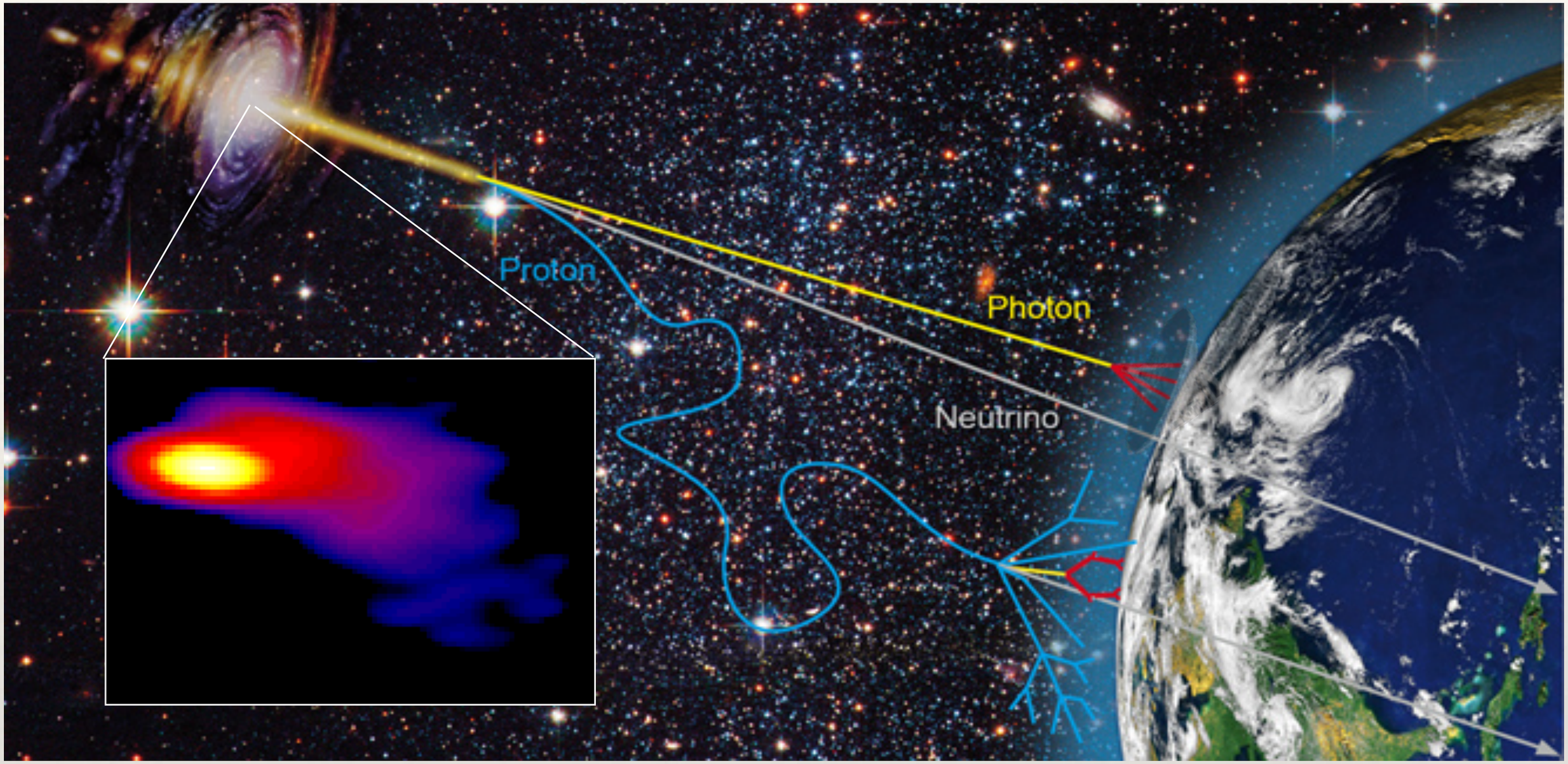
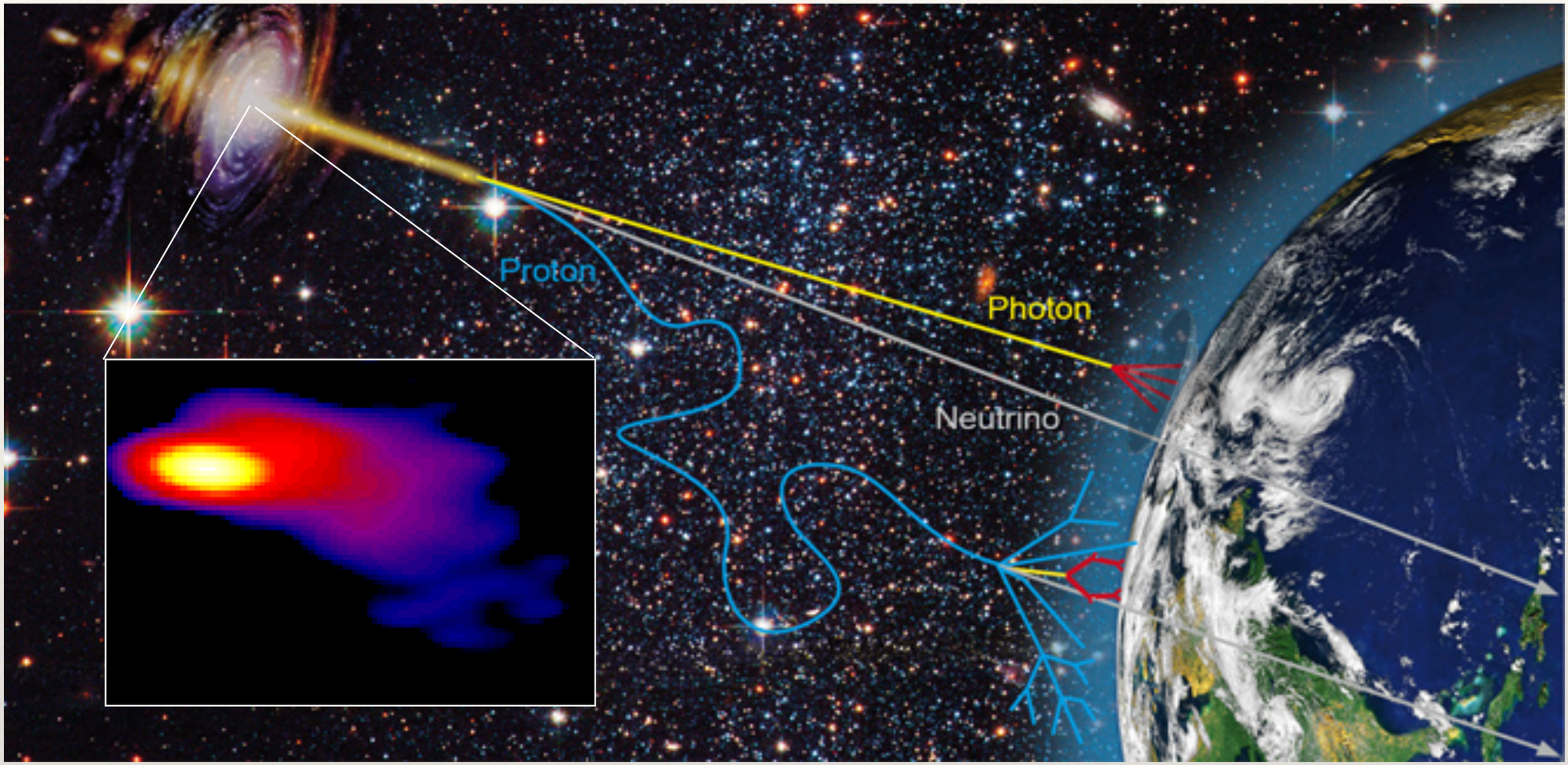


Observational Connection between Blazar Neutrino and Radio Emission

Matthias Kadler
Julius-Maximilians-Universität Würzburg

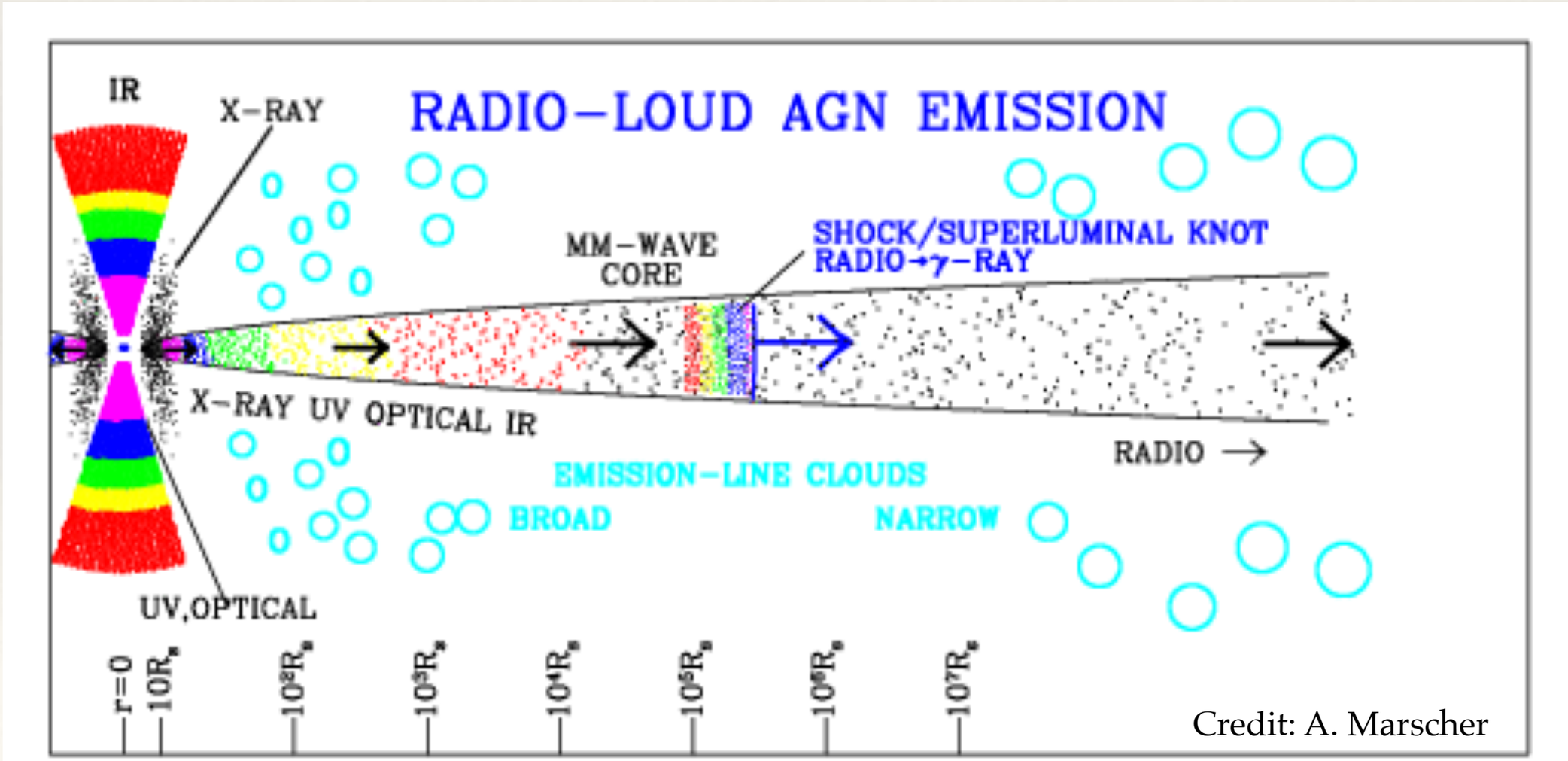
KM3NeT Town Hall Meeting,
September 20, 2022



In Collaboration with: P. G. Edwards, F. Eppel, M. Giroletti, T. Hovatta, Y. Kovalev, M. Lister, C. Nanci, R. Ojha, A. Plavin, A. Pushkarev, A. C. Readhead, F. Rösch, E. Ros and the Teams of MOJAVE, TANAMI, TELAMON, OVRO and RATAN-600 AGN Monitoring

Radio Emission in AGN Jets

Radio emission traces the response of the relativistic jet to dynamic processes in the inner 10^4-10^6 R_G from the central engine

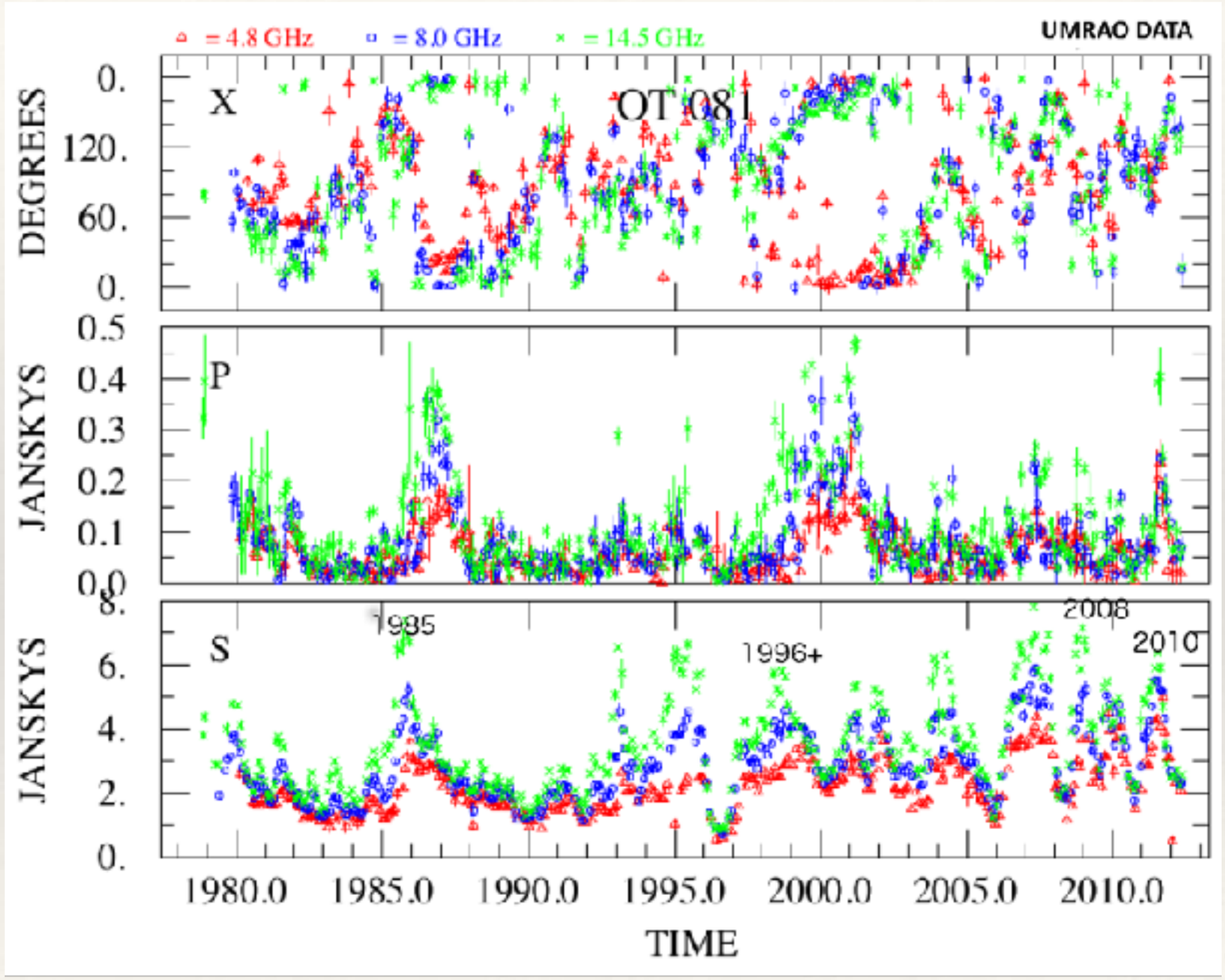


Credit: A. Marscher

Single-Dish Monitoring

- Long tradition of highly successful AGN cm-band flux-density monitoring programs
  - UMRAO, Metsähovi, OVRO, F-GAMMA, RATAN-600, TELAMON

