Multifrequency studies of S-shaped Radio Galaxies

JAGIELLONIAN UNIVERSITY IN KRAKÓW

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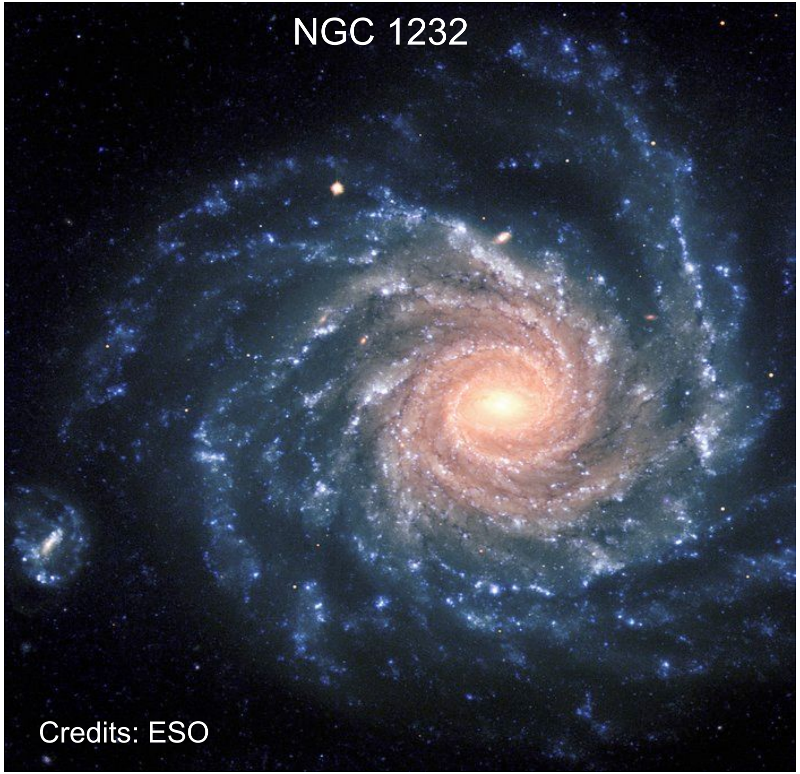
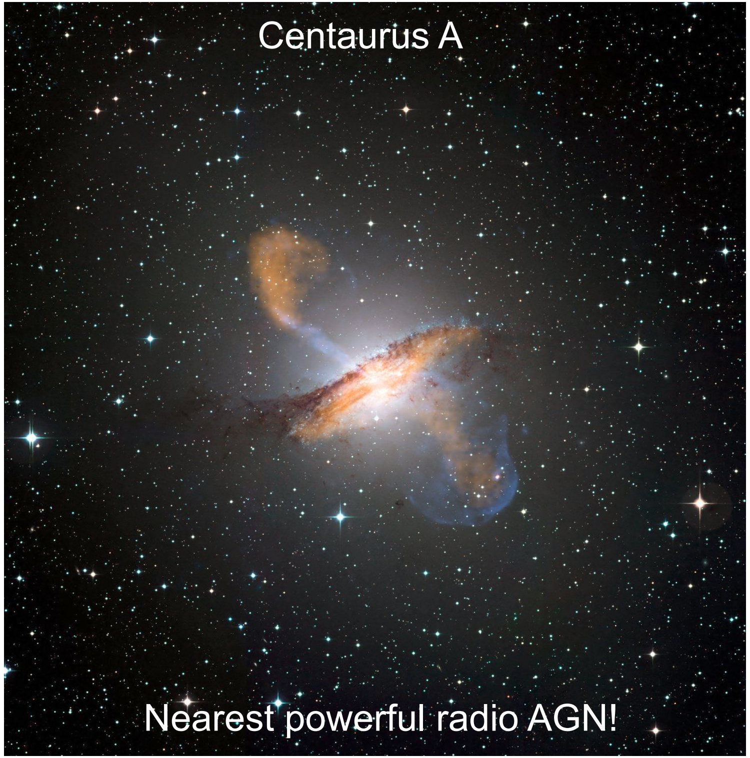
Outline

- Introduction
- Motivation
- Formation of S-shaped sources
- CGCG 292-057: X-shaped radio galaxy
- PKS 2300-18: S-shaped radio galaxy
- Atlas of S-shaped sources observed with uGMRT
- Final conclusion

Active Galactic Nucleus (AGN)

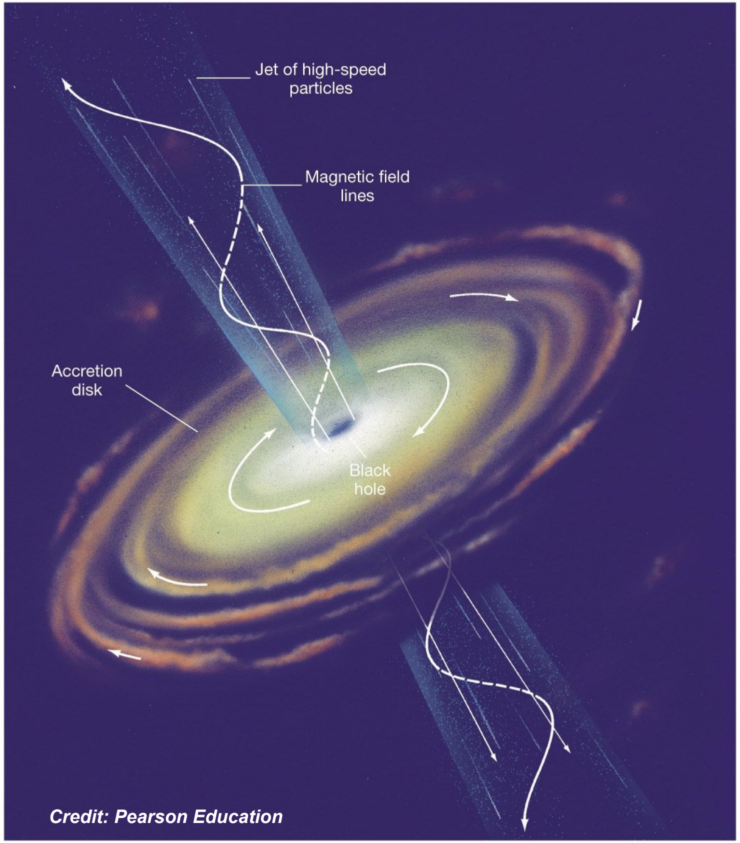


Credits: ESO

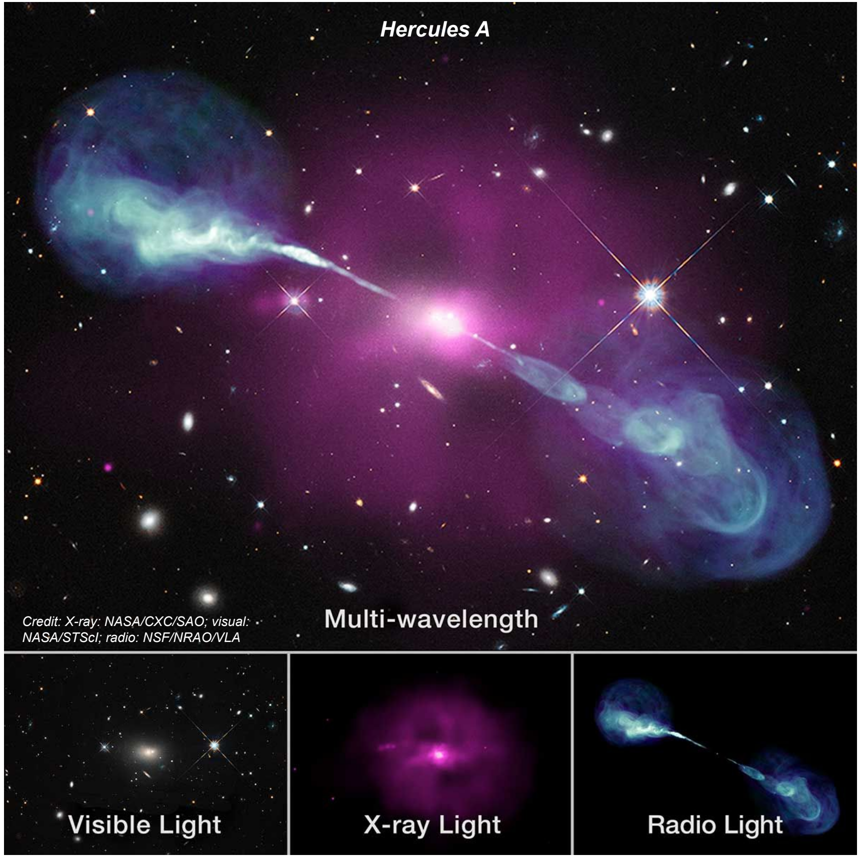


Nearest powerful radio AGN!

Active Galactic Nucleus

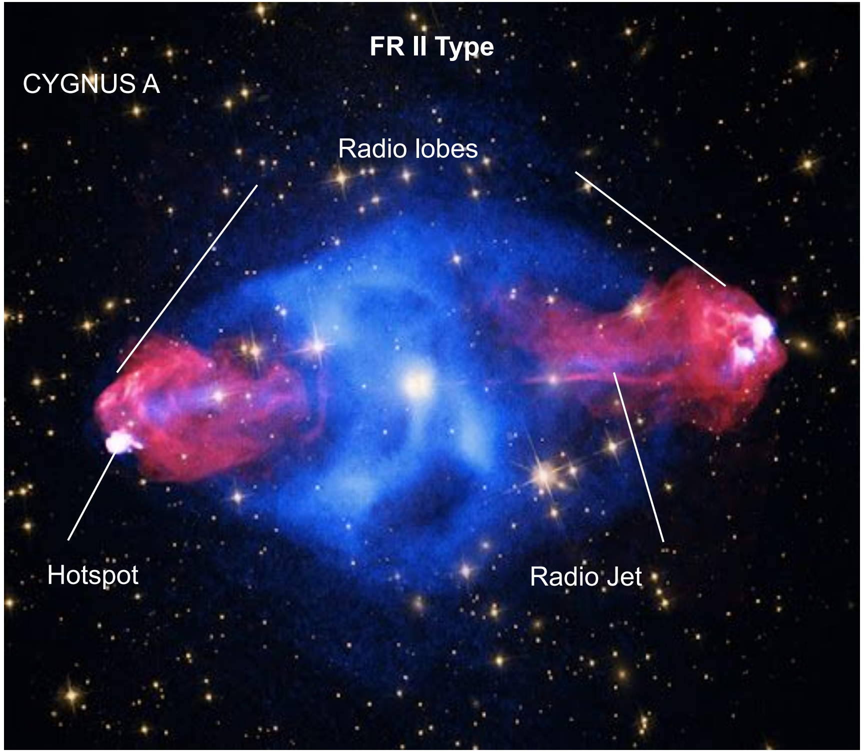


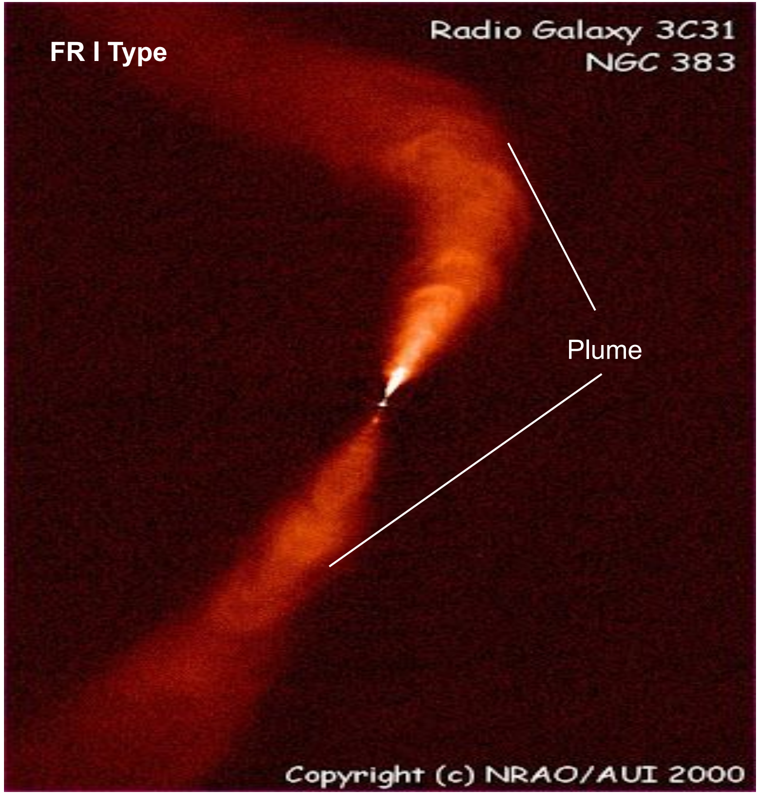
Credit: Pearson Education



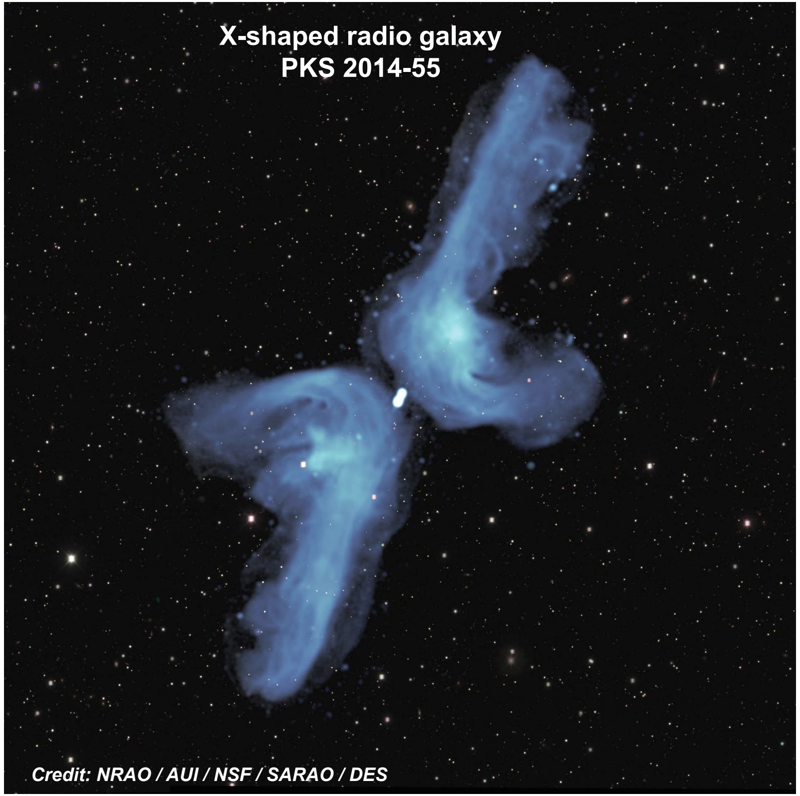
Credit: X-ray: NASA/CXC/SAO; visual: NASA/STScI; radio: NSF/NRAO/VLA

