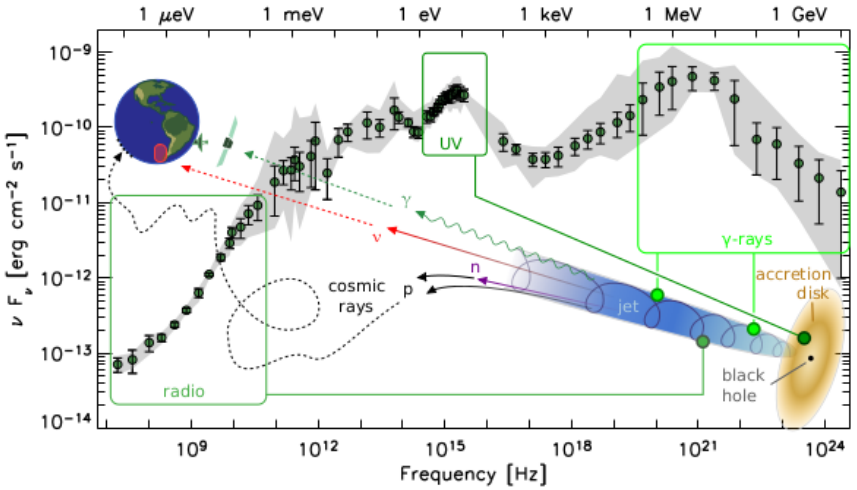
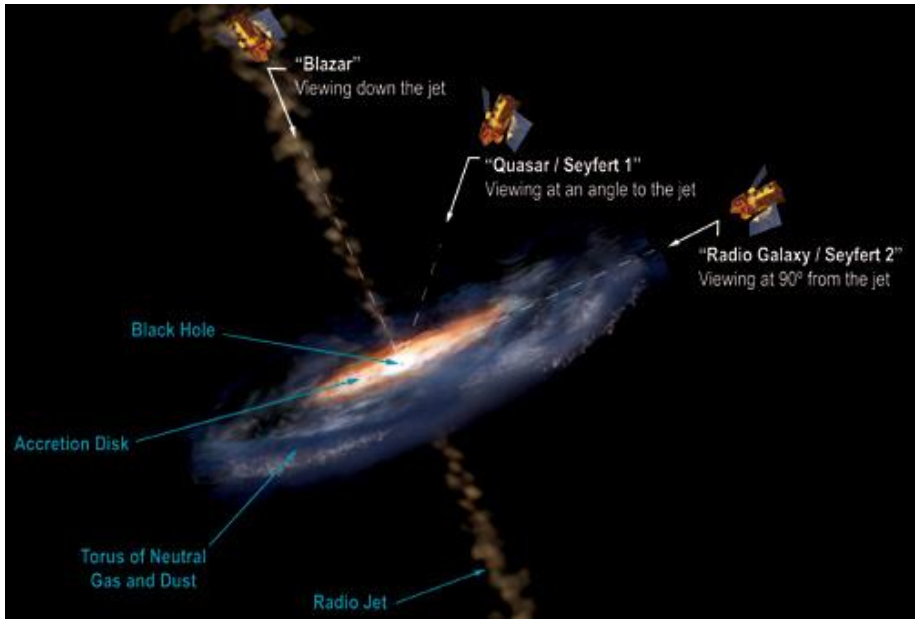


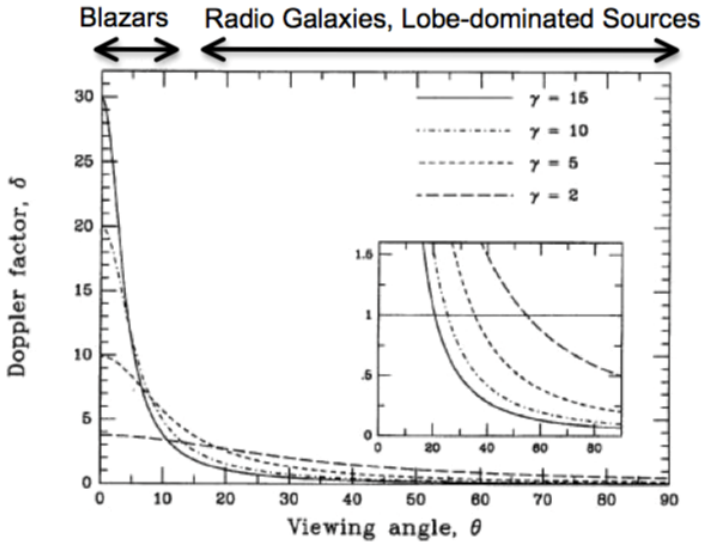
Multi-frequency studies of powerful relativistic jets from AGN in the multi-messenger era

Filippo D'Ammando (INAF-IRA Bologna)

on behalf of 37 INAF and associated scientists

Powerful relativistic jets in AGN





Doppler factor $\delta = [\ \Gamma\ (1 - \beta \cos\theta)\ ]^{-1}$

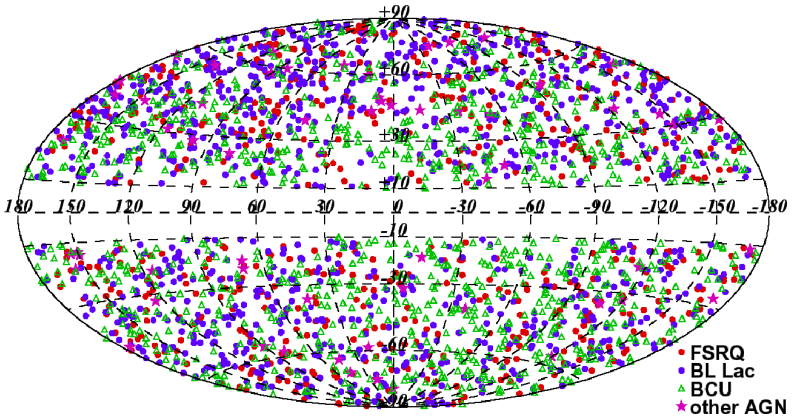
$\Gamma = (\ 1 - \beta^2\ )^{-½}$ bulk Lorentz factor, θ viewing angle

