X-shaped radio sources

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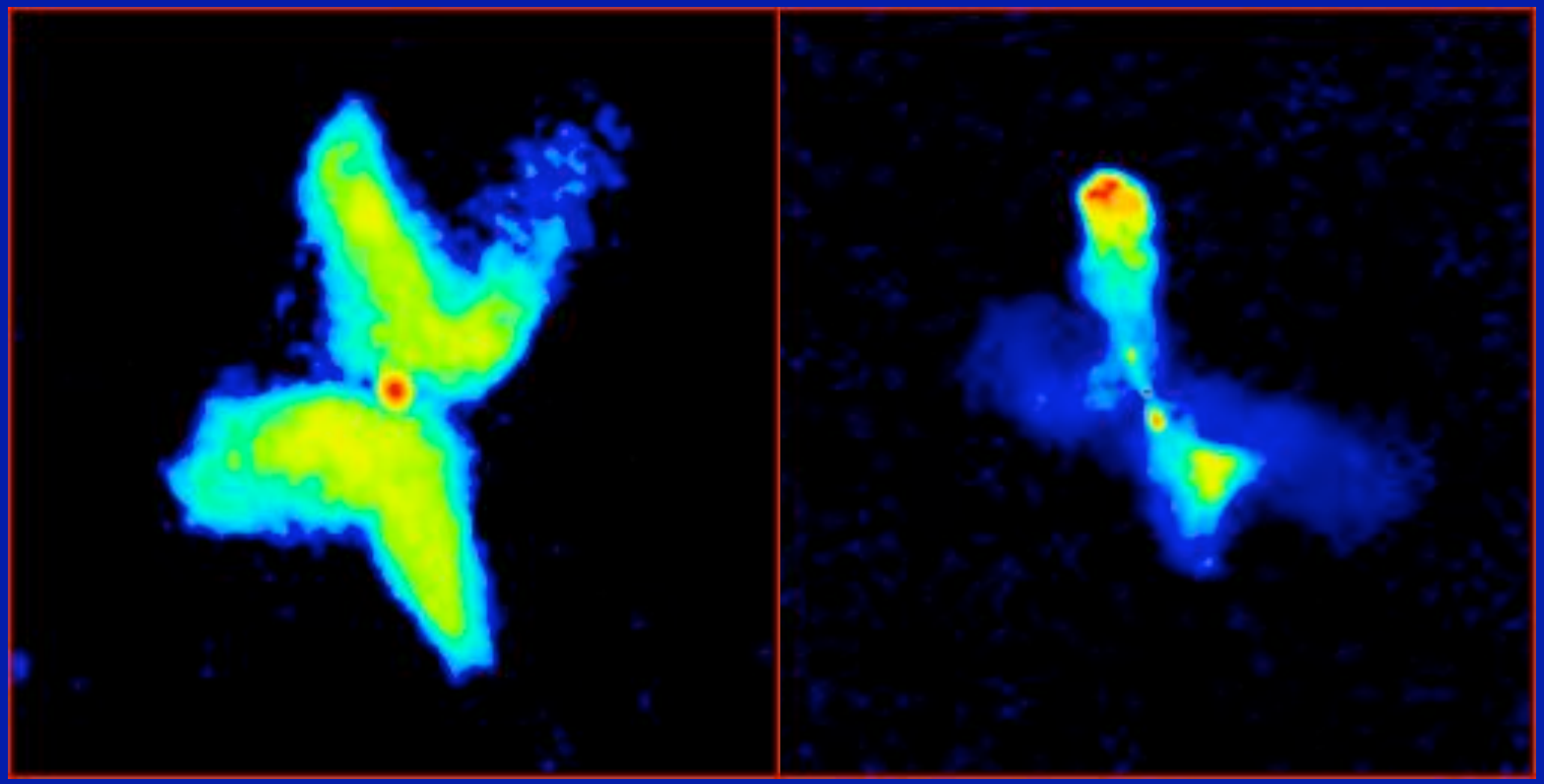
Merging Black Holes in Galaxies: Galaxy Evolution, AGN and Gravitational Waves

Katoomba, 15 to 20 June 2008

X-shaped Radio Sources

Simple origins of spectacular manifestations? or
Simple *and* spectacular origins of spectacular manifestations?



3CRR Atlas

X-shaped Radio Sources

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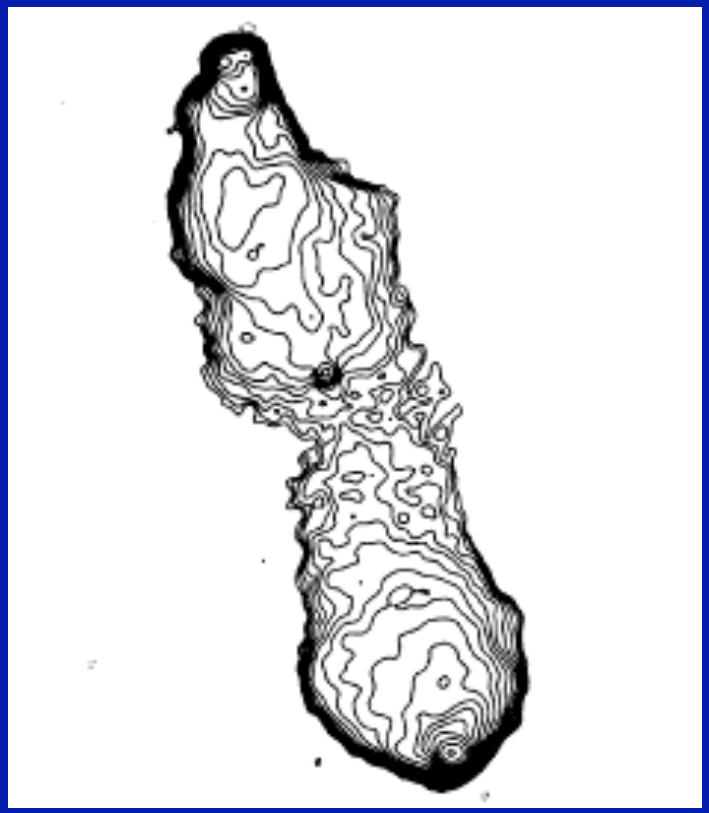
Ravi Subrahmanyan Raman Research Institute, India

Distinctive structures in

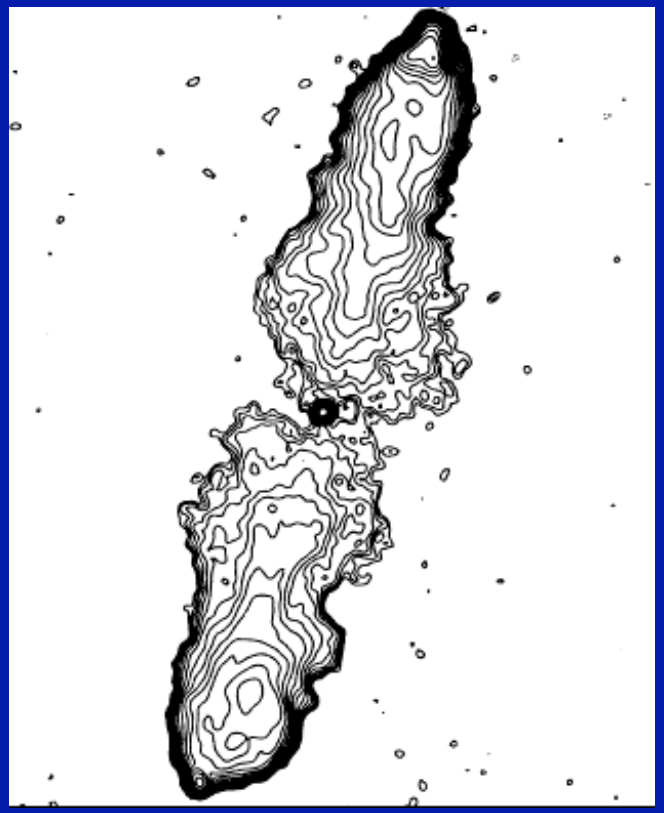
Powerful radio galaxies

(1) edge-brightened lobes

(2) hot-spots at the outer ends of lobes

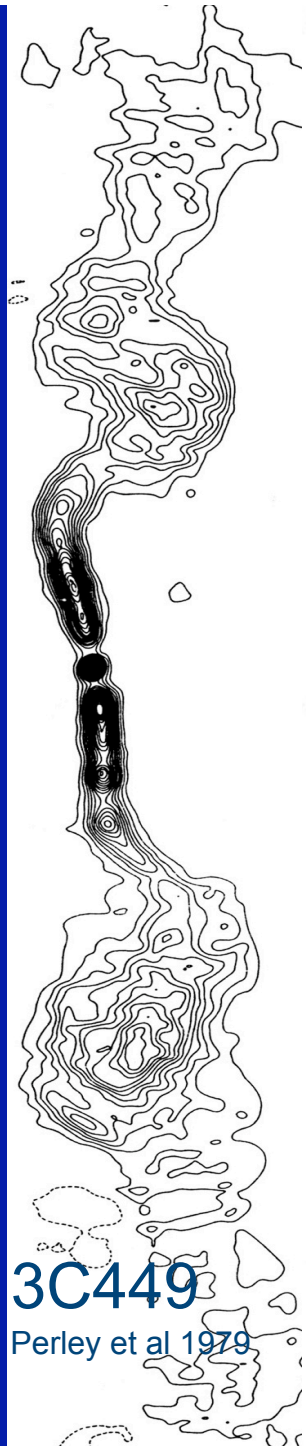


3C173.1



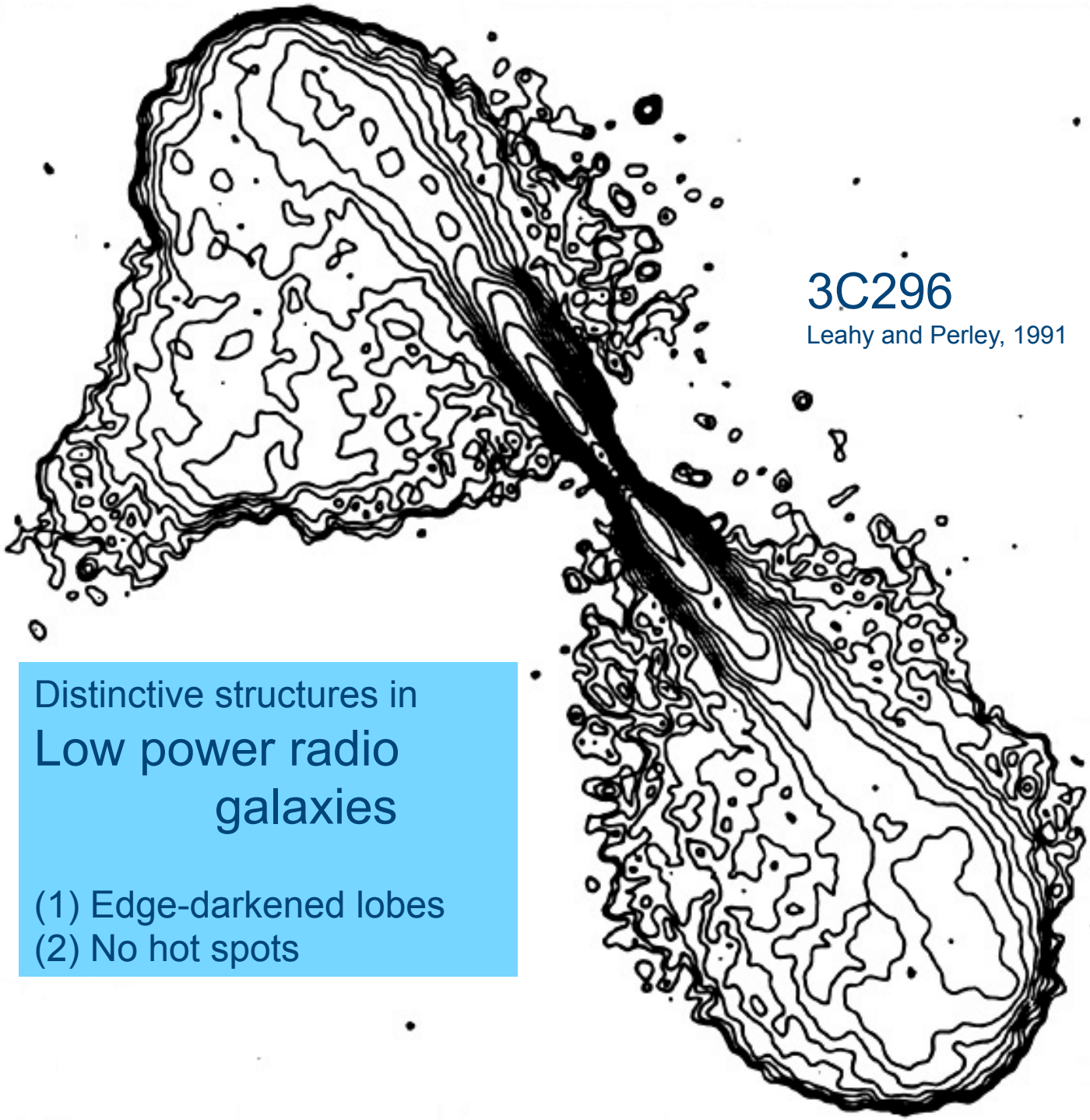
3C223

Leahy and Perley, 1991



3C449

Perley et al 1979



3C296

Leahy and Perley, 1991

Distinctive structures in

Low power radio galaxies

(1) Edge-darkened lobes
(2) No hot spots

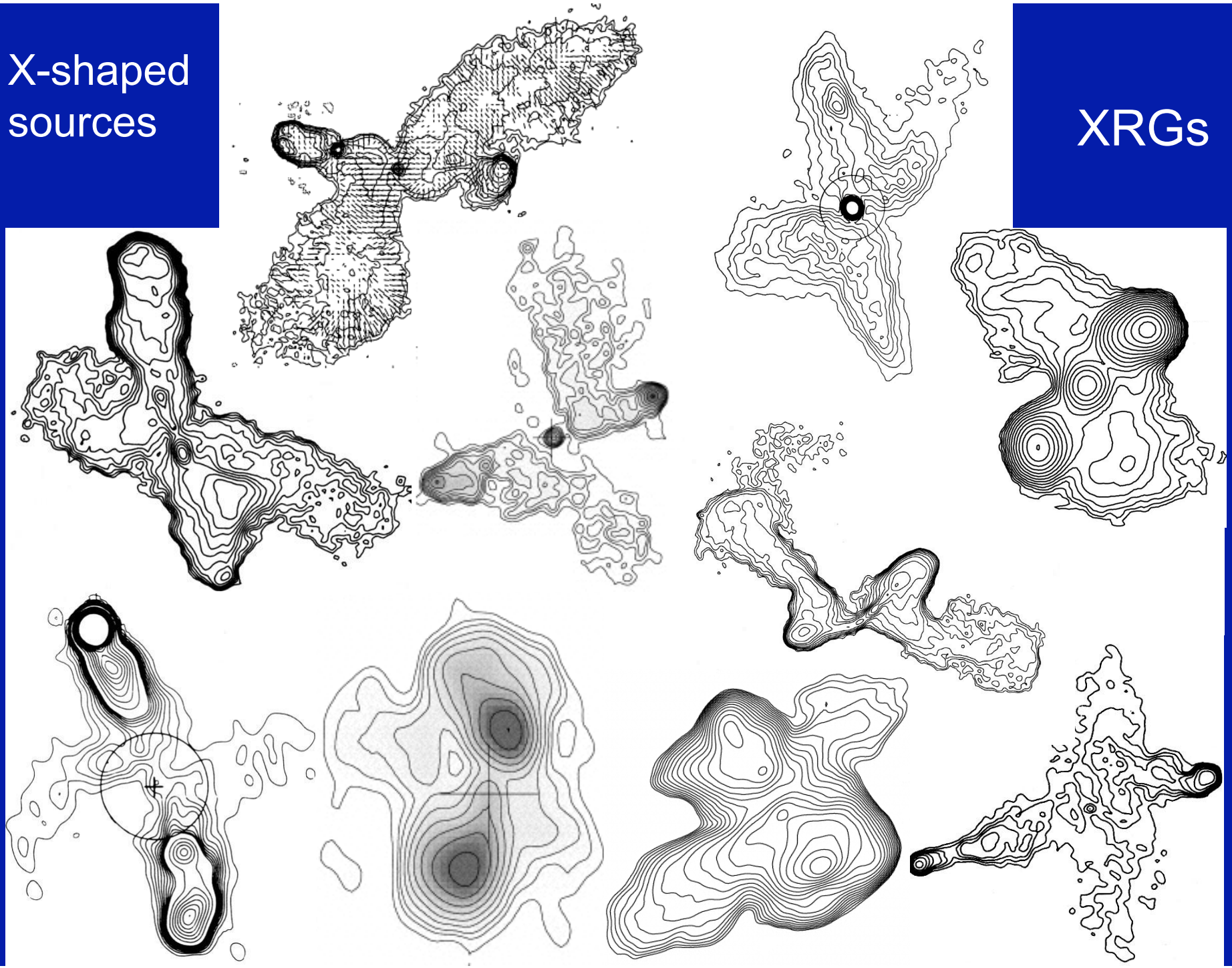
Most extended radio sources show a basic

DOUBLE LOBE STRUCTURE

A pair of lobes on two sides of a core

X-shaped sources

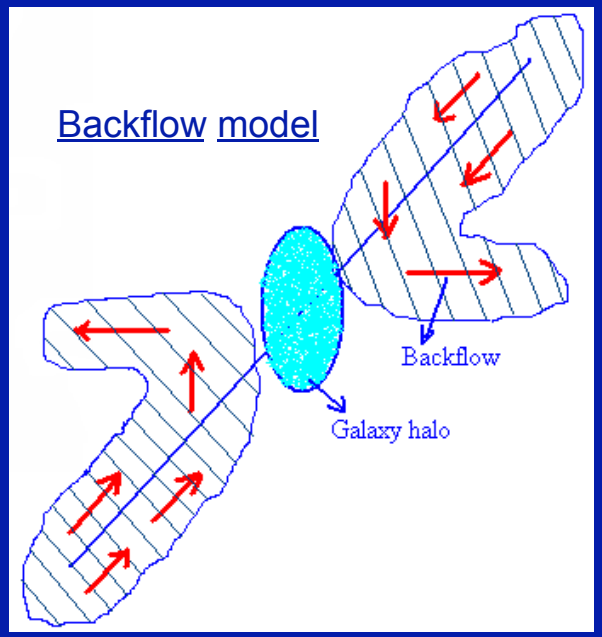
XRGs



Models for formation of X shaped radio sources

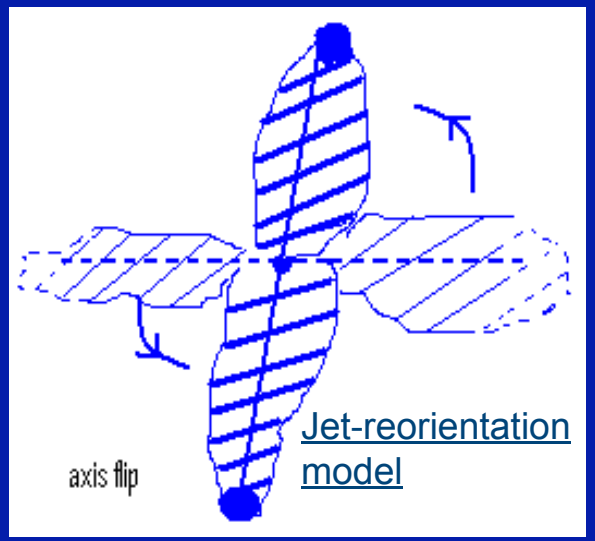
1. The backflow model:

   Lobe material back flowing from the hotspot towards the core is deflected by the thermal gas halo associated with the host galaxy to form wings

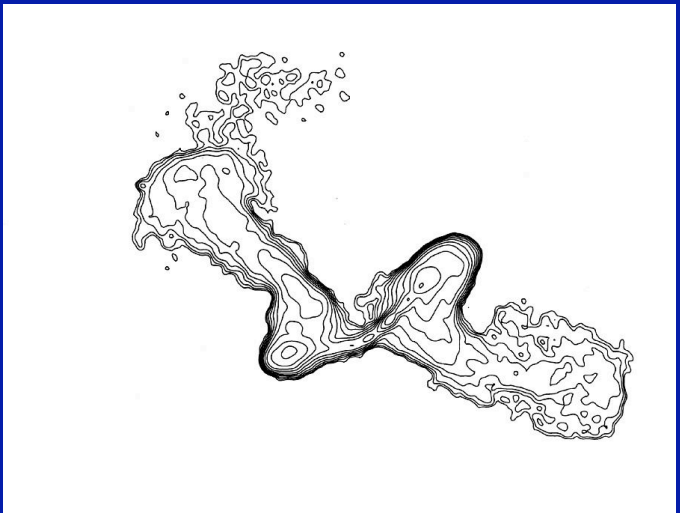


2. Jet re-orientation model
   (not to be confused with jet precession)

   Jet axis undergoes a flip over a large angle resulting in new lobes at large angle to relict lobes



Are the wings in XRGs a result of backflow?



