

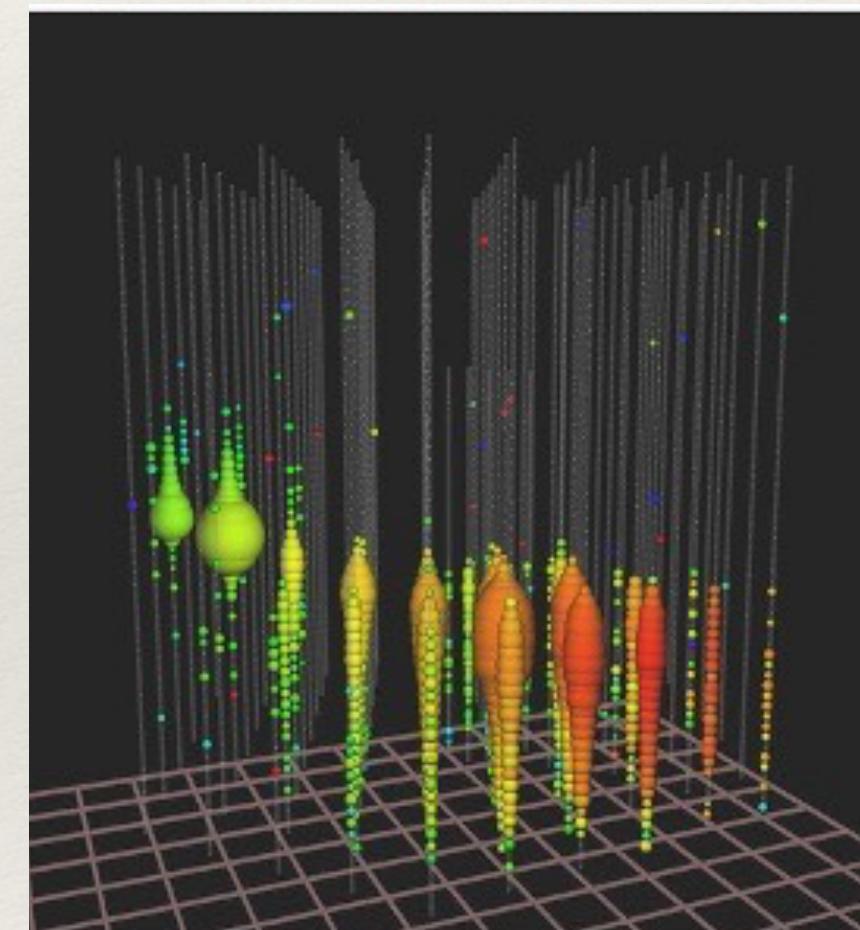
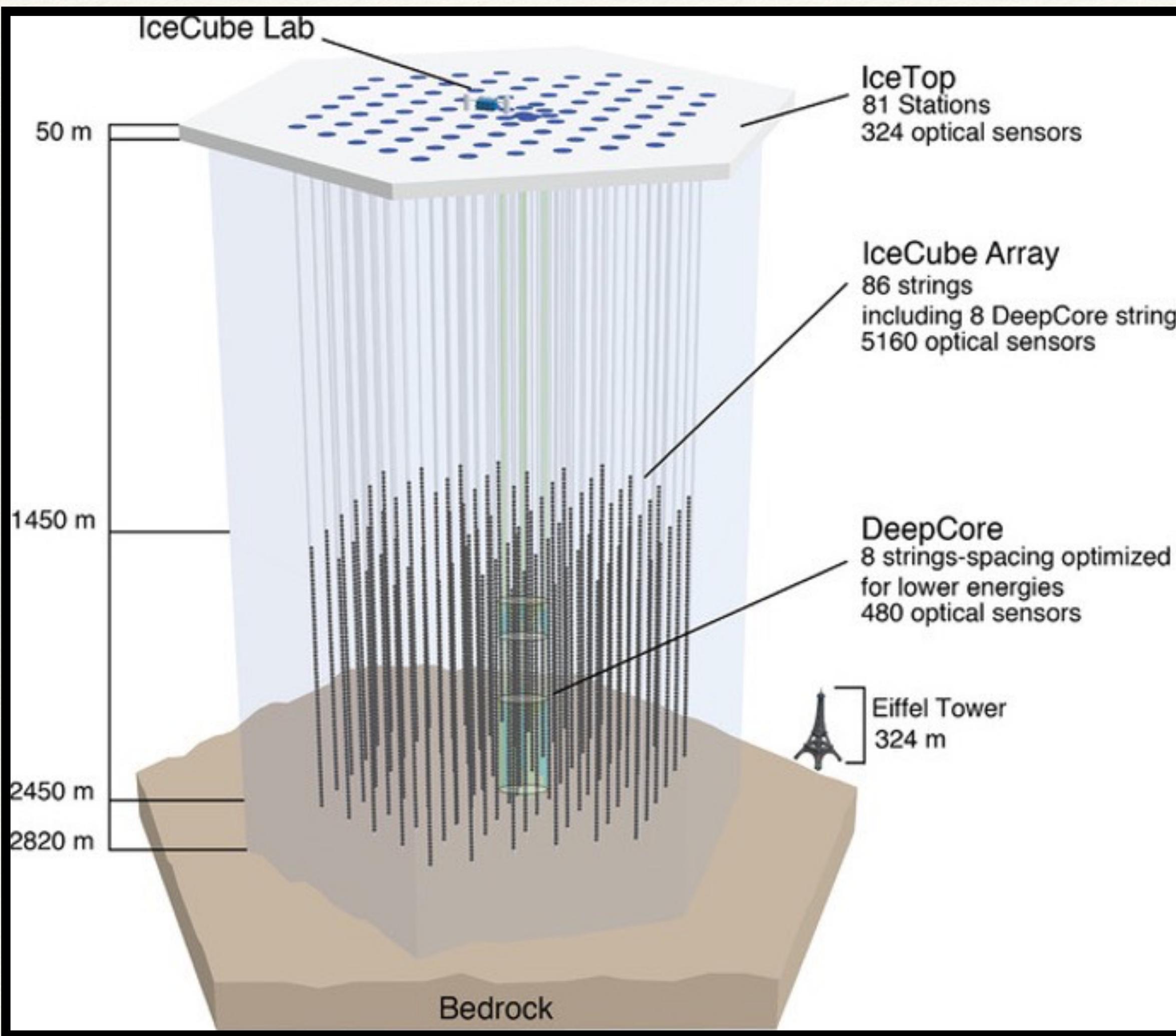
VLBI Probes of Neutrino Emission Processes in Blazars

Matthias Kadler
JMU Würzburg

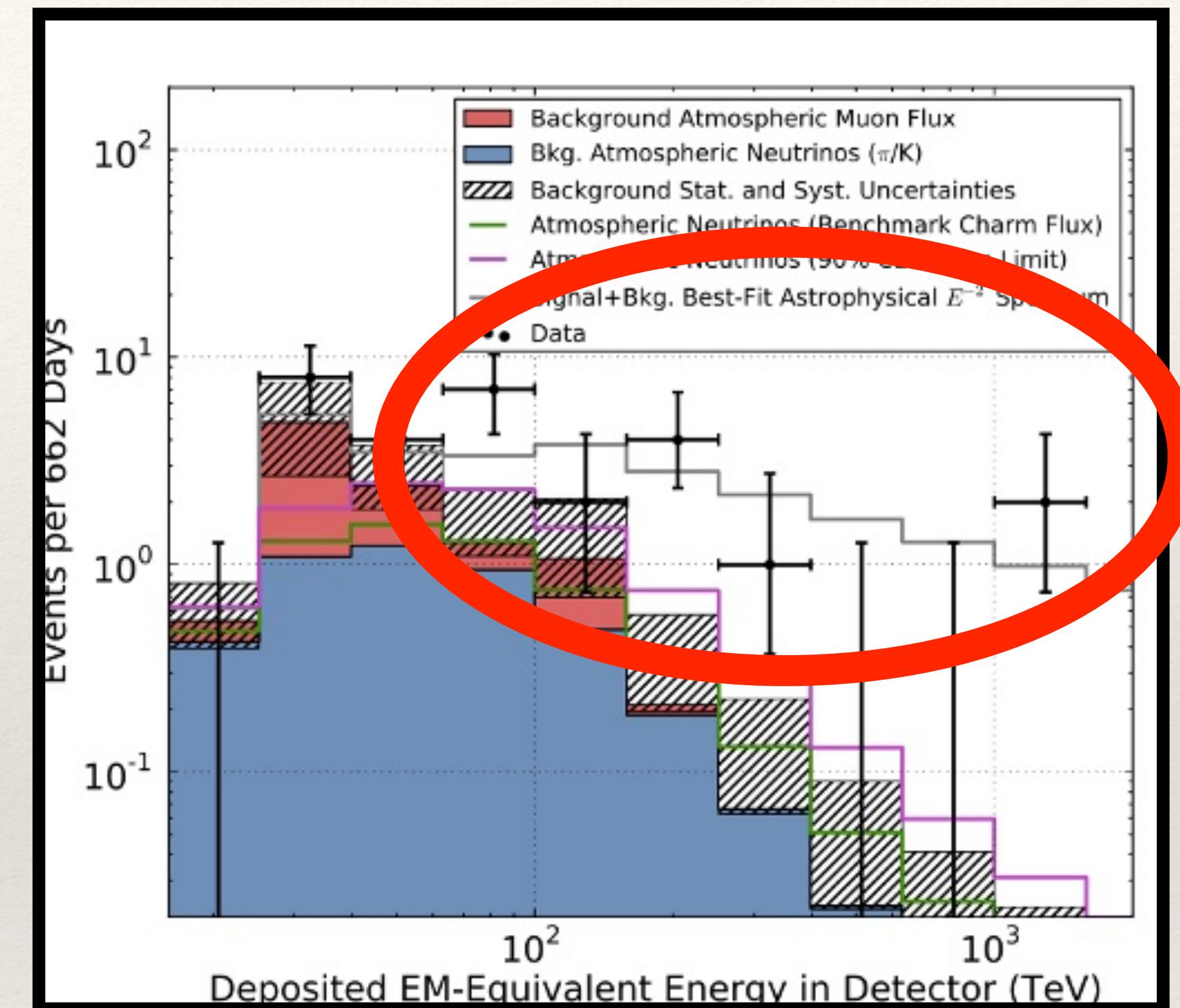
With contributions from: F. Eppel, F. Rösch, E. Ros, Y. Kovalev and others



Recent Breakthroughs in Neutrino Astronomy



Annalen der Physik,
Volume: 533, Issue: 11

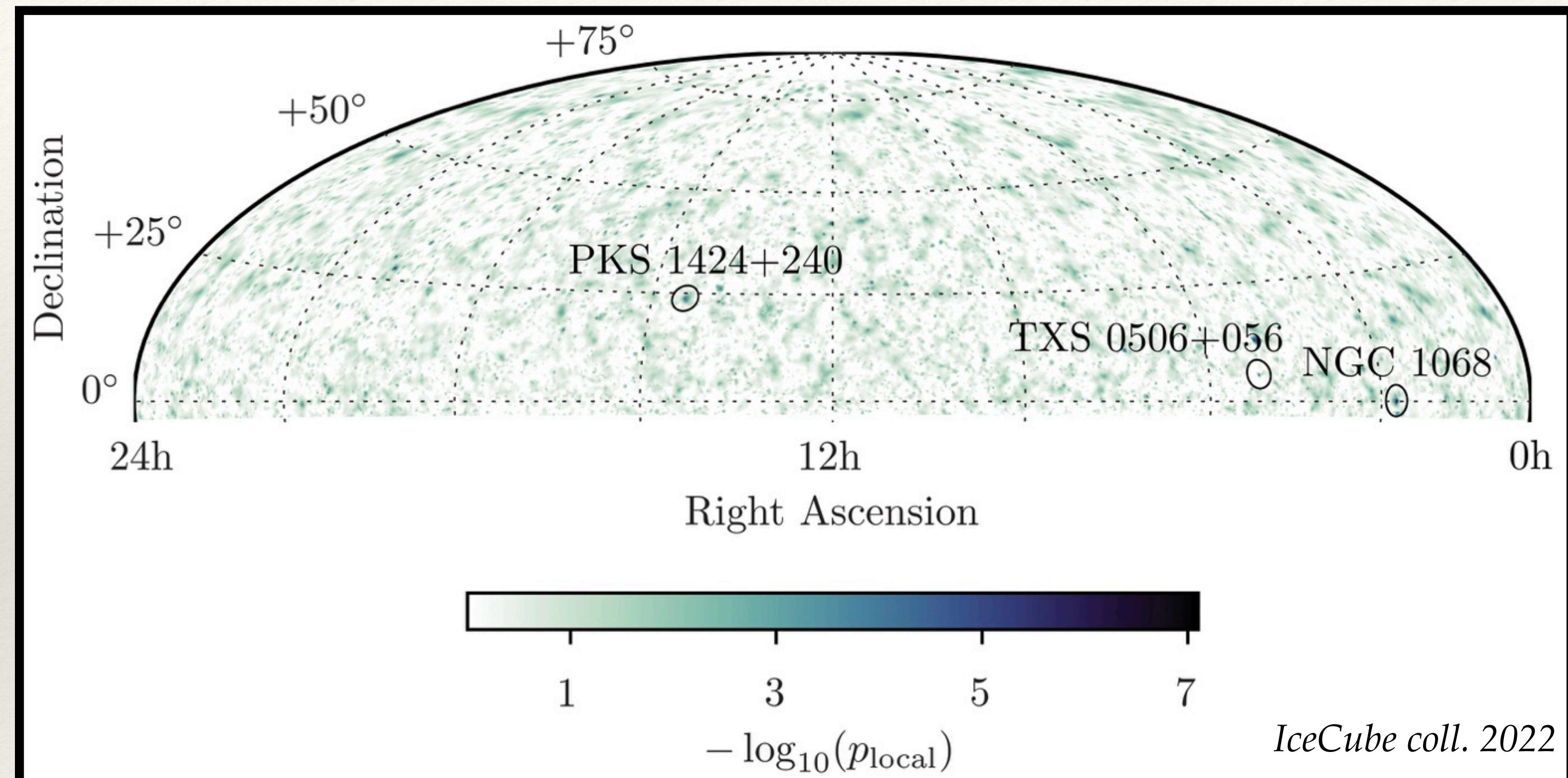


IceCube Collaboration 2013;
Aartsen et al. 2014

Recent Breakthroughs in Neutrino Astronomy

Latest IceCube Searches:

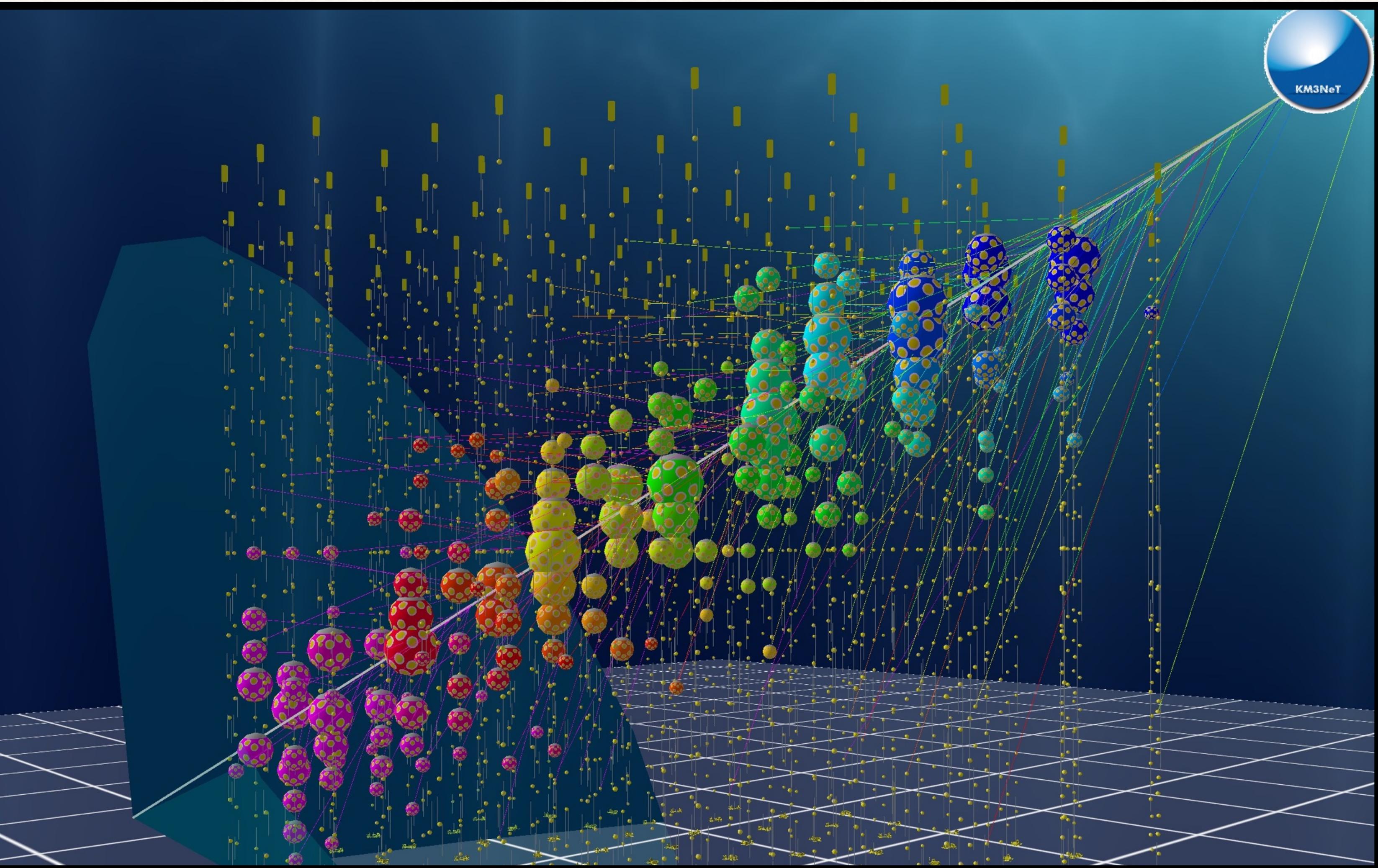
- Blind all-sky search (10-years IC data)
- Correlations with tested list of sources (northern catalog, $\sim 3\sigma$ post-trial)
- Most significant spots (pre-trial):
 - NGC 1068 (4.2σ), PKS 1424+240 (3.7σ), TXS 0506+056 (3.5σ)



Events largely isotropically distributed, favouring extragalactic origin

Recent Breakthroughs in Neutrino Astronomy

KM3NeT Collaboration



Recent Breakthroughs in Neutrino Astronomy

KM3NeT Collaboration 2025a, 2025b, 2025c,...