- flux density enhanced $F_\nu\ (\nu) = \delta^{2+\alpha}\ F'_{\nu'}\ (\nu)$
- variability time scale decreased $\Delta t = \Delta t'/\delta$
- frequencies blue-shifted $\nu = \delta\nu$
- variable emission over all the EM spectrum
- unpredictable variability
- time scales from minutes to years

Fermi-LAT and IceCube

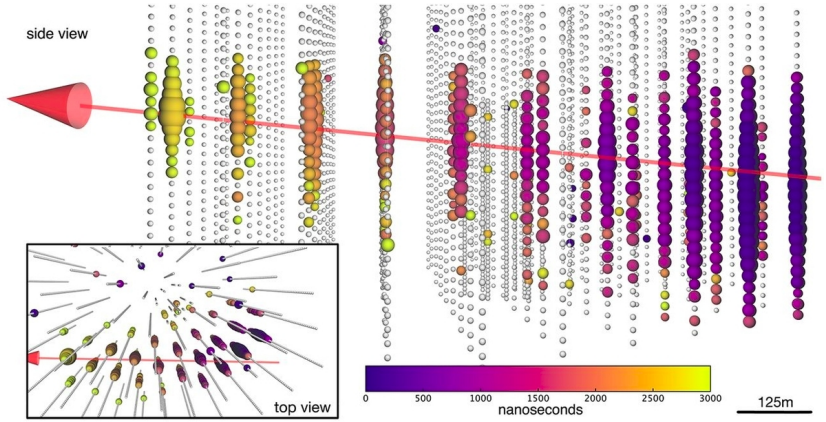
Despite decades of effort, the physics of relativistic jets remains elusive. With the advent of the **Fermi satellite** the number of AGN detected in γ-rays has increased by two orders of magnitude allowing for the first time a population study of these objects. In addition to **blazars** and **radio galaxies**, powerful relativistic jets were also discovered in **narrow-line Seyfert 1 galaxies**

4LAC



Ajello+20, ApJ, 892, 105

The recent association between a **high-energy neutrino** revealed by **IceCube** and the blazar TXS 0506+056 provided the first evidence that relativistic jets in AGN can be sources of neutrinos and UHECR



IceCube, Fermi, MAGIC et al. 2018, Science, 361, eaat 1378

MUTE SORCERER in a nutshell

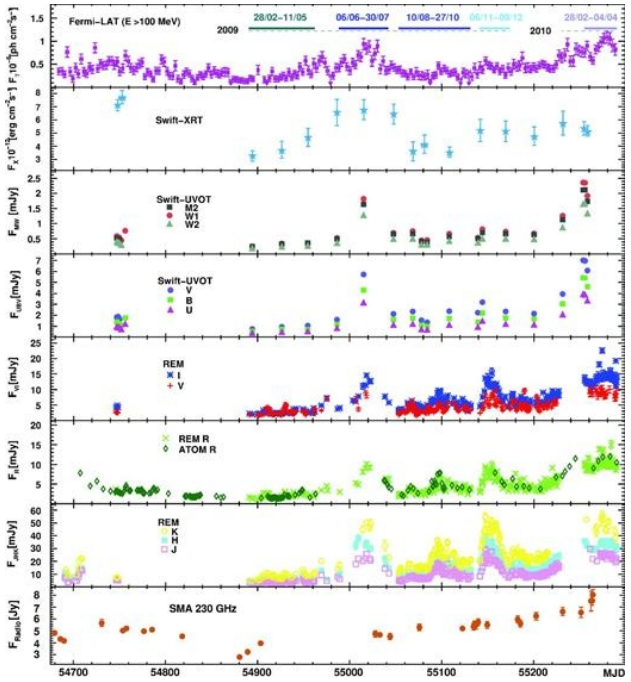
- Primary CSN4 / Secondary CSN1
- 8 INAF Institutes and 5 Universities
- 37 Scientists (29 INAF Researchers + 8 INAF Associated Researchers)
- 7.0 FTE INAF during 2021-2023
  0.8 FTE INAF Associated during 2021-2023
- Funds up to 2020: 552 kEuro
  Funds 2021-2023: 0 kEuro
- Duration: 2009-2030

Powerful relativistic jets are laboratories for studying the physics of matter and magnetic field in extreme conditions in AGN. The first neutrino-blazar connection provided the evidence that AGN are multi-messenger sources, offering the unique opportunity to combine more than one messenger to solve important puzzles of AGN jet physics: how jets dissipate their energy to accelerate particles, where and how jets produce high-energy emission and neutrinos, what physical mechanisms drive the particle acceleration. With this program we investigate the temporal and spectral evolution of the radio-to-very-high-energy emission, the jet structural properties, the connection between neutrinos and electromagnetic emission, and the acceleration processes in different classes of AGN.

Aims of the program (I)

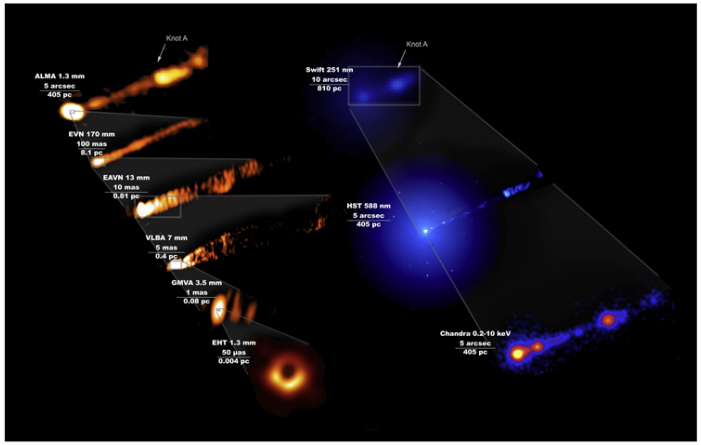
Understanding the **temporal and spectral evolution** of the multi-frequency emission of relativistic jets in AGN from intensive multi-wavelength monitoring and from refined **modelling of multi-epoch spectral energy distributions**

