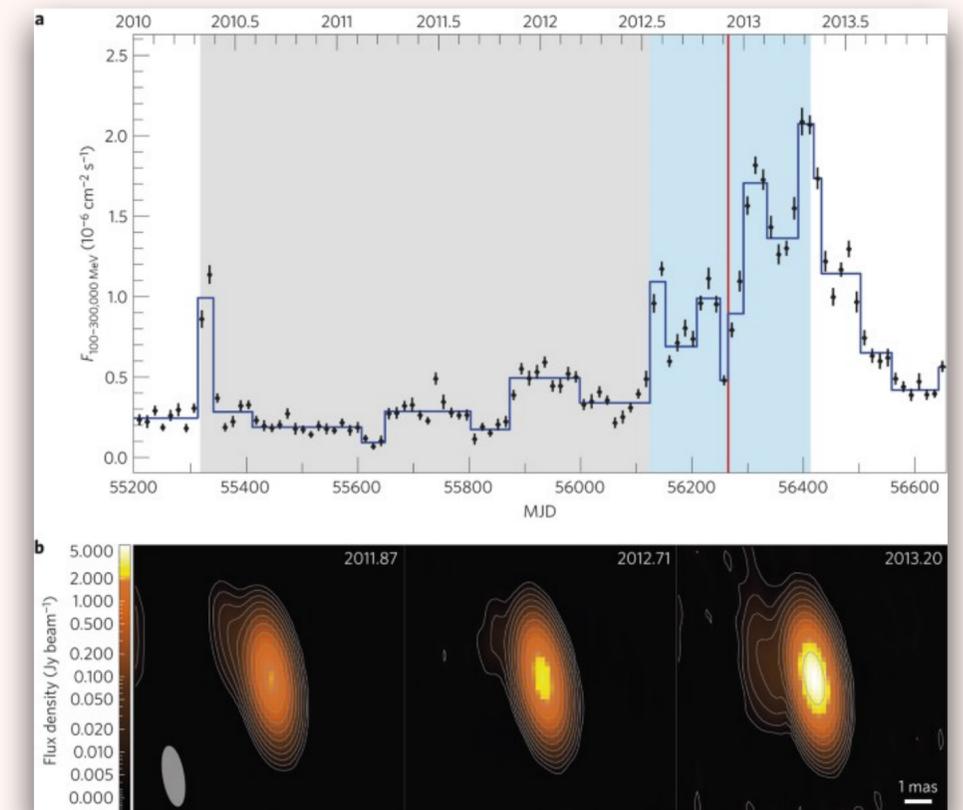
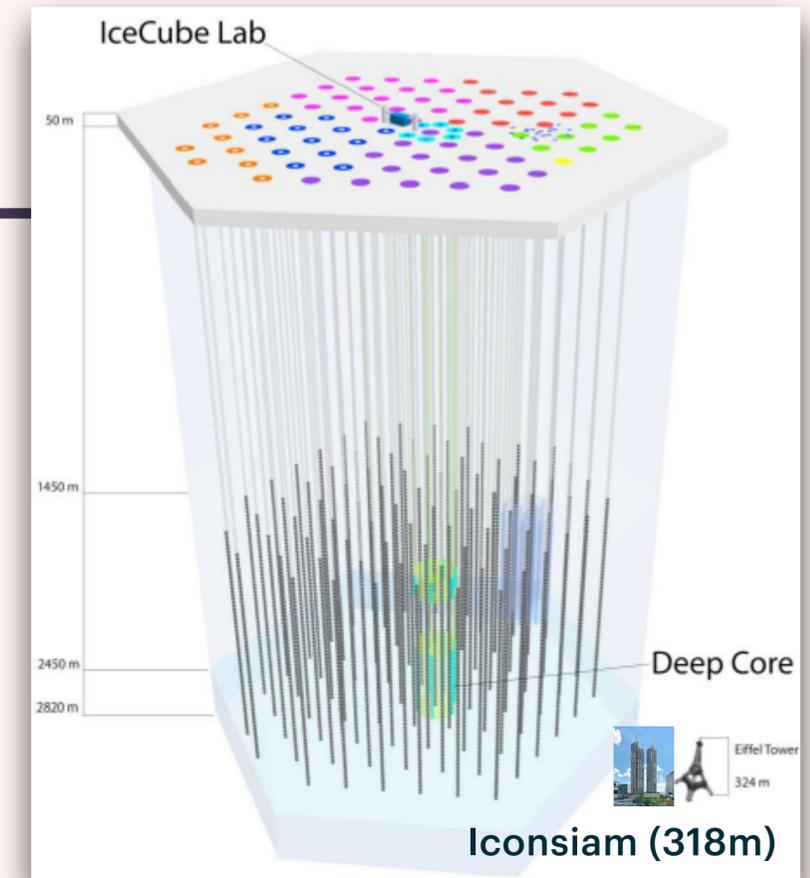