The international journal of science / 13 February 2025

ABSTRACT

The KM3NeT observatory detected the most energetic neutrino candidate ever observed, with an energy between 72 PeV and 2.6 EeV at the 90 % confidence level. The observed neutrino is likely of cosmic origin. In this article, it is investigated if the neutrino could have been produced within the Milky Way. Considering the low fluxes of the Galactic diffuse emission at these energies, the lack of a nearby potential Galactic particle accelerator in the direction of the event and the difficulty to accelerate particles to such high energies in Galactic systems, we conclude that if the event is indeed cosmic, it is most likely of extragalactic origin.

non-negligible proton fraction produced at the highest energies. At the same time, an additional diffuse extragalactic component is plausible, accounting for neutrinos produced in source environment. This aligns with the expectation that at the highest energies, the observed neutrino flux is not entirely cosmogenic; instead, it likely includes contributions from various astrophysical sources.

COSMIC CATCHER

Deep-sea telescope detects neutrino with highest energy ever recorded

ton fraction produced at the highest same time, an additional diffuse extra- it is plausible, accounting for neutrino source environment. This aligns with what at the highest energies, the ob- ject is not entirely cosmogenic; instead, contributions from various astrophysi-

DE JONG, ^{50, 25} P. DE JONG, ^{32, 25} B. J. JUNG, ²⁵ P. KALACZYŃSKI, ^{51, 52} G. KALA
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 AROSA, ²⁶ C. LASTORIA, ¹⁸ J. LAZAR, ⁴² A. LAZO, ⁸ S. LE STUM, ⁷ G. LEHAUT, ¹⁸ R.
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 K. MEHTA, ⁵² A. MESKAR, ⁵⁹ G. MIELE, ^{9, 10} P. MIGLIOZZI, ¹⁰ E. MIGNECO, ²⁶ M. I
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 OLIVIERO, ^{9, 10} A. ORLANDO, ²⁶ E. OUKACHA, ¹⁵ L. PACINI, ¹ D. PAESANI, ²⁶ J
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 FFER, ¹⁰ P. PIATELLI, ²⁶ A. PLAVIN, ^{10, 53, 60} C. POIRÉ, ^{30, 10} V. POPA, ³¹,
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 IENZA, ²⁶ M. SCARINGELLA, ¹ M. SCARNERA, ^{42, 15} J. SCHNABEL, ⁴⁴ J. SCHUM
 CA, ²⁵ N. SENNAN, ⁴⁶ P. A. SEVLE MYHR, ⁴² I. SGURA, ⁴¹ R. SHANIDZE, ⁵⁴ A
 SIMKOVIC, ¹⁹ A. SIMONELLI, ¹⁰ A. SINOPOULOU, ³ B. SPISIO, ¹⁰ M. SPURIO, ²¹
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 A, ^{59, 52} A. VACHERET, ¹⁸ V. VALSECCHE, ²⁶ V. VAN ELEWYCK, ^{56, 15} G. VAN
 SILEADIS, ⁶⁴ F. VAZQUEZ DE SOLA, ²⁵ A. VEUTRO, ^{11, 36} S. VIOLA, ²⁶ D. VIV
 I, ^{32, 25} I. LHENRY-YVON, ¹⁵ S. ZAVATARELLI, ¹⁶ A. ZEGARELLI, ^{11, 36} D. ZITO,
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In this paper, a study of blazar candidates as possible associations of the KM3NeT event KM3-230213A (Aiello et al. 2025) is presented. In total, seventeen

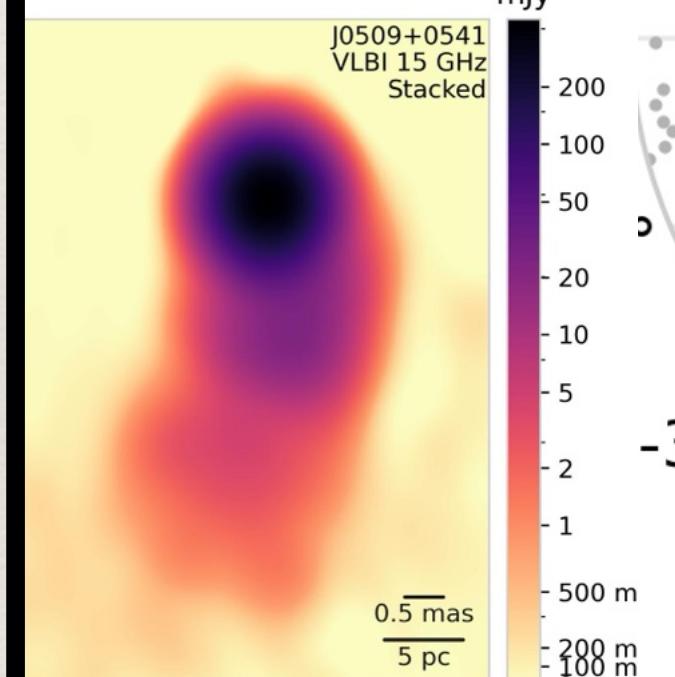
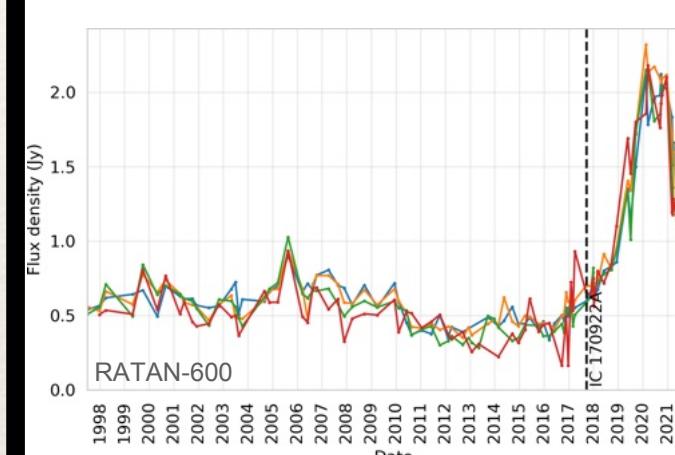
sources are found within the 95% uncertainty region. Among them, the three most interesting candidates are highlighted in [Figure 1](#) and [Figure 2](#):

1. Object MRC 0614-083 is the closest object, located 0.6° away from the best-fit neutrino position. An indication of an X-ray flare can be noted.
2. Object 0605-085 is one of the fifty brightest blazars on the sky on parsec scales. A long-term gamma-ray flare peaking before the neutrino arrival is observed.
3. Object PMN J0606-0724 has presented the major radio flare, which peaks at 15 GHz within 5 days from the neutrino arrival time. The pre-trial chance coincidence p-value is estimated to be 0.26 %.

High-energy neutrinos are associated with VLBI-selected radio-bright blazars in Plavin et al. (2020, 2021) at a 4.1σ significance level.

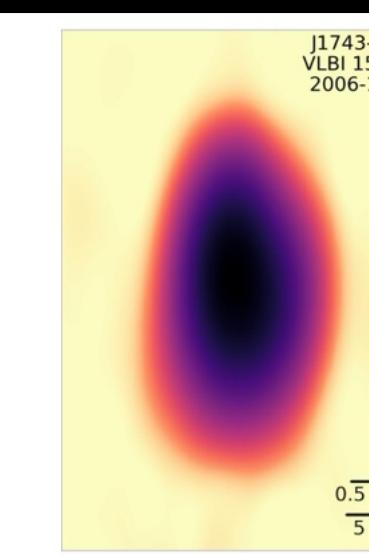
Recent IceCube neutrino events confirm those predictions and bring even more evidence.

Here, we highlight several notable neutrino-blazar associations on the basis of VLBI and single-dish results.



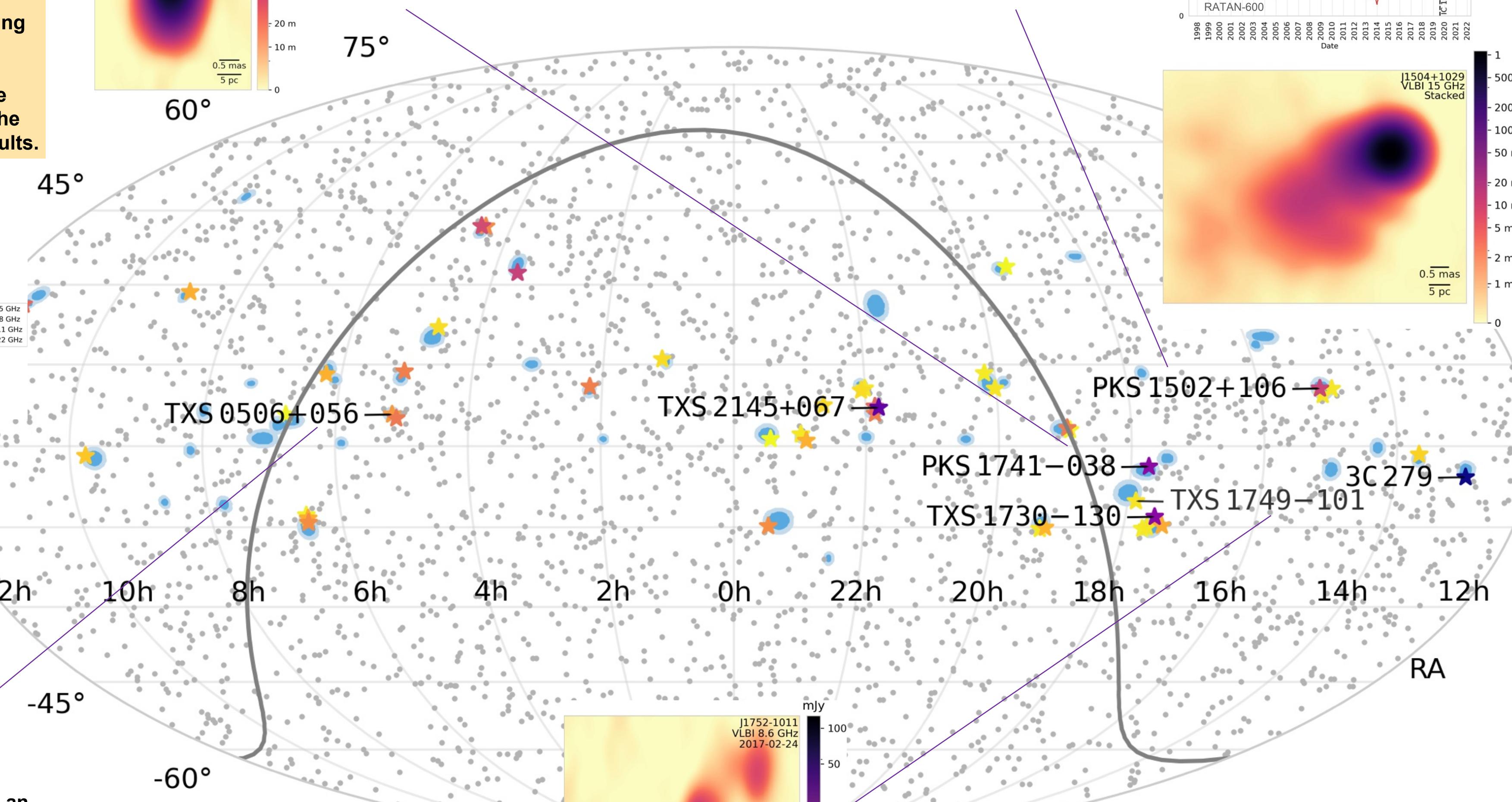
TXS 0506+05

- The first blazar associated with an IceCube neutrino from 2017
- Turns out to be a typical case: VLBI-bright, neutrino arrival coincident with a major radio flare



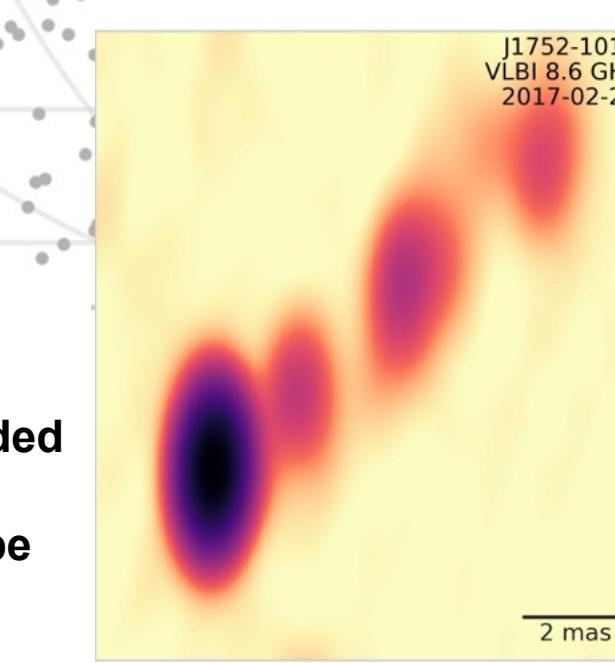
PKS 1741-03

- one of the four selected in Plavin+2020
- coincides with recent IceCube 220205 neutrino, chance probability 3%



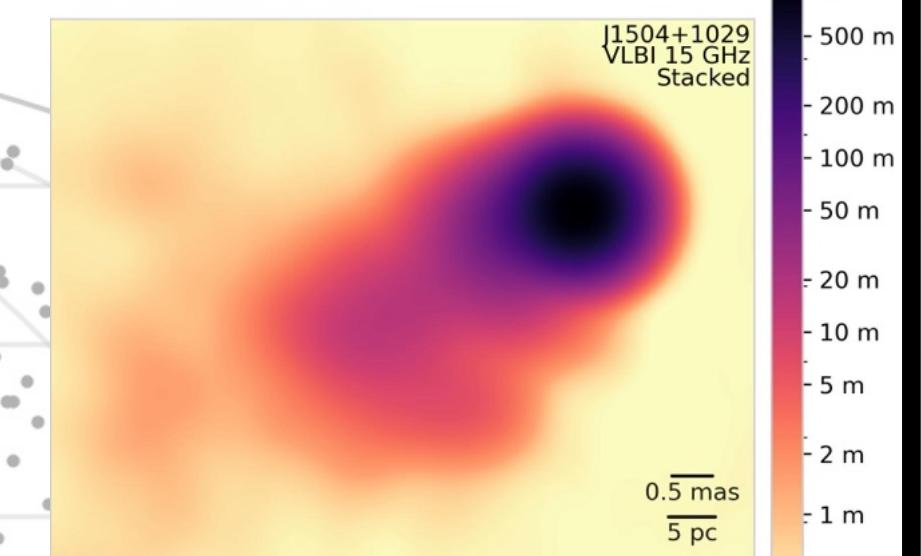
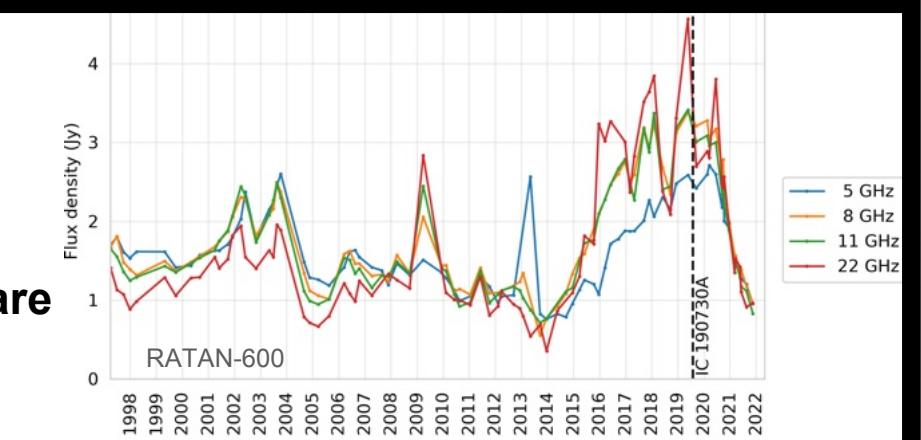
TXS 1749-10

