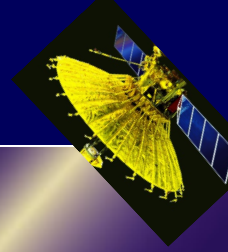
Radio-neutrino studies of blazars: inspiring progress and exciting opportunities

Yuri Kovalev
Max Planck Institute for Radio Astronomy, Bonn

Objectives



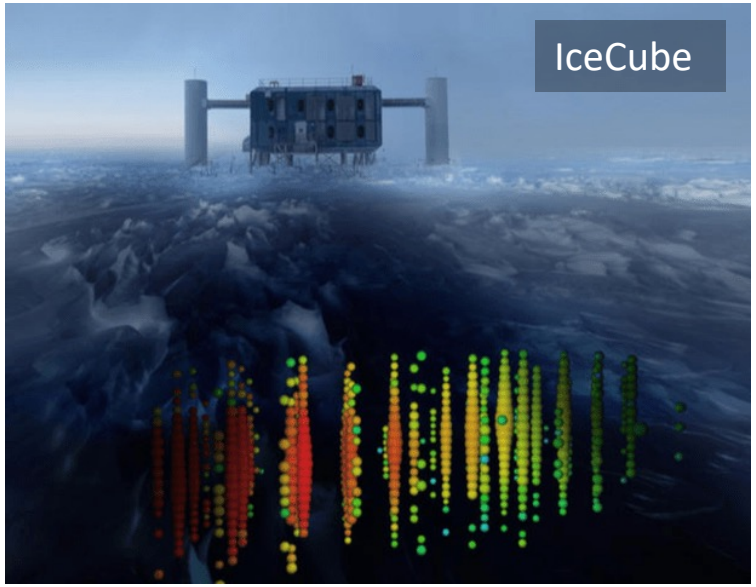
Extreme cosmic supercolliders

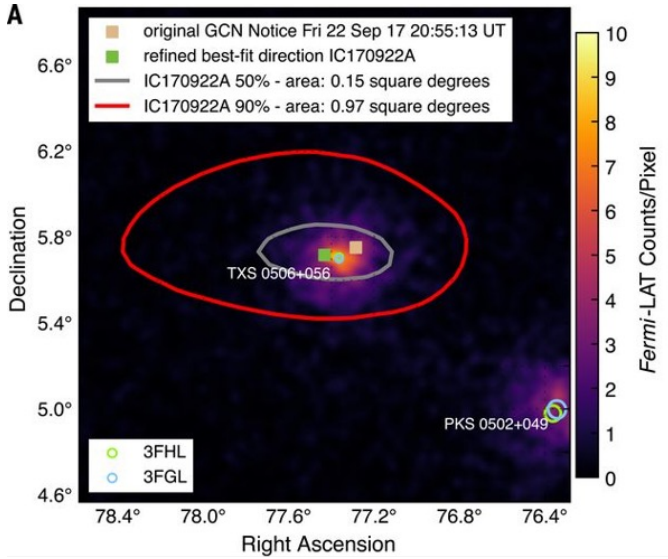
Active Galactic Nuclei:

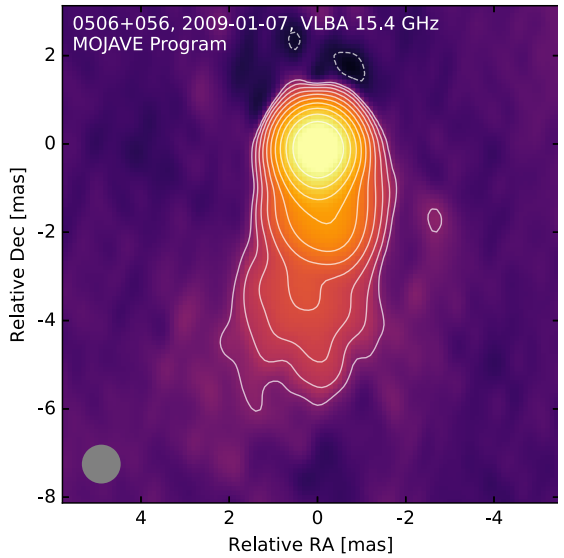
1. Acceleration of particles: especially, massive protons
   (recent observations indicate a presence of efficient acceleration - RadioAstron)

