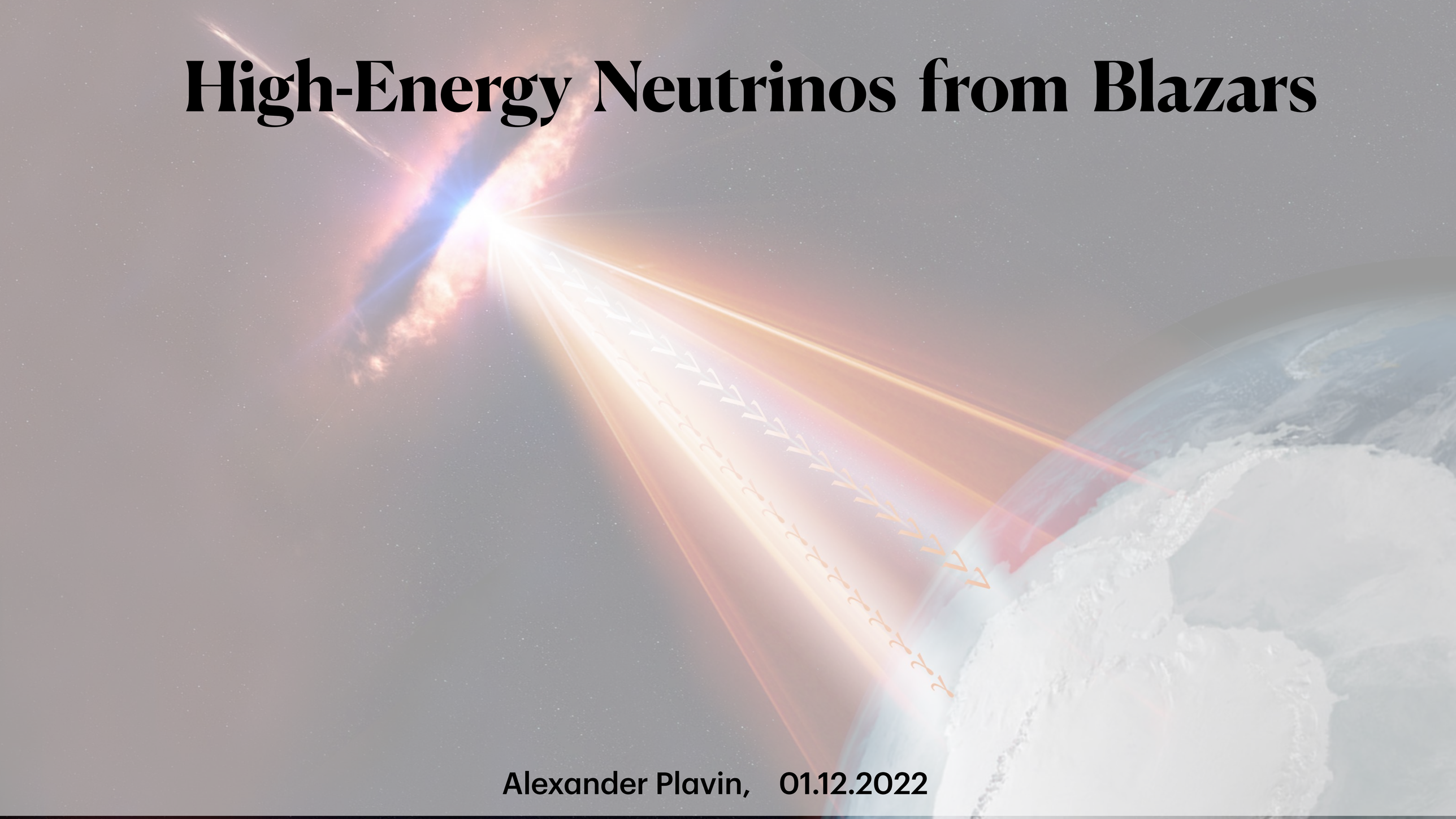
High-Energy Neutrinos from Blazars



Alexander Plavin, 01.12.2022

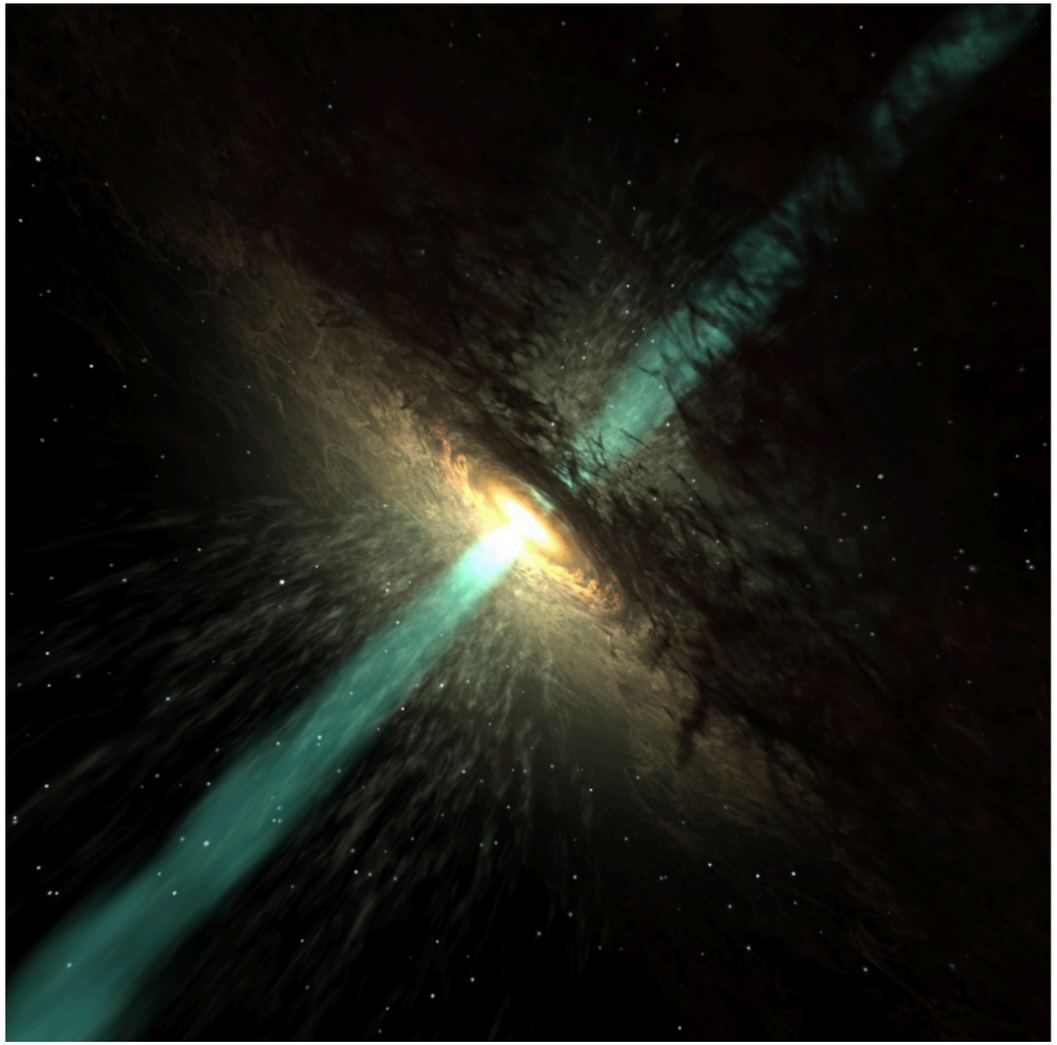
Active galaxies, quasars, blazars...

