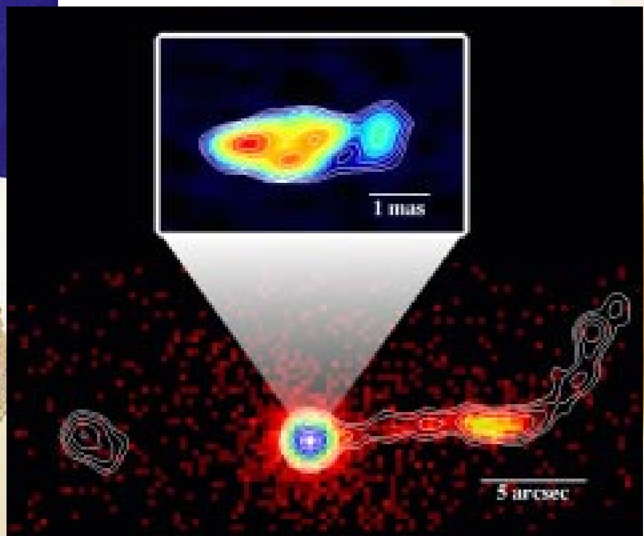
Chandra Observations of Powerful Relativistic Jets in AGN

Dan Schwartz

High Energy Astrophysics Division

LUNCH TALK

2005 March 02



INTRODUCTION

- **What Do Jets Do?**
  - **Carry large quantities of energy, to feed radio lobes**
  - **Significant part of black hole energy generation budget**
  - **Interact with gas in galaxies and clusters of galaxies**

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- **What Do We Want to Learn**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**

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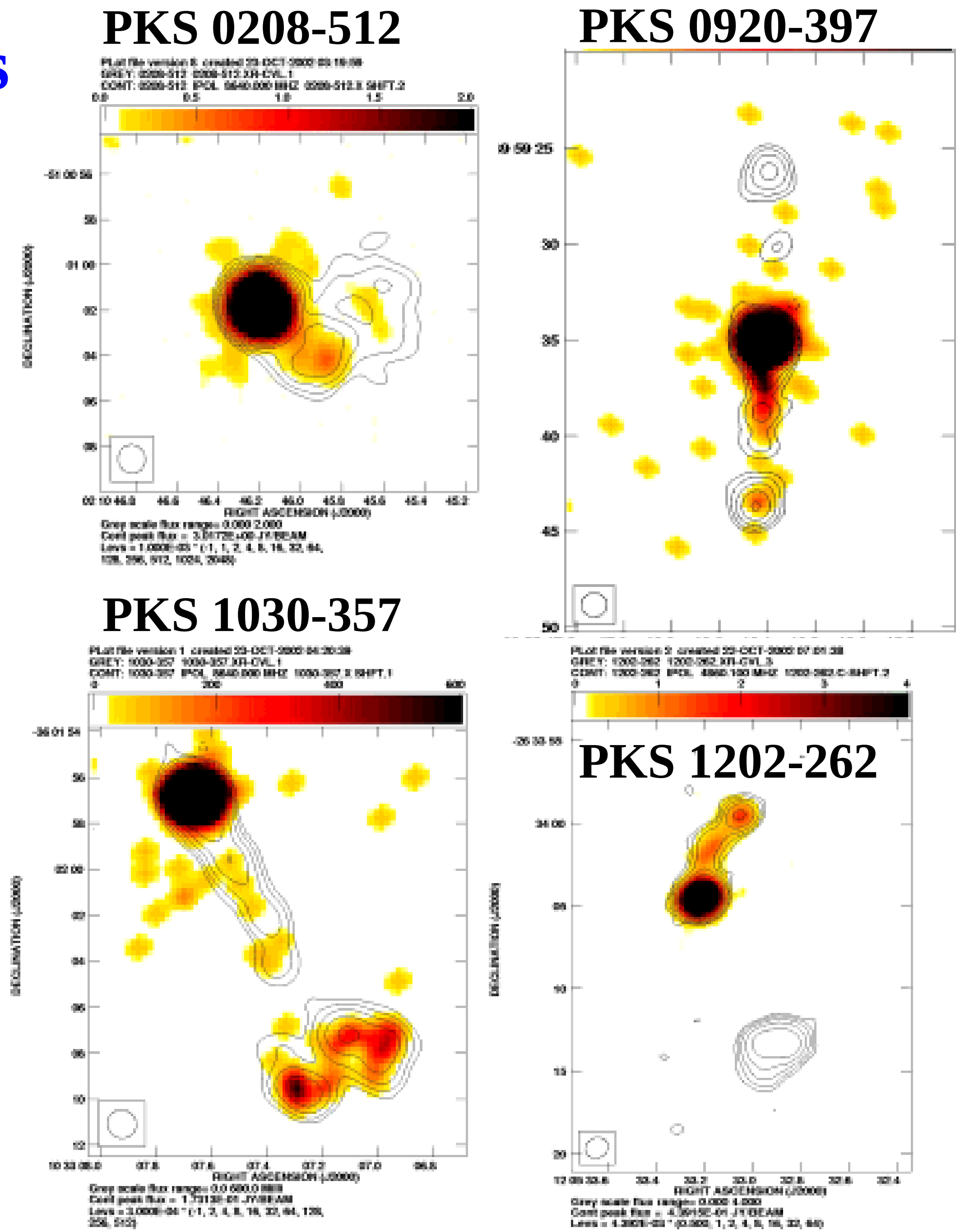
  - Significant part of black hole energy generation budget
  - Interact with gas in galaxies and clusters of galaxies
- What Do We Want to Learn
  - Particle composition and acceleration
  - Jet acceleration and collimation
- Why Do We Need X-Ray Data?
  - Spectral Energy Distribution (SED) gives mechanism
  - Particle lifetimes change with observed band

Outline

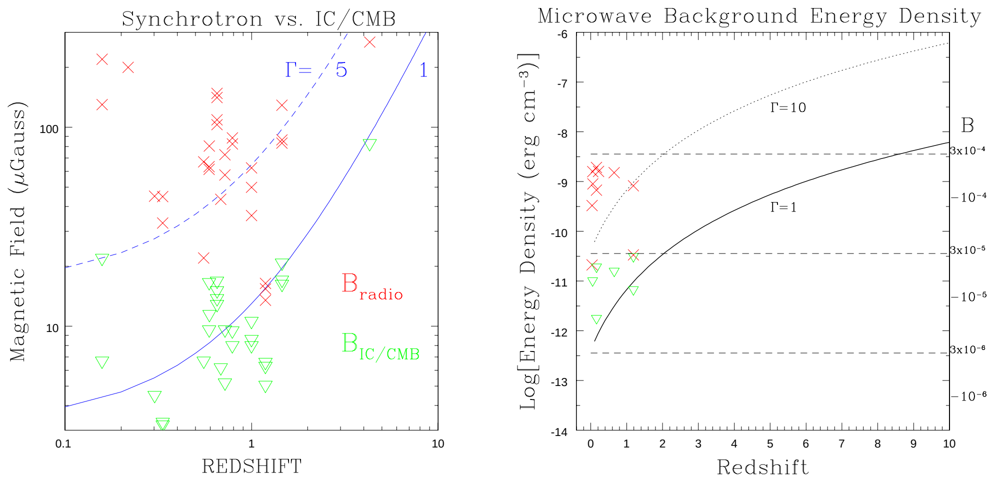
1. **Observations of Quasar Jets**
   - **Quasar jets are relativistic.**
   - **X-ray surveys of Jets**
2. **Interpretation as IC/CMB**



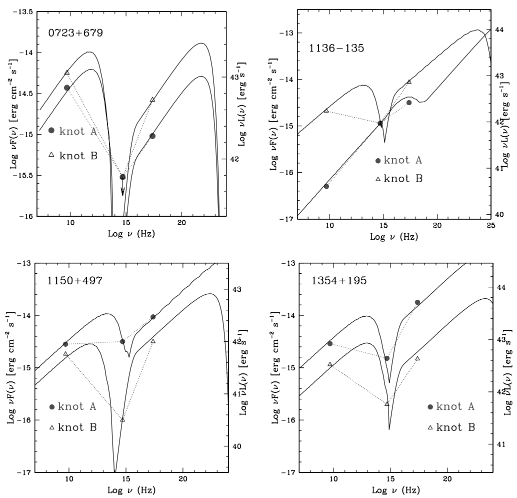
3. **Parameters and Implications**

Outline

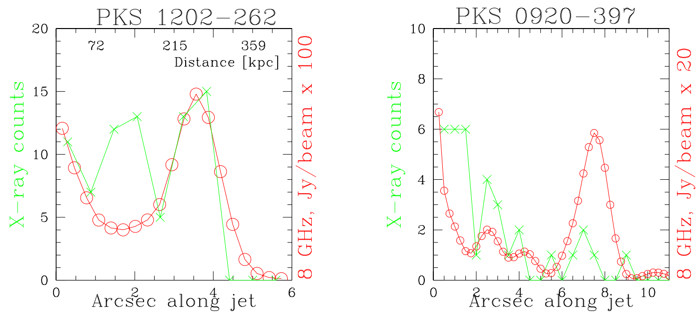
1. Observation of Quasar Jets



2. Interpretation as IC/CMB
    - Energy densities: B^2 vs. $kT(1+z)^4$
    - Broadband SED

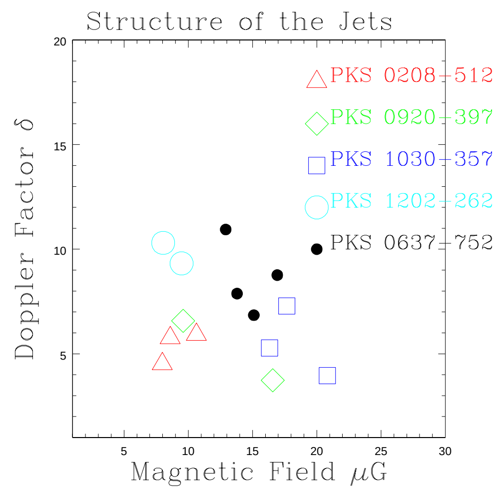


    - Profiles

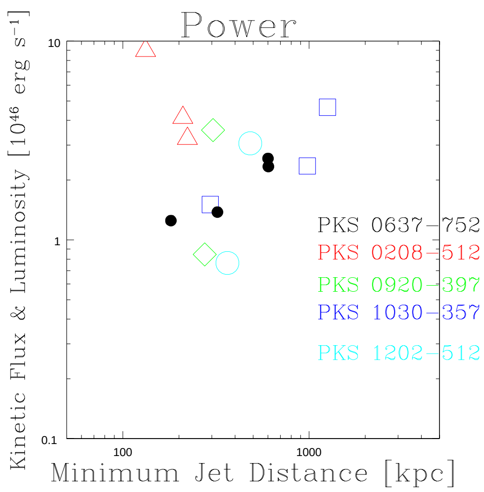


3. Parameters and Implications

Outline

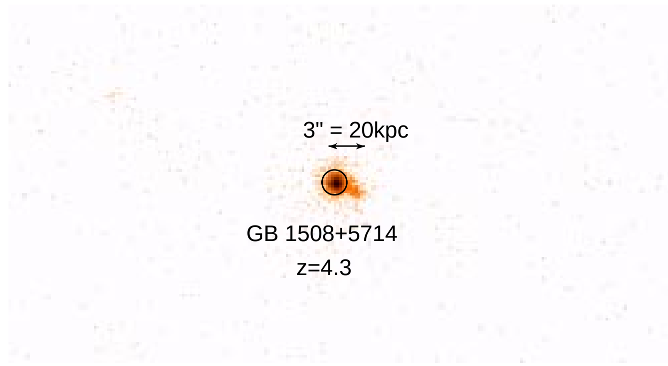


1. Observations of Quasar Jets



2. Interpretation as IC/CMB

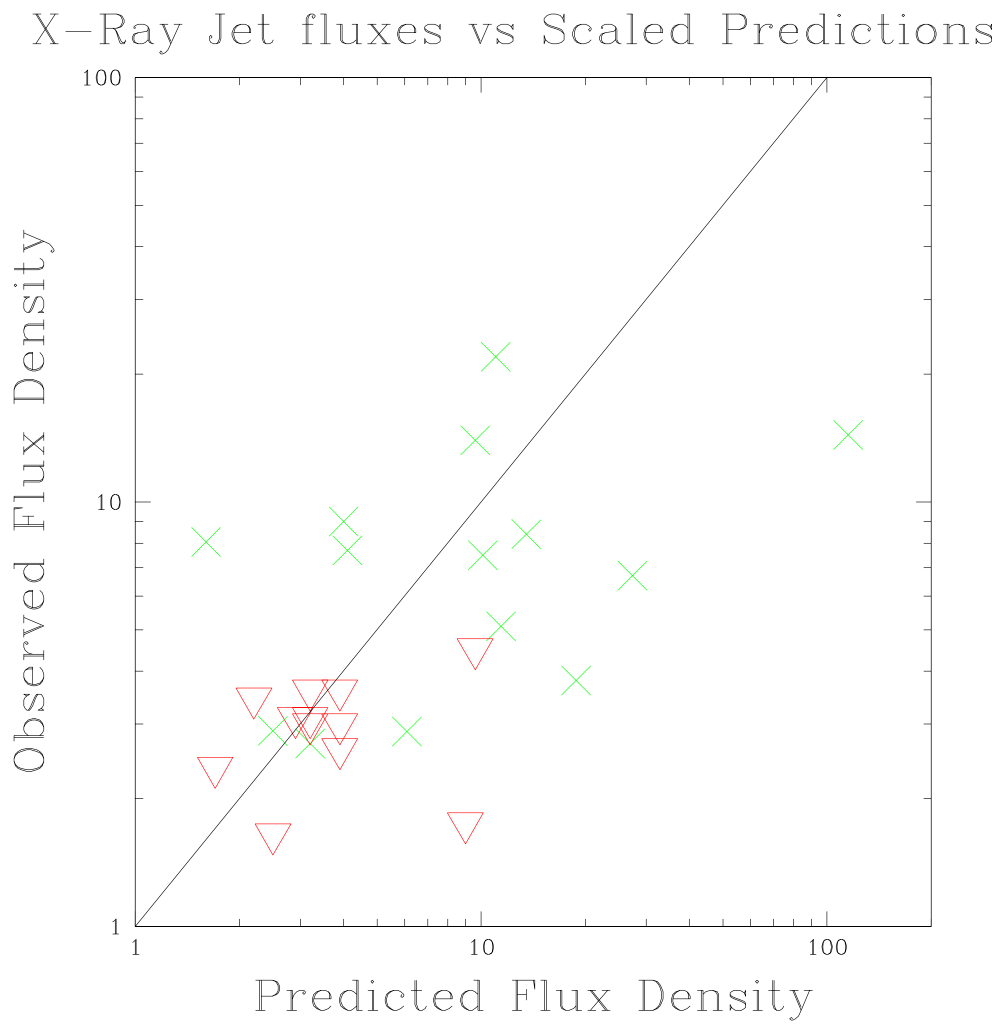
3. **Parameters and Implications**
   - B, δ, γ_{min}
   - Kinetic Flux
   - Beacons at Large Redshift



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

The Jet Sample

- **Flat Spectrum Quasars. Two Samples: $S_{5GHz} > 1Jy^{a}$ or $S_{2.7GHz} > 0.34\ Jy^{b}$**
- **Radio Maps with< 2″resolution have jets >2″with detection expected by analogy to PKS 0637-752.**
- **Detected 17 of the first 30 Observed.**



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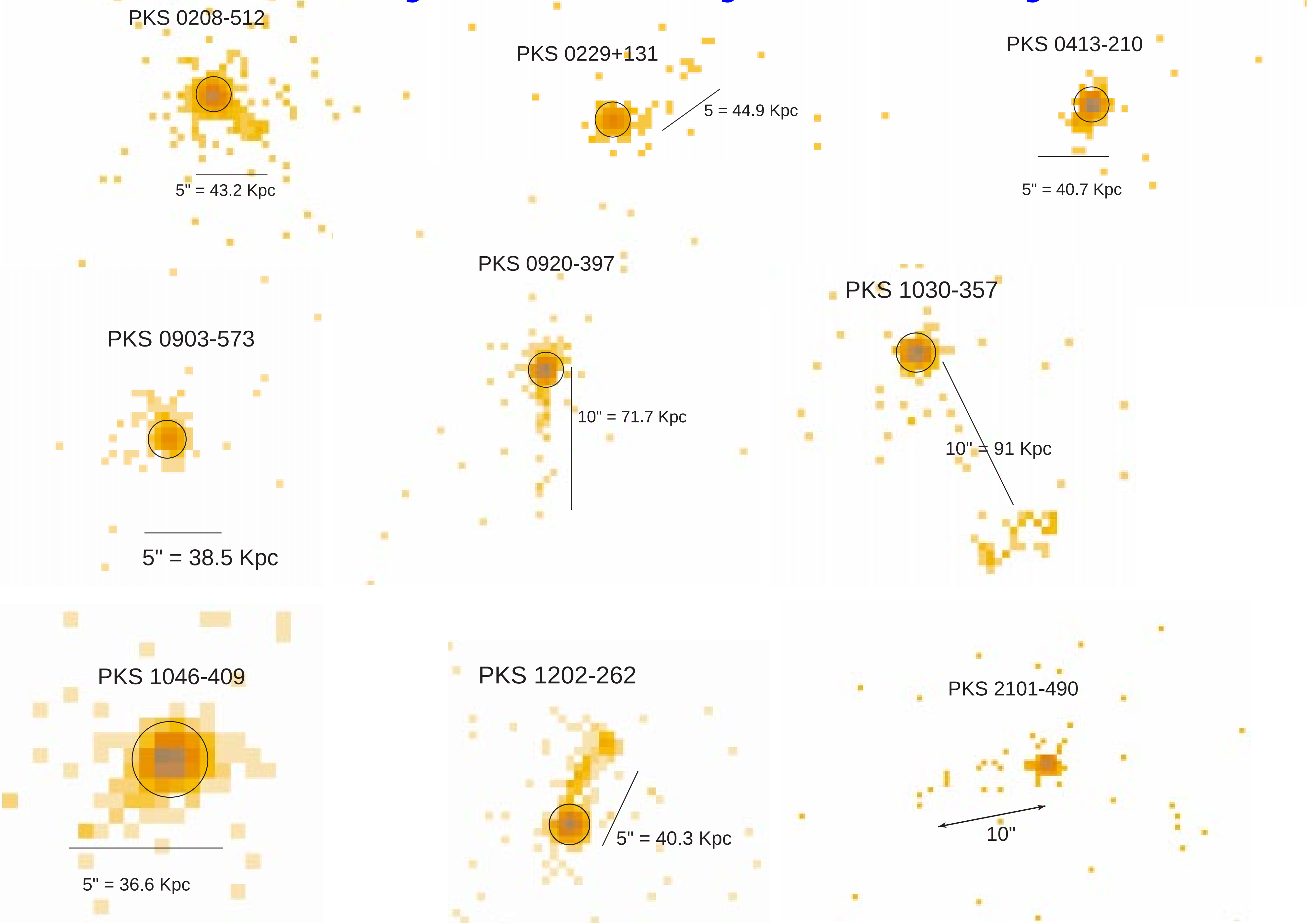
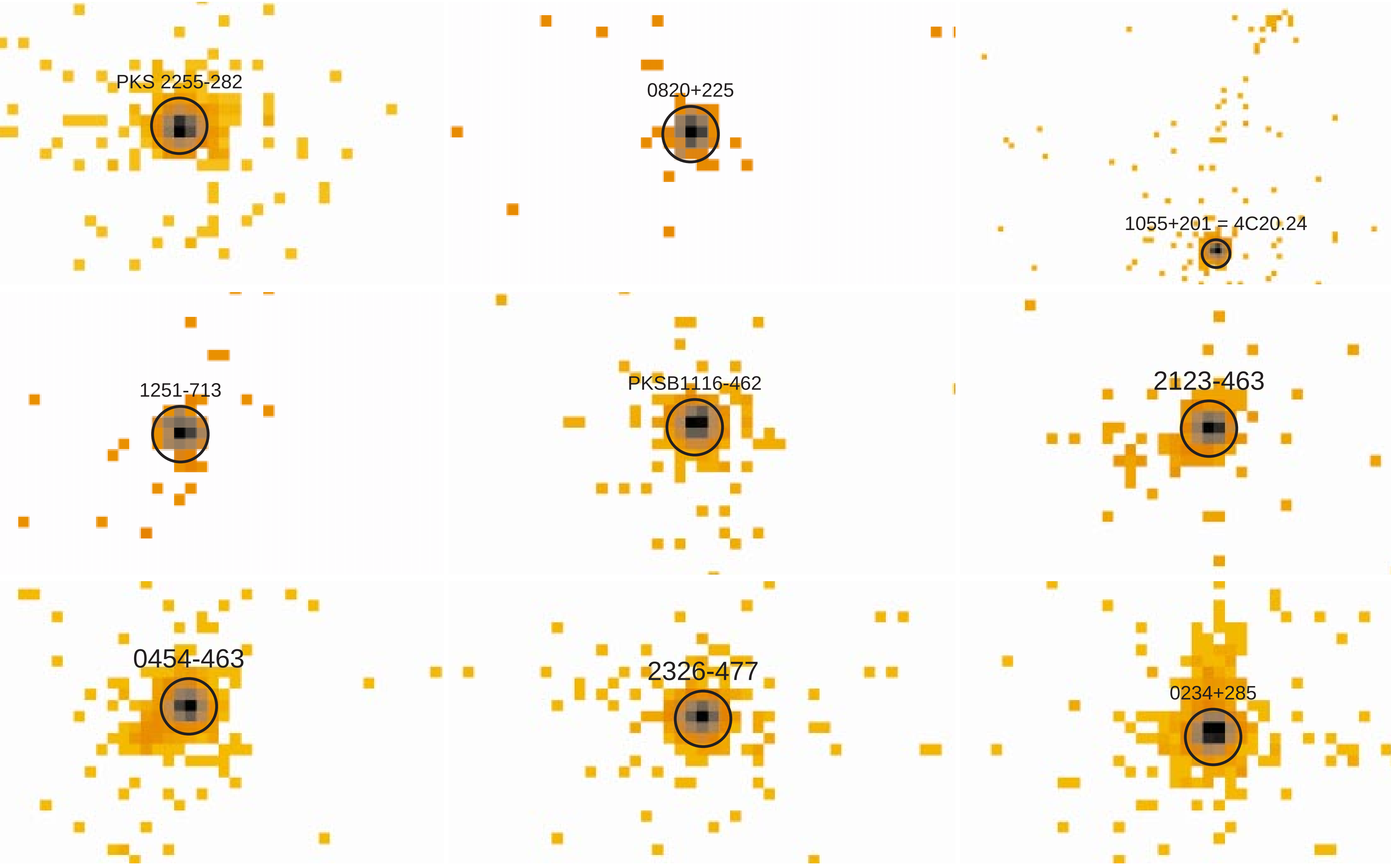
[a]Murphy, Browne & Perley 1993
[b]Lovell 1997