- IceCube neutrino in 2018 coincided with a radio flare
- recently: associated with IceCube 220425A



PKS 1502+10

- selected in Plavin+2020 by the highest neutrino-radio flare correlation
- further monitoring confirms a strong flare

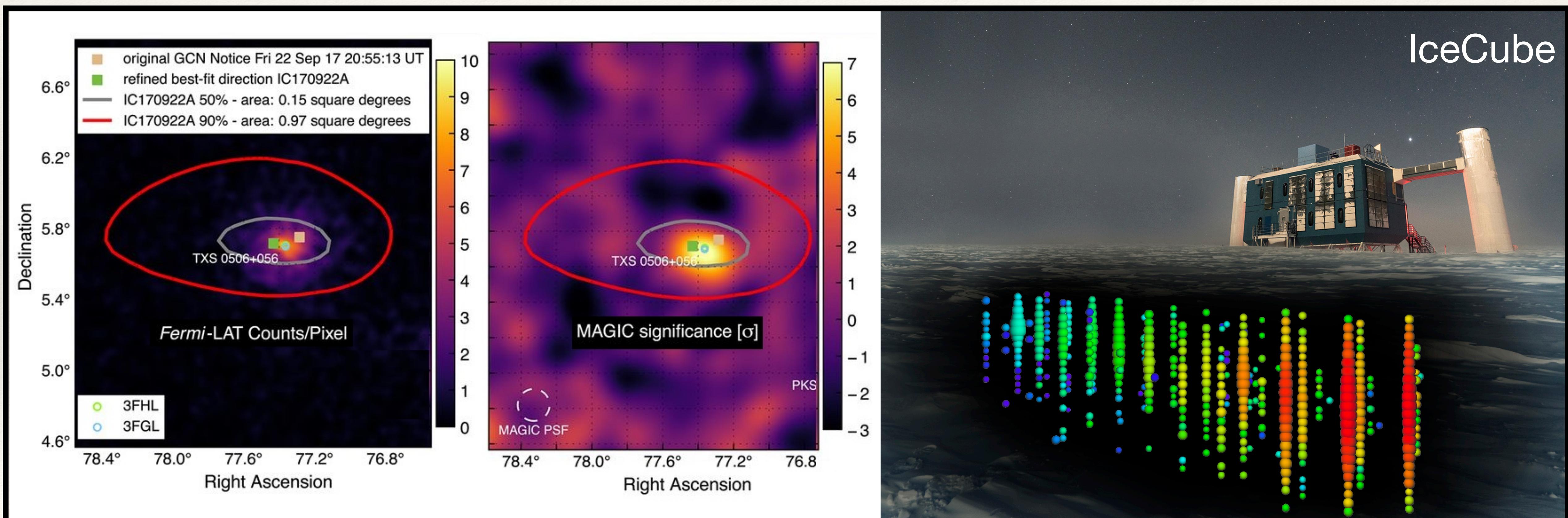


Together with
Alexander Plavin,
Yuri A. Kovalev,
Sergey Troitsky

Published results:
Plavin et al. (2020, ApJ, 894, 101)
Plavin et al. (2021, ApJ, 908, 157)

Recent Breakthroughs in Neutrino Astronomy

3 σ Association of an individual neutrino with Blazar TXS0506+056

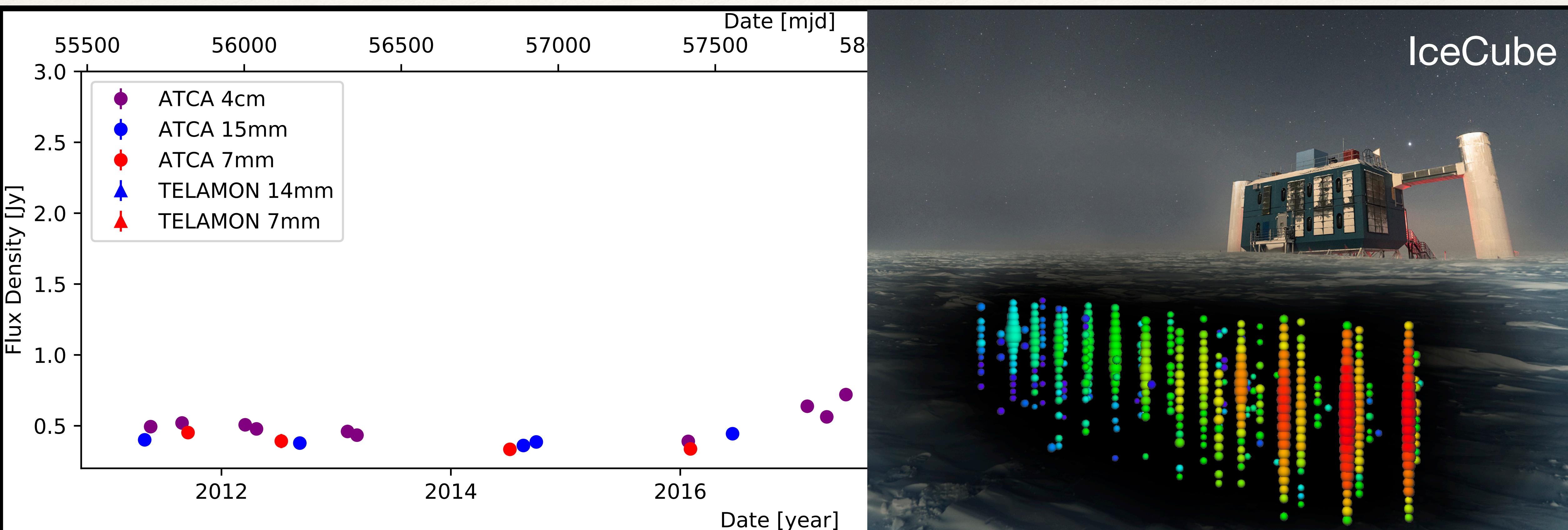


IceCube Coll., Fermi Coll. MAGIC Coll. et al. 2018

The Highest Angular Resolution Frontier, AAS #247 - Jan 7, 2026

Recent Breakthroughs in Neutrino Astronomy

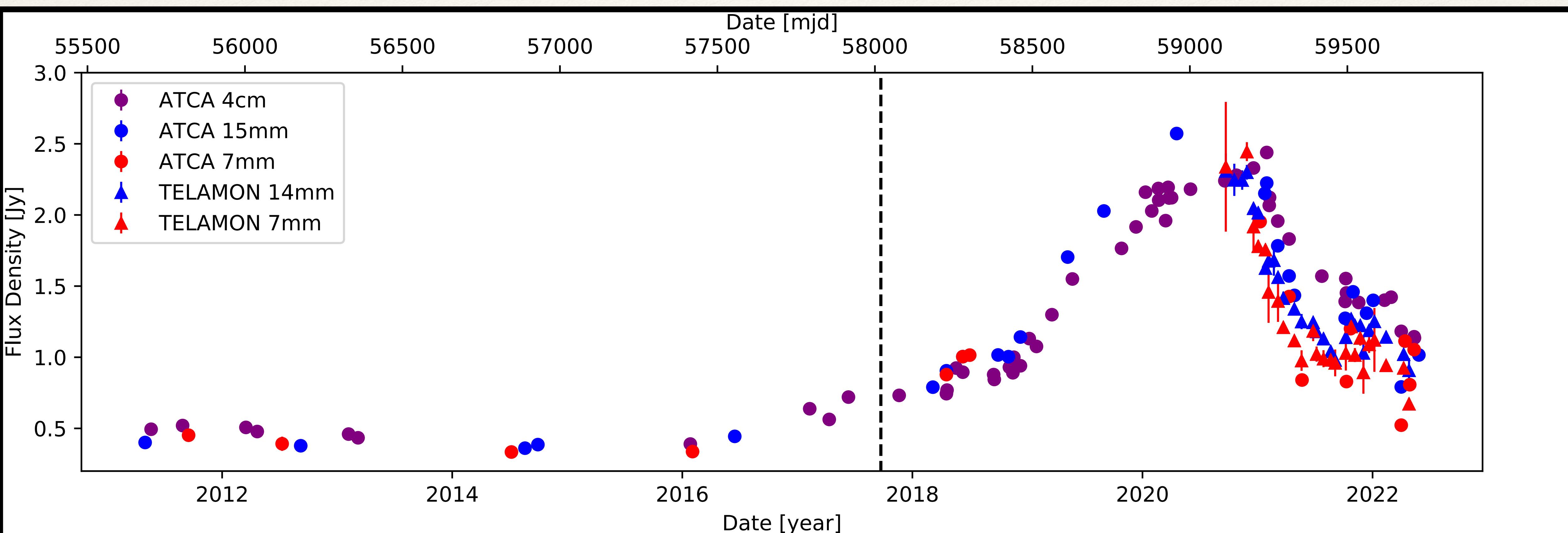
3 σ Association of an individual neutrino with Blazar TXS0506+056



Rösch 2026, in prep.

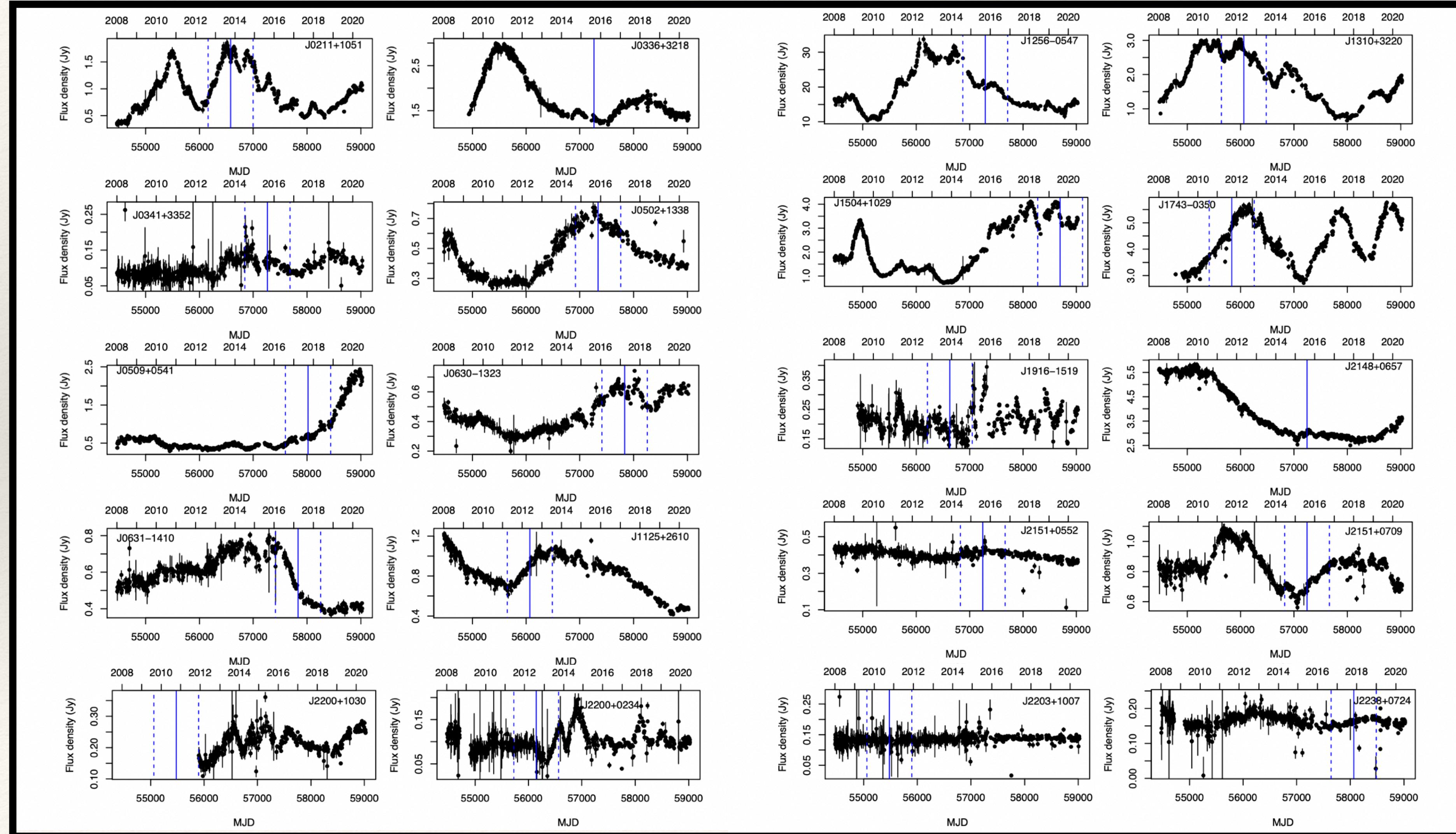
Radio Observations are Crucial for Neutrino Astronomy!

3σ Association of an individual neutrino with Blazar TXS0506+056



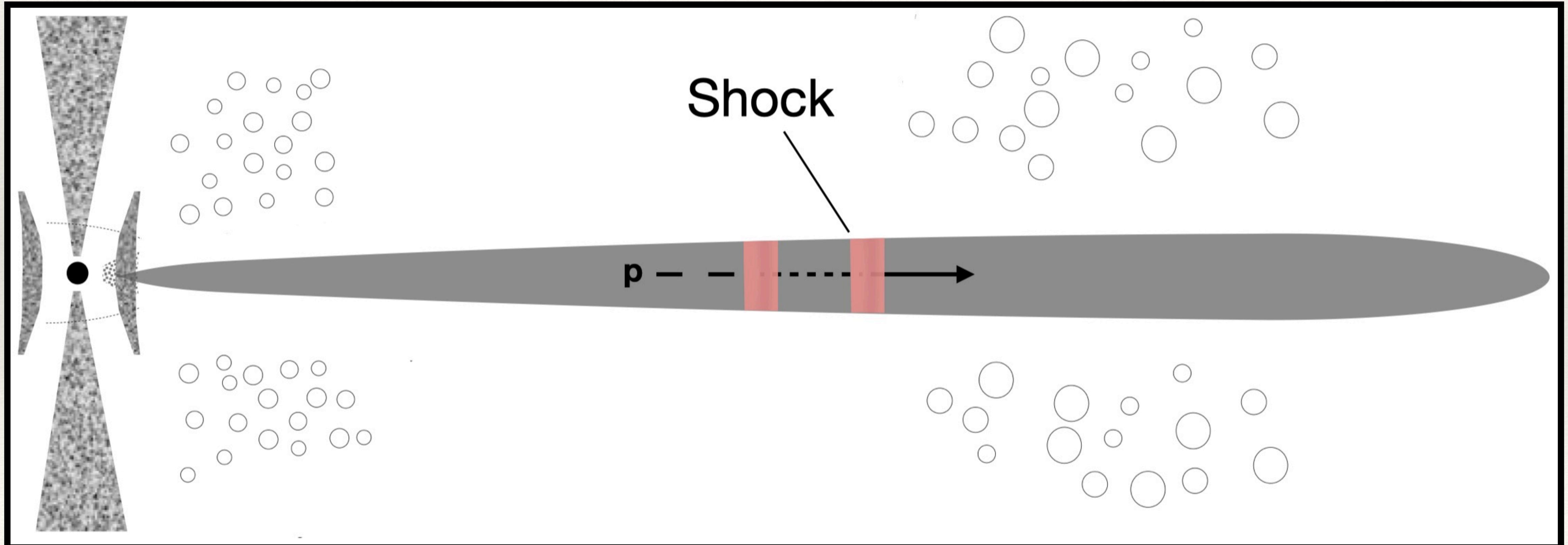
Statistical correlation of Neutrinos with Radio Flares in Blazars

Hovatta et al. 2021



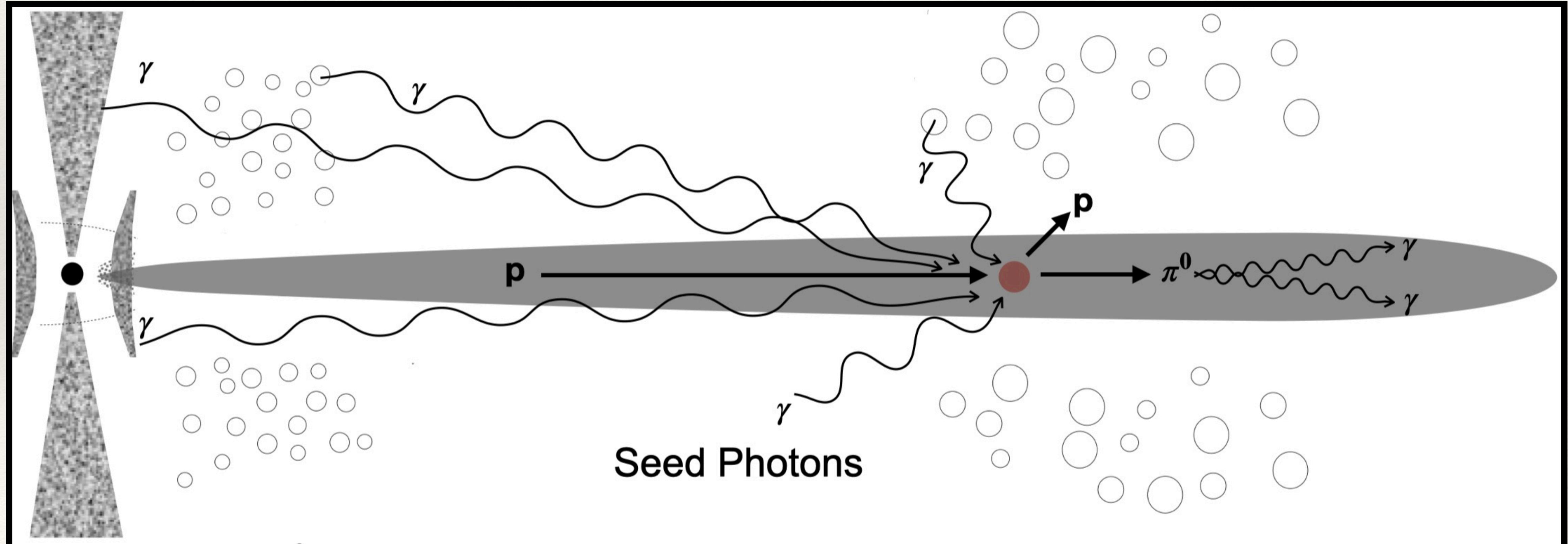
AGN Jets as Sources of Ultrahigh-Energy Cosmic rays

Relativistic protons might be accelerated near the central SMBH, e.g., in shocks.