Marcello Giroletti, INAF Istituto di Radioastronomia, Bologna

VLBI OBSERVATIONS OF POSSIBLE COUNTERPARTS OF NEUTRINOS

**Main collaborators: Cristina Nanci,
T. An, S. Buson, S. Garrappa, M. Kadler, E. Ros, B.W. Sohn, et al.**

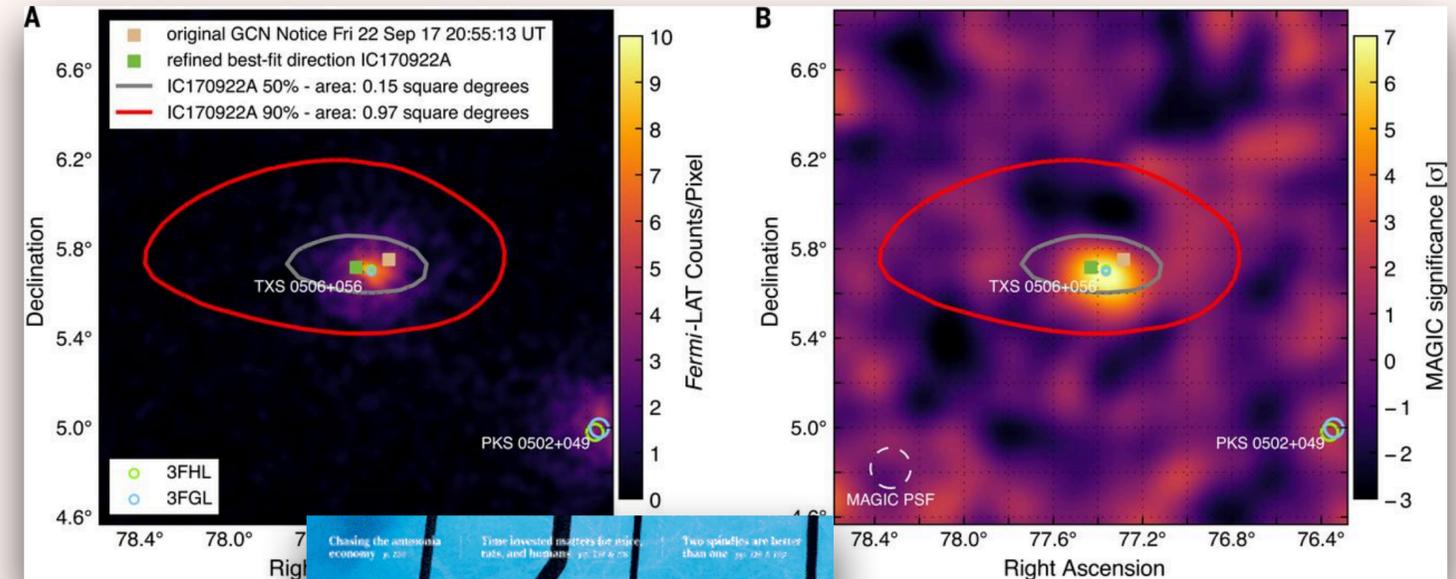
INTRODUCTION

- **Extreme physical conditions in relativistic jets: hadronic processes would produce gamma rays AND neutrinos**
- **Neutrinos are very challenging to detect; Icecube exploits Cherenkov radiation below South Pole ice**
- **localisation typically constrained to within a few degrees**
- **Blazar gamma-ray light curves are regularly sampled by Fermi-LAT**
- **Kadler et al. (2016) reported a major gamma-ray outburst of B1424-418 in temporal and positional coincidence with a PeV IceCube neutrino event (HESE-35)**

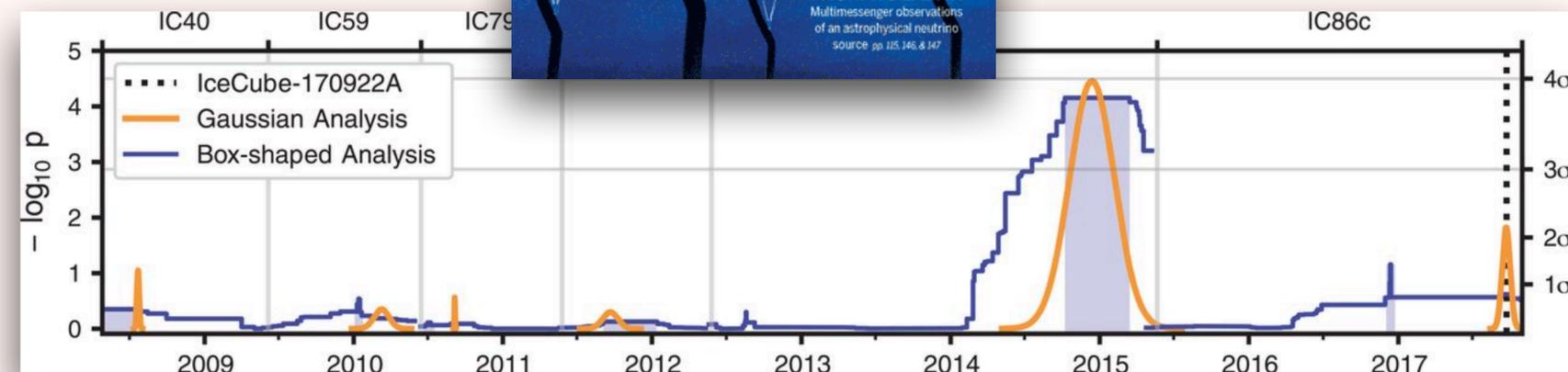


IC 170922A

- On 2017, Sep 22, IceCube detected a 290 TeV ν
- >50% probability of being of astrophysical origin
- 0.97 deg² 90% localisation
- cospatial with TXS 0506+056, a blazar undergoing a gamma-ray *Fermi* and MAGIC flare
- new milestone of MM astronomy (after GW 170817)
- re-inspection of earlier data shows earlier excess of high-energy neutrino events from TXS 0506+056
- 3.5 σ evidence for neutrino emission from the direction of, independent of and prior to the 2017 flaring episode



