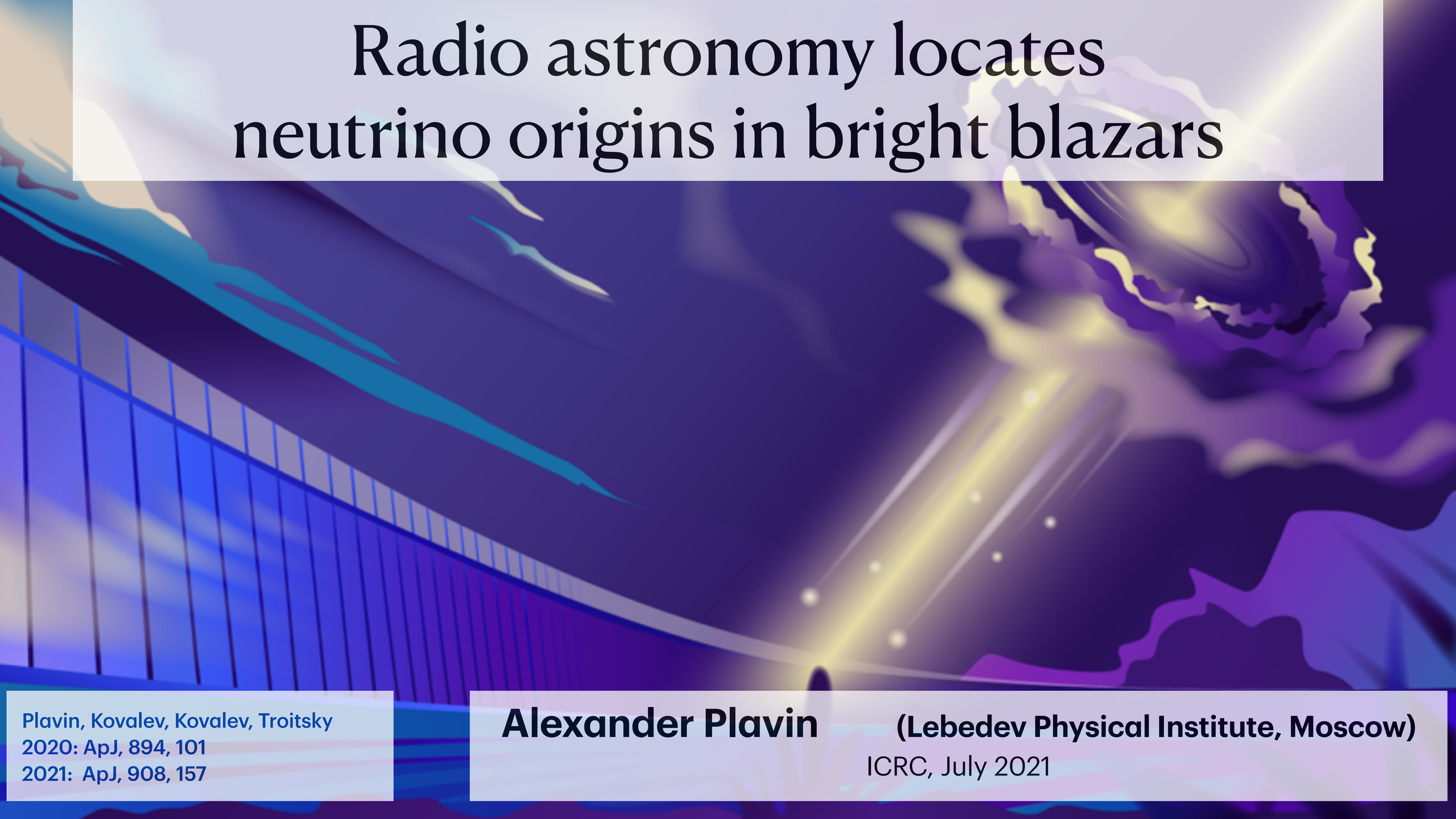
# Radio astronomy locates neutrino origins in bright blazars