Radio Galaxies



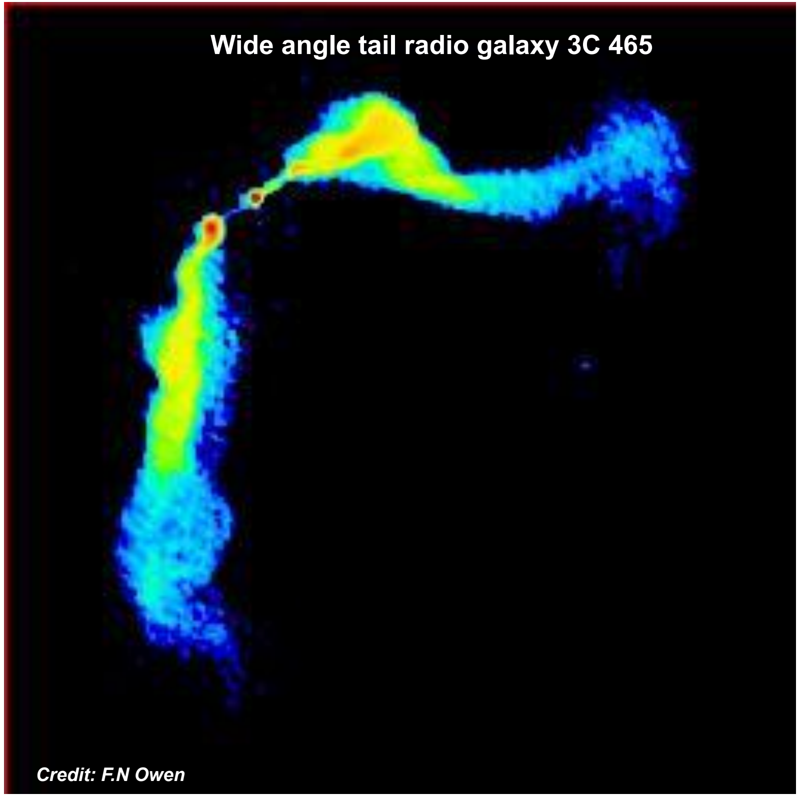


Radio Galaxy Morphologies



X-shaped radio galaxy
PKS 2014-55

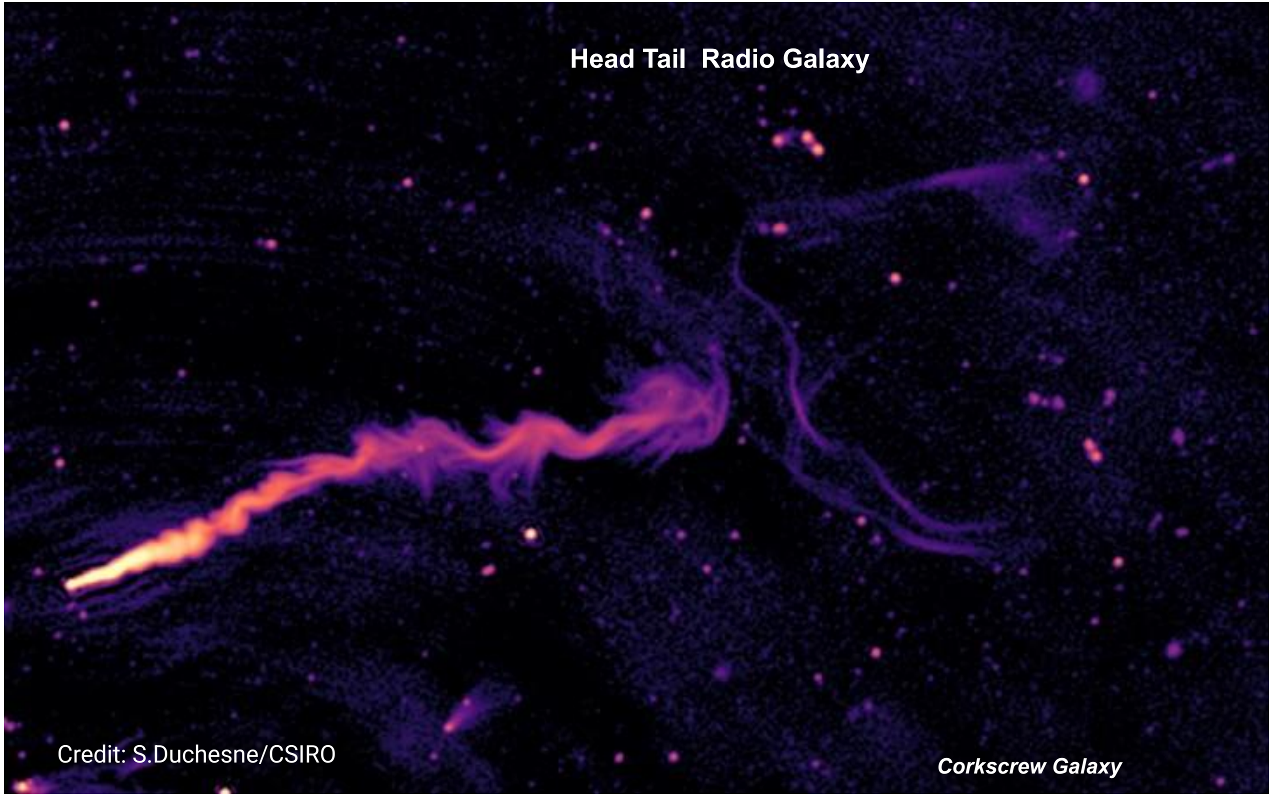
Credit: NRAO / AUI / NSF / SARAO / DES



Wide angle tail radio galaxy 3C 465

Credit: F.N Owen

Radio Galaxy Morphologies



Credit: S.Duchesne/CSIRO

Double Double Radio Galaxy 3C 293

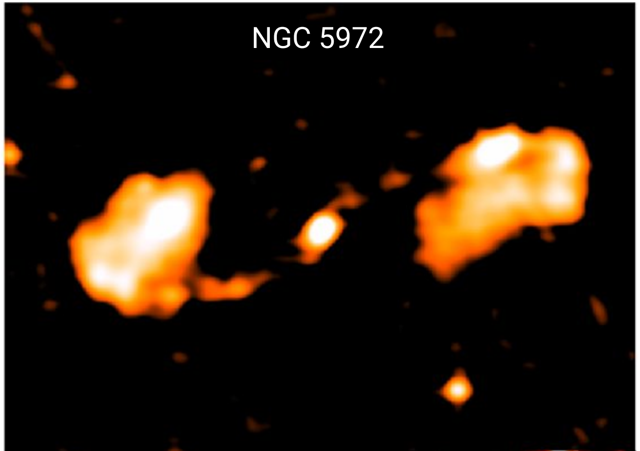
S-shaped Radio Galaxies

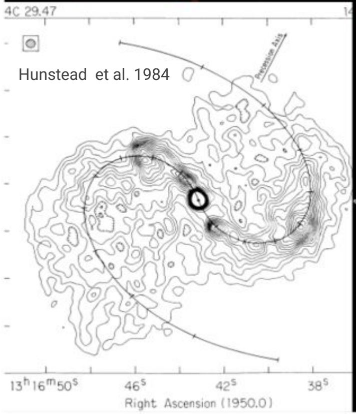
Classified by

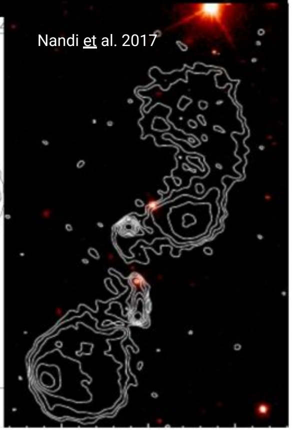
- Inversion symmetric morphology.
- Curved and S-shaped jets.

Motivation

- Quite rare sources among winged radio galaxies.
- Excellent to study precession of distant supermassive black holes
- Key to study galaxy evolution via mergers and nuclear activity.

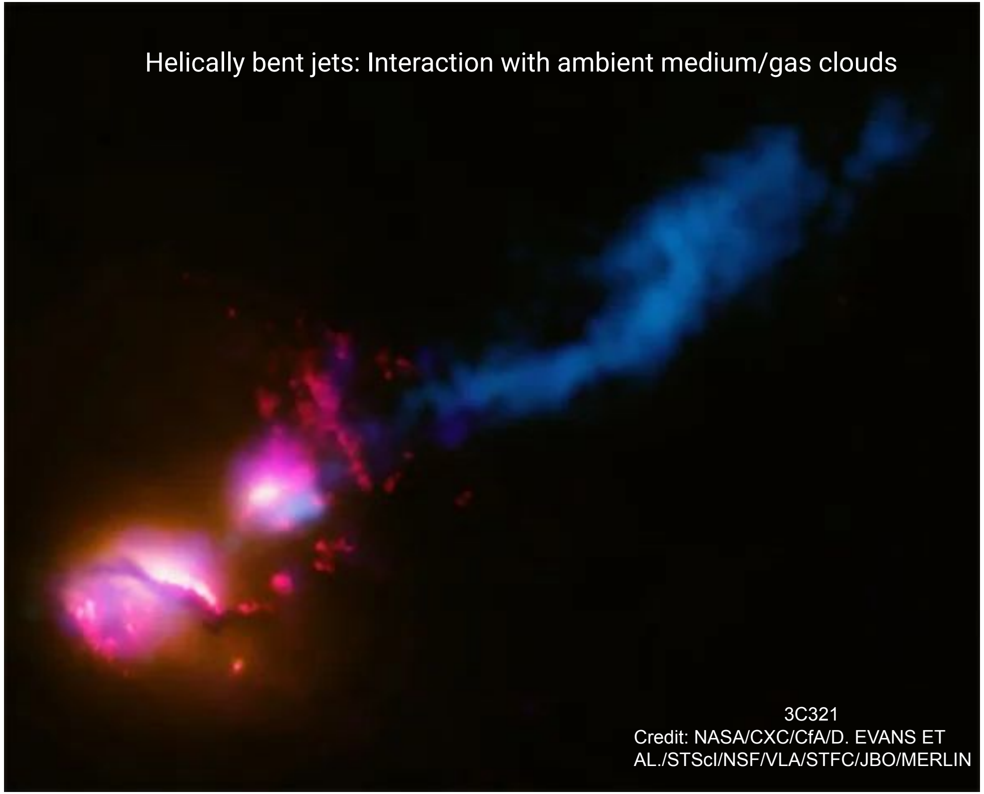



Hunstead et al. 1984


Nandi et al. 2017

How S-shaped and bent sources can be formed


Ballistic helical jet: Precessing jets


Helically bent jets: Interaction with ambient medium/gas clouds

3C321
Credit: NASA/CXC/CfA/D. EVANS ET AL./STScI/NSF/VLA/STFC/JBO/MERLIN

How S-shaped and bent sources can be formed

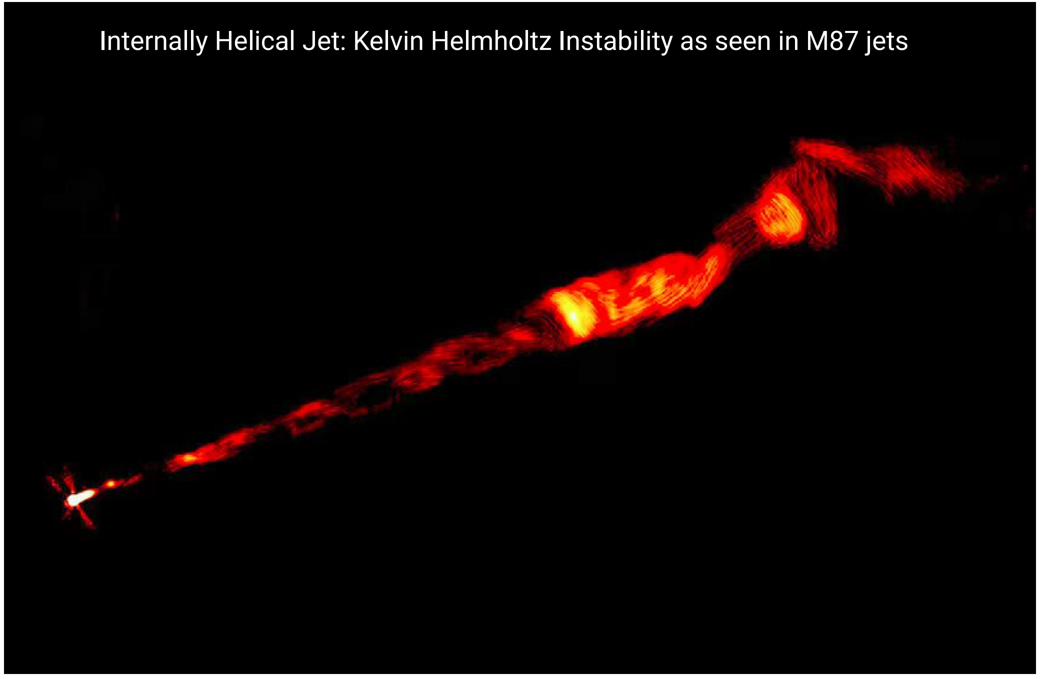
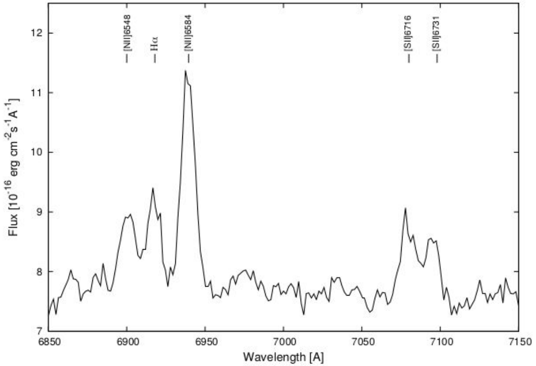

