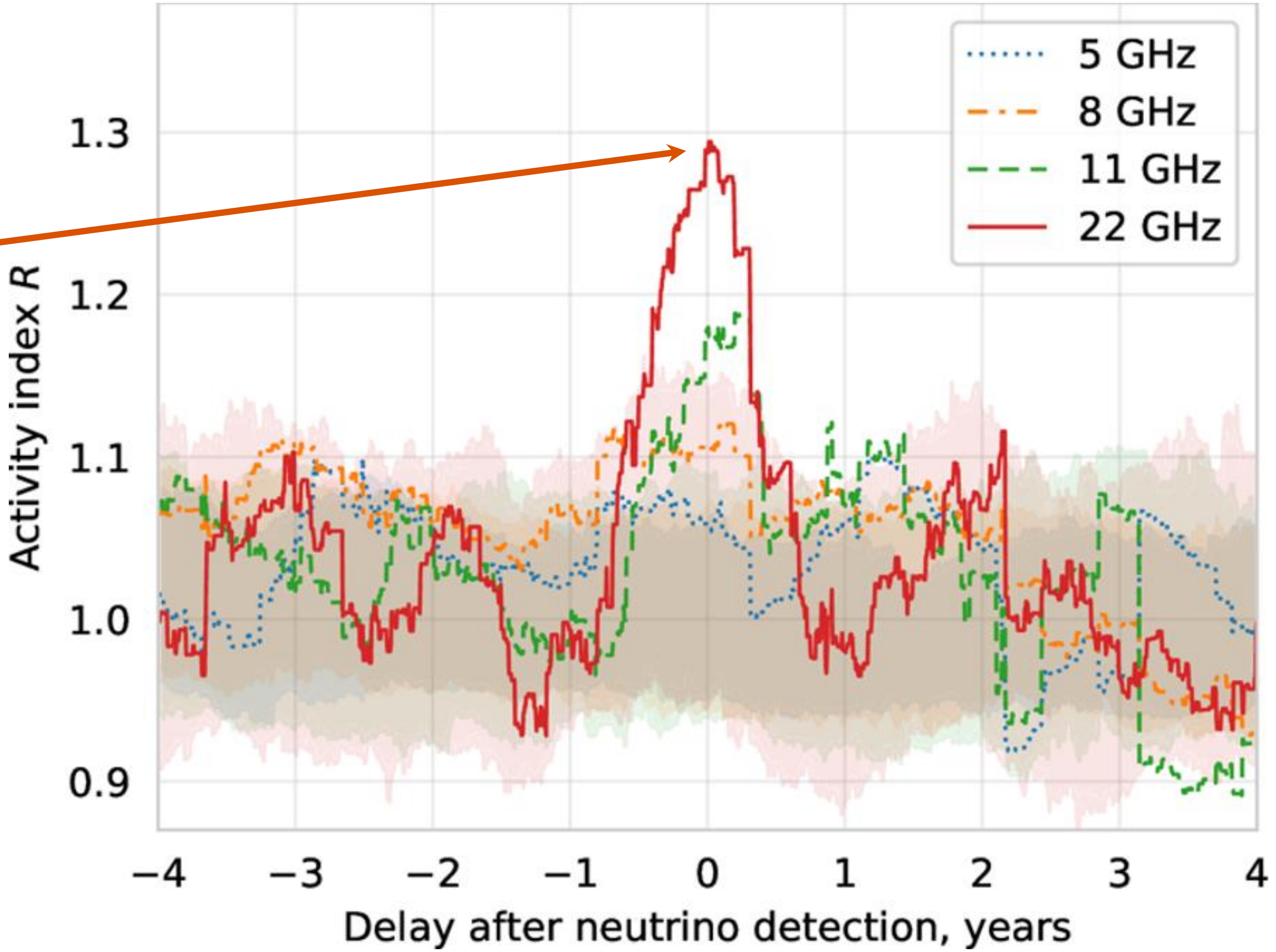
Correlate arrival times with radio flux and find out!

When Blazars Produce Neutrinos?