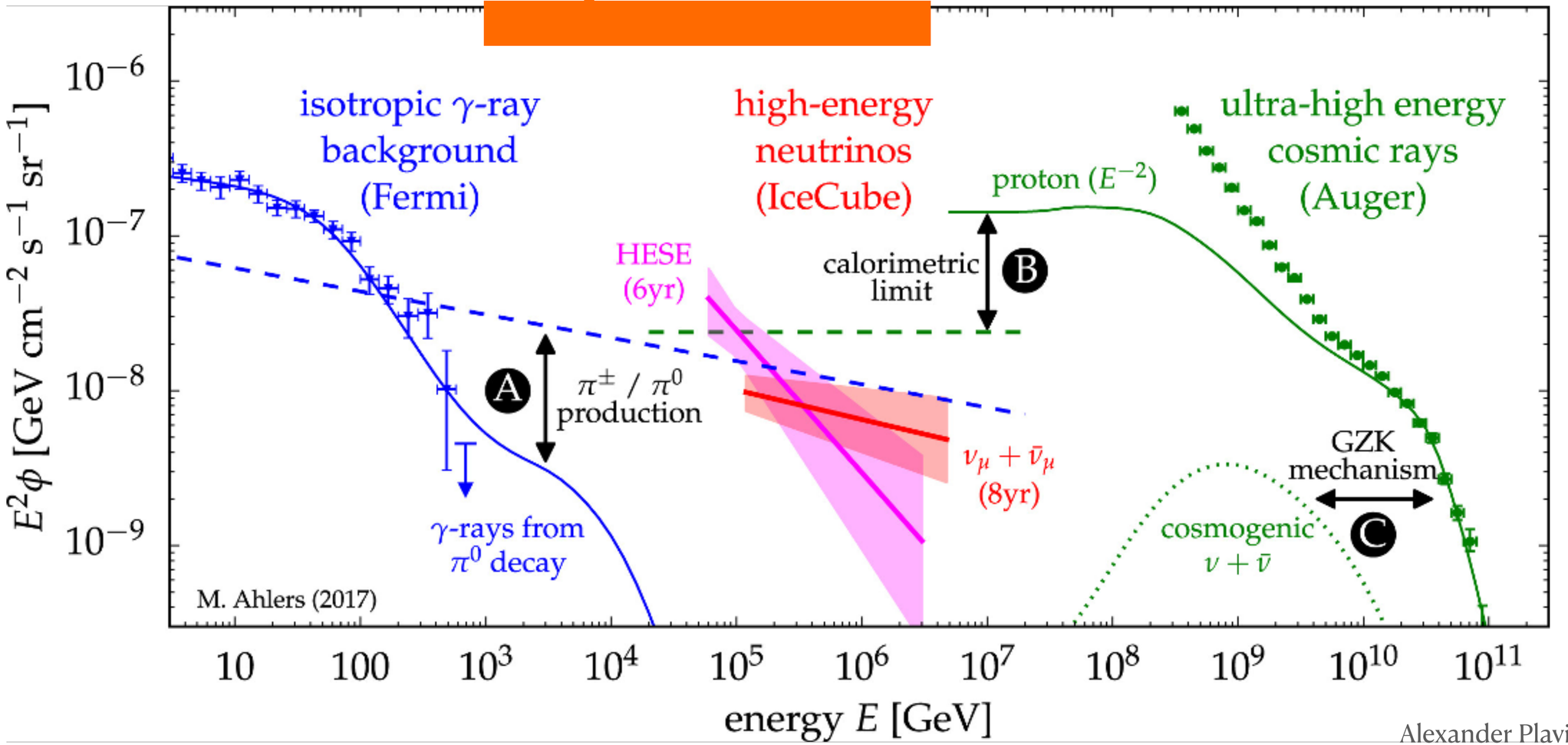
Plavin, Kovalev, Kovalev, Troitsky
2020: ApJ, 894, 101
2021: ApJ, 908, 157

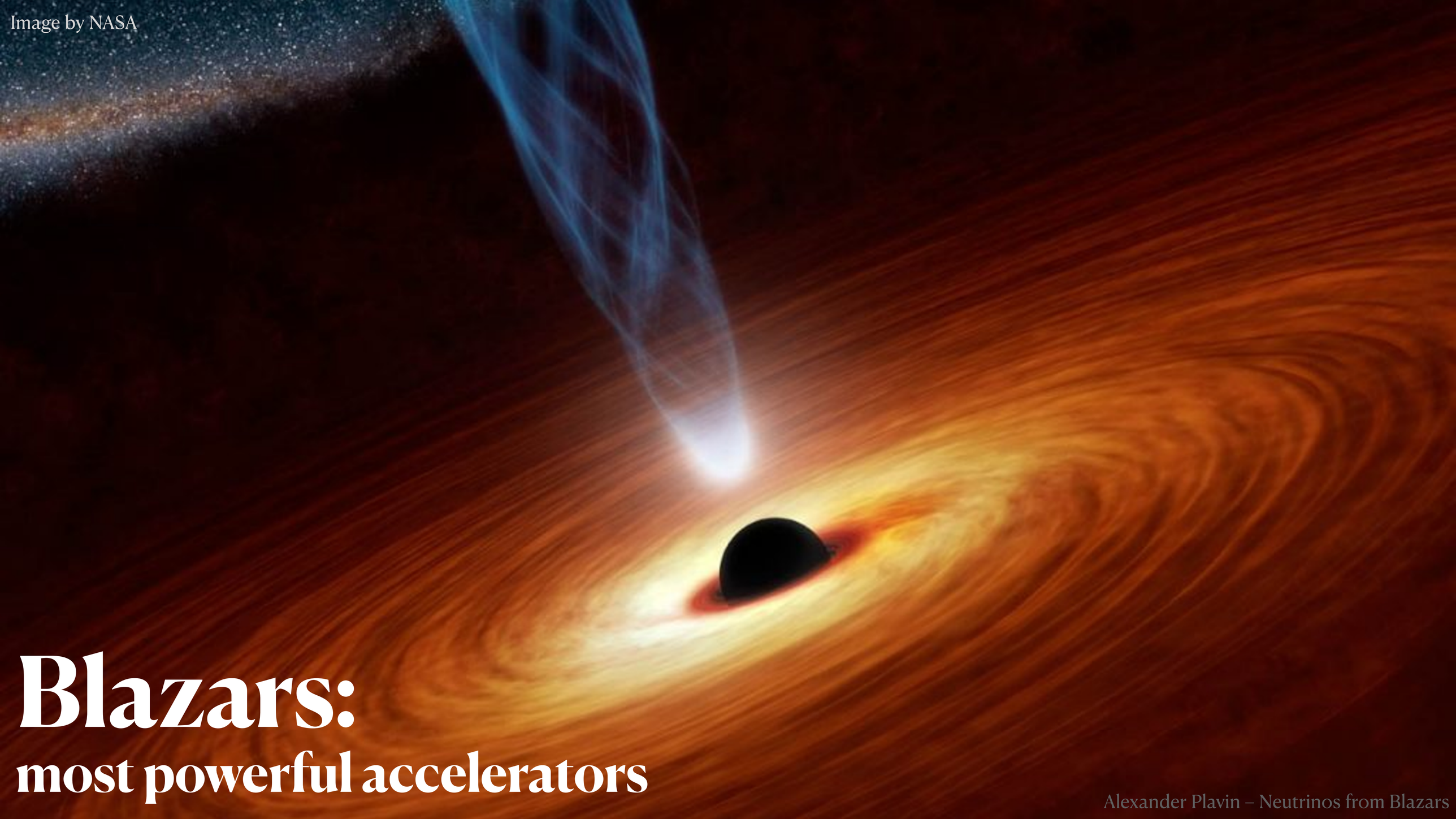
**Alexander Plavin** **(Lebedev Physical Institute, Moscow)**