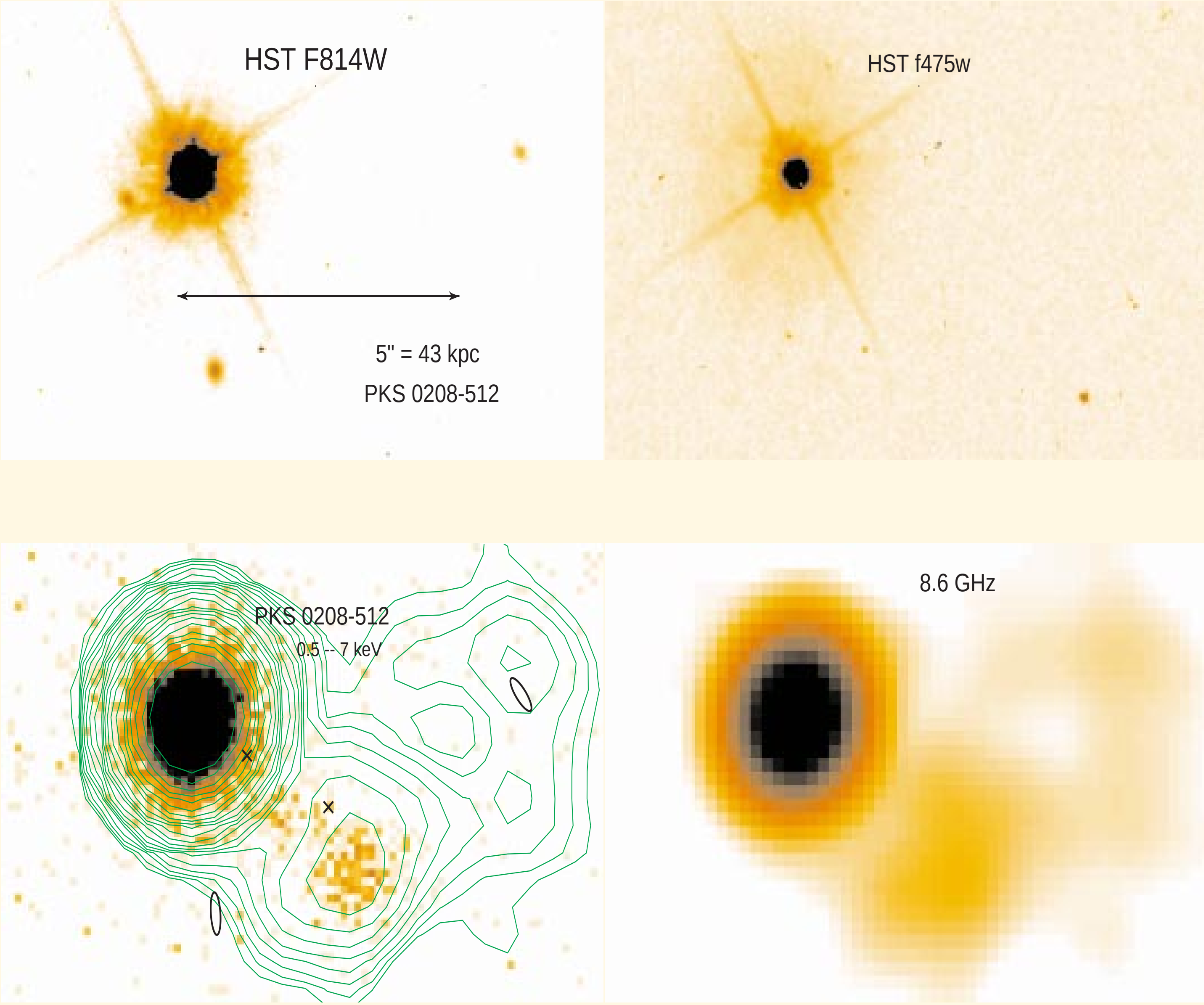
A Survey for X-ray Jets – Cycle 3



A Survey for X-ray Jets – Cycle 5

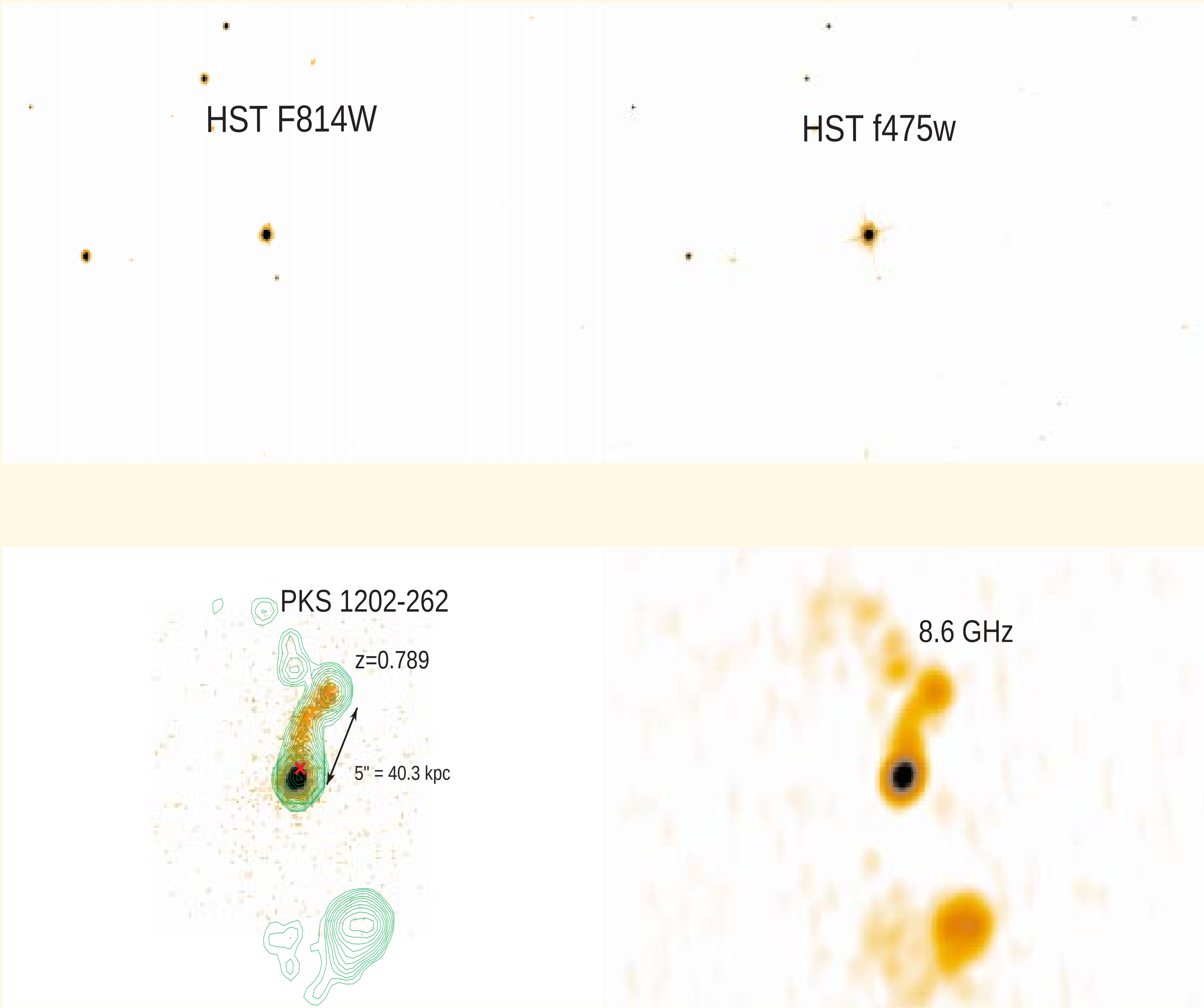


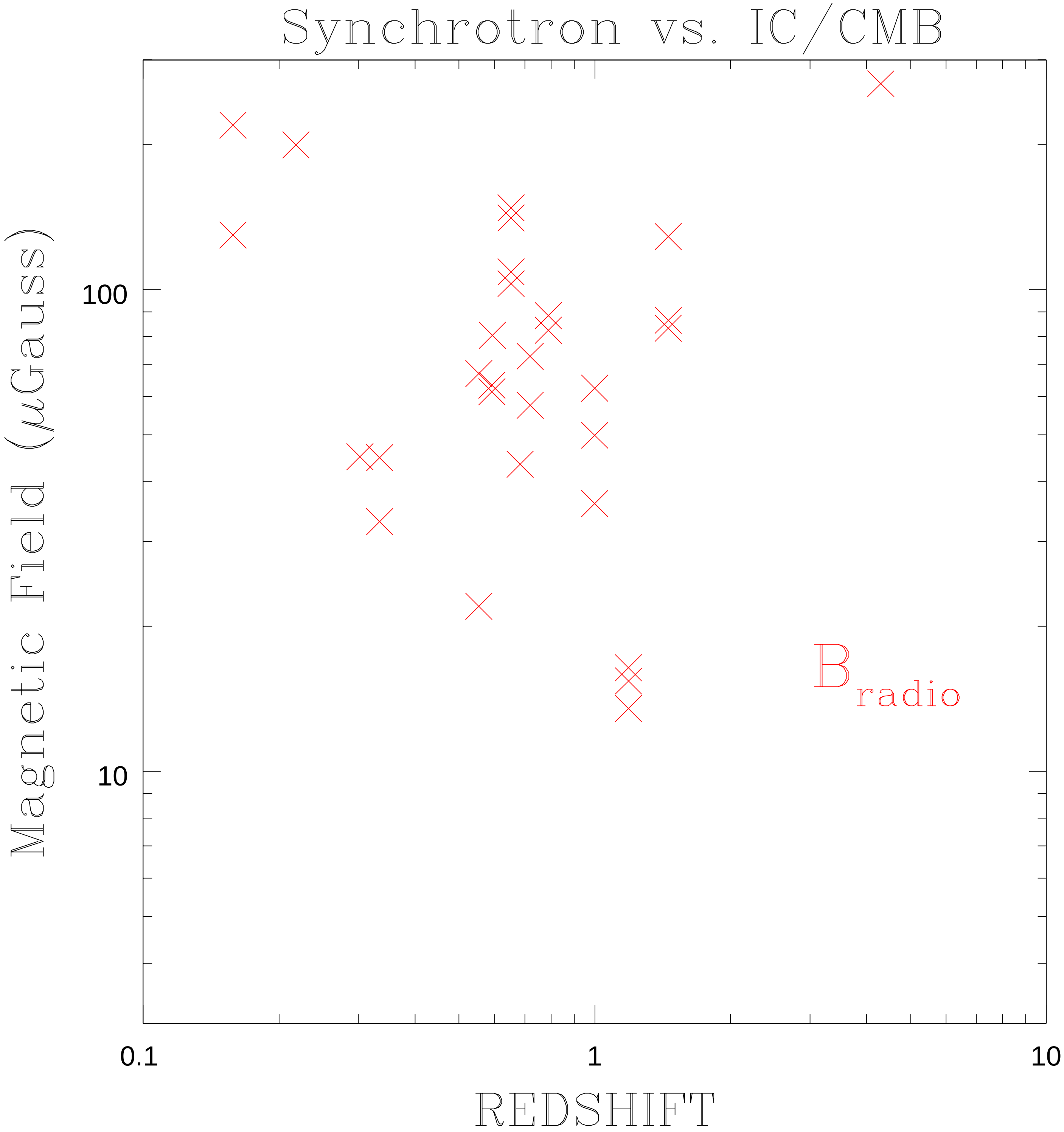
PKS 0208-512



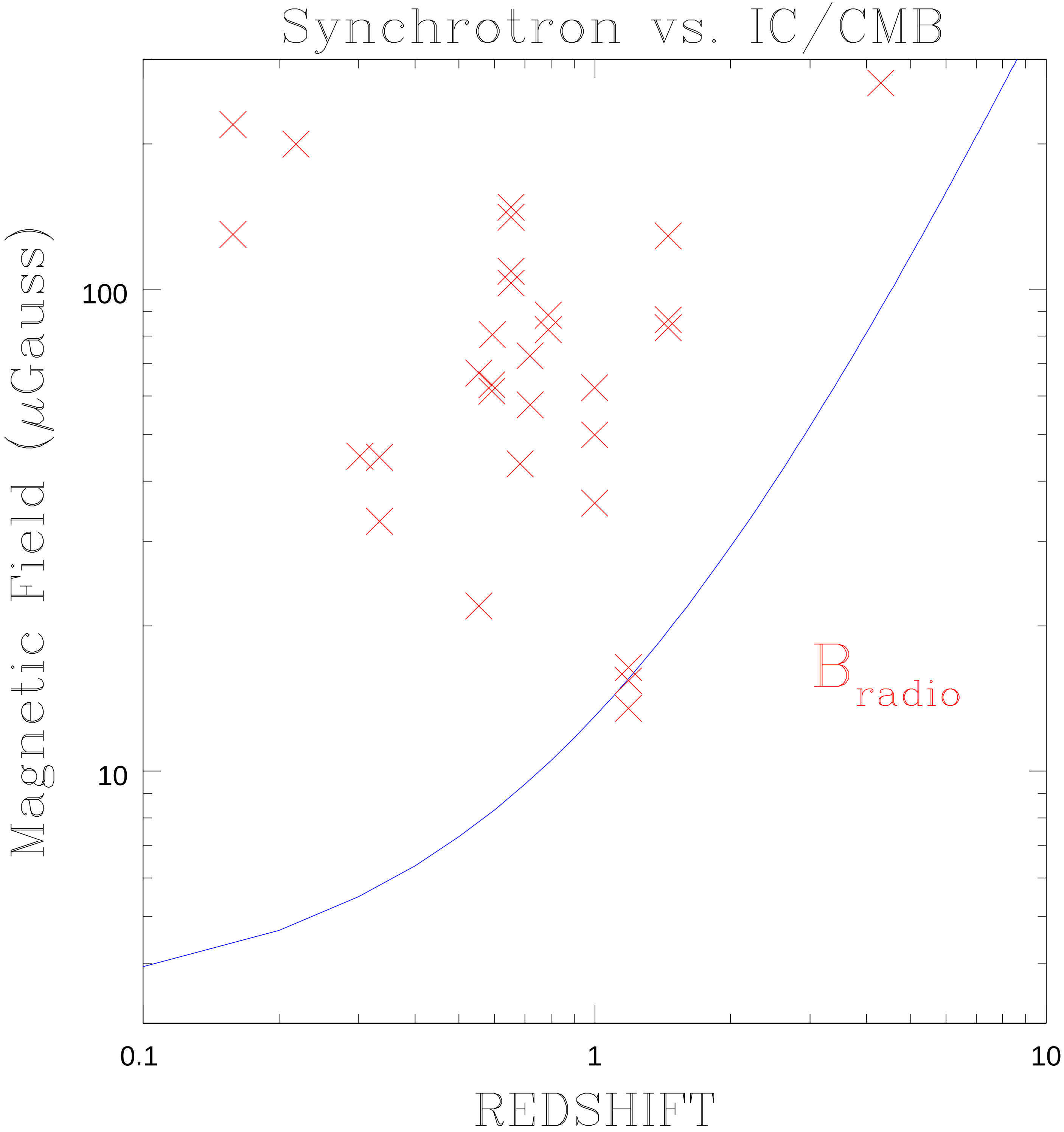
HST F814W
5" = 43 kpc
PKS 0208-512
HST f475w
PKS 0208-512
0.5 -- 7 keV
8.6 GHz

PKS 1202-262

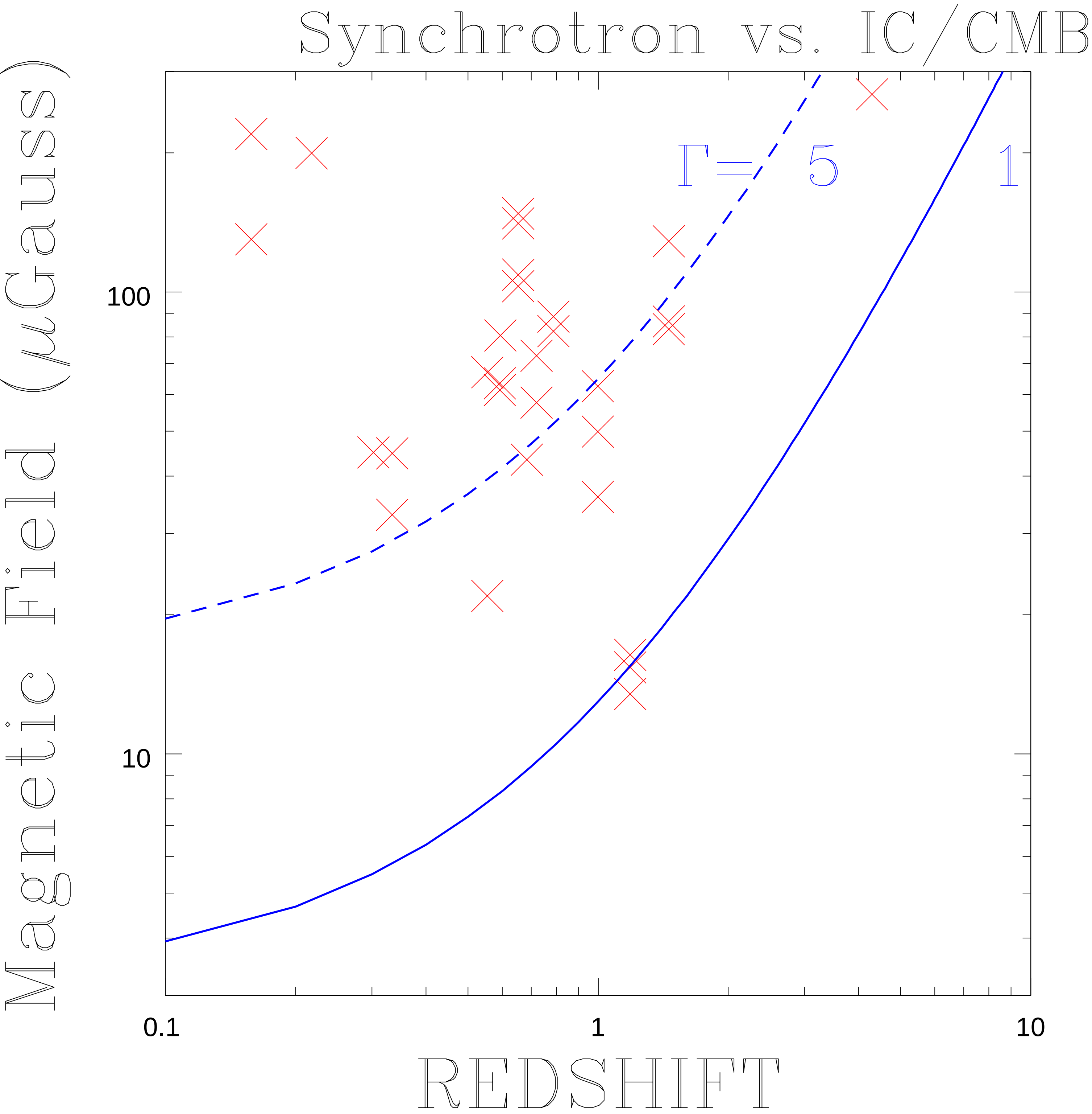




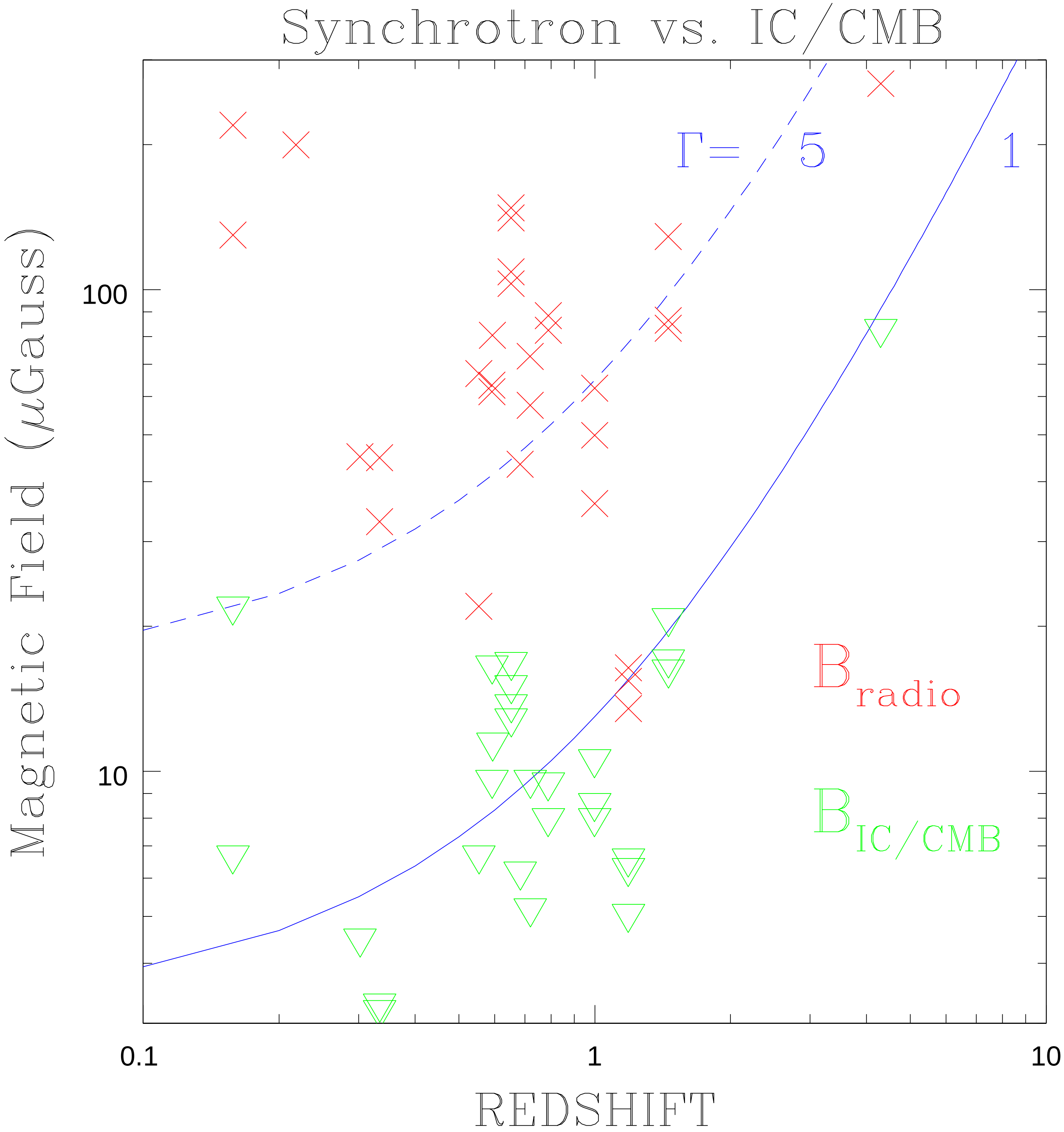
Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B_{radio}