Support

for:

- X-ray halos observed to be ubiquitous in ellipticals
- XRGs are mostly FRII type, and
- FRII models naturally include backflows
- Evidence in radio & X-ray & emission-line-gas for interaction of radio lobes with thermal plasma

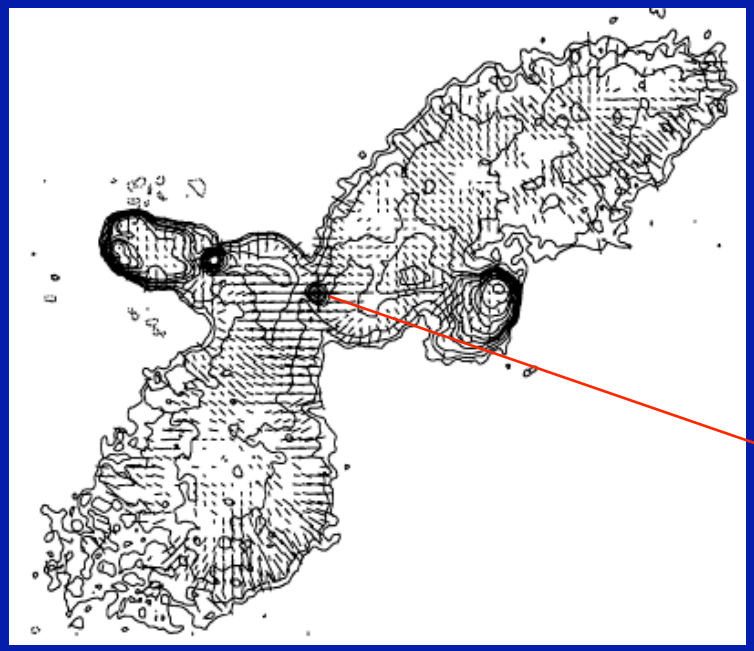
Evidence

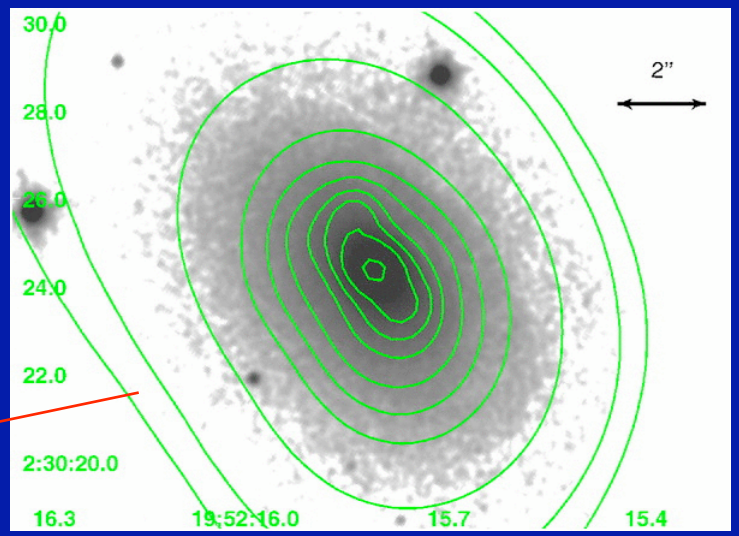
against:

- Some wings are longer than the main lobes

Observational clues to the creation of XRGs 1

Elliptical X-ray halo observed in 3C403, which is an X-shaped radio galaxy





X-ray contours

Kraft et al. 2005

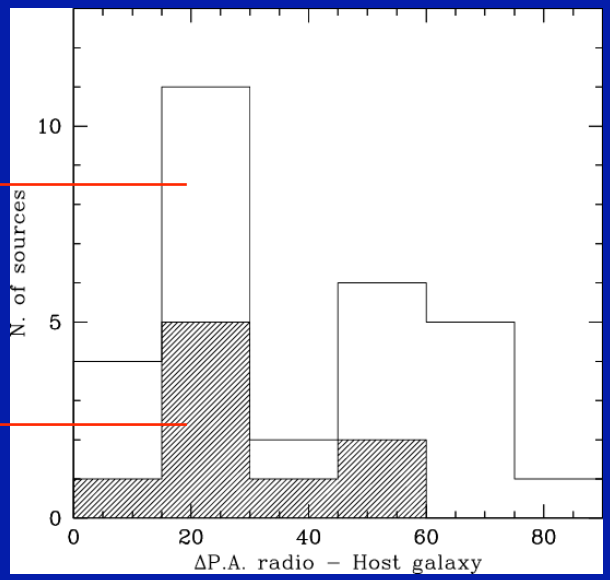
Observational clues to the creation of XRGs 2

Results from a sample study of XRGs (Capetti et al. 2002)

- Main radio axis of some XRGs found to be closer to the host major axis
- Wings of some XRGs found to lie closer to host minor axis

Control 3CR sample

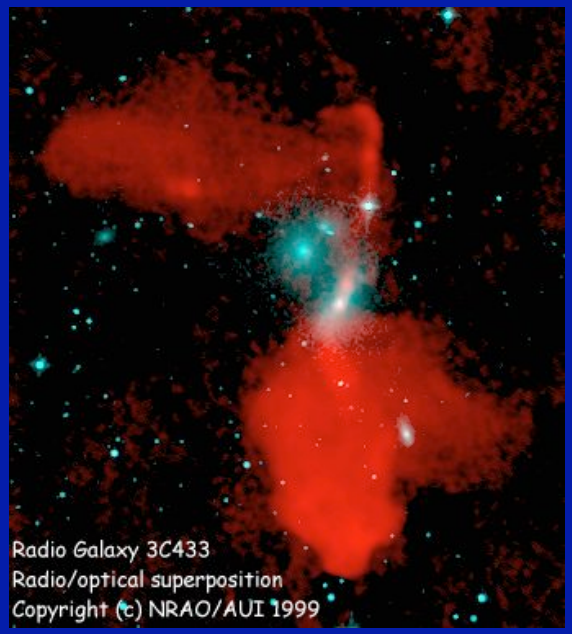
XRGs

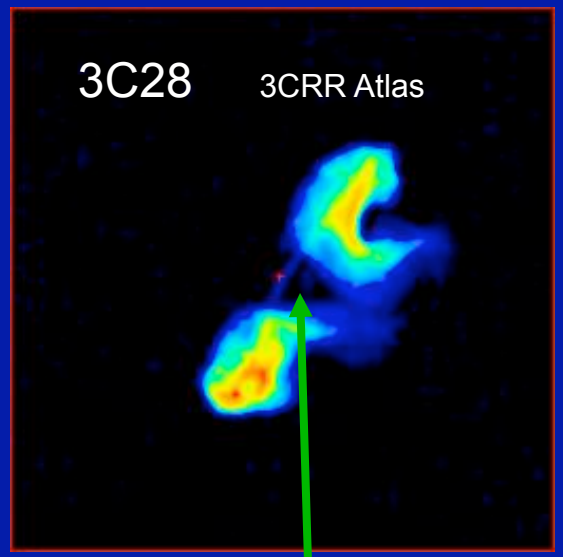


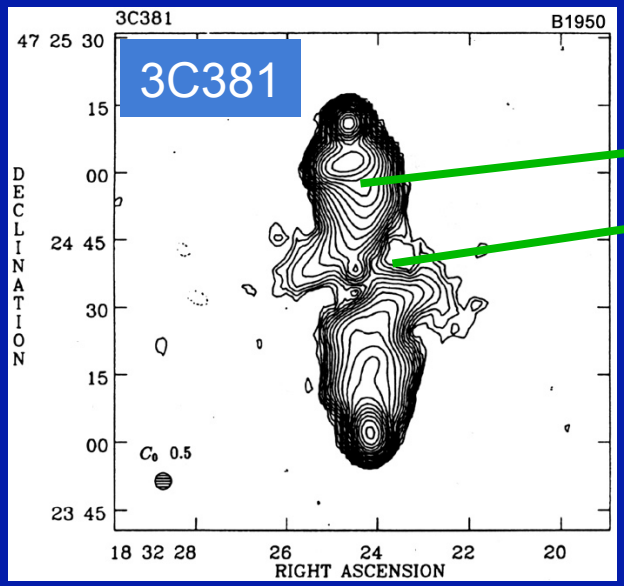
Capetti et al. 2002

Observational clues to the creation of XRGs 3

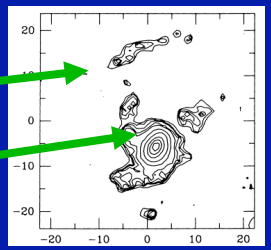
Observations of interaction between lobe material and thermal plasma



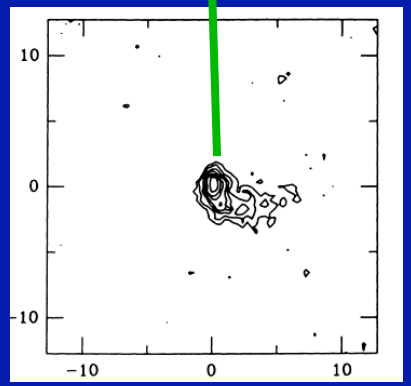




Leahy & Perley, 1991



McCarthy et al. 1995



3C28 McCarthy et al. 1995

Are the wings in XRGs relicts of previous activity along a different axis?

Evidence

For:

- Evidence for merger history in galaxies
- Evidence for binary black holes in some galaxies
- XRG production rate consistent with merger rate
- Evidence for radio axis change in non-XRGs

Against:

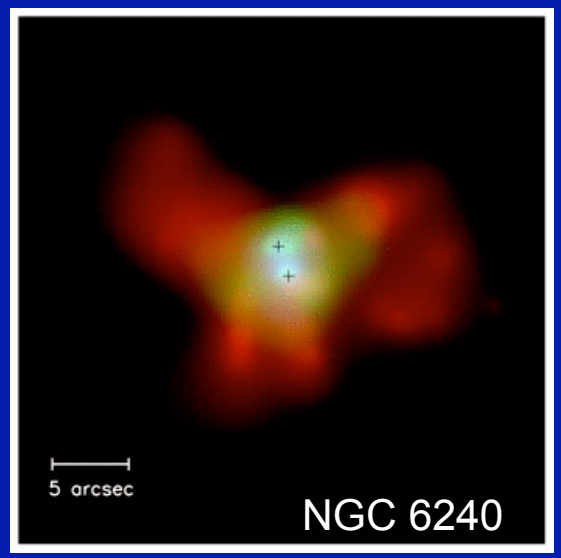
- Relic lobes are required to remain visible while new lobes form: unlikely since relics are rare!

Observational clues to the creation of XRGs 4

Binary Nuclei are known to exist and at least in one XRG

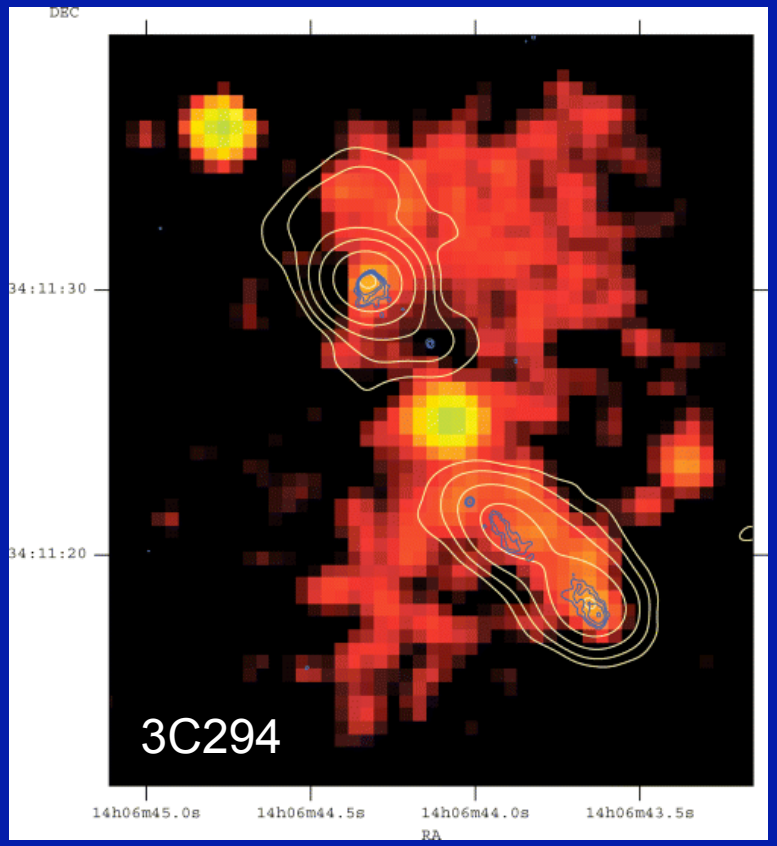
- Several examples of binary nuclei (e.g. 3C75, OJ287, NGC 6240)
- Double-peaked broad emission line in X-shaped radio source SDSS J1130+0058 (Zhang et al. 2008):

  Possible binary nucleus <0.04 pc

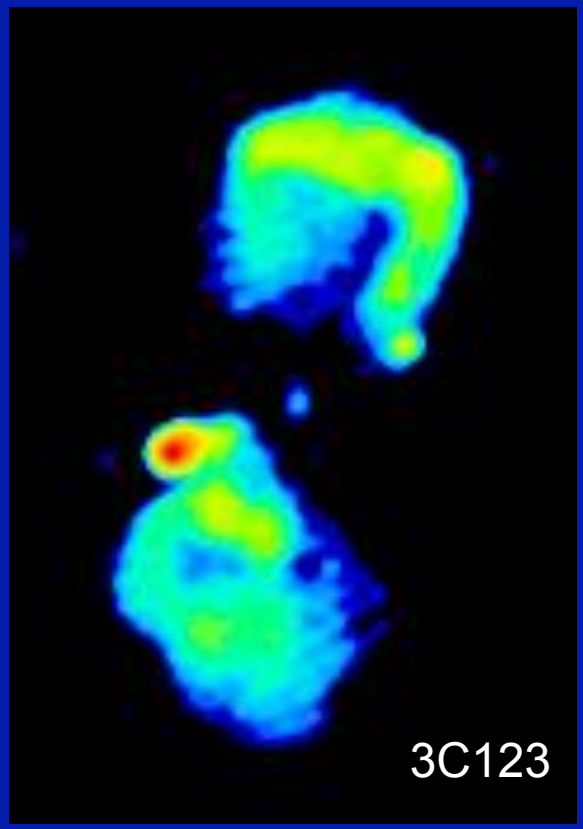


Komossa et al. 2003

Observational clues to the creation of XRGs 5



Erlund et al. 2006



3CRR Atlas

Evidence for jet precession in radio galaxy morphology

indicates that jet axis may change with time

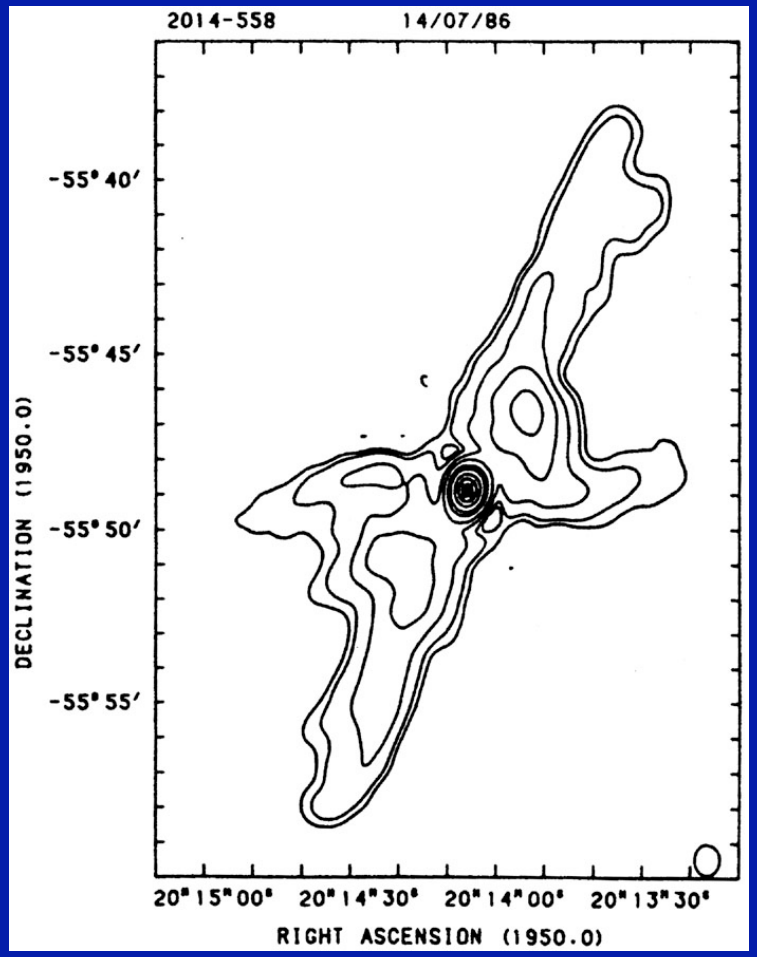
Introducing a new class of X-shaped sources:

Edge-darkened, double-double X-shaped sources

B2014-558

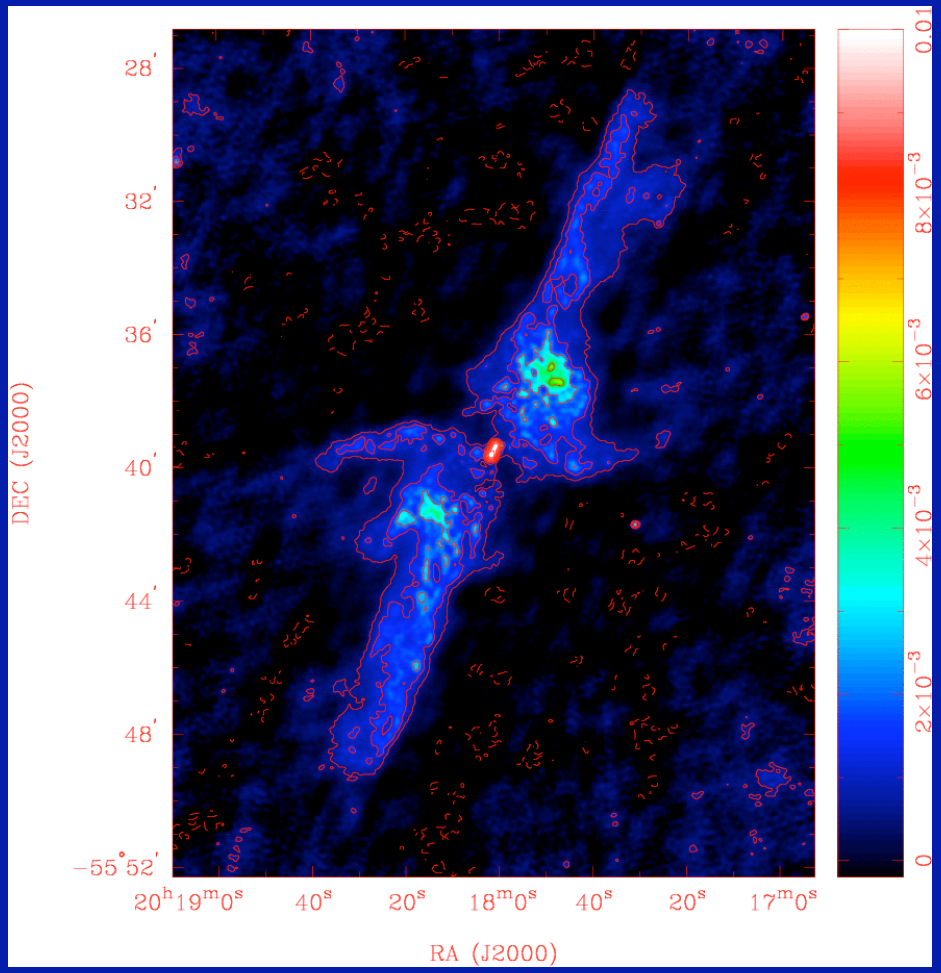
- Linear size: 1.53 Mpc
- FR-I structure
- Existence of FR-I X-shaped sources is potentially trouble for the backflow model