Fermi, Swift, REM, ATOM, SMA monitoring of PKS 0537-441



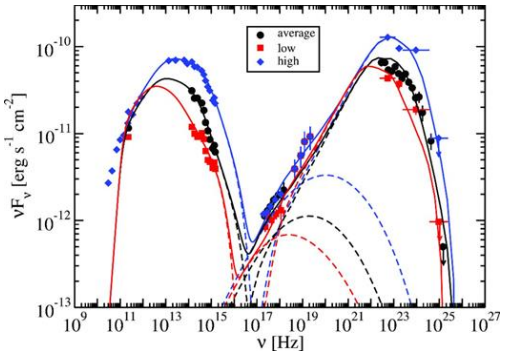
D'Ammando+13, MNRAS, 431, 2481

MWL Properties of M87 during the 2017 EHT Campaign



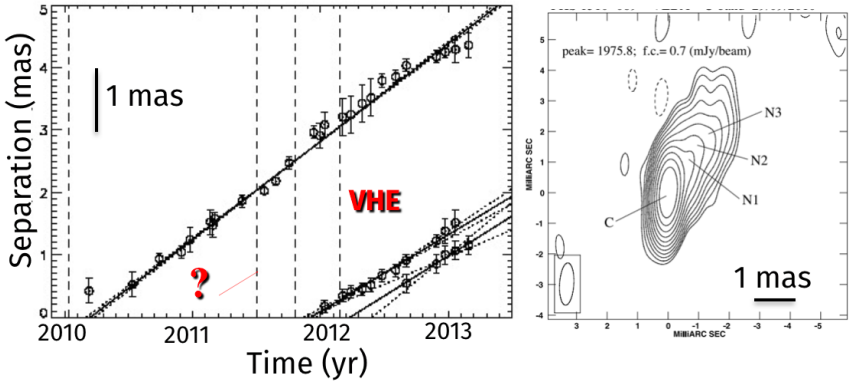
Algaba+21, ApJ, 991, L1

PKS 0537-441



Aims of the program (II)

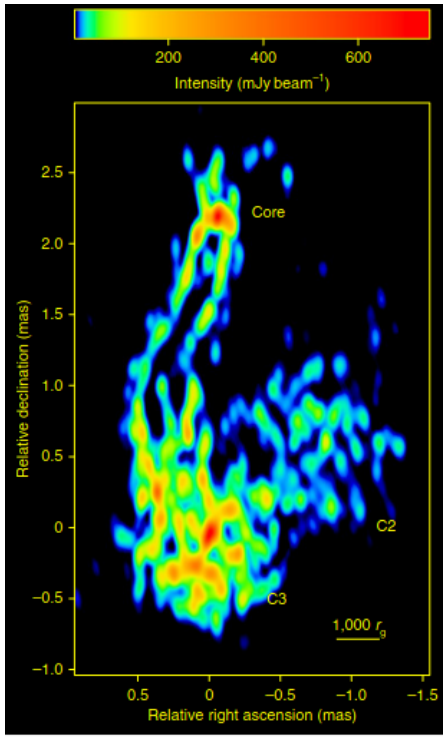
Get an observational and theoretical description of the **structural properties of jets**, with particular attention to the existence of a **velocity structure**, and to the connection between **new jet components** ejected near the SMBH and the high-energy phenomena



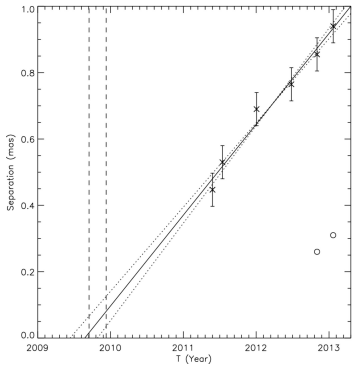
Connection between knot ejection and HE and VHE γ-ray flares in the FSRQ PKS 1510-089

Adapted from Orienti+13, MNRAS, 428, 2418

A wide and collimated radio jet in 3C 84 on the scale of a few hundred gravitational radii using RadioAstron observations



Giovannini+18, Nature Astronomy, 2, 472



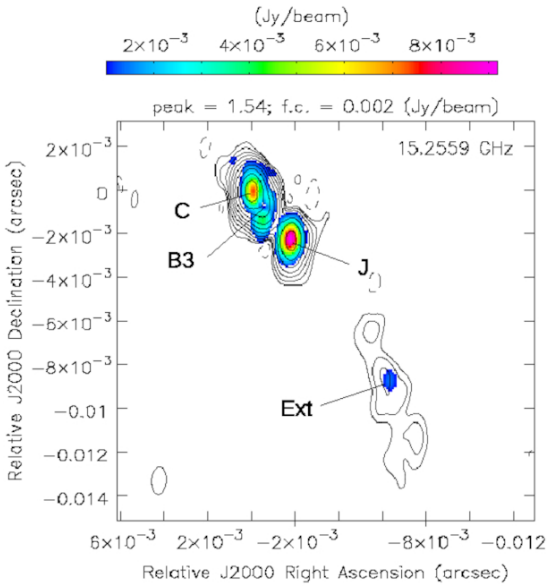
First detection of apparent superluminal motion in the jet of a NLSy1 (SBS 0846+513)

