The GRACE project

High energy giant radio galaxies and their duty cycle

G. Bruni
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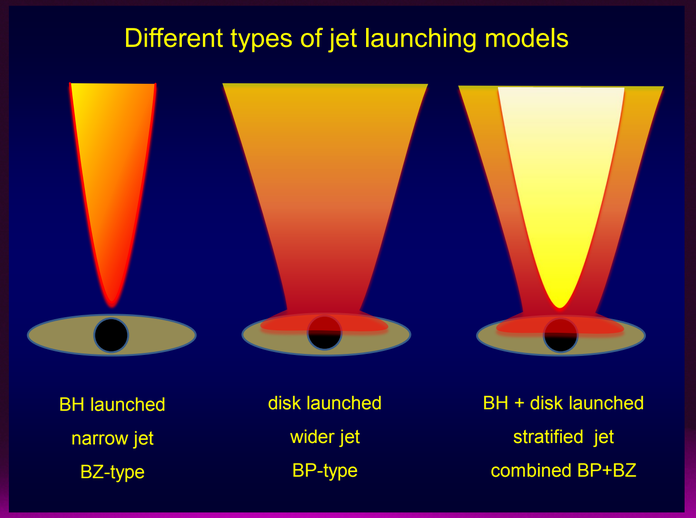
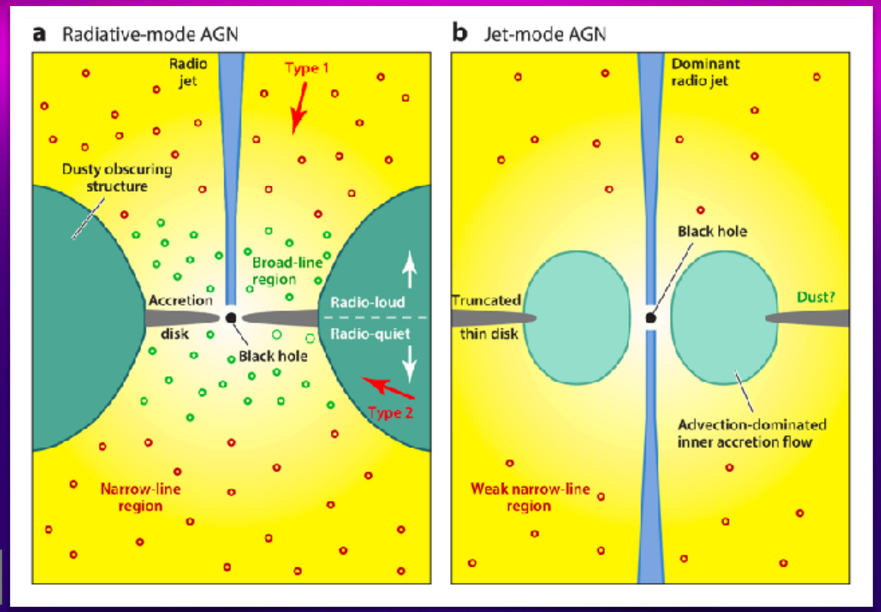
Jets in accreting systems

- Jets are ubiquitous: from stellar BH to supermassive (10^6 Msun) BH
- Mainly 3 ingredients: accretion rate, B, spin
- Low accretion rate (<0.01 Edd) results in an advection dominated, radiative inefficient regime (jet-mode), while higher rates (>0.01 Edd) in a radiatively efficient regime (radiative-mode)

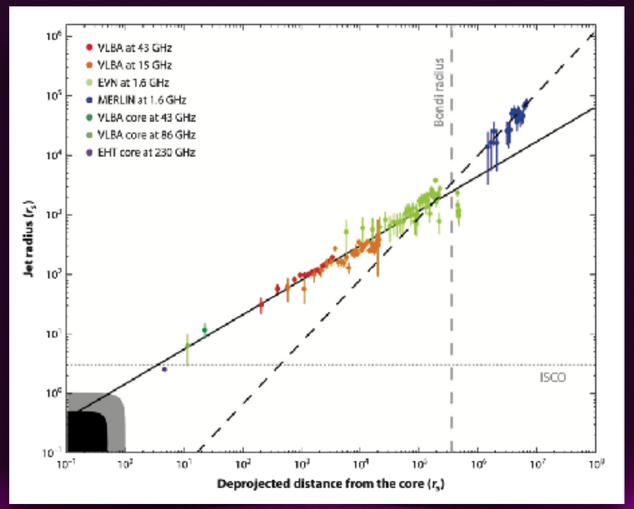


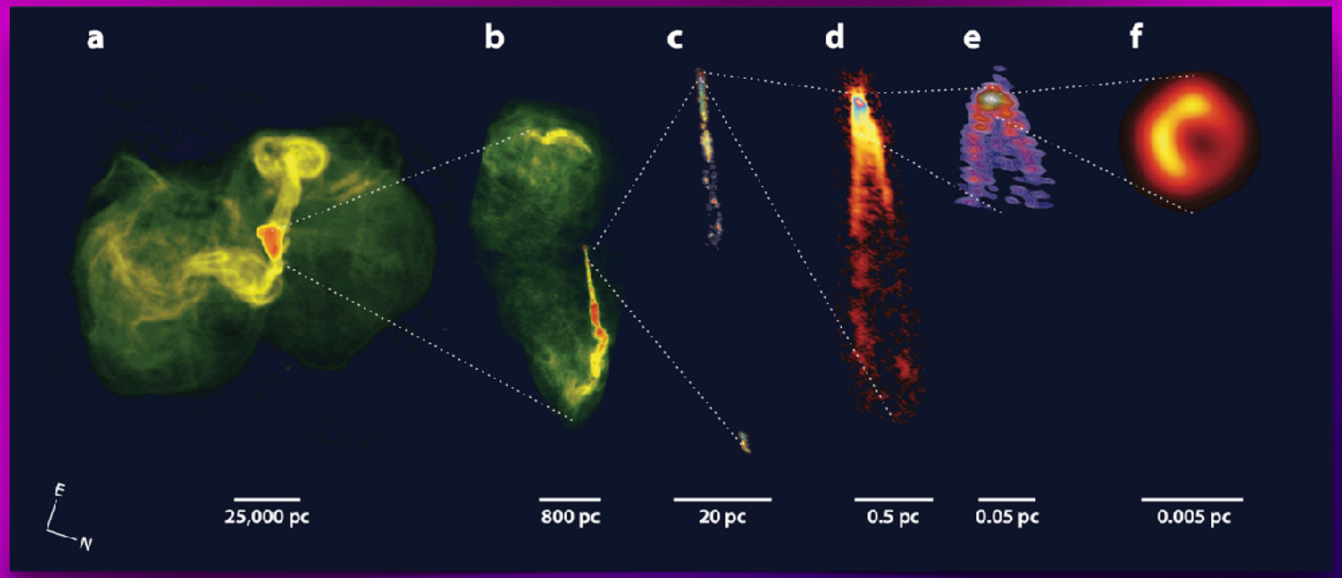


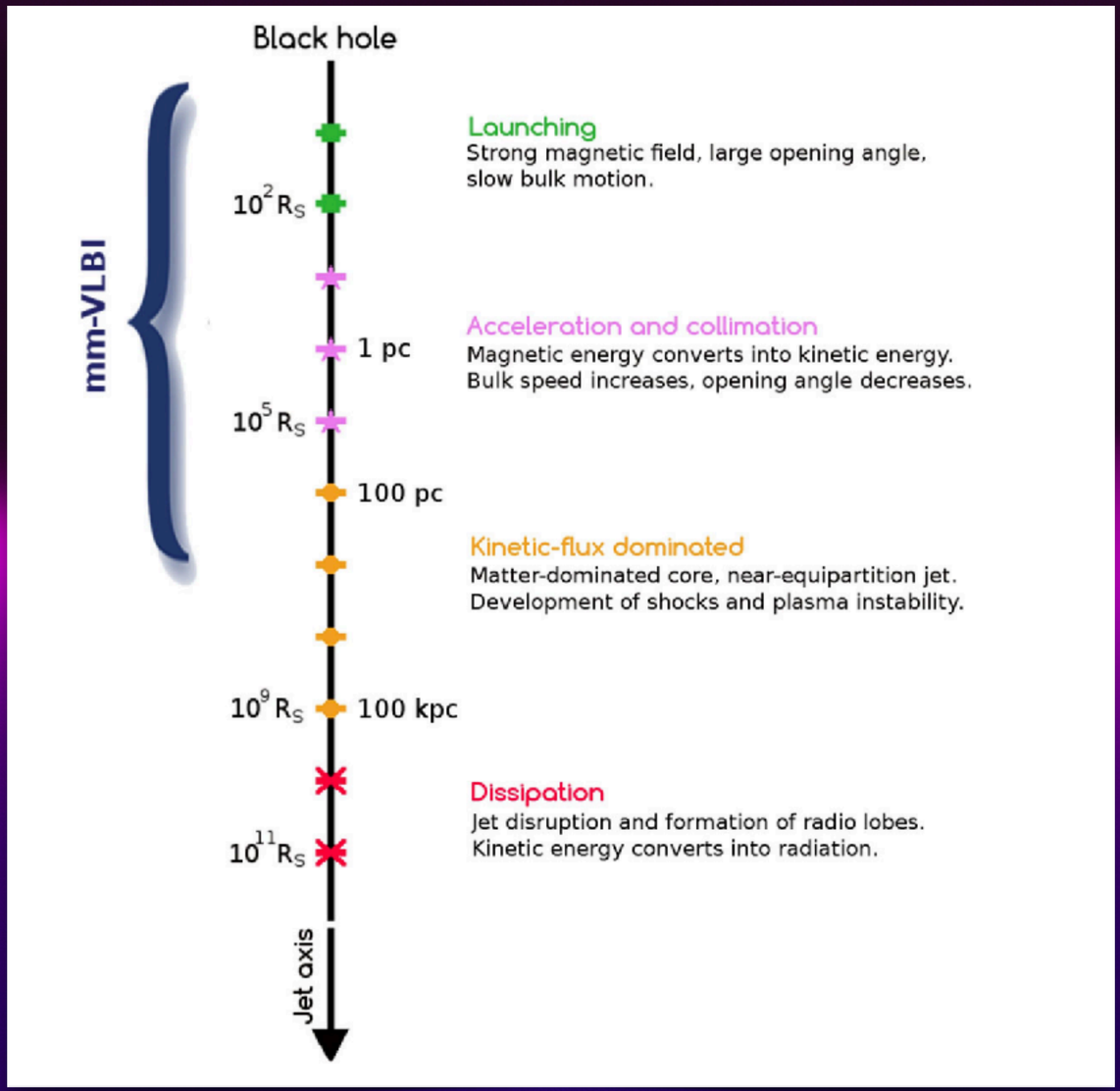
Heckman & Best 2014

Delving into jets structure

M 87

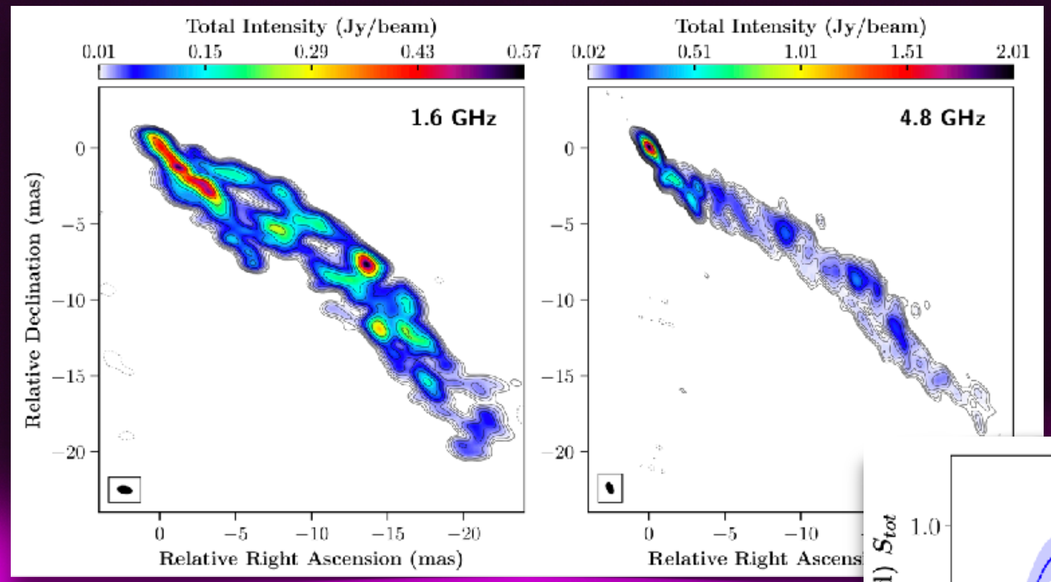


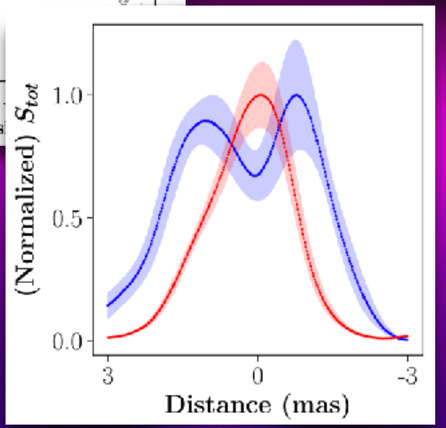




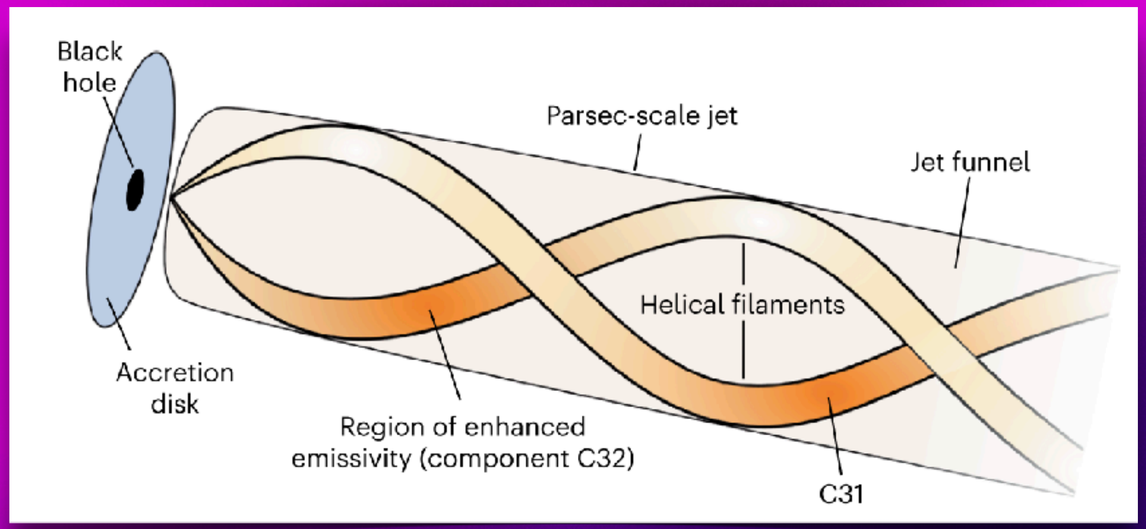
Delving into jets structure

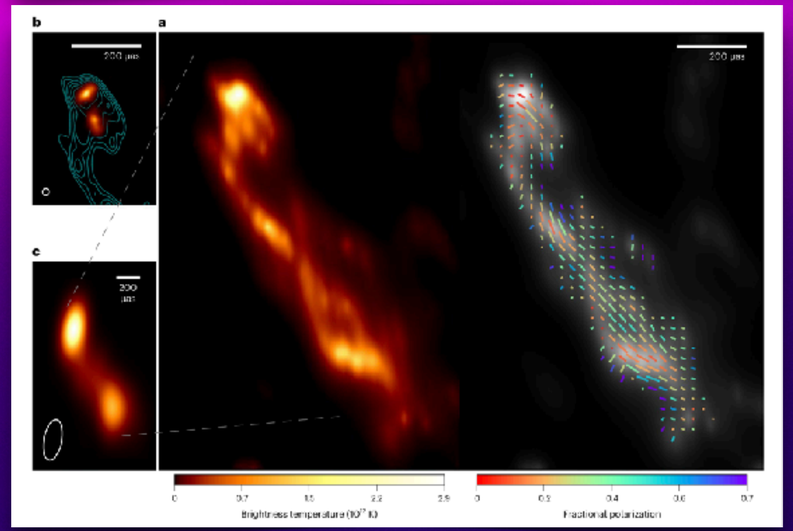
- Recent RadioAstron (Space-VLBI) images at uas resolution revealed internal features in the jet flow
- Helical magnetic field and plasma energy stratification are required