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

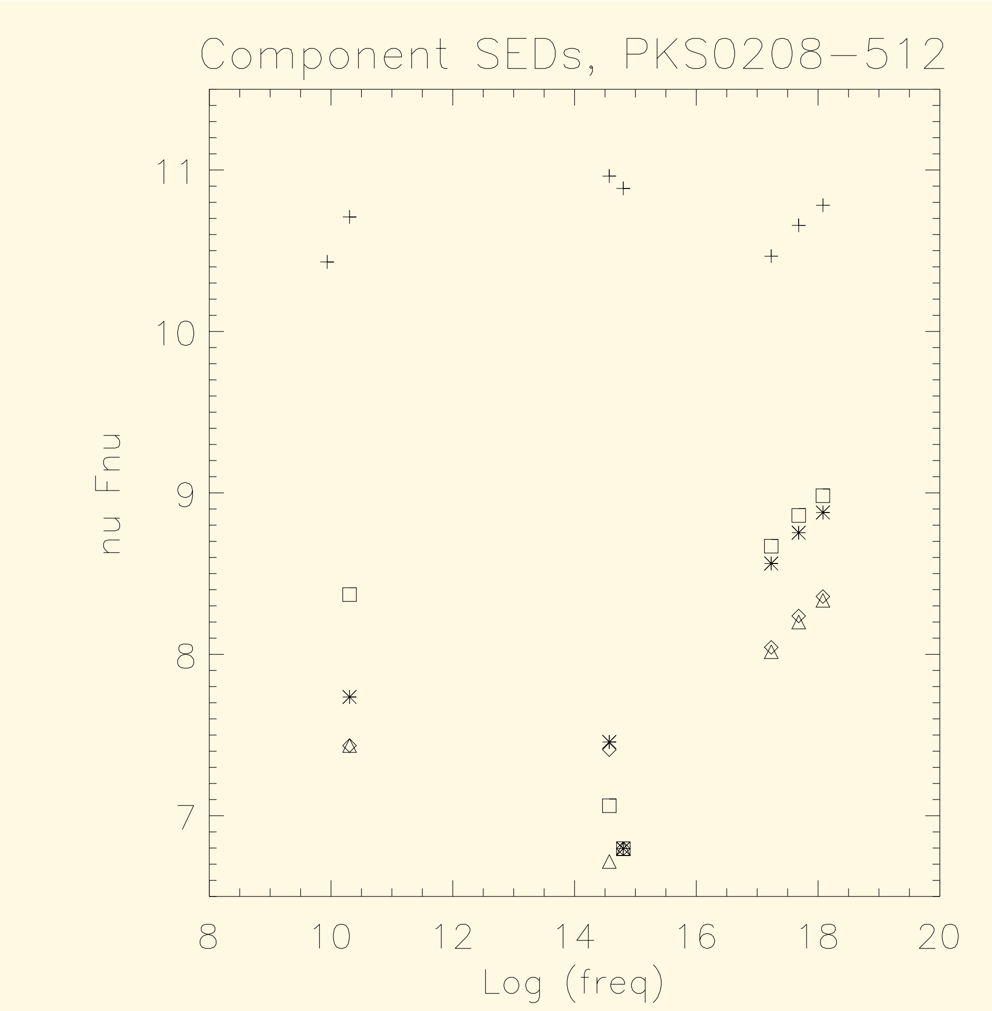


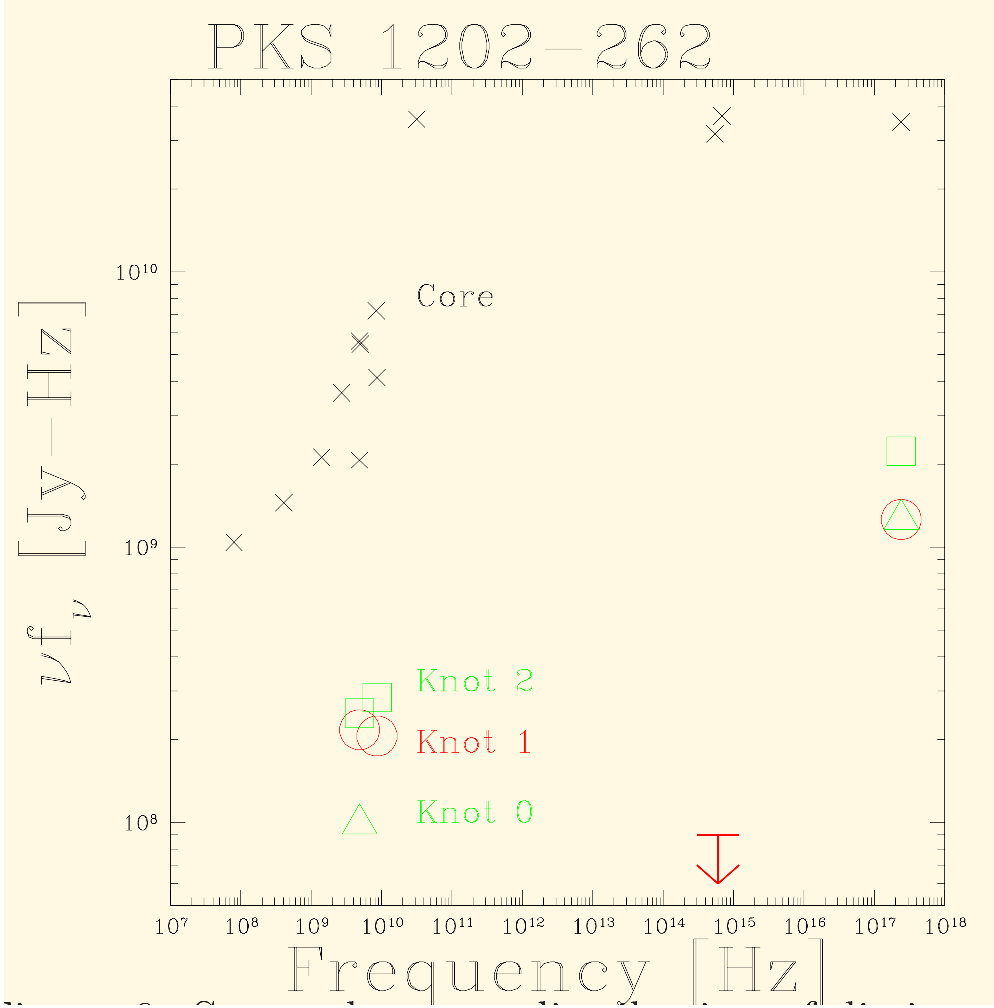
Synchrotron vs. IC/CMB
Γ= 5
1
100
10
0.1
1
10
Magnetic Field (μGauss)
REDSHIFT



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

Spectral Energy Distribution often indicates against Synchrotron X-rays





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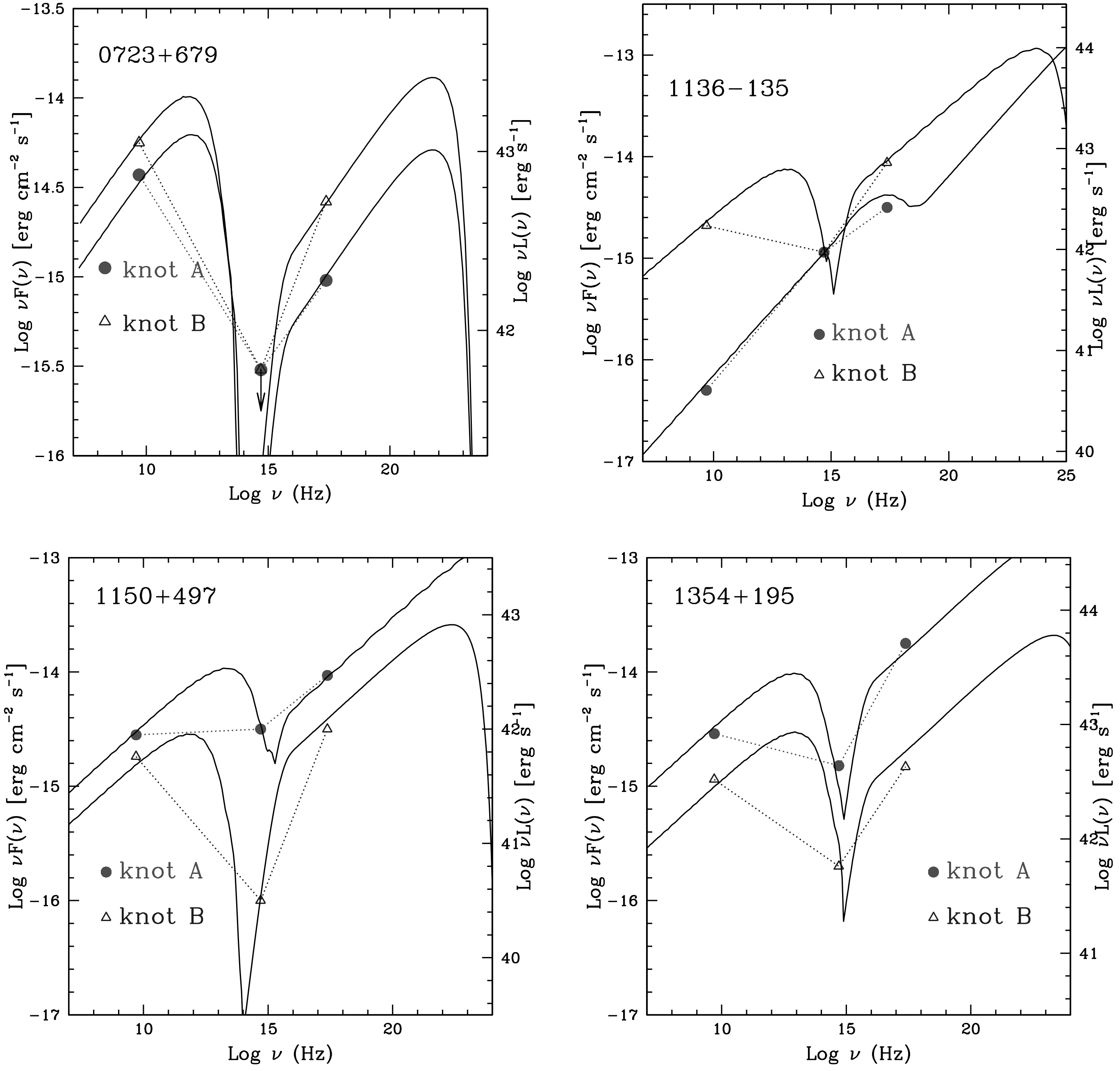
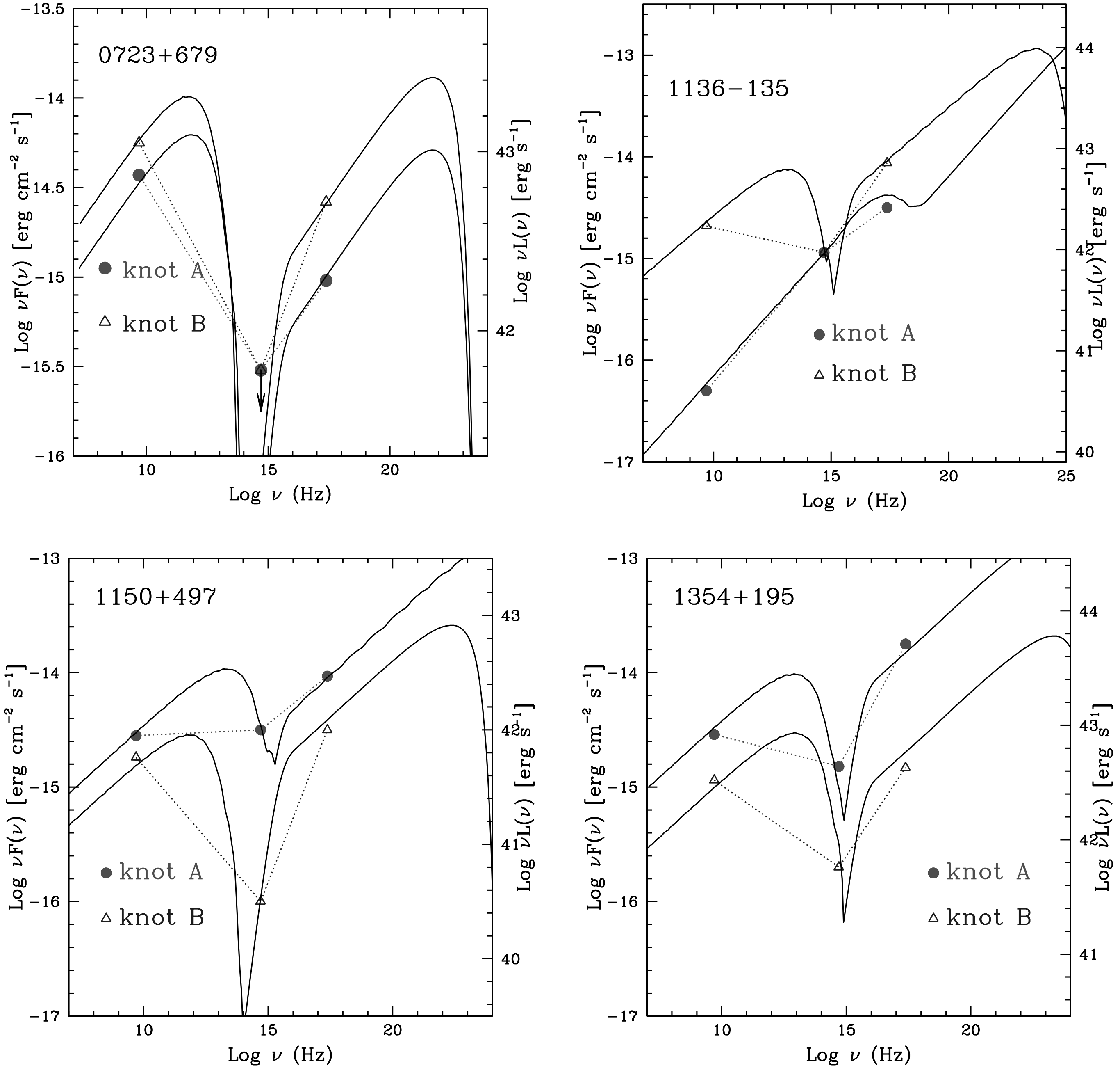


Sambruna et al., 2002ApJ...571..206S

Spectral Energy Distribution often indicates against Synchrotron X-rays



Inverse Compton X-rays from the CMB:

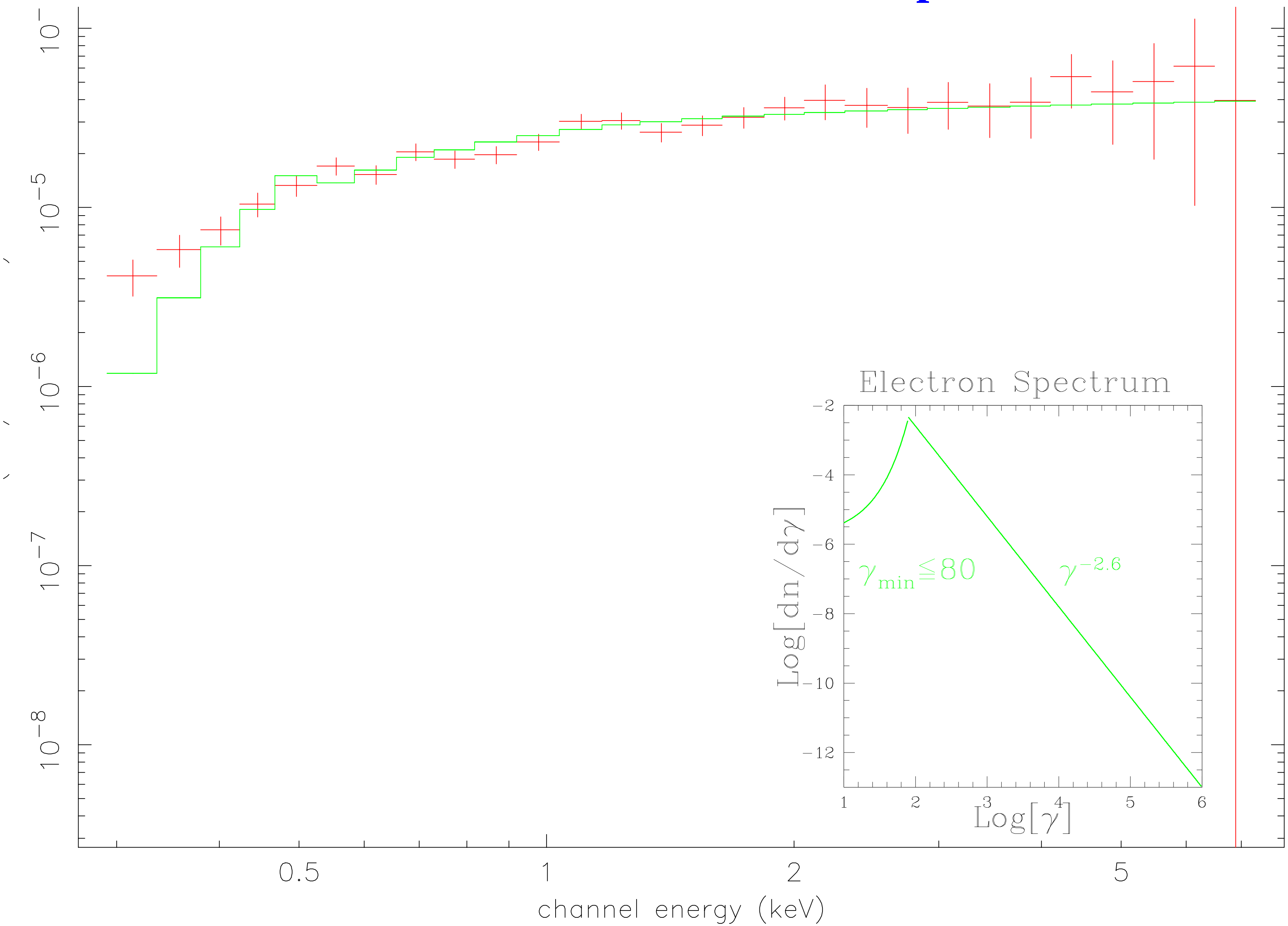
$$\gamma_x \approx 10^{2-3}$$

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

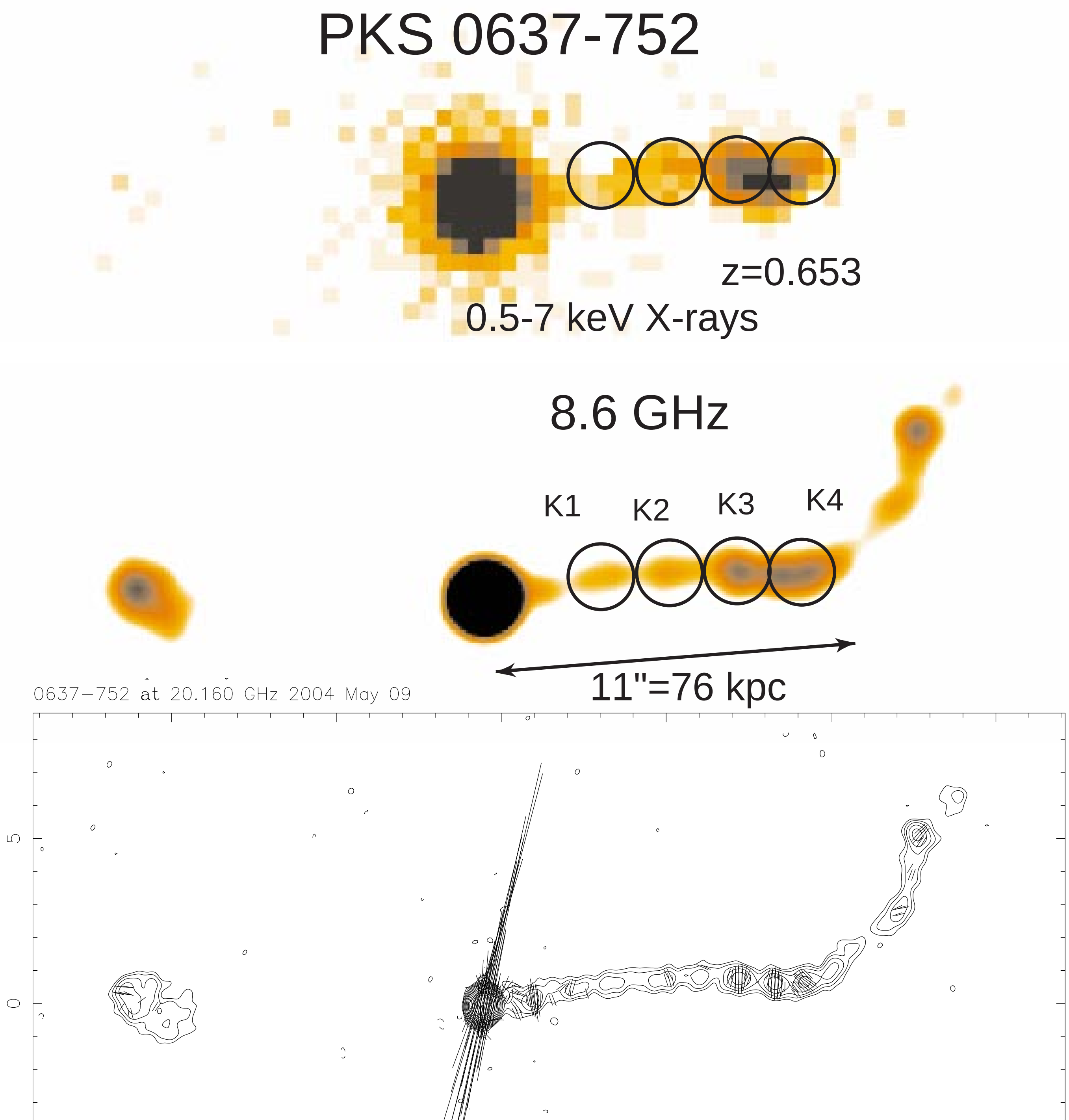
Some kpc scale jets may be detectable by GLAST, at 10^{-13} to 10^{-12} ergs cm^{-2} s^{-1}