IceCube Collaboration et al. (2018a,b)

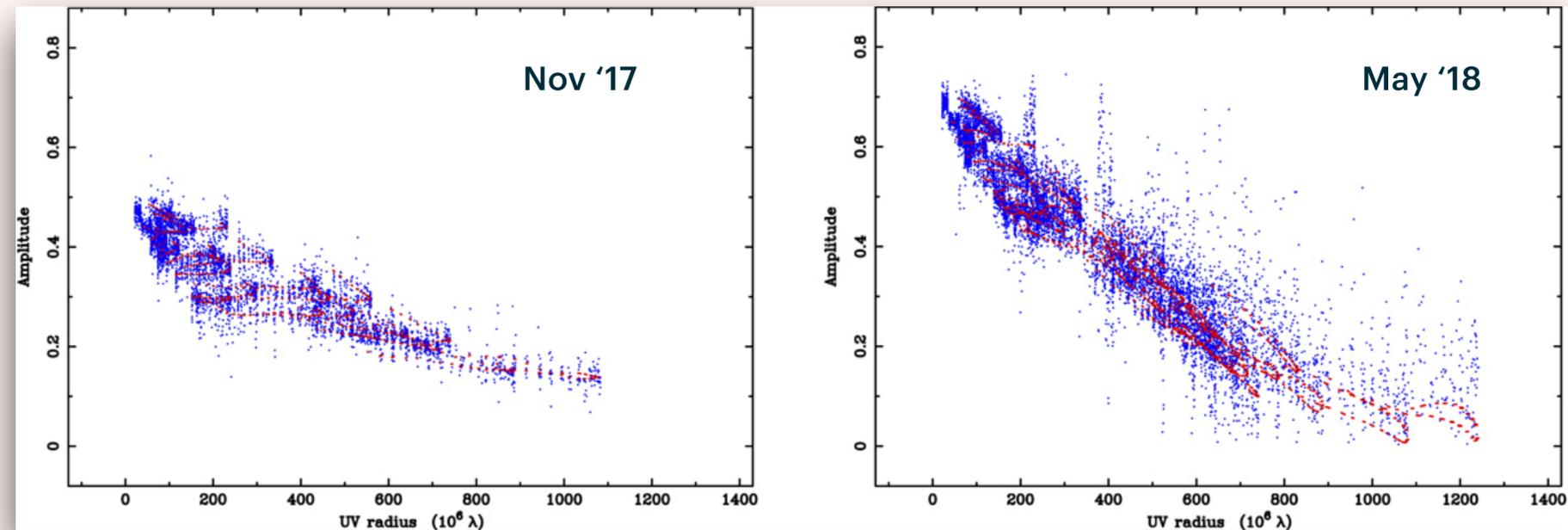
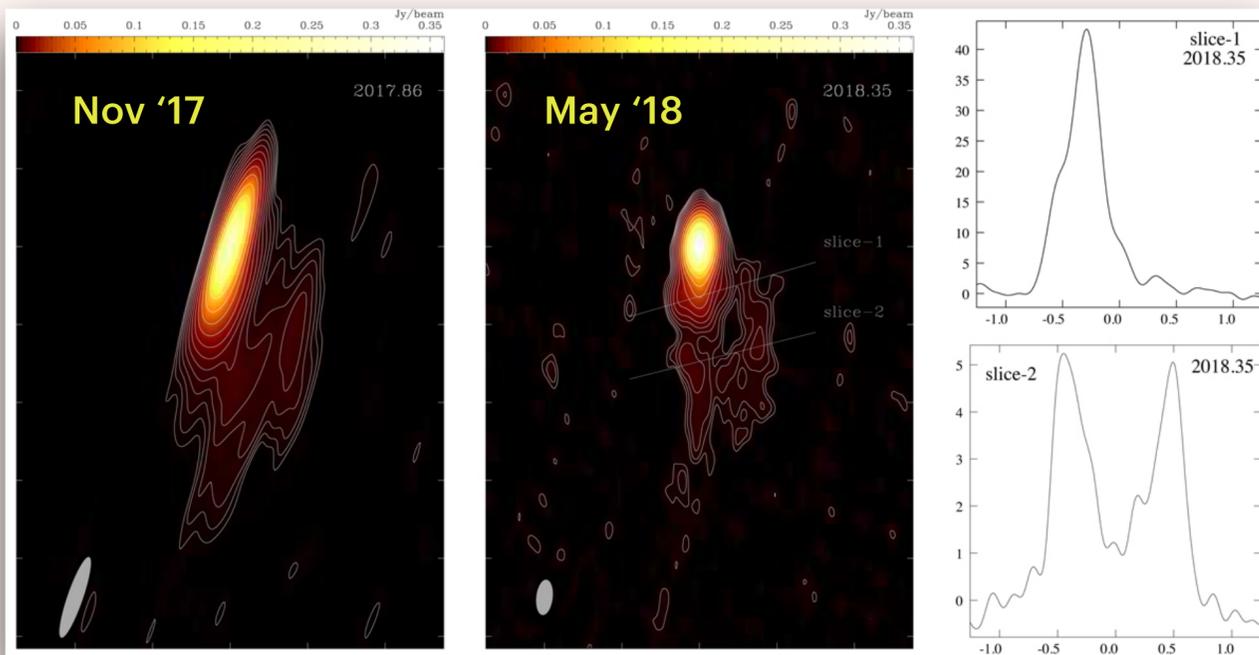