Observationally

Central "core" brighter than the rest

High luminosity, strong variability

Relativistic jet, dominates when beamed



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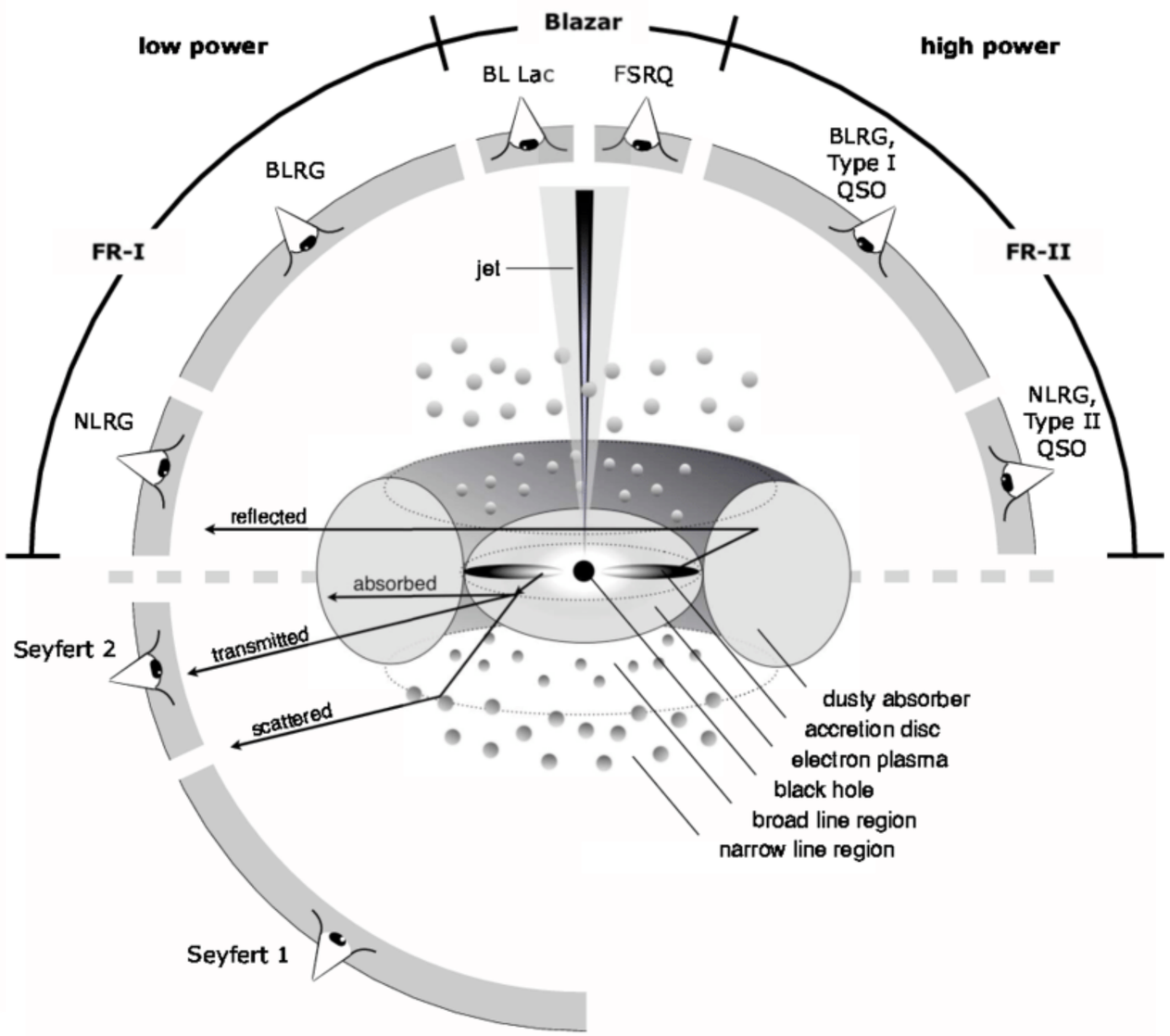
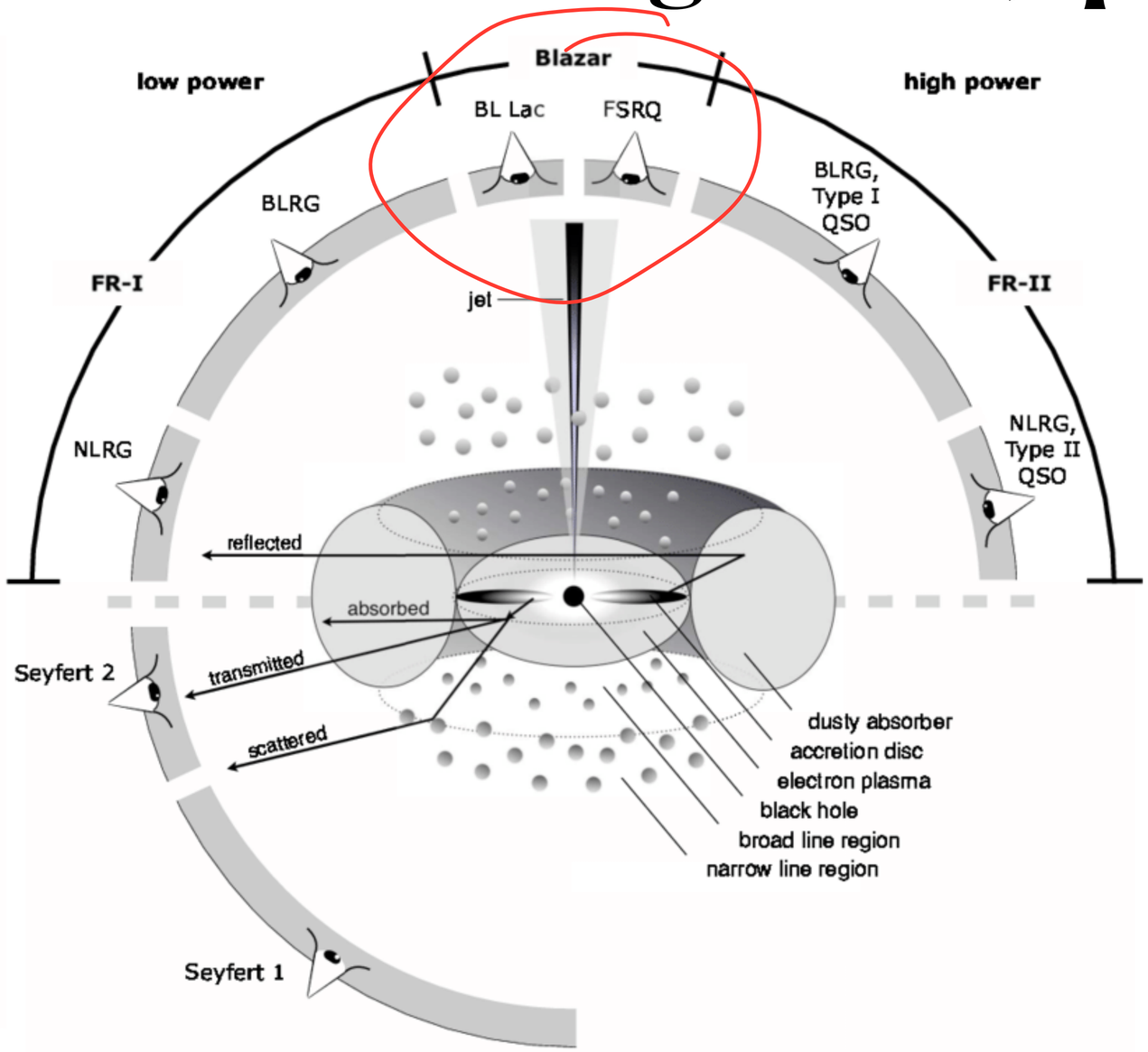


Unification scheme

Same kind of objects

Different observing conditions

Active galaxies, quasars, blazars...



Blazars: jets towards us

Strong beaming

Flat radio spectrum, radio-loud: synchrotron emission

Often gamma-ray loud

Accelerate electrons – for sure

Heavier particles?..

TeV-PeV neutrinos from active galaxies?