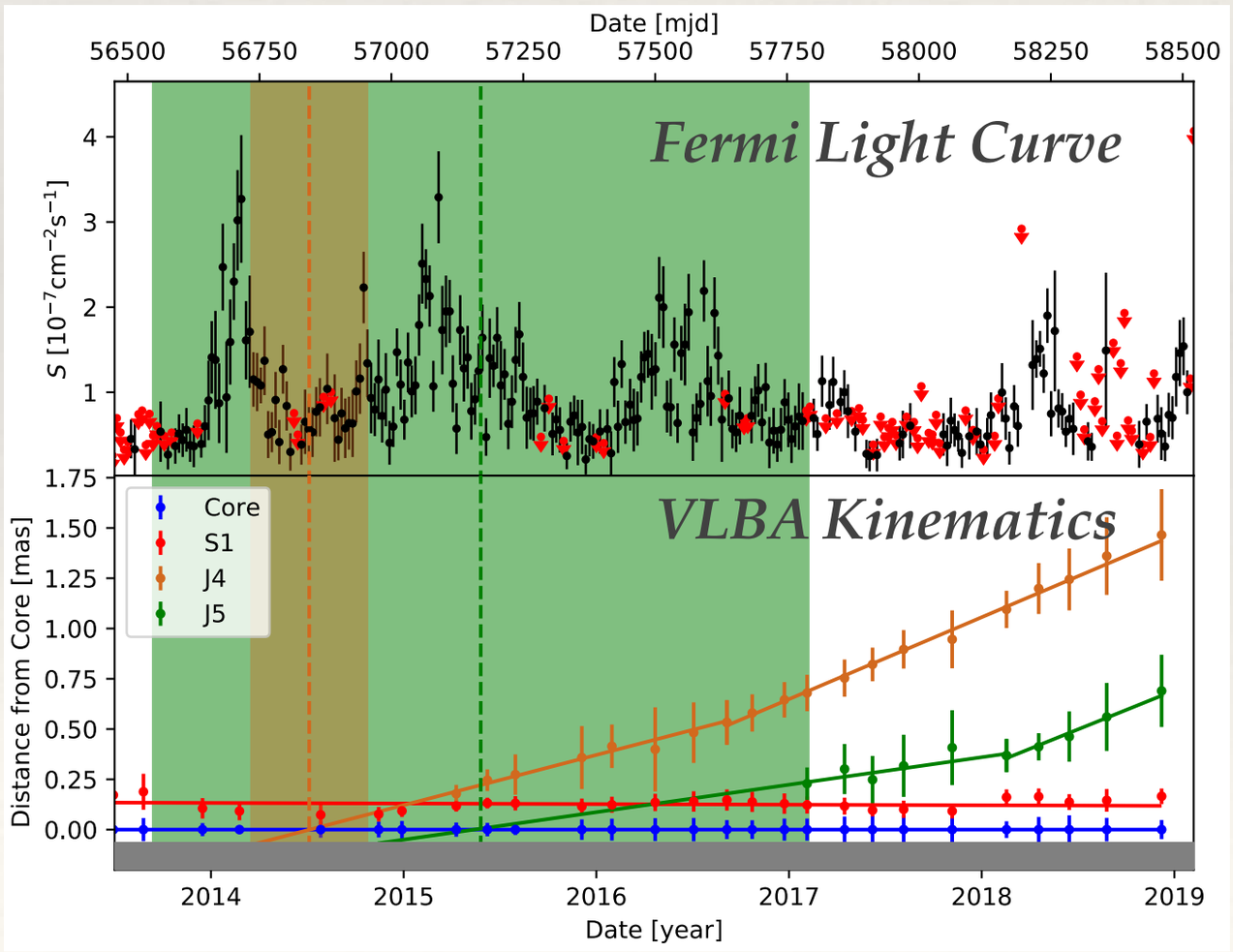
- Direct connection to gamma-ray emission, e.g.:
  - Correlation between gamma and radio flares
  - EVPA swings

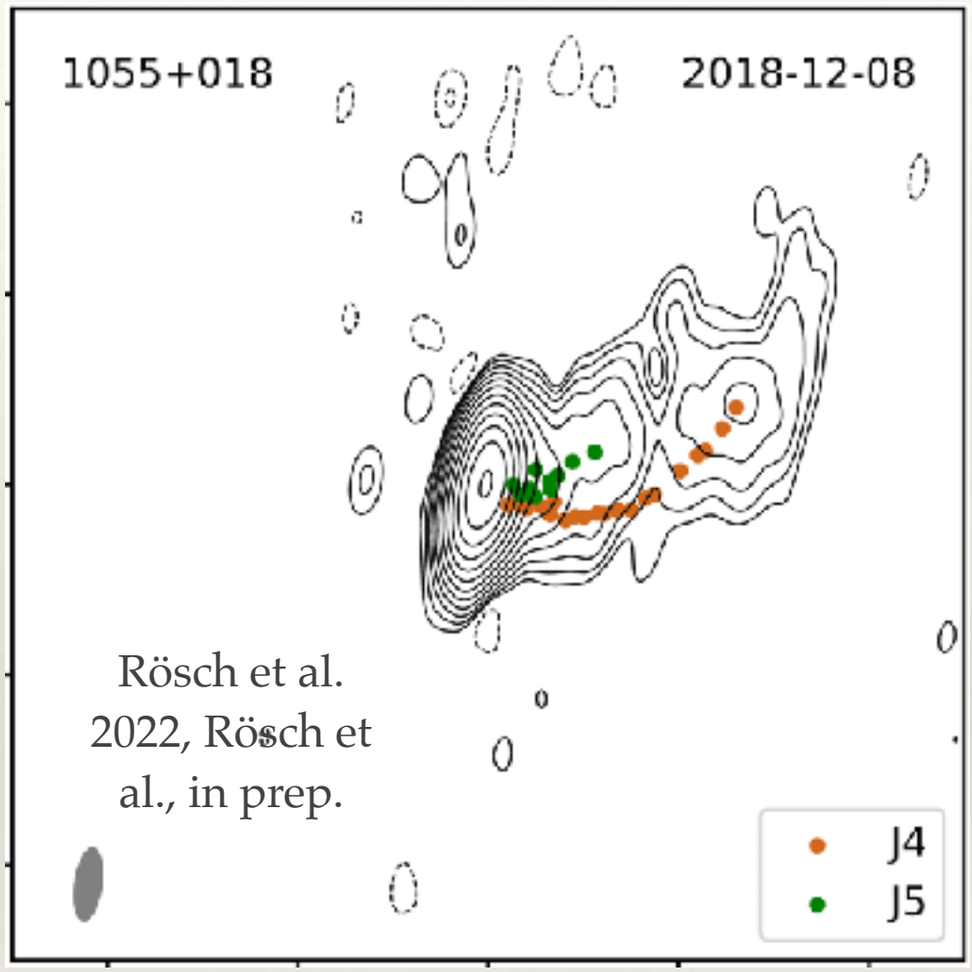


Aller et al. 2020, Galaxies 8, 22

Very Long Baseline Interferometry

VLBI yields sub-milliarcsecond resolution and real-time tracking of jet kinematics

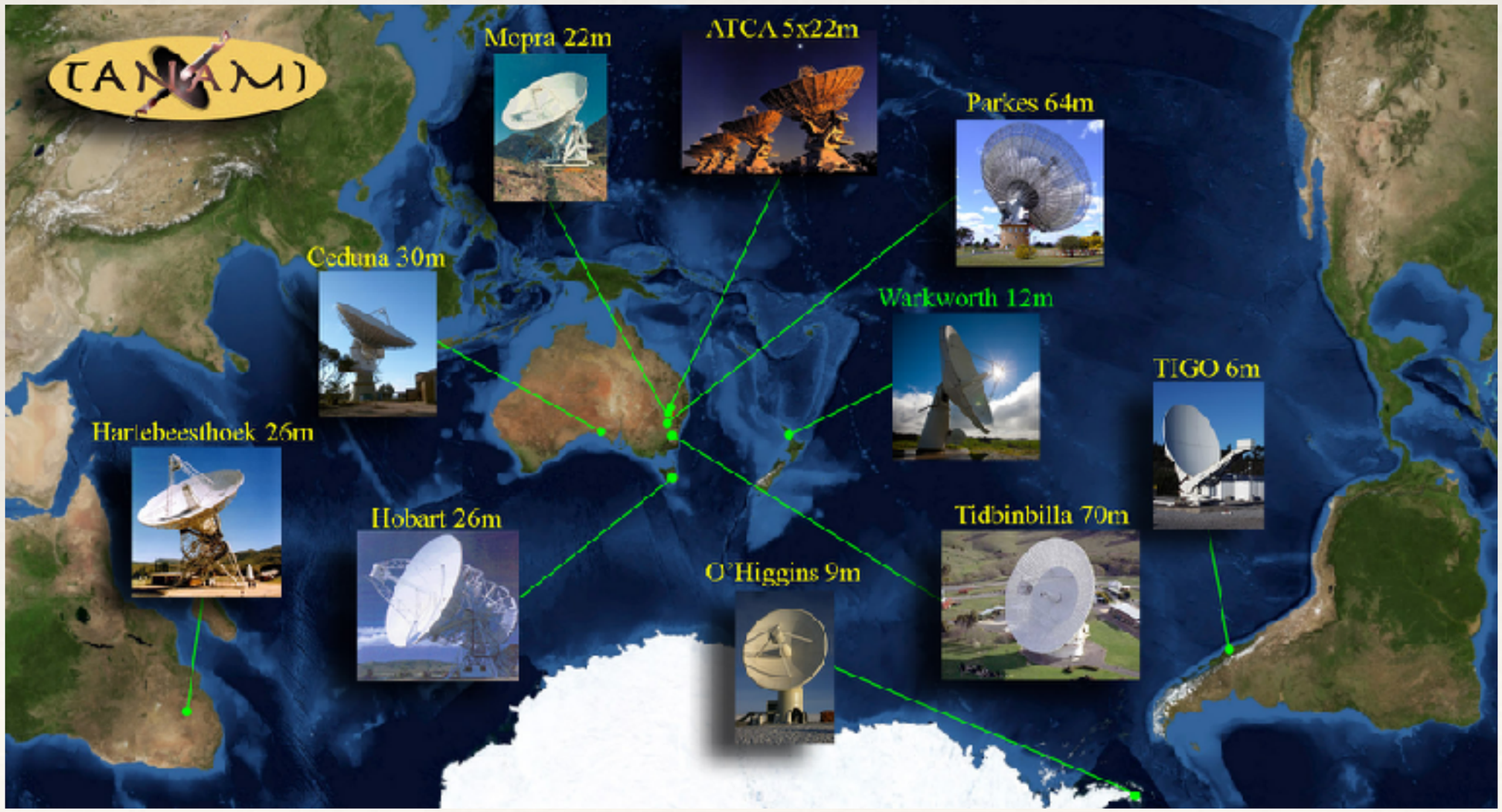




1. Long-term monitoring programs, e.g., MOJAVE, TANAMI
2. Target-of-Opportunity observations

VLBI and Spectral AGN Monitoring in the Southern Hemisphere

Ojha et al. 2010; Kadler et al. 2015



VLBI and Spectral AGN Monitoring in the Southern Hemisphere

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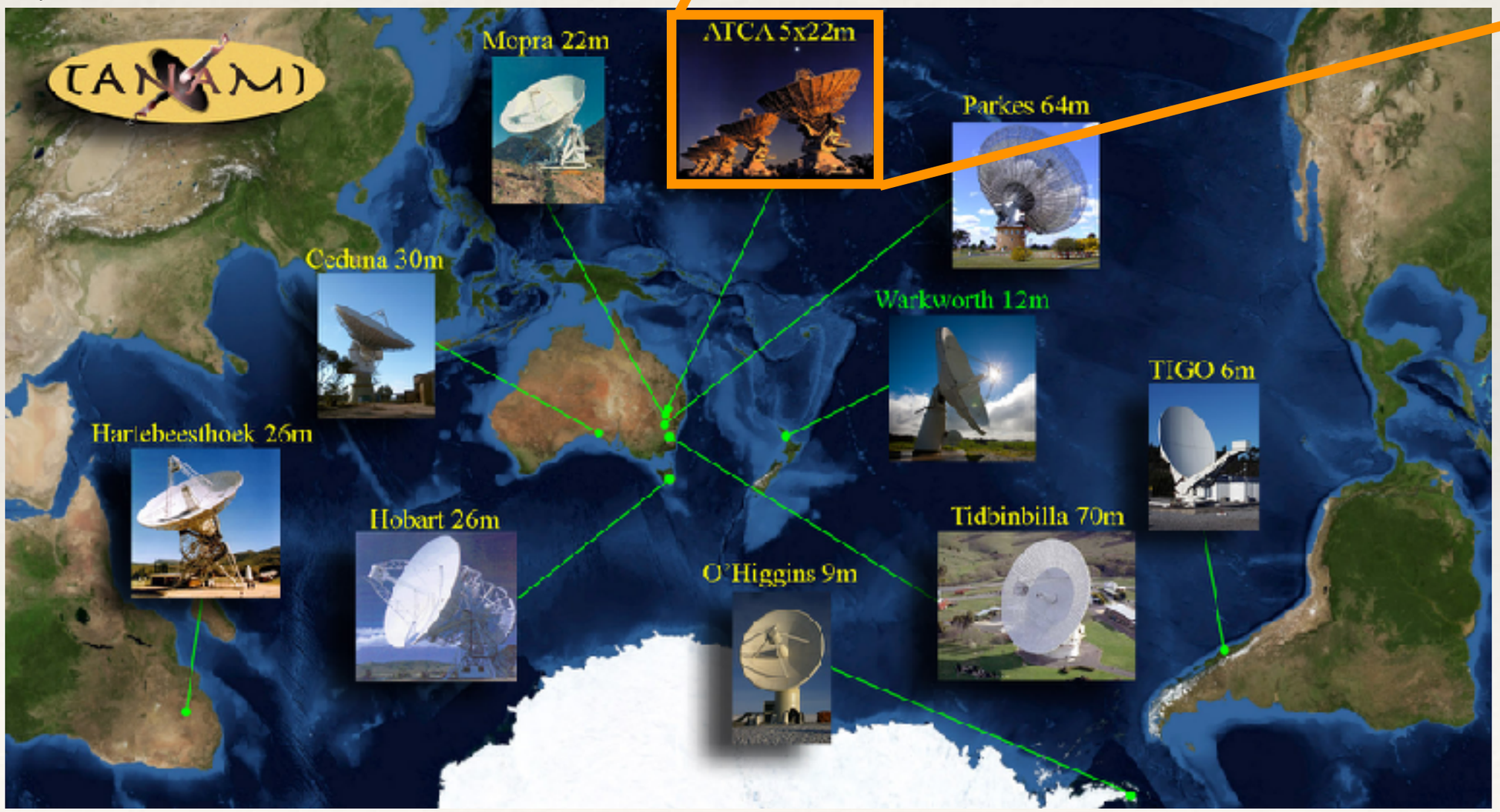
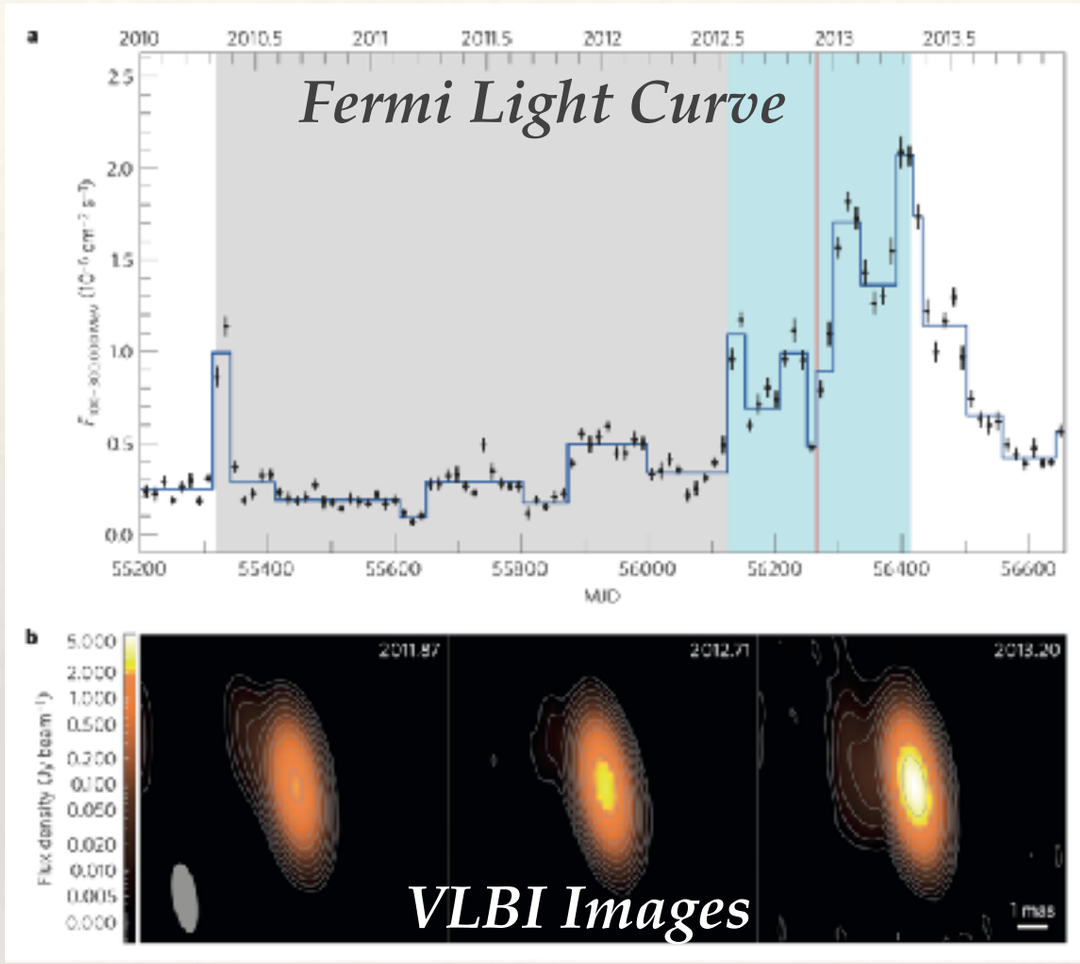