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

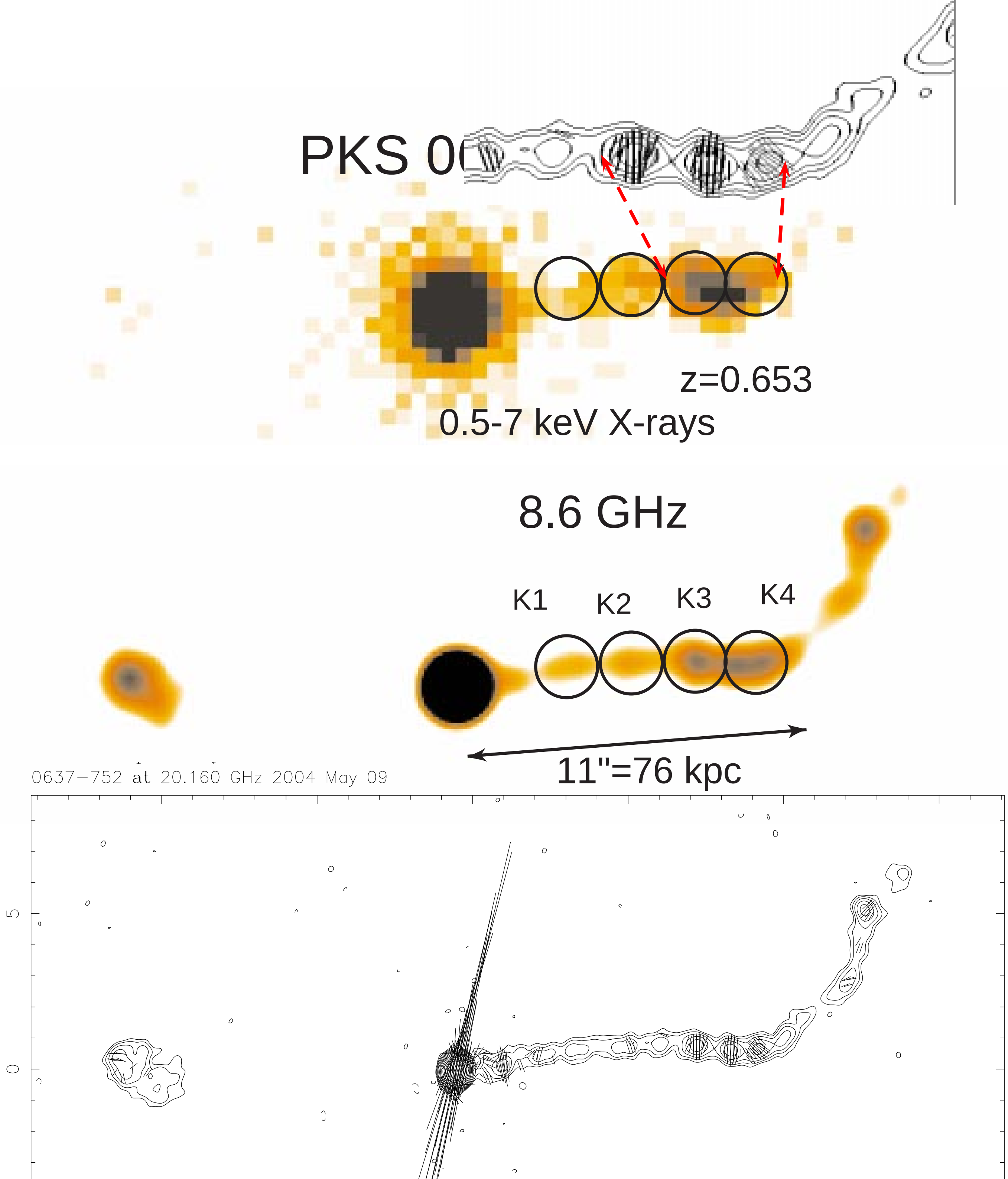
PKS 0637-752 Jet Spectrum

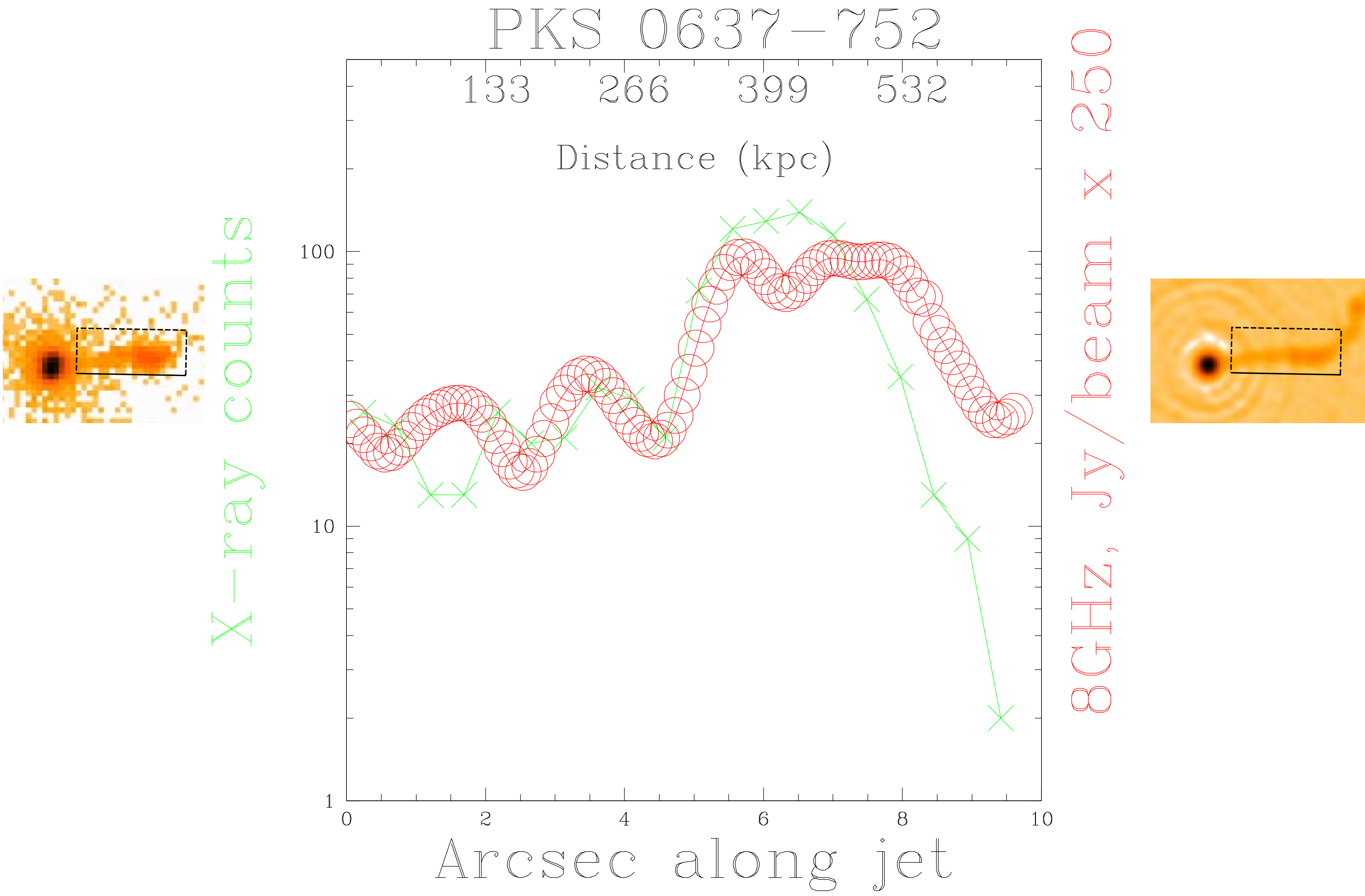


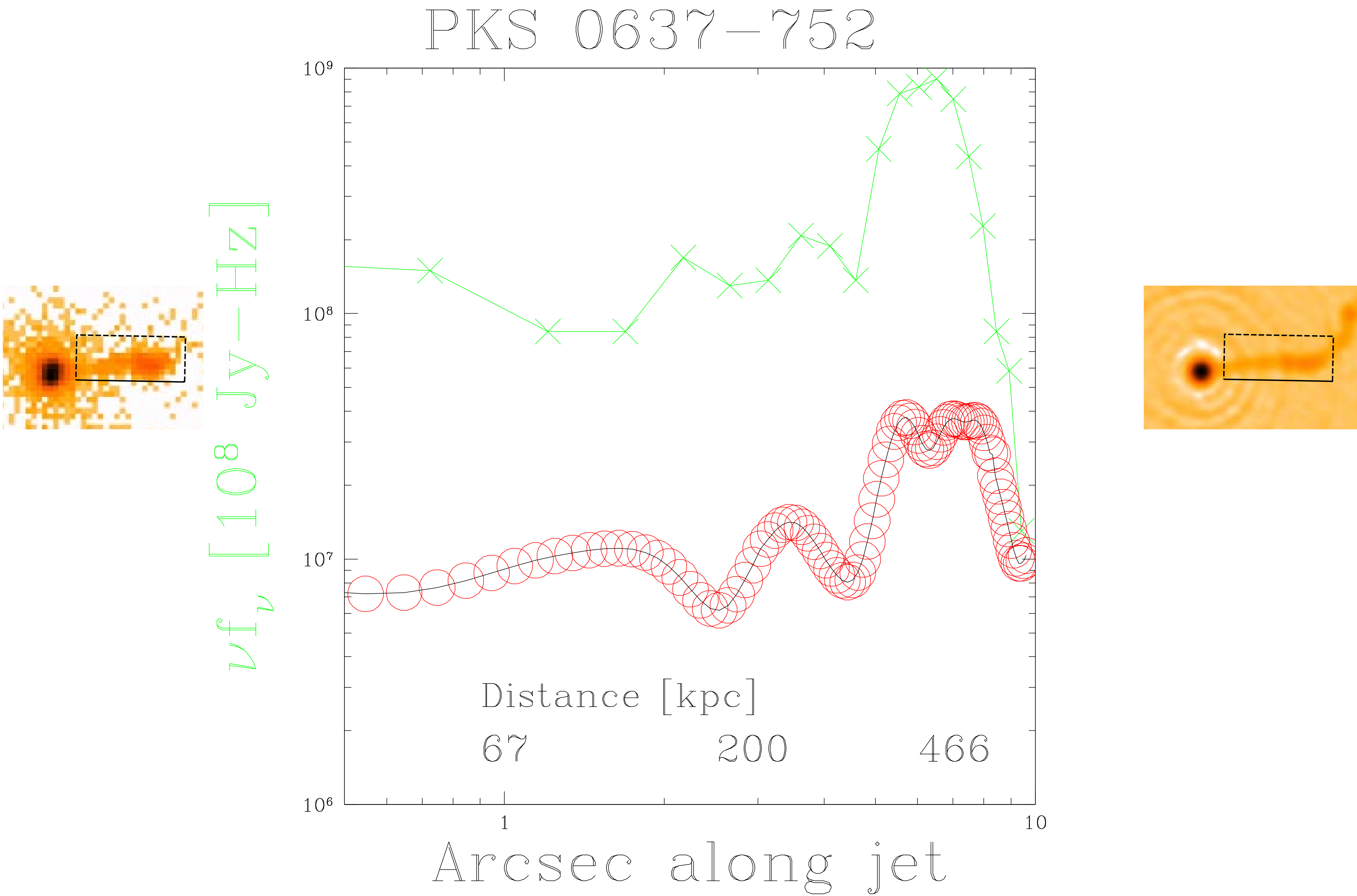
mmueller 4-Dec-2004



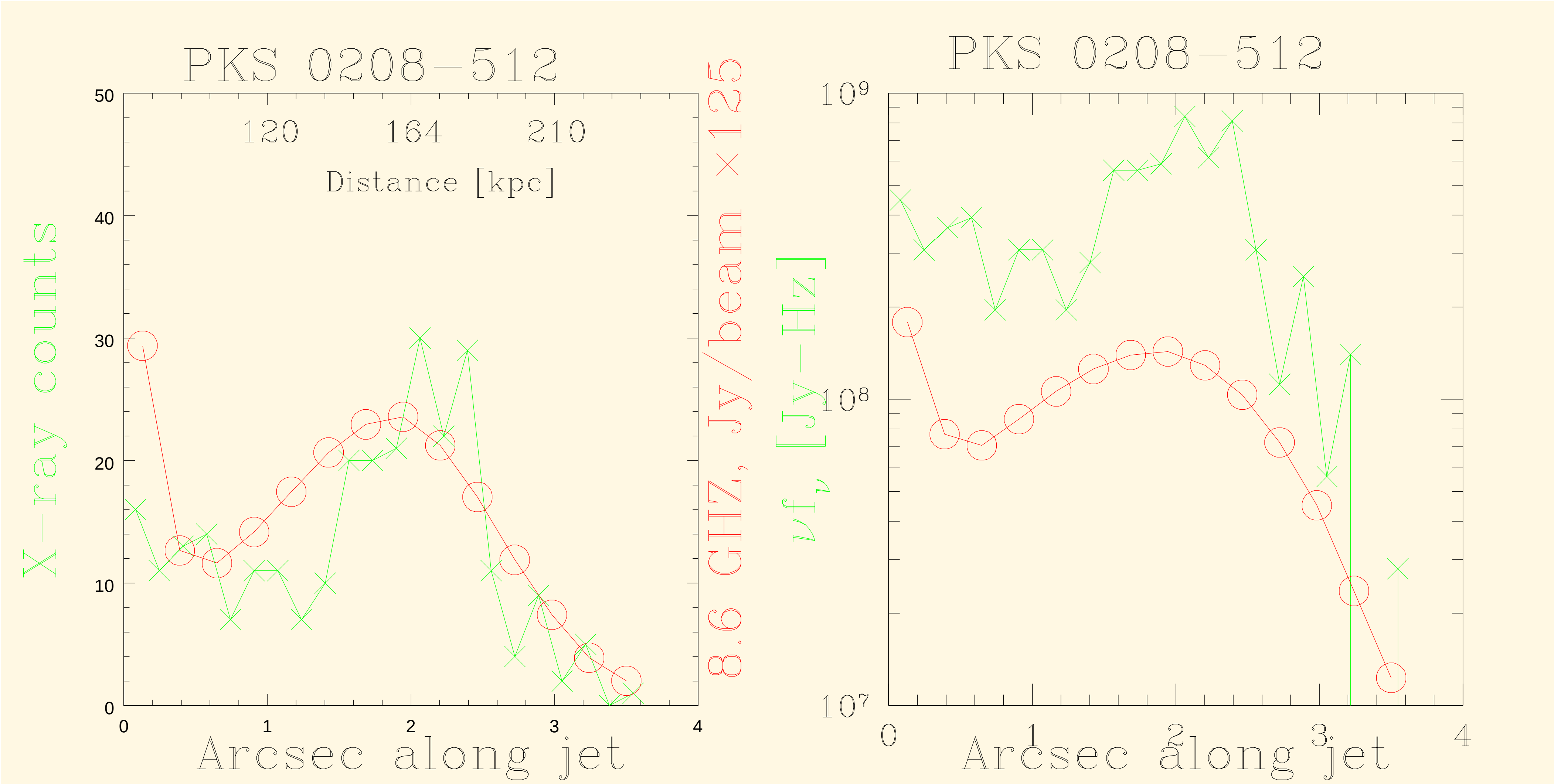
PKS 0637-752
z=0.653
0.5-7 keV X-rays
8.6 GHz
K1
K2
K3
K4
11"=76 kpc
0637−752 at 20.160 GHz 2004 May 09
5
0


PKS 06
z=0.653
0.5-7 keV X-rays
8.6 GHz
K1
K2
K3
K4
11"=76 kpc
0637−752 at 20.160 GHz 2004 May 09
5
0

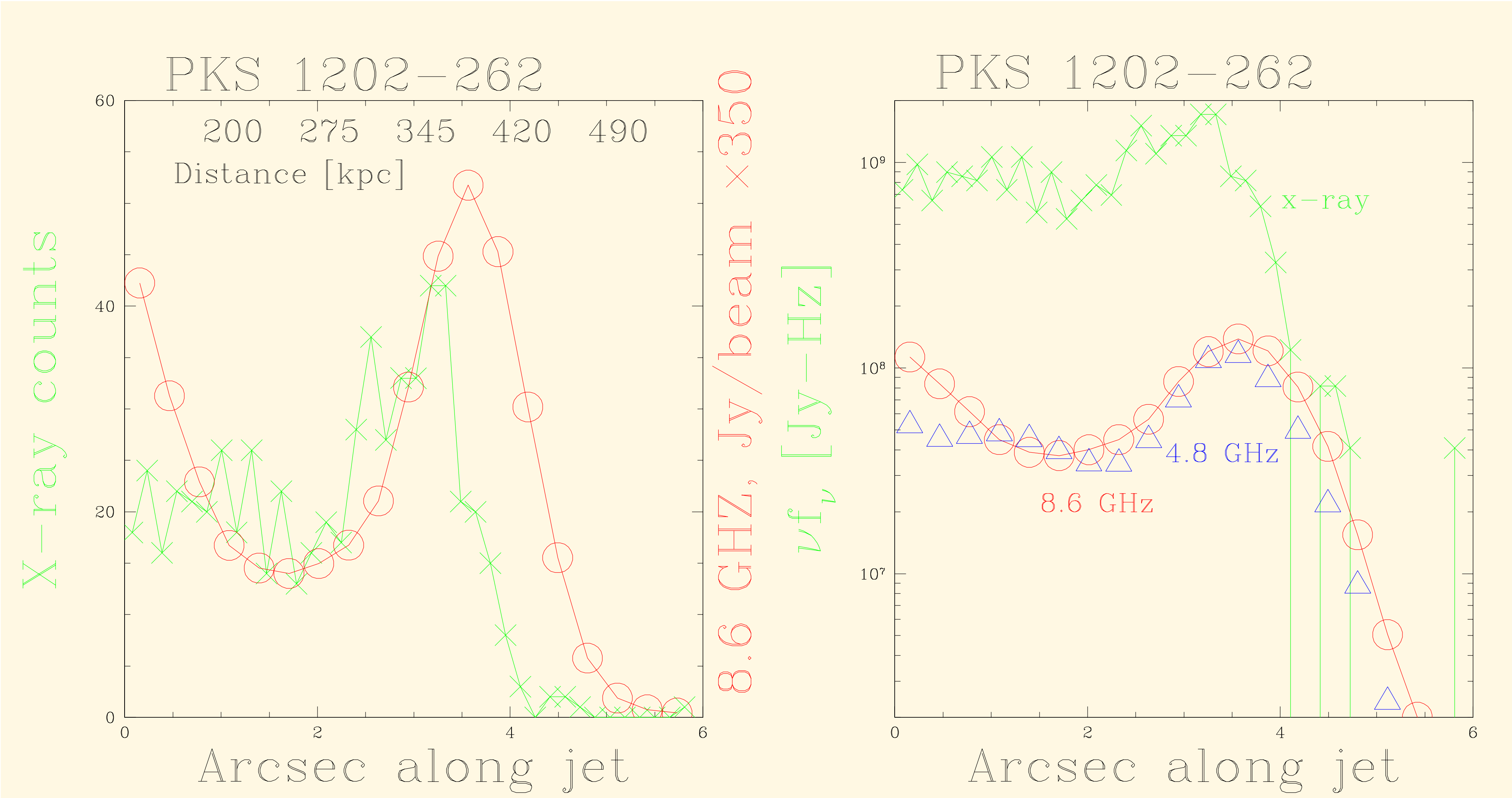

PKS 0637−752
133
266
399
532
Distance (kpc)
100
10
1
0
2
4
6
8
10
Arcsec along jet
X−ray counts
8GHz, Jy/beam x 250



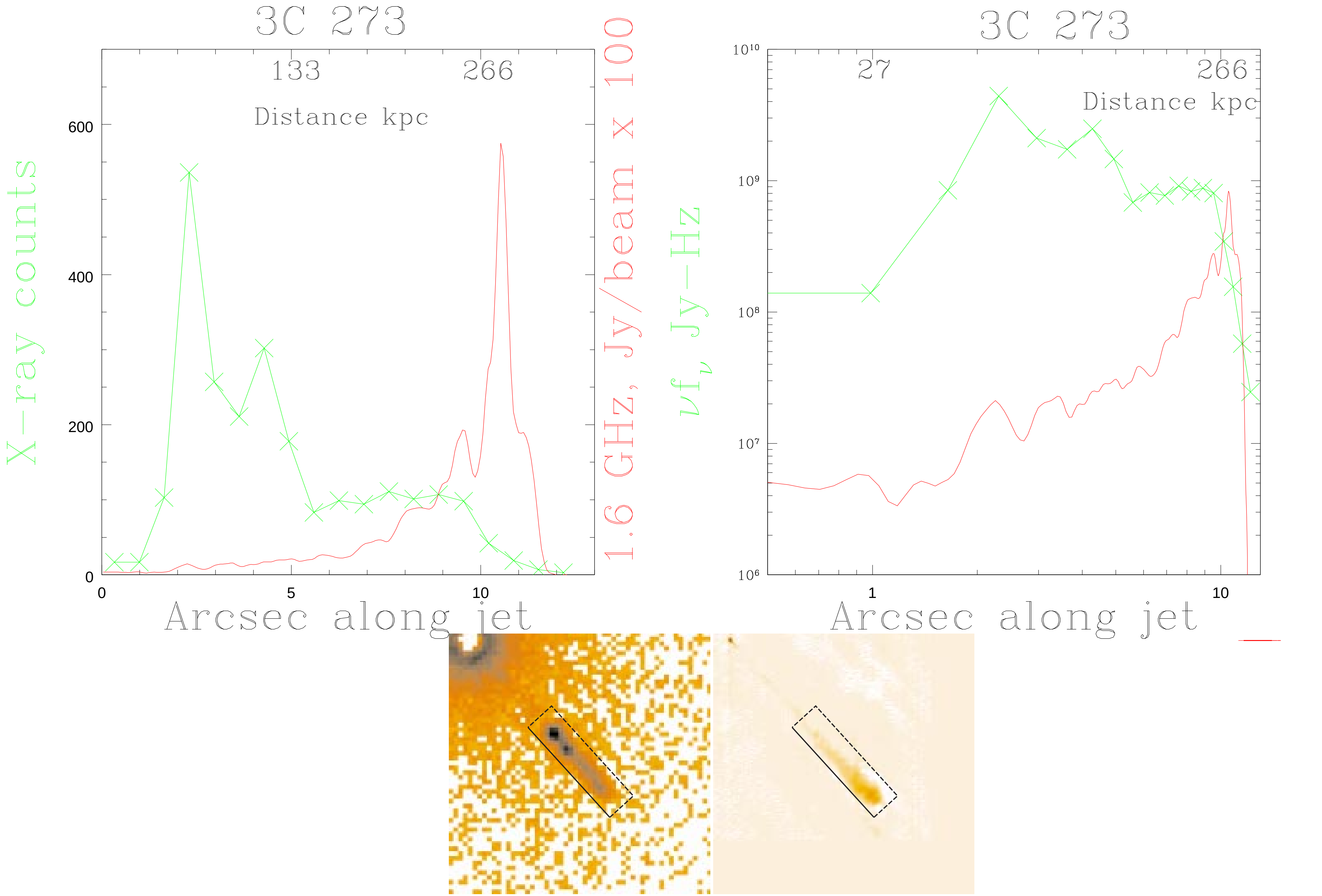
PKS 0637−752
10^9
10^8
10^7
10^6
νf_ν [10^8 Jy−Hz]
Distance [kpc]
67
200
466
1
10
Arcsec along jet



PKS 0208−512
120
164
210
Distance [kpc]
X−ray counts
8.6 GHZ, Jy/beam ×125
Arcsec along jet
0
10
20
30
40
50
1
2
3
4
PKS 0208−512
νf_ν [Jy−Hz]
10^9
10^8
10^7
Arcsec along jet

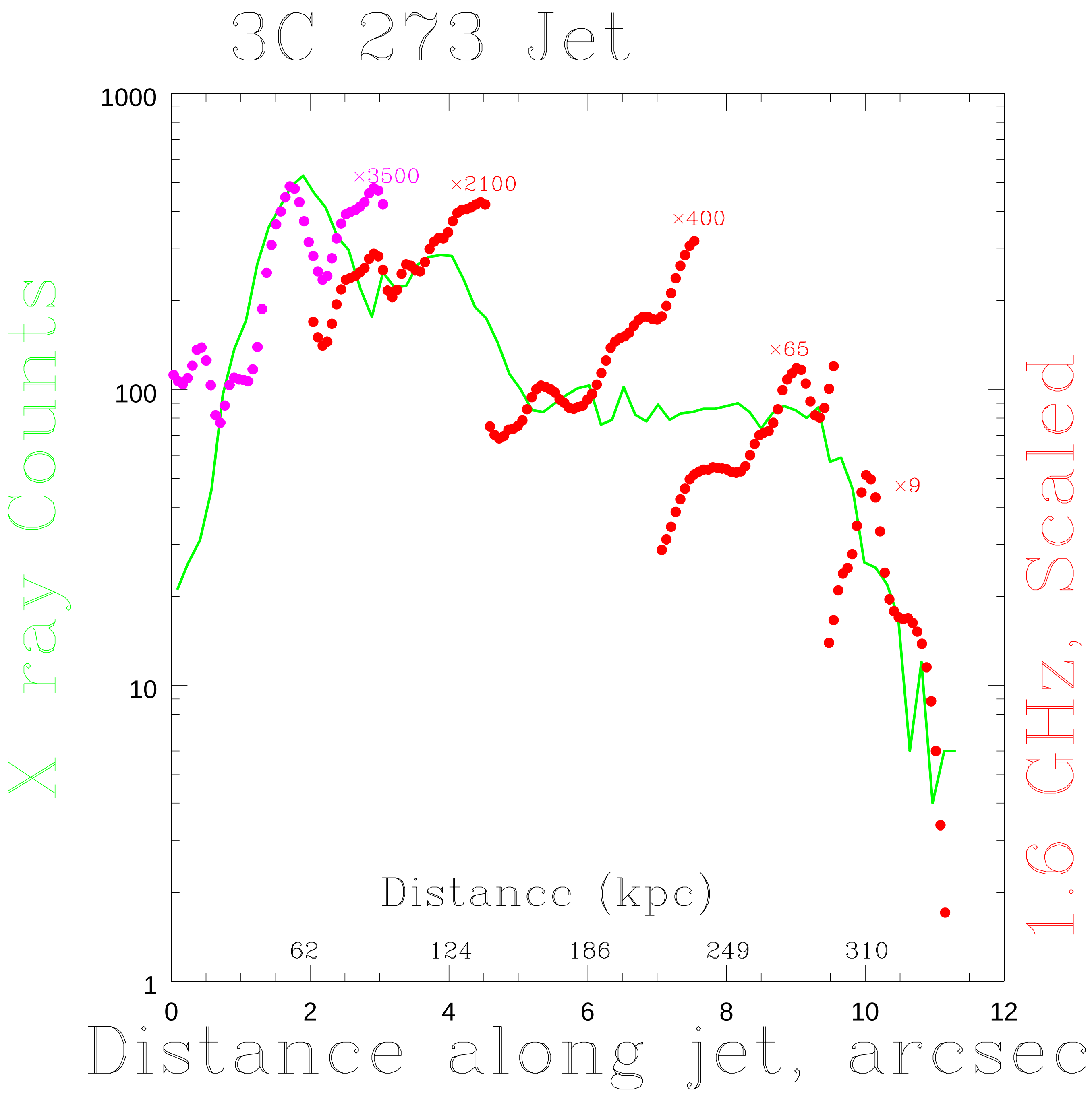


PKS 1202−262
200 275 345 420 490
Distance [kpc]
X−ray counts
8.6 GHZ, Jy/beam ×350
νf_ν [Jy−Hz]
Arcsec along jet
PKS 1202−262
x−ray
4.8 GHz
8.6 GHz
Arcsec along jet