Average radio flux around neutrino arrivals
RATAN-600 monitoring

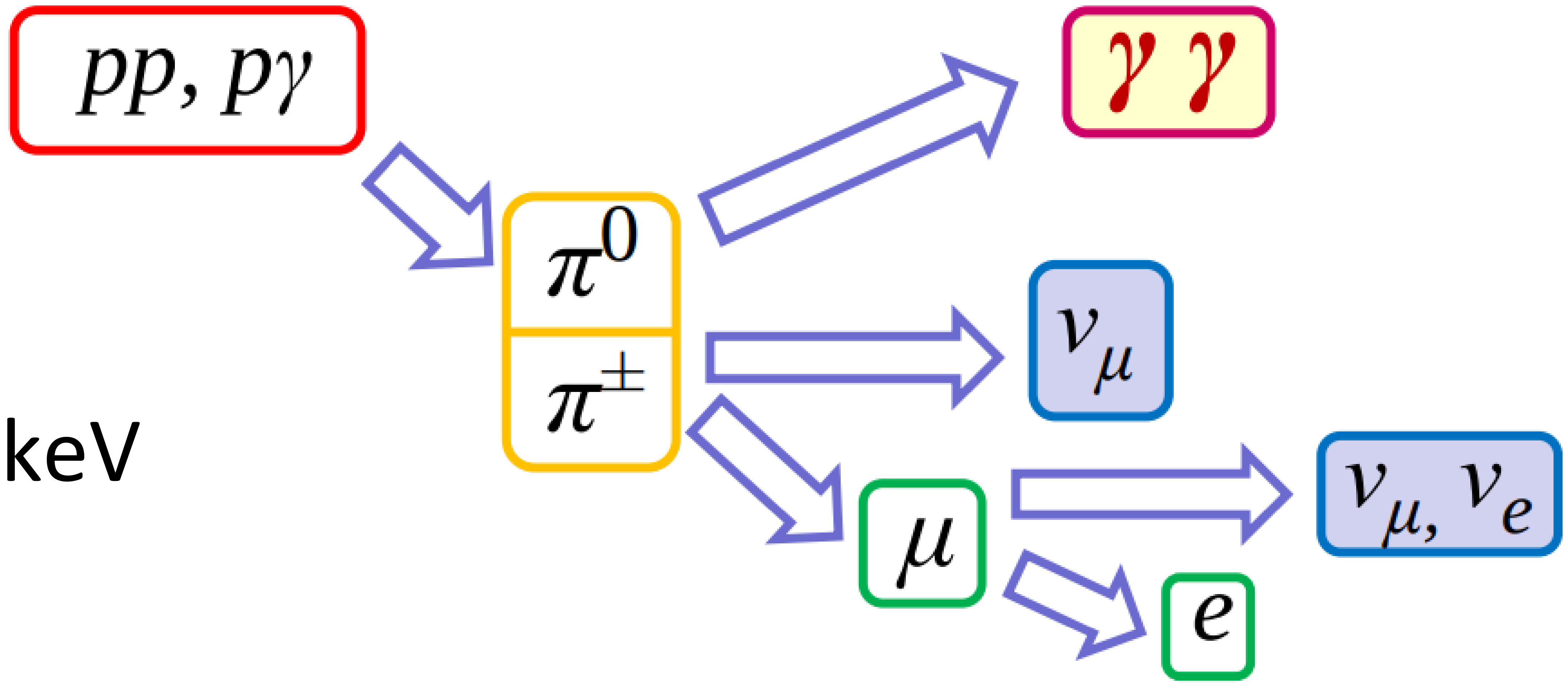
Predominantly during flares in the jet!