Radio Observations of Candidate Neutrino Blazars

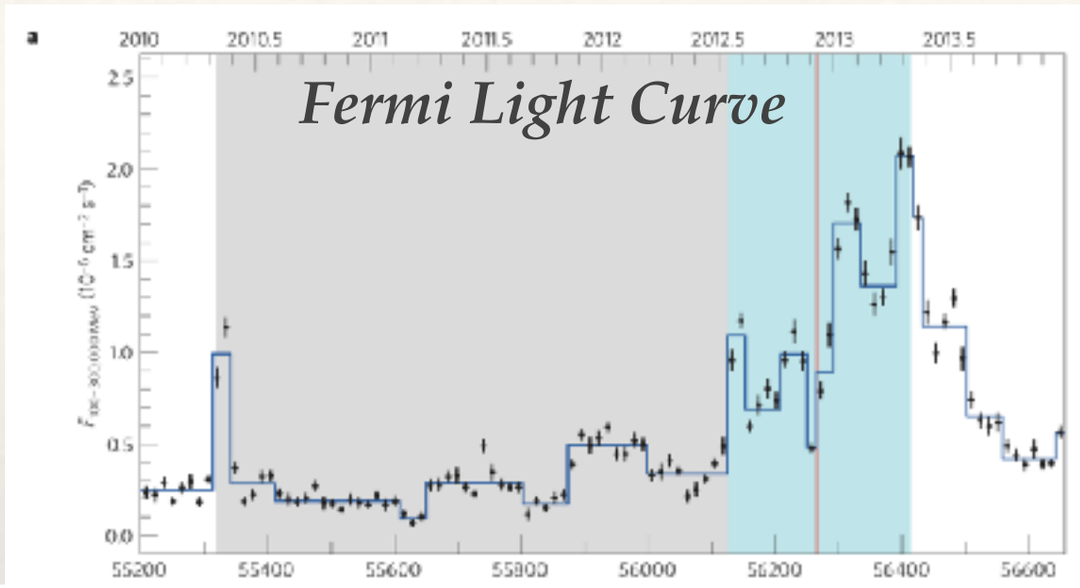


Kadler et al. 2016, Nature Physics 12, 807

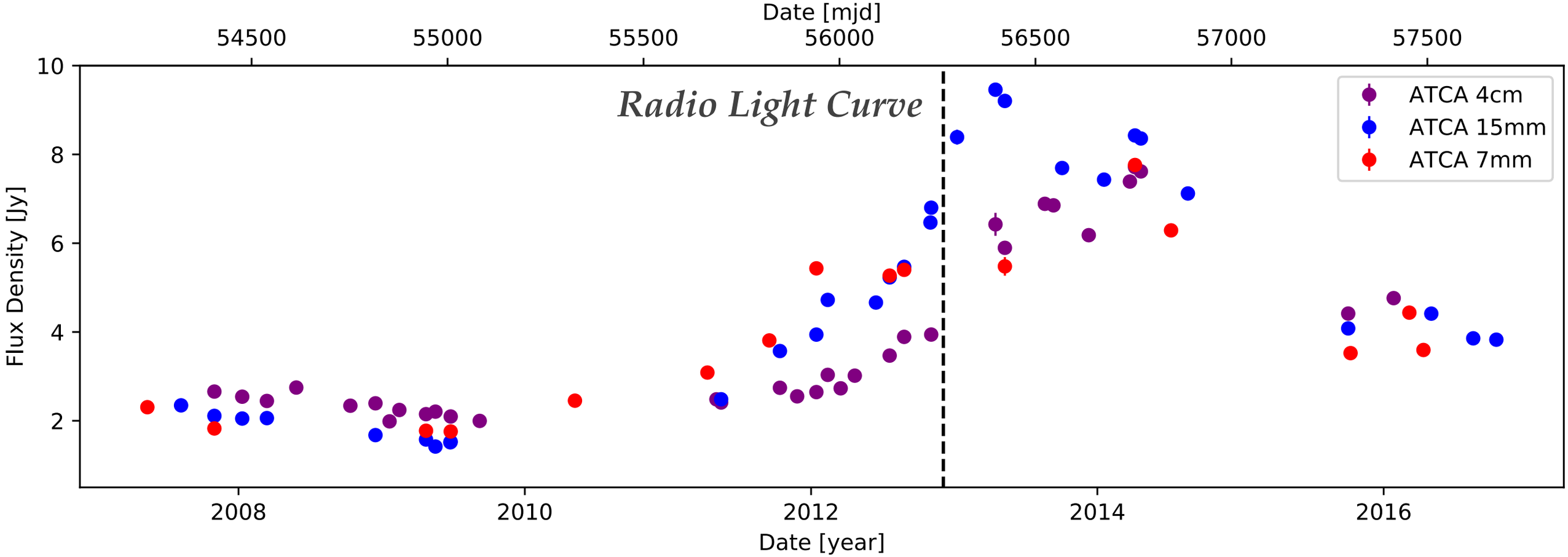
Correlated radio-gamma outburst of PKS1424-418 in coincidence with PeV IceCube neutrino in 2012

2σ significance (cascade event)

Radio Observations of Candidate Neutrino Blazars

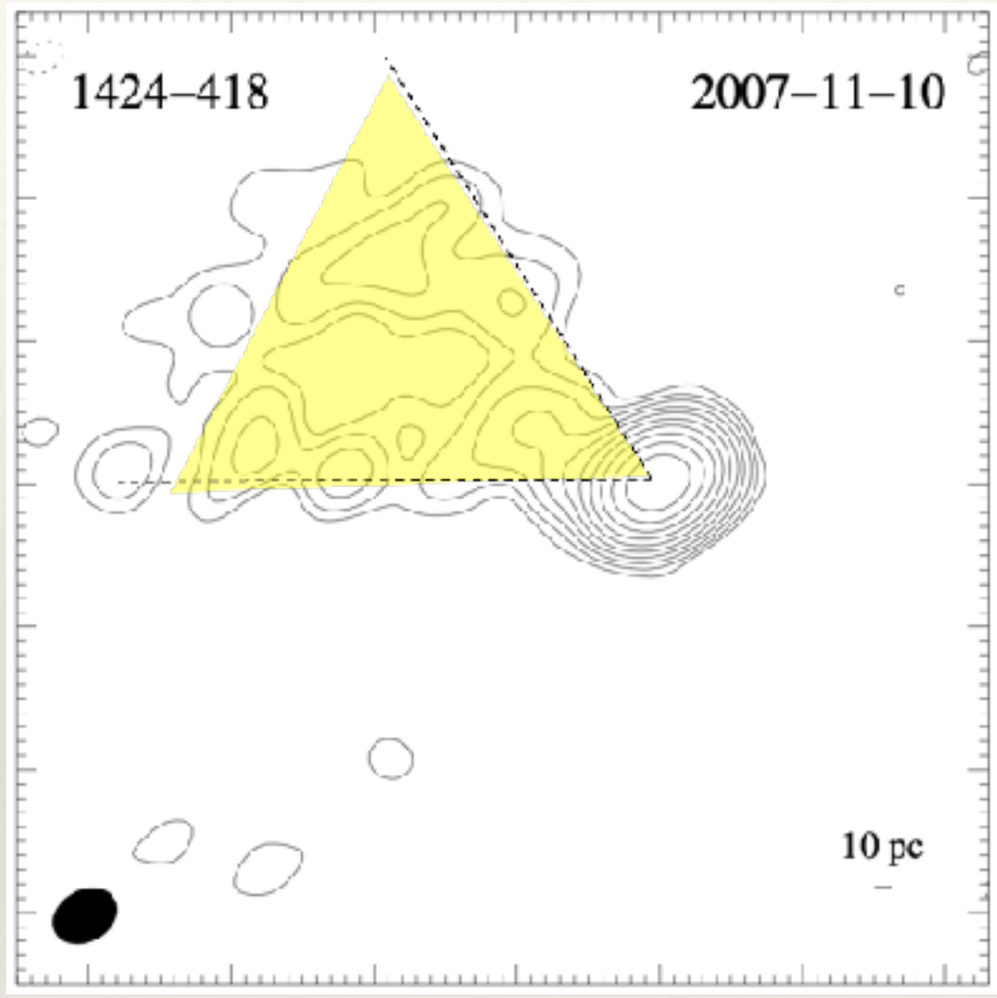


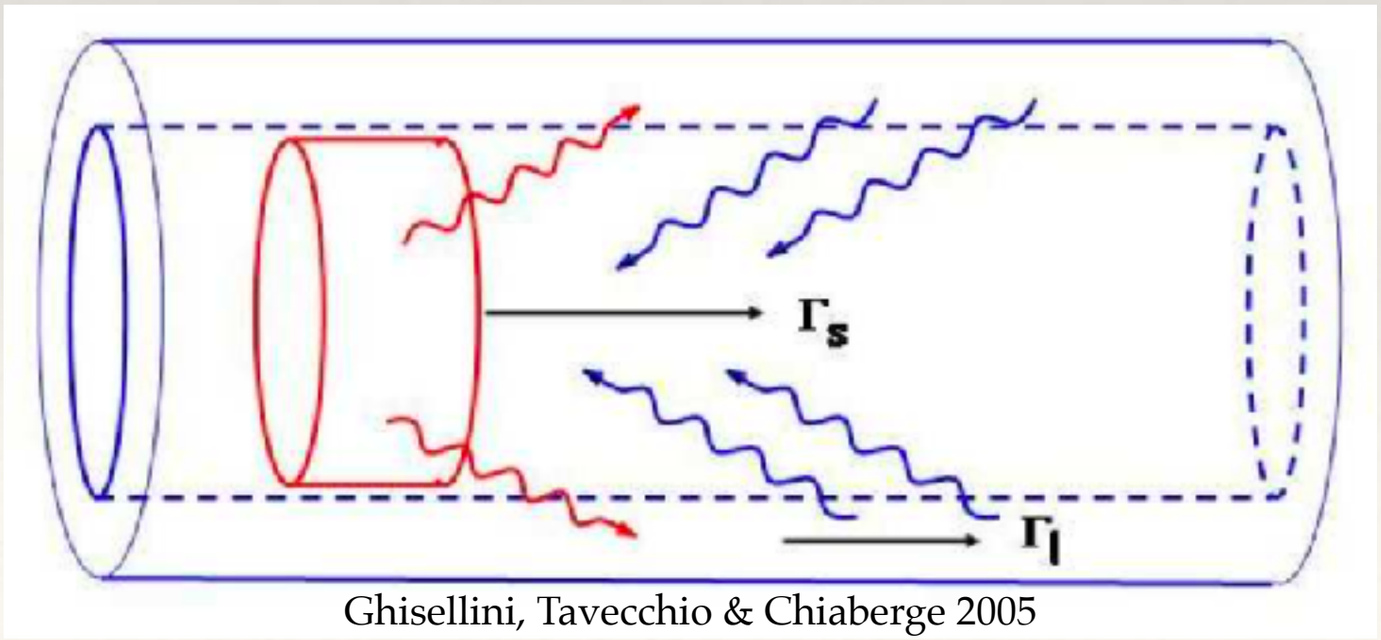
Kadler et al. 2016, Nature Physics 12, 807



Radio Observations of Candidate Neutrino Blazars

- TANAMI (LBA+) tapered images show wide opening angle and limb-brightened jet
- Slow jet sheath as a possible seed photon field for photopion production (Tavecchio et al. 2014)



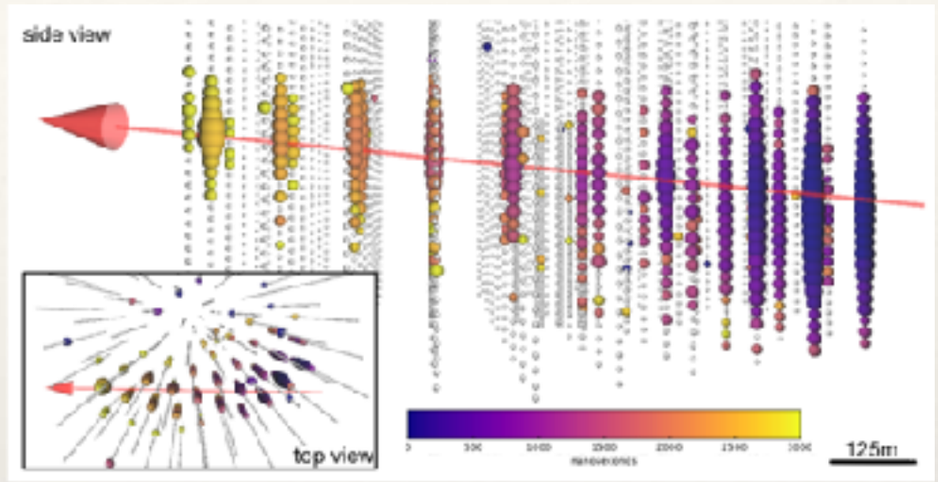


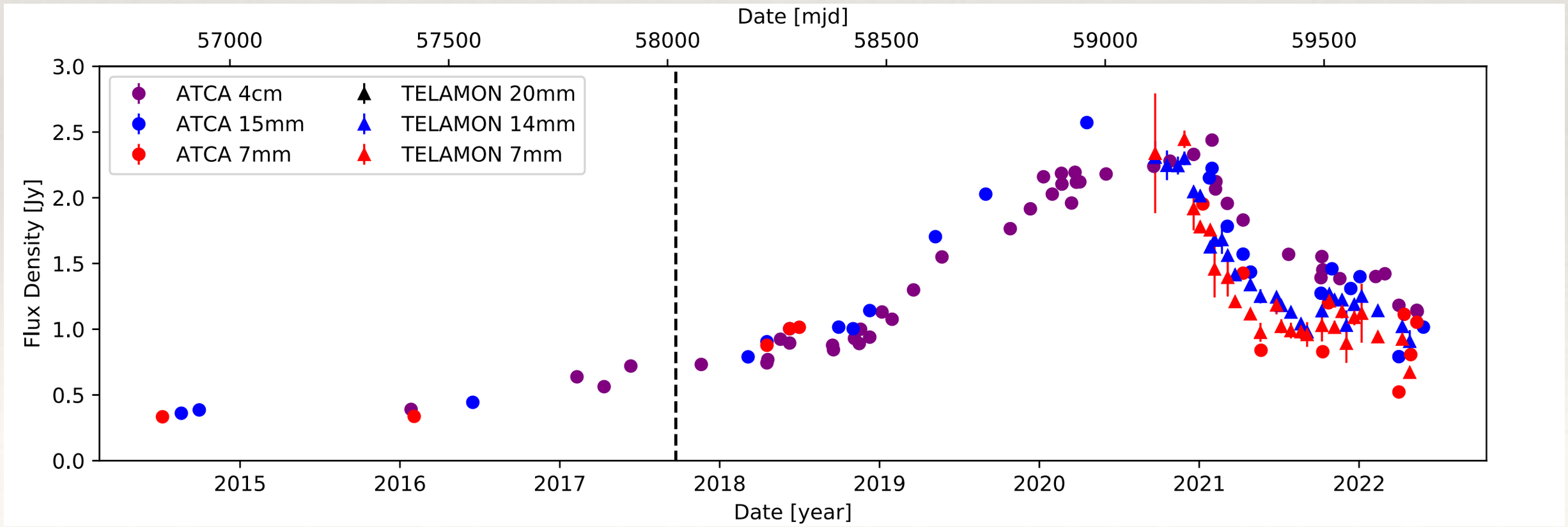
Ghisellini, Tavecchio & Chiaberge 2005

Radio Observations of Candidate Neutrino Blazars

- **TXS 0506+056**
  - Only 3σ blazar association so far
  - Also correlated with multi-year radio outburst

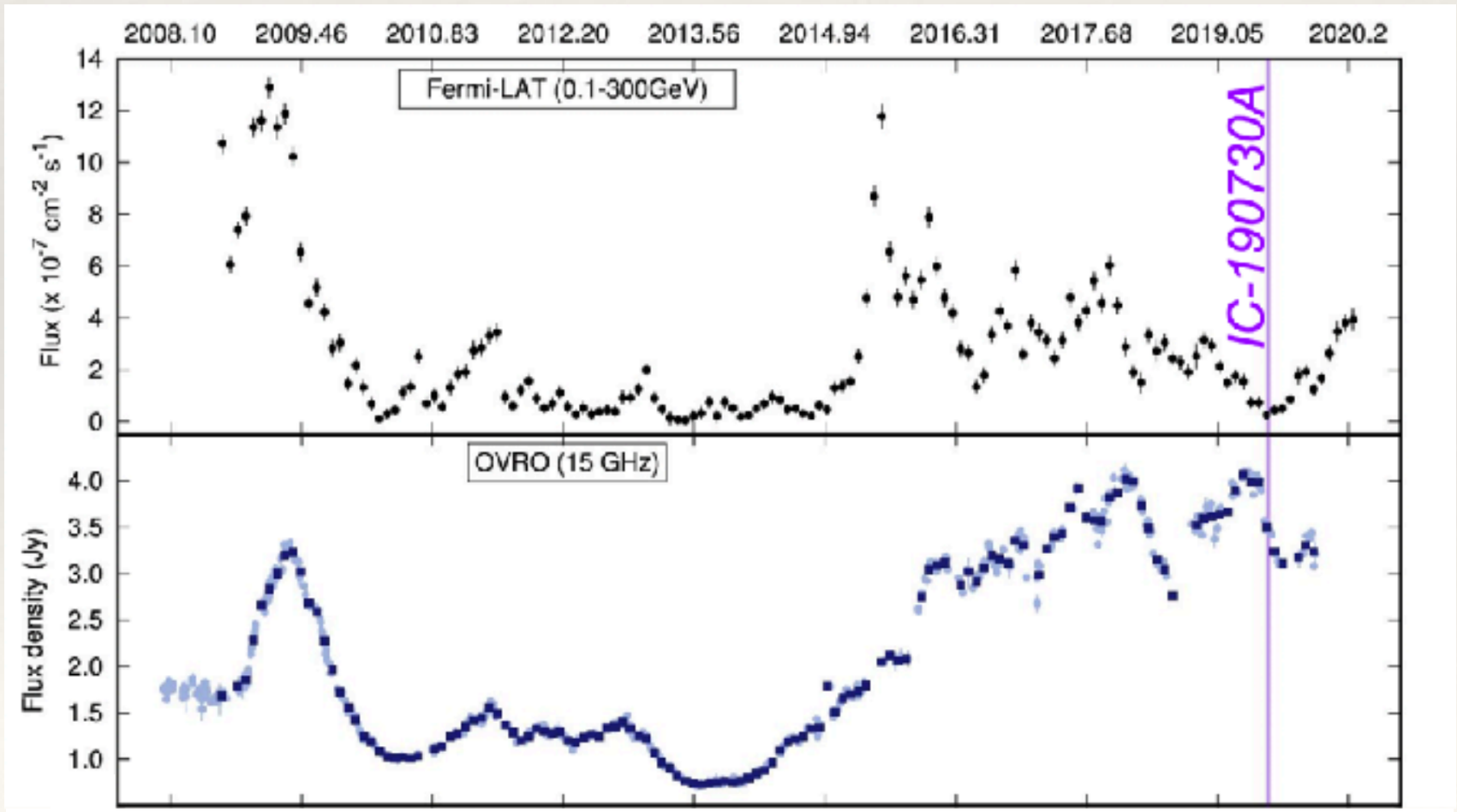
IC170922A / TXS0506+056: IceCube, Fermi / LAT, et al. 2018