Expectations

Expected for a long time: Berezinsky 77, Eichler 79

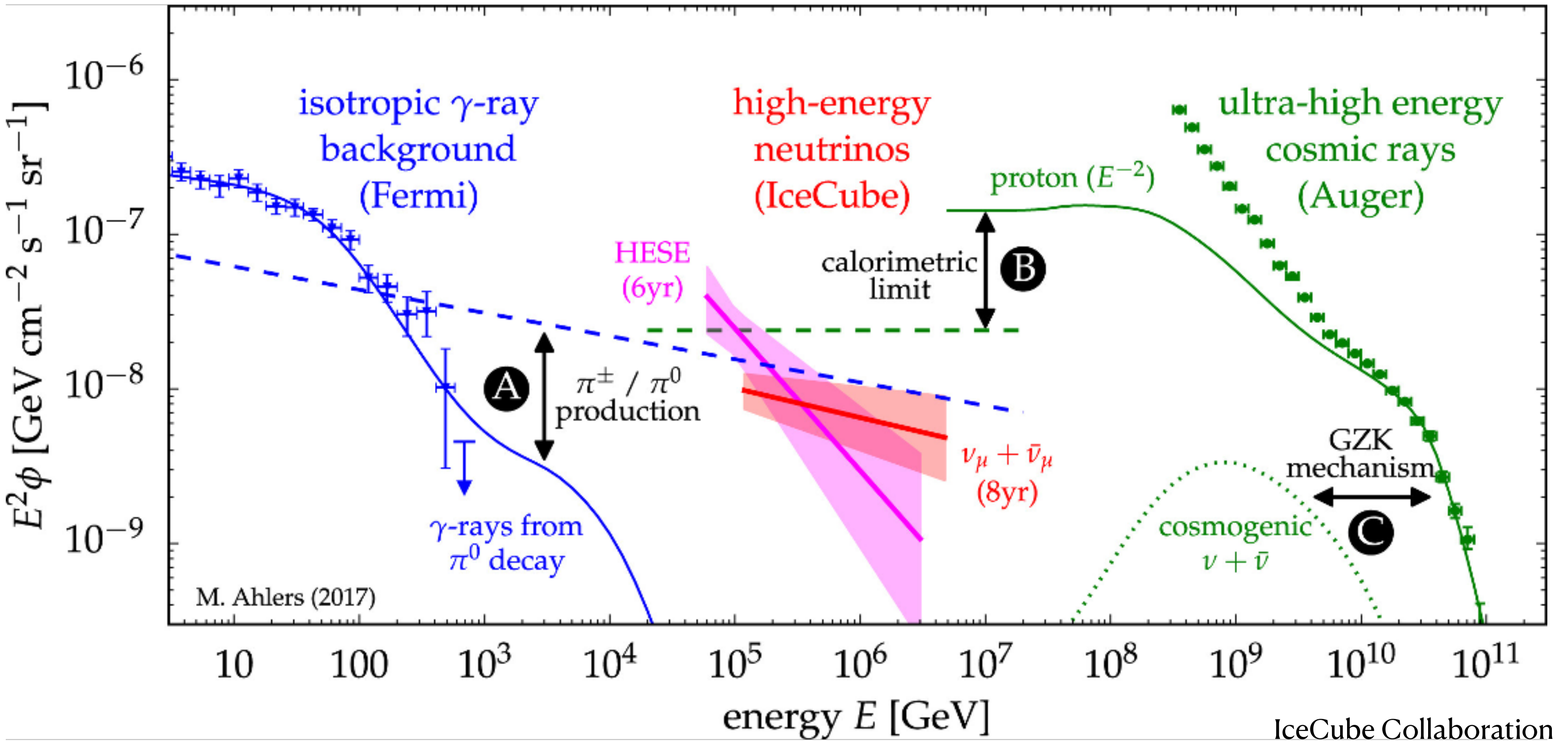
Many possible production scenarios:

Close to BH and disk? Begelman+90

Around the disk corona? Inoue+19

Near the jet origin? Halzen+97

...



IceCube Collaboration

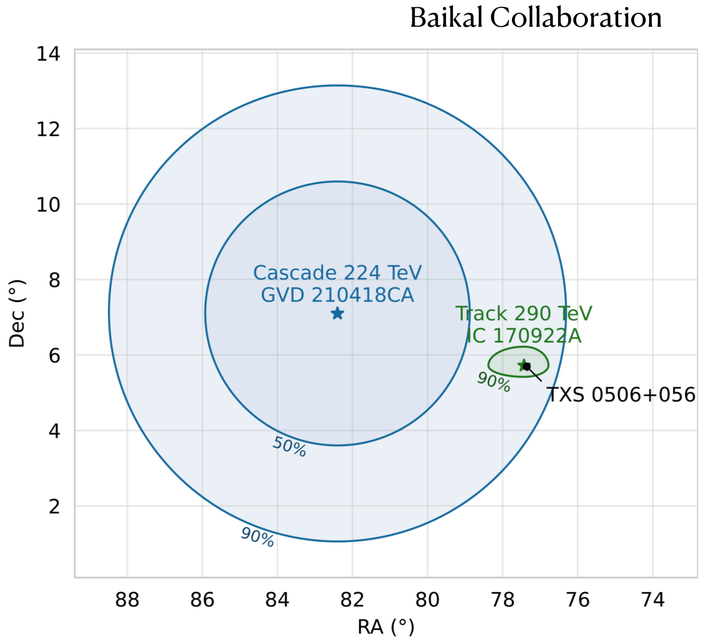
Neutrinos from active galaxies

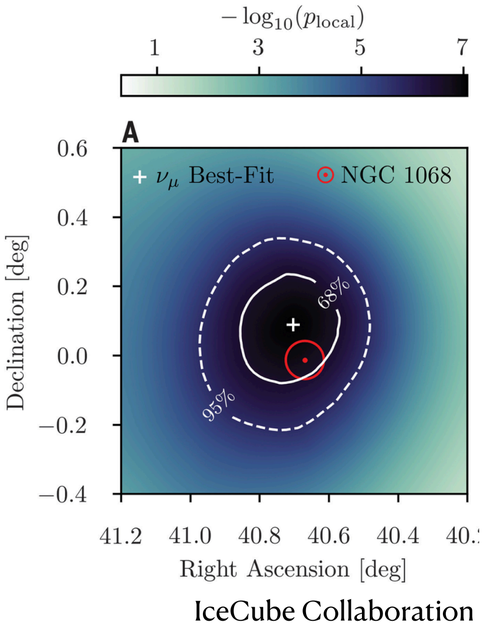
IceCube individual associations

- TXS 0506+056: bright blazar, 2 Gpc
  IceCube in 2017, Baikal-GVD in 2021
- NGC 1068: AGN, 15 Mpc

Two very different objects!

Different mechanisms? Two independent AGN populations?





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A multiwavelength view of BL Lac neutrino candidates

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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*
http://icecube.wisc.edu/collaboration/authors/icrc19_icecube
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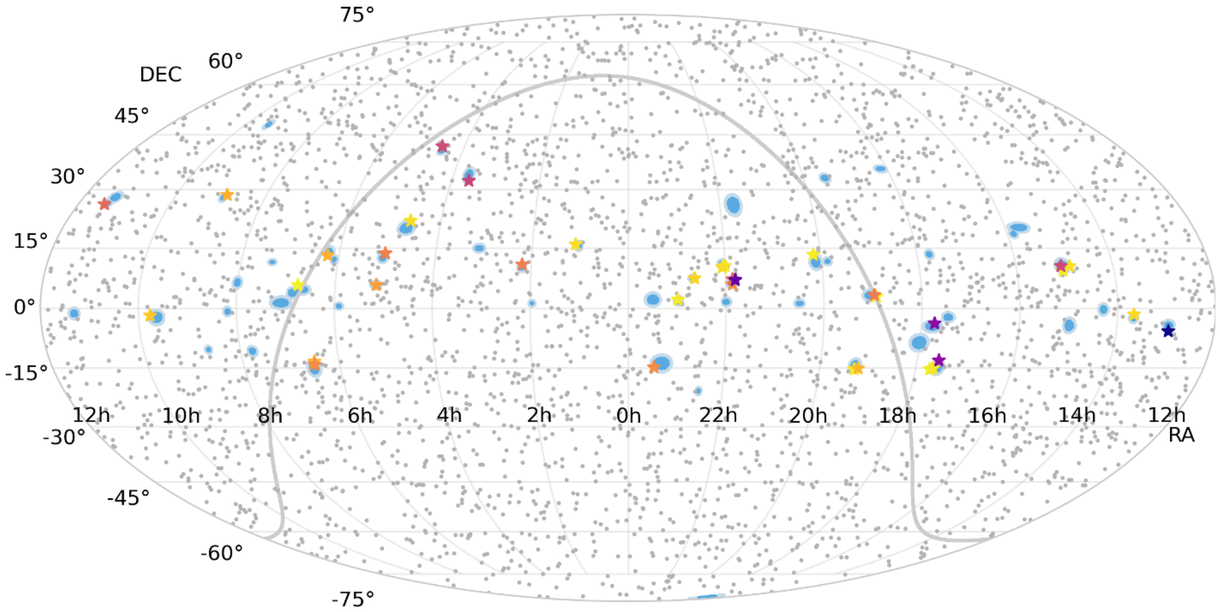

