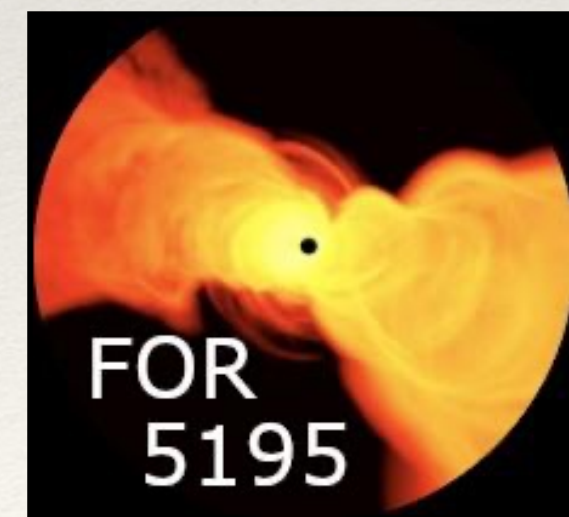


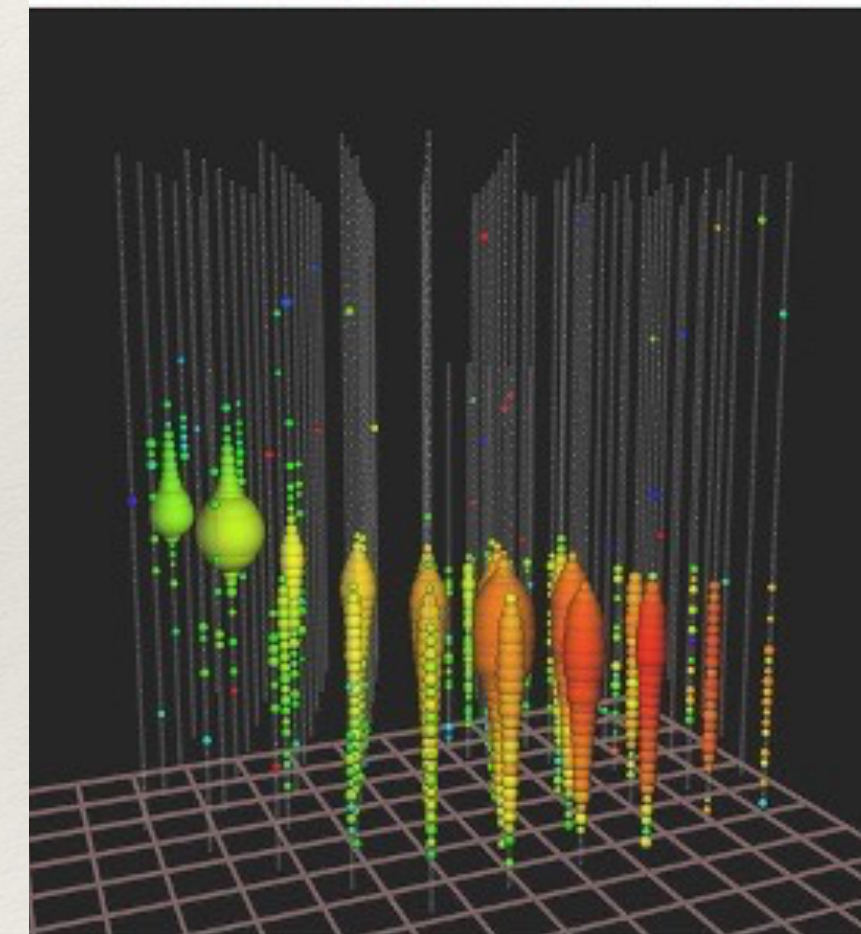
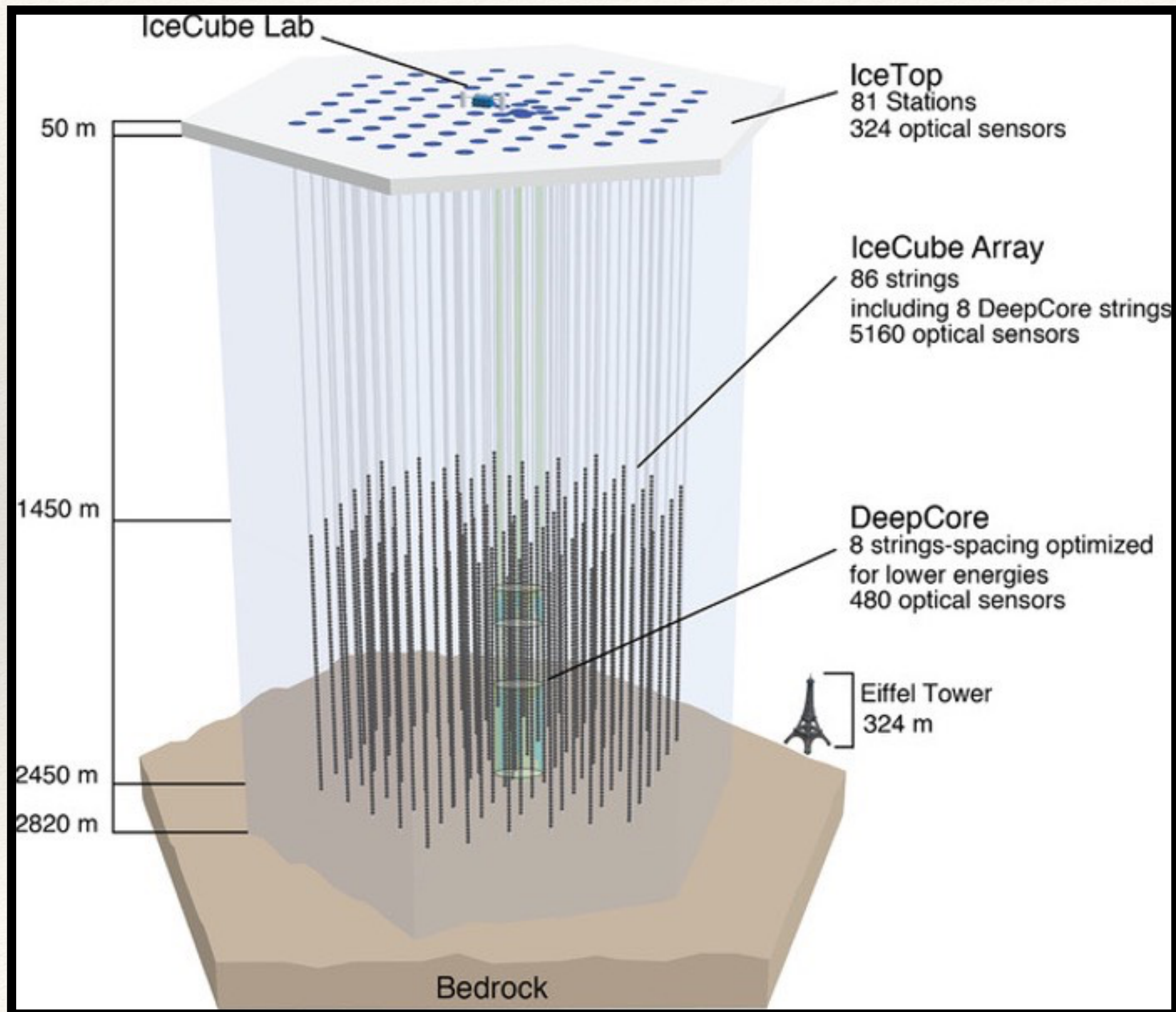
VLBI Probes of Neutrino Emission Processes in Blazars

Matthias Kadler
JMU Würzburg

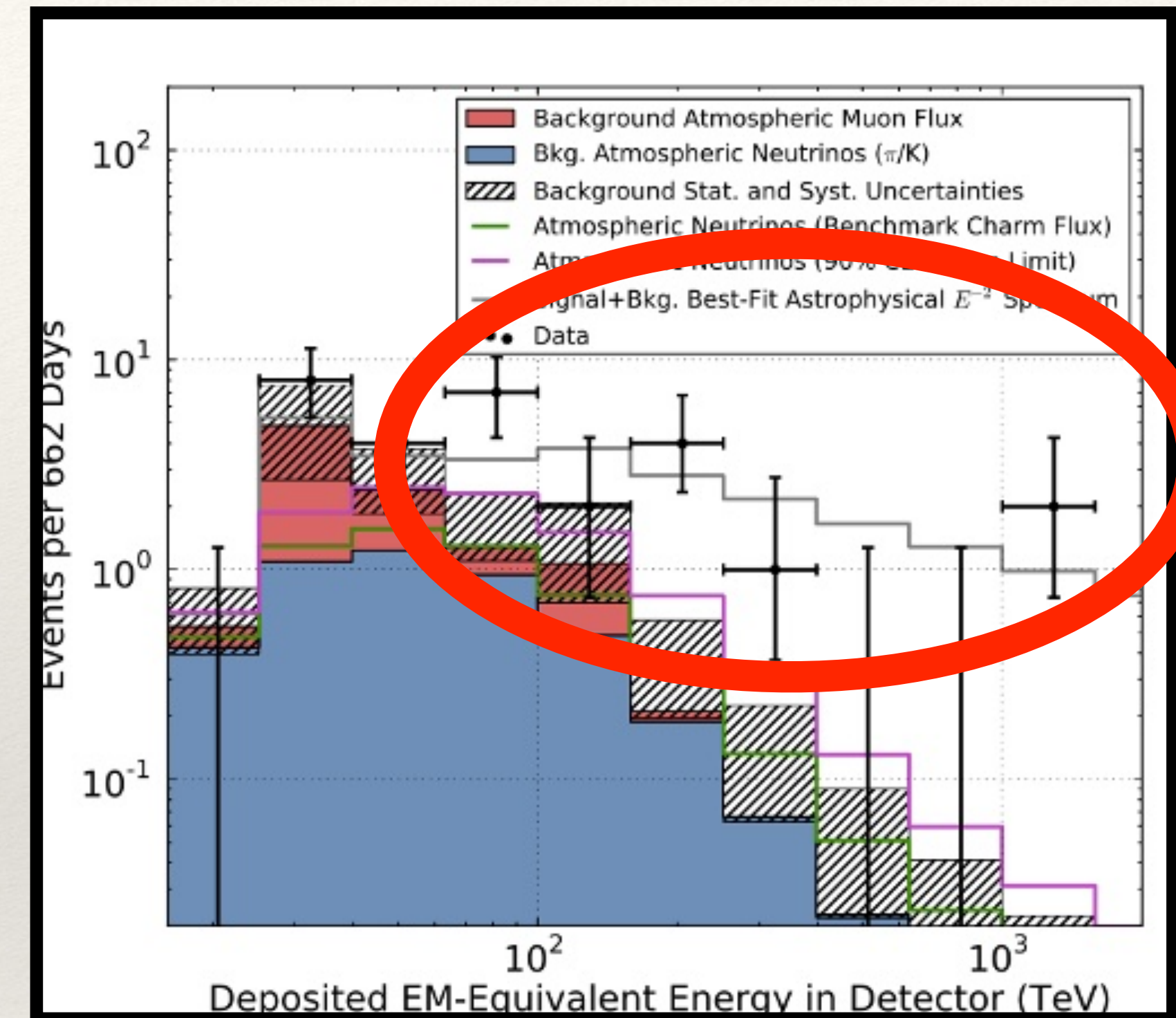
With contributions from: F. Eppel, F. Rösch, E. Ros, Y. Kovalev and others



Recent Breakthroughs in Neutrino Astronomy



Annalen der Physik,
Volume: 533, Issue: 11

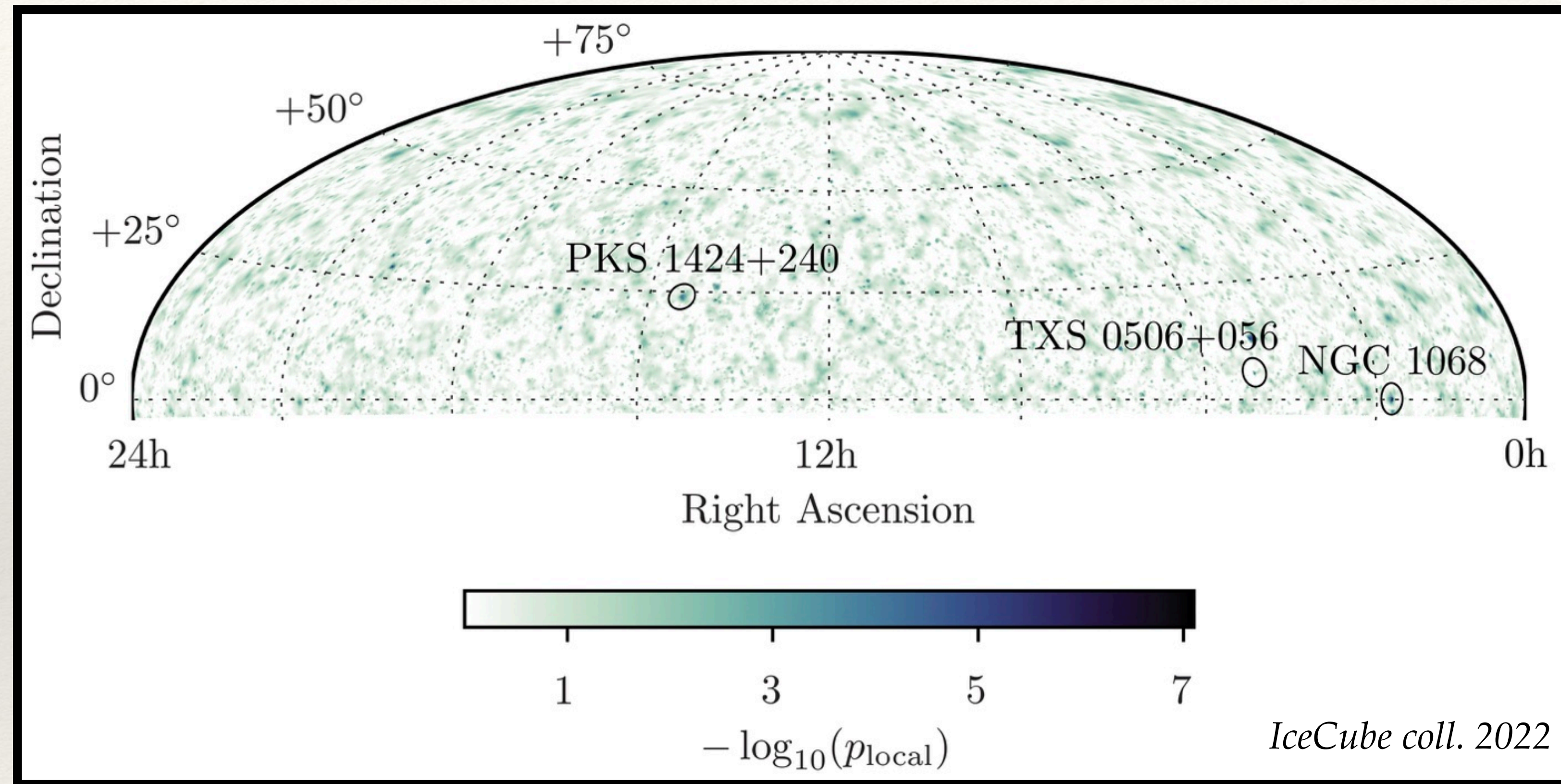


IceCube Collaboration 2013;
Aartsen et al. 2014

Recent Breakthroughs in Neutrino Astronomy

Latest IceCube Searches:

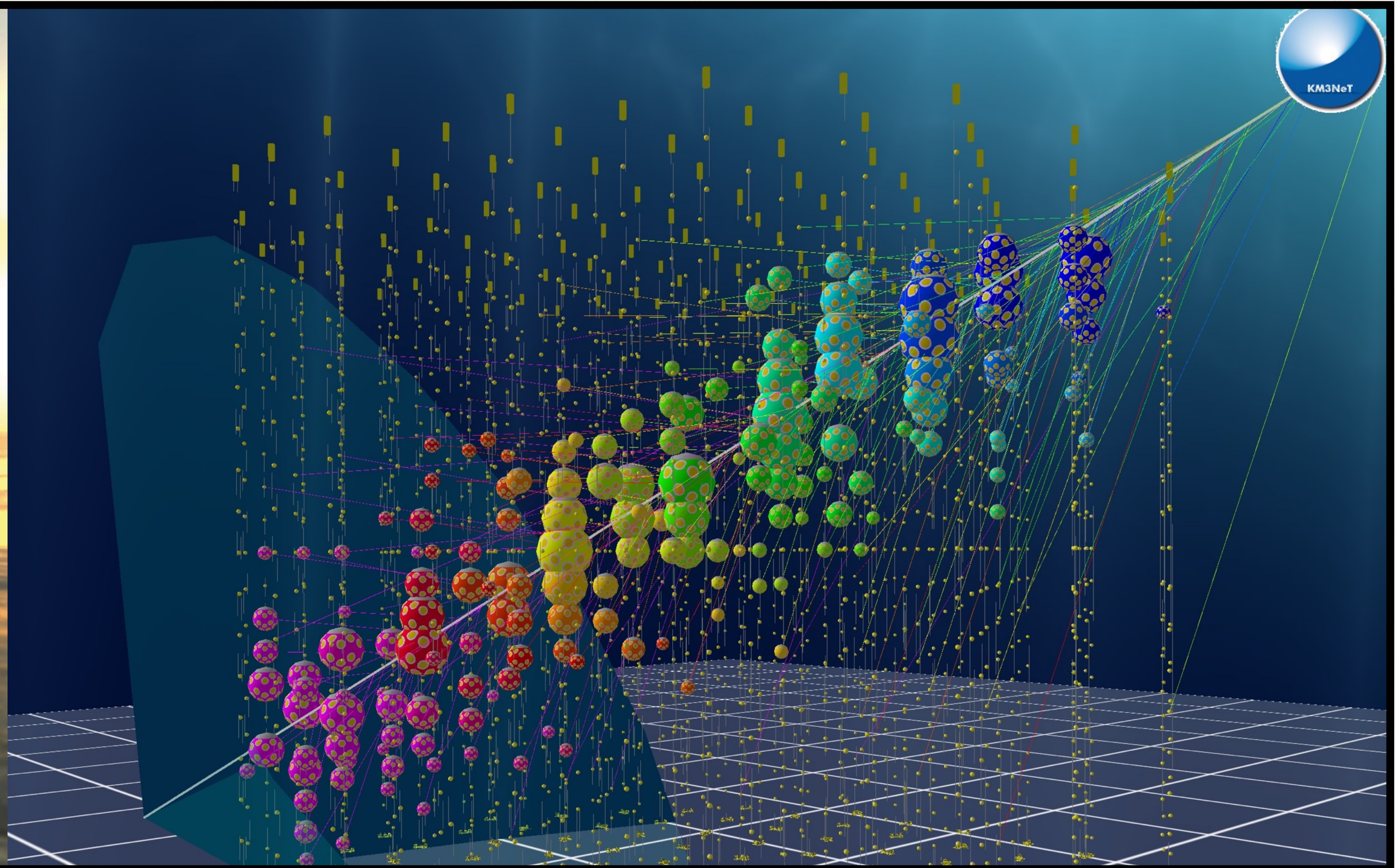
- Blind all-sky search (10-years IC data)
- Correlations with tested list of sources (northern catalog, $\sim 3\sigma$ post-trial)
- Most significant spots (pre-trial):
 - NGC 1068 (4.2σ), PKS 1424+240 (3.7σ), TXS 0506+056 (3.5σ)



Events largely isotropically distributed, favouring extragalactic origin

Recent Breakthroughs in Neutrino Astronomy

KM3NeT Collaboration



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

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**.