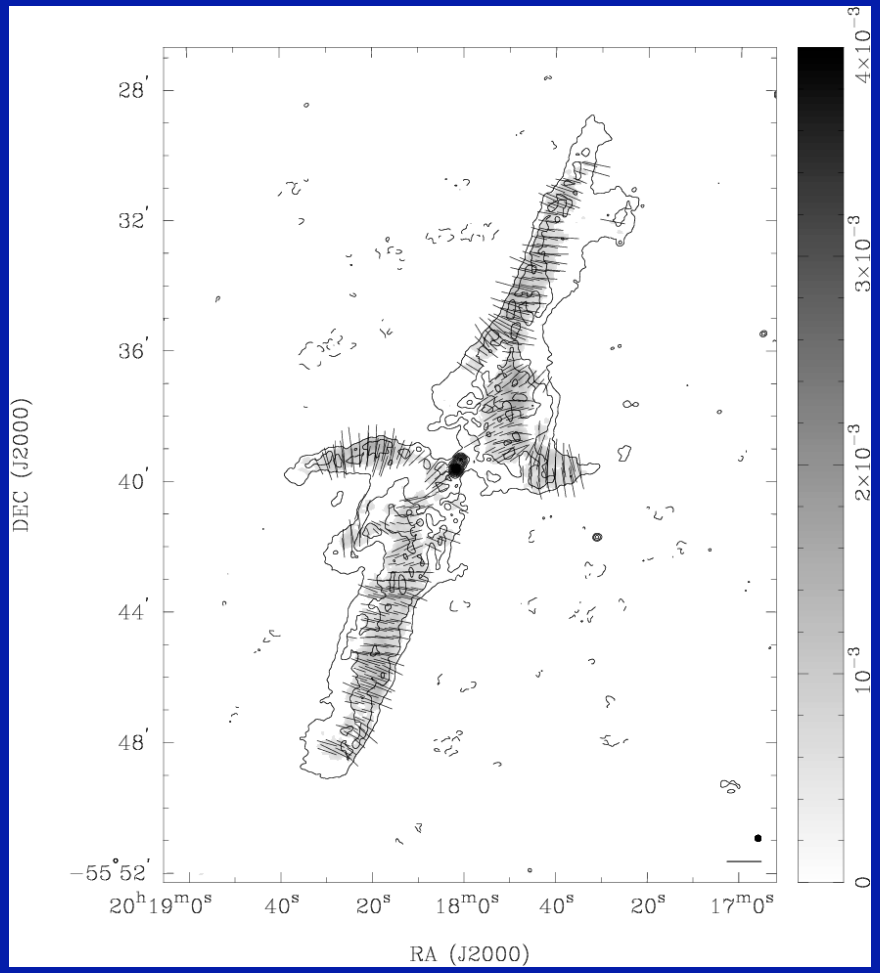
  because backflow is not believed to be present in FR-I sources



MOST 843 MHz
Jones & McAdam 1992

ATCA radio imaging of this giant FR-I X-shaped source B2014−558 (Saripalli et al. 2008)



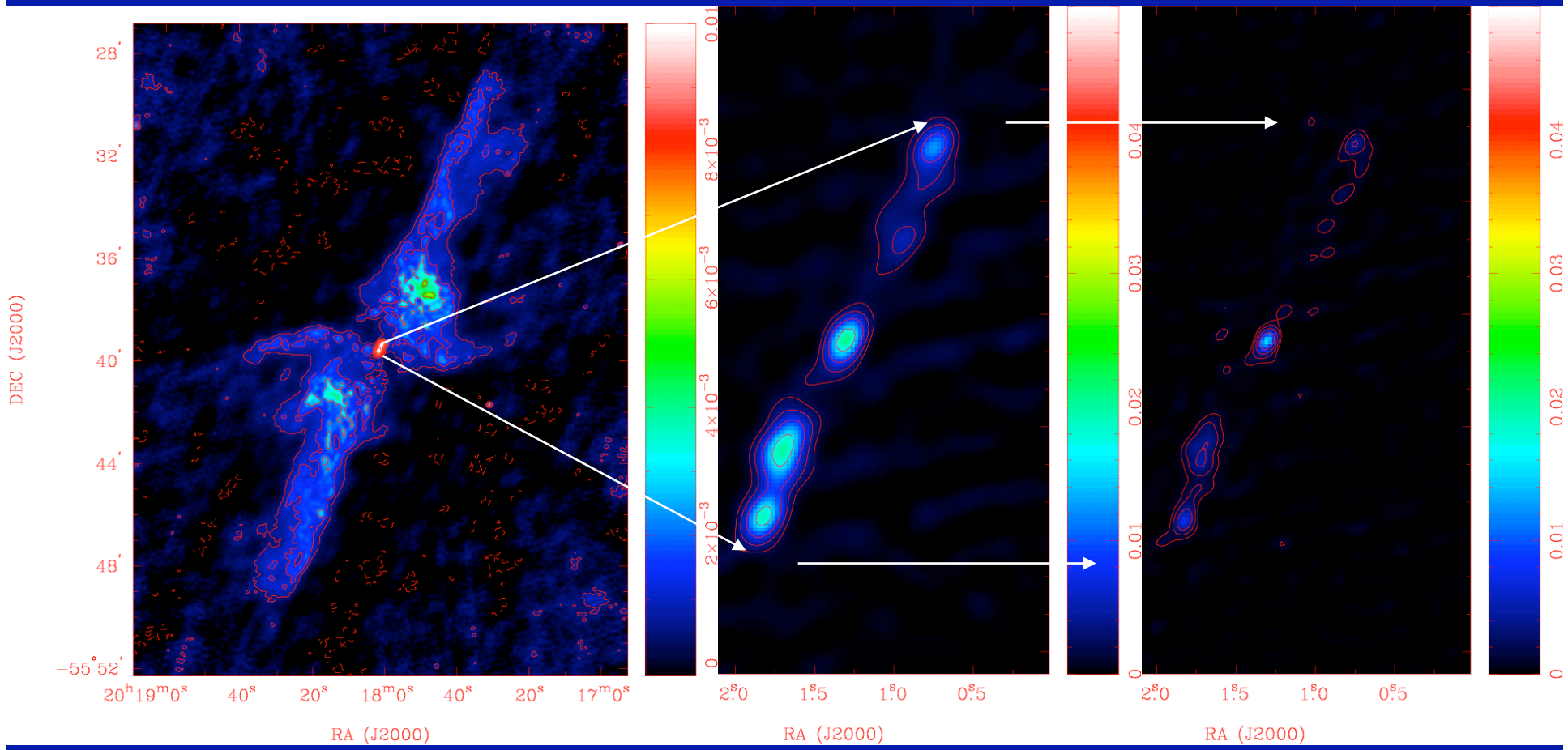


ATCA 1.4 GHz

The FR-I source has a 30 kpc edge-brightened inner double at the centre!

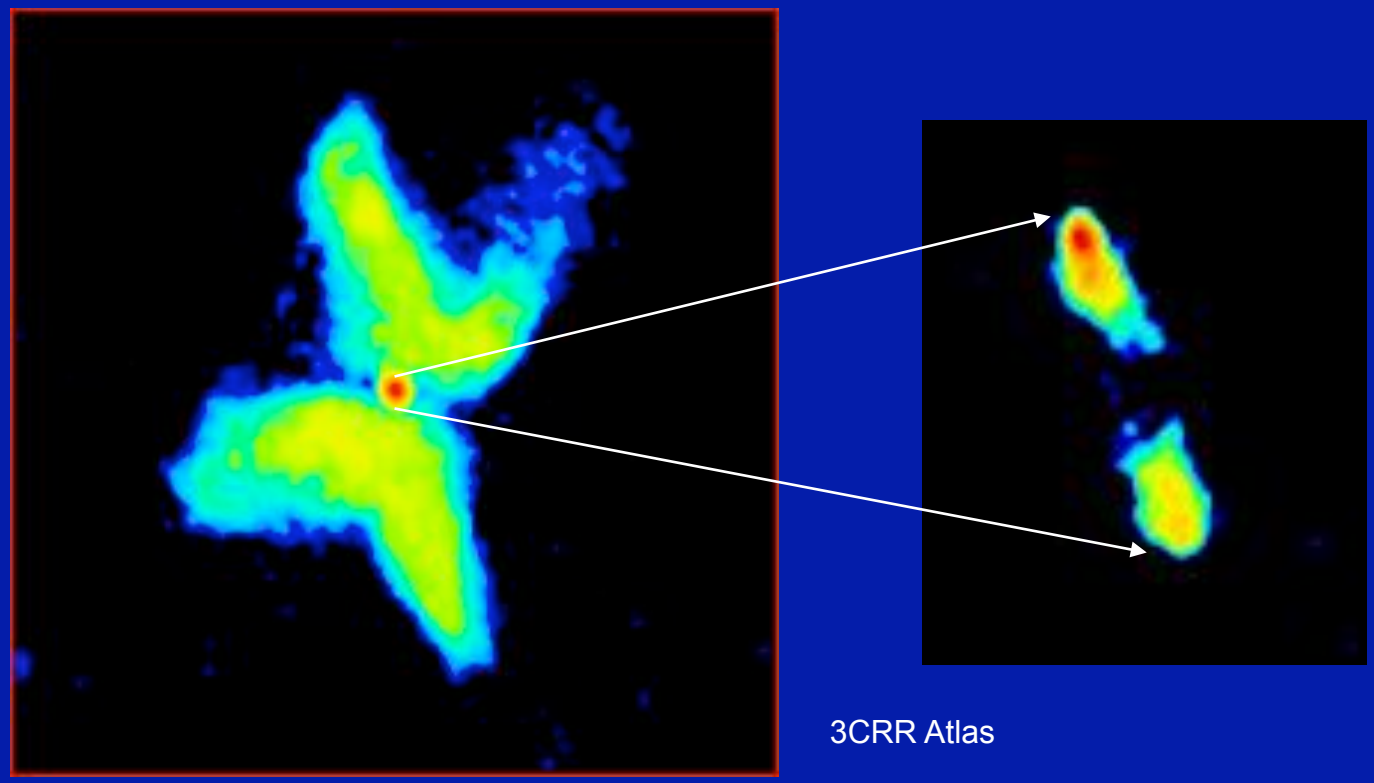
With PA same as the 1530 kpc outer double

It is restarting!



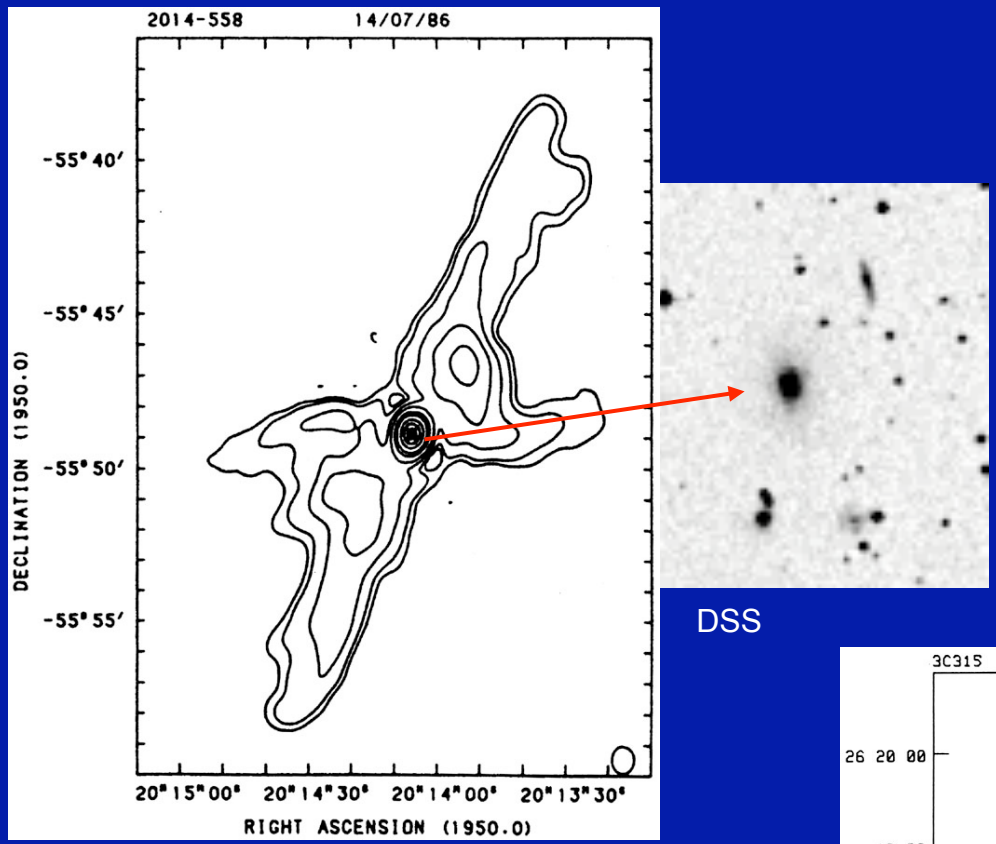
ATCA 1.4 GHz ATCA 4.8 GHz ATCA 8.4 GHz

We have identified more examples of
FR-I restarting X-shaped sources



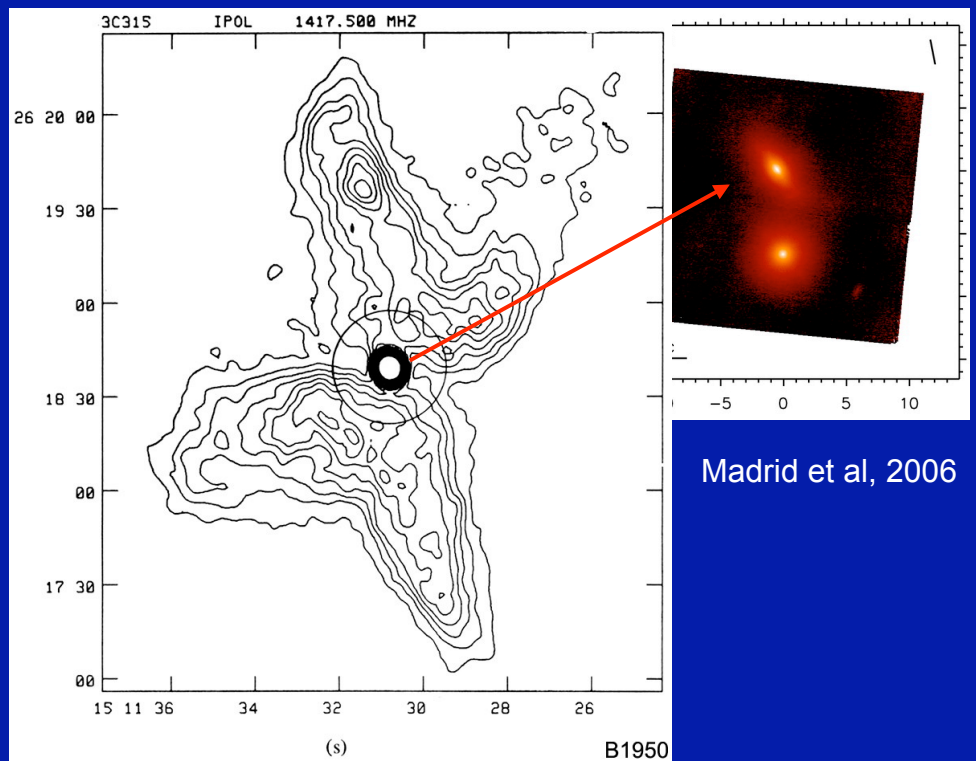
3CRR Atlas

- 3C315 has an 8 kpc inner edge-brightened double
- Position angle same as the outer double



DSS

Both these FR-I X-shaped sources B2014-558 & 3C315 have main radio axis close to optical major axis!

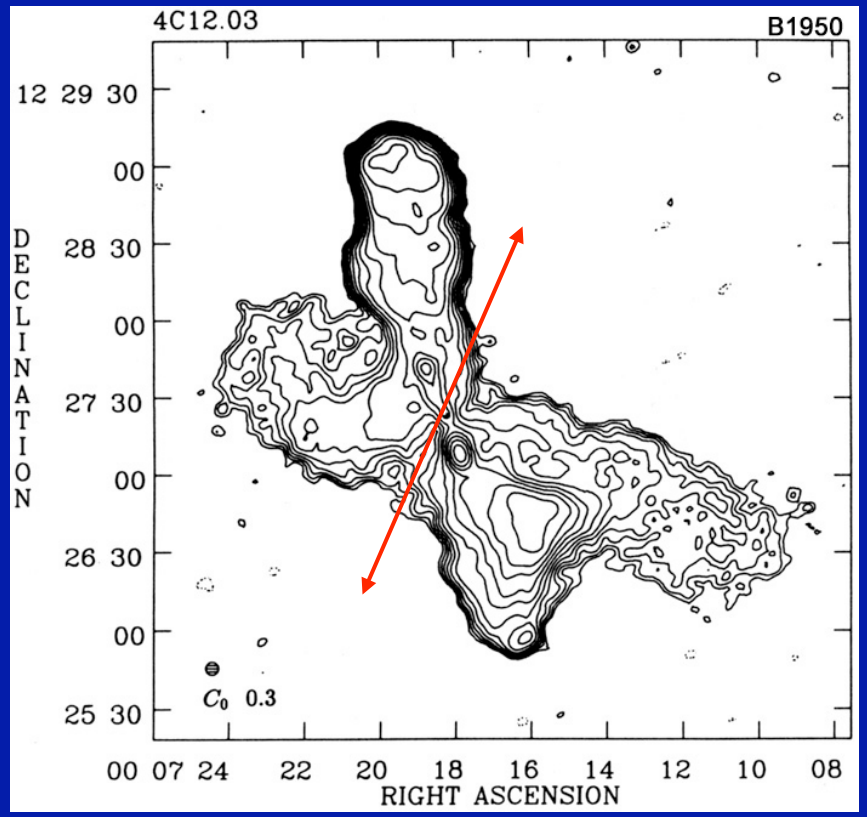


Madrid et al, 2006

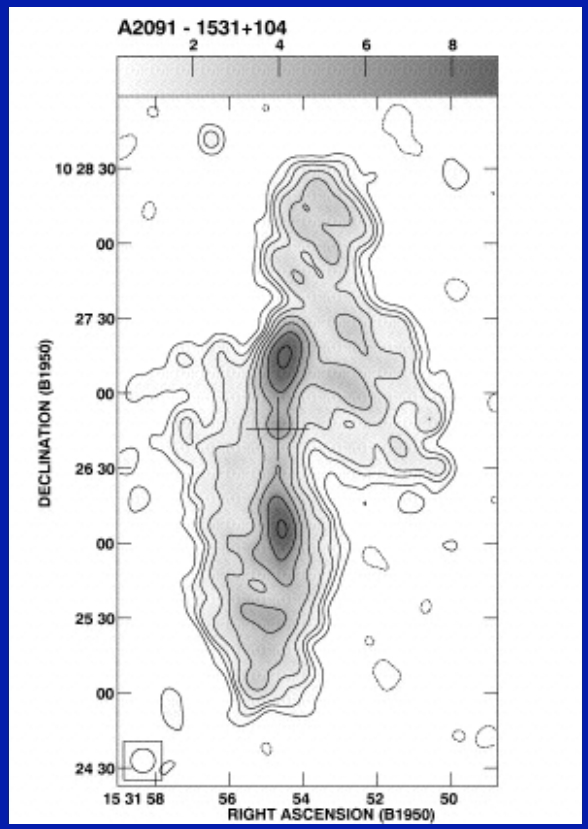
Both FR-I X-shaped radio galaxies have lobe-wing pairs on same side of optical major axis!

As expected in a backflow model

We have also identified XRGs that lack hotspots at the ends (and possess restarting inner doubles at the centre)



4C12.03
Leahy & Perley, 1991



1531+104
Ledlow and Owen, 1997

Conclusion so far:

Concerning FR-I X-shaped radio sources and the backflow model

- B2014-558 and 3C315 are of the “wrong type” and appear to be evidence against the backflow model
- However, both sources have relict outer lobes and are observed to be restarting
- Our understanding: both were hotspot radio sources in a previous epoch, when strong backflows created the wings we see today via interaction with an elliptical halo associated with the host galaxy

Further investigations

- Backflow deflection via asymmetric thermal gas appears to account for X-structures whether in FRII type or FRI type sources
- Is the underlying physical process more widespread?
- Is it also responsible for other, more frequent milder lobe distortions?