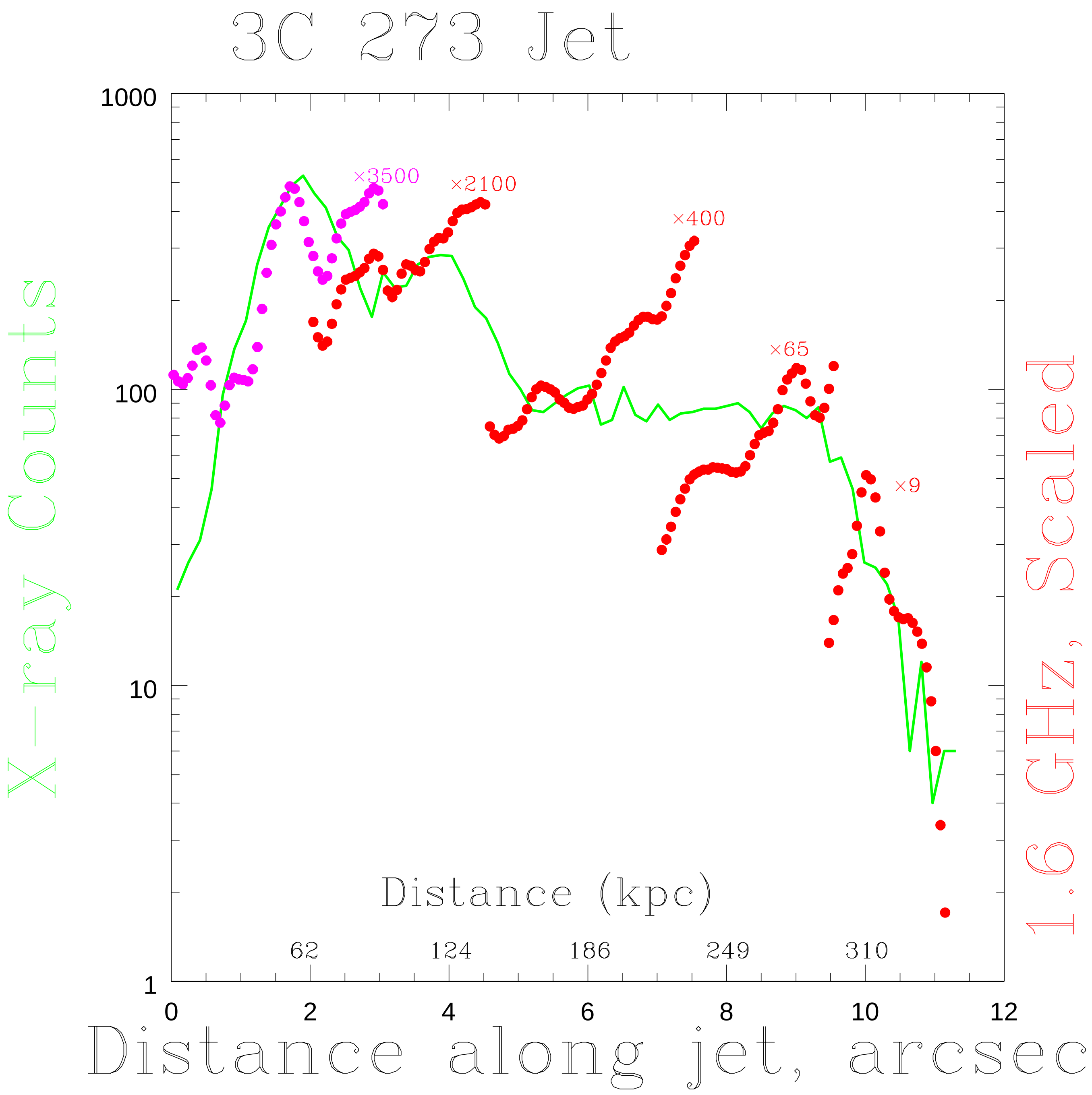


3C 273
133
266
Distance kpc
X-ray counts
600
400
200
0
0
5
10
Arcsec along jet
1.6 GHz, Jy/beam x 100
νf_ν, Jy-Hz
3C 273
27
266
Distance kpc
10^10
10^9
10^8
10^7
10^6
1
10
Arcsec along jet

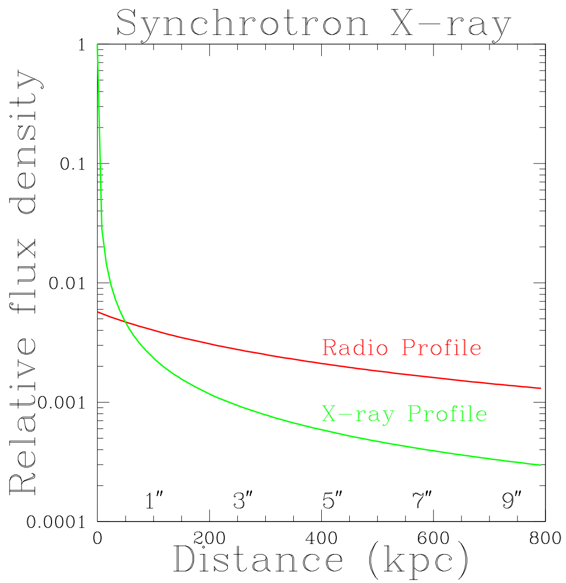
Confront IC/CMB with Morphology

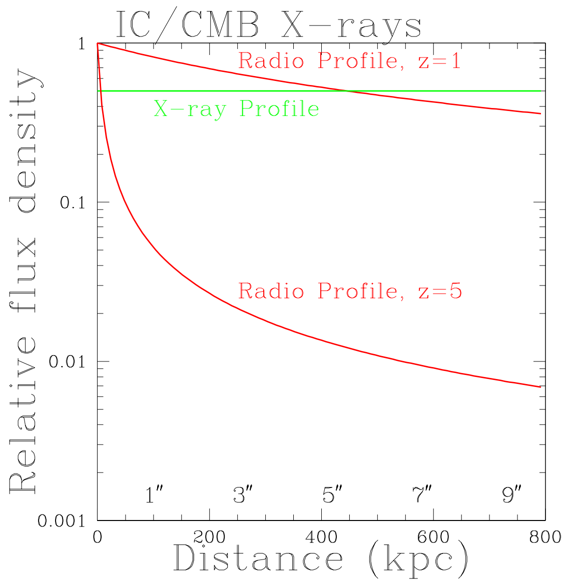


Confront IC/CMB with Morphology

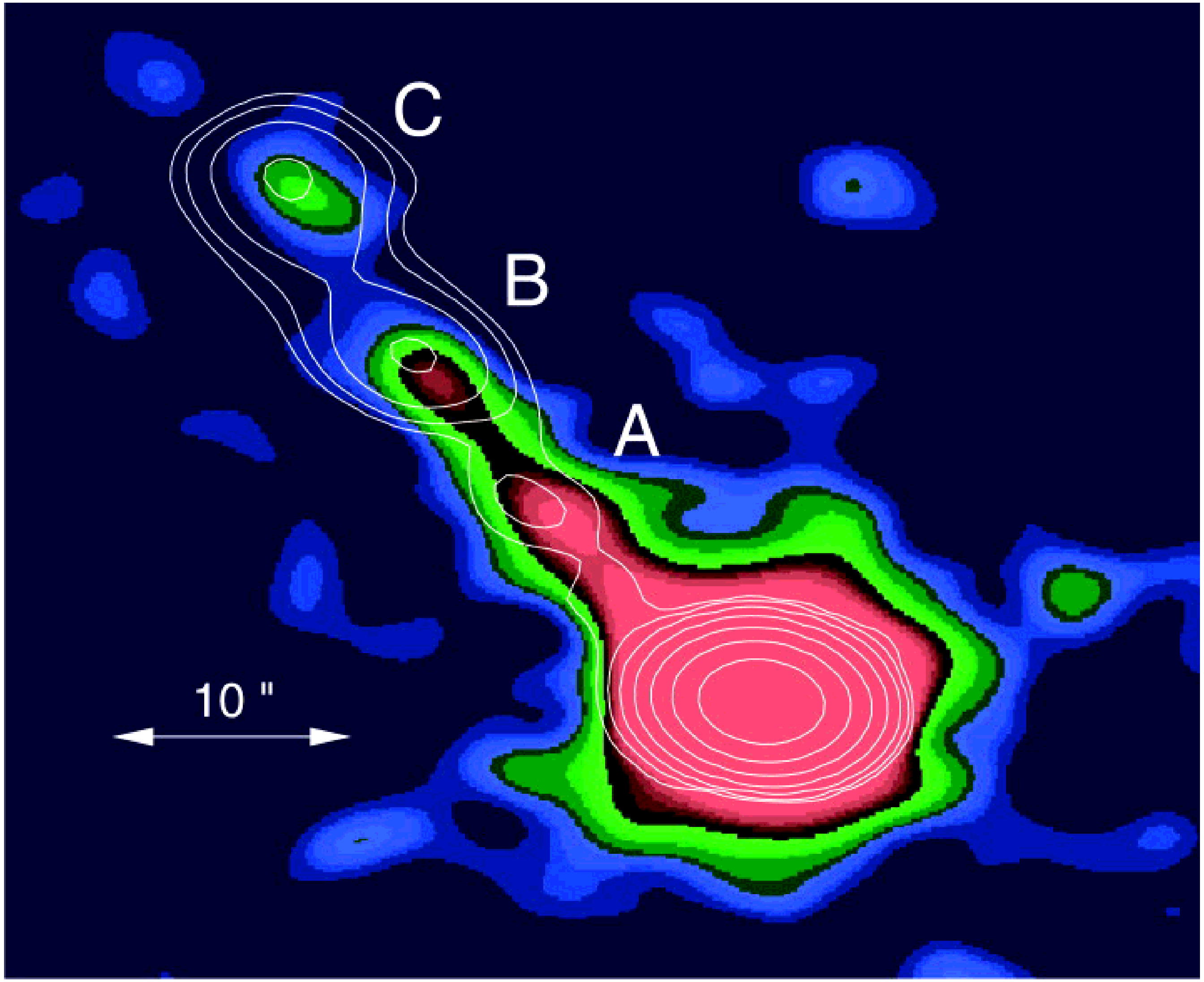


Naive Models





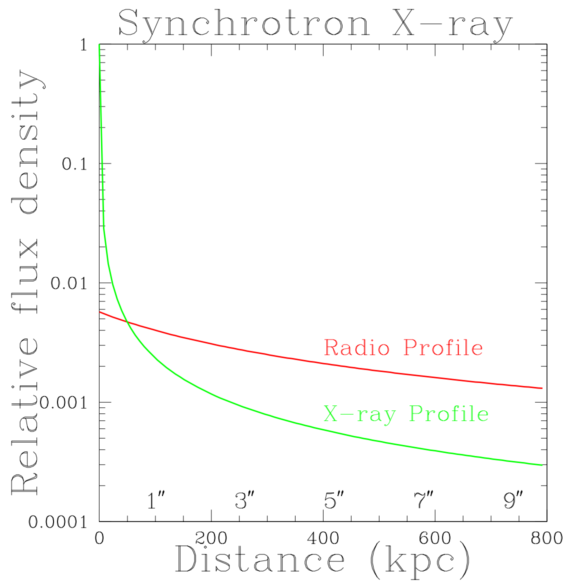
Confront IC/CMB with Morphology

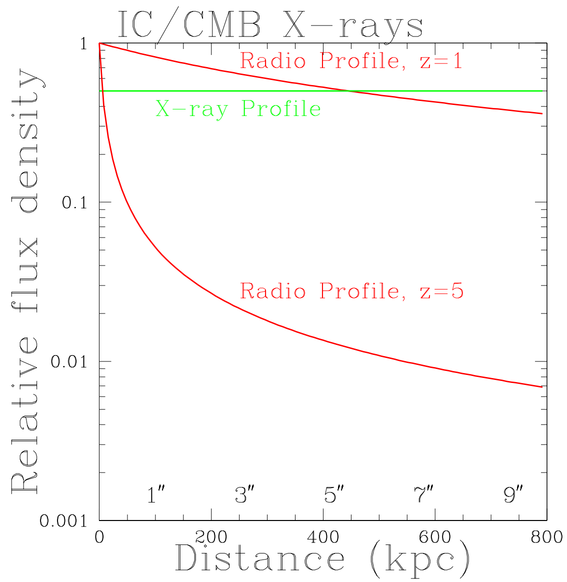


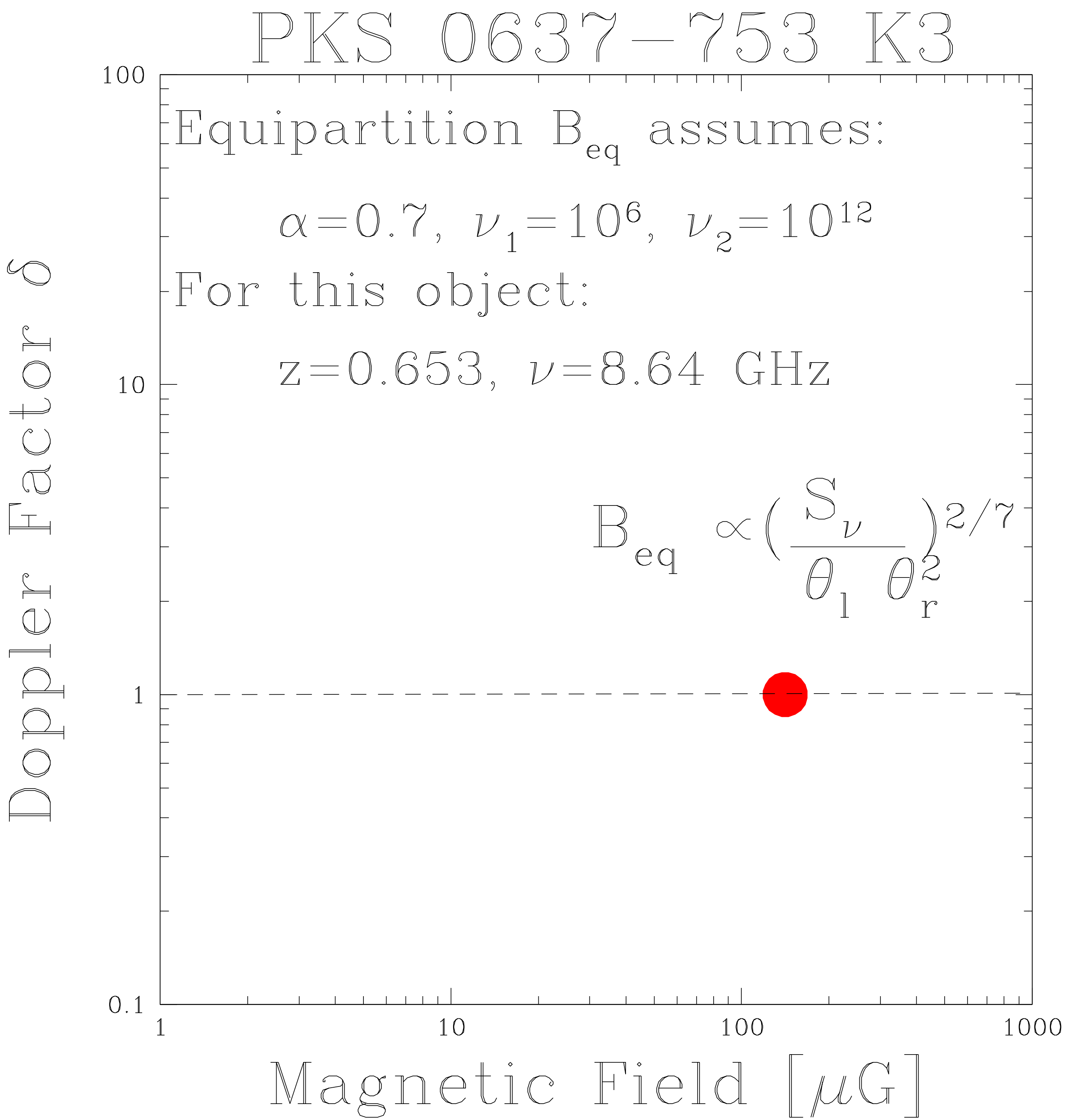
Siemiginowska et al. 2002 ApJ...570..543S

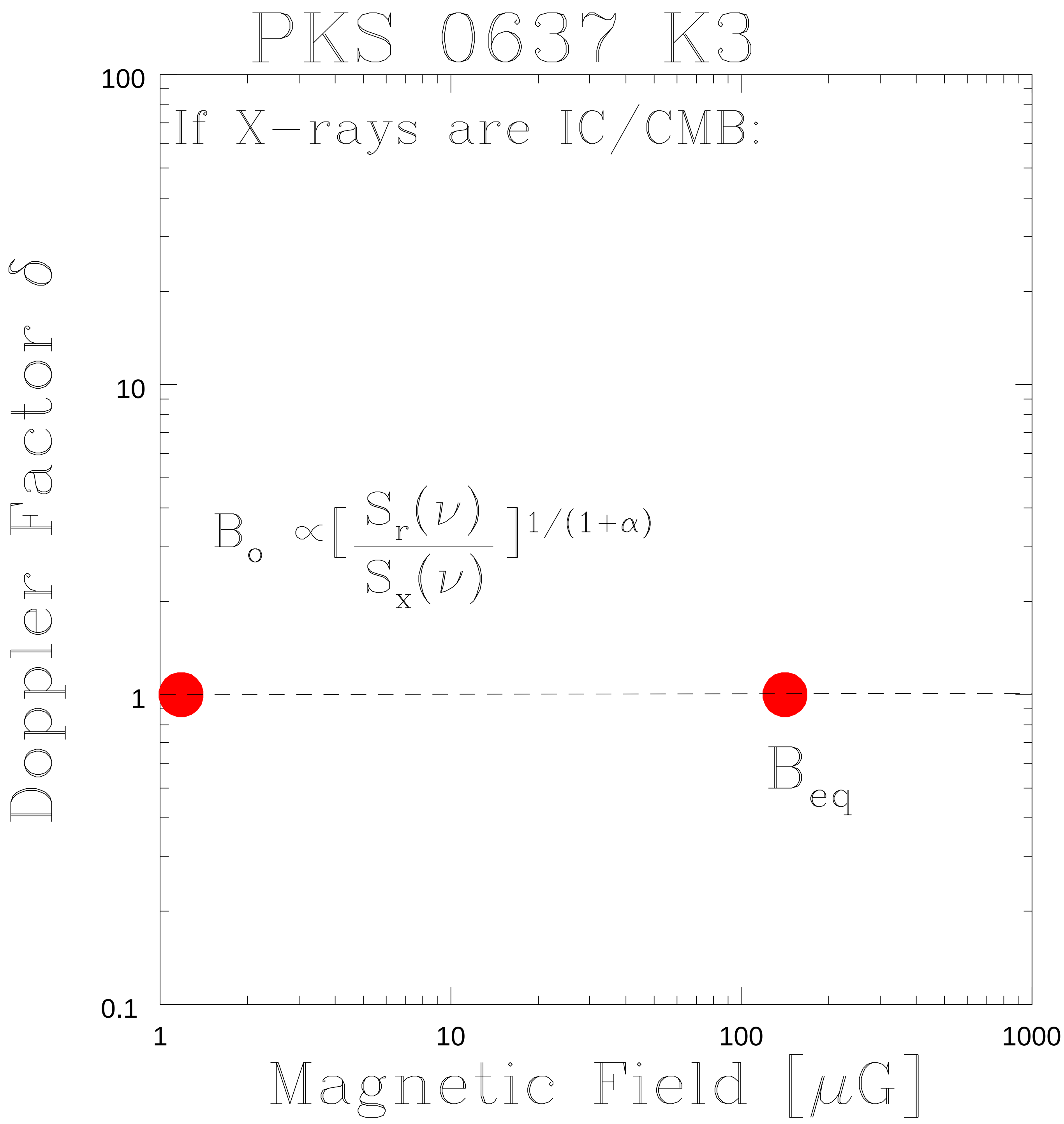
PKS 1127-145 at z=1.187

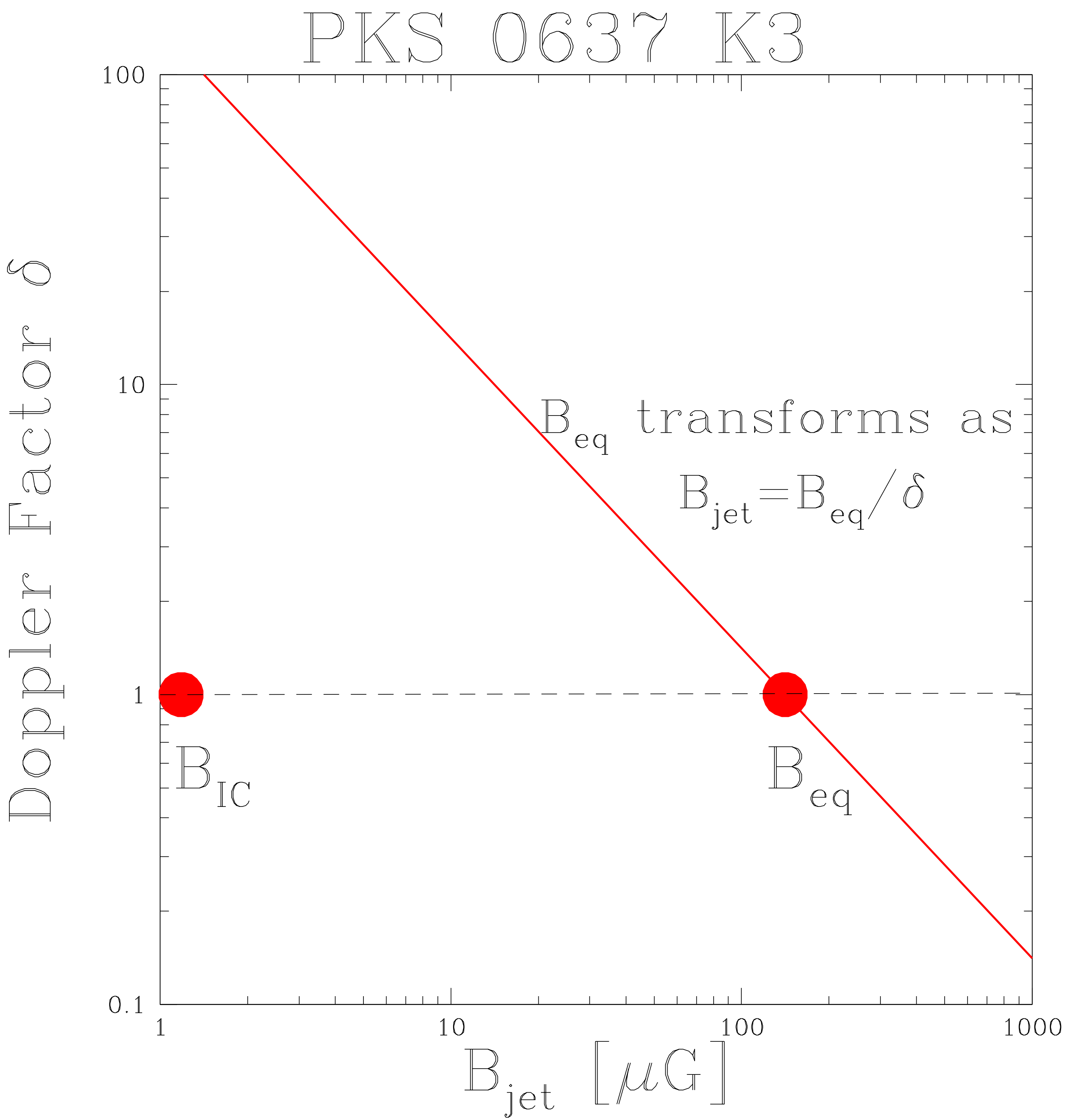
Naive Models



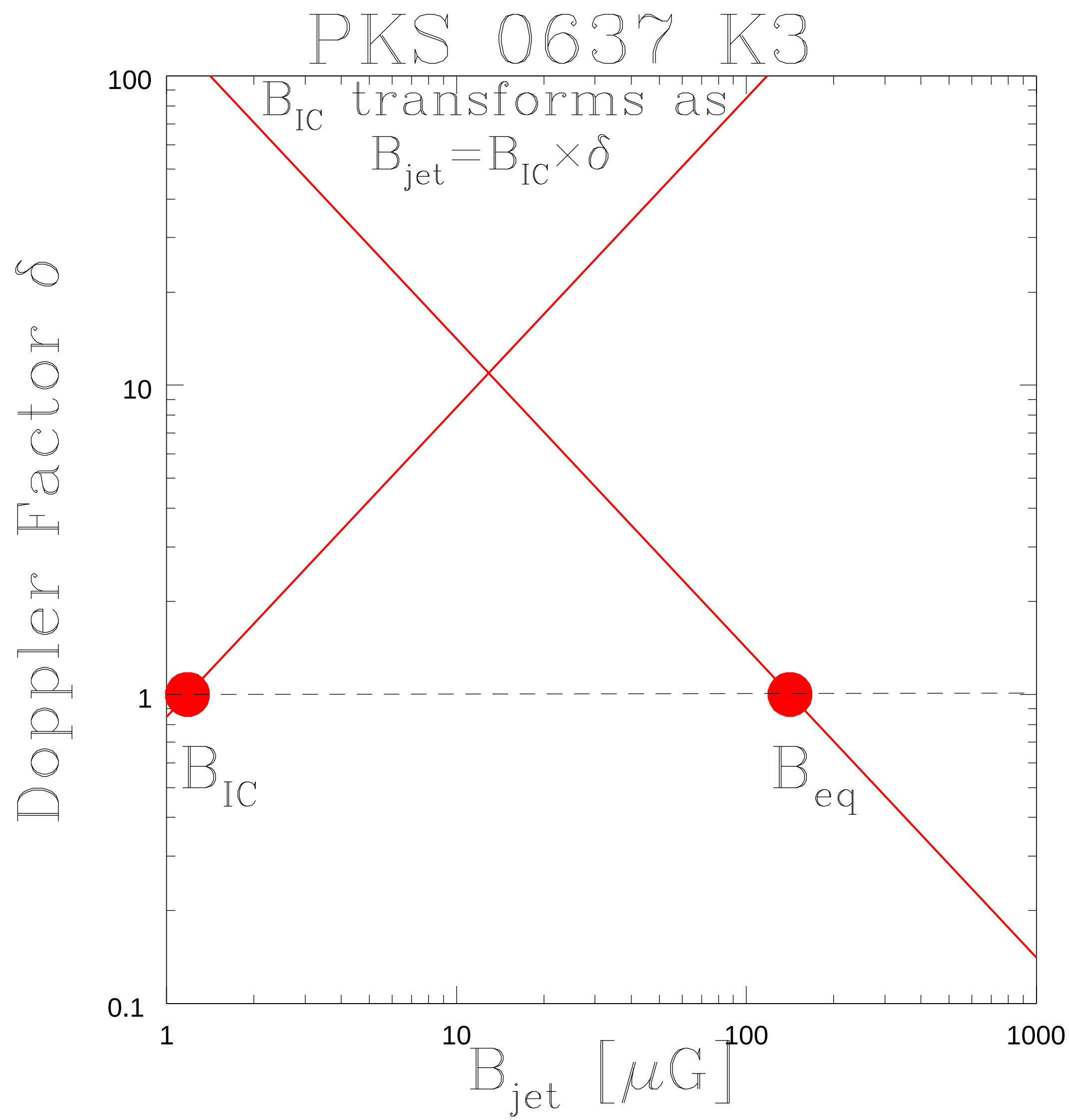



PKS 0637−753 K3
Equipartition B_{eq} assumes:
$\alpha=0.7$, $\nu_1=10^6$, $\nu_2=10^{12}$
For this object:
$z=0.653$, $\nu=8.64$ GHz
$B_{eq} \propto \left(\frac{S_\nu}{\theta_l\ \theta_r^2}\right)^{2/7}$
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000