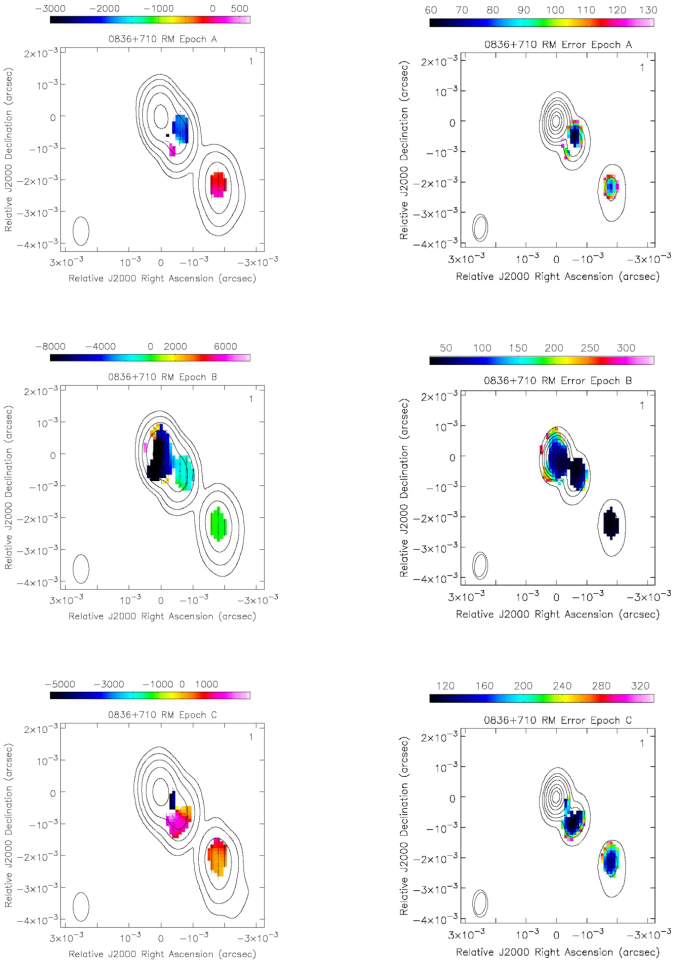
D'Ammando+13, MNRAS, 436, 191

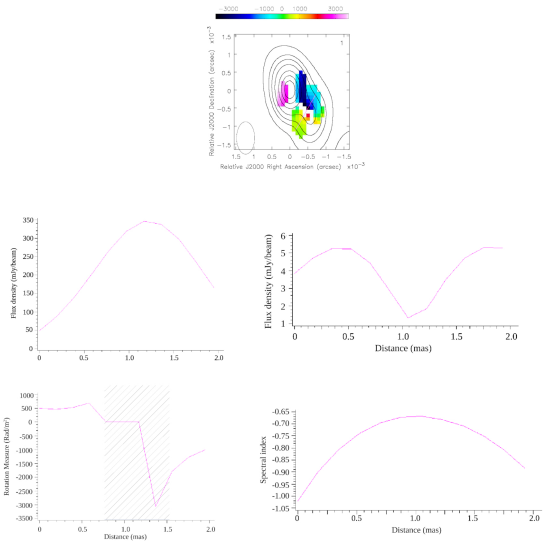
Aims of the program (III)

Determine the **structure of the magnetic field** in the emitting region of jetted AGN by studying the **polarization properties** in **radio**

VLBI polarimetric monitoring of the high-z FSRQ S5 0836+710 during a high γ-ray activity period







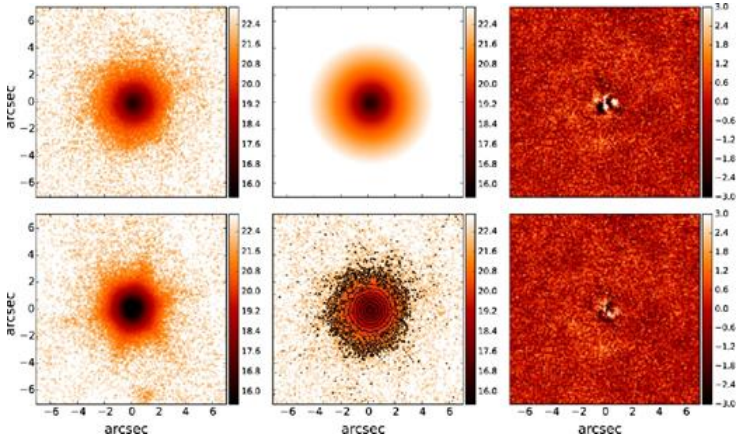
Orienti+20, MNRAS, 491, 858

First multi-epoch Rotation Measure study of a high-z γ-ray flaring FSRQ

Aims of the program (IV)

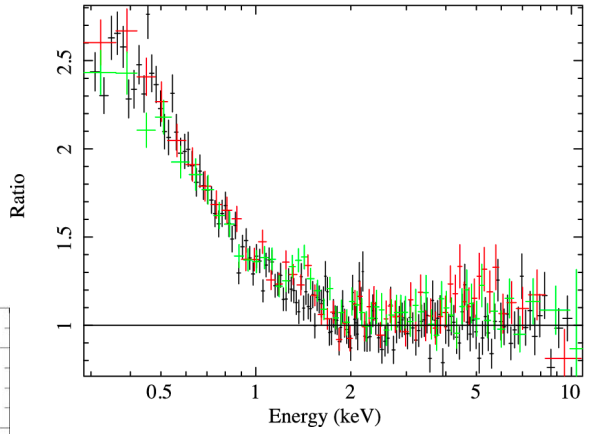
Characterize the properties of the γ-ray emitting NLSy1, in particular the morphology of the **host galaxy** and the measurement of the mass of the SMBH and the presence of thermal components related to the **accretion flow (i.e. soft X-ray excess, Fe line)**

