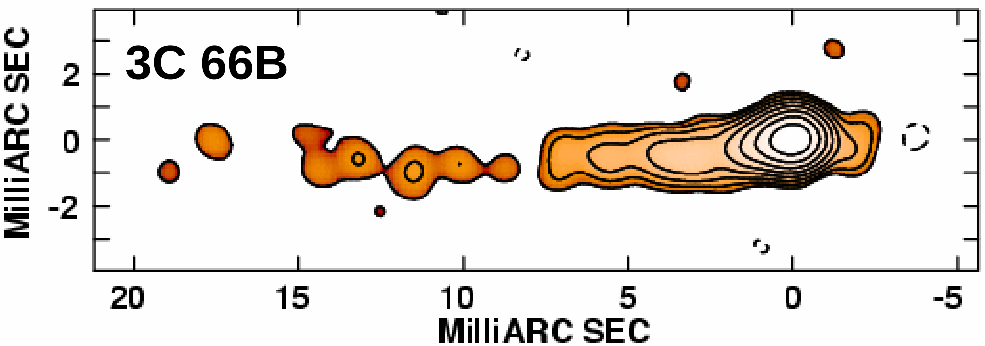
# Jets in Low Power Compact Radio Galaxies

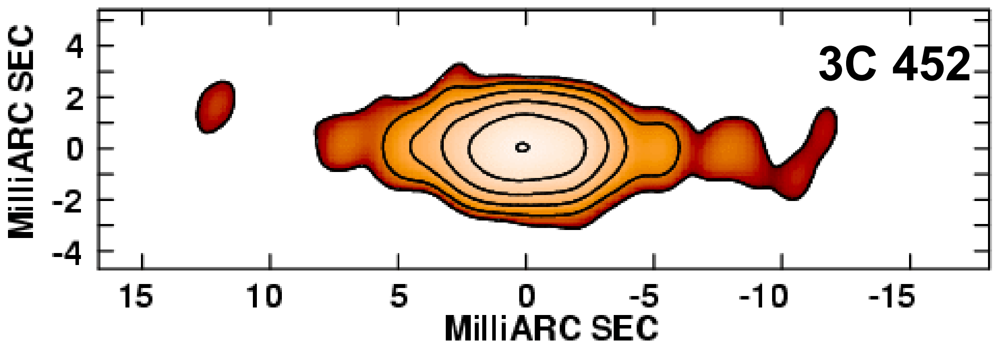
Marcello Giroletti
Department of Astronomy, University of Bologna
INAF Institute of Radio Astronomy
&
G. Giovannini (UniBO, IRA)
G. B. Taylor (KAVLI, NRAO)

# Outline

- Parsec scale radio jets…
  - …in classical extended radio galaxies
  - …and in compact radio sources
- The Bologna Complete Sample
- Low Power Compact sources
  - New high resolution radio observations
  - Jets, linear size, brightness, spectrum, Doppler factor, evolution
- Conclusions

# Parsec scale jets




Images adapted from Giovannini et al. (2001, ApJ)

- parsec scale observations with VLBI
  - show both one- and two-sided jets
  - yield support for intrinsically symmetric jets
  - discover superluminal motions
  - suggest that parsec scale jets are relativistic

# Relativistic parsec scale jets

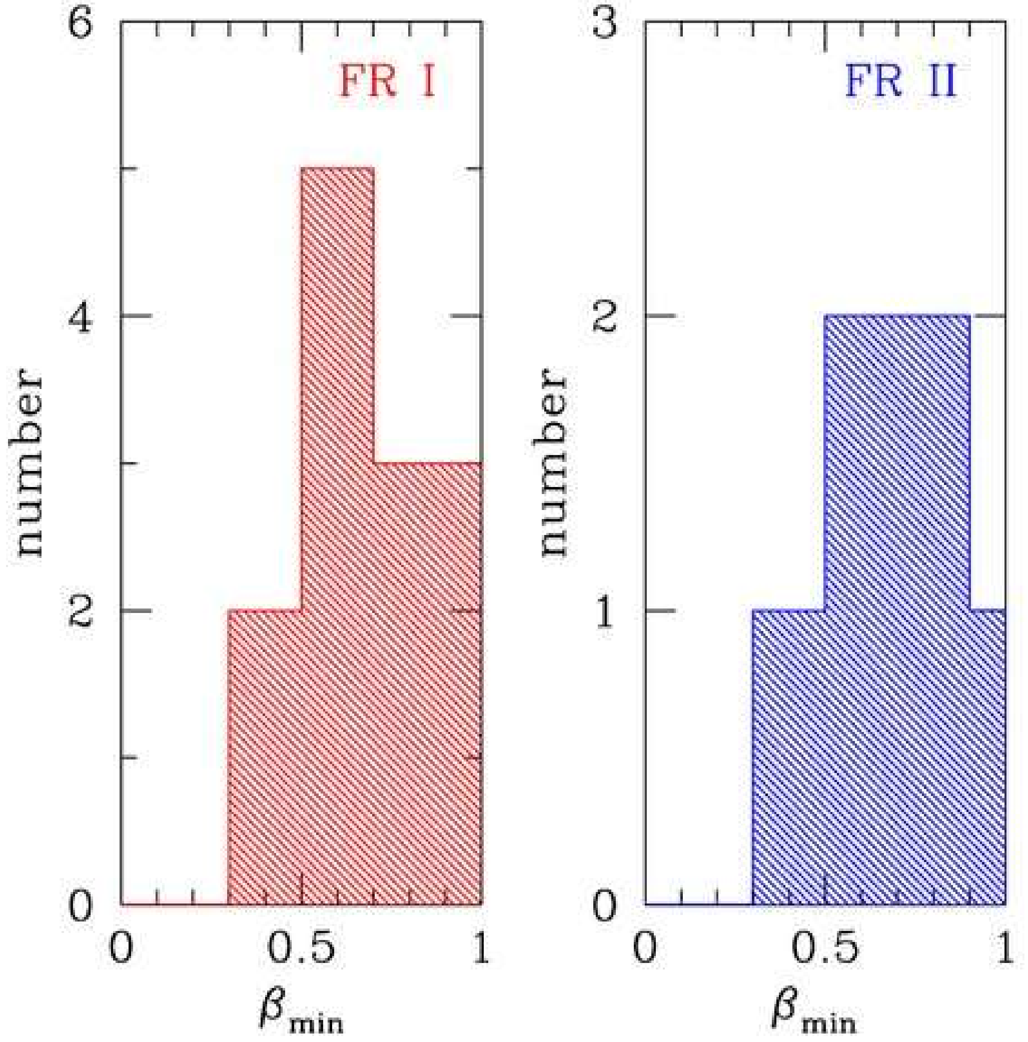
in 19 radio galaxies observed with VLBI (Giovannini et al. 2001) we find

- proper motions
- jet/counterjet ratios >1
- large core dominance

evidence for:

- relativistic parsec scale jets
- without distinction between FRI and FRII

now, what about compact sources?