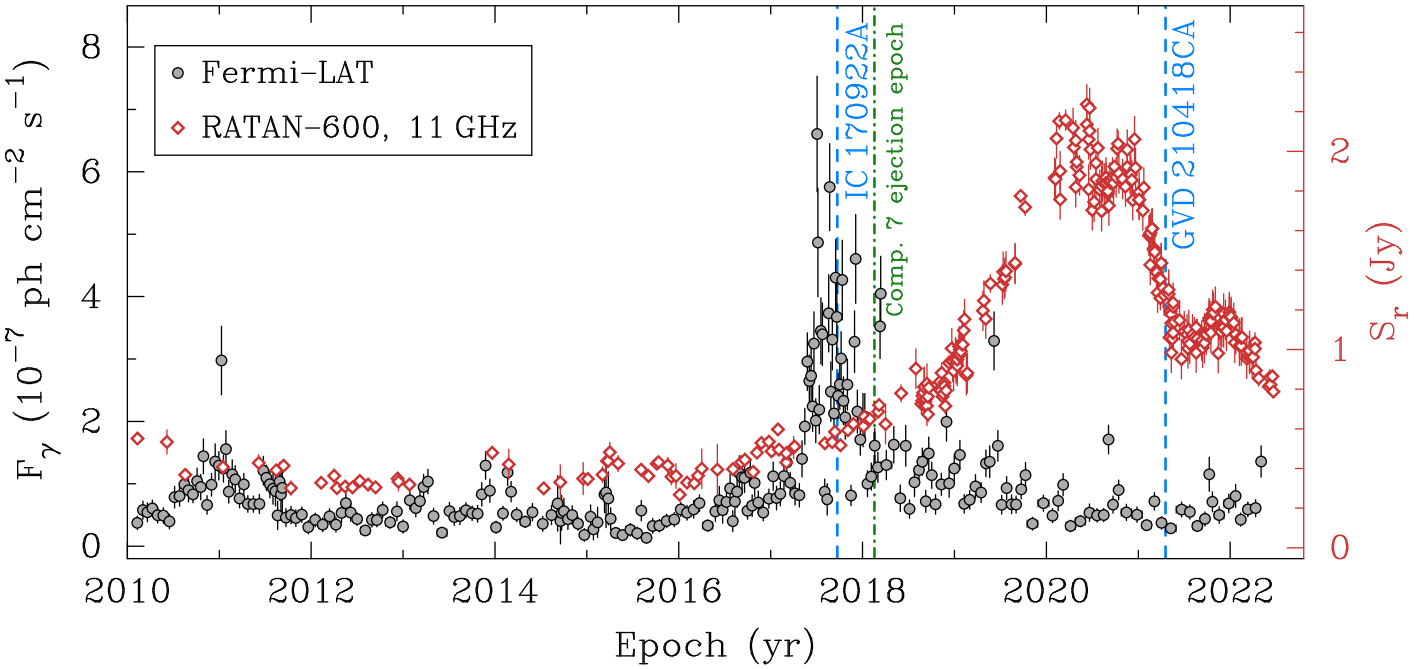
2. High-energy neutrino production

Blazars and high energy neutrinos: 0506+056









Allakhverdyan+23

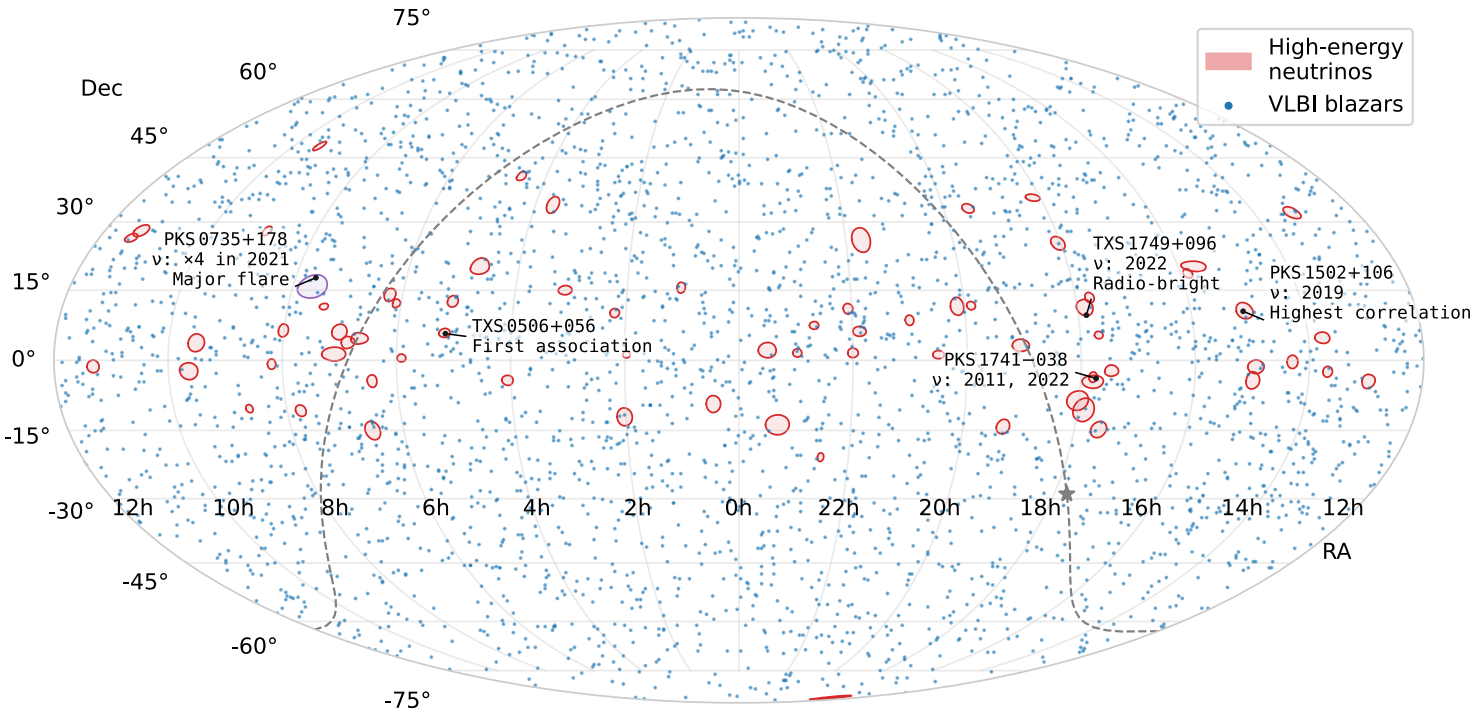
Blazars and high energy neutrinos: sample studies