GTC/CIRCE observations of the host galaxy of FBQS J1644+2619 in near-infrared

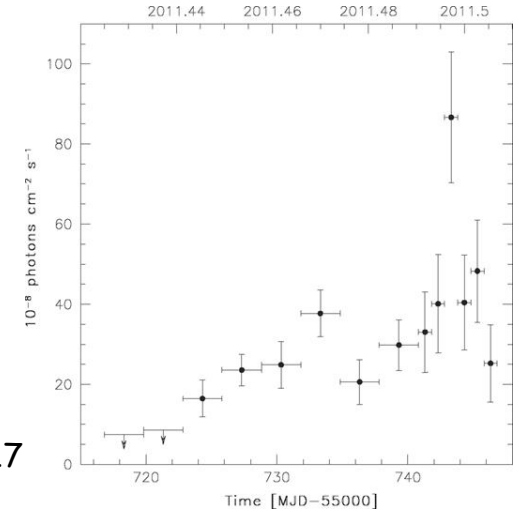


D'Ammando+17, MNRAS, 469, L11

First (deep) XMM-Newton observations of PMN J0948+0022



D'Ammando+14, MNRAS, 438, 3521



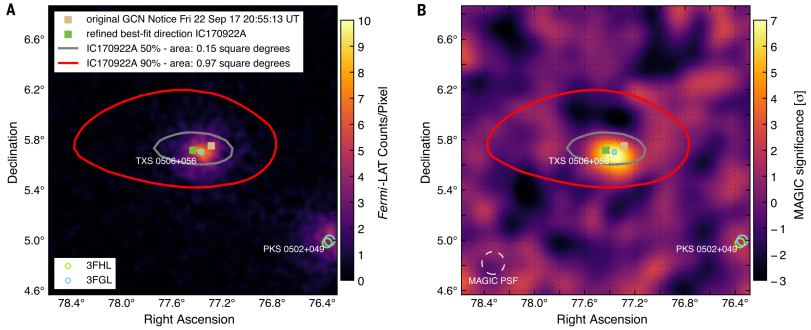
D'Ammando+12, MNRAS, 426, 317

Strong γ-ray flare of SBS 0846+513 detected by Fermi-LAT

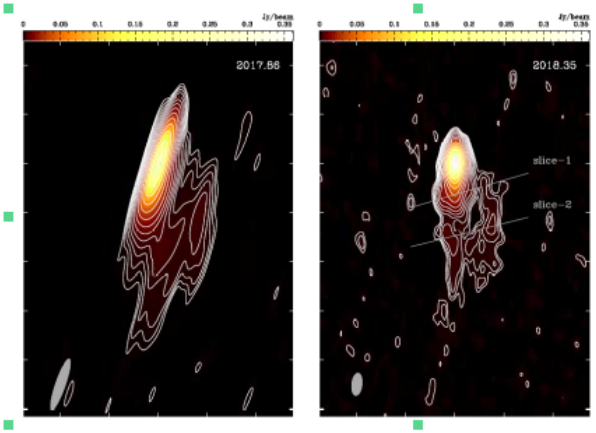
Aims of the program (V)

Investigate from an observational and theoretical point of view the connection between the emission of **high-energy neutrino events** and the emission in the electromagnetic spectrum from the jet of AGN, in particular in **radio** using **high-resolution interferometric data** and in **γ-rays** using **Fermi-LAT** and **MAGIC** data

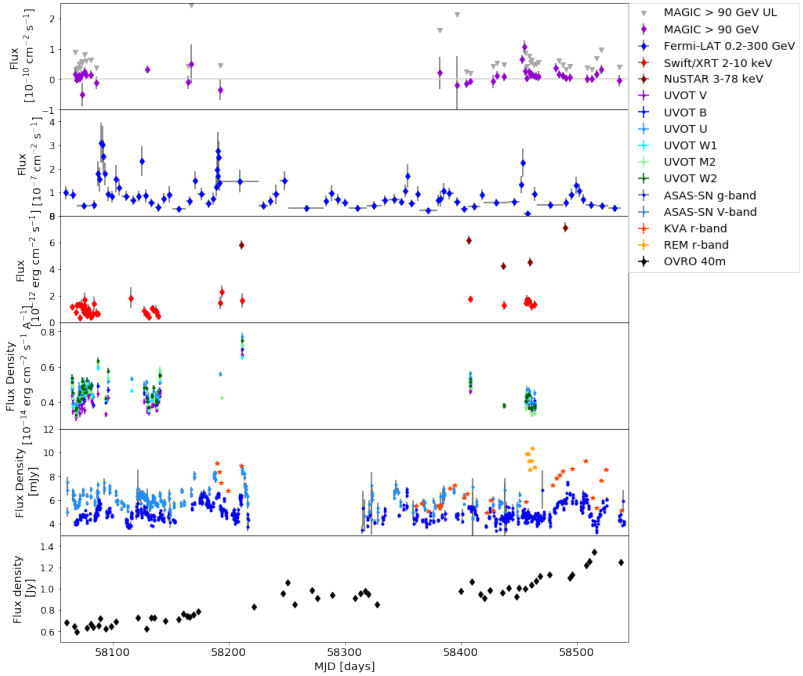
First neutrino-EM connection for the blazar TXS 0506+056



IceCube, Fermi, MAGIC+18, Science, 361, eaat 1378



Ros+20, A&A, 633, L1



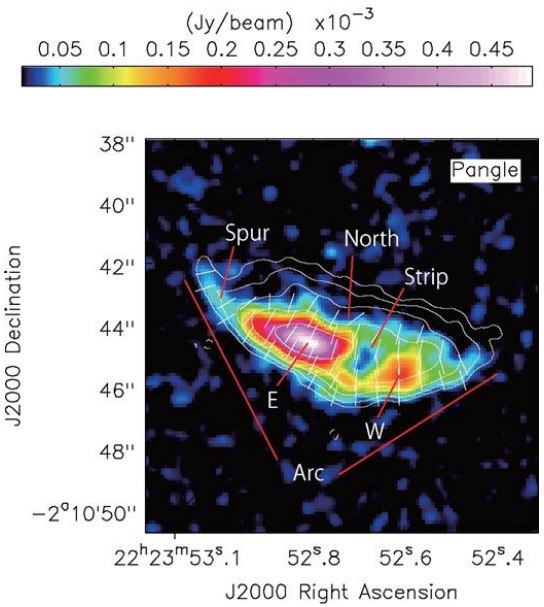
MAGIC, Fermi, NuSTAR, Swift, ASAS-SN, KVA, REM, and OVRO monitoring of TXS 0506+056 during 2017-2019

VLBI 43 GHz observations of the jet structure of TXS 0506+056

Aims of the program (VI)

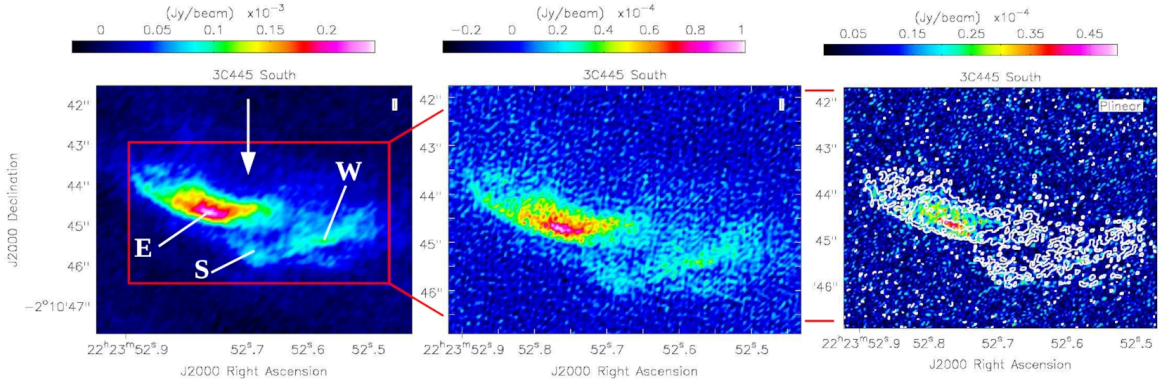
Study the **particle acceleration processes** and the **magnetic field topology** in the **hotspot** of radio galaxies with radio and X-ray observations