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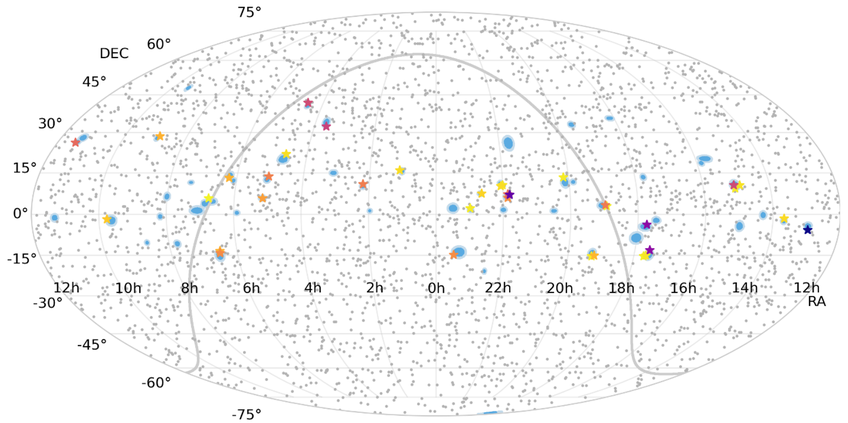


After 2020: multiple works that connect neutrinos with various bright blazar samples

Eg: Giommi+20, Plavin+21, Hovatta+21, Aublin+22, Buson+22

Not every analysis detects a correlation: Zhou+21, Desai+21

Neutrinos from active galaxies

Looking for the population

It's 2022: three years since our first neutrino-blazar population association

- Was it a real result, or turned out to be a correaltion?

Multiple related works with controversial findings

- General picture of neutrino production mechanisms in AGNs?

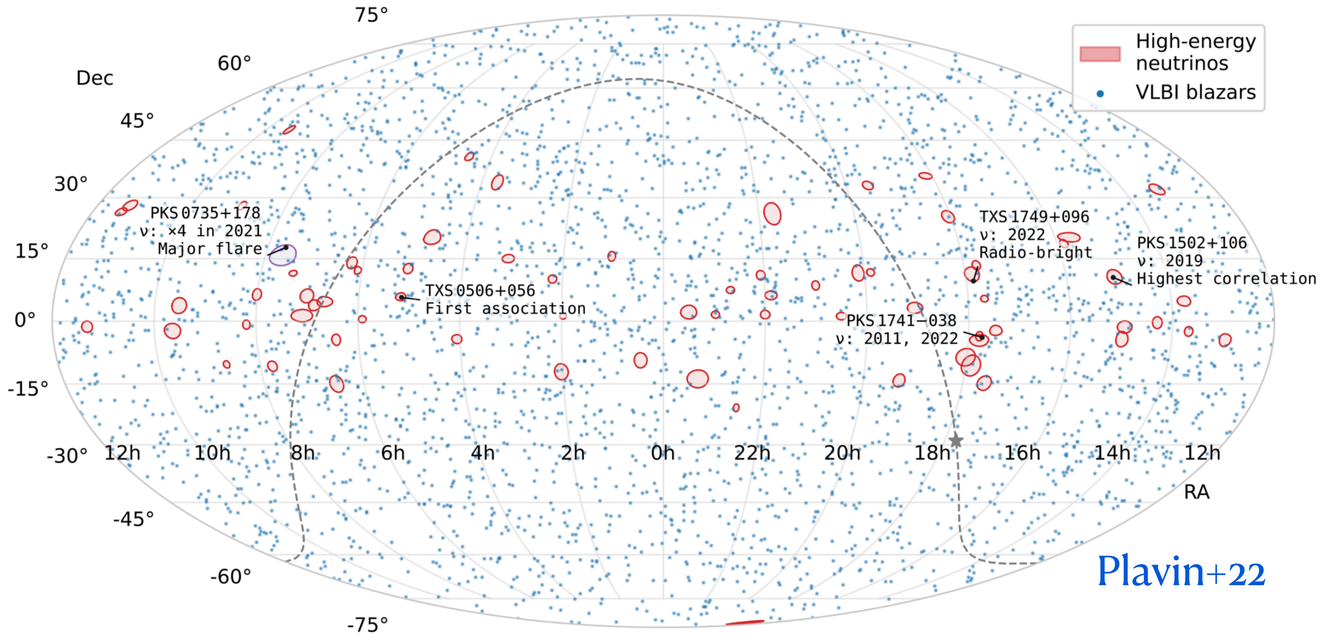
How TXS 0506 and NGC 1068 fare?

- What to expect in the future?

Radio blazar – neutrino association

Ver. 2022

- 3.5k VLBI-bright blazars
- 71 IceCube neutrinos above 200 TeV
- Correlate with blazars, trying to take systematics into account
- *Statistical test:*
  blazars around neutrino arrival directions tend to be brighter?
- Scramble in RA: direct and robust approach



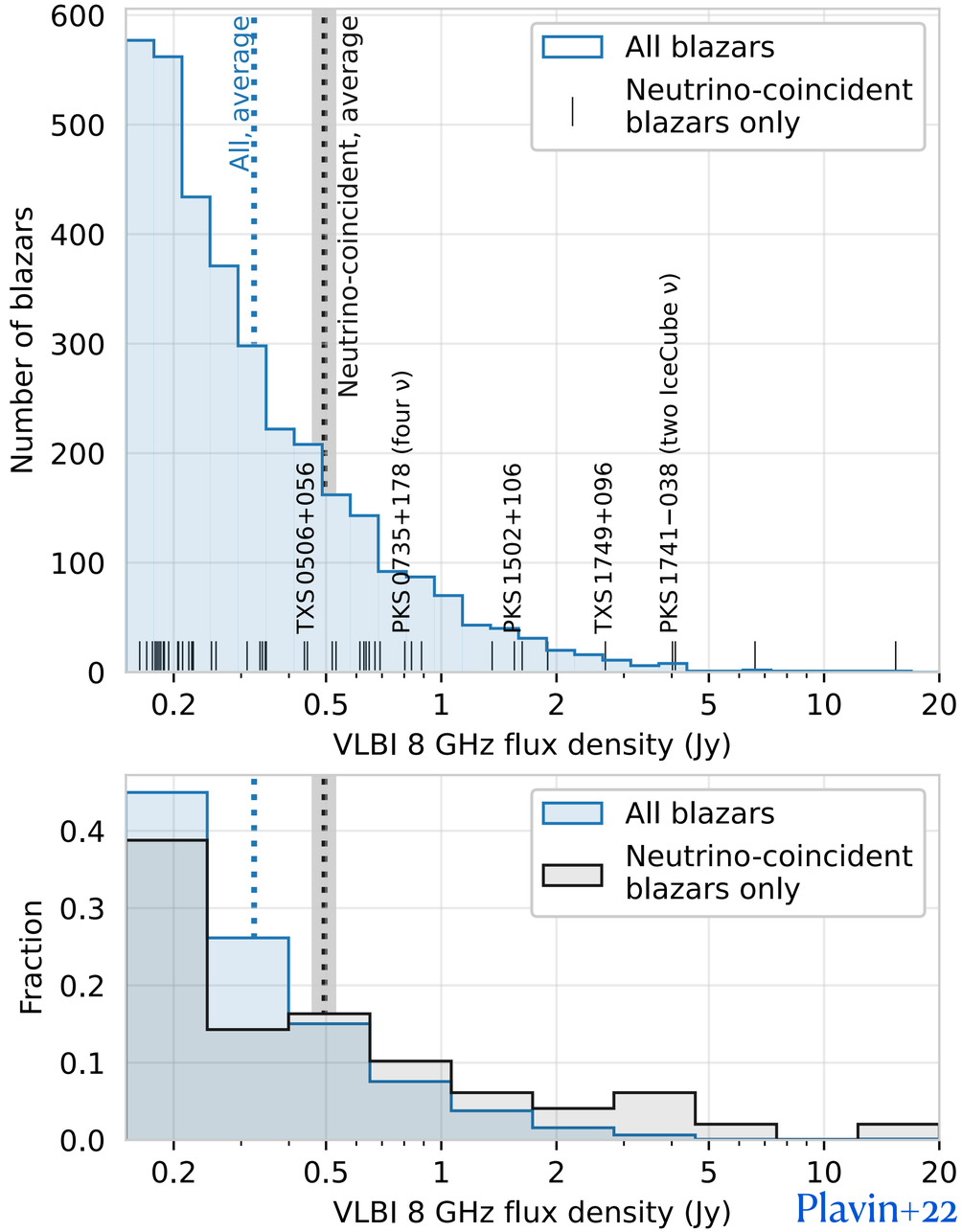
- Same procedure as in 2020, even more details are given for reproducibility