Energy Event KM3-230213A

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Y. BECHERINI,¹⁵ M. BENDAHMAN,¹⁰
NOIT,²⁴ E. BERBEE,²⁵ E. BERTI,¹
A. B. BOUASLA,²⁸ J. BOUMAAZA,²⁹
F. BRETAEU,¹³ M. BREUHAUS,⁷

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 99 % 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 %.

**COSMIC
CATCHER**

Deep-sea telescope detects
neutrino with highest
energy ever recorded

4 Feb 2025

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E. ECKEROVÁ,^{20,21} A. EDDY,³⁶

o-ph.HE]

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E. ECKEROVÁ,^{20,21} A. EDDY,³⁶
S. EL MENTAWI,⁷ V. ELI,³⁷
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1 [astro-ph]

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KM3NeT COLLABORATION

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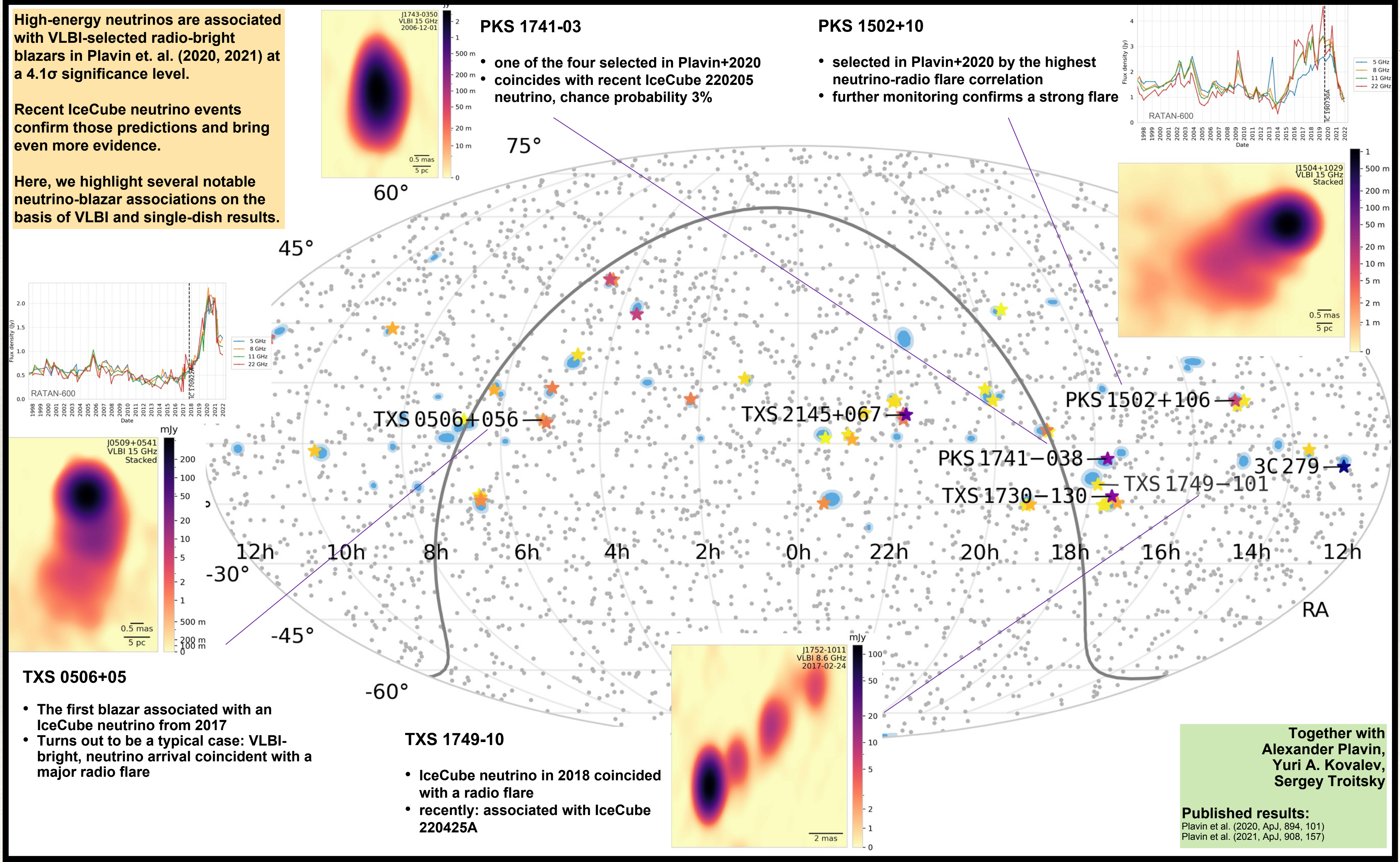
arXiv:2502.00000

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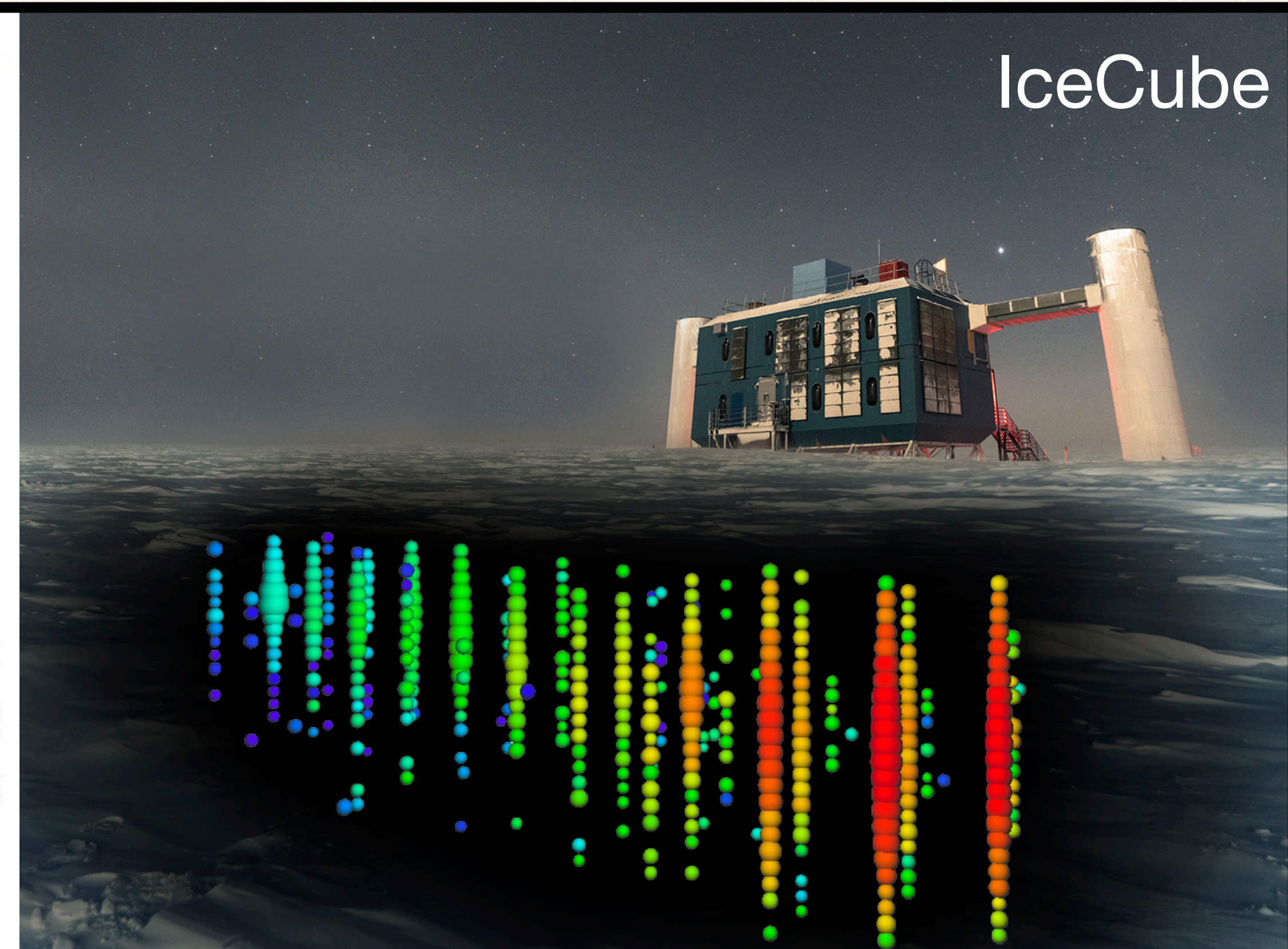
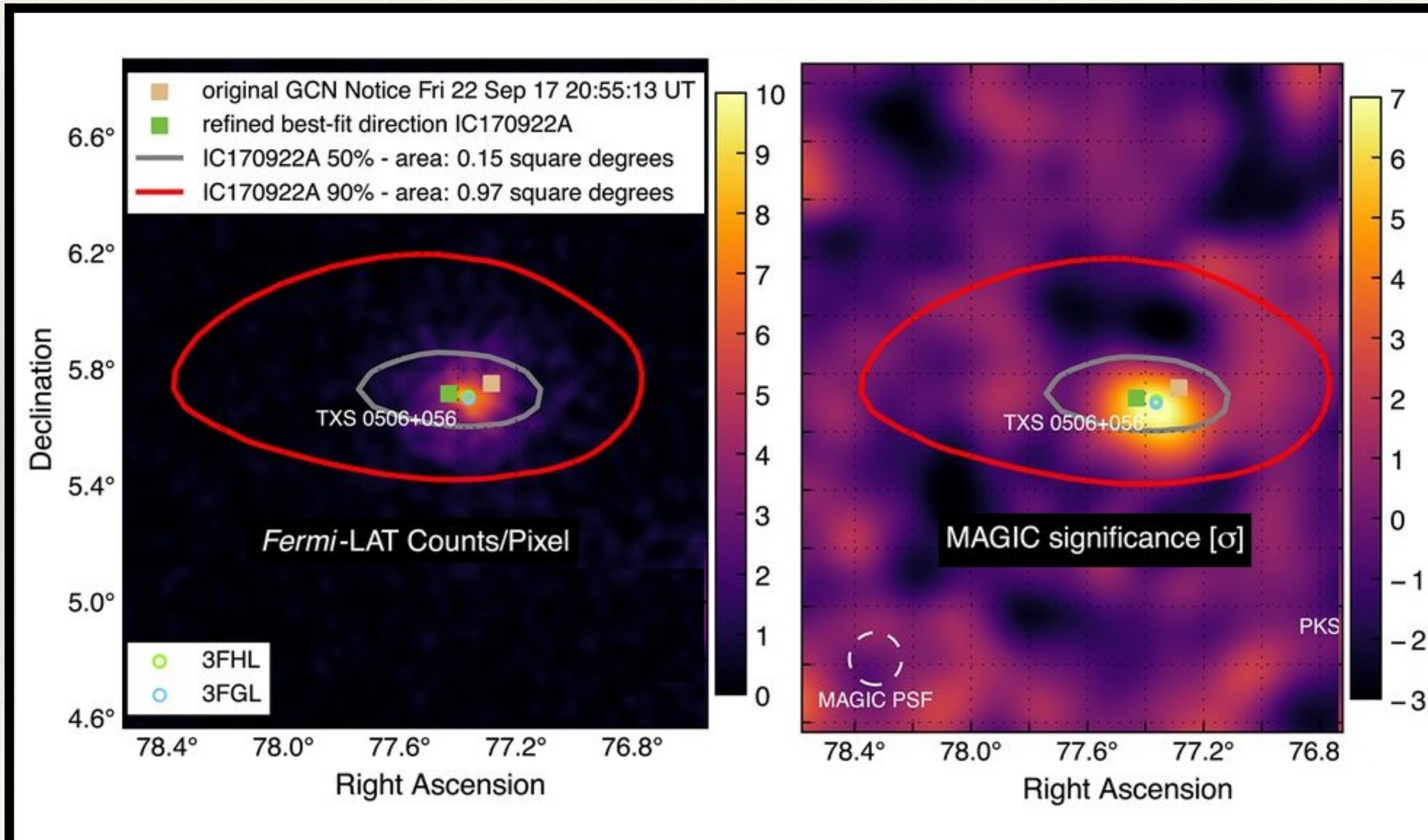
¹ INFN
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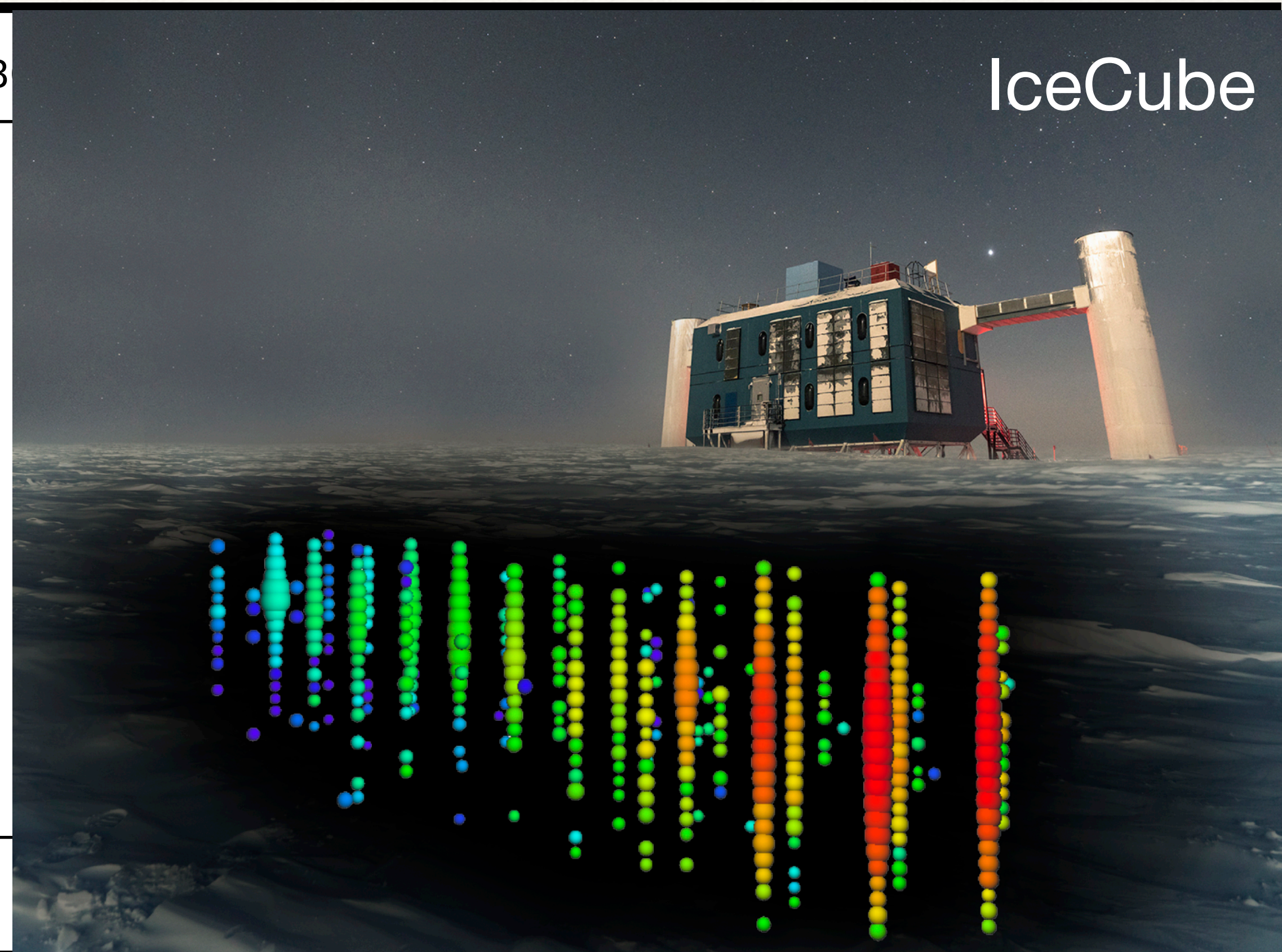
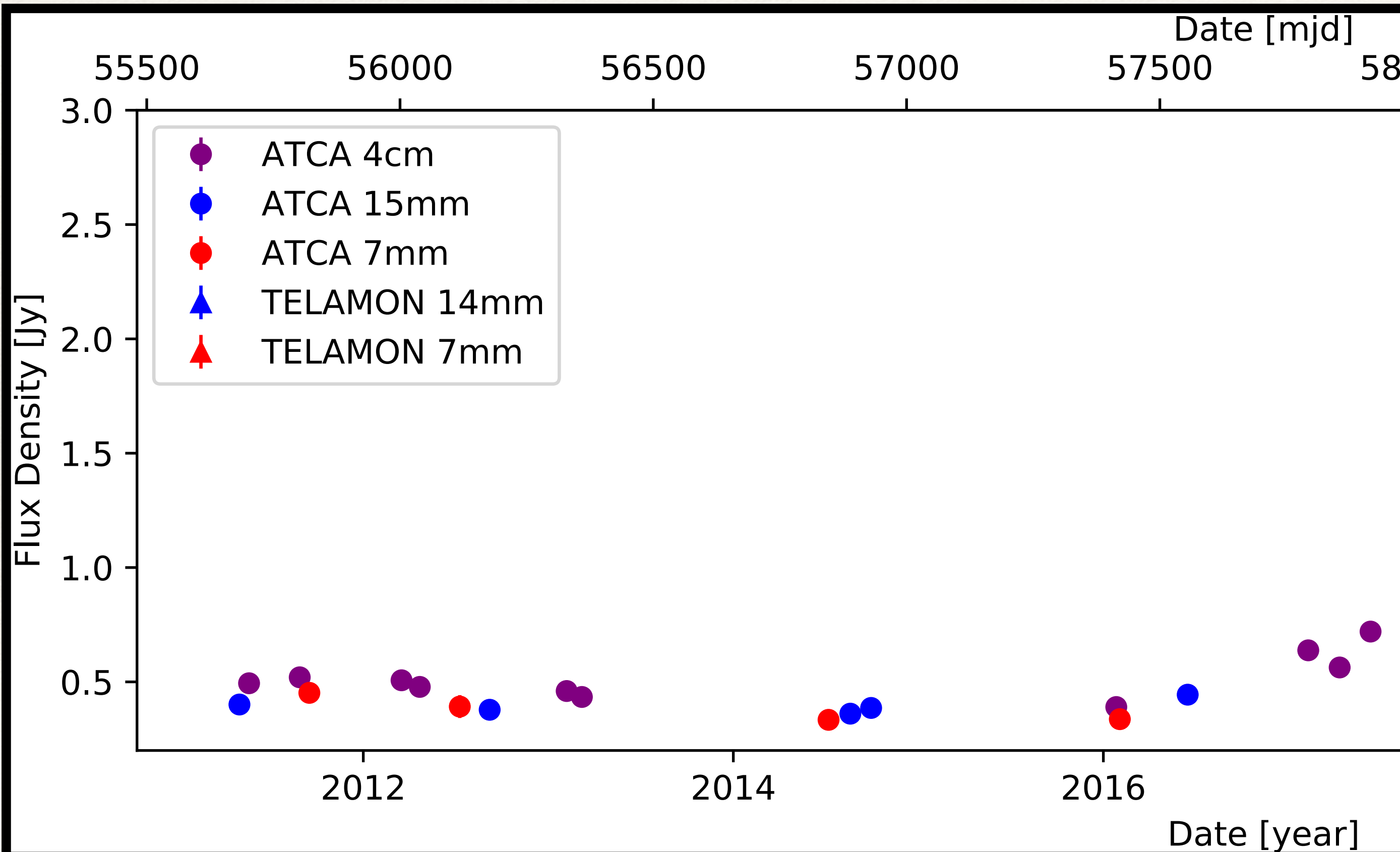
Recent Breakthroughs in Neutrino Astronomy