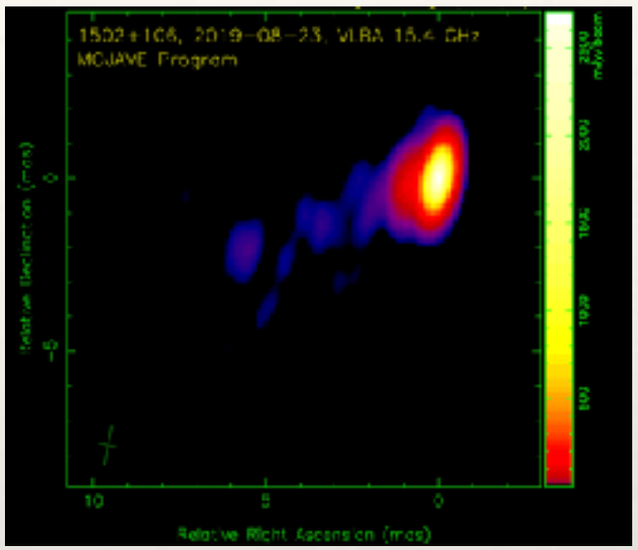


Radio Observations of Candidate Neutrino Blazars

- **PKS 1502+106**
  - IC20190730A coincident with bright Fermi 4FGL 1504.4+1029 (aka PKS1502+106)



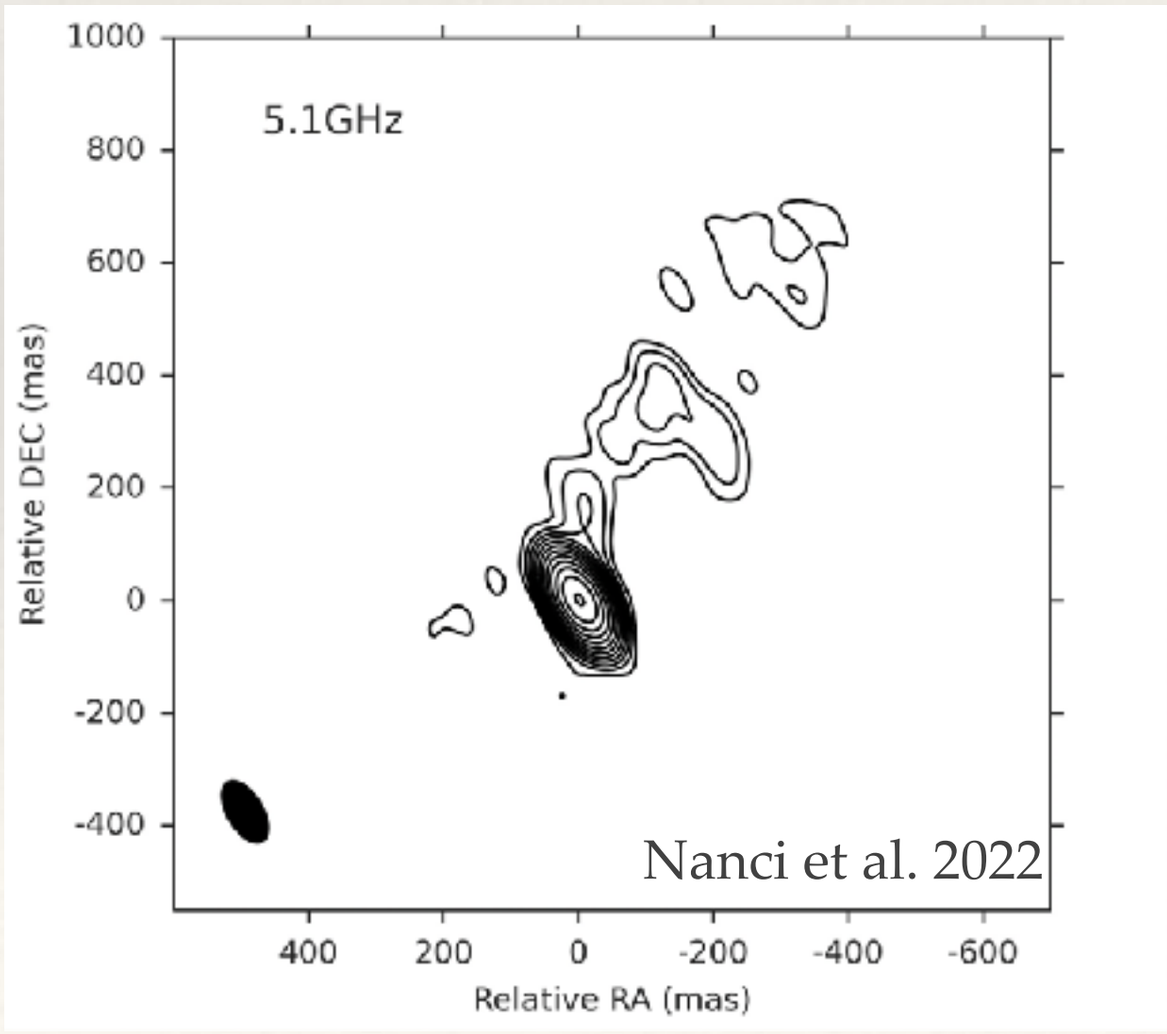
Kun et al. 2021

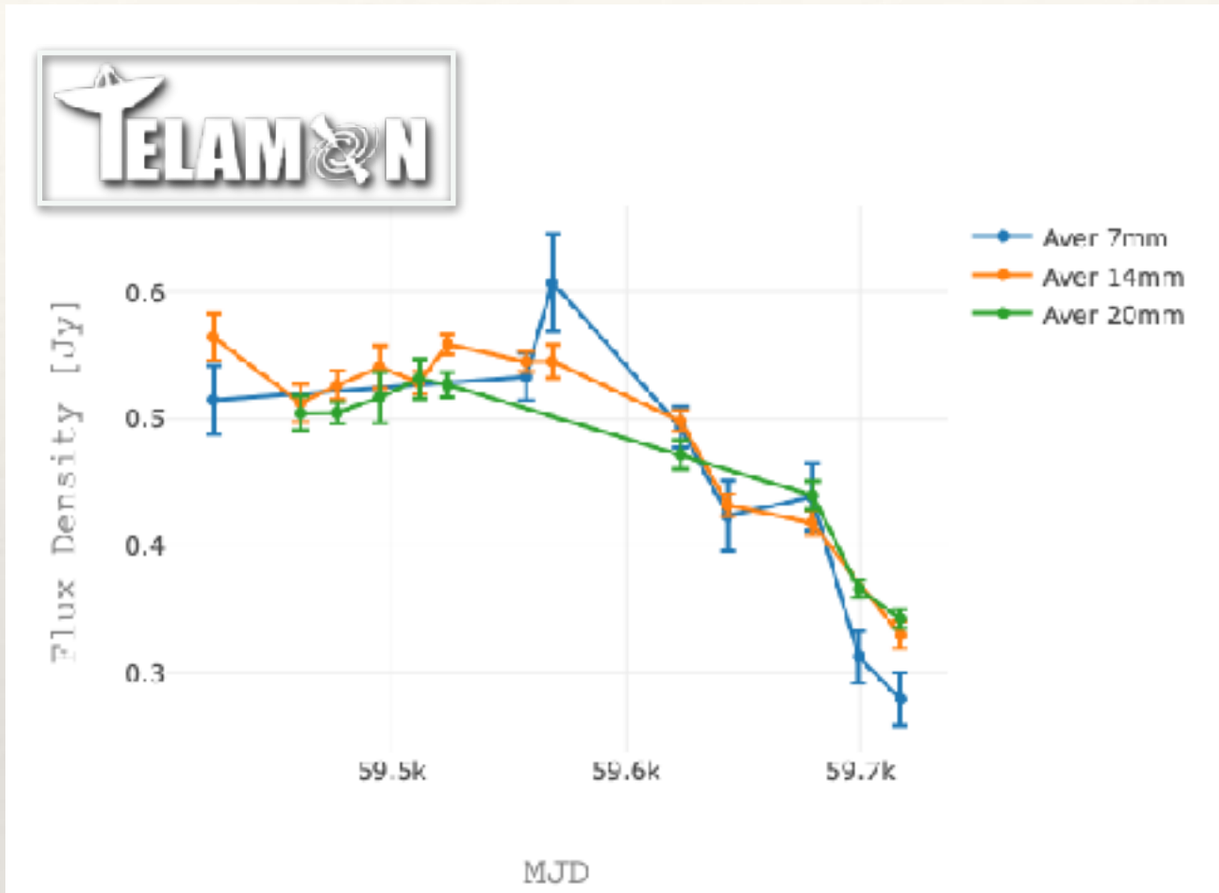


- Gamma emission local minimum !.?
- Radio light curve in long-term outburst (Kiehlmann, Hovatta, Kadler et al. 2019)

Radio Observations of Candidate Neutrino Blazars

- **PKS 1725+123**
  - Suggested as likely counterpart to IC201021A by Nanci et al. 2022





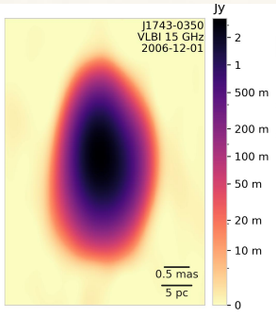
- Only sparse pre-event radio data available
- Follow-up observations show decrease of the light curve

Statistical correlation: Plavin et al. 2020, 2021

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.

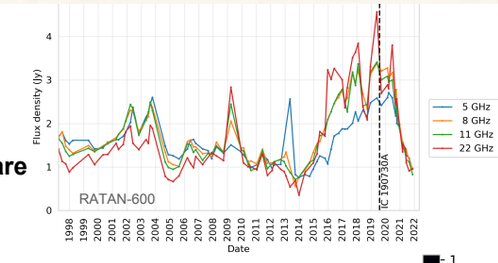


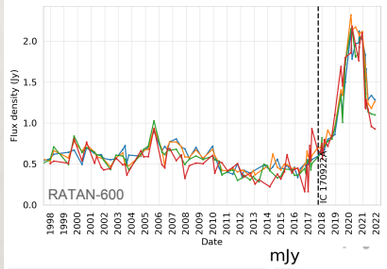
PKS 1741-03

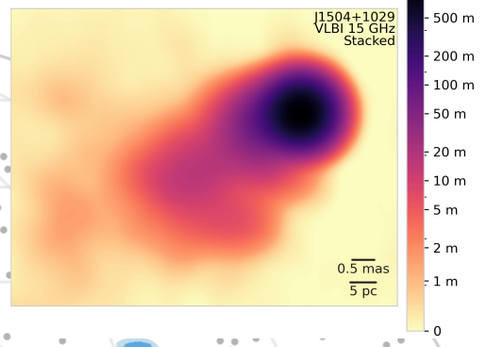
- one of the four selected in Plavin+2020
- coincides with recent IceCube 220205 neutrino, chance probability 3%

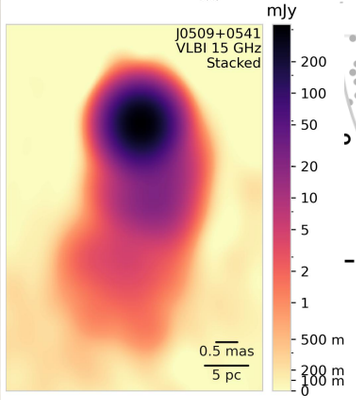
PKS 1502+10

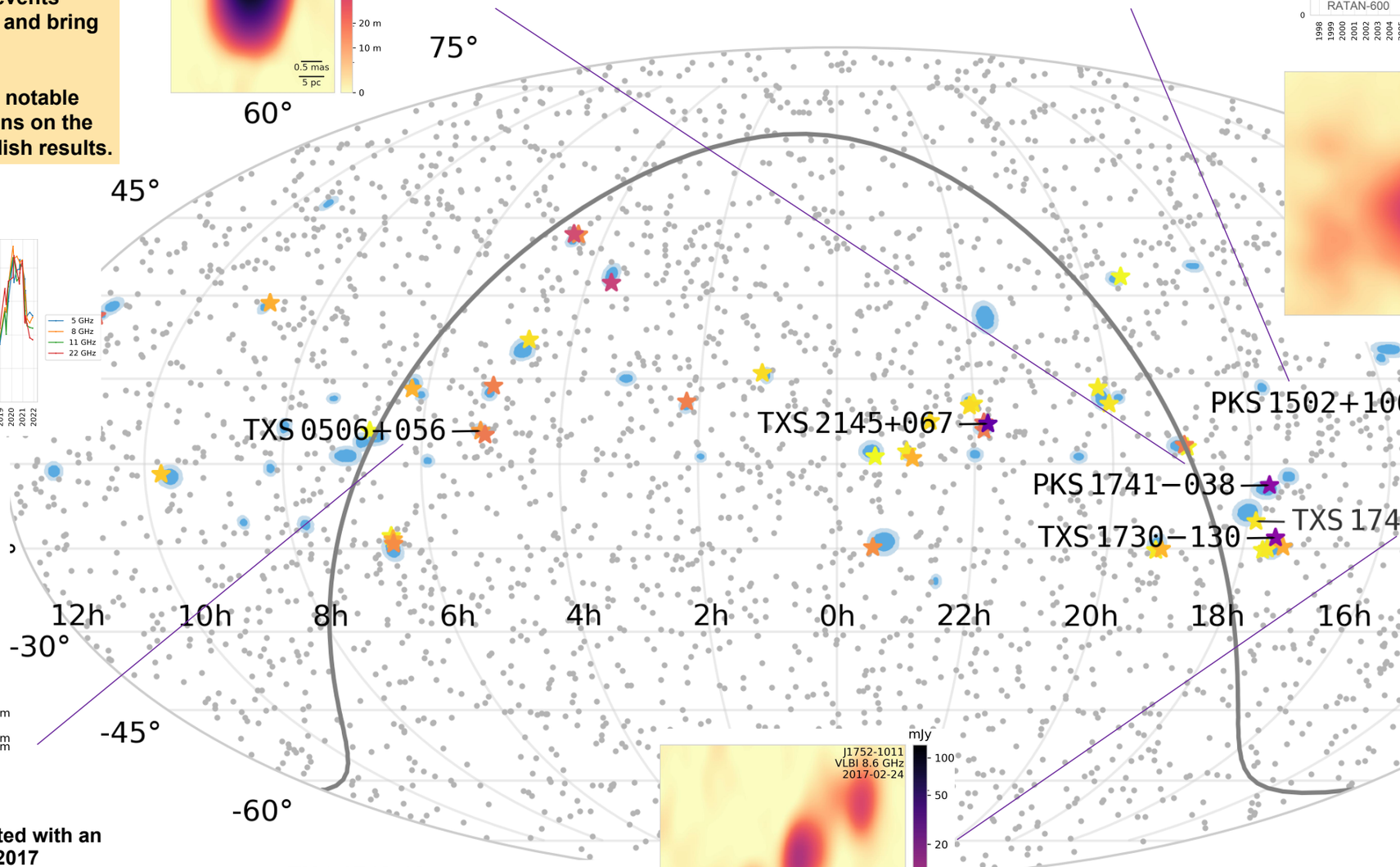
- selected in Plavin+2020 by the highest neutrino-radio flare correlation
- further monitoring confirms a strong flare