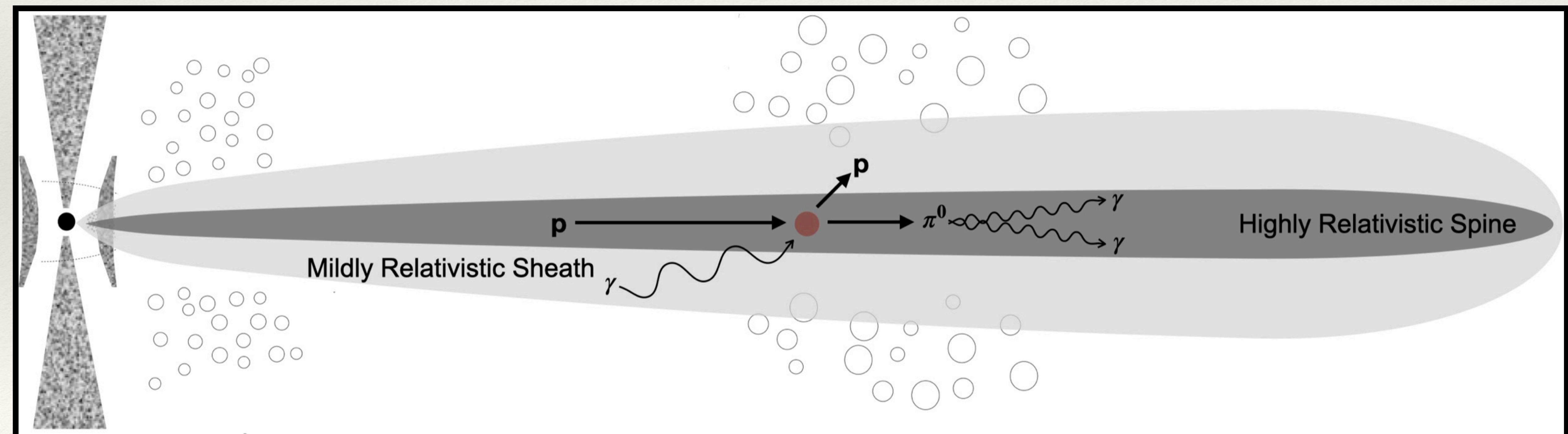
Hadronic Processes as Origin of Gamma-Ray Emission

Relativistic protons in the fast spine of a jet interact with soft ambient photon field (accretion disk, corona, NLR, BLR, etc.) \Rightarrow photopions \Rightarrow gamma rays



Hadronic Processes as Origin of Gamma-Ray Emission

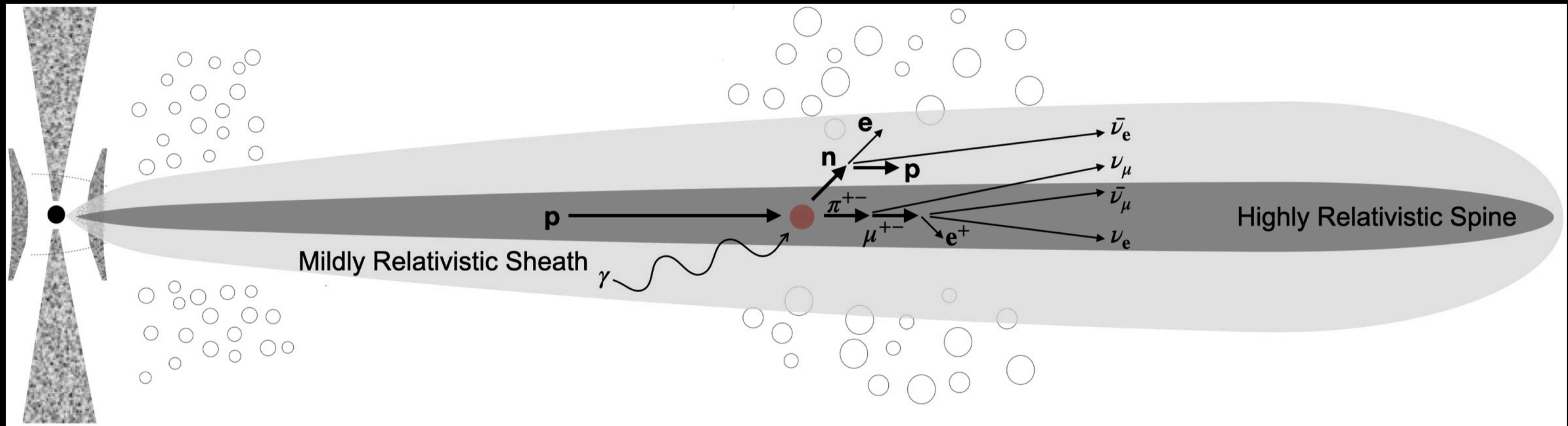
Attractive option for seed photon field: outer, slower jet sheath



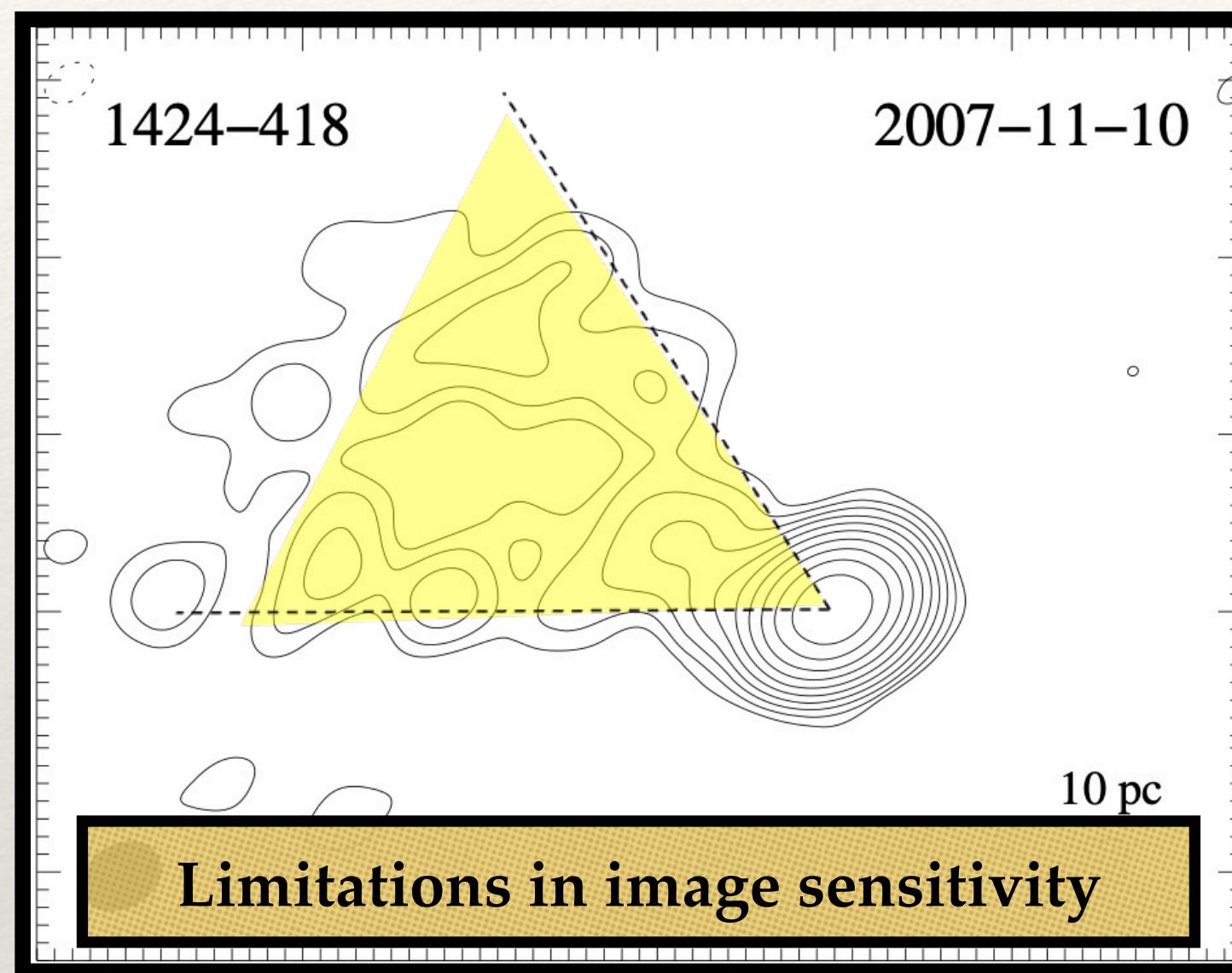
Hadronic Processes as Origin of Neutrino Emission

Same model might also explain neutrino emission

Need for high-sensitivity and high-angular-resolution VLBI observations to yield quantitative input for high-energy emission models

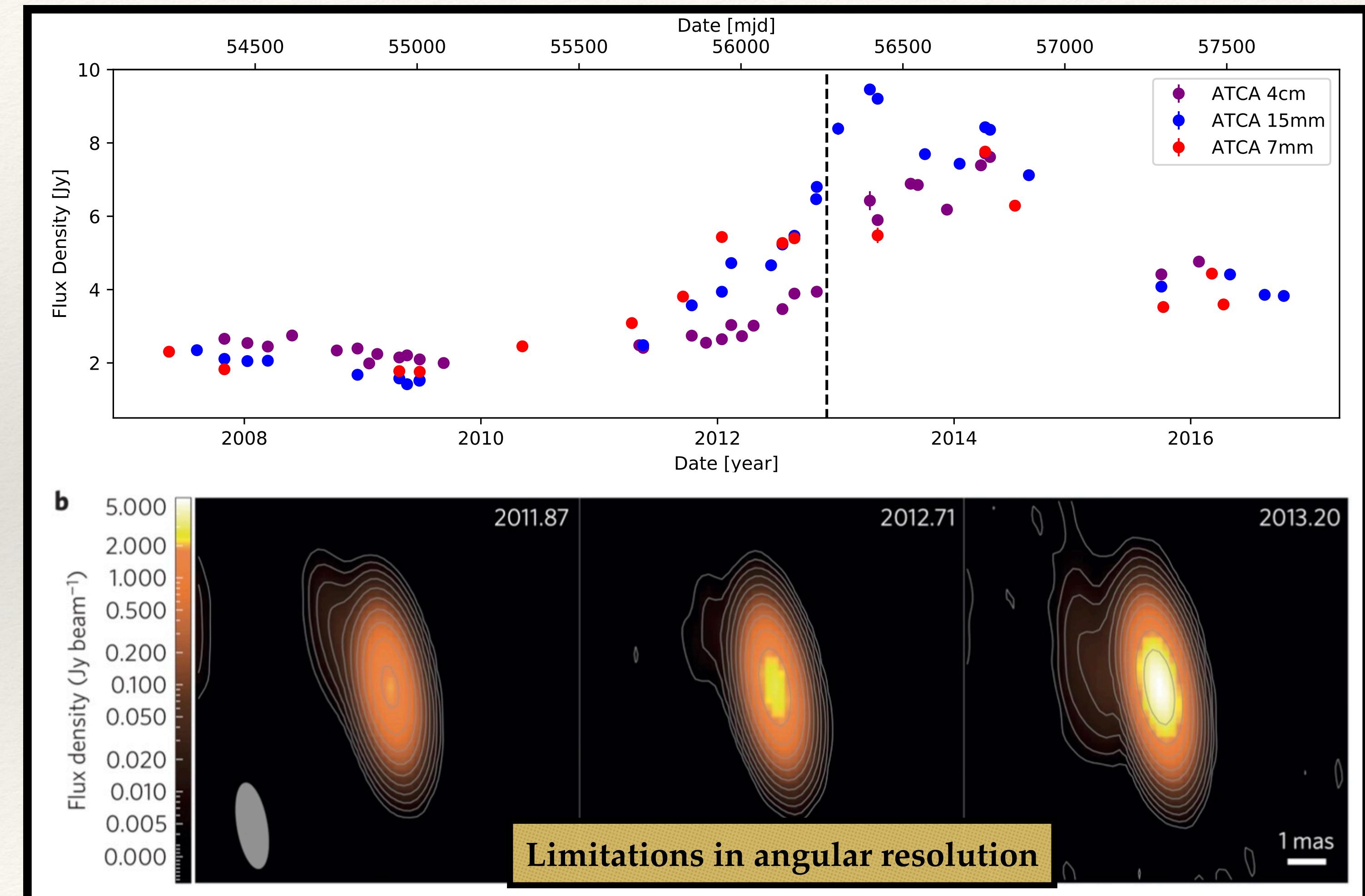


VLBI Observations of Candidate Neutrino Blazars: PKS 1424-418



- ❖ TANAMI VLBI images (LBA+) show wide opening angle and limb-brightened jet
- ❖ Light curve shows multi-year radio outburst

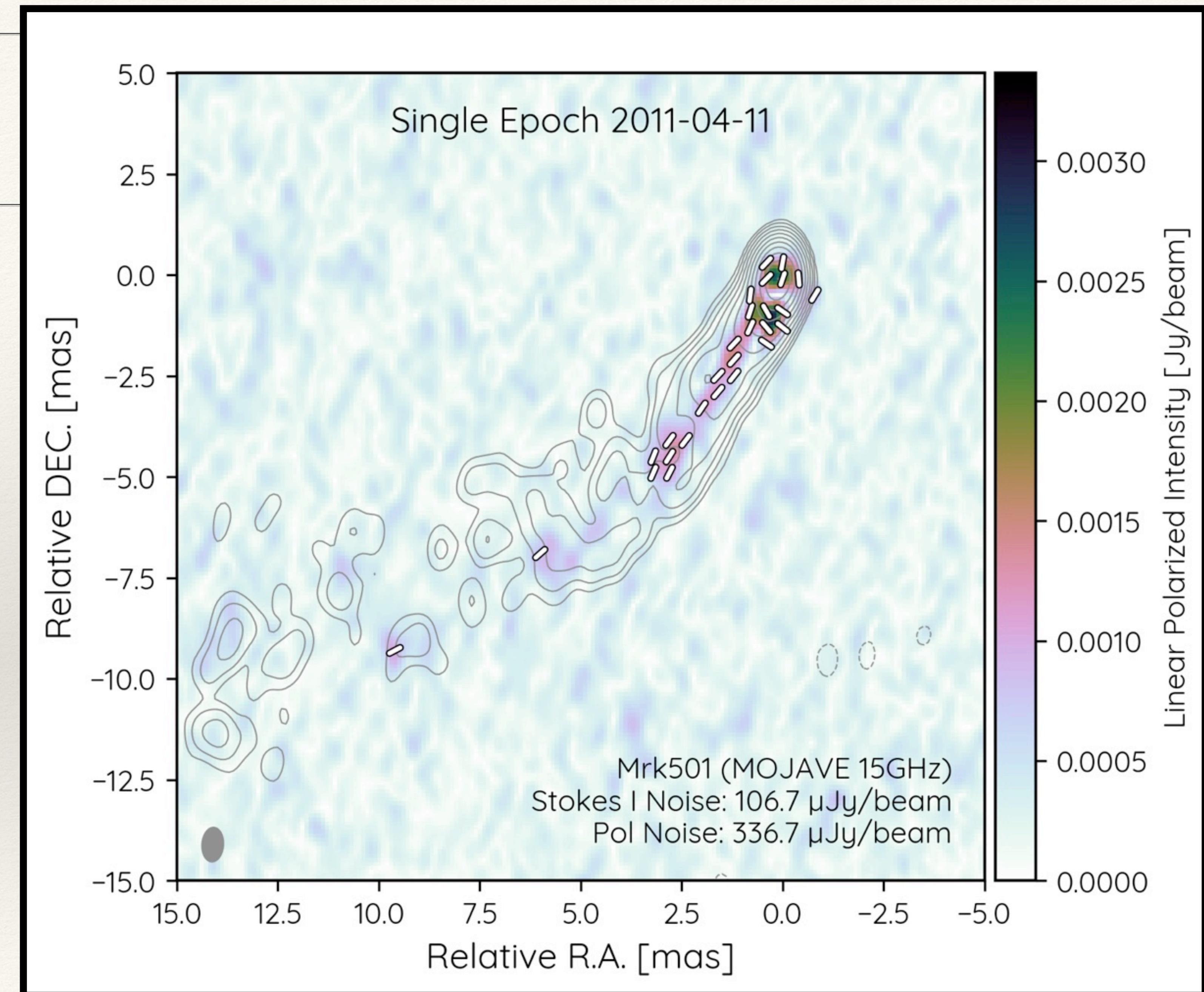
Kadler et al. 2016



VLBA Polarization

Mrk 501 (700mJy):