Internally Helical Jet: Kelvin Helmholtz Instability as seen in M87 jets

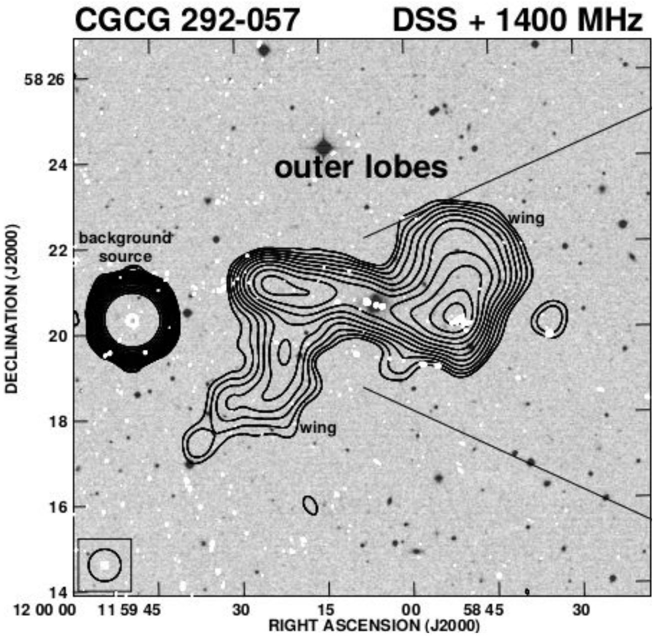
Photo: Pasetto et al., Sophia Dagnello, NRAO/AUI/NSF

Multifrequency analysis of the radio emission from a post-merger galaxy CGCG 292-057

Optical Observations of CGCG 292-057

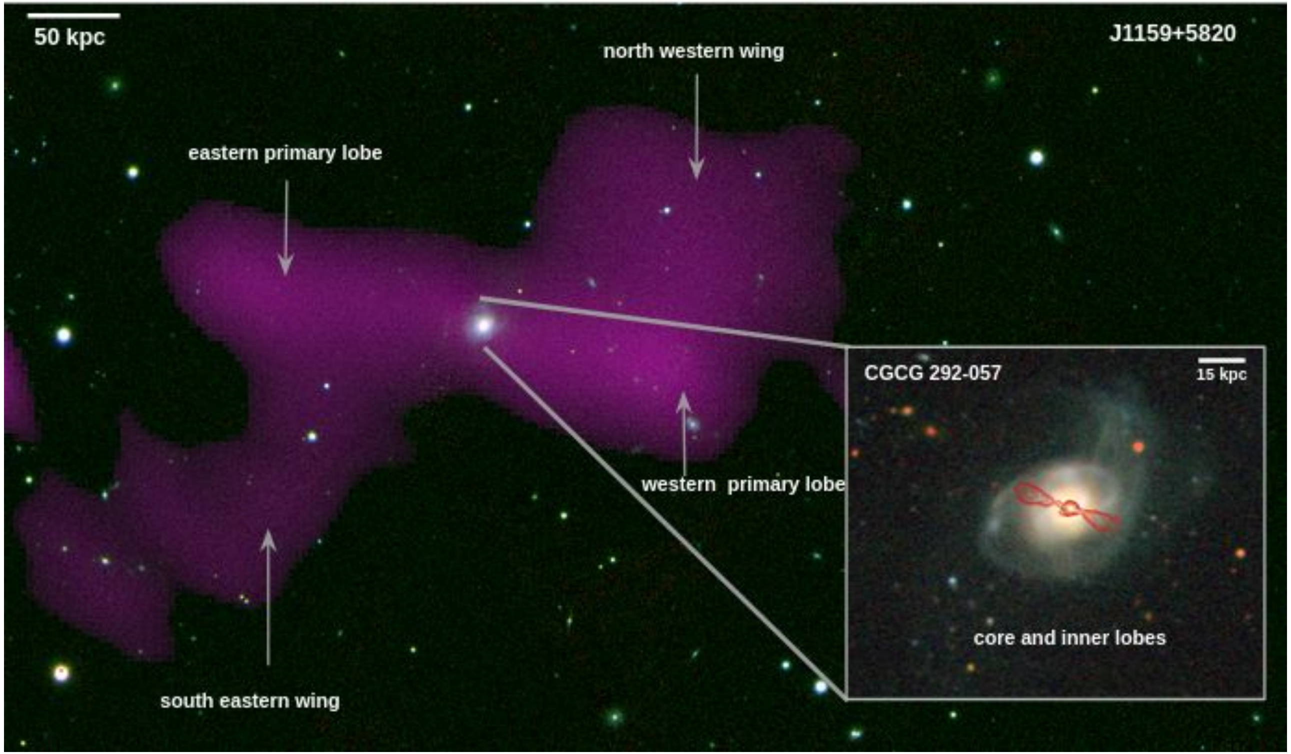
- Redshift - 0.0537
- Optical morphology (elliptical and spiral)
- Post-merger system
- Unusual radio morphology
- Double peaked emission lines
- Low-excitation radio galaxy





Kozieł-Wierzbowska et.al (2012)

Radio Morphology

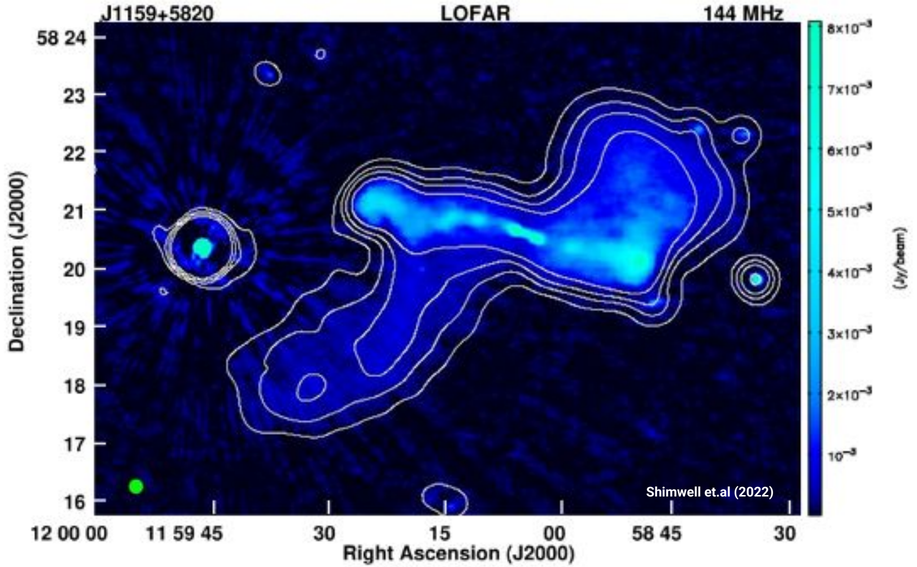


Extended radio emission- GMRT 150 MHz

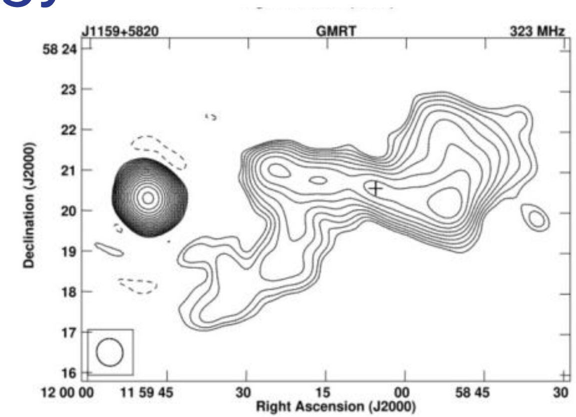
Core+inner lobes - VLA 5 GHz

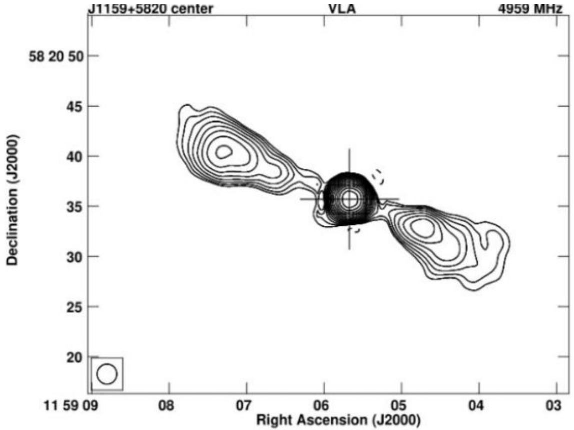
Misra et.al (2023), MNRAS

Radio Morphology



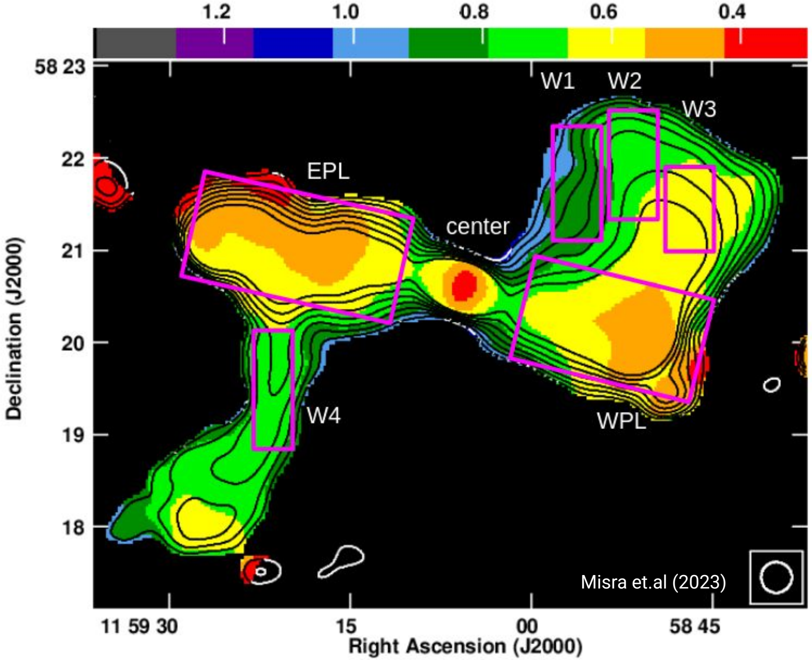
LOFAR DR2 - High resolution map (6”) +low resolution contours (20”)





Spectral Index Analysis

- Particle lose energy via **synchrotron** and **inverse-Compton losses**.
- Spectral index map provides information about activity of the source.
- The primary lobes and the core show **flatter spectra** than the wings.
- The core also shows inverted spectrum.
- The **gradient** in the SI in the north western wing ca hint at the **direction of plasma flow (clockwise)**.
- The wings are separated into 4 regions W1, W2,W3,W4 based on same/similar SI value to perform ageing analysis.



Misra et.al (2023)

SI map between LOFAR 144 MHz and VLA 5 GHz

Particle Injection Models

- Synchrotron power depends on particle energy

$P_{\mathrm{syn}} \propto \gamma^2 \mathrm{B}^2$ (energetic particles age faster)

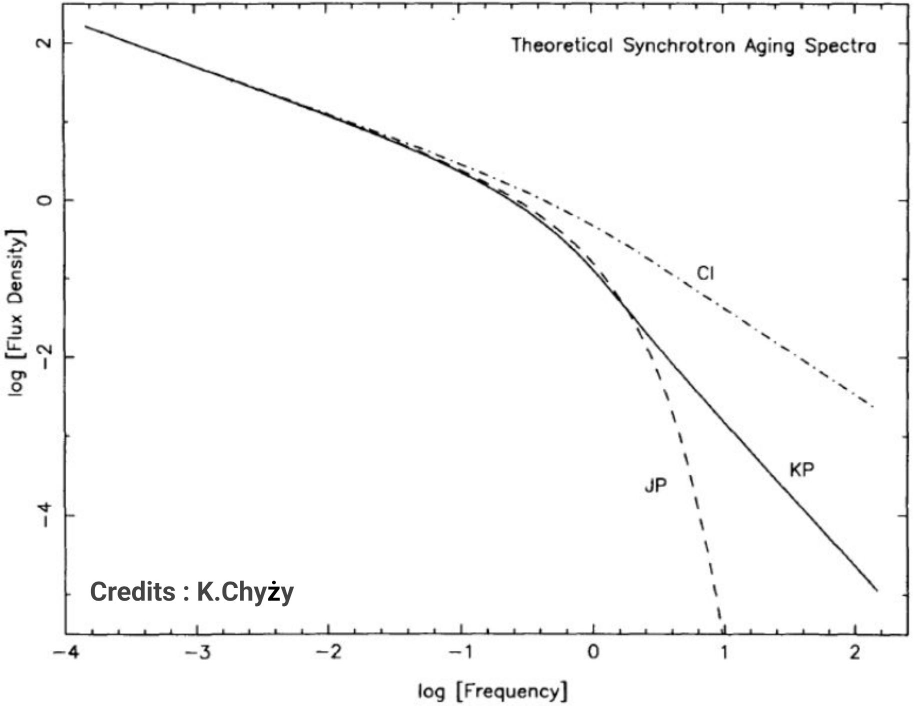
- Initial assumed radio spectrum follows power law

$$N(\gamma)\mathrm{d}\gamma \propto \gamma^{-\delta}\mathrm{d}\gamma \Rightarrow P_{\mathrm{syn}}(\nu) \propto \nu^{-\alpha}$$

Deviation occurs from power law due to ageing of particles, leads to break in the power law spectrum.