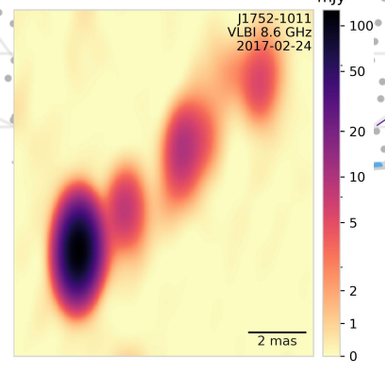


TXS 0506+05

- 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

TXS 1749-10

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

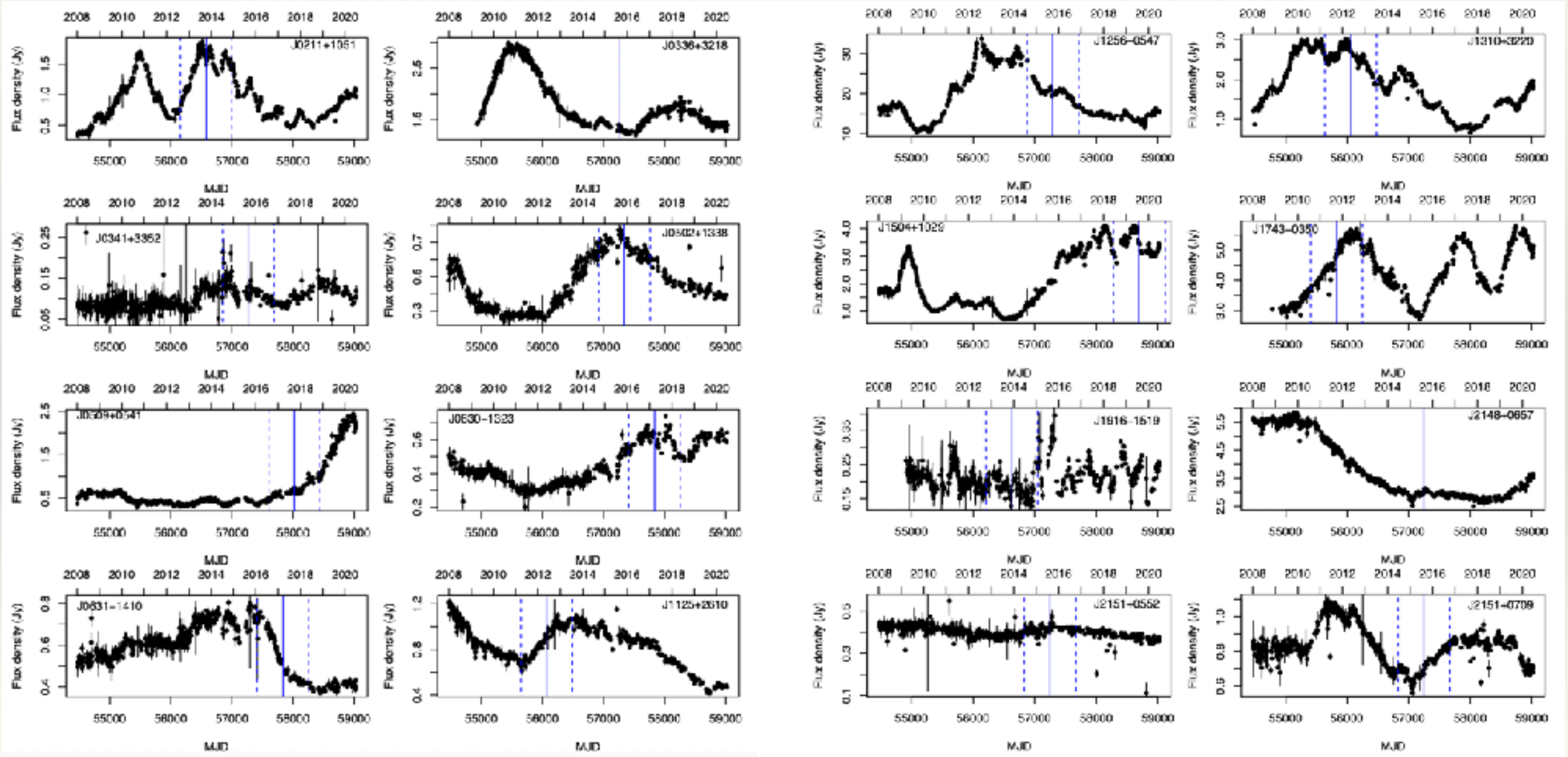


Alexander Plavin,
Yuri A. Kovalev,
Sergey Troitsky

Published results:

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

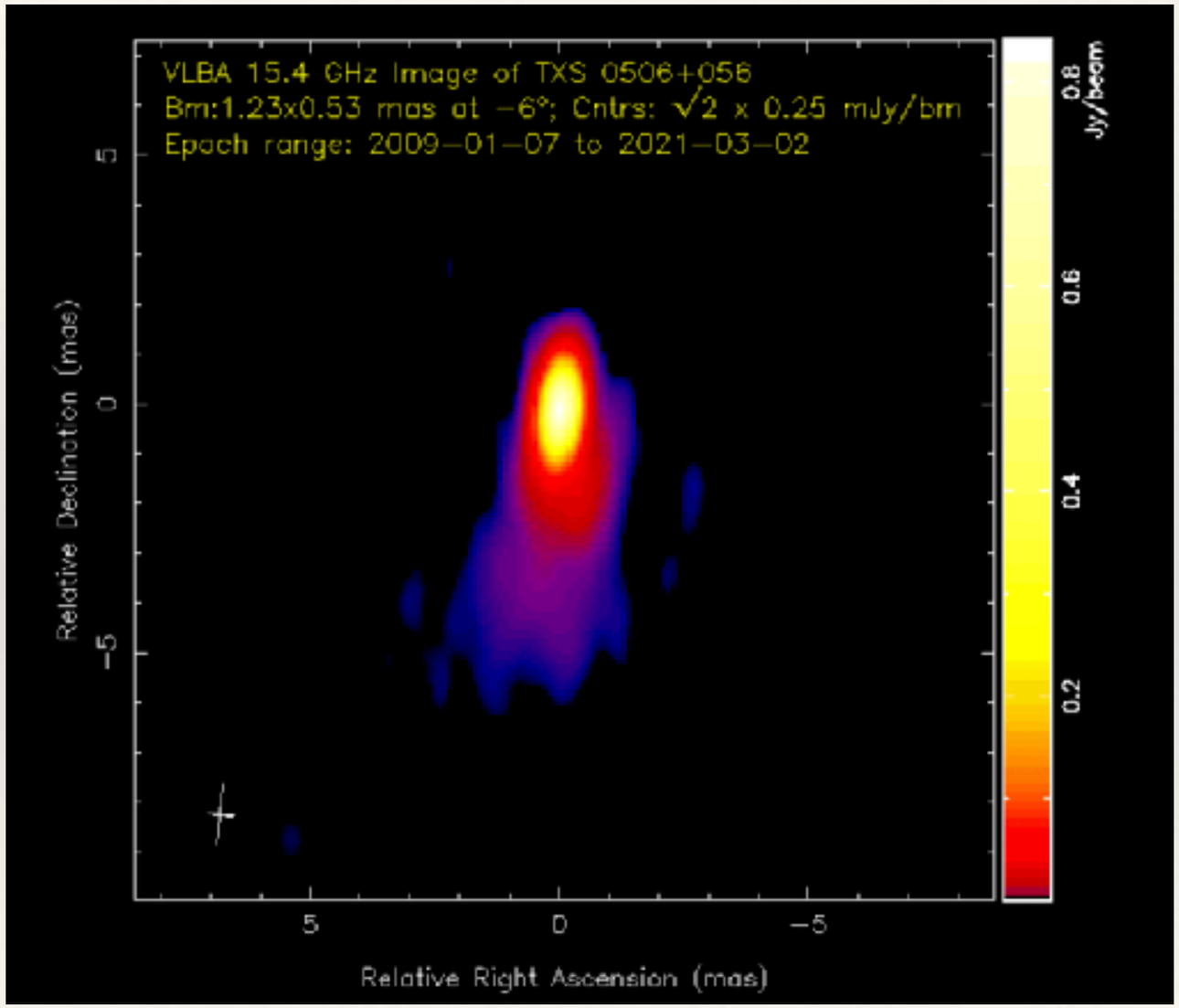
Statistical correlation: Hovatta et al. 2021



VLBI Observations: Highest Angular Resolution

TXS 0506+056:

- Studied by various radio groups (Kun et al., Britzen et al., Sumida et al., Li et al.,…) based on VLBA data from the MOJAVE data base
- Significant differences in modeling and interpretation regarding jet speed and kinematics

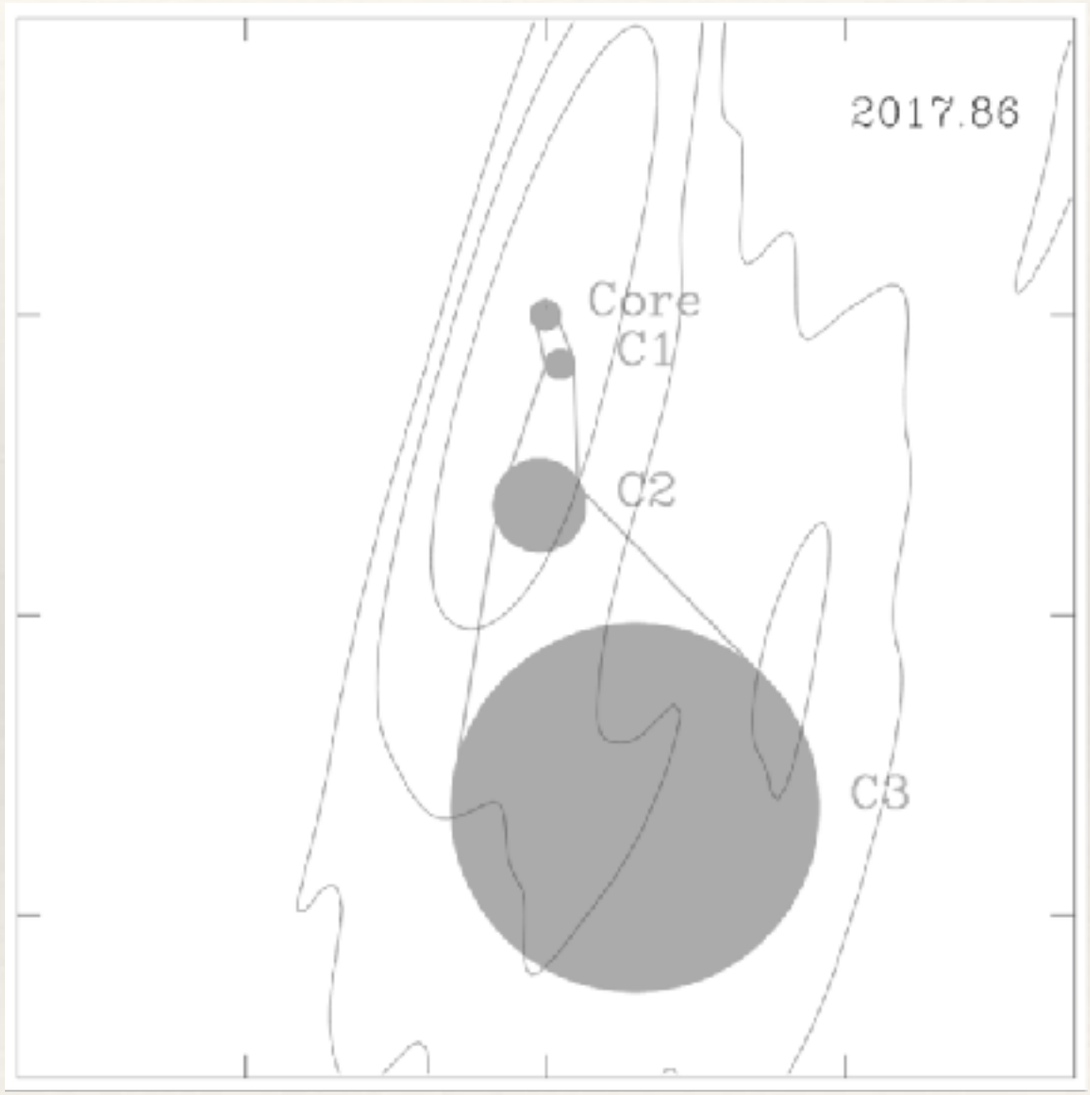


VLBI Observations: Highest Angular Resolution

TXS 0506+056:

- 7mm VLBI imaging reveals wide opening angle

Ros, Kadler et al. 2020

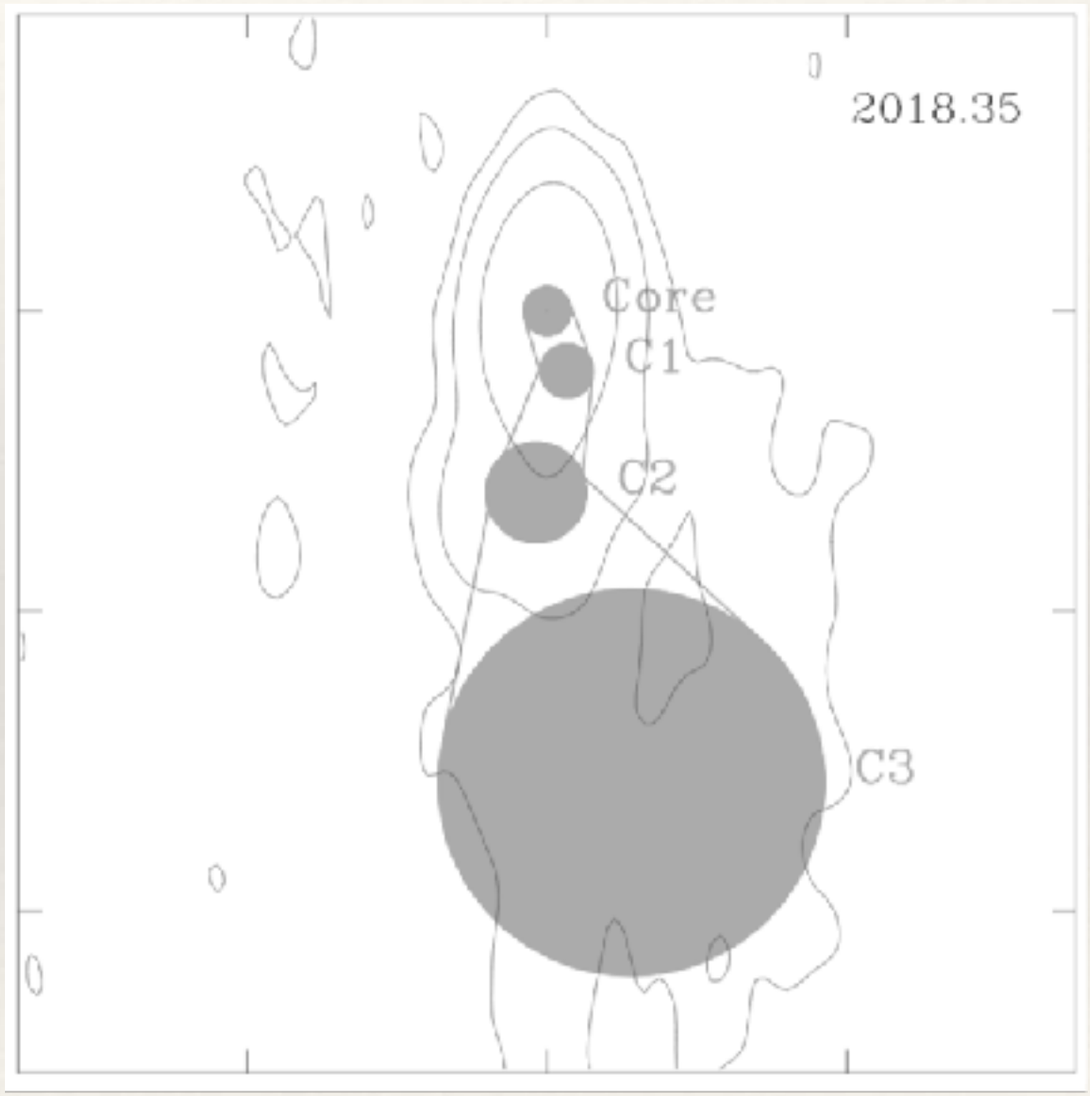


VLBI Observations: Highest Angular Resolution

TXS 0506+056:

- 7mm VLBI imaging reveals wide opening angle
- The core shows apparent superluminal expansion,…
-