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



Recent Breakthroughs in Neutrino Astronomy

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

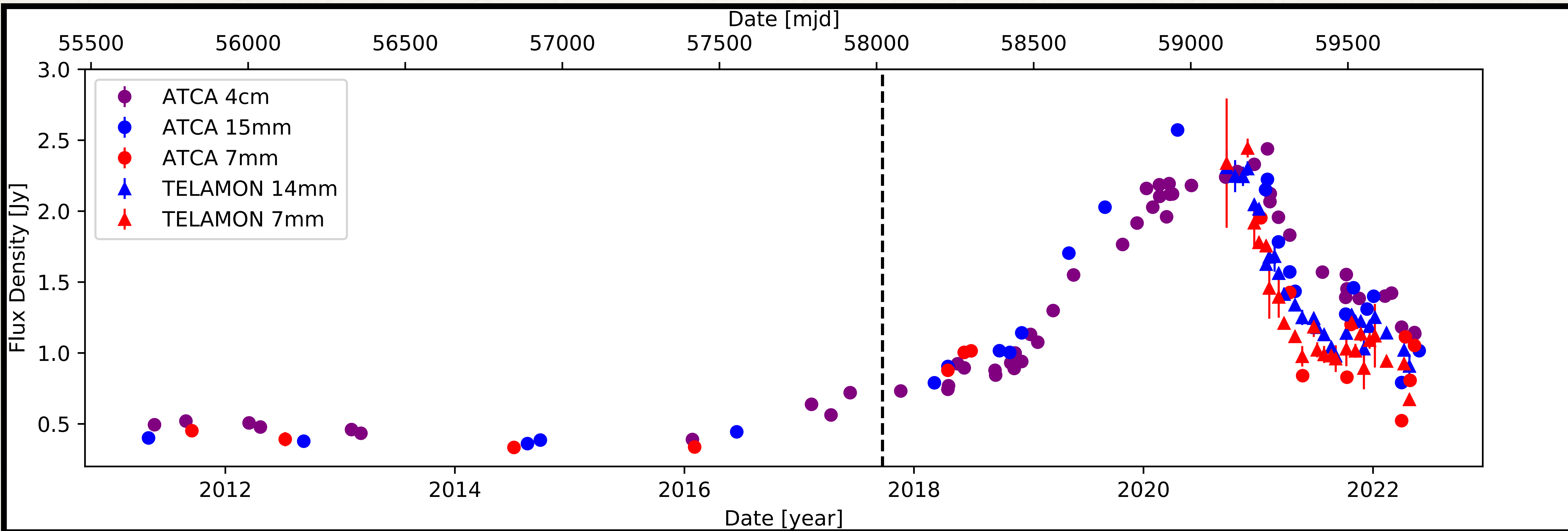


Rösch 2026, in prep.

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

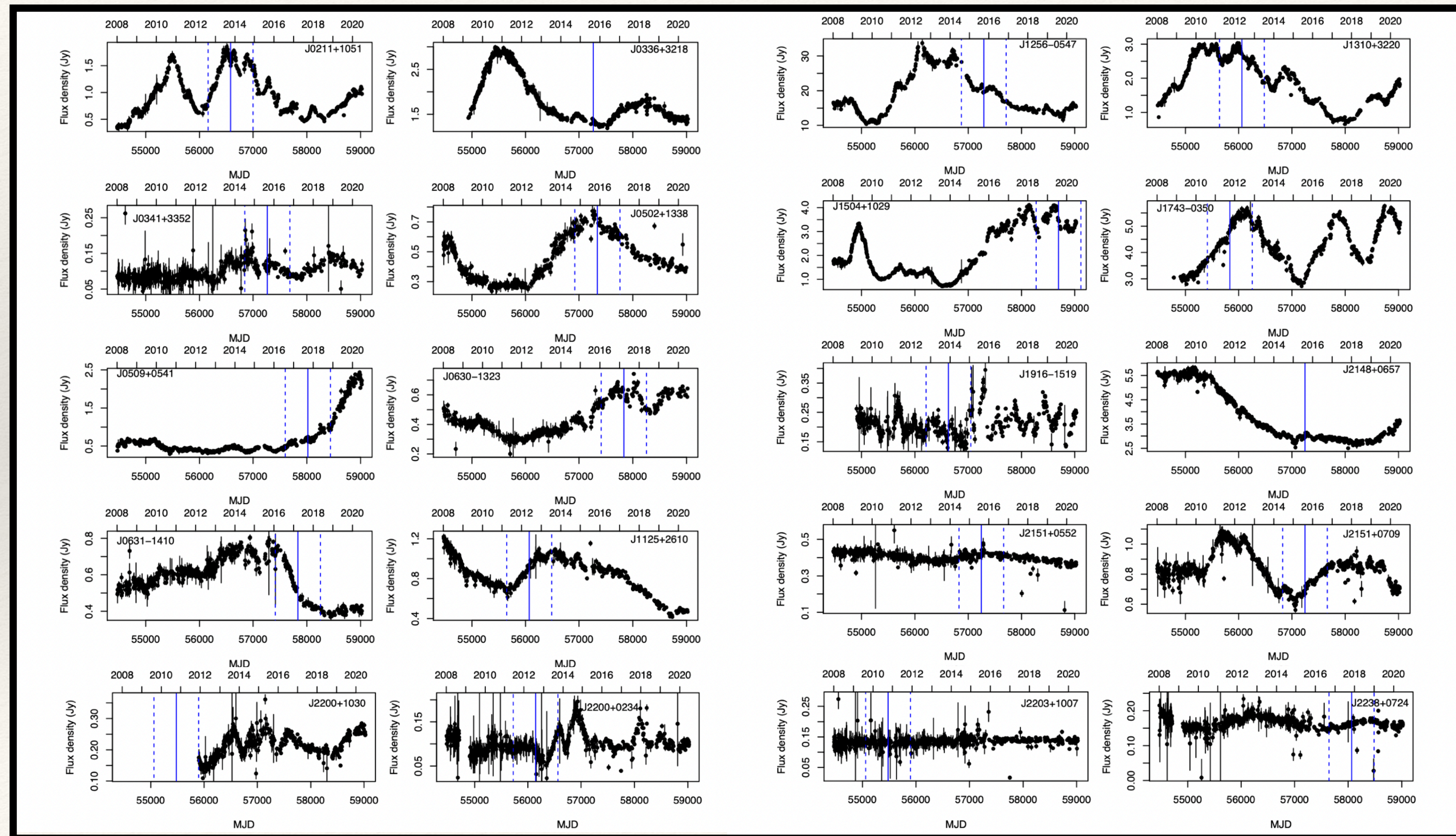
Radio Observations are Crucial for Neutrino Astronomy!

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



Rösch 2026, in prep.

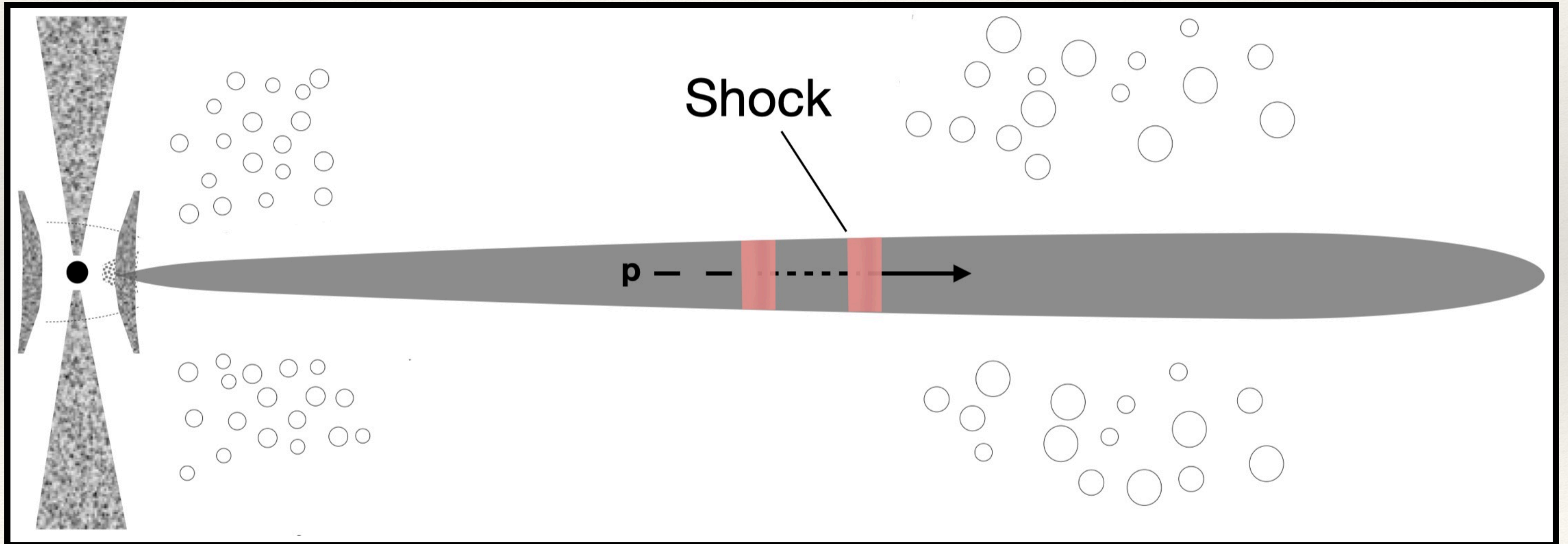
Statistical correlation of Neutrinos with Radio Flares in Blazars



Hovatta et al. 2021

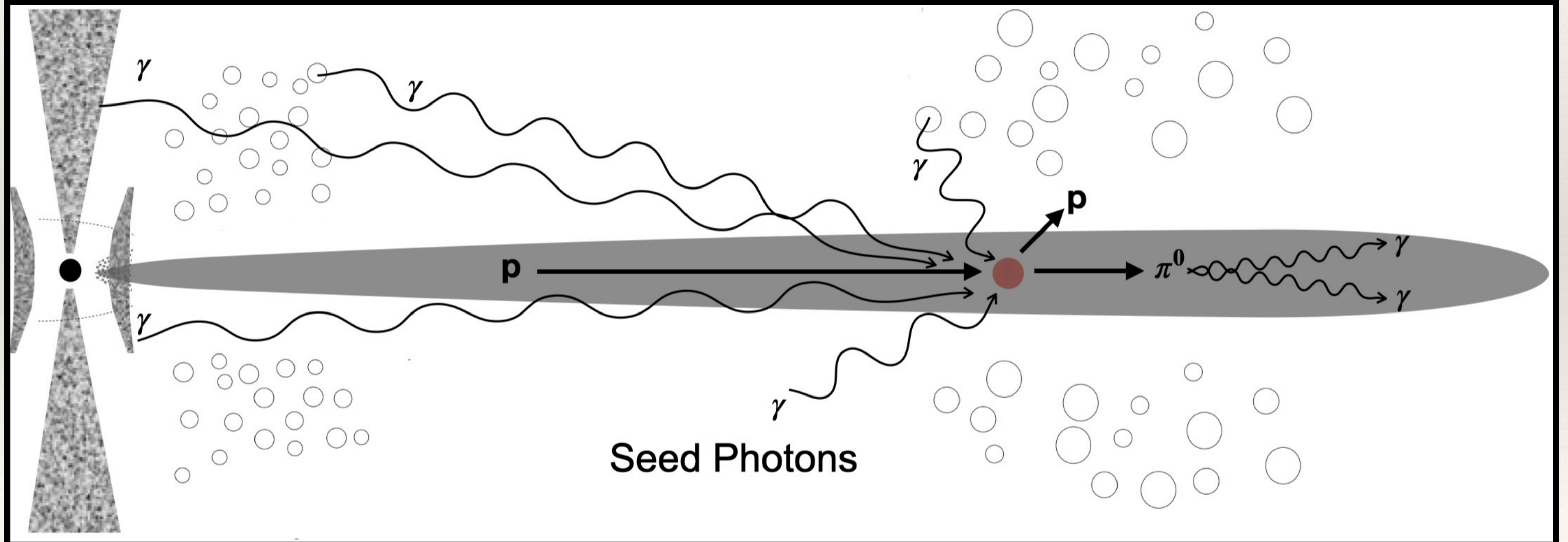
AGN Jets as Sources of Ultrahigh-Energy Cosmic rays

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



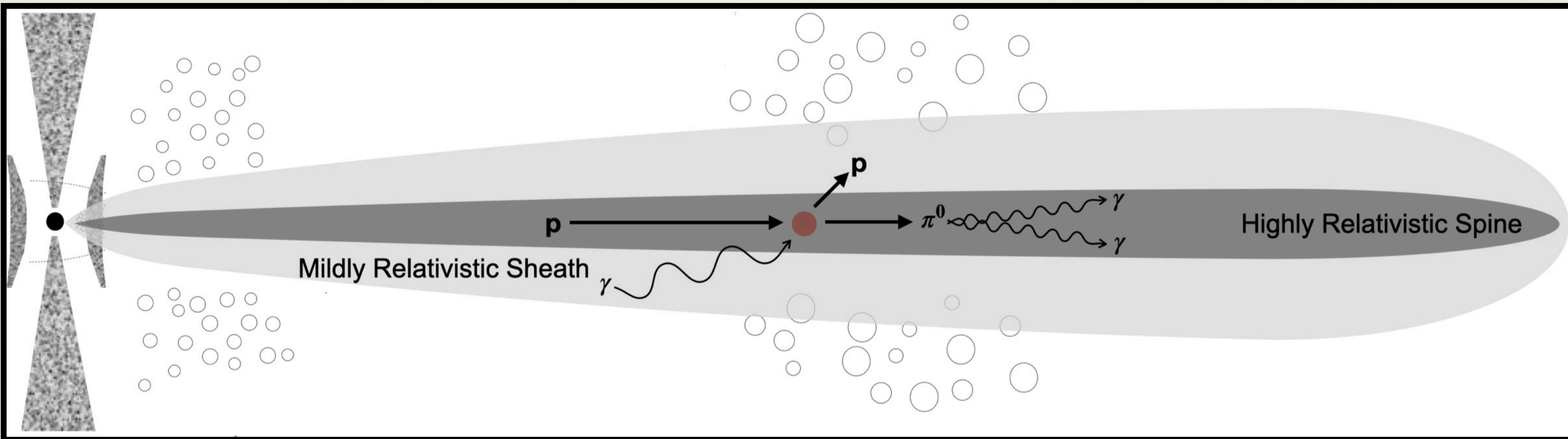
Hadronic Processes as Origin of Gamma-Ray Emission