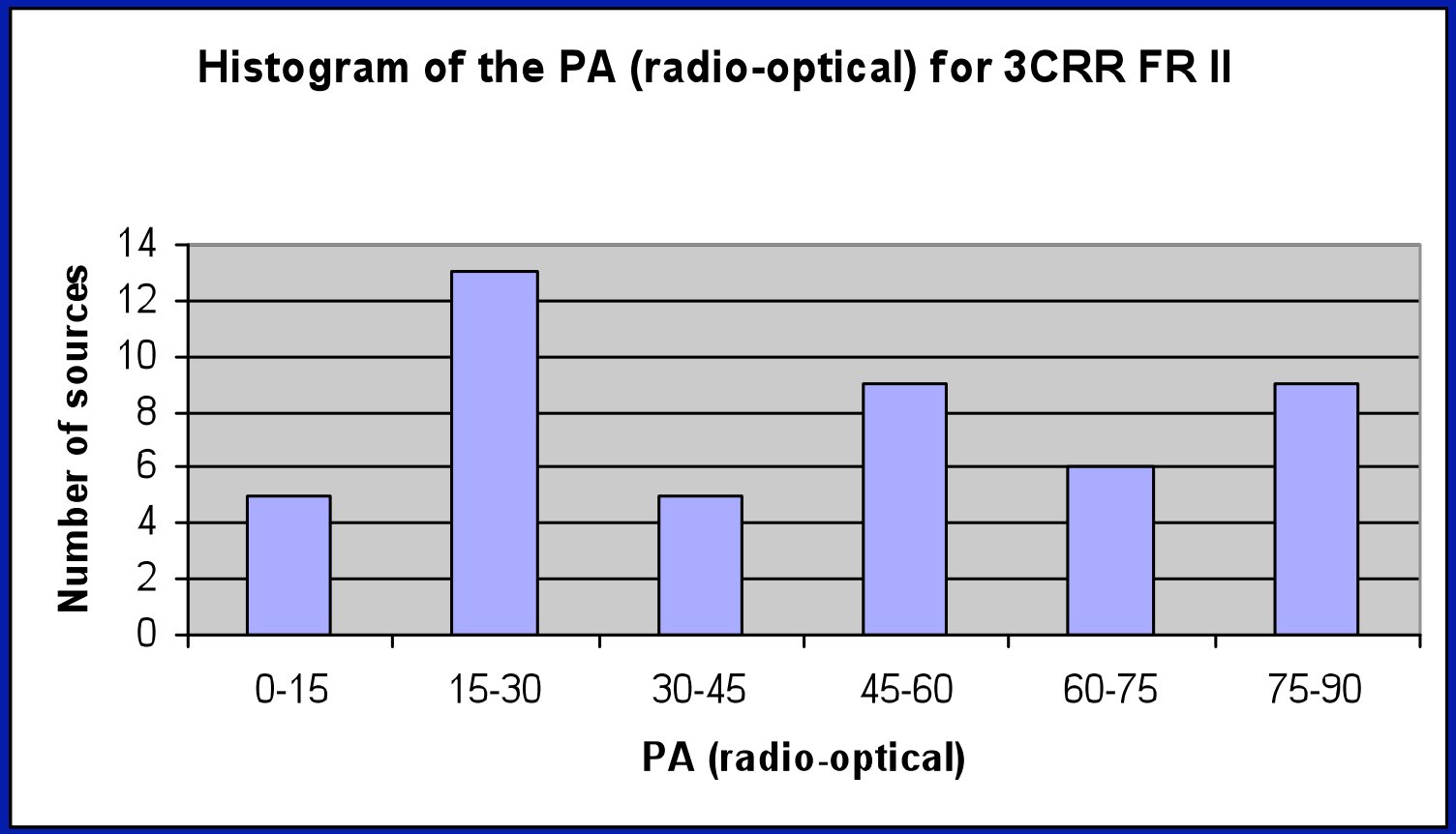
Results from our recent work on this topic

A study of the relative orientation of radio sources and their hosts

In three samples:

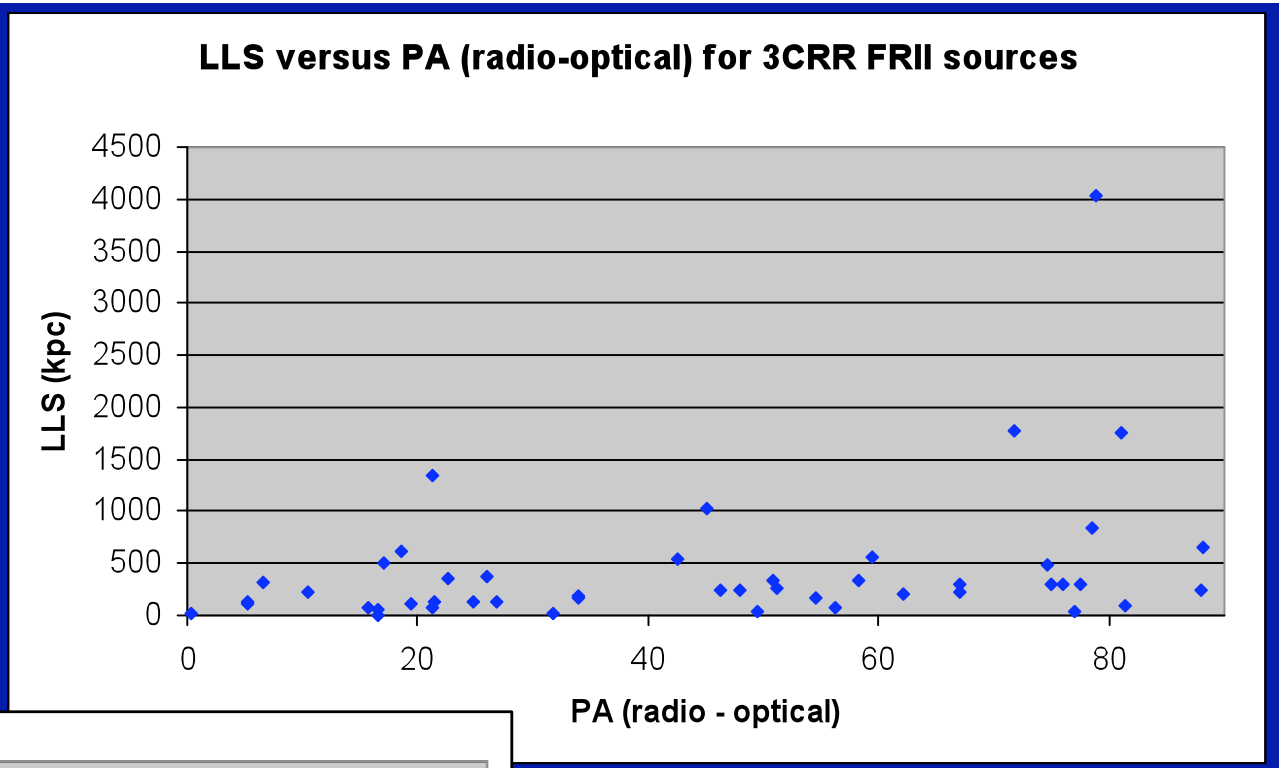
1. 3CRR: 3C revised sample ($z<0.5$)
2. GRG: Giant radio sources
3. XRG: X-shaped radio sources

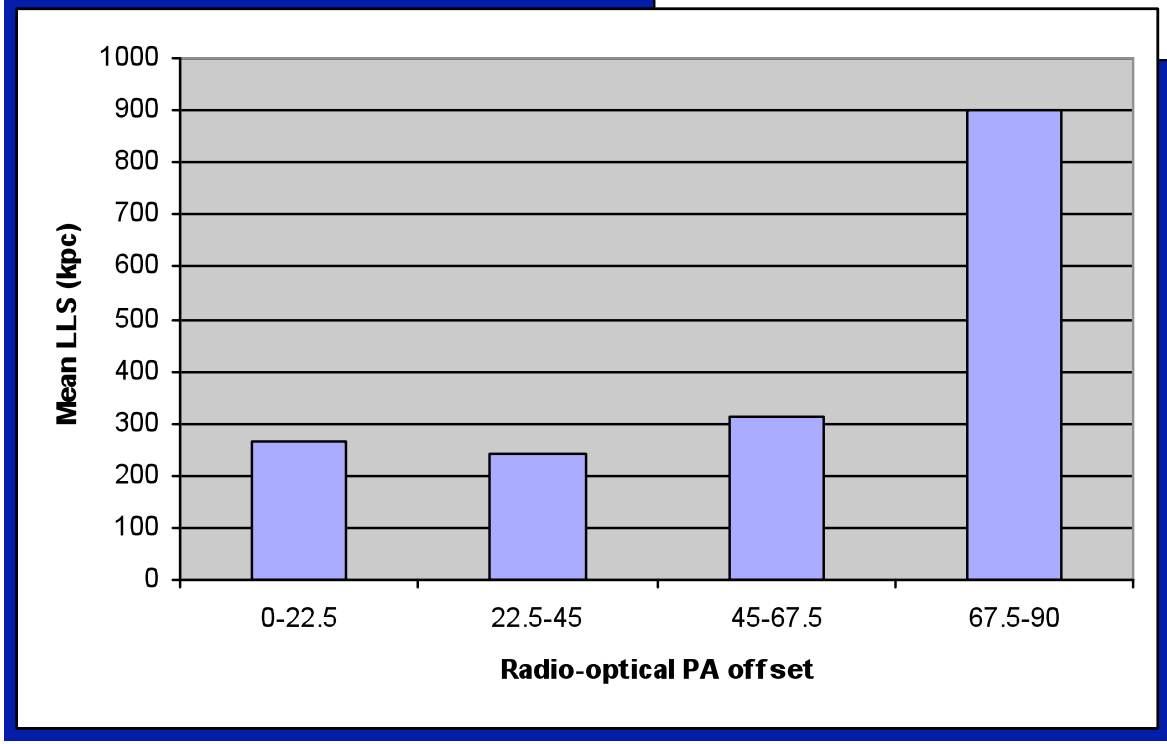
3CRR sample of FRII radio sources



3CRR sources have a distribution in PA over 0-90 degrees

3CRR sample of FRII radio sources

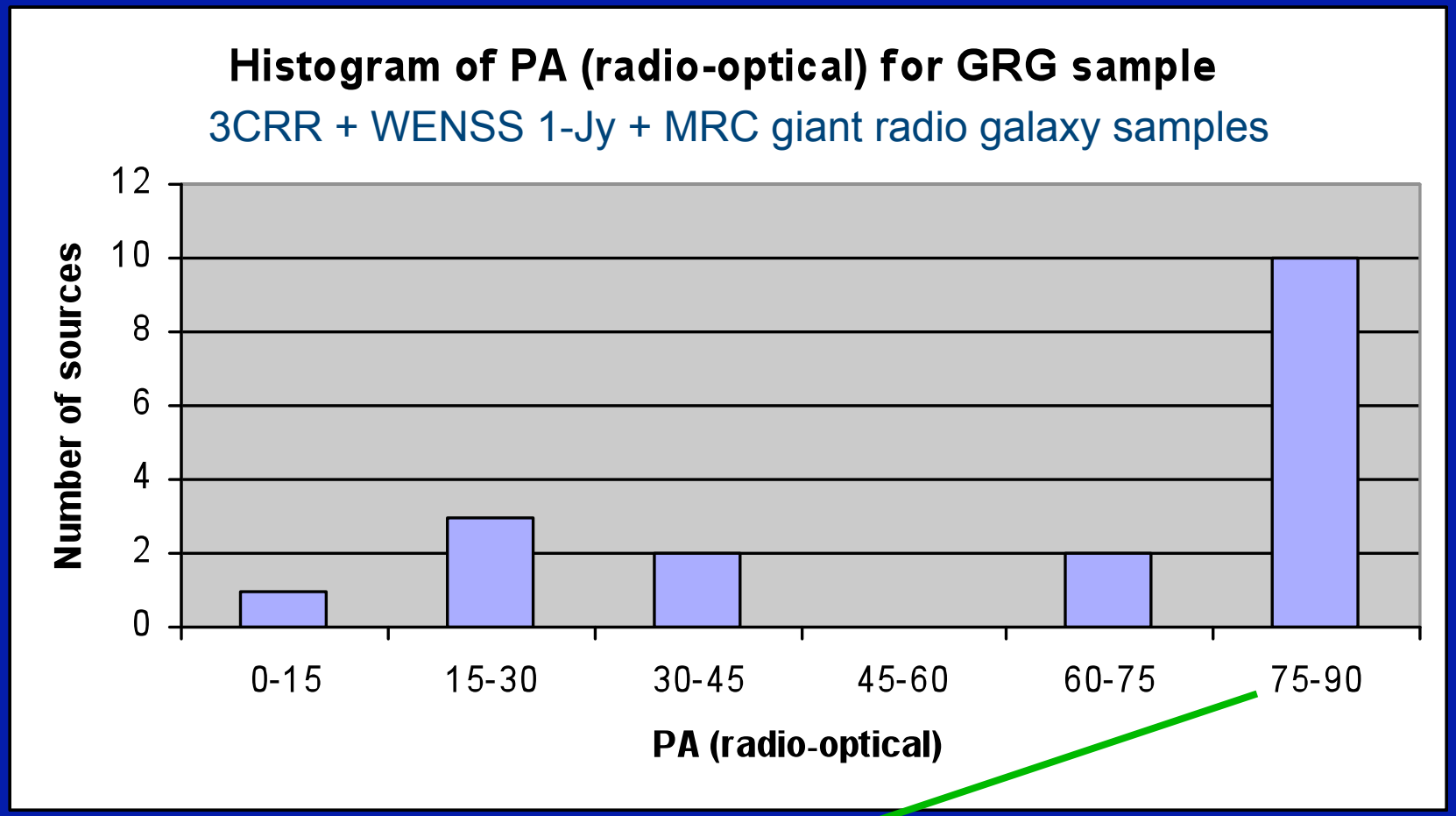




Giant radio sources appear to lie close to the minor axis!

	Whole sample	LLS < 700 kpc	LLS > 700 kpc
Median	46 deg	43 deg	72 deg

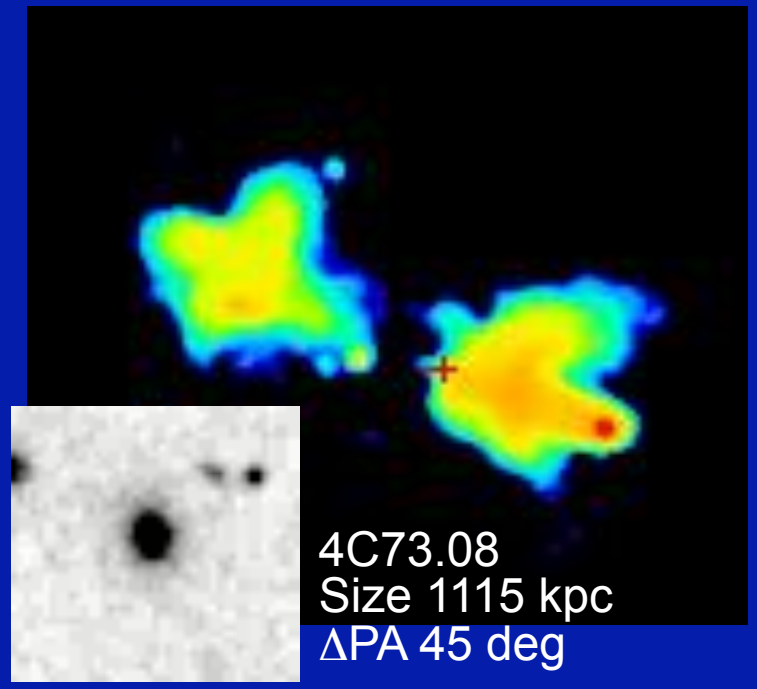
Giant radio galaxies appear to be minor axis sources!

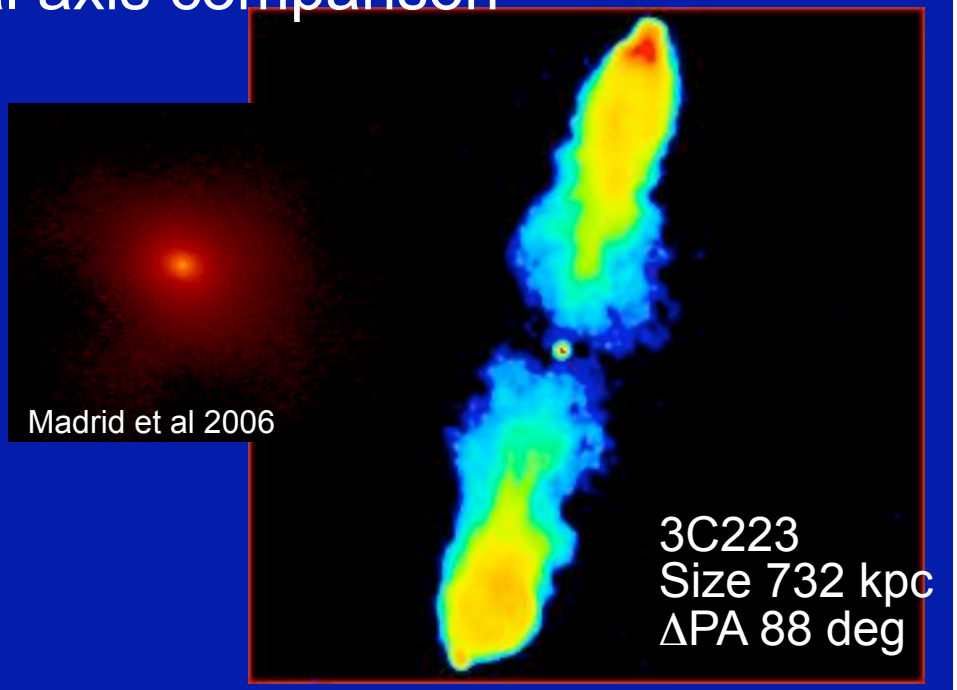


Median offset in radio-optical PA = 79 deg

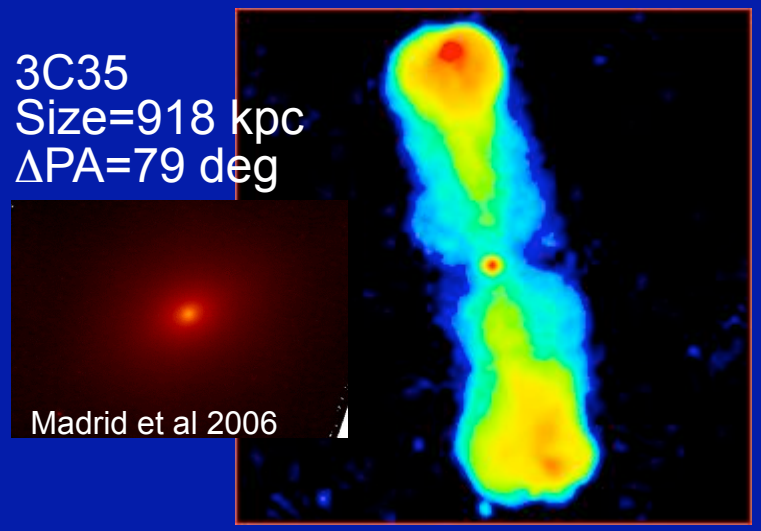
Most Giant Radio Galaxies are minor axis sources!

Giant radio sources: radio-optical axis comparison





Radio images from
3CRR Atlas



GRGs along minor axis lack wings!

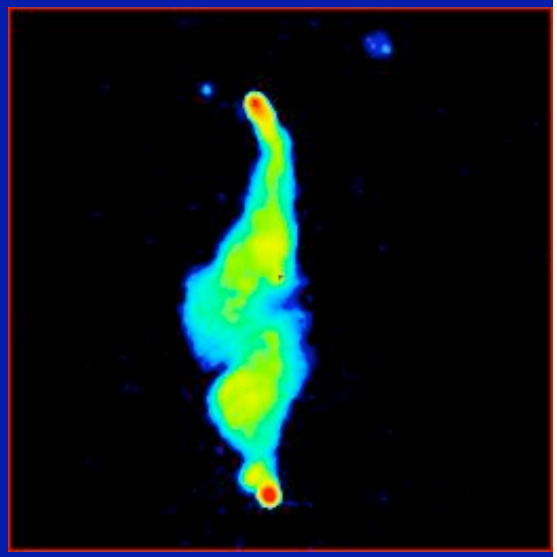
GRGs off the minor axis show prominent wings!

