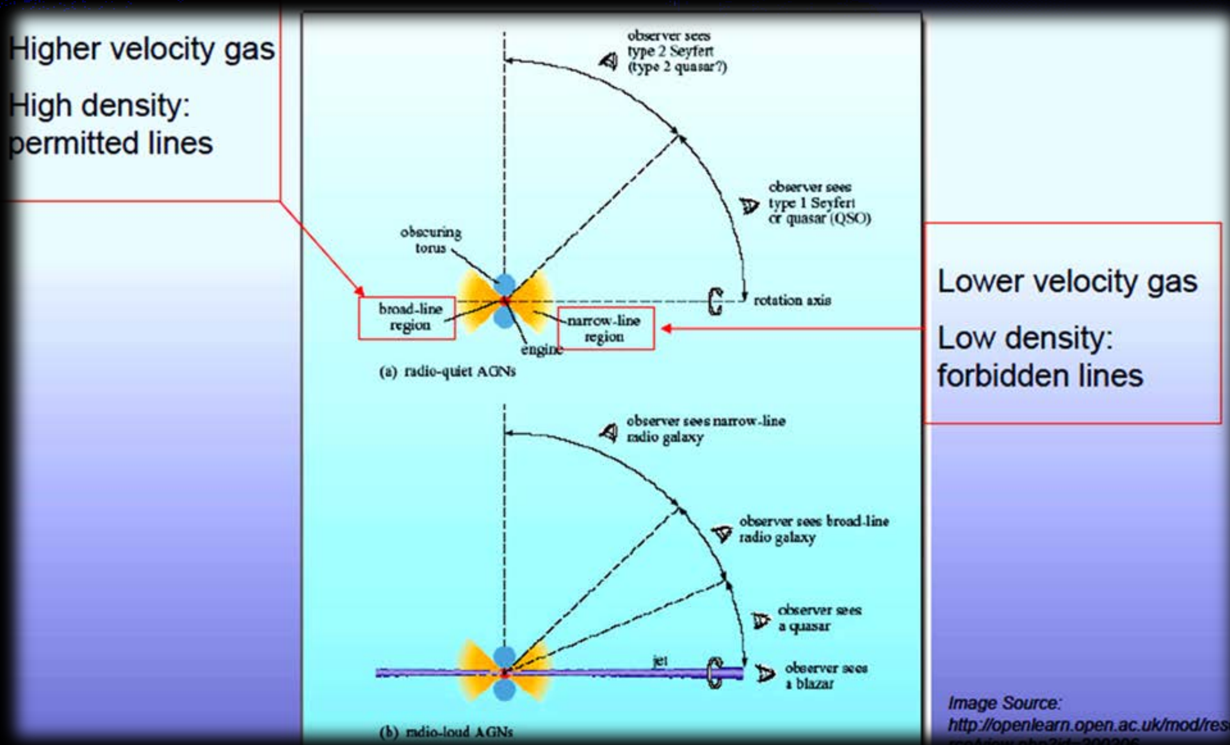
On the role of pc- to kpc-scale jet asymmetry and cosmic ray acceleration

Gizani[1], Nectaria A. B. & Garett[2], M.A.G.

1. Hellenic Open University, School of Science and Technology
2. Astron, the Netherlands Foundation for Research in Astronomy



Outline

Introduction

The case of two powerful radio galaxies

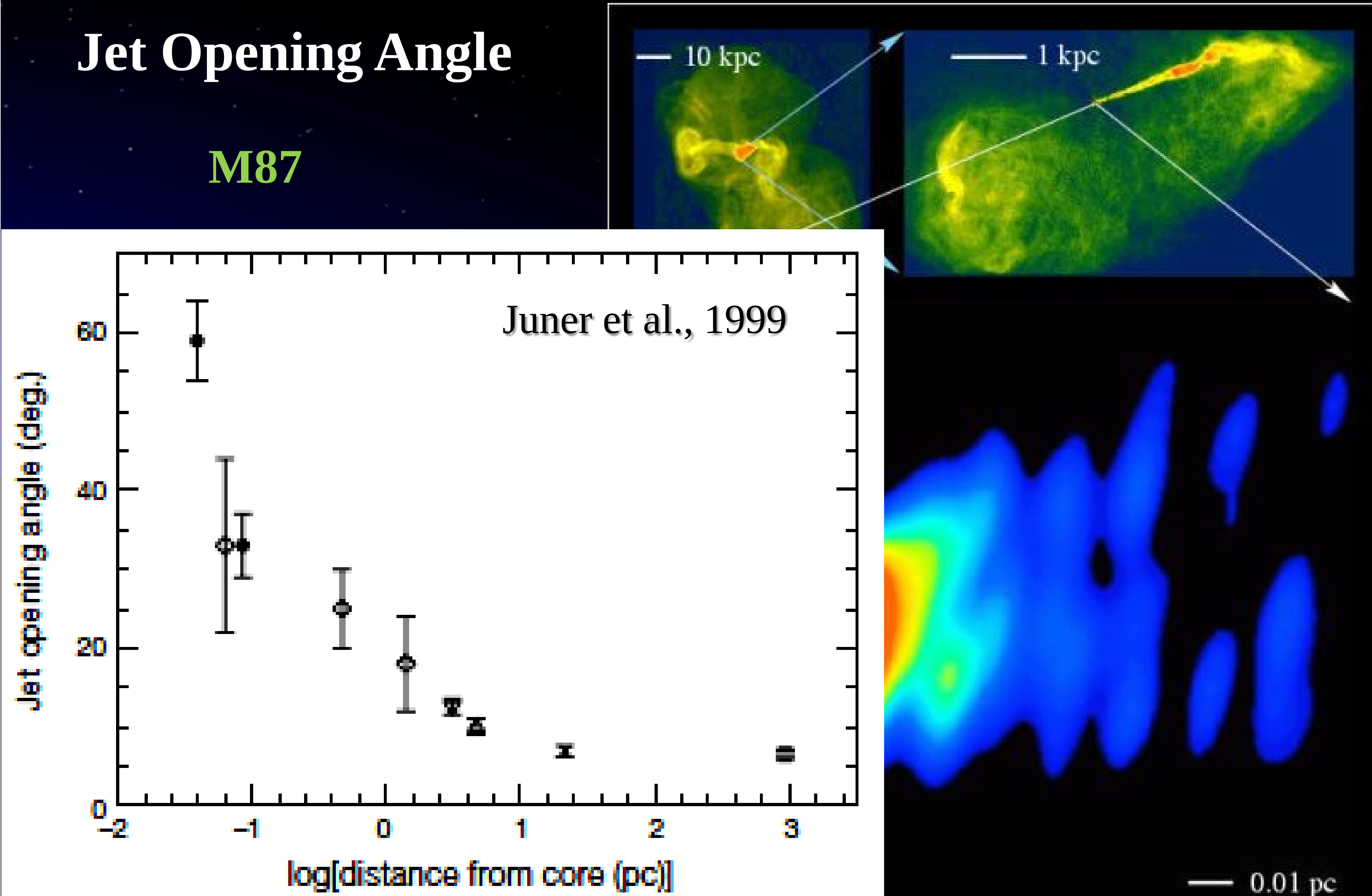
What we know until now

Discussion

Cosmic ray generation, acceleration, propagation

Jet Opening Angle

M87



M

A

G

N

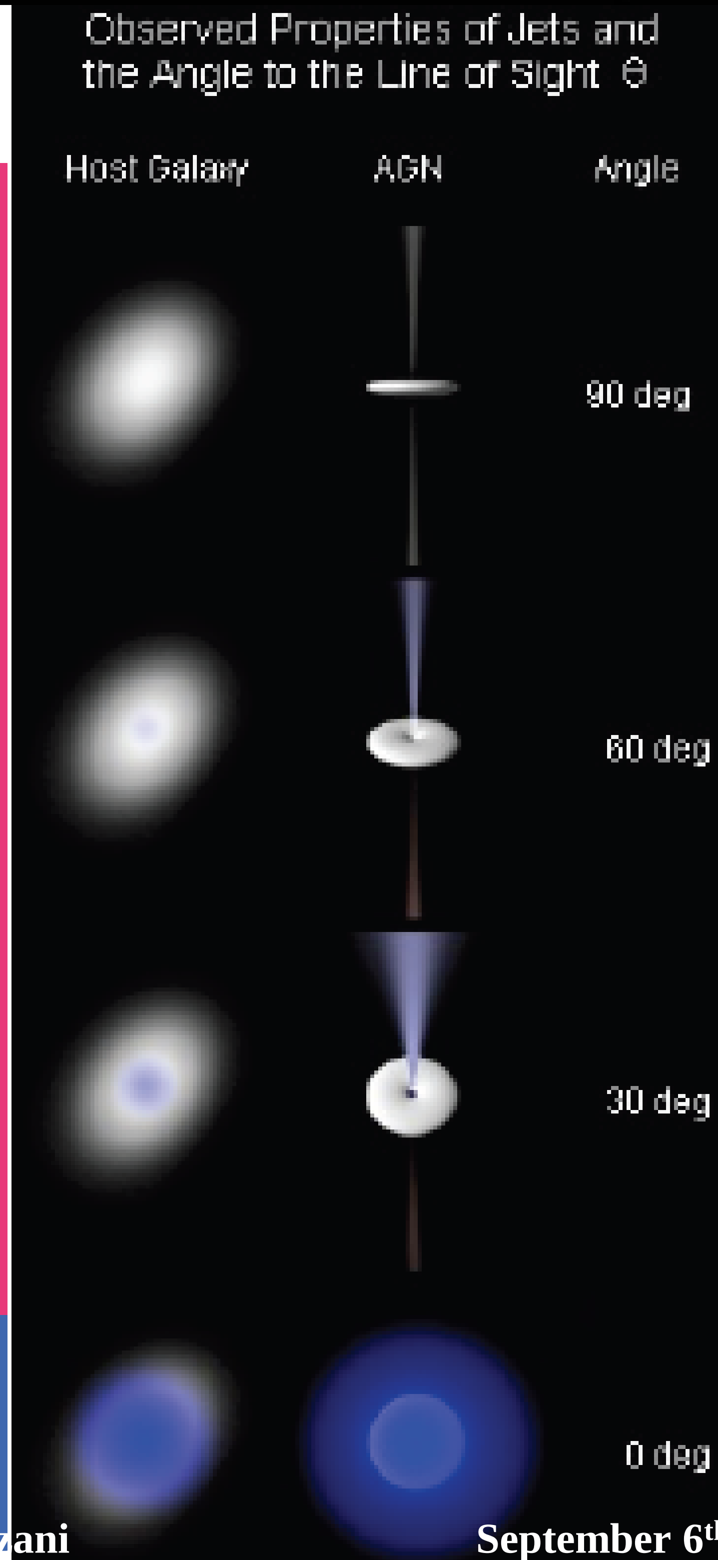
Grandi, 2011

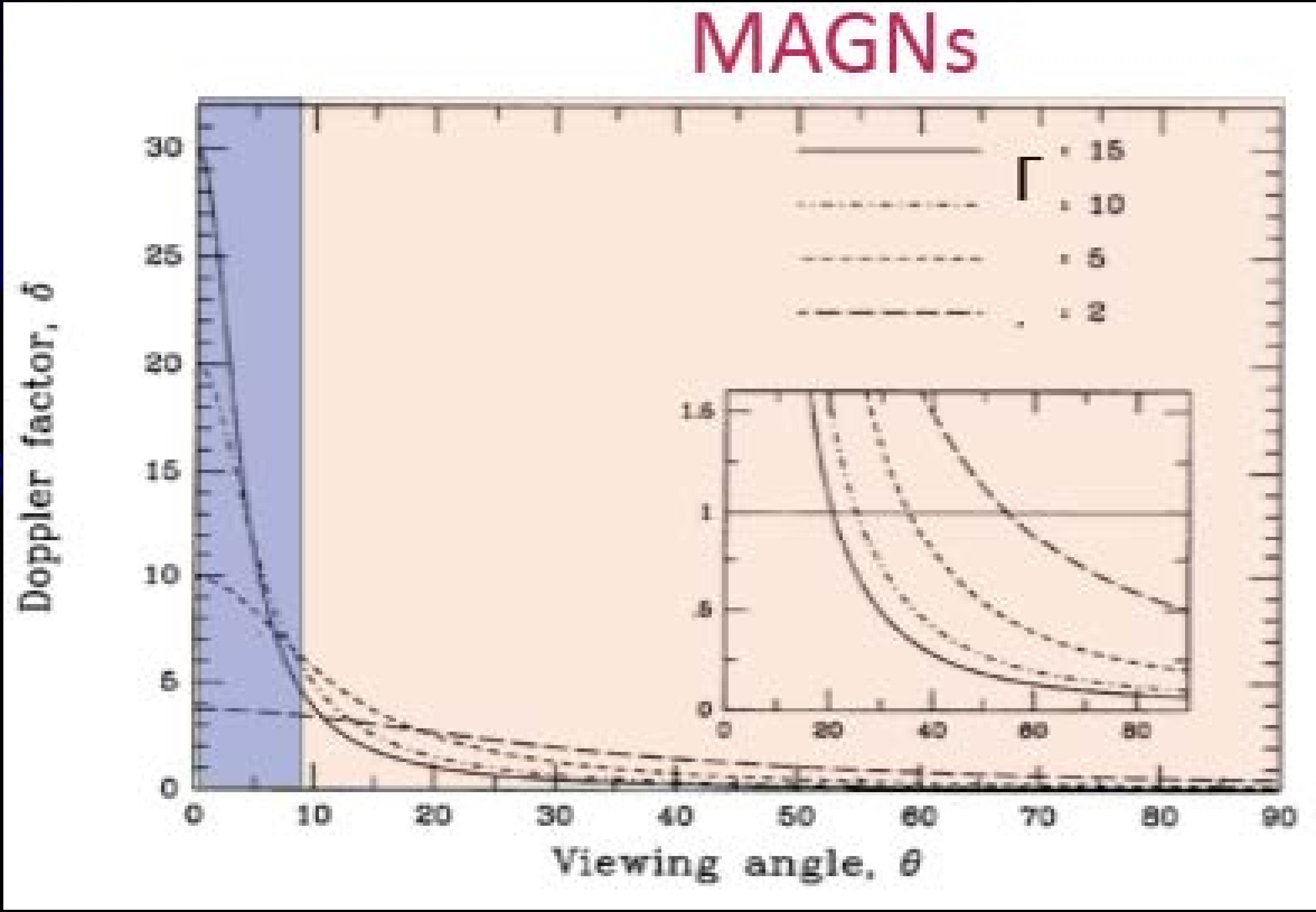
MAGNs

- NLRG
- BLRG
- SSRQs

Blazars

- BL LACs
- FSRQS

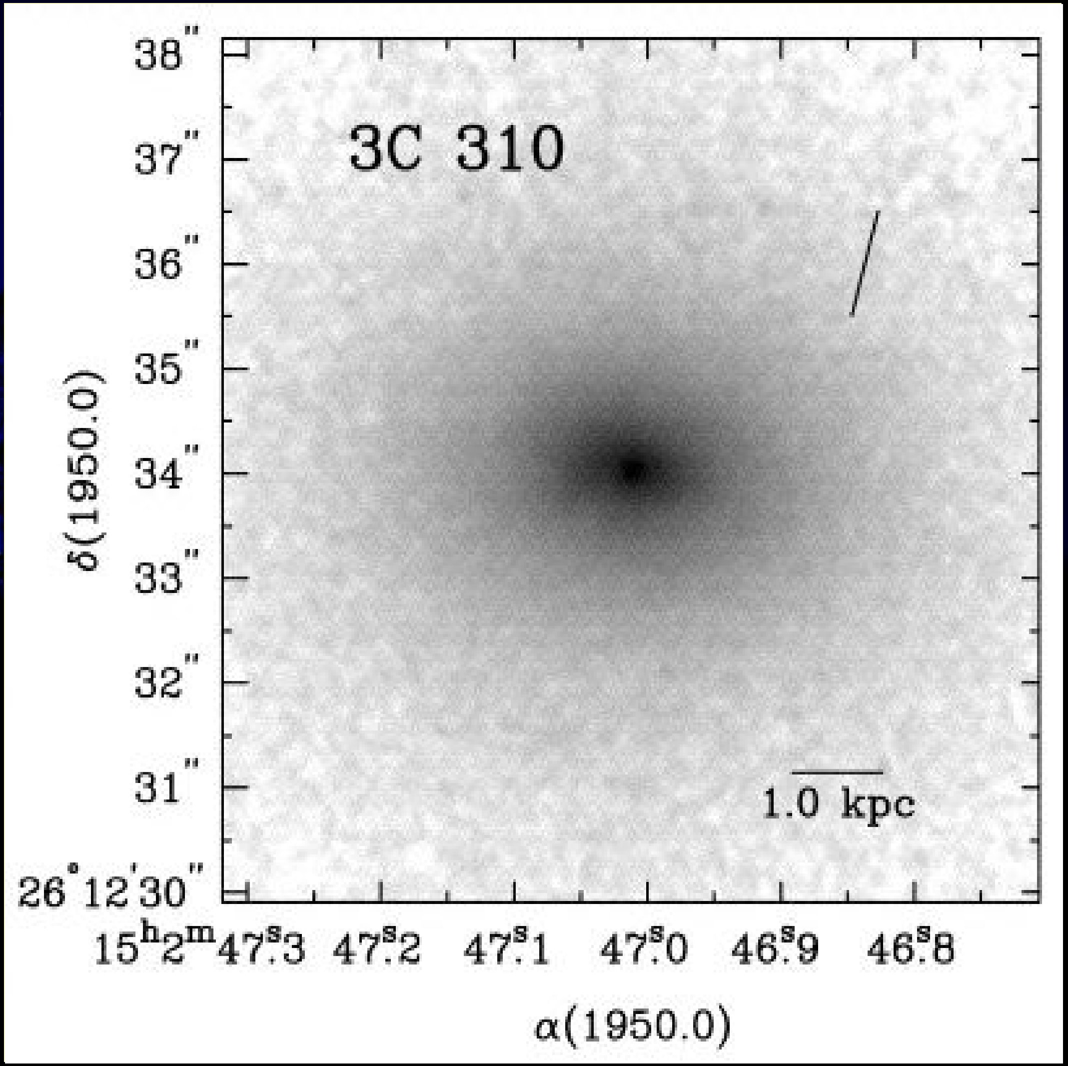




Her A : Lorentz factor $\Gamma \cong 1.6$, Doppler factor $\cong 1$ for $\theta \approx 50^{o}$

HST/WFPC2 0.05´´

Chiaberge et al., 1999



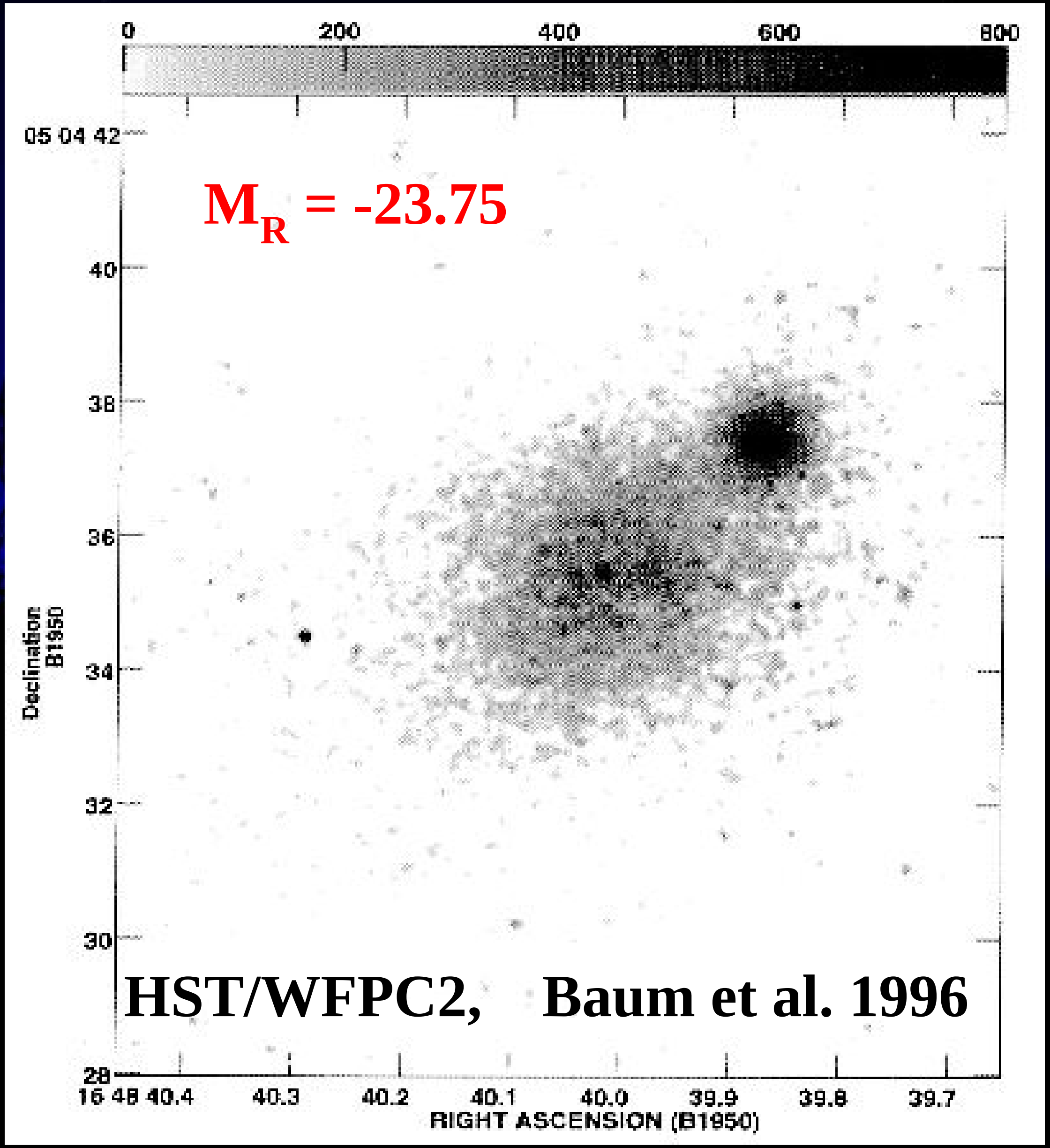
Z =0.054

central kpc emission
~⊥ radio jet axis,
Bright pair,
$M_R \cong -23$
Martel et al., 1999

linear correlation of optical flux of compact core with radio core

Hercules A

optical



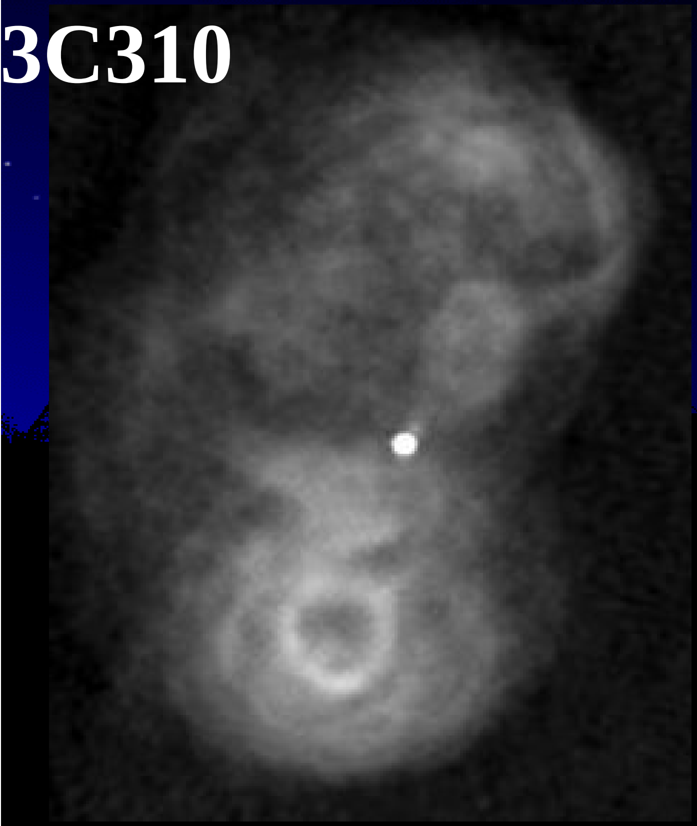
z = 0.154

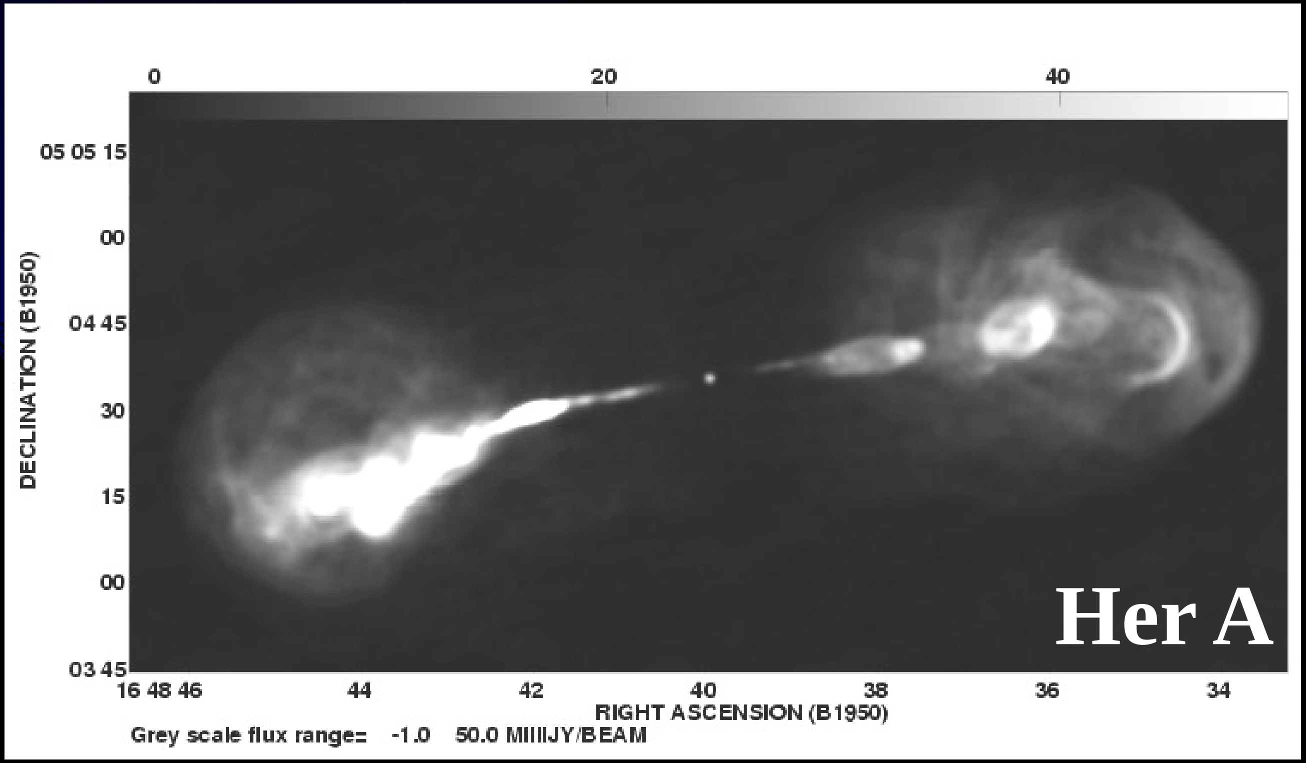
- Very elongated cD galaxy: double nucleus & tail
- radio emission from dimmer, larger galaxy

VLA total intensity distribution

Van Breugel & Fomalont, 1984

Gizani 1997





21cm, 4 arcsec

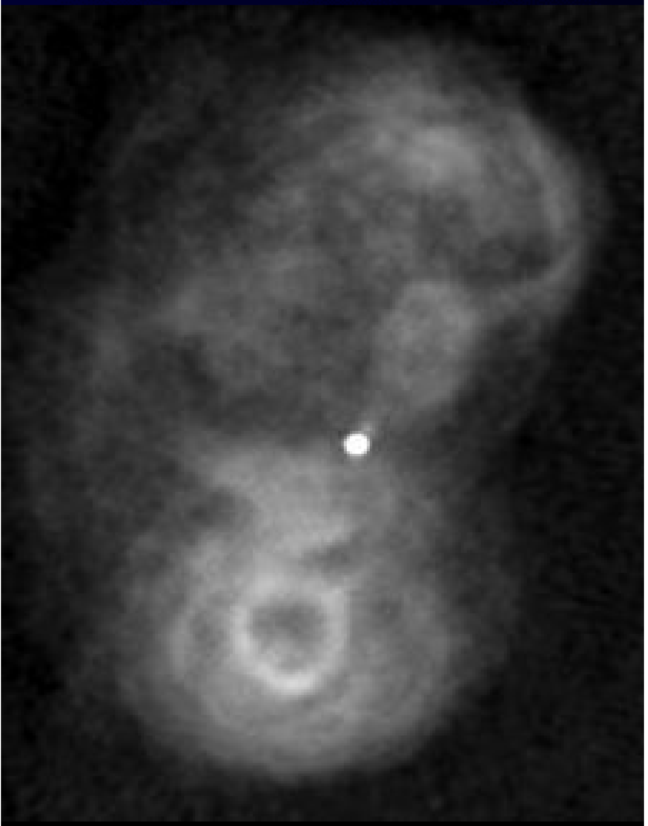
$P_{178\ MHz} \sim 3.57 \times 10^{25}$ Whz^{-1}

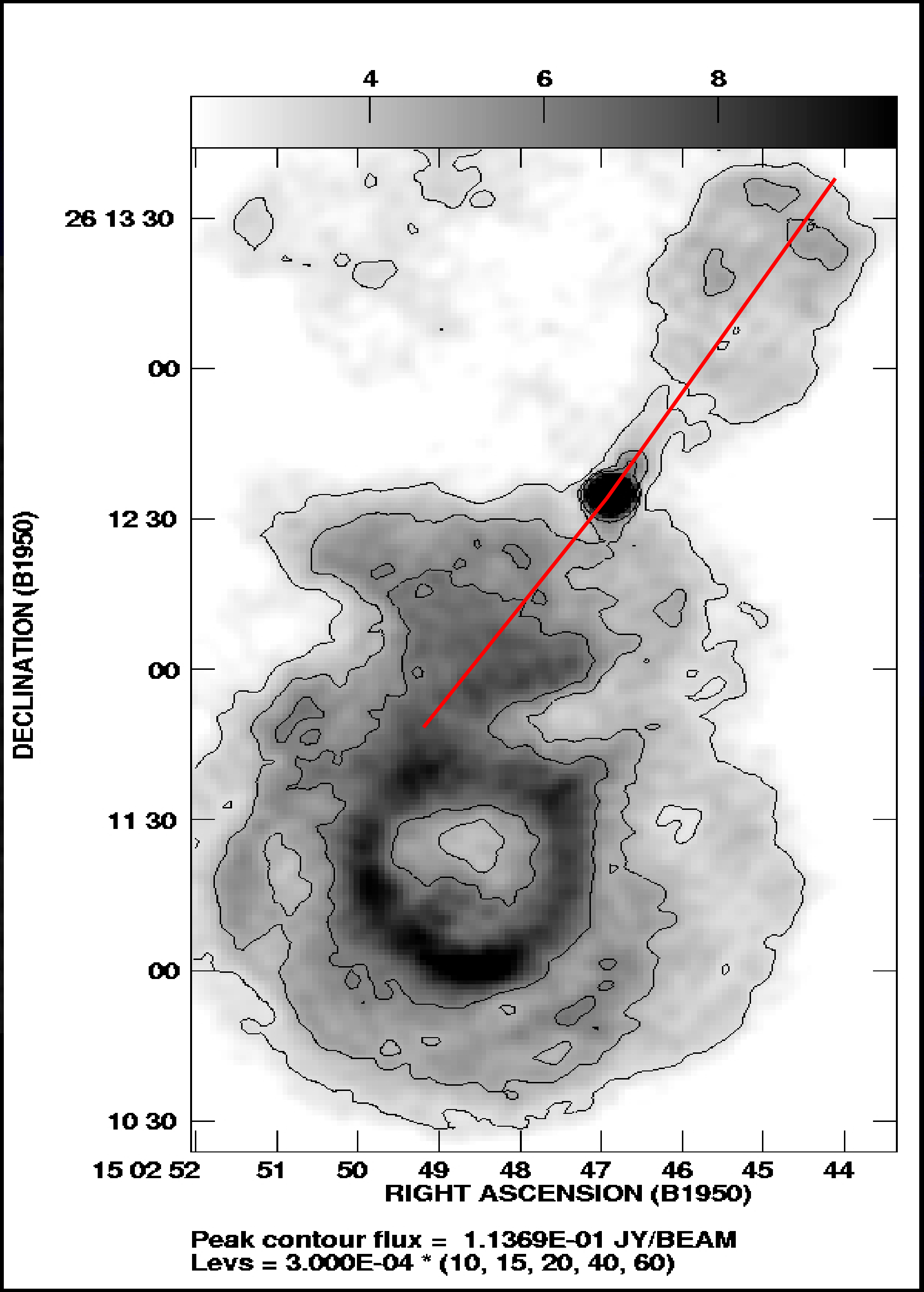
18 cm, 1.4 arcsec

$P_{178\ MHz} = 2.3 \times 10^{27}\ WHz^{-1}$

Steep spectrum $\alpha \sim -1$, FR1.5

3C310



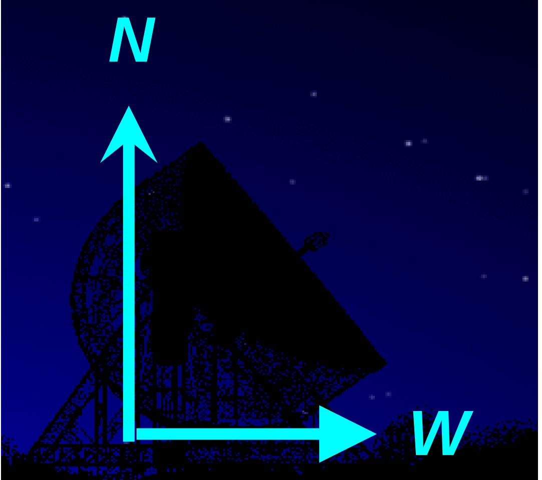


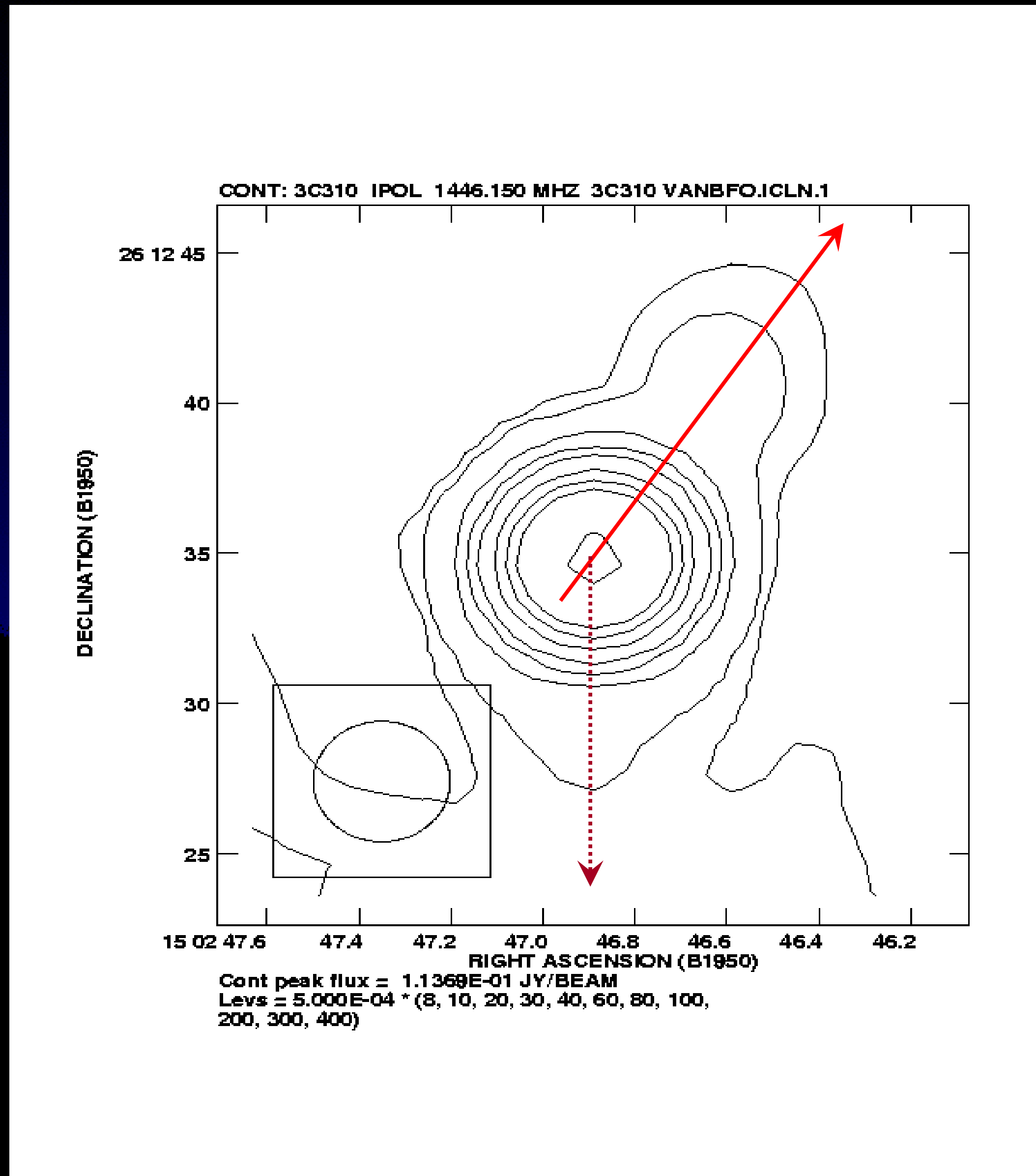
Kpc-jet(s)

VLA, 21 cm, 4 arcs

linear size 173 kpc

21 cm, 4 arcsec



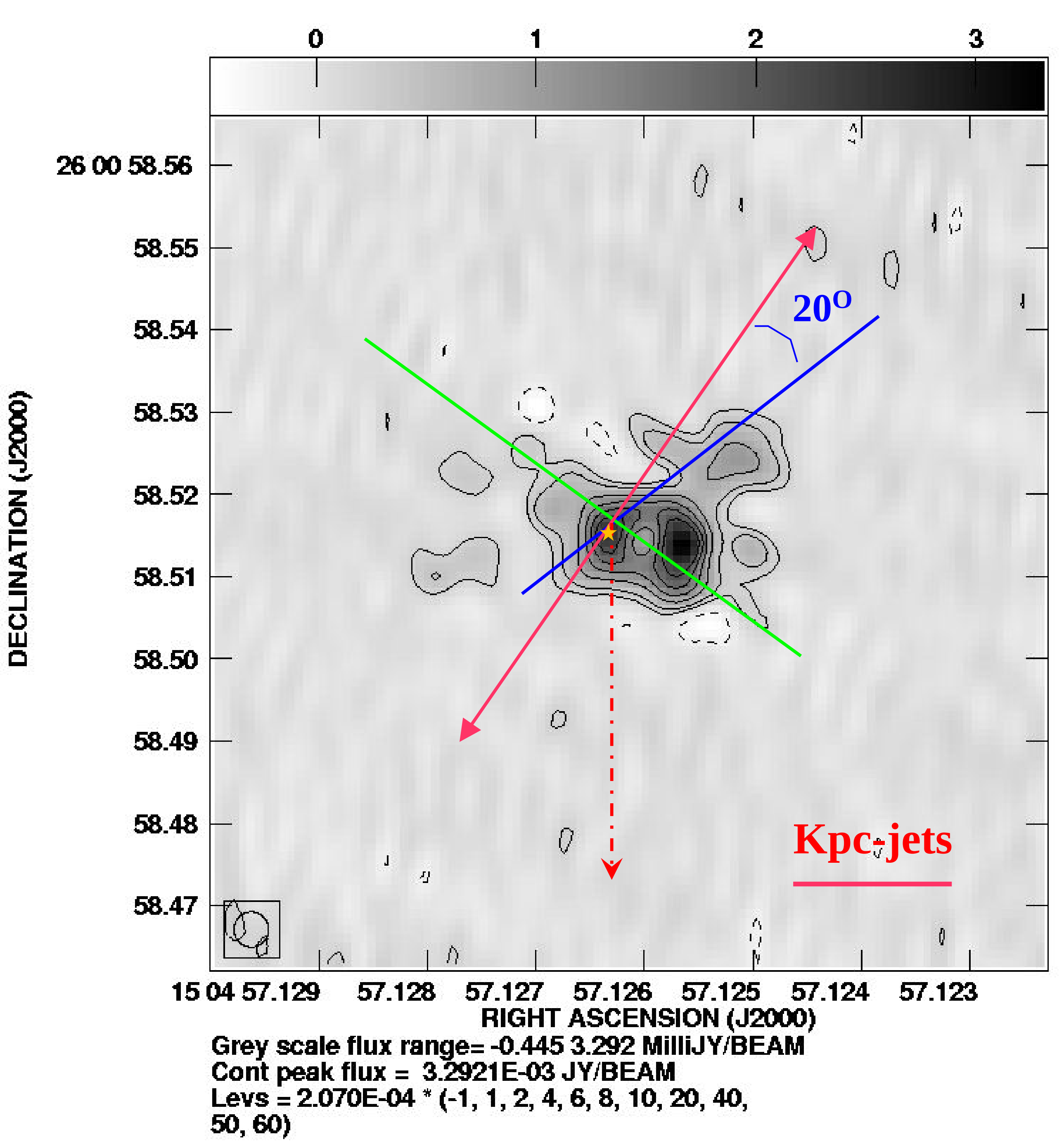


~ 130 mJy

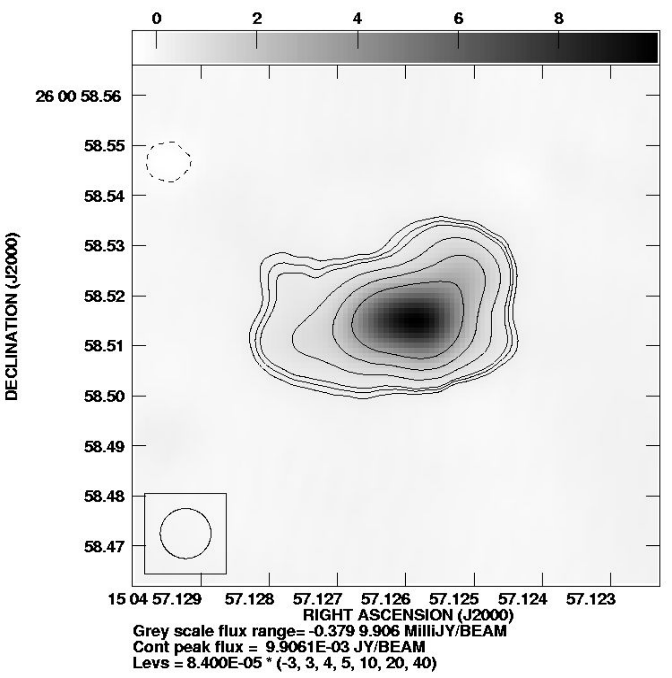
$$P^{core}_{6\ cm} \sim 7.25 \times 10^{23}\ \mathrm{WHz^{-1}}$$

4 mas, R = –1

Global VLBI, 18 cm, phase referencing



Natural weighted
10 mas

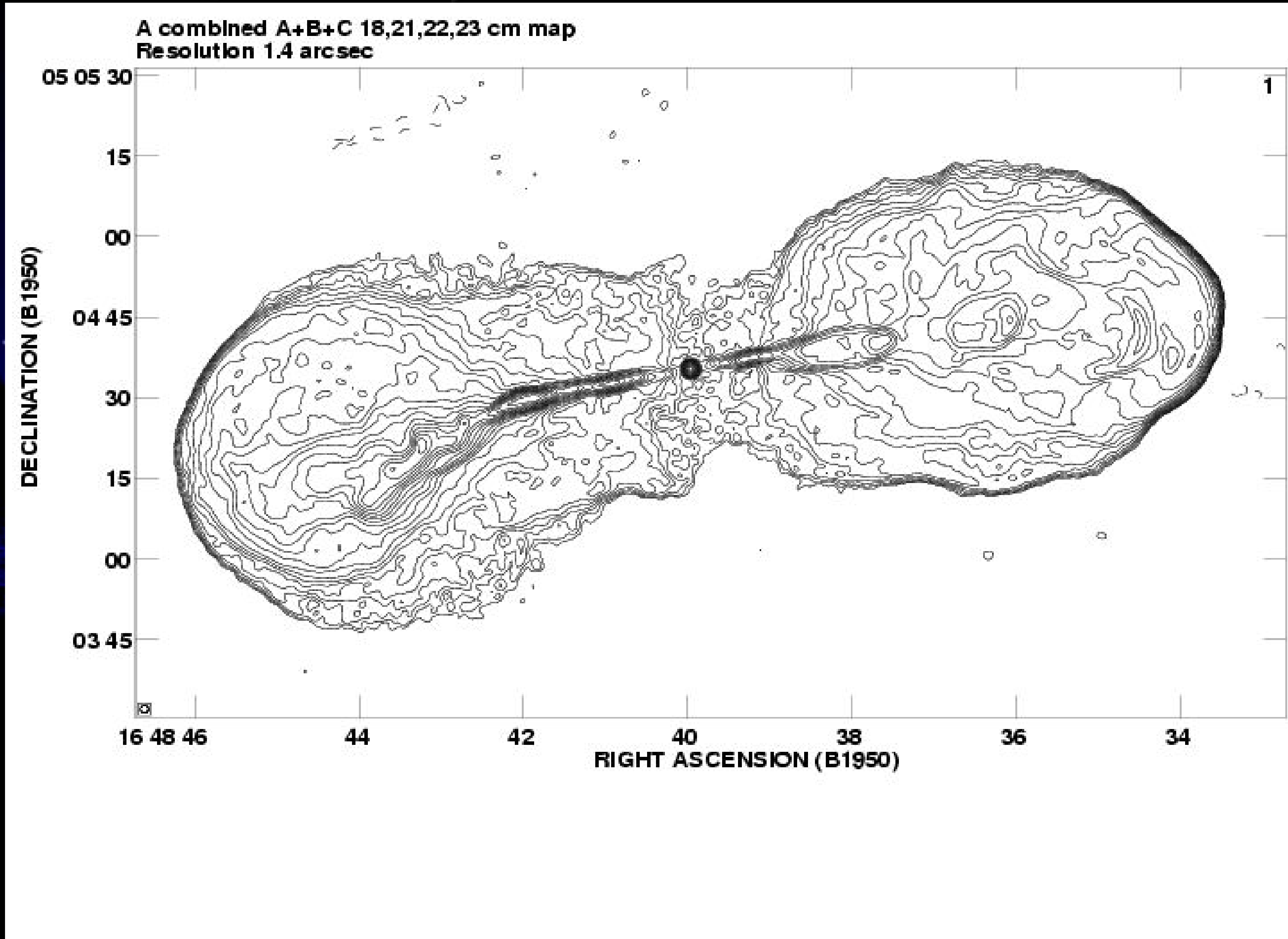


~16.5 mJy

≈17× 5 mas

~ 85°

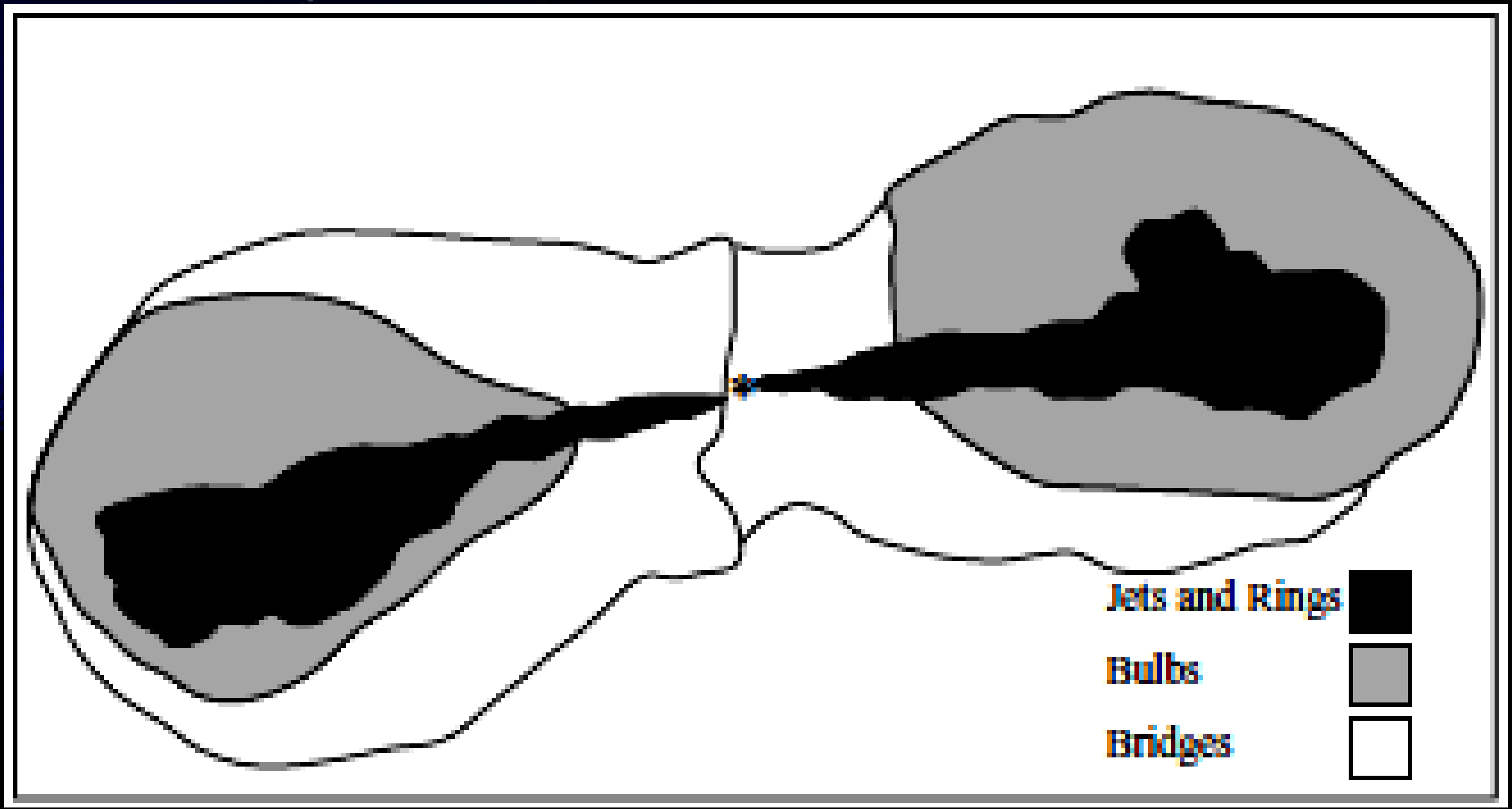
$T_b \sim 2.5\times 10^7$ K

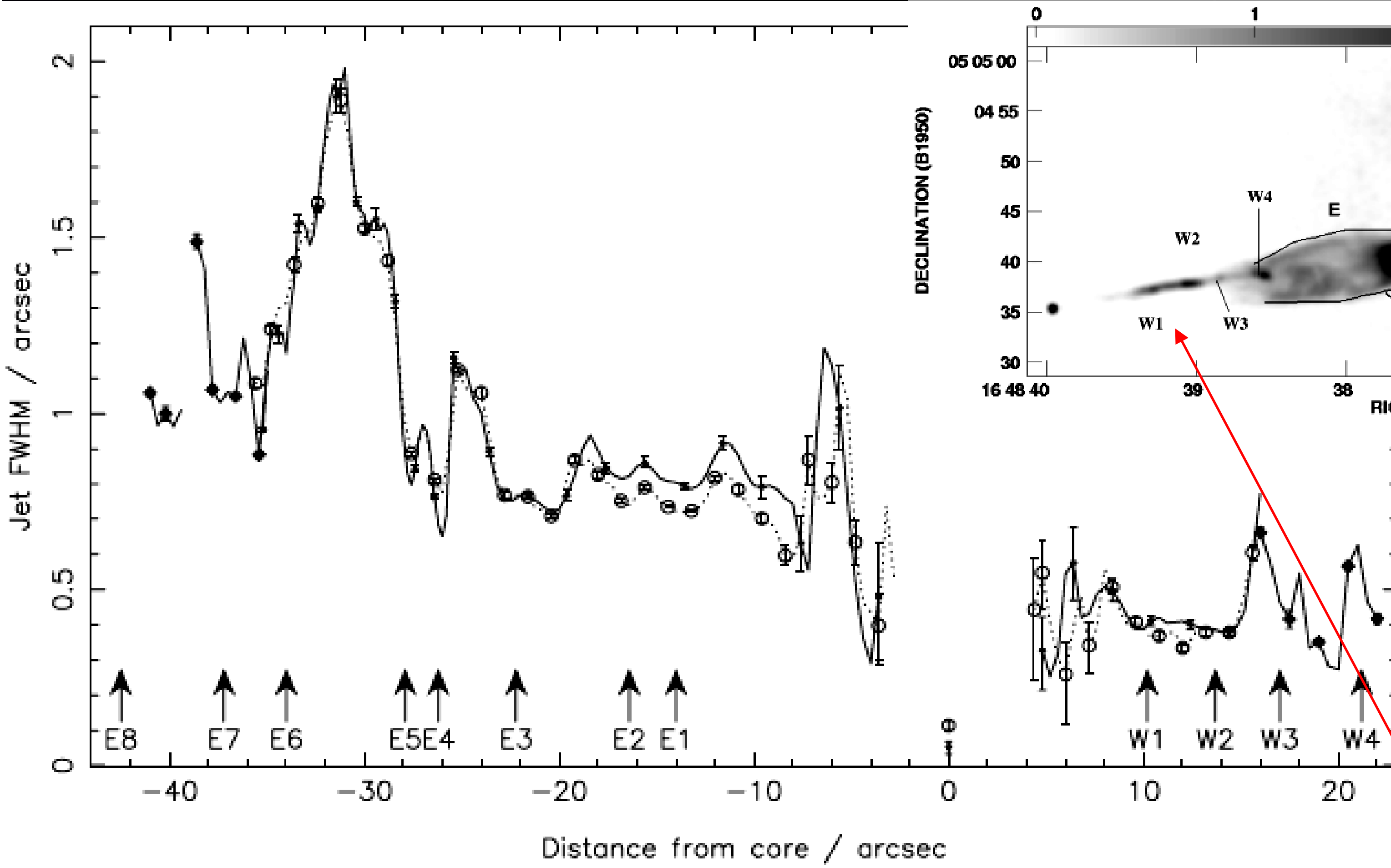


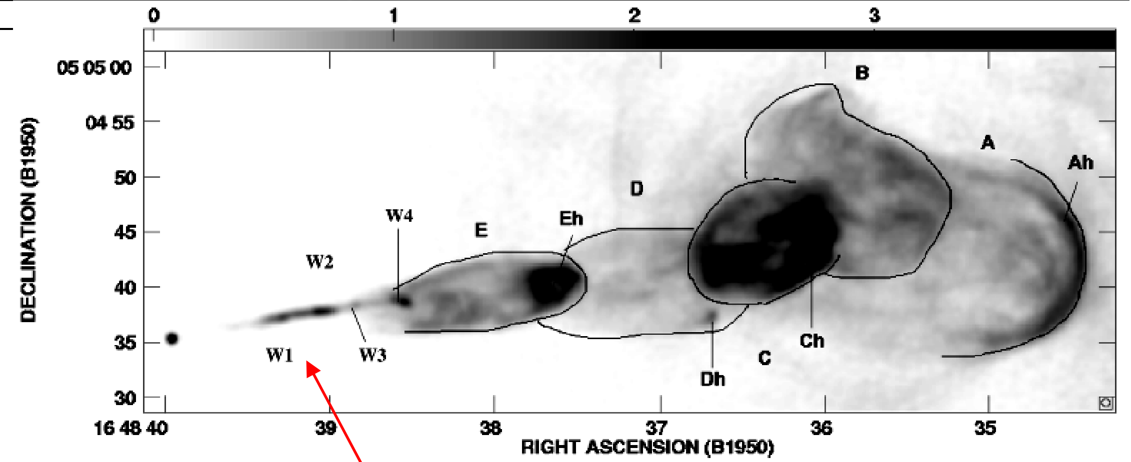
$L_{tot} \sim 3.8\times10^{37}$ W, (10 MHz — 100 GHz) $H_o = 65$ *km/Mpc s*, $q_o = 0$

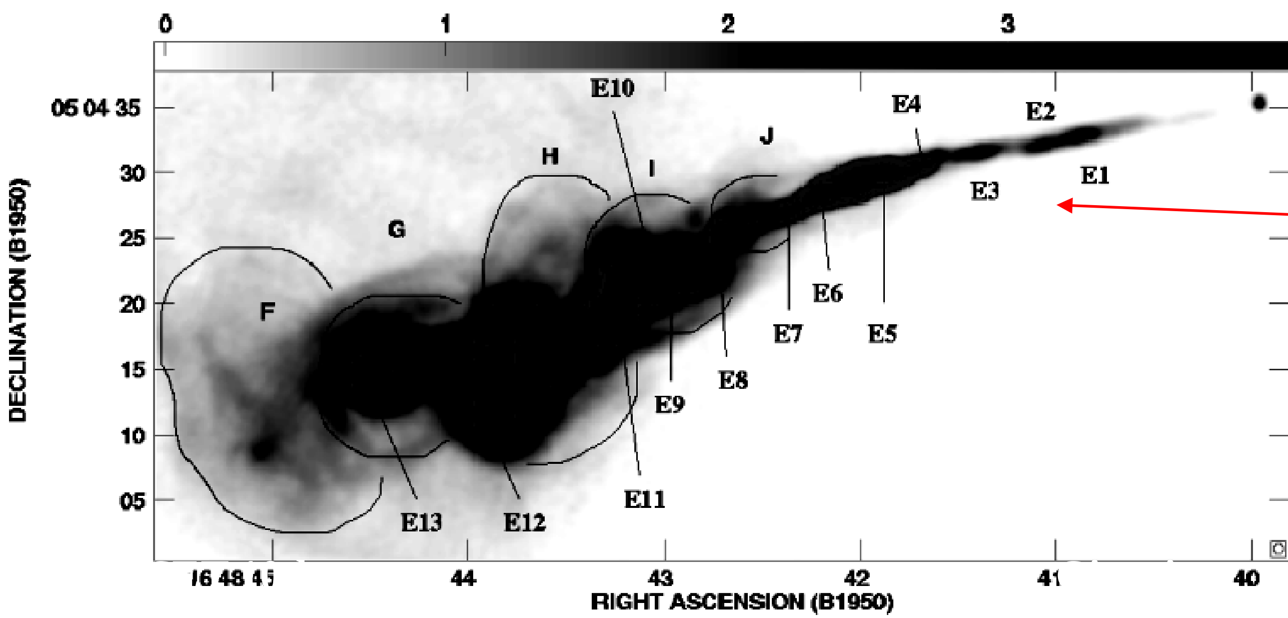
linear size ~ 194" (540 kpc), width ~ 70" (250 kpc)

$P_{178\ MHz} = 2.3 \times 10^{27}\ WHz^{-1}sr^{-1}$


Jets and Rings
Bulbs
Bridges







Collimation of jets

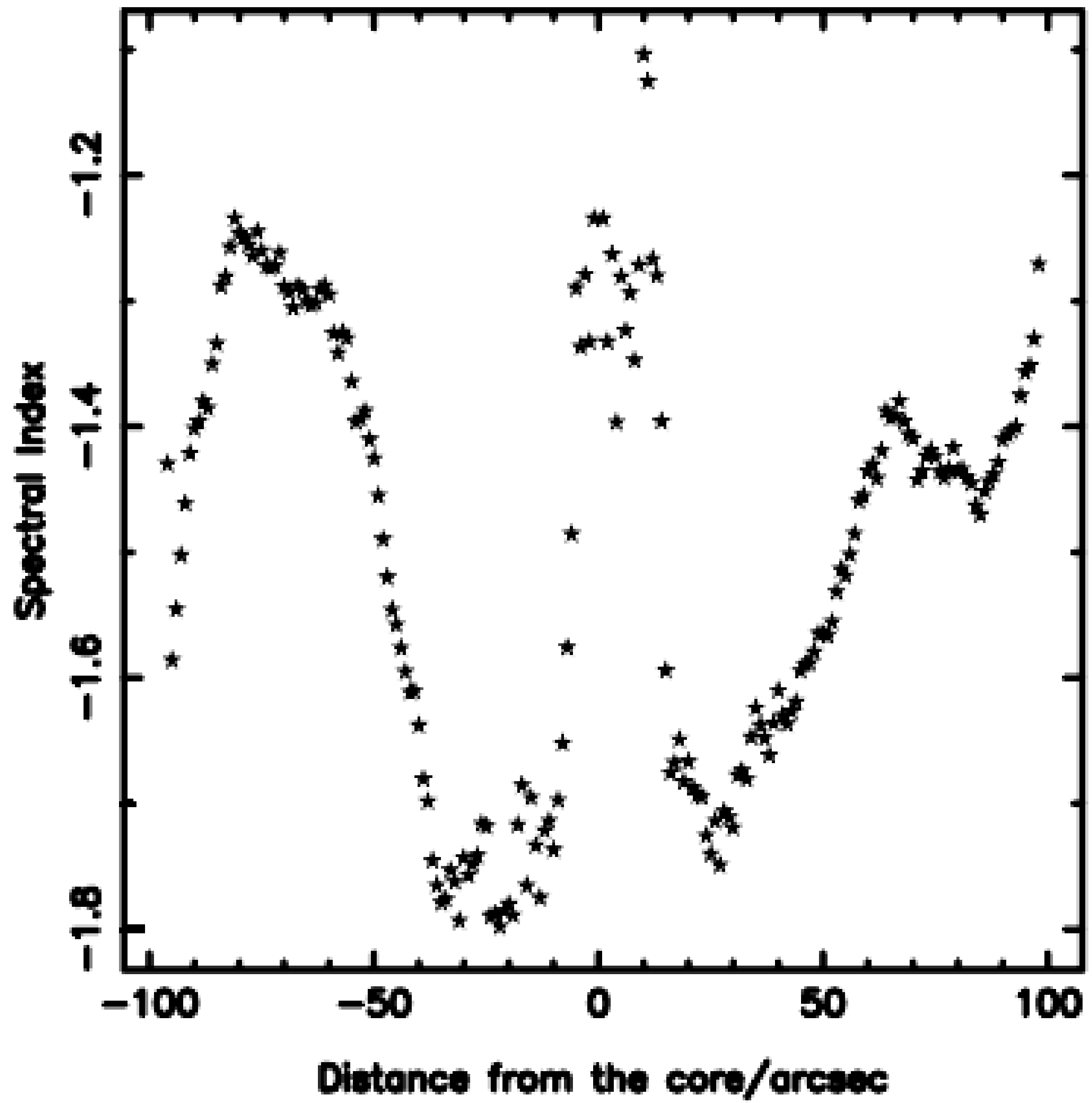
. Average

Region
Total
East side
West side
East bulb[a]
East bridge
East jet
West bulb[a]
West bridge
West jet/rings
Core

[a]Excluding the jets

ectral tomography.

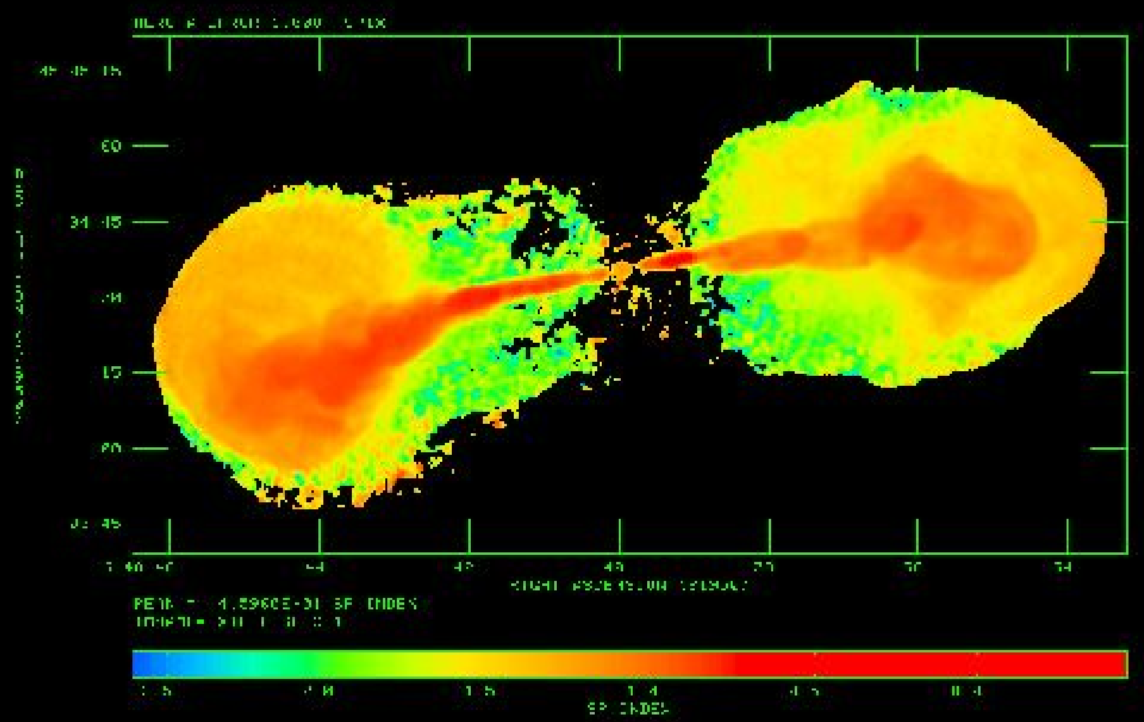
$\alpha(4.8, 8.4)$
-0.72 ± 0.03
-0.76 ± 0.04
-1.04 ± 0.05
-0.98 ± 0.03
-0.98 ± 0.03
-0.70 ± 0.03
-1.06 ± 0.04
-0.94 ± 0.03
-1.04 ± 0.03
-1.04 ± 0.03
-1.14 ± 0.04
-0.90 ± 0.03
-0.76 ± 0.03
-0.87 ± 0.02
-0.90 ± 0.03
-0.87 ± 0.03
-0.88 ± 0.04
-0.92 ± 0.03
-1.02 ± 0.04
-1.04 ± 0.06



Plot of strip averages of the spectral index α at 1.4-arcsec resolution against the distance from the core.

Whole source: $\alpha \cong -1.5$; young jets, rings $\alpha \cong -.7$; older lobes $\alpha \cong -1.5$; faint material $-2.5 \leq \alpha \leq -1.5$

$\alpha_{core} \approx -1.3$, steep spectrum, optically thin

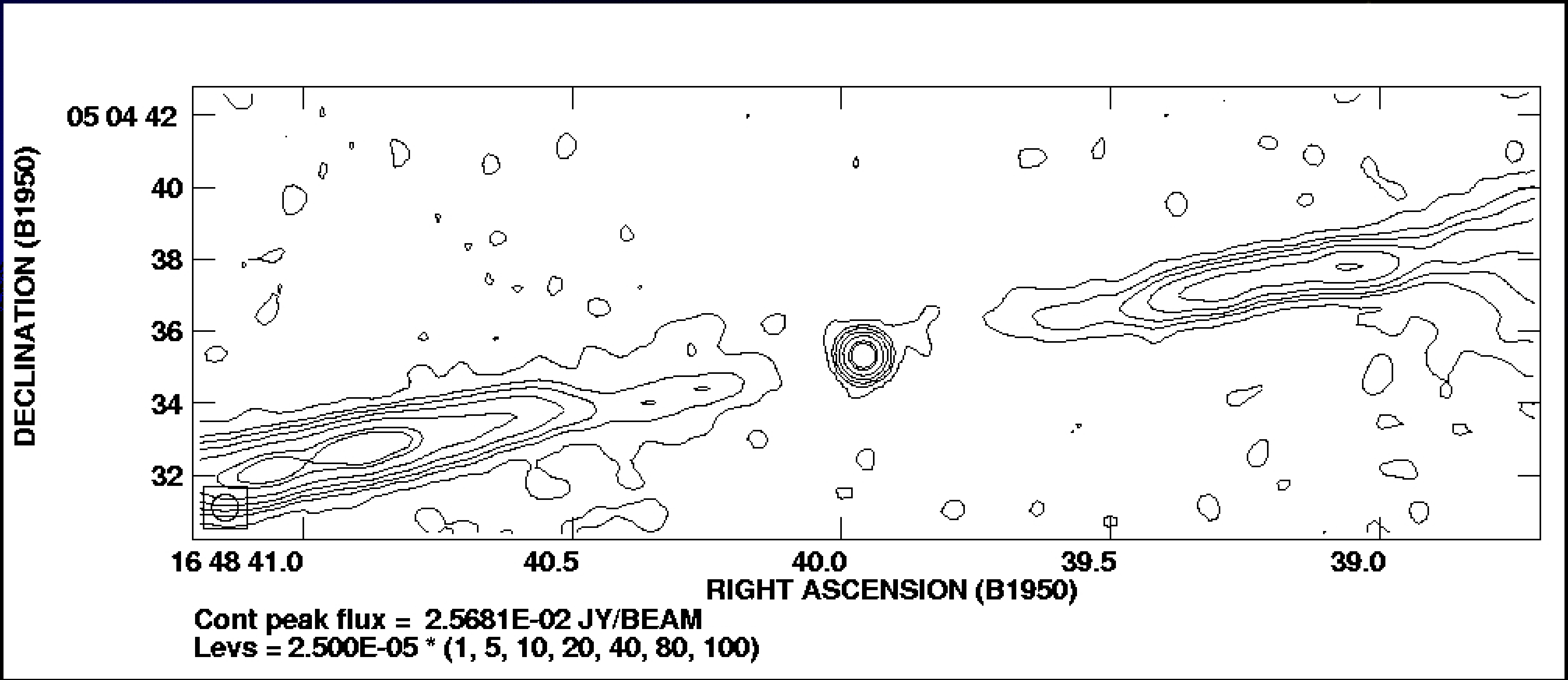


$S_\nu \propto \nu^\alpha$, $\alpha<0$

AIPS User 1020 A MAP AT 1.4 ARCS, X,C,L

Hercules A

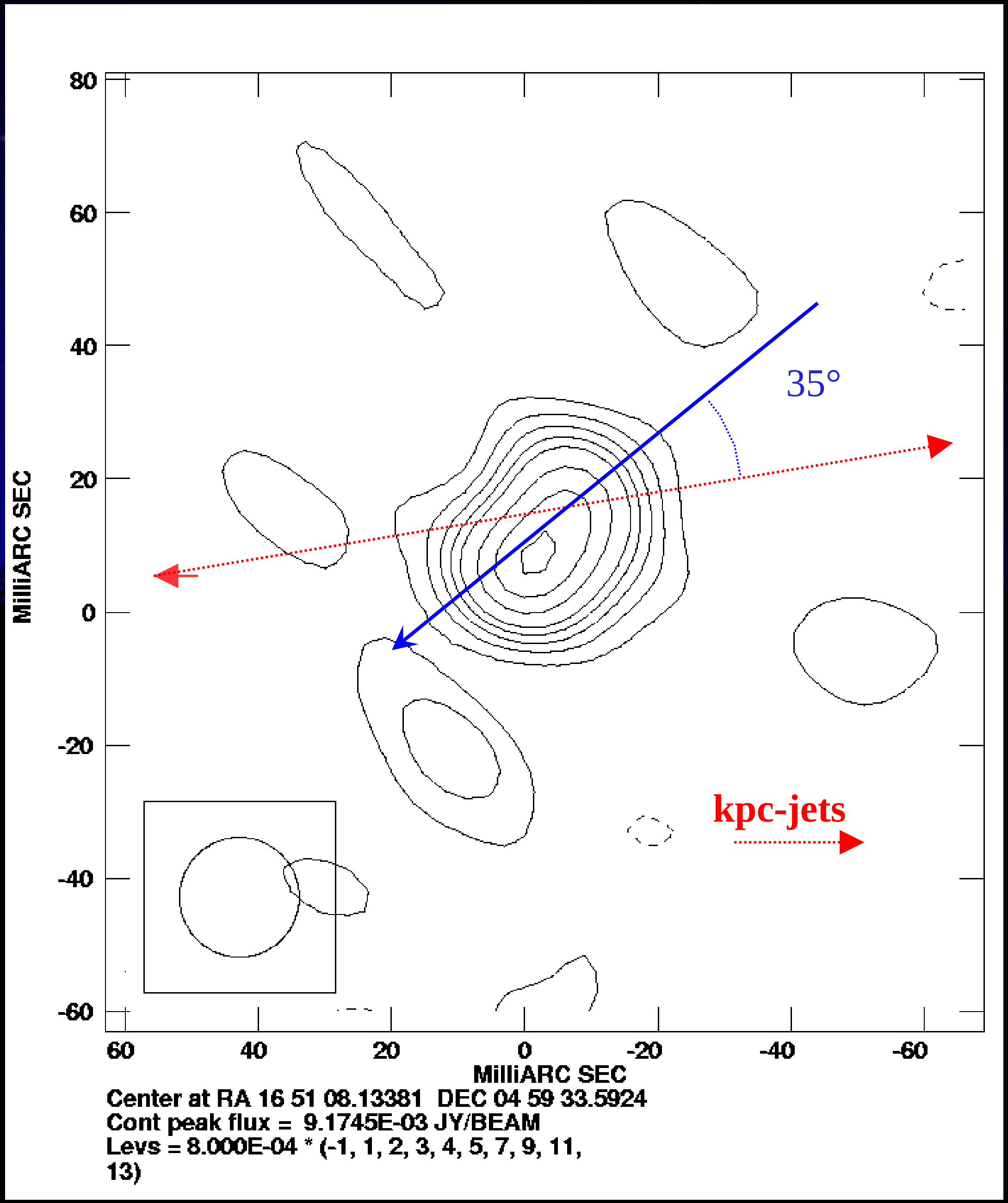
VLA B+C+D , 3.6 cm, 0.74 asec, rms ~ 11 μJy



~ 6.0 mJy

18 cm: ~41 mJy

EVN, 18 cm, 0.018 arcsec



<u>1– Gaussian fit</u>

rms≈ 3.6×10^{-4}Jy/beam

≅ 14.6 mJy

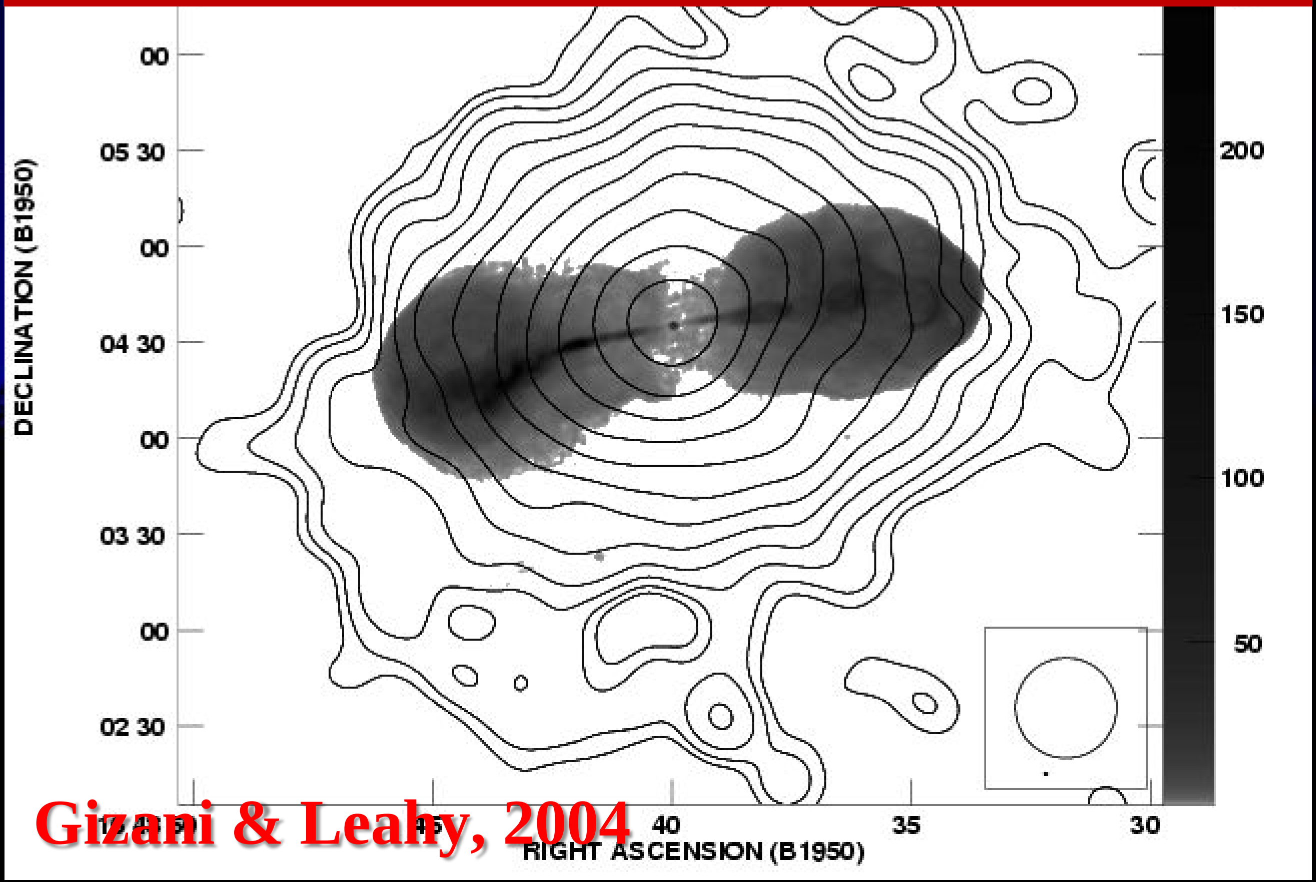
~18.2×7 mas

p.a. ~ 139°

$T_b \cong 2 \times 10^7$ K

Contour map: PSPC + HRI 0.5 - 2 keV, 32´´, 1st cont 2.94×10^{-10} $Wm^{-2} sr^{-1}$

Lobes confined by thermal pressure of ICM. Little entrainment ⇒ lobe energy~particles (more),fields



Gizani & Leahy, 2004

Grey: log- 20cm radio 1.4´´

$L_x \approx 4.8\times10^{37}$ W
$L_x^{point} \approx 2\times10^{36}$ W,
size=15 kpc

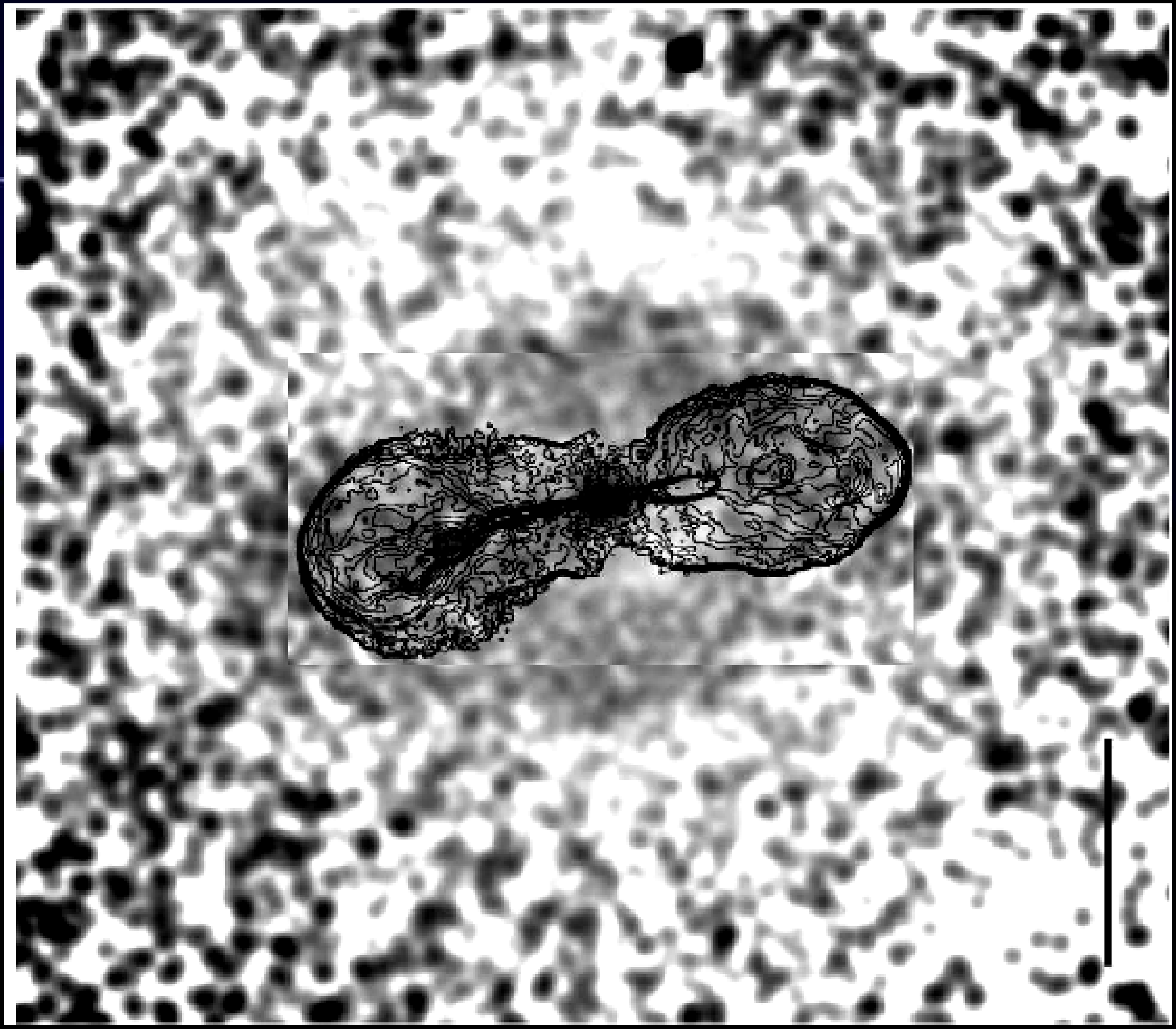
Multiphase gas

ROSAT: $0.5 < kT$ (keV) < 1, $N_H \approx 6.2\times10^{20}$ cm^{-2} — Gizani & Leahy, 2004

BeppoSax: $3 \leq kT$ (keV) ≤ 5, — Trussoni et al., 2001,

ASCA: $kT \approx 4.25$ keV, — Siebert & Brinkmann, 99

Chandra: ICM confines inner jets, presence of cavities not associated with radio lobes and front shock surrounding radio source→cocoon shock



Chandra map in (0.3-7.5)keV, smoothed at 2″ devided by β model
Nulsen et al., 2006

Combining
radio (Faraday rotation) + X-ray data (e$^-$ density):
n is the electron density found from

$$n(r) = n_o\left[\left(r/r_o\right)^{\alpha_1} + \left(r/r_o\right)^{\alpha_2}\right] \quad , \quad \alpha_2 > \alpha_1$$

Angle to the line of sight θ ≈ 50^o

extragalactic magnetic field of ICM has central typical value of $3 \le B_o$ (μG) ≤ 9, and radial dependence

$$B(r) = B_o n^{m-1}$$

On tangling scales $4 \le D_o$ (kpc) ≤ 35

ICM confines the lobes very well
$P_{min} << P_{th}$

Results of Minimum-energy calculations and β model fits

DRAGN	$\lg(P_{178})$	α	$u_{min}/3$	D	R_{core}	β	n_0	kT
	$\mathrm{W\,Hz^{-1}\,sr^{-1}}$		pPa	kpc	kpc		$10^3\,\mathrm{m^{-3}}$	keV
Hercules A	27.33	1.01	0.30, 0.38	540	121	0.74	6.5	2.45
3C 310	25.57	0.92	0.019, 0.028	340	84	0.5	2	2.5

B-fields (μG) implied by Inverse Compton arguments

Her A	**4.3**	
3C310	**3.6**	$\rightarrow B_{IC} \approx 3B_{me}$

Cosmic Rays: What we know

Stochastic particle acceleration of UHECRs to high energies (10^{20} eV) is possible within large-scale lobes of powerful radiogalaxies, but sources at low redshift.

radio galaxies are powerful enough to heat and support the cluster gas with injected cosmic-ray protons and magnetic field densities within a cluster radius of ~1 Mpc.

Relativistic e^- loose energy via numerous cooling mechanisms:
1) quickly through synchrotron emission whilst spiraling IC magnetic fields 2) via Compton scattering through collisions with photons of CMB.
These processes not effective for energetic p: Compton & synchrotron cooling times >> Hubble-time.

Sub-parsec scale acceleration is efficient as long as the scales are comparable to the scale of jet generation or initial collimation.

Steepening of spectral index of radio emission$\rightarrow$ cooling of electrons Steep spectral indices found in lobes of Hercules A and 3C310 imply short lifetimes of radiating particles and reacceleration of electrons. $\rightarrow$ energy redistribution in ICM: energy lost by the energetic particles could be gained by the magnetic fields also heating the ICM. The clusters seem to grow. As a result the energy of CRs in the ICM should increase adiabatically.

Synchrotron cooling time is too short for the relativistic electrons to diffuse in the whole lobes considering the growth speed of the lobes. The short cooling time of the emitting cosmic ray electrons and the large extent of the radio sources suggest an ongoing acceleration mechanism in ICM.

Energy input into the central region of clusters (central cosmic ray energy) from the host RG ≅ 1.7×10^{22} W kpc^{-3}
Injected jet power may dissipate and heat the gas, or could accumulate and support the ICM (magnetic fields and particles).

The production rate of gamma rays above 100 MeV by π_o decay after hadronic interactions of the energetic protons with the background gas

Cluster	B_{RM} μG	B_{IC} μG	ϵ_{CR} 10^{-12} m^{-3} Ws^{-1}	dn_γ/dt 10^{-20} m^{-3} s^{-3}
Her A	3-9	4.3	2.4-4.8	0.94-1.9
3C 310	-	3.6	2.4	0.19

γ-ray emission could dominate the bolometric luminosity of the kiloparsec jet if the magnetic fields are of the order of ~10 μG along the jet.

Cluster	L_X^{bol} 10^{36} W	L_X^{AGN} 10^{35} W	P_{178MHz}^{AGN} 10^{26} W Hz^{-1} sr^{-1}	β	n_{eo} 10^4 m^{-3}	kT keV	r_c kpc	r_{tot} kpc	cooling flow
Her A	48	20	19	$0.74 \pm .03$	1	0.5-1	121	2200	y
3C 310	1	~7	0.37	0.5	0.2	2.5	84	> 670	y

In radiogalaxy jets, boundary layers are often clearly visible in radio polarization. Boundary layers in jets are sites of particle acceleration

Fossil AGN jets and cocoons leave a huge MHD storage even if the AGN is 'dead'

Initial X-ray cavities will have disappeared by the time that cosmic rays fill the large radio-emitting volume in the cluster gas and a dense filament will be formed. Combined observations of thermal filaments and radio lobes can be used to trail the propagation of cosmic rays, and study the magnetic structure in the hot ICM and the total cosmic ray energy involved.


Ευχαριστώ – Thank you