This break can be calculated using the following models:

- Continuous Injection model (CI) - continuous injection of relativistic electrons
- Kardashev-Pacholczyk model (KP) - single injection with pitch angles preserved
- Jaffe-Perola model (JP) - single injection with continuous scattering of pitch angles (isotropization)

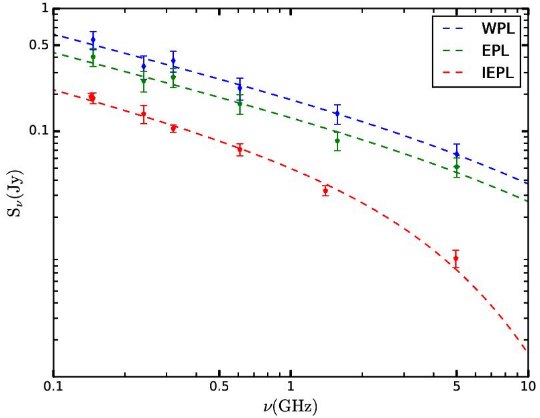


Credits : K.Chyży

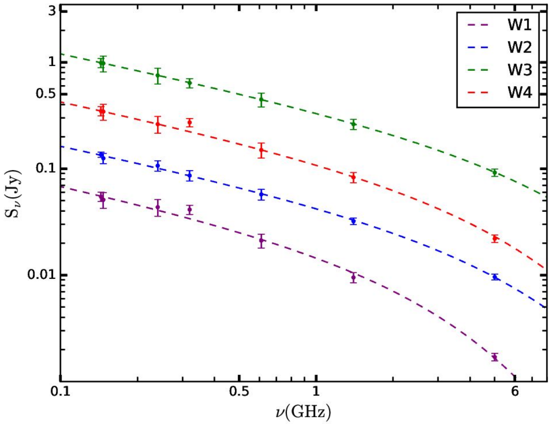
Particle Injection Models

- Models use initial power law distribution to compute time evolution of the energy losses in particles.
- Primary lobes and wings were fitted with **JP** and **CI** models for calculating radiative losses.
- Best fit for **primary lobes** was **CI model** and for the regions of the **wings** was **JP model**.

Radio spectra of primary lobes



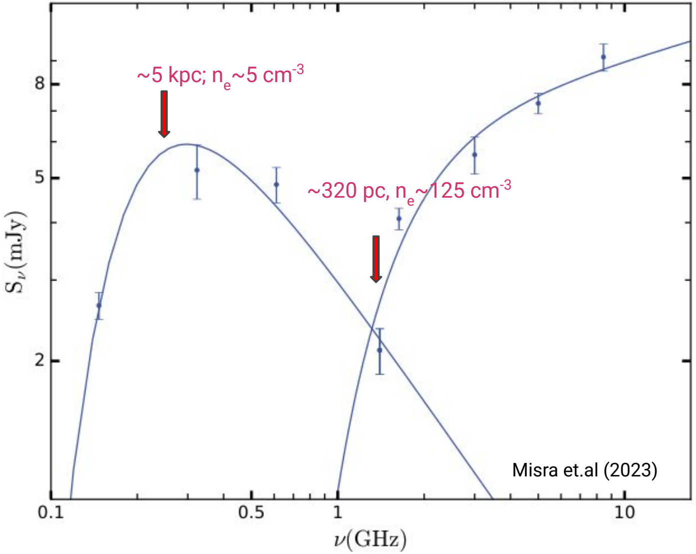
Radio spectra of wing regions



Radio Core

Free Free Absorption model for core

Attenuation of radiation → External homogeneous ionized screen around synchrotron emitting plasma



~5 kpc; n_e~5 cm^{-3}

~320 pc, n_e~125 cm^{-3}

Misra et.al (2023)

Radio spectra of the core with the double homogeneous FFA model

Absorbing medium is given by :

$$S_\nu = a\nu^{-\alpha} \mathrm{e}^{-\tau_\nu}$$

Turnover frequency and the projected linear size are related by :

$$\log(\nu_t) = -0.21(\pm 0.05) - 0.65(\pm 0.05)\log(l)$$

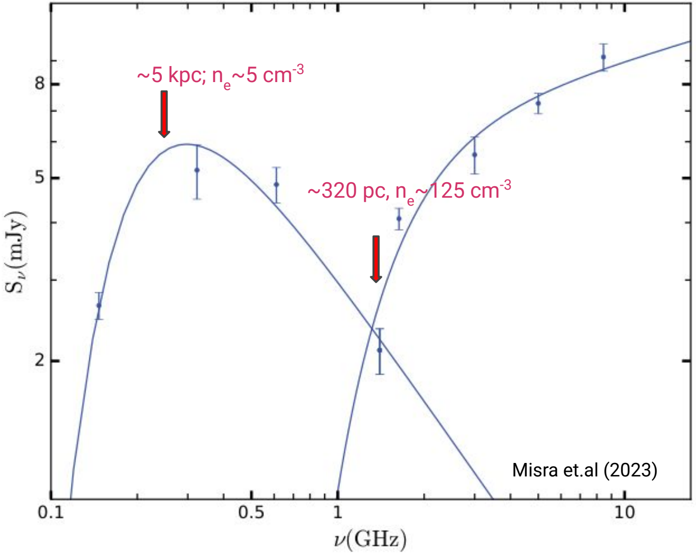
The electron density in these regions was calculated using the emission measure for FFA :

$$(n_\mathrm{e})^2 l \simeq 3.05 \times 10^6 \tau \left(\frac{T}{10^4\mathrm{K}}\right)^{1.35} \left(\frac{\nu}{1\mathrm{GHz}}\right)^{2.1} \mathrm{cm}^{-6}\mathrm{pc}$$

Radio Core and Inner lobes

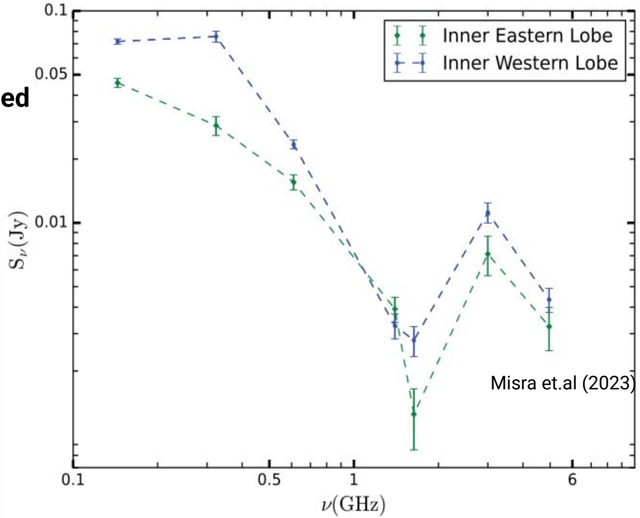
FFA model for core

Attenuation of radiation → External homogeneous ionized screen around synchrotron emitting plasma



Misra et.al (2023)

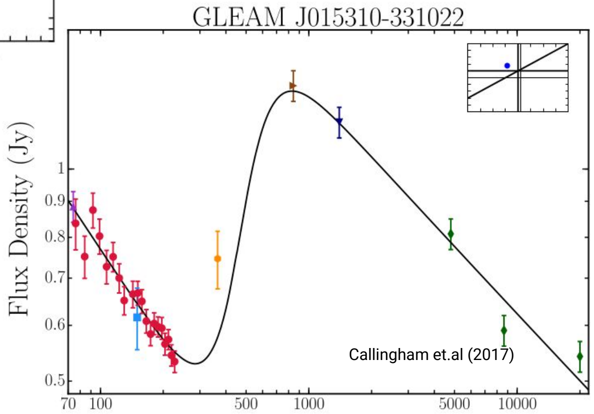
Radio spectra of the core with the double homogeneous FFA model



Misra et.al (2023)

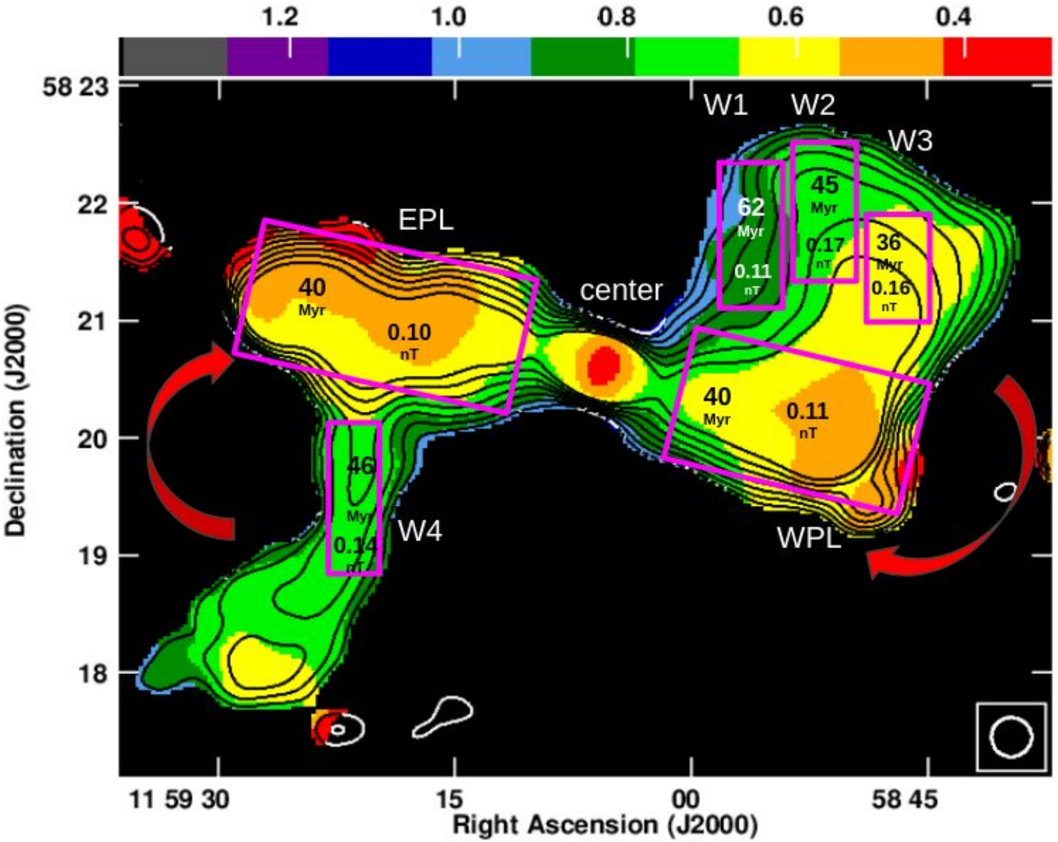
Radio spectra of inner lobes

No good particle injection model fit for inner lobes



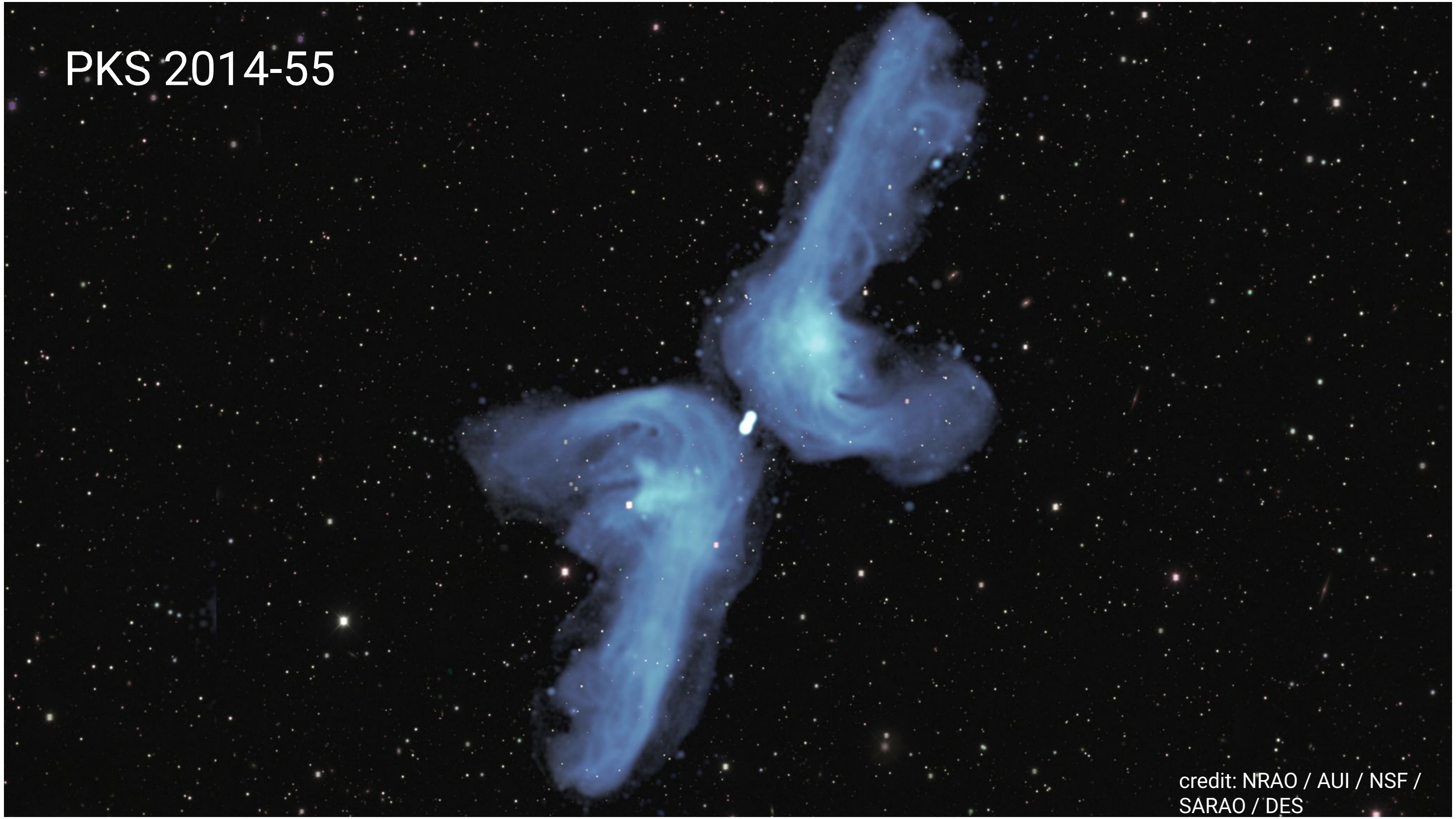
Callingham et.al (2017)