Radio blazar – neutrino association

Ver. 2022

Result: average radio flux is higher for blazars around neutrinos!
$p=3\cdot10^{-4}$ (3.6 σ)

For comparison, in 2020 (56 evts): $p=2\cdot10^{-3}$



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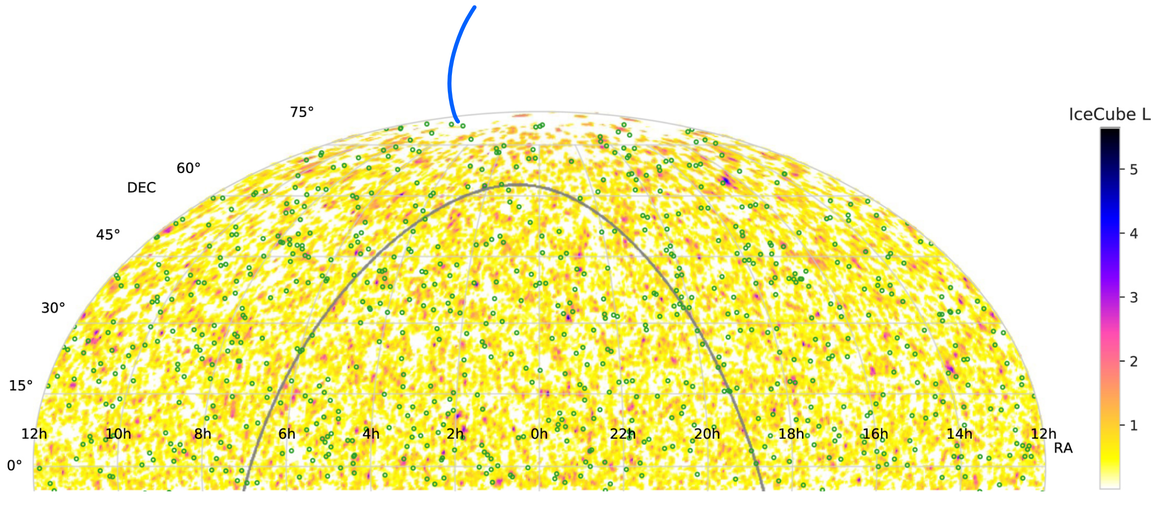
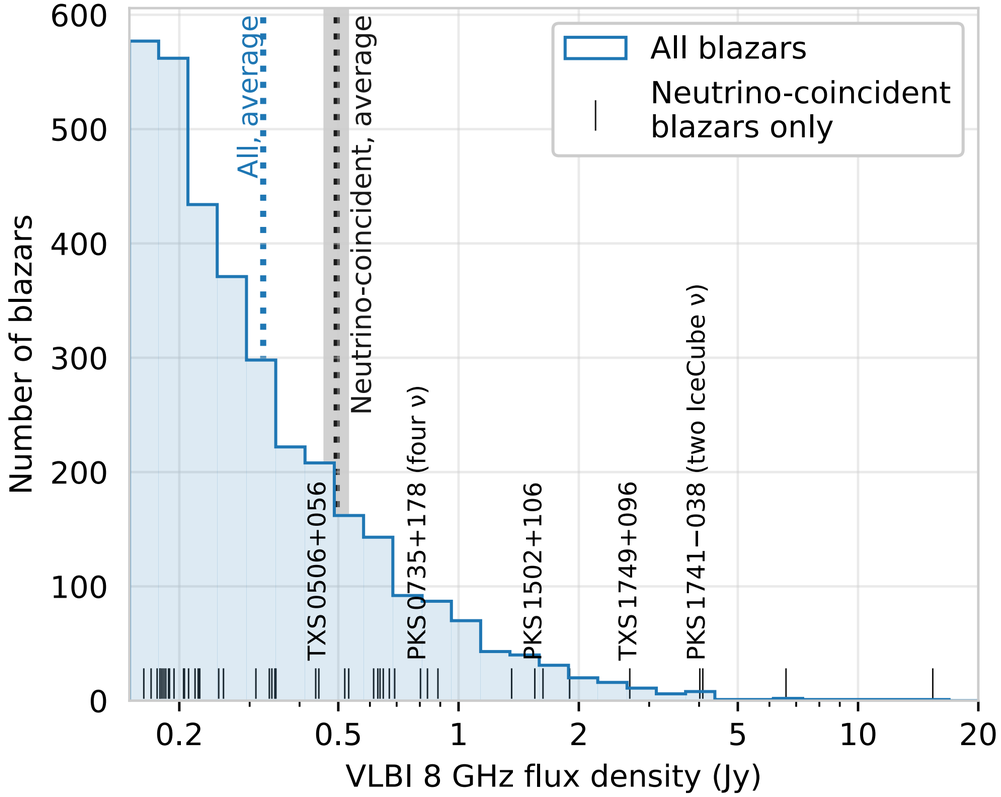
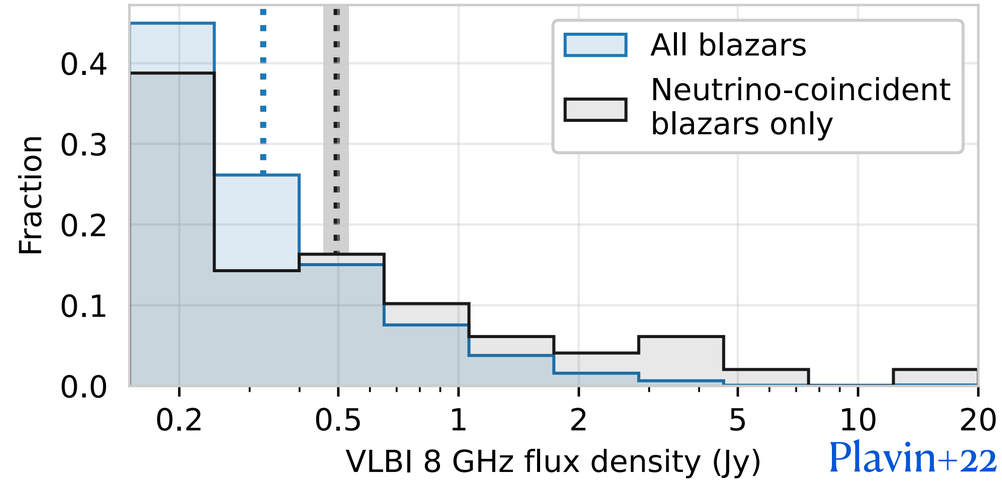
Together with independent TeV+ analysis (Plavin+21): $p=2\cdot10^{-5}$ (4.3 σ)