- Neutrinos arrive when blazars are brighter at high radio frequencies
- Effect strongest for PKS 1502+106



Independent confirmation:
Hovatta+2021, OVRO & Metsahovi

Interpretation



- Bright AGN ⇨ neutrinos produced in p + ɣ process
  (Stecker+91, Neronov+02, Kalashev+15, Cerruti 19, Bottcher+19)
- Photons – from accretion disk or jet base, E ~ 0.1-200 keV
- Need high energy protons, E ~ 10^{16} eV

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

- VLBI selects AGN with small viewing angle ⇨ neutrinos are also beamed

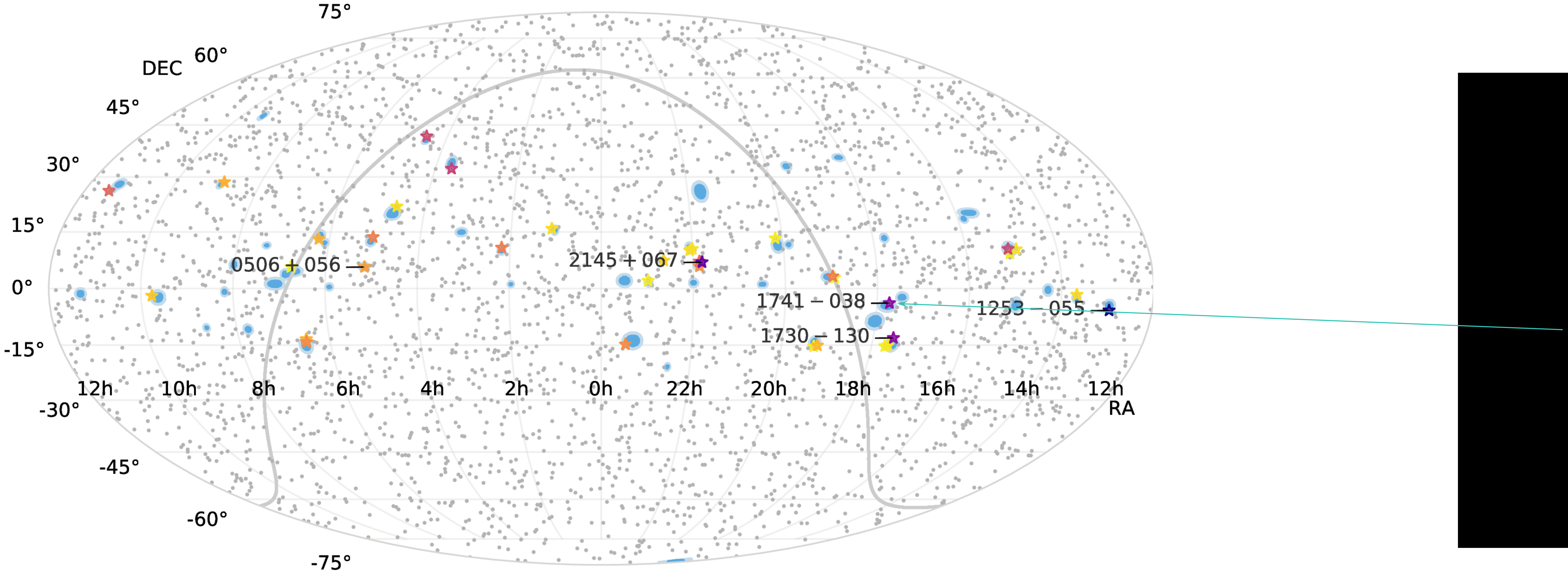
- **Note:** observed radio-, ɣ-ray photons and neutrinos can be produced by different mechanisms, a multi-zone model.