First ALMA polarimetric study of the hotspot of a radio galaxy (3C 445S)



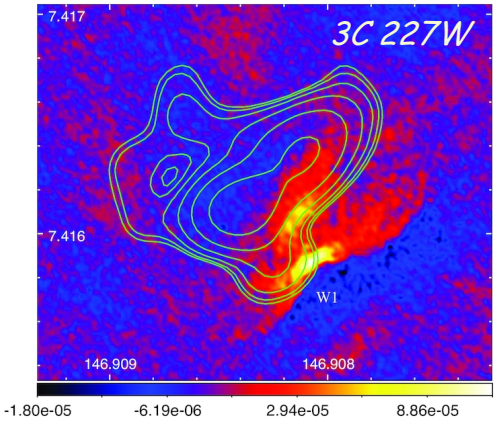
Orienti+17, MNRAS, 469, L123

First high-resolution VLA polarimetric study of a sample of hotspots of radio galaxies



Orienti+20, MNRAS, 494, 2244

X-ray (Chandra) and radio (JVLA) high-resolution observations of a sample of hotspots of radio galaxies with mis-matched emission

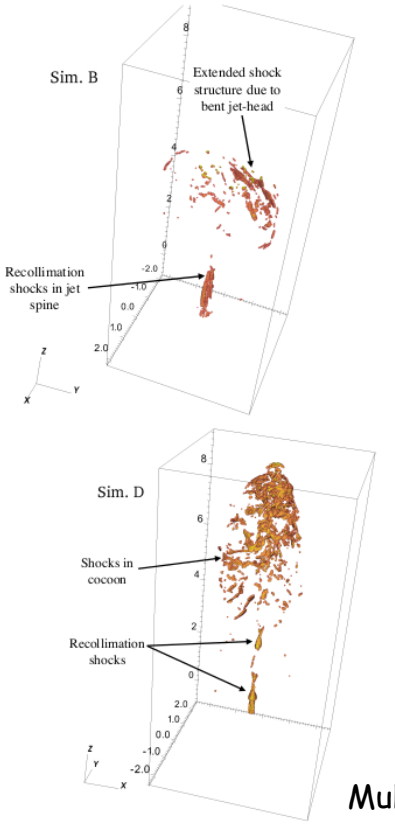


Migliori+20, MNRAS, 495, 1593

Aims of the program (VII)

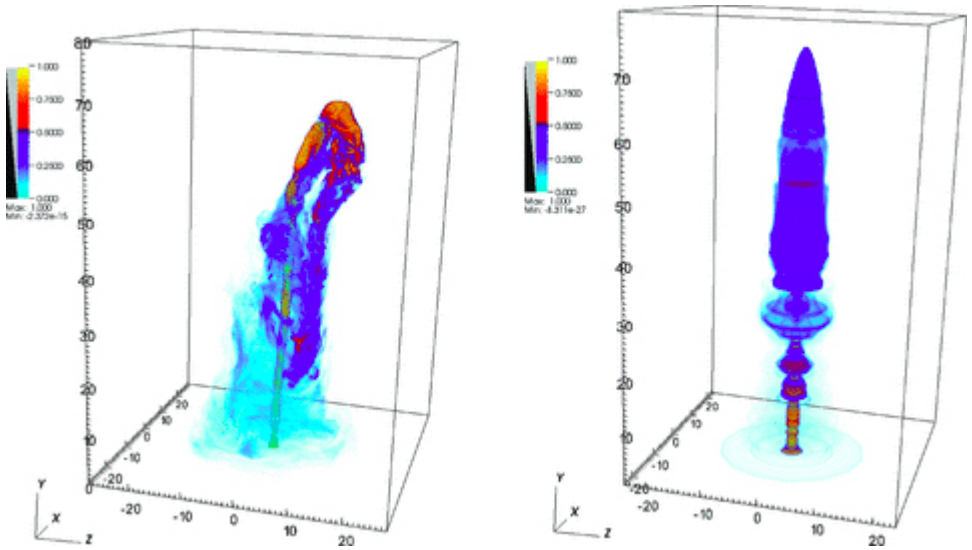
Development of **general-relativistic magnetohydrodynamic simulations** to reproduce the formation of the jet, its propagation and the acceleration processes at work in different parts of the structure to be compared with observational results