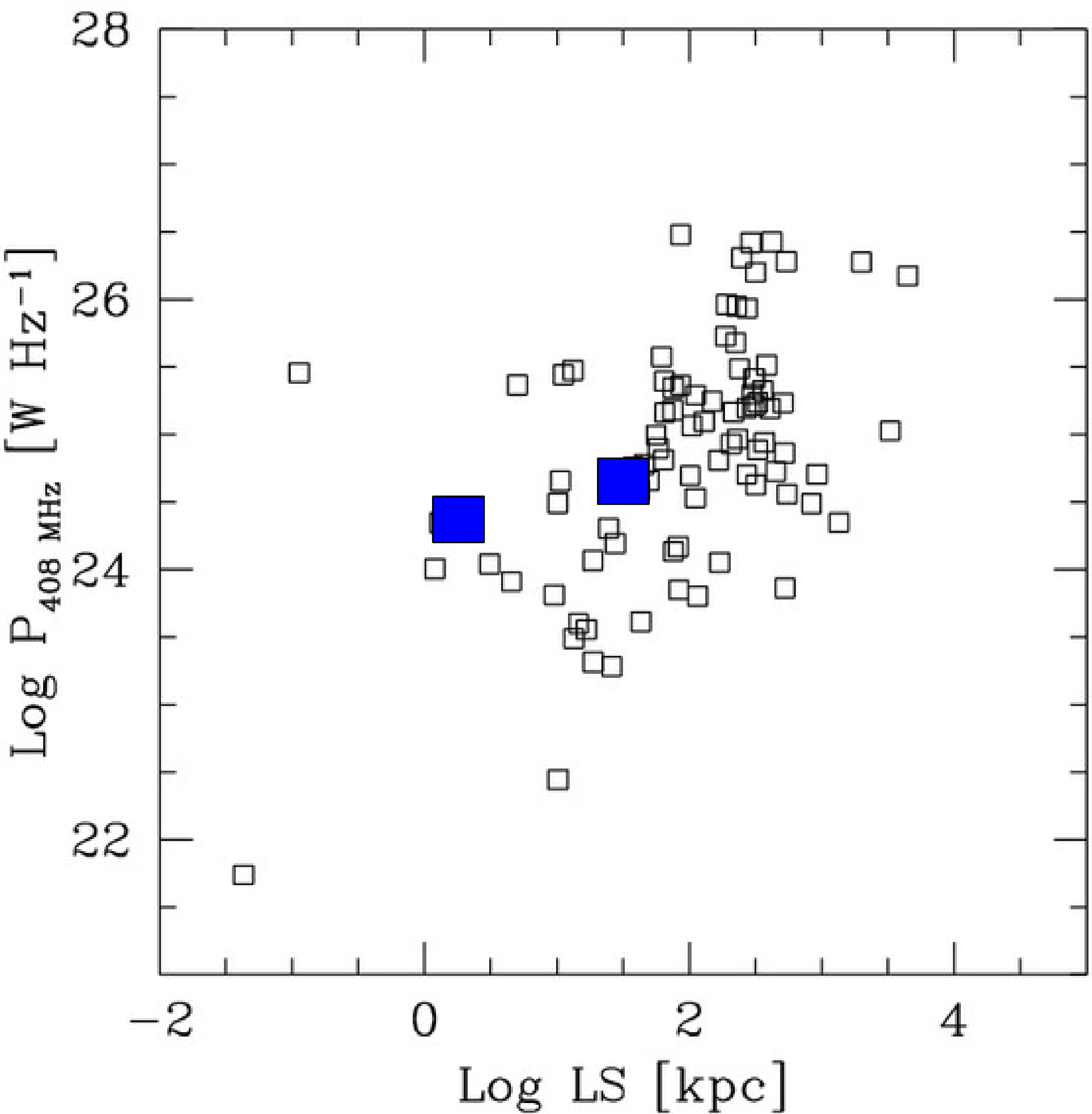


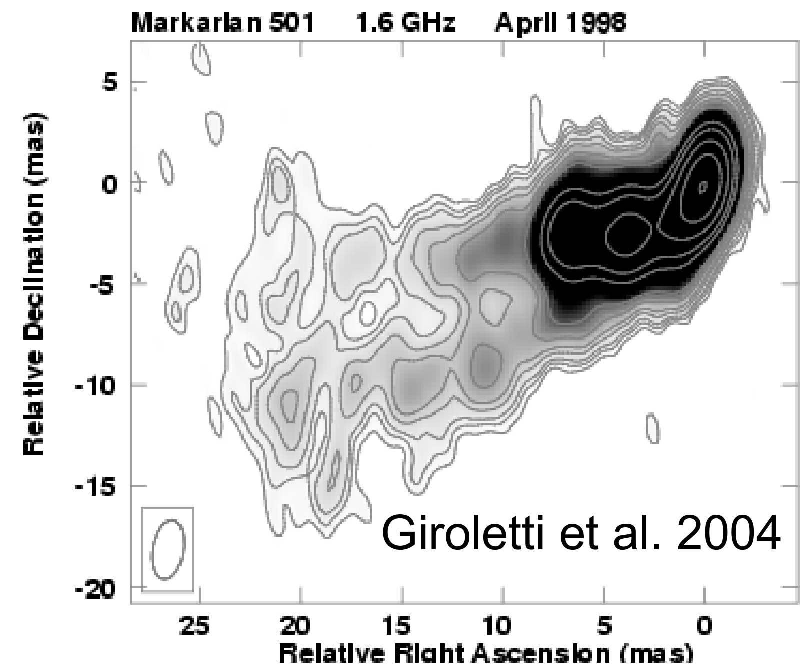
# *Bologna Complete Sample*

Giovannini et al. 2005, ApJ 618

- 95 sources selected at low frequency (from B2 and 3C surveys)
- no selection on core properties, thus **no bias in favour of relativistic beaming**
- z < 0.1
  - 81 extended radio galaxies: 65 FR I, 15 FR II, 1 FRI/II
  - 14 compact sources: nuclei? sub-structures? intrinsic properties (power, dimension)? evolution? young? weak? frustrated?

# Radio power vs. linear size: **BL Lacs**

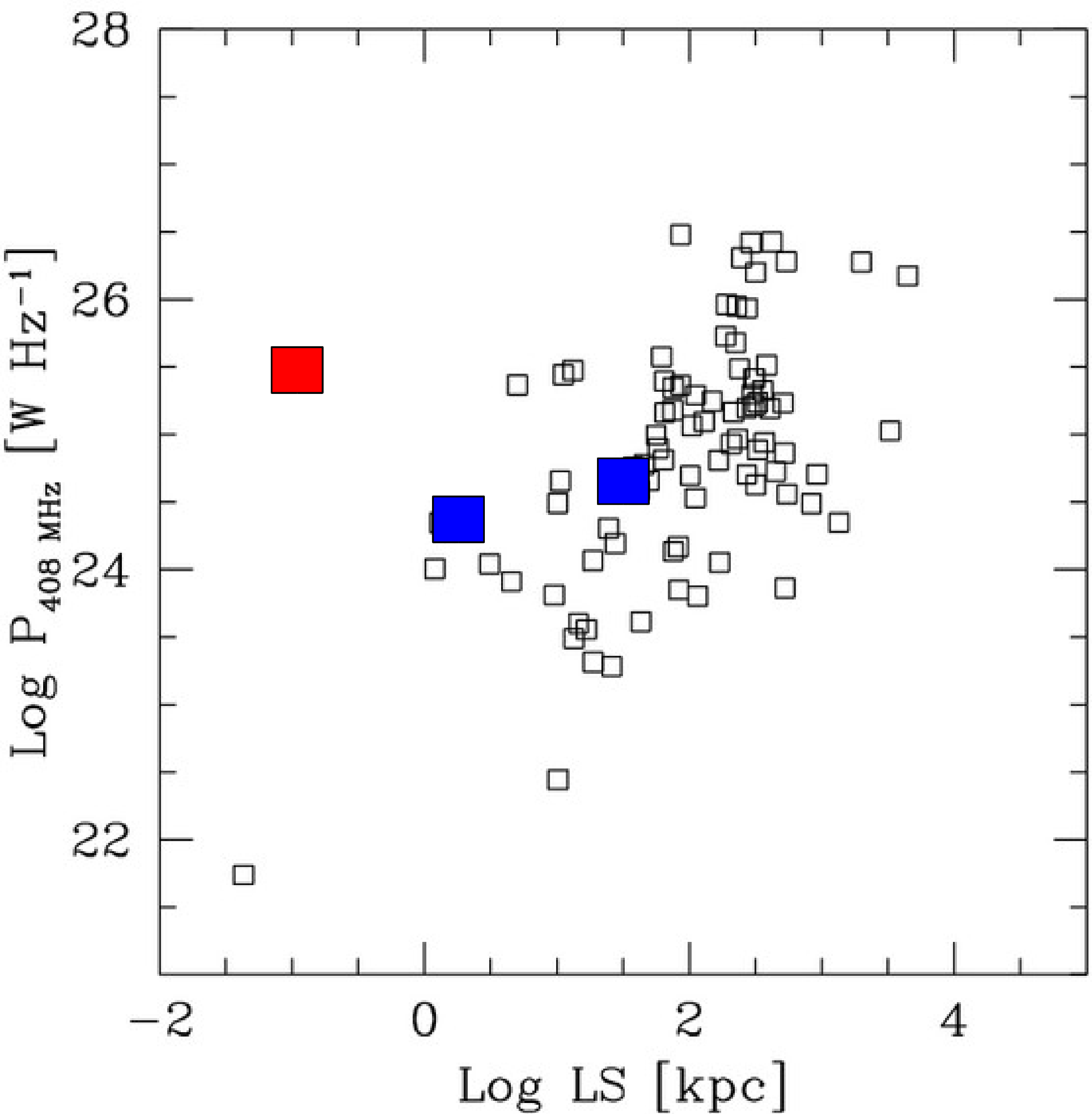


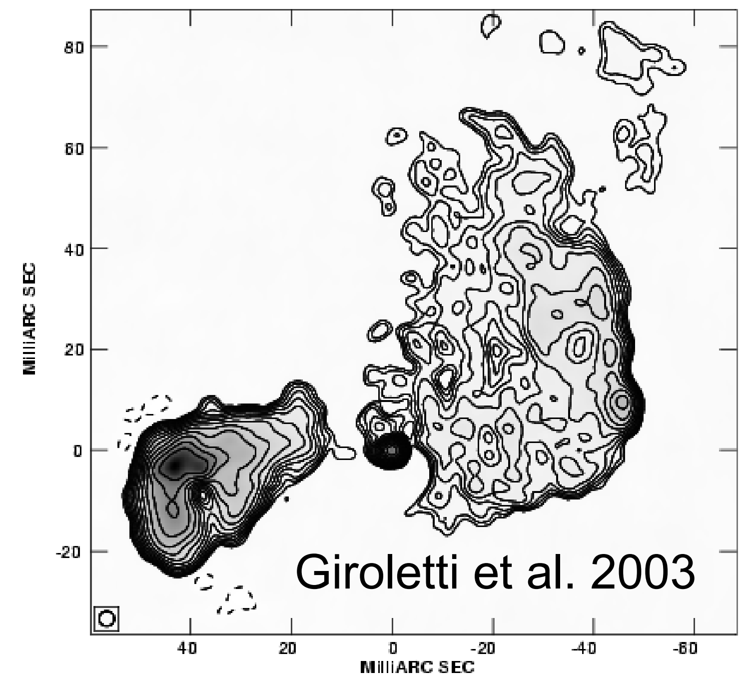




**Mkn 421, Mkn 501**

- flat spectrum
- relativistic beaming
  - one sidedness
  - superluminal motion
  - high energy activity (optical, X, $\gamma$)
- poster by Giovannini et al.