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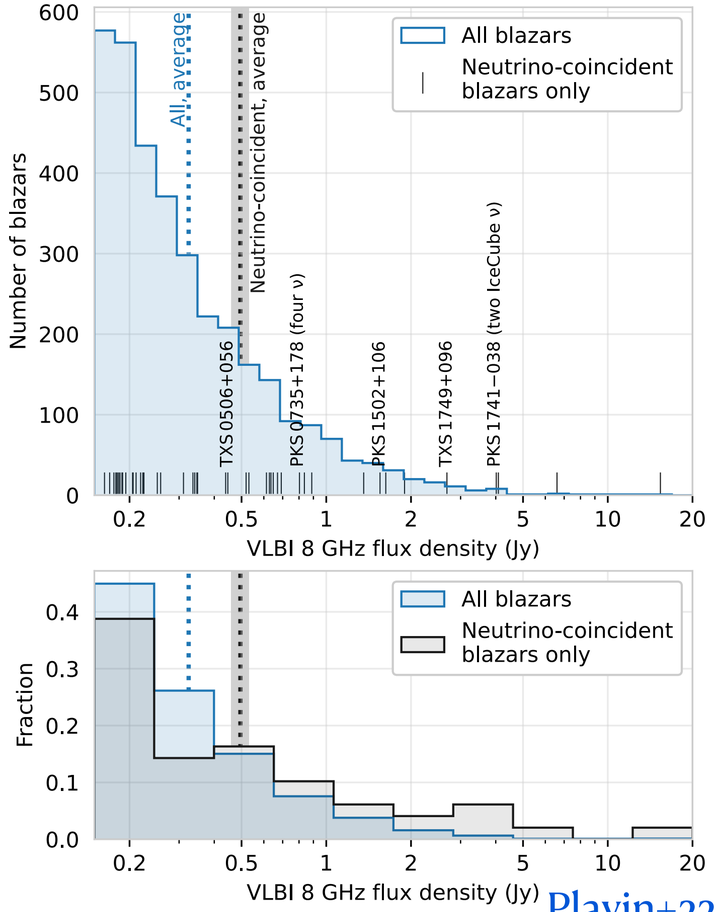
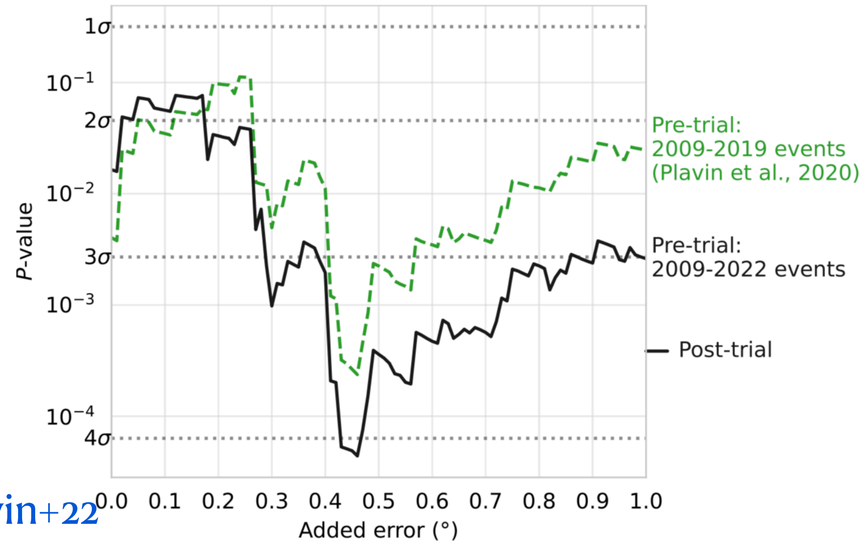


Plavin+22



Plavin+22

Trying to account for systematic errors: expand error regions by some value.

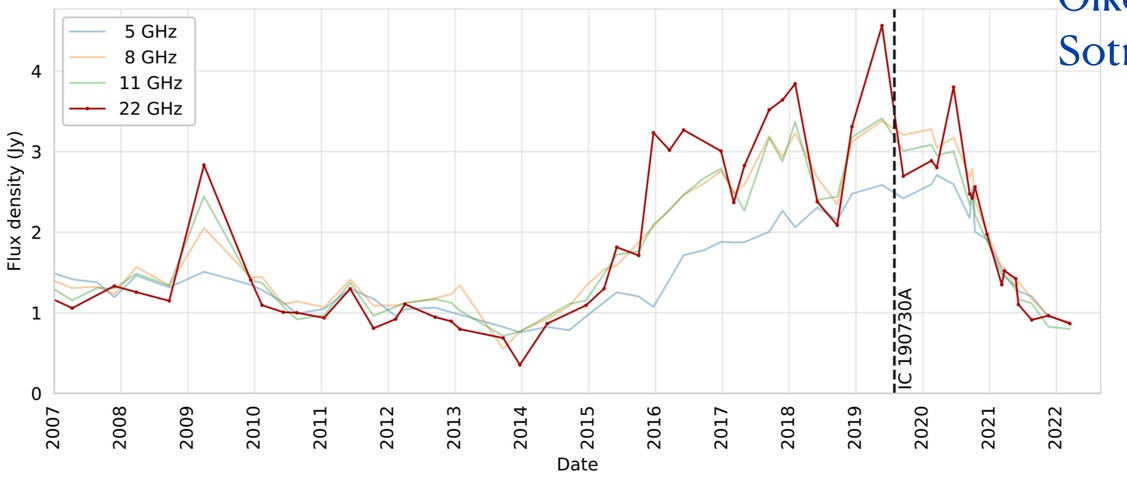
Optimal magnitude: 0.45 deg

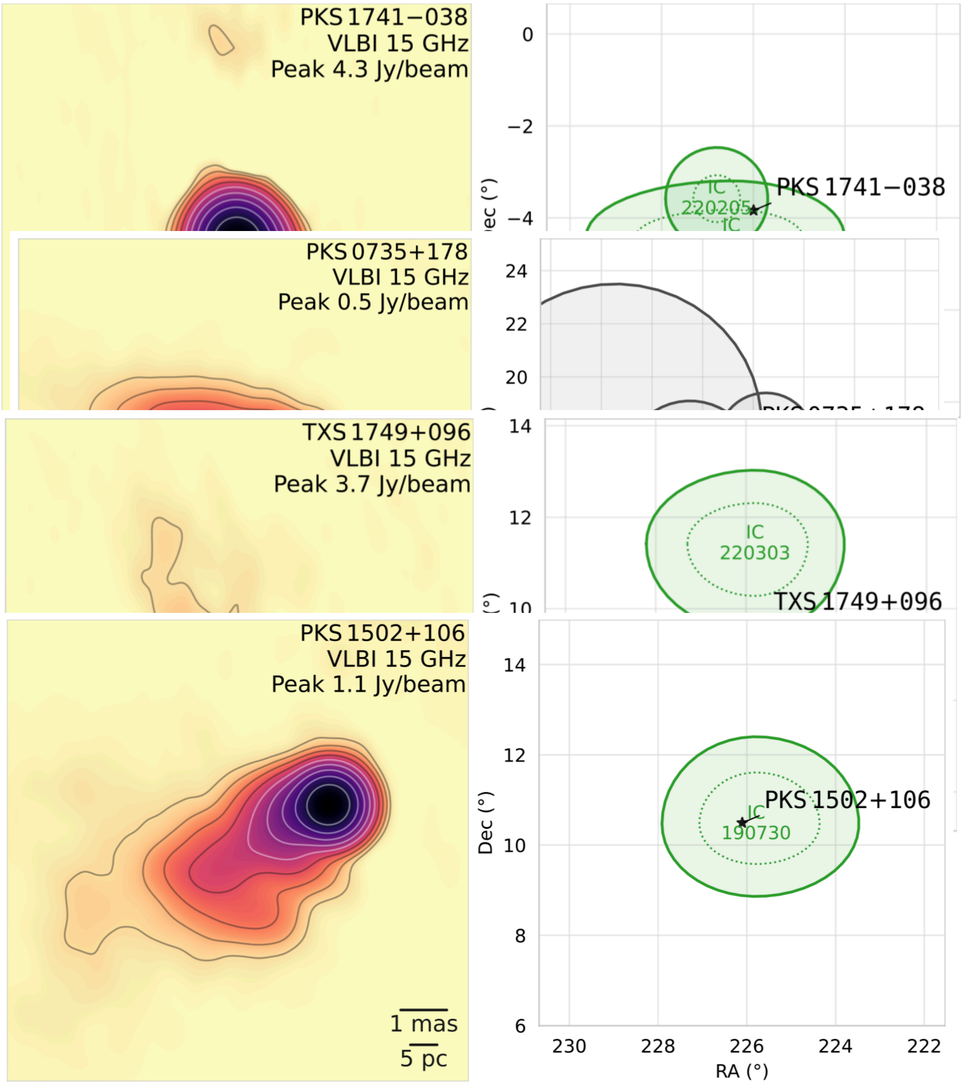
In 2020: 0.5 deg

Notable individual associations

- PKS 1741-038: selected in Plavin+20, now a dublet
- PKS 0735+178: neutrinos in Dec 2021 reported by IceCube, Baikal-GVD, KM3Net, Baksan
- TXS 1749+096: brightest & most beamed since 2020
- PKS 1502+106: Plavin+20 first paper to note as a likely neutrino source. Flare coincidence confirmed later, multiple works with modeling:

Rodrigues+21, Oikonomou+21, Sotnikova+22.



