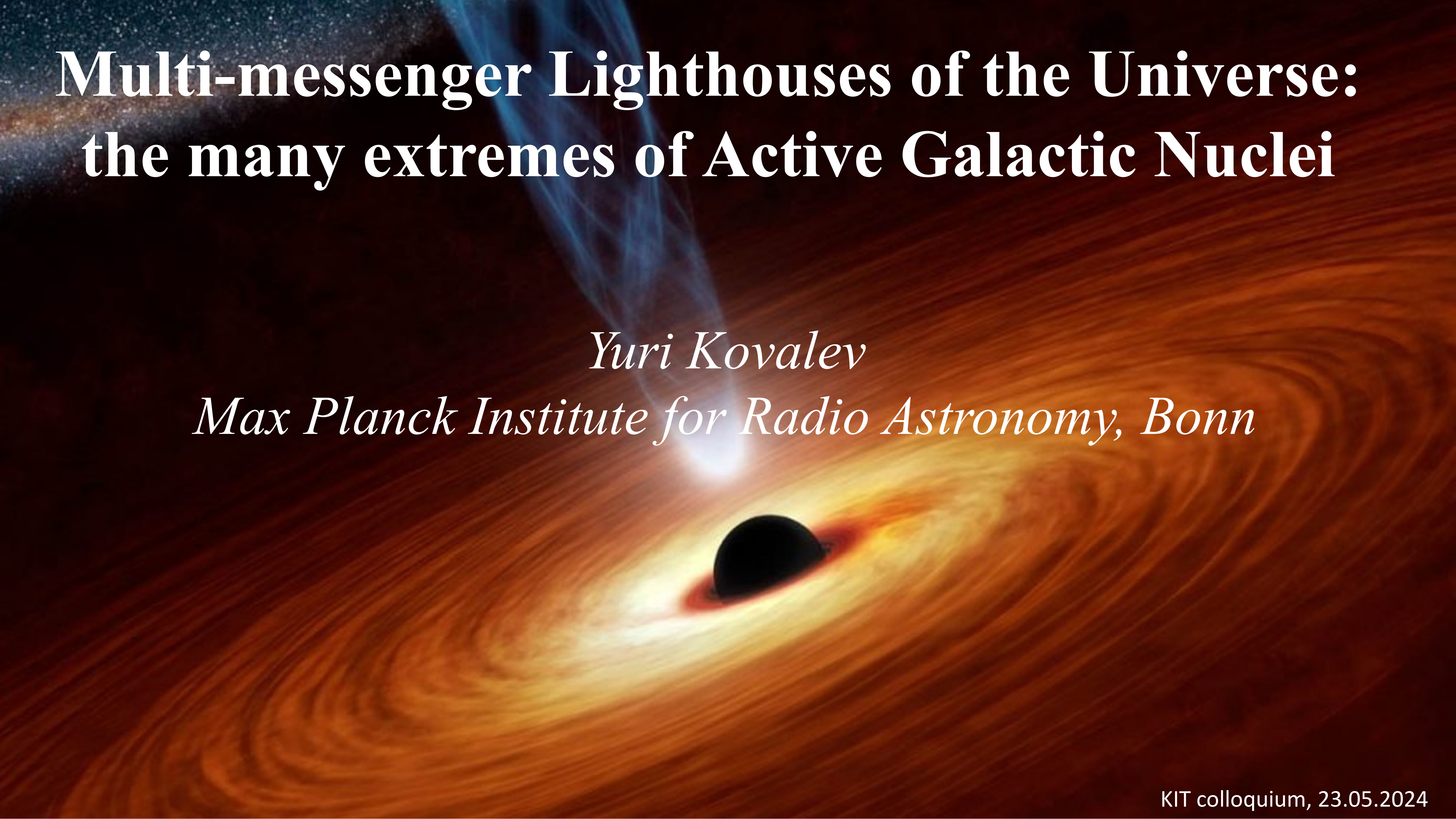


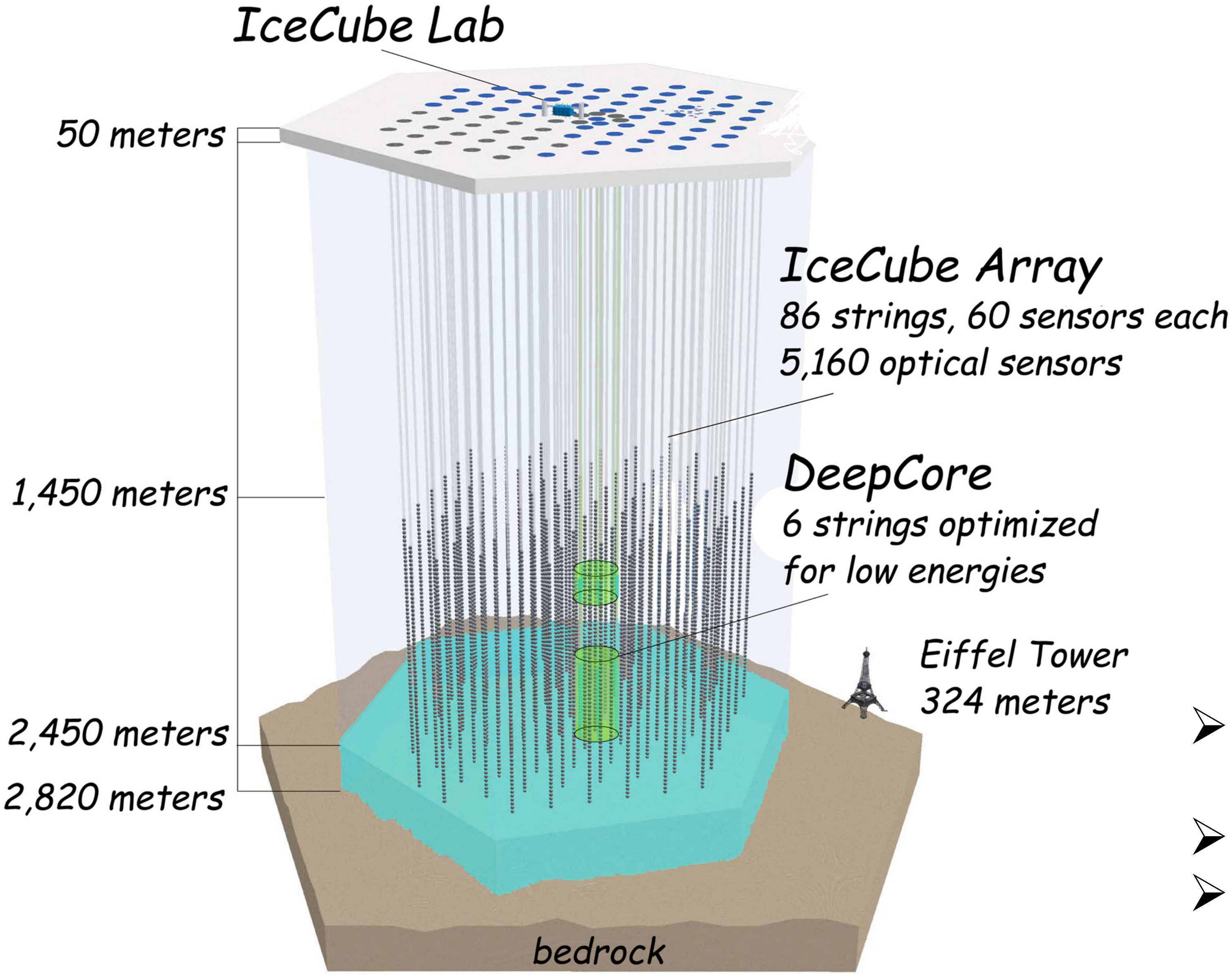
Multi-messenger Lighthouses of the Universe: the many extremes of Active Galactic Nuclei

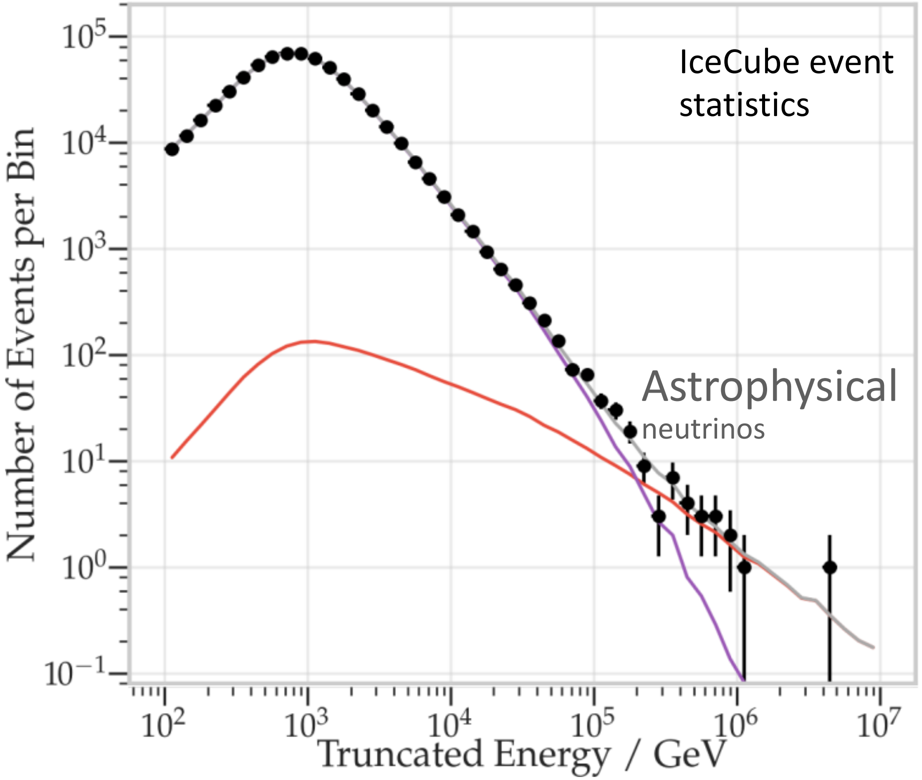
Yuri Kovalev

Max Planck Institute for Radio Astronomy, Bonn

KIT colloquium, 23.05.2024

Cosmic neutrino: IceCube, ANTARES, Baikal-GVD





- Space origin of high energy neutrino: confirmed (IC, ANTARES, Baikal-GVD).
- Sources are still strongly debated.
- Neutrino: our best probe of cosmic proton accelerators.

Objectives

Extreme cosmic supercolliders

Active Galactic Nuclei:

1. Acceleration of particles: especially, massive protons
(recent observations indicate a presence of efficient acceleration - RadioAstron)

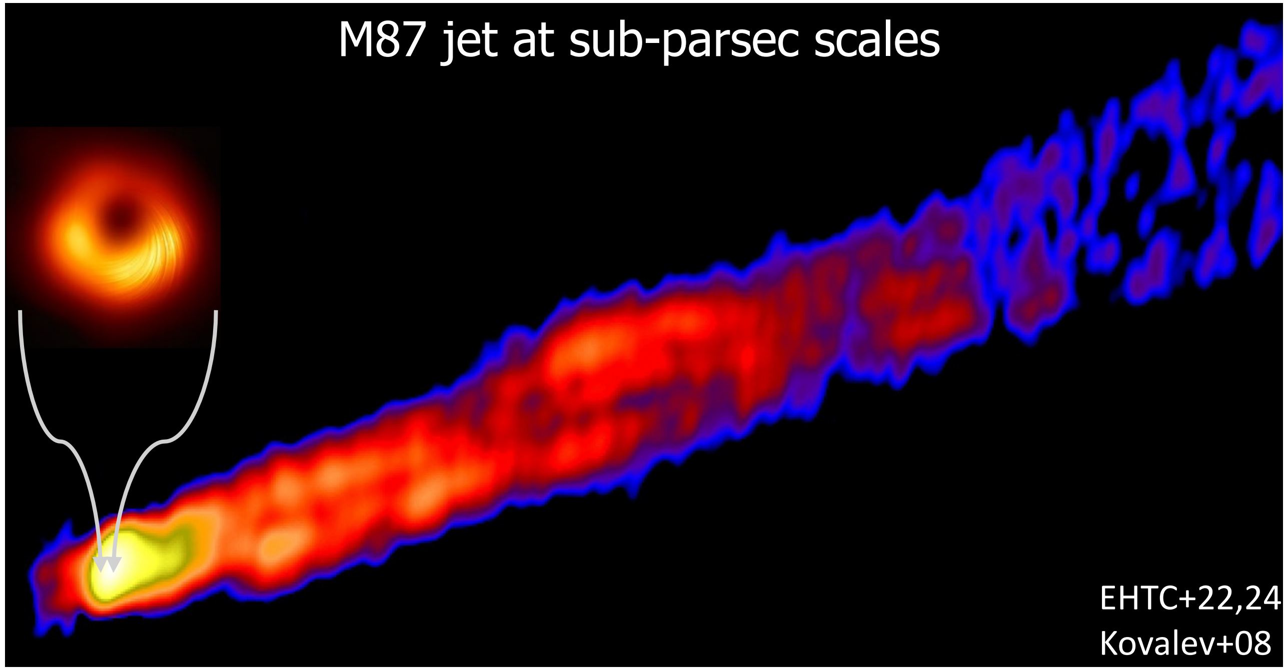
2. High-energy neutrino production

© MIPT

VLBI and AGN jets

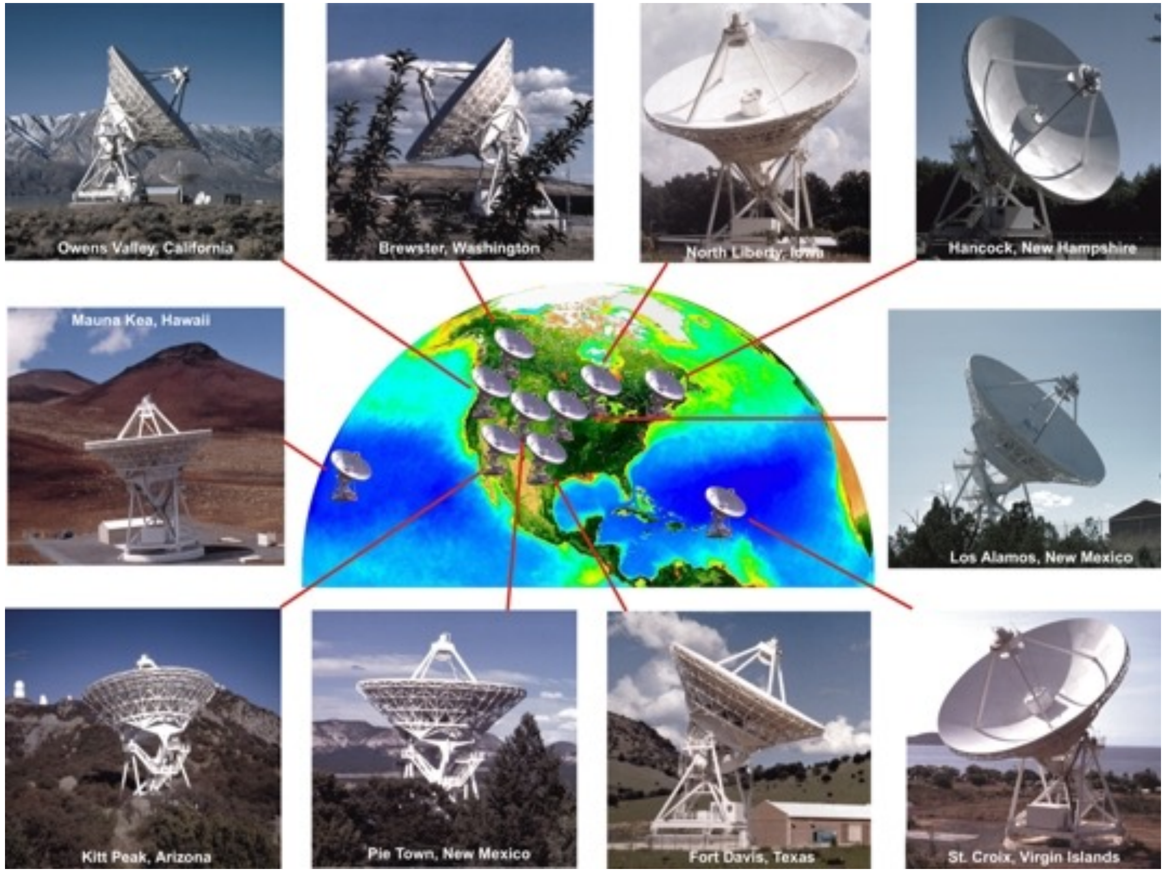
A direct observational probe of central engine and jets: Very Long Baseline Interferometry (VLBI).

- ➢ Parsec-scale structure
- ➢ Geometry
- ➢ Jet kinematics, acceleration



M87 jet at sub-parsec scales

EHTC+22,24
Kovalev+08



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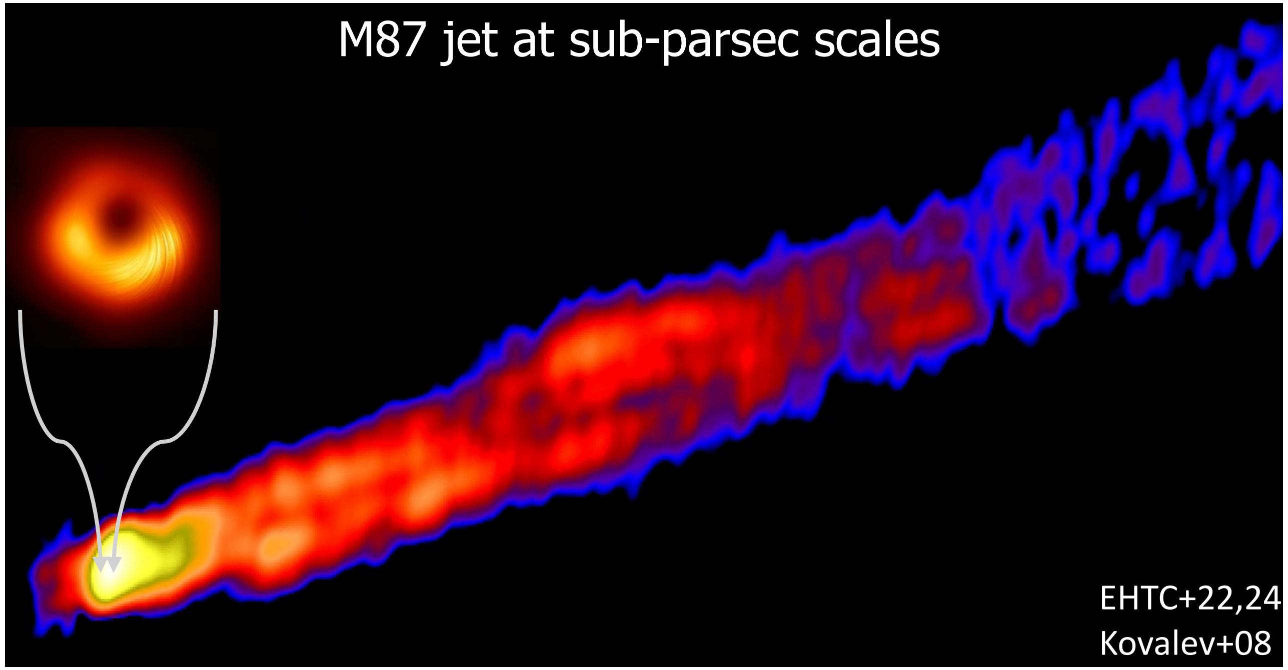

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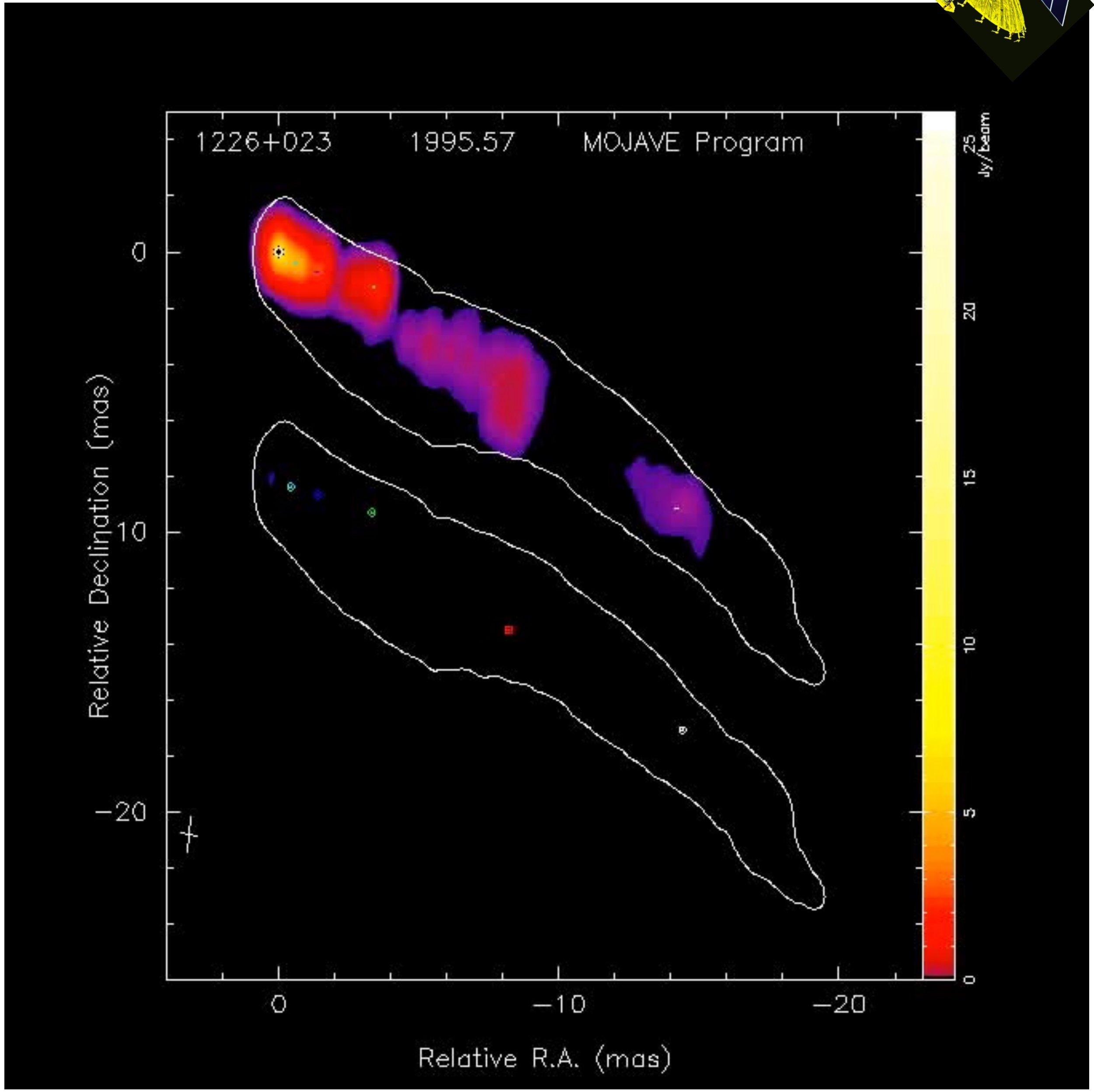
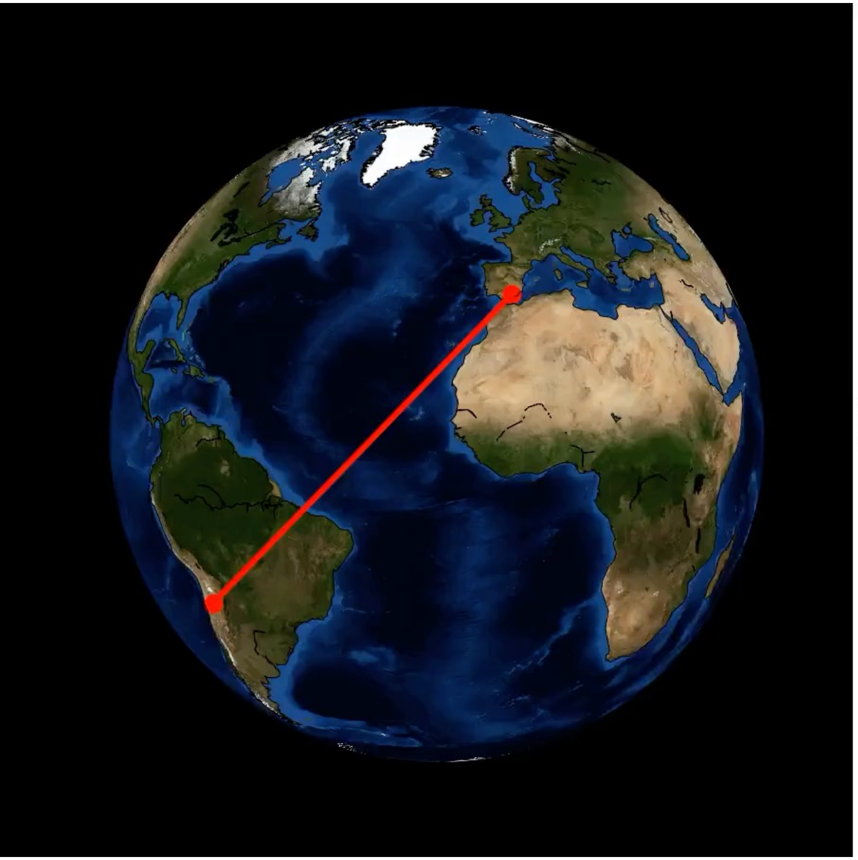
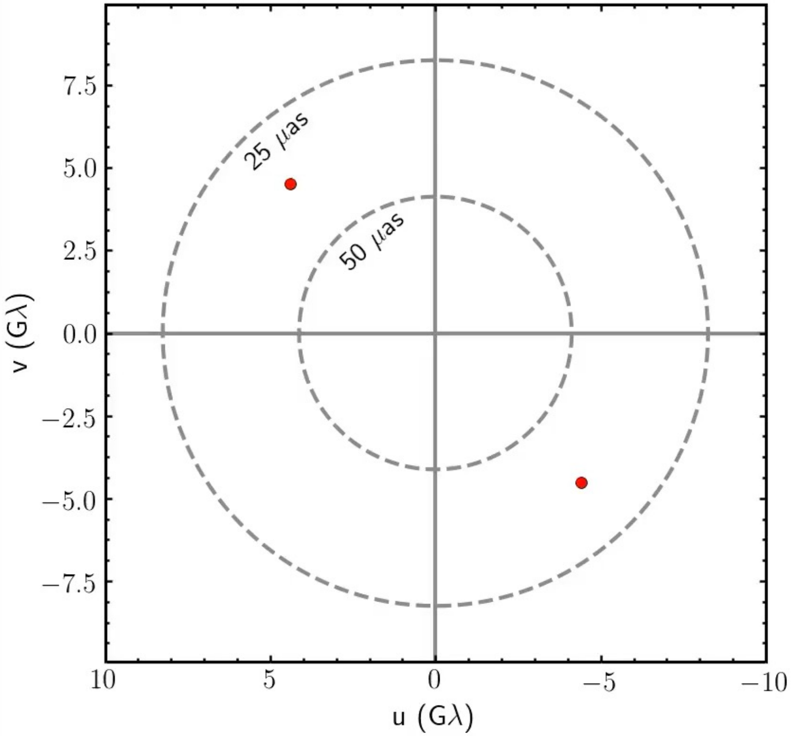
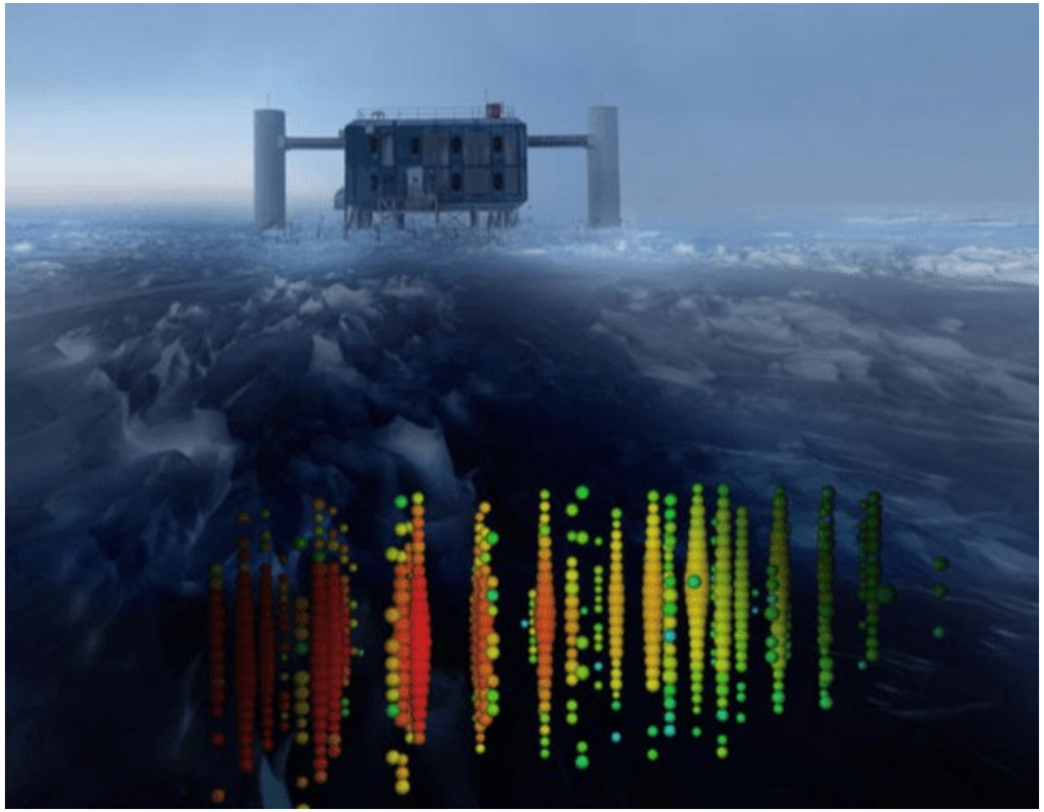


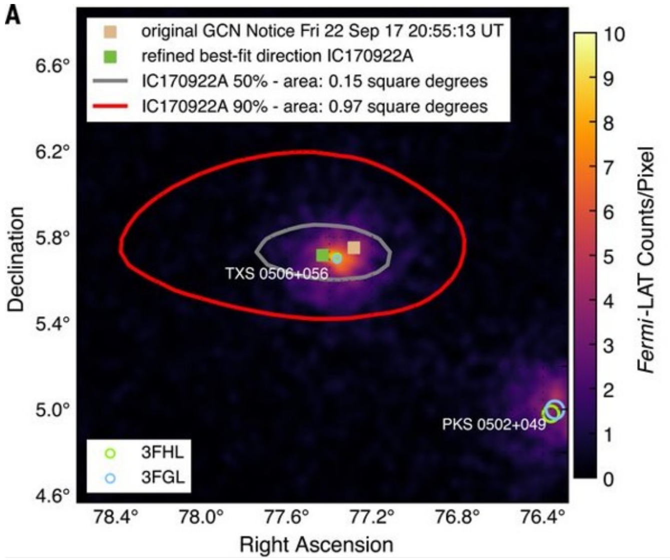
Blach hole shadow: example how VLBI works

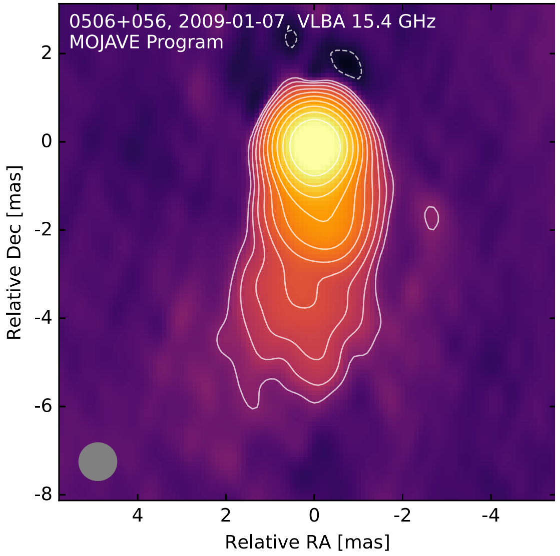


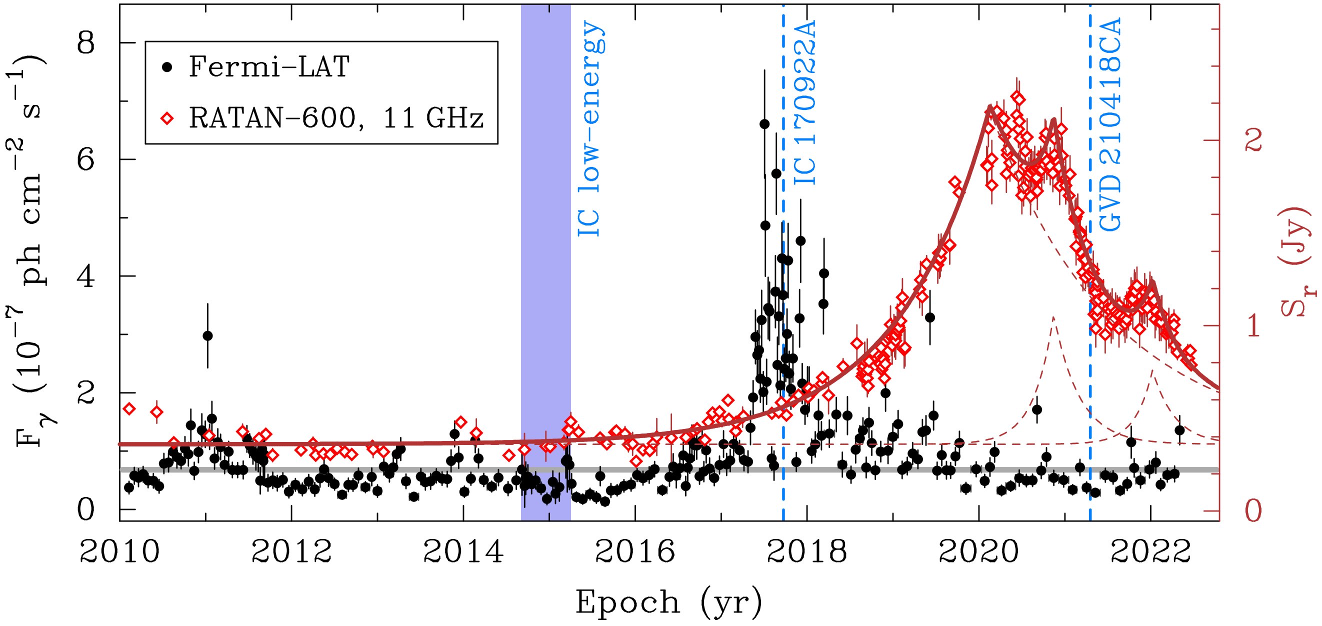


Blazars and high energy neutrinos: 0506+056



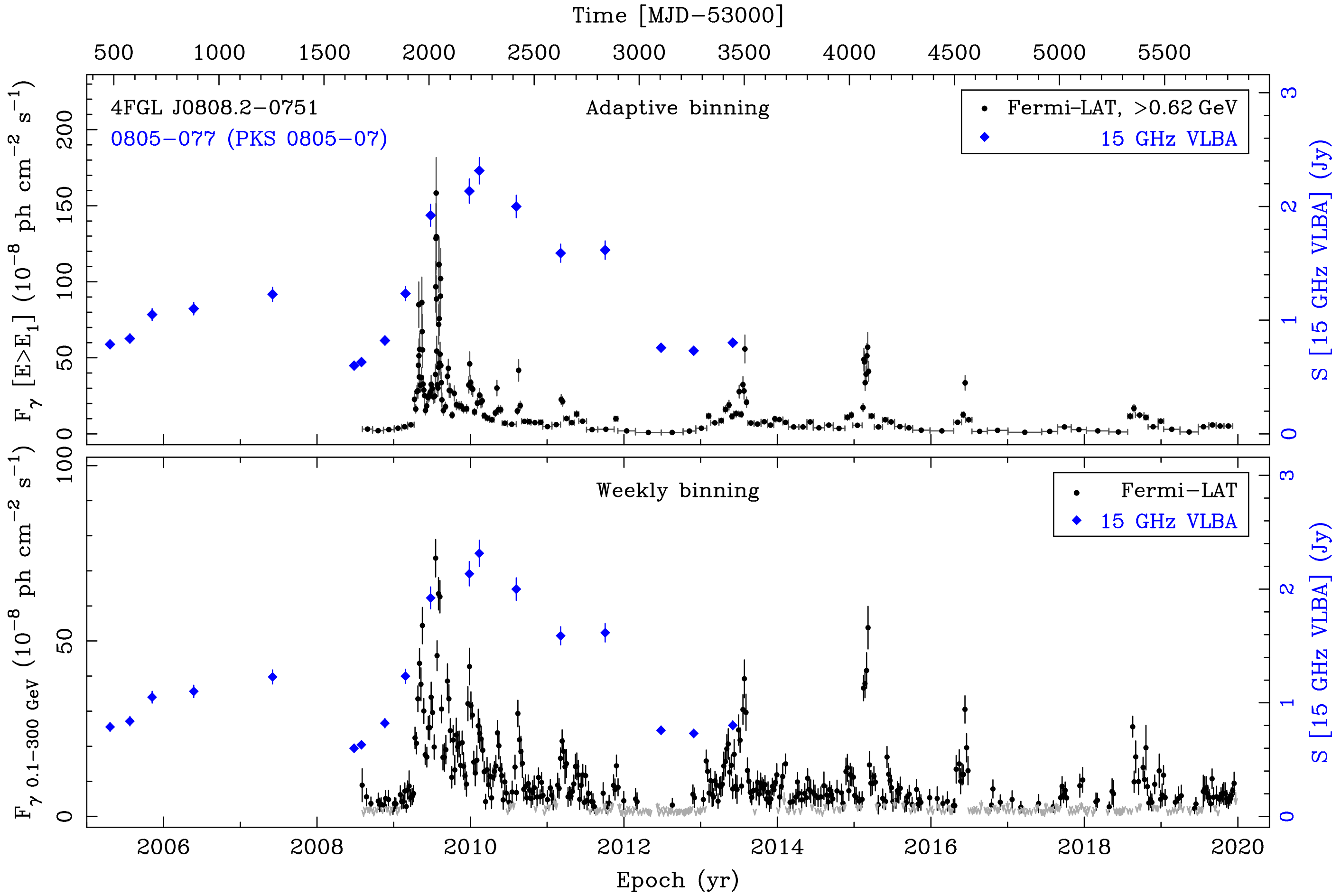


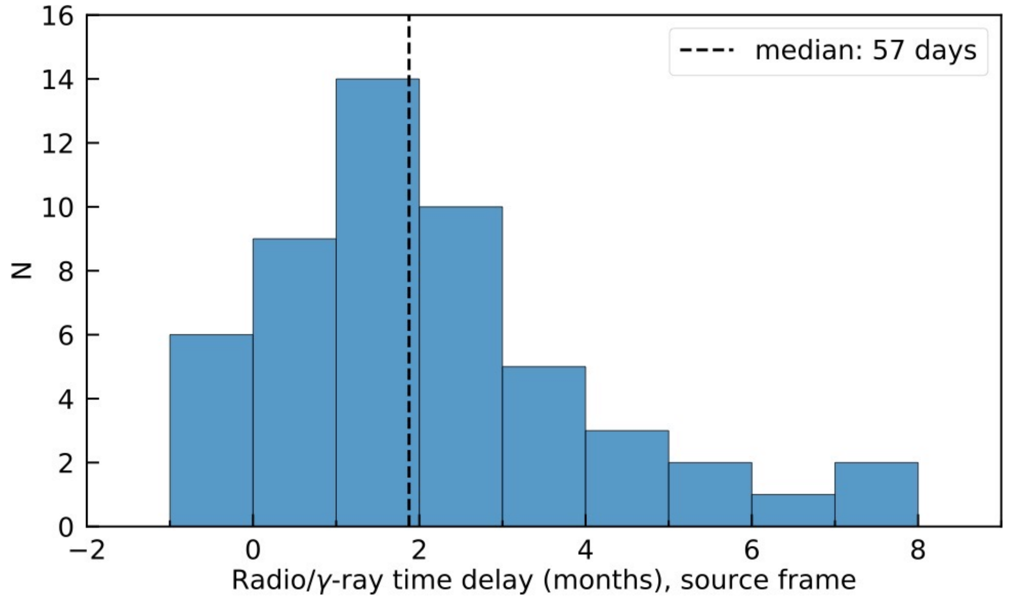


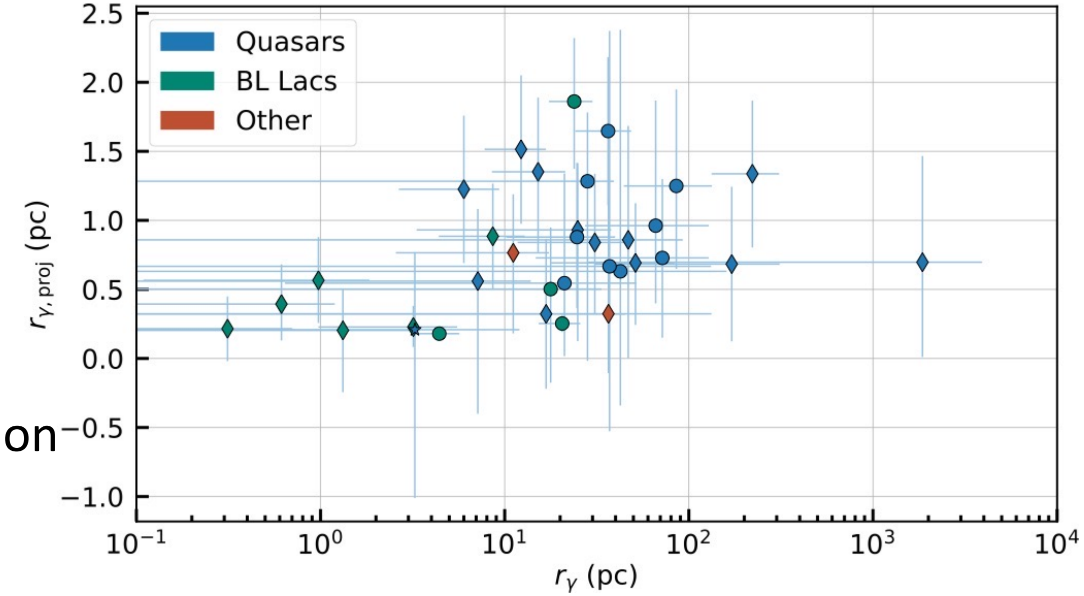


Allakhverdyan+24

VLBA – Fermi LAT 10-yr analysis







Gamma-ray emission typicaly leads 15 GHz radio by two months, source frame.

Using core-shift measurements, we locate the gamma-ray production region 10-100 pc (deprojected) from the nucleus.

Kramarenko, …, Kovalev+21

Blazars and high energy neutrinos: sample studies

VLBI (RFC): 3412 bright blazars (dots) with S > 150 mJy, 35 years of observations; probe central parsecs

Neutrino (IceCube):

71 events (2009-2022) with energy ≥ 200 TeV, positional error < 10 deg^2.

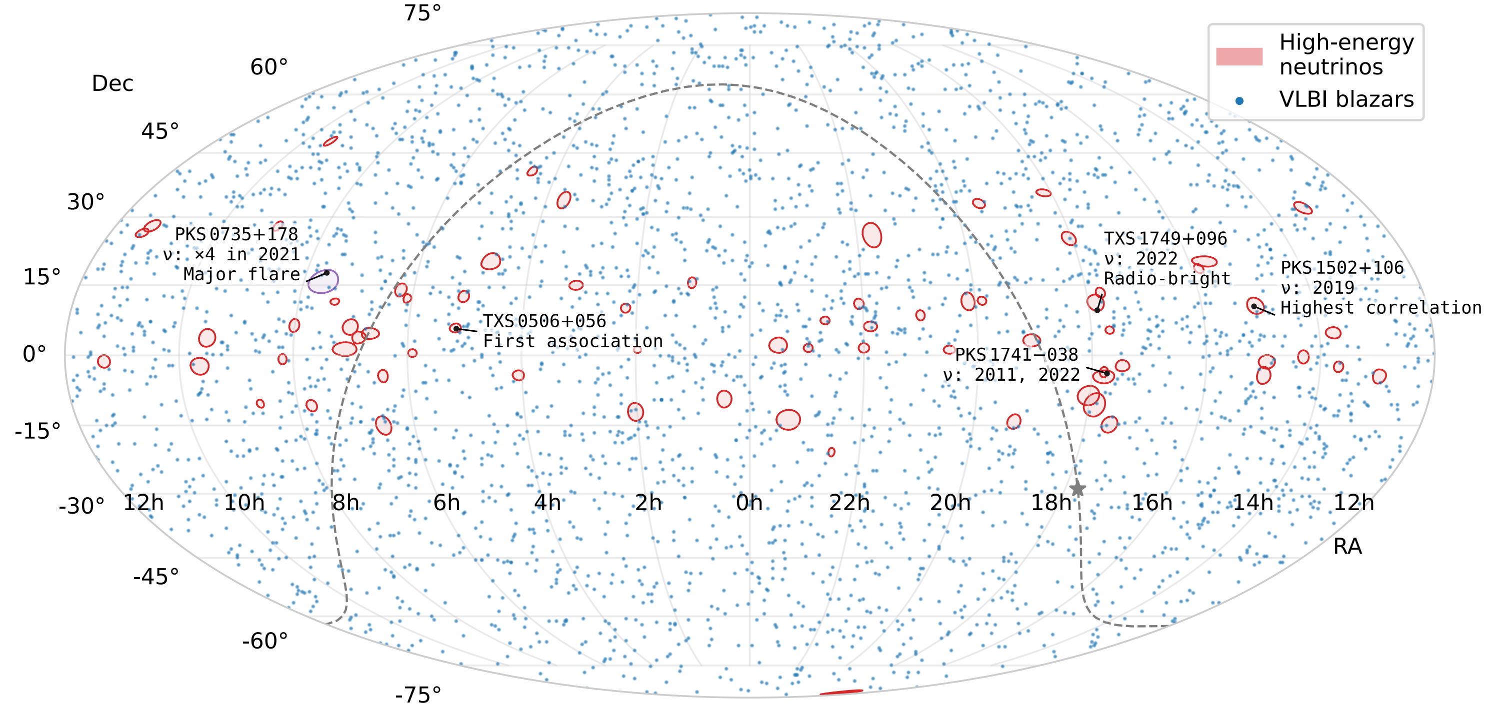
2/3 of them: astrophysical origin.

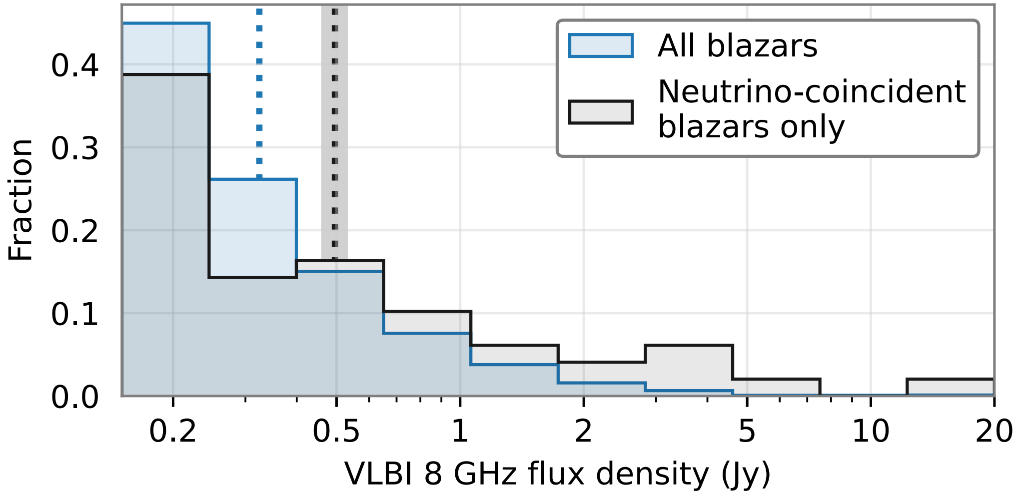
Additional IceCube positional error: 0.8°.

AGN-neutrino post-trial p-value = 3×10^{-4}, 3.6σ (>4σ if lower energy neutrinos are introduced in the analysis).

This result confirms our original findings on the basis of 2009-2019 data.

Significance increases following the increased number of neutrino events for the extra 2.5 years.





Plavin+20,23; see also Ros+20, Zhou+21, Britzen+21, Kun+22, Buson+22,23, Abbasi+23

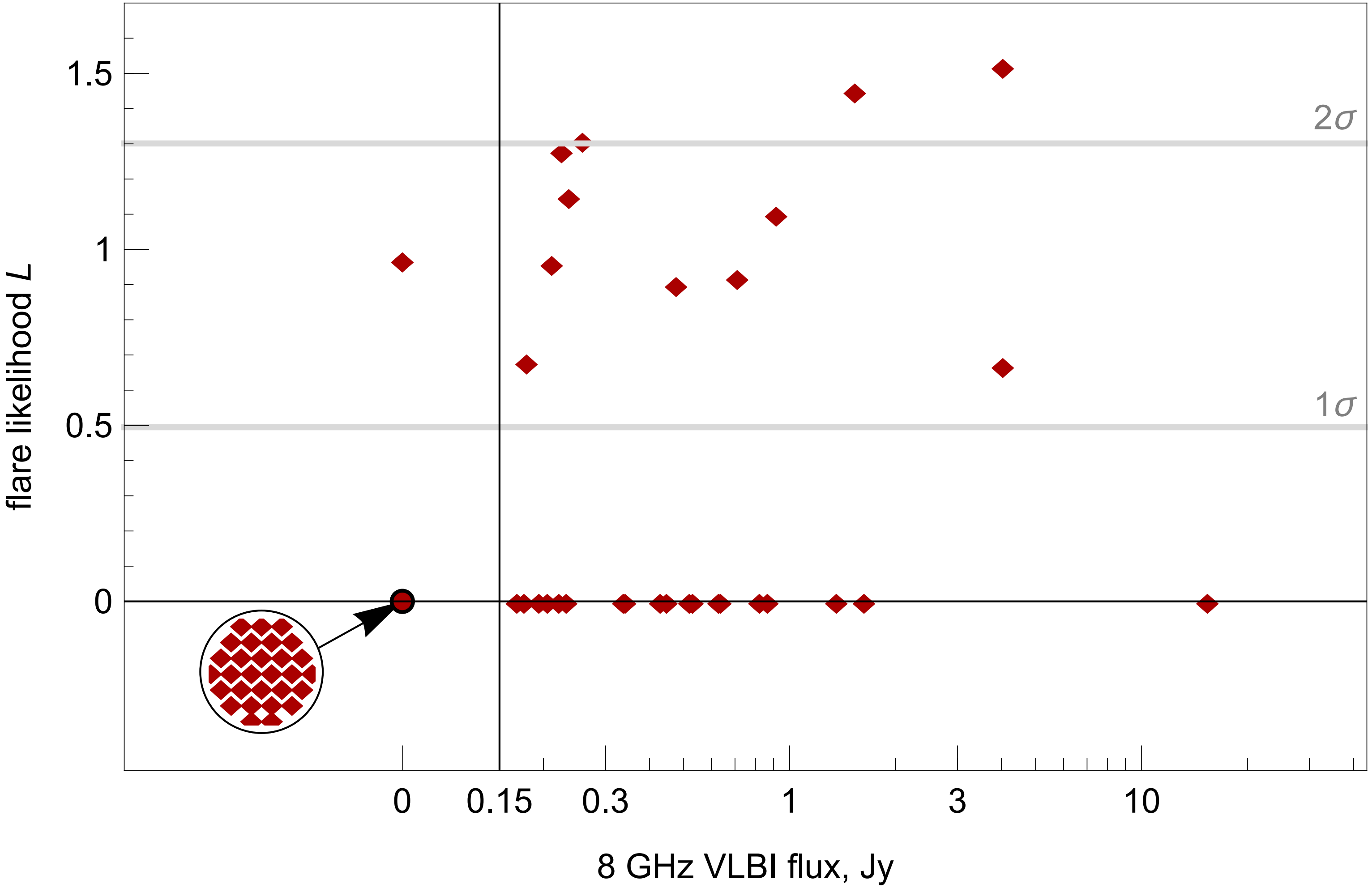
Low & high energy neutrino flares

Blazars strongly correlated with IceCube day-scale lower-energy neutrino flares.

P-value: 3.6×10^{-4}.

11 out of 12 events with low-energy neutrino flares are associated with blazars.

Only 19 out of 48 events without neutrino flares have blazar counterparts.



- **Seed photons of a wide energy range in blazars are required to reproduce this or**
- **More than one high energy neutrino per flare is detected.**

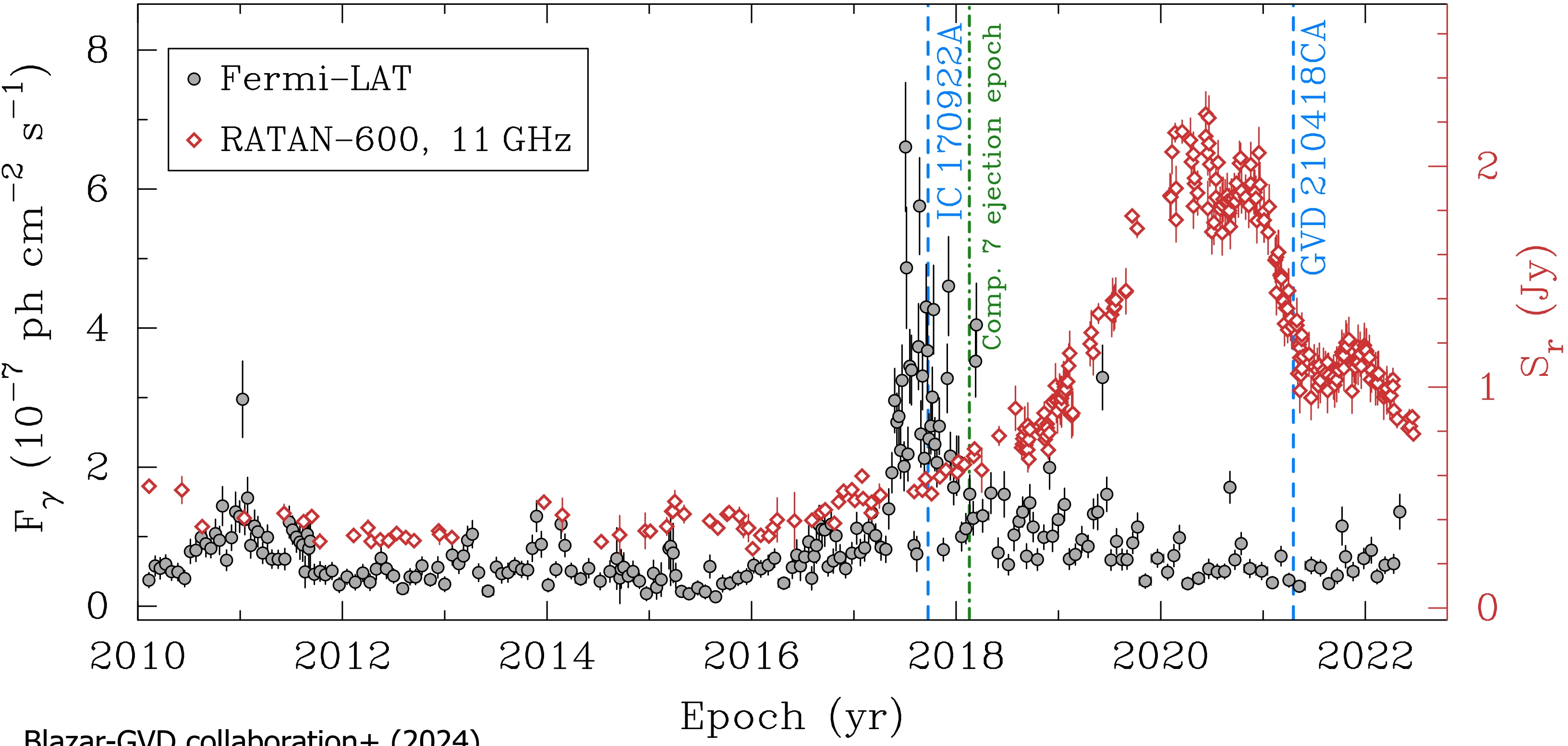
Suray & Troitsky 2023

TXS 0506+056: VLBI ejections + light curves

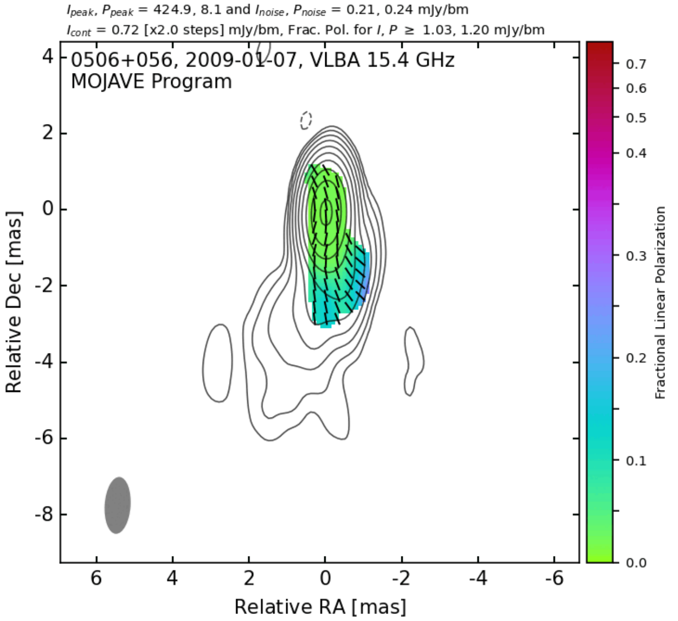
Neutrino arrival: start of a major radio flare.

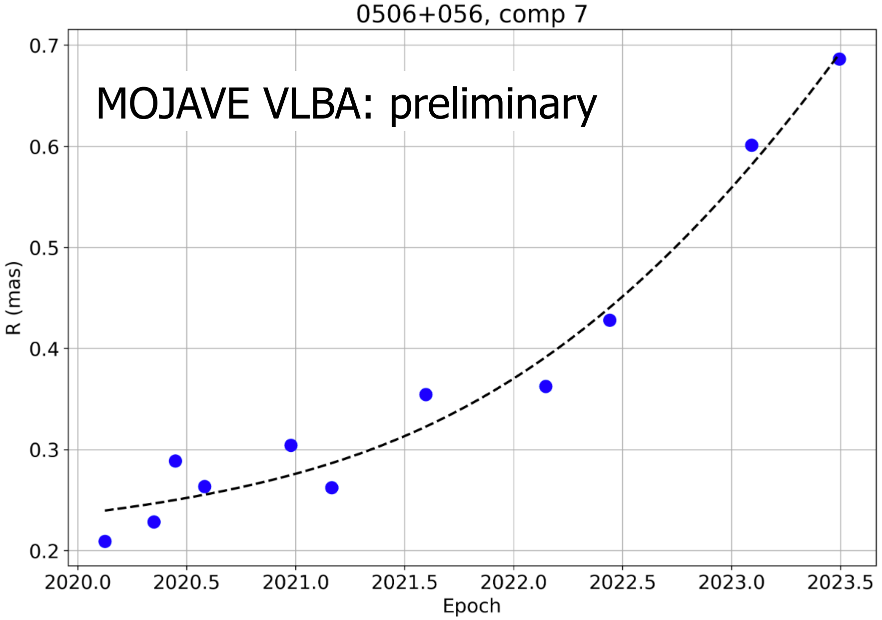
Longer flares in radio due to larger synchrotron opacity.

Parsec-scale component eject around (after) neutrino arrival.

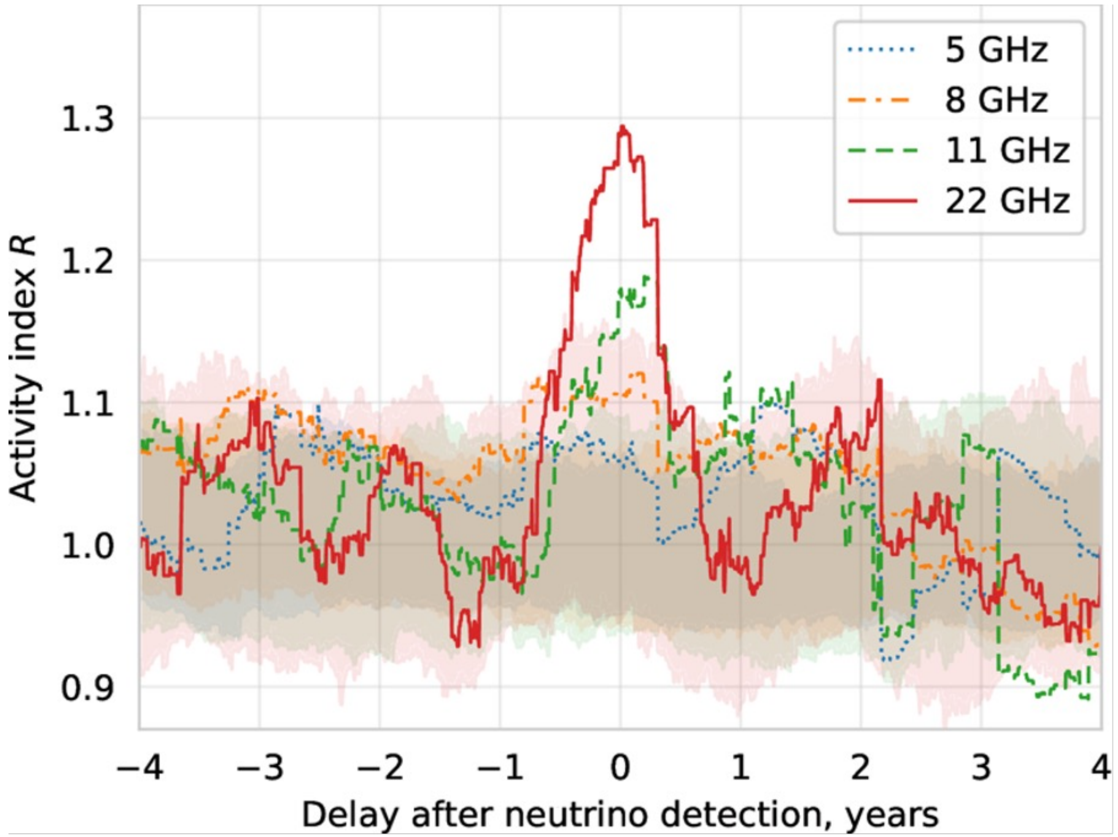


Blazar-GVD collaboration+ (2024)





RATAN-600: When blazars produce neutrino?

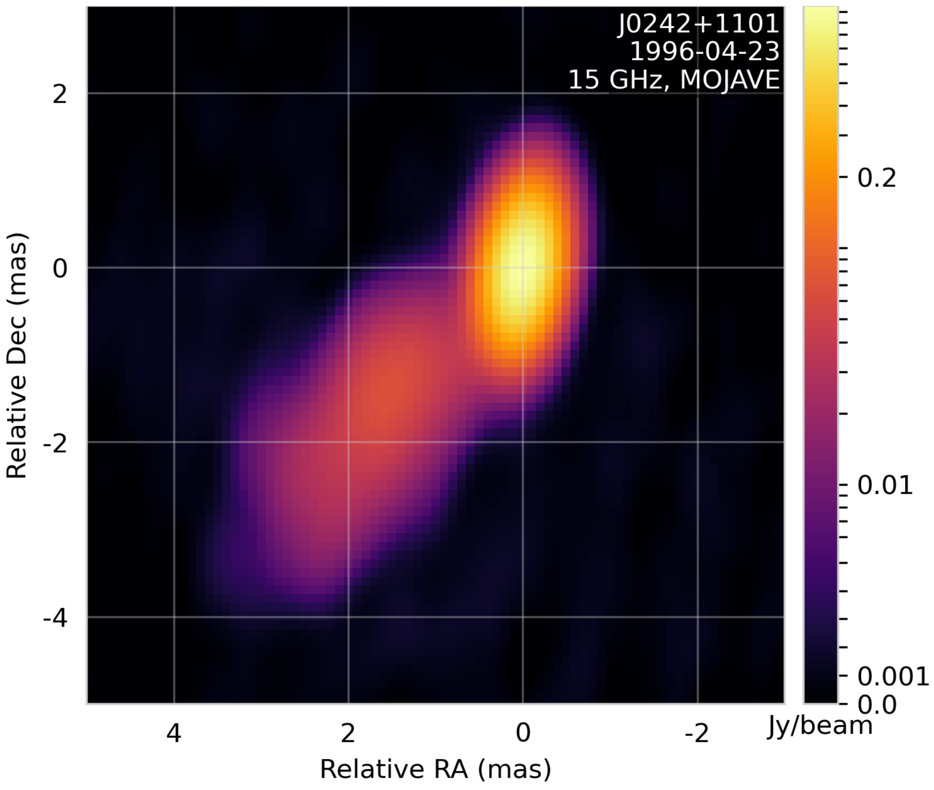


Plavin+20

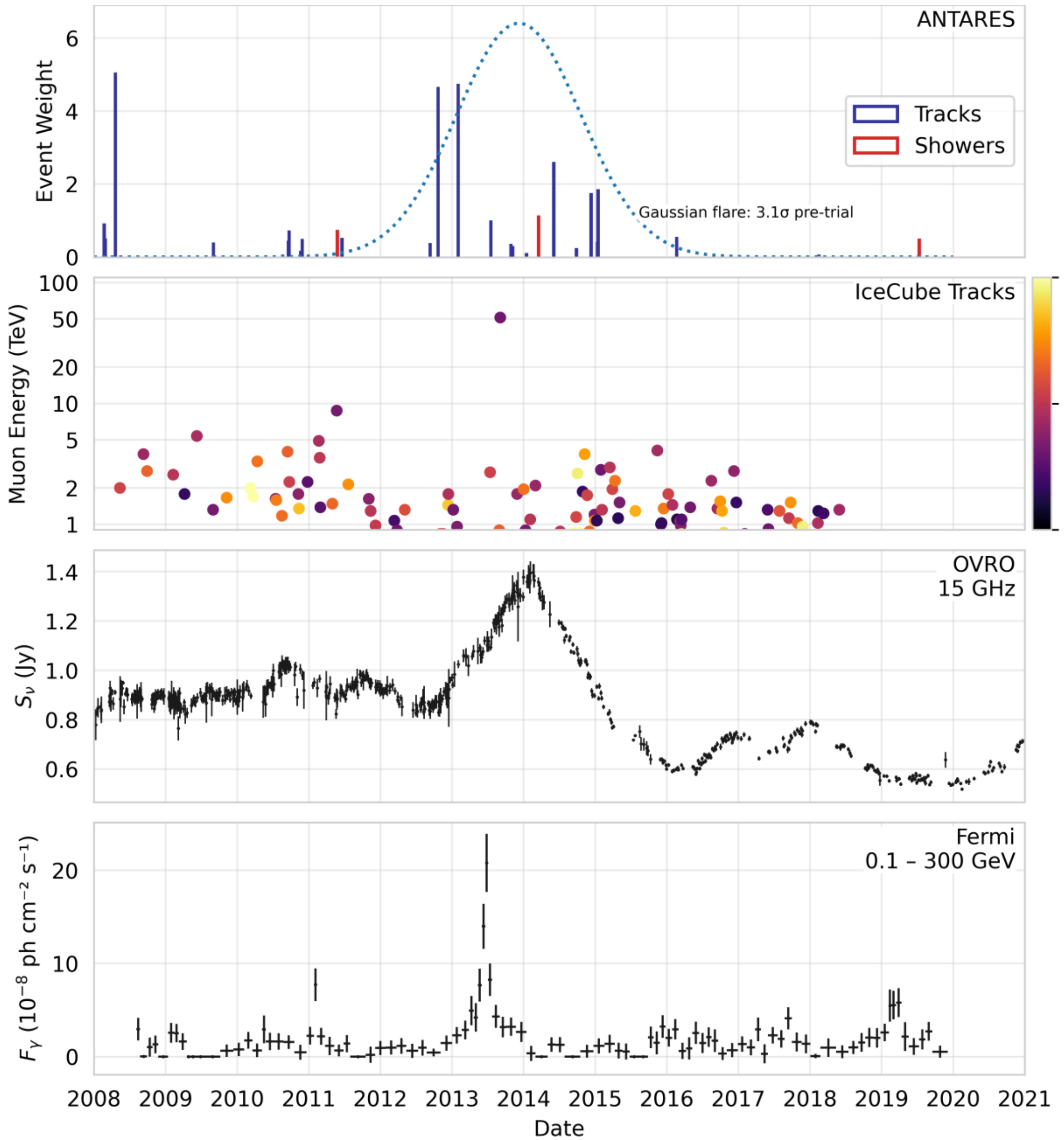
Analysis of the sample confirms that neutrinos prefer to arrive during major radio flares.
Significance: 5% only.

Confirmed by OVRO and Metsahovi (Hovatta+21).
A dense radio monitoring is needed.
See Liodakis+22.

Multi-band and multi-messenger studies: PKS 0239+108



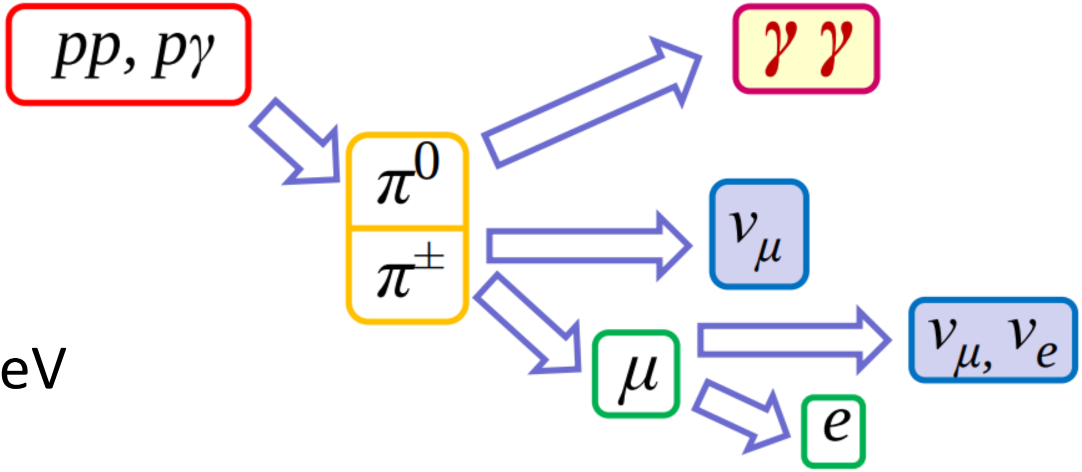
PKS 0239+108 multi-messenger light curve:



ANTARES+24

Neutrino–radio–gamma flare coincidence p-value: 0.5 %.

What is going on?

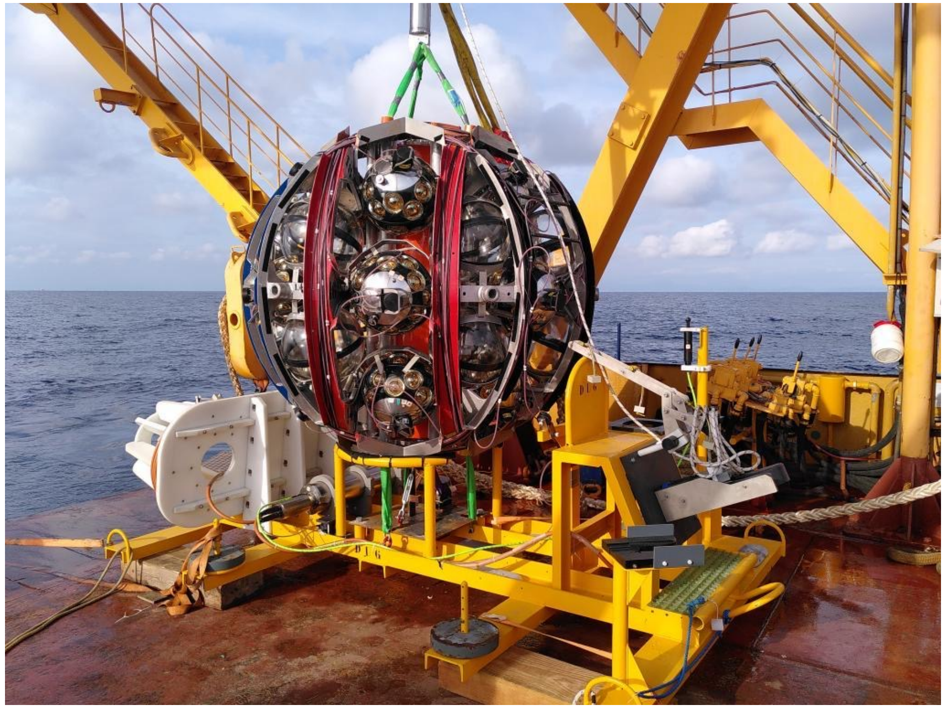


- Bright AGN: p + ɣ process is currently preferred
  (Stecker+91, Neronov+02, Kalashev+15, Cerruti 19, Bottcher+19)
- Target photons: from corona or jet base, E ~ 0.1-200 keV
- Need high energy protons, E ~ 10^{16} eV

- VLBI selects AGN with small viewing angle (blazars). Electro-magnetic and neutrino emission are both beamed.

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

Prospects: multi-messenger AGN studies



- Checking significance of the blazar-neutrino connection with new data from IceCube and KM3NeT
- Understanding extreme energy release in AGN
- Acceleration of relativistic protons: where and how?
- Origin of high energy neutrino: where and how? What is the source of seed photons?

Observationally: what happens at (sub)parsec scales? Where is the action? Many ongoing e/m programs including thousands of hours of VLBI observations (complete samples and triggers).

Complications:

- Require huge observing efforts to reach high significance
- Most interesting regions are not transparent to radio waves at cm wavelengths. We want high radio frequencies.
- Neutrinos tend to change their characteristics with time. How well is systematics known?

Summary

- Indications are growing for blazars to be neutrino emitters. Doppler boosting is important.
- High frequency radio / VLBI blazar observations are key to neutrino associations and studies.
- Exciting times are coming to answer questions on proton acceleration and neutrino production together with IceCube and KM3NeT.

Extra slides

Blazars: potential neutrino candidates

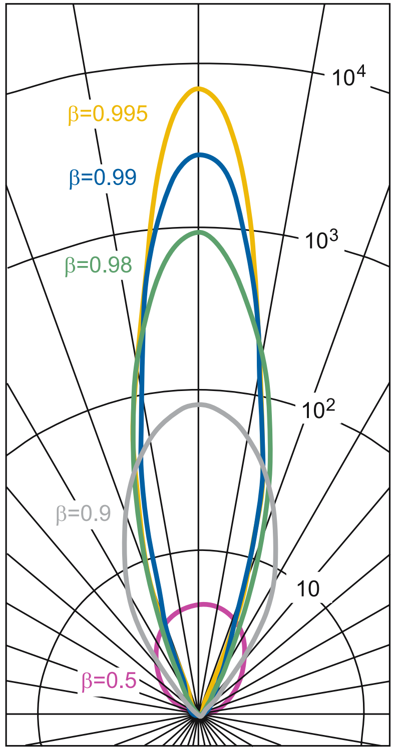
- ➢ Pointed at us;
- ➢ Strong beaming;
- ➢ Compact, radio loud, typically gamma-ray loud;
- ➢ Recently, extreme brightness discovered by *RadioAstron*.

Can accelerate particles, can produce photons, they boost radiation towards an observer – can be neutrino emitters.

90-95% of **VLBI-selected samples of active galaxies are blazars** with jets looking at us due to the beaming bias.

VLBI flux density is a measure of its parsec-scale radio emission.

Fig. 2 Luminosity Doppler boosting factor for the case where $n = 3$ shown in polar coordinates. The radial lines indicate angles at intervals of 10 degrees and the circles the luminosity boosting factor. *Red*: $\beta = 0.5$, $\gamma = 1.15$; *grey*: $\beta = 0.9$, $\gamma = 2.3$; *green*: $\beta = 0.95$, $\gamma = 3.2$; *blue*: $\beta = 0.98$, $\gamma = 5.0$; $\beta = 0.99$, $\gamma = 7.1$; $\beta = 0.995$, $\gamma = 10.0$



Kellermann et al. (2007)

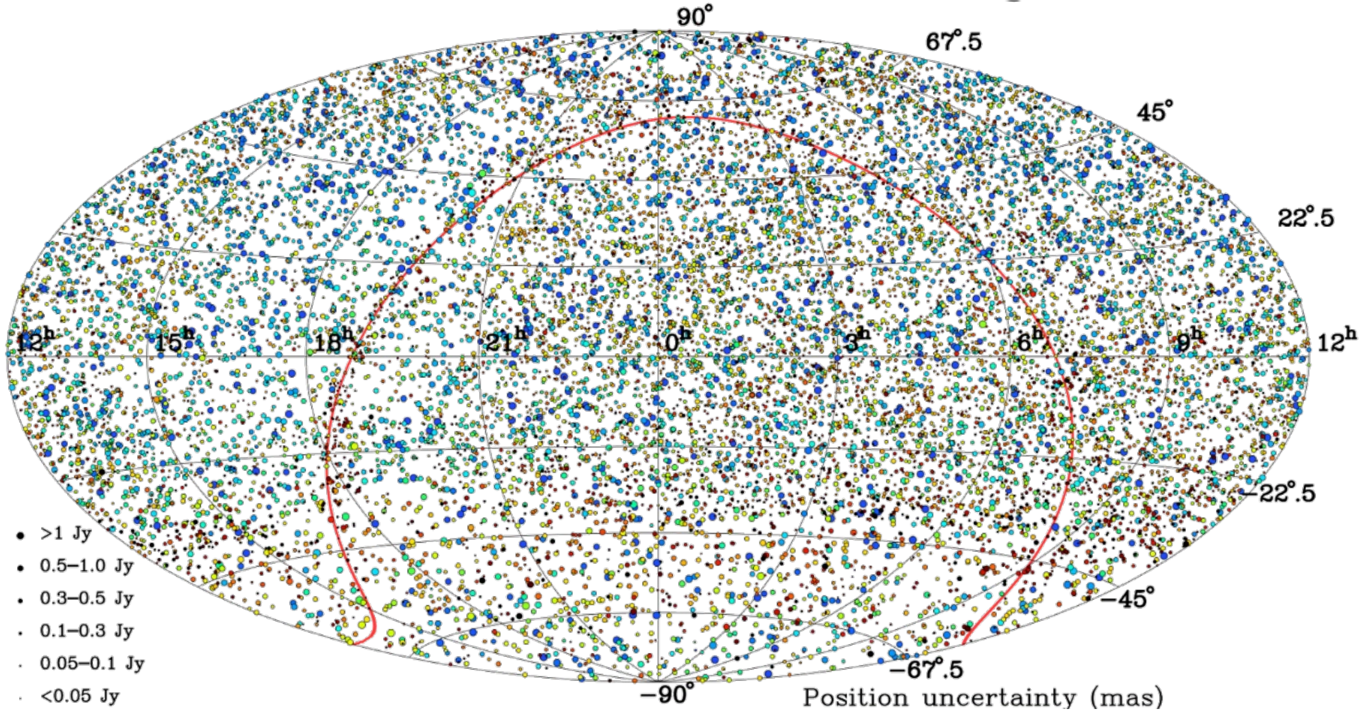
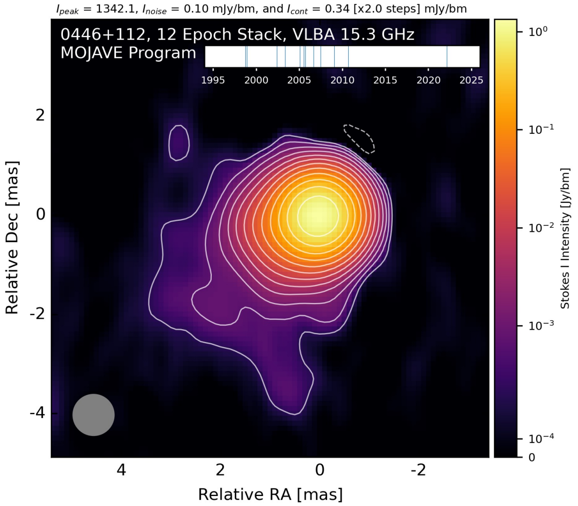
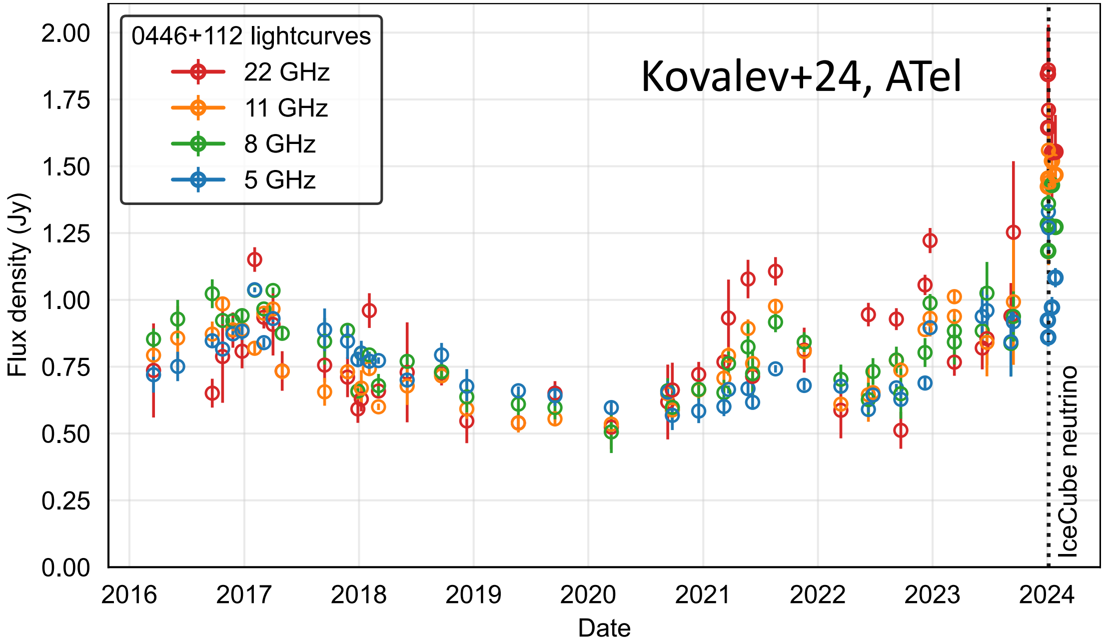


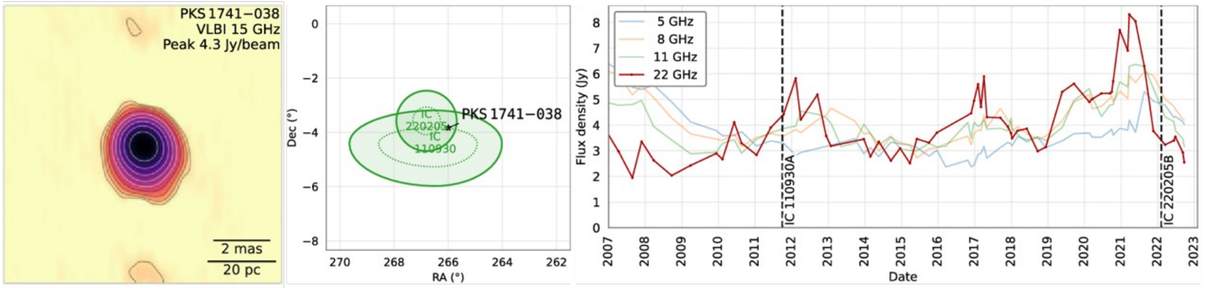
Image by NASA

More examples: RATAN-600

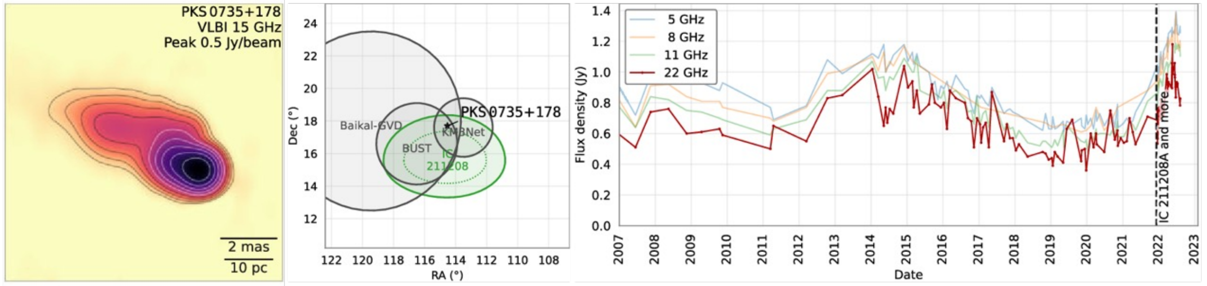
Plavin+23



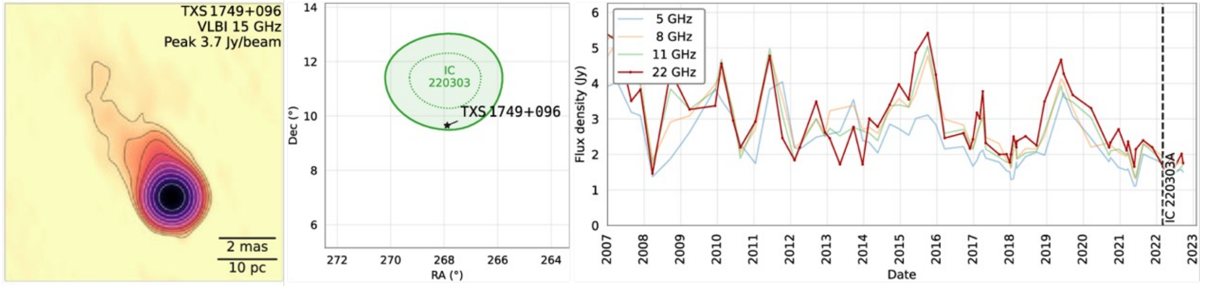




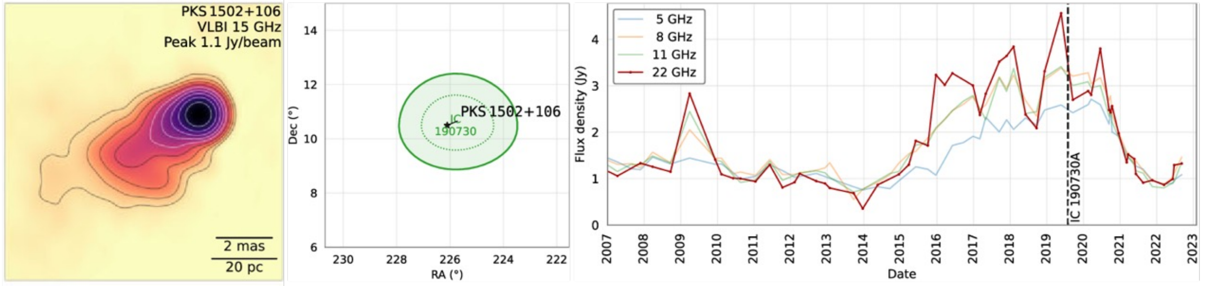
(a) PKS 1741−038: a likely source of the doublet among high-energy neutrino events selected in Section 2.1. This source is one of the brightest blazars in the sky with 4 Jy average VLBI flux density at 8 GHz. The light curves indicate that both the 2011 and the 2022 events were detected close to major radio flares.



(b) PKS 0735+178: a bright blazar with a major radio flare coinciding with the 2021 IceCube neutrino. The neutrinos detected in December 2021 by Baikal-GVD, KM3NeT and Baksan (BUST) observatories are also shown in the plot with their 50% containment regions.



(c) TXS 1749+096: the brightest among the blazars newly matched with the 2020-2022 IceCube events. Its 2.7 Jy average VLBI flux and strong variability indicate high Doppler boosting, discussed in Section 4.3.



(d) PKS 1502+106: selected for the highest temporal correlation between the neutrino detections and the radio flares in P20. Later monitoring