# Radio power vs. linear size: **CSOs**

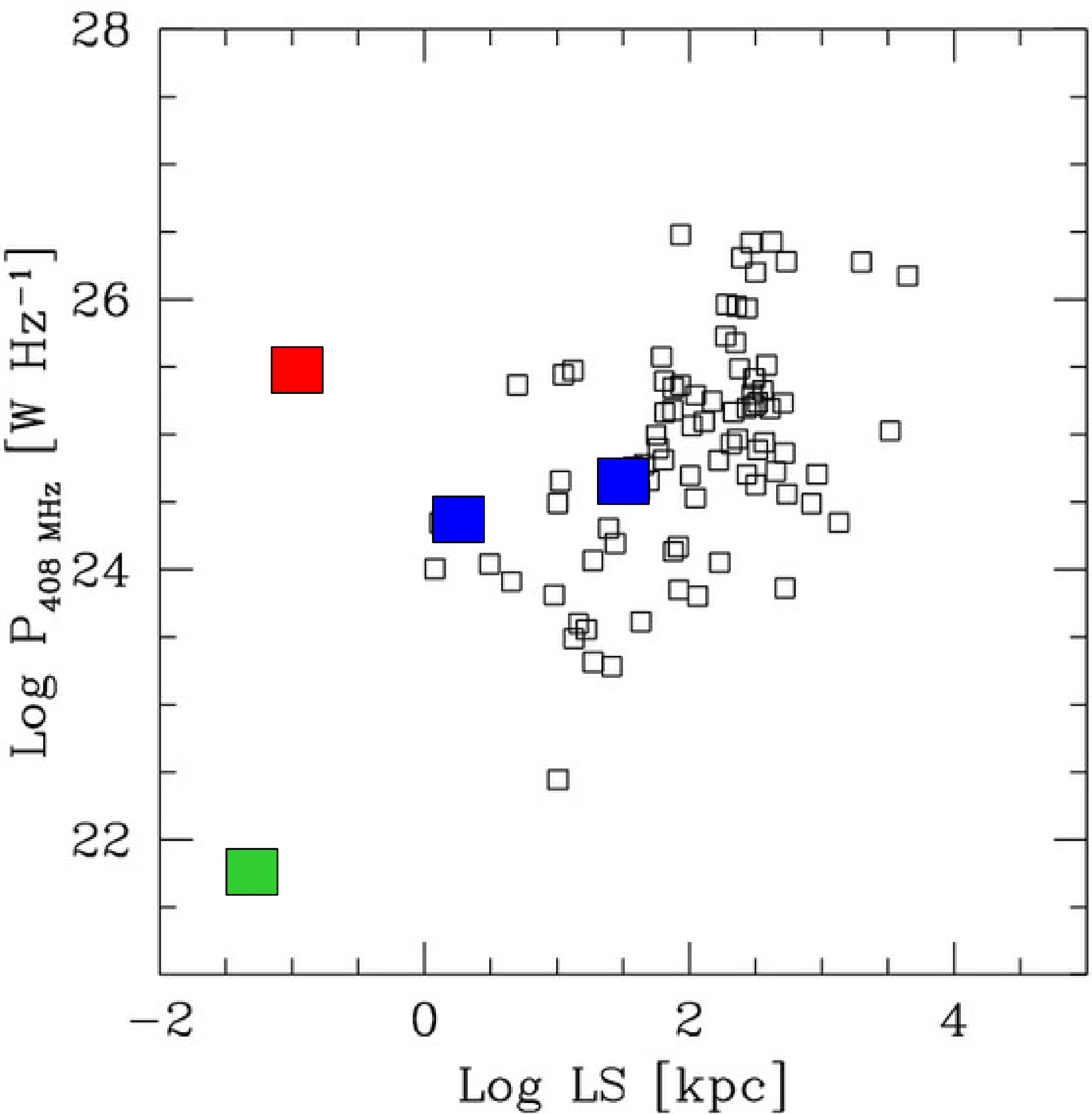


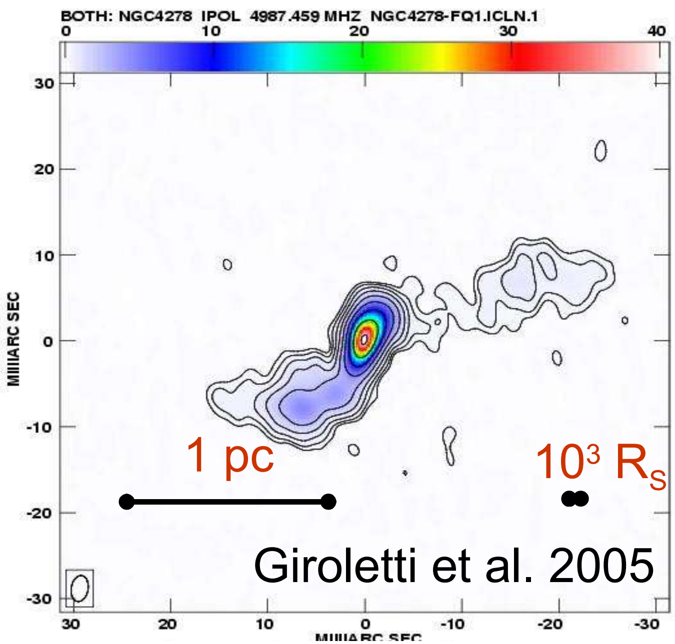




**4C 31.04**

- steep spectrum
- symmetric
- not beamed
- young radio galaxies (Owsianik & Conway 1998)
- HS advancing at ~0.1 c
- relativistic jet knots (Taylor et al. 2000)

# Radio power vs. linear size: LLAGN

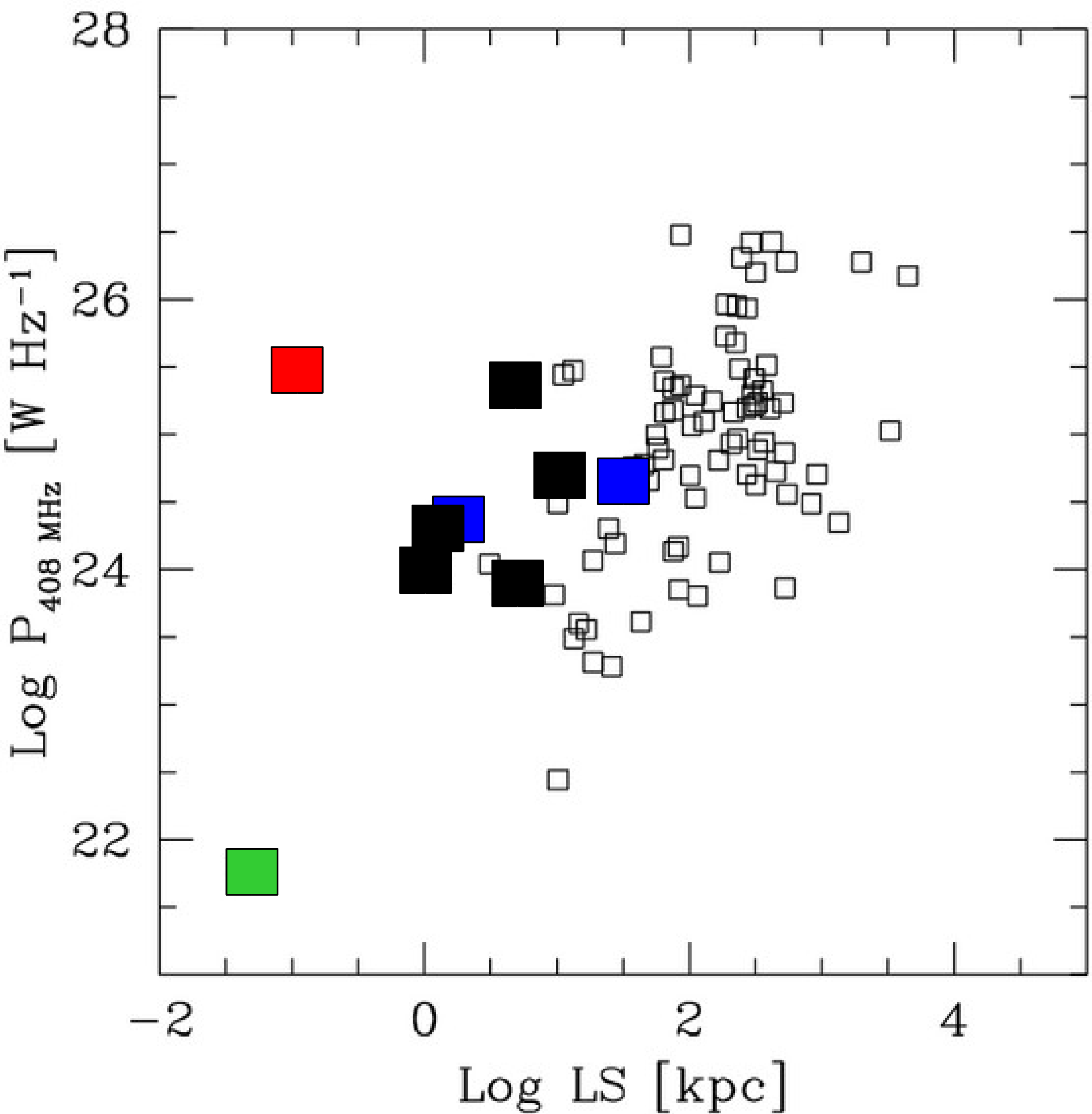



## NGC 4278

- intermediate spectra
- weak nuclear activity
- evidence of non thermal emission (Nagar et al. 2002)
- relativistic jet?
- common in "normal" nearby galaxy

# Radio power vs. linear size: **LPC**




**Low Power Compact sources:**

$23.9 < \mathrm{Log}\ P_{tot} < 25.5$ [W $Hz^{-1}$]

$1.5 < LAS < 10$ [asec]

RADIO: NVSS, FIRST, some literature (e.g. Fanti et al. 1987, **large scale**); power similar to FRIs but much smaller size

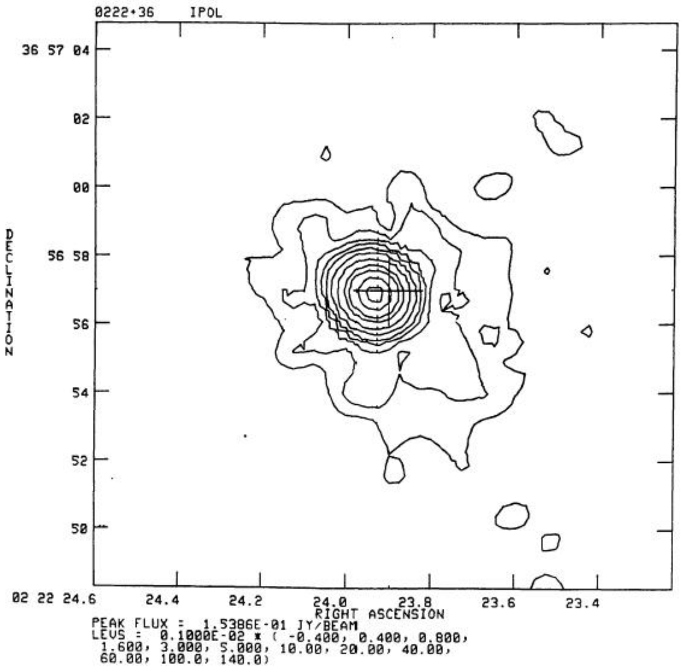
OPTICAL: ellipticals, narrow lines, HST for e.g. 0648+27 (dust)

X-rays: few studies, low luminosity ($<10^{42}$ erg $s^{-1}$)

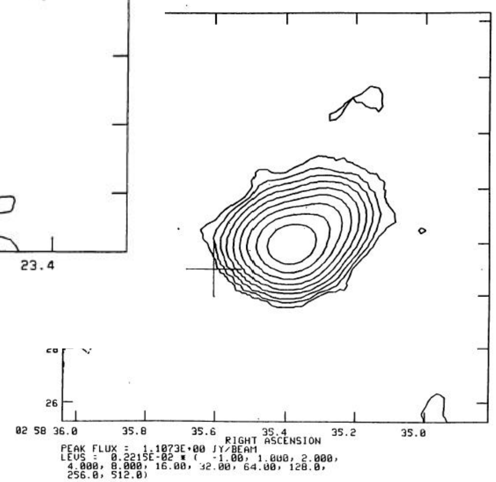
# New observations

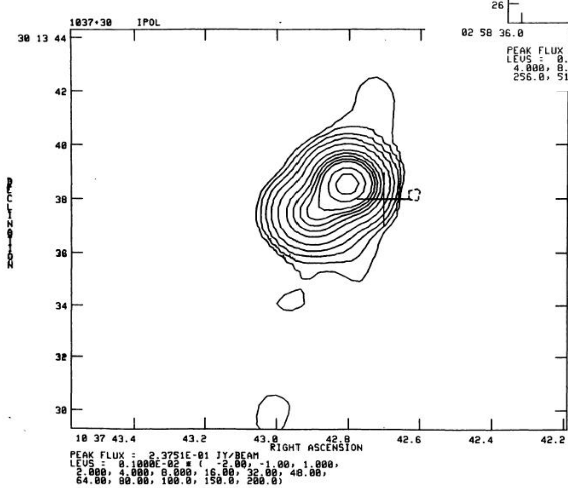
- High resolution
  - VLA @8, 22 GHz
  - VLBA @1.6 GHz, phase referenced (≈5 mas resolution and ≈0.5 mJy sensitivity)
- Main goals:
  - resolve sub-kpc scale structure, e.g. jets
  - identify core
  - study spectral index
  - new accurate measures for parsec scale properties (position, flux density, …)
  - determine intrinsic power, age, evolution…