Ros, Kadler et al. 2020



VLBI Observations: Highest Angular Resolution

Ros, Kadler et al. 2020

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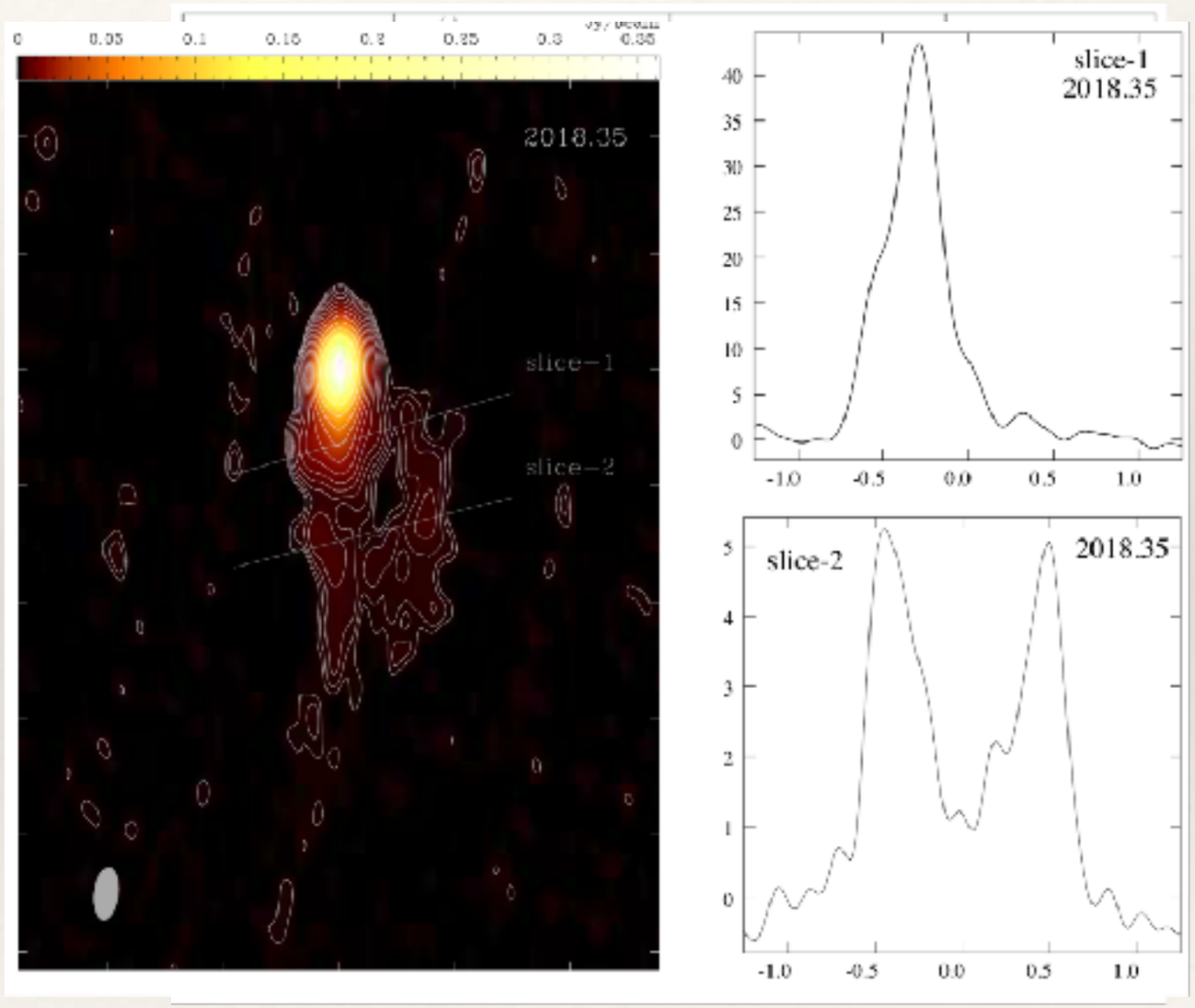
- 7mm VLBI imaging reveals wide opening angle
- The core shows apparent superluminal expansion,…
- …and the jet limb brightening



VLBI Observations: Highest Angular Resolution

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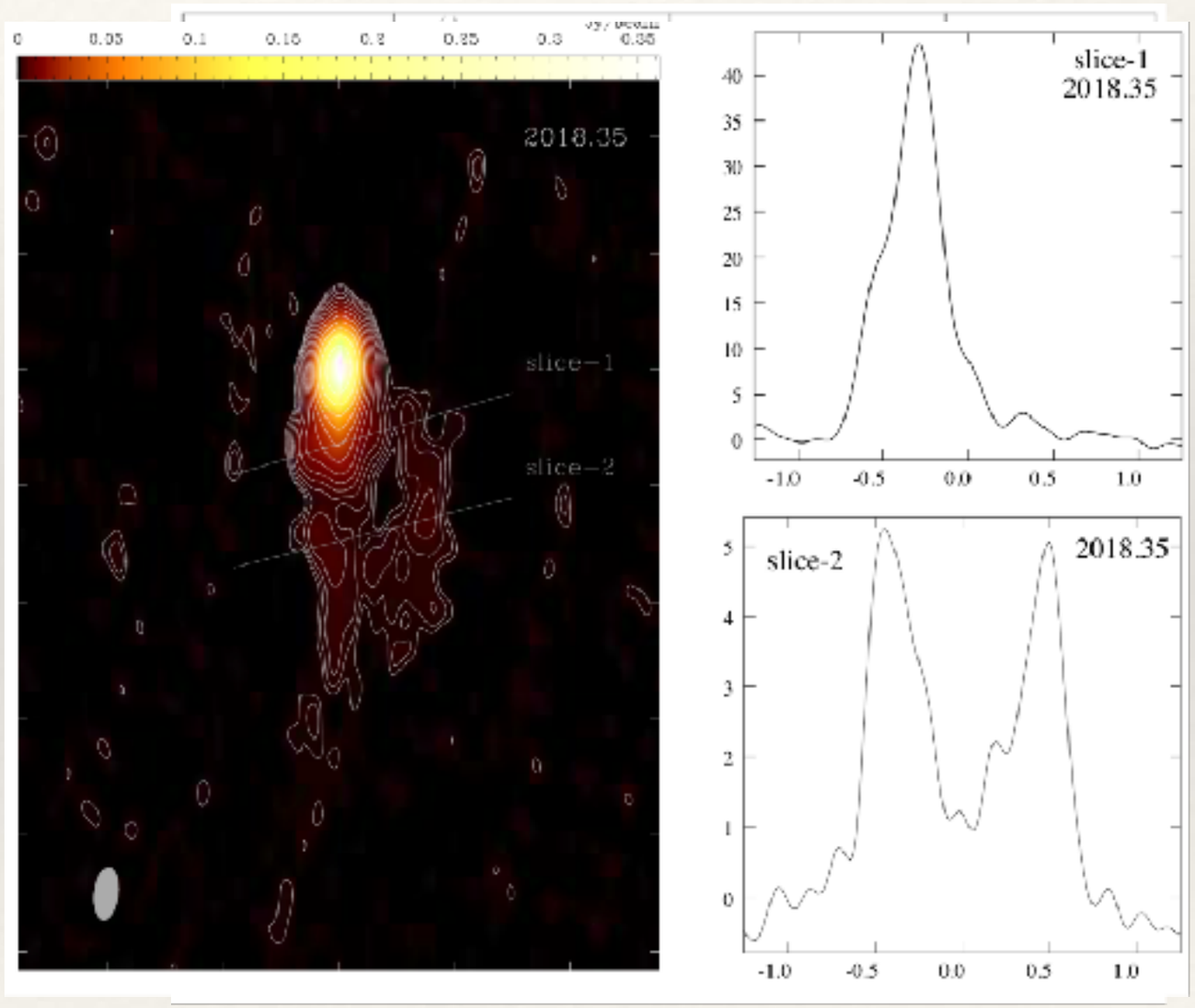


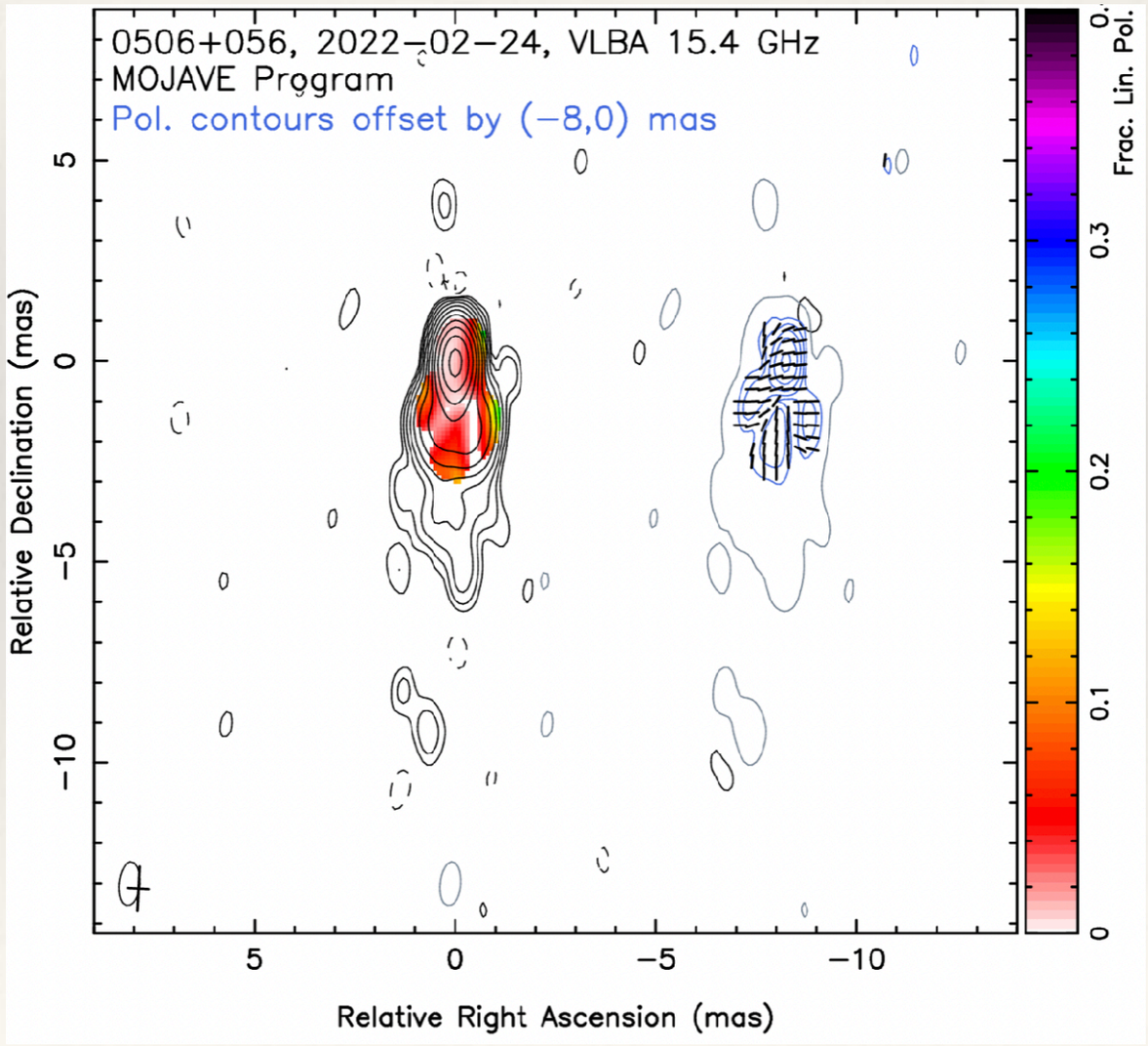
3 epochs, multi-frequency, polarization

(PhD thesis project F. Eppel)

VLBI Observations: Polarization

Cf. Pushkarev et al. 2022 (arXiv2209.04842)

TXS 0506+056



VLBI Observations: Polarization

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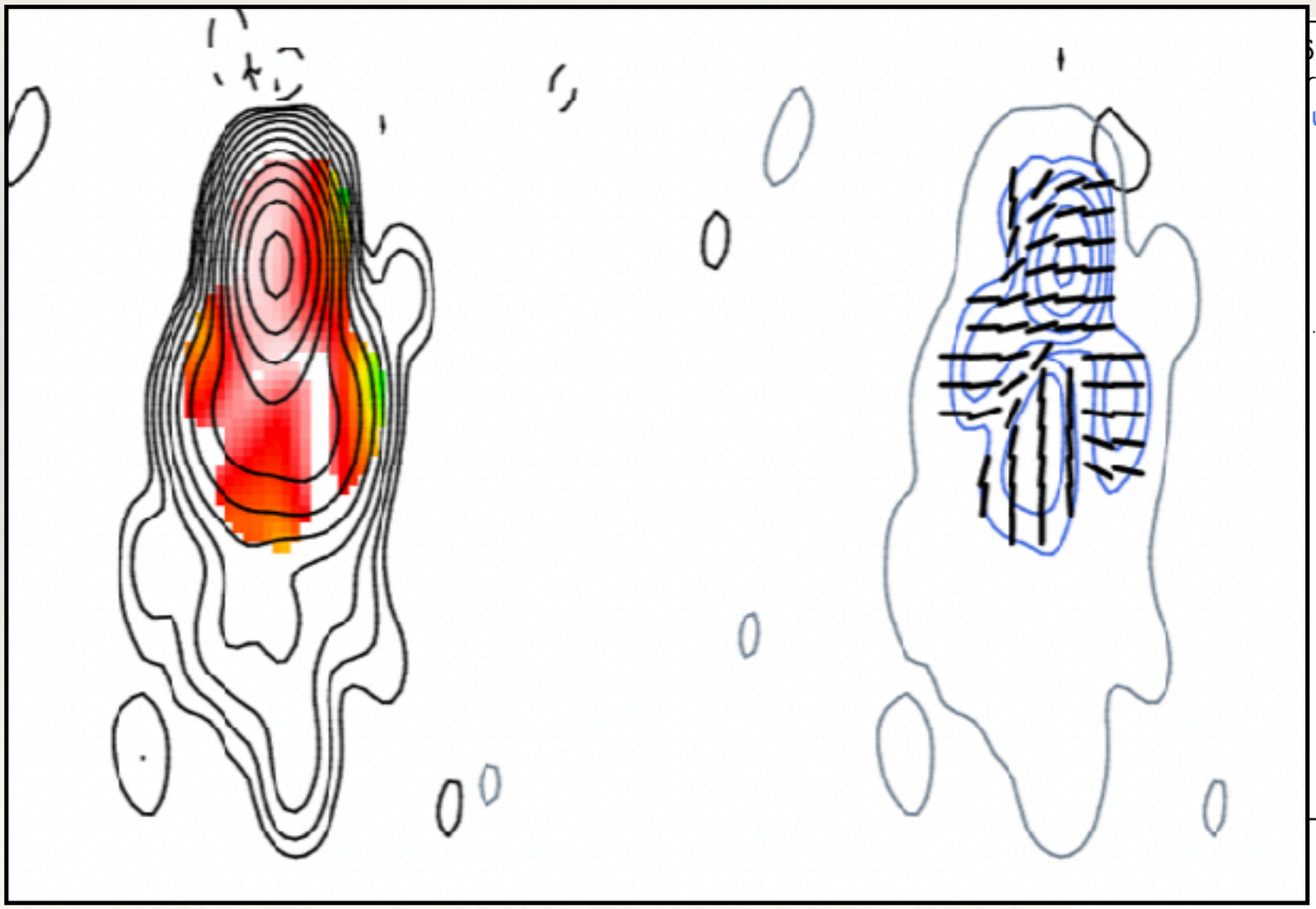
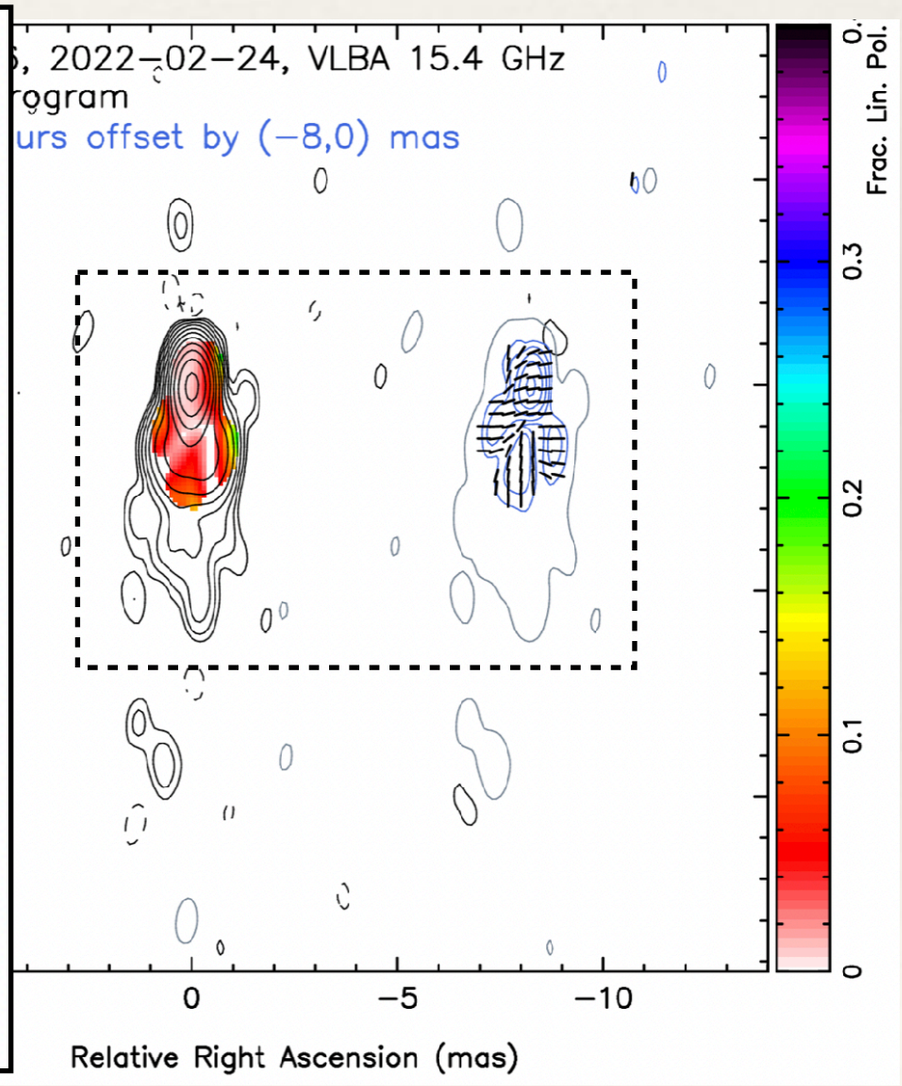