3CRR radio sources with prominent wings

Definition of the sample:
Central distortions > 50% of respective lobes

This gives 13 sources with

- Median linear size = 143 kpc
- Median radio-optical PA = 22.5 deg



3C61.1
3CRR Atlas

ΔPA=17 deg

Radio sources with prominent wings tend to be

1. Smaller, and
2. Major axis sources

Minor axis sources

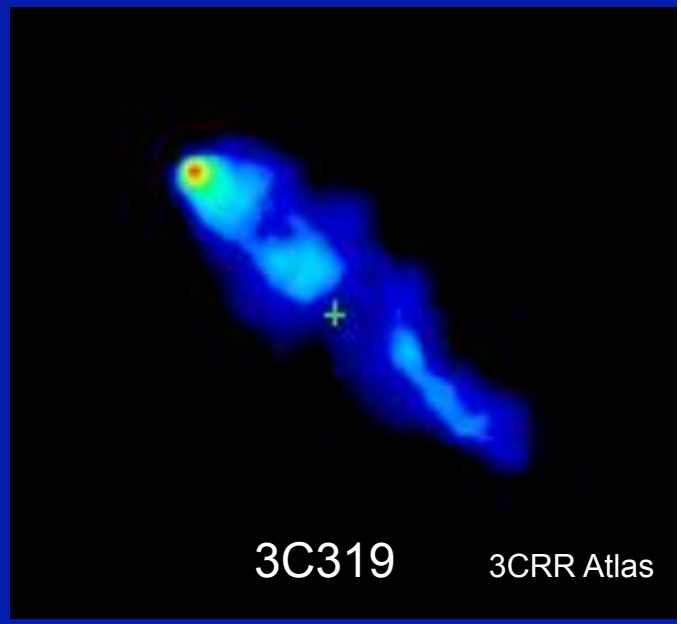
Definition: 3CRR radio sources with radio axis within 25 deg of host minor axis:

This gives 12 sources

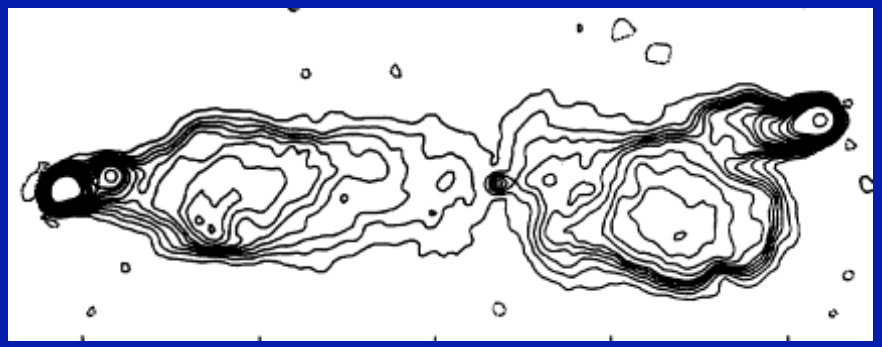
Median linear size = 410 kpc

None has central wings

5 are giant radio galaxies



3C319 3CRR Atlas



3C79 Spangler et al. 1984

(1) Wings have difficulty forming when radio axis is close to host minor axis.
(2) Minor axis sources often grow to giant sizes.

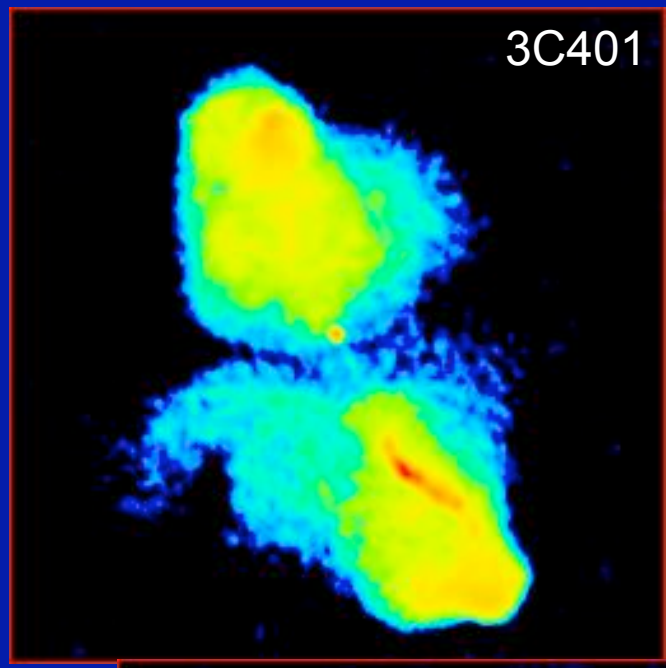
Major axis sources

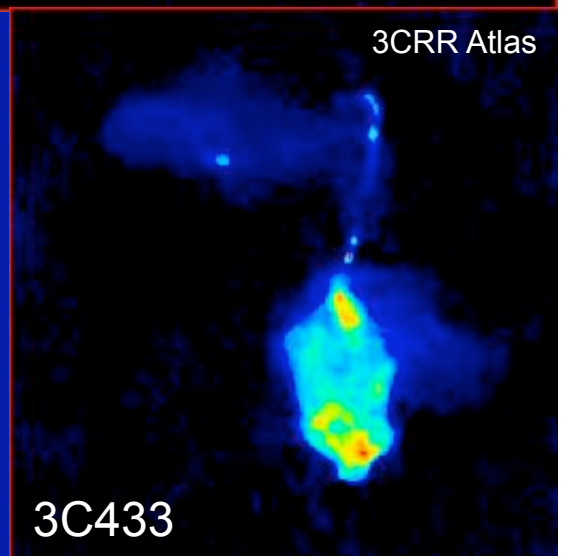
Definition: 3CRR sources with radio axis within 25 deg of host major axis

This gives 16 sources
Median linear size = 132 kpc

Sources with central distortions = 8
Sources with prominent wings = 5 of these 8

Sources with no lobe distortions = 6
Number of giant radio sources = 1
Sources with round lobes = 2



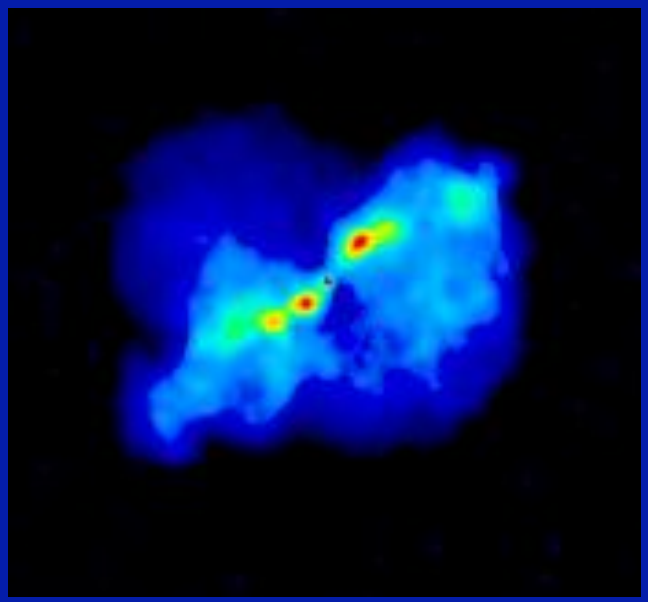


Radio sources with axis close to optical major axis tend to be
(1) smaller, and
(2) often have central lobe distortions

The X-shaped source sample
XRG sample

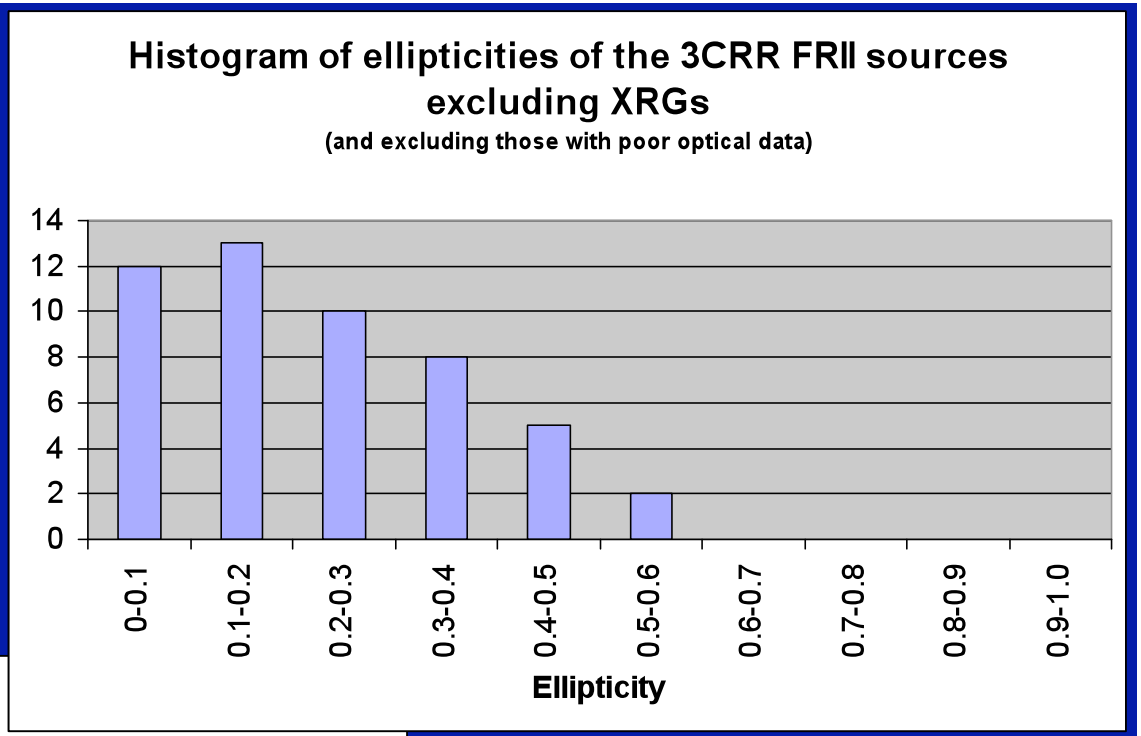
Definition of the sample:

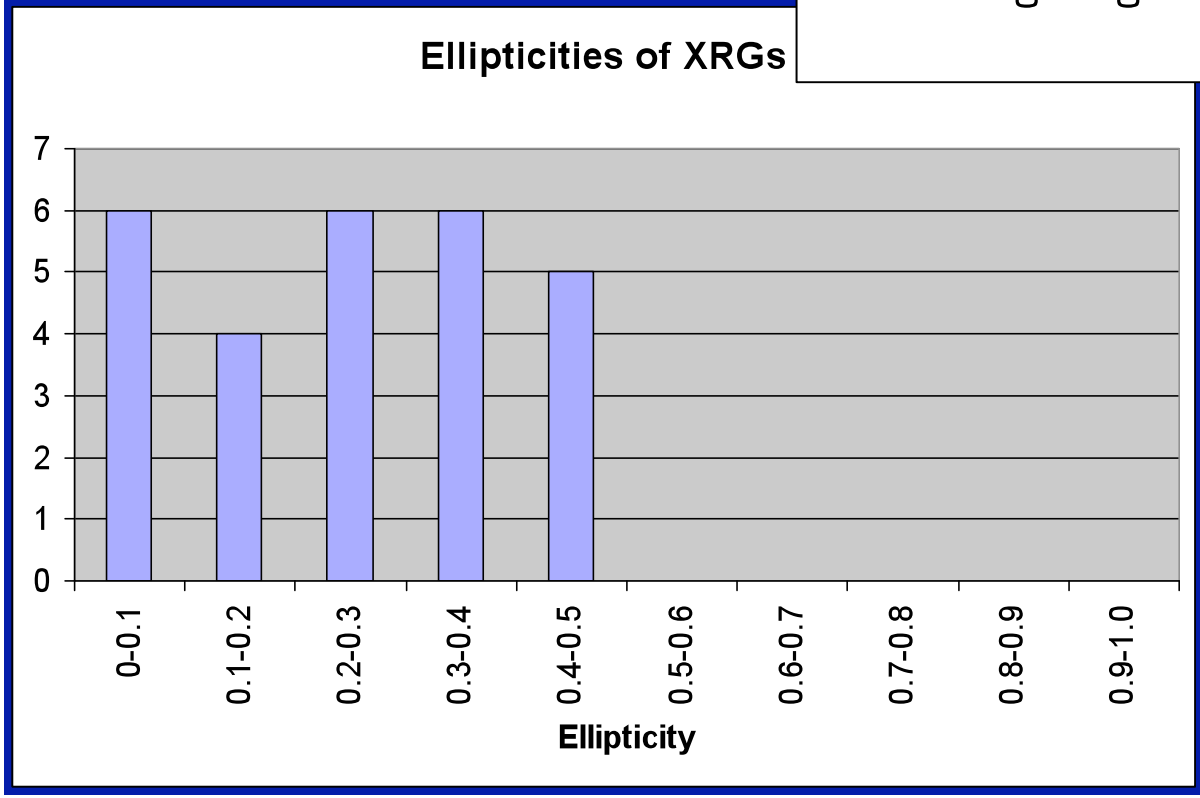
- Lobe distortion centrally located
- Opposing wings in both lobes
- At least one wing extent > 50% of corresponding lobe extent



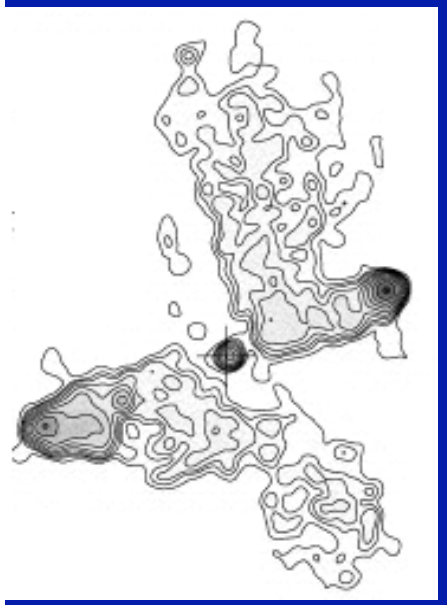
3C76.1 3CRR Atlas

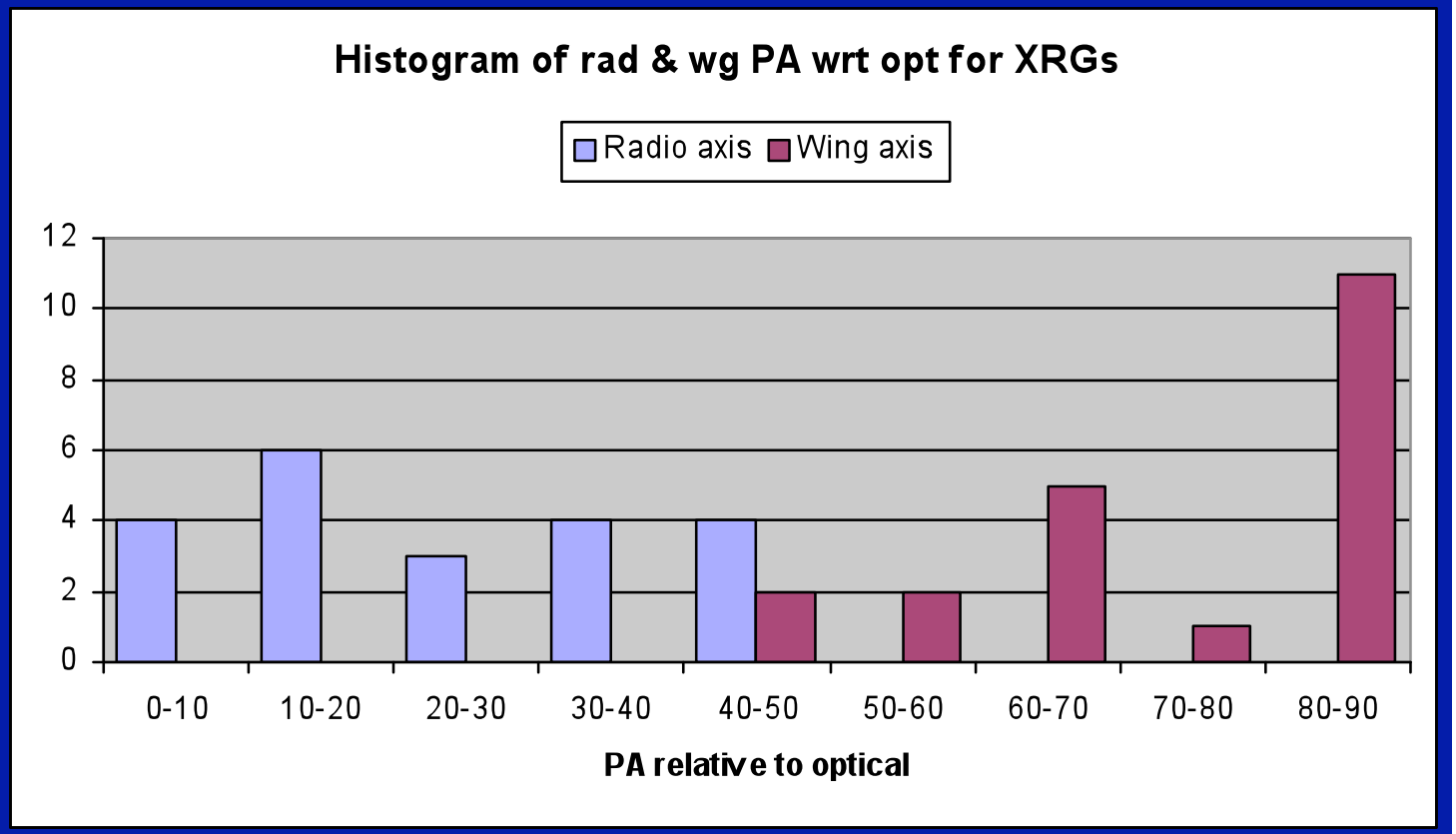
Host ellipticities





XRG hosts tend to be more elliptical !

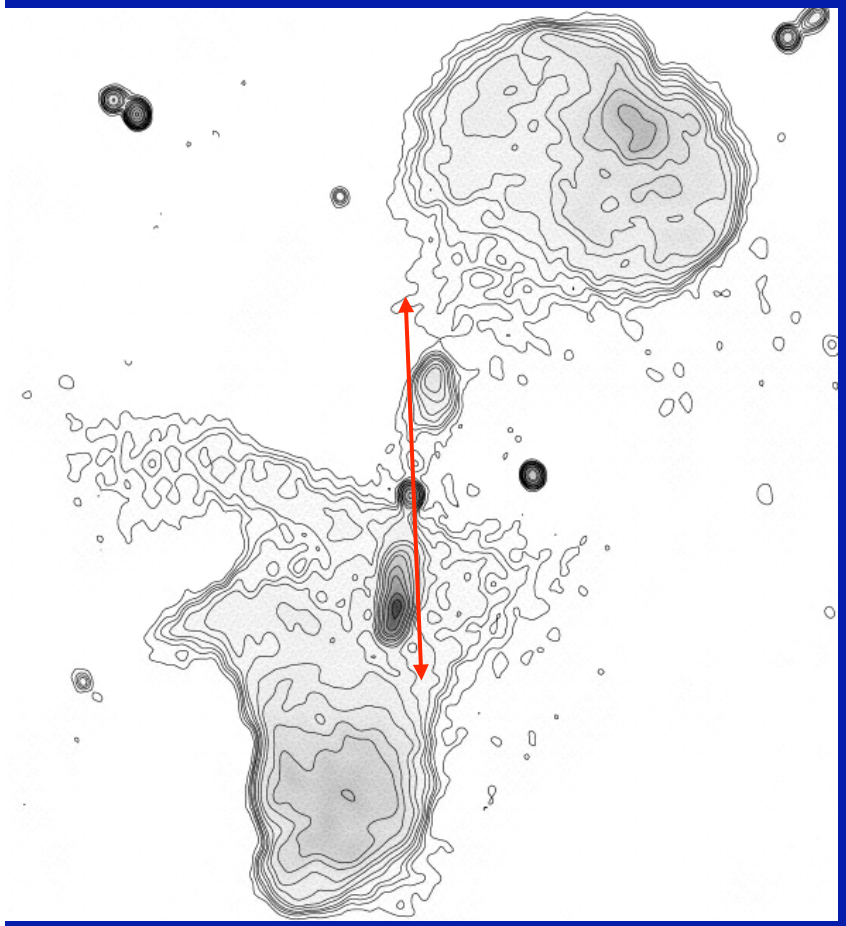




1. X-shaped sources have radio axis closer to optical major axis
2. Wings are closer to optical minor axis
3. Main radio axis is uniformly distributed over 0-50 degrees
4. Wings prefer to be close to the optical minor axis

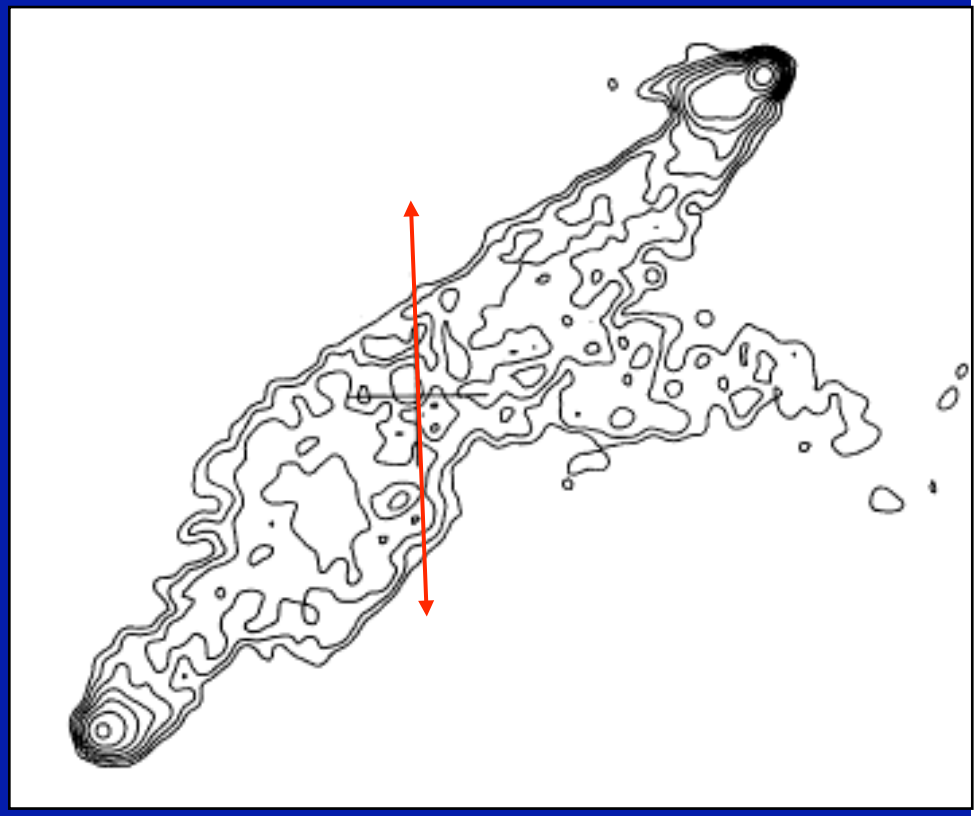
Examples of Giant radio sources with prominent wings:

Are these X-shaped radio sources?