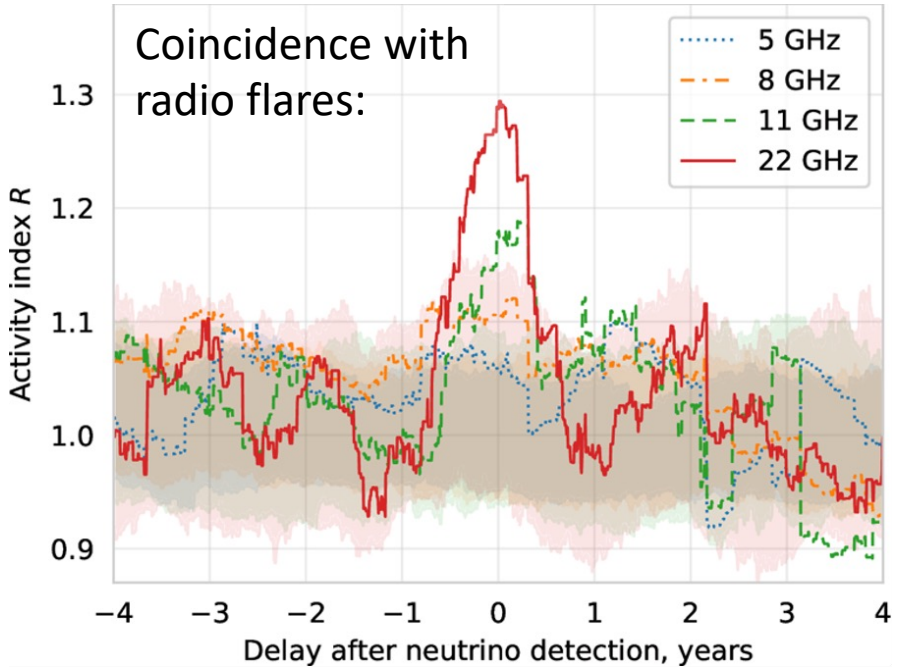
Hypothesis: VLBI-bright AGN prefer high energy neutrino arrival directions

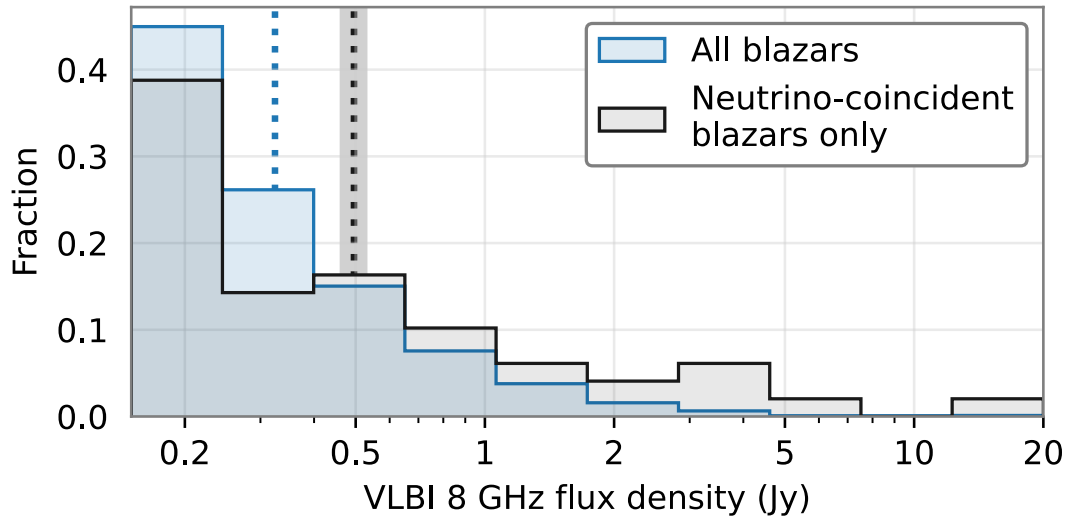
VLBI: 3412 bright blazars (dots) with S > 150 mJy

Neutrino (IceCube): 71 events (2009-2022), energy ≥ 200 TeV, pos. error<10 deg^2.