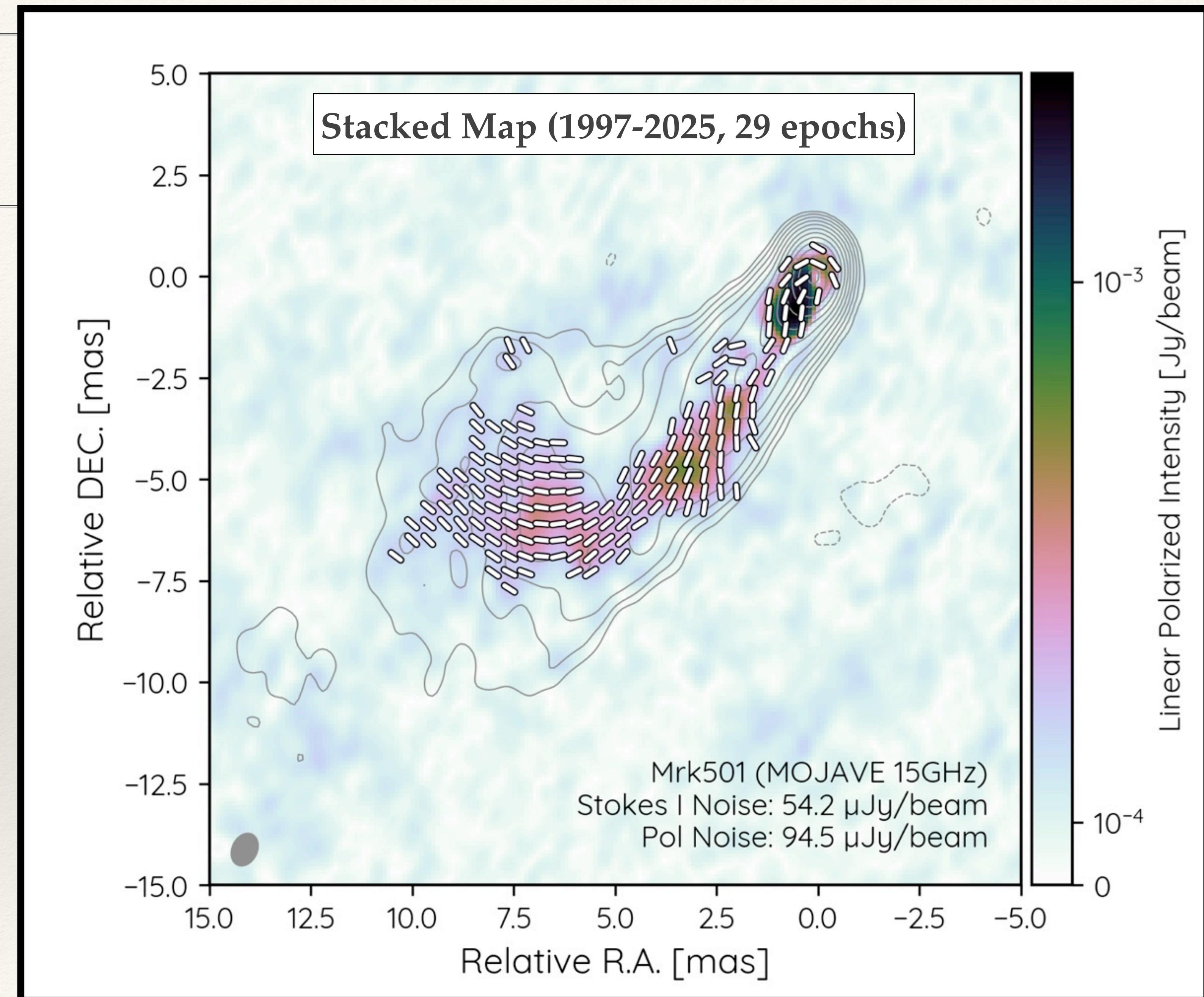
Spine visible in linear polarization in single VLBA snapshots



VLBA Polarization

Mrk 501 (700mJy):

Transversal polarization
structure only visible in
stacked images

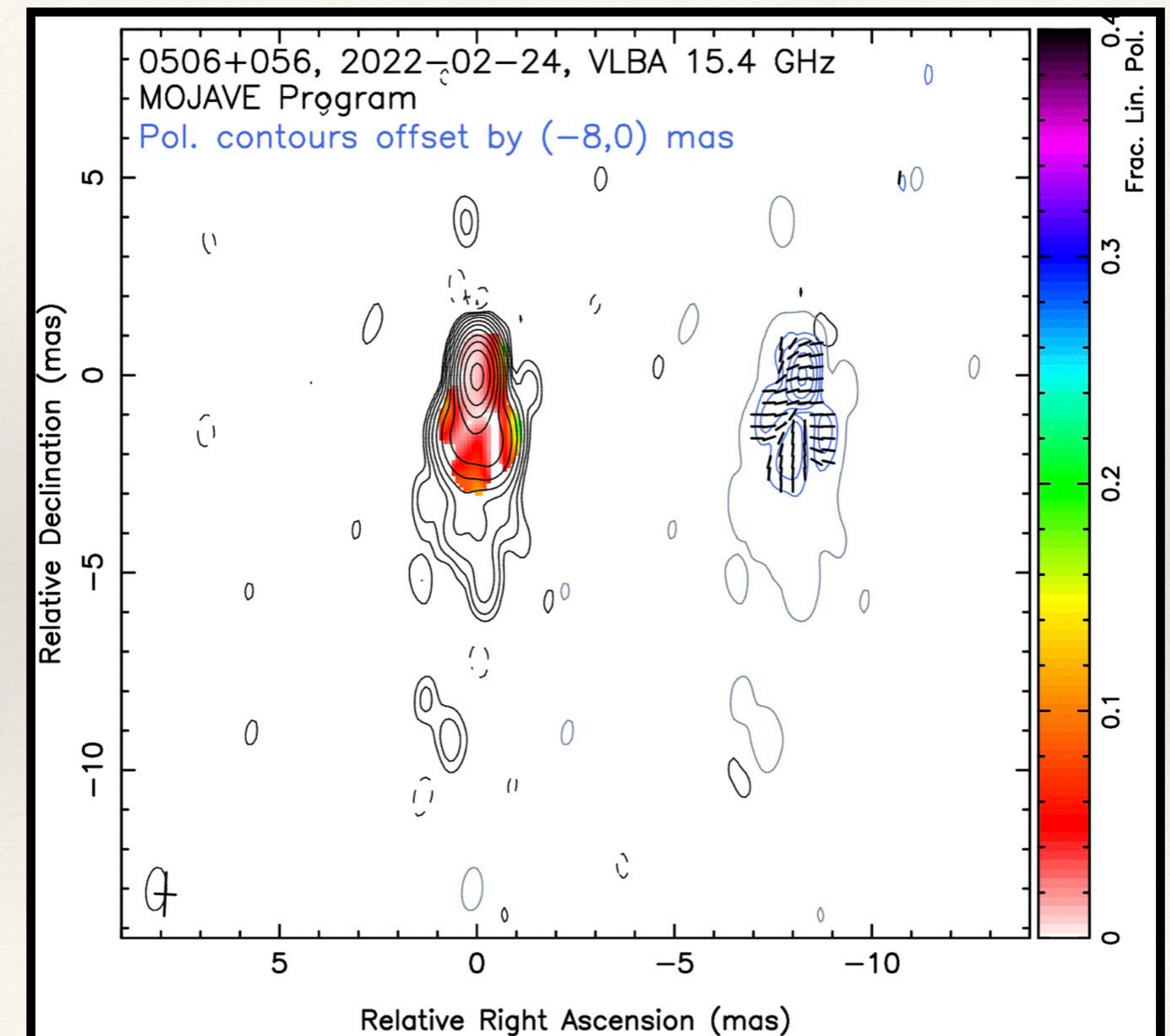


VLBA Observations: Polarization

TXS 0506+056:

Only high-probability neutrino-associated blazar.

Emission models underconstrained by current observational data.

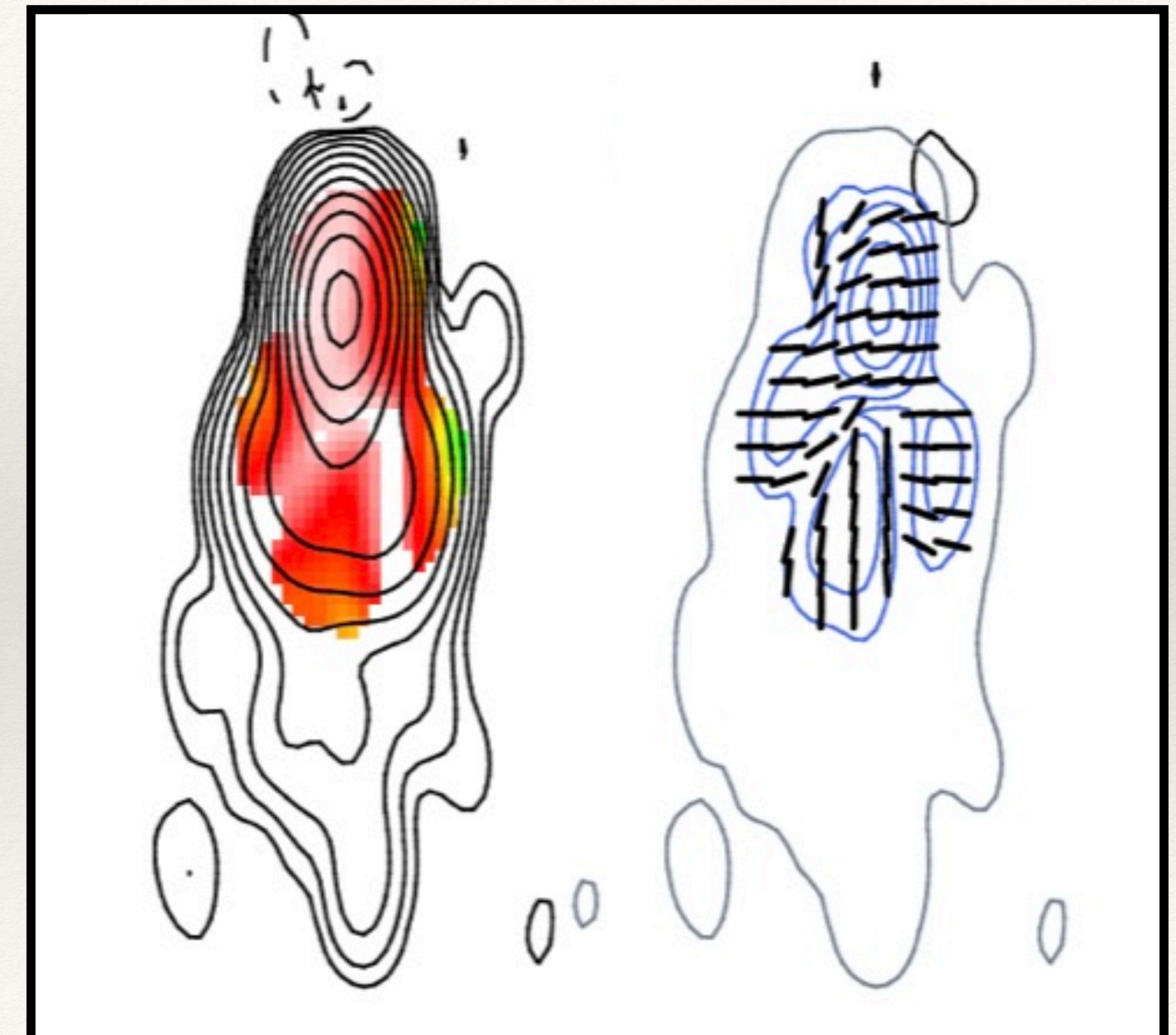


VLBA Observations: Polarization

TXS 0506+056:

Limb-brightened structure
visible in linear polarization
in „good VLBA epochs“

Can be used as a mask to
constrain sheath photon
field?