TXS 0506+056, 43 GHz

➤ Radio emission from TXS 0506+056 was also flaring; we investigated the parsec scale structure with two-epoch 43 GHz VLBA observations (Ros et al. 2020)

➤ $z=0.3365$, 1 mas=4.8 pc

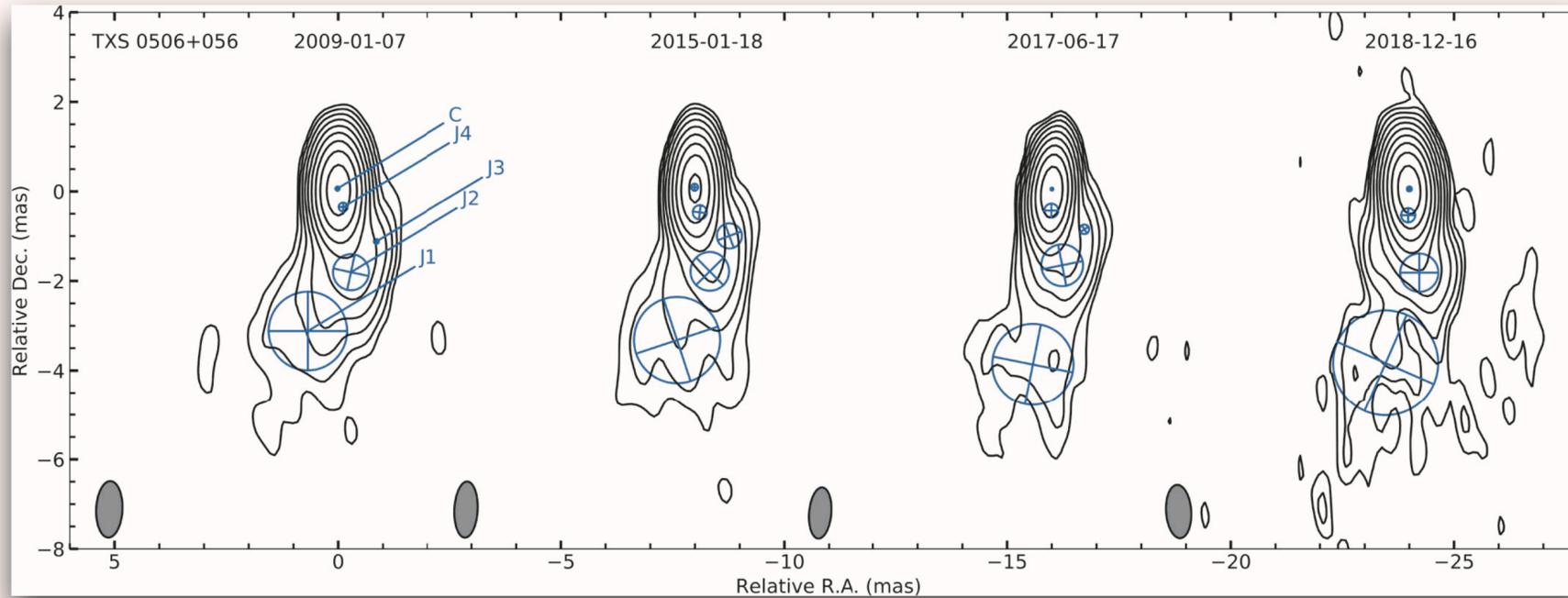
Date	beam [mas x mas]	S_{tot} [mJy]	S_{peak} [mJy beam ⁻¹]	S_{min} [mJy beam ⁻¹]
2017 Nov	1.1 x 0.2	500	320	0.63
2018 May	0.45 x 0.21	720	403	0.73