ICRC, July 2021

# Astrophysical neutrinos: where they come from?

Relevant energies: TeV to PeV





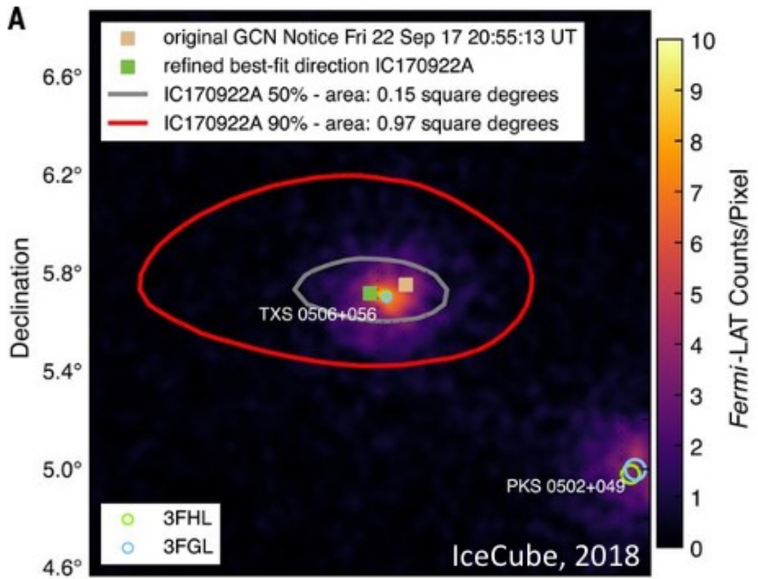

# Blazars:
## most powerful accelerators

# 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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Accepted 2018 April 3. Received 2018 March 26; in original form 2018 January 31

**A multiwavelength view of BL Lac neutrino candidates**

**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 stati
a sample of 23 264 AGN at z
sources. We find no significan
events, although we get the st
relatively high velocities and
AGN outflows are neutrino en
be tested with better statistics
explaining the IceCube data a

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

C. Righi,[1,2,3★] F. Tavecchio[2] and L. Pacciani[4]

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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

**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
at or above a reconstructed energy of 100 TeV, but belo
are positionally consistent with the neutrino events abo
larger sample allows us to better constrain the scaling fa
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

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

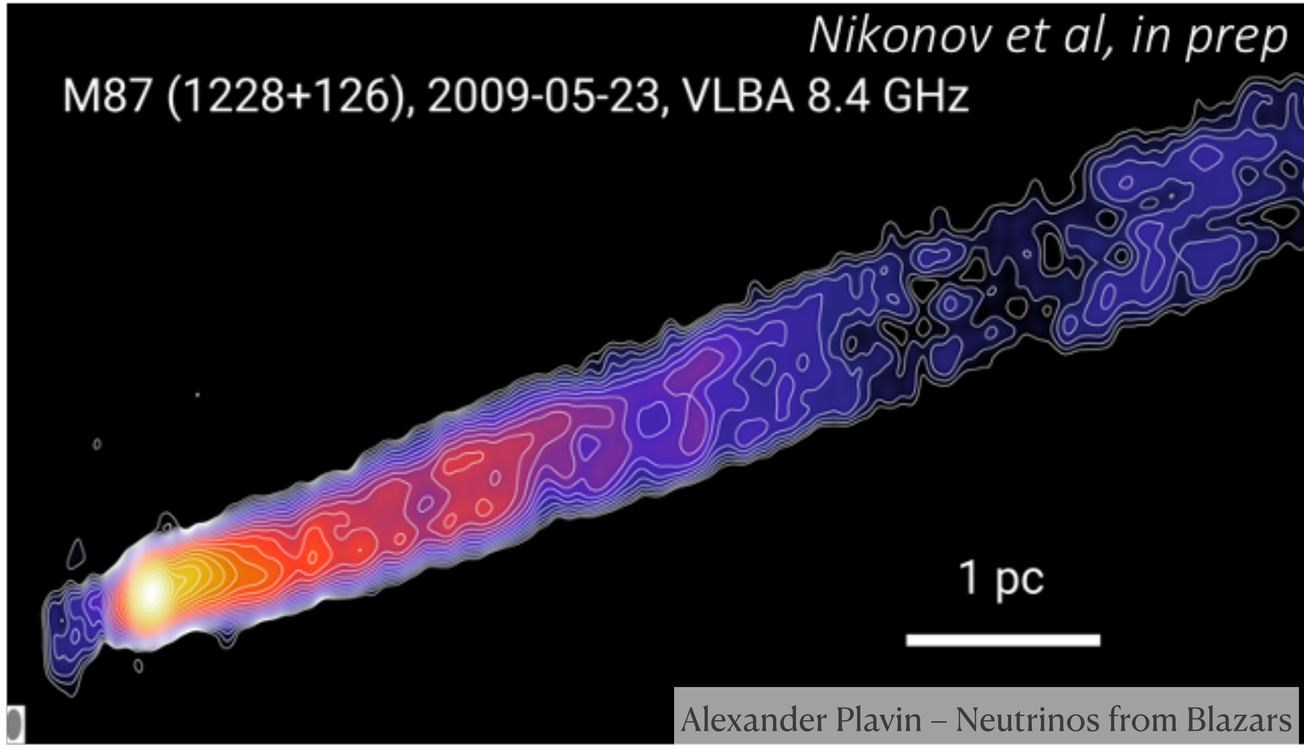
**Searches for steady neutrino emission from 3FHL blazars using eight years of IceCube data from the Northern hemisphere**