AGN-neutrino connection significance: 3×10^{-4}, 3.6σ.

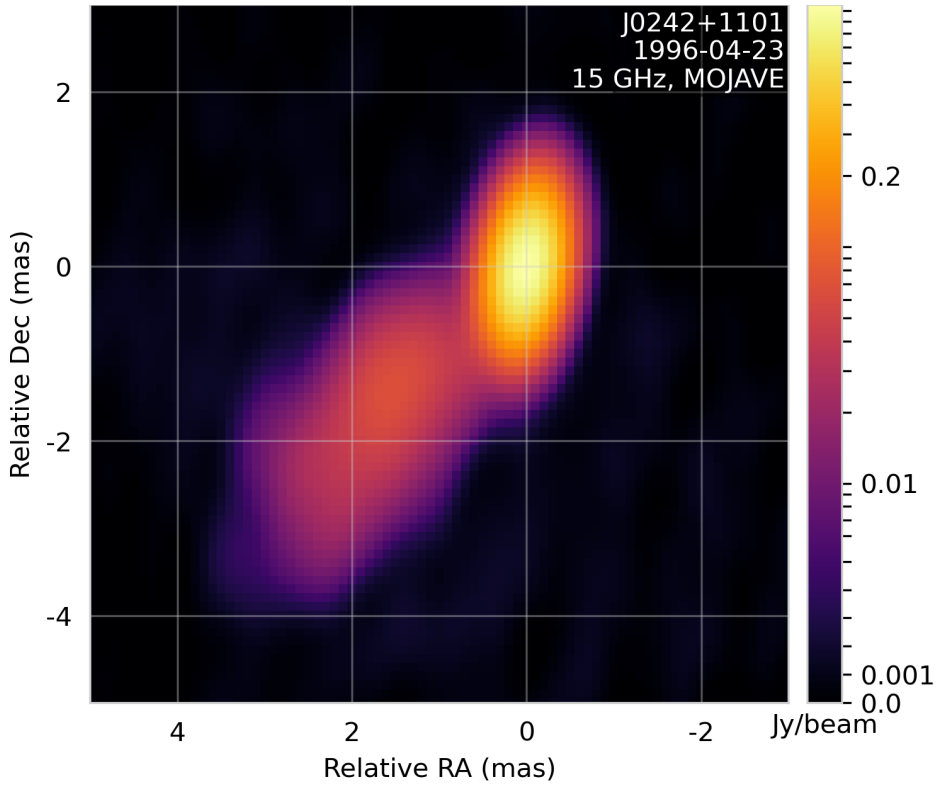




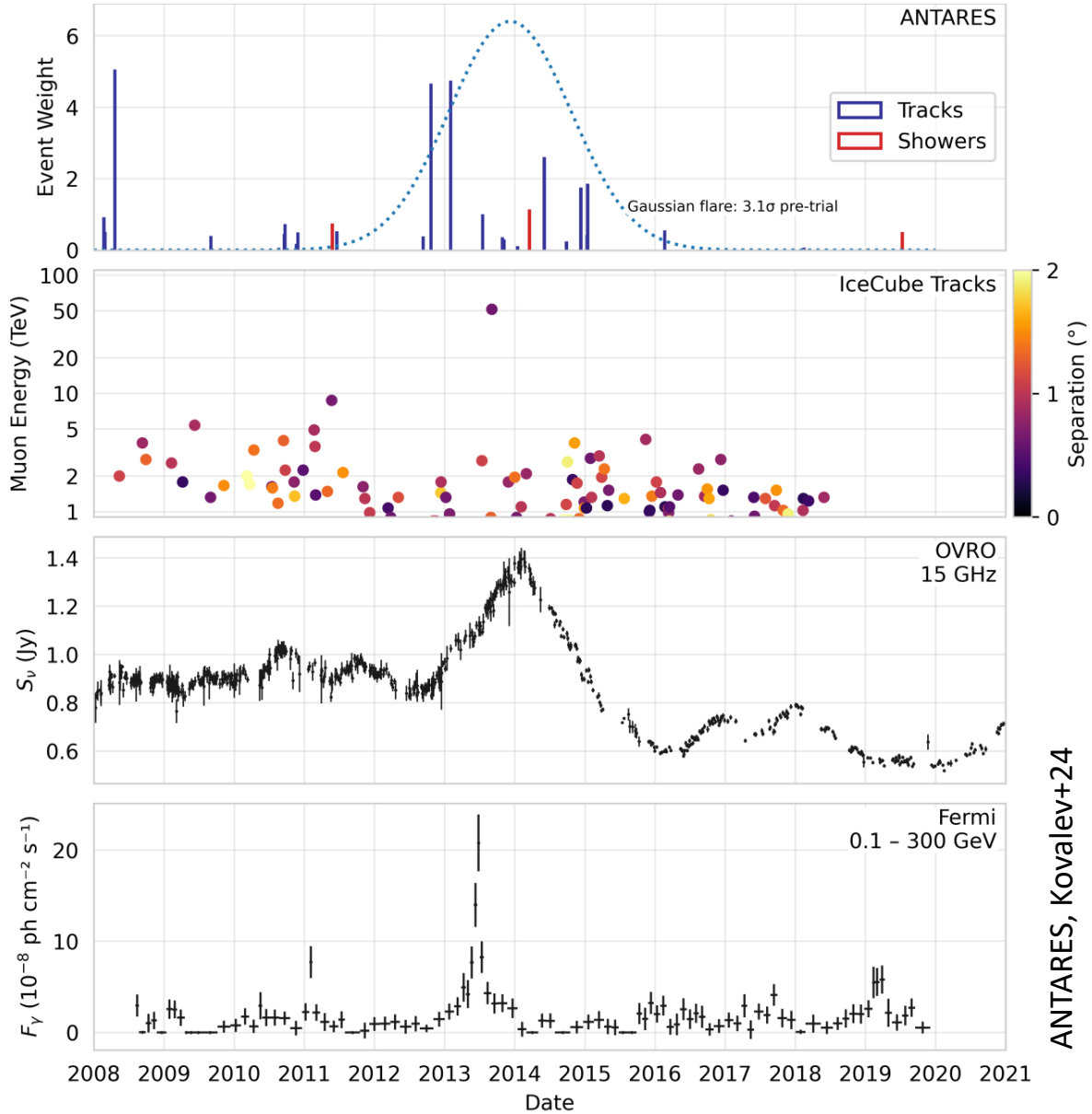


Plavin,Kovalev+20,23; see also Hovatta+21, Ros+20, Zhou+21, Britzen+21, Kun+22, Buson+22,23, Abbasi+23