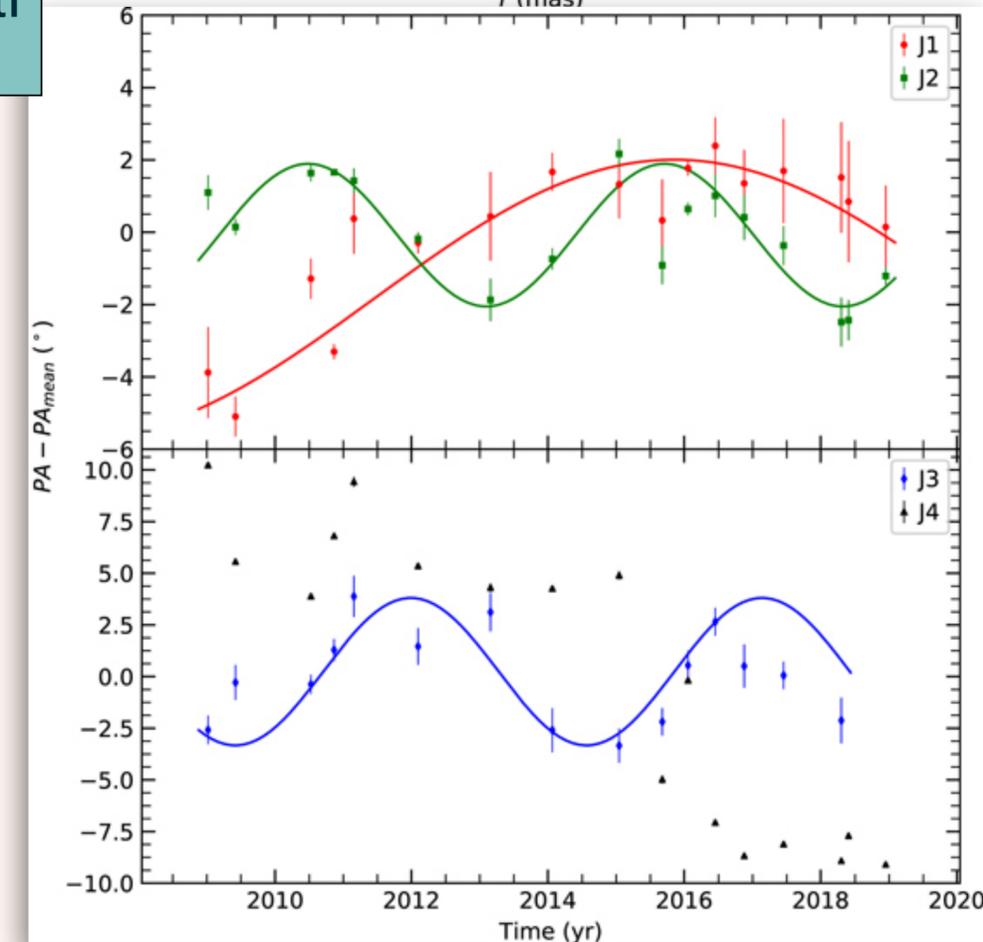
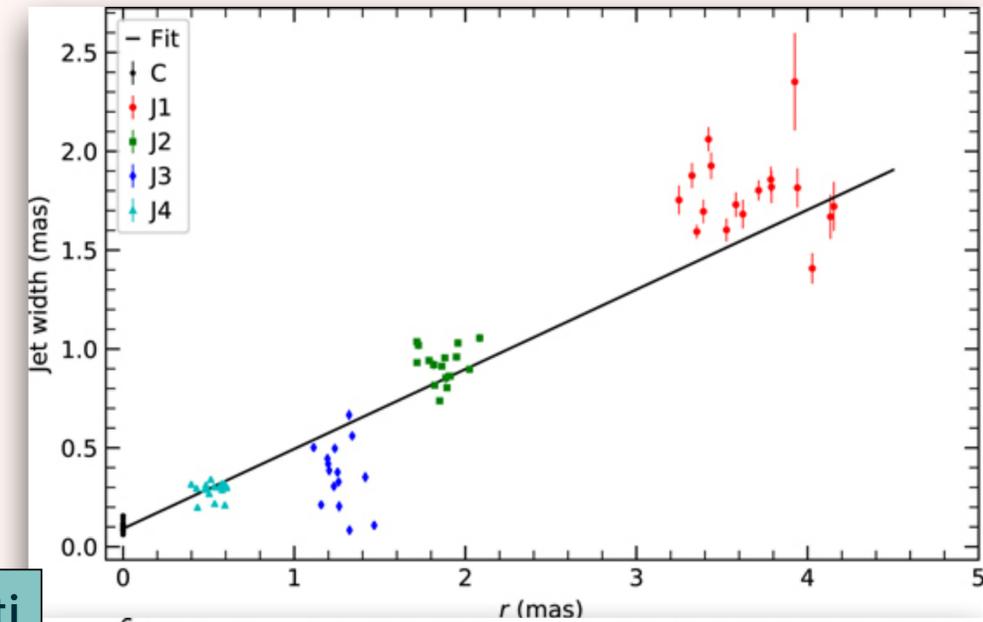
➤ limb brightened jet - possible signature of velocity structure, suggested to be one region of efficient ν production (e.g. Tavecchio et al., 2014)

➤ 45 μ as increase in core size during 6 months; corresponding to $\sim 2c$ expansion speed