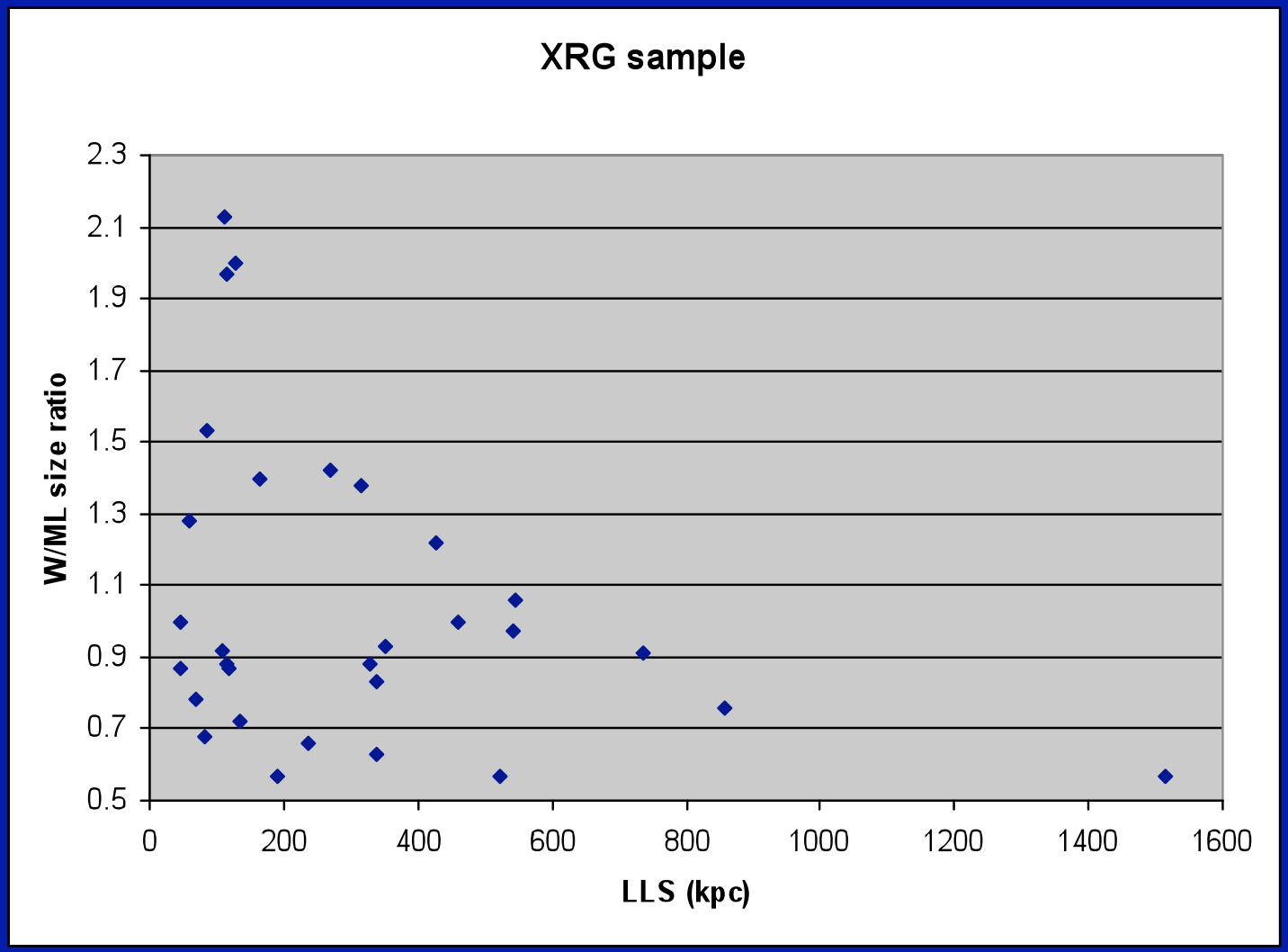
J0116-473

Saripalli et al. 2002



PKS 2356-611

Subrahmanyan et al. 1996



Large radio sources do not form wings
with large ratio of wing/main-lobe extent

In summary I

- A new class of X-shaped radio source has been introduced:
  - edge-darkened, hotspot-less XRGs and,
  - edge-darkened, hotspot-less XRGs with double-double structures
- Despite lacking hotspots their X-structures may be understood within the backflow model

In Summary II

A body of evidence has been presented showing the relations between radio morphology and direction of propagation of the radio jets relative to the host major axis:

Major axis propagation results in sources that

- are relatively smaller in size
- form prominent wing structures

Minor axis propagation

- aids in the formation of giant radio galaxies
- inhibits formation of wing structures

In Summary III

- X-shaped radio galaxies are characterised by
  - Tendency for alignment of the radio axis along the host major axis
  - Wings away from the major axis and preferentially close to the minor axis
  - Main lobes and associated wings on the same side of the host major axis
- Wing alignment with host minor axis may be stronger for more powerful sources

Conclusion I: Concerning the backflow model:

- The radio morphology in powerful radio sources depends on the orientation of the radio axis relative to the host galaxy major axis.
- Backflows interact with an asymmetric environment.
- Jets propagating along the major axis advance less, may have strong backflows which interact with host gaseous halo leading to prominent wings and X-shaped radio sources.
- Jets propagating along the host minor axis advance rapidly – often forming giant radio sources – may have weak backflows, resulting in poor formation of wings and almost never forming X-shaped sources.
- It is of interest to ask whether an asymmetric gas halo is all that is needed to explain the observed range of structures.
- Or whether asymmetric winds or super winds play a significant role.

Conclusion II: Concerning the jet-reorientation model:

A model combining backflow and jet reorientation

- The jet-reorientation model inherently requires a rejuvenation of the relict lobe: because the rarity of relicts implies that relicts disappear in a fraction of the lifetime of a source of similar linear size.

- It may be that low density channels along the minor axis are carved out of the ambient thermal halo in a previous epoch, which are later filled by backflow from a major axis source following a flip in axis.

- In this incarnation of the jet-reorientation model:

X-shaped radio sources result when
- a jet flips from minor axis to the major axis, and
- strong backflow – which happens in the case of major axis sources, rejuvenates the relict lobe to form an X-shaped radio source.

- The existence of X-shaped radio sources with wings longer than main axis favors such a model.

Consequence of the combined model:

If jet-reorientation is the mechanism for the formation of X-shaped radio sources:

- As radio sources have no preferred orientation, axis flips may occur from any initial orientation, minor axis or major axis
- X-shaped sources with radio along minor axis and X-ray lobes along major axis ought to be as common as X-shaped radio sources
- These are the major axis sources that flipped to be oriented along the minor axis.
- And the abundance of sources with significant flips in axis, - and the numbers of black-hole mergers – might be underestimated by counting only X-shaped radio sources.

X-shaped Radio Sources

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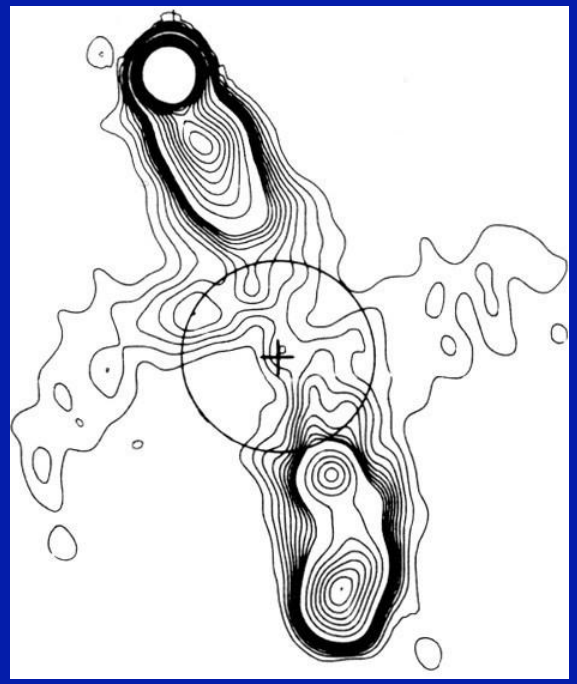
Ravi Subrahmanyan *Raman Research Institute*

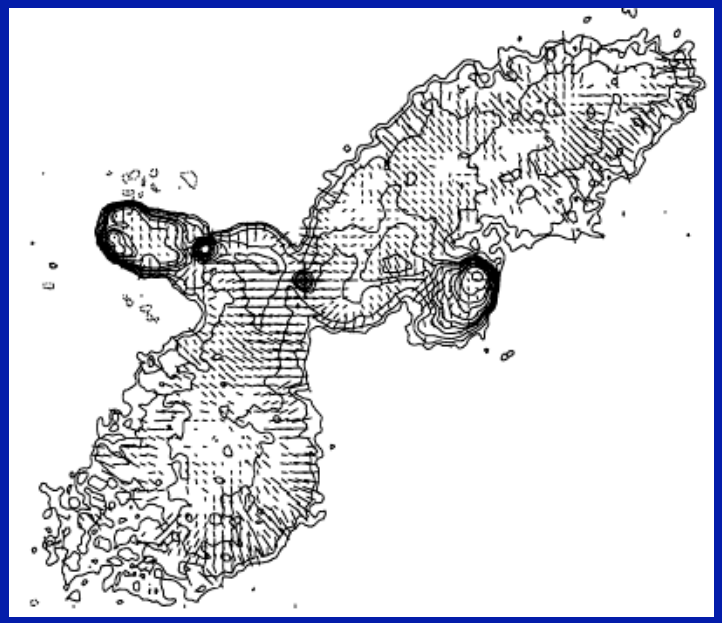
Backflow model

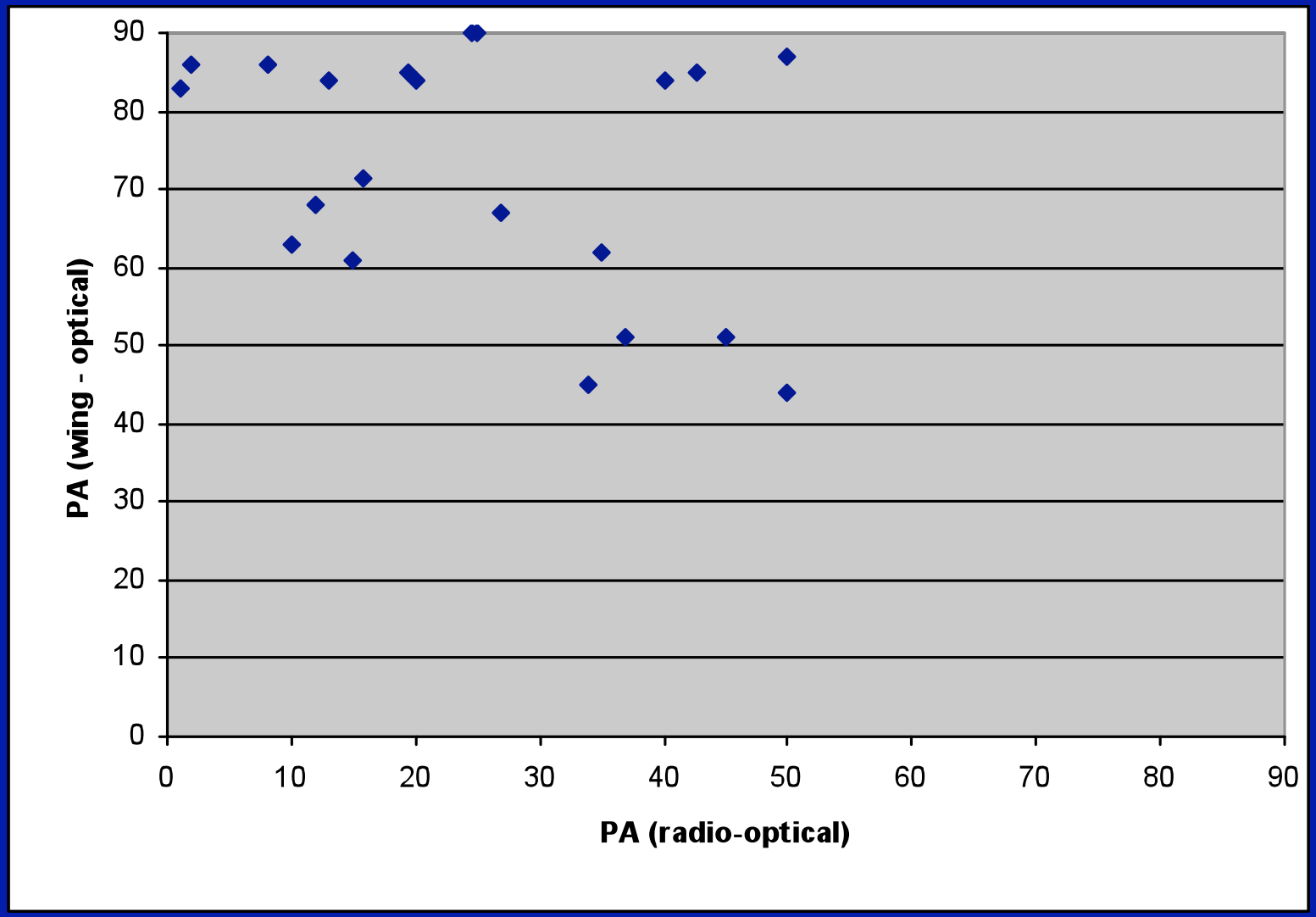
- Key requirements
  - Backflows
  - Asymmetric gas distribution