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

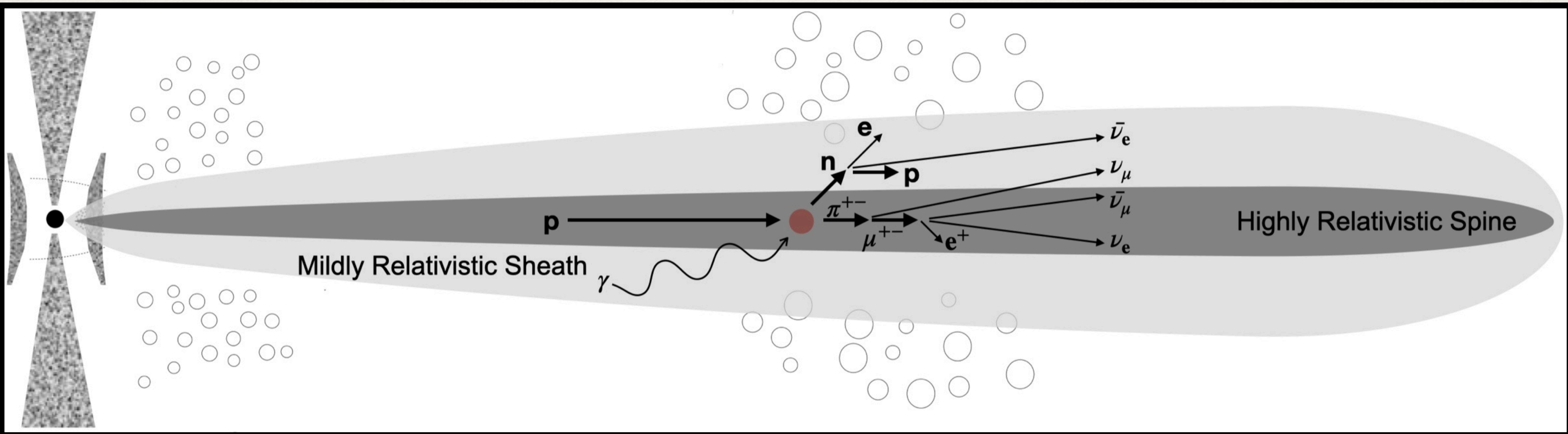
Attractive option for seed photon field: outer, slower jet sheath



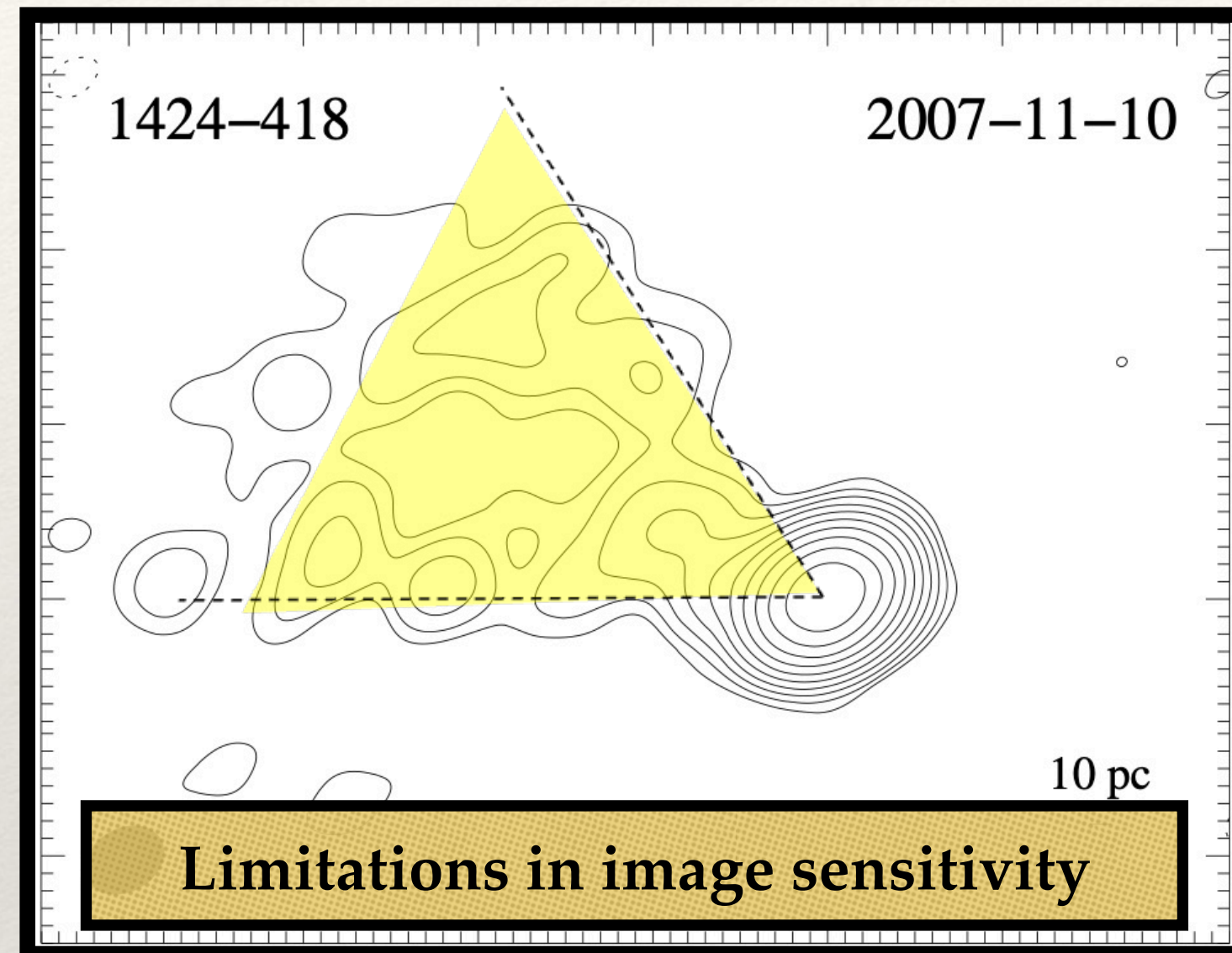
Hadronic Processes as Origin of Neutrino Emission

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

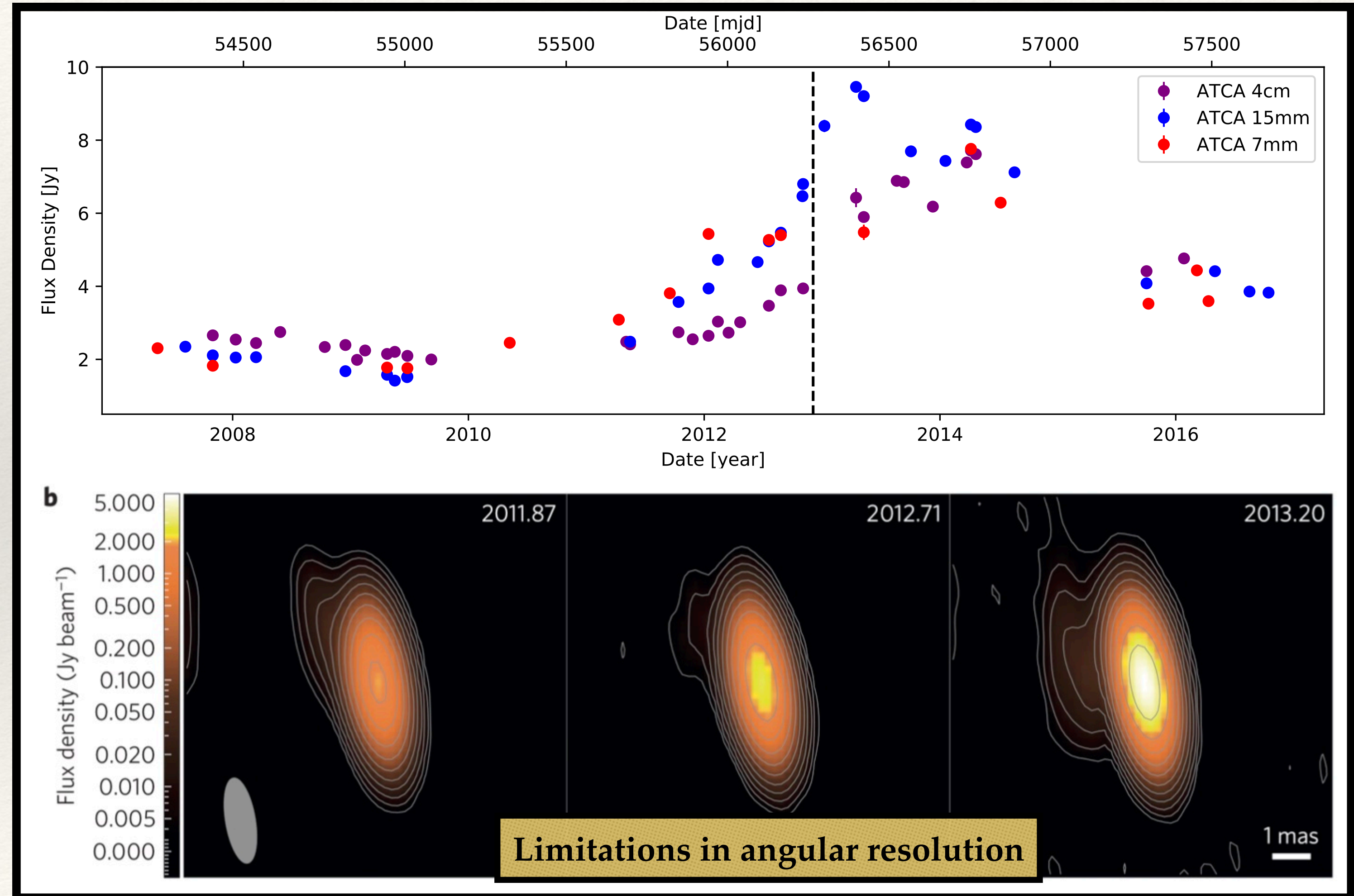


VLBI Observations of Candidate Neutrino Blazars: PKS 1424-418



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

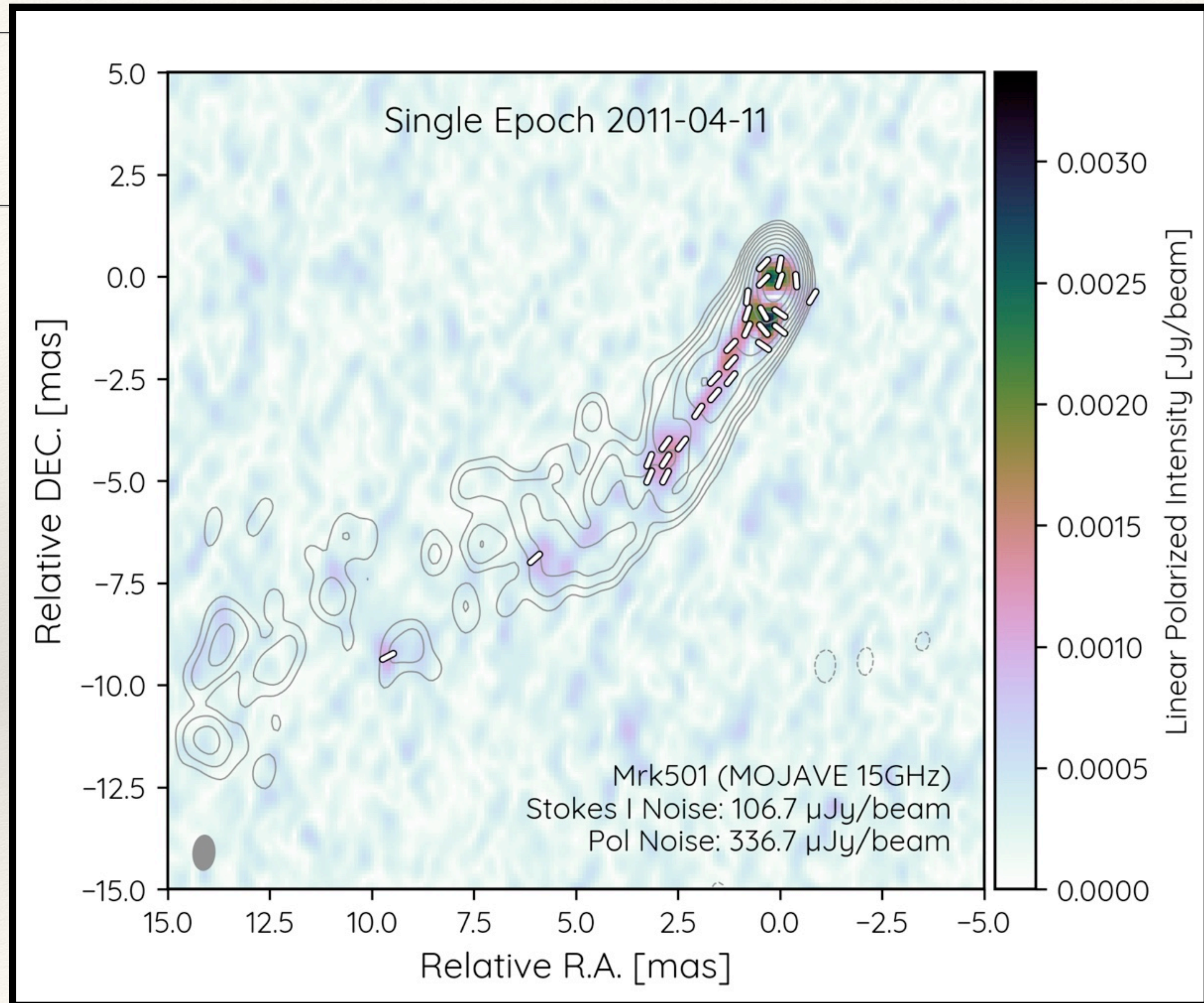
Kadler et al. 2016



VLBA Polarization

Mrk 501 (700mJy):

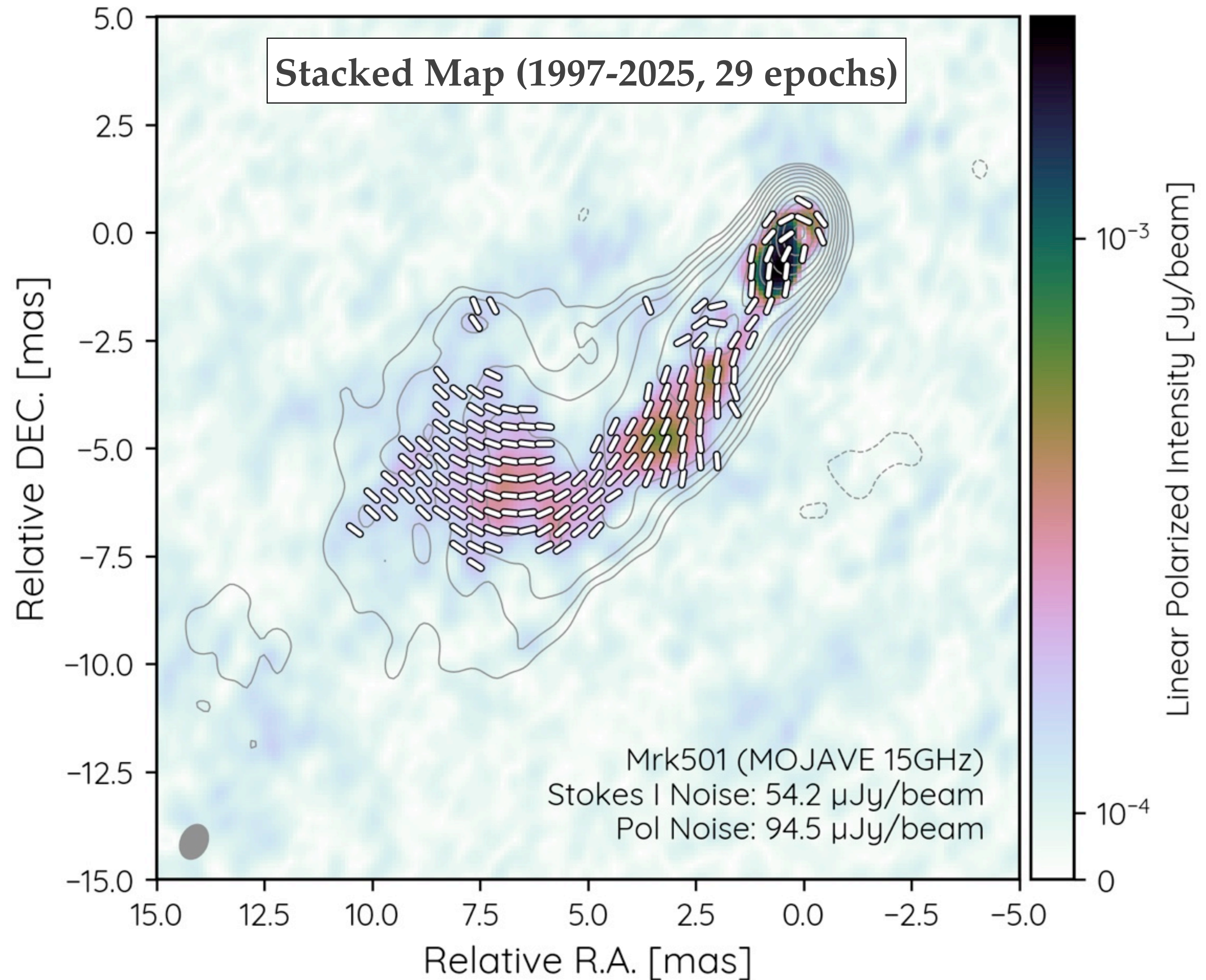
Spine visible in linear polarization in single VLBA snapshots



VLBA Polarization

Mrk 501 (700mJy):