Bruni et al. 2021

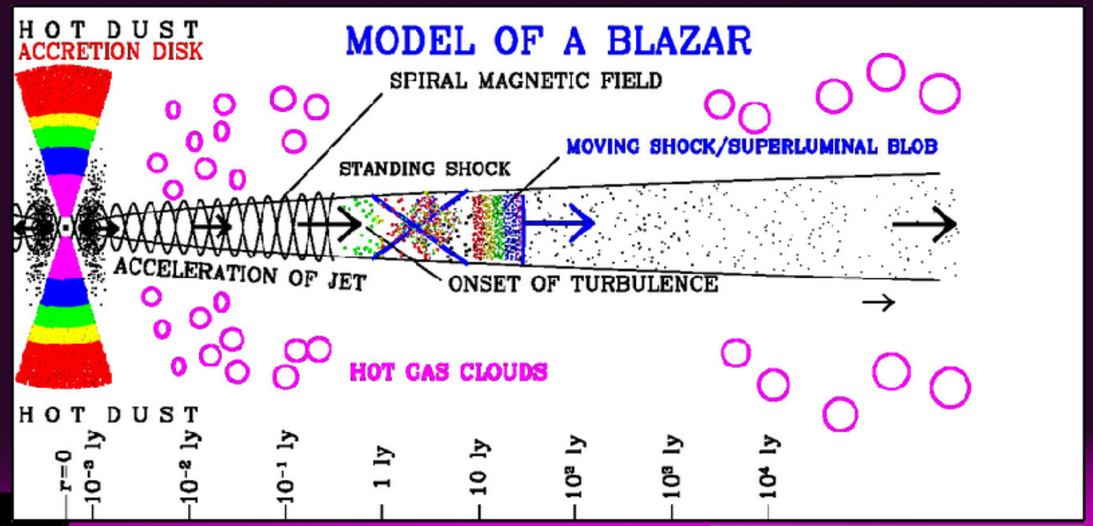




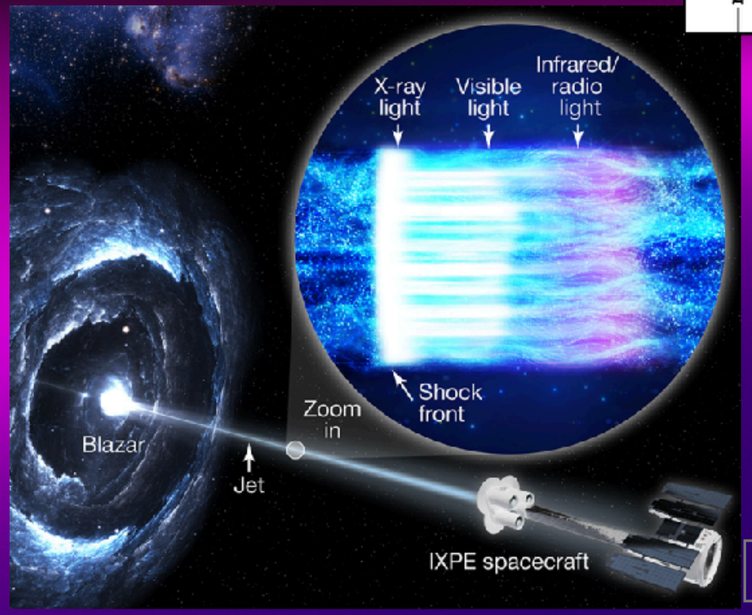
Fuentes et al. 2023

Delving into jets structure

- Jets are visible at different wavelengths, with shorter ones highlighting more internal regions
- Recent IXPE results confirms the shock-in-jet paradigm for particles acceleration



Marsher et al. 2018



Liodakis et al. 2022

Jets in AGN: open questions

- How and when jets are triggered/restarted?
  - Study the recently restarted radio phase at pc-scale resolution

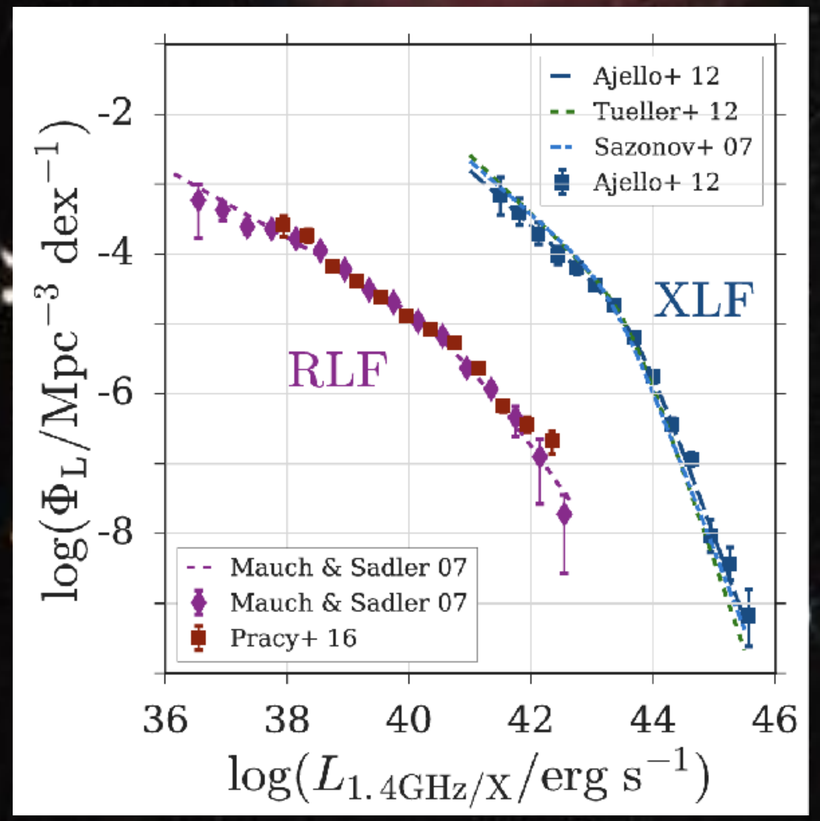
- How jets evolve and what's their dynamics?
  - Study the Mpc-scale lobes morphology to recover the information on the evolution and dynamics of these sources on the Mega-years time scale.
  - Spot any hint of jet precession
  - Probe the presence of binary supermassive BH systems in precessing jets

- What is the jets duty cycle?
  - Synchrotron aging

All of these points are paramount in understanding the AGN-host coevolution

Radio galaxies at high energies

Weigel+17



- Radio galaxies, recognised through their core, jets, and lobes radio morphology, constitute only a small fraction of high-energy AGN

8% in the INTEGRAL/IBIS (keV) AGN sample

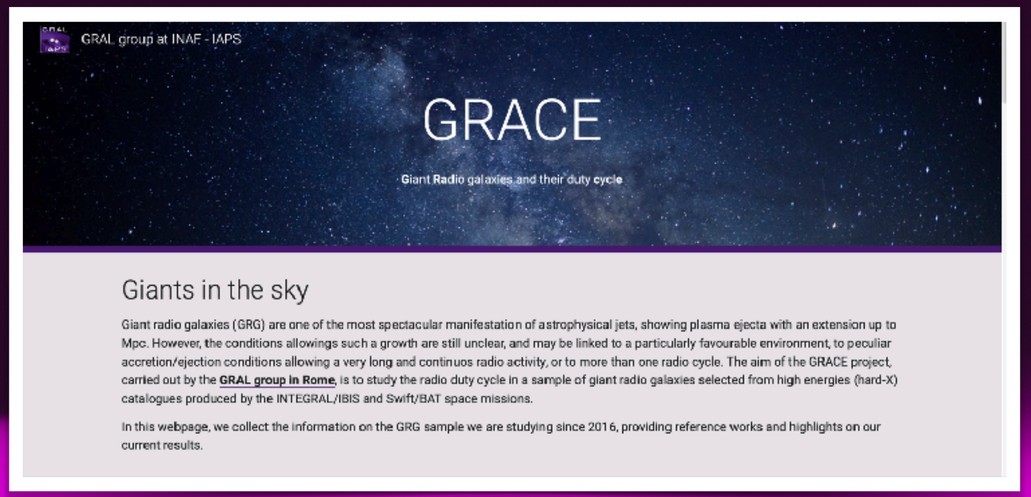
1% in the Fermi/LAT (GeV) AGN sample

- Emerging population of FRI/FRII associated with INTEGRAL and Fermi sources in recent works (e.g. Bruni+22, Paliya+23)
- FR0 as well (Grandi+16, Paliya+21, Pannikkote+23)

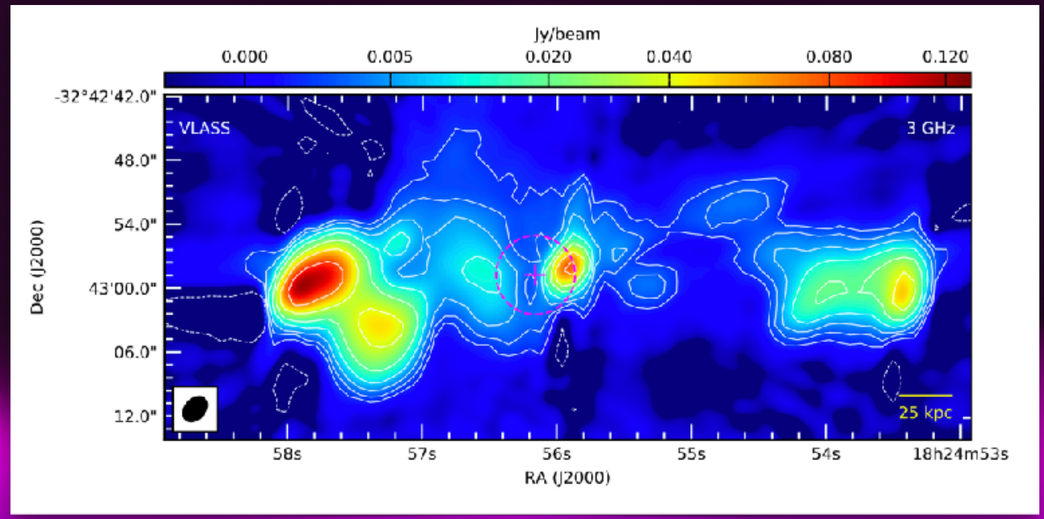
Despite their rarity, they offer the unique possibility to study at the same time jets and accretion processes, and their connections

Synergies with new surveys

HX-GRG



GEV-RG



0.150 GHz

0.880 GHz

3 GHz

TGSS Alternative Data Release

LOFAR

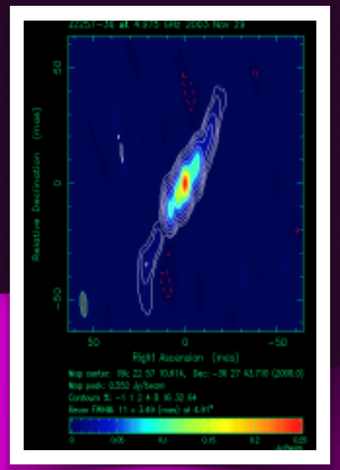
VLA SKY SURVEY

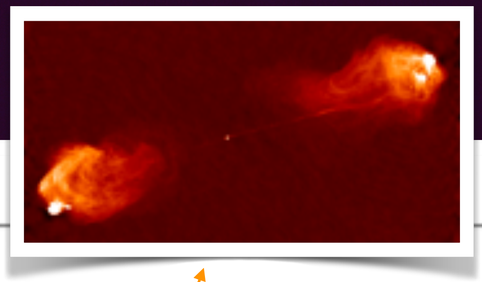
Synergies with new generation surveys

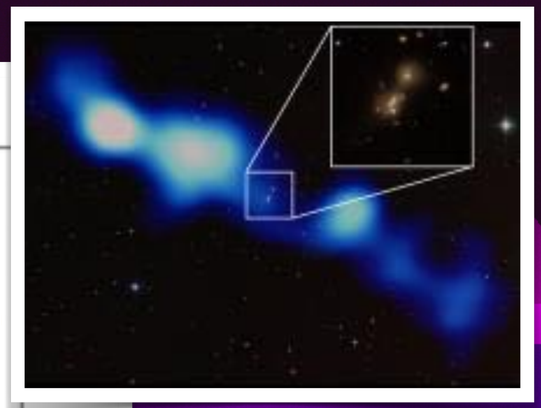
- VLA Sky Survey (VLASS) 2017-2024
- Dec>-40 (80% of the sky)
- 3 GHz, 2.5” resolution, RMS: 70 uJy/beam

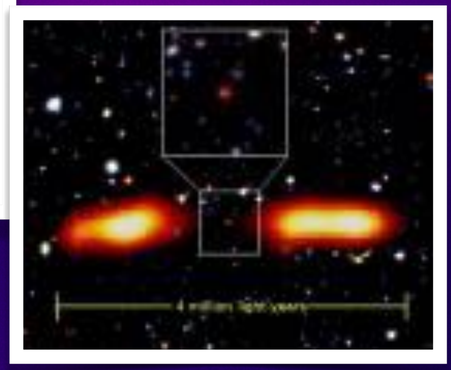
- Rapid ASKAP Continuum Survey (RACS)
- Dec<40 (80% of the sky)
- 0.8 GHz, 15” resolution, RMS: 250 uJy/beam

Radio galaxies life cycle



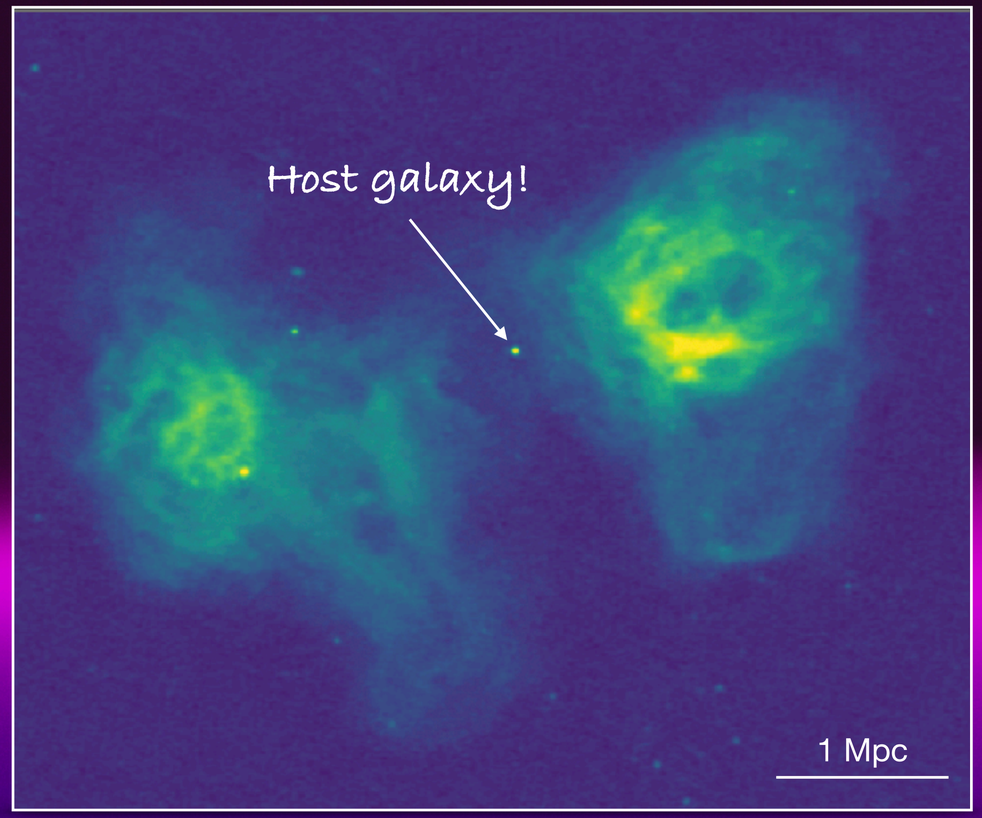






Giant Radio Galaxies (GRG)

- GRG are the largest single-entities in the Universe (>0.7 Mpc)
- Low surface brightness, complex morphology, difficult to discover
- In historical radio surveys, only 1-6% of objects are GRG
- Census increased to ~500 GRG thanks to LOFAR
- Size due to environment, or high jet power, or long activity time?