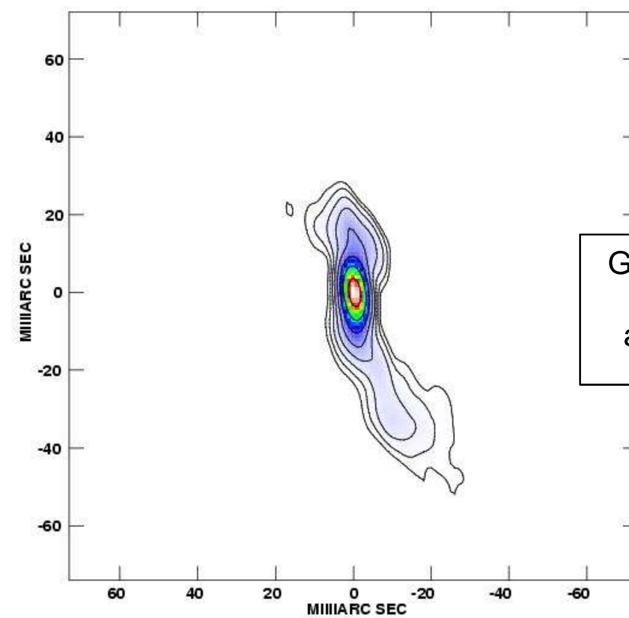
# From “*blobs*” to *jets*

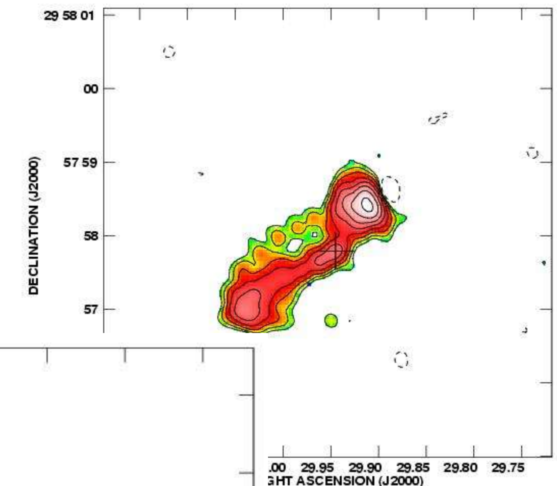



At low resolution, sources are compact, core dominated



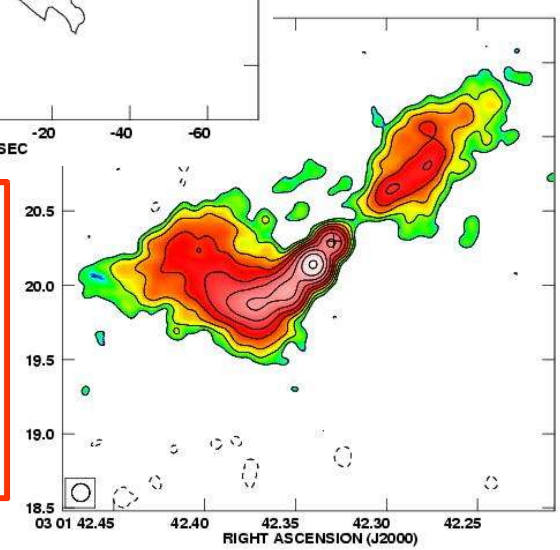



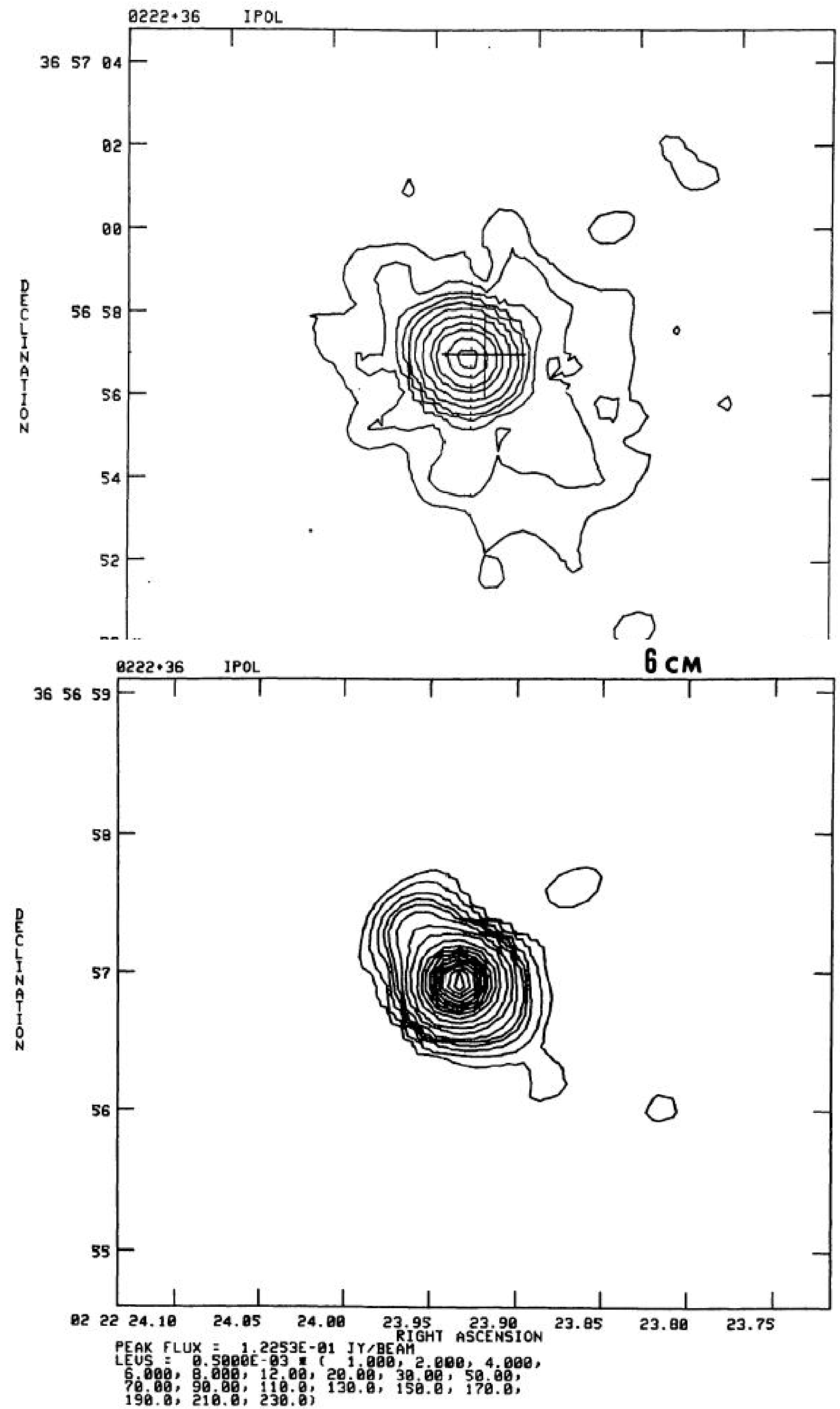

Giroletti et al. 2005, (A&A in press, astro-ph/0506497)

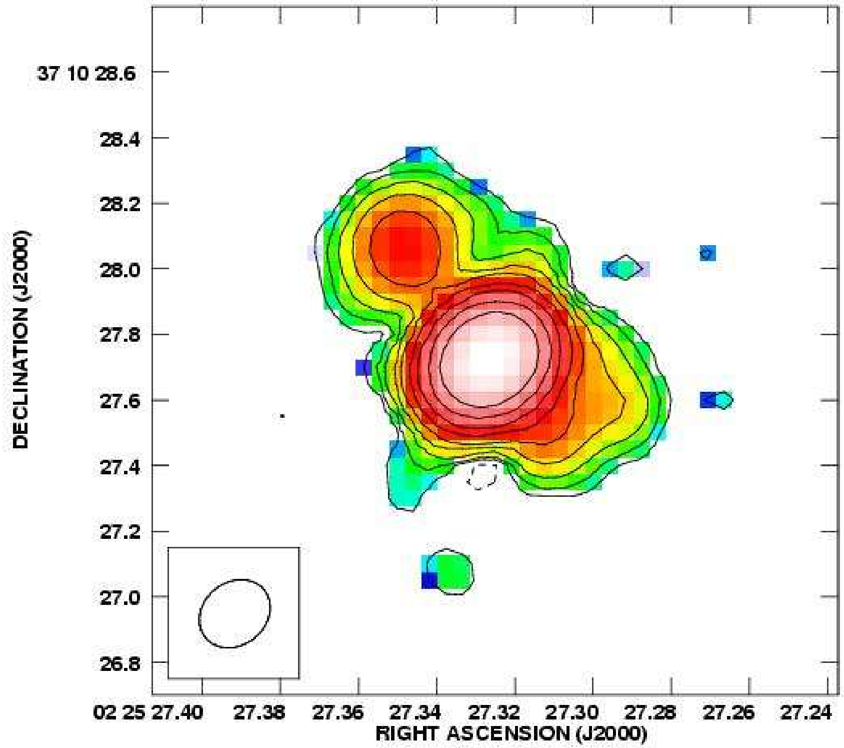
High resolution observations reveal rich substructures, including jets, resembling extended FRI and FRII on 10-1000 times smaller scales.

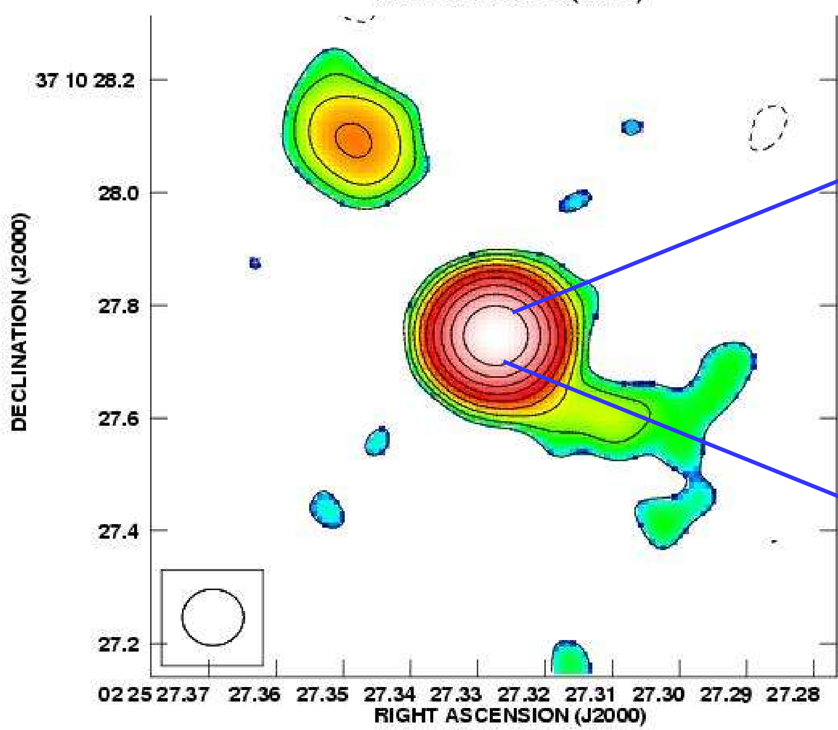


# 0222+36

- $S_{408}$ = 337 mJy
- z = 0.03
- P = $10^{23.9}$ W $Hz^{-1}$
- LAS = 8”
- Literature
  - kpc scale: Fanti et al. (1987)
  - pc scale: ???