Spectral Ageing Analysis



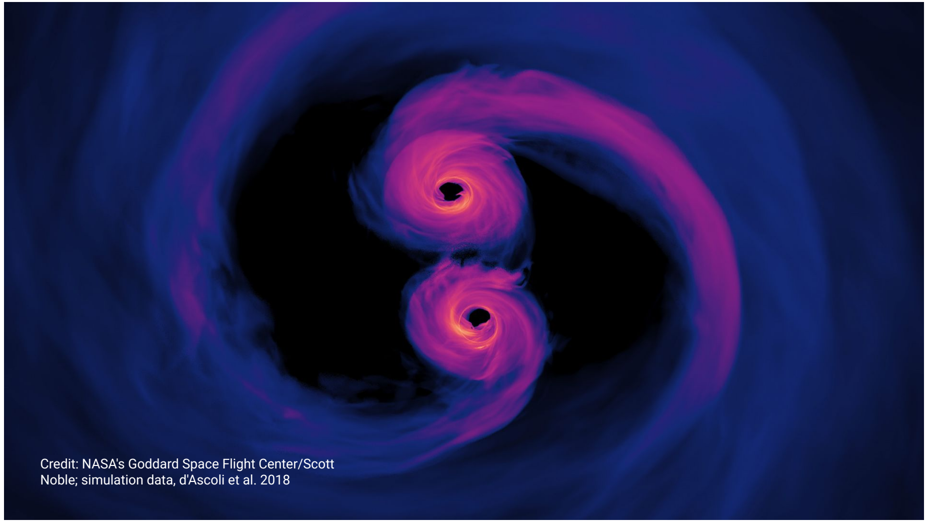
Jet reorientation

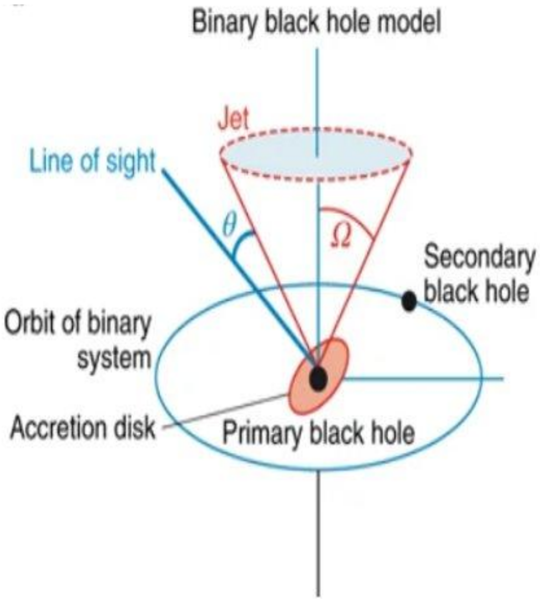
Possible Formation Mechanisms : Hydrodynamical Backflow



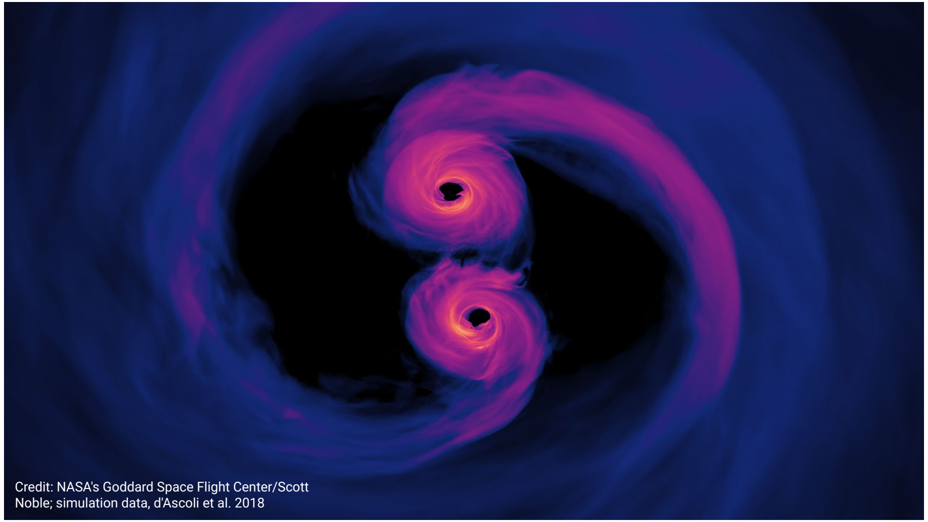
credit: NRAO / AUI / NSF / SARAO / DES

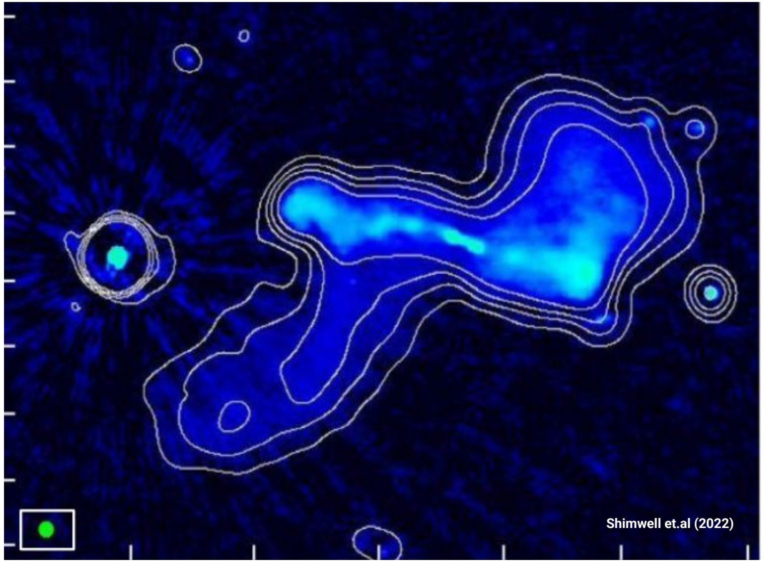
X-shaped morphology: Jet Precession


Credit: NASA's Goddard Space Flight Center/Scott Noble; simulation data, d'Ascoli et al. 2018



X-shaped morphology: Jet Precession


Credit: NASA's Goddard Space Flight Center/Scott Noble; simulation data, d'Ascoli et al. 2018


Shimwell et.al (2022)

- Post-merger system
- Misalignment between jet and lobe axis

- Wiggles in jet
- Multiple or wide terminal hotspots

Summary of the study on CGCG 292-057

We conducted multifrequency observations using GMRT and VLA in the range of 150 MHz - 5 GHz.

We fit particle injection models and performed ageing analysis using the radio spectra.

The X- shaped morphology could be the result of orbital motion of a binary SMBH pair, causing jet precession lasting a few million years.

CGCG 292-057 is an exceptional source as it shows multiple stages of galaxy evolution at once:

- Evidence of a past merger
- X-shaped morphology
- AGN rebirth

Still unanswered questions :

- What is causing strong absorption of inner lobes around 1.4 GHz?
- Have the binary SMBH merged or are they still in the process of merging?

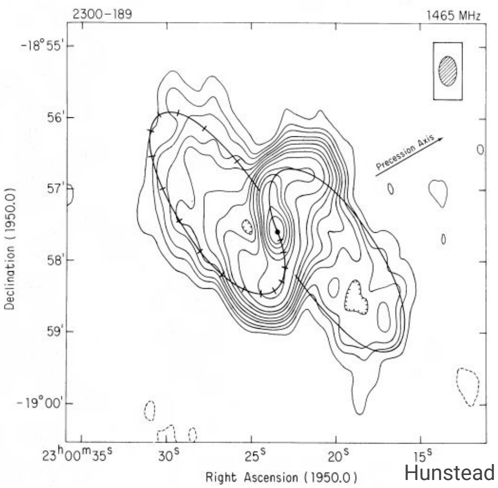
Multiwavelength investigations of PKS 2300–18:

S-shaped radio quasar with precessing jets and double-peaked broad emission-line spectrum

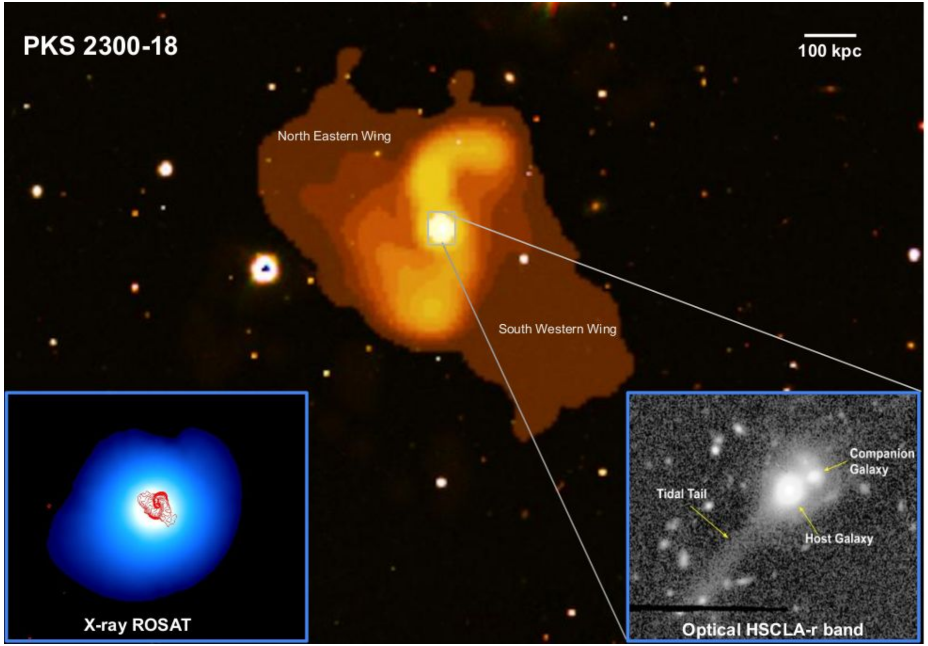
PKS 2300-18: Clearest Precessing Jets in Quasar

Radio quasar first studied by Hunstead et.al 1984

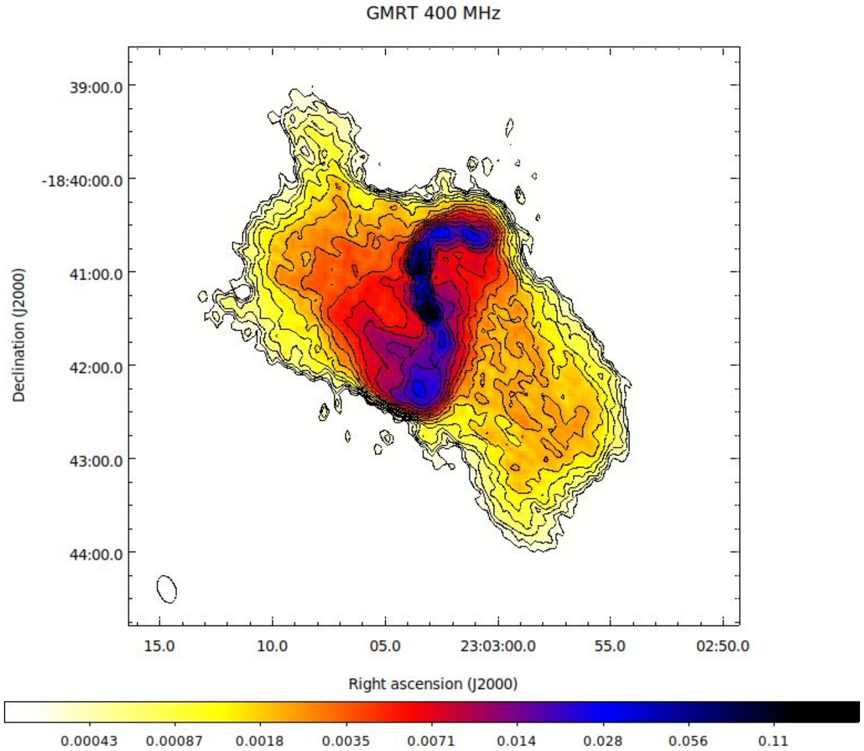
- Redshift - 0.128
- Optical morphology - elliptical and disturbed
- Merger system with companion at 14 kpc
- S-shaped radio morphology
- Double peaked broad emission lines
- 5 arcmin, ~760 kpc in linear size