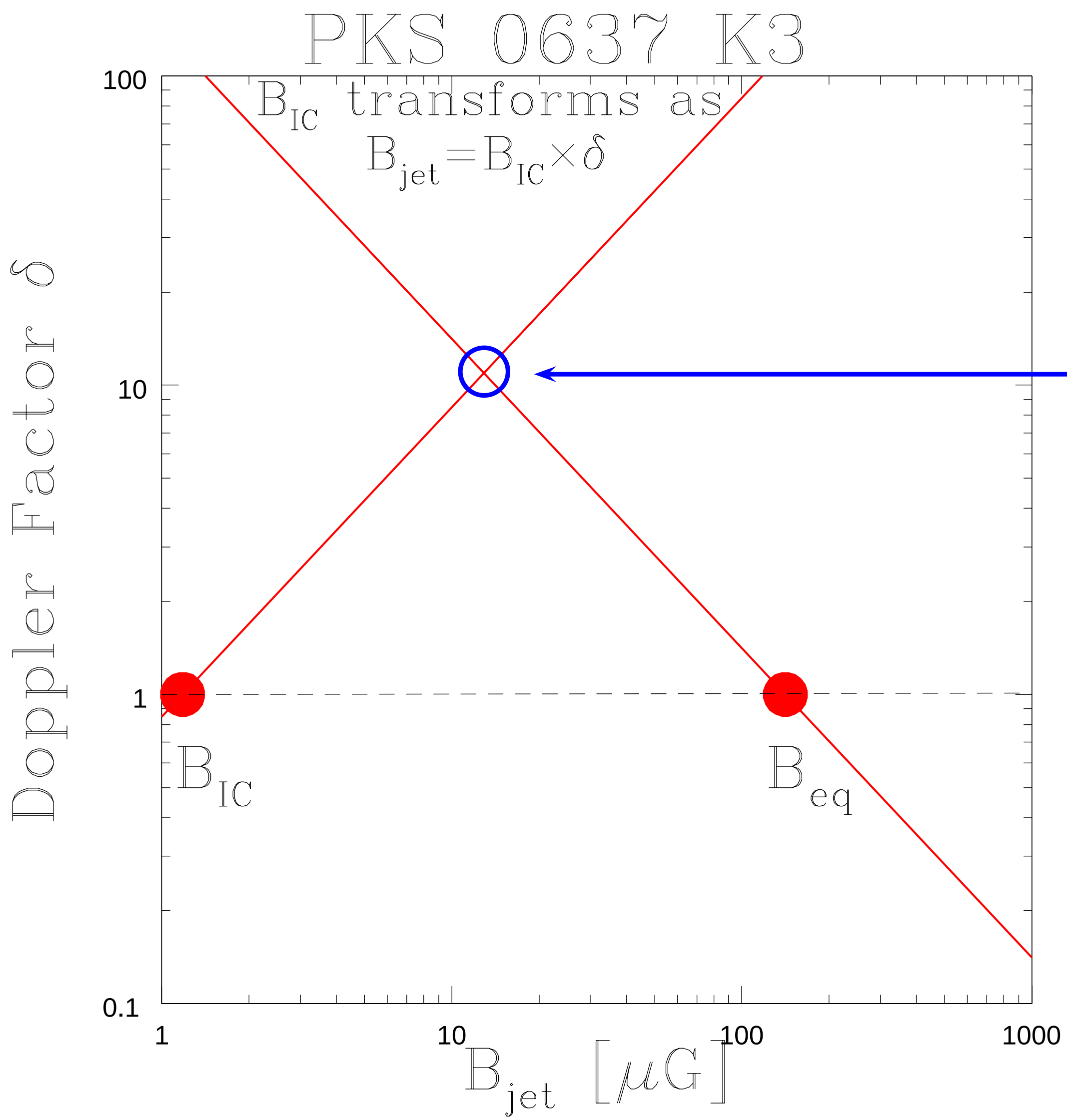

PKS 0637 K3
If X-rays are IC/CMB:
$B_o \propto [\frac{S_r(\nu)}{S_x(\nu)}]^{1/(1+\alpha)}$
B_{eq}
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000



PKS 0637 K3
100
10
1
0.1
1
10
100
1000
Doppler Factor δ
B_{jet} [μG]
B_{eq} transforms as
$B_{jet}=B_{eq}/\delta$
B_{IC}
B_{eq}



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

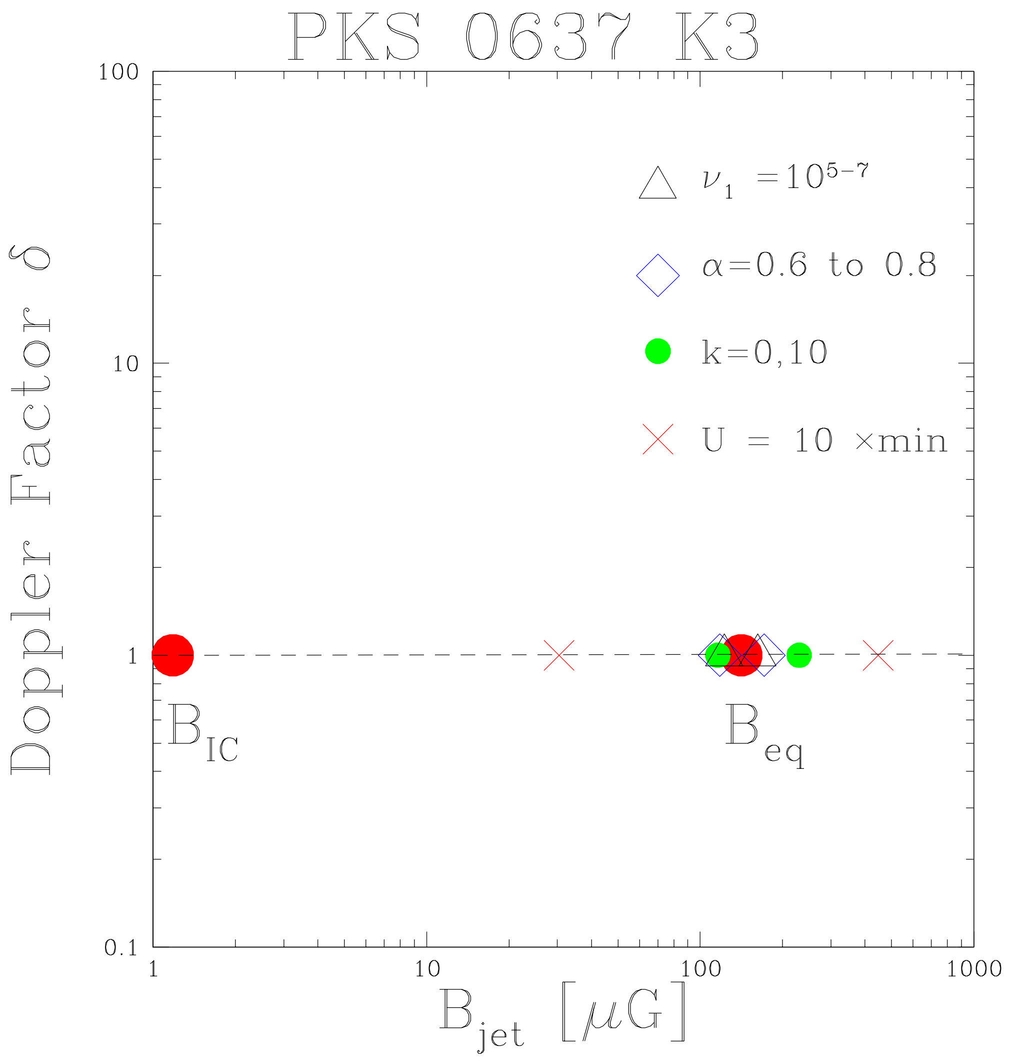


The intersection gives a solution for the magnetic field, B, in the rest frame, and for the apparent Doppler factor,

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

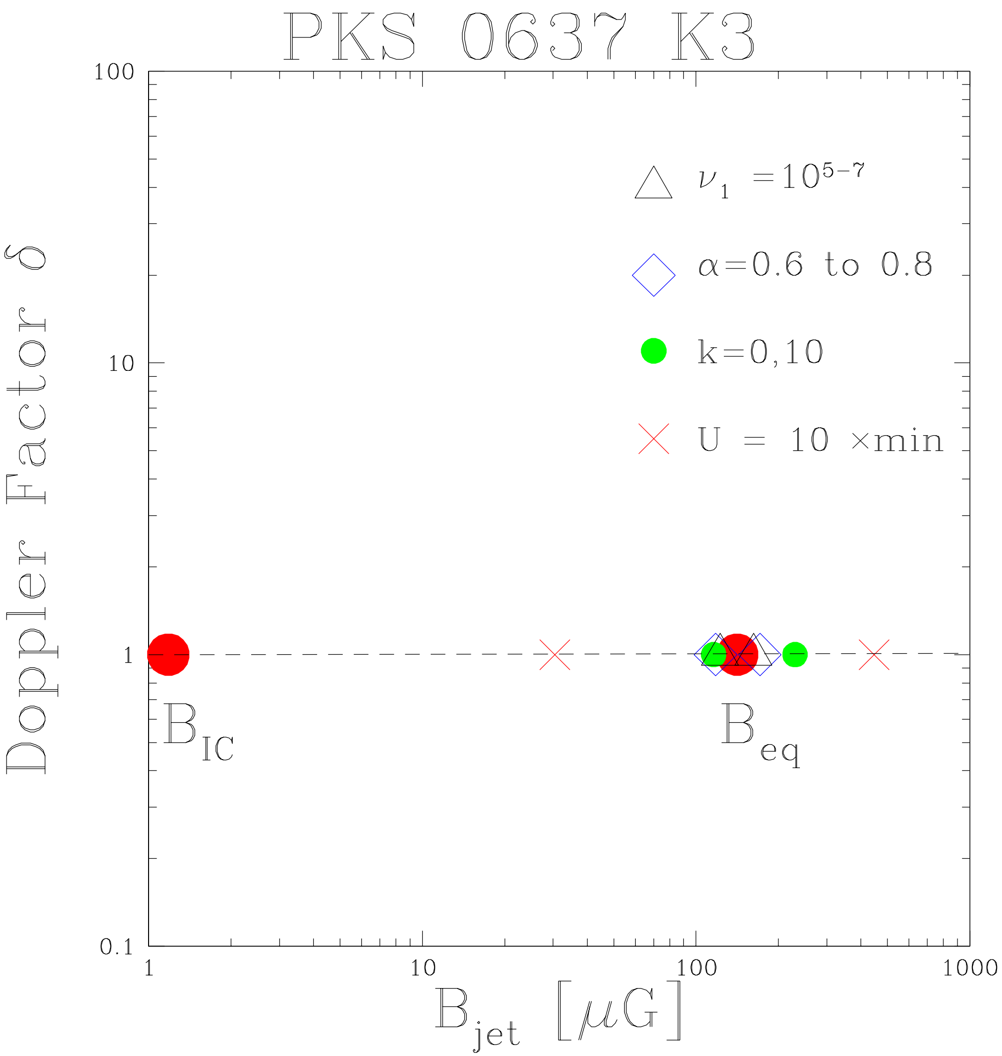
Uncertainties in the Magnetic Field Estimates

Equipartition

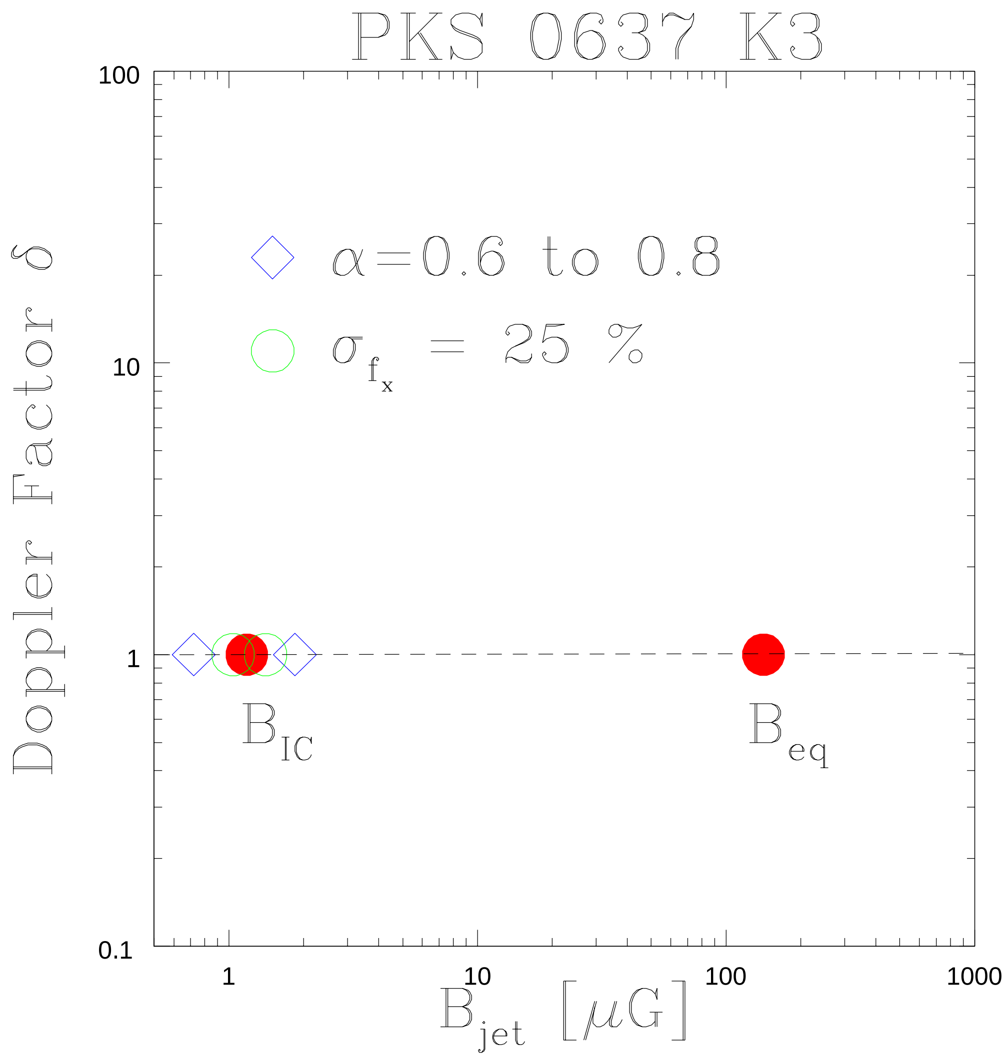


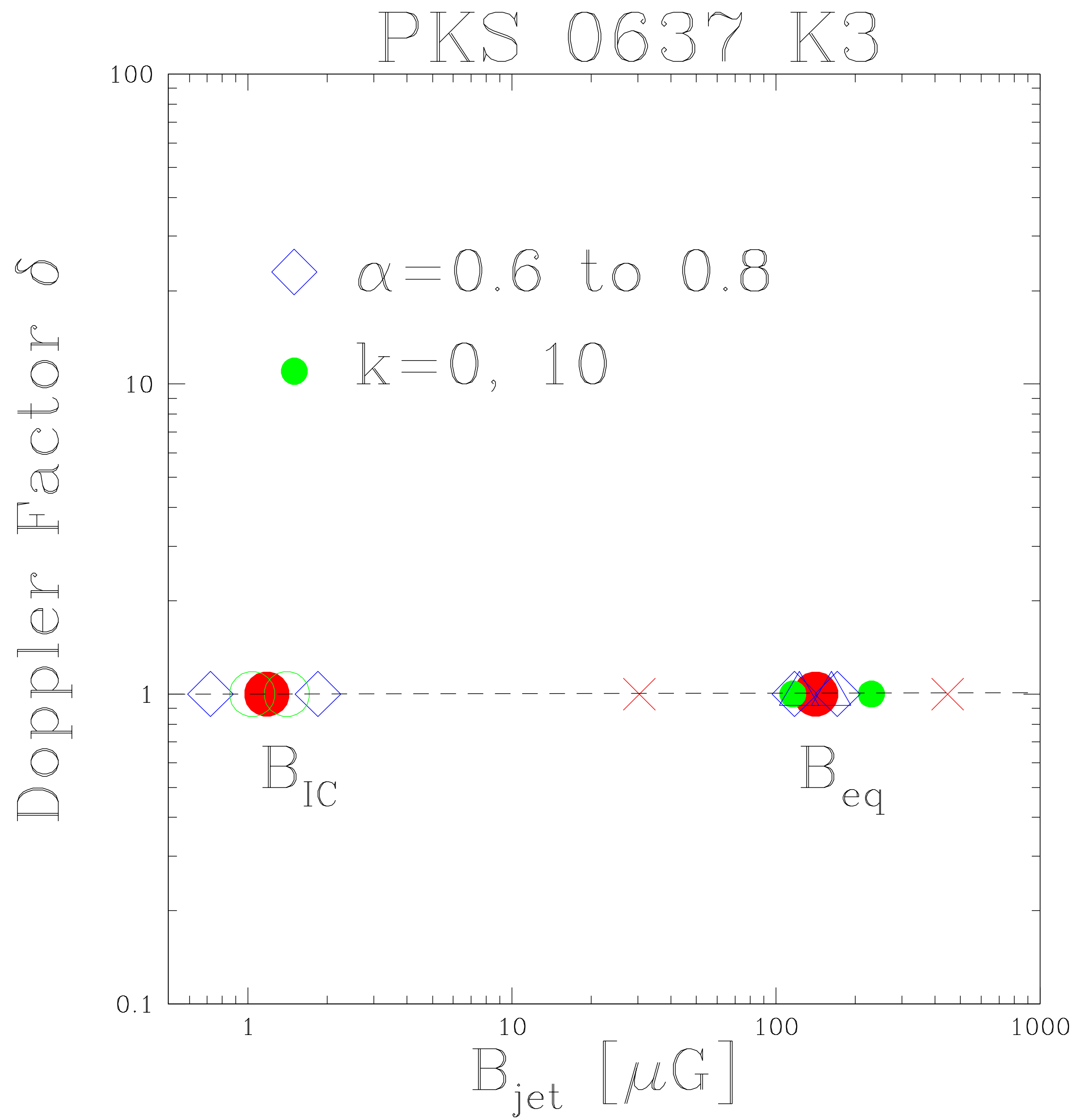
Uncertainties in the Magnetic Field Estimates