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

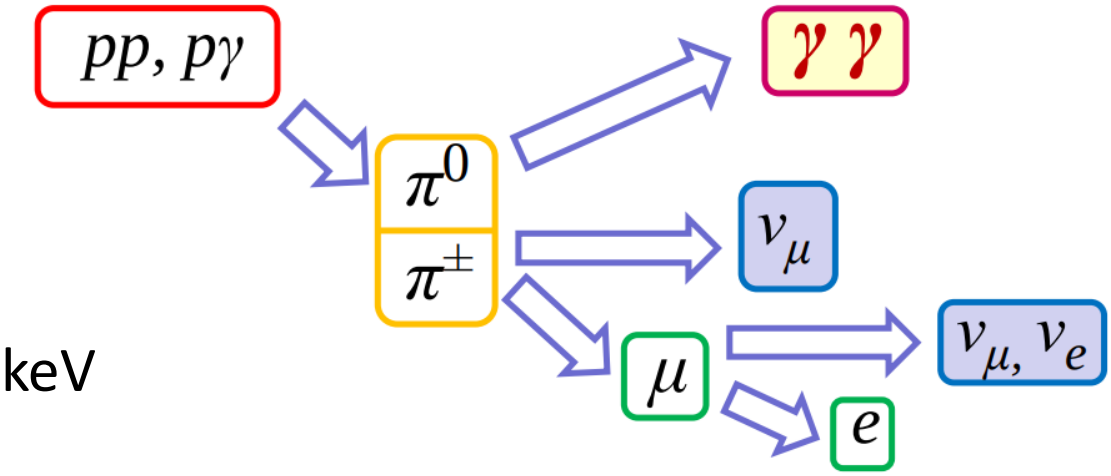


PKS 0239+108 multi-messenger light curve:



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

What is going on?