Transversal polarization
structure only visible in
stacked images

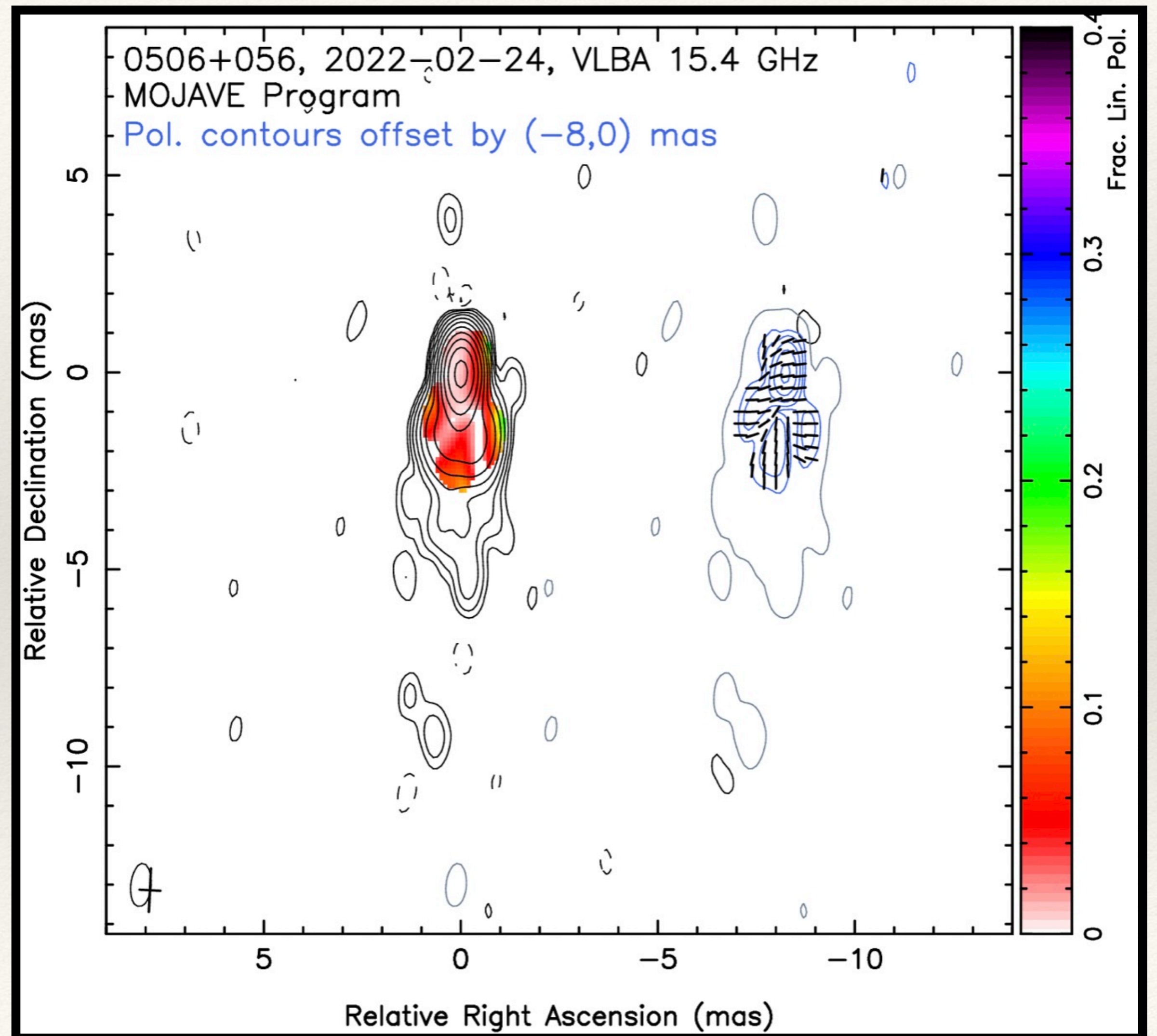


VLBA Observations: Polarization

TXS 0506+056:

Only high-probability
neutrino-associated blazar.

Emission models
underconstrained by
current observational data.

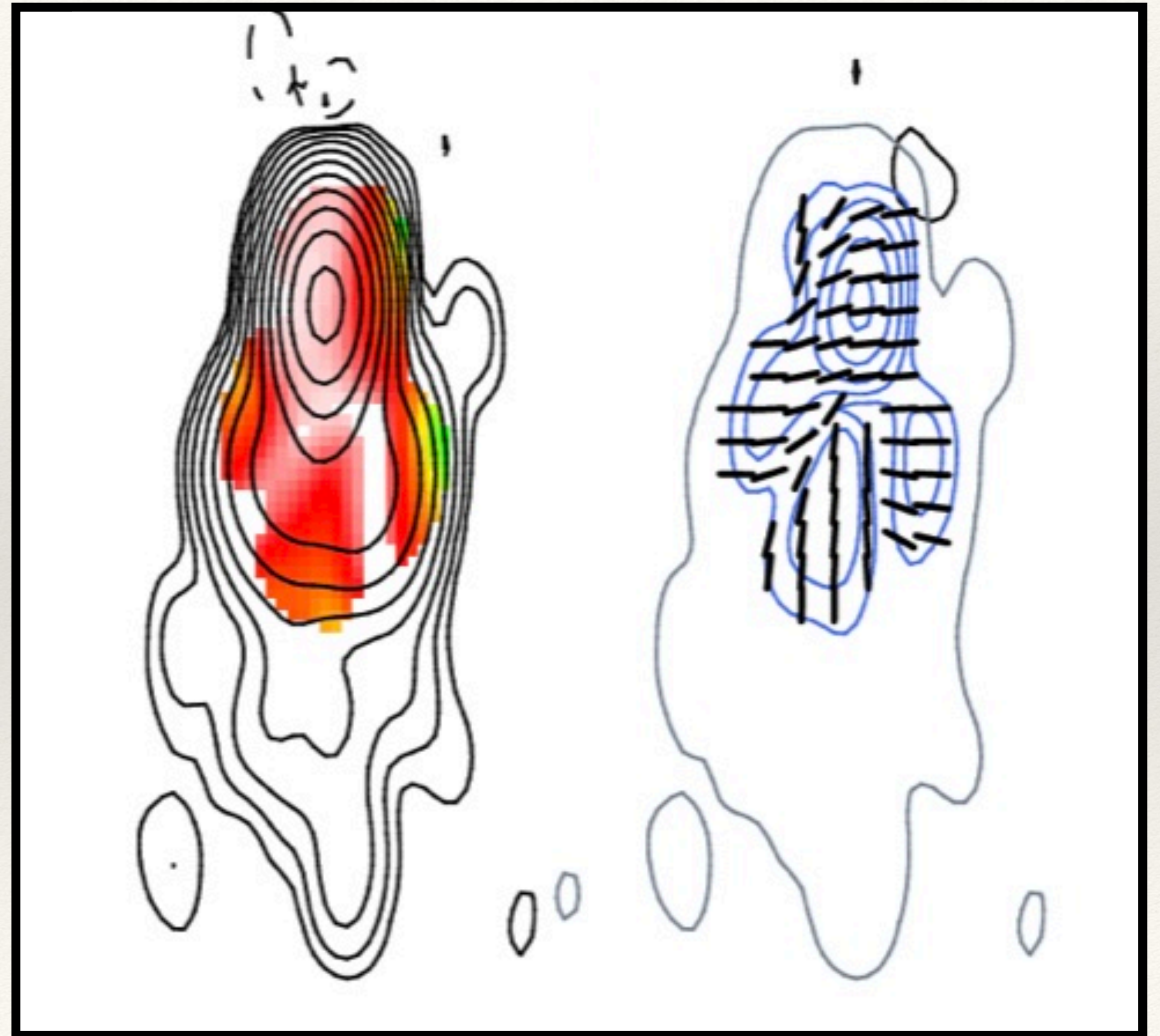


VLBA Observations: Polarization

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?

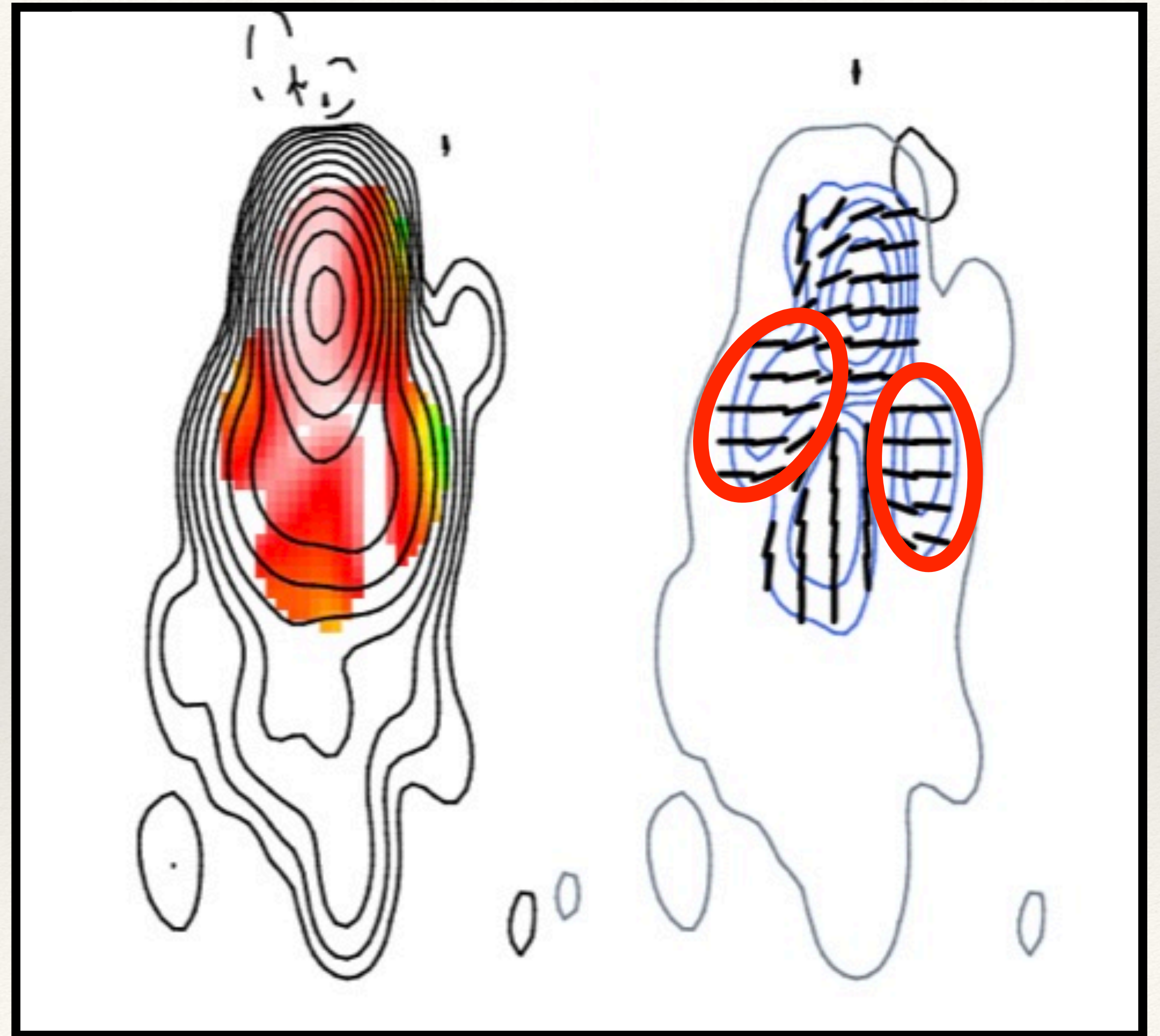


VLBA Observations: Polarization

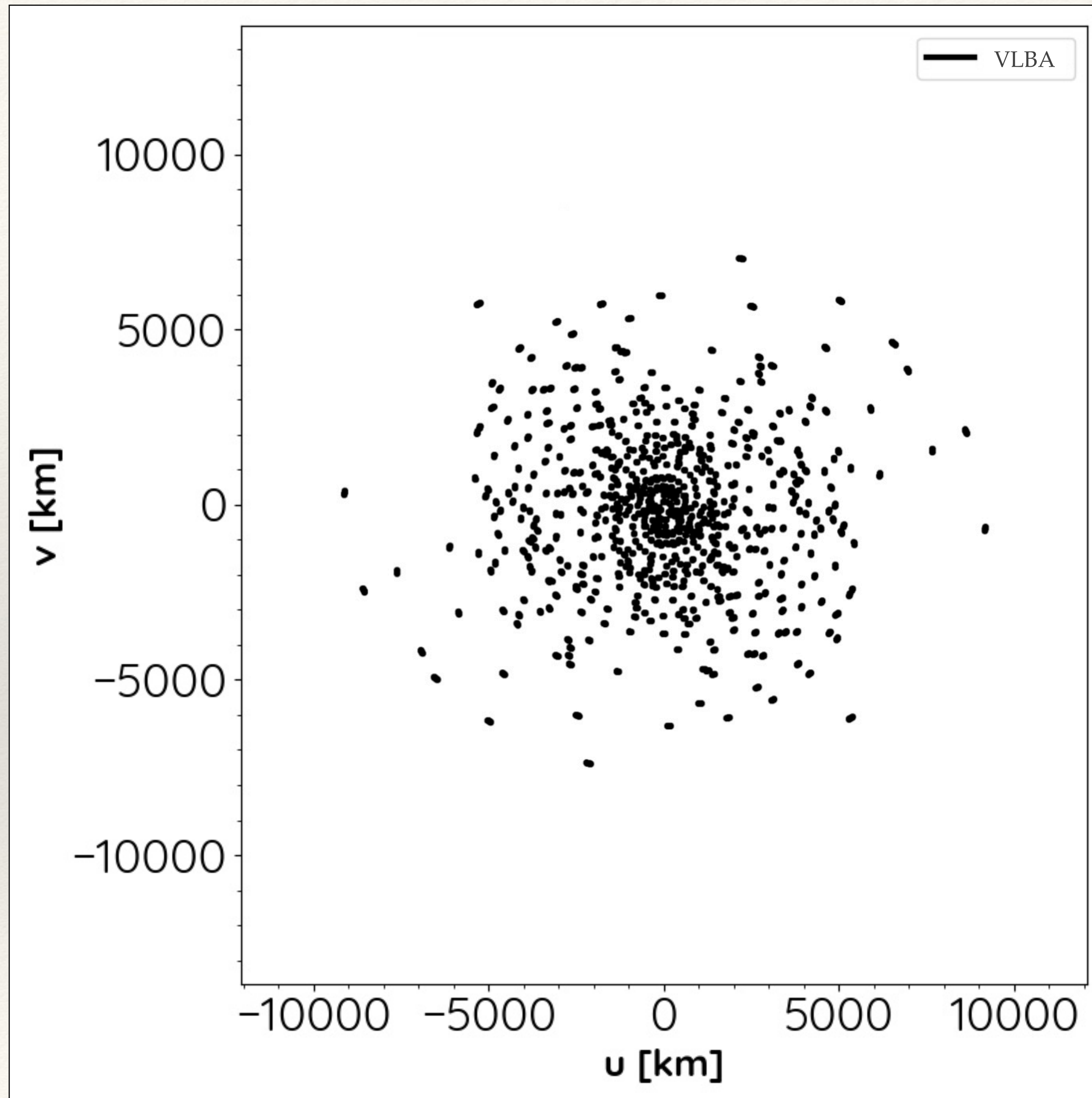
TXS 0506+056:

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

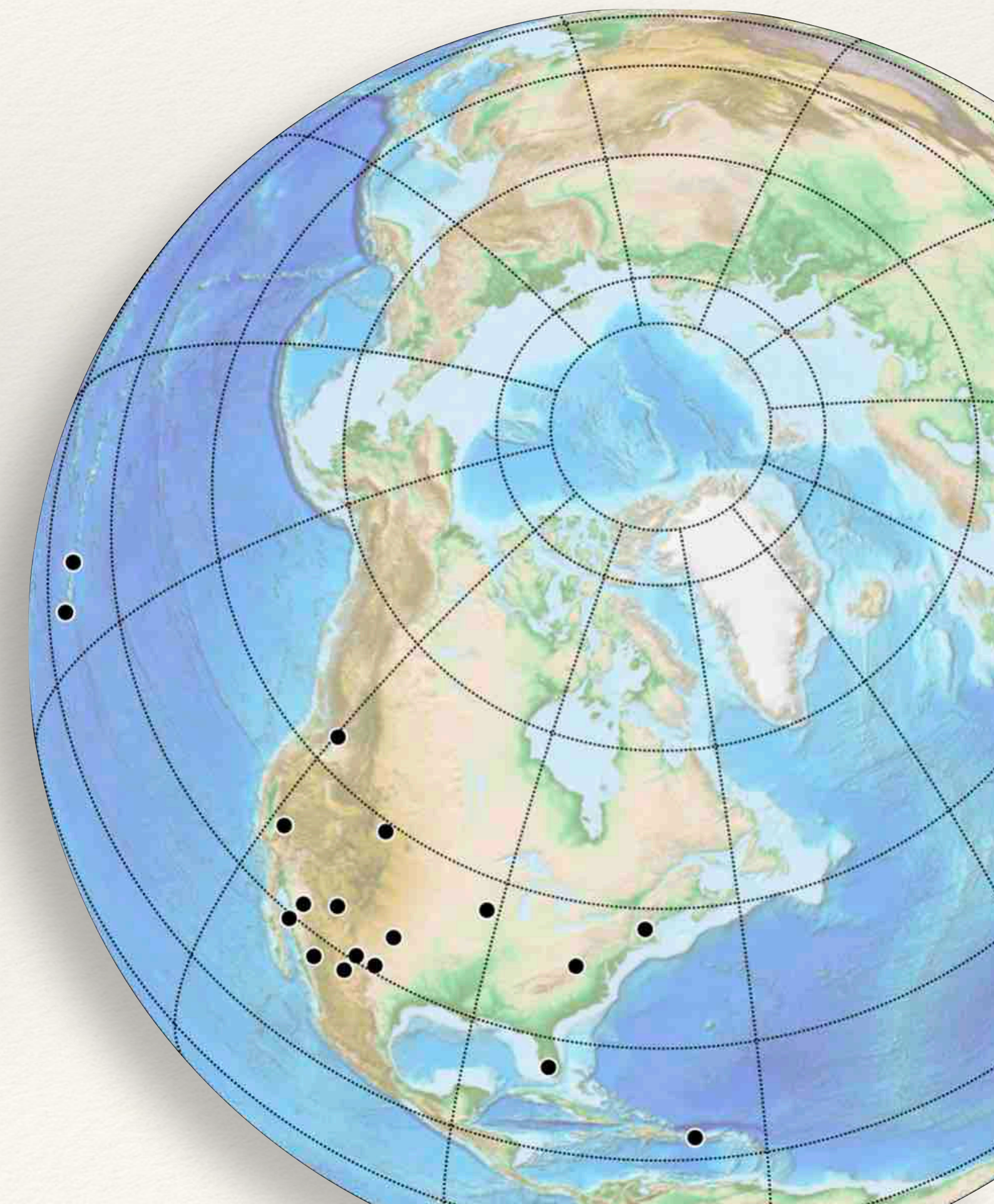
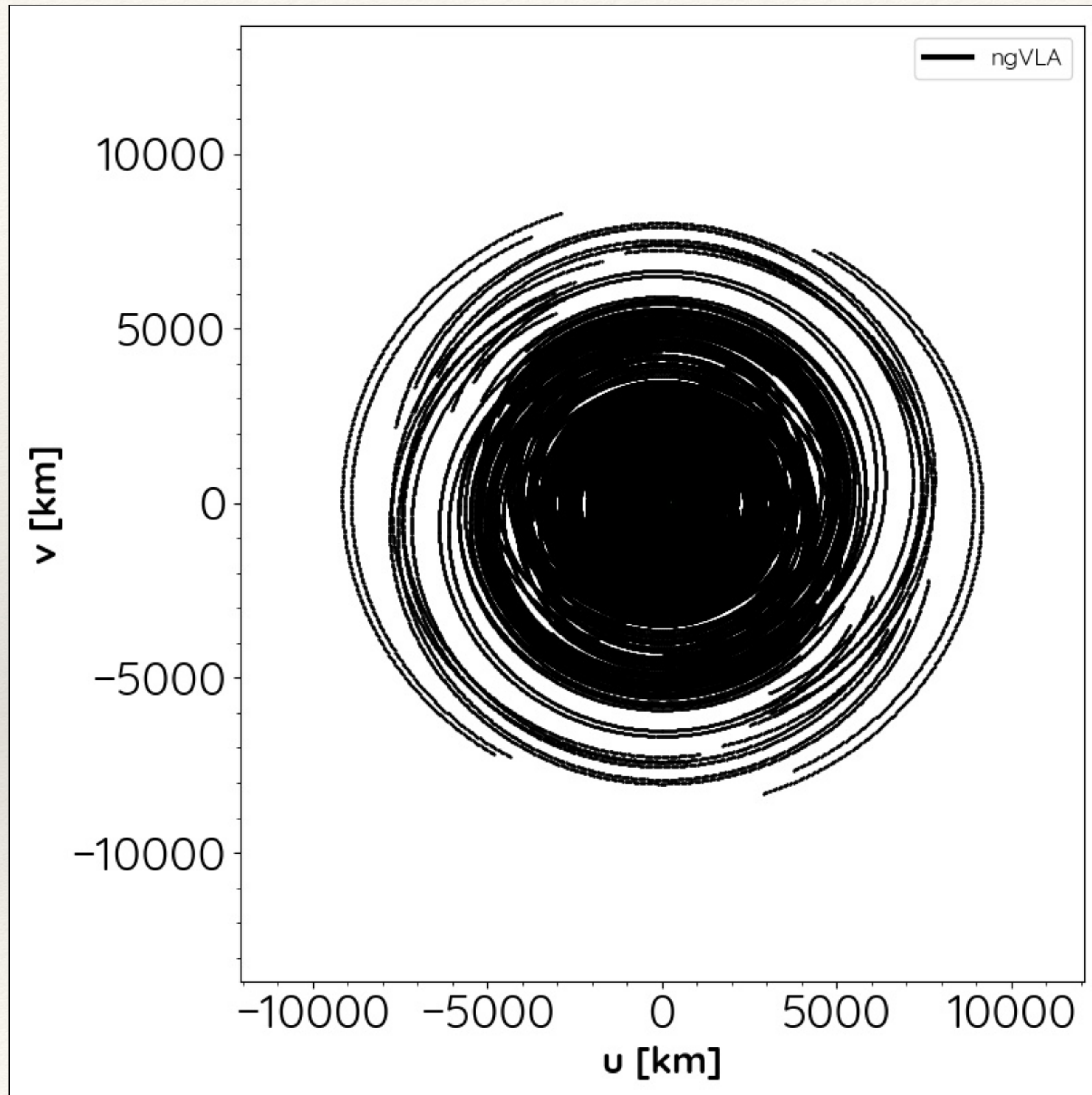
Can be used as a mask to constrain sheath photon field?



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

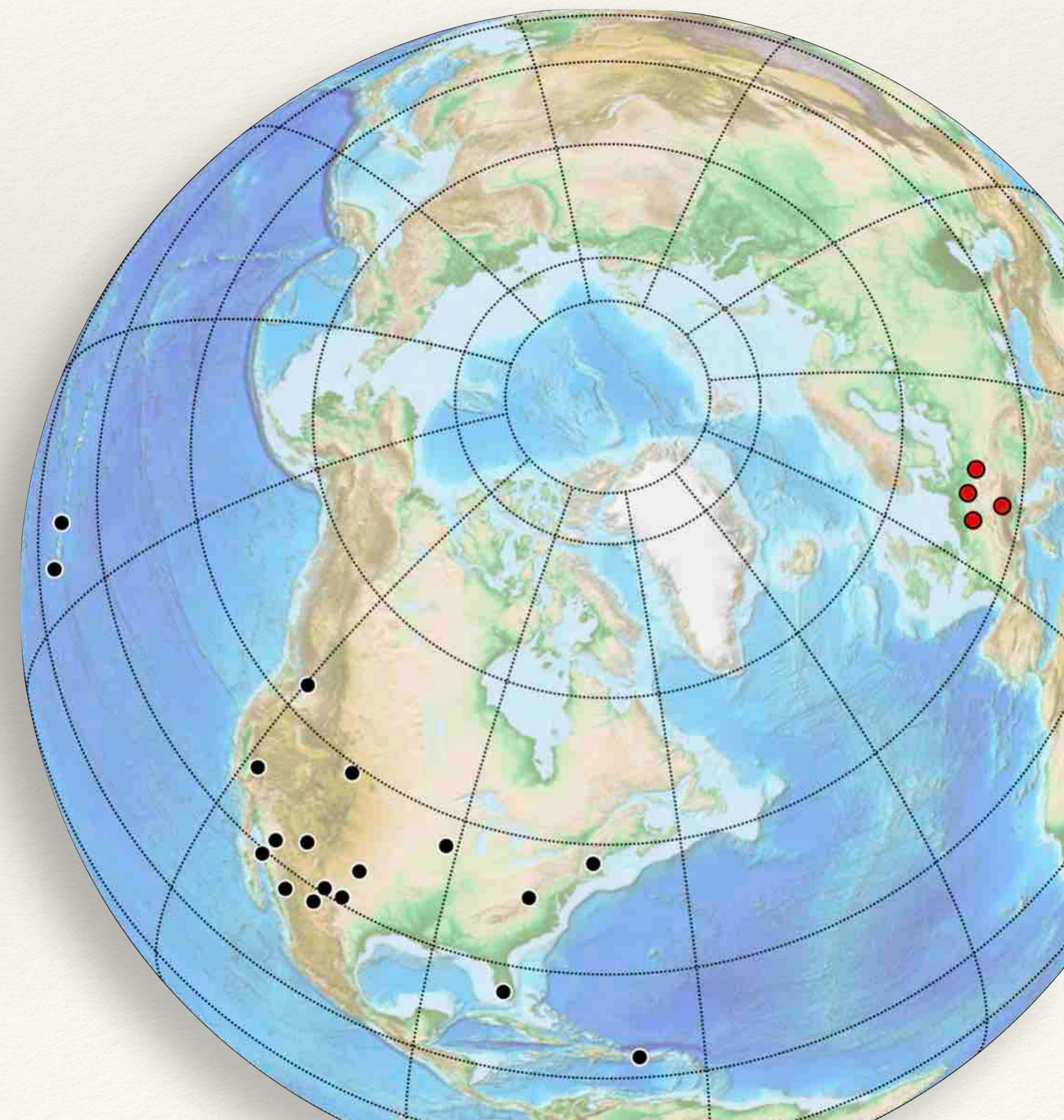
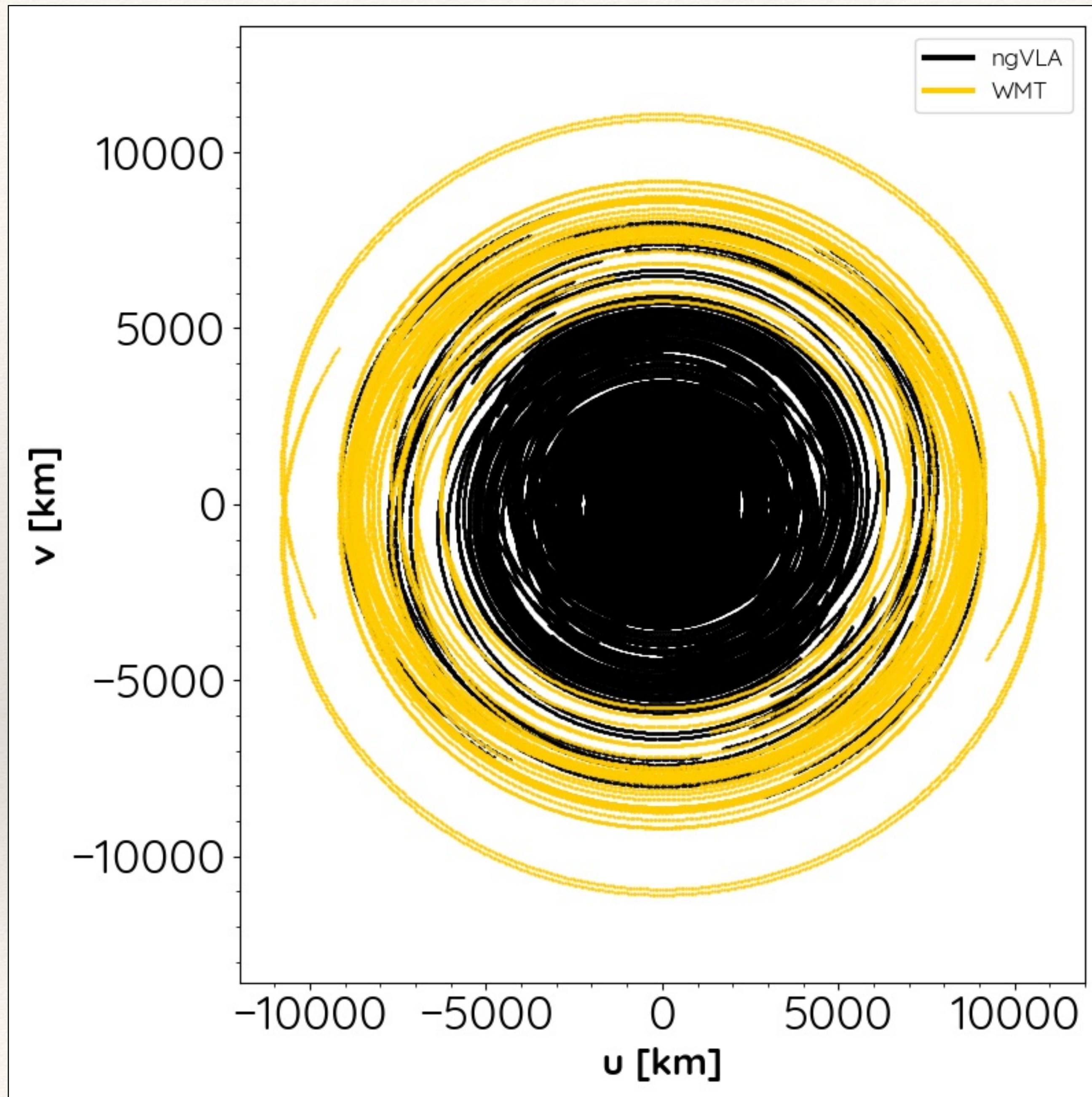


ngVLA (u,v)-Coverage



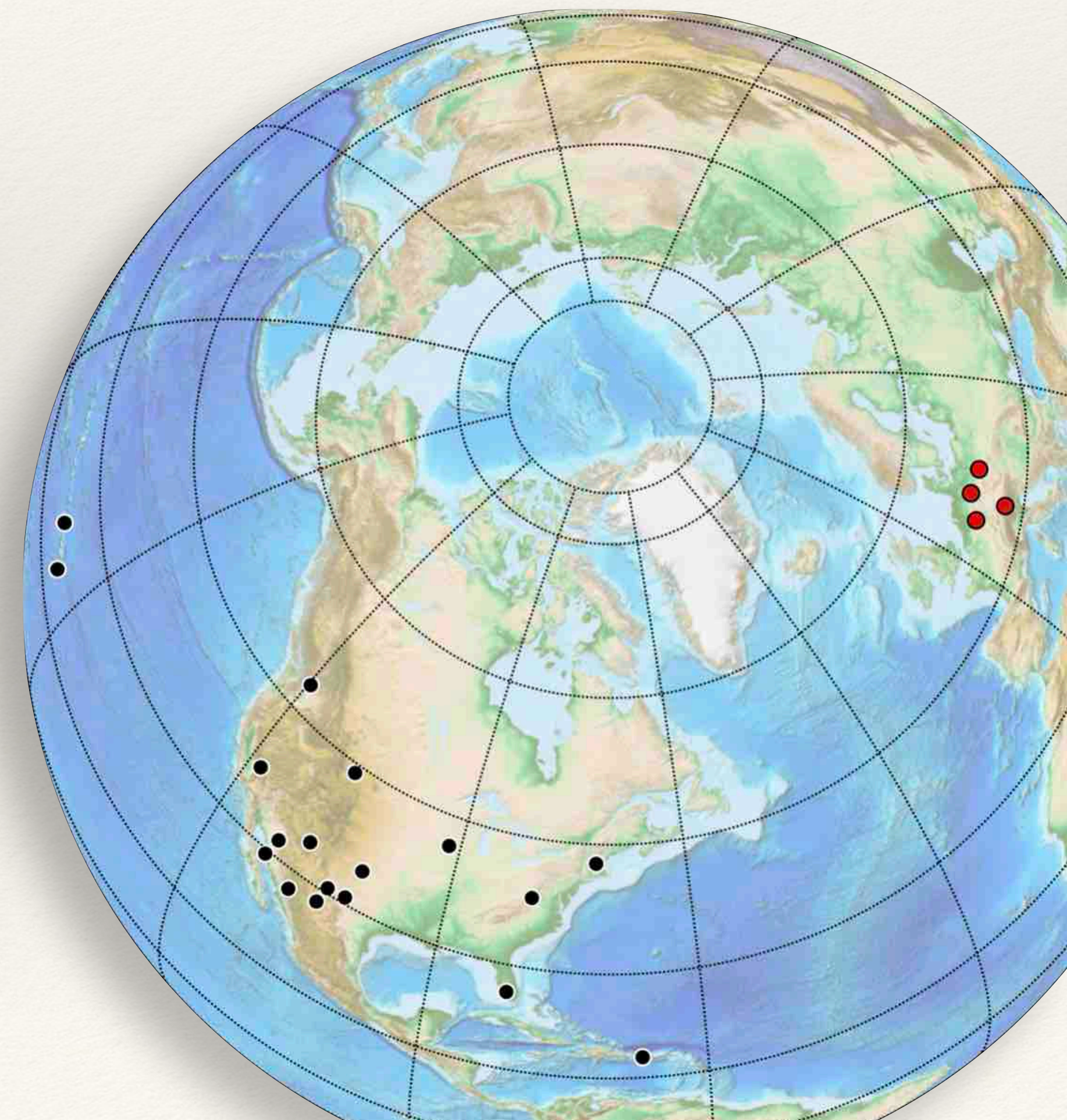
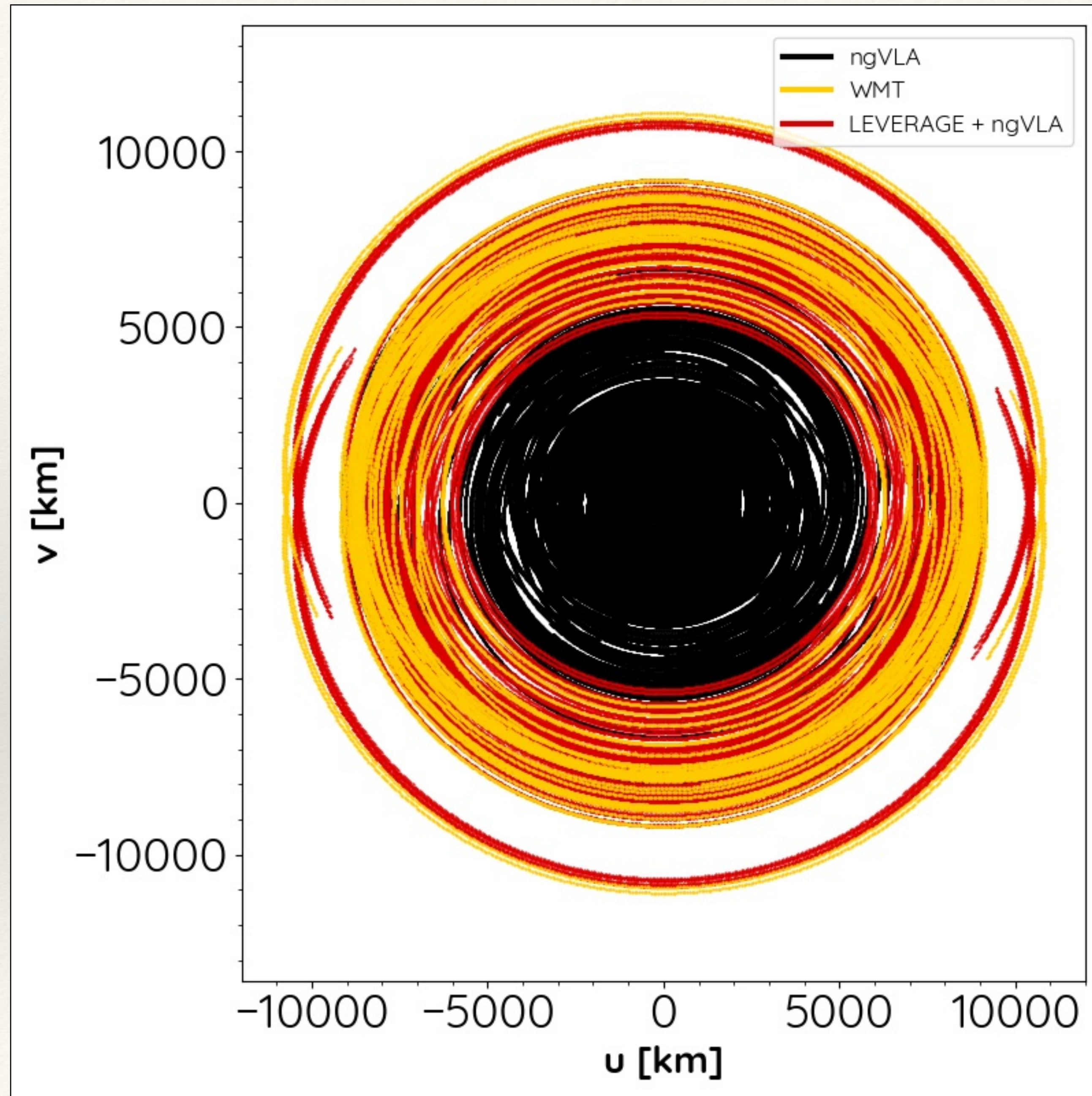
ngVLA (u,v)-Coverage