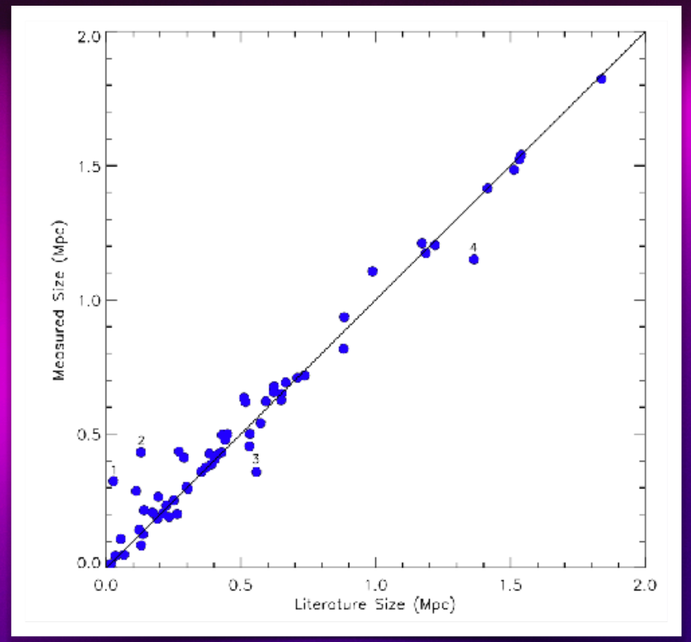


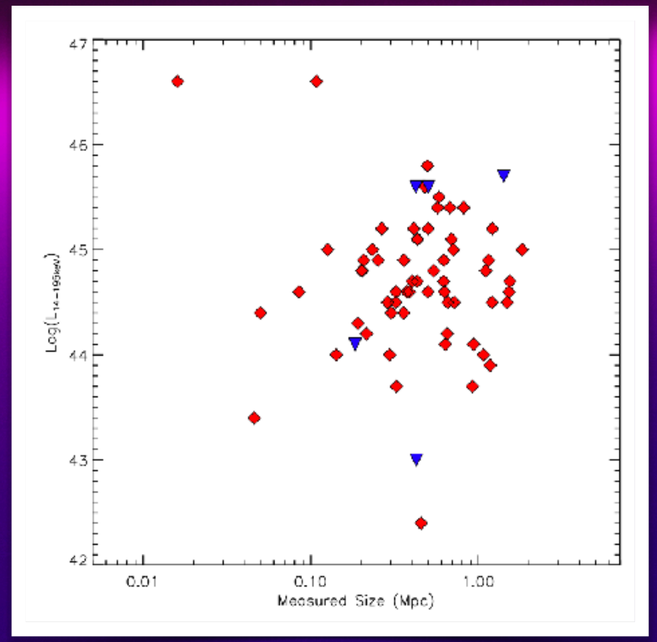
4C40.08, LoTSS DR2 (LOFAR , 150 MHz)

...Ideal laboratory to study the jet duty cycle

Hard X-ray GRG

- Back in 2015, cross-correlation between INTEGRAL+Swift catalogues and NVSS, FIRST, and SUMSS
- Visual inspection of 1000 images, searching for extended, symmetrical structures… (also involving citizen science)
- …and measuring the largest angular size, and linear size in Mpc

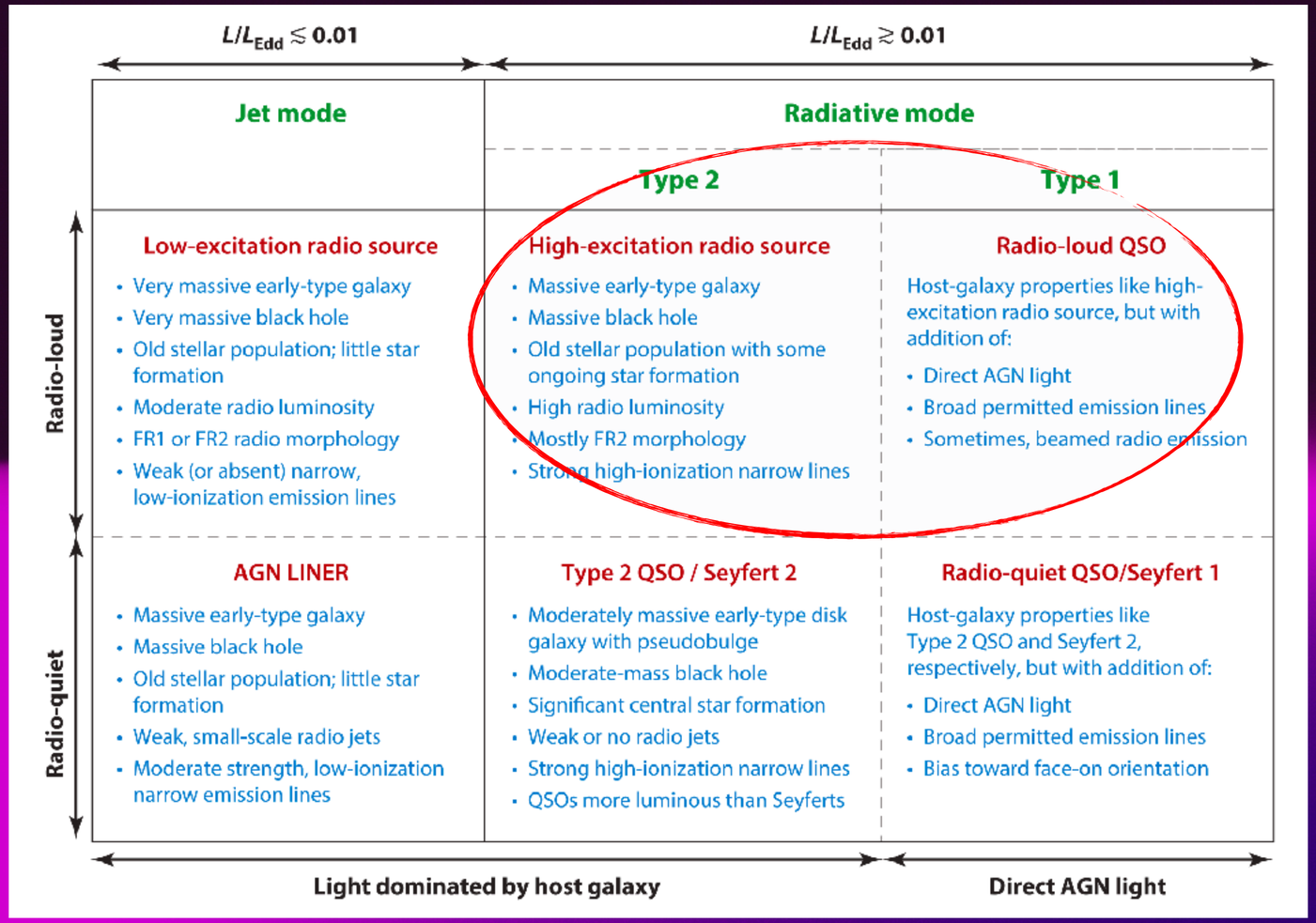




67 radio galaxies
31 RG with size >0.5 Mpc
15 GRGs >0.7 Mpc (22%)

Bassani et al. 2016

Hard X-ray GRG

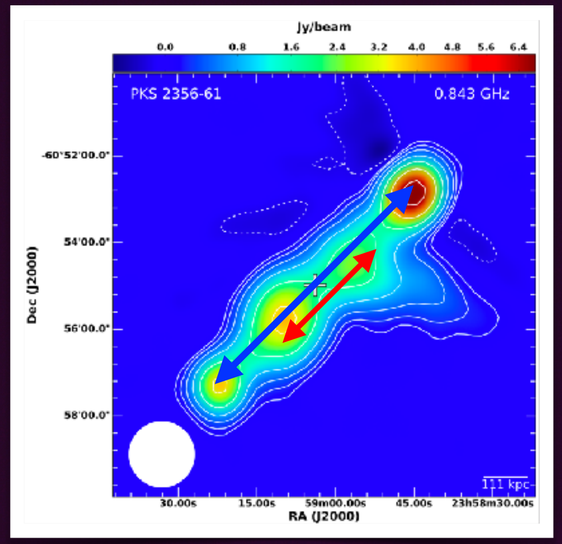


Heckman & Best 2014

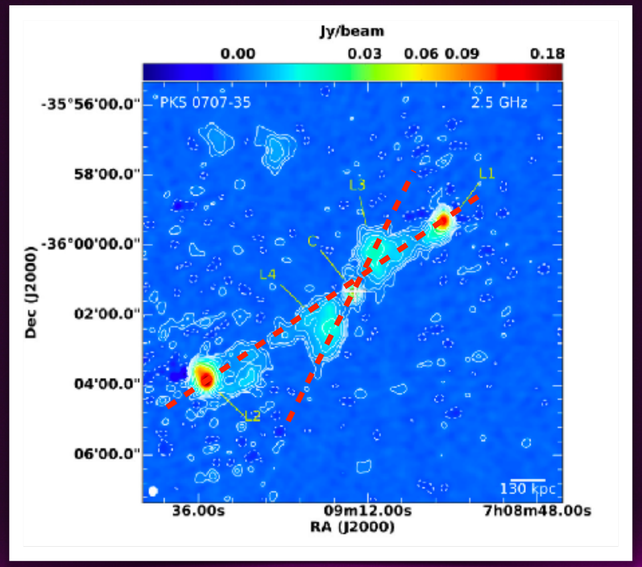
- Hard X-ray detection picks up AGN with a radiatively efficient accretion mode
- Together with the criterium of radio symmetrical structures, this leads to HERGs and in particular FRII
- This high-energy selection is thus biased towards high-end of the accretion rate distribution, while traditional radio-selected samples pick up a mixture of HERGs and LERGs

SIGNS OF RESTARTING ACTIVITY

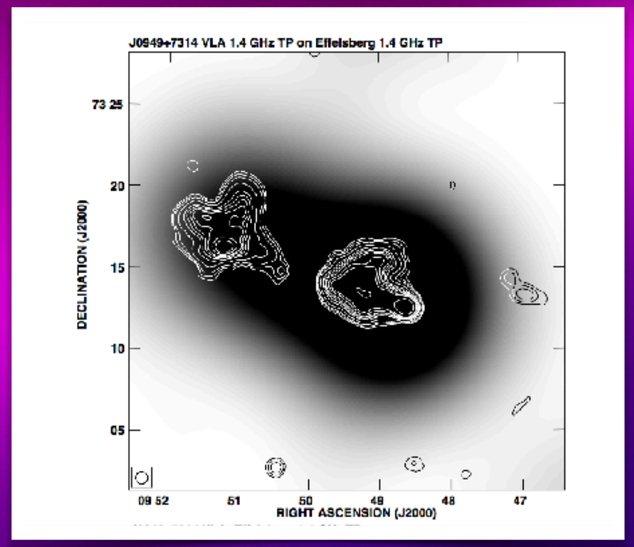
Double-Double RG



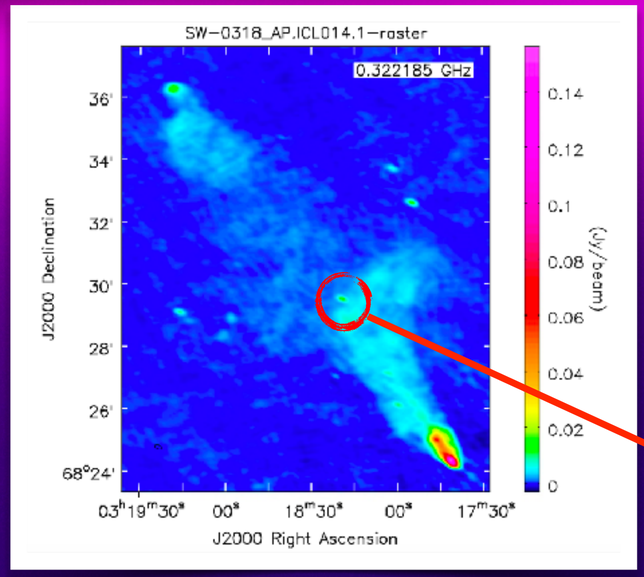
X-shaped RG

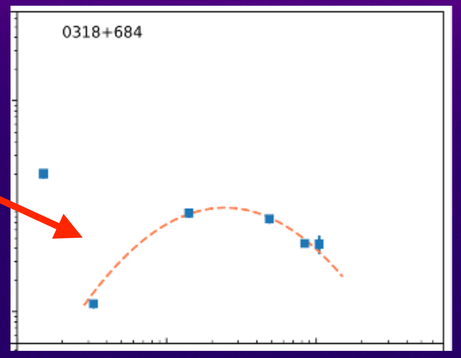


Radio cocoon



GPS-like core

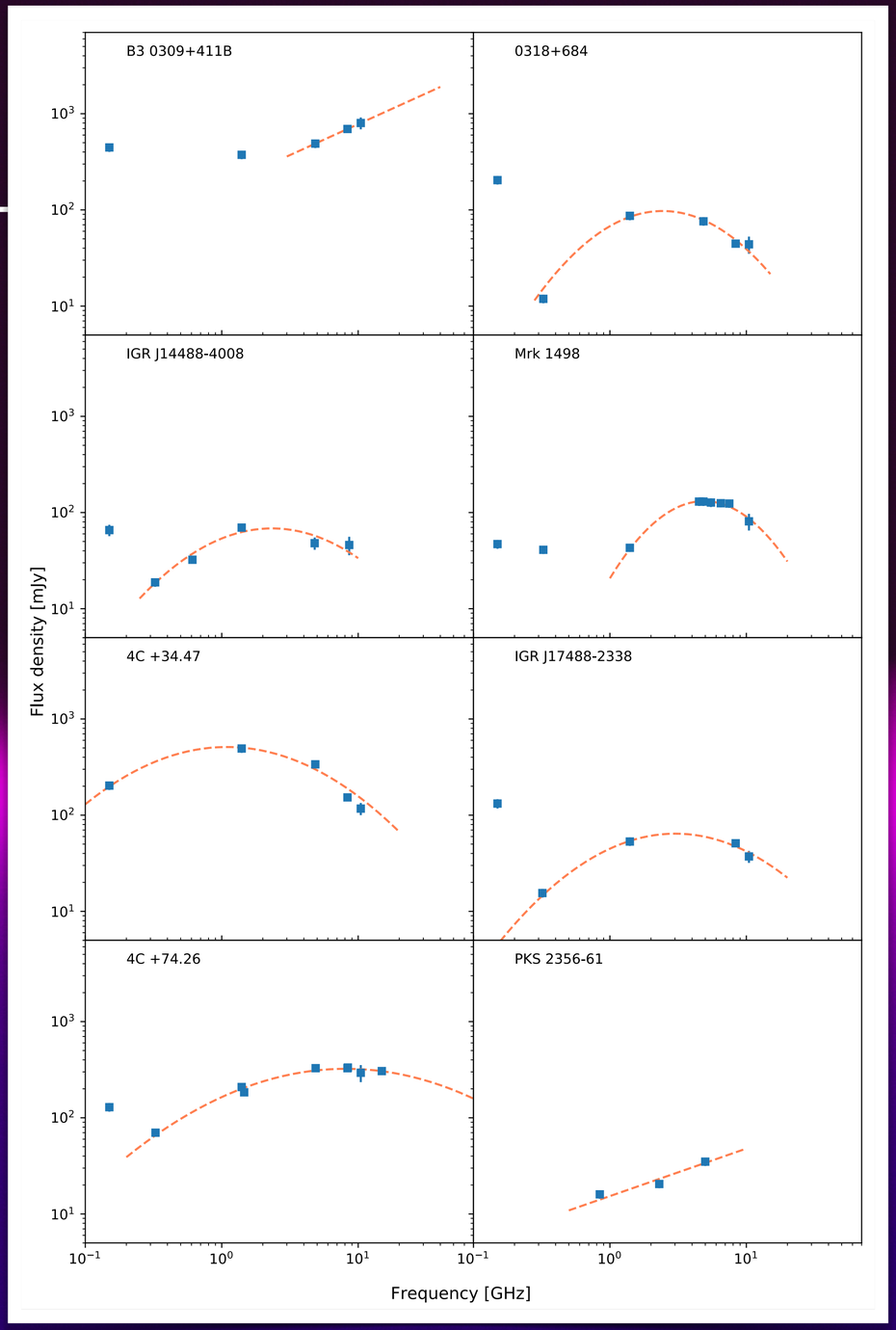




Restarted jets fraction

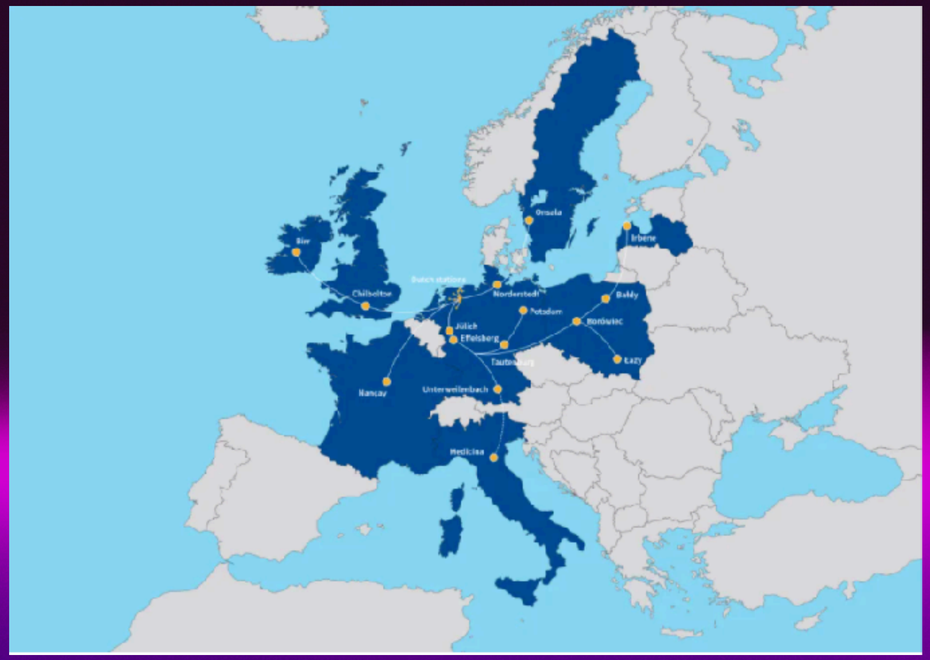
GPS fraction

- Collecting data from archive in the MHz-GHz range for all sources
- A GPS fraction of 61(+30 -21)% is found
- Cores are often young radio sources