# VLA

$S_{8\ GHz}$ = 190 mJy

$S_{22\ GHz}$ = 90 mJy

$\alpha_{core}$ = 0.6

halo is resolved

two sided structure

# VLBA

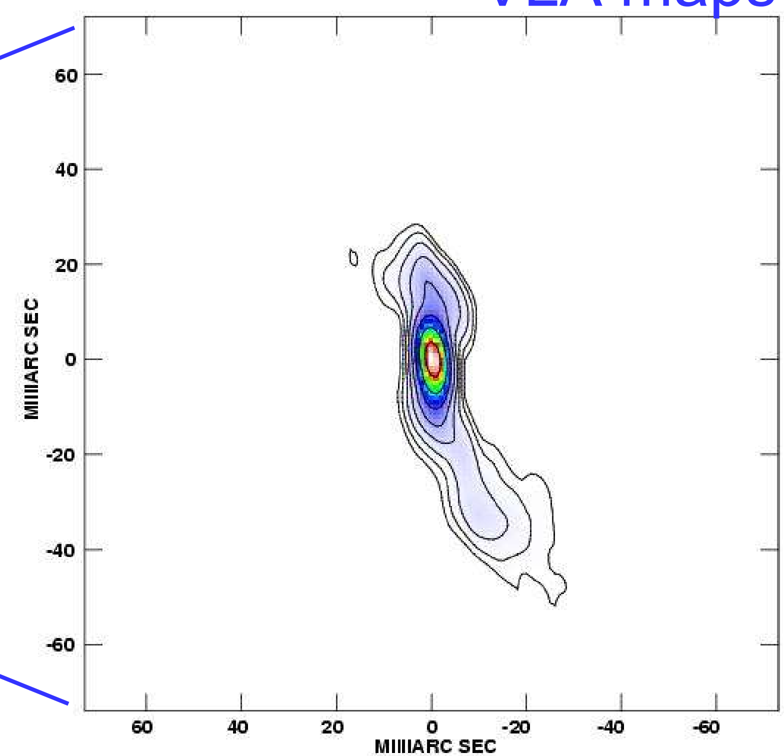
$S_{1.6\ GHz}$ = 102 mJy

**two sided jets**

no hot spots

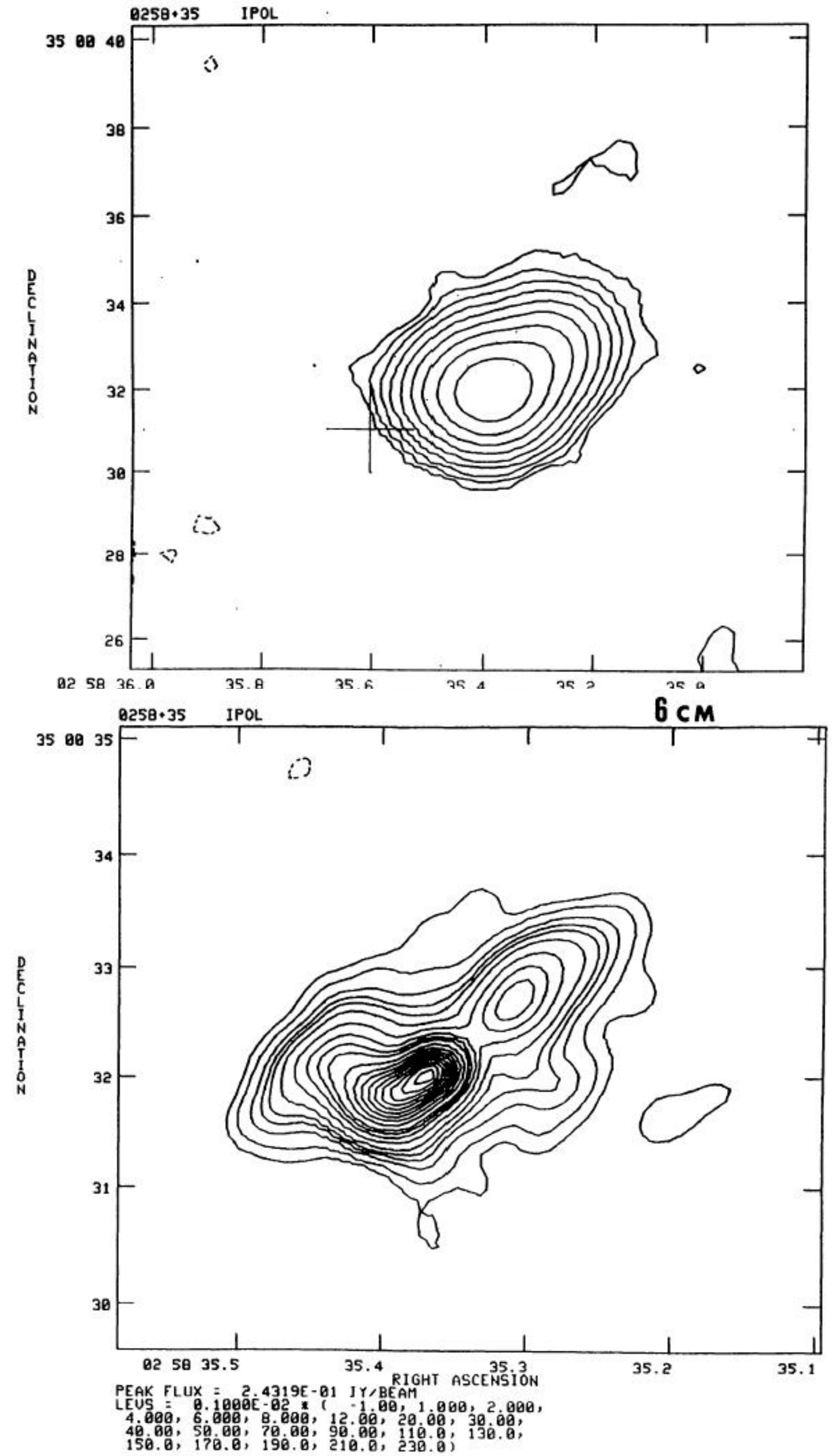
definitely in the plane of the sky

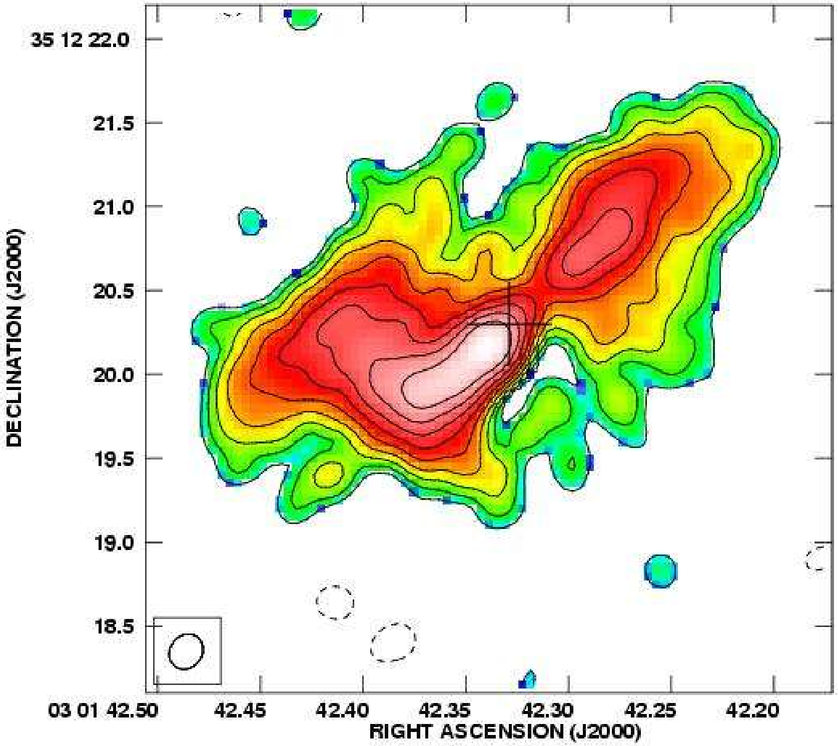
nicely connected to VLA maps



# 0258+35

- $S_{408}$ = 3.9 Jy
- z = 0.016
- P = $10^{24.4}$ W $Hz^{-1}$
- LAS = 4”
- Literature
  - kpc scale: Fanti et al. (1987)
  - pc scale: compact, with flux density excess on short spacings






# VLA

$S_{8\ GHz}$ = 620 mJy

$S_{22\ GHz}$ = 270 mJy

symmetric FRI-like,
but LS ~ 5 kpc

two knots in jet

zero hot spot

# VLBA

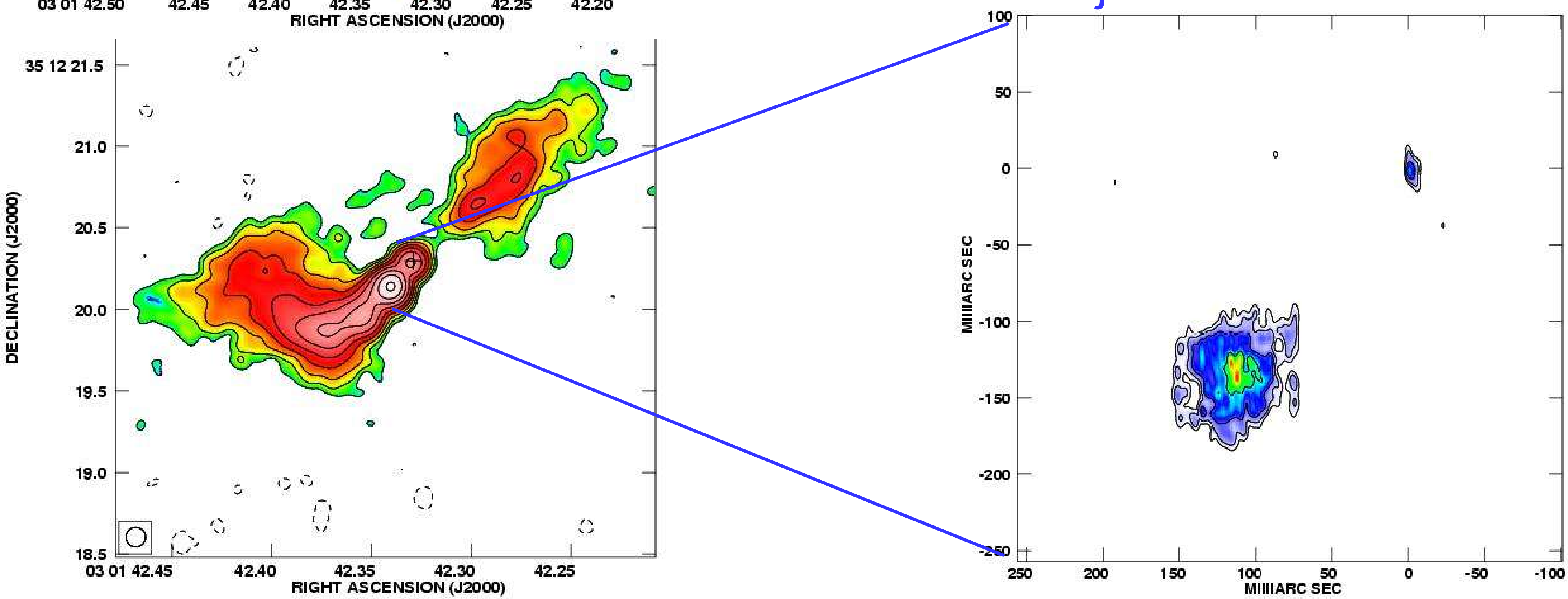
phase-ref essential

$S_{core}$ = 7 mJy

$S_{blob}$ = 240 mJy

one-sided

jet/blob/shock/more?