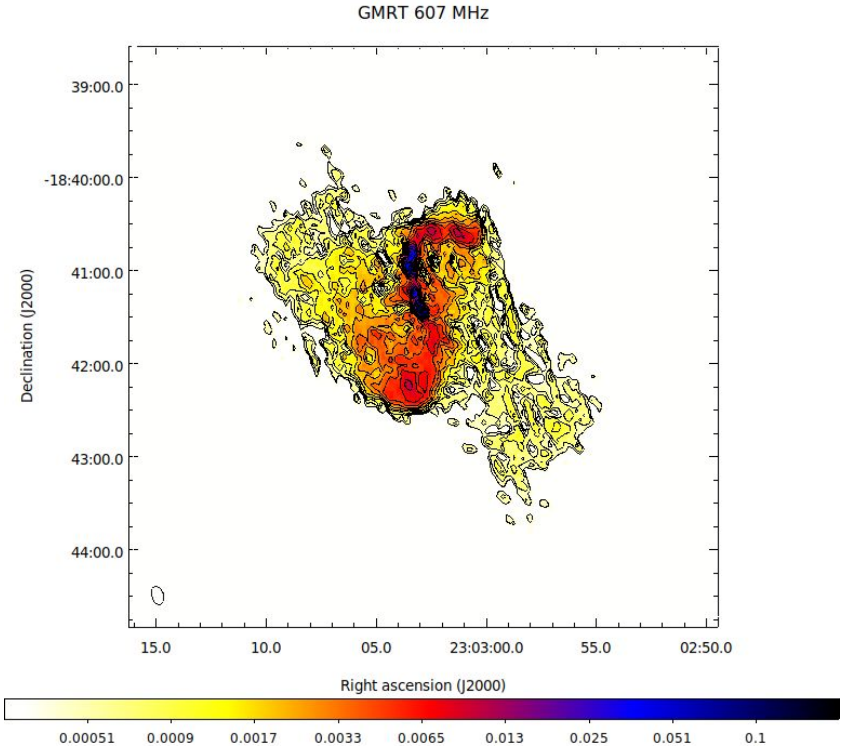
Hunstead et.al 1984



GMRT Radio Maps

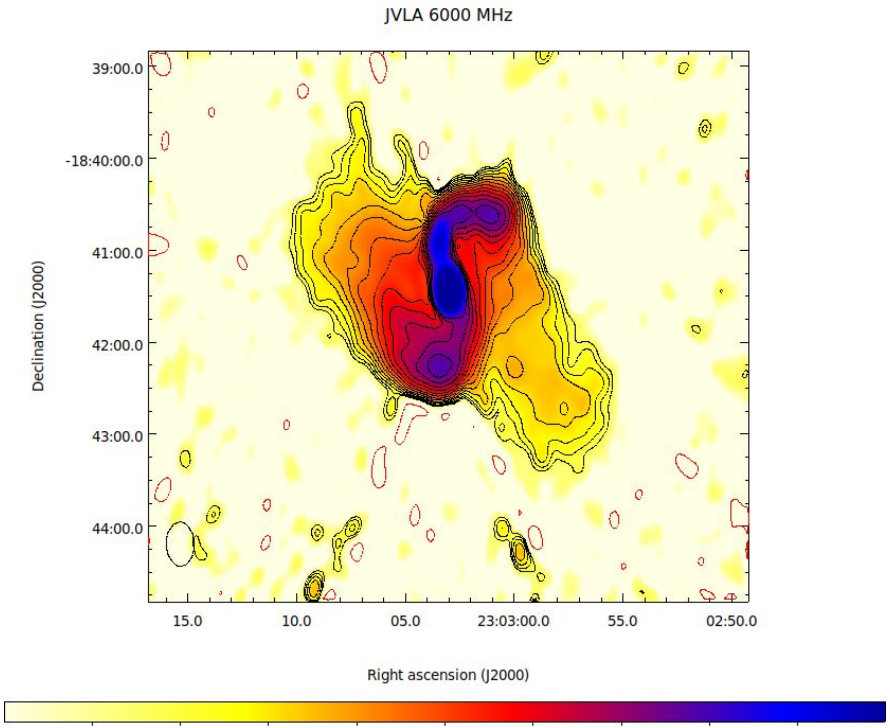


Flux density: Jy/beam

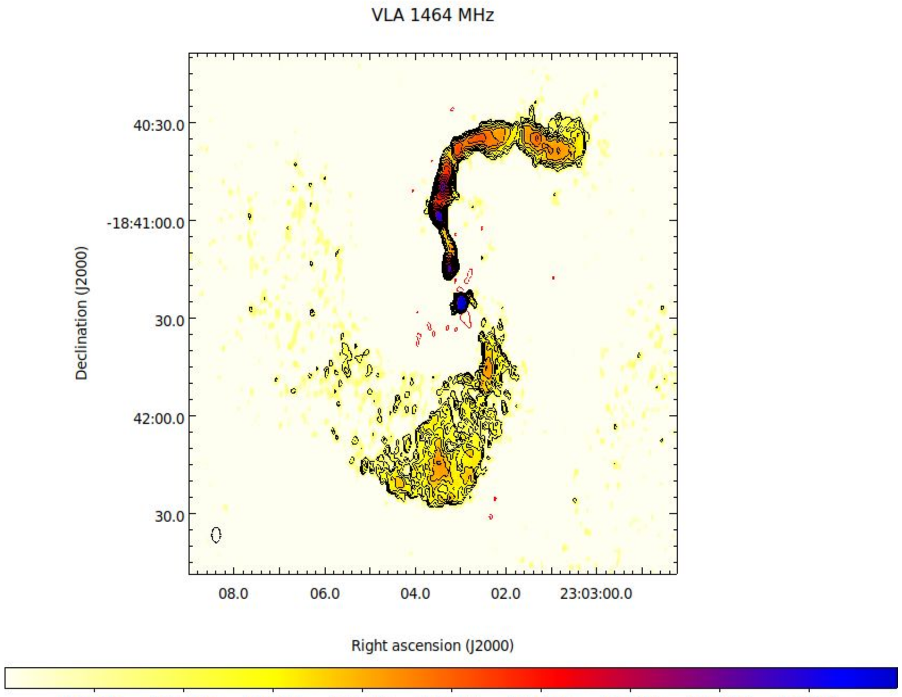


Flux density: Jy/beam

VLA Radio Maps

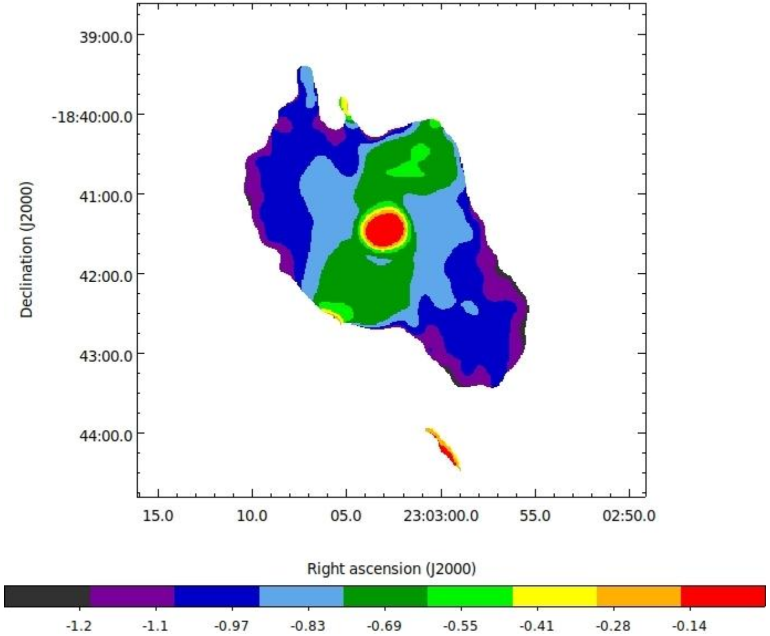


Flux density: Jy/beam

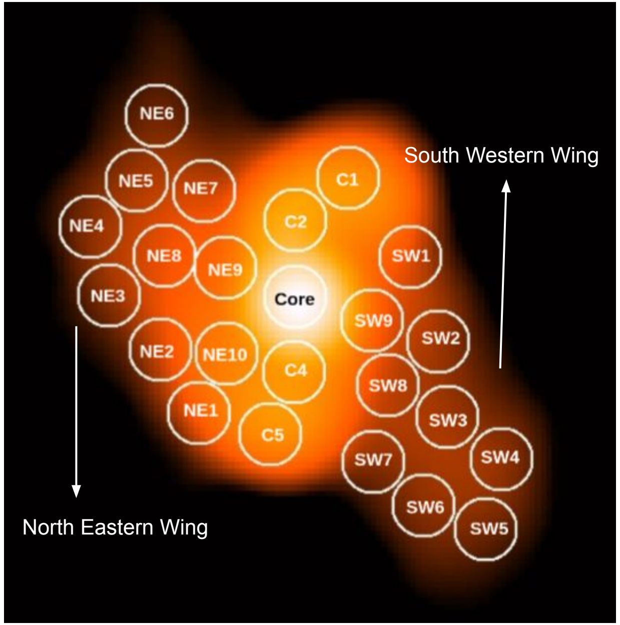


Flux density: Jy/beam

S-shaped quasar PKS 2300-189

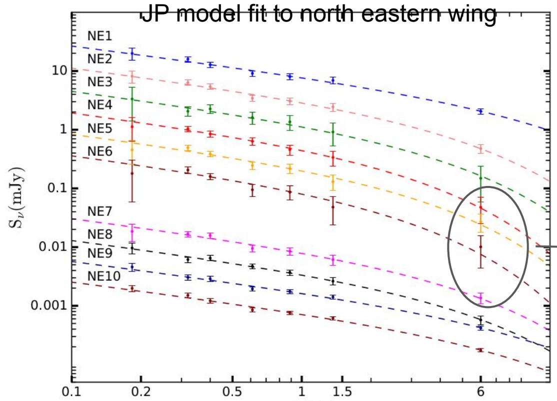


SI map between uGMRT 400 MHz and the VLA 5998 MHz



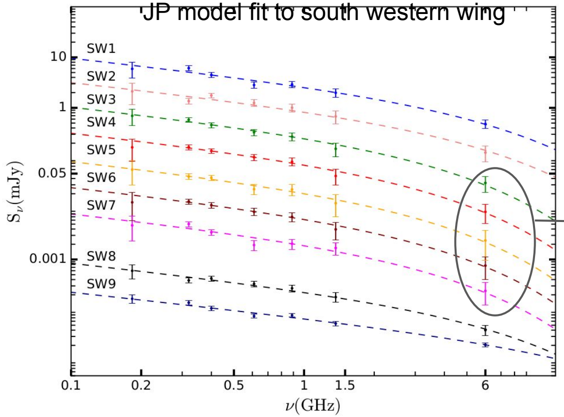
Region map at 6 GHz

Source Energetics

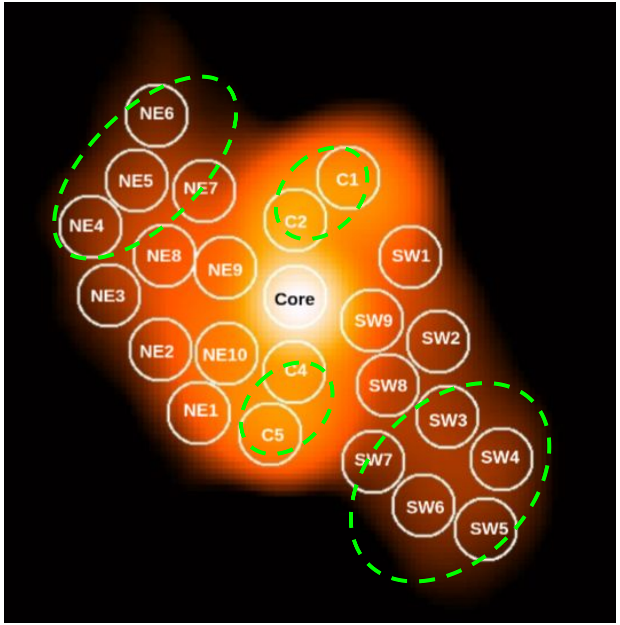


Steepest plasma in NE4-NE7
Spectral ages: 30-40 Myrs

Spectral ages of C1-C4: 17-22 Myrs



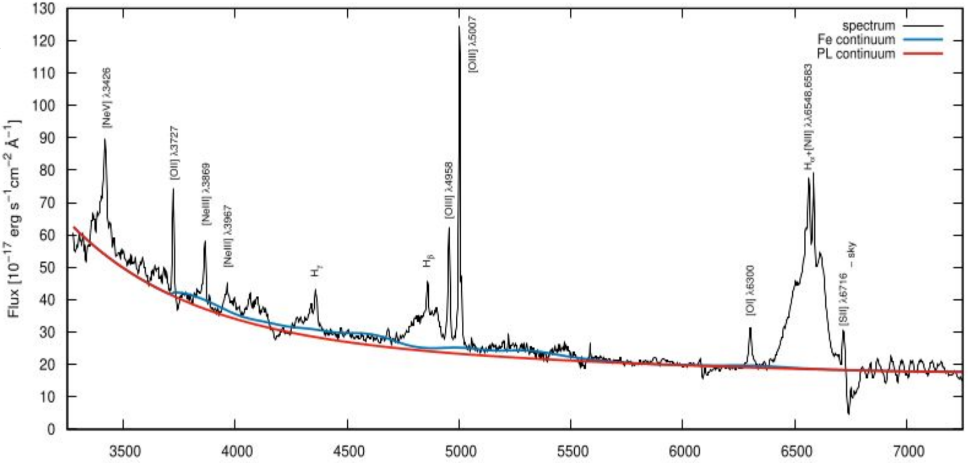
Steepest plasma in SW3-SW7
Spectral ages: 38-40 Myrs



Region map at 6 GHz

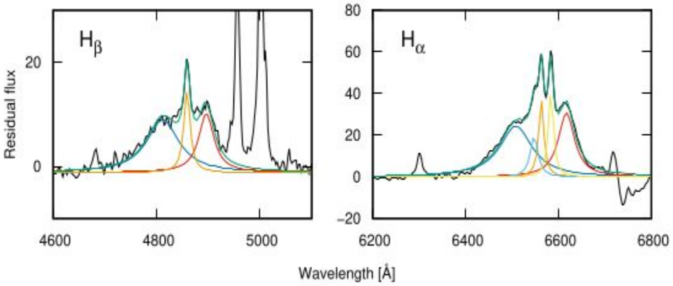
Optical Spectrum

- Archival William Herschel Telescope data for optical spectrum.
- Double peaked and broad H_{alpha} and H_{beta} profile.
- Modelled with Lorentzian profiles.
- Estimated black hole mass $2.3\text{x}10^8 M_\odot$
- Size of Broad line region ~14 light days.



Double peaked broad emission lines is rare feature in AGNs:

a) Either due to binary SMBH
b) Irradiated disc
c) Irradiated disc with spiral perturbation.

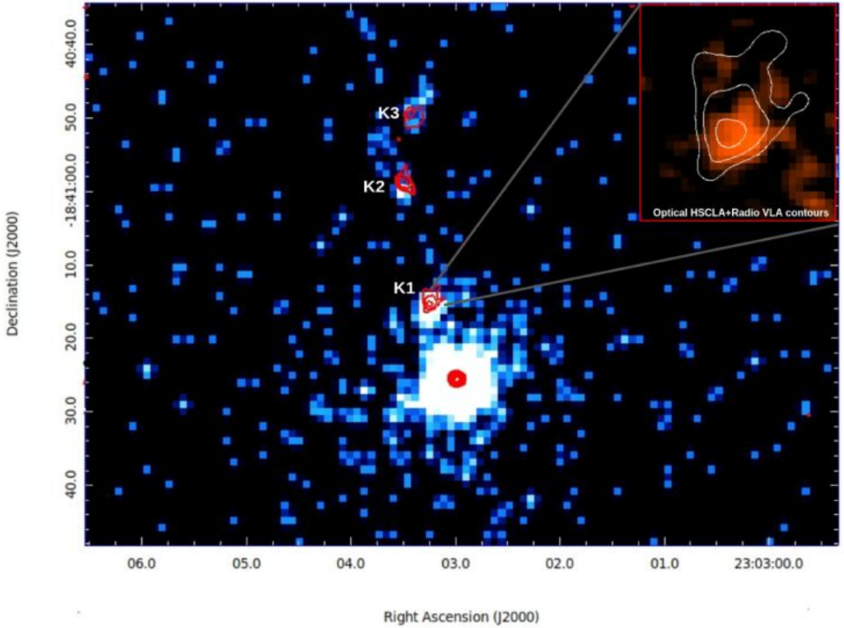


Binary SMBH has 3 possibilities:
i) both SMBH with their own BLR clouds - tested and ruled out!!
ii) both SMBH active but with common BLR cloud
iii) only one SMBH active

To confirm other scenarios, long spectral monitoring or reverberation mapping!