Bruni et al. 2019

The LOFAR view



Number of operational stations:

The number of operational stations in January 2020 are:

- 24 Core Stations (which can be split into 48 substations when using HBA Dual mode)
- 14 Remote Stations
- 14 International Stations
- Number of stations available for LBA observations: 52
- Number of stations available for HBA Dual observations: 76

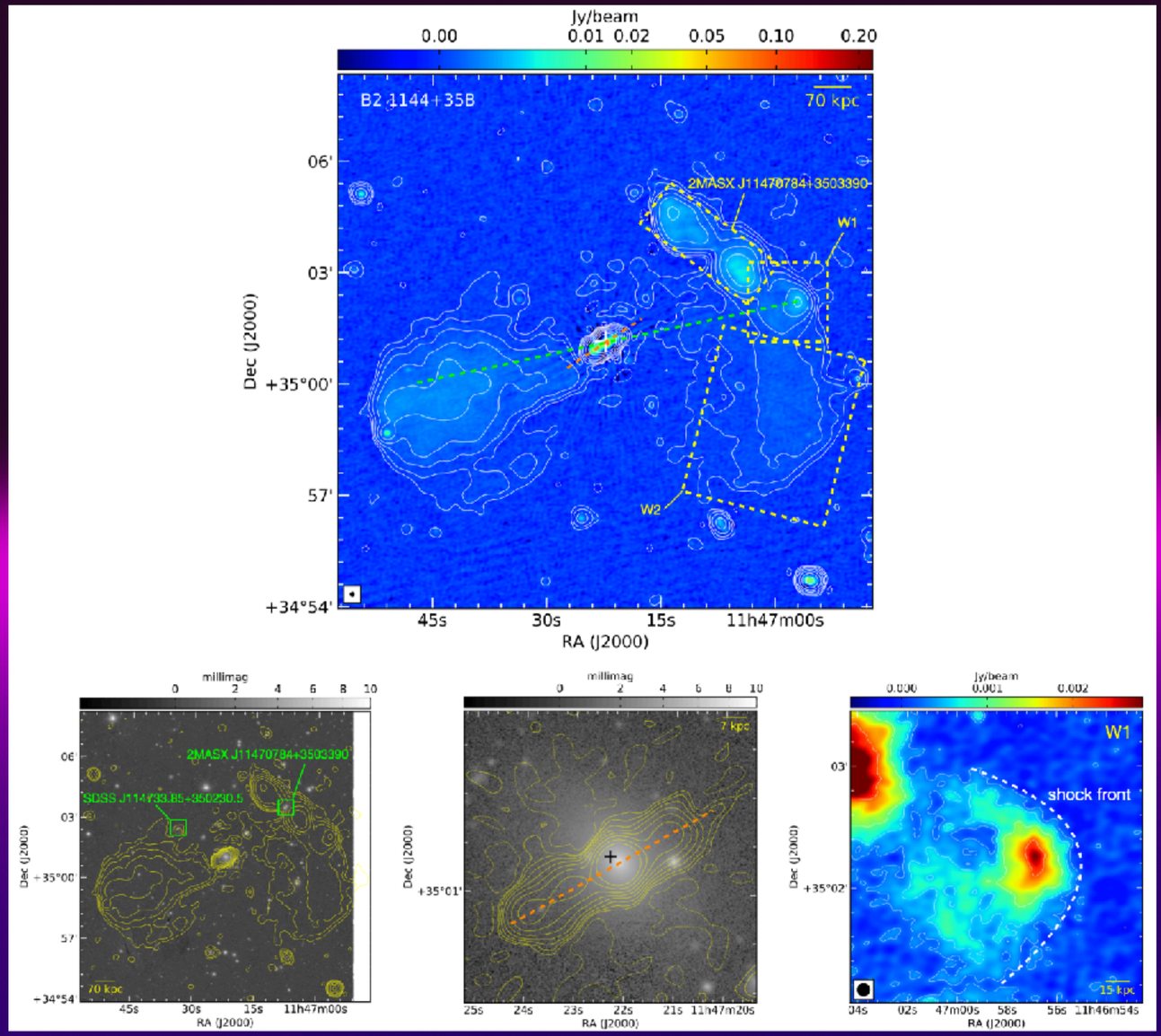
Frequency Ranges:

Observers can choose between the following frequency ranges:

- LBA: 10-90 MHz (200 MHz clock)
- LBA: 30-90 MHz (200 MHz clock)
- HBA: 110-190 MHz (200 MHz clock)

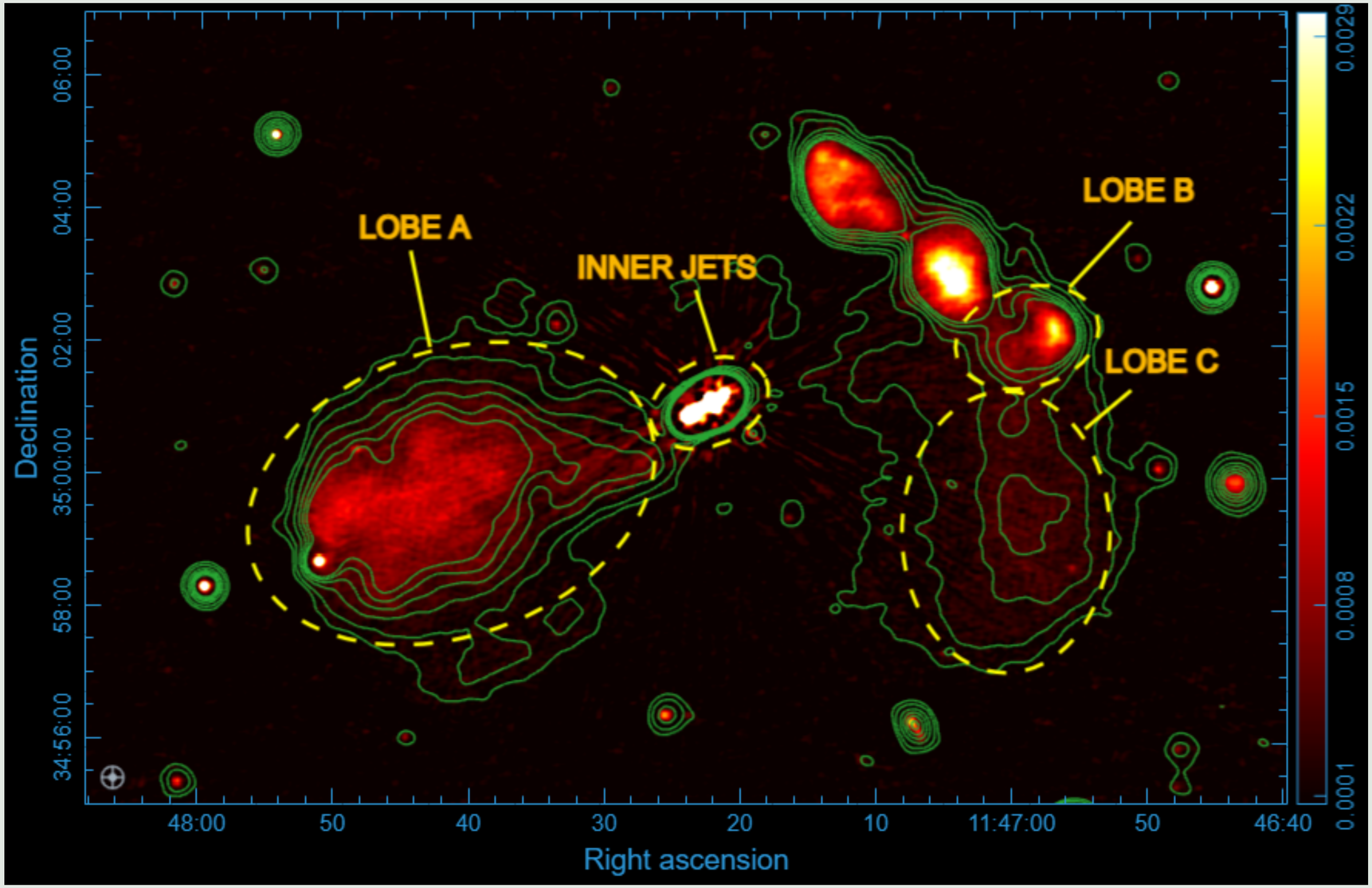
The LOFAR view

- Faint, diffuse emission on the SW sector restored, possible “fat-double” classification
- Inner-jet axis differs by ~30 deg from lobes one
- Possible gravitational perturbation by associated cluster, producing jet reorientation on Myr time scale.



Bruni et al. 2021

B2 1144+35B:ZONES DIVISION

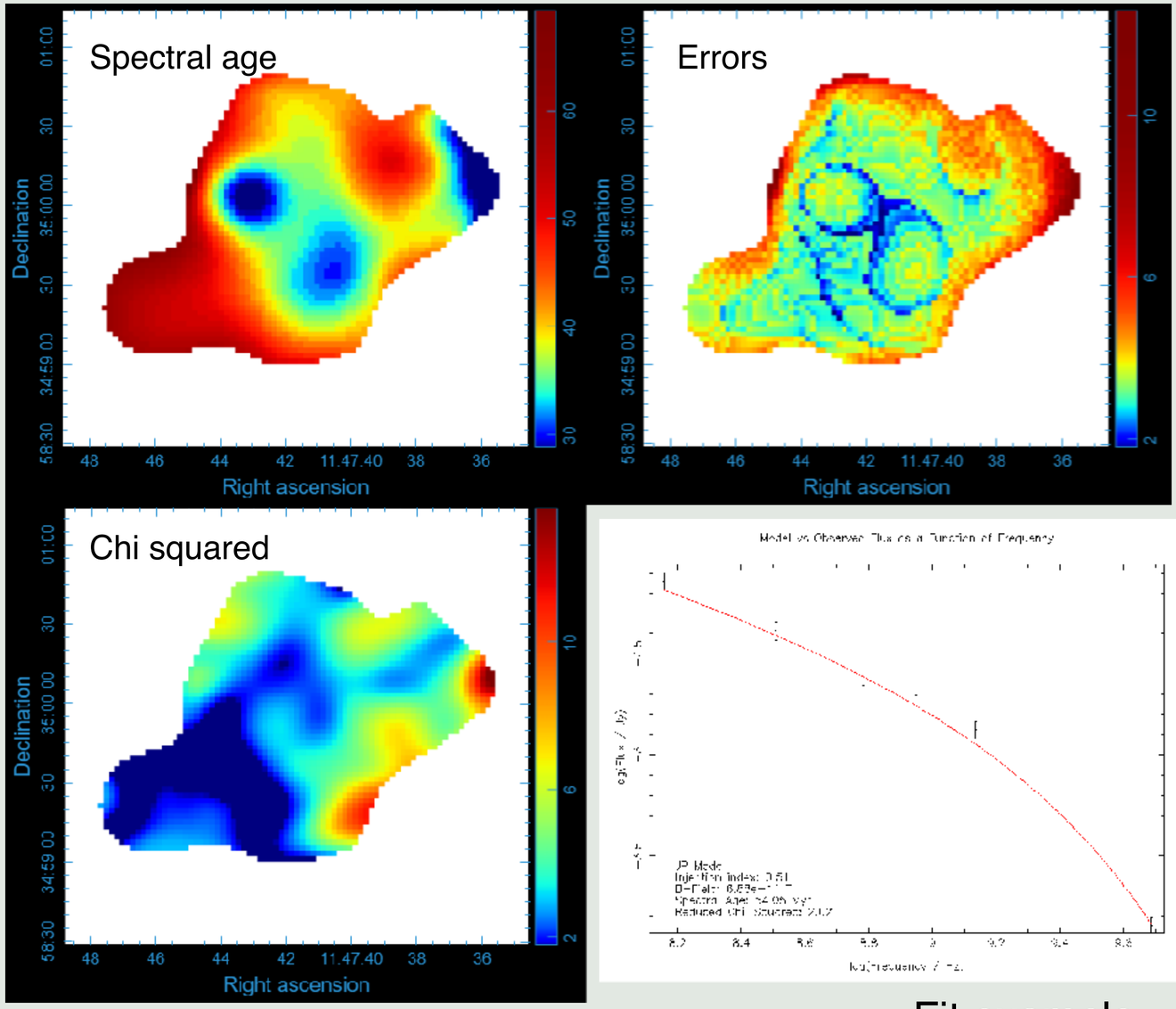


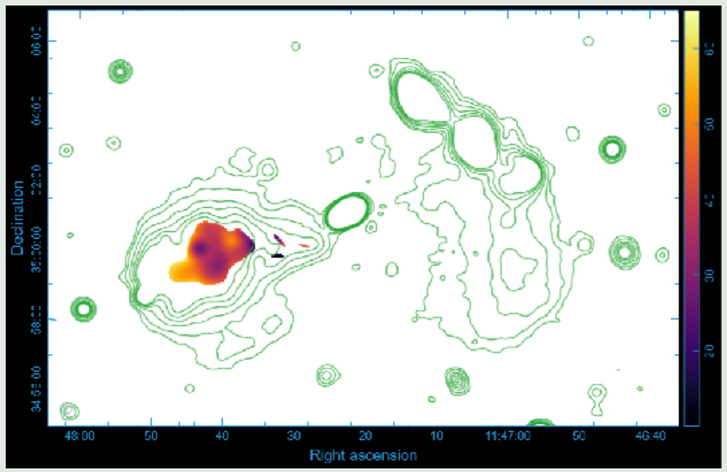
M. Fanelli
Master thesis

B2 1144+35B: LOBE A

M. Fanelli
Master thesis

- Age rises as far as we get away from the core
- Central shock, older ‘’tail’’ at the left side
- Minimum age: ~40 Myr
- Maximum age: ~70 Myr