**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

# Our approach: use VLBI!

**Select bright blazars**
**Directly resolve central parsecs**

# Neutrino & VLBI

## Datasets

Complete VLBI sample of 3411 blazars

http://astrogeo.org/rfc/: 30 yr of observations, S > 0.15 Jy

Neutrinos: IceCube tracks, public

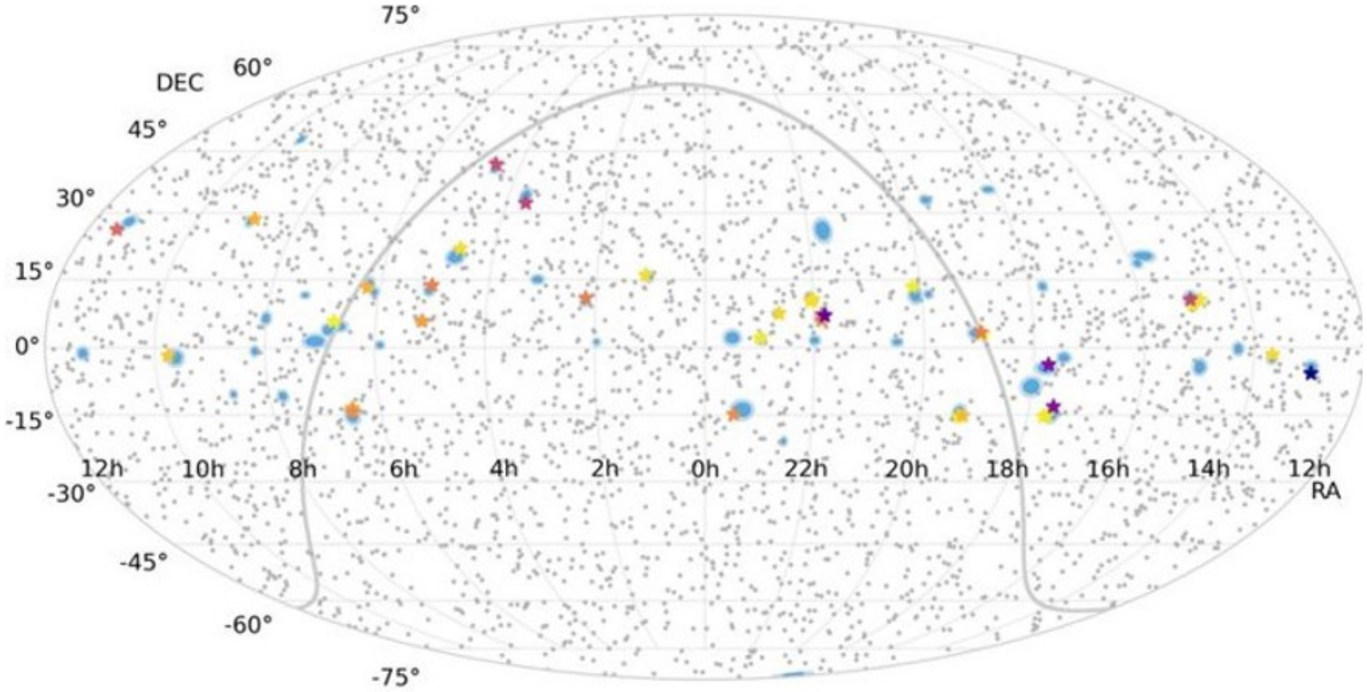
- Above 200 TeV: “alerts”, 57 events

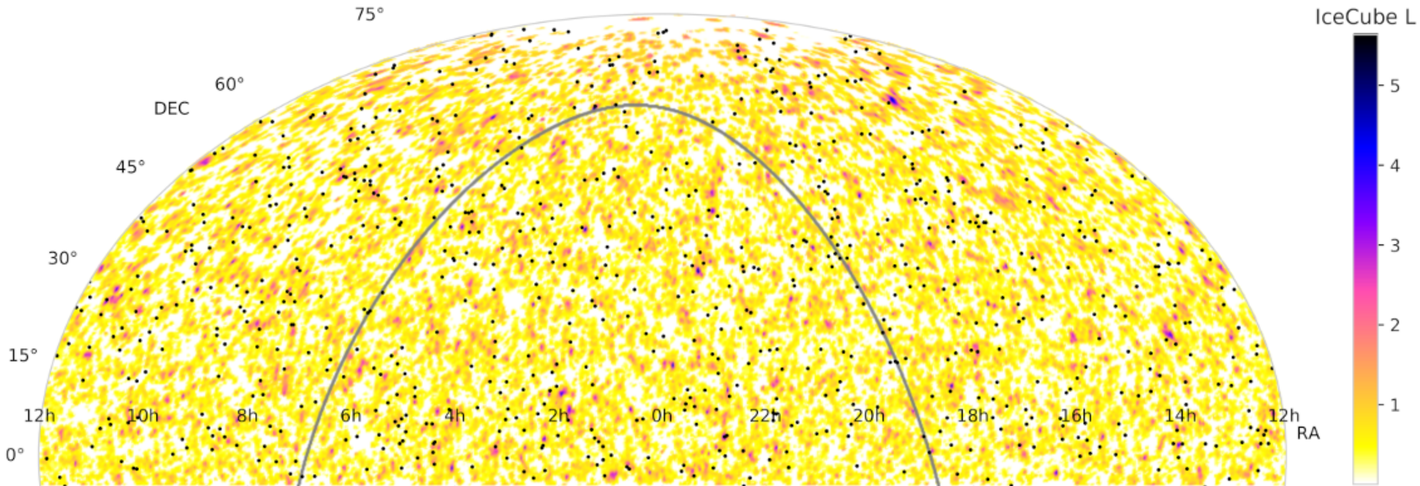
2009-2019, around half are astrophysical

- All energies: likelihood map

Events ~10 TeV dominate

712830 events in 2008-2015, around 2000 astrophysical



# Neutrino-Blazar Connection

**Neutrinos tend to arrive from bright blazars?**

Test this hypothesis...