+ LEVERAGE



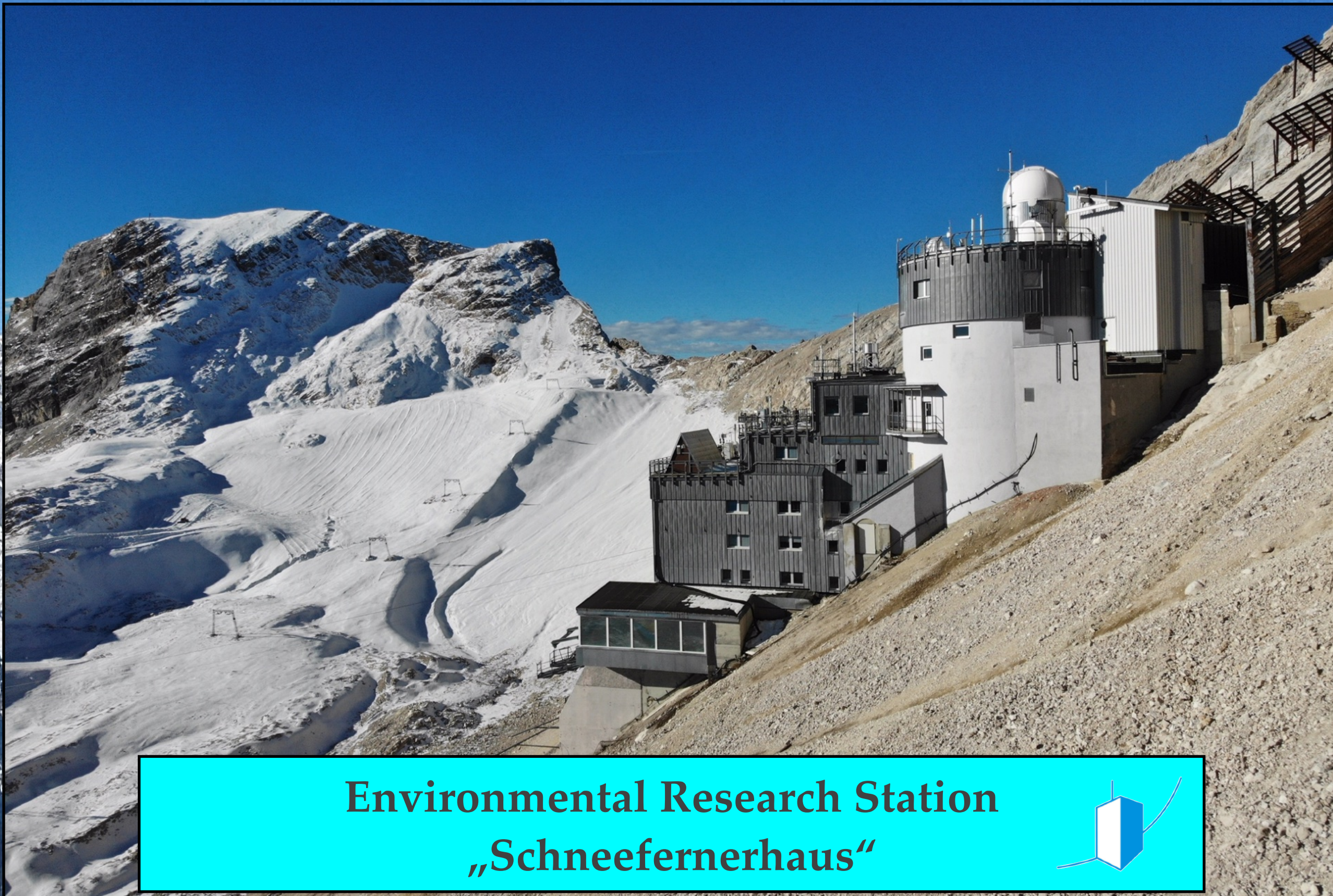
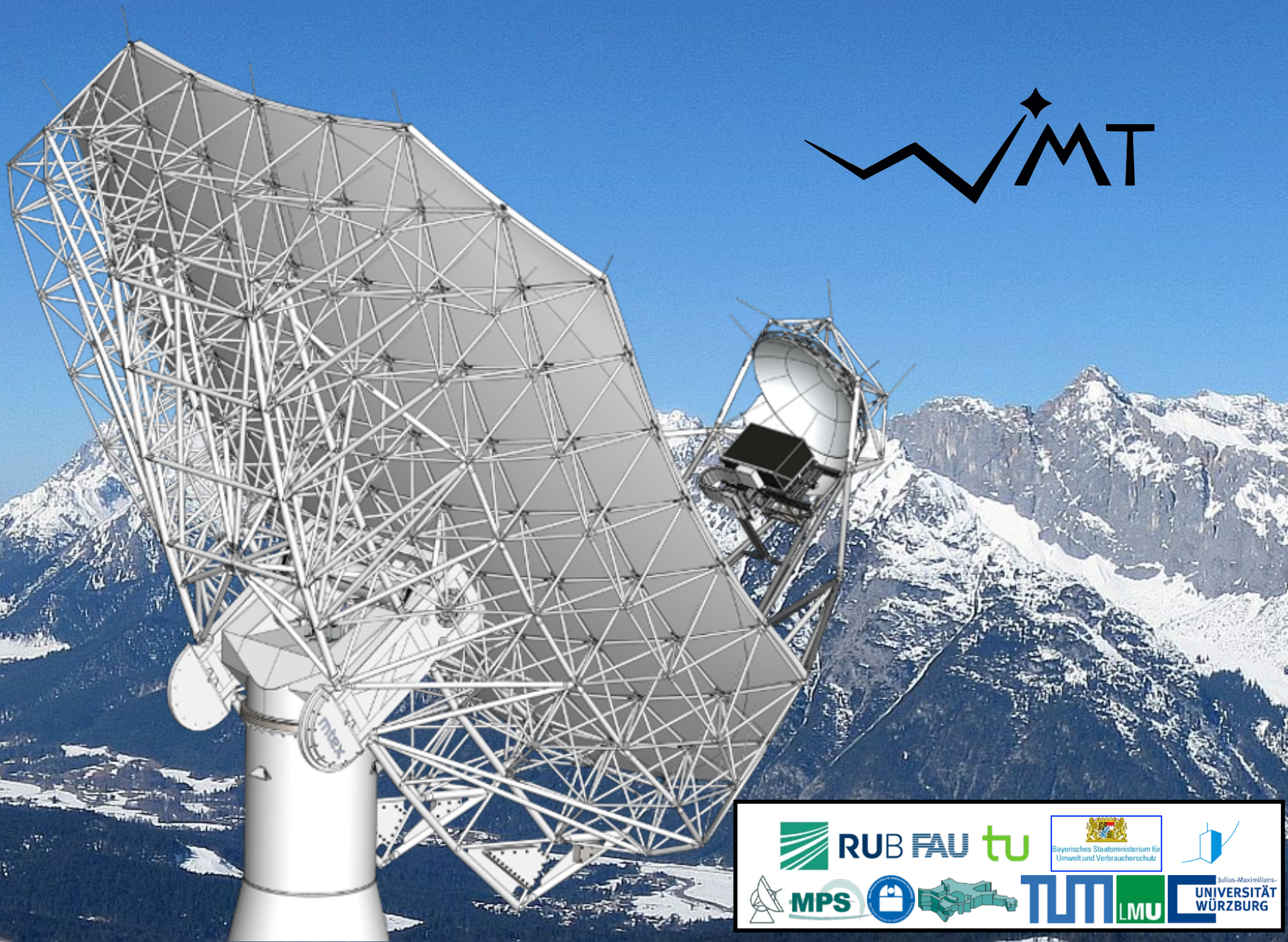
ngVLA (u,v)-Coverage

+ LEVERAGE



Wetterstein Millimeter Telescope

First Planned German ngVLA Telescope



Environmental Research Station
„Schneefernerhaus“





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

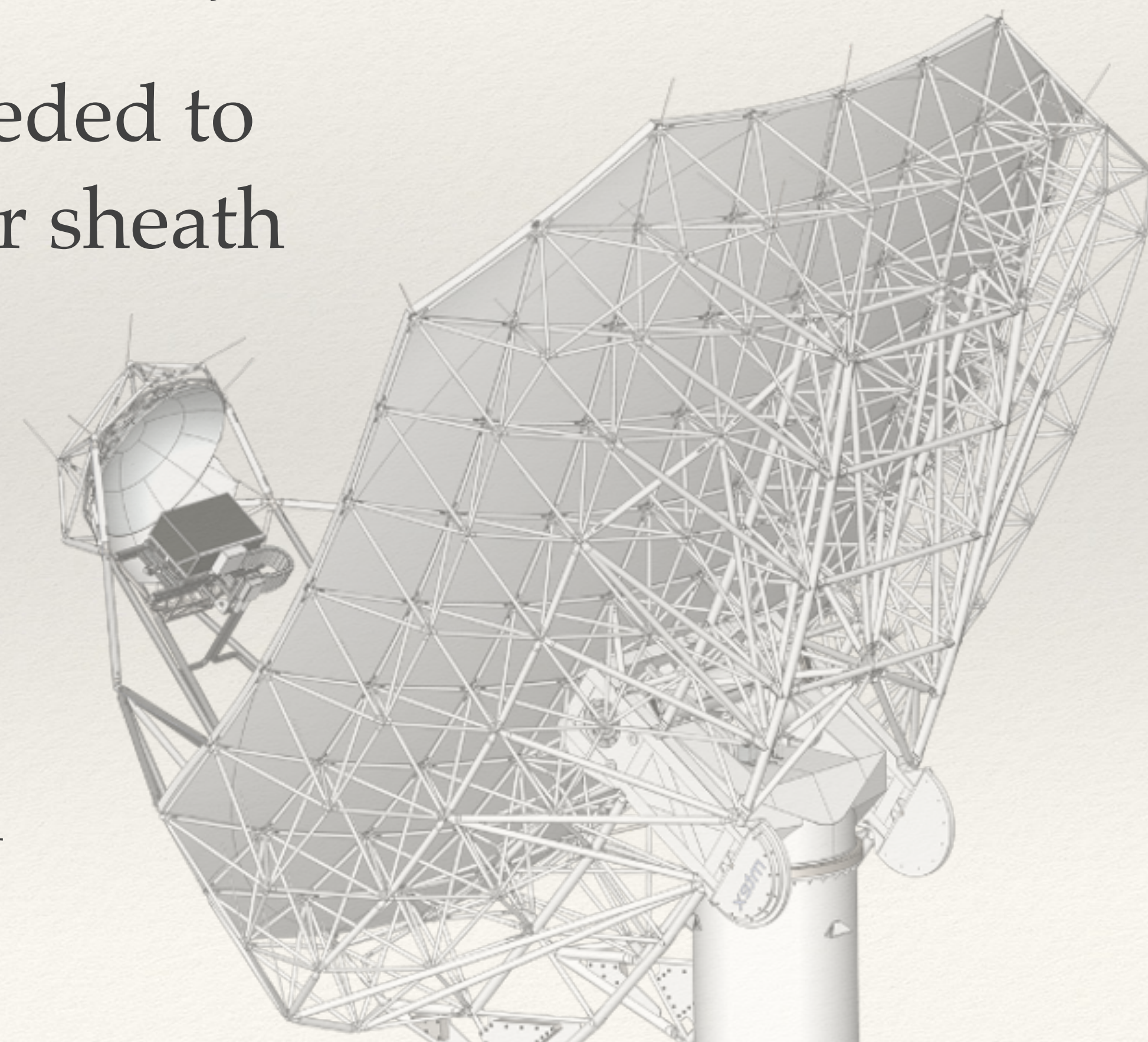


Extensive infrastructure through association with „Schneefernerhaus“

Summary and Perspectives for the Early ngVLA Era

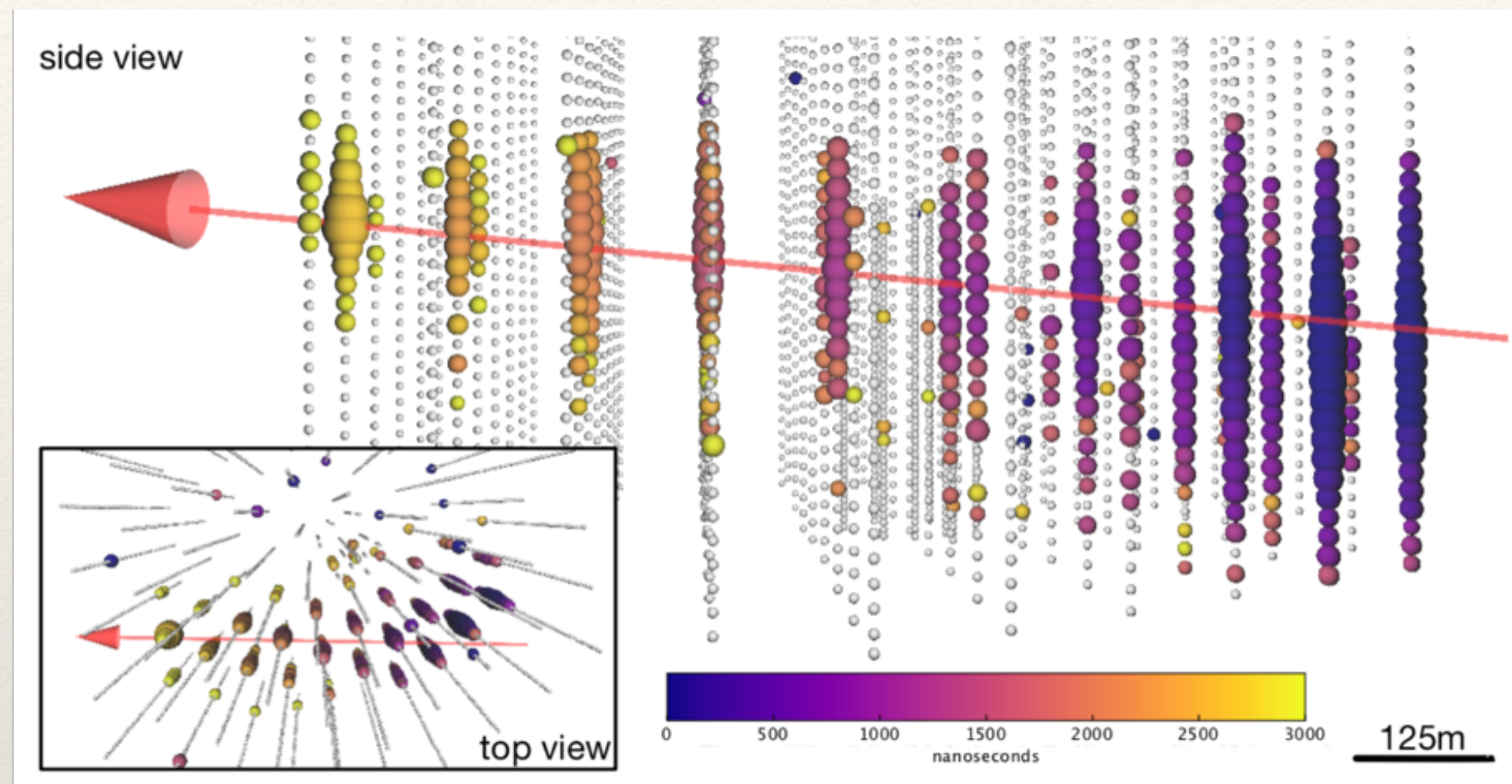


- ❖ Radio interferometry at milliarcsecond resolution can reveal the physics of neutrino production in structured blazar jets
- ❖ High sensitivity and high dynamic range needed to separate highly-relativistic spine from slower sheath
- ❖ Polarization can be key
- ❖ VLBA + ngVLA long-baseline stations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