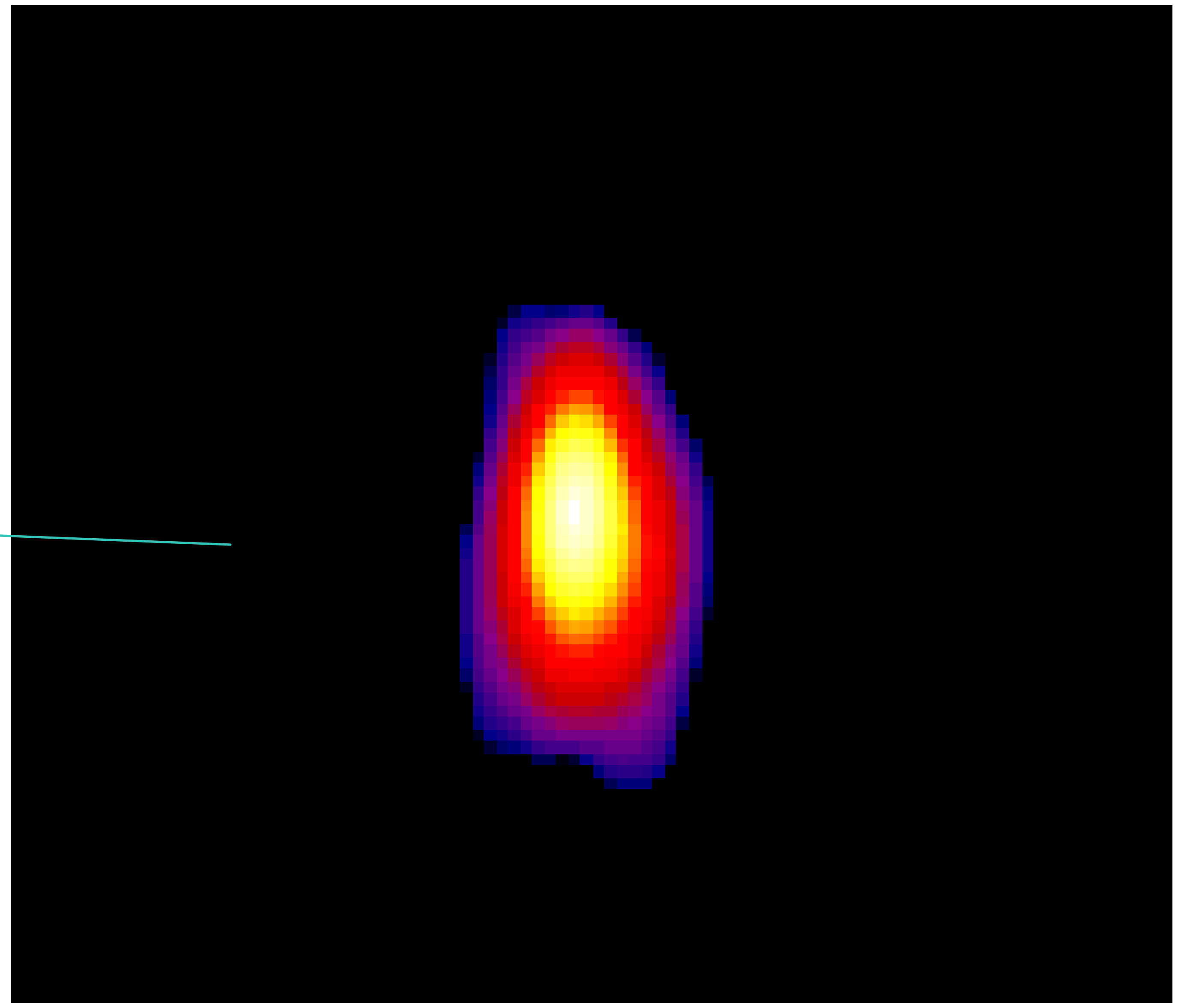
Recent confirmations: IceCube data

1. December 2021: PKS 0735+178: the first double-neutrino from a blazar by IceCube and Baikal-GVD. Simultaneous multi-band flare.

2. February 2022: PKS 1741–03: second IceCube neutrino alert for the blazars selected by us earlier as a highly probable neutrino candidate. 3% chance probability.

3. 3. April 2022: TXS1749-101 – another blazar with a flare previously selected by us.