# Neutrino-Blazar Connection

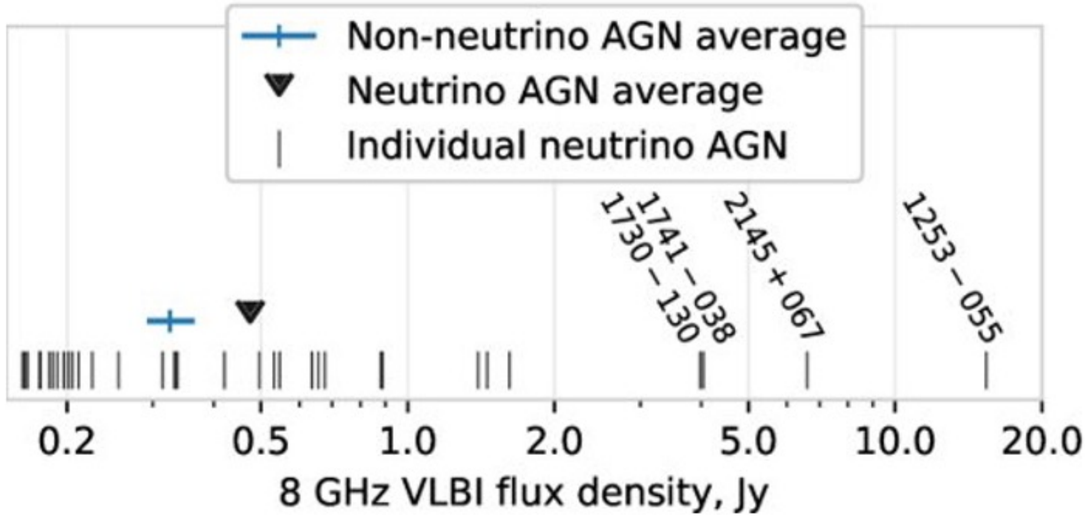
**Neutrinos tend to arrive from bright blazars?**

Test this hypothesis...

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

- Events above 200 TeV: p-value = 0.2%

Blazar close to neutrinos are brighter than average




- Lower energies map: p-value = 0.3%

- Joint: p-value = $4 \cdot 10^{-5}$ or $4.1\sigma$

# Neutrino-Blazar Association

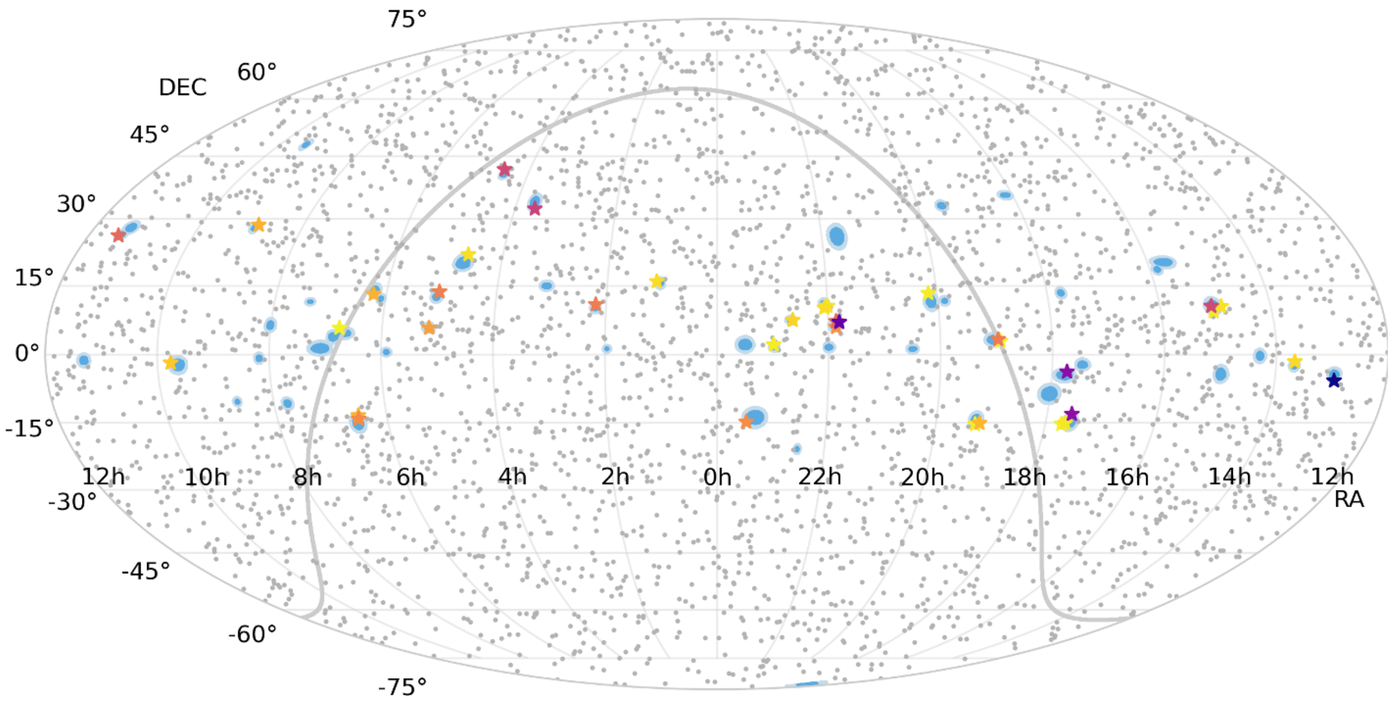
## Accounting for systematics

IceCube events typically include *stochastic* uncertainties only.

We attempt to consider systematic errors as well:
expand provided uncertainty regions.

Expansion magnitude is unknown, so we fit it as part of the analysis.