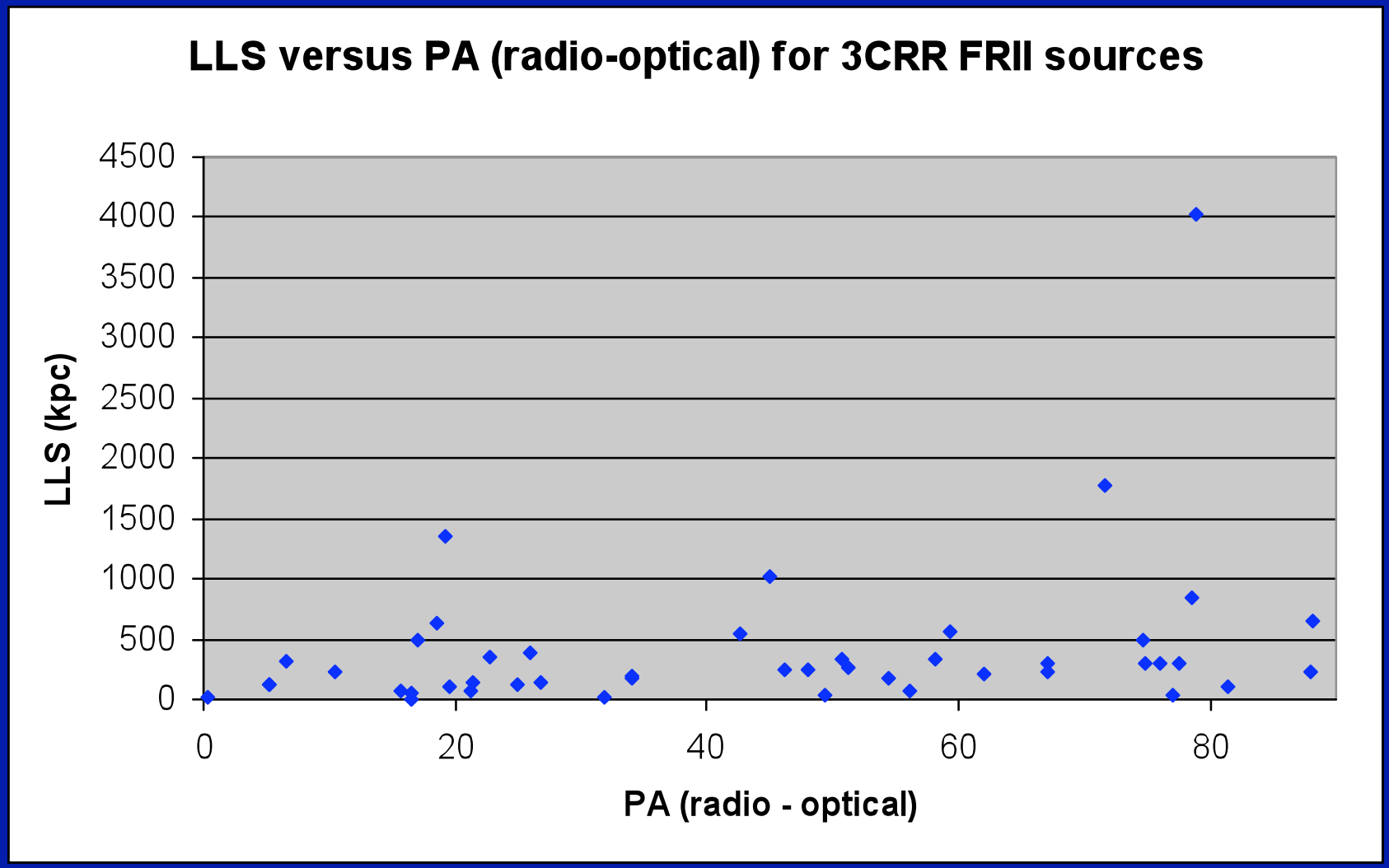


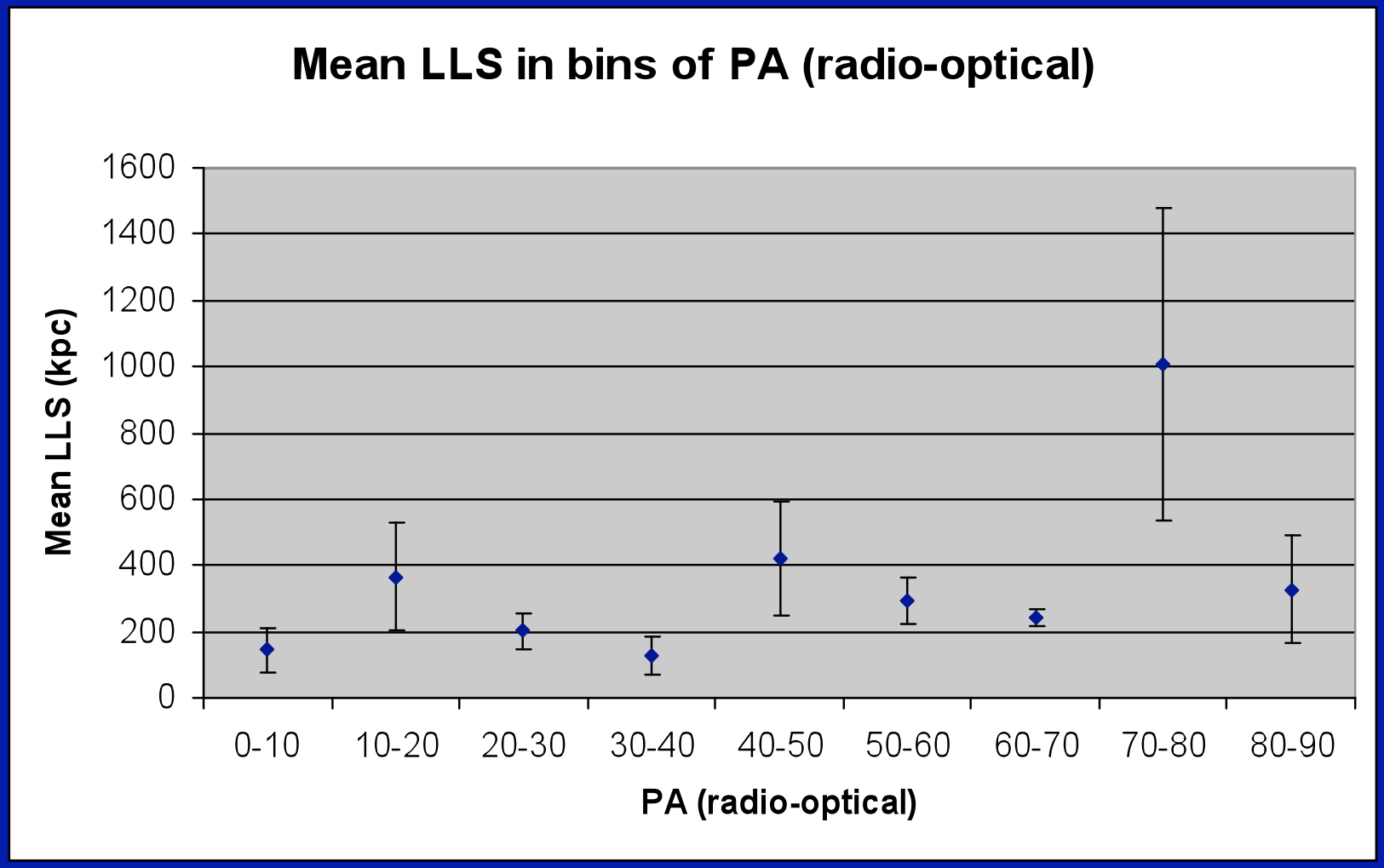
Jet re-orientation model

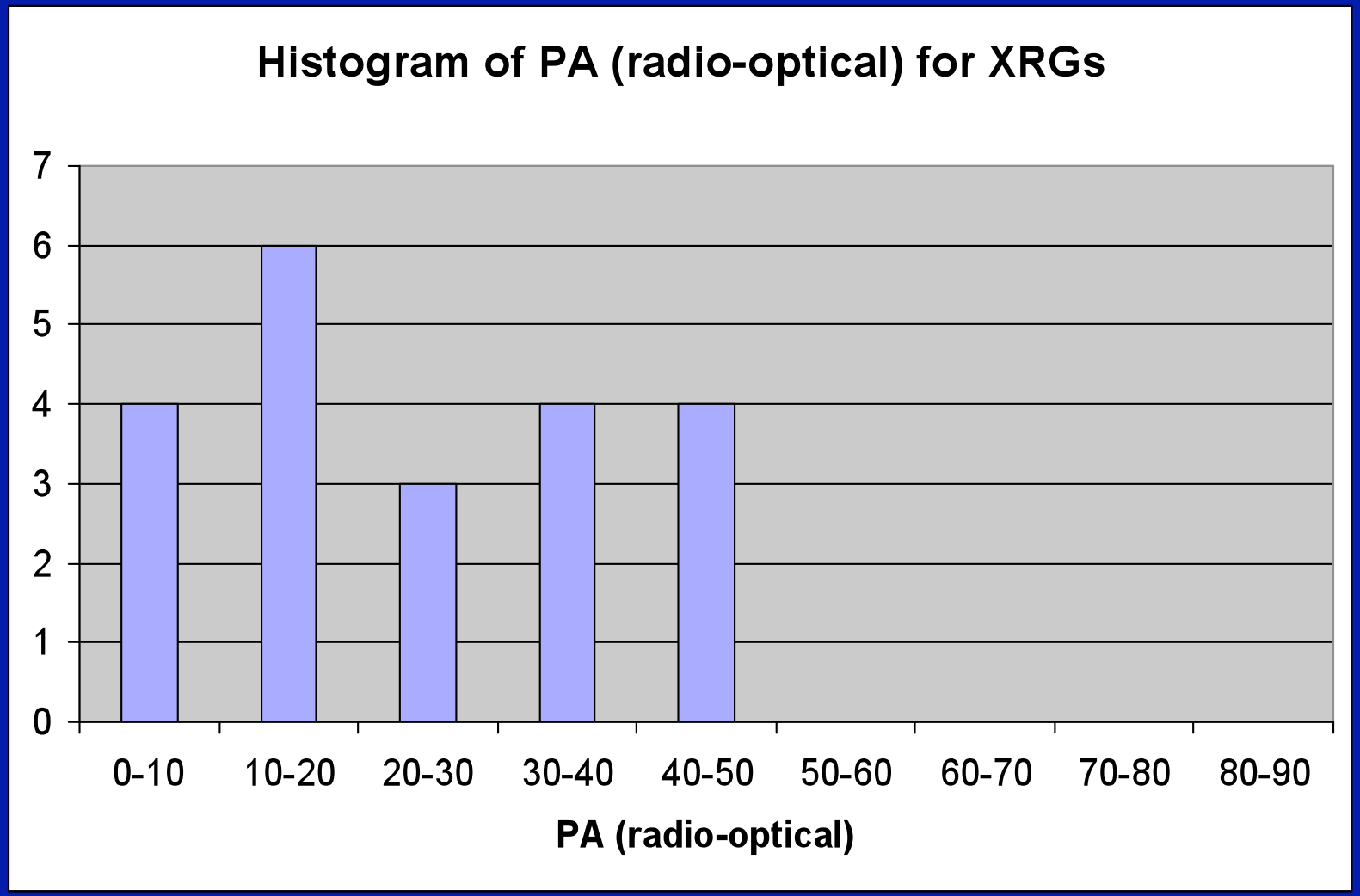
- Key requirements
  - Rapid and large angle flip in jet axis
  - Relic lobes to remain visible




PA (wing - optical)
PA (radio-optical)
0
10
20
30
40
50
60
70
80
90


LLS versus PA (radio-optical) for 3CRR FRII sources
LLS (kpc)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
PA (radio - optical)


Mean LLS in bins of PA (radio-optical)
Mean LLS (kpc)
1600
1400
1200
1000
800
600
400
200
0
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
PA (radio-optical)



All radio-optical PAs of XRGs are less than 50 degrees

3CRR sources with ‘mini’ wings

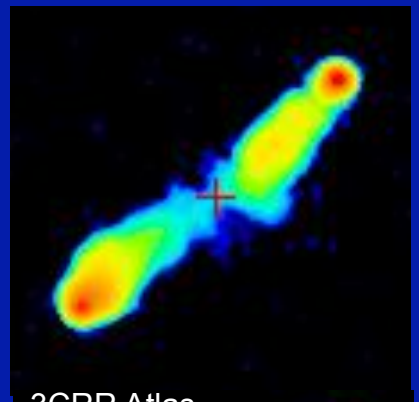
Definition of the sample:
Central distortions < 50% of respective lobe

This gives 11 radio sources
6 have non-circular hosts

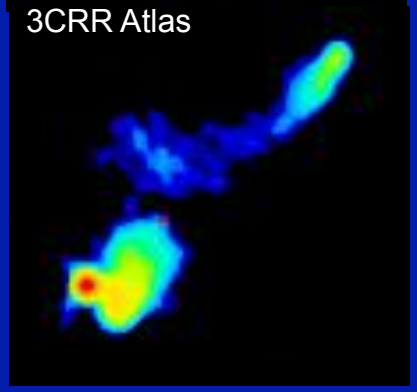
2/6 are within 25 deg of host major axis – similar to the finding for sources with prominent wings.

4/6 sources have ΔPA = 50 – 78 degrees
- And are closer to host minor axis
- All 4 sources are associated with EELR or have a close neighboring galaxy, which may be the cause of the mini-wing

3C42 ΔPA=21

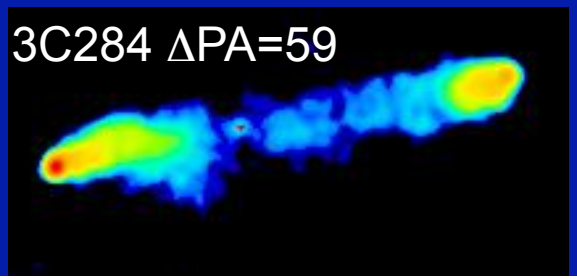


3CRR Atlas



3C300 ΔPA=23

3C284 ΔPA=59



Mini-wing sources may be caused by interactions with EELRs or galaxy neighbours, and may not be aligned close to host major axis, unlike prominent-wing or X-shaped sources.

Radio morphologies

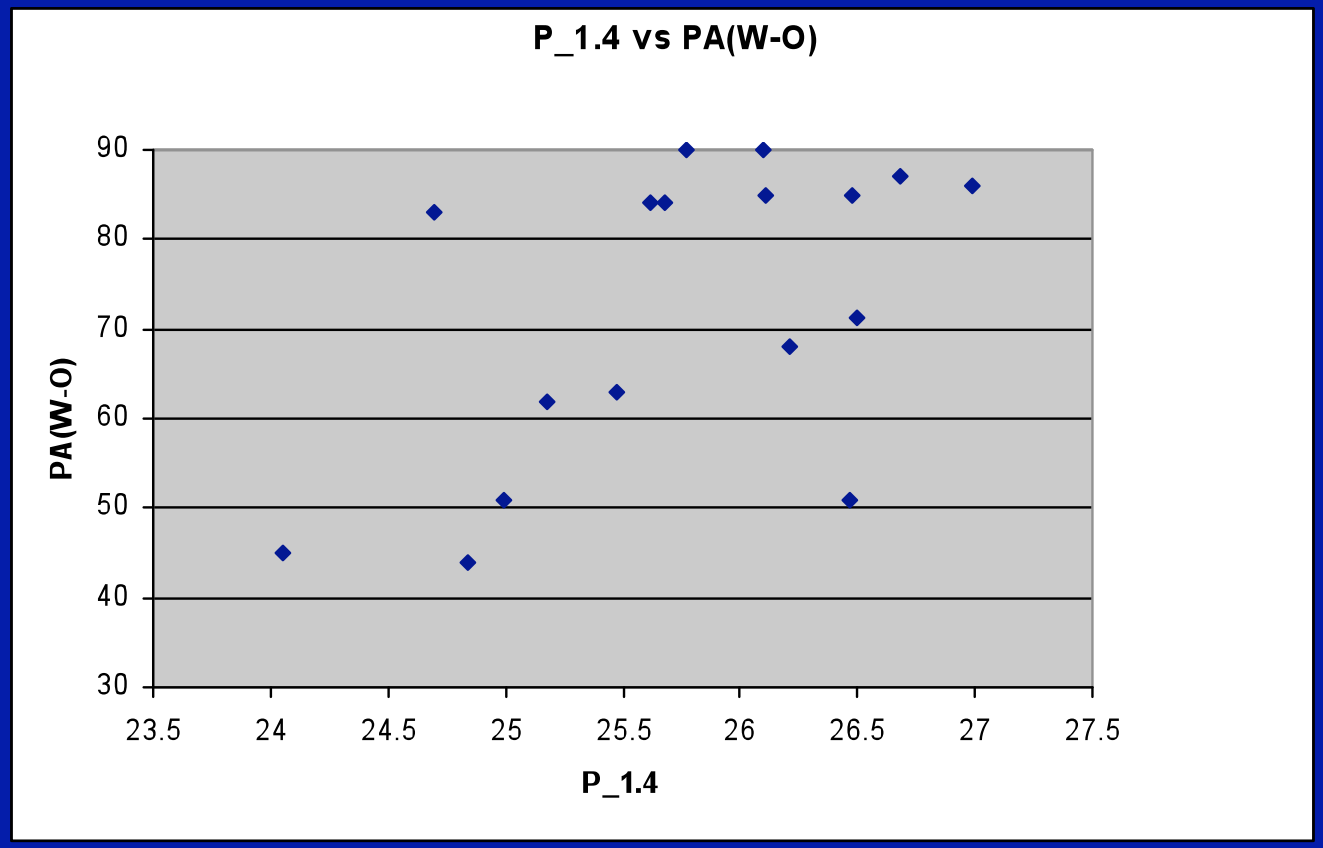
3CRR radio galaxies with sizes > 700 kpc

-- 9 sources

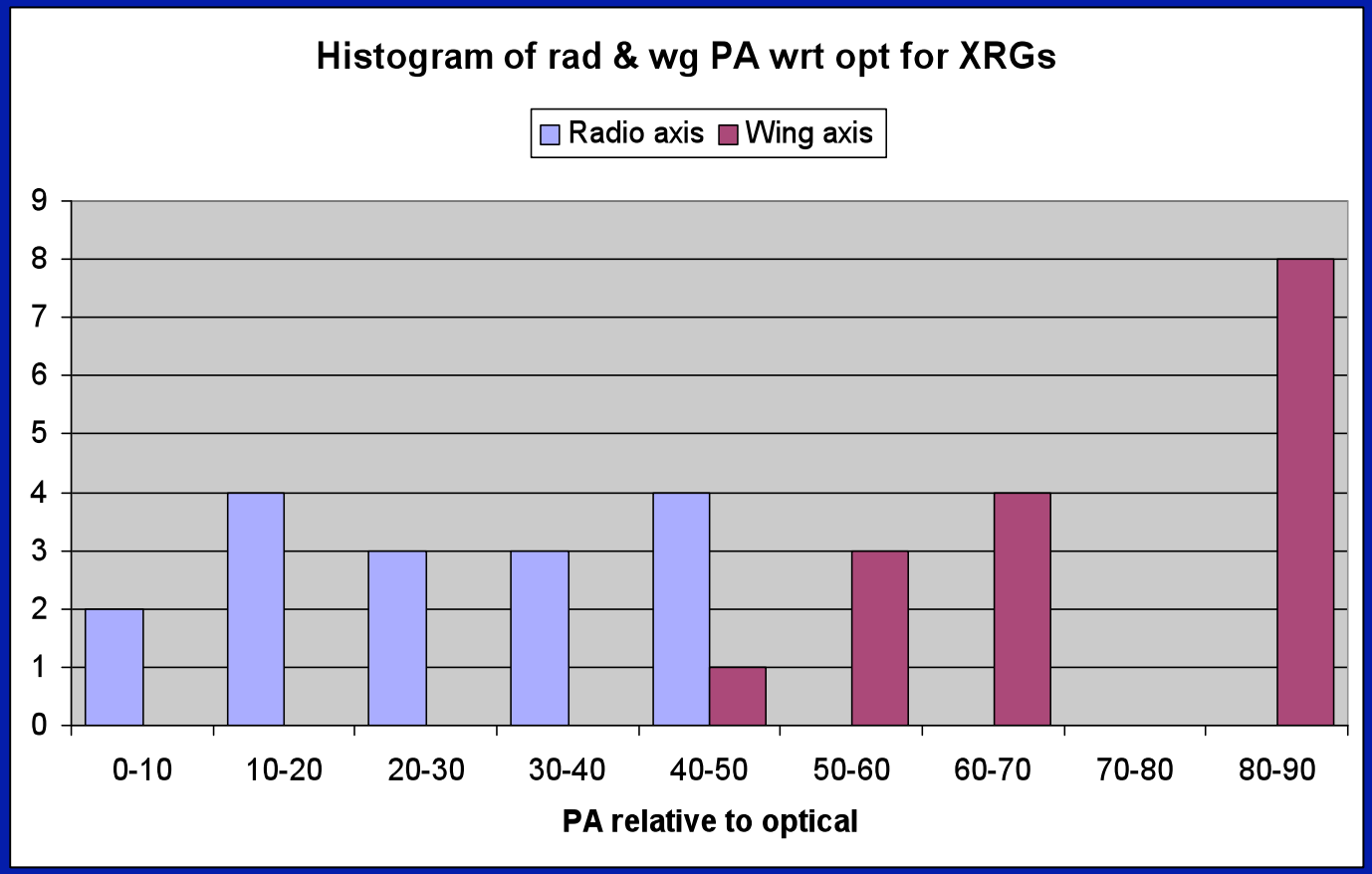
-- only 1 / 6 with non-circular host has a central distortion

Wings have difficulty forming in large size radio galaxies.

Source radio power and wings



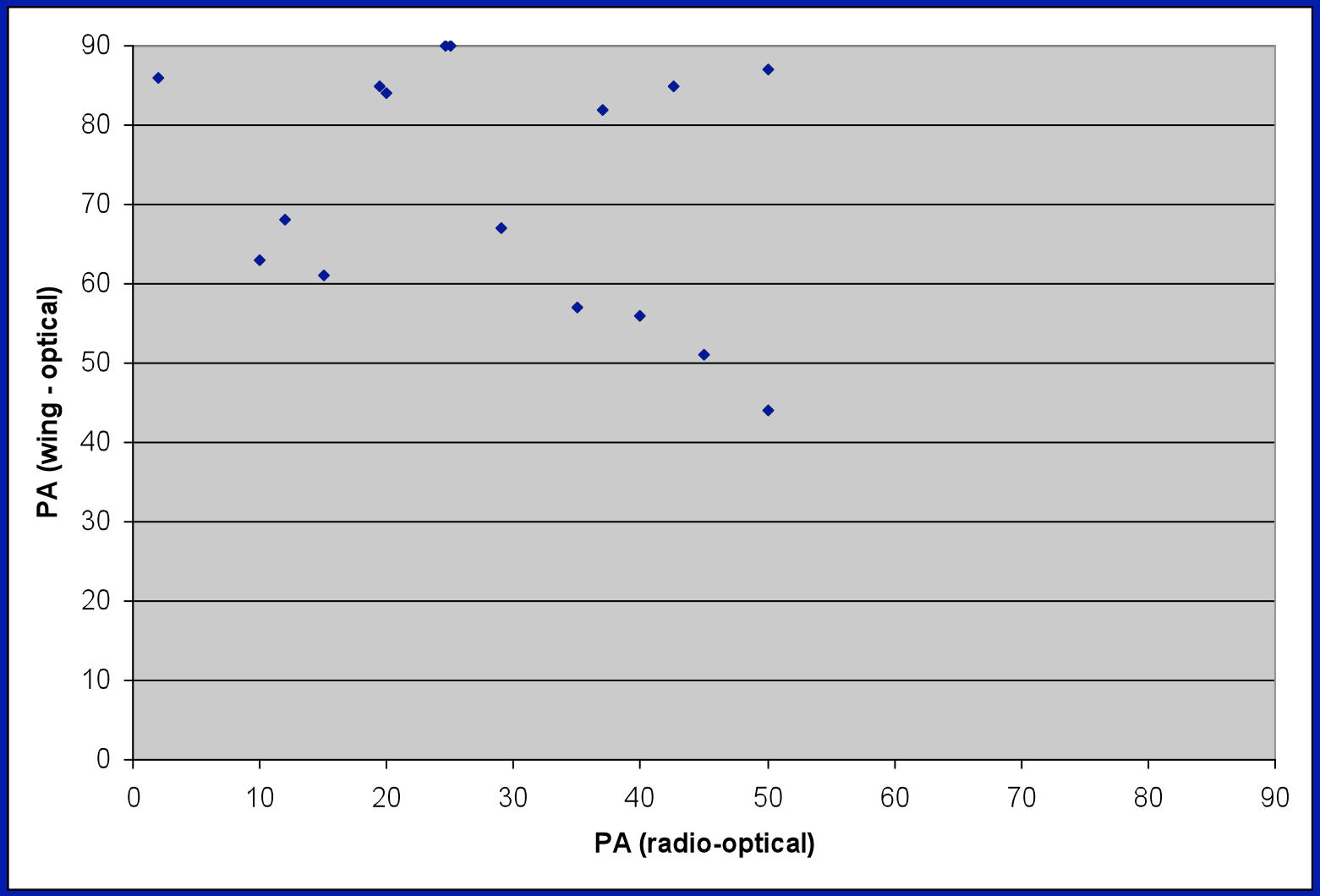
High power sources may have wings preferentially along host minor axis



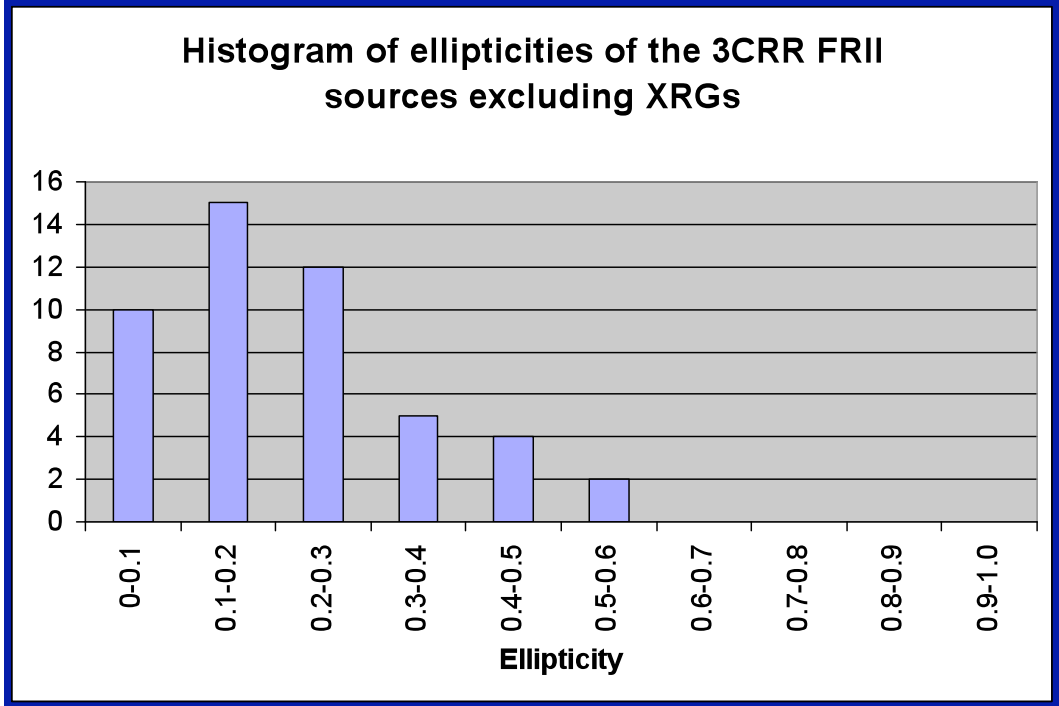
X-shaped sources do not have radio axes along minor axes and the wings in X-shaped sources are not observed along the major axis.