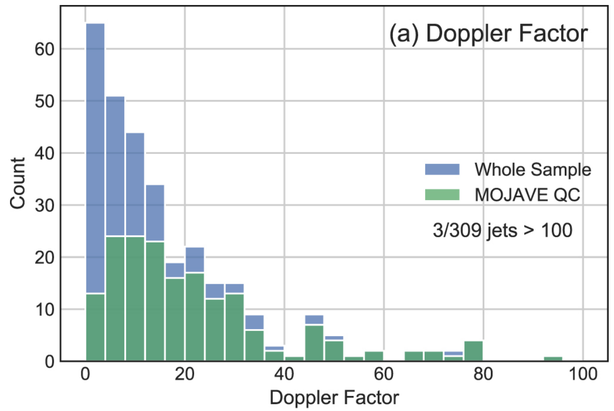


Neutrinos from active galaxies

Interpretation as of 2022

Neutrino production related to jets, beamed in the same direction

- Strong correlation with VLBI that selected bright & compact
- High Doppler boosting:
  3C279 and TXS 1749+096 are two of three with D > 100 Homan+21

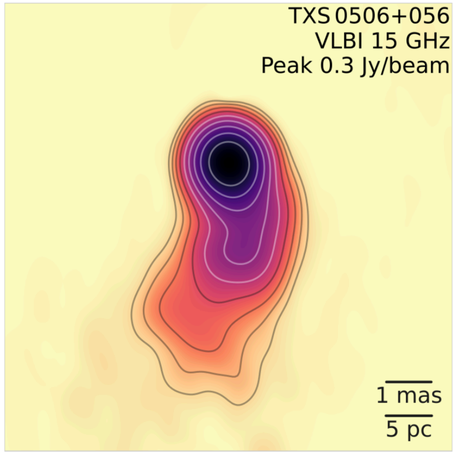


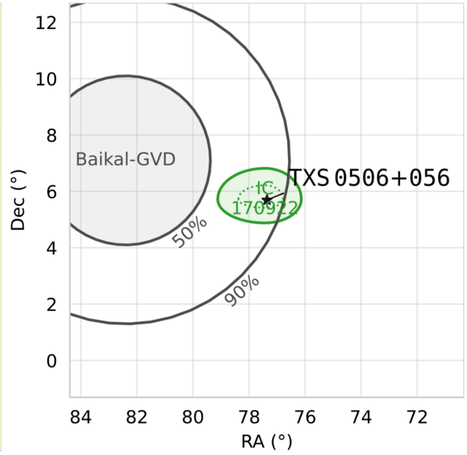
Neutrinos from active galaxies

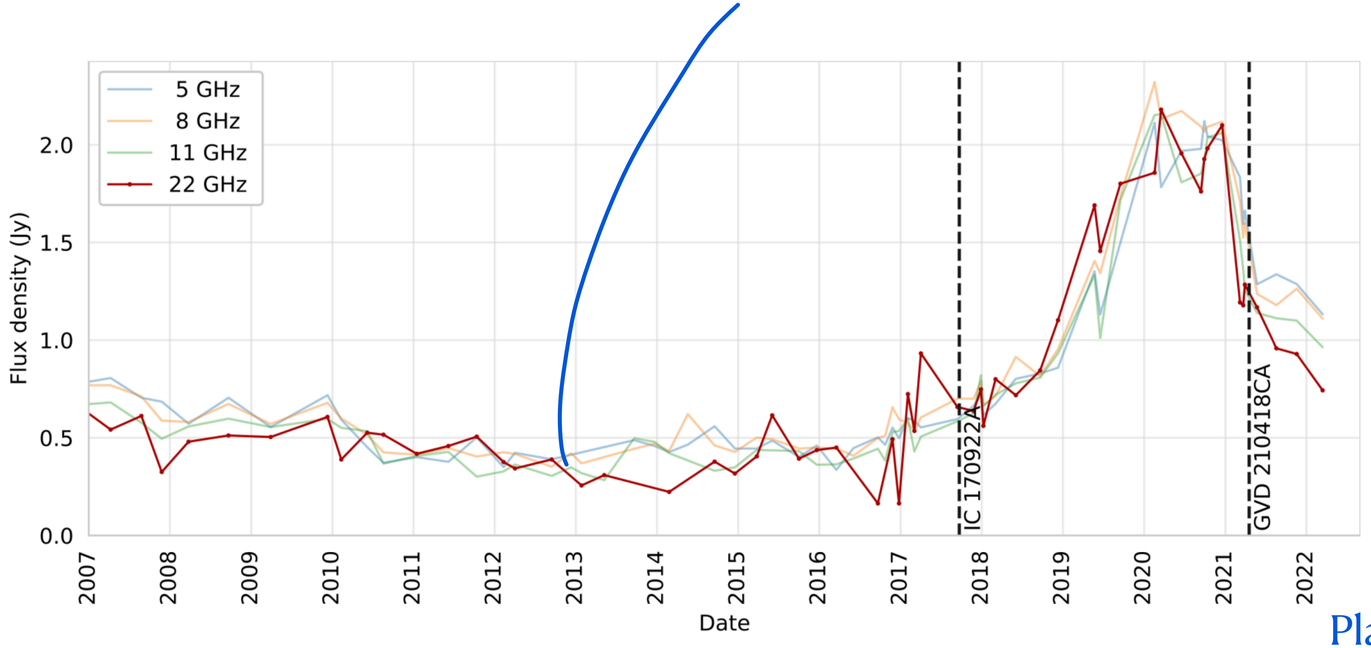
Interpretation as of 2022

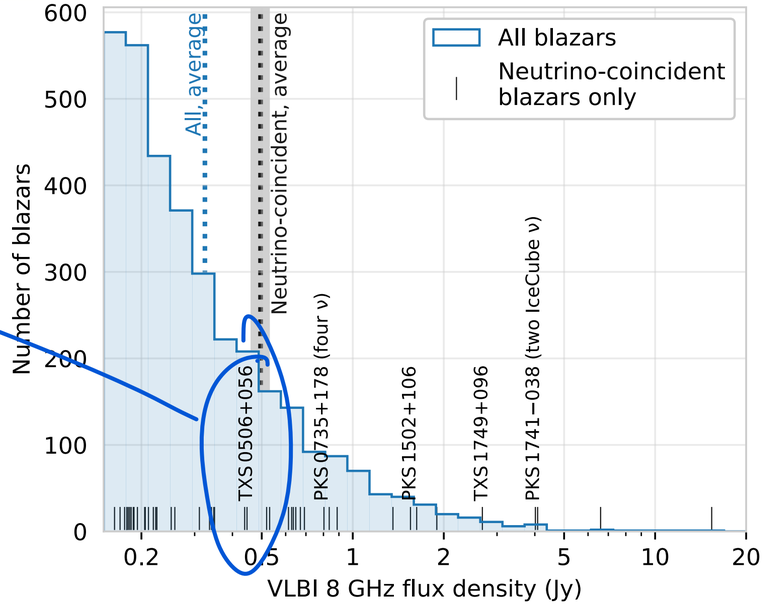
TXS 0506+056: typical VLBI-bright blazar

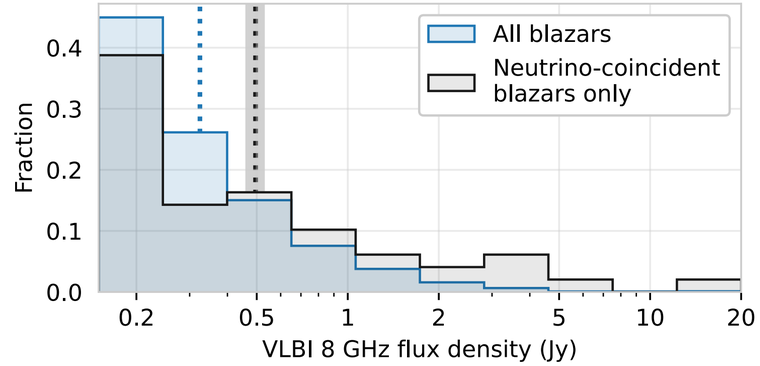
Not distinguished in our analysis:
VLBI catalog flux describes its quiescent state