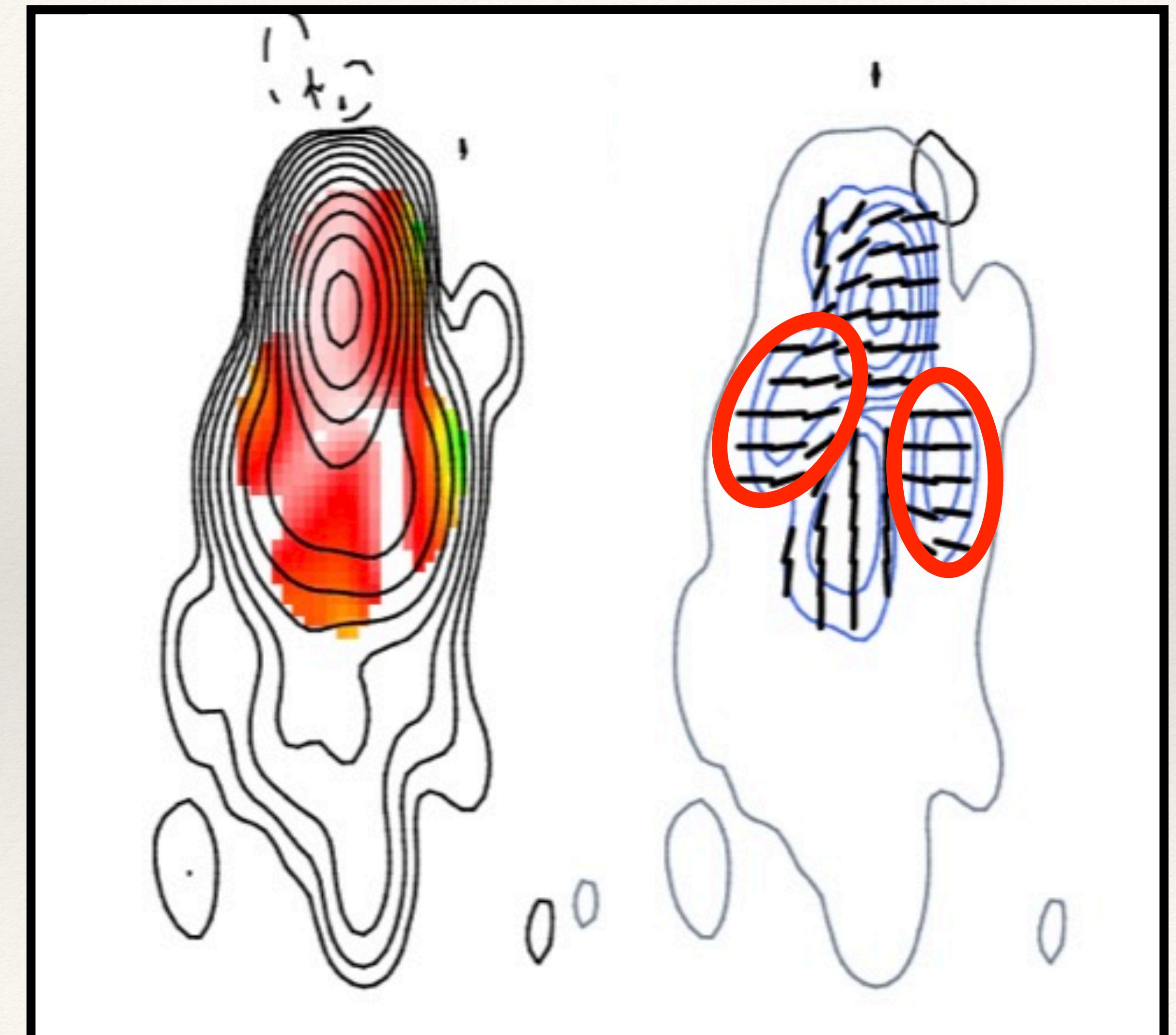


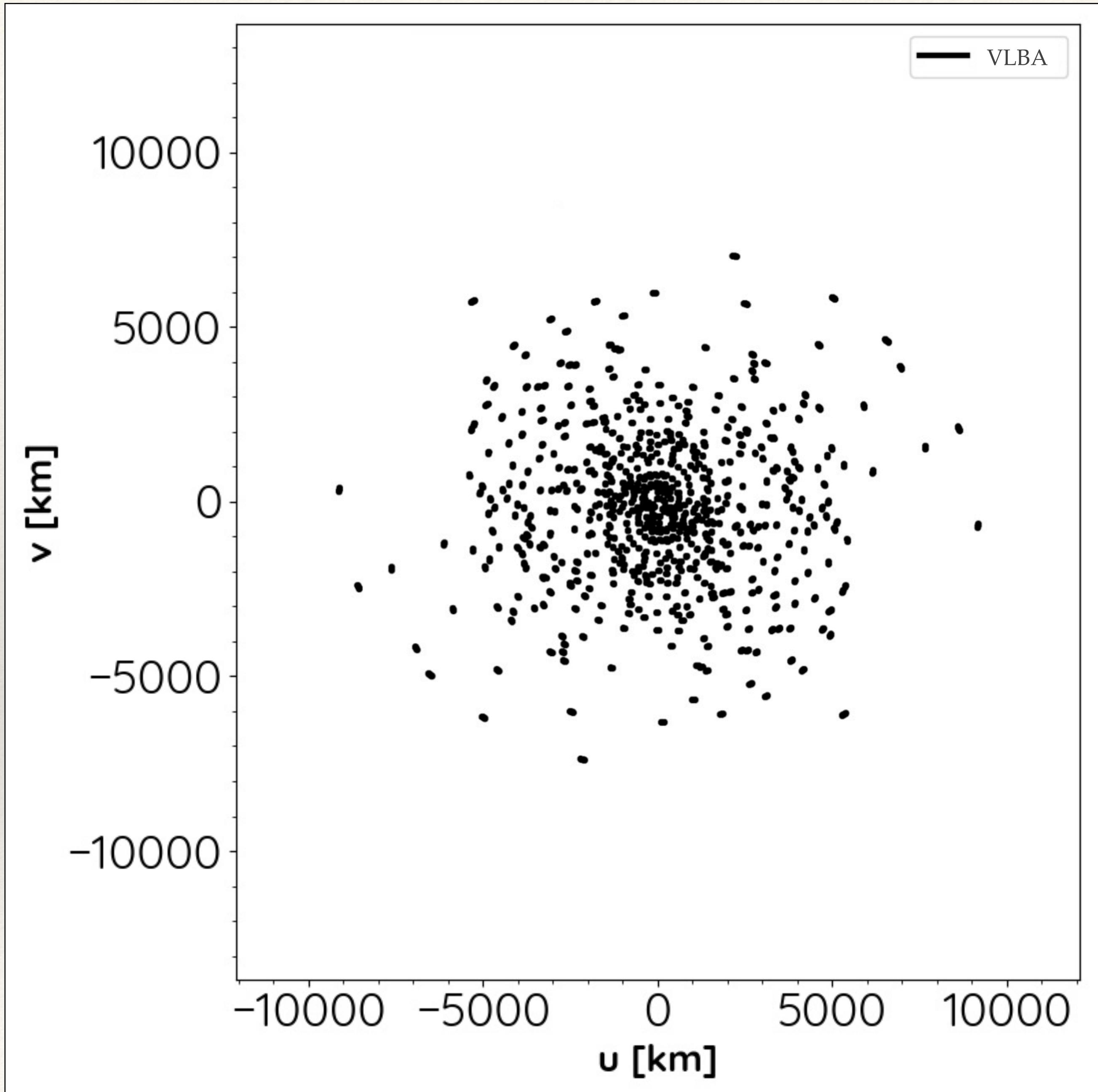
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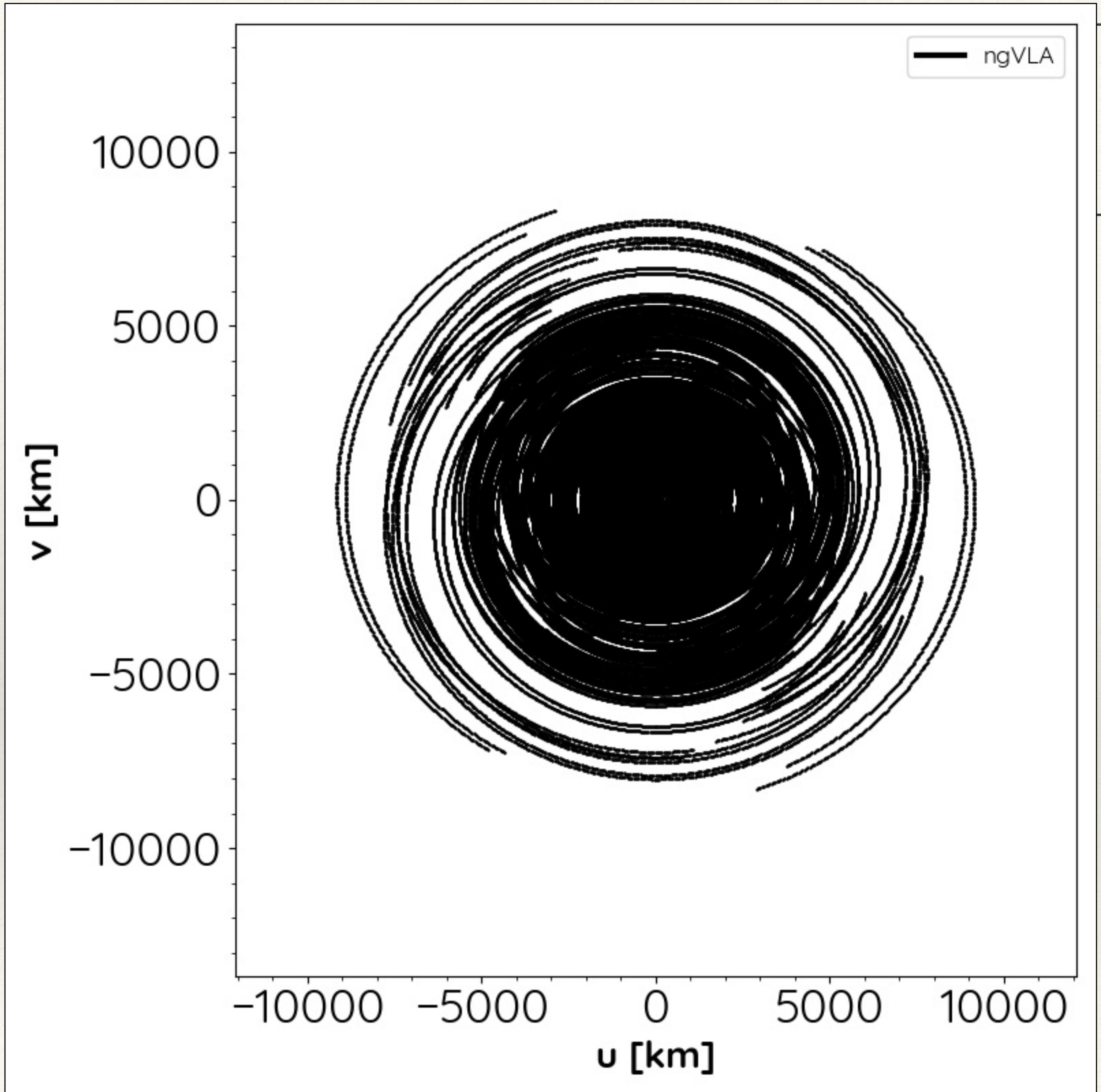
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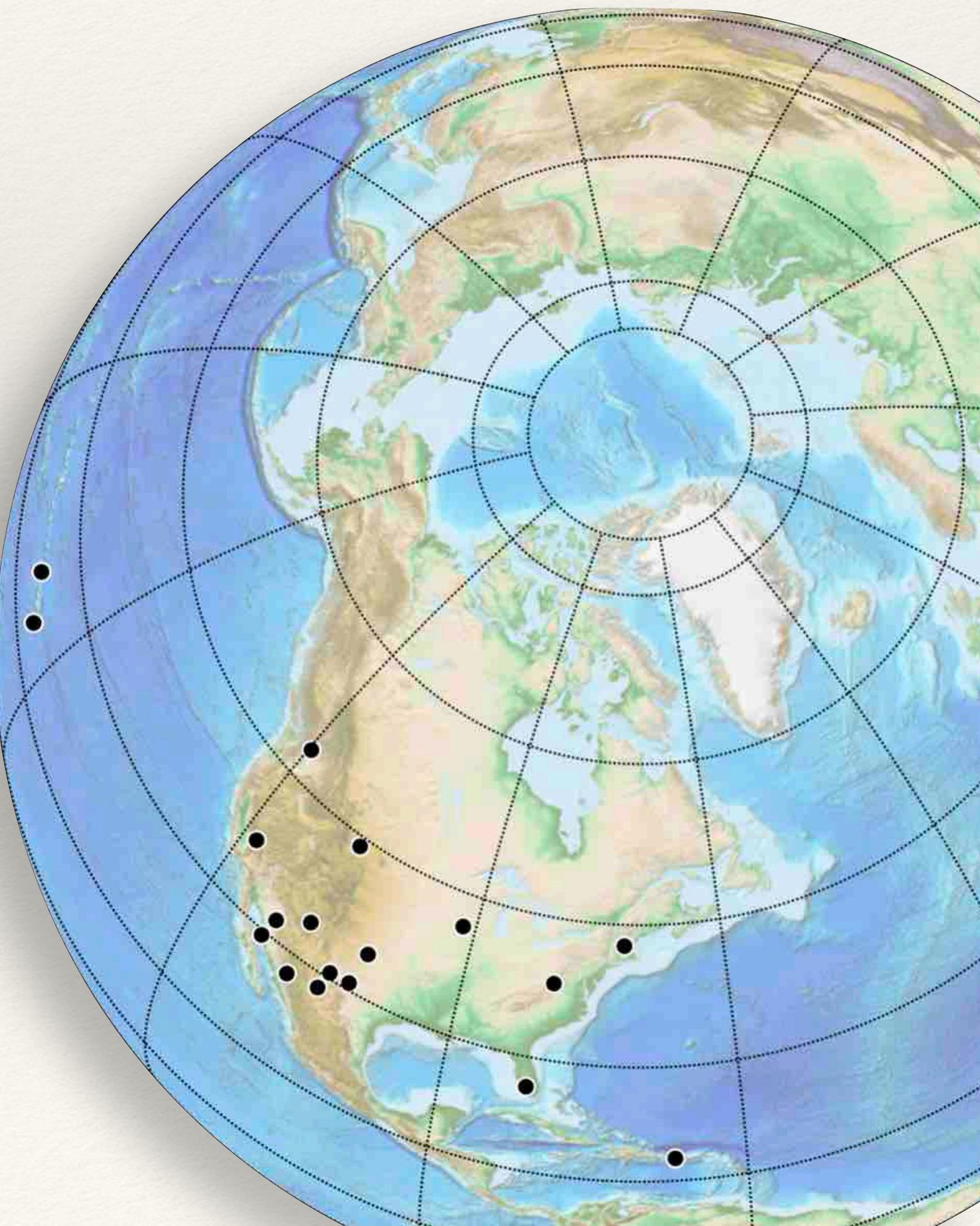


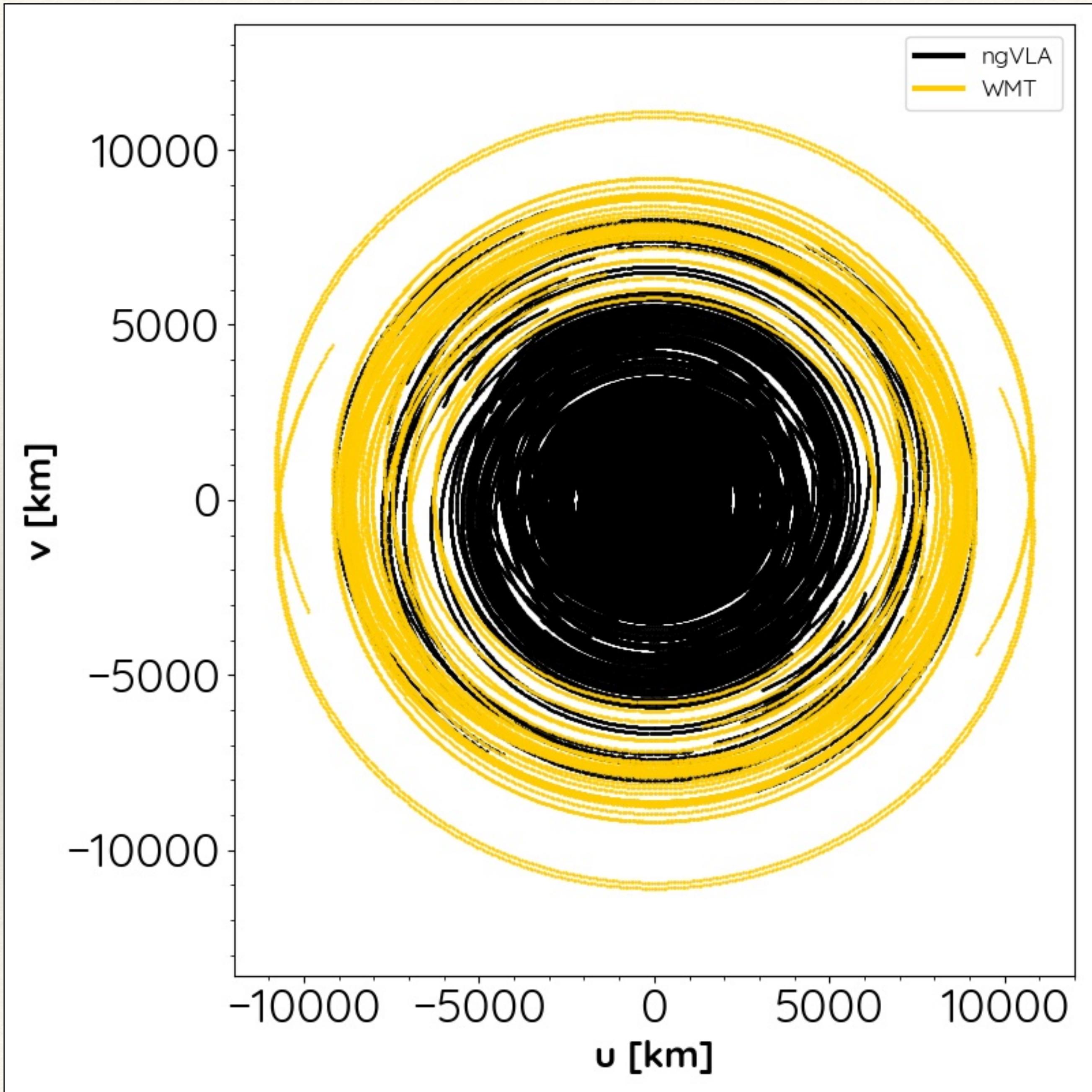
VLBA Image Fidelity Limited
by (u,v) -Coverage