TXS 0506+056, 15 GHz



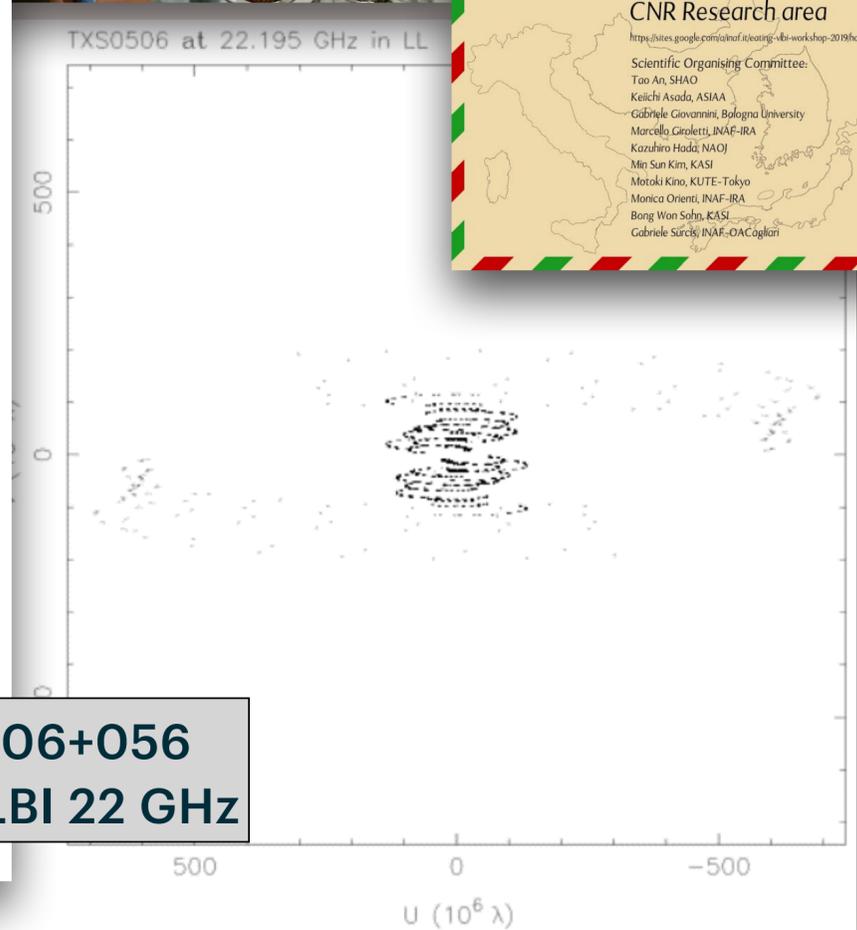
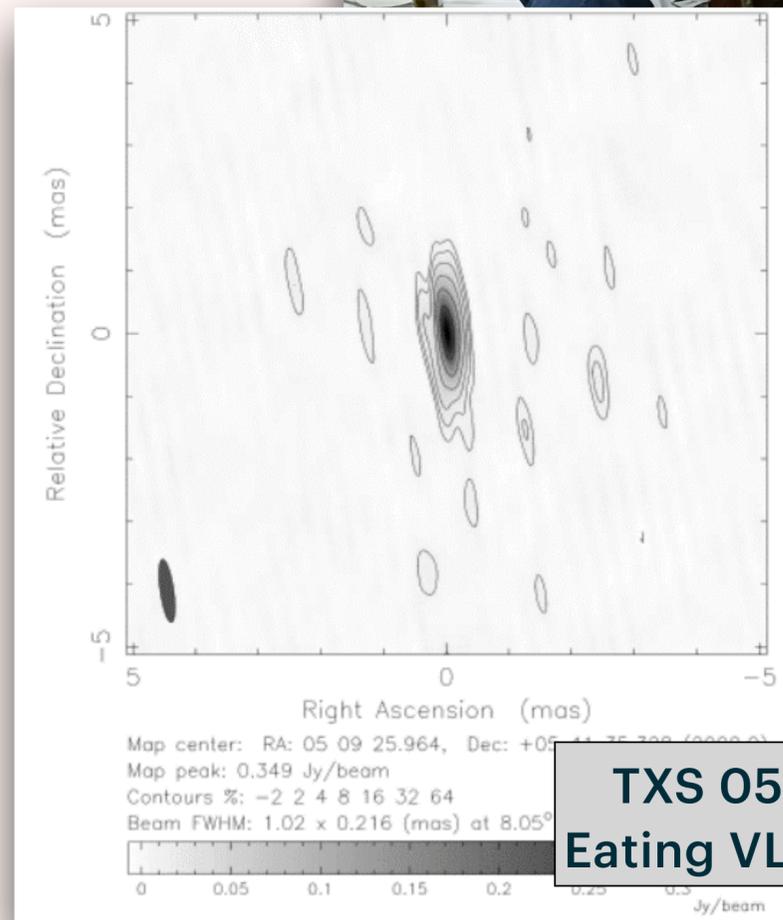
Li, An, Mohan, Giroletti
(2020 ApJ)



- **multifrequency archive VLBI data (8/15/24/43 GHz)**
- **half opening angle of the jet beam $\sim 38^\circ$, inclination angle $\sim 20^\circ$**
- **helical trajectory with a precessing period of 5–6 yr, (pc scales instabilities operating)**
- **beaming parameters (Doppler, bulk Lorentz factor) suggest a moderately relativistic jet**
- **$B \sim 0.2\text{--}0.7$ G (from core shift and variability), decreased from larger value during the quiescent period before flare**

TXS 0506+056 & EATING VLBI

- East Asia To Italy: Nearly Global VLBI
- Collaboration developed over a decade
- exchanges, workshops, collaboration, joint observations, ...and dinners
- Now formalised in an MoA between INAF and KASI for granted telescope time
- goal to expand to whole EAVN
- facilitated by installation of CTR on INAF telescopes
- Preliminary 22 GHz Eating VLBI images of 0506+056 in Feb 18 show transversally resolved structure