X-Ray Study

- Chandra X-ray broadband (0.2-7 KeV) image
- X-ray image mostly catches the central AGN and knots in the northern jet.
- First multiwavelegth radio knot detection in S-shaped jet for knot k1!
- The X-ray spectrum was fit with a model using thermal and power law components.
- Hot gas detected in central ~10 kpc region
- Metallicity was found 3% solar, which hints at photoionization of gas in the direct vicinity of the SMBH due to quasar.
- In ROSAT we detect a Mpc scale halo around the host galaxy.



X-ray Image from Chandra with red VLA contours at 5 GHz

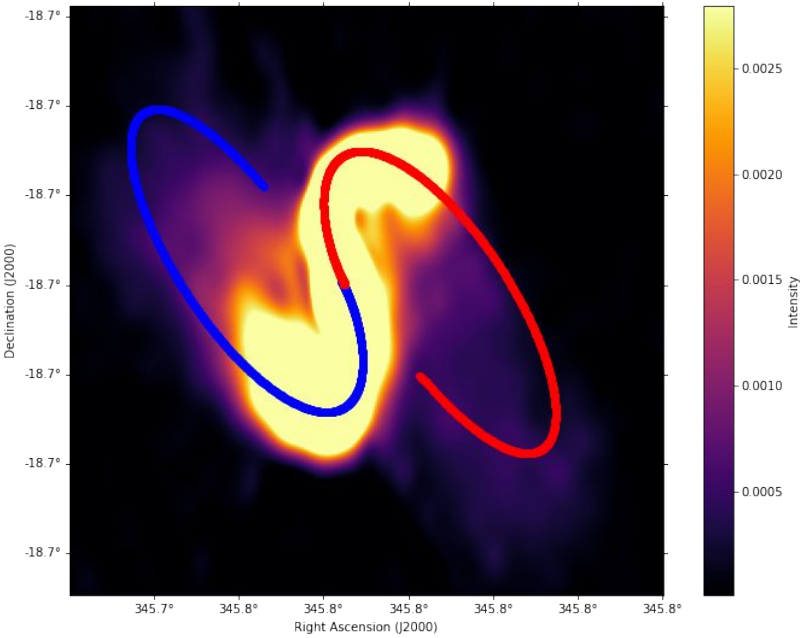
S-shaped quasar PKS 2300-189

Kinematical jet precession model (Gower et. al 1982) fit to VLA 6 GHz map

- Jet velocity range : 0.01c - 0.18c
- Precession period : 12±8 Myrs.
- Inclination angle : 67± 4 deg
- Jet half opening angle : 66±4 deg.

Spectral Ageing

- Oldest plasma in wings ~40 Myrs
- Youngest plasma in S-shaped jet ~ 18 Myrs.

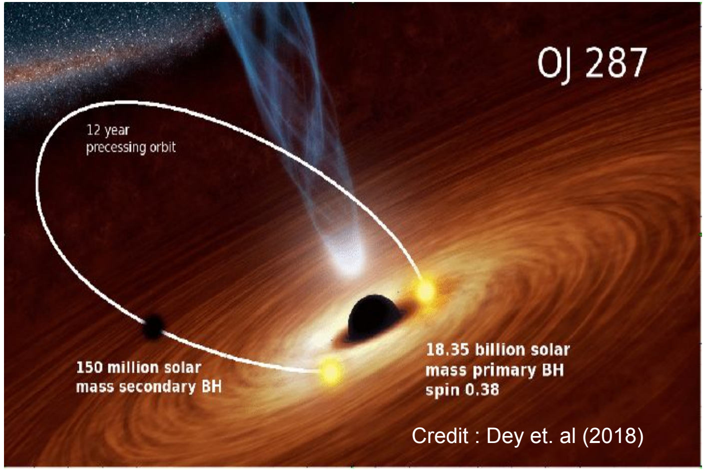


Mechanisms for Jet Precession

1. Binary SMBH

Reorientation of the jets due to the presence of supermassive black hole in the same nucleus while orbiting to coalesce undergoing geodetic precession.

Binary separation: 335 - 133 light days!, below VLBA limits!



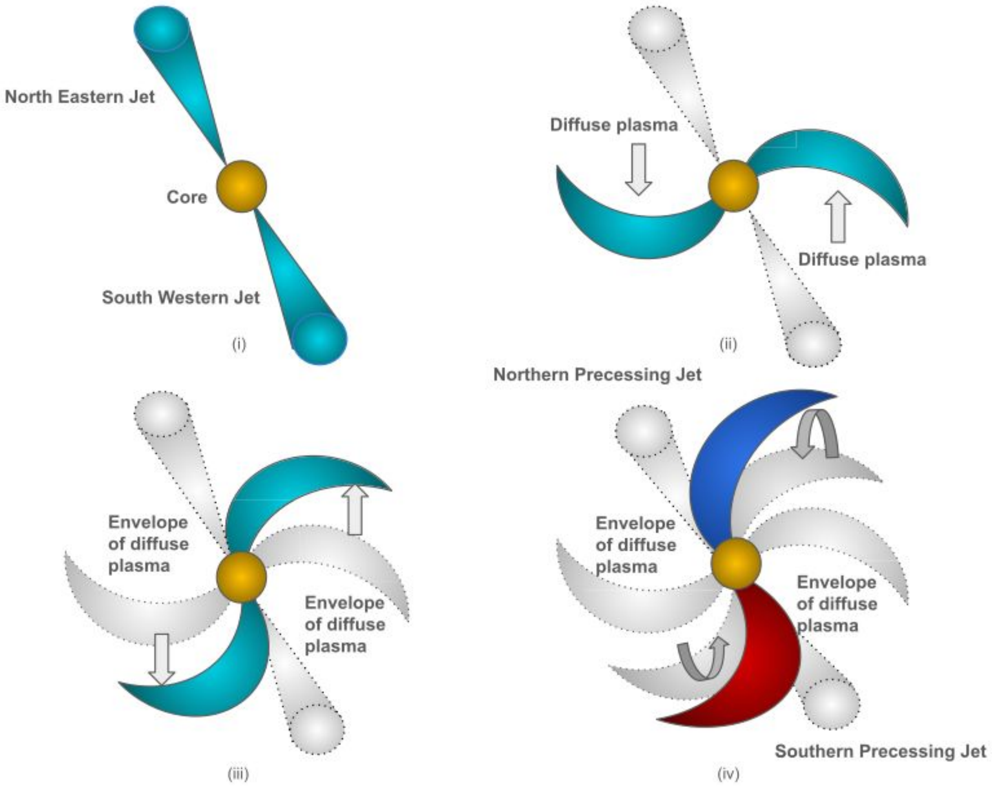
Credit : Dey et. al (2018)

2. Surrounding tilted accretion disk

If the accretion disk is tilted with respect to spin axis of SMBH, the disk - jet system undergoes Lense - Thirring precession and approaches alignment.

Estimated from period luminosity relation: 6-20 Myrs, similar to kinematical precession model!

Illustration for Jet Precession



Coherent Multiwavelength Picture

- We observed the source in radio from 183 MHz to 6 GHz.
- In X-rays using Chandra we detected hot gas at the centre and photoionization of gas in the direct vicinity of the SMBH.
- In optical we modelled broad and double peaked emission lines and ruled out the possibility of two separate BLR's clouds.
- We also found radio core variability and superluminal motion of parsec scale jets in VLBA.
- Spectral age of the oldest plasma in the wings was found to be near 40 Myrs and youngest plasma was 20 Myrs.
- Precession period from Kinematical jet precession model was found to be 12±8 Myrs.

The S-shaped morphology is the result of jet reorientation taking place in anti-clockwise direction over a period of ~12 Myrs either due to binary SMBH or tilted accretion disk.

- Simulation based study of the source in future.
- XMM- Newton study of the wings to estimate accurately magnetic field values.

Atlas of S-shaped Sources seen through GMRT

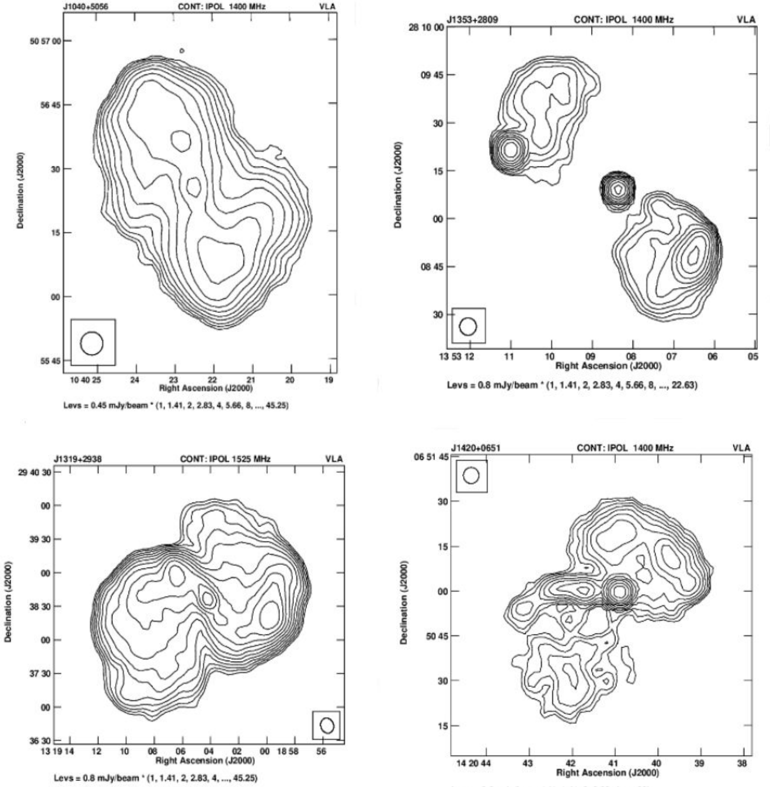
Sample of S-shaped Sources

- Large scale inversion symmetric jets are rare.
- Limited detailed studies.

My work

Created Sample of S-shaped jets from FIRST survey (Proctor 2011):

- Limited to Low-moderate redshift AGNs (0.1 < z <0.3)
- Angular size (> 1’)
- Clear S-shaped morphology confirmed at high-frequency maps (e.g. FIRST and VLASS)



Archival maps of few sources

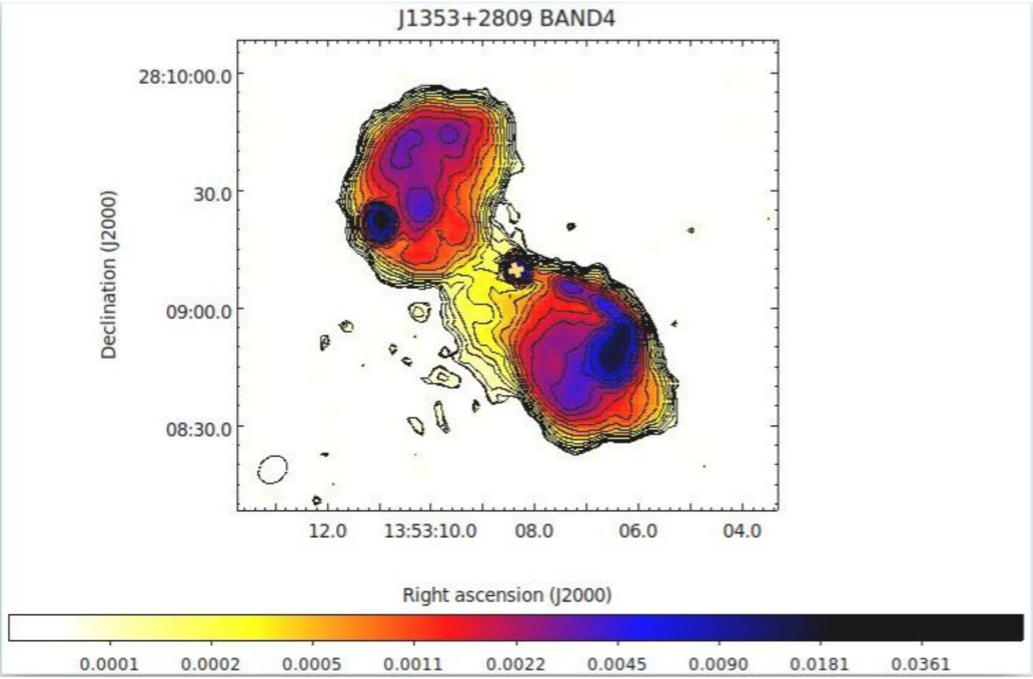
Dedicated Radio Observations of Sample

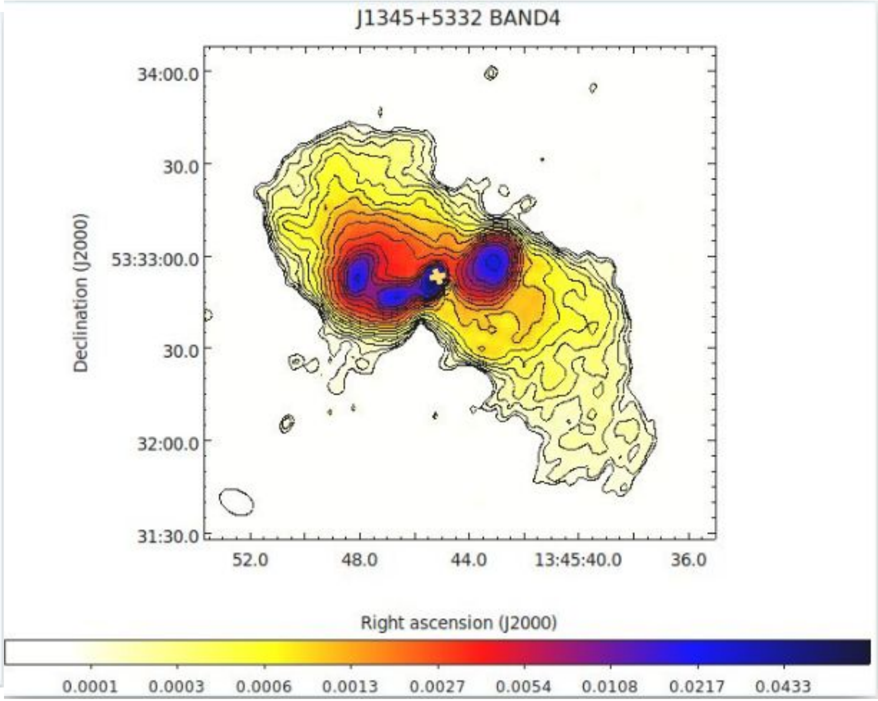
- Multifrequency observations using GMRT and the VLA
- 150 MHz - 5000 MHz
- Sample of 7 S-shaped sources were observed
- Reduced data using SPAM pipeline