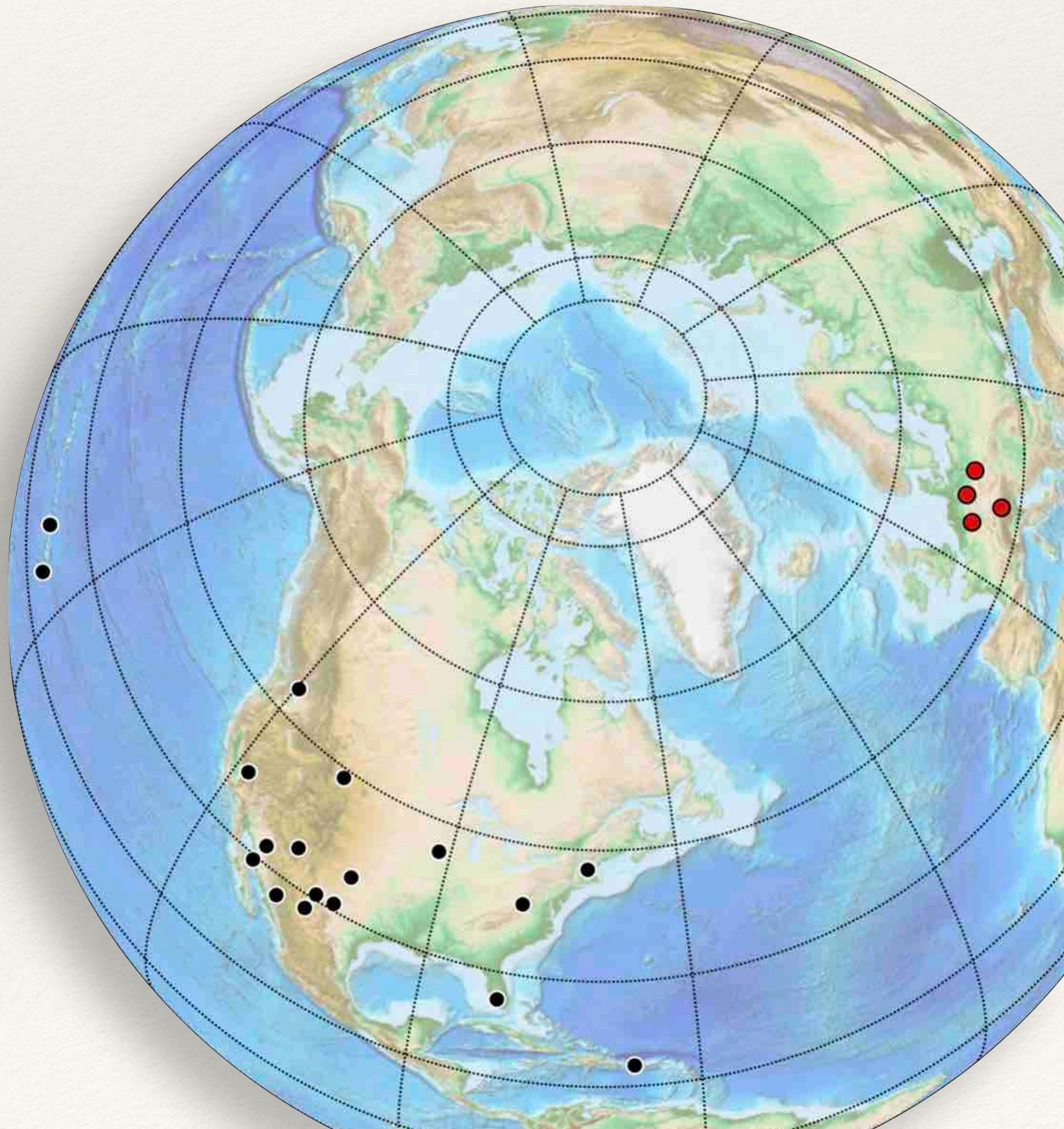
ngVLA (u,v)-Coverage

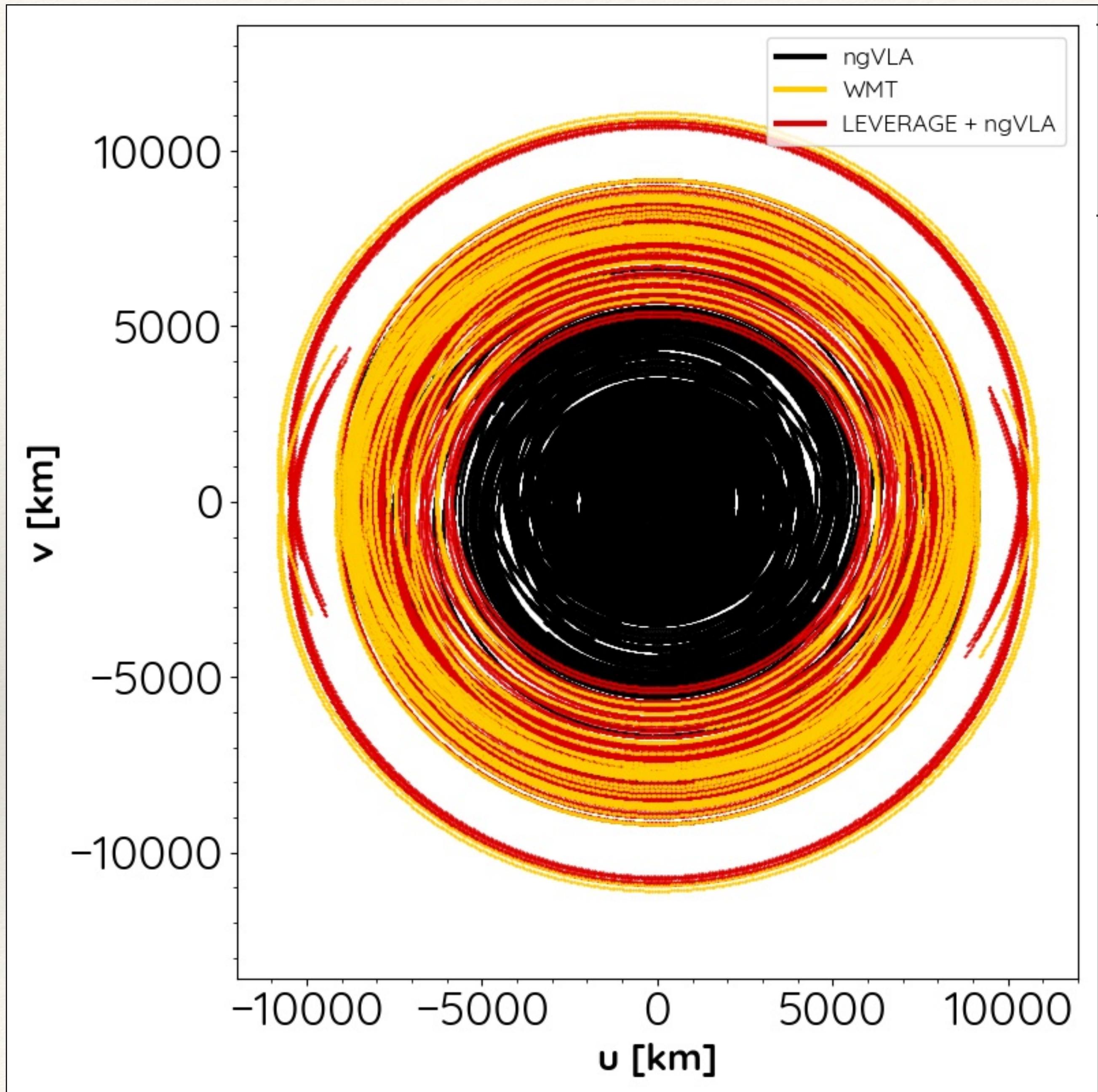




ngVLA (u, v)-Coverage

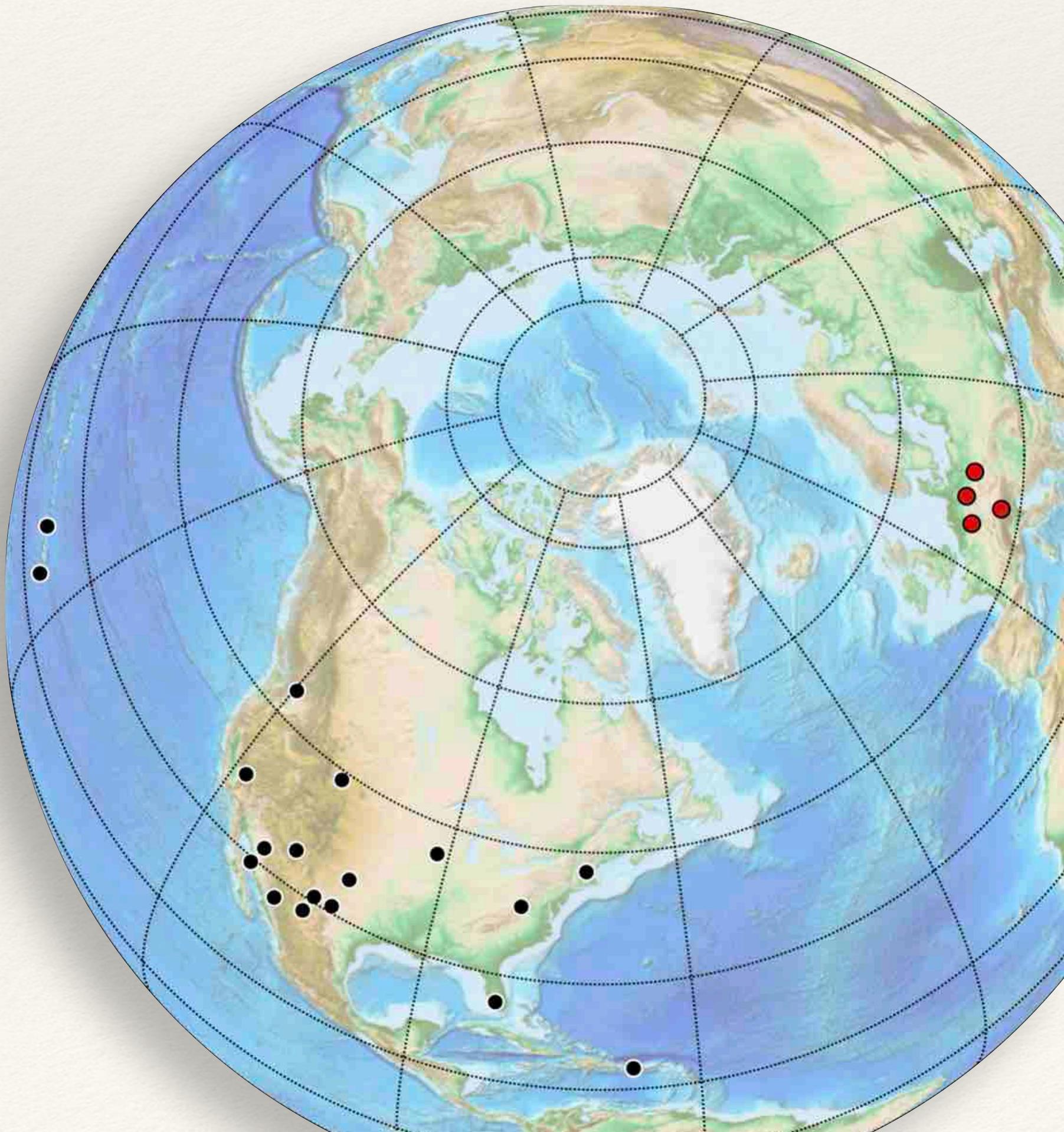
+ LEVERAGE





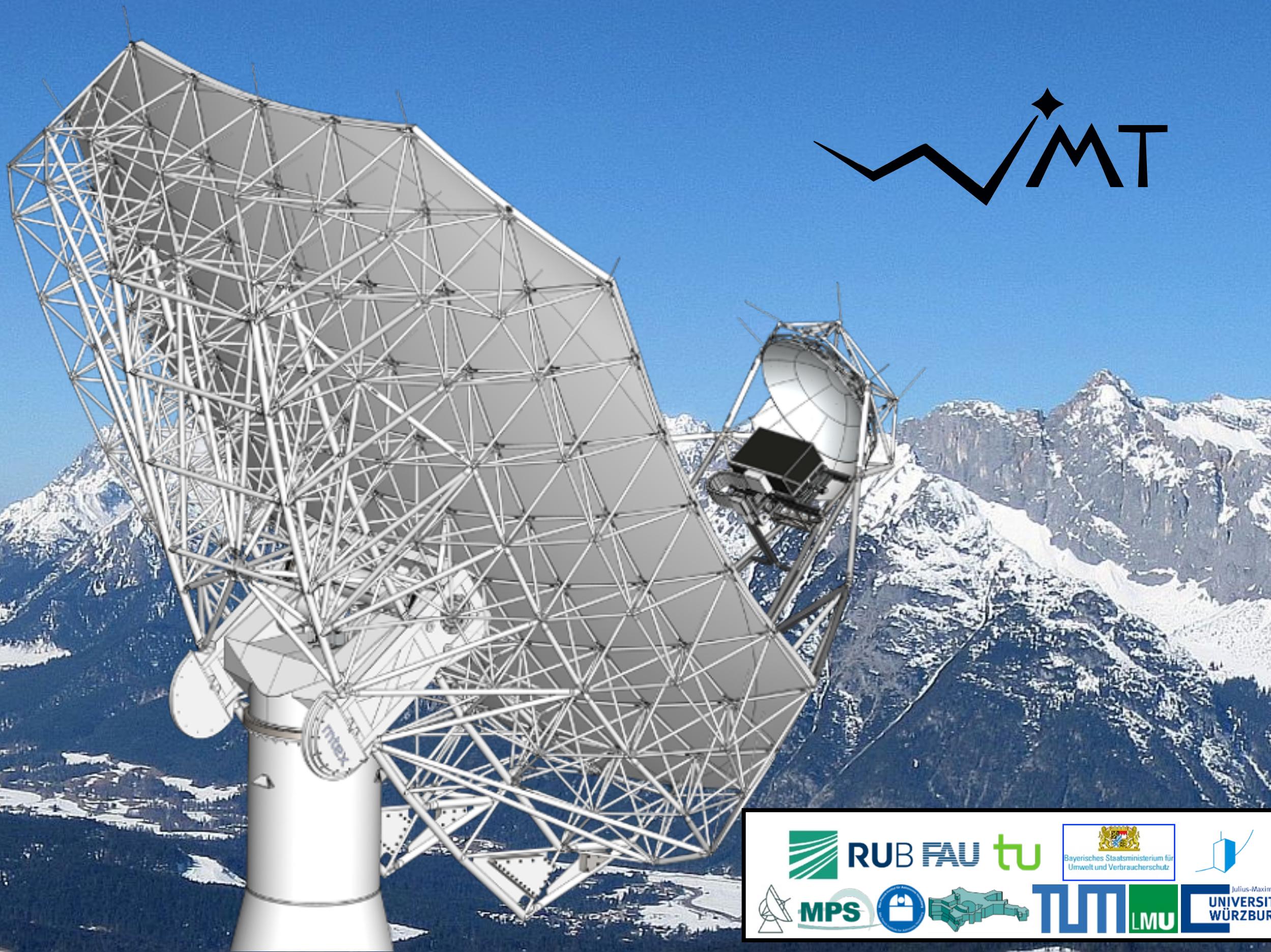
ngVLA (u,v)-Coverage

+ LEVERAGE



Wetterstein Millimeter Telescope

First Planned German ngVLA Telescope

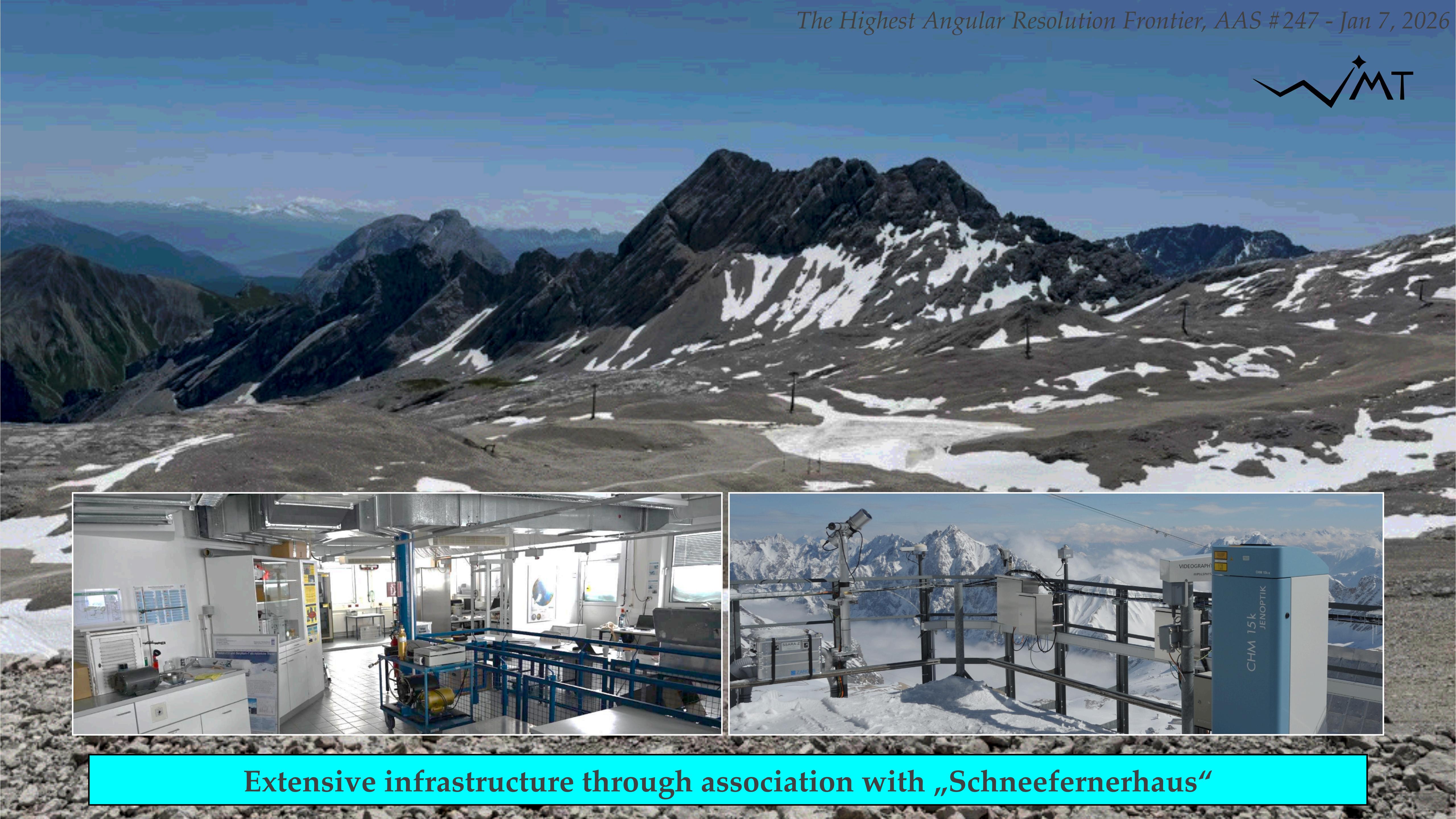


Environmental Research Station
„Schneefernerhaus“





High plateau „Zugspitzplatt“ at ~2600m in the German alps.