Fit example

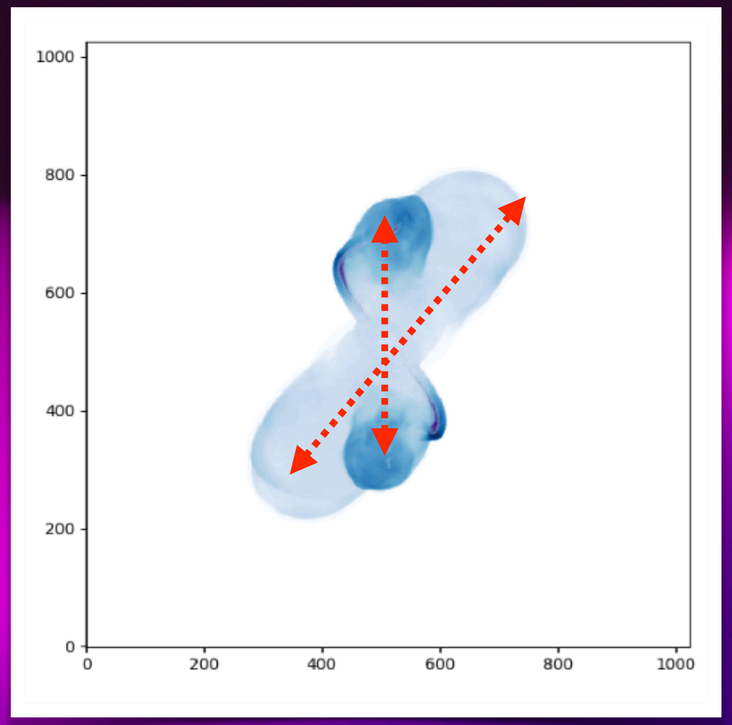
B2 1144+35B: DUTY CYCLE

M. Fanelli
Master thesis

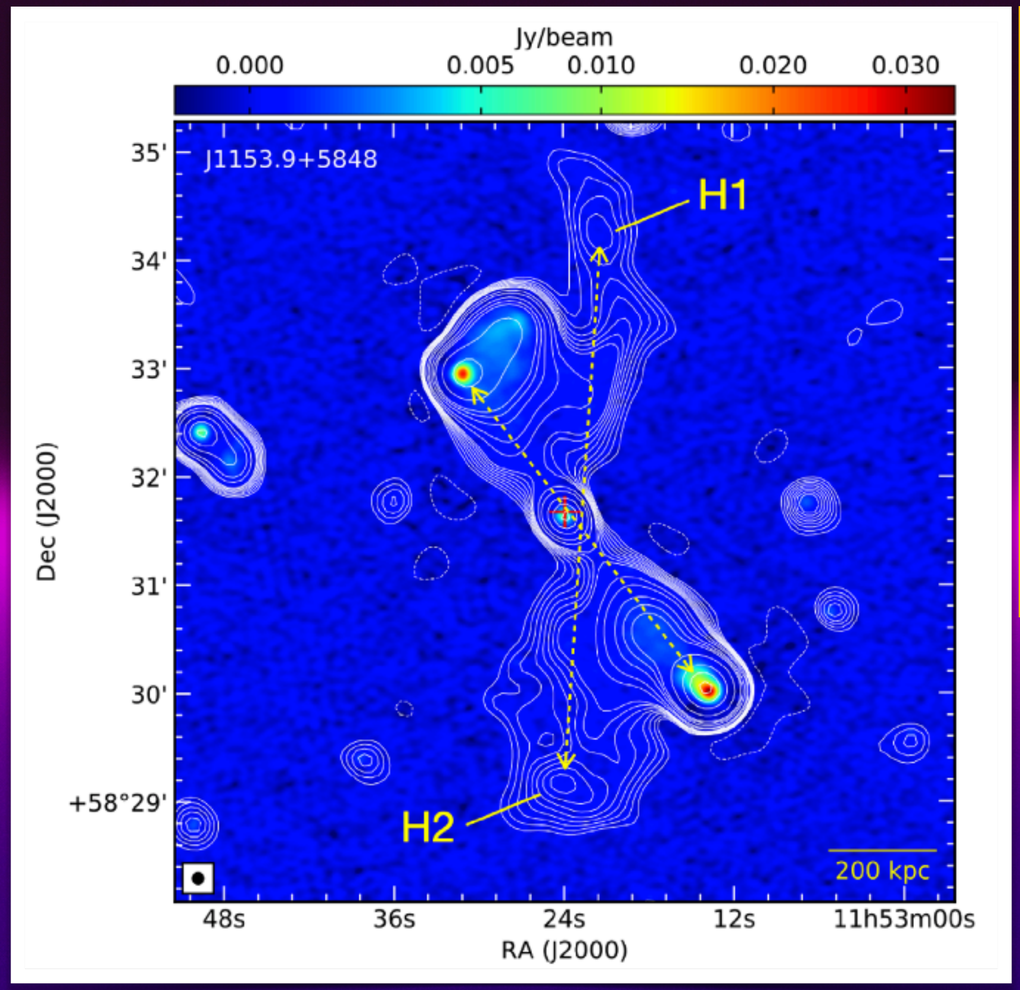
Total lifetime	70 Myr
Young radio phase	12.5 Myr
Quiescence phase	27.5 Myr
Ancient radio phase	≥30 Myr
Duty cycle (active time /total time)	~60%

Zooming into the newborn jets

- LOFAR discovery of possible relic lobes, on an axis ~45 deg away from the known lobes (X-shaped)
- Candidate for jet precession/reorientation, following simulations results. Dual BH?



Horton et al. 2020



New VLBA observations

Bruni et al. 2021

Zooming into newborn jets

EVN+LBA large program

Jets in AGN: open questions

- How and when jets are triggered/restarted?
  - Study the recently restarted radio phase at pc-scale resolution

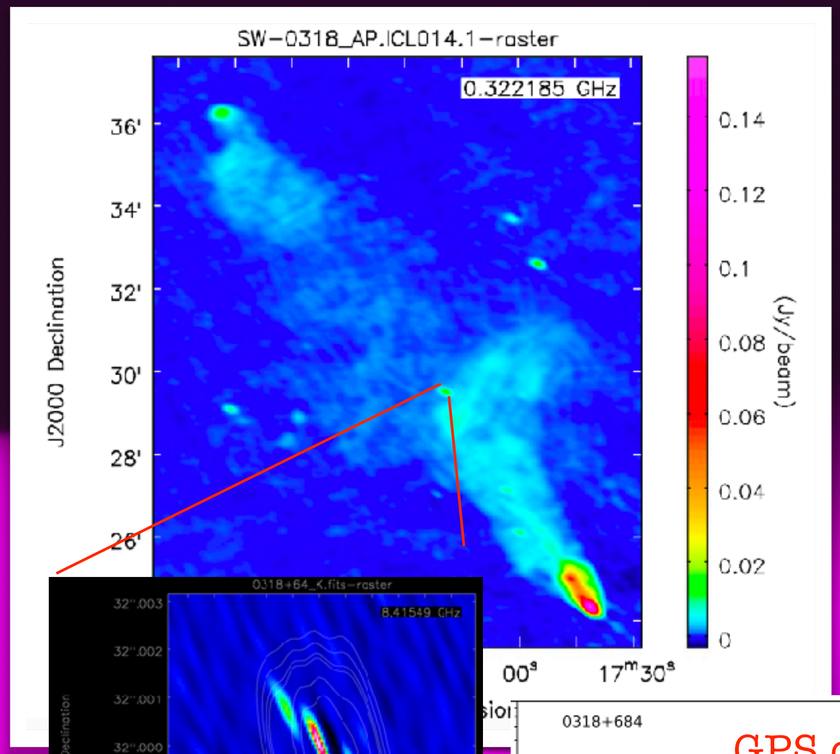
- How jets evolve and what's their dynamics?
  - Study the Mpc-scale lobes morphology to recover the information on the evolution and dynamics of these sources on the Mega-years time scale.
  - Spot any hint of jet precession
  - Probe the presence of binary supermassive BH systems in precessing jets

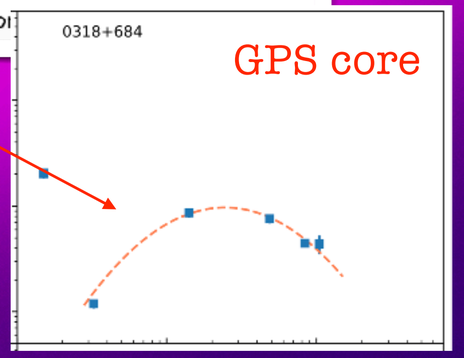
- What is the jets duty cycle?
  - Synchrotron aging

All of these points are paramount in understanding the AGN-host coevolution

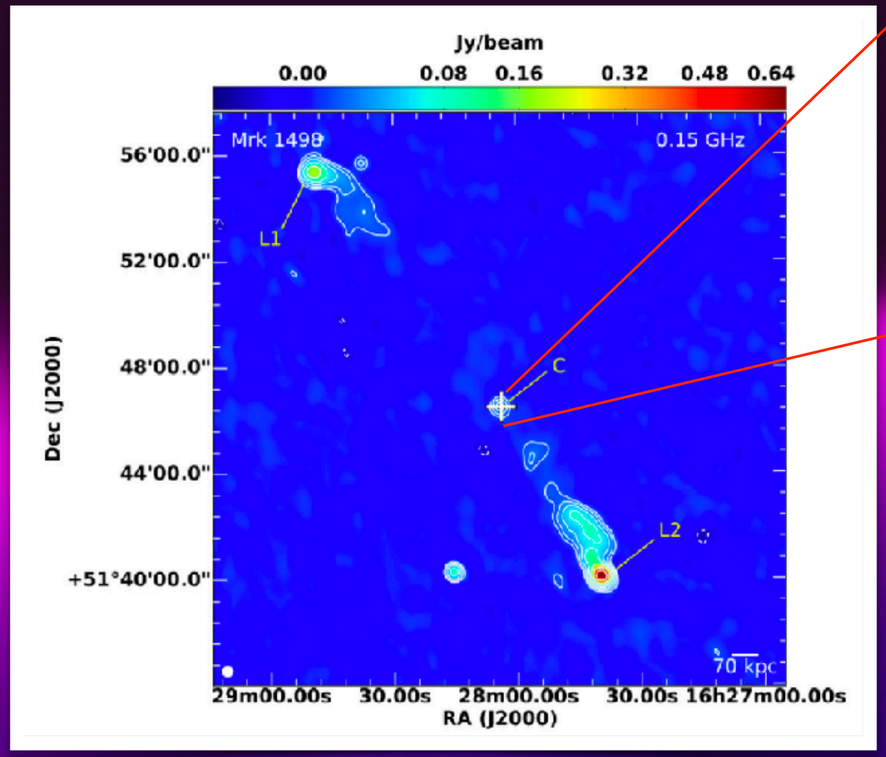
Zooming into the newborn jets

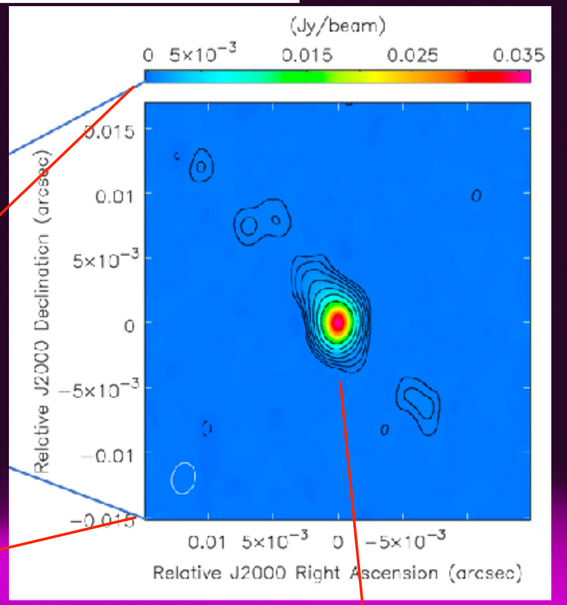
SW-0318+68

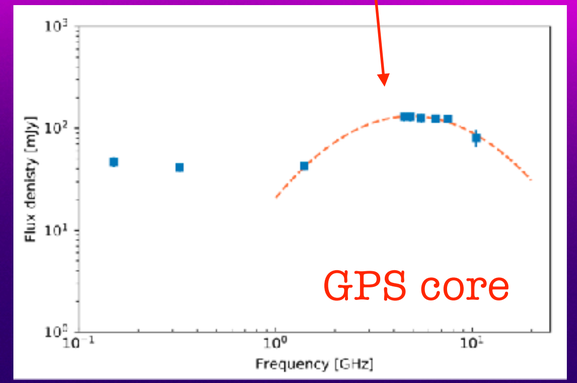




Mrk 1498

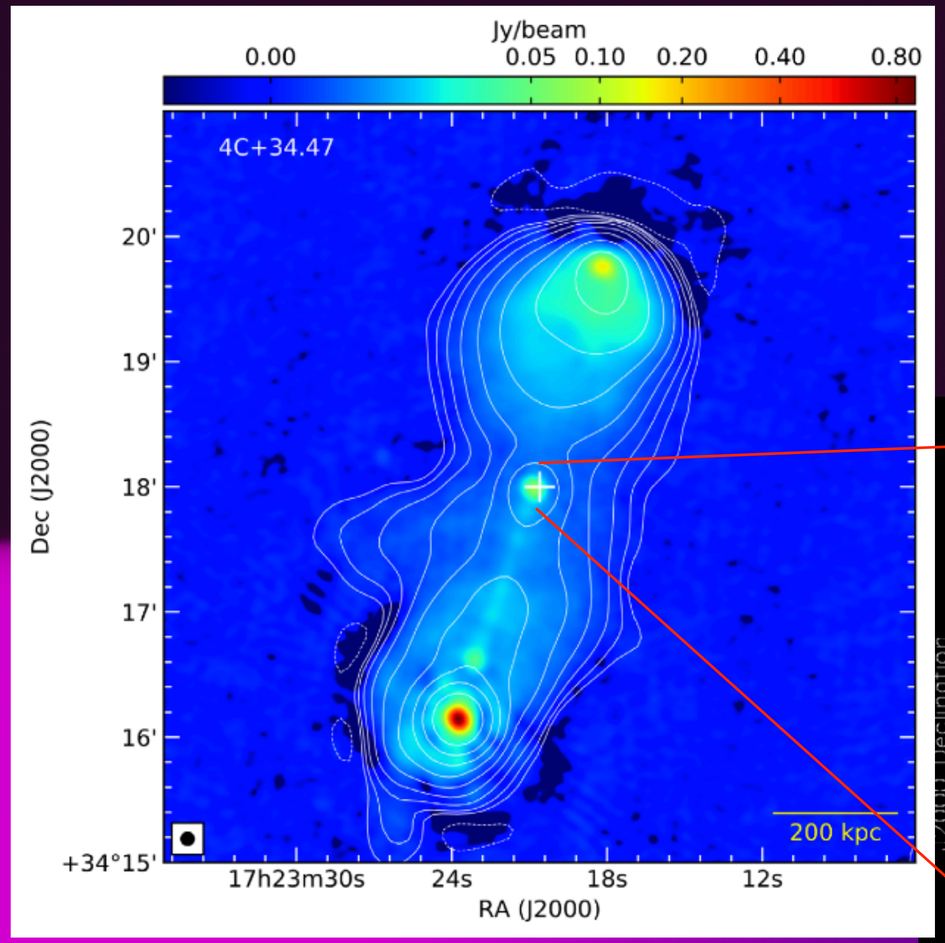




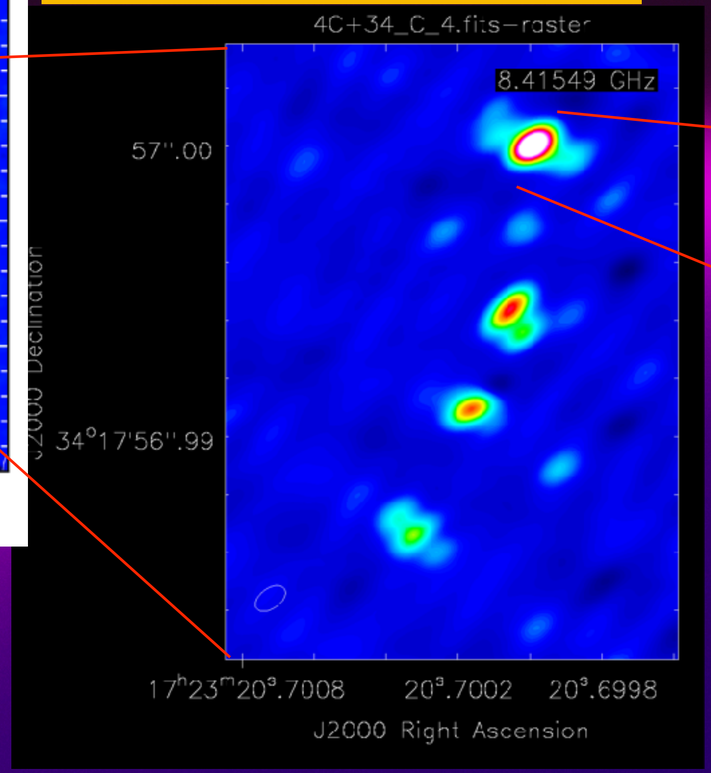


Bruni et al. 2020
Hernandez-Garcia et al. 2019
Bruni et al. In prep.