TXS 0506+056
Eating VLBI 22 GHz

AFTER 0506+056

- **Icecube continues to report the detection of neutrino events**
 - **“Golden” events reported at a rate of ~ 0.75 month⁻¹**
 - **mean 90% positional uncertainty of 2.5°**
 - **$\sim 50\%$ with a candidate gamma-ray counterpart (positional uncertainty $\sim 0.1^\circ$)**
- **Note also**
 - **radio-emitting tidal disruption event, AT2019dsg, possibly associated with IC190110A (Stein+21)**
 - **bright VLBI sources 3C 279, NRAO 530, PKS 1741-038, 1502+106 positionally consistent with other ν events (Plavin+20)**
 - **3.0σ significance correlation between IC likelihood map and spatial distribution of compact sources (Plavin+21)**

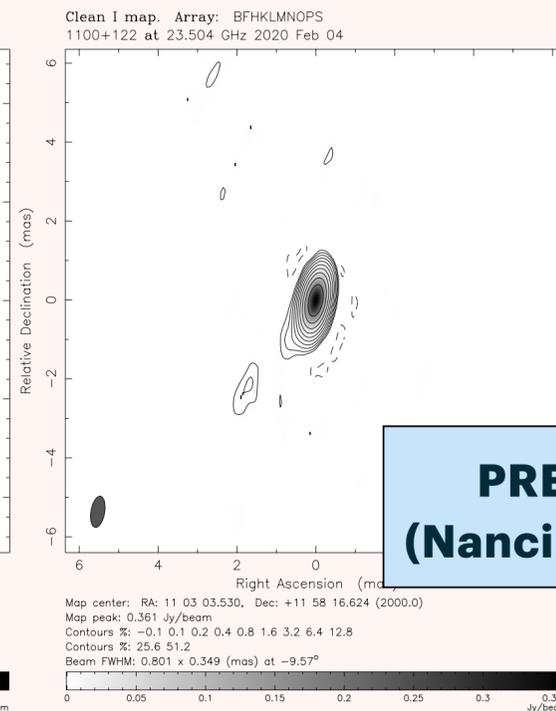
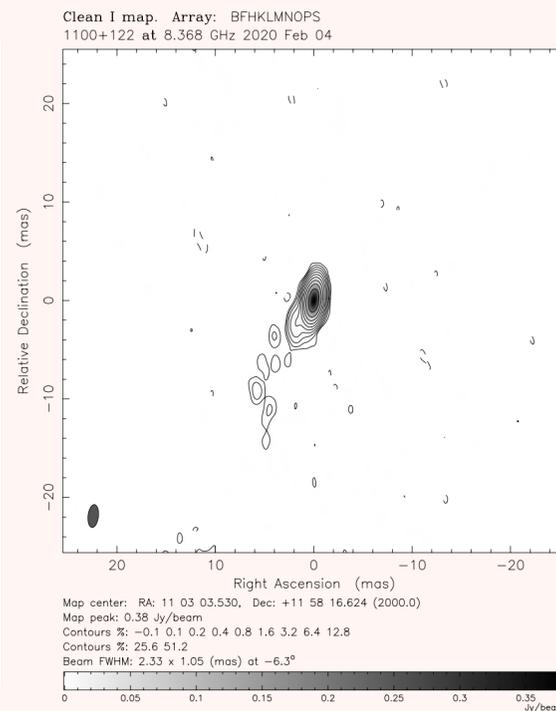
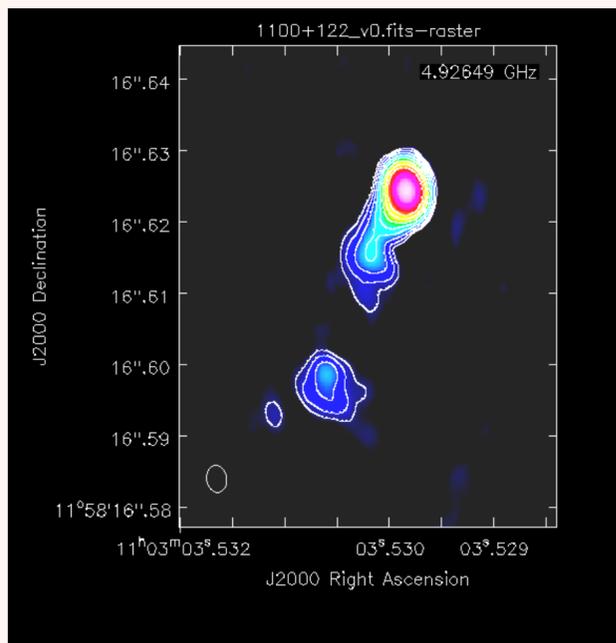
OPEN QUESTIONS/VLBI GOALS

- **Determine if any of the blazars positionally consistent with the ν are in a state of enhanced radio activity in comparison to historical activity levels: (starting) indication of a possible association between the ν and the VLBI source**
- **Determine if any of the other radio sources within the ν arrival direction have a compact core, and are thus possible sites of particle acceleration: discriminate if there are competing candidates for the blazar/ ν association.**
- **Constrain β , Γ , θ , δ , B , through the study of brightness temperature, core dominance, jet sidedness, fraction and orientation of the polarised emission: to be compared with MWL and MM modelling of the sources**
- **Determine the evolution of the jet properties through multi-epoch observations, investigating the total and core flux density and size evolution, the presence of superluminal motions/expansions**