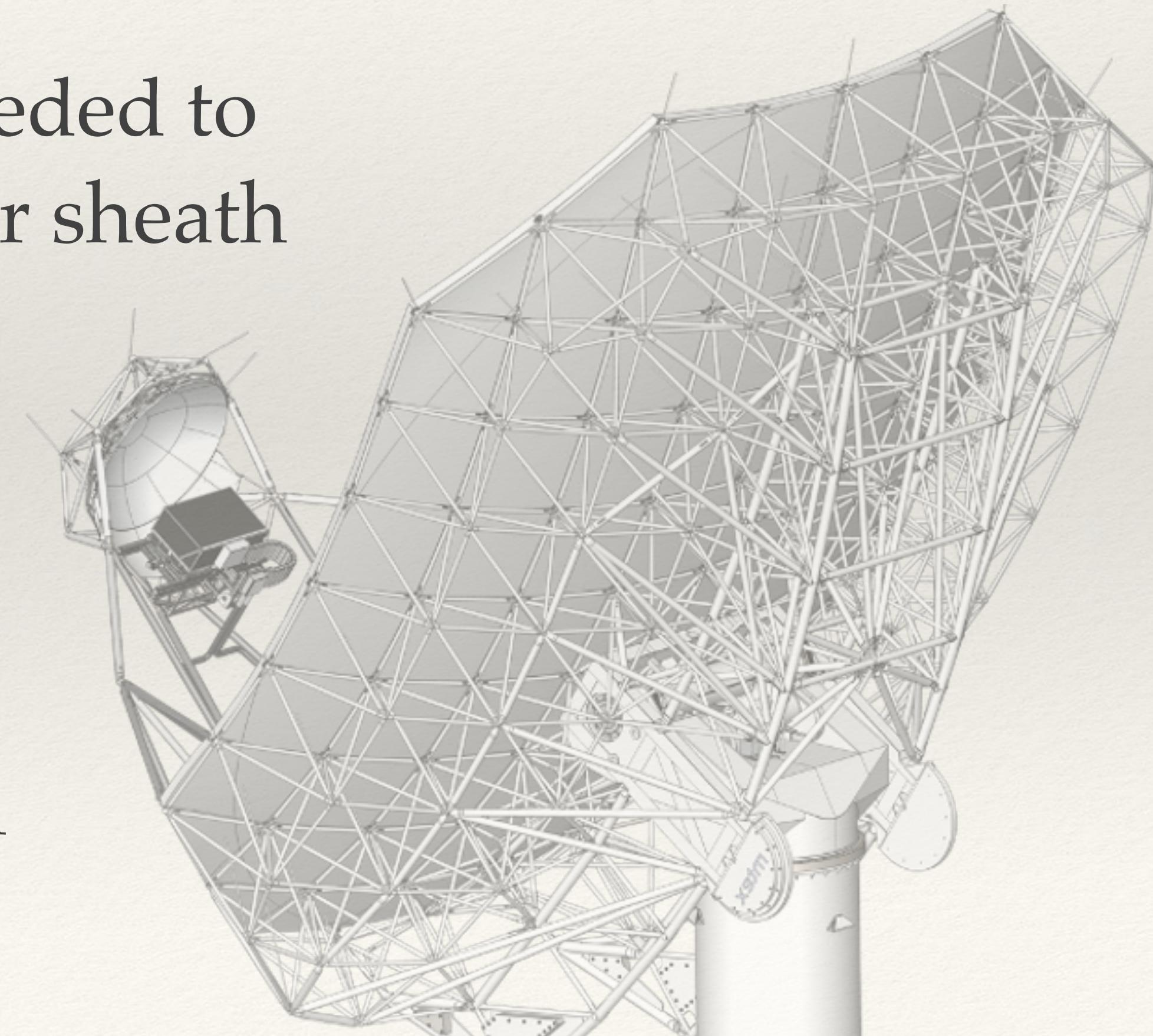


Extensive infrastructure through association with „Schneefernerhaus“

Summary and Perspectives for the Early ngVLA Era

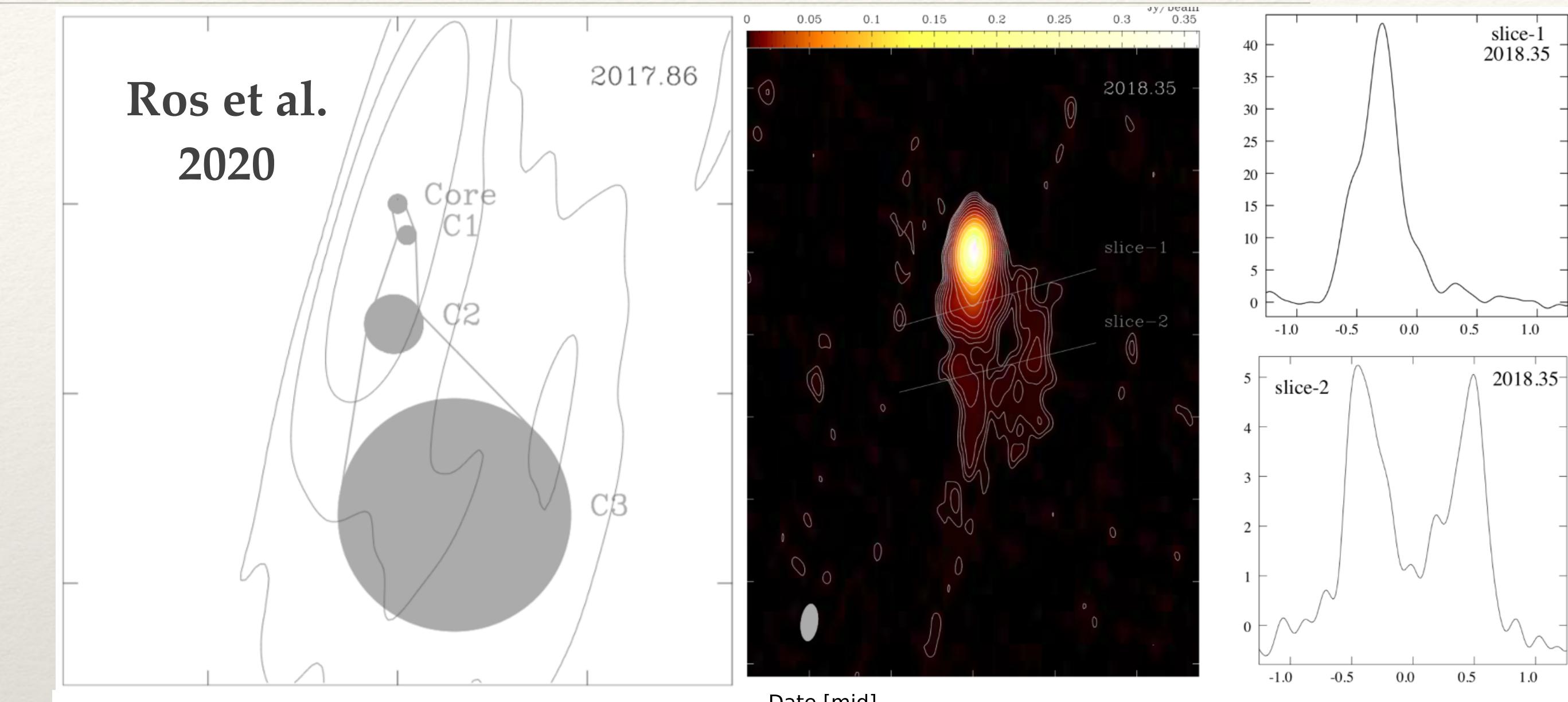
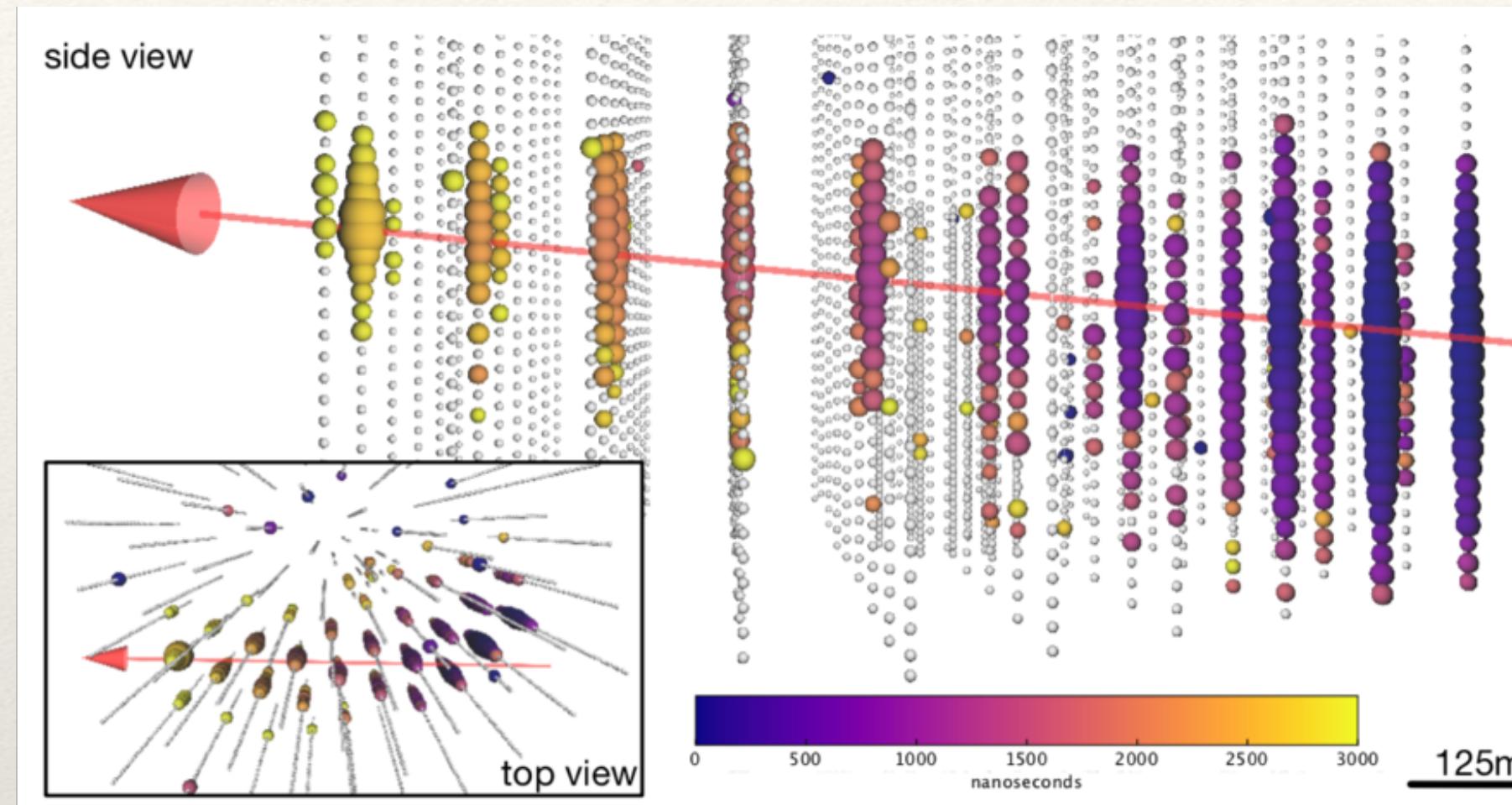


- ❖ Radio interferometry at milliarcsecond resolution can reveal the physics of neutrino production in structured blazar jets
 - ❖ High sensitivity and high dynamic range needed to separate highly-relativistic spine from slower sheath
 - ❖ Polarization can be key
- ❖ VLBA + ngVLA long-baseline stations will advance over current VLBI arrays
- ❖ LEVERAGE through transatlantic cooperation

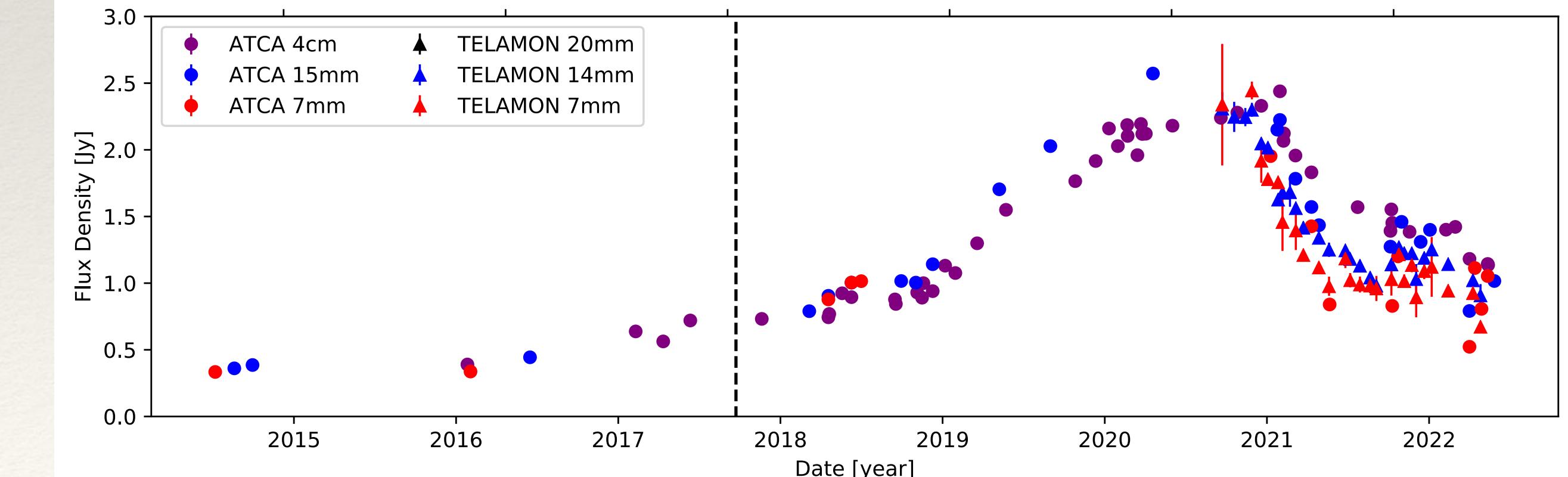


Additional Slides

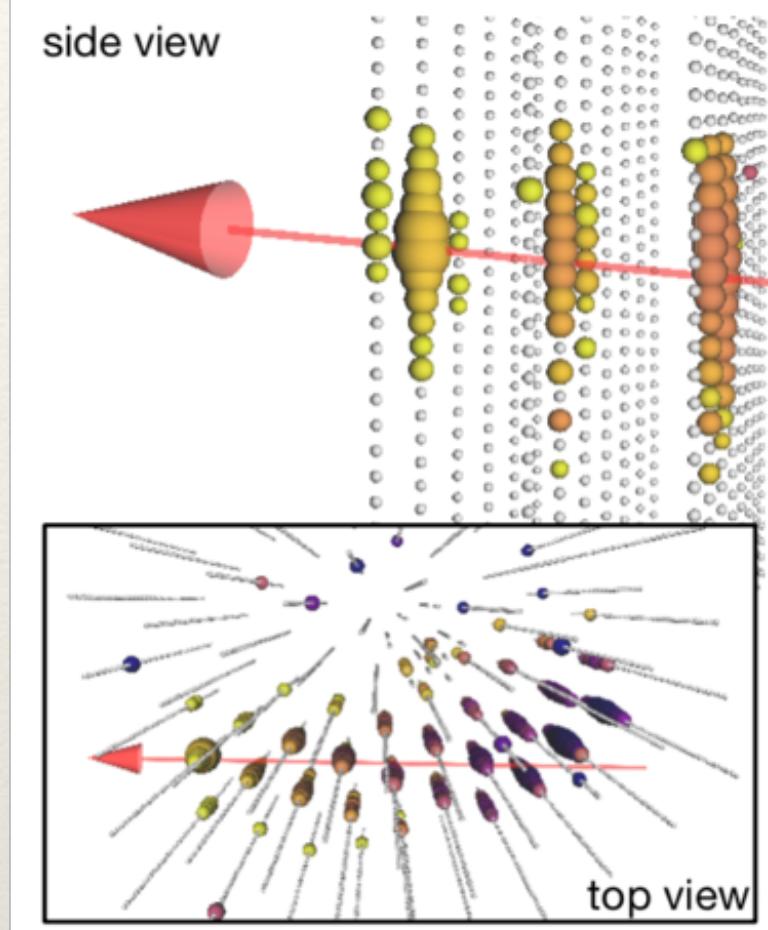
VLBA Observations of Candidate Neutrino Blazars: TXS 0506+056



- ❖ VLBA images show apparent superluminal core expansion and limb-brightened jet
- ❖ Light curve shows multi-year radio outburst



VLBA Ob



Ros et al.
2020

Limitations in image fidelity at
highest angular resolution

- ❖ VLBA images show superluminal components and limb-brightening
- ❖ Light curve shows an outburst