# 0648+27

$S_{408}$ = 0.27 Jy

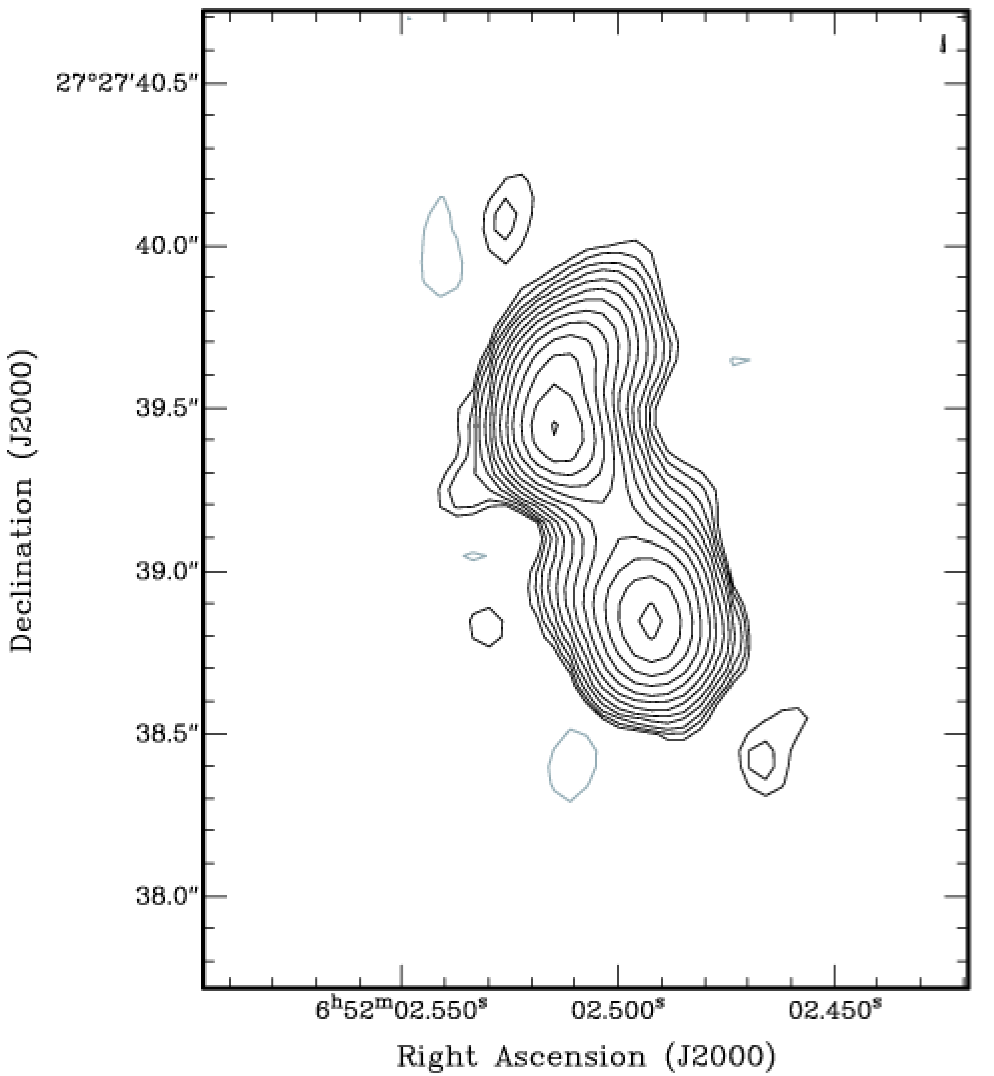
z = 0.04

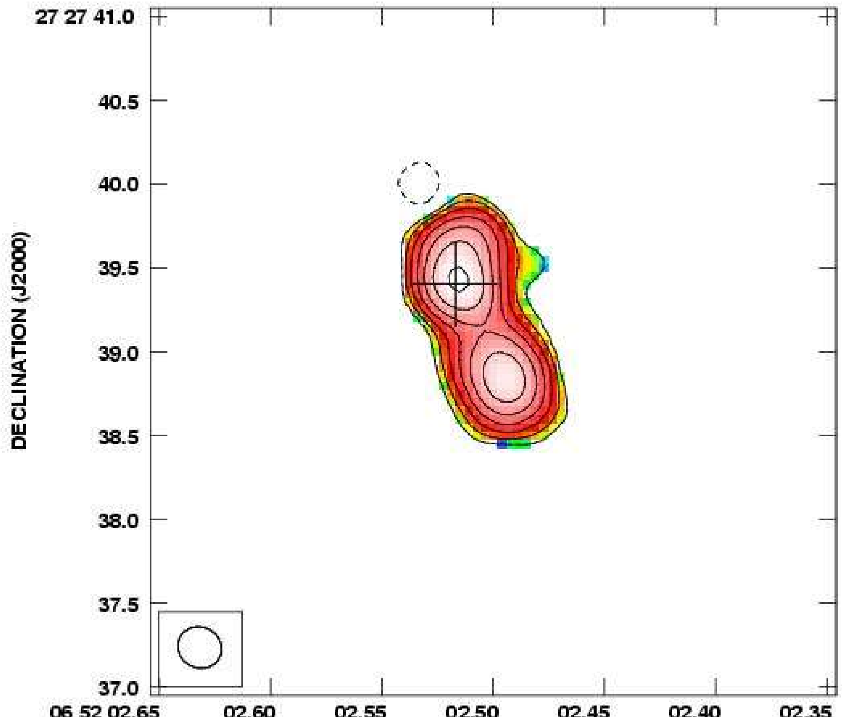
P = $10^{24.0}$ W $Hz^{-1}$

LAS = 1.5”

Literature

- kpc scale: Morganti et al. (2003), large amount of H I






# VLA

$S_{8\ GHz}$ = (19 + 14) mJy

$S_{22\ GHz}$ = 10 mJy

symmetric double at 8 GHz…

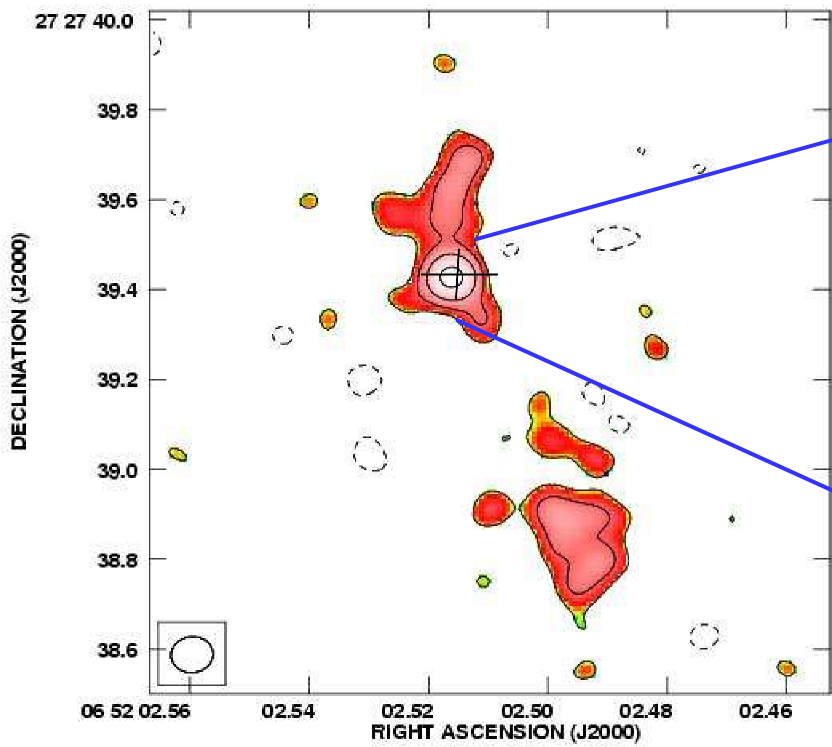
…resolved with compact core at 22 GHz!

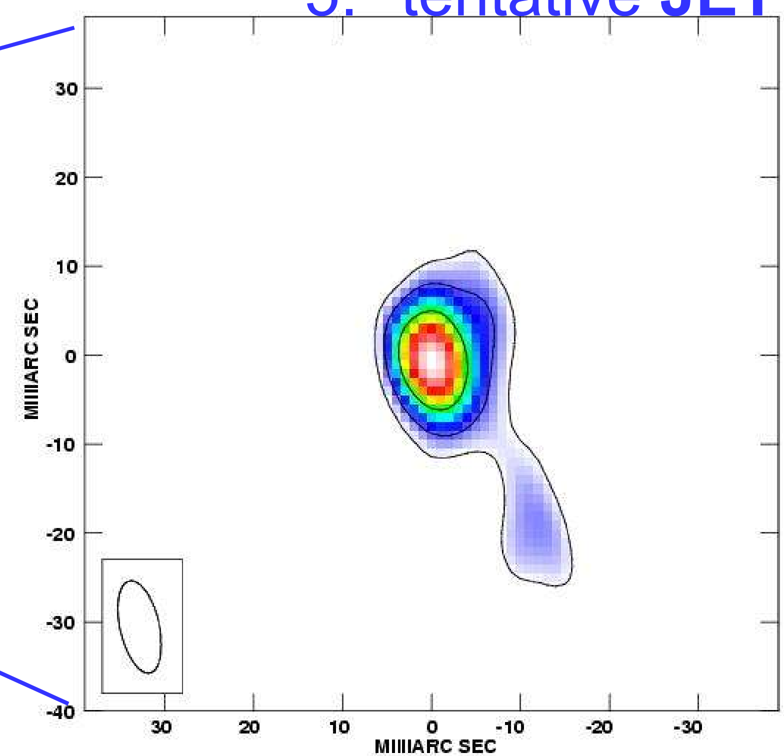
NO HS!