In X-shaped sources the radio axes are within 50 deg of the major axes and their wings are within 50 deg of the minor axes.

While the radio axes in X-shaped sources are fairly uniformly distributed within 50 deg of the major axes, the wings are preferentially close to the minor axes, with 10 deg.



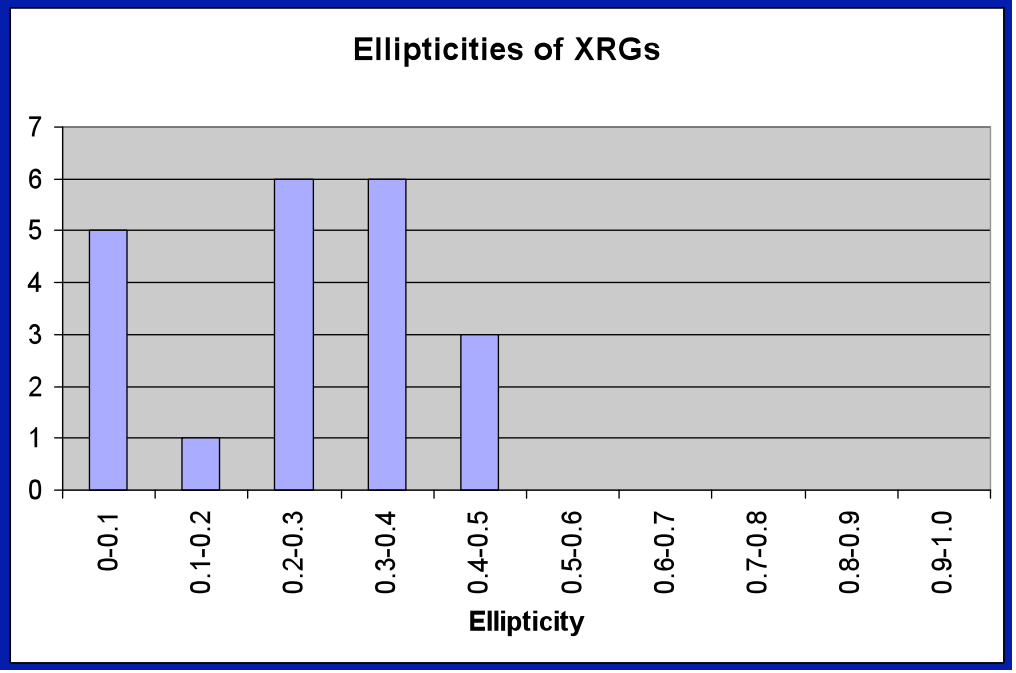
As the radio axis shifts from the major axis 11/14 sources maintain their orientation close to the minor axis to within 30 deg.

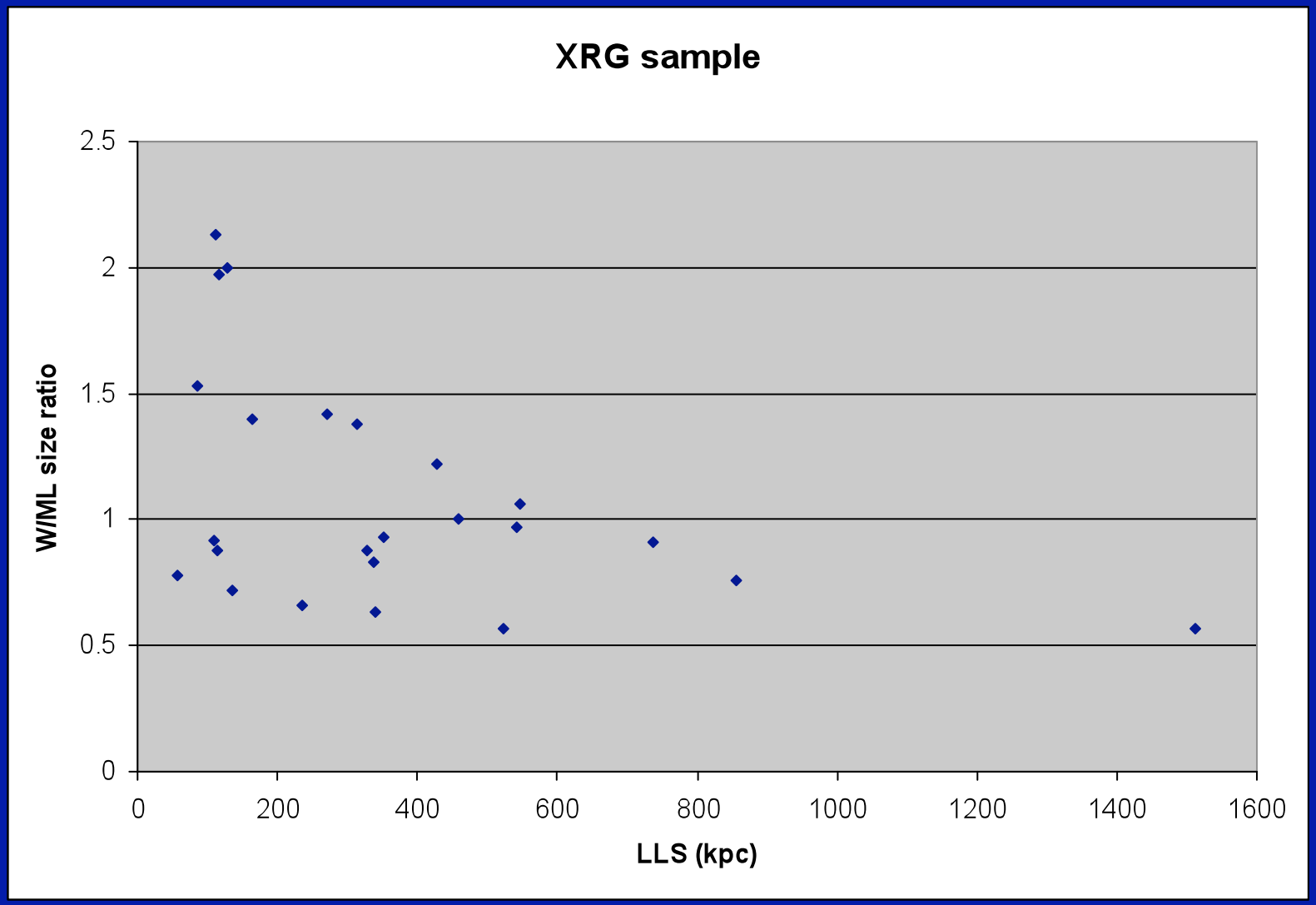


All 3CRR FRII radio galaxies
Median ellipticity = 0.2 ± 0.03

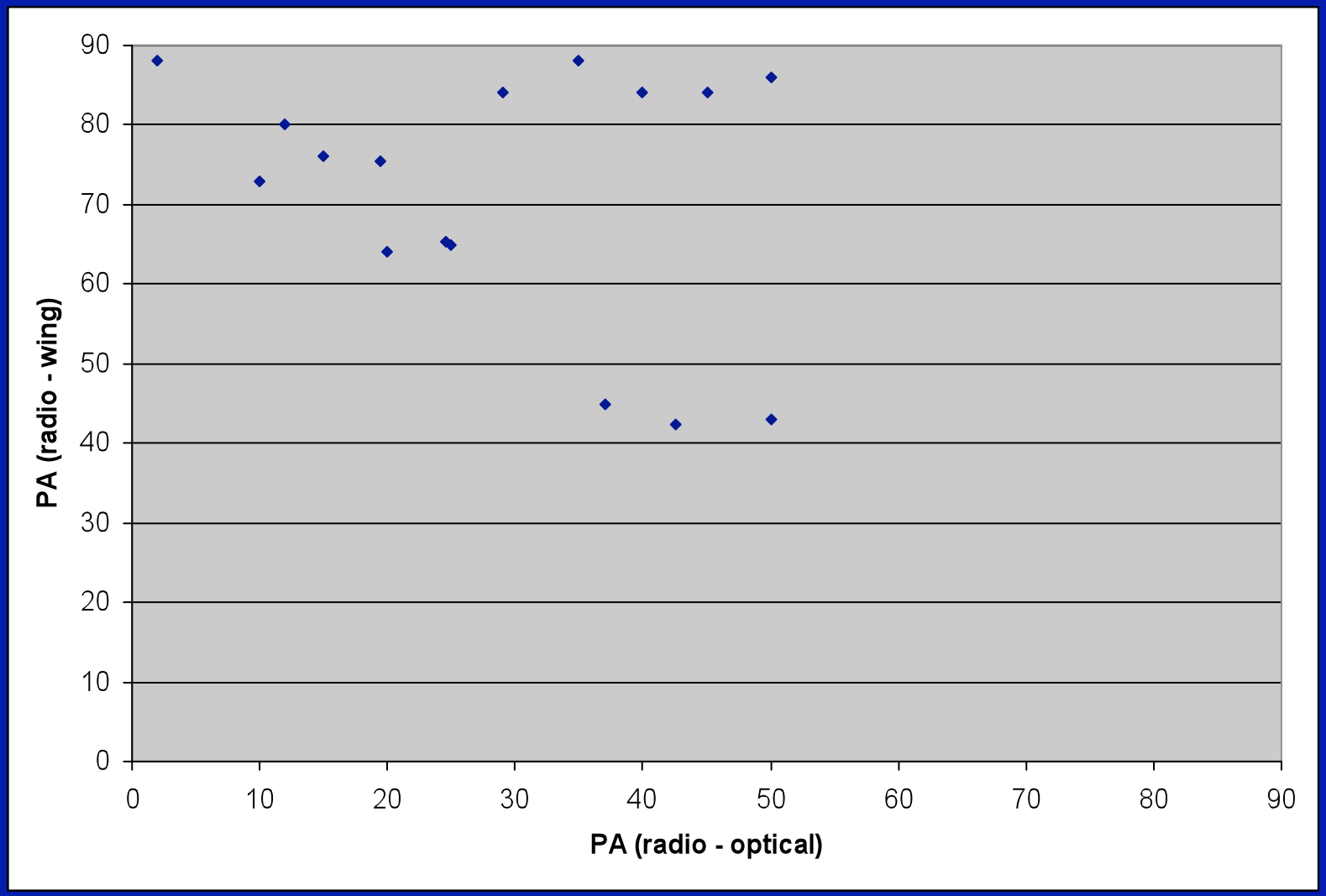
The hosts of X-shaped sources have a range of ellipticities from 0 – 0.5
Median ellipticity = 0.3 ± 0.05

Host galaxies of X-shaped radio sources appear to have higher ellipticity





The fractional extent of the wings decreases as a function of source size.



As the radio axis shifts away from the host major axis wings of most sources continue to remain close to the minor axis.

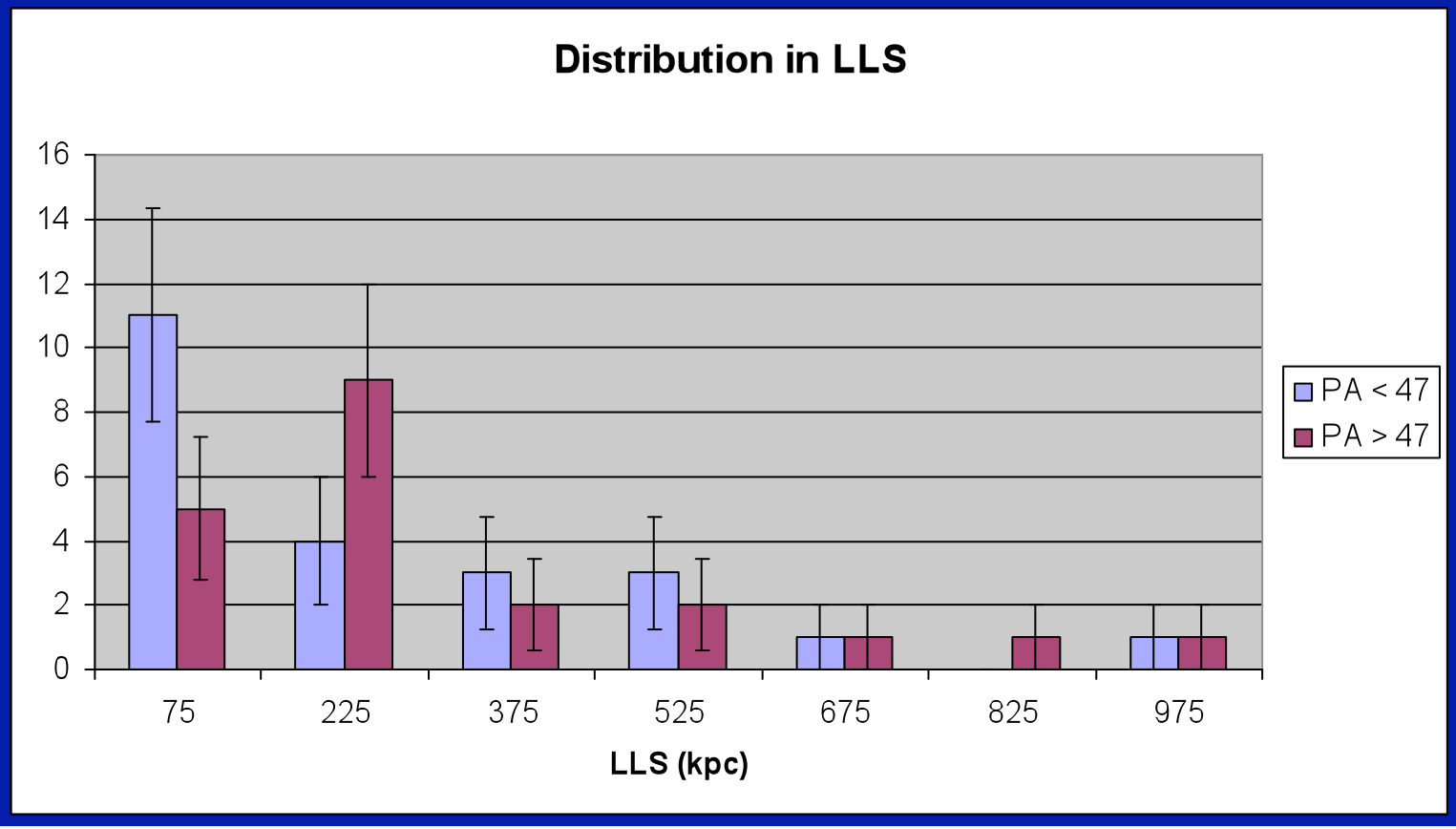
Median LLS for the whole 3CRR sample = 246 kpc

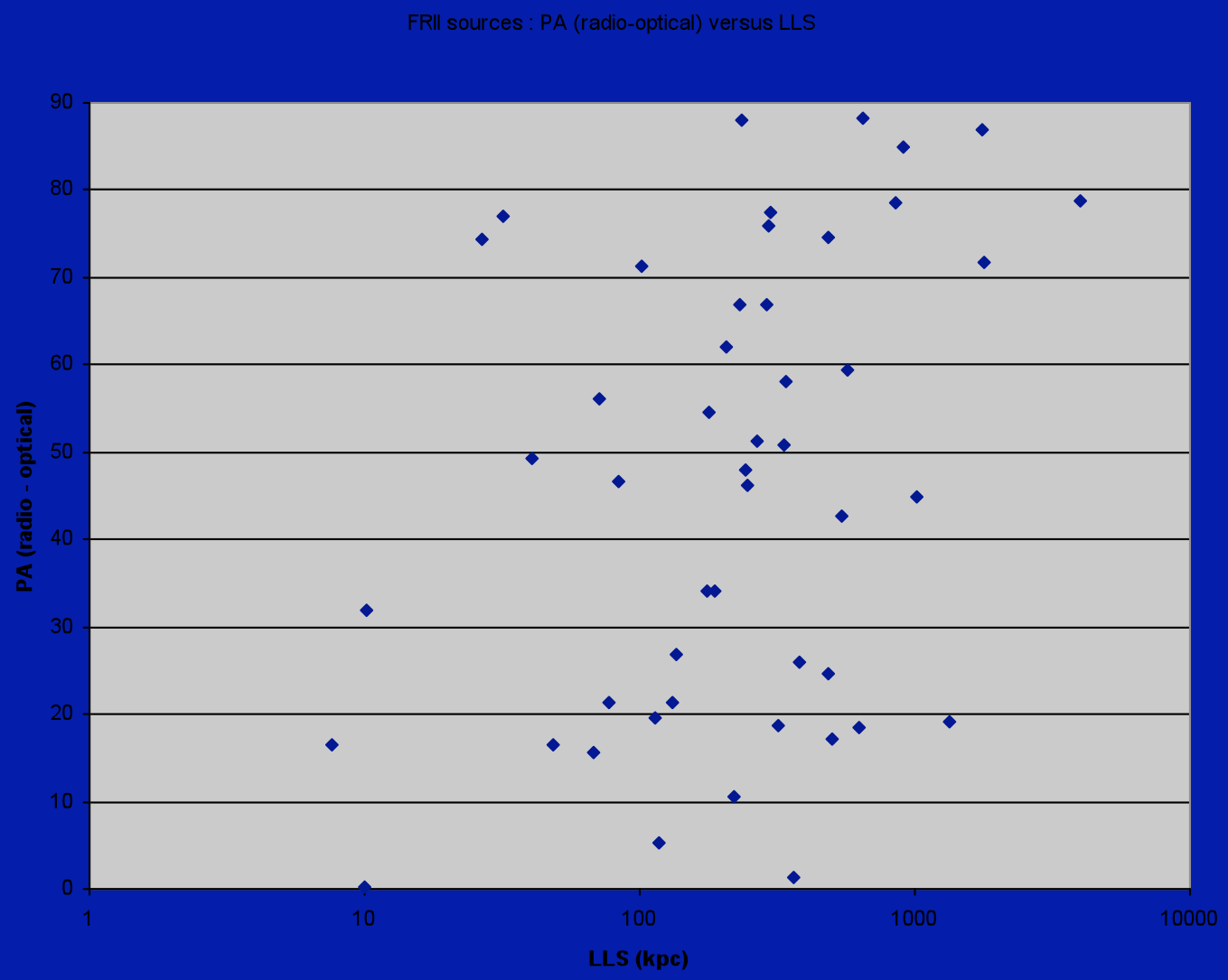
	LLS<246 kpc	LLS>246 kpc
Median	34 deg	55 deg
Mean	40 deg	53 deg

	LLS<700 kpc	LLS>700 kpc
Median	46 deg	79 deg
Mean	43 deg	66 deg

Median ΔPA (3CRR) = 47 deg

	ΔPA <47	ΔPA >47
Median	182 kpc	293 kpc
Mean	301 kpc	592 kpc





Correlation coefficient for the entire distribution = 0.35

Conclusions

- Backflow scenario is the preferred model for the formation of X-structures

- Wings may be aided in their growth by a combination of factors:
  - Buoyancy
  - High cocoon pressure
  - Galactic winds