Chandra Observations of Kiloparsec-Scale Jets

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INTRODUCTION

- **What Do Jets Do?**
  - **Carry large quantities of energy, to supply radio lobes**
  - **Interact with gas in galaxies and clusters of galaxies**
- **What Do We Want to Learn?**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**
- **Why Do We Need Multiwavelength Data?**
  - **Spectral Energy Distribution (SED) gives mechanism**
  - **Particle lifetimes change with observed band**

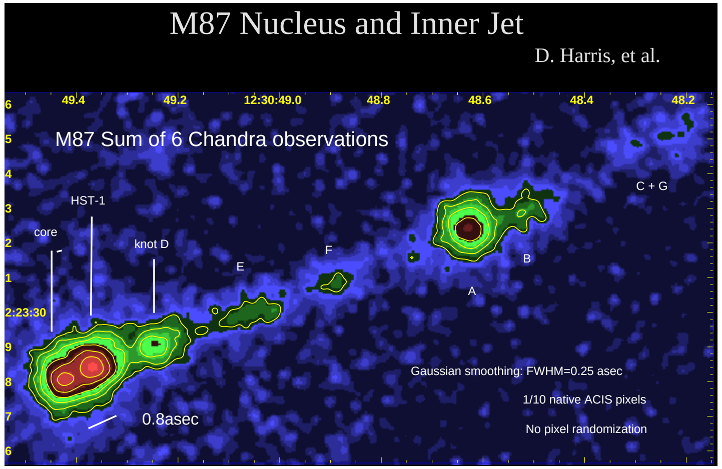
IMAGING ISSUES

- **Morphology**
  - **Radio/Optical/X-ray comparison**
  - **Knots vs. hotspots vs. continuum**
- **Detailed Spatial Relations**
  - **How do we define a region?**
  - **Where are acceleration sites?**
  - **Lifetime issues**
- **Change of Direction**

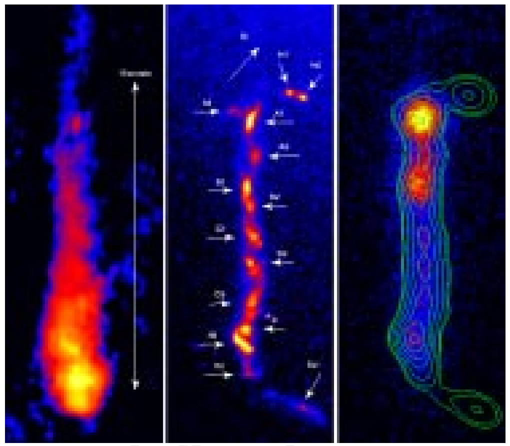
Outline

1. Nearby Jets
    - Cen A, 3.4 Mpc
    - M87, 16 Mpc
    - 3C 273, 750 Mpc
2. Quasar/FRII Jets

Cen A, Kraft et al.



3. Jets at Large Redshift



Marshall et al. 2001ApJ...549L.167M

Outline

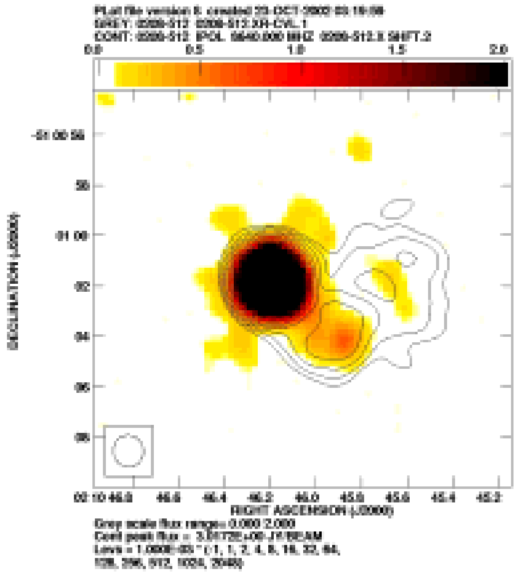
1. Nearby Jets

2. Quasar/FRII Jets

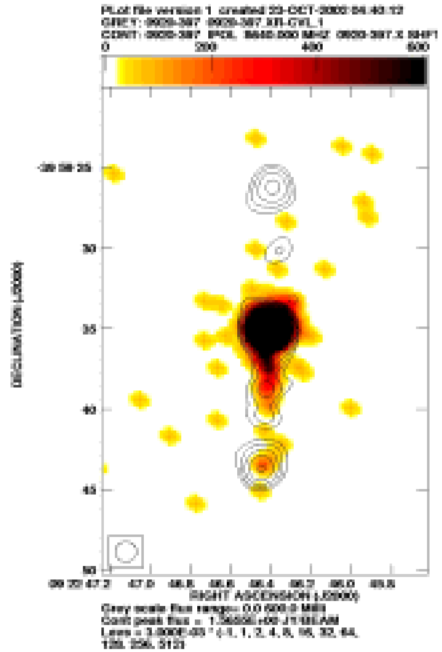
   - Spatially resolved analysis
   - Broadband SED
   - Interpretation as IC/CMB
   - Kinetic flux and efficiency

3. Jets at Large Redshift

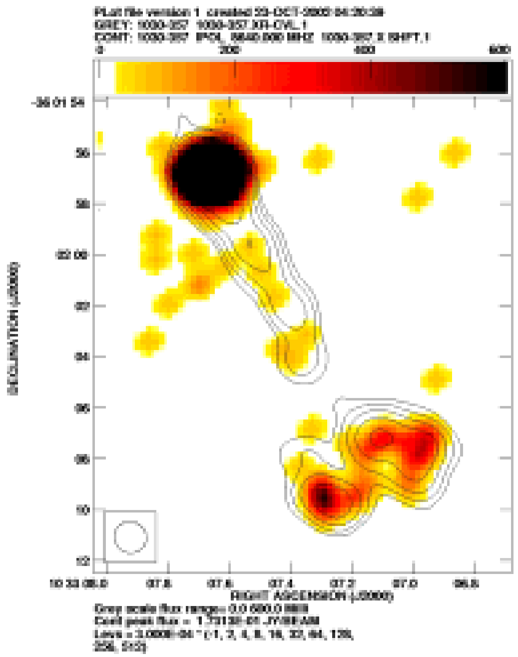
PKS 0208-512

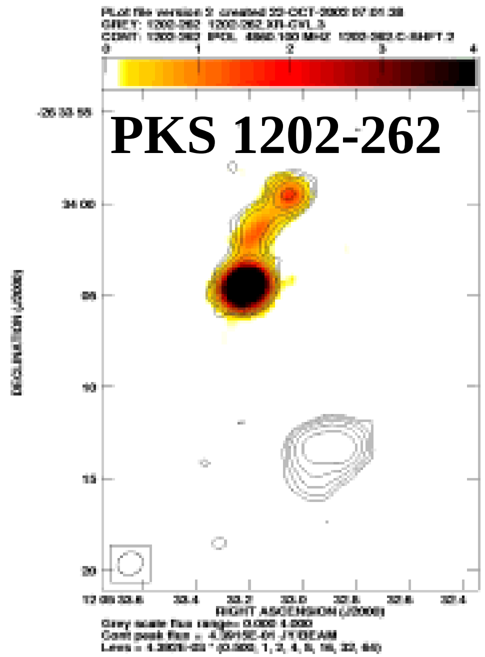


PKS 0920-397



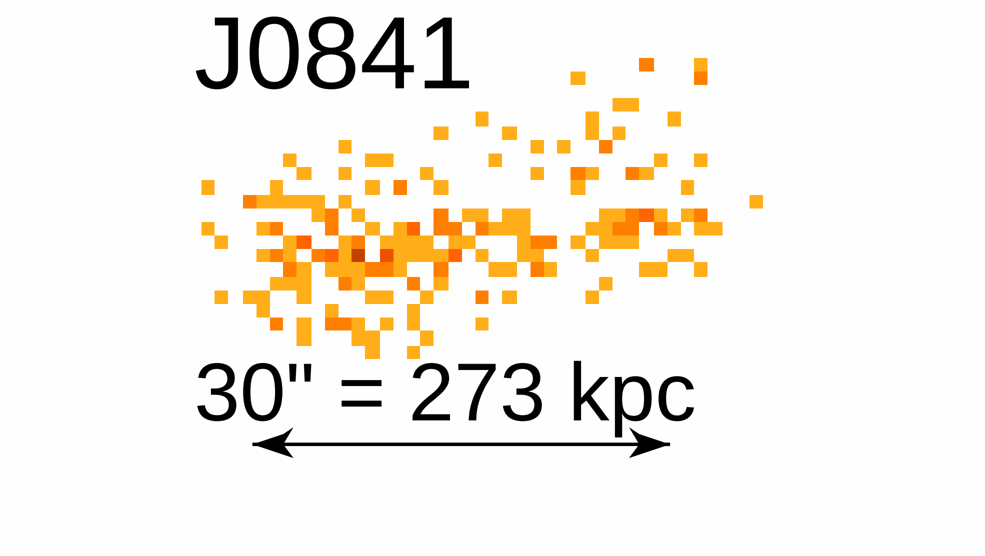
PKS 1030-357





Outline

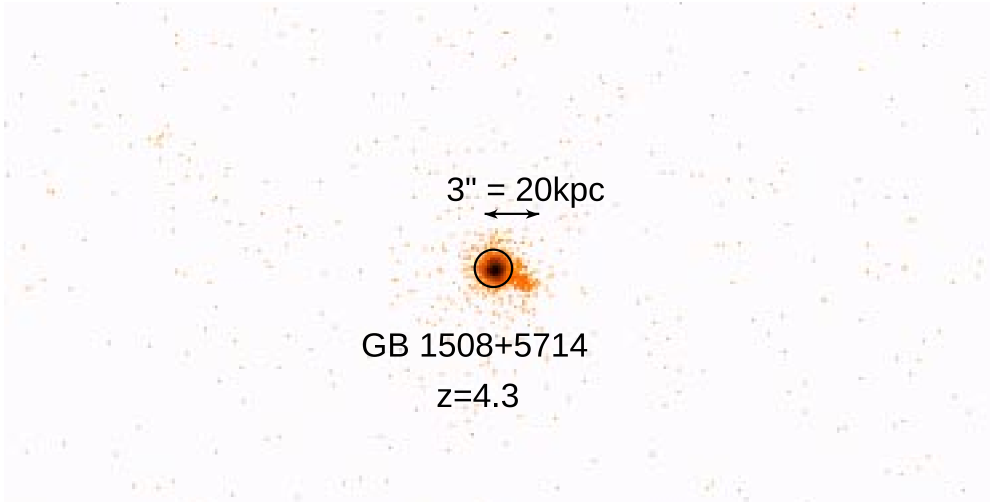
1. Nearby Jets



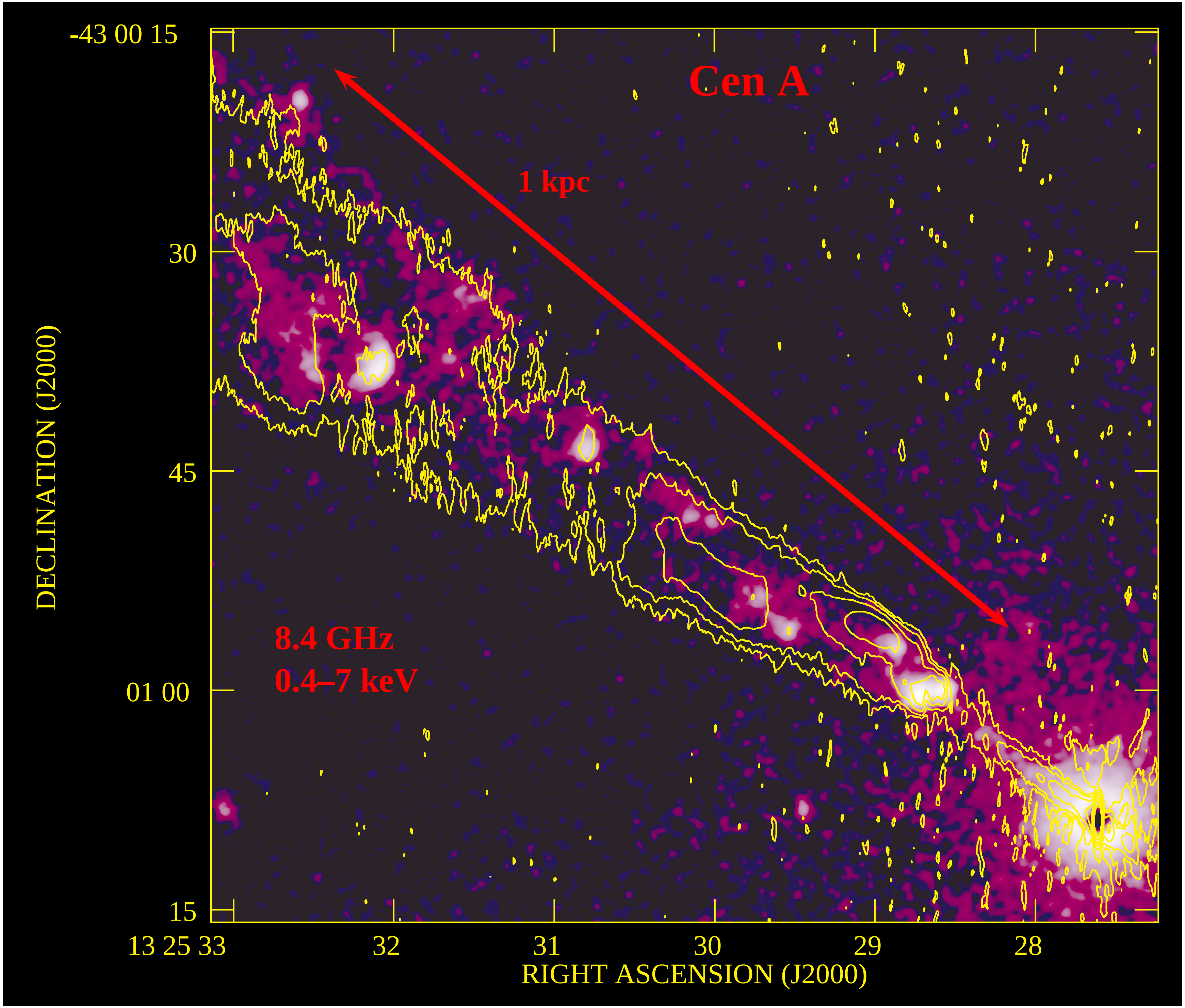
2. Quasar/FRII Jets

Schwartz et al., 2004ApJ...605L.105S

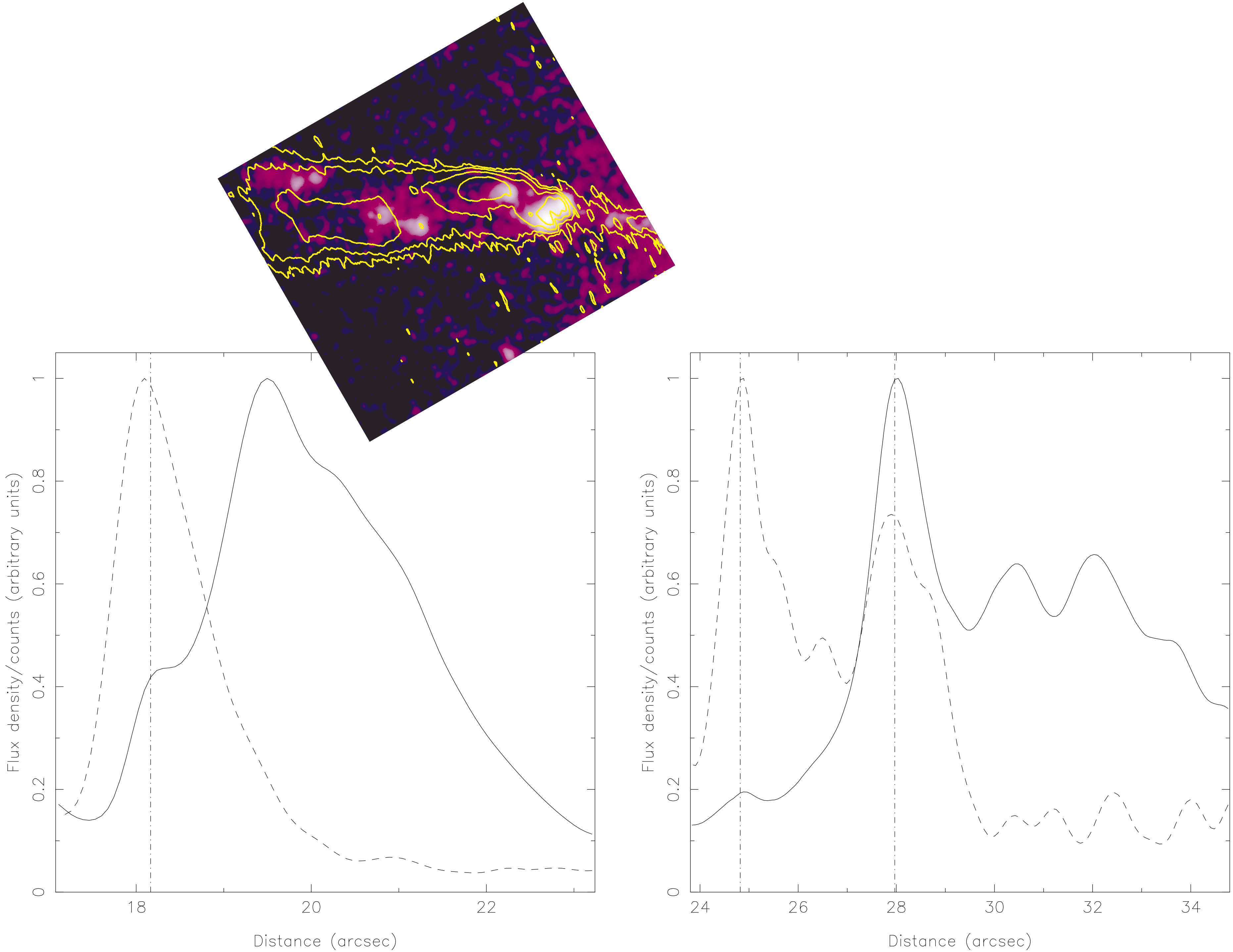
3. Jets at Large Redshift
   - Beacons to Large Redshift?
   - Radio quiet X-ray jets?



Siemiginowska et al., 2003ApJ...598L..15S

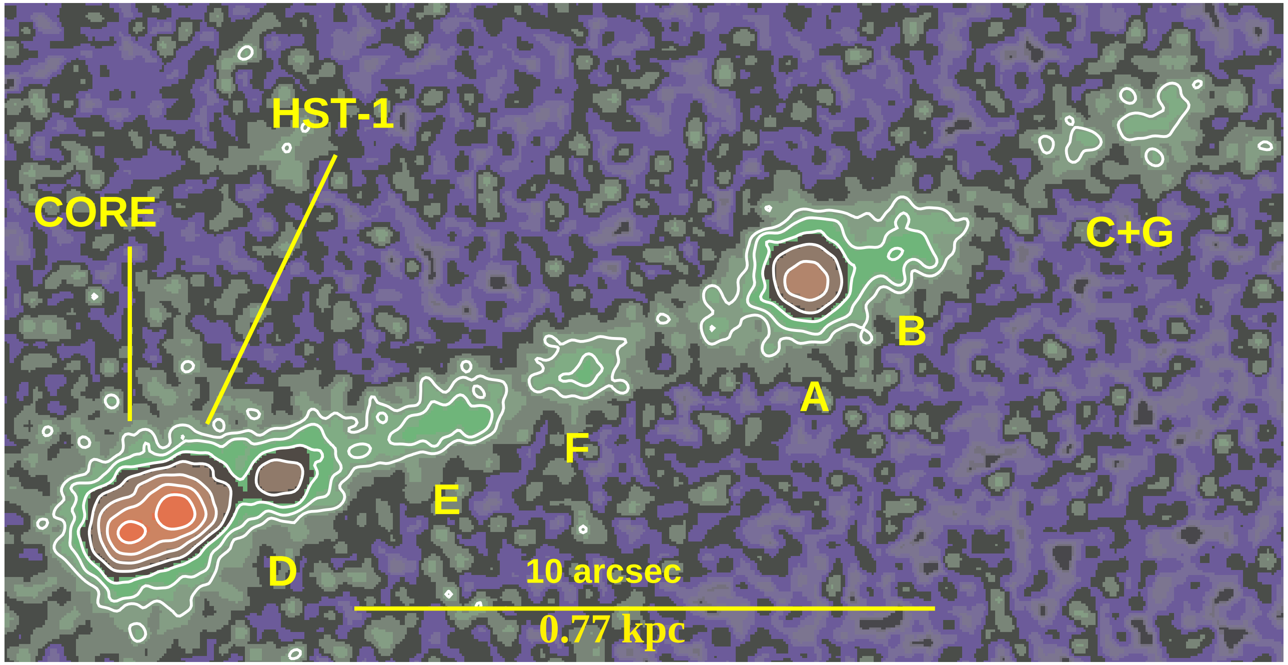


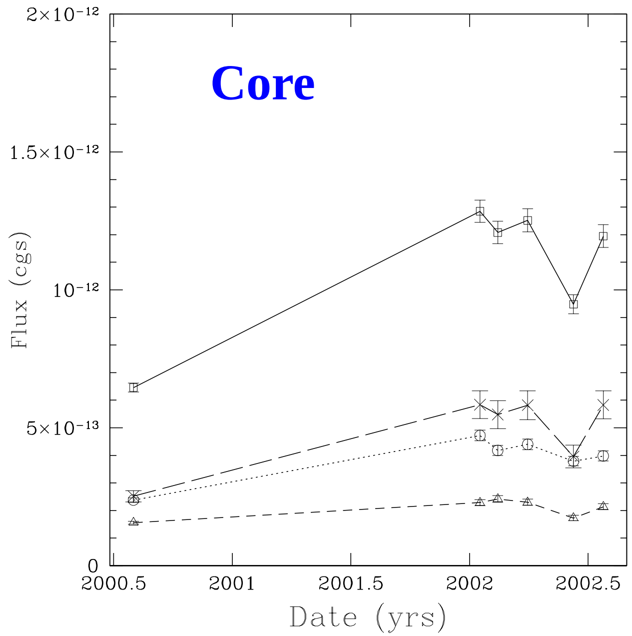
Hardcastle et al., 2003ApJ...593..169H

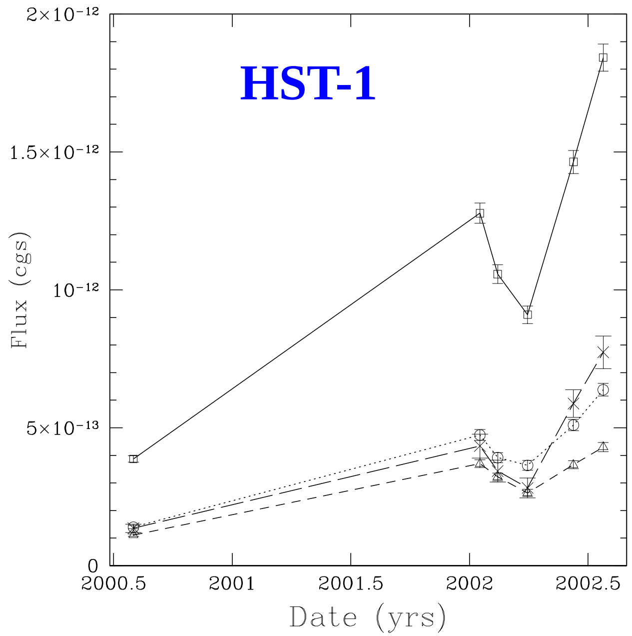


Flux density/counts (arbitrary units)
0
0.2
0.4
0.6
0.8
1
18
20
22
Distance (arcsec)
Flux density/counts (arbitrary units)
0
0.2
0.4
0.6
0.8
1
24
26
28
30
32
34
Distance (arcsec)