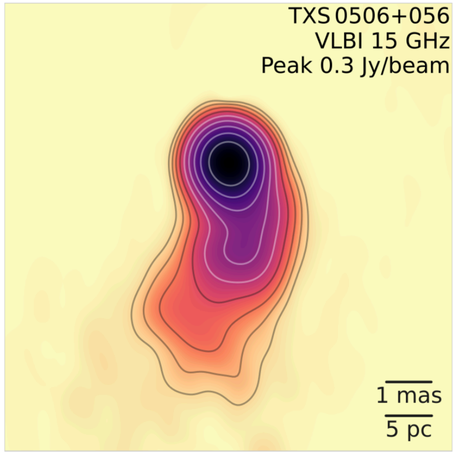


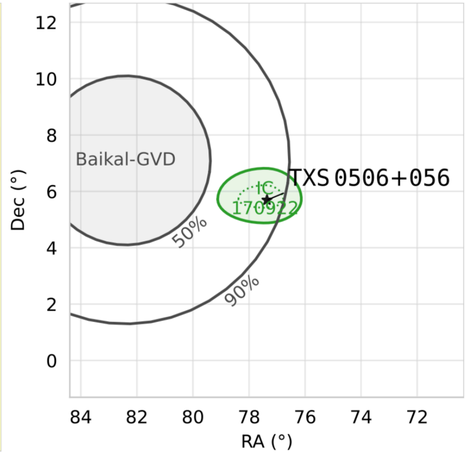


Plavin+22

Neutrinos from active galaxies

Interpretation as of 2022



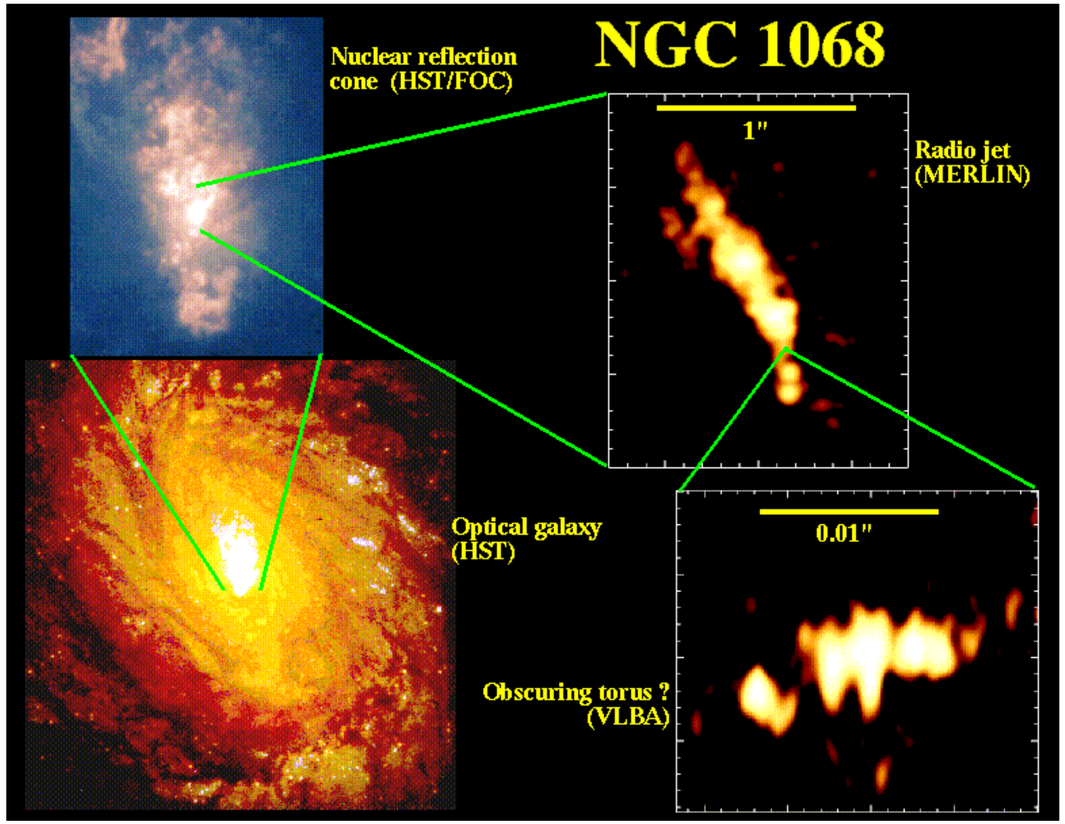


TXS 0506+056: typical VLBI-bright blazar

Not distinguished in our analysis:
VLBI catalog flux describes its quiescent state

NGC 1068: also an AGN, but far less beamed

Same as EM: beaming not required for nearby sources



Neutrinos from active galaxies

Interpretation as of 2022

Neutrino production related to jets, beamed in the same direction

- Strong correlation with VLBI that selected bright & compact
- Typically high Doppler boosting, but not required to see nearby objects – same as EM

Accompanying gamma rays: not produced in large quantities or cascade down in energy

- No IceCube vs Fermi correlation found

p-gamma mechanism preferred, but p-p not excluded Neronov+21

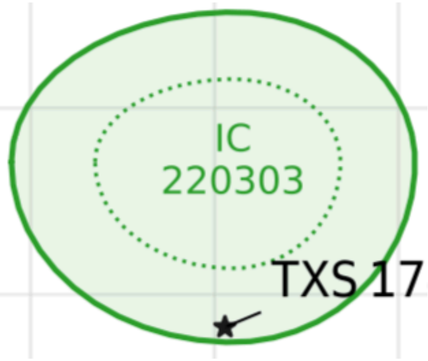
- Look for target photons? Their nature also not clear for now.
- Accelerated protons required, 10^{15} eV

Neutrinos from active galaxies

Statistical Search: notable points

Complete source samples with well-defined selection criteria crucial for both analysis and interpretation

Eg, Buson+22 found significant neutrino correlation with BZCat, but how uniform is that catalog? What source population it contains? Definite inclusion criteria needed!



Taking systematics into account remains important, some new associations lie outside original errors. Works such as Lagunas+21 also point out issues in uncertainty geometry.

Relative to Plavin+20, significance grows as sqrt(# events). Extrapolating, we expect 5σ in 5-7 years.

Summary

Bright blazars are neutrino sources

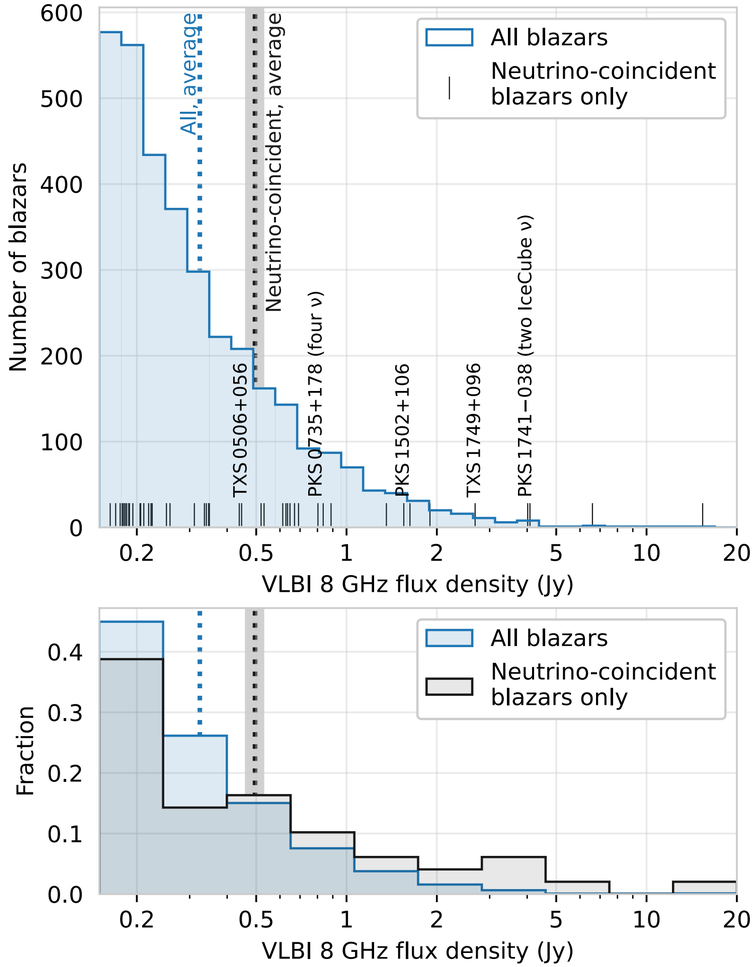
Spatial correlation of TeV-PeV neutrinos with radio blazars confirmed: $p=2\cdot10^{-5}$ (4.3 σ)

Bright, beamed, distant blazars drive this correlation

Neutrino production related to AGN jets

Results remain statistical: uniform complete catalogs are crucial!

Where & how they are produced? Many unknowns still...



Plavin, Kovalev, Kovalev, Troitsky, MNRAS submitted