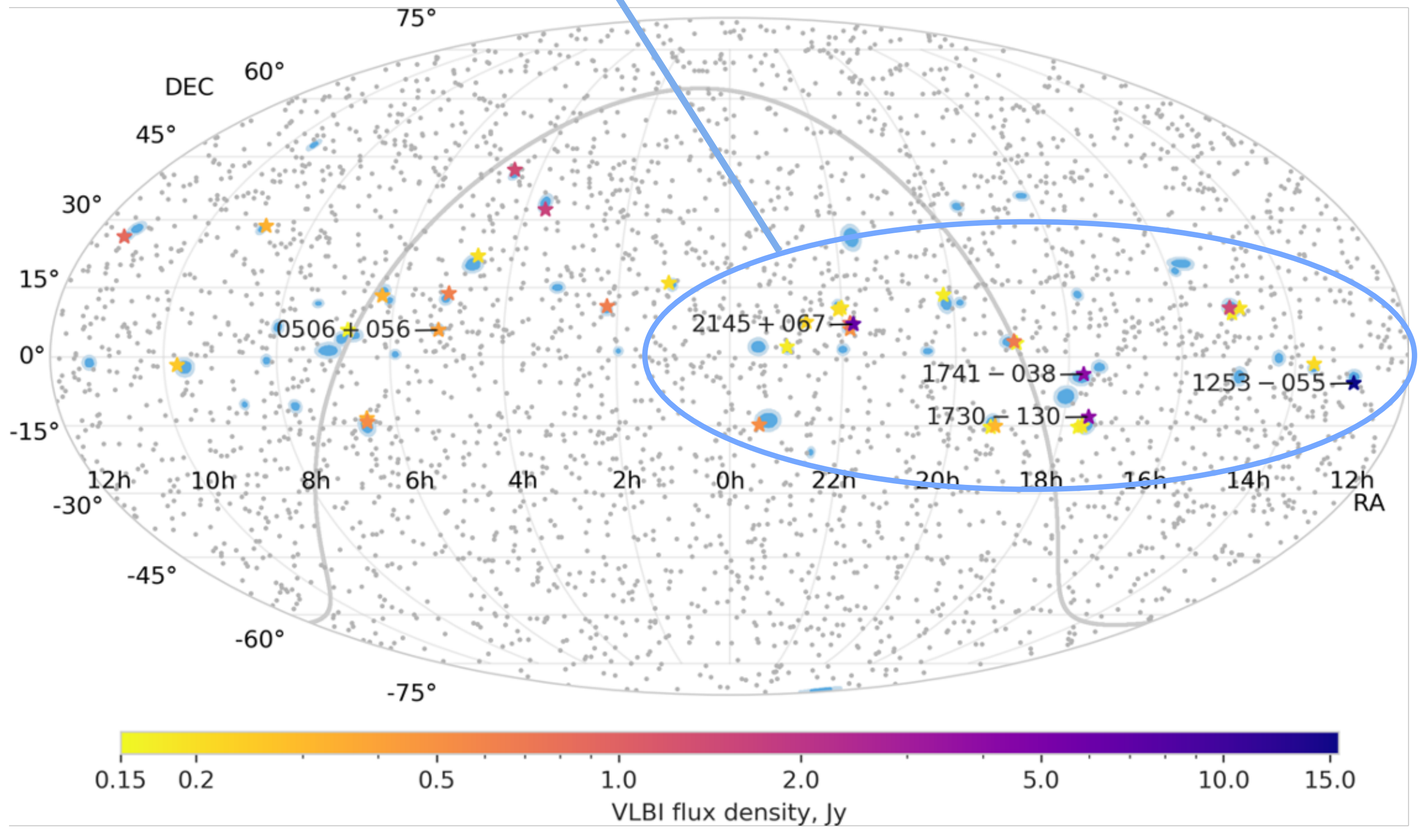
Best value: 0.5 degree.