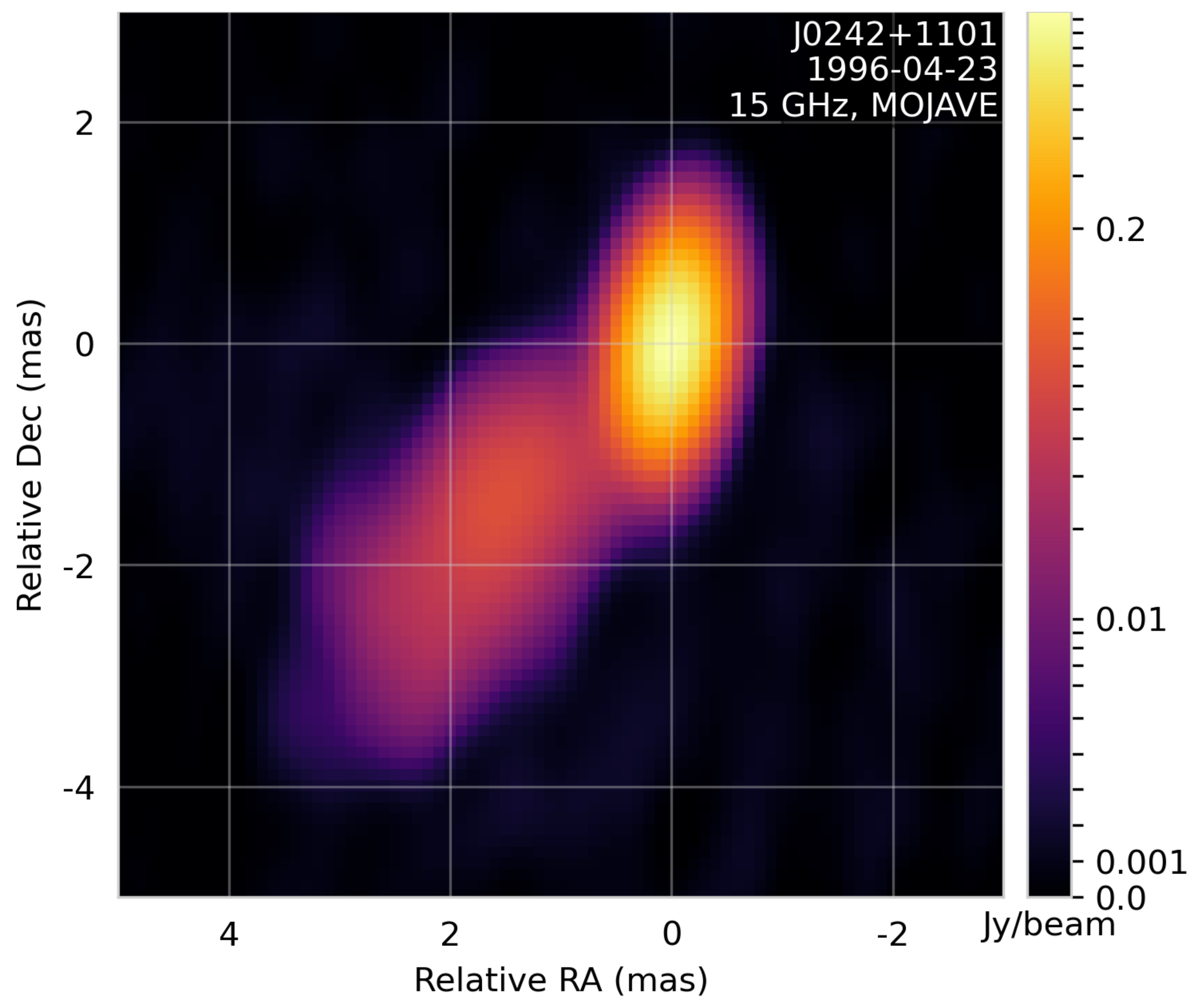


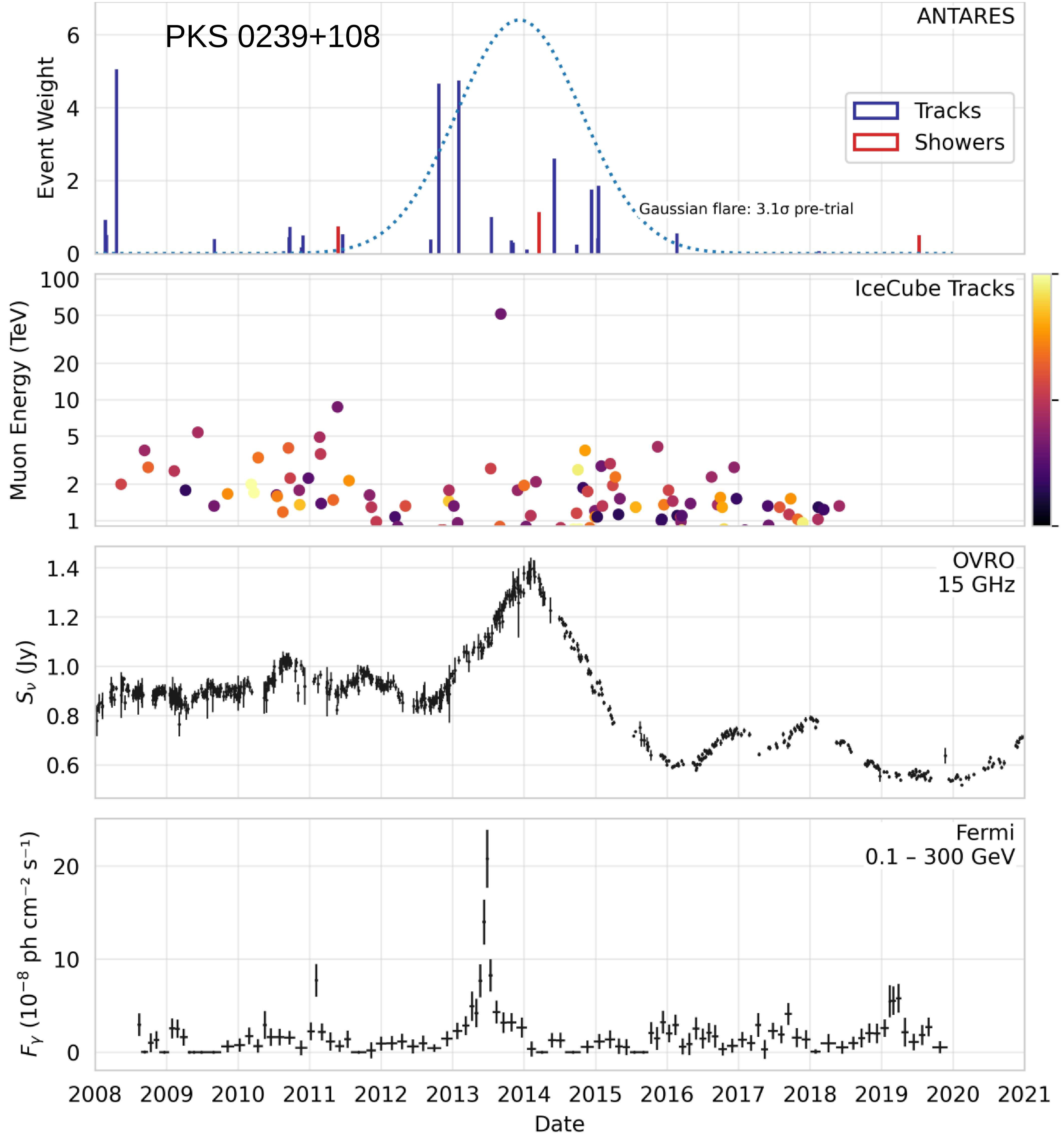


Early results with ANTARES

- Cross-correlation of a complete sample of VLBI-selected blazars with ANTARES neutrinos provided the p-value=2%.

- The search for «untriggered flares» has