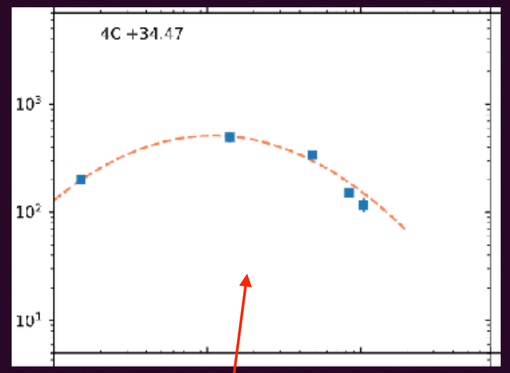
Zooming into the newborn jets

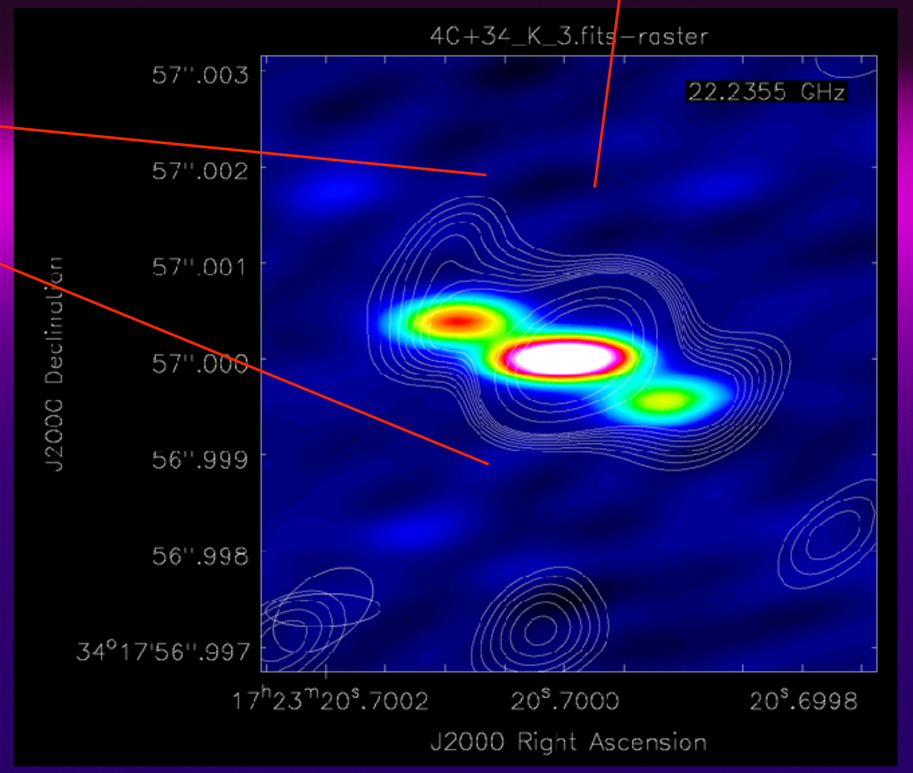


Reorientation of the new jet?



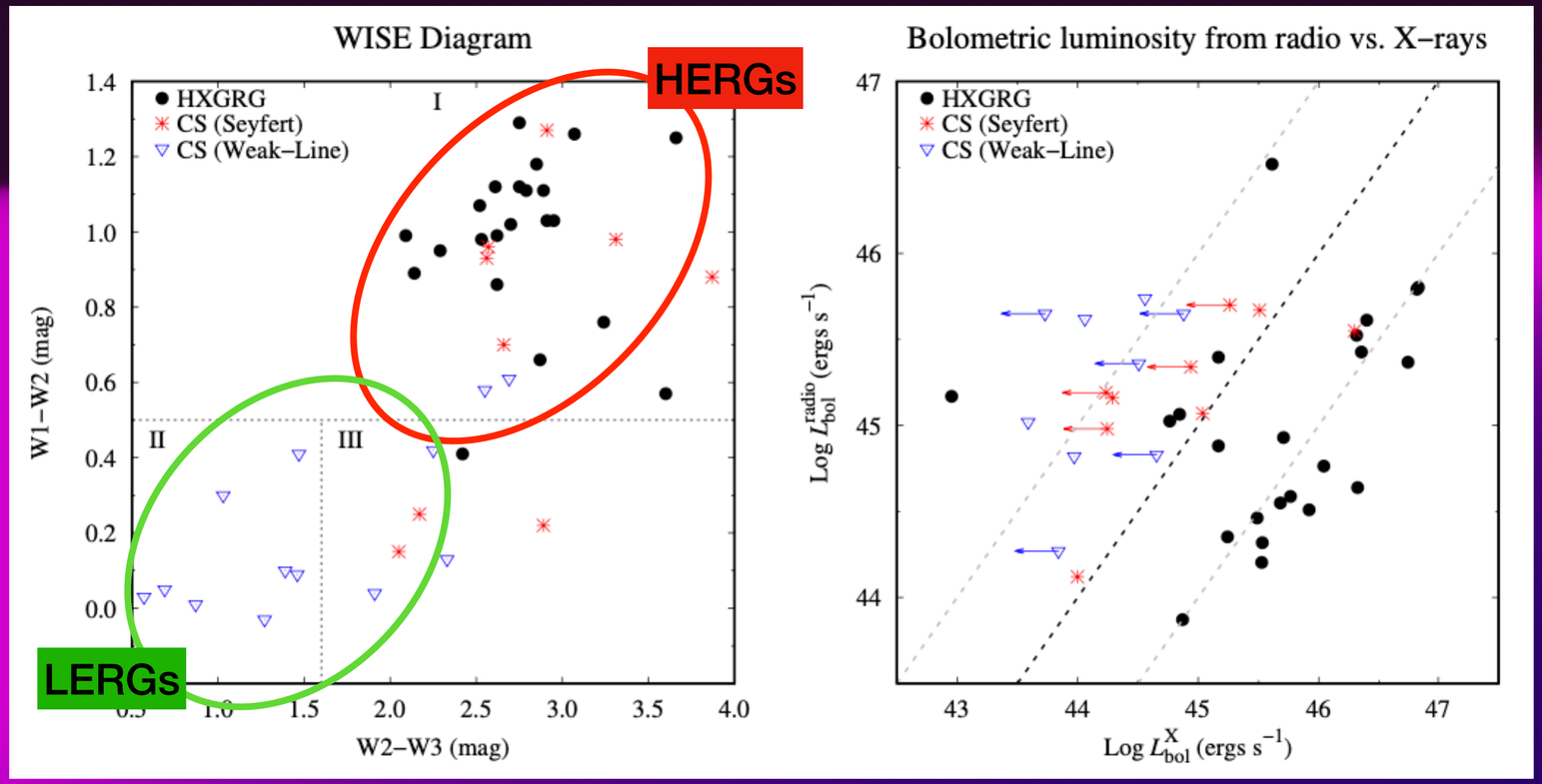
Bruni et al. in prep.

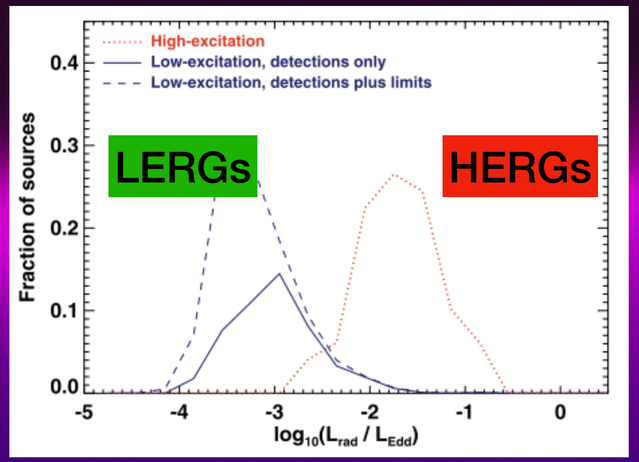




HERGs vs LERGs

- Comparison with Hard-X “quiet” GRG (LERGs) from Schoenmakers+2000
- Consistent fraction of restarted activity (from morphology+GPS/CSS)
- Different accretion modes does not seems to influence jet evolution or duty cycle





Best & Heckman 2012

Bruni et al. in prep.

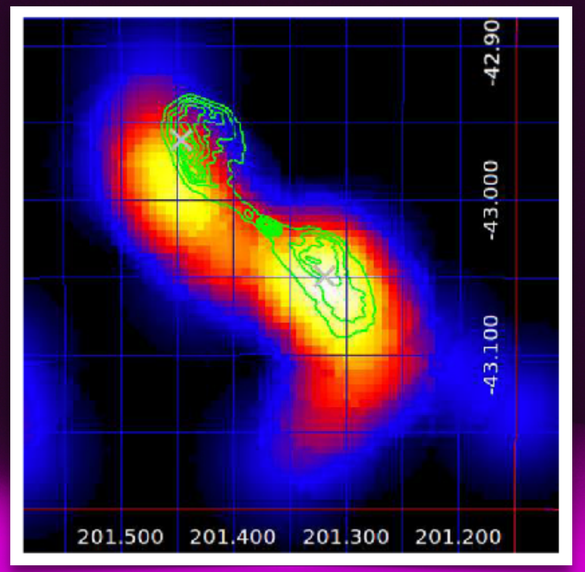
Preliminary

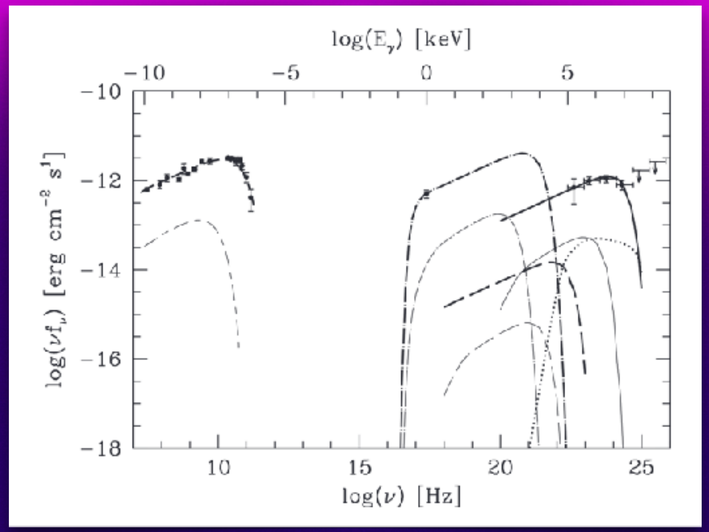
GeV Radio Galaxies

GeV emission from radio galaxies lobes

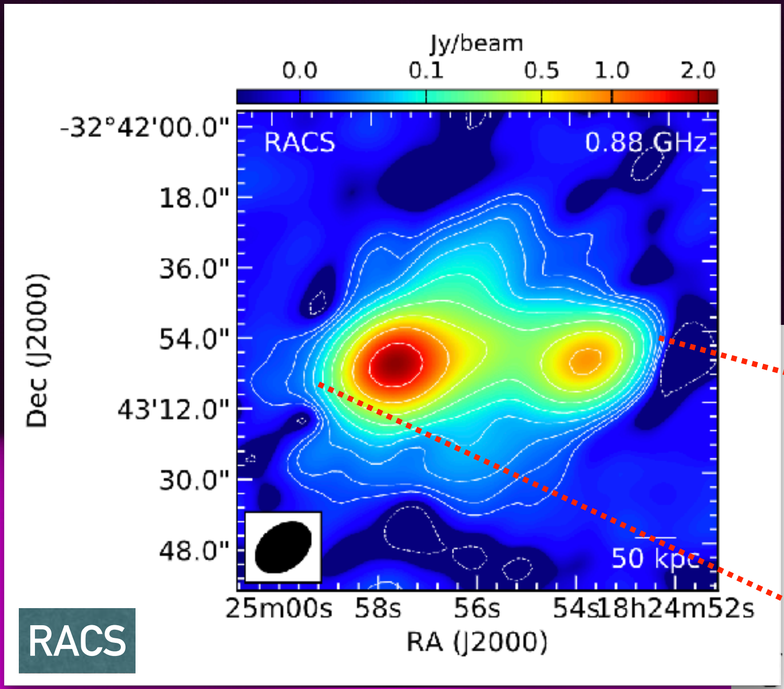
- Centaurus A and Fornax A are extended enough (several deg) to be resolved by Fermi/LAT, lobes were detected in gamma-rays
- First modelling of lobes emission considered p-p collisions and subsequent pionic decay as possible origin (McKinley+15, Ackermann+16), implying a very high proton energy density in the lobes
- A recent series of papers re-model lobes emission of several Fermi/LAT detected lobes, explaining that as IC off the ambient photon field (CMB+host galaxy starlight, Persic & Rephaeli 19a, 19b, 20)

...more radio galaxies could be present among unresolved Fermi/LAT gamma-ray sources...