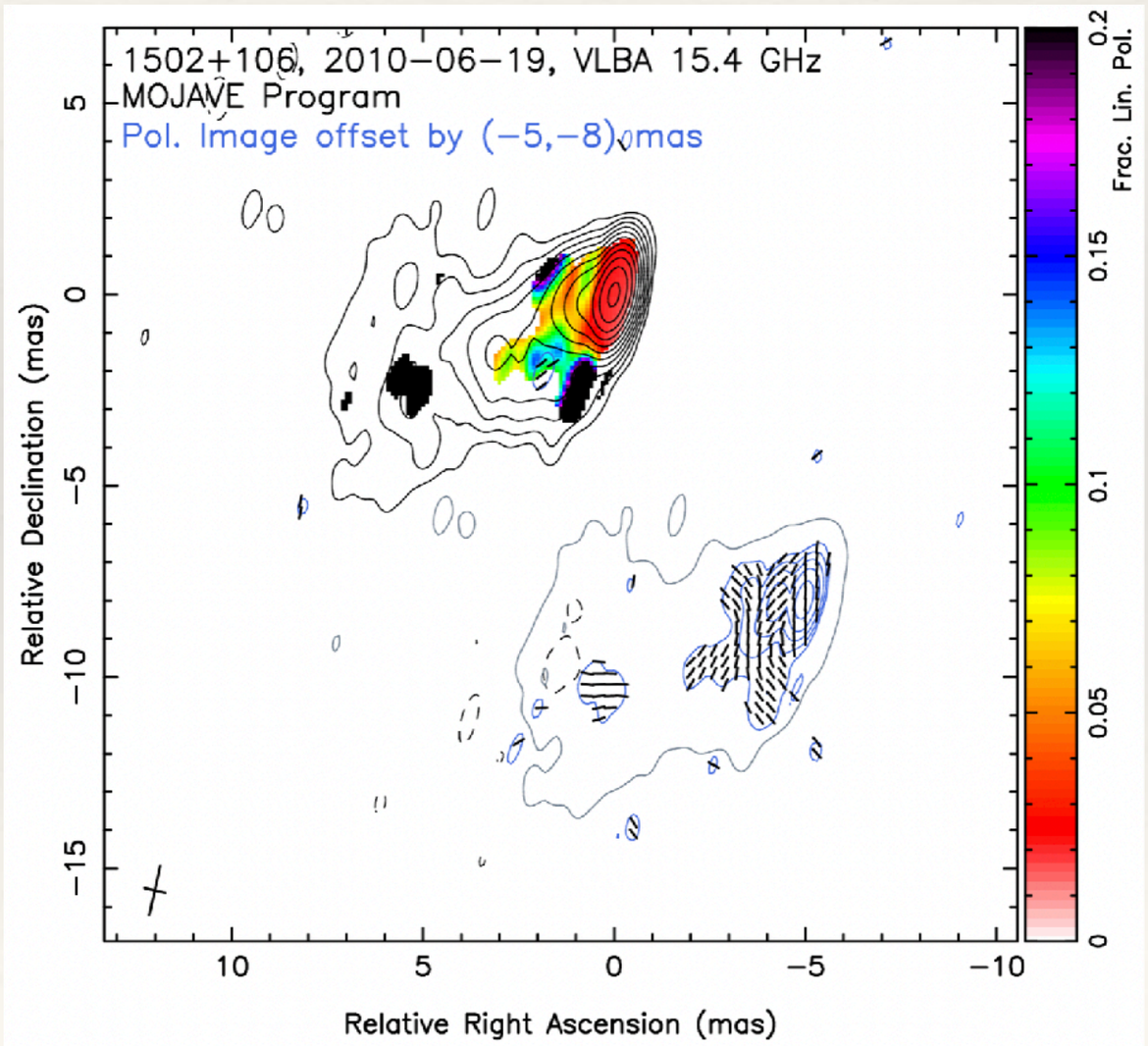
TXS 0506+056



VLBI Observations: Polarization

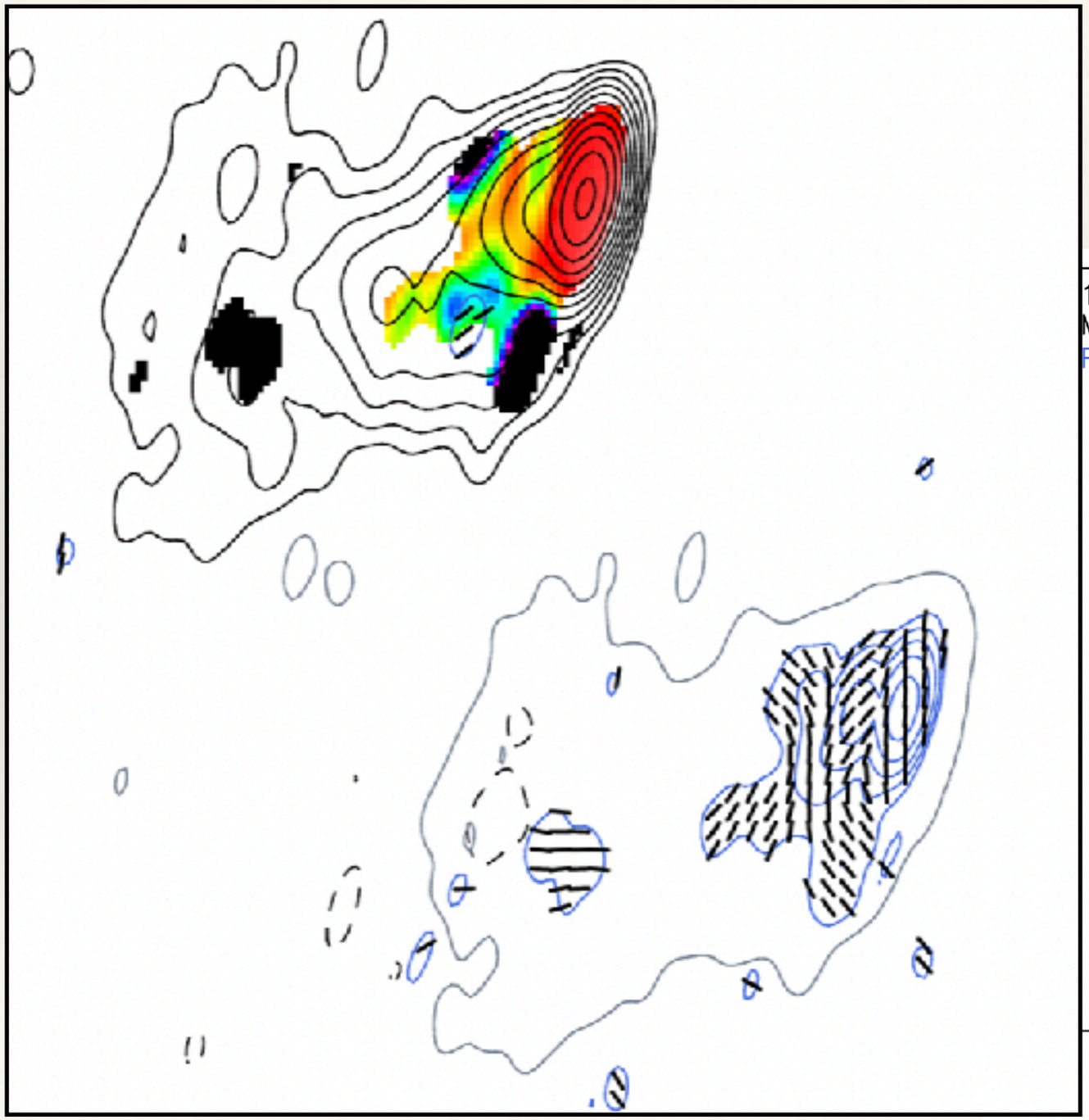
Cf. Pushkarev et al. 2022 (arXiv2209.04842)

PKS 1502+106

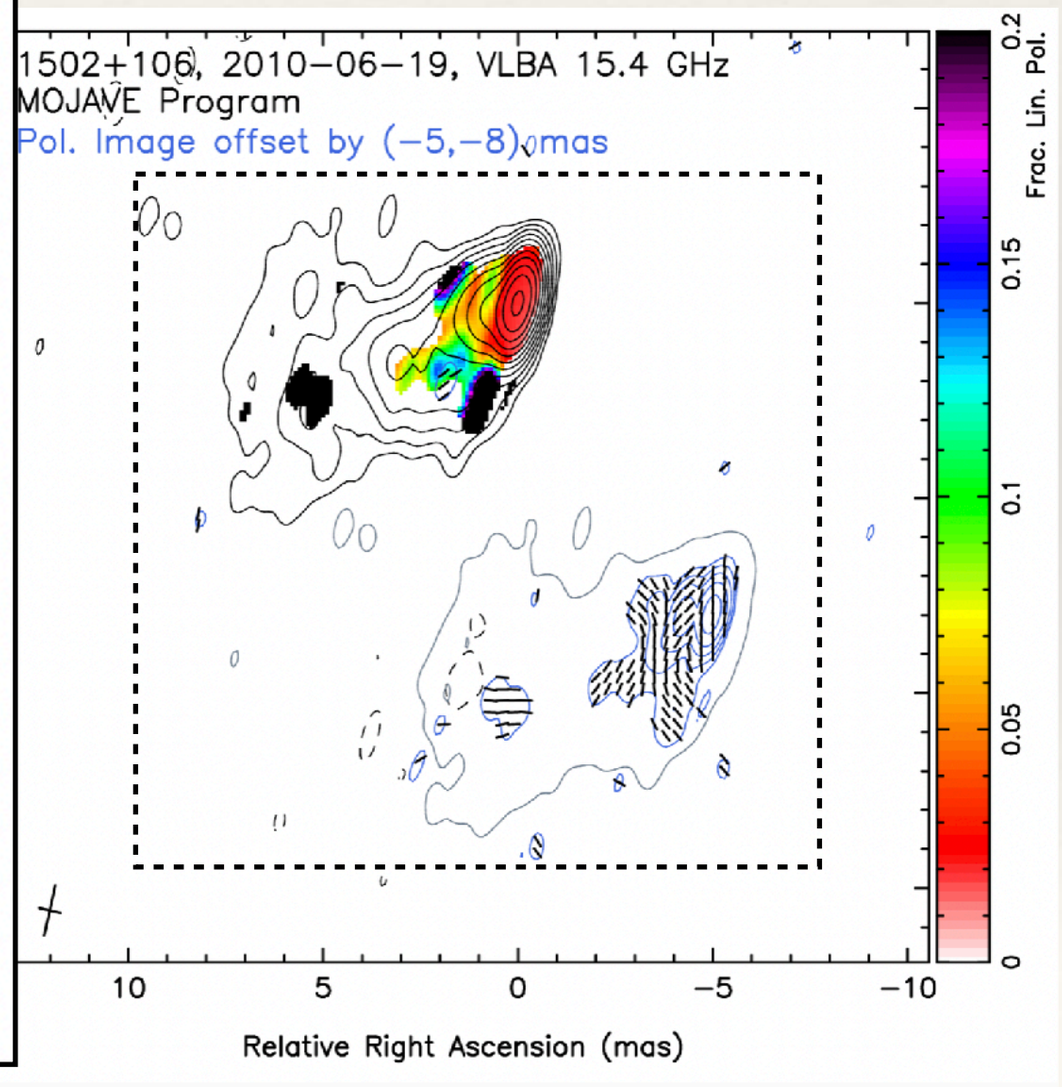


VLBI Observations: Polarization

Cf. Pushkarev et al. 2022 (arXiv2209.04842)



PKS 1502+106

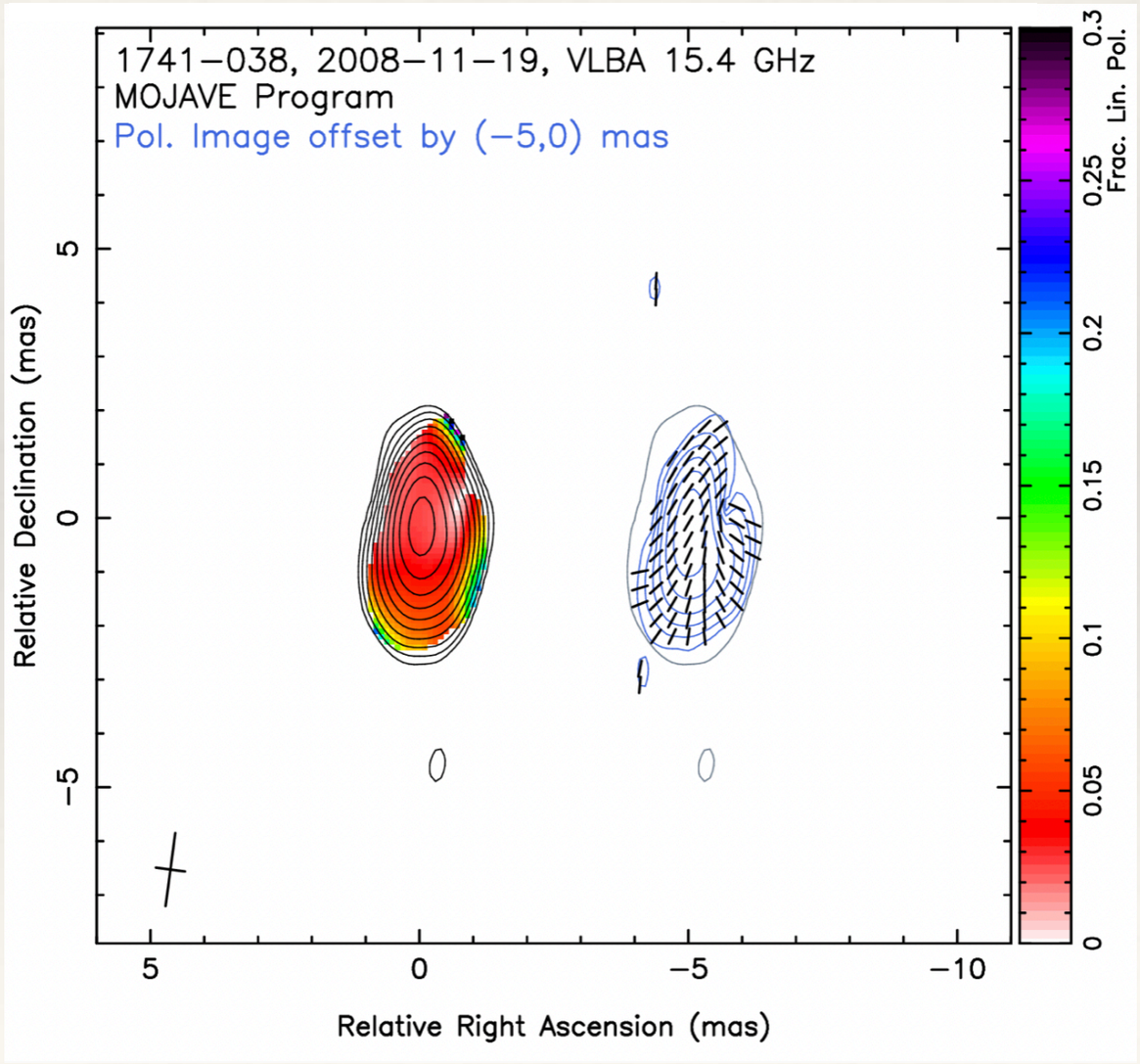


VLBI Observations: Polarization

Cf. Pushkarev et al. 2022 (arXiv2209.04842)

Associated with IC 220205B (Kovalev et al. 2022, ATel 15215) and previously pointed out in Plavin et al 2020