# VLBA

phase-ref provides:

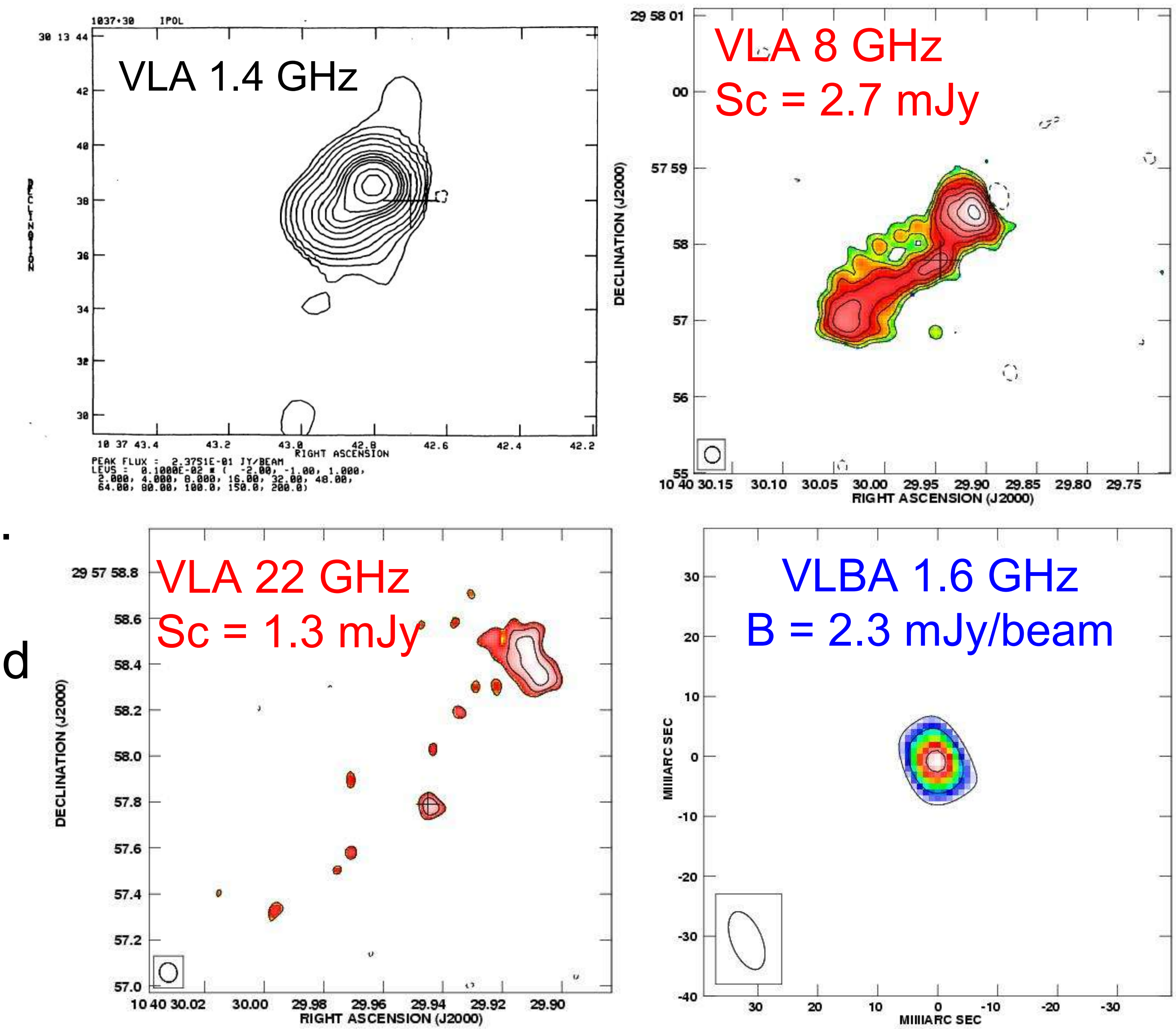
3. **DETECTION** ($S_{core}$ = 4 mJy)
4. **POSITION**
5. tentative **JET**



# 1037+30

- $S_{408}$ = 1.1 Jy
- z = 0.09
- P = $10^{25.4}$ W $Hz^{-1}$
- LAS = 3”
- Literature
  - kpc scale: Fanti et al. (1987)
  - pc scale: not detected
- New results
  - two-sided, with jets and hot spot
  - $T_{kin}$ = 4.5 x $10^4$ yr



# Jets in LPCs

- LPCs reveal rich, complex structures at high resolution
  - lobes, hot spots, fed by jets
- radio power typical of FR Is suggests relativistic regimes
  - 0222+36: $\beta > 0.6$, $\theta \sim 85°$
  - 0258+35: $\beta > 0.9$, $40° < \theta < 50°$
- jets typically <1 kpc long
- structure is often two-sided

# Radio spectra

One more piece of information…

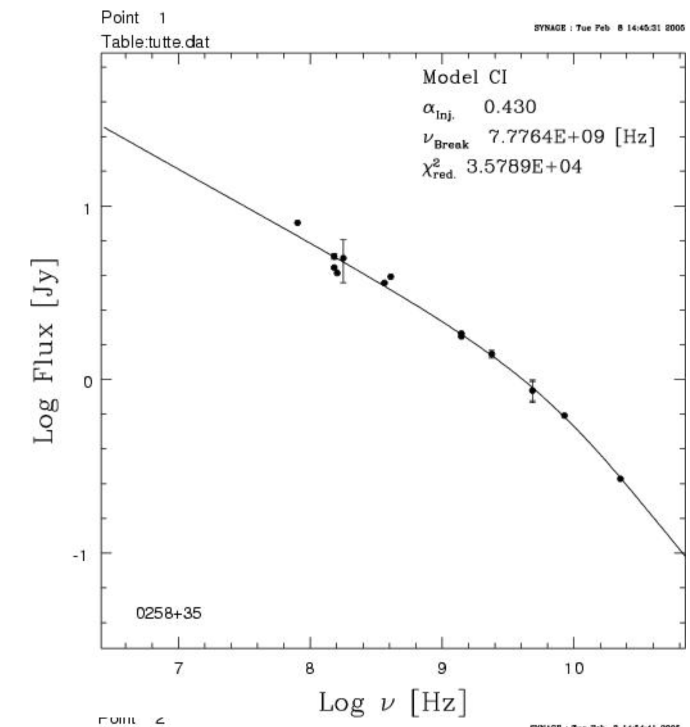
little contamination from core

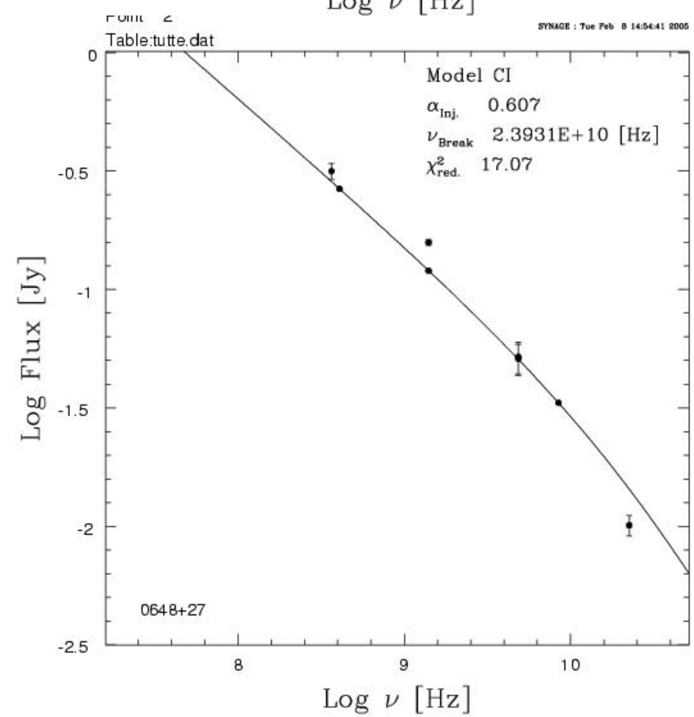
$B_{eq} \sim 10^2\ \mu$ G

$T_{syn} \sim 10^5$-$10^6$ yr

$v_{adv,\ syn} << c$

consistent with slow/ceased advance in the external medium



# Why are these sources compact, then?

no beaming   no projection

one source with hot spots   youth

many sources without hot spots

frustration, low power jets, short lived

one source with worthless core   dying, intermittent

*will young sources ever grow to kiloparsec scale size?*

# Summary

- 5 low power compact radio sources
  - power similar to FR I but size < 1 kpc
- high frequency VLA observations
  - *resolved structures*
  - well identified cores
  - two-sided, one source with hot spots
- phase ref. VLBA observations
  - 4/5 detections
  - *3/5* detections of *parsec scale jets*
- main observational results
  - objects on the plane of the sky (two-sidedness, low core dominance)
  - *intrinsically small*
  - radiative ages about $10^5 – 10^6$ yrs

# Conclusions

Reasons of compactness

1. youth
2. frustration or short lived activity
3. intermittent nucleus
4. (projection)

Different physical state

powerful jets with Doppler beaming vs low kinematic power jets

lack of hot spots: end of interaction? end of growth? short lived sources?

transition to radio quiet and non active nuclei

Samples as the BCS

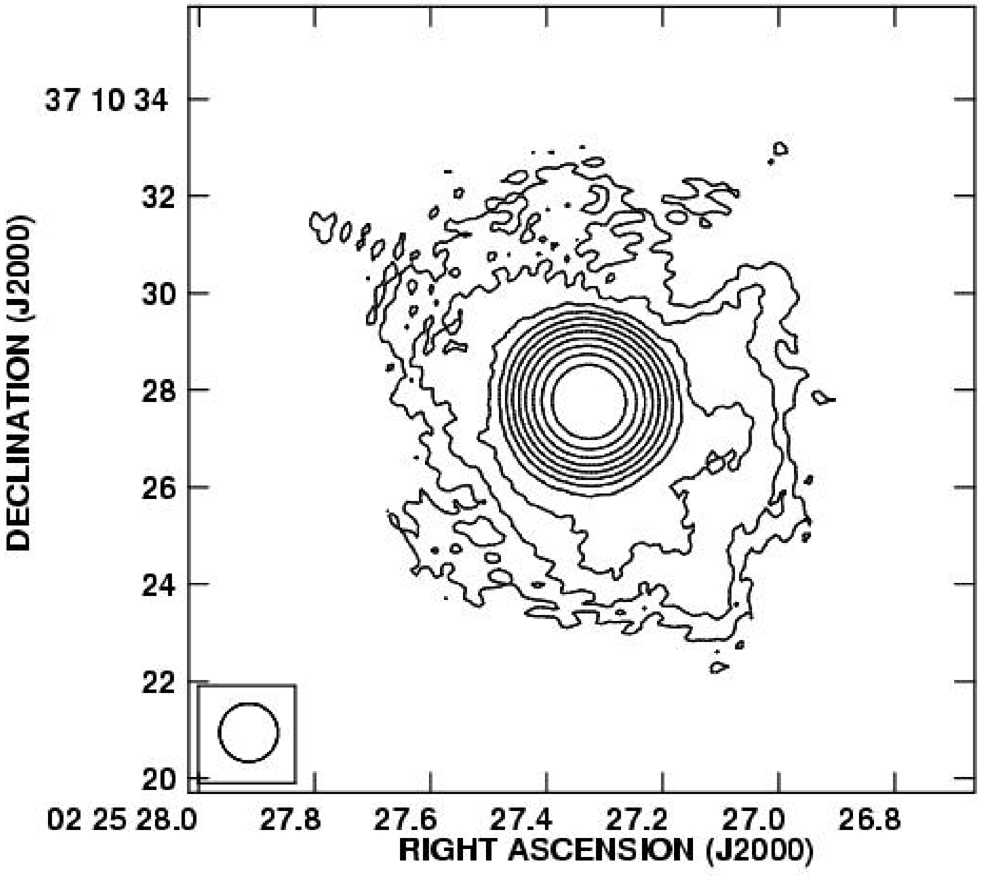
are important to understand these differences