3-D volume rendering of shock surfaces in jets



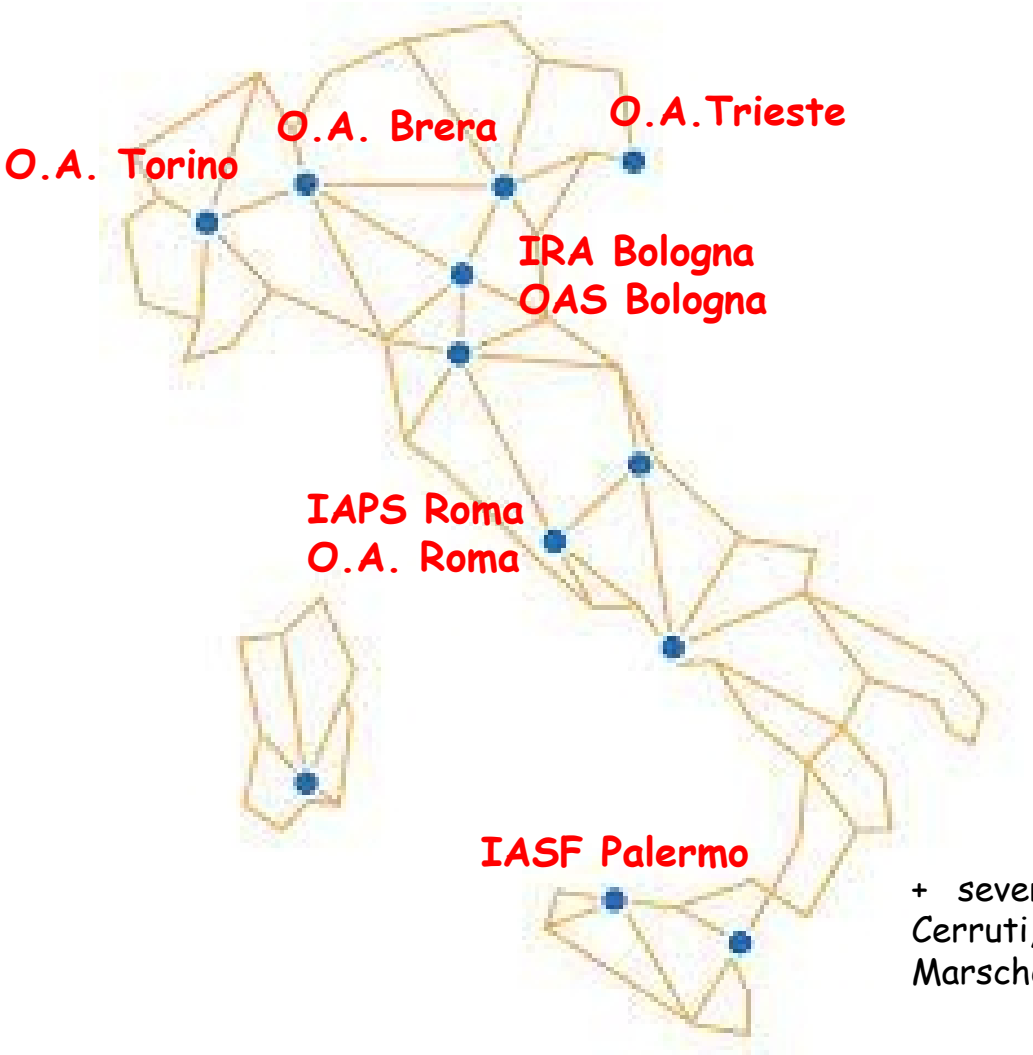
Mukherjee+21, MNRAS, in press

Volume renderings of the passive scalar distributions for the high-resolution 3D run and 2D axisymmetric in jets



Mignone+10, MNRAS, 402, 7

Institutes involved



SISSA

Università di Bologna

Università degli Studi Federico II di Napoli

Università di Padova

Università degli Studi di Torino

8 INAF Institutes and
5 Universities involved

+ several external collaborators (e.g. Acosta-Pulido, Cerruti, Finke, Jorstad, Hada, Hovatta, Kino, Larsson, Marscher, Nagai, Siemiginowska, Satalecka, Won Sohn)

International Collaborations involved: SKA, VRO, Athena, Theseus, eXTP, Fermi-LAT, MAGIC, CTA

People involved (37)

IRA Bologna (11)
D'Ammando
Orienti
Migliori
Giroletti
Mack
Stanghellini
Liuzzo
Baldi
Marchili
Brunetti
Venturi

OAS Bologna (4)
Pian
Malizia
Grandi
Torresi

IAPS Roma (3)
Pacciani
Panessa
Bruni

O.A. Roma (2)
Stamerra
Lucarelli

O.A. Torino (5)
Capetti
Raiteri
Villata
Bodo
Rossi

O.A. Brera (2)
Covino
Sbarrato

IASF Palermo (1)
Pinto

O.A. Trieste (1)
Calderone

Univ. Bologna (2)
Giovannini
Dallacasa

Univ. Padova (2)
Prandini
Bottacini

SISSA (1)
Celotti

Univ. Torino (2)
Massaro
Paggi

Univ. Napoli (1)
Paolillo

FTE INAF 2021-2023 : 7.0
FTE INAF associated 2021-2023 : 0.8

Team Expertise

- Radio data analysis: Baldi, Bruni, Giroletti, Liuzzo, Mack, Marchili, Orienti, Stanghellini, Venturi; Dallacasa, Giovannini
- Optical and infrared data analysis: Baldi, Calderone, Capetti, Covino, D'Ammando, Mack, Pian, Raiteri, Torresi, Villata; Massaro, Paggi
- X-ray data analysis: D'Ammando, Grandi, Malizia, Migliori, Pacciani, Panessa, Pian, Raiteri, Sbarrato, Stamerra, Torresi, Villata; Bottacini, Massaro, Paggi, Paolillo, Prandini
- HE and VHE data analysis: D'Ammando, Giroletti, Grandi, Lucarelli, Migliori, Orienti, Pacciani, Pian, Raiteri, Sbarrato, Stamerra, Torresi; Bottacini, Prandini
- Theoretical interpretation: Brunetti, Celotti, Migliori, Pian, Villata
- Numerical simulations: Bodo, Rossi

Others programs connected

- Very Long Baseline Interferometry (VLBI; **Venturi**)
- Whole Earth Blazar Telescope (WEBT; **Villata**)
- PROgram for Gamma Ray astrophysics with chErenkov obServatorieS (PROGRESS; Antonelli)
- Sfruttamento scientifico della missione Fermi (Fermi Science; Caraveo)
- Programma monitoraggio blazar nel radio (PMBr; **Marchili**)
- Physics and evolution of young radio galaxies (YRG; **Stanghellini**)
- JEtted AGN at High energies (JEAH; **Grandi**)
- Blazars with Rubin-LSST (BlaRub; **Raiteri**)
- Simulazioni numeriche di getti da AGN (3D-Jets; **Rossi**)
- The high energy transient sky INTEGRAL-2 (THETSKY; **Panessa**)
- Time domain precursor studies for AGN science (TimeDomes; **Paolillo**)
- Super-Eddington Accretion: Wind, INflow and Disk (SEAWIND; **Pinto**)
- Scienza e partecipazione INAF al progetto Rubin-LSST (Rubin-LSST; Brescia)
- Enhanced X-ray Timing Polarimetry (eXTP) mission (eXTP; Feroci)
- The Transient High-Energy Sky and Early Universe Surveyor space mission (THESEUS; Amati)
- Centro di ricerca congiunto per studi di fisica gravitazionale (GRAPHJC; **Stamerra**)