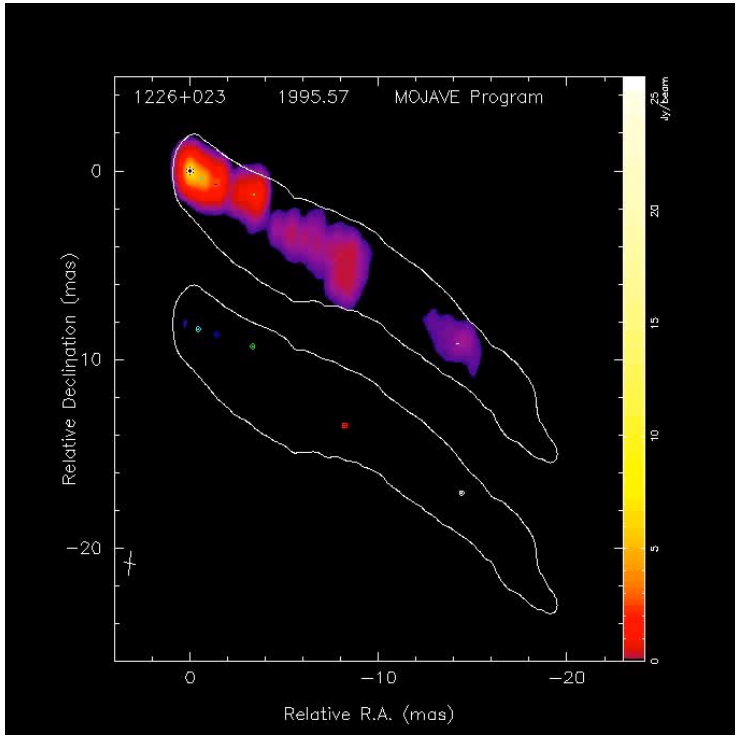


- Bright AGN: p + ɣ process is currently preferred
  (Stecker+91, Neronov+02, Kalashev+15, Cerruti 19, Bottcher+19)
- Target photons: from corona or jet base, E ~ 0.1-200 keV
- Need high energy protons, E ~ 10^{16} eV

- 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 mod

Prospects: Studying blazar-neutrino



Address the following questions related to neutrino production, most probably in the vicinity of the central SMBH:

- Understanding extreme energy release in AGN
- Origin of relativistic protons and high energy neutrino

Observationally: what happens at (sub)parsec scales? Flares, newborn jet features, changes in magnetic field, particle density: where is the action? Around accretion disk, jet base, further downstream the jet in shocks?

Ongoing radio programs led by Kovalev (MPIfR) and Kadler (Wurzburg), comlimentary to neutrino observations:

- VLBA and EVN neutrino alert programs.
- Southern hemispere and Northen hemisphere LBA (TANAMI) and VLBA (MOJAVE, BEAM-ME): monitoring at 8, 15, 43 GHz of large AGN samples
- Single dish cm and mm: Effelsberg (TELAMON), OVRO, RATAN-600, etc.

Complications:

- Require huge observing efforts to reach high significance
- Most interesting regions are not transparent to radio waves at cm wavelengths. We need mm VLBI with FPT.

Summary

- 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, KM3NeT, and Baikal-GVD. All the exciting questions are still open.

- Critical complimetary radio observing programs are being actively pursued and developed at cm and mm wavelengths including ngEHT and ngVLA science cases.

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.