The Very Large Array, US

Giant Metrewave Radio Telescope, India

Sample of S-shaped Sources

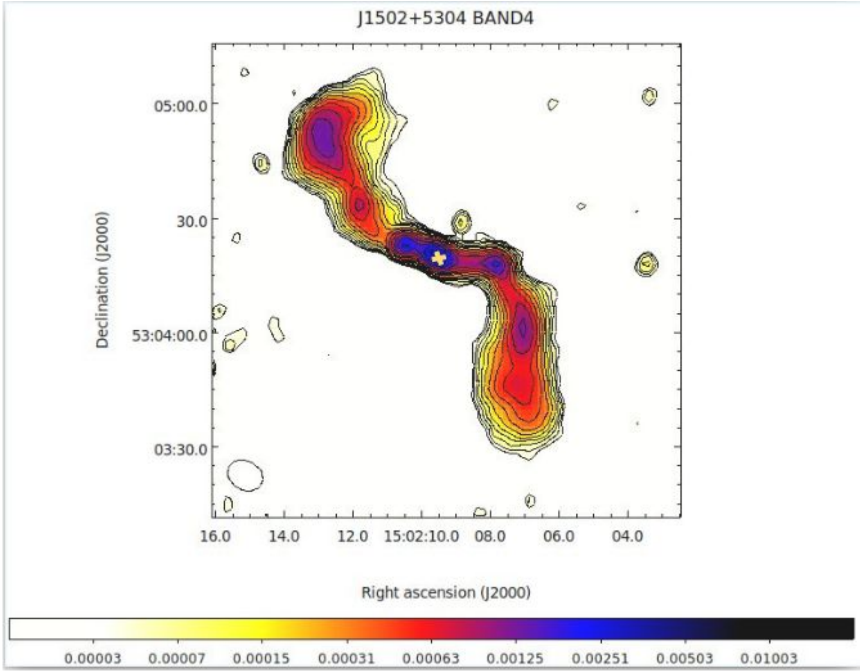




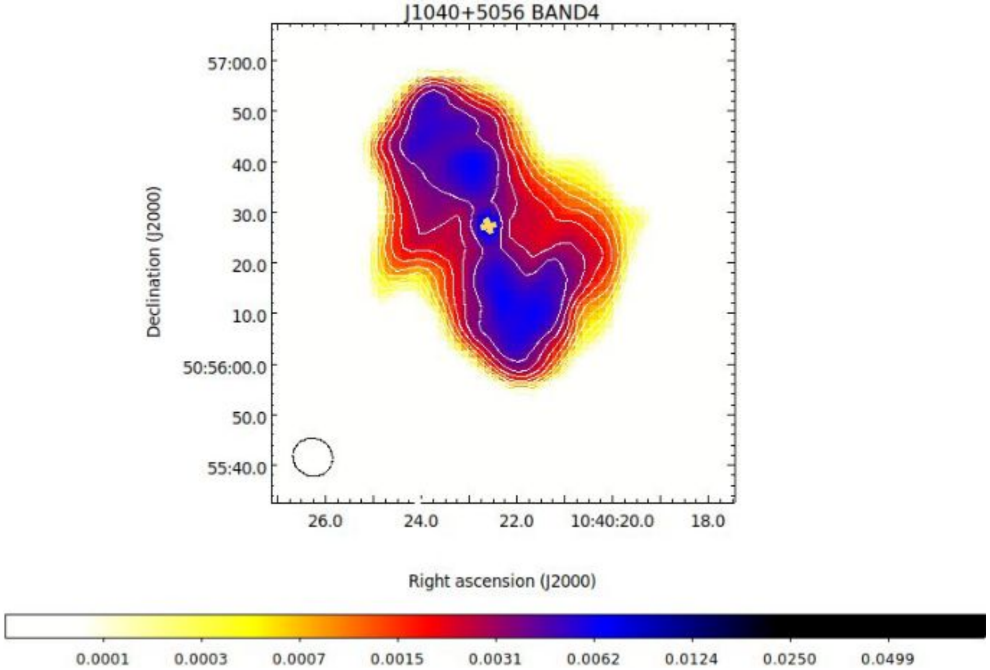
Size of the source: 670 kpc
Precession indicators: curvature of the jets, S-shaped symmetry, the presence of hotspots at the edges of the lobe, and appearance of multiple or broad hotspots

Size of the source: 370 kpc
Precession indicators: curvature of the jets, presence of multiple or complex knots, and asymmetric diffuse emission

Sample of S-shaped Sources

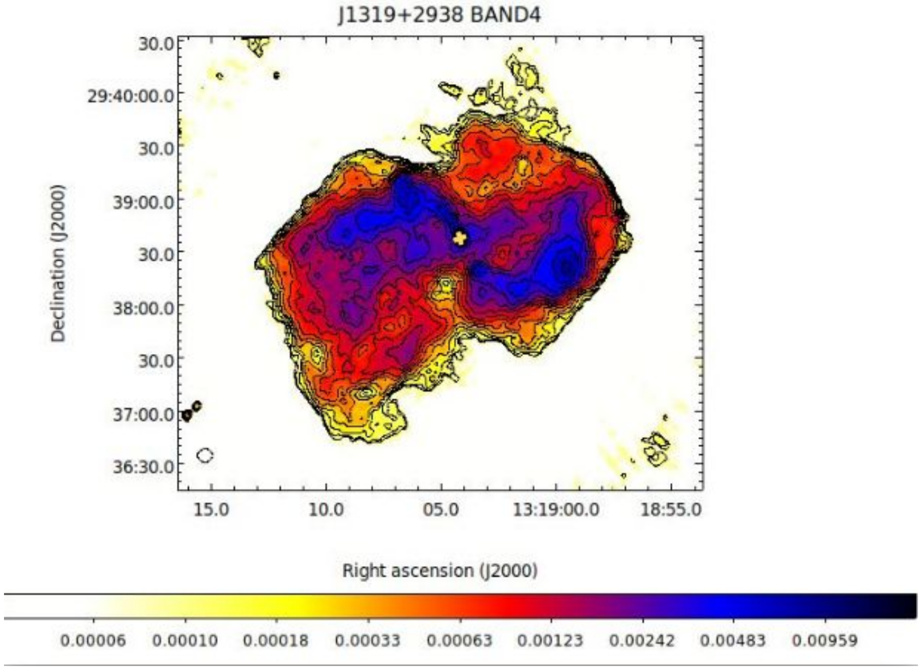

J1502+5304 BAND4

Size of the source: 260 kpc
Precession indicators: curved large-scale morphology, S-shaped symmetry, and the presence of broad hotspots

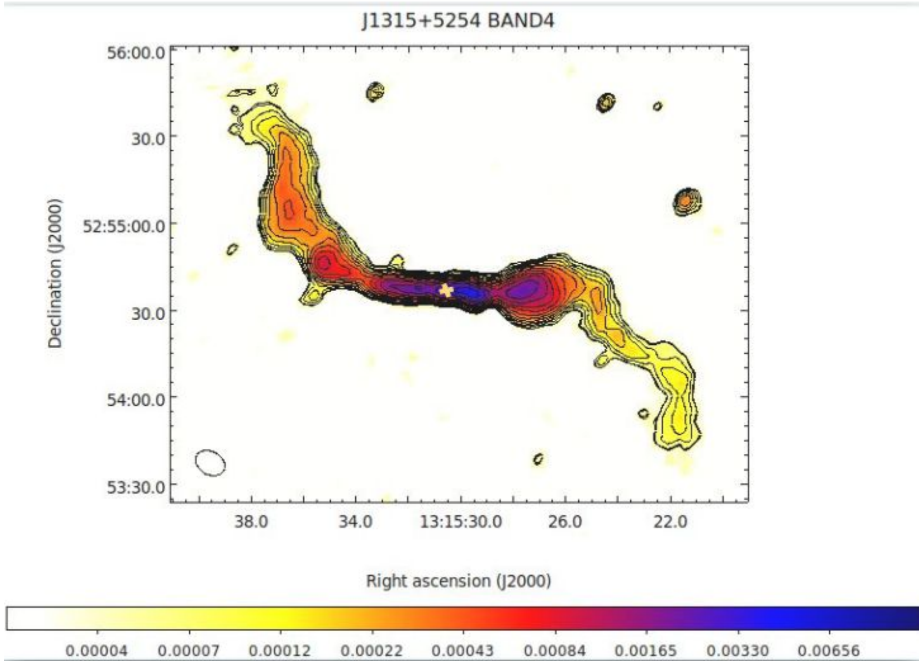

J1040+5056 BAND4

Size of the source: 240 kpc
Precession indicators: curved jets and S-shaped symmetry

Sample of S-shaped Sources

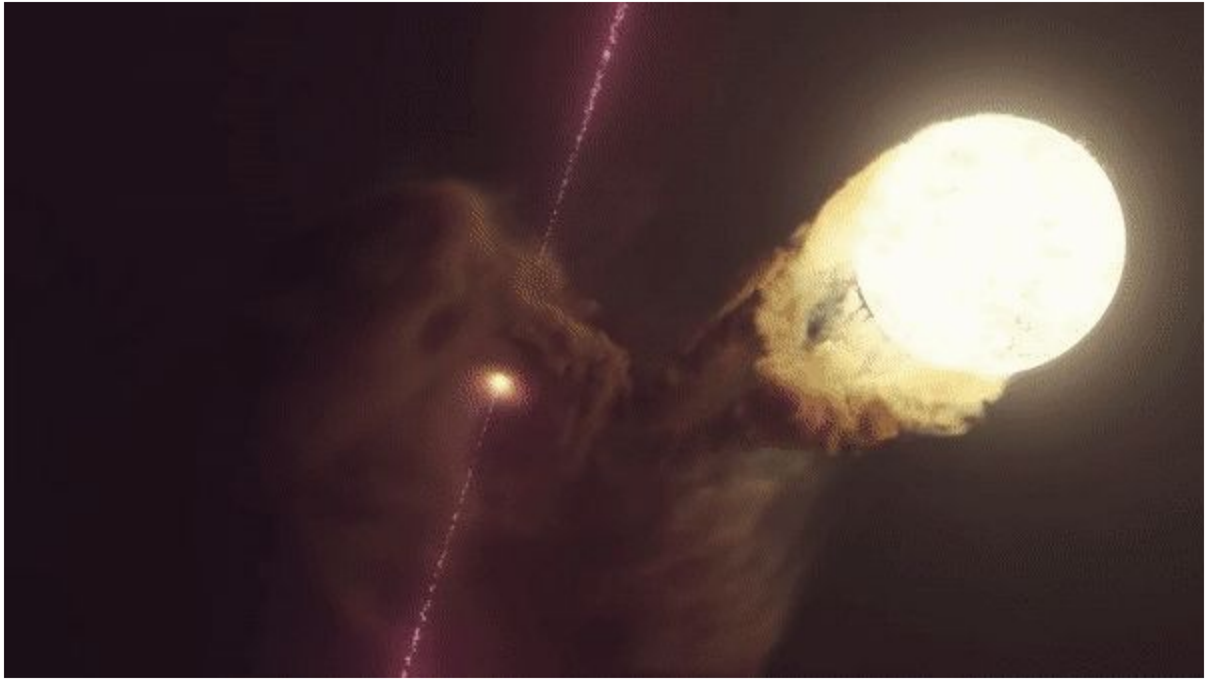


Size of the source: 330 kpc
Precession indicators: large-scale curved morphology and clear inversion symmetric S-shaped jets



Size of the source: 654 kpc
Precession indicators: large-scale curved morphology and the S-shaped jets

S-shaped Precessing Jets: SS433 Microquasar



Credit: Science Communication Lab for MPIK/H.E.S.S.

Conclusion and Key Takeaways

- My work presents the first systematic effort to create a sample and study S-shaped radio galaxies evolution and origin.
- A sample of seven S-shaped sources were selected and were observed using dedicated observations at GMRT and VLA between 2020-2023. I reduced the data and analysed the morphology as seen in the low frequency maps.

  CGCG 292-057 was studied which is a rare X-shaped radio source in a post-merger galaxy, offering key insights into the link between galaxy mergers and radio jet evolution.
- First detailed study combined spectral ageing analysis and host galaxy properties
- Revealed a **precessing jet origin** for the X-shaped structure
- Showcased **post-merger features**, **restarted nuclear activity**, and **distinct X-shaped lobes**
- Serves as an **exceptional case study** for galaxy merger–jet evolution connections

The PKS 2300-18 study pioneered a multiwavelength methodology to probe jet and host galaxy evolution across vast spatial scales.

- **First comprehensive optical–radio–X-ray analysis** of this kind
- Explored **morphological evolution** and **host galaxy properties** from light-day to megaparsec scales
- **Precession period calculated using two independent methods**: spectral ageing and kinematical jet precession model
- Marked a **methodological advancement** for studying radio source evolution

Key Takeaways and Futurescope

- This work primarily investigates two exceptionally rare and significant radio sources, which serve as natural laboratories for probing the co-evolution of SMBH and their host galaxies.
- Specifically, it shows the role of galaxy mergers in driving evolutionary processes that influence SMBH precession and its manifestations in the form of large-scale radio jets.
- Future work will include detailed spectral ageing analyses and jet precession modeling for the rest of the sample, allowing for a broader comparative understanding of their evolutionary stages.
- These efforts will be further supplemented with 3D hydrodynamical simulations to model jet reorientation and test precession scenarios.
- In upcoming years discovery of more S-shaped sources using upcoming deep and wide-area radio surveys such as SKA, Evolutionary Map of the Universe (EMU), and upgraded LOFAR.
- Goal will be to investigate the host galaxy properties of these exceptional sources and uncover what makes them so rare.

THANK YOU! DZIĘKUJĘ BARDZO!