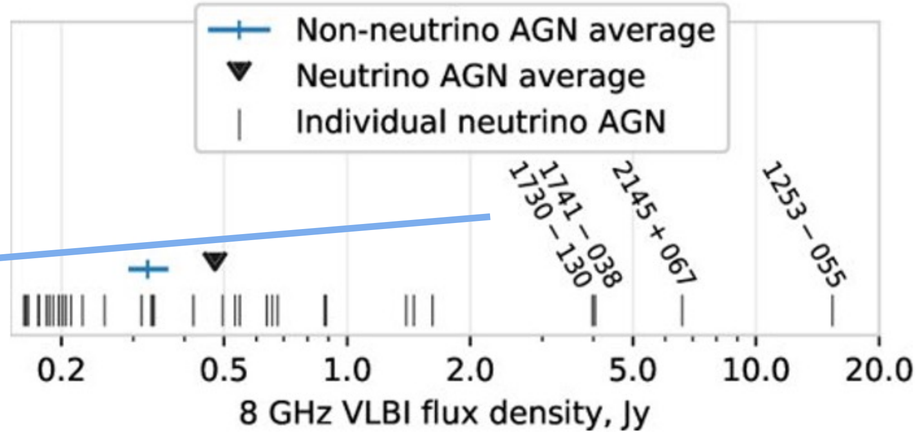


# Neutrino-Blazar Association

## How many blazars emit neutrinos?

Events above 200 TeV:
four brightest blazars drive the correlation



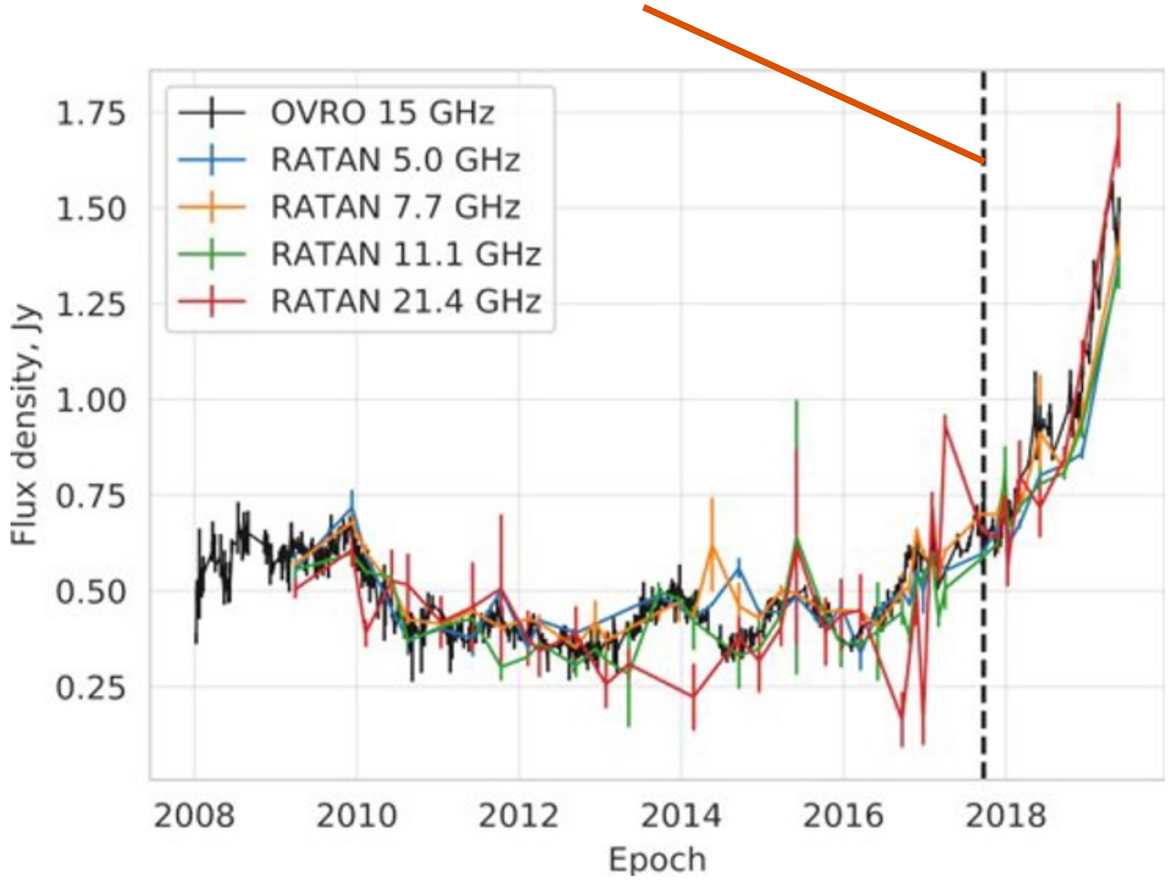




Lower energies:
> 70 blazars associated with neutrinos

(Can be) enough blazars to explain the whole astrophysical neutrino flux.

# When Blazars Produce Neutrinos?

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




Theoretical predictions also exist: e.g. Murase 17

**Are neutrinos always related to jet flares?**

Correlate arrival times with radio flux and find out!

# When Blazars Produce Neutrinos?

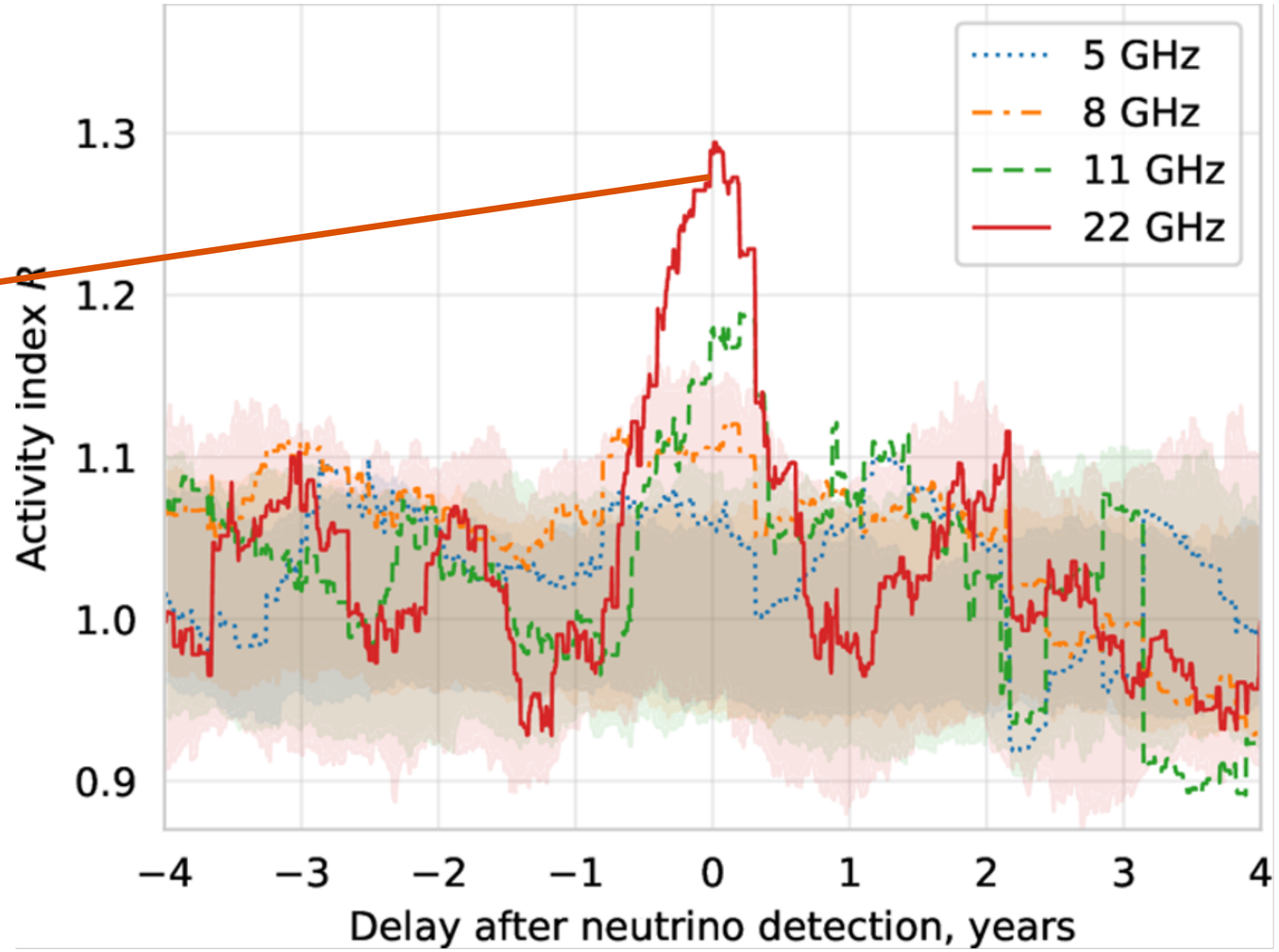
**Predominantly during flares in the jet!**