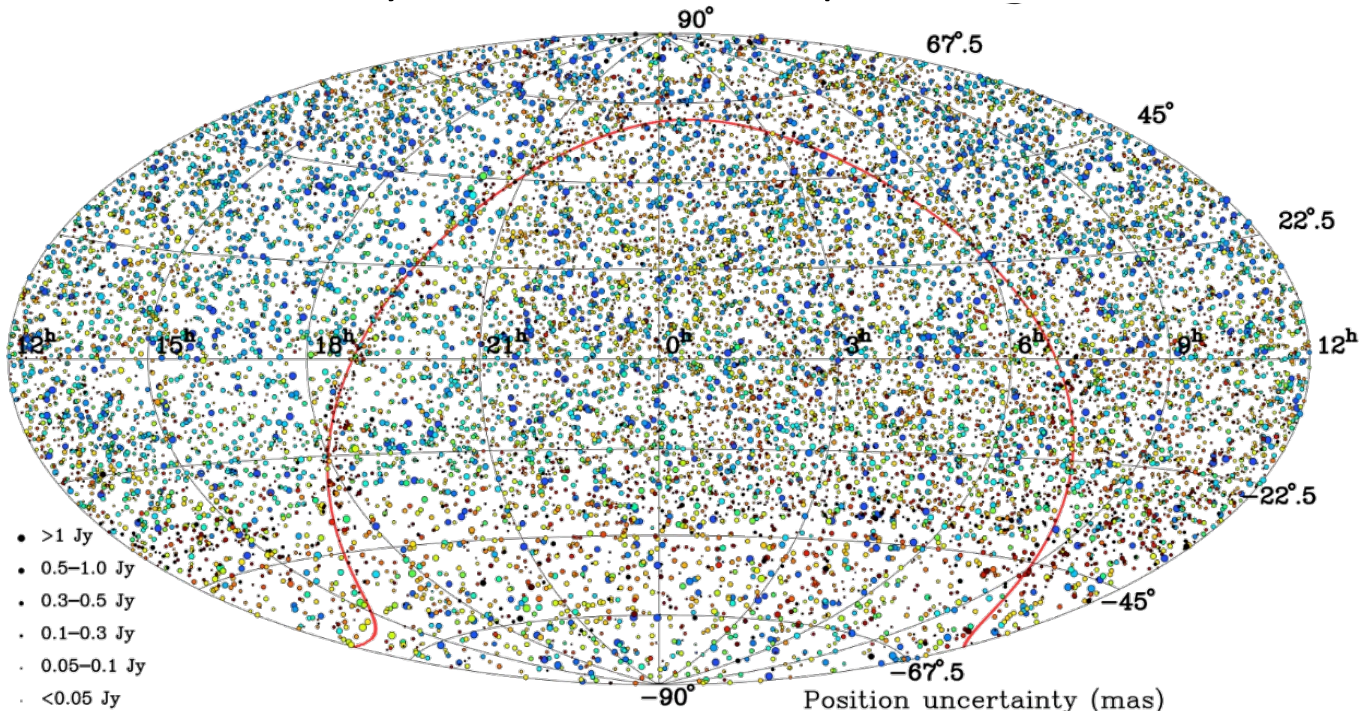
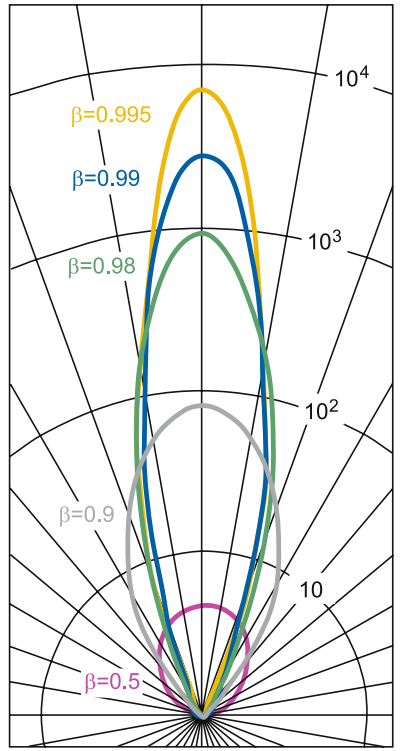
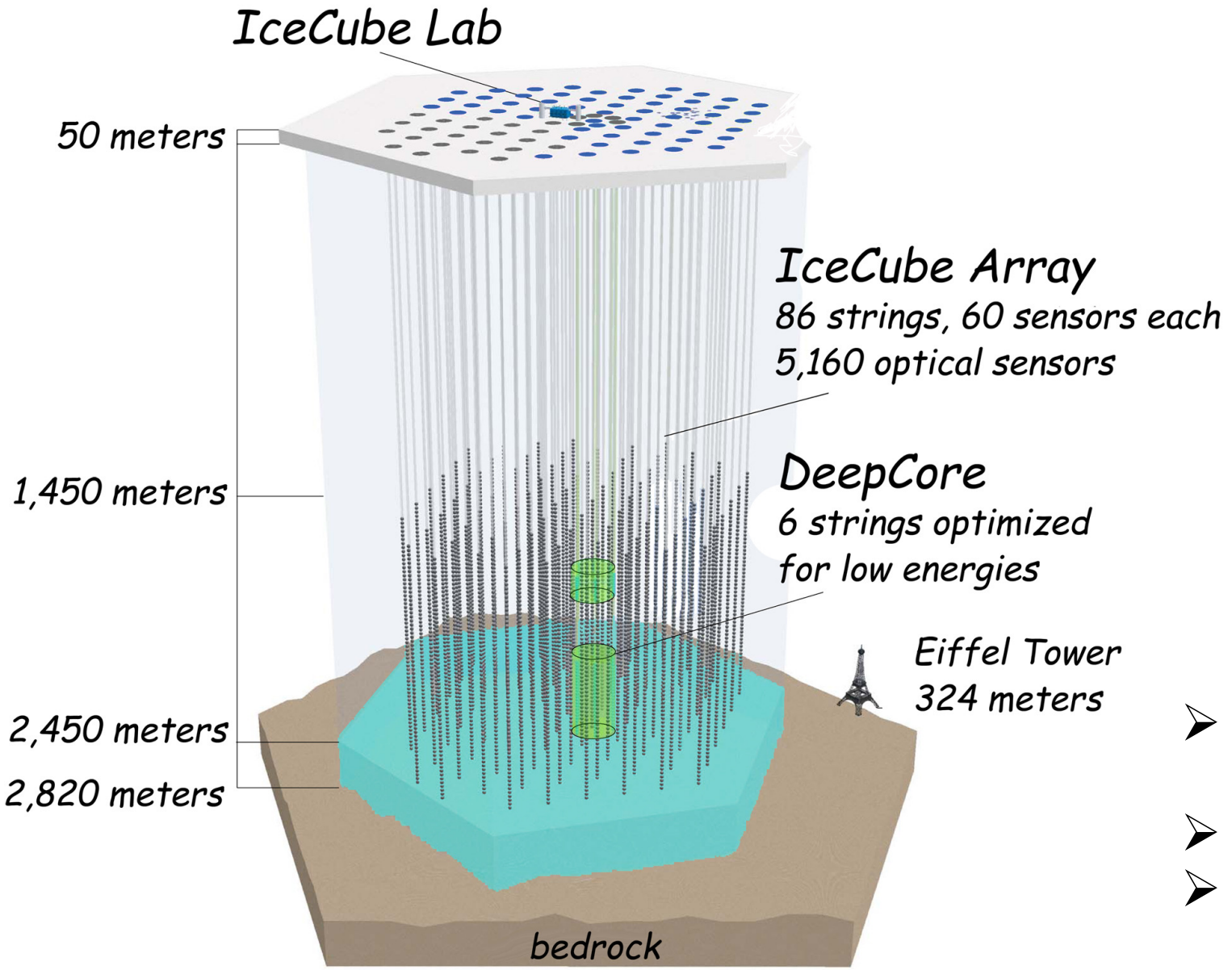