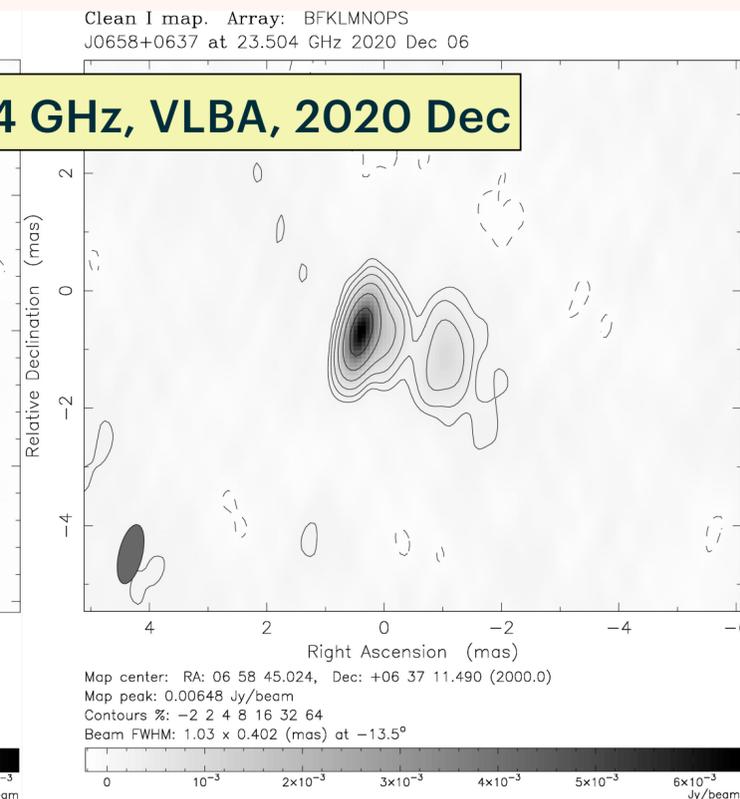
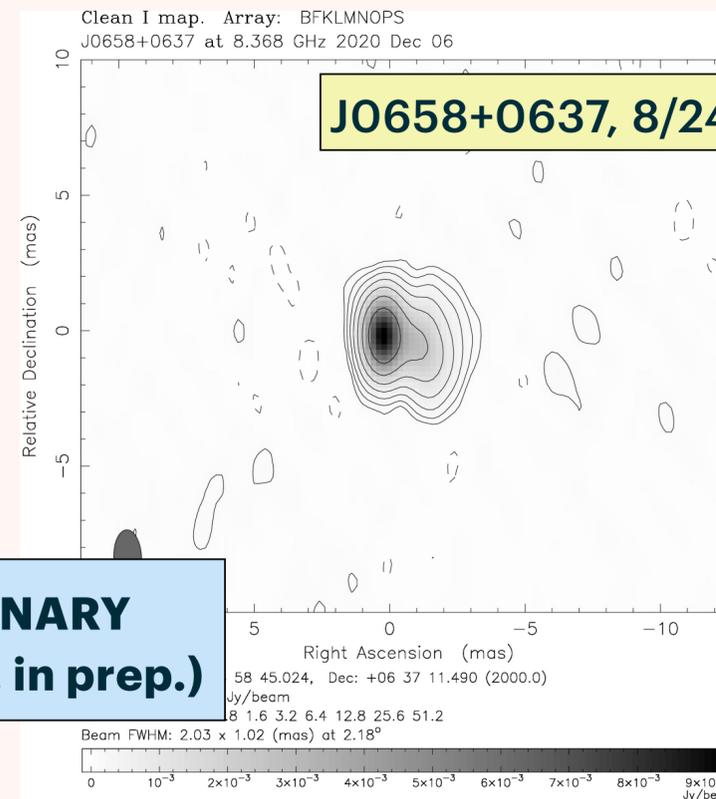
EVENTS IN 2019-20 AND FOLLOW-UPS

v event name	event type	GCN #	radio follow up
190704A	bronze + gamma-ray	24981	VLBA 4-7 GHz, two epochs
200109A	gold + gamma-ray	26696	VLBA 8-24 GHz, EVN 5 GHz
201021A	bronze + gamma-ray	28715	e-MERLIN 5 GHz
201114A	gold + gamma-ray	28887	EVN 5 GHz, VLBA 8-24 GHz, 3-epochs
200115A	gold (no gamma-ray)	28889	Effelsberg 5-21 GHz

1100+122, 5(EVN)/8/24(VLBA) GHz, 2020 Feb



**PRELIMINARY
(Nanci et al. in prep.)**



TAKE HOME NOTES

- 1. Neutrino astrophysics is a reality - and connection to blazars an intriguing possibility**
- 2. VLBI remains the ideal probe of physical properties in jets - providing inputs/constraints for MWL/MM modelling**
- 3. We look forward to continuing coordinated activities between INAF and East Asia (in all fields!)**