M87 Jet

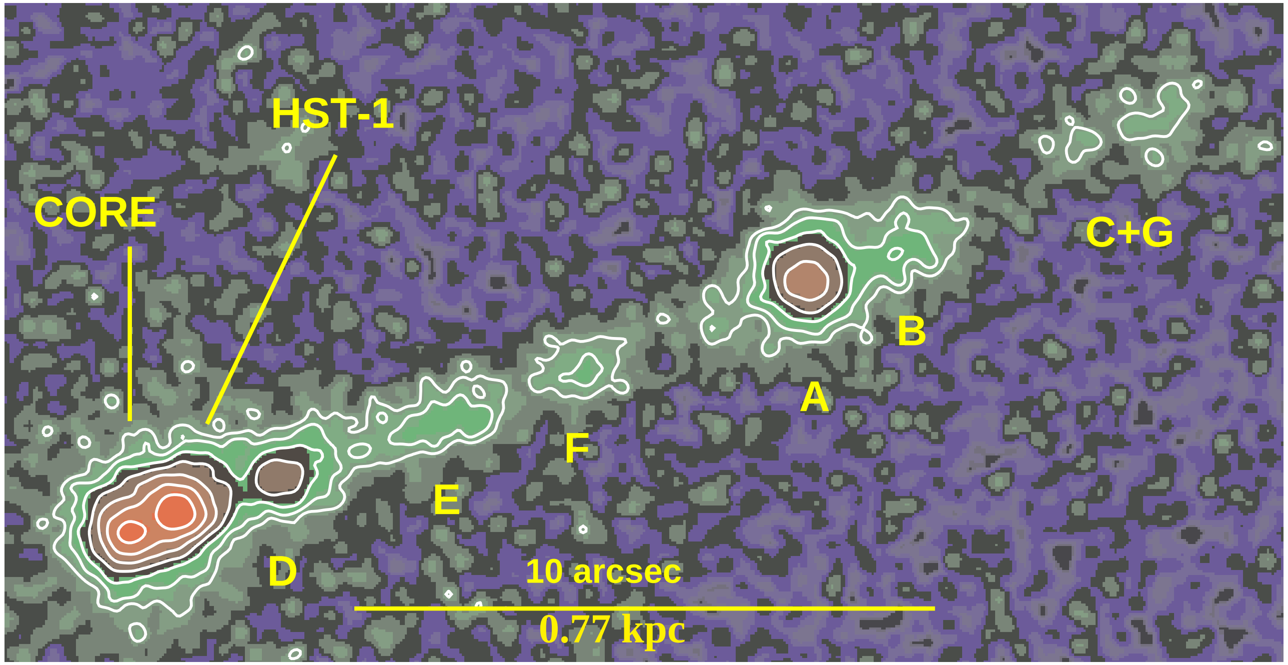


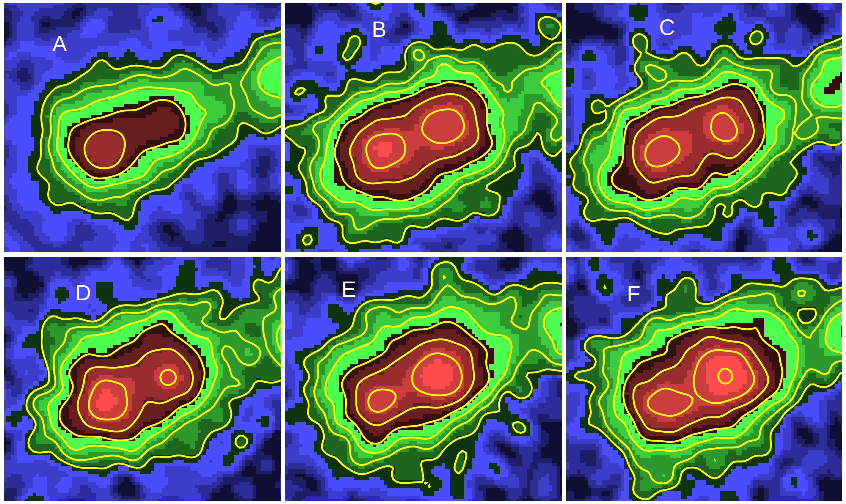


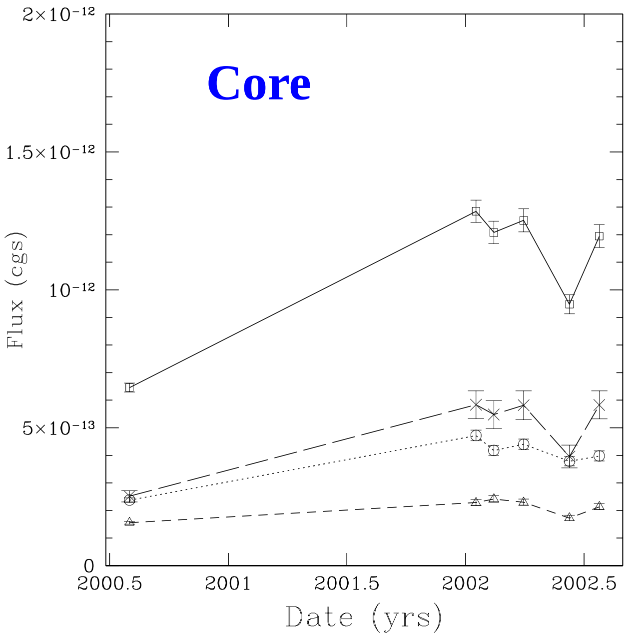


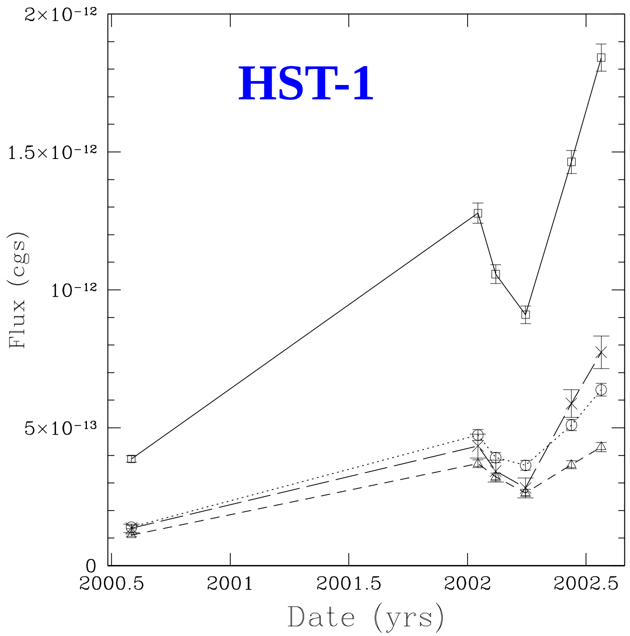
Harris et al., 2003ApJ...586L..41H

M87 Jet

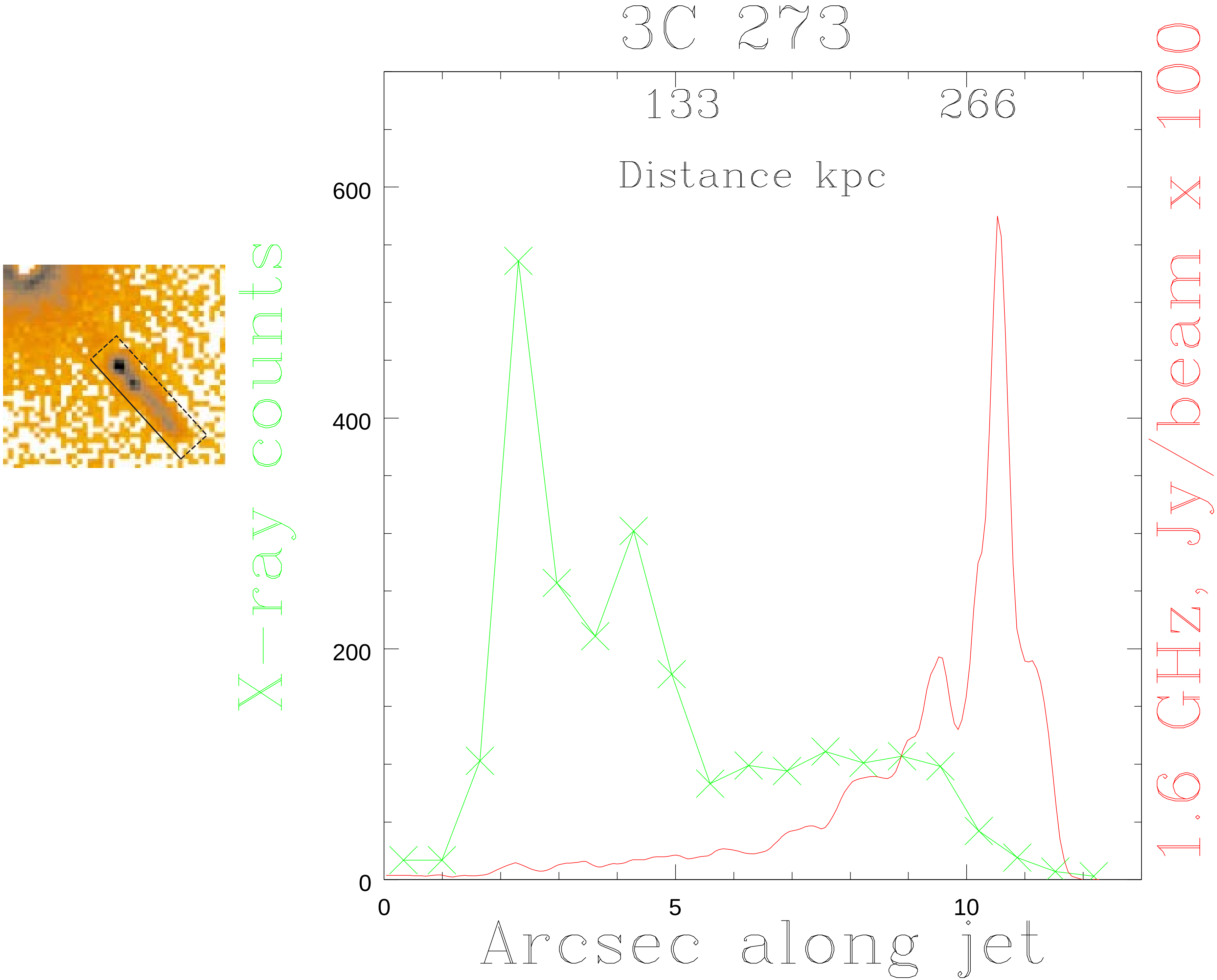




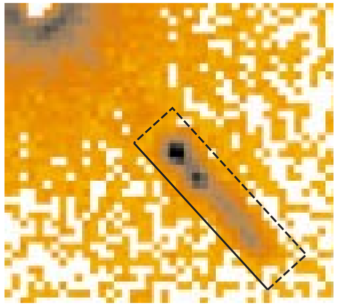


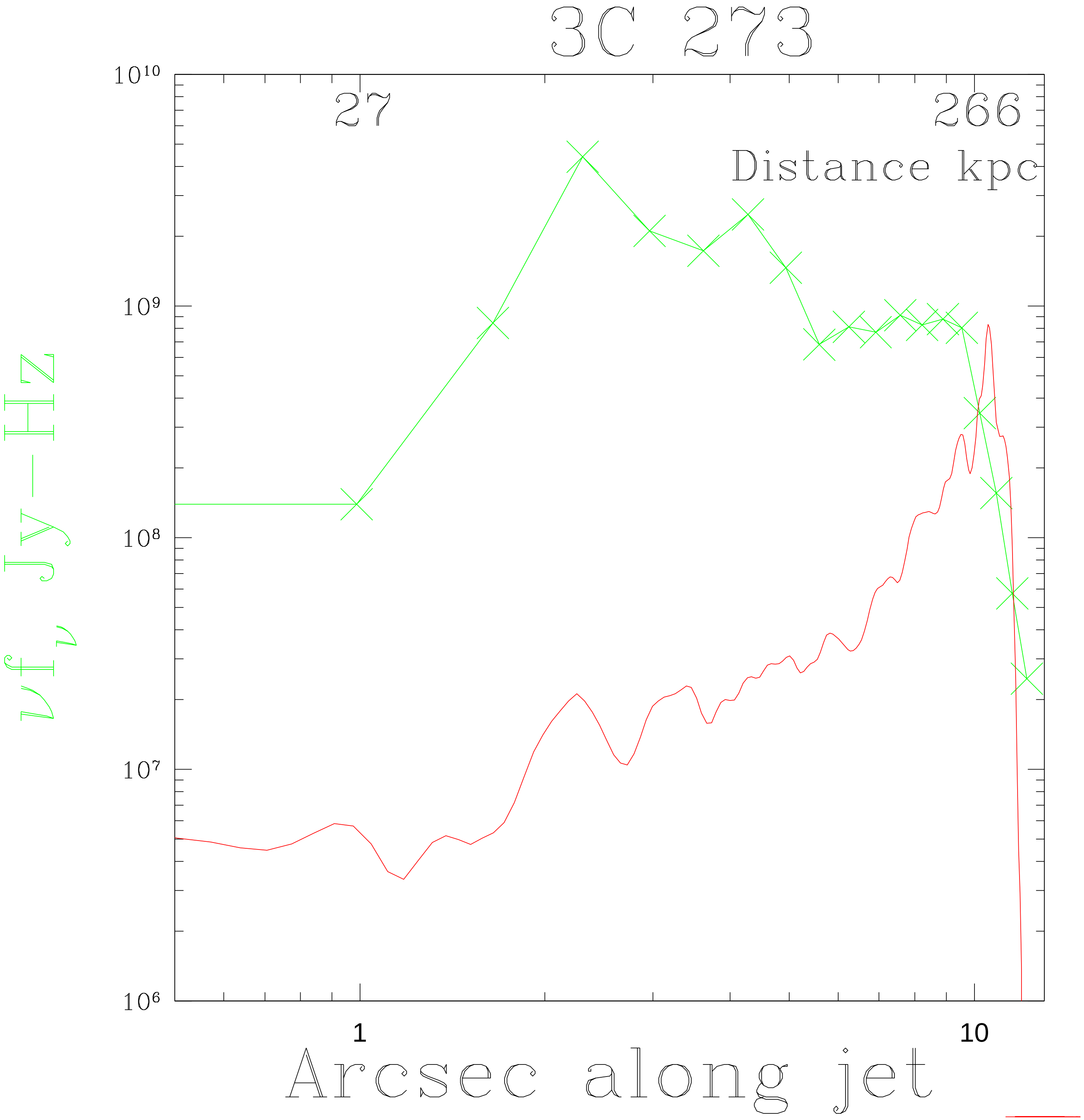


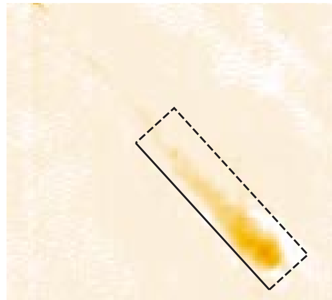
Harris et al., 2003ApJ...586L..41H



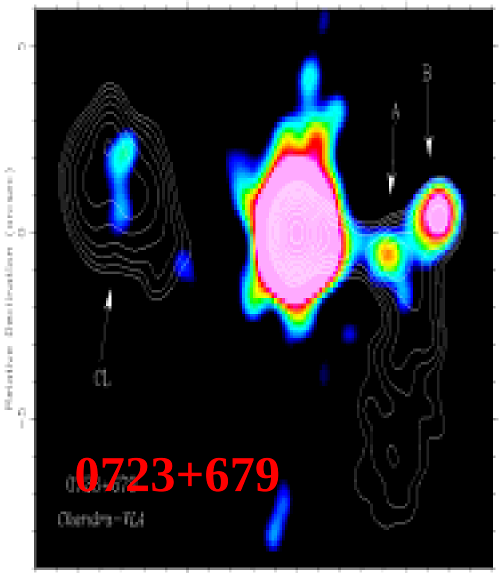
3C 273
133
266
Distance kpc
600
400
200
0
0
5
10
X-ray counts
1.6 GHz, Jy/beam x 100
Arcsec along jet



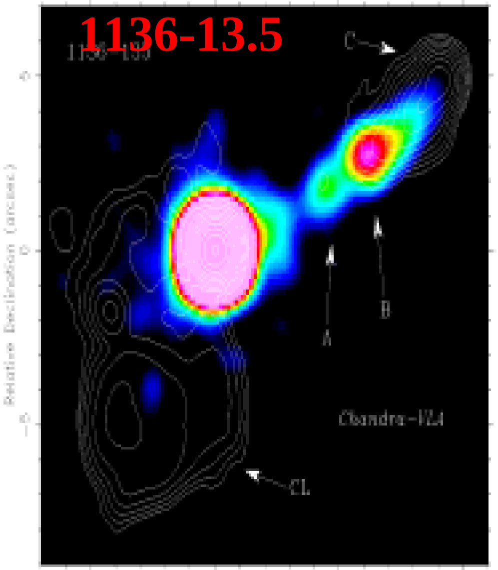

3C 273
27
266
Distance kpc
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
νf_ν Jy-Hz
1
10
Arcsec along jet



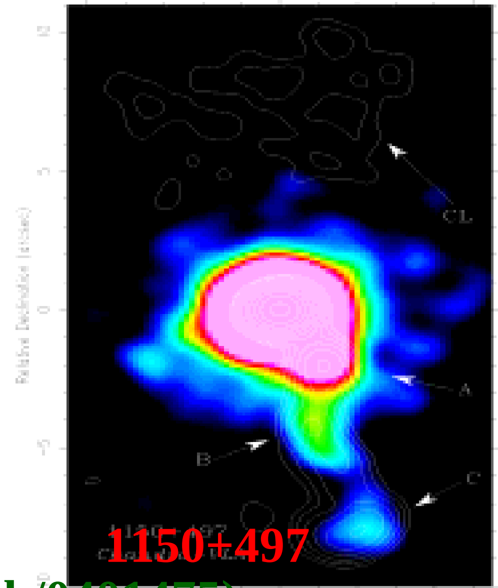
Multiwavelength observations of FR II Jets



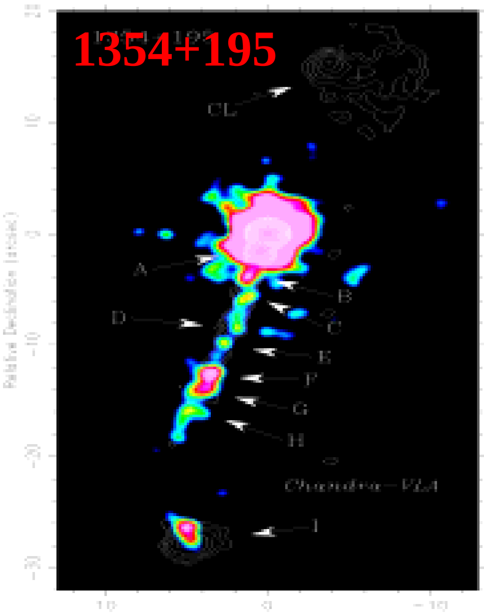
0723+679



1136-13.5

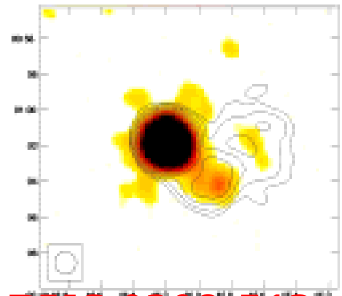


1150+497

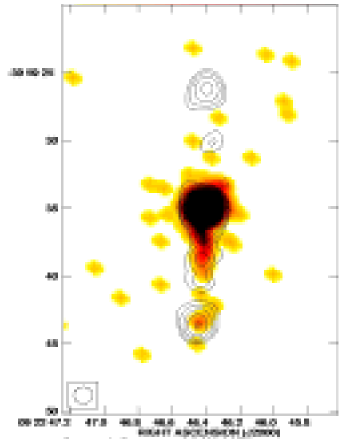


1354+195

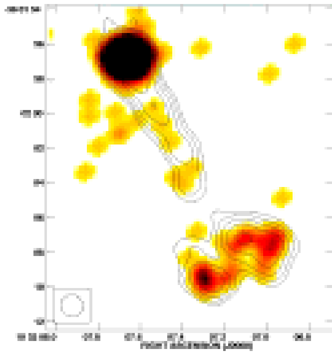
Sambruna et al. (2002ApJ...571..206S; astro-ph/0401475)



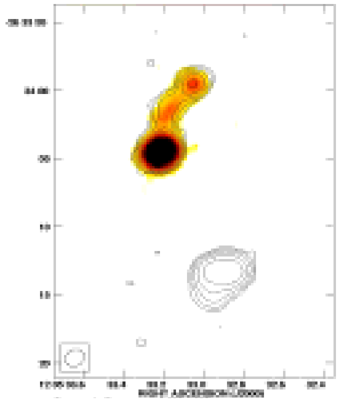
PKS 0208-512



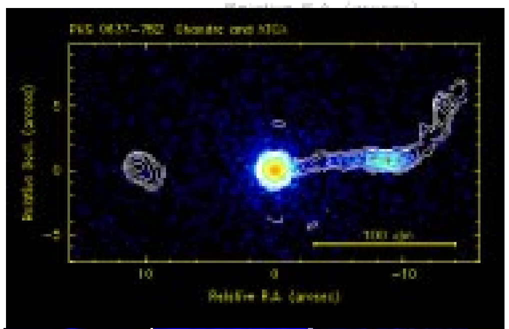
PKS 0920-397

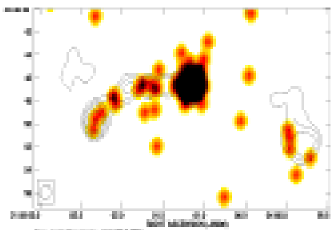


PKS 1030-357

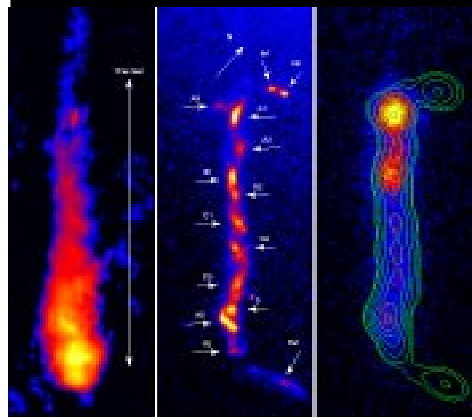


PKS 1202-262





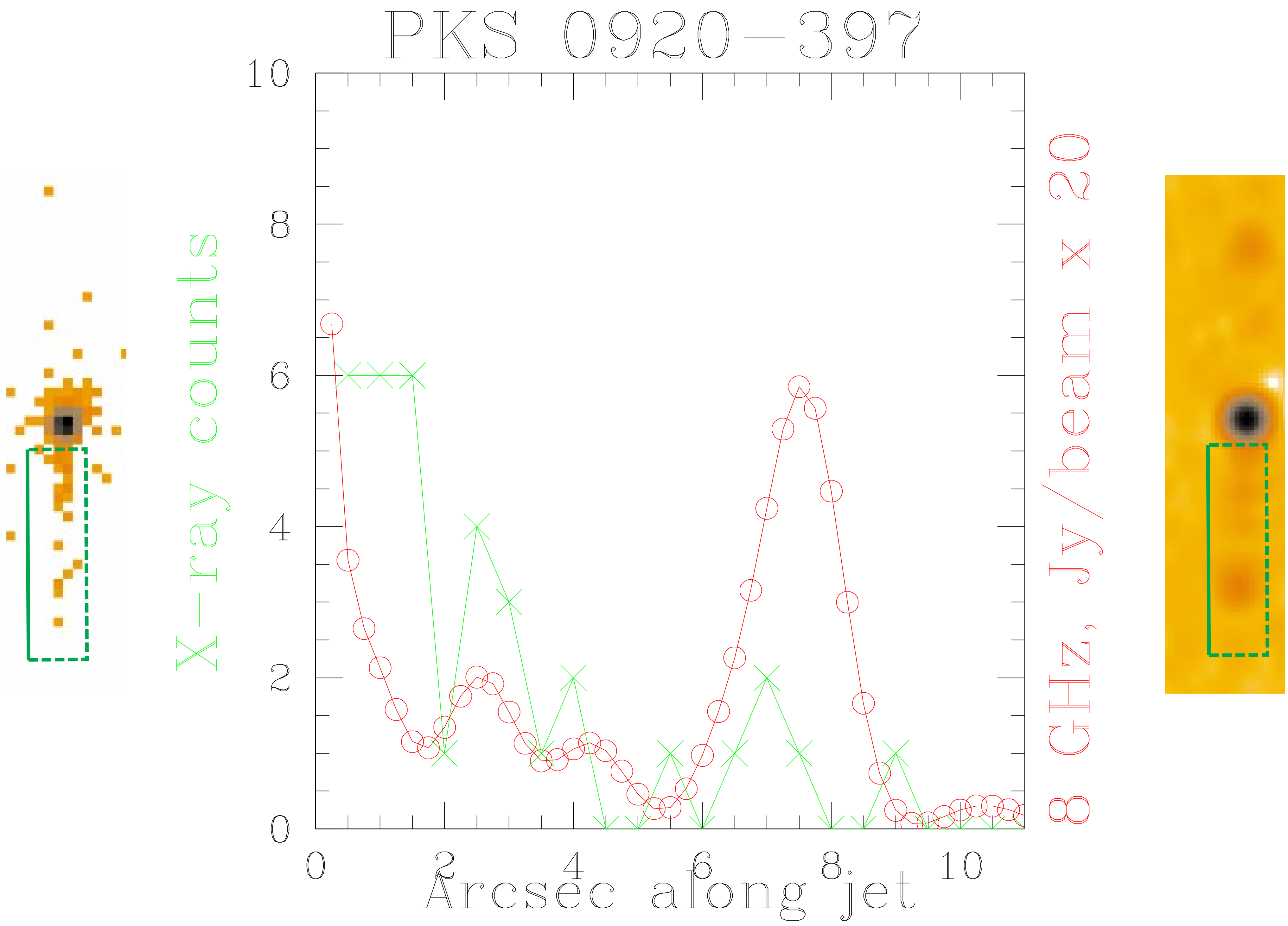
PKS 2101-490



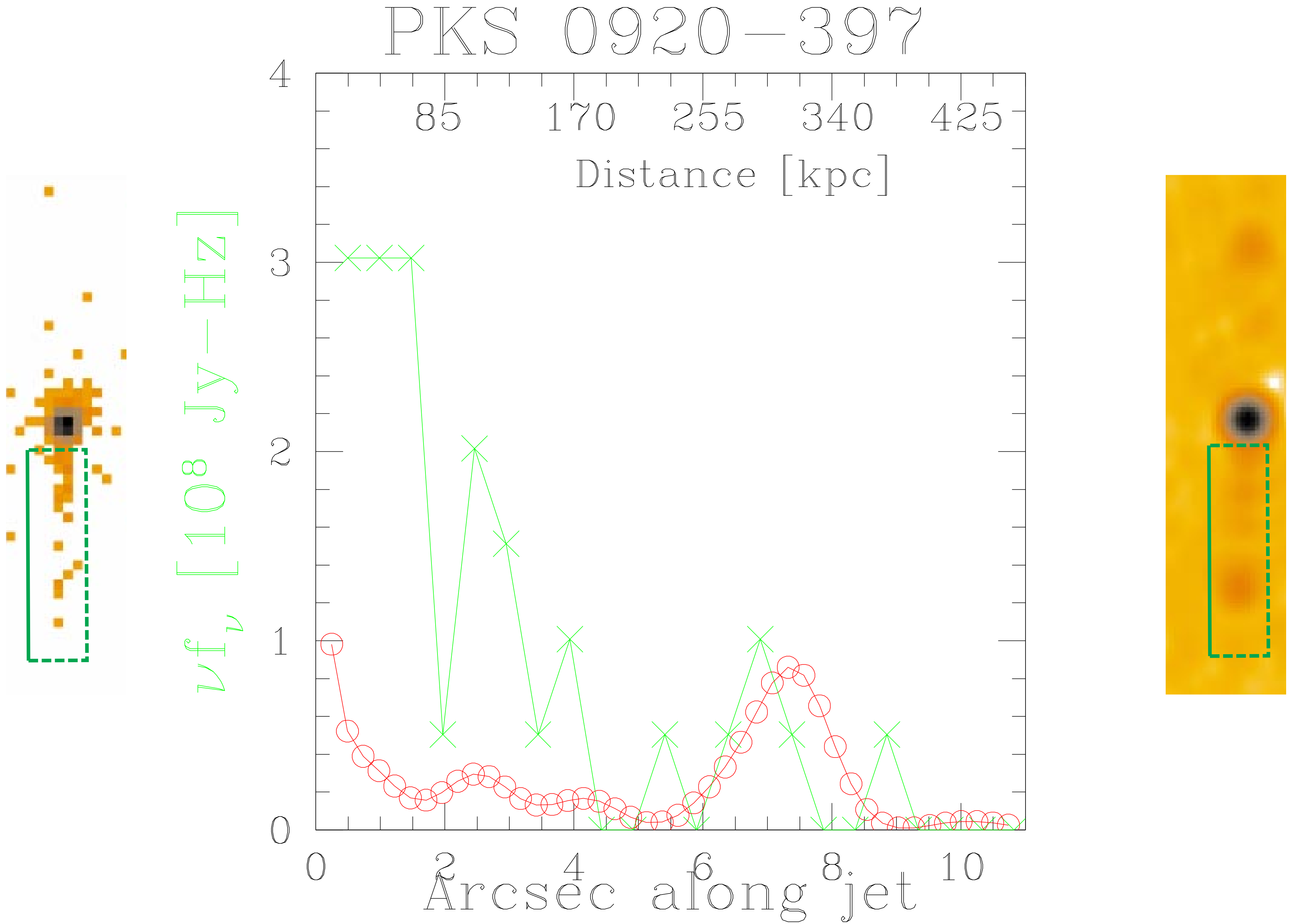
3C 273

Schwartz et al. (2000ApJ...540L..69S,2003agnc.conf..359S)