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

- Independent confirmation: Hovatta+2021 at 15 GHz, OVRO

Average radio flux around neutrino arrivals

*RATAN-600 monitoring*



# Physical Interpretation

*(Stecker+91, Neronov+02, Kalashev+15, Cerruti 19, Bottcher+19)*

- Neutrinos produced in central parsecs of bright blazars, pγ process
- Emitted predominantly along the jet direction *(predicted in Neronov+02)*

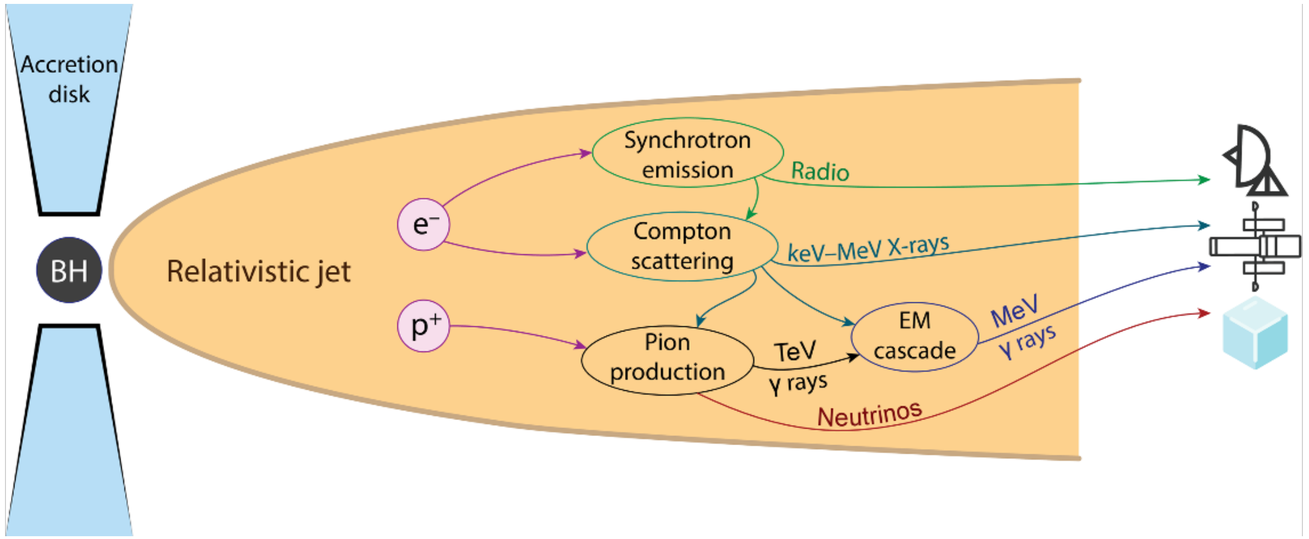
Require photons from 100 eV to 200 keV...

SSC photons in the jet?

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

Acceleration in shocks?

*(Bykov+12, Lemoine+09)*

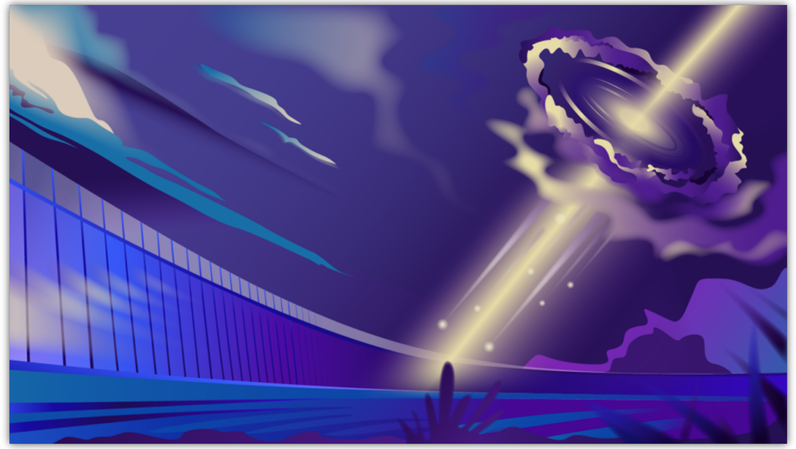



Neutrinos accompanied by γ-rays but no correlation is seen:
photons lose energy to pair production.

# Summary

*Take-home message:*

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



- More than 80 blazars are associated with IceCube neutrinos
- Intriguing results with ANTARES and Baikal *At this conference*
- Jet observations are key to this association
  *especially, VLBI*

- Blazars emit neutrinos along the jet direction
- Require high-energy protons up to $10^{16}$ eV: how to accelerate?
- Photons of 0.1-200 keV: self-Compton jet photons?

- Future/ongoing studies: IceCube, ANTARES, Baikal, VLBI, single-dish, ...

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