Equipartition

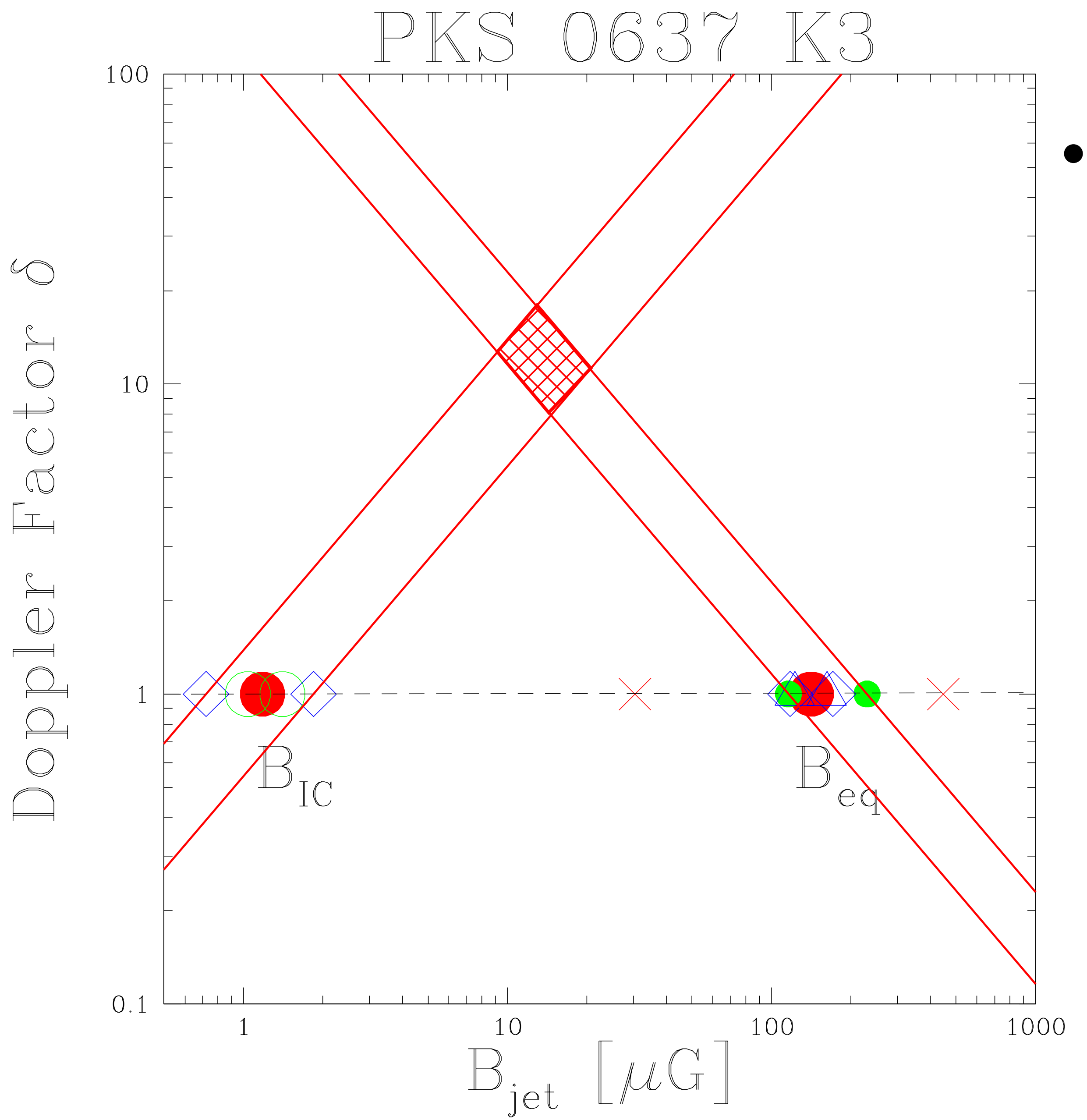


Inverse Compton

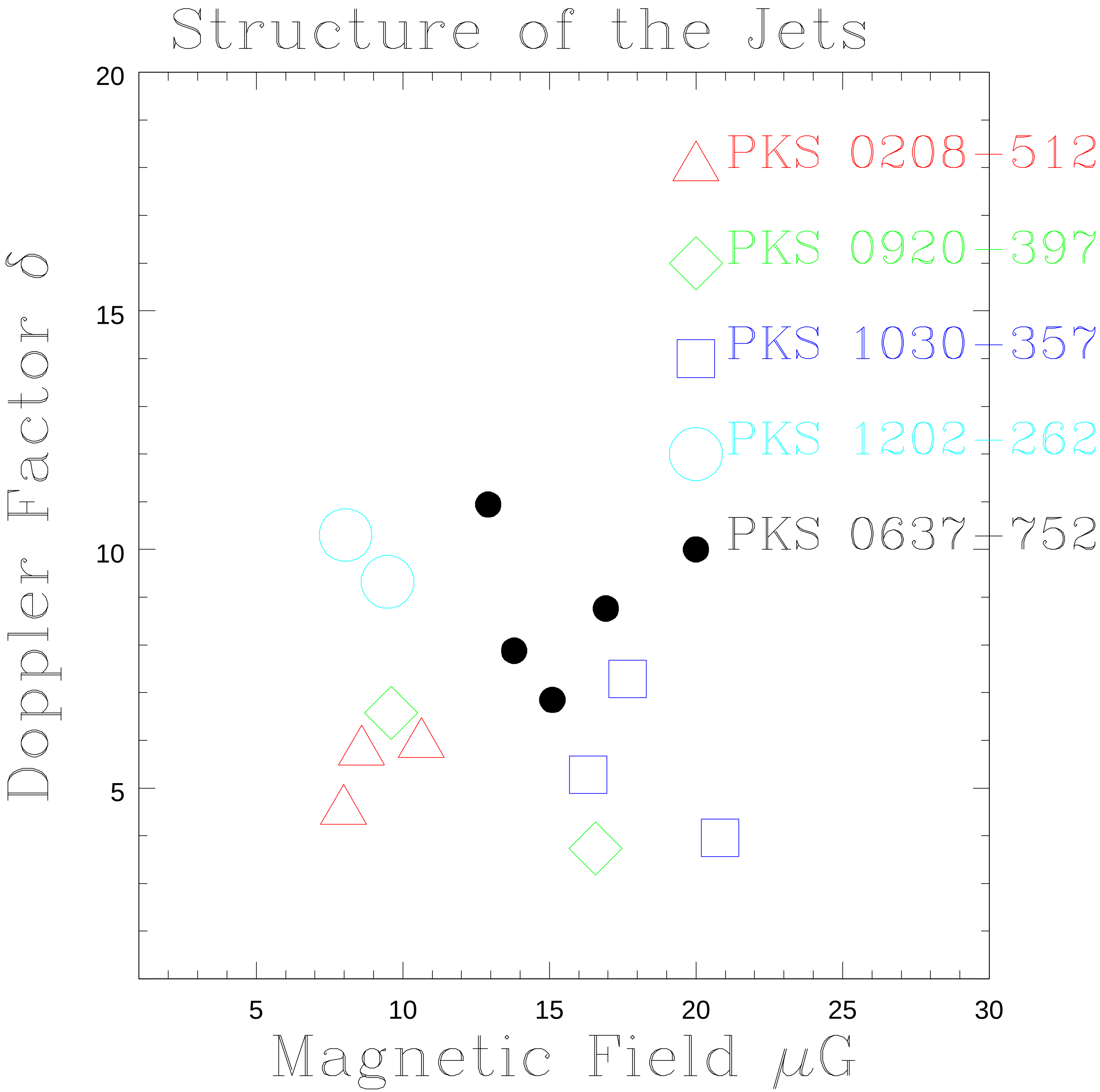




PKS 0637 K3
100
10
1
0.1
Doppler Factor δ
α=0.6 to 0.8
k=0, 10
B_IC
B_eq
1
10
100
1000
B_jet [μG]

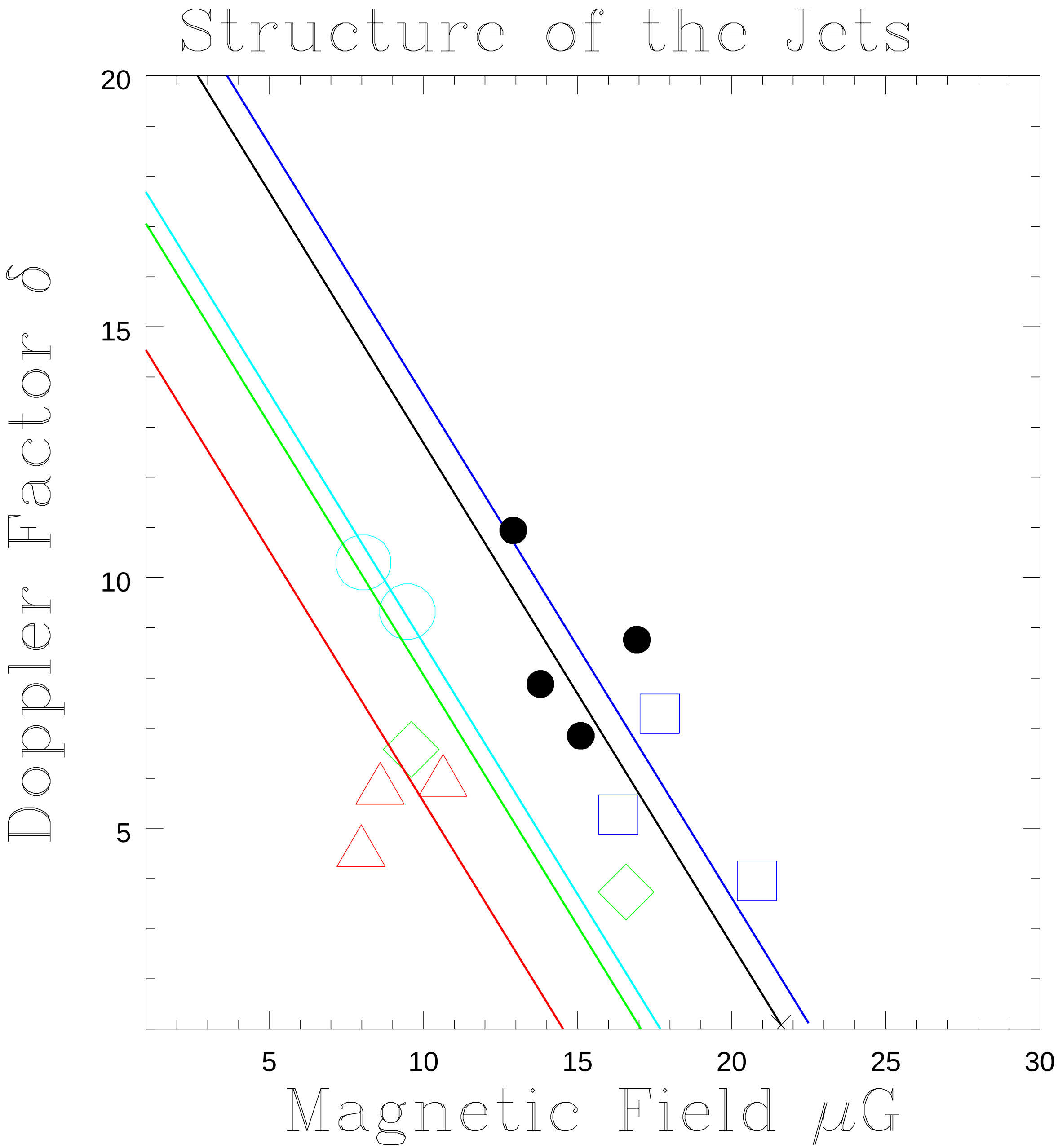


- **Determined B and δ within a factor of ≈2**



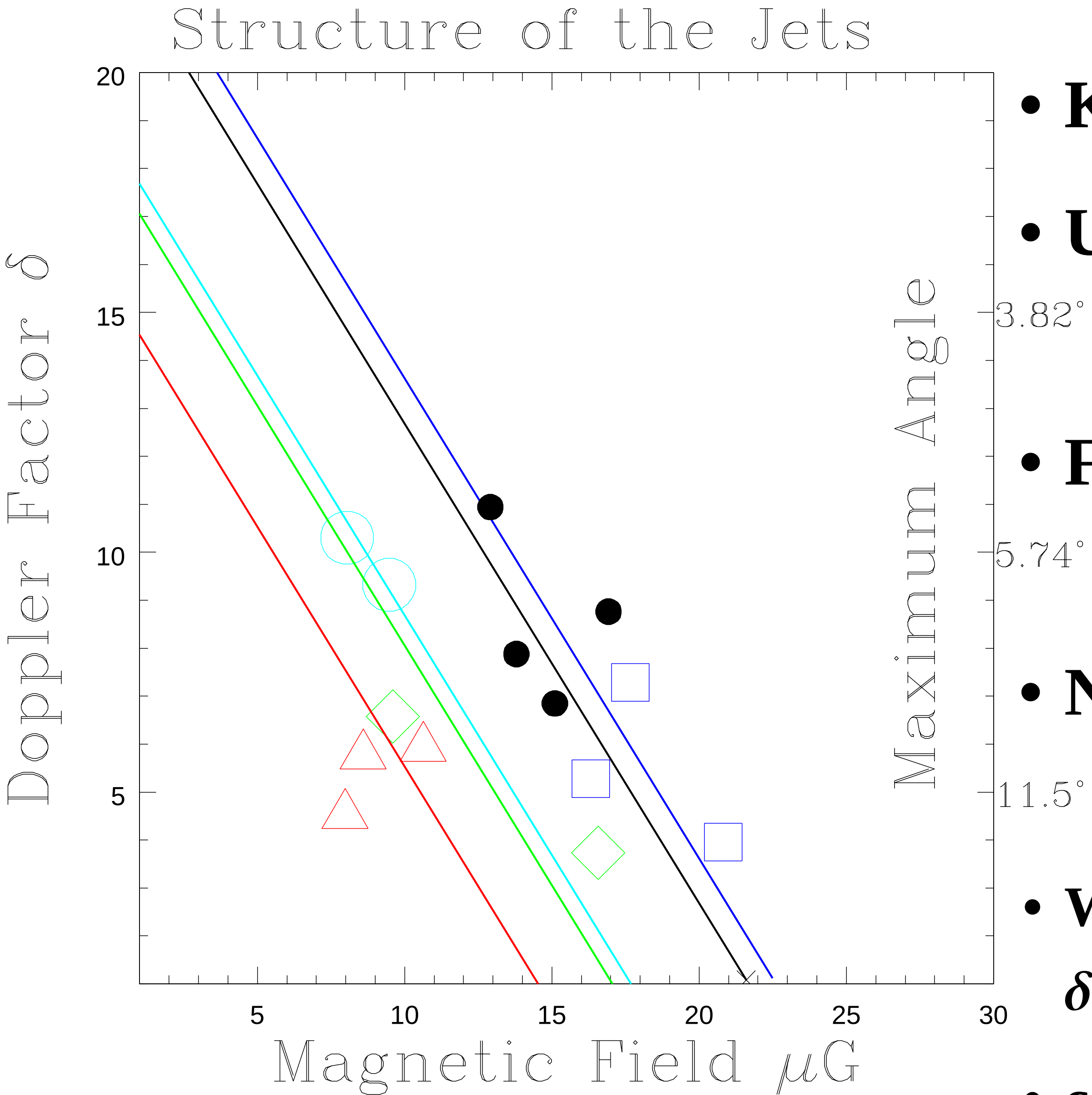
Structure of the Jets
Doppler Factor δ
Magnetic Field μG
20
15
10
5
5
10
15
20
25
30
PKS 0208–512
PKS 0920–397
PKS 1030–357
PKS 1202–262
PKS 0637–752

Kinetic Flux



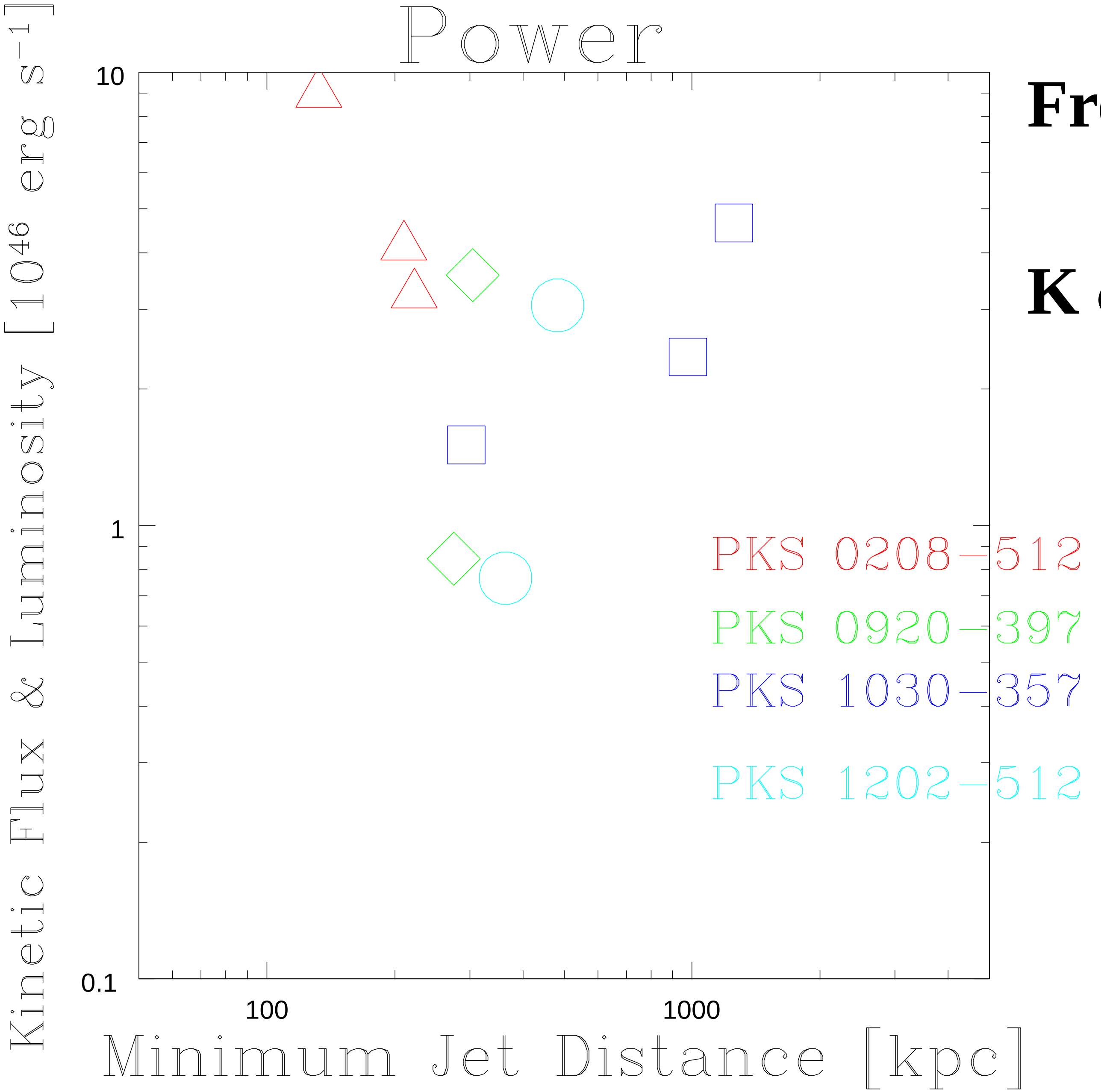
- $K = \Gamma^2 \pi\, r^2 \beta\, c\, U$
- U is total internal energy density, $U_B + U_e + U_p$
- For equipartition, $U = \frac{B^2}{8\pi}(2 + k)$
- NOTE: K constant $\Rightarrow$ $(B\,\Gamma)^2$ = constant

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

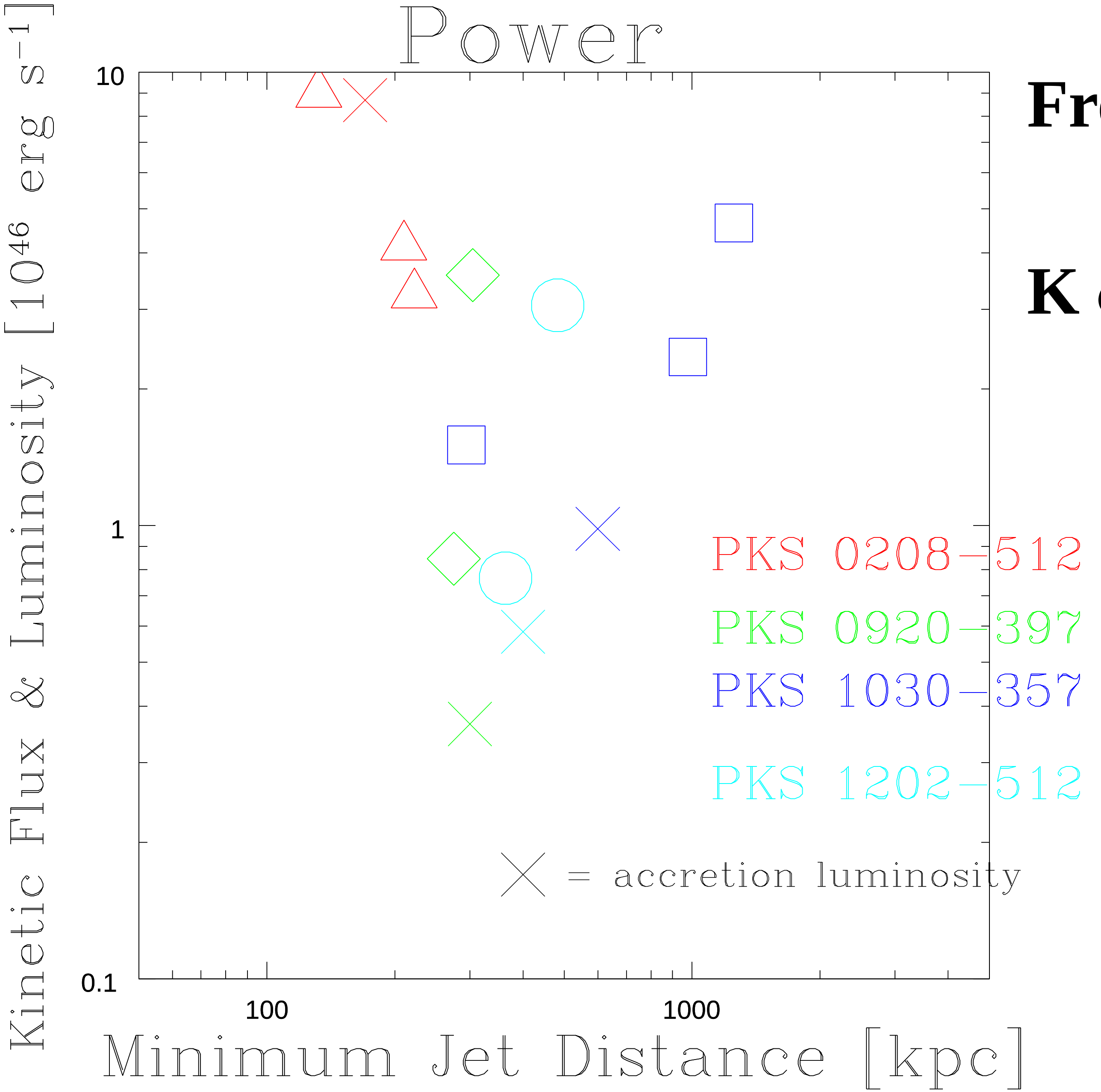
Kinetic Flux



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

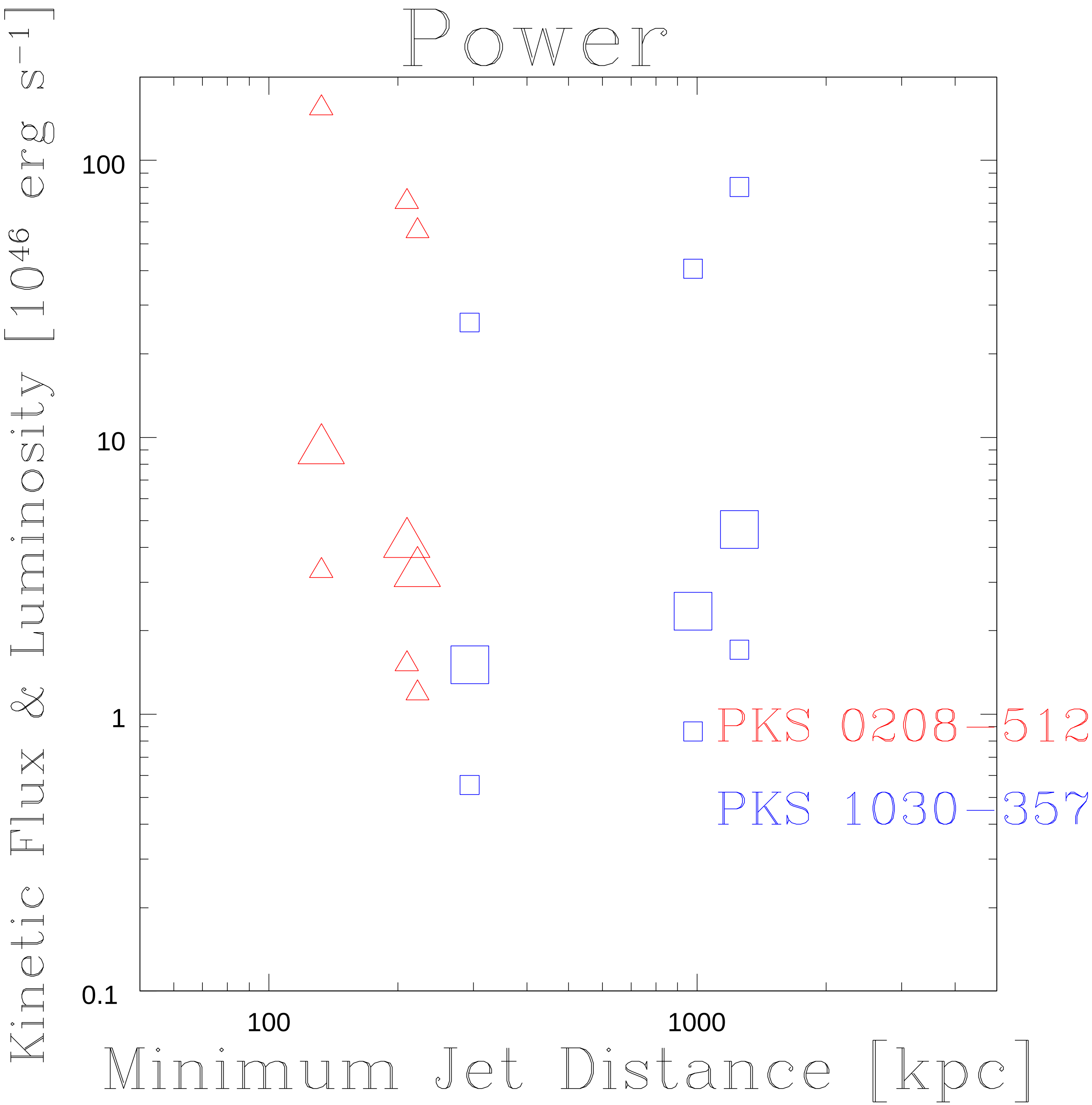
$\mathbf{K \propto \delta^2 \theta_r^2 (3\, B^2/(8\, \pi))}$

Kinetic Flux



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

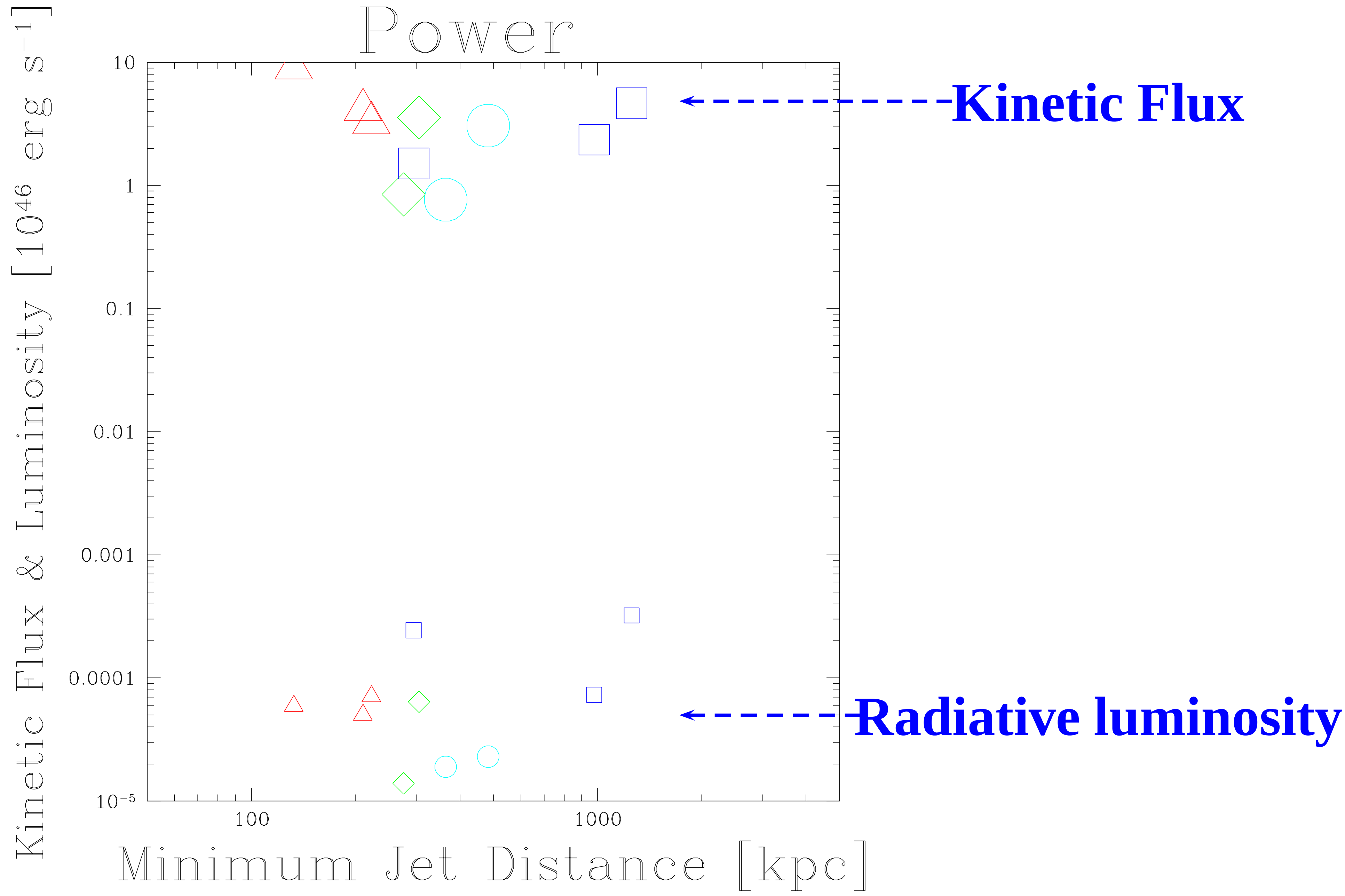
$K \propto \delta^2 \theta_r^2 (3\, B^2/(8\, \pi))$



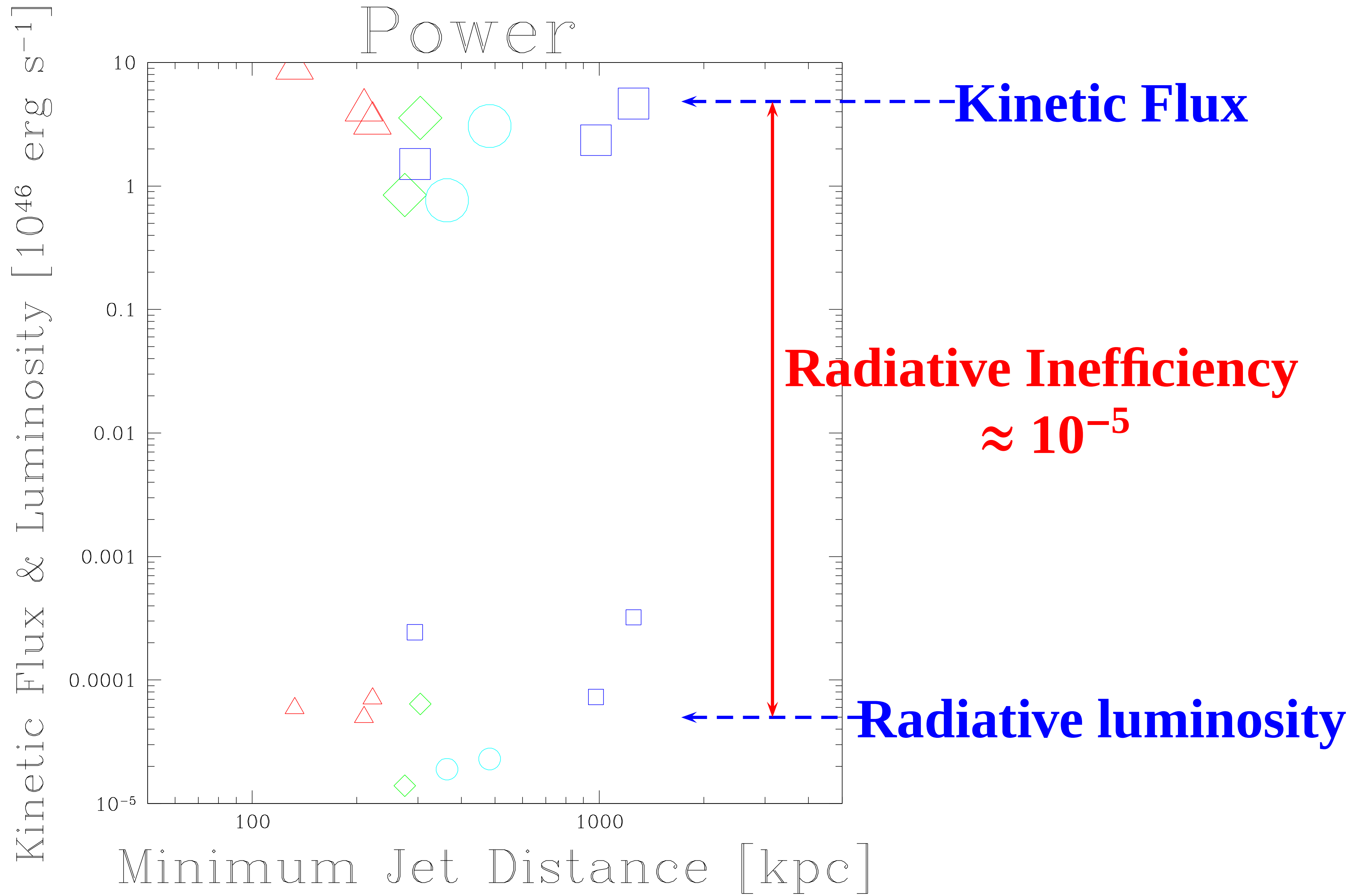
Kinetic Flux

Energy in Protons?

- Large symbols assume $U_p = U_e$
- Lower symbols assume pure $e^{\pm}$ plasma
- Upper symbols assume cold protons, n_p=n_e, and $< \gamma >_e$ = 183



Power
Kinetic Flux & Luminosity [10^46 erg s^-1]
10
1
0.1
0.01
0.001
0.0001
10^-5
100
1000
Minimum Jet Distance [kpc]
Kinetic Flux
Radiative luminosity



Power
Kinetic Flux & Luminosity [10^{46} erg s^{-1}]
10
1
0.1
0.01
0.001
0.0001
10^{-5}
100
1000
Minimum Jet Distance [kpc]
Kinetic Flux
Radiative Inefficiency
$\approx 10^{-5}$
Radiative luminosity

Implications of the AGN Jets

- **Eddington Luminosity might not limit Accretion Rate**

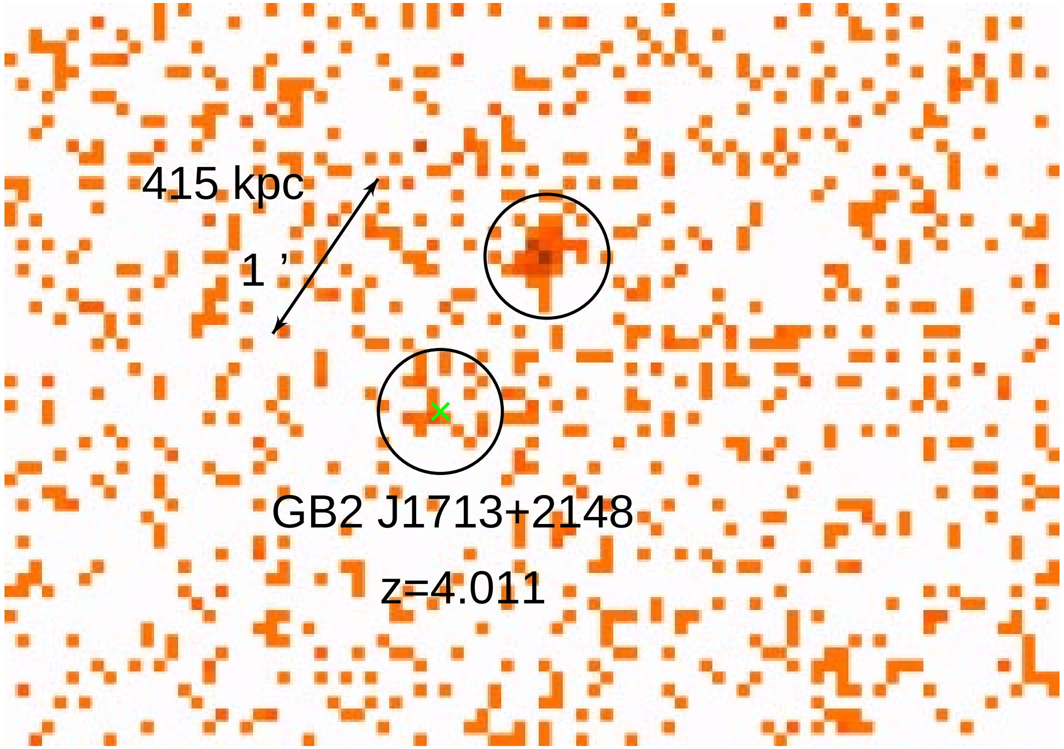
- **Jets may Power Cluster Cavities – Stop Cooling Flows**

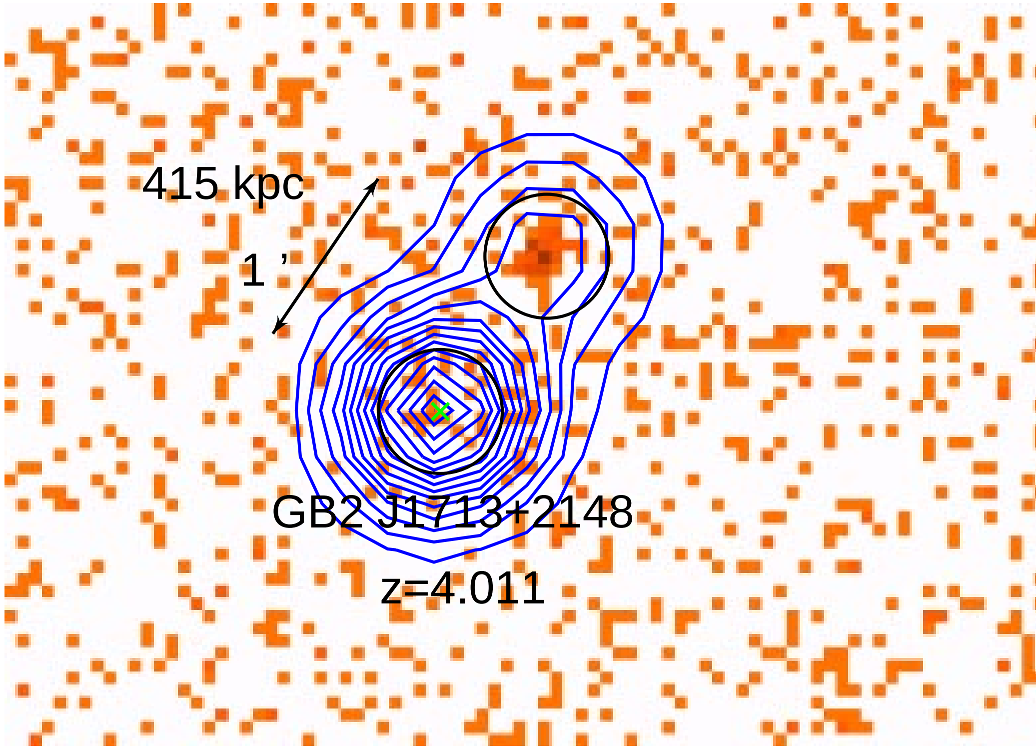
- **IC/CMB X-ray jets Maintain Constant Surface Brightness vs. z. We will detect them at Arbitrarily Large Redshift.**

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

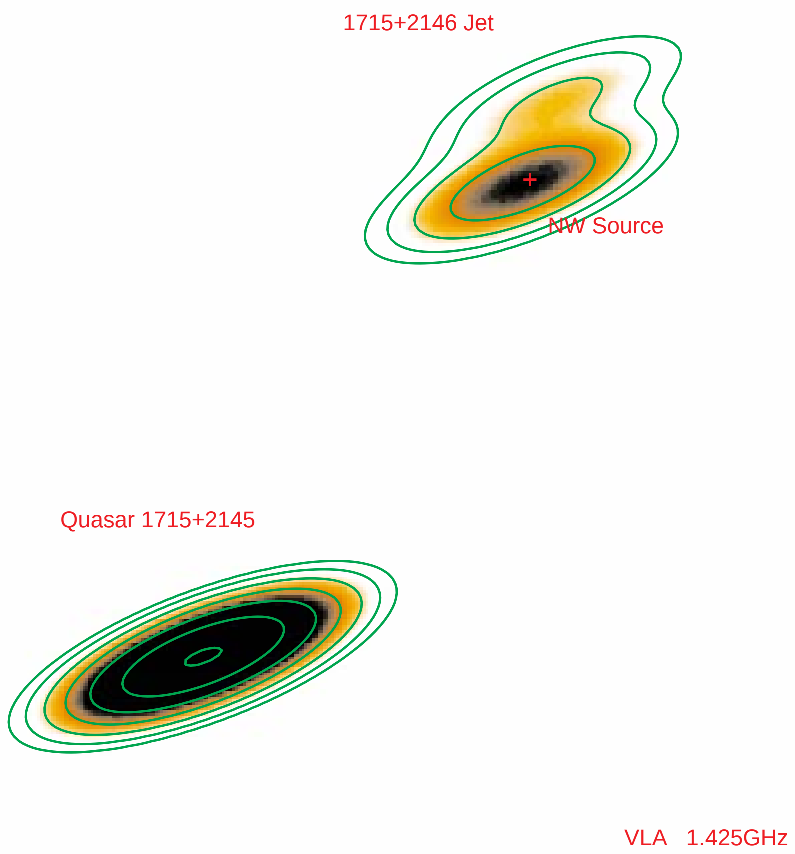
- **Unidentified ROSAT sources?**
- **Bright ROSAT, ASCA, EINSTEIN quasar identifications?**
- **Extreme X-ray/Optical sources (Koekemoer et al. 2004ApJ...600L.123K) in Chandra Deep Surveys?**

Anonymous ROSAT source

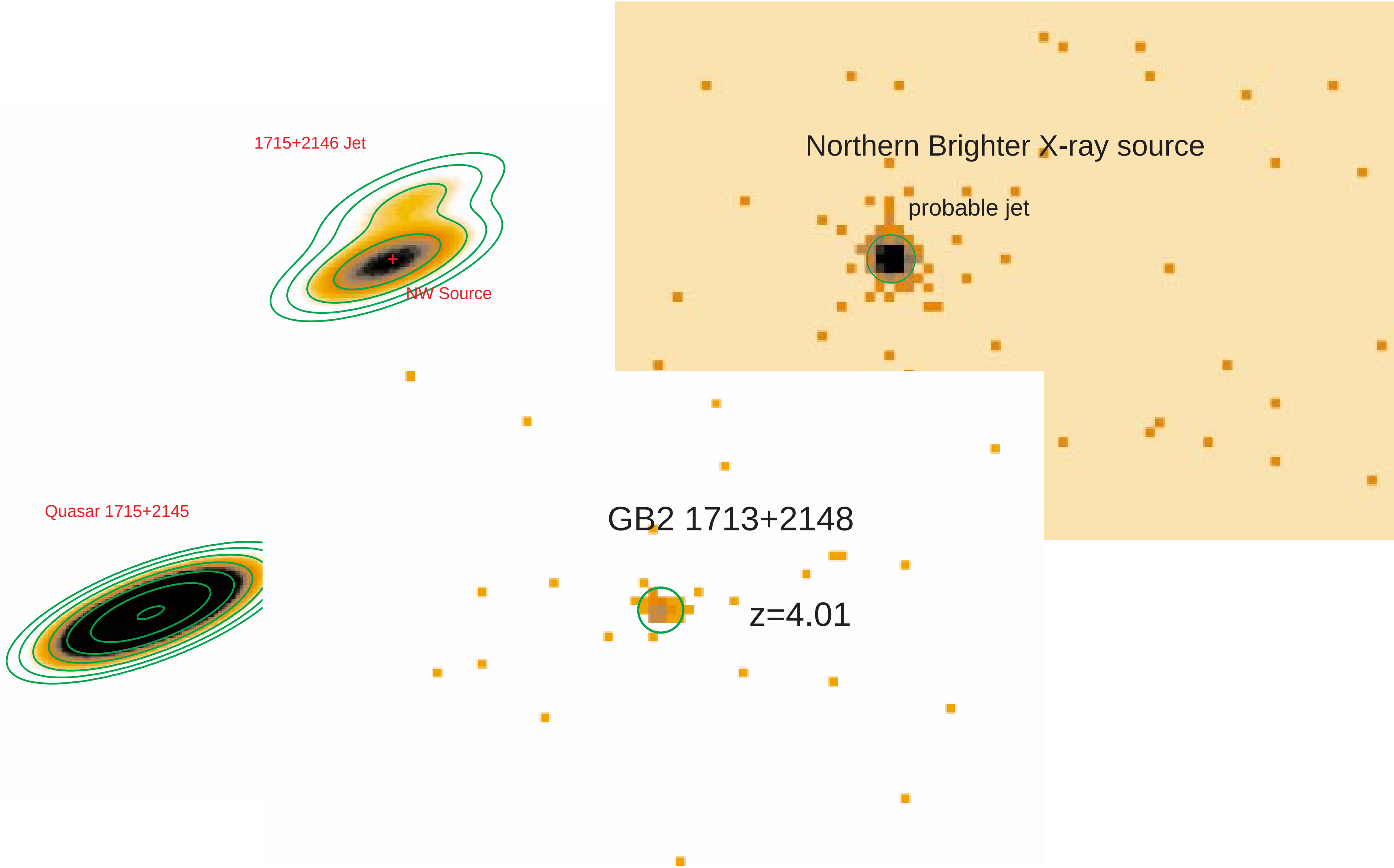




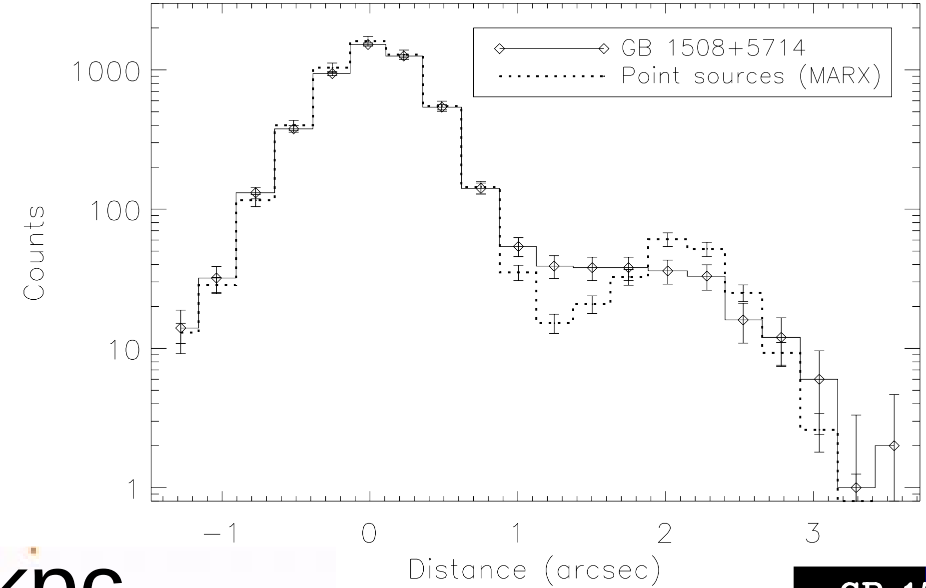
Anonymous ROSAT source

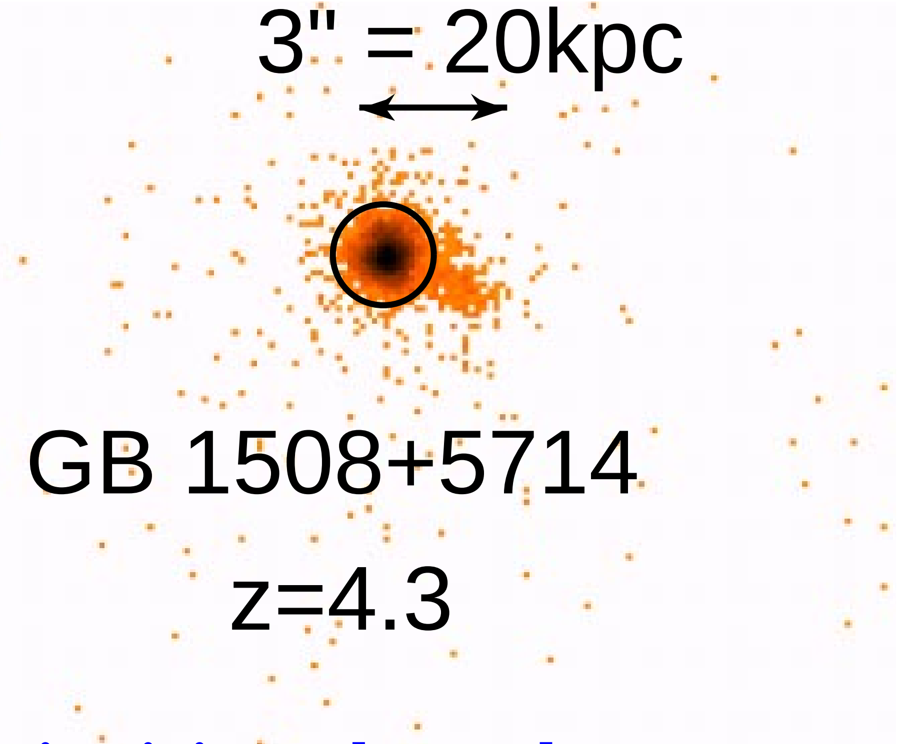


Anonymous ROSAT source