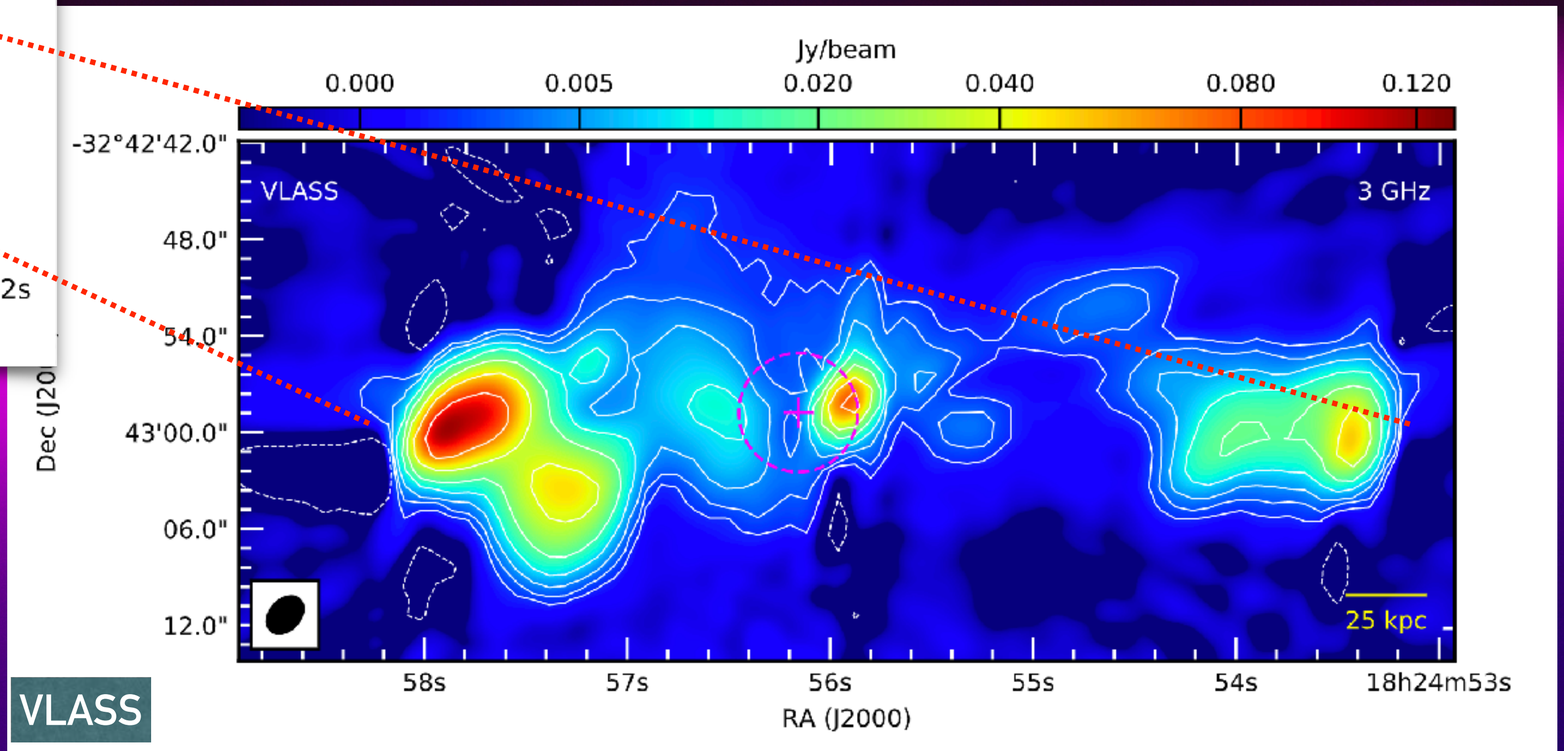


The case of IGR J18249-3243



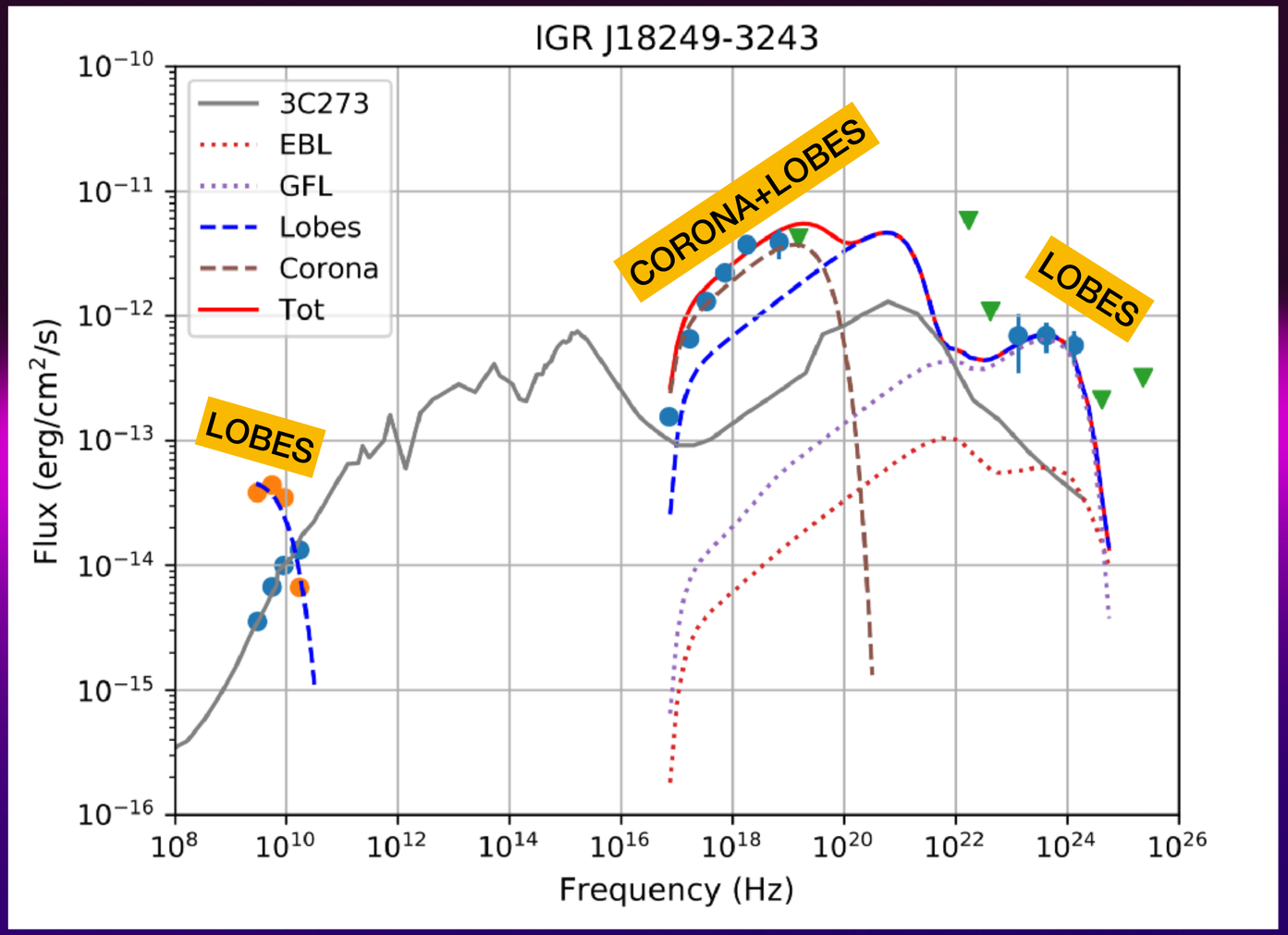
Bruni et al. 2022

- Recent discovery of an INTEGRAL radio galaxy detected at GeV energies by Fermi/LAT
- Morphology was resolved thanks to recent radio surveys

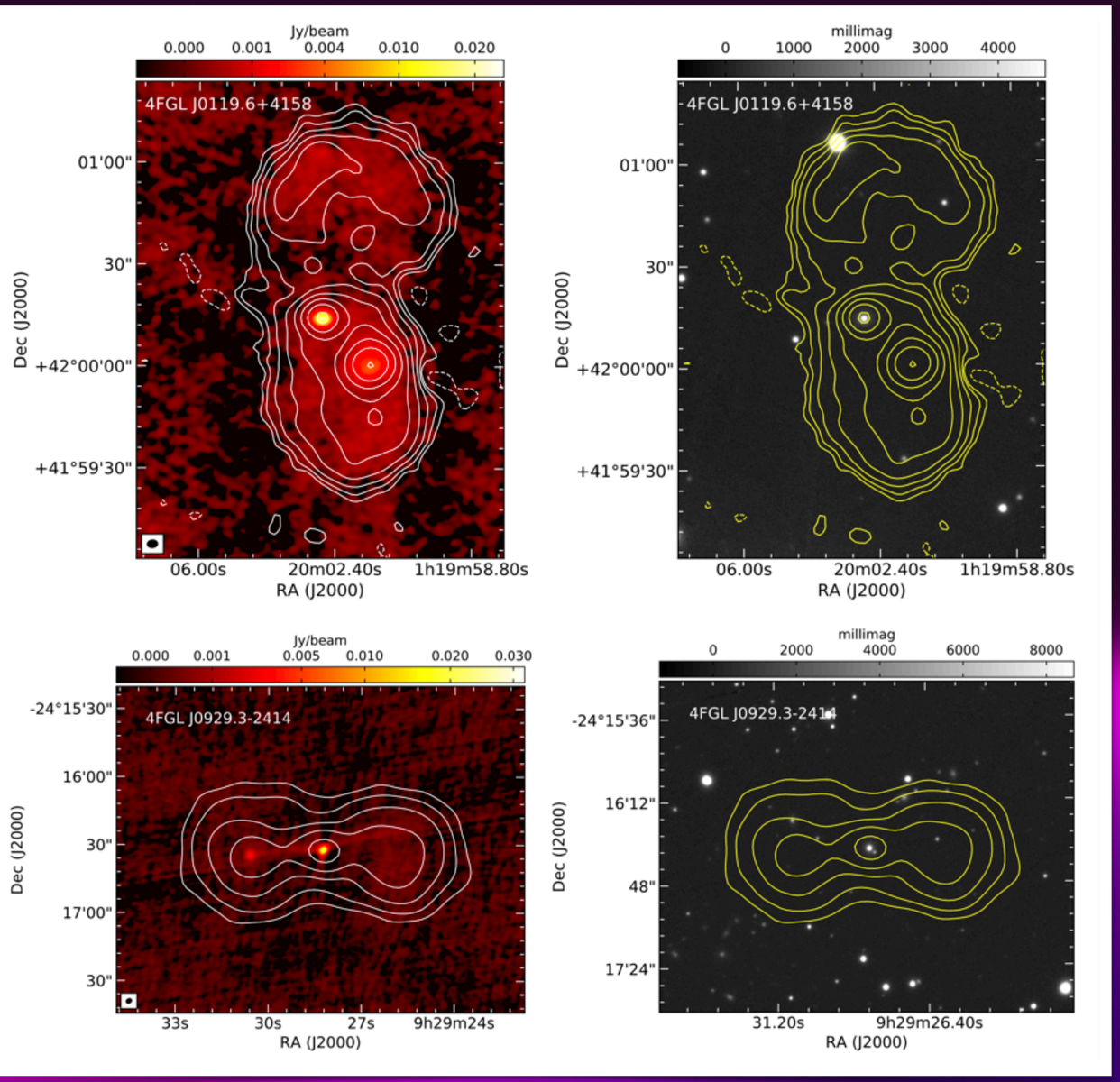


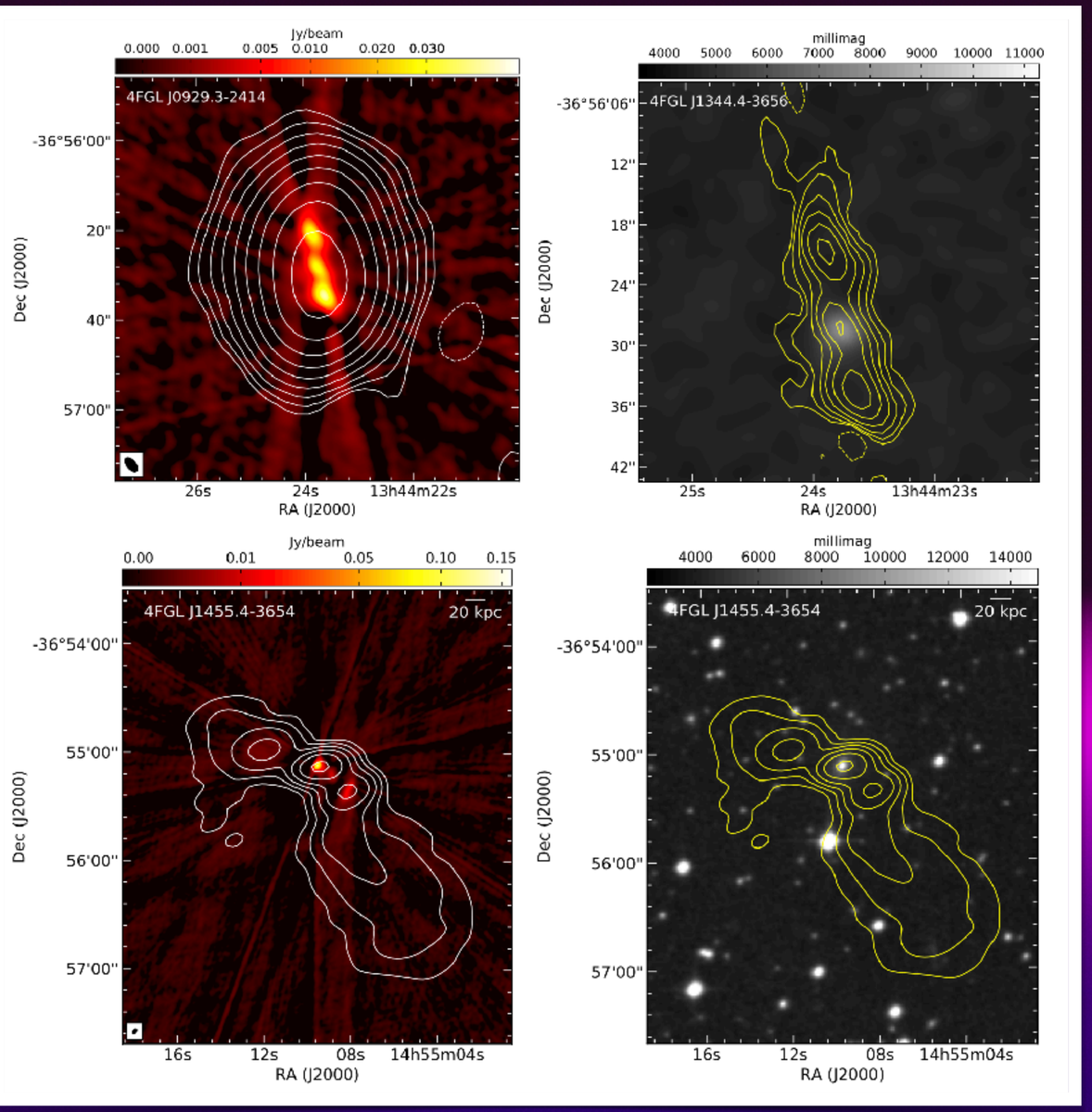
The case of IGR J18249-3243

- GeV emission from the core is 10 times larger than expected
- SED modelling suggests substantial lobes contribution via IC on ambient photon fields
- Further GeV RG will be identified thanks to SKA precursors



Bruni et al. 2022





Bruni et al. 2022

MeerKAT+ survey

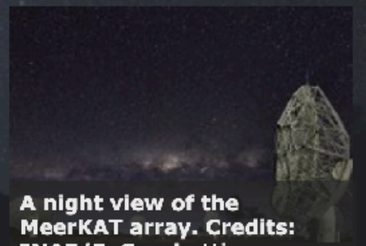
- More radio galaxy counterparts of high-energy sources from MeerKAT+ survey (SKA precursor, starting in 2024)
- Privileged access to data through INAF participation

You are here: Home › INAF News › INAF joins the MeerKAT+ Project

INAF joins the MeerKAT+ Project

The South African Radio Astronomy Observatory and the Max-Planck-Gesellschaft welcome the Italian Istituto Nazionale di Astrofisica as partner on the MeerKAT extension project

The National Research Foundation, through its national facility the South African Radio Astronomy Observatory (SARAO), and the Max Planck Gesellschaft (MPG) welcome the Istituto Nazionale di Astrofisica (INAF) as an additional partner on the MeerKAT extension project (MeerKAT+).



A night view of the MeerKAT array. Credits: INAF/E. Sacchetti

The MeerKAT+ extension founded by SARAO and MPG will increase both, sensitivity and spatial resolution of the existing MeerKAT telescope array and thus provide a powerful instrument to study the formation and evolution of galaxies throughout the history of the universe.

"INAF and the Italian community are eager to contribute to the MeerKAT+ scientific program and to participate in the technological advance related to its development" says the INAF President, **Marco Tavani**. "MeerKAT+ is an important step towards the SKA Telescope that will open great "unexplored windows" of our Universe".

MeerKAT+ will see **20 new dishes** being added to the existing array of **64 dishes**, a joint project initiated and funded by SARAO and the MPG.

INAF will support MeerKAT+ with an additional financial investment of €6-million. As a result, MeerKAT+ will not only see improved scientific capability, but will also benefit through the scientific participation of INAF.

Neutrinos from Radio Galaxies ?

3C403 A wobbling jet with neutrino association

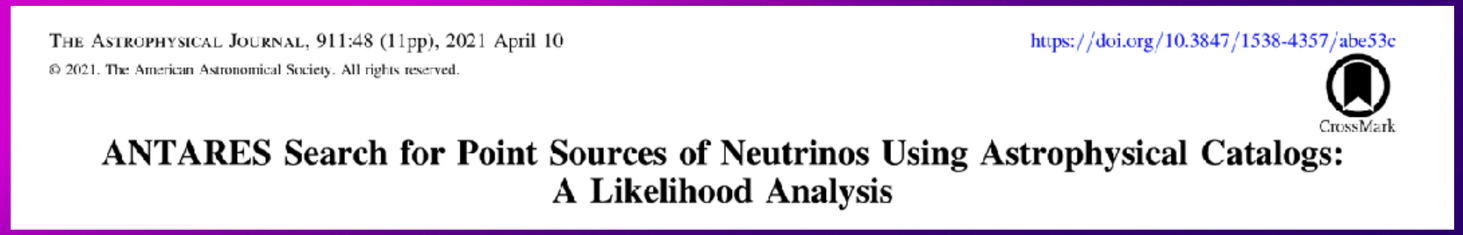
- Recent ANTARES work on data collected from 2007 to 2017
- Cross correlation analysis show a possible association with an INTEGRAL source: 3C403
- 3C403 is one of the hard X-ray selected radio galaxy from the sample of Bassani et. al. 2016

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **461,** 3165–3171 (2016) doi:10.1093/mnras/stw1468
Advance Access publication 2016 June 20

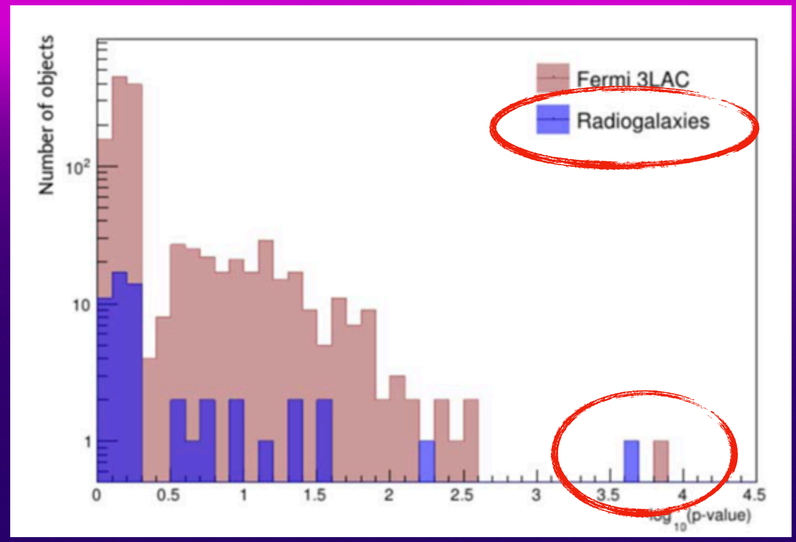
Soft γ-ray selected radio galaxies: favouring giant size discovery