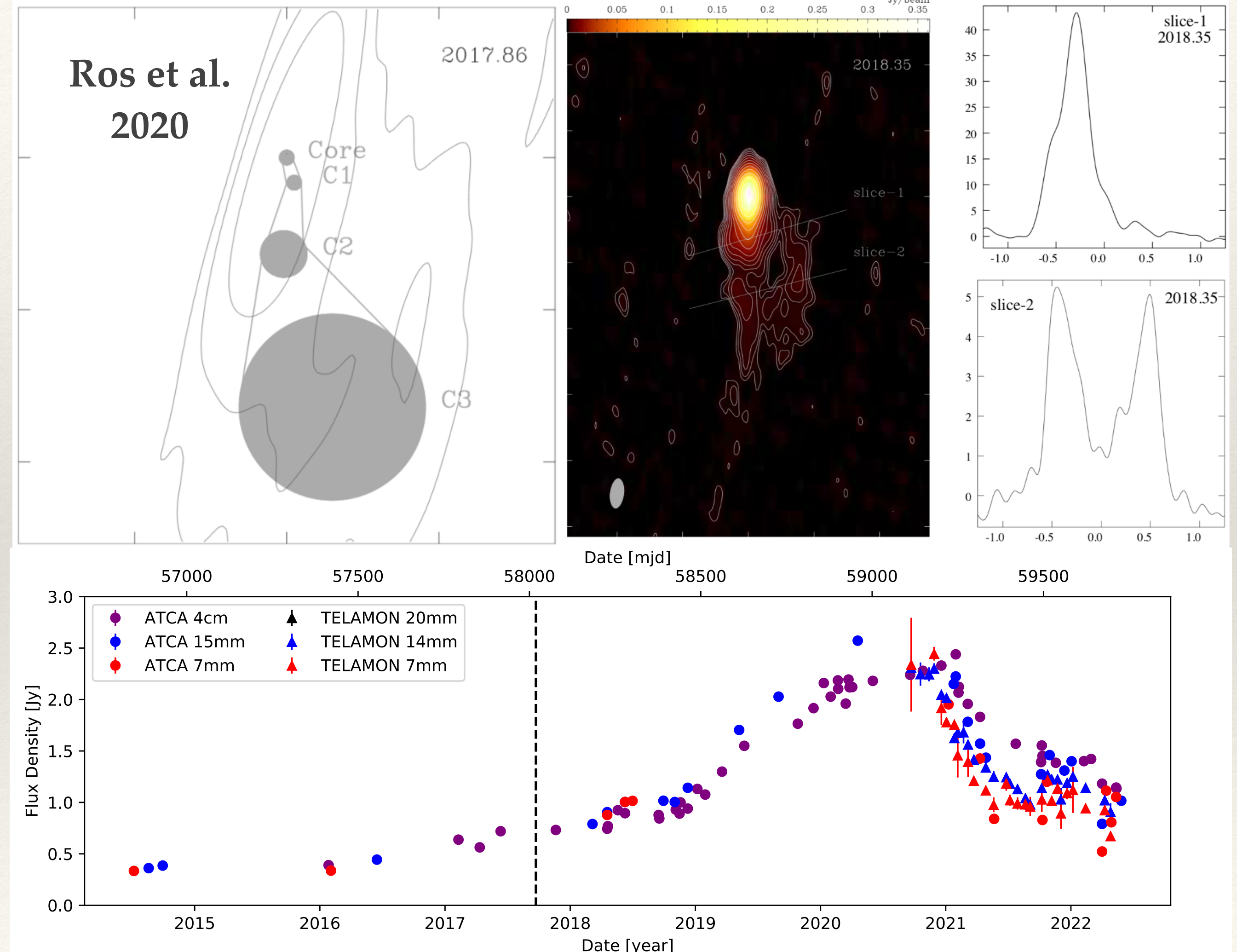


Additional Slides

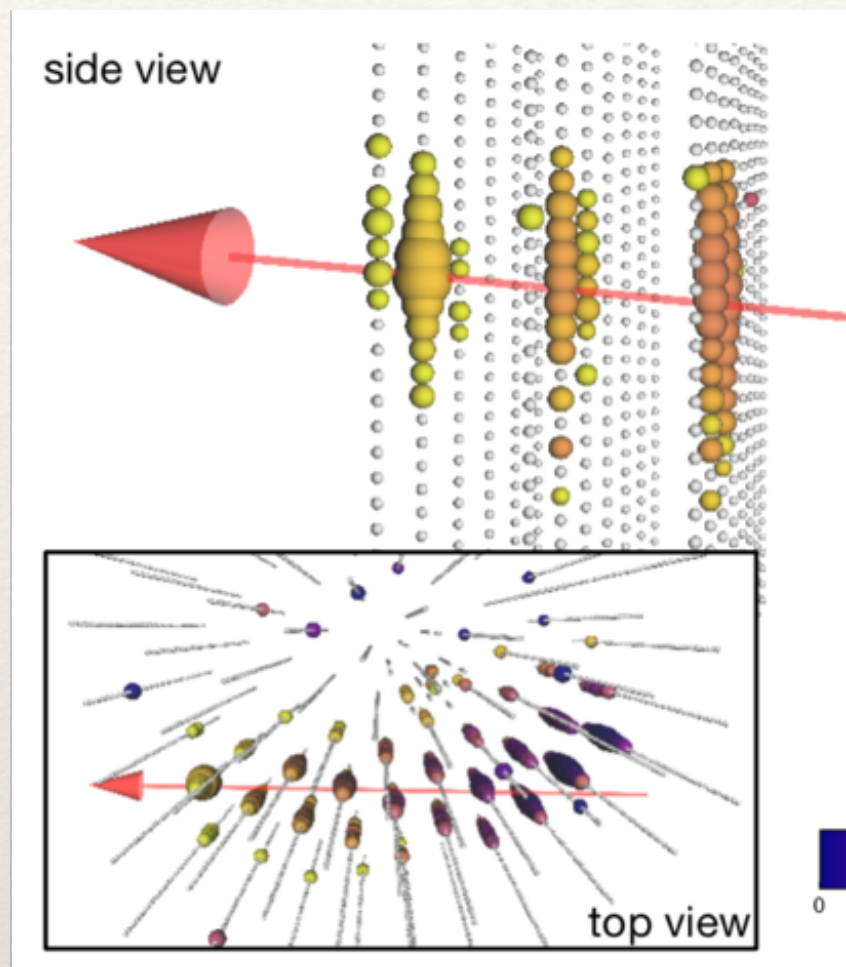
VLBA Observations of Candidate Neutrino Blazars: TXS 0506+056



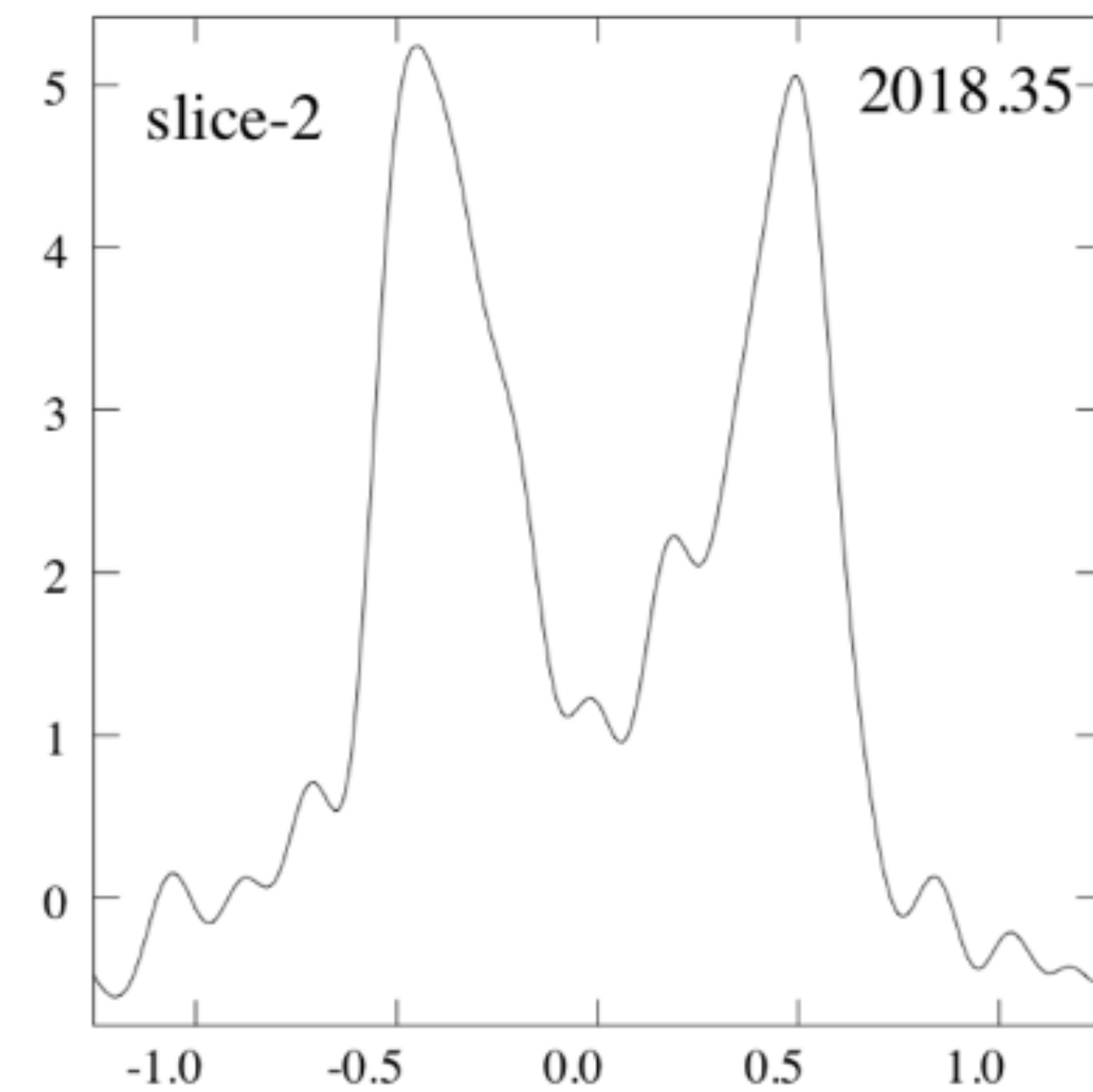
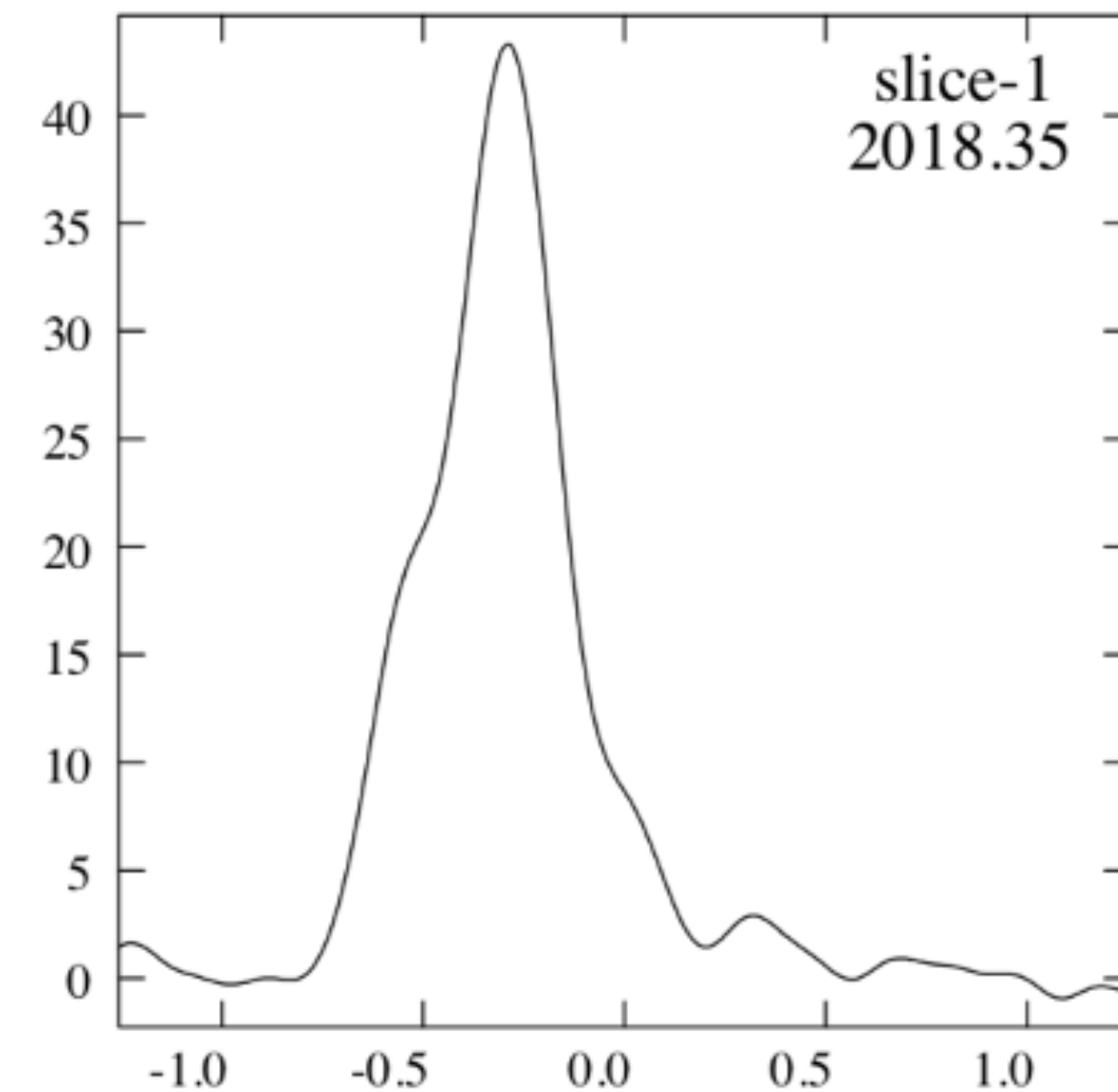
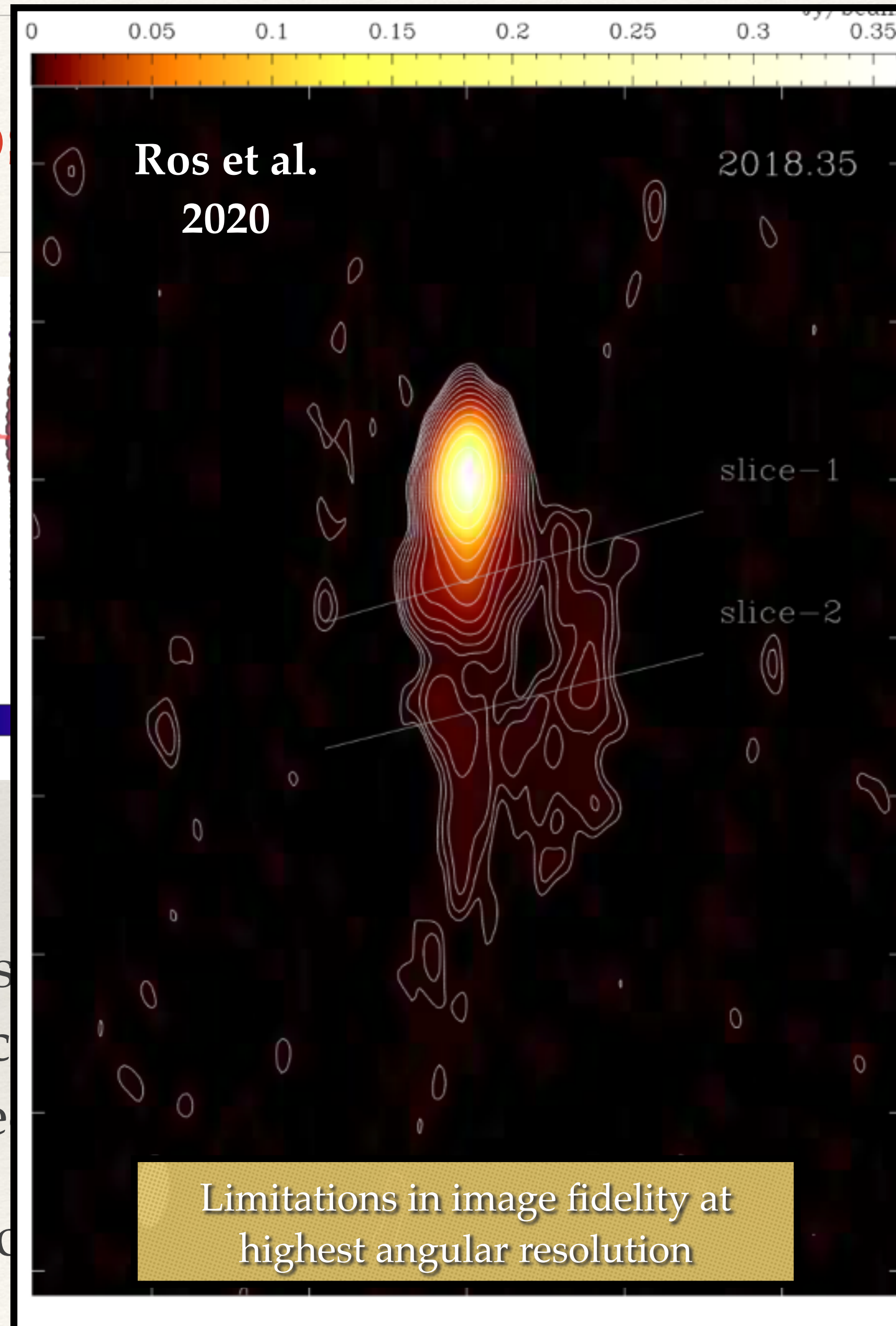
- ❖ VLBA images show apparent superluminal core expansion and limb-brightened jet
- ❖ Light curve shows multi-year radio outburst



VLBA Ob



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



506+056