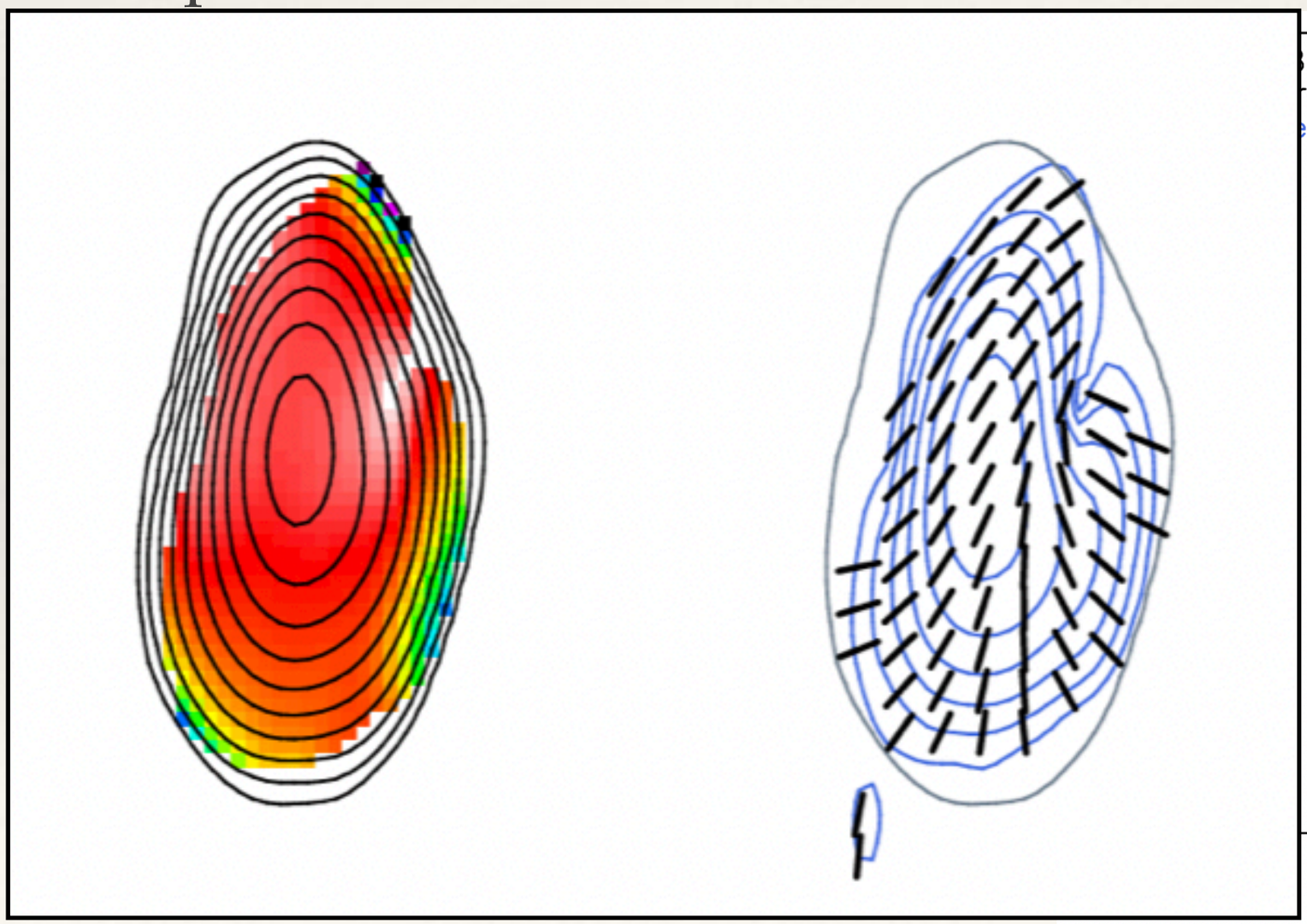
PKS 1741-038



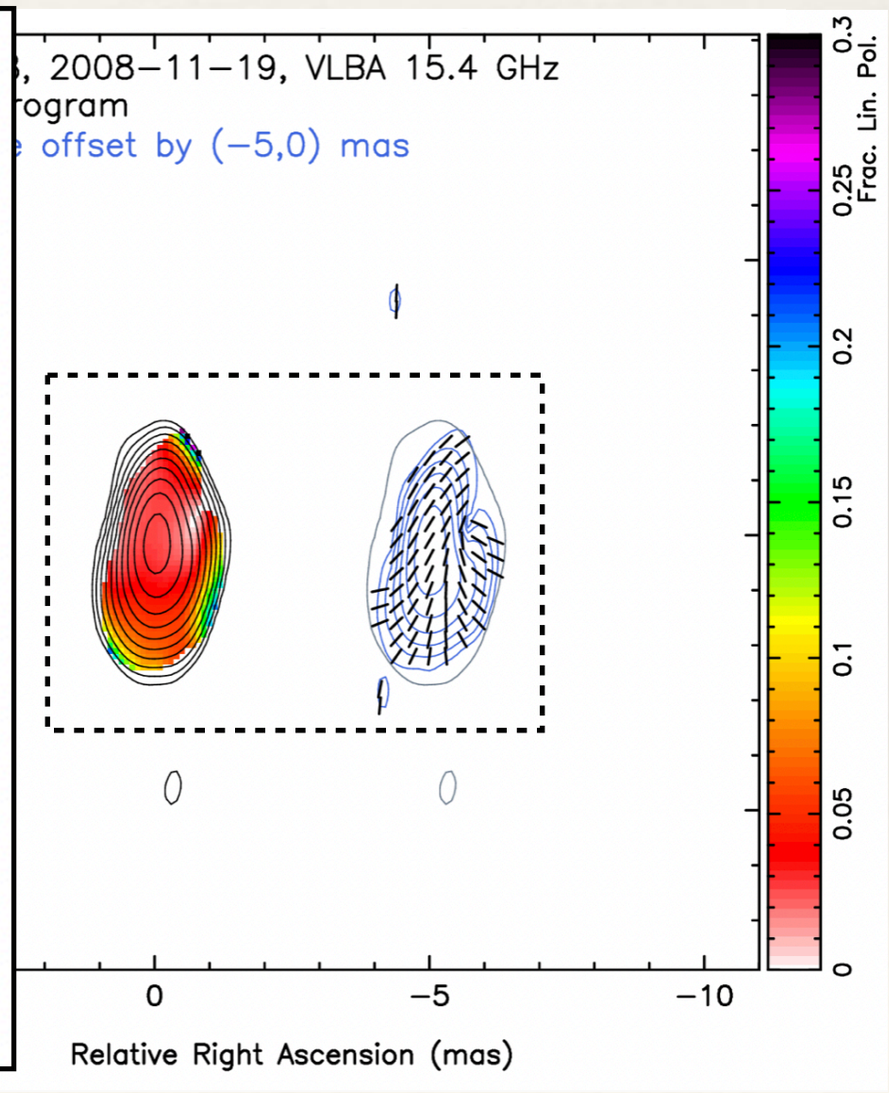
VLBI Observations: Polarization

Cf. Pushkarev et al. 2022 (arXiv2209.04842)

Associated with IC 220205B (Kovalev et al. 2022, ATel 15215) and previously pointed out in Plavin et al 2020



PKS 1741-038



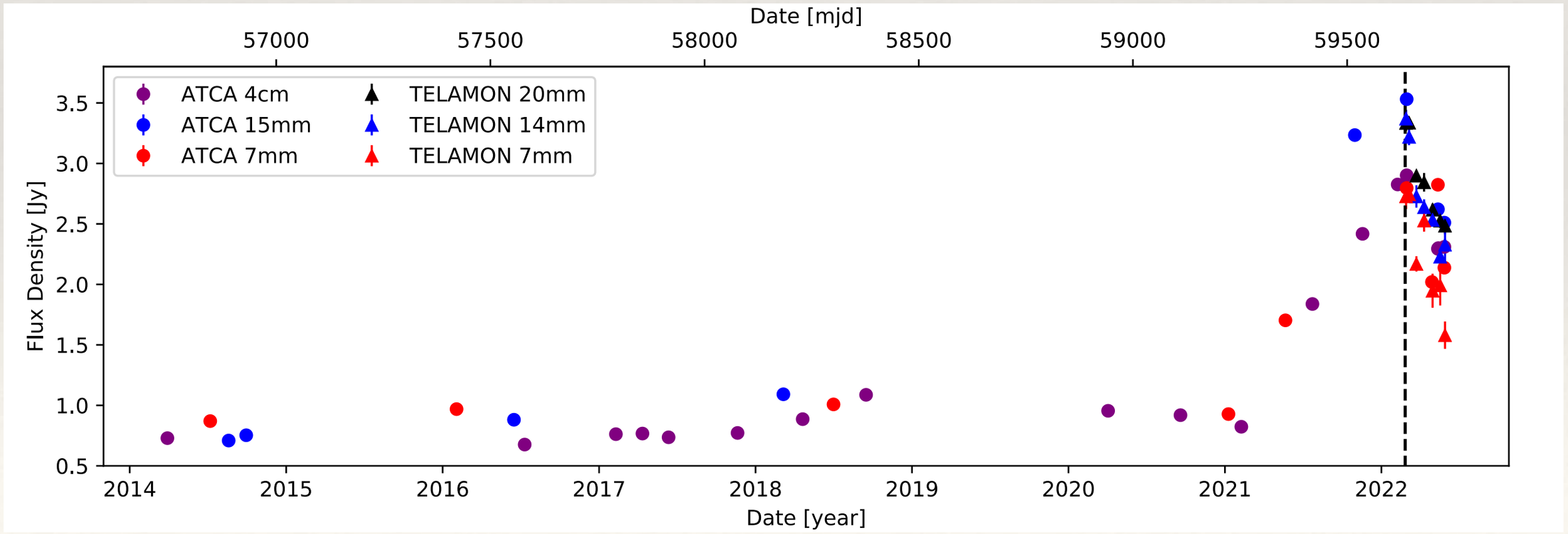
VLBI Monitoring and Target-of-Opportunity Observations

- **MOJAVE**
  - 15GHz, long-term monitoring (PI Lister): includes complete >1.5Jy sample of 147 AGN in the IceCube footprint (-10° to +40°)
- **TANAMI**
  - 2.3 & 8.4GHz, long-term monitoring (PIs Ojha, Kadler): covers Southern sky and fainter sources
- **Individual Events (VLBA, EVN, eMERLIN)**
  - Gold/Bronze events with localization <10deg^2 and E>200TeV (PIs Kovalev, Plavin), multi-ν high frequency, VLBA
  - Fermi blazars inside gold-event regions (PIs Giroletti, Nanci), EVN@5GHz, VLBA, eMERLIN, Nanci et al. 2022
  - Flaring radio blazars inside gold/bronze neutrino localizations (PIs Kadler, Eppel), VLBA, GMVA

VLBI Monitoring and Target-of-Opportunity Observations

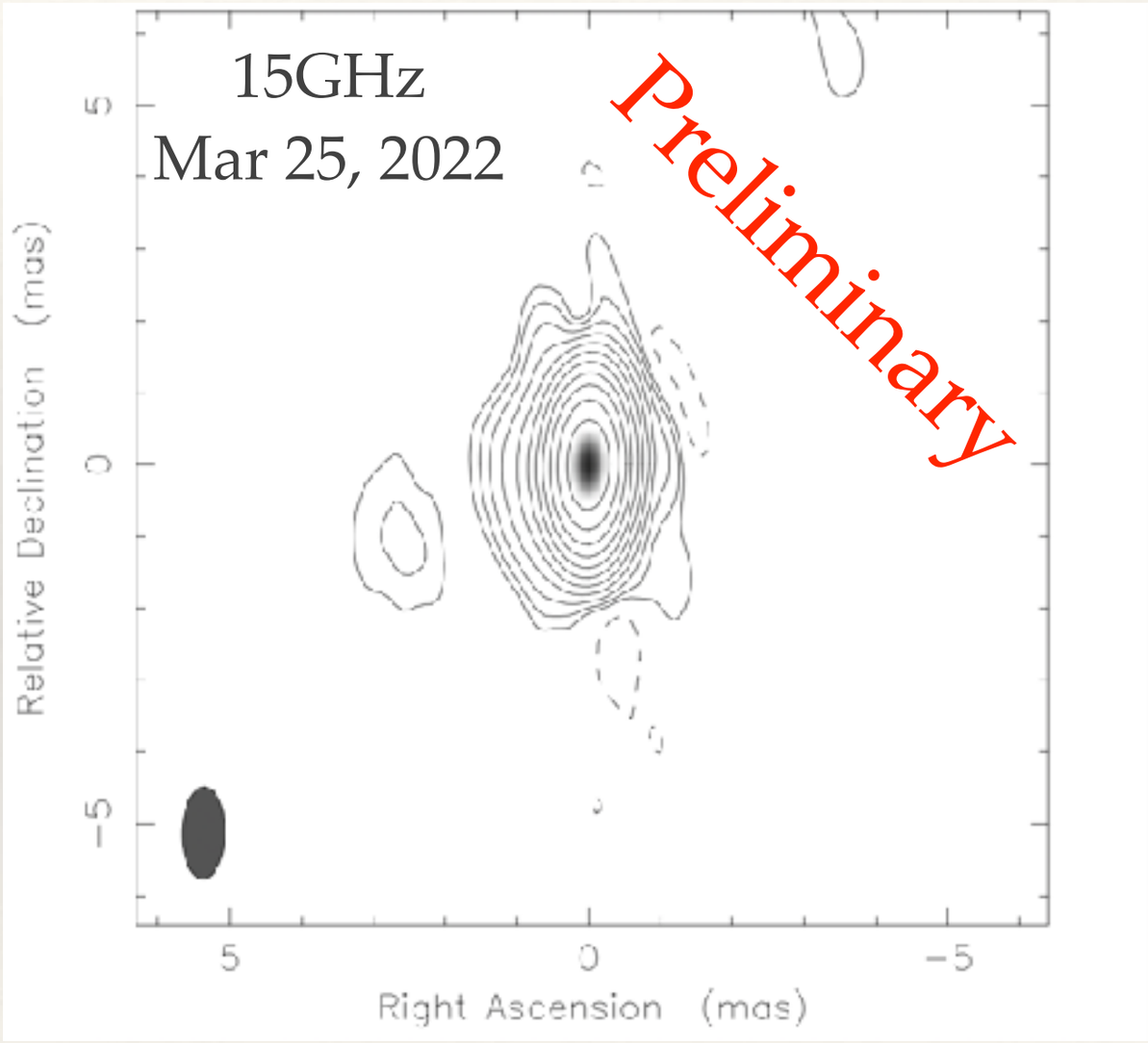
PKS 0215+015

- Coincident with IceCube Neutrino IC220225A (154 TeV)
- Only known gamma-ray source in the field: Flaring!
- Radio light curve: Flaring! ⟹ VLBA DDT Proposal (Eppel et al.)

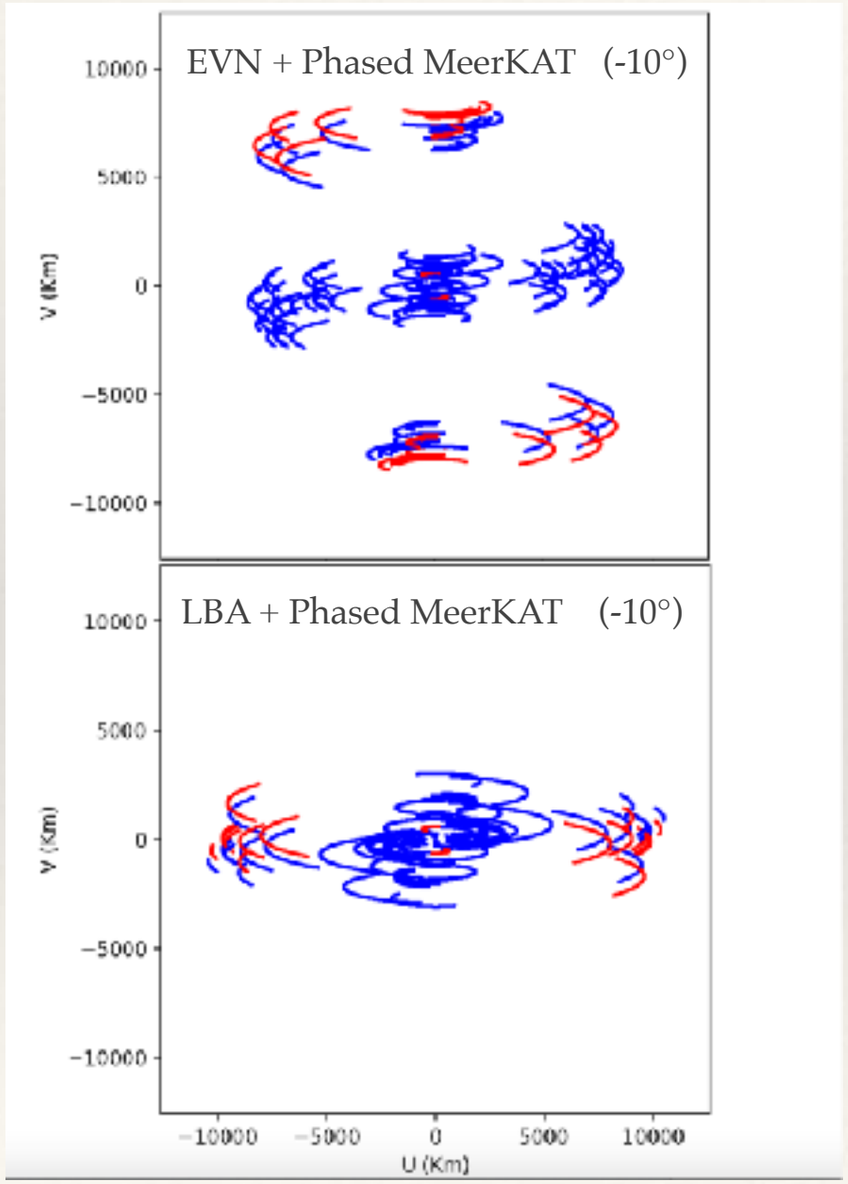


VLBI Monitoring and Target-of-Opportunity Observations

- DDT VLBA Proposal submitted on March 8; 1st epoch observed 4 weeks after ν
- 3 frequencies: 15, 22, 43GHz; full polarization
- 6 epochs to follow jet evolution over half a year



Future Southern-Sky VLBI for KM3NeT



- **TANAMI+**
- **Phasing MeerKAT** will synthesize the most sensitive cm-band (110m) antenna in the Southern Hemisphere
- Boost for long-baseline array fidelity (EVN and LBA)
- **SKA-VLBI**

Summary and Perspectives for the KM3NeT Era

- **Evidence for radio-neutrino correlation in blazars is growing**
- **Radio monitoring is a crucial long-term effort**
- **VLBI can reveal the physics in structured neutrino-blazar jets**
  - **High sensitivity and high dynamic range needed to separate highly-relativistic spine from slower sheath**
  - **Polarization can be key**
  - **Coordination with multi wavelength facilities needed**
- **SED emission models need to be advanced in order to make use of VLBI information**

Thank You!