L. Bassani,[1★] T. Venturi,[2] M. Molina,[1] A. Malizia,[1★] D. Dallacasa,[2,3] F. Panessa,[4] A. Bazzano[4] and P. Ubertini[4]



The Astrophysical Journal, 911:48 (11pp), 2021 April 10 https://doi.org/10.3847/1538-4357/abe53c

ANTARES Search for Point Sources of Neutrinos Using Astrophysical Catalogs: A Likelihood Analysis



Albert et al. 2021

3C403 A wobbling jet with neutrino association

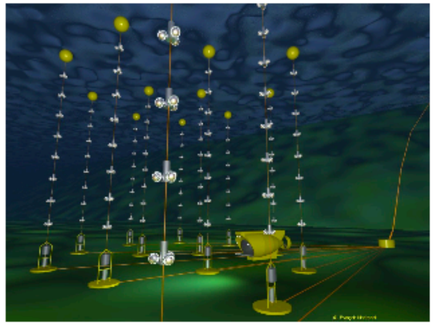
ANTARES Telescope and Data Set

ANTARES telescope:

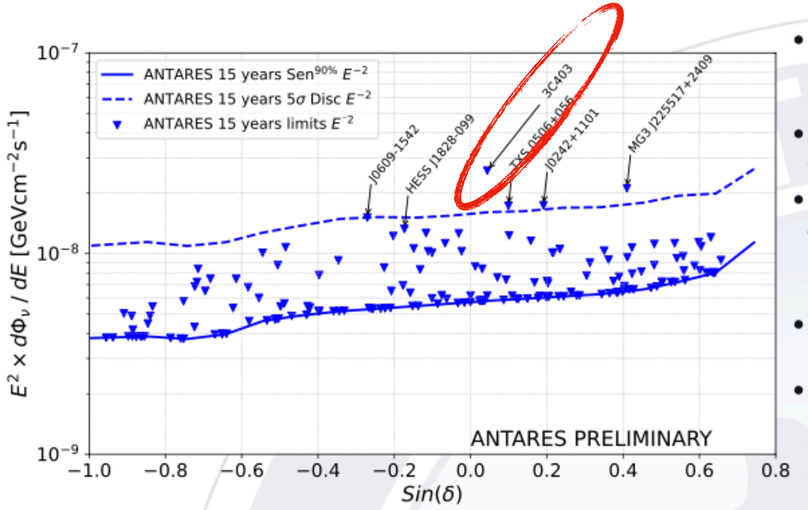
- Three-dimensional array of **885 photomultiplier tubes**.
- 2500 m below the surface of the **Mediterranean Sea**.
- Completed in 2008, decommissioned in 2022.

Data set:

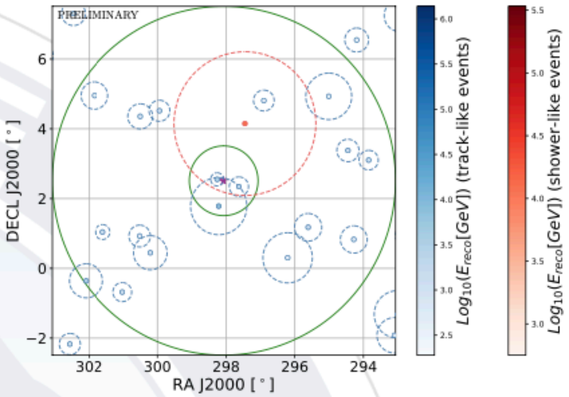
- **Complete coverage:** from January 29, 2007 to February 13, 2022 (4541 days of lifetime).
- **11029 track** and **239 shower** good-quality events.
- Tracks: **$\sim$0.4° median angular resolution**.
- Showers: **$\sim$3° median angular resolution**.



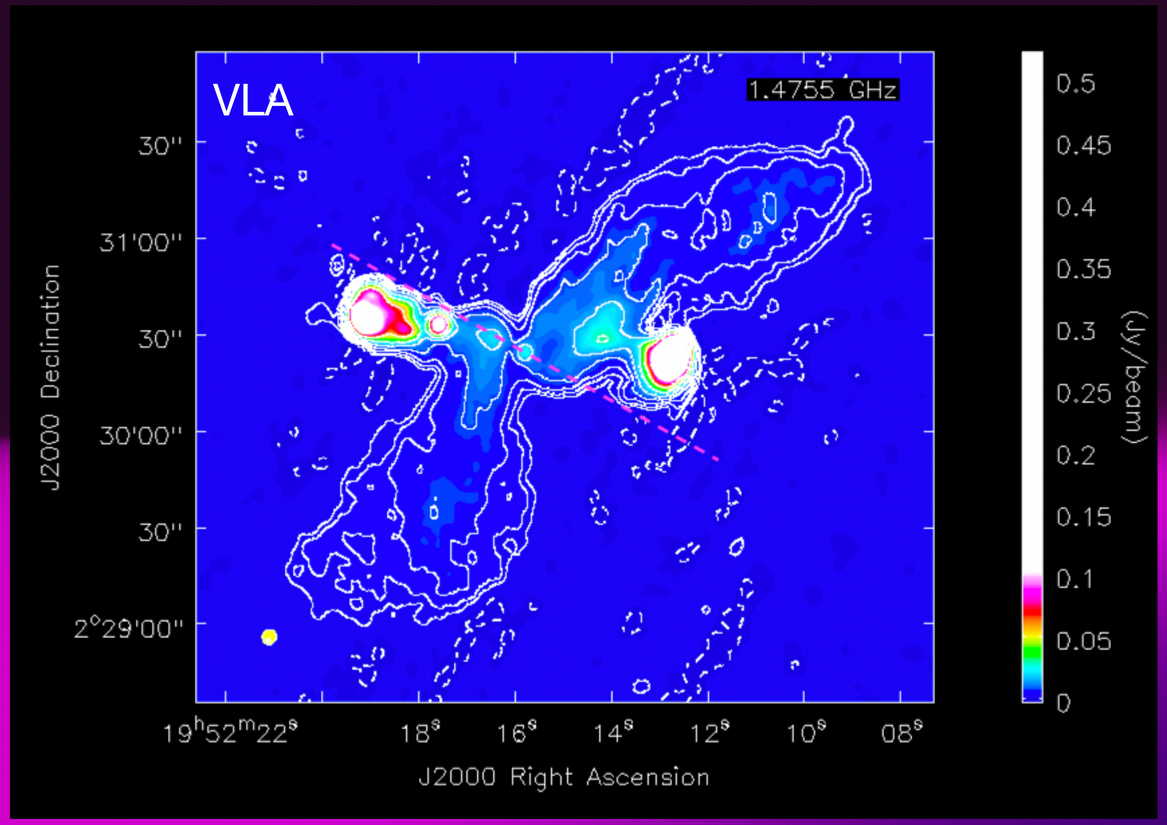
Candidate-List Search

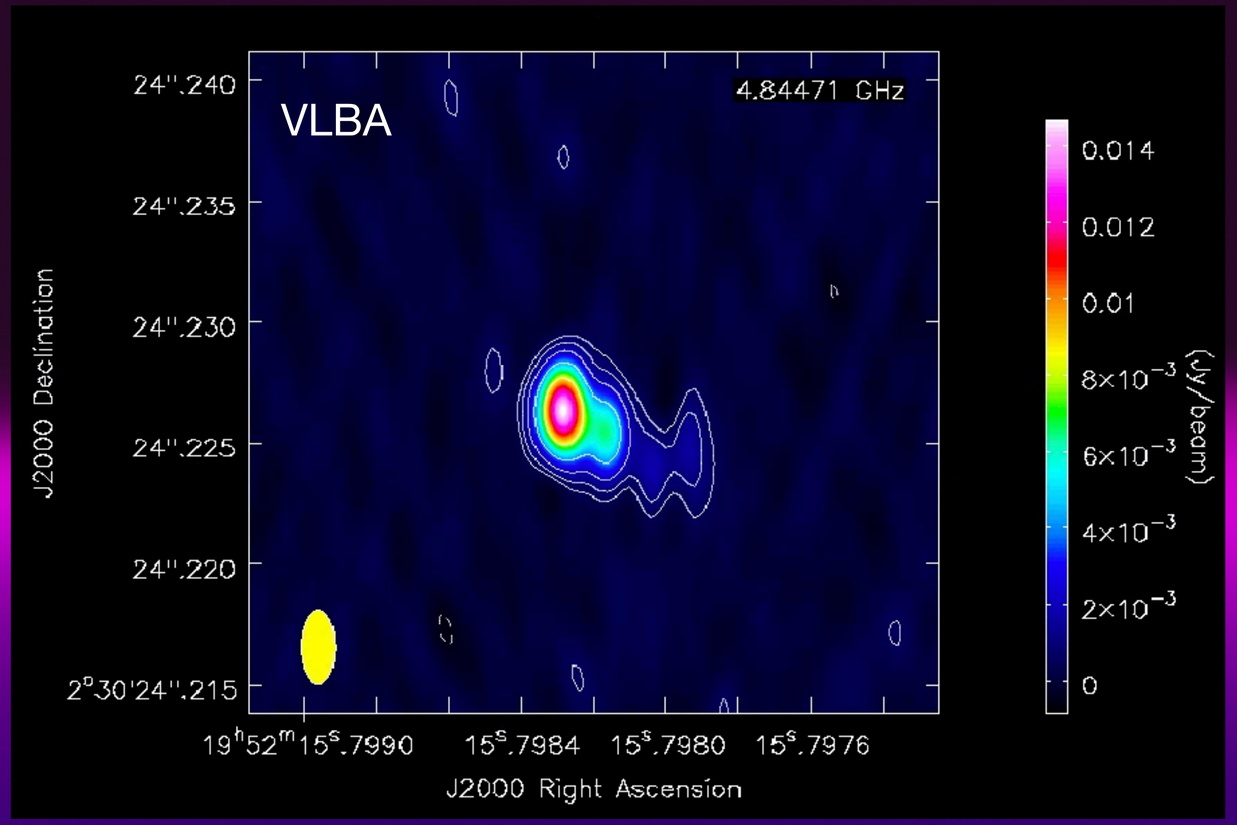


- **167 sources investigated**. No significant evidence of cosmic neutrino sources found (list available at contribution proceeding).
- **Highest significant source: AGN 3C403**, 4.1σ pre-trial (2.7σ post-trial) significance.
- **Other significant sources: MG3 J225517+2409** (2.9σ),**TXS 0506+056** (2.6σ), **J0242+1101** (2.6σ), **J0609-1542** (2.5σ) and **HESS J1828-099** (2σ).
- **Left: 90% C.L. limits** on the one-flavour neutrino flux normalization.
- **Right: Skymap** of the events found around the direction of the most promising source. Color indicates the energy and dashed ellipses the angular uncertainty. Green ellipses show the 1o and 5o distances to the source.



3C403 A wobbling jet with neutrino association





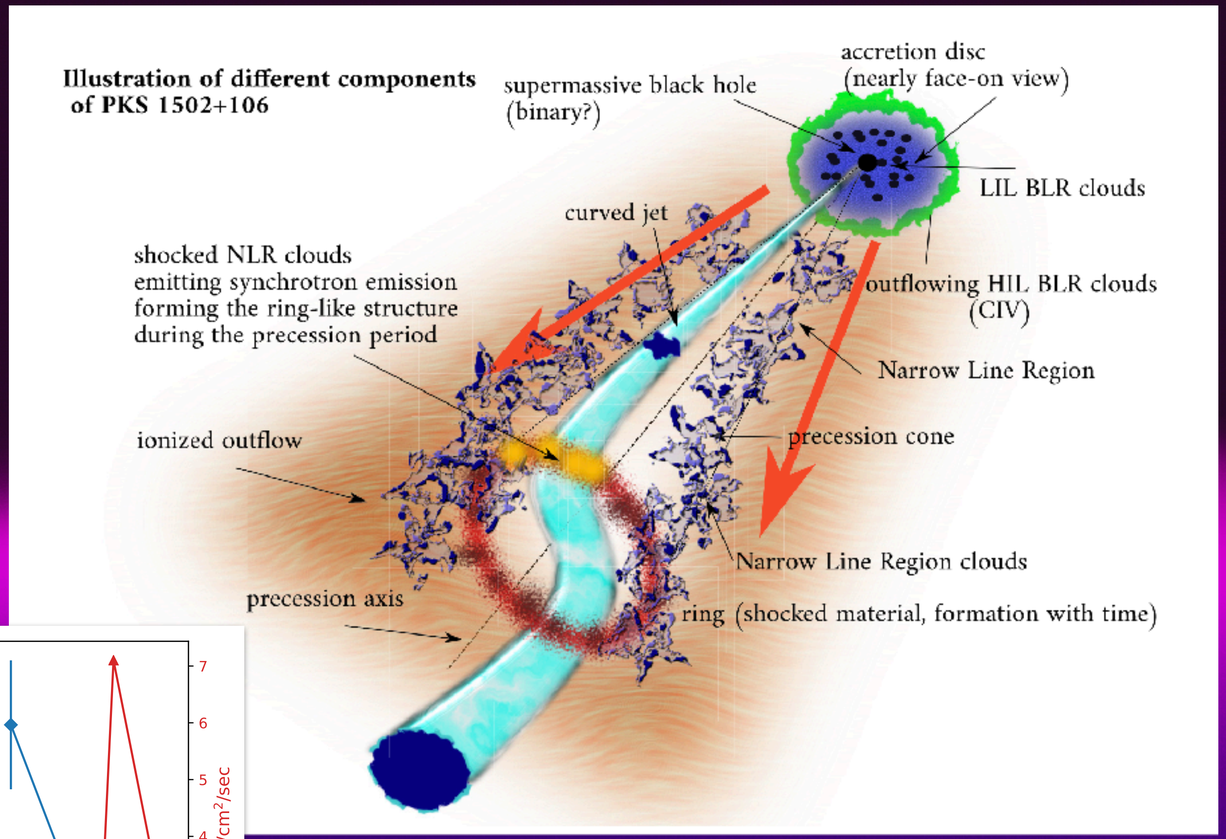
- 1.49 GHz, B-conf., June 1994
- beam=4.6x4.2 arcsec
- RMS=6 mJy

- 4.8 GHz, Feb 2009
- beam=3x1 milli-arcsec
- RMS=0.16 mJy

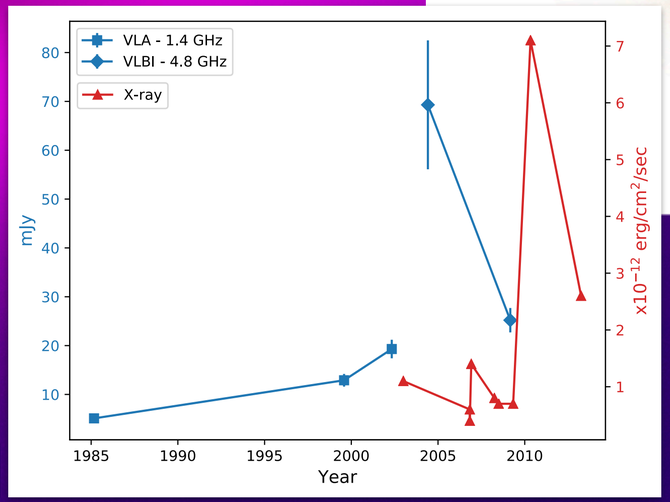
Bruni et al. In prep.

3C403 A wobbling jet with neutrino association

- Precessing jets are possible neutrino emitters, as proposed for the IceCube candidate PKS 1502+106
- The strong radio and X-ray variability found for 3C403 seems to favour the precessing jet scenario
- More radio data obtained (e-MERLIN) to zoom into the central region…
- …more news in the next months



Britzen et al. 2021



Bruni et al. In prep.

GRACE project: next steps

- Comparison of HERG vs LERG: how accretion mode influence jet duty cycle?
- Synchrotron aging of a pilot sample of 3 Hard X-rays GRG to date the different radio phases
- VLBI (pc-scale) investigation of recently restarted jets
- Archives mining to study possible X-ray flickering of the core, and correlated jet activity

Side quests

- Search for GeV radio galaxies with ongoing and future deep radio surveys (MeerKAT+, RACS, VLASS, looking forward to SKA and ngVLA)
- Improving our understanding of neutrino-emitting processes in misaligned AGN