revealed a very interesting case of the blazars PKS 0239+108.





ANTARES ICRC-2021 proceedings

Summary

The early finding

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

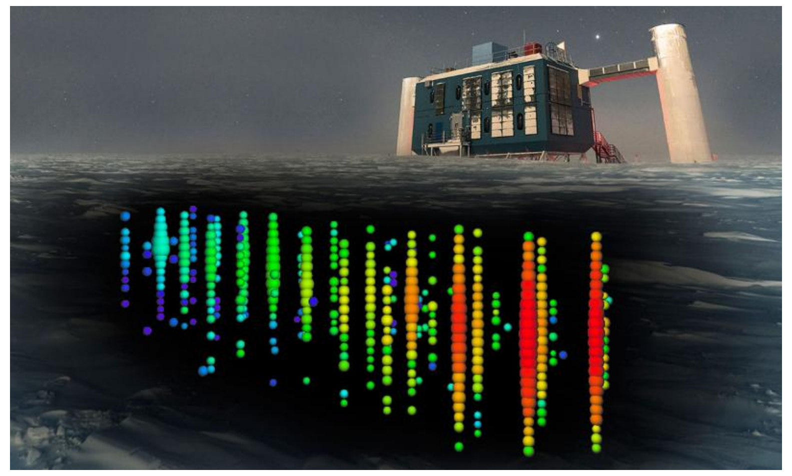
is confirmed by recent observational results.