need to be completed to the faintest sources

# 0222+36, spectrum of components

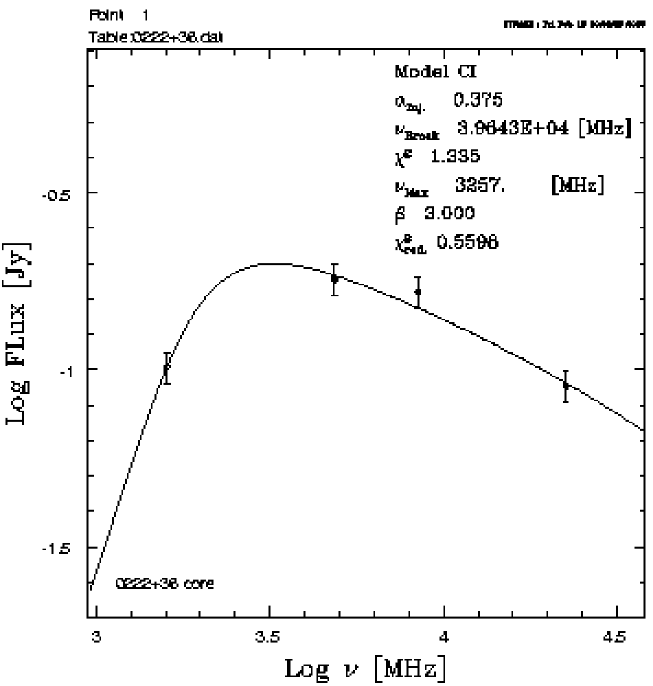
VLA archival data reanalyzed:

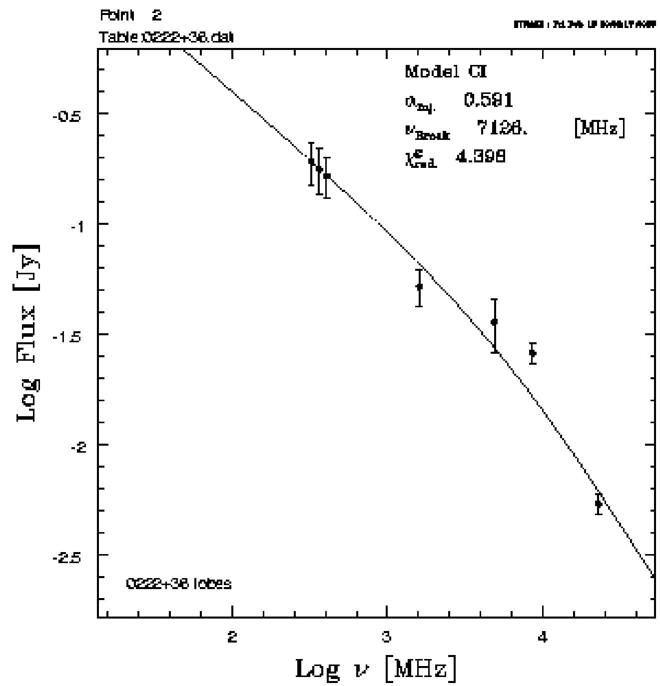
B configuration, 5 GHz

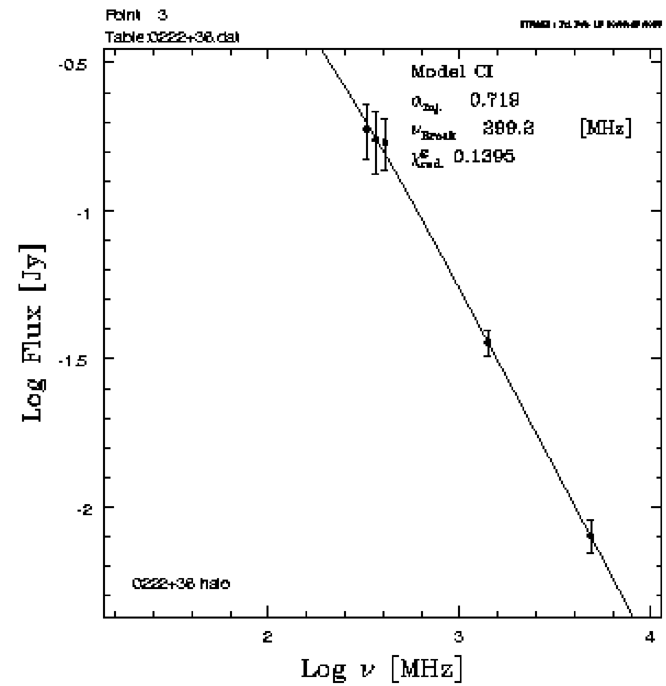



| Freq. (GHz) | Halo (mJy) | Lobes (mJy) | Core (mJy) |
|---|---|---|---|
| 0.325 | 188 | 191 | 0.9 |
| 0.365 | 174 | 177 | 1.2 |
| 0.408 | 170 | 165 | 1.8 |
| 1.4 | 36 | 52 | 102 |
| 5.0 | 8 | 36 | 180 |
| 8.4 | <1 | 26 | 166 |
| 22.5 | <1 | 6 | 90 |

# 0222+36, age of components




CORE

$\nu_{self}$ = 3.3 GHz

B = 50 mG

LOBES

$\nu_{br}$ = 9 GHz

$B_{eq}$ = 130 $\mu$ G

$T_{syn}$ = 4 x $10^5$ yr

HALO

$\nu_{br}$ = 300 MHz

$B_{eq}$ = 7 $\mu$ G

$T_{syn}$ = 1.3 x $10^8$ yr

# 0258+35: spectrum and age

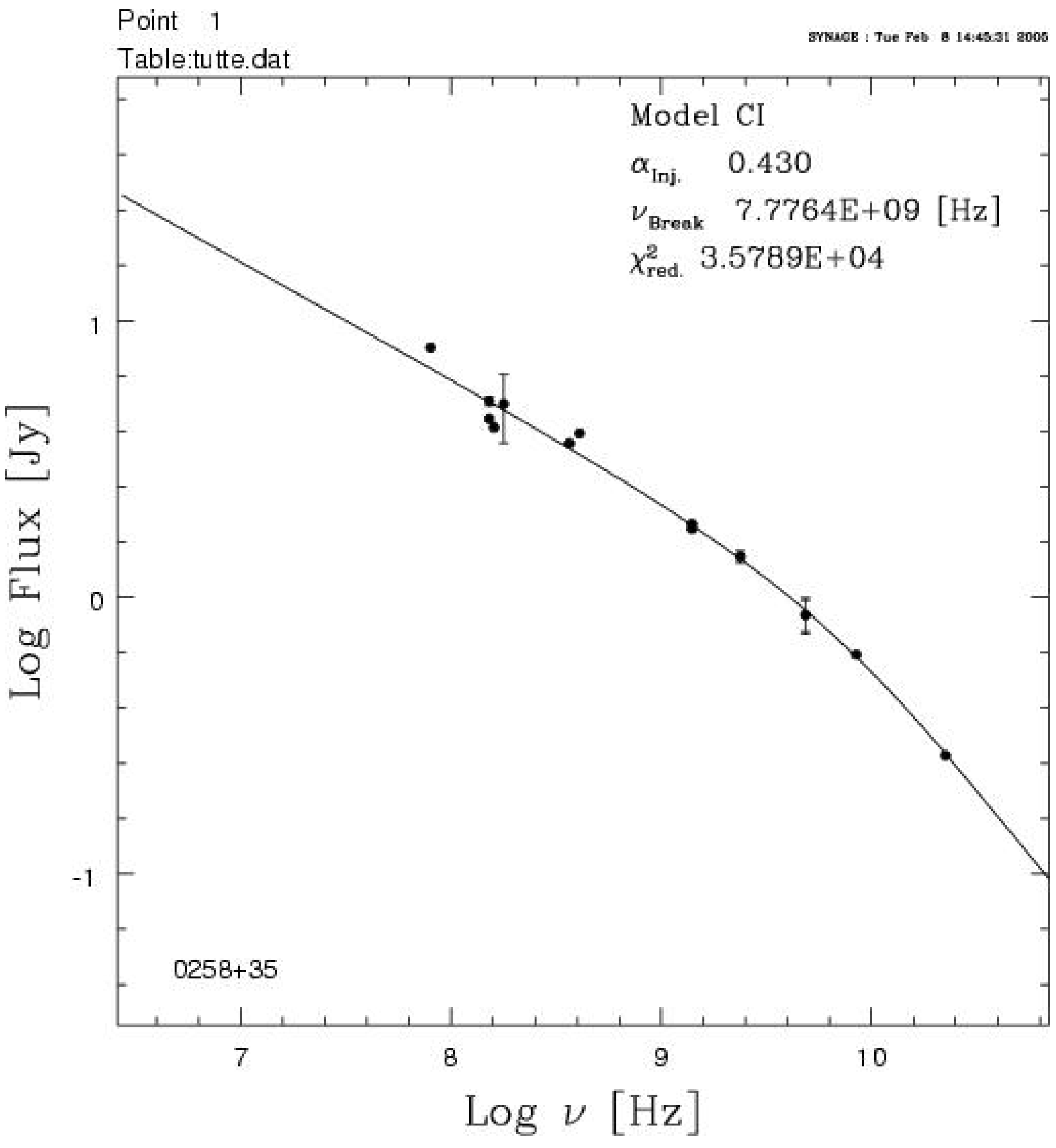
good coverage between 74 MHz and 22 GHz

little contamination from core

$B_{eq}$ = 90 $\mu$ G

$T_{syn}$ = 7 x $10^5$ yr

$v_{adv,\ syn}$ = 0.005 c



# 0648+27: spectrum and age

- some literature data at low freq.
- dominant core
- $B_{eq}$ = 95 μ G
- $T_{syn} = 3.5 \times 10^5$ yr
- large uncertainty