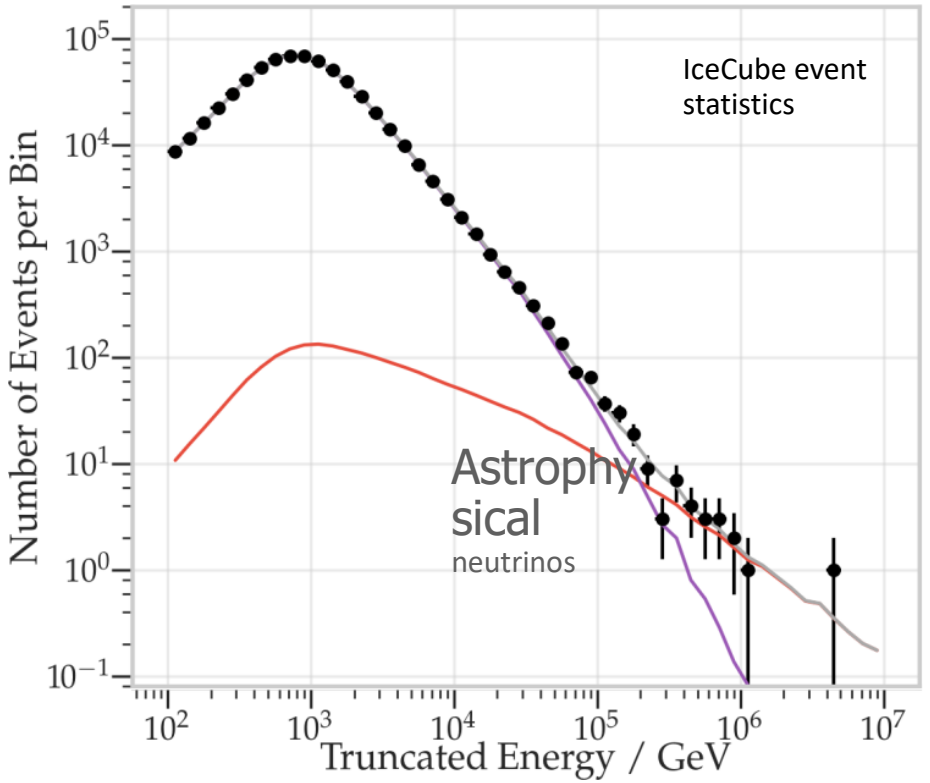
Fig. 2 Luminosity Doppler boosting factor for the case where $n = 3$ shown in polar coordinates. The radial lines indicate angles at intervals of 10 degrees and the circles the luminosity boosting factor. *Red*: $\beta = 0.5$, $\gamma = 1.15$; *grey*: $\beta = 0.9$, $\gamma = 2.3$; *green*: $\beta =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



Kellermann et al. (2007)

Cosmic neutrino: IceCube, ANTARES, KM3NeT, 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.

Complementary Radio-MM Approaches in Würzburg (M. Kadler et al.)

DFG Deutsche Forschungsgemeinschaft

TANAMI

TELAMON

- **TELAMON: High-frequency Monitoring with the Effelsberg 100m telescope**
  - Designed to study neutrino-candidate and TeV-emitting AGN
  - Dynamic spectra and polarization between 5 and 45GHz
- **TANAMI: S- and X-Band VLBI Monitoring**
  - Southern Hemisphere: LBA, SKA-MPI, MeerKAT
- **Targeted Coordinated Radio and MWL Campaigns**
  - E.g., TXS0506+056, PKS0735+17, PKS0446+11, PKS0215+015,…
- **DFG Research Unit FOR5195: „Relativistic Jets in Active Galaxies“**
  - Würzburg, Bamberg, Bonn, Hamburg, Heidelberg, Potsdam
  - Joint Splinter with SFB1491 at AG2024 Meeting