Observational facilities

- Radio (single dish telescopes): **Medicina**, Metsahovi, **Noto**, OVRO, SMA, SRT
- Radio (interferometers): **ALMA**, **EAVN**, **eMERLIN**, **EVN**, GMRT, MWA, **VLA**, **VLBA**
- Infrared and optical bands: **GTC**, HST, **REM**, TESS, TNG, **VLT**, **WHT**
- X-rays: **Chandra**, **NICER**, **NuSTAR**, **Swift**, **XMM-Newton**
- HE and VHE γ-rays: **AGILE**, **Fermi**, MAGIC, VERITAS

+ Whole Earth Blazar Telescope (https://www.oato.inaf.it/blazars/webt/)

PI of several observational proposals in many international facilities from radio to γ-rays (in bold face in the list above)

Team members are involved in the scientific working groups of CTA, Astri Mini-Array, AMEGO, eASTROGAM, Athena, Theseus, eXTP, Vera Rubin Observatory and SKA. Therefore during 2021-2023 there will be a time investment dedicated to these future large projects

Program Fundings

The main sources of financing for this program have been:

- **PRIN INAF 2011** "Blazar jets at the highest spatial resolution" (75 kEuro, PI: Giroletti)

- **PRIN INAF 2014** "Jet and astro-particle physics of gamma-ray blazars" (95 kEuro, PI: Tavecchio; estimated 32 kEuro)

- Executive Programme of **Co-Operation in the Field of Science and Technology between the Government of Japan and the Government of Italy** "Radioastronomy from space" considered of strategic importance by **MAE** during 2010-2016 (350 kEuro; PI: Giovannini)

- Programme about **International Collaboration between Korea and Italy** "Supermassive black holes: turning on the most powerful engines in the Universe" (PI: Giroletti; included in the programme VLBI and not here)

Other fundings (for a total of about 23 kEuro) have been obtained by:

- ASI-INAF "Scientific Simulations for the enhanced X-ray timing polarimetry mission eXTP" (PI: De Rosa)

- ASI-INAF "Exploring the radio morphology-accretion mode link in AGN through X-rays" (PI: Torresi)

- ASI-INAF "Science case study and scientific simulations for the enhanced X-ray Timing Polarimetry mission, eXTP" (PI: De Rosa)

- INAF Mainstream 2018 "Exploring the radio morphology-accretion mode link in Radio-Loud non-blazar AGN" (PI: Grandi)

+ contributions from DIFA Bologna for 6 AdR co-financed with IRA Bologna for a total of 72 kEuro

Post Doc and Students

- Team Members now INAF Staff Researchers have been financed by funds from this program (D'Ammando, Liuzzo, Migliori, Orienti)
- PhD students: Lico, **Nanci**
- Master's Degree students: **Baldini**, **Bartolini**, **Bifolchetti**, Blasi, Bontempi, D'Antonio, Ippoliti, Spingola, **Travaglini**
- Bachelor's Degree students: > 20
- Several Japanese and Korean students have been in visit at IRA Bologna between 2010 and 2019, in particular Kazuhiro Hada spent 2 years in Bologna

Excellent in training young researchers

Scientific production & meetings

The scientific production related to this program is extensive and of excellent level. (Not considering people that have only shown an interest for the program) from 2009 to now we have published on topics strictly related to this program:

- **119 peer-reviewed publications** in international journals as first author with **> 2400 citations** (not considering the publications from large collaborations in which we are Contact Authors)

- **566 peer-reviewed publications** in international journals with **> 24000 citations**

We have been involved in the **organization of various national and international meetings** on the topics of this program, in particular:

- East Asia To Italy: Nearly Global VLBI workshops:
  I. Bologna, 15-16 October 2012
  II. Bologna, 13-14 October 2014
  III. Jeju (Korea), 30 October-1 November 2017
  IV. Bologna, 15-17 April 2019

- Perseus in Sicily: from black hole to cluster outskirts (IAU S342), Noto, 13-18 May 2018

- Physics of Relativistic Jets on all Scales (IAU Focus Meeting 1), Busan (Korea), Aug 2022

INAF leadership

- This program is very well-placed on the world stage in various topics related to the study of relativistic jets of SMBH. Our studies will be crucial also for a better **characterization of different populations of AGN with powerful relativistic jets** that will be studied by the next generation of facilities **(CTA, Athena, VRO, eXTP, SKA);**

- This program makes **extensive use of data from ESA, ESO, NRAO and NASA facilities of strategic importance for INAF** as well as various infrastructures managed by INAF, increasing the impact of the results obtained with these facilities;

- Being involved as **members of International Collaborations such as Fermi, CTA, Vera Rubin Observatory, MAGIC, Athena, Theseus, eXTP, SKA**, this program strengthens the collaboration between INAF and the other countries involved in these collaborations both at the level of individual researchers and research institutions;

- Members of this program were key members in the scientific activities related to the "Radioastronomy from space" (PI: Giovannini) project selected by the MAE among the projects of significant importance in the **scientific collaboration between Italy and Japan** for the period 2010-2016, and to the **international collaboration project between Italy and the Republic of Korea** "Supermassive black holes: turning on the most powerful engines in the Universe" (PI: Giroletti) during 2017-2019.

Criticalities and skills to be acquired

- To maintain the very high international reputation of this program it is important that the activity is sustained on a regular basis. In this context, the major criticality is **the lack of certain funds for the period 2021-2023** which currently precludes the possibility of hiring new TD/AdR who can work in a dedicated way on this research program **with a salary adequate to European standards for more than 2 years;**

- Possible new skills to be acquired concern the **use of numerical codes** (e.g. PLUTO) to produce simulations for the study of relativistic jets and the acceleration of particles in hotspots in radio galaxies;

- Given the continuous evolution of the topics of this program, in particular (but not only) for connections with **multi-messenger astrophysics** and **plasma physics**, the addition of researchers with particular skills in the **development of theoretical models** for the interpretation of data can be beneficial for the research group.