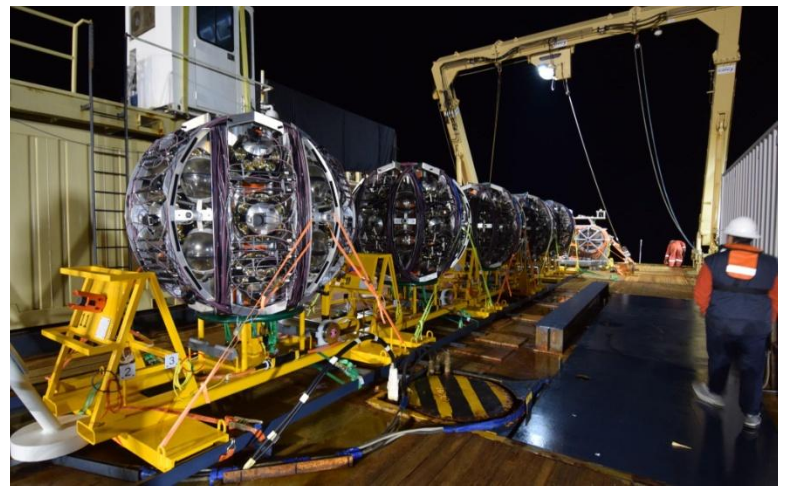
- VLBI AGN jet observations are key to neutrino associations
- Blazars emit neutrinos along the jet direction
- Require high-energy protons up to 10^{16} eV and photons of 0.1-200 keV

Multi-messenger prospects

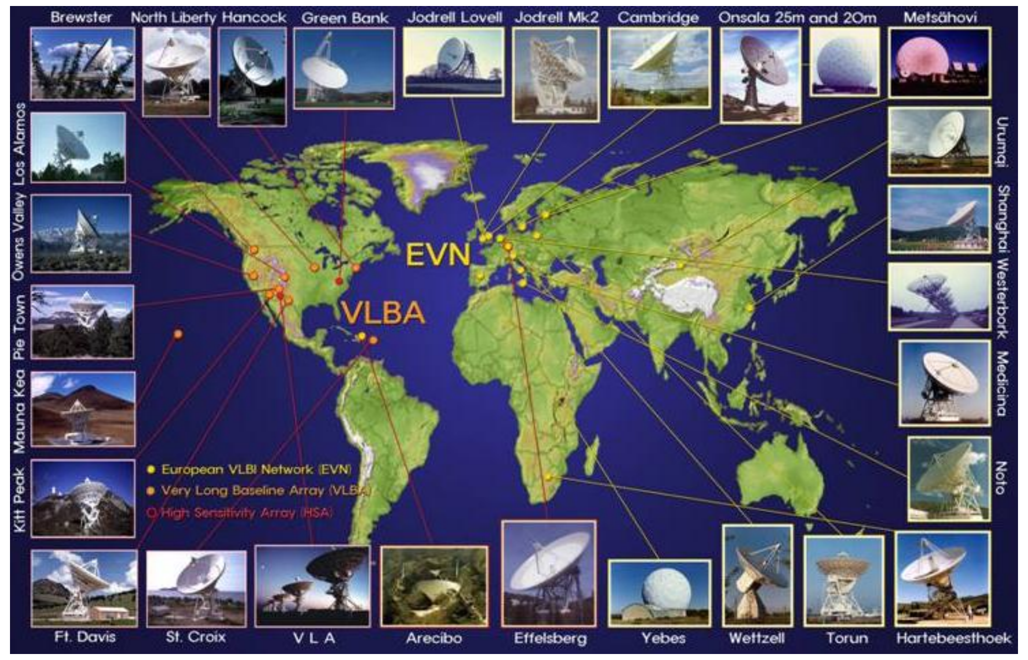
Developing a new exciting field to address pivotal aspects of cosmic neutrino production:

- How and where are neutrinos produced: p+ɣ or p+p?
- How and where are protons accelerated? By the central engine? In shocks?
- How and where are the photons produced? Accretion disk, SSC from the jet?
- Is it linked to parsec and sub-parsec jets? Flares, changes in magnetic field, particle density? Where? Accretion disk, jet base, further downstream the jet in shocks?

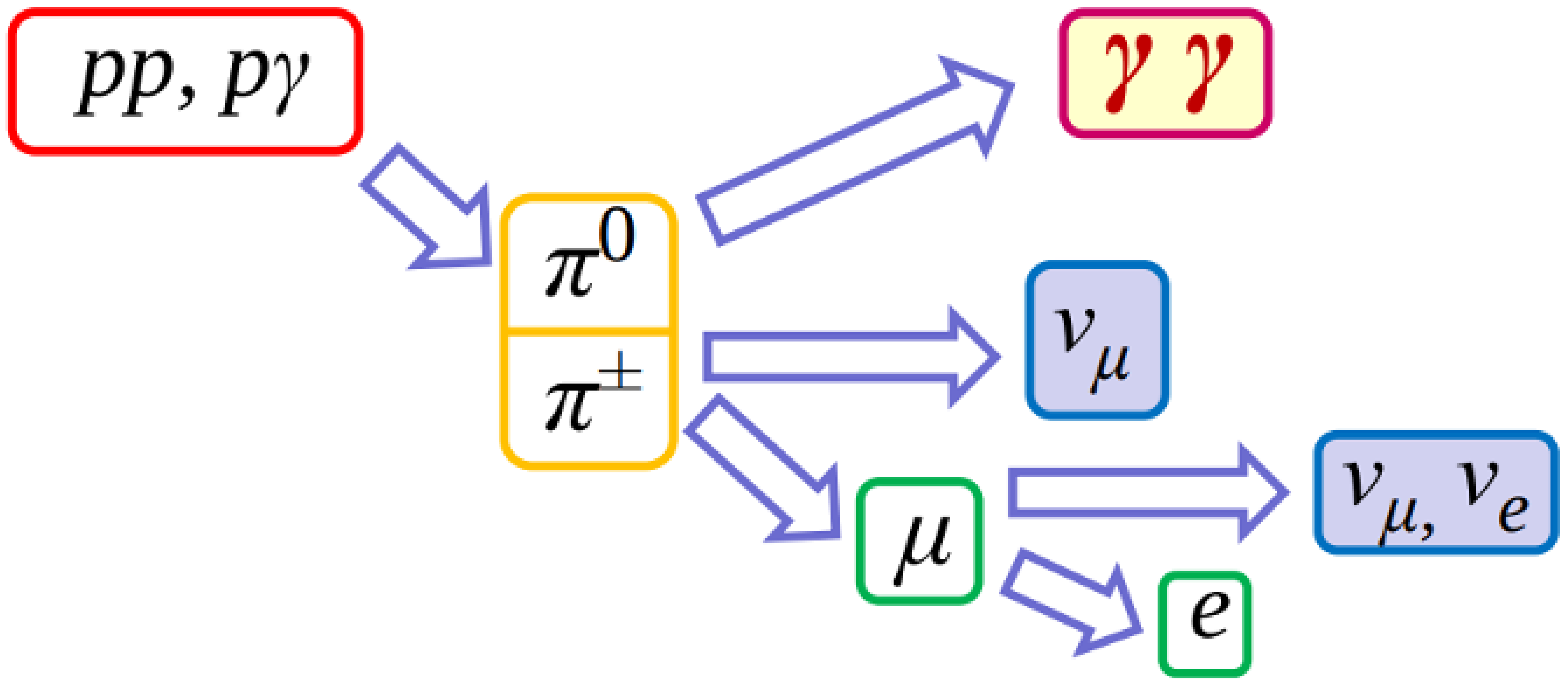




Rich observational data to come from IceCube, Baikal-GVD, KM3NeT supplemented by VLBI. Best: monitoring of complete samples.



Astrophysical Neutrinos



Relevant energies: TeV to PeV