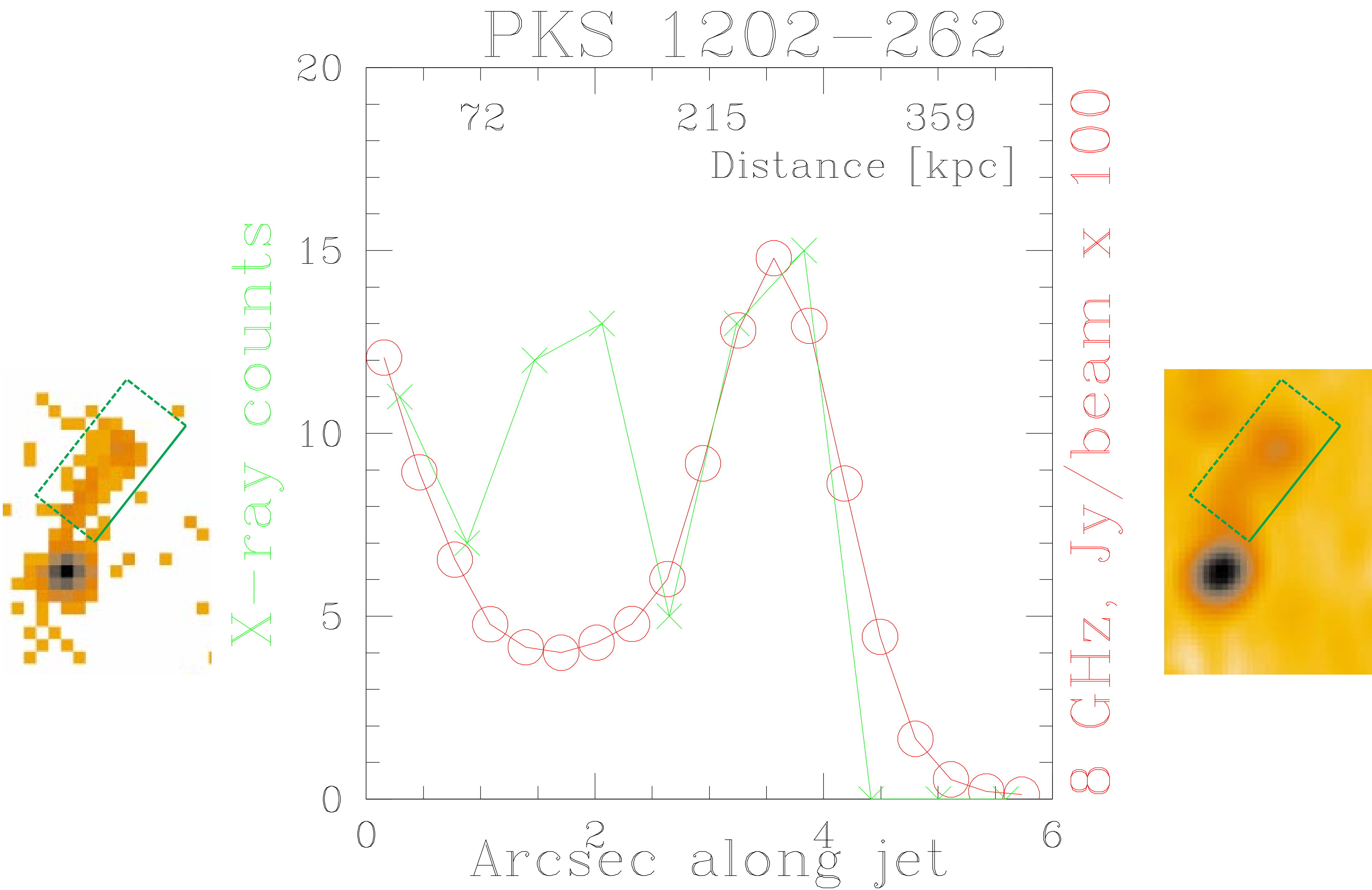
Marshall et al.(2001ApJ...549L.167M)



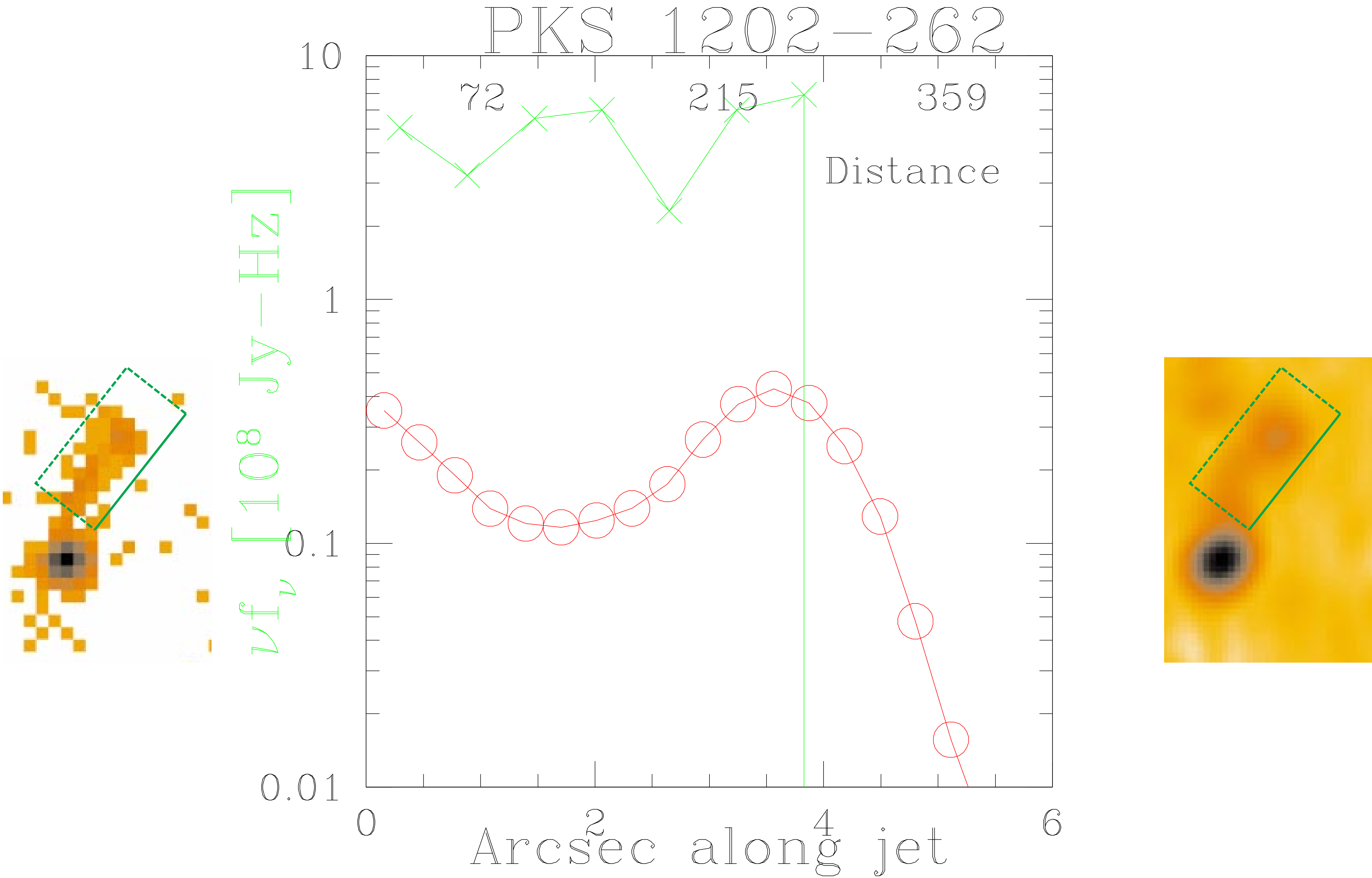
PKS 0920−397
X−ray counts
8 GHz, Jy/beam x 20
Arcsec along jet
0
2
4
6
8
10

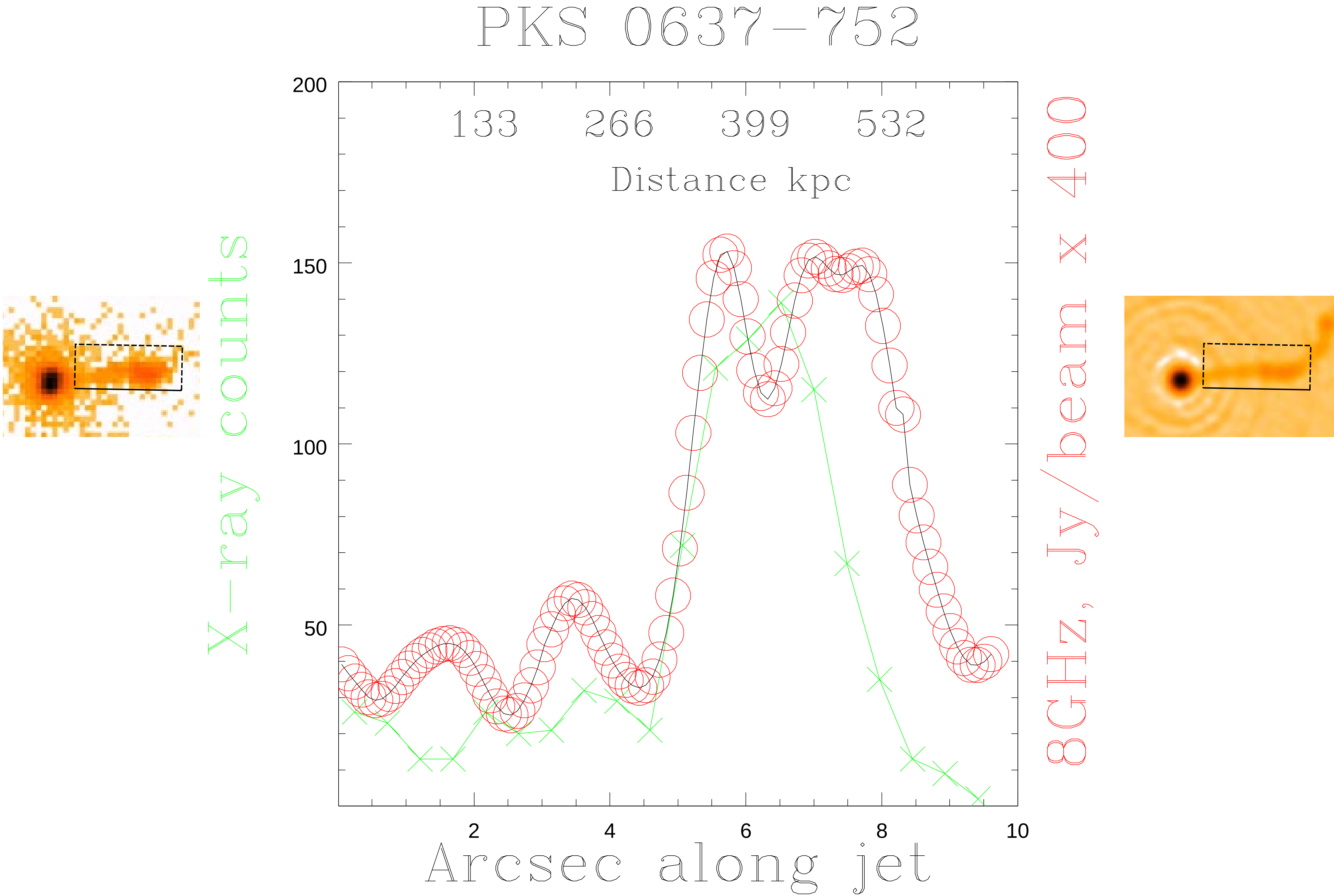


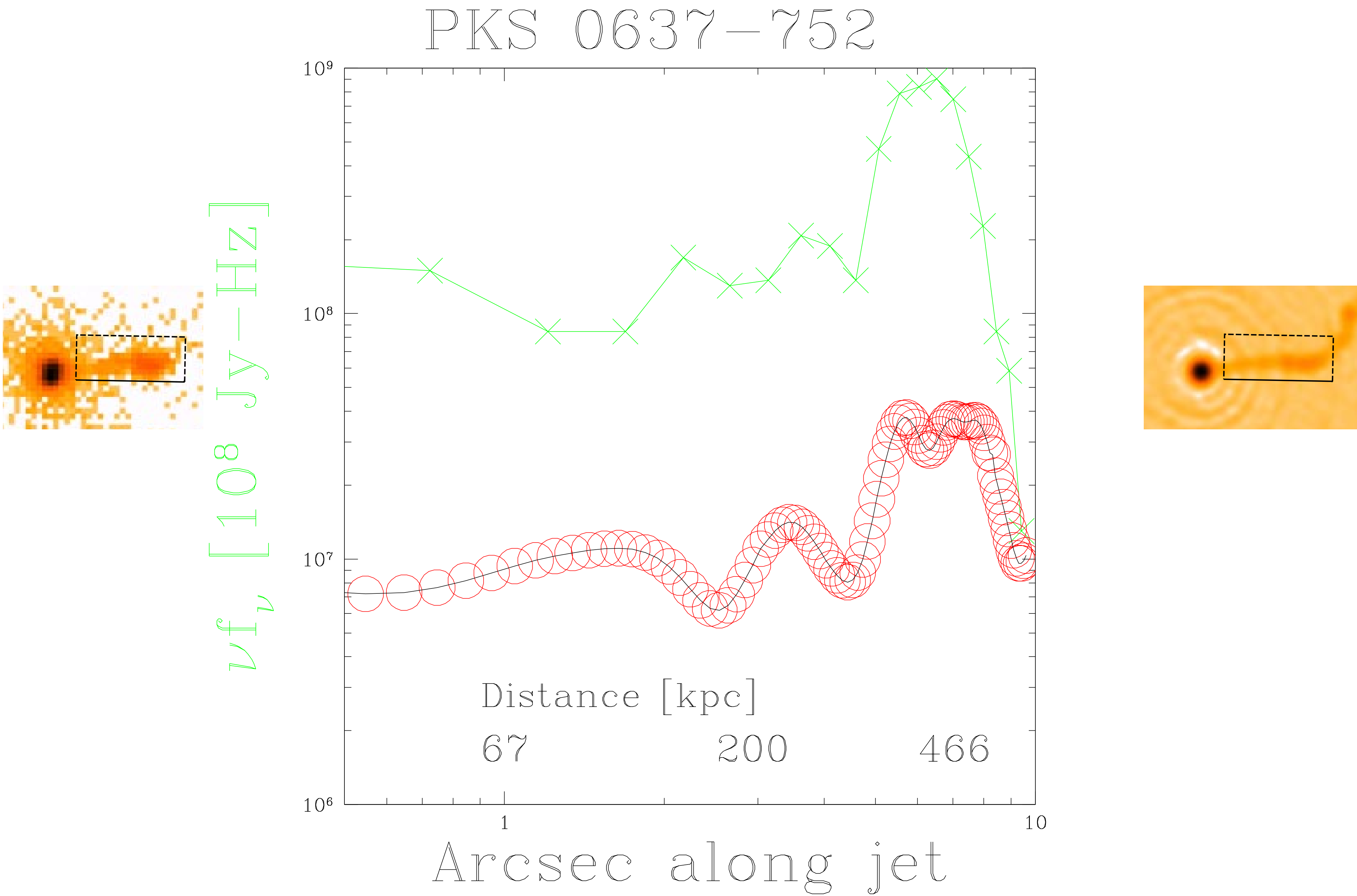
PKS 0920−397
Distance [kpc]
85
170
255
340
425
νf_ν [10^8 Jy−Hz]
0
1
2
3
4
Arcsec along jet
0
2
4
6
8
10

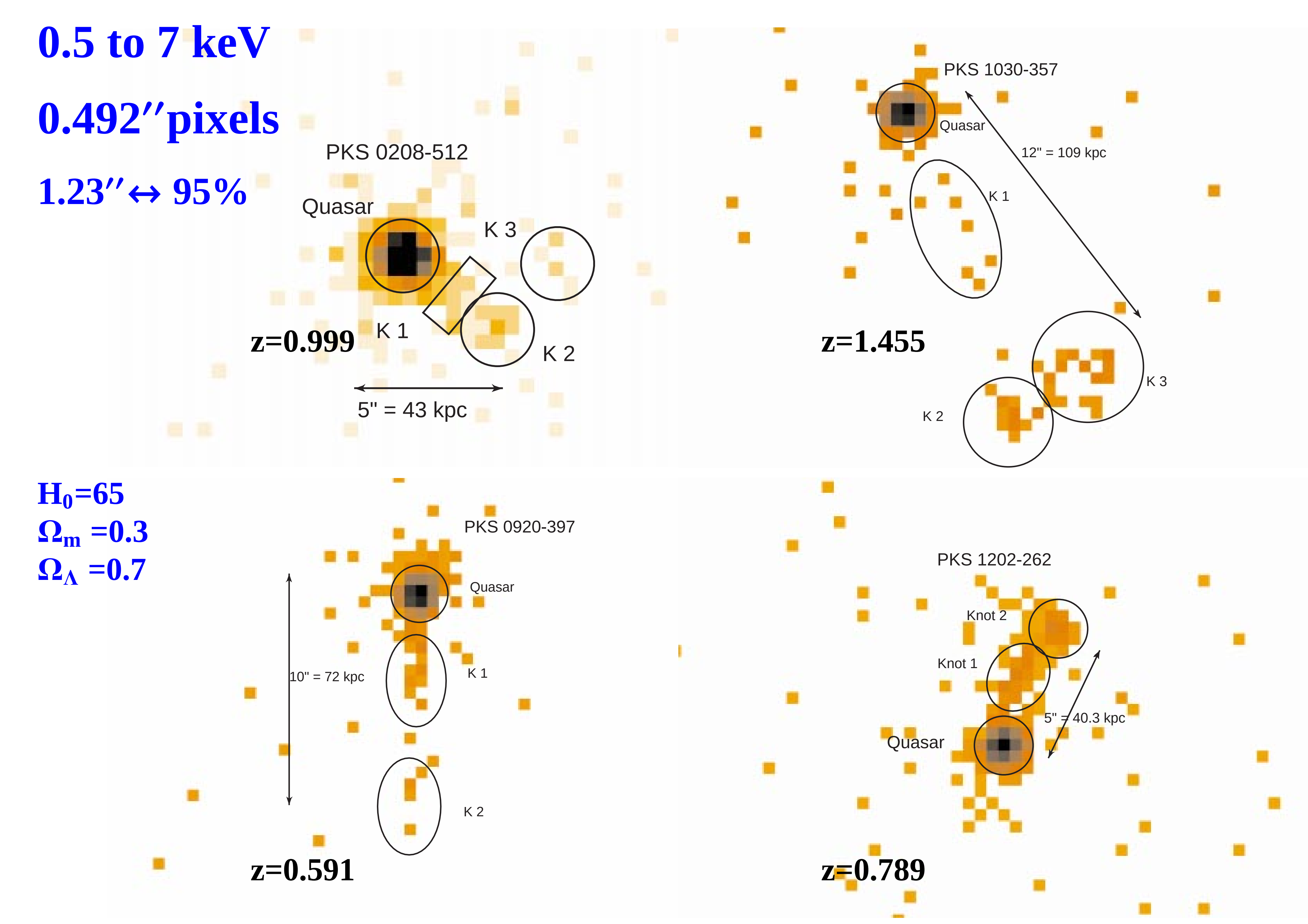


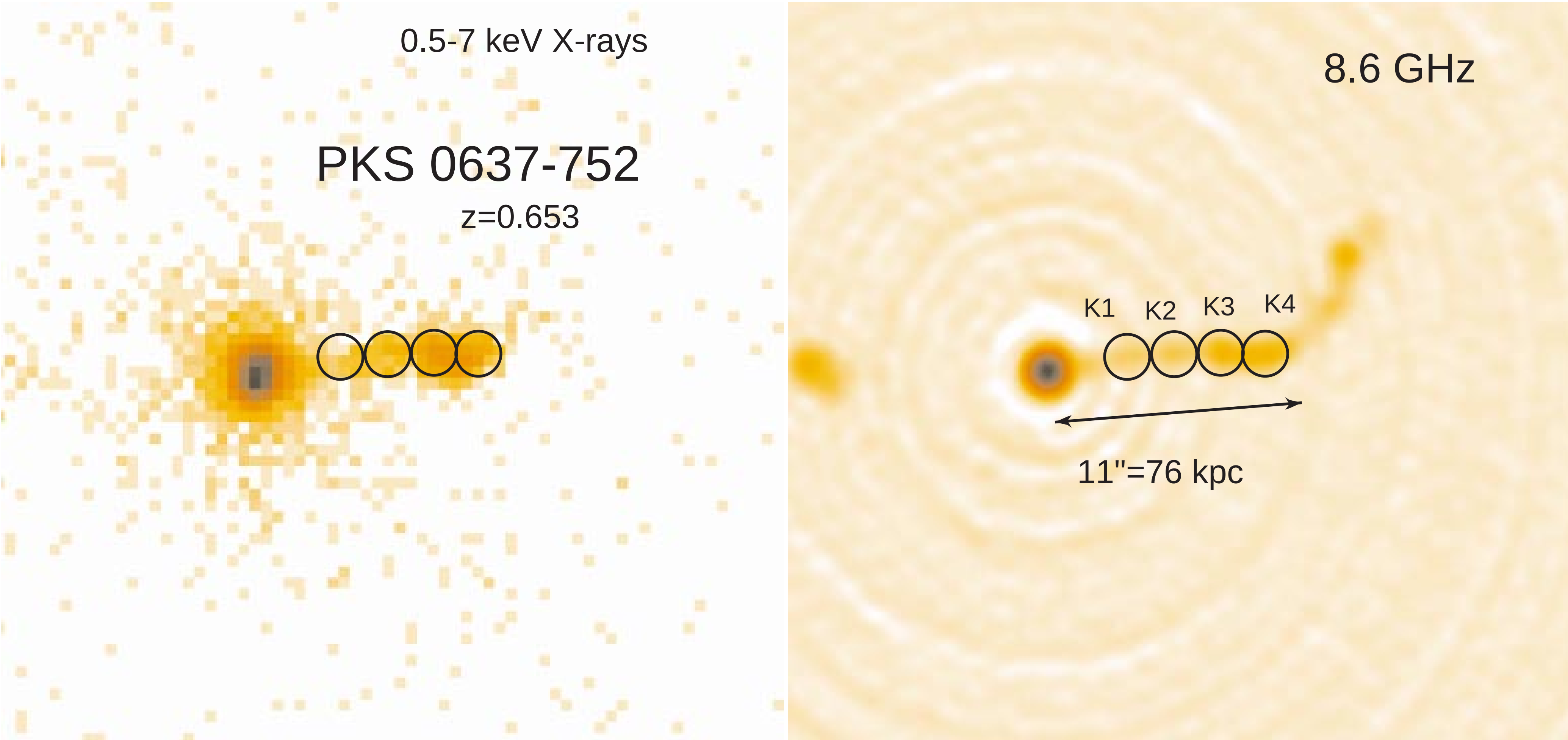
PKS 1202−262
Distance [kpc]
72
215
359
X−ray counts
8 GHz, Jy/beam x 100
Arcsec along jet
0
2
4
6
5
10
15
20


PKS 1202−262
10
1
0.1
0.01
72
215
359
Distance
νf_ν [10^8 Jy−Hz]
0
2
4
6
Arcsec along jet

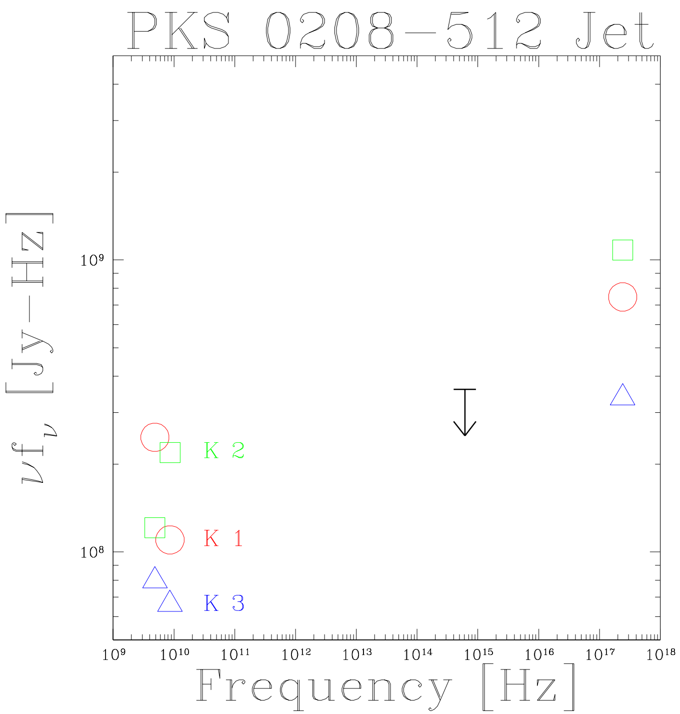

PKS 0637−752
Distance kpc
133
266
399
532
X−ray counts
8GHz, Jy/beam x 400
Arcsec along jet
200
150
100
50
2
4
6
8
10

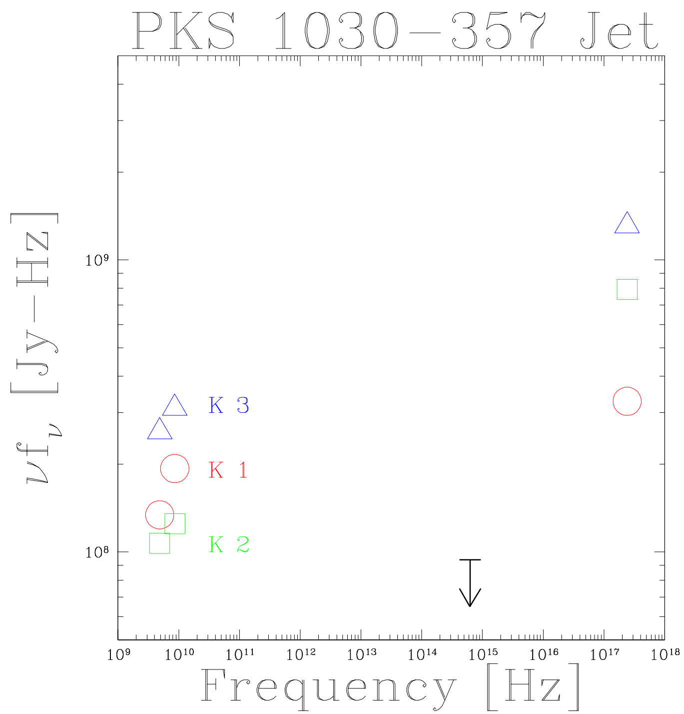

PKS 0637−752
10^9
10^8
10^7
10^6
1
10
νf_ν [10^8 Jy−Hz]
Distance [kpc]
67
200
466
Arcsec along jet

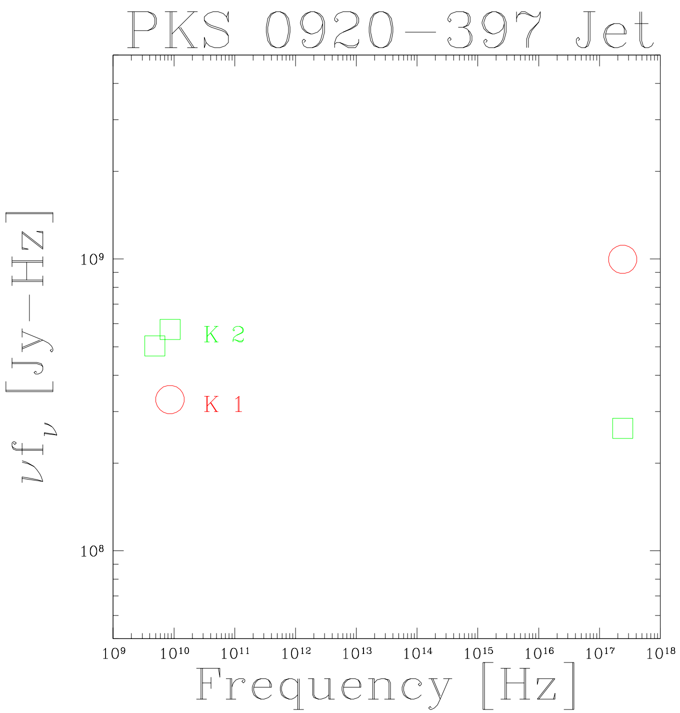

0.5 to 7 keV
0.492″pixels
1.23″↔ 95%
PKS 0208-512
Quasar
K 3
K 1
K 2
z=0.999
5" = 43 kpc
PKS 1030-357
Quasar
12" = 109 kpc
K 1
z=1.455
K 3
K 2
H_0=65
Ω_m =0.3
Ω_Λ =0.7
PKS 0920-397
Quasar
10" = 72 kpc
K 1
K 2
z=0.591
PKS 1202-262
Knot 2
Knot 1
5" = 40.3 kpc
Quasar
z=0.789

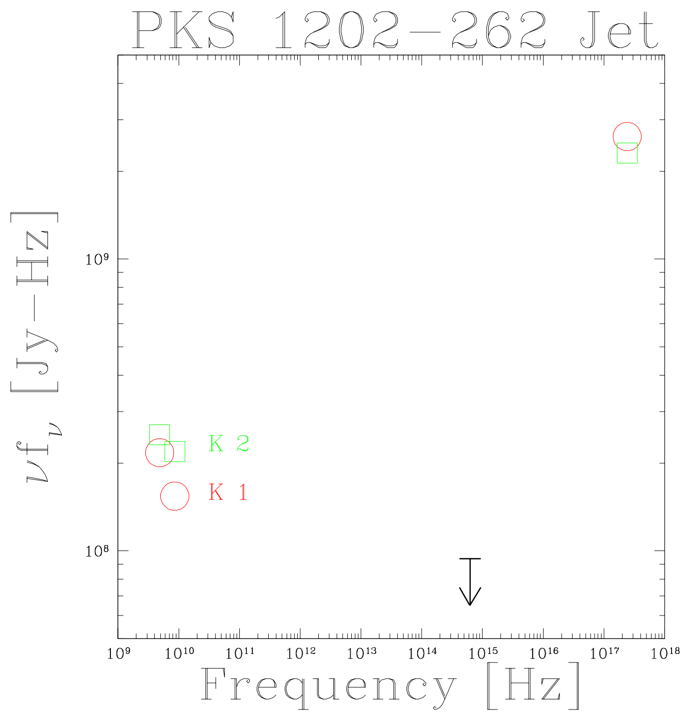

0.5-7 keV X-rays
PKS 0637-752
z=0.653
8.6 GHz
K1
K2
K3
K4
11"=76 kpc

Spectral Energy Distribution often indicates against Synchrotron X-rays

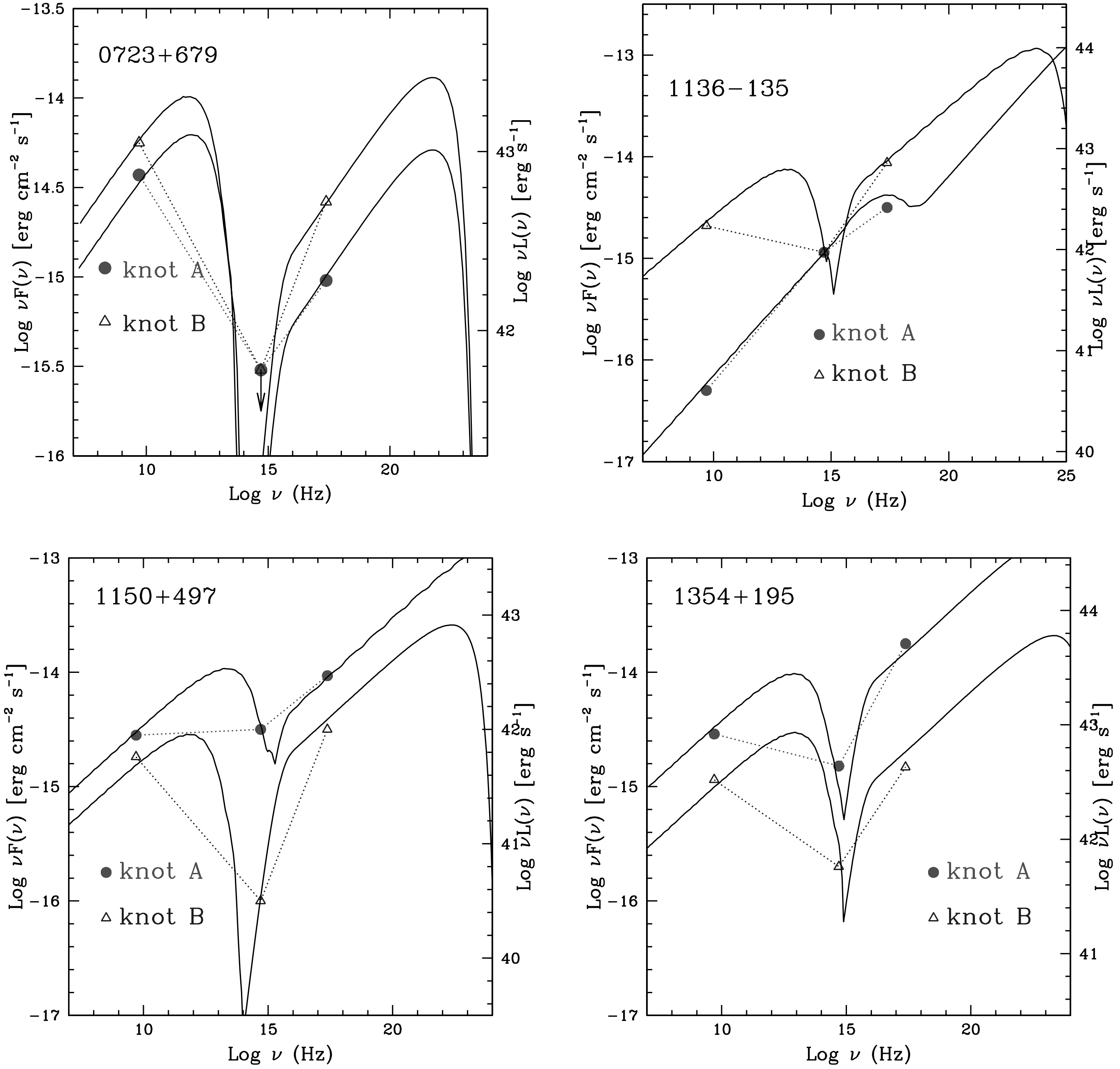






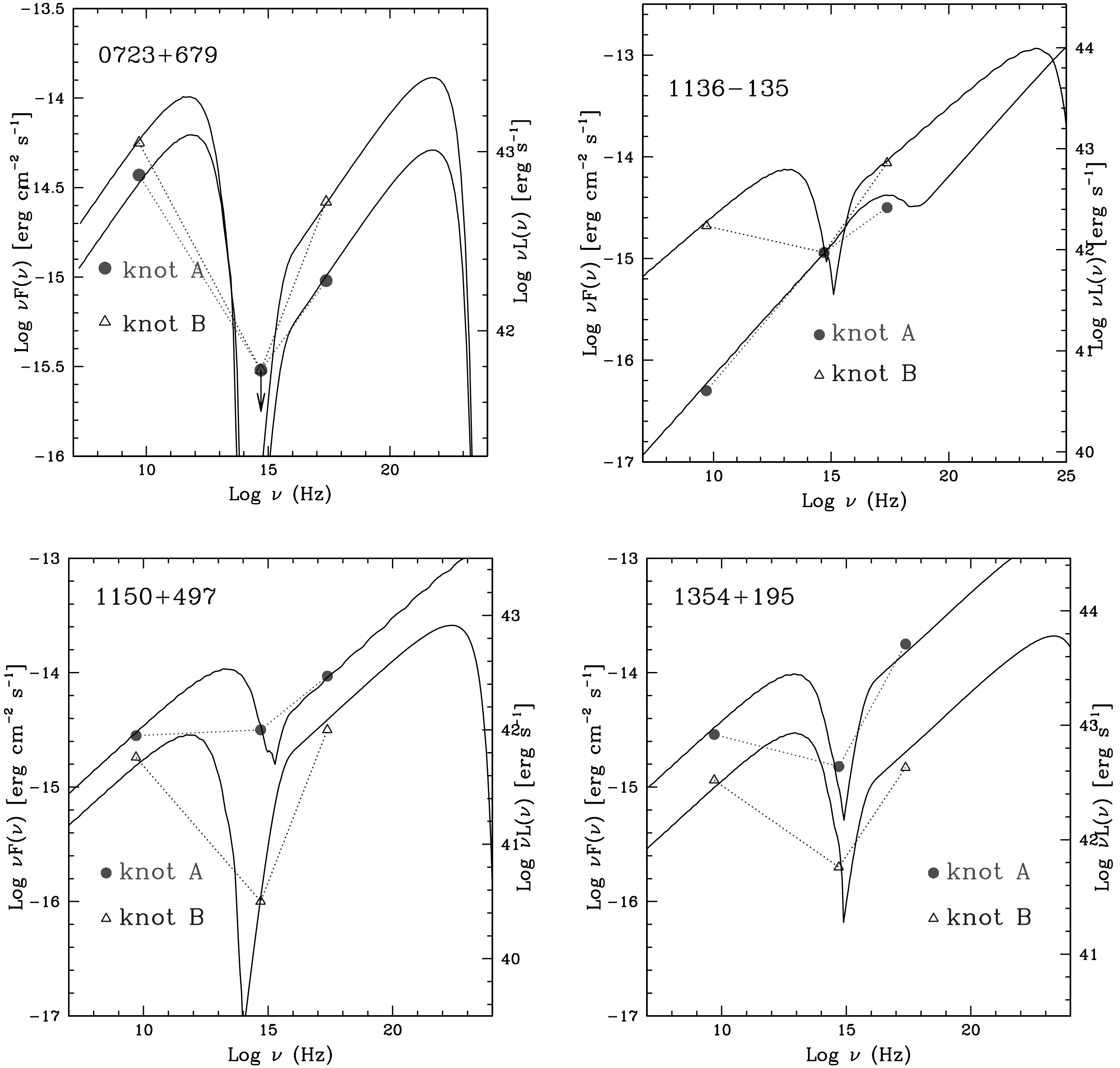


Spectral Energy Distribution often indicates against Synchrotron X-rays



Sambruna et al., 2002ApJ...571..206S

Spectral Energy Distribution often indicates against Synchrotron X-rays



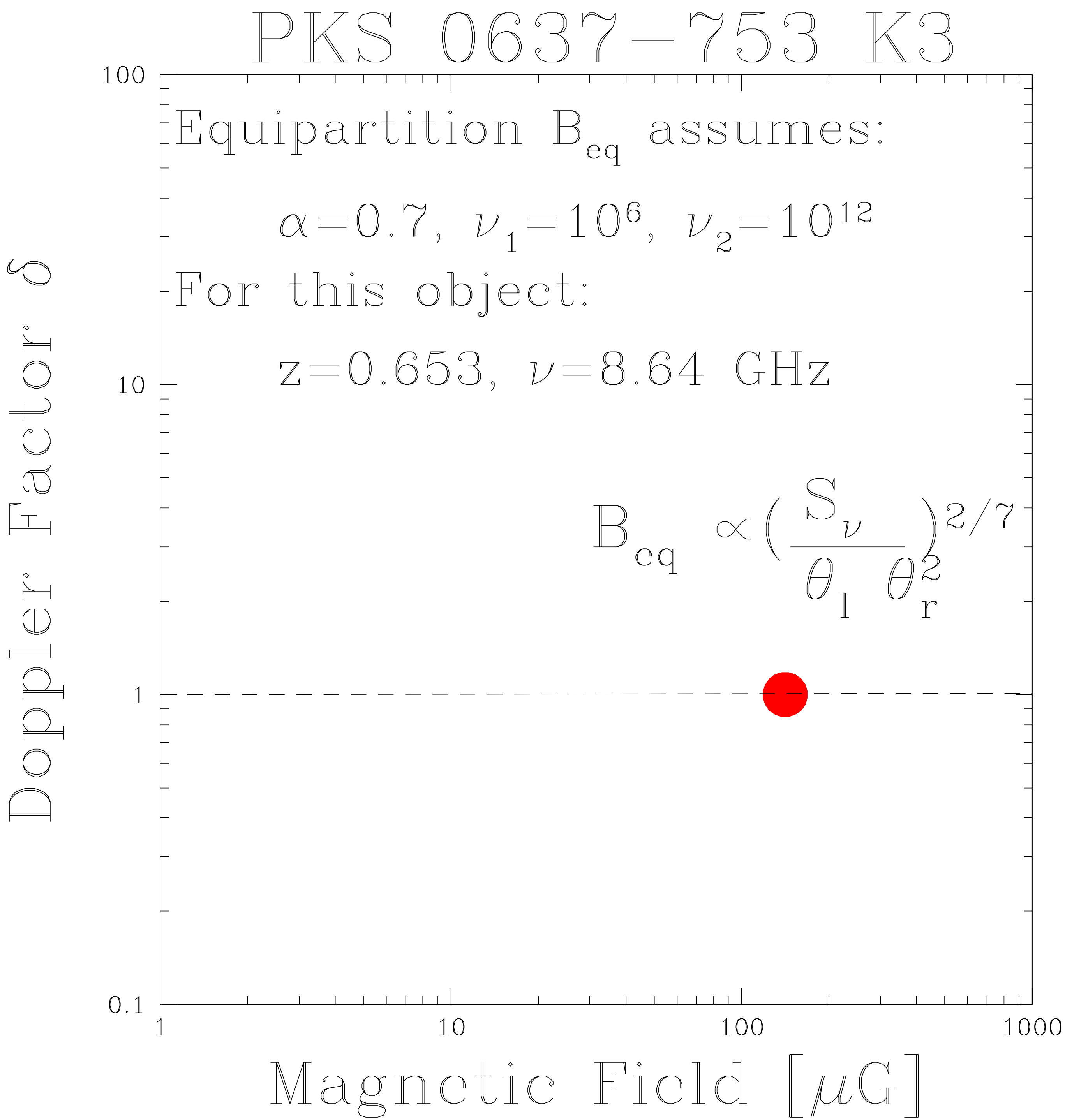
Inverse Compton X-rays from the CMB:

$$\gamma_x \approx 10^{2-3}$$

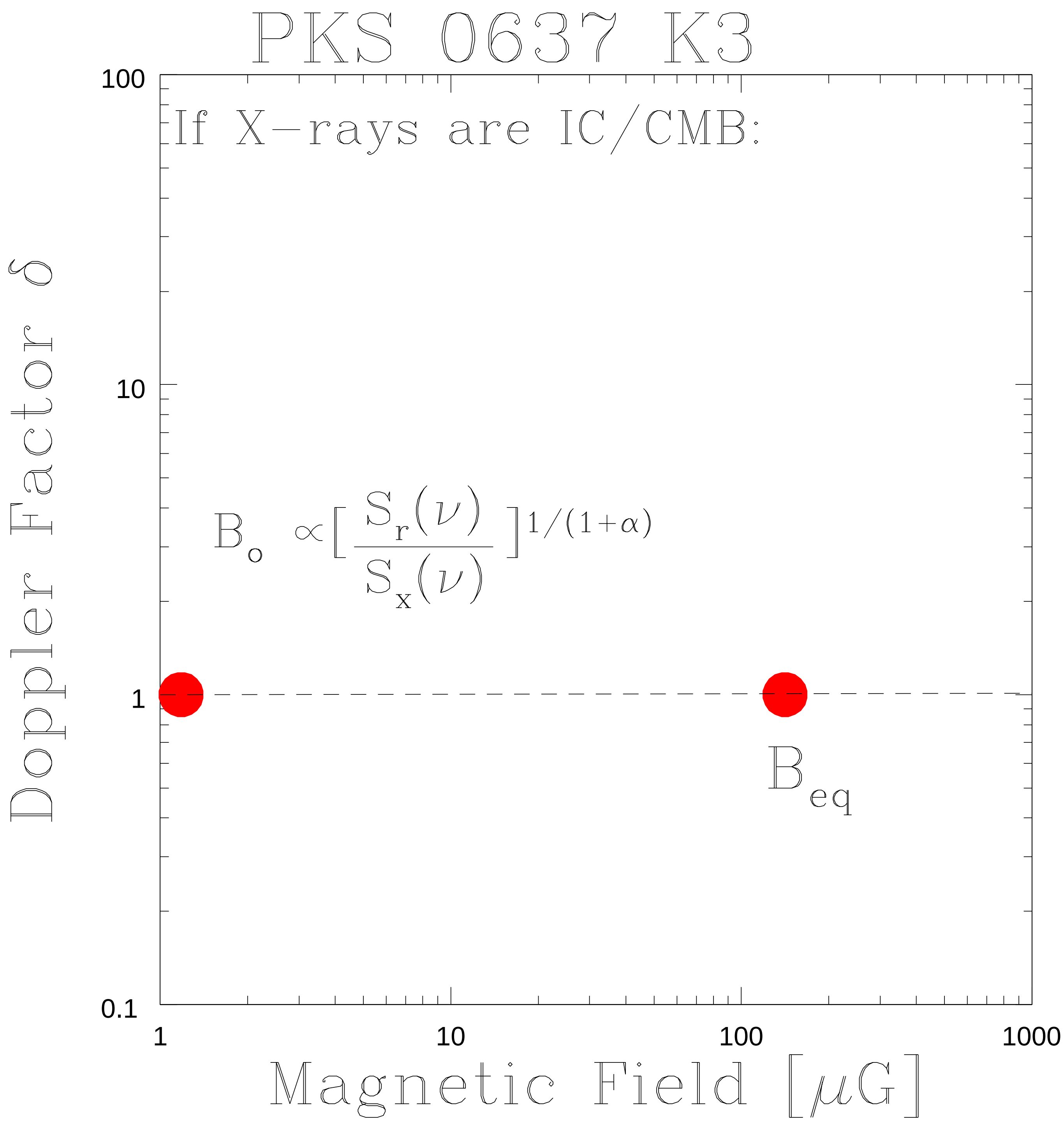
$$\gamma_r \approx 10^{4-5}$$

Some jets may be detectable by GLAST, at 10^{-13} to 10^{-12} ergs cm^{-2} s^{-1}

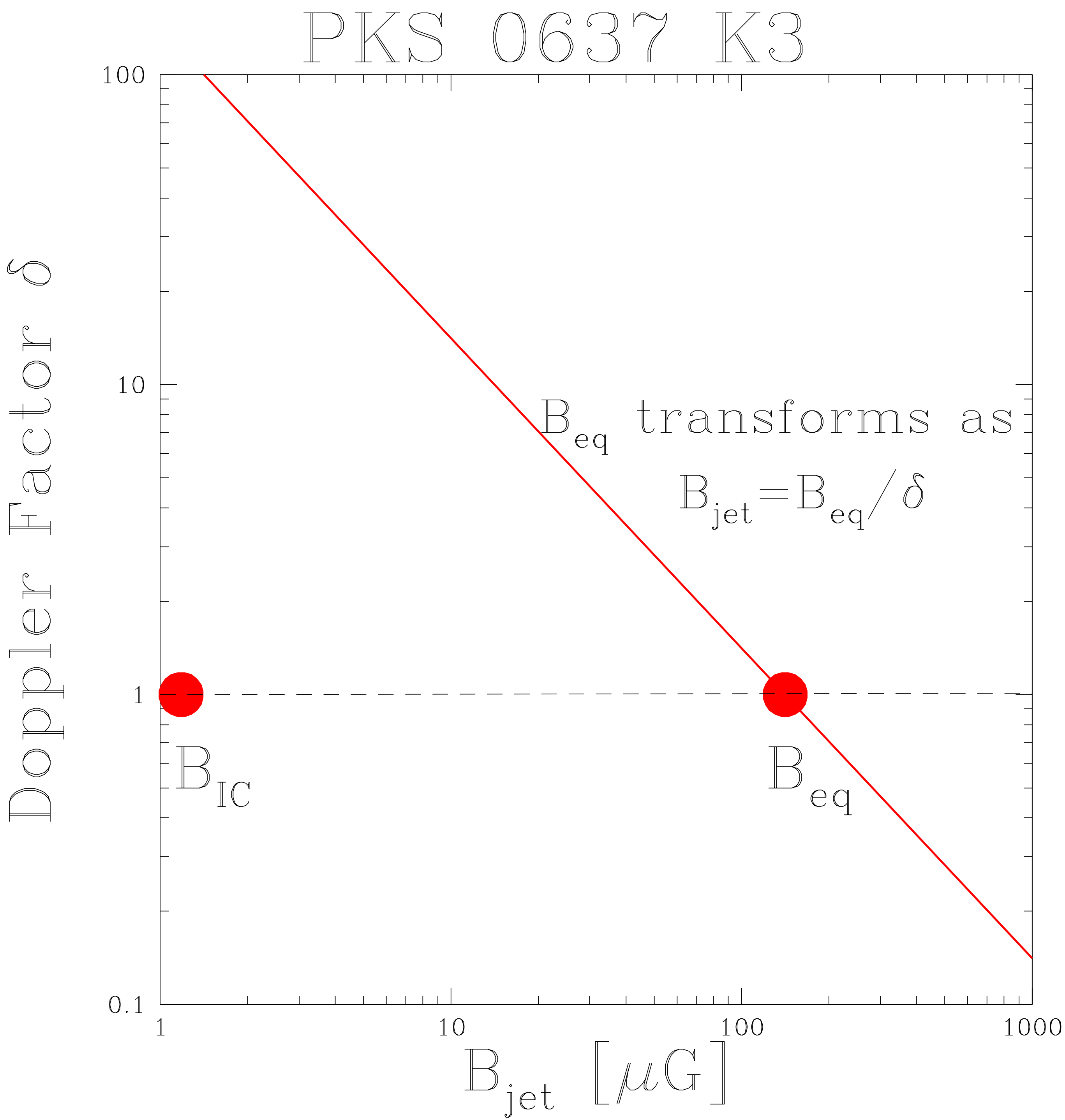
Sambruna et al., 2002ApJ...571..206S



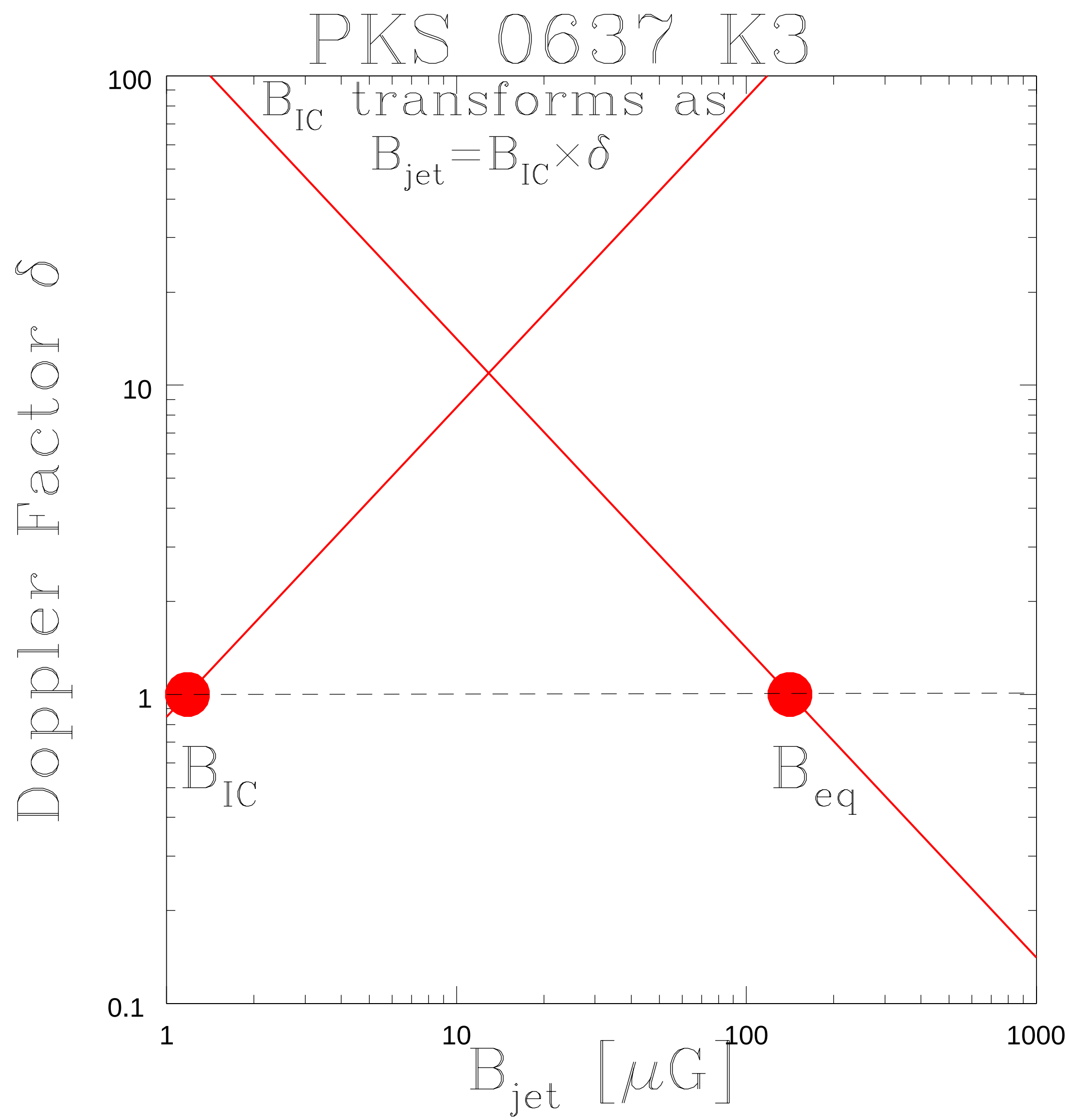
PKS 0637−753 K3
Equipartition B$_{eq}$ assumes:
α=0.7, ν_1=10^6, ν_2=10^{12}
For this object:
z=0.653, ν=8.64 GHz
$B_{eq} \propto (\frac{S_\nu}{\theta_l \theta_r^2})^{2/7}$
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000

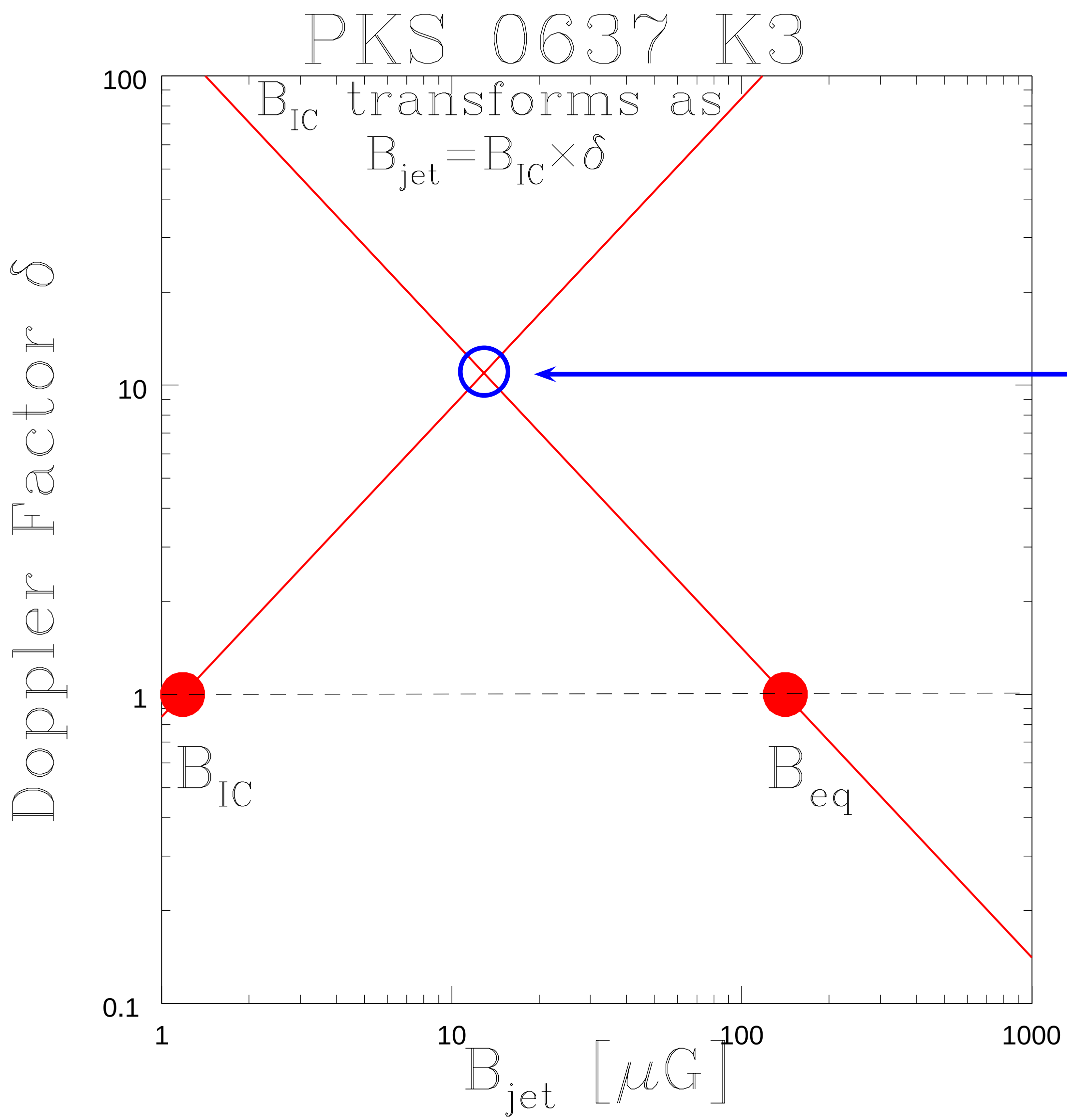


PKS 0637 K3
If X-rays are IC/CMB:
$B_o \propto [\frac{S_r(\nu)}{S_x(\nu)}]^{1/(1+\alpha)}$
B_{eq}
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000



PKS 0637 K3
Doppler Factor δ
100
10
1
0.1
1
10
100
1000
B_jet [μG]
B_eq transforms as
B_jet=B_eq/δ
B_IC
B_eq


PKS 0637 K3
B_IC transforms as
B_jet=B_IC×δ
Doppler Factor δ
B_IC
B_eq
100
10
1
0.1
1
10
100
1000
B_jet [μG]



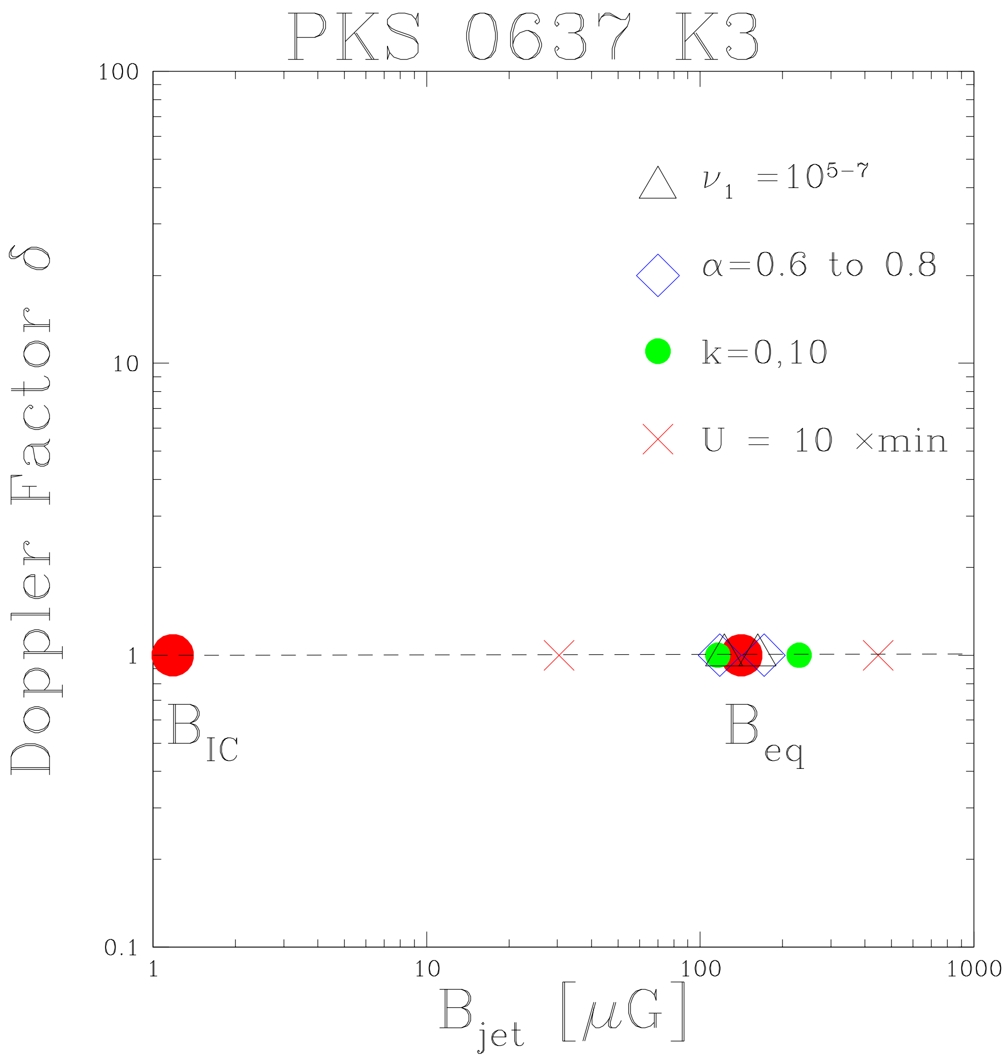
The intersection gives a solution for the magnetic field, B, in the rest frame, and for the apparent Doppler factor,

$$\boldsymbol{\delta = (\Gamma(1 - \beta\cos(\theta))^{-1}.}$$

Uncertainties in the Magnetic Field Estimates

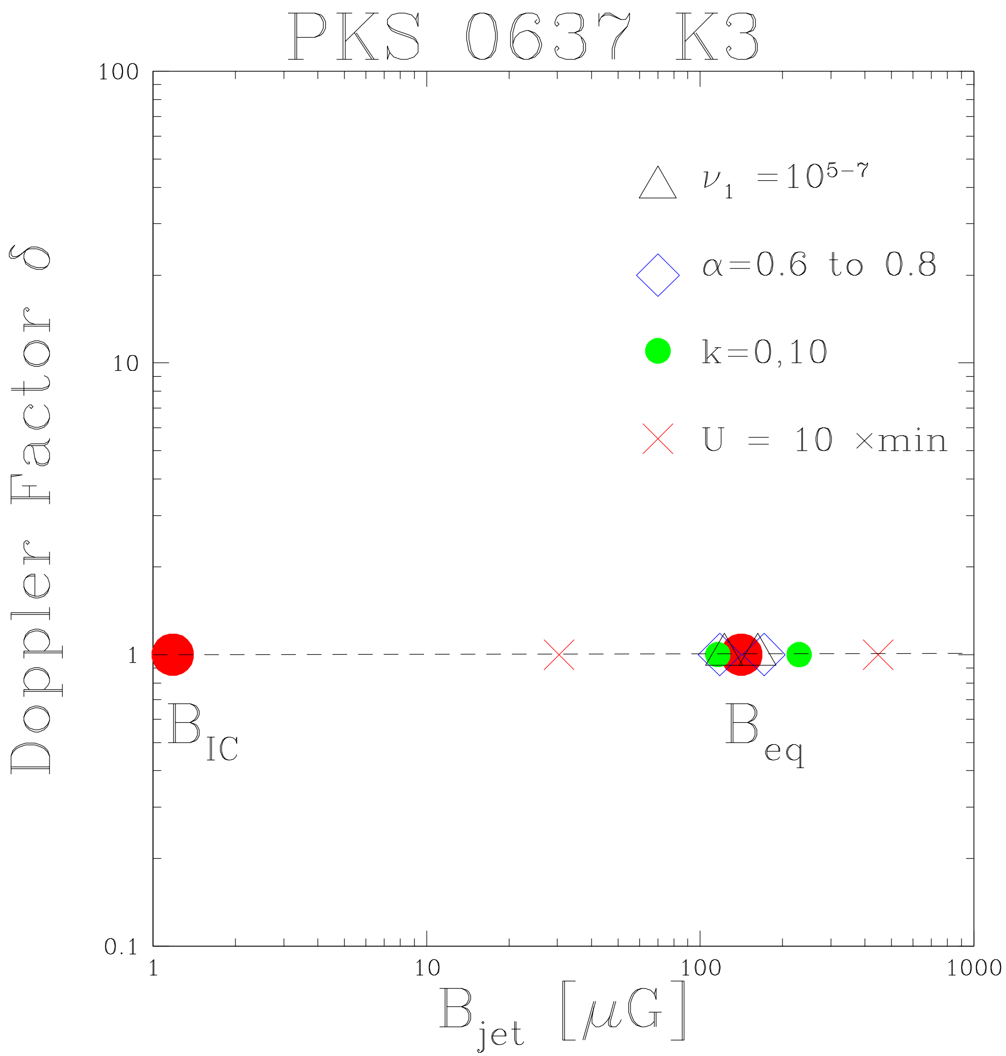
Uncertainties in the Magnetic Field Estimates

Equipartition

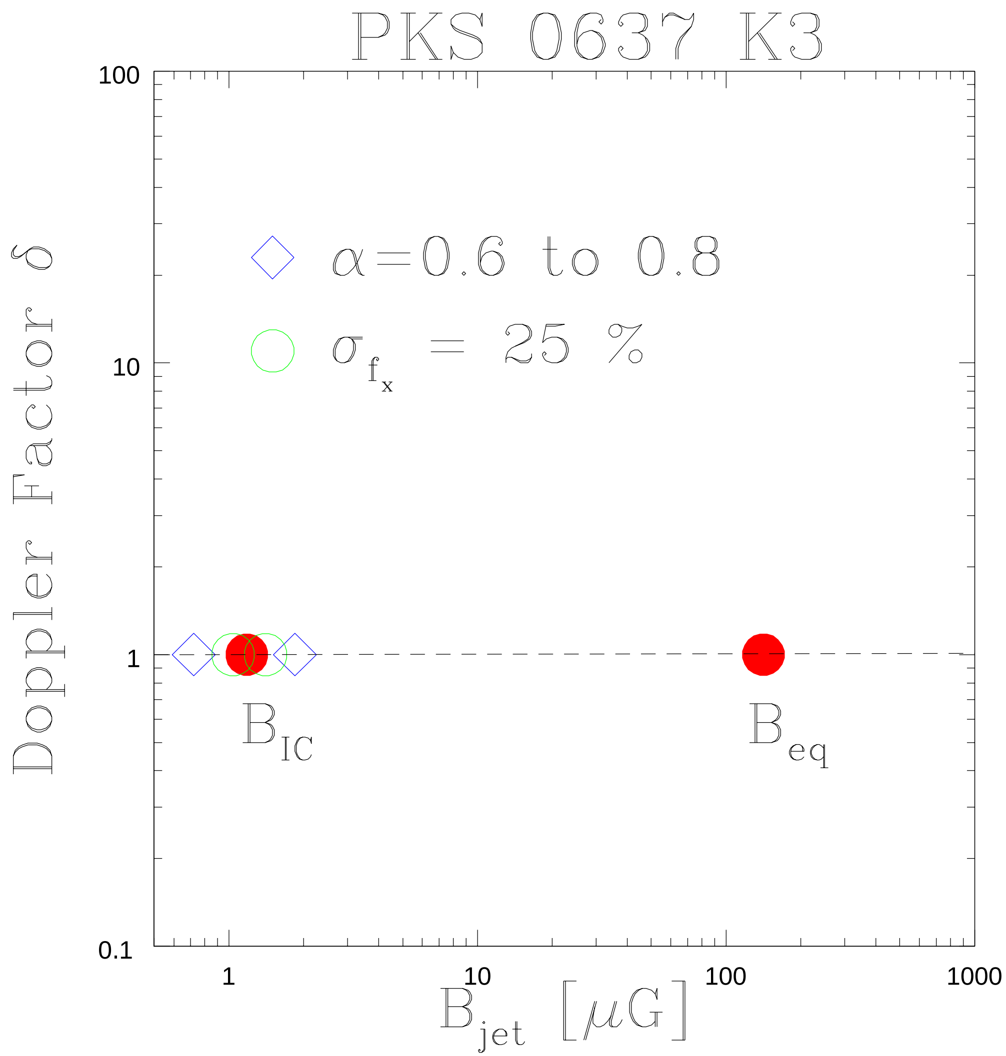


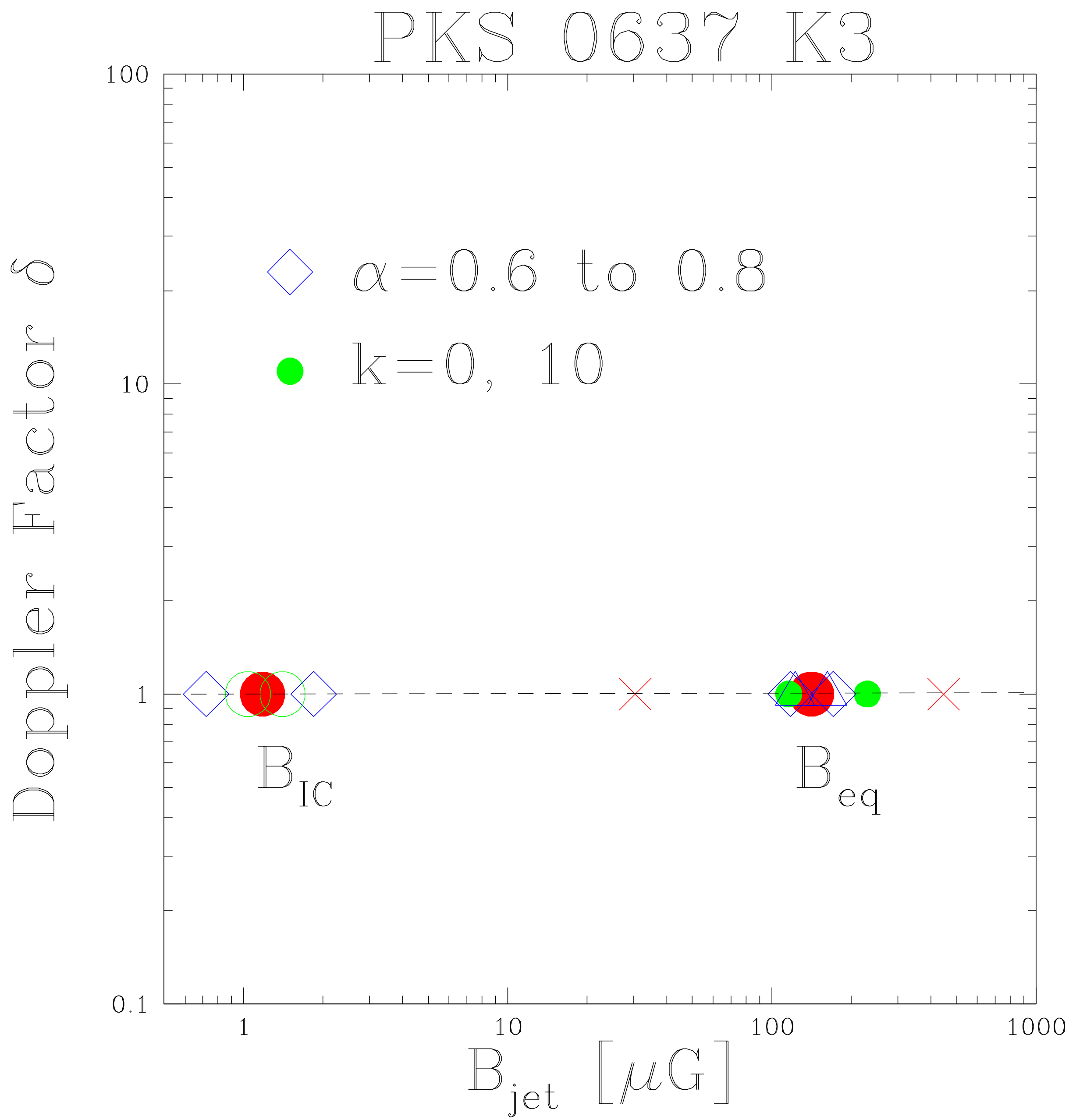
Uncertainties in the Magnetic Field Estimates

Equipartition

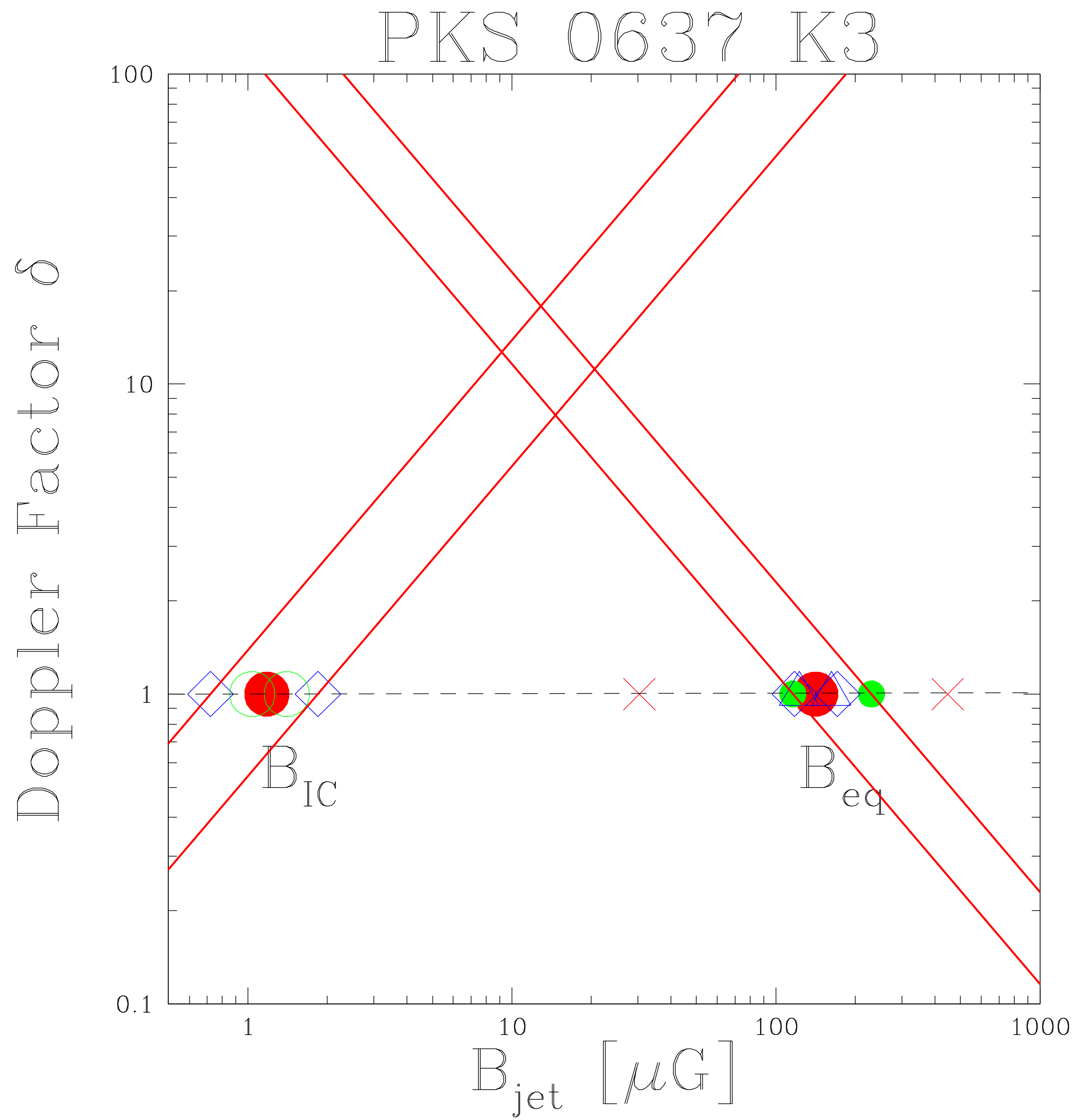


Inverse Compton

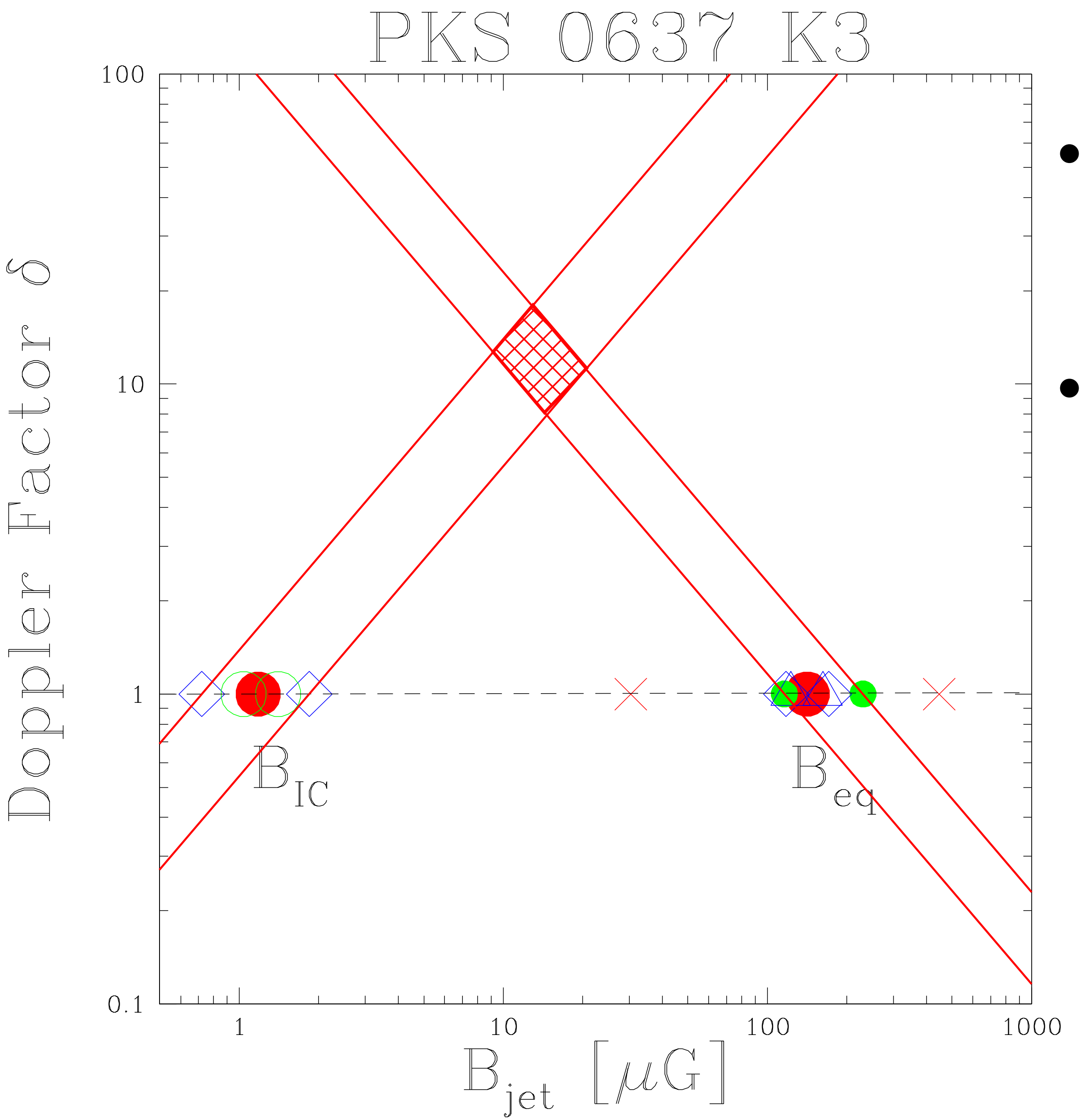




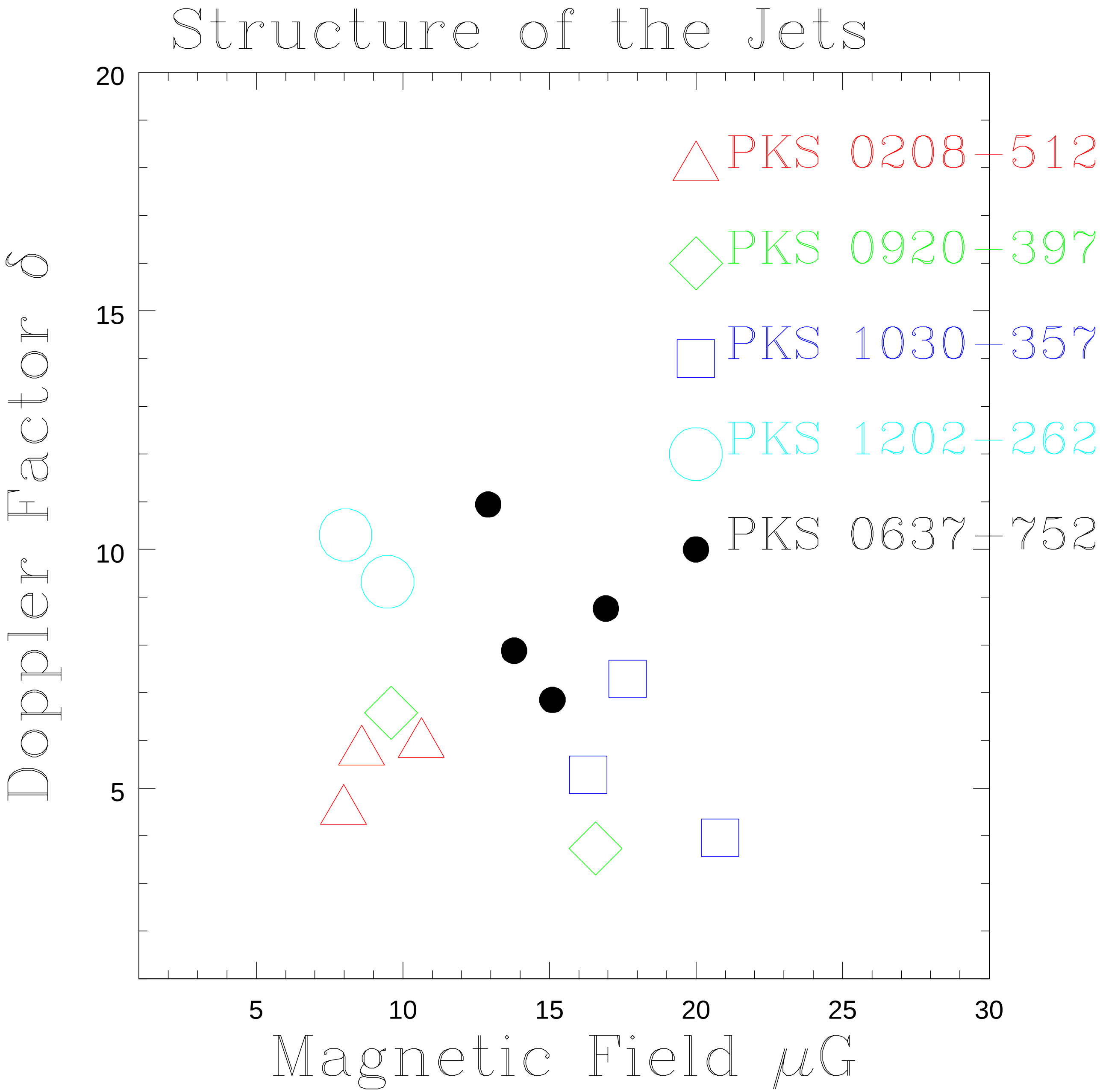
PKS 0637 K3
Doppler Factor δ
α=0.6 to 0.8
k=0, 10
B_IC
B_eq
B_jet [μG]
100
10
1
0.1
1
10
100
1000



PKS 0637 K3
Doppler Factor δ
100
10
1
0.1
1
10
100
1000
B_IC
B_eq
B_jet [μG]

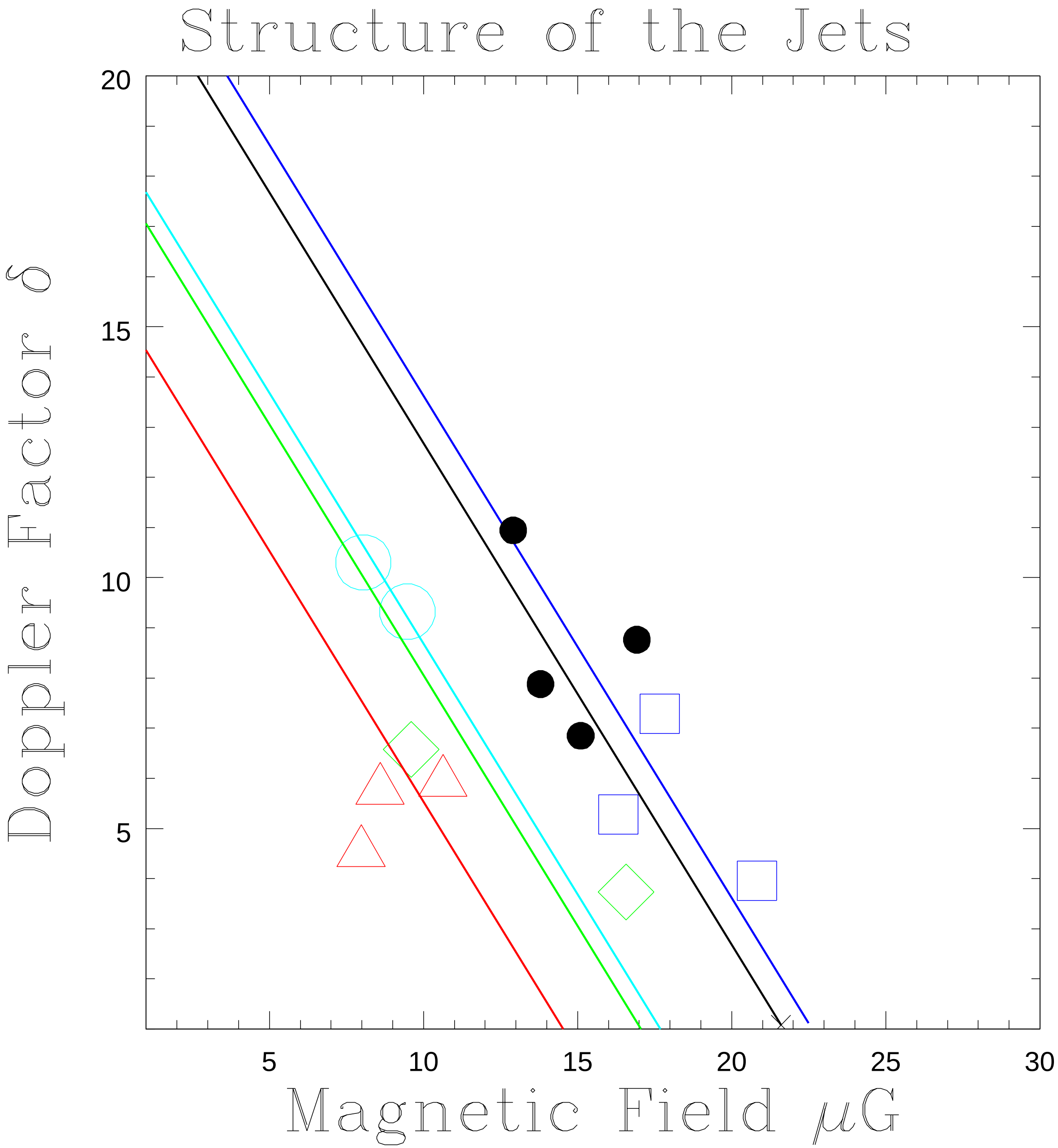


- **Determined B and δ within a factor of 2**
- **Kinetic flux is $\propto (B\delta)^2$, for equipartition**

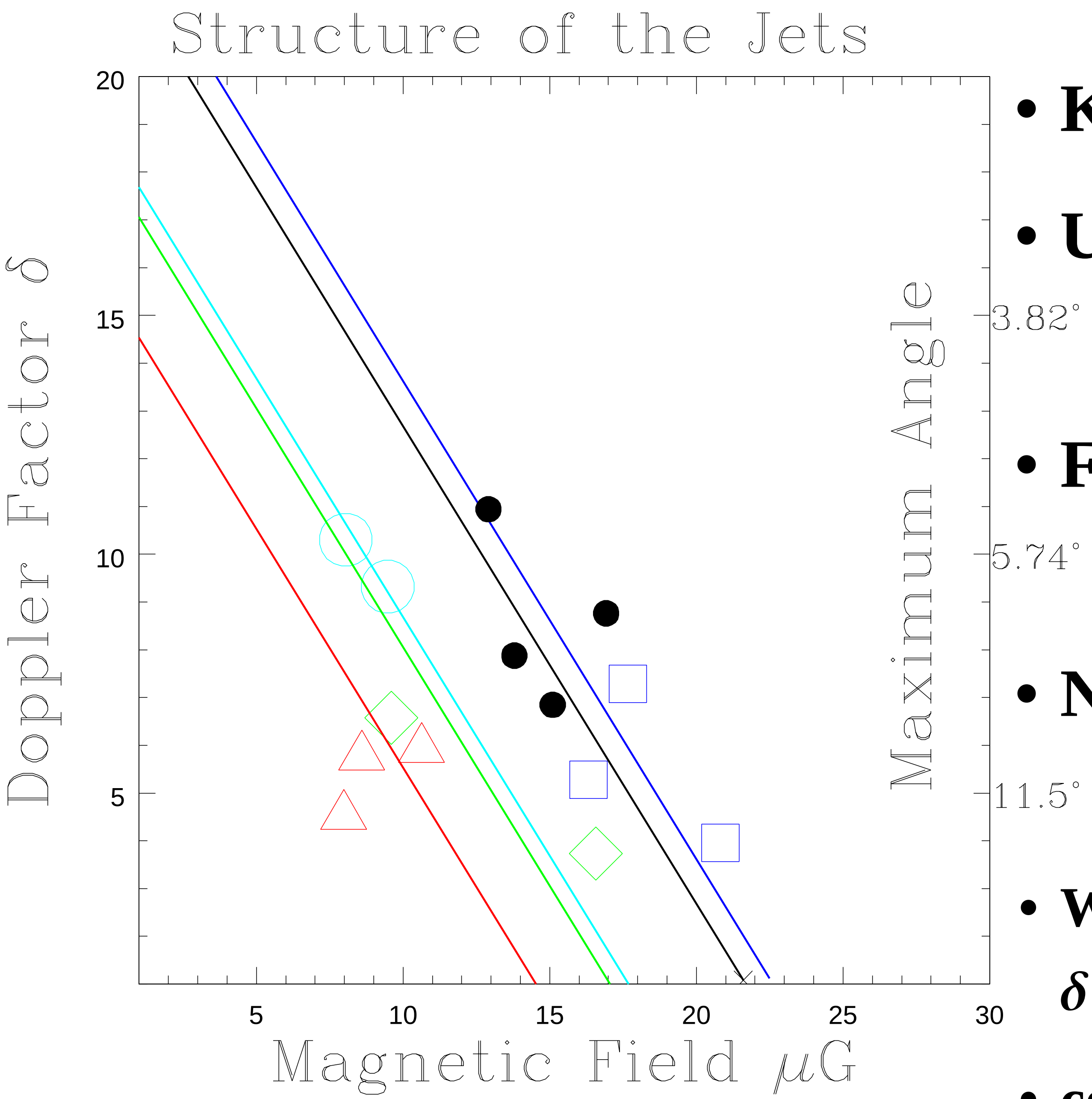


Structure of the Jets
PKS 0208−512
PKS 0920−397
PKS 1030−357
PKS 1202−262
PKS 0637−752
Doppler Factor δ
Magnetic Field μG
20
15
10
5
5
10
15
20
25
30

Kinetic Flux



- $K = \Gamma^2 \pi r^2 \beta c U$
- U is total internal energy density, $U_B + U_e + U_p$
- For equipartition, $U = \frac{B^2}{8\pi}(2 + k)$
- NOTE: K constant $\Rightarrow$ $(B\,\Gamma)^2$ = constant

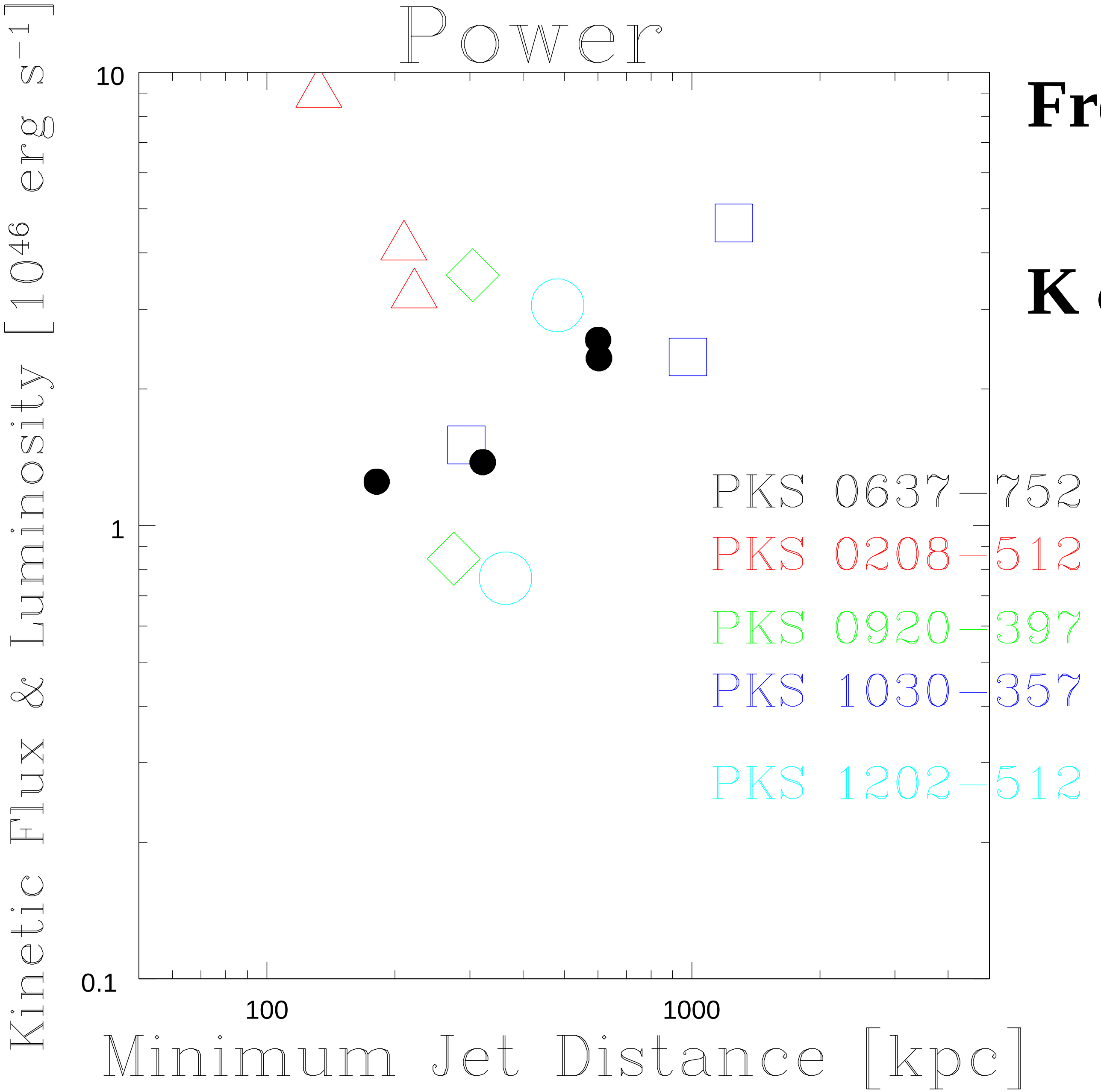


Kinetic Flux

- $K = \Gamma^2 \pi\, r^2 \beta\, c\, U$
- U is total internal energy density, $U_B + U_e + U_p$
- For equipartition, $U = \frac{B^2}{8\pi}(2 + k)$
- NOTE: K constant $\Rightarrow$ $(B\,\Gamma)^2$ = constant
- We take $\Gamma \approx \delta$

  $\delta = (\Gamma(1 - \beta\cos(\theta)))^{-1}$
- $\cos(\theta_{max}) = \frac{\delta - 1/\delta}{\sqrt{(\delta^2 - 1)}}$

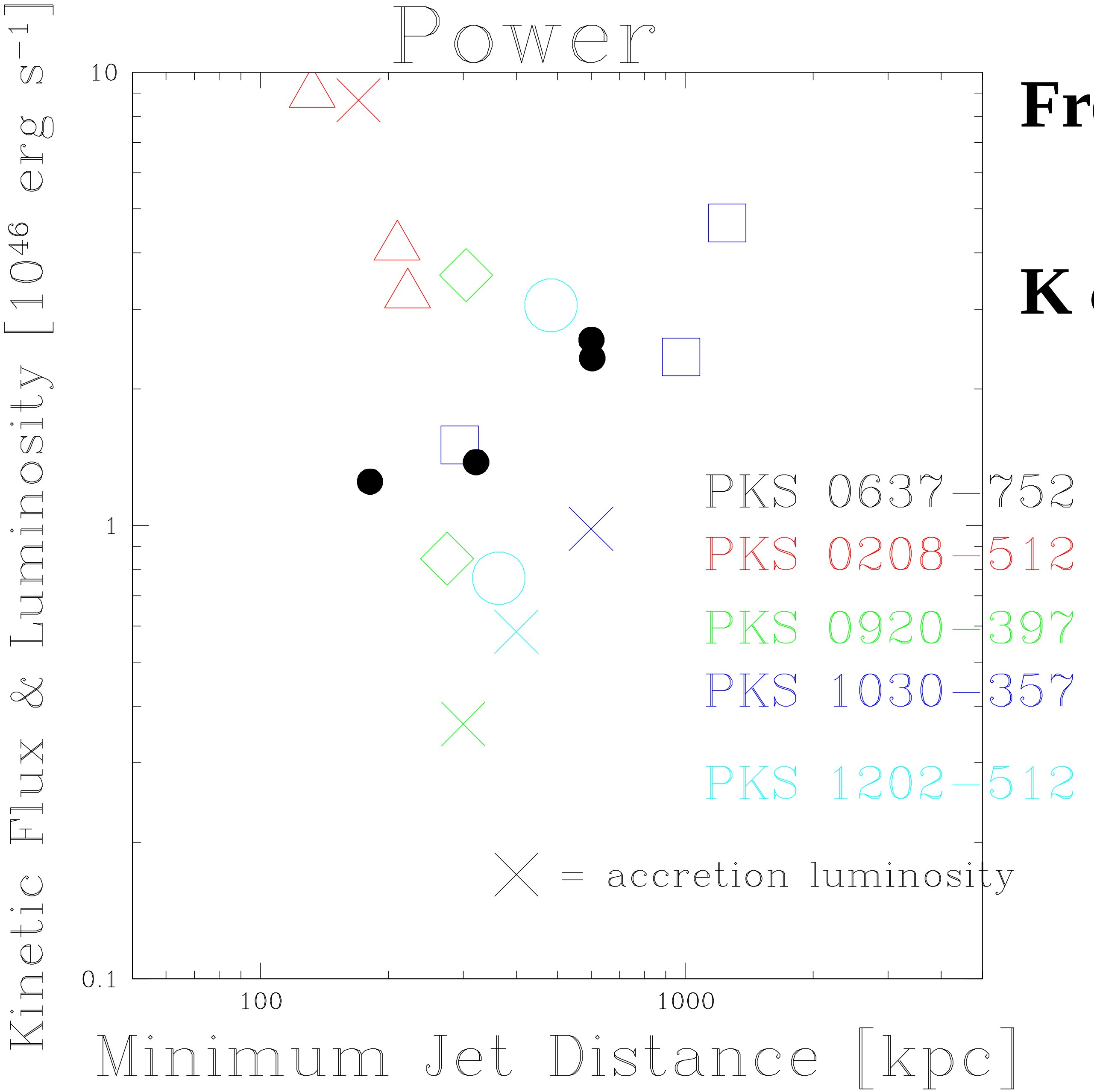
Kinetic Flux



From $K = \Gamma^2 \pi \, r^2 \beta \, c \, U$,

$K \propto \delta^2 \theta_r^2 (3\, B^2/(8\, \pi))$

Kinetic Flux



From $\mathbf{K = \Gamma^2 \pi\, r^2 \beta\, c\, U,}$

$\mathbf{K \propto \delta^2 \theta_r^2 (3\, B^2/(8\,\pi))}$

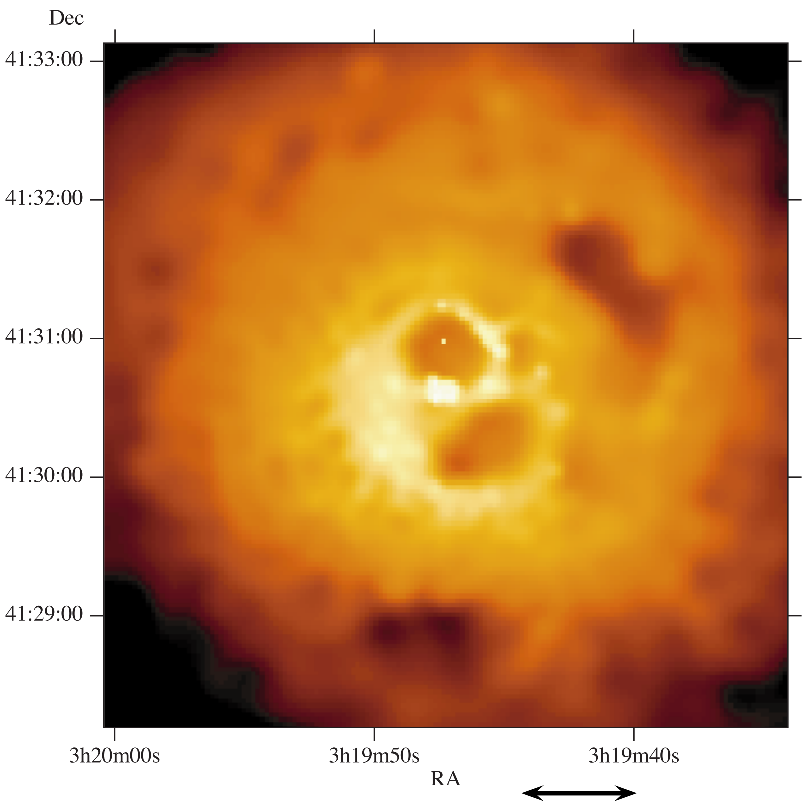
Kinetic flux is a significant, even dominant, portion of the accretion energy budget.

Implications of the FR II Jets

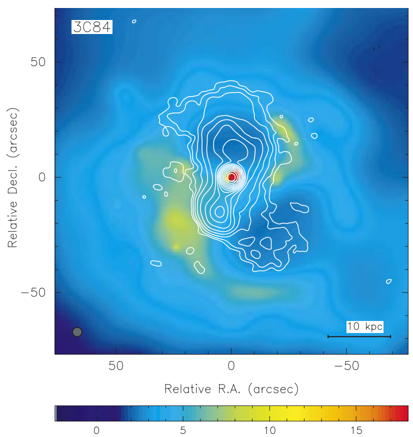
- **Eddington Luminosity might not limit Accretion Rate**
- **Jets may Power Cluster Cavities – Stop Cooling Flows**
- **IC/CMB X-ray jets Maintain Constant Surface Brightness vs. z. We will detect them at Arbitrarily Large Redshift.**

PERSEUS A

Fabian et al. (2000MNRAS.318L..65F)



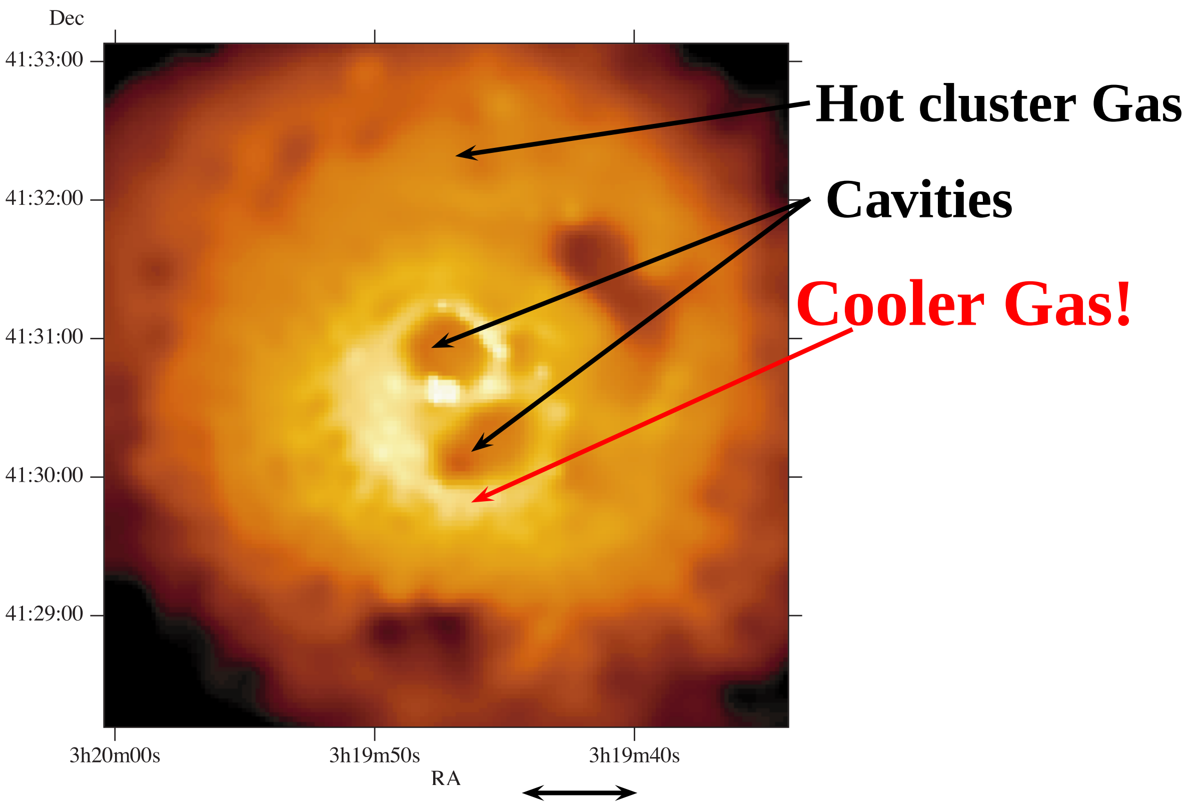
50″=18.4 kpc



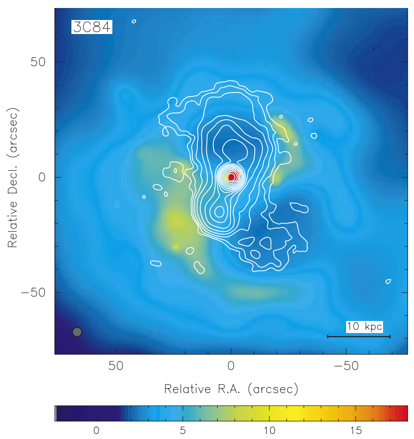
1.4 GHz VLA

PERSEUS A

Fabian et al. (2000MNRAS.318L..65F)



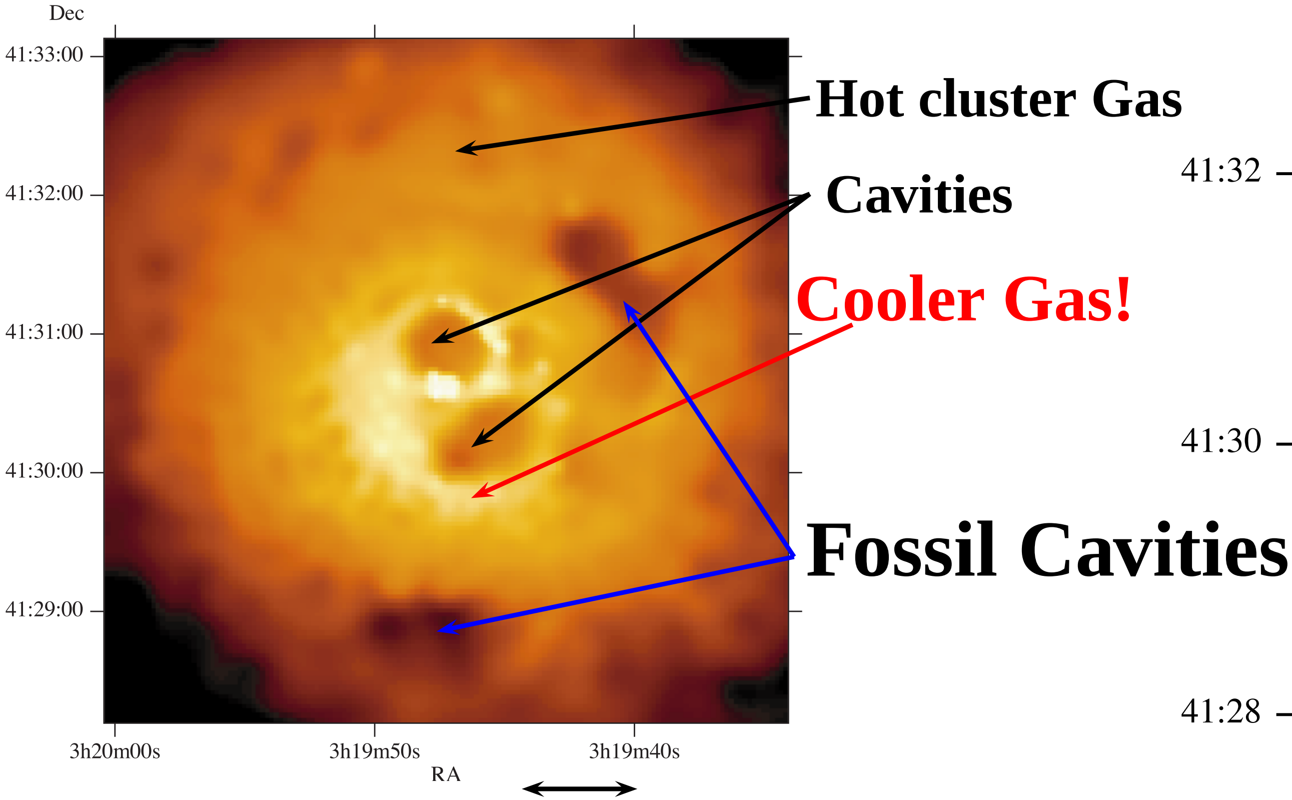
50″=18.4 kpc



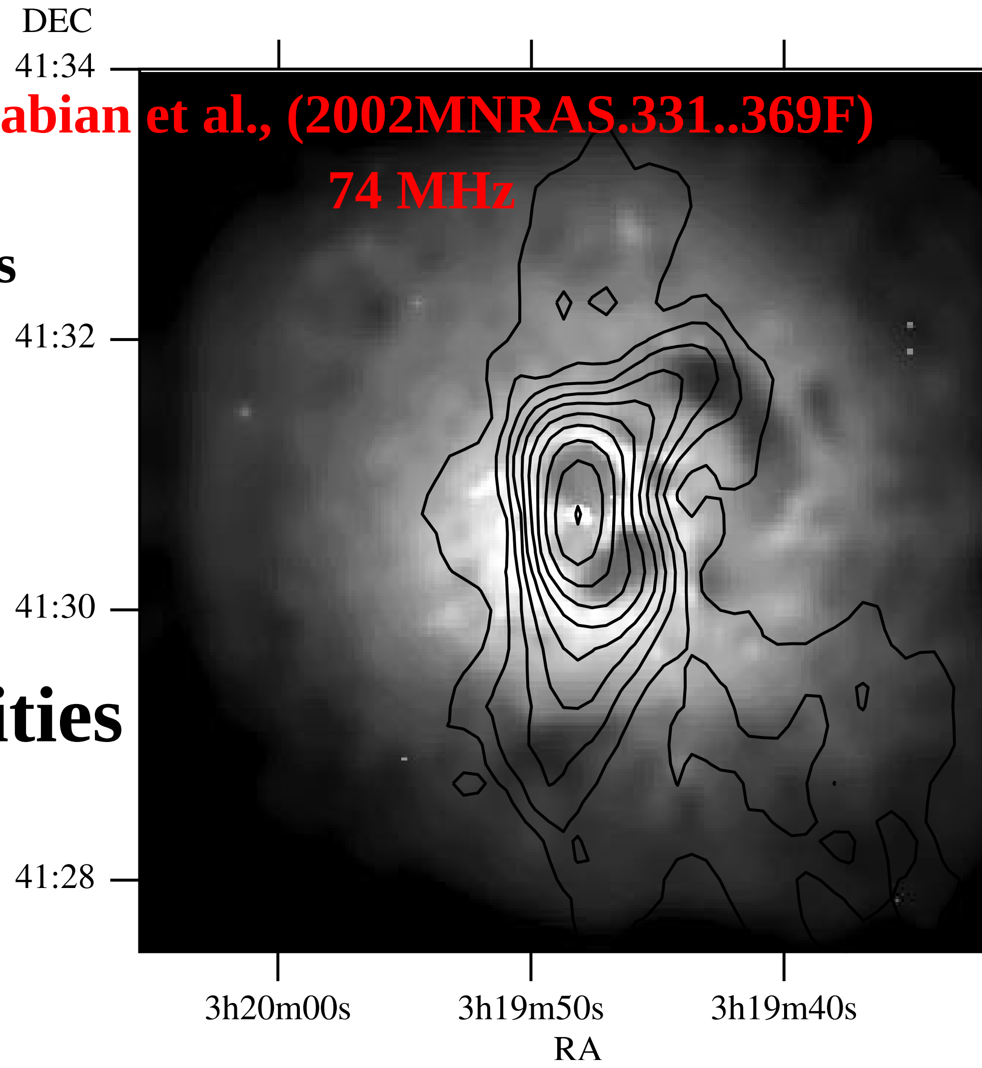
1.4 GHz VLA

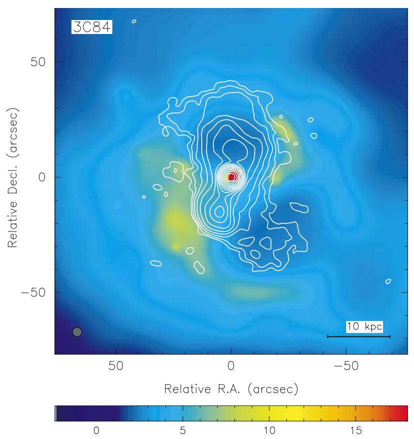
PERSEUS A

Fabian et al. (2000MNRAS.318L..65F)



50″=18.4 kpc





1.4 GHz VLA

PERSEUS A

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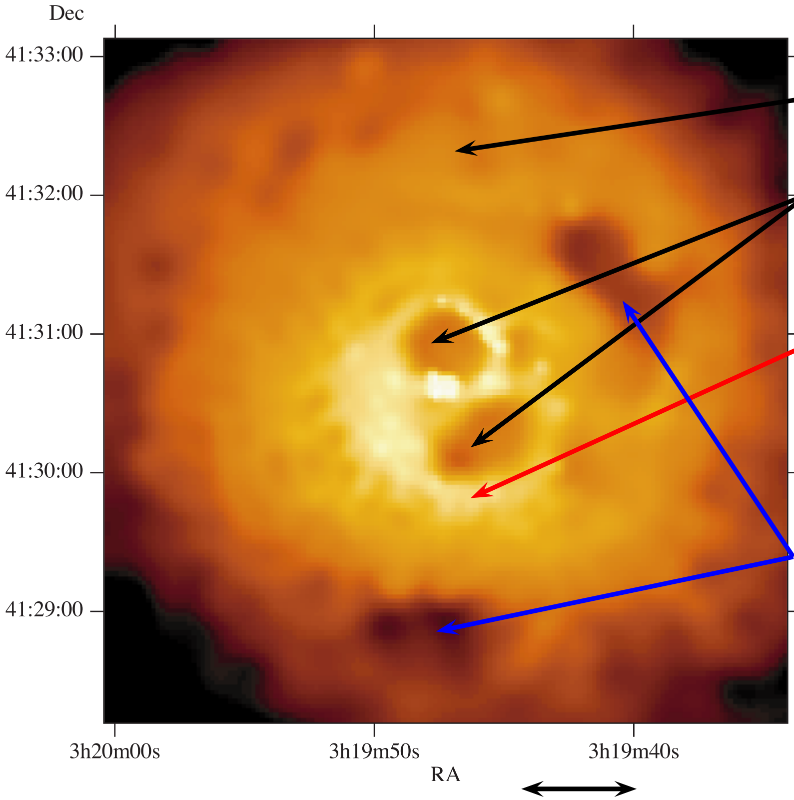


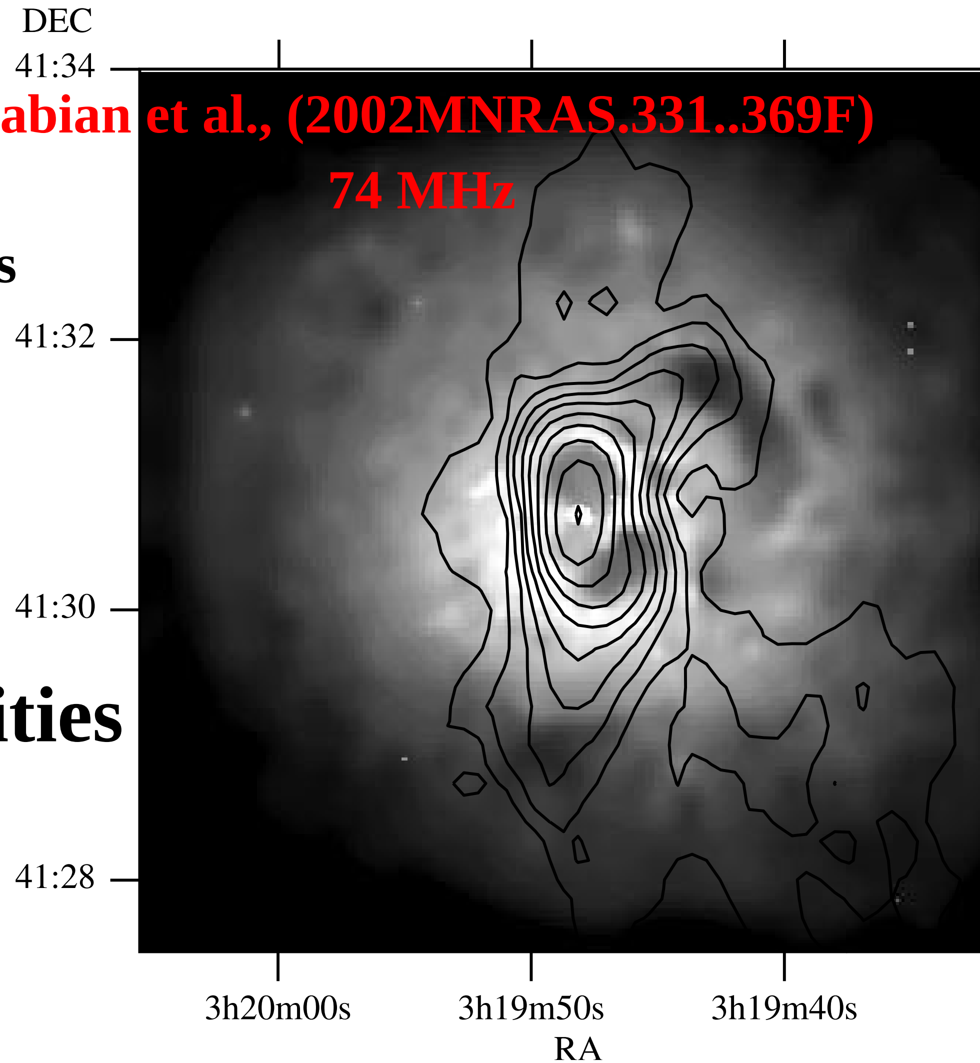
Hot cluster Gas

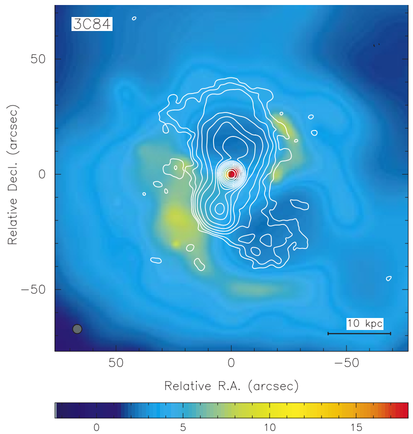
Cavities

Cooler Gas!

Fossil Cavities

50″=18.4 kpc





1.4 GHz VLA

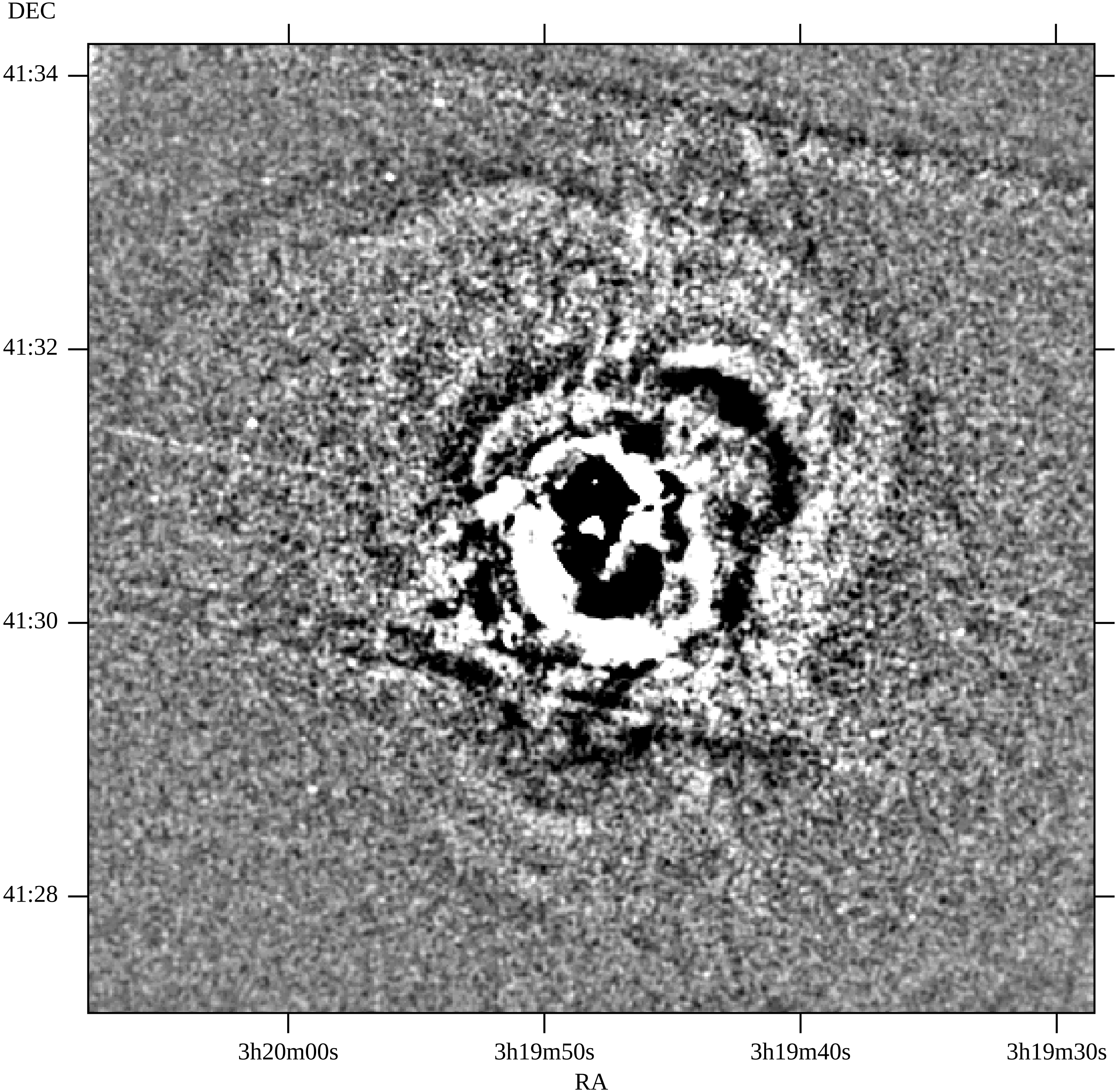
$p\,\Delta V \approx 2 \times 10^{58}$ ergs

$u_{me}\,\Delta V \approx 4 \times 10^{56}$ ergs

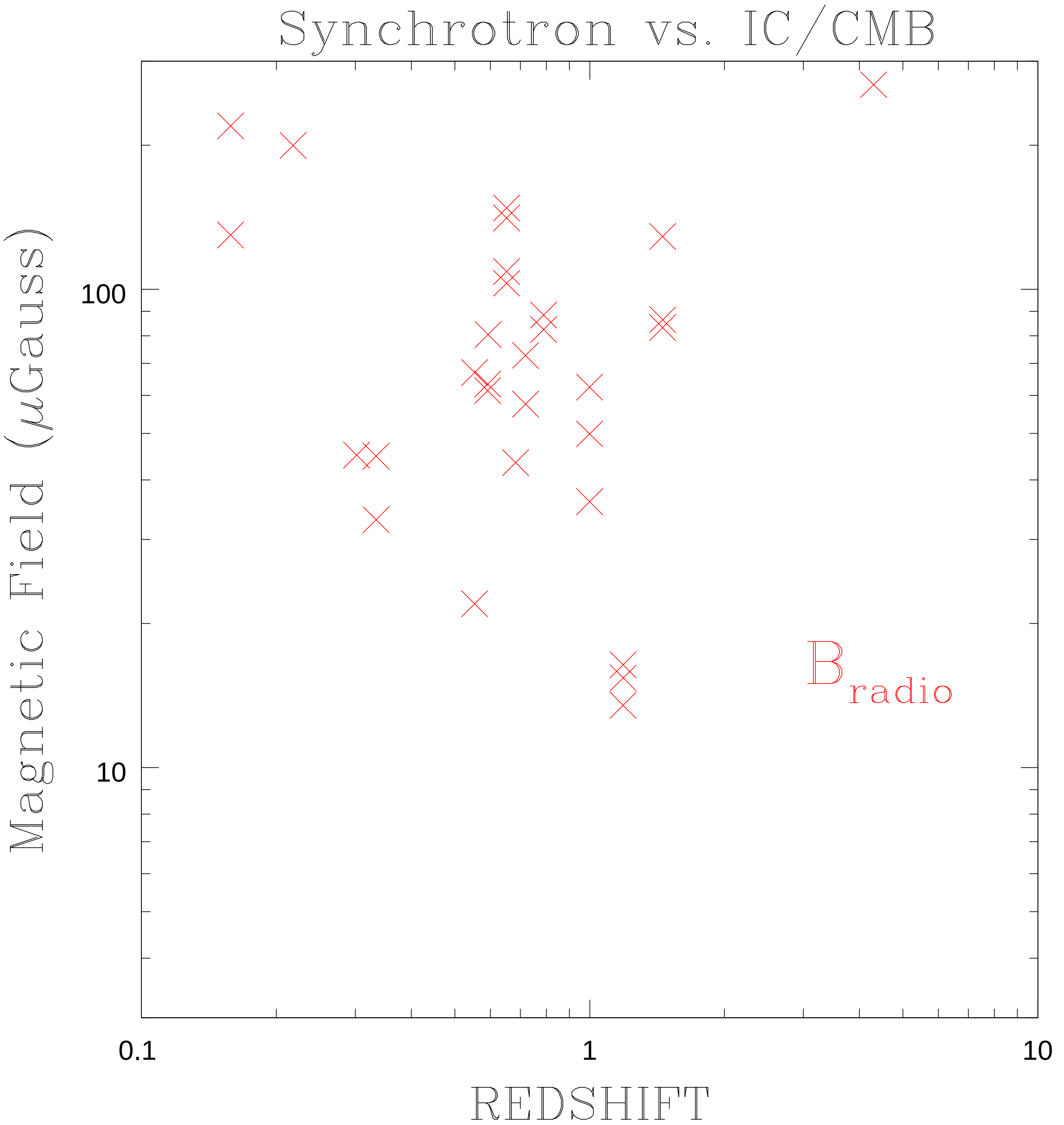
Pressure equality $\Rightarrow k/f \geq 180$

Lifetimes $\Rightarrow B \leq B_{me}/4$

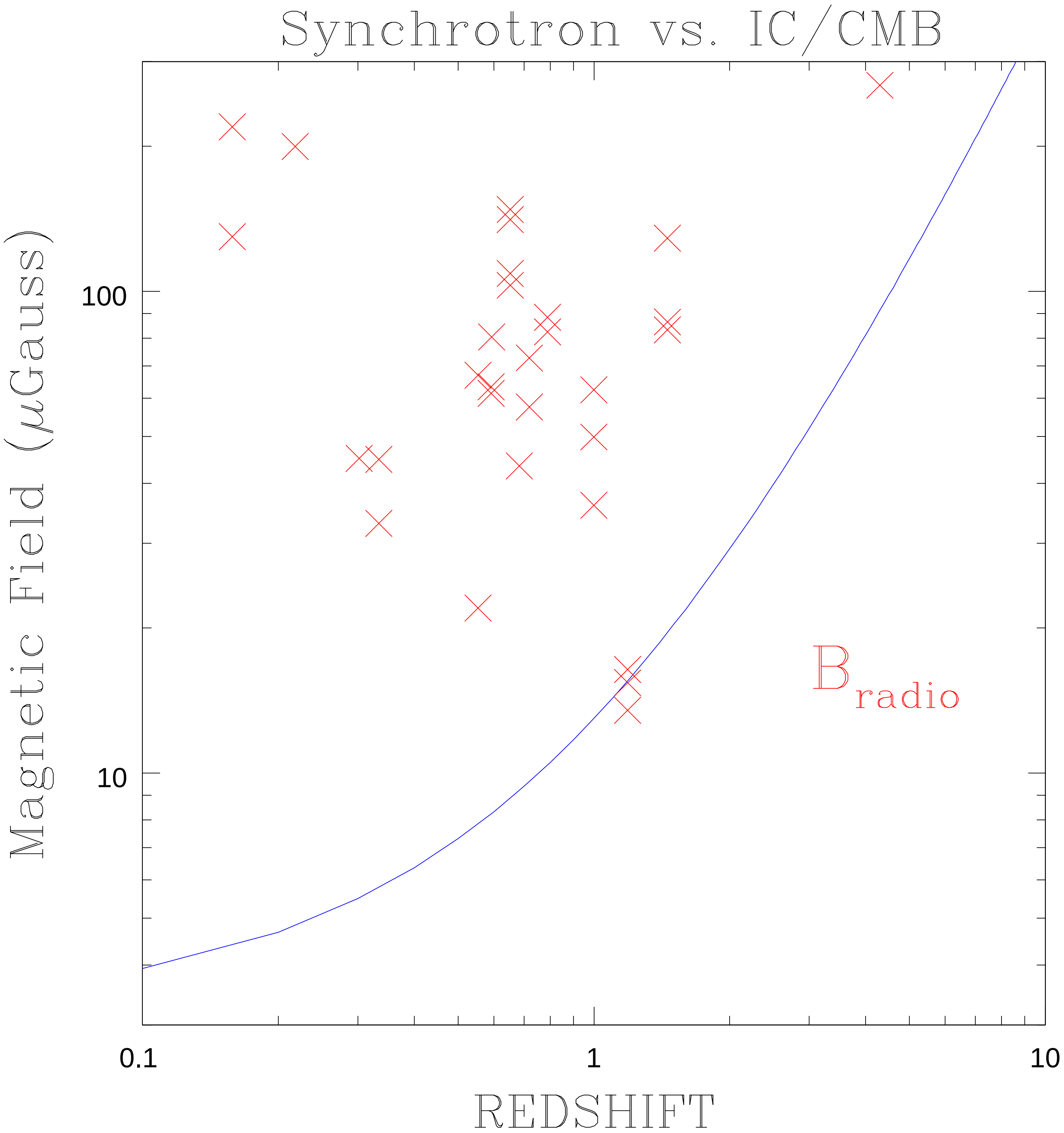
Do Sound Waves Provide the Energy?

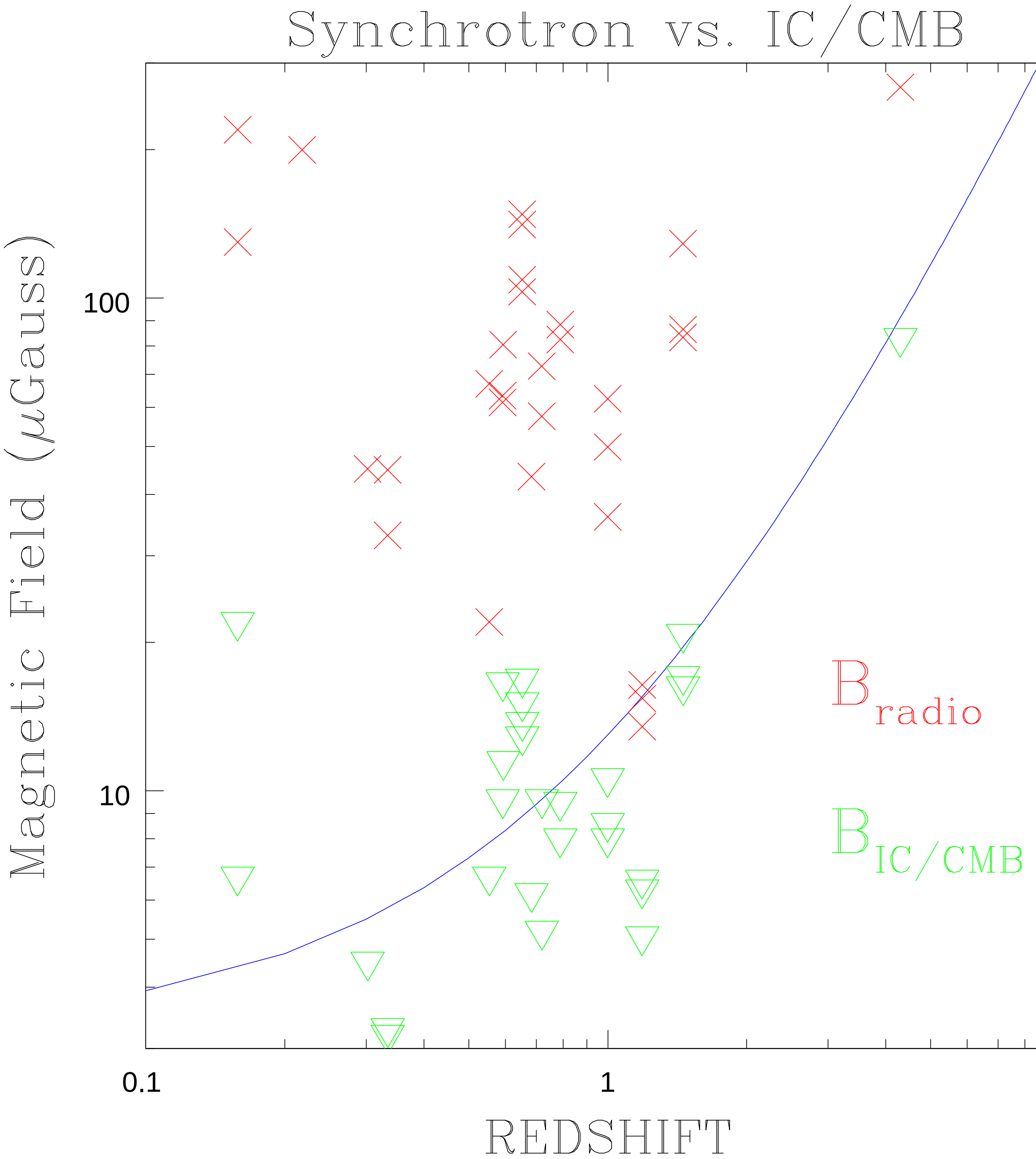


Fabian et al. 2003
astro-ph/0306036

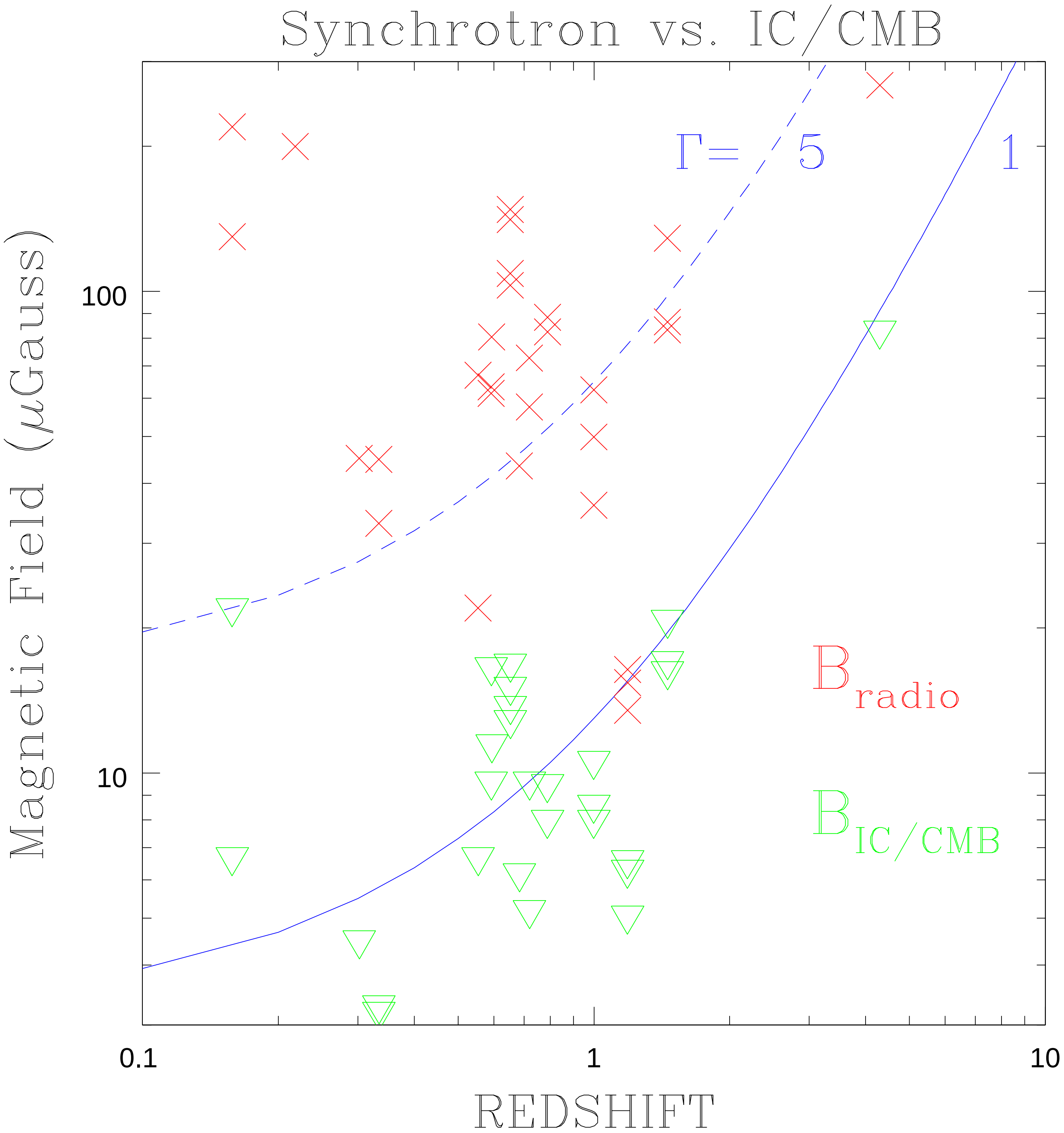


Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B radio


Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B radio



Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B radio
B IC/CMB

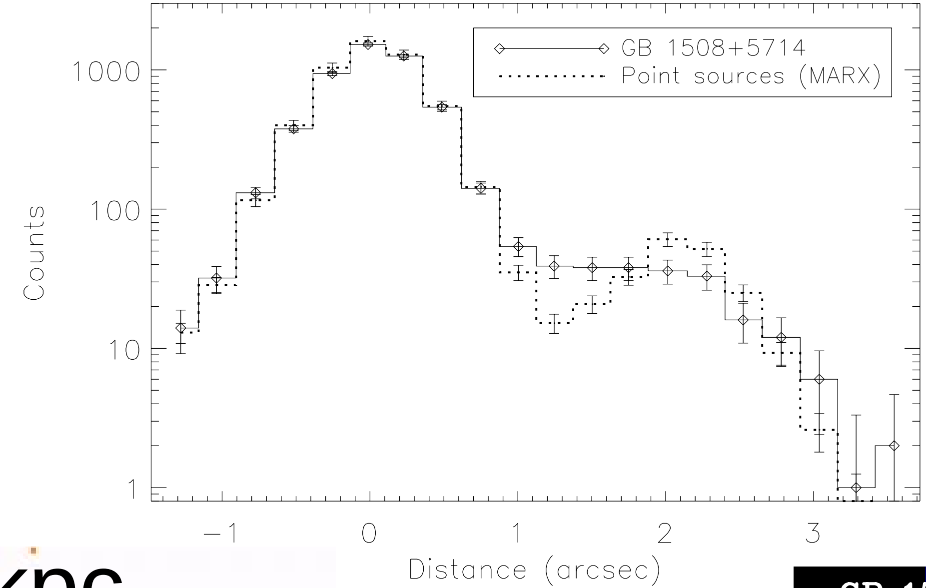


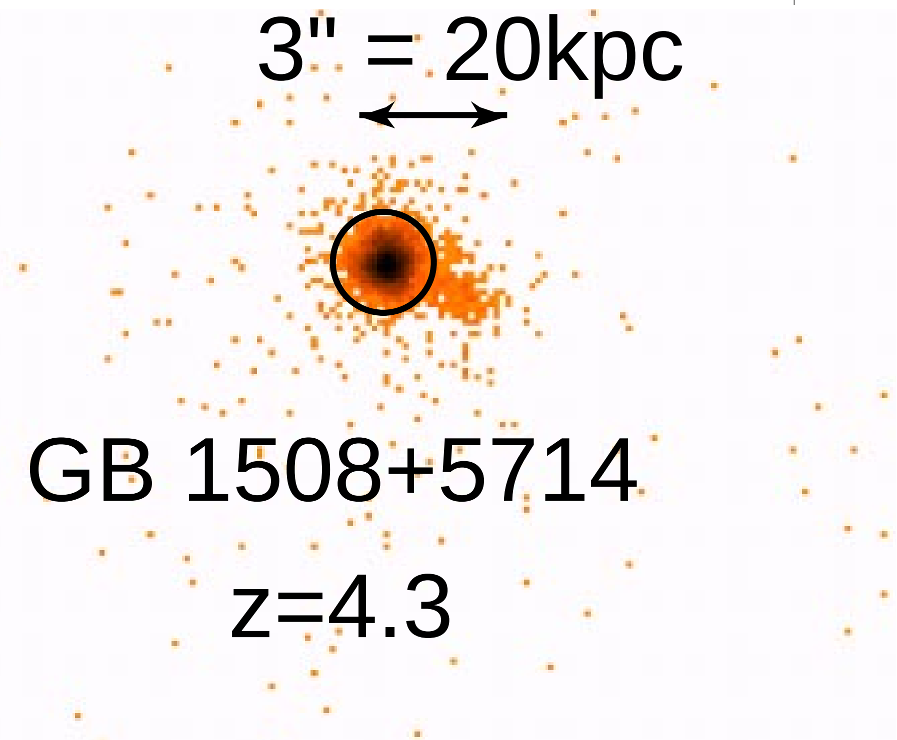
Synchrotron vs. IC/CMB
Γ= 5
1
B radio
B IC/CMB
100
10
0.1
1
10
Magnetic Field (μGauss)
REDSHIFT

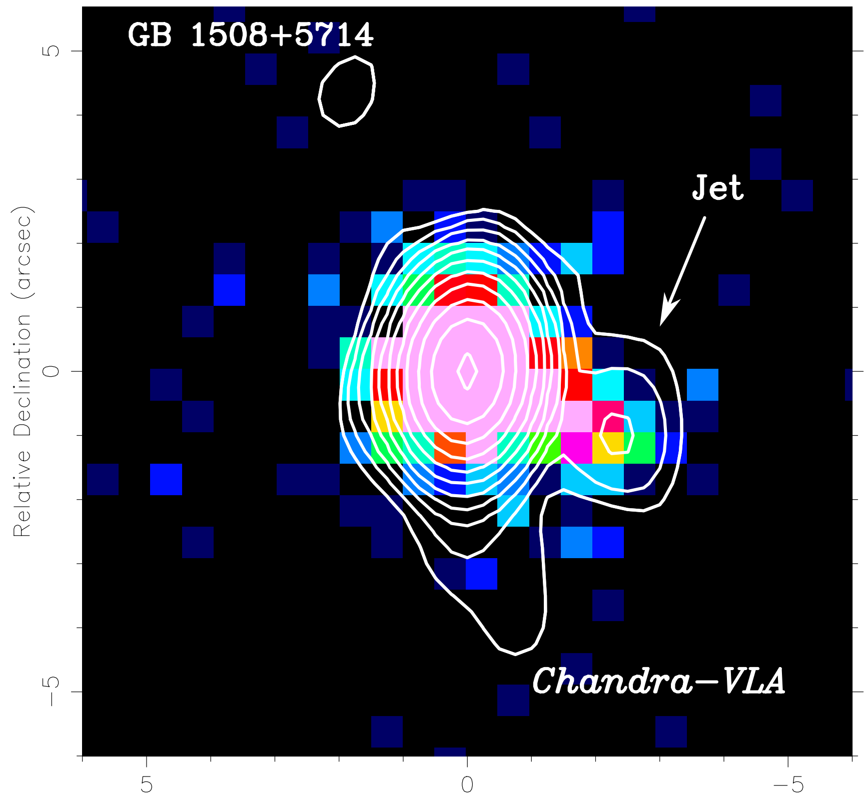
Where ARE the bright X-ray Jets at High Redshift?

- **Unidentified ROSAT sources?**
- **Bright ROSAT, ASCA, EINSTEIN quasar identifications?**
- **Extreme X-ray/Optical sources (Koekemoer et al. 2004ApJ...600L.123K) in Chandra Deep Surveys?**

Where ARE the bright X-ray Jets at High Redshift?







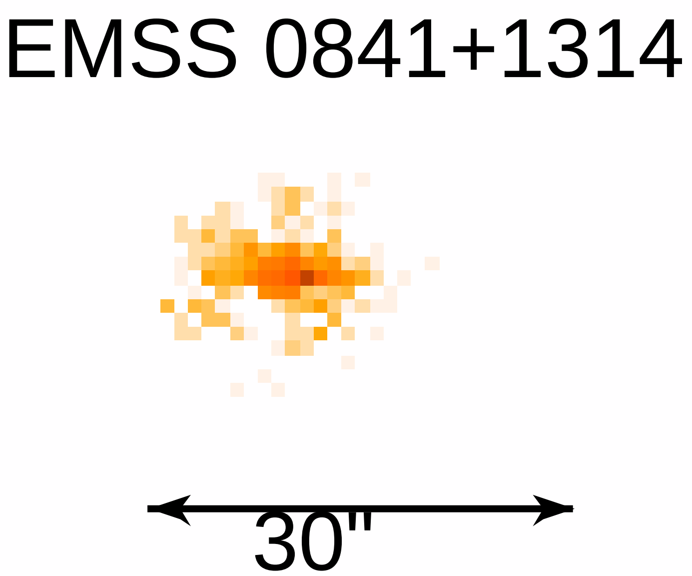
Siemiginowska et al. 2003ApJ...598L..15S

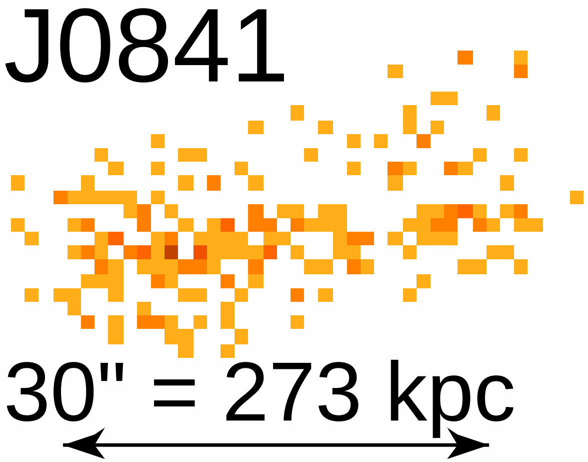
Cheung,2004ApJ...600L..23C

There Should Be Radio Quiet X-Ray Jets!

- **1 keV X-rays produced by $\gamma \approx 1000/\Gamma$**
- **$\nu = 4.2 \times 10^{-6} \gamma^2$ H[μG] $\approx$ 10 MHz**

A Radio Quiet X-Ray Jet?

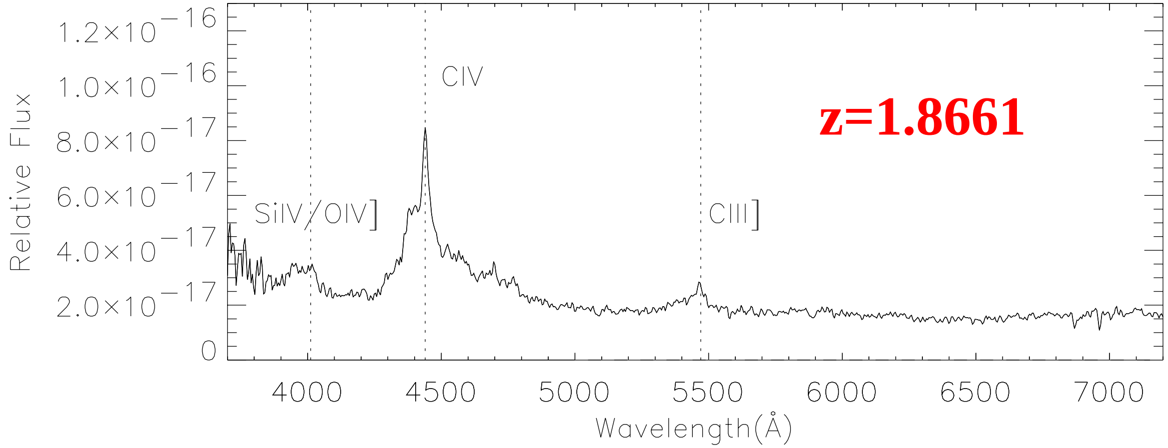


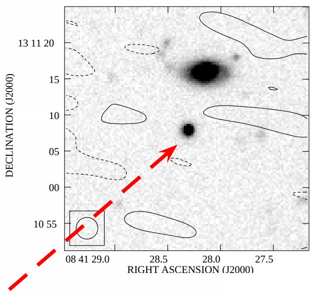


A Radio Quiet X-Ray Jet?

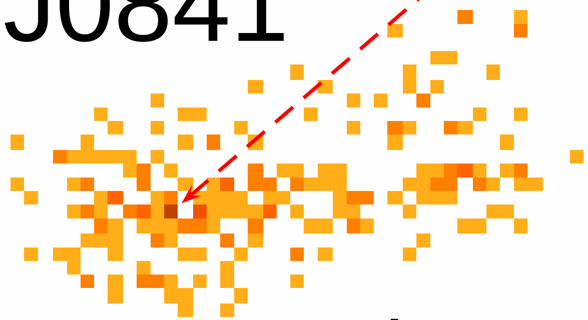
EMSS 0841+1314

30"



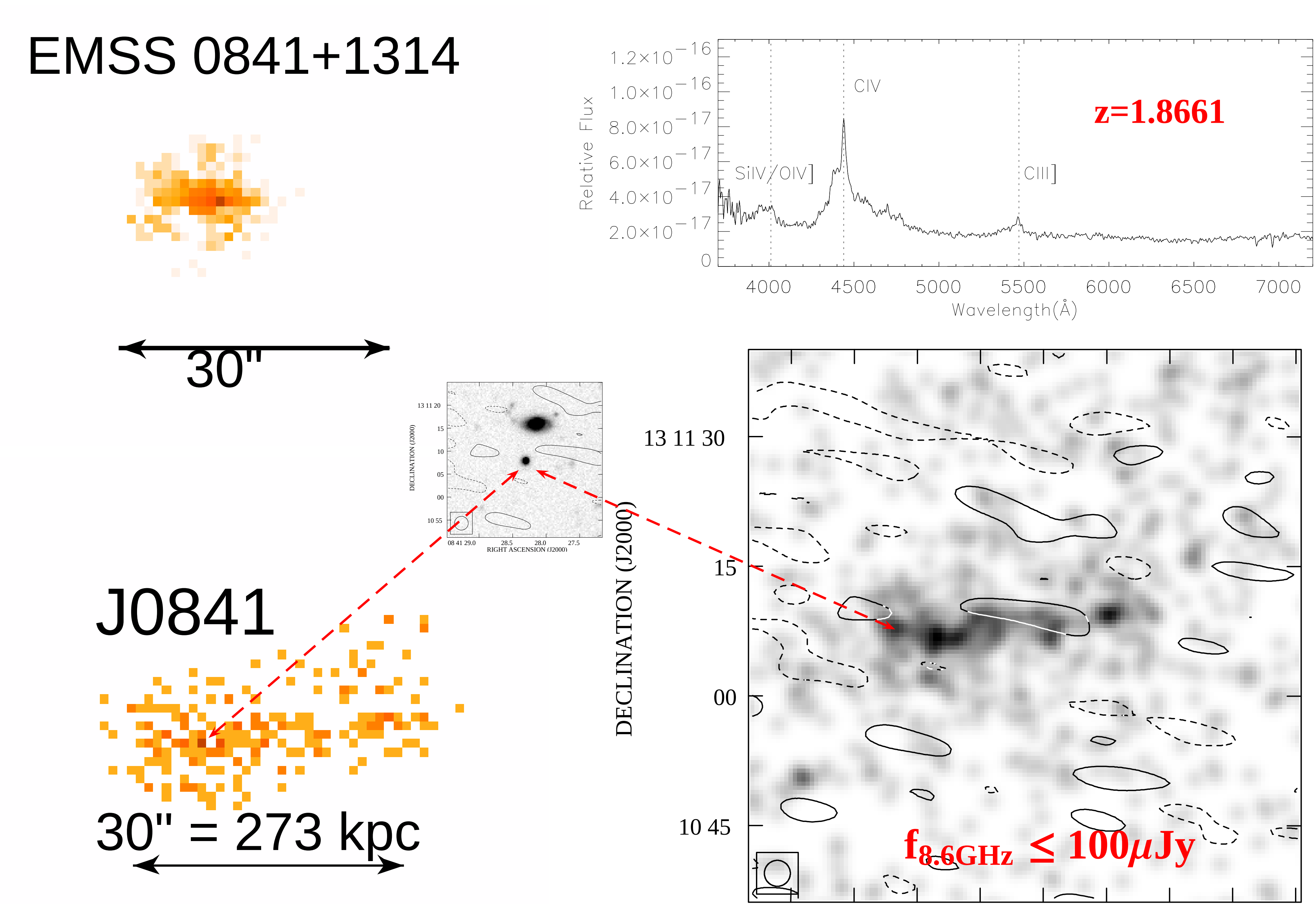


J0841

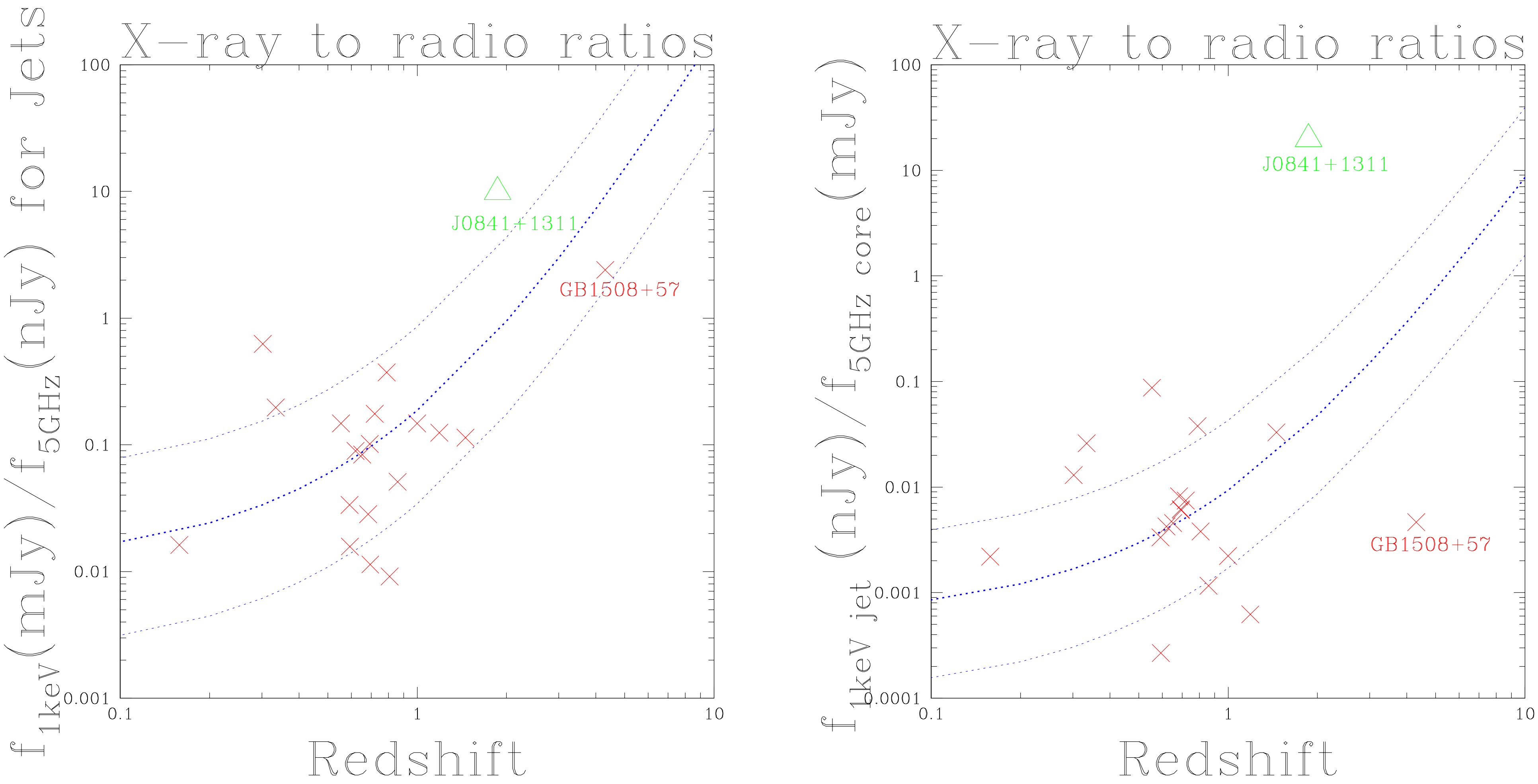


30" = 273 kpc

A Radio Quiet X-Ray Jet?



Correlation of X-ray Jet and Radio Flux Densities



Significance of the X-ray Emission

1. **X-rays typically radiate the most energy**
2. **Quasar/Black hole core X-ray emission may be dominated by jets (in radio sources)**

If emission is inverse Compton on CMB, and emission region is in equipartition:

3. **X-rays give the effective Doppler factor and rest frame B**
4. **X-ray jets will be detectable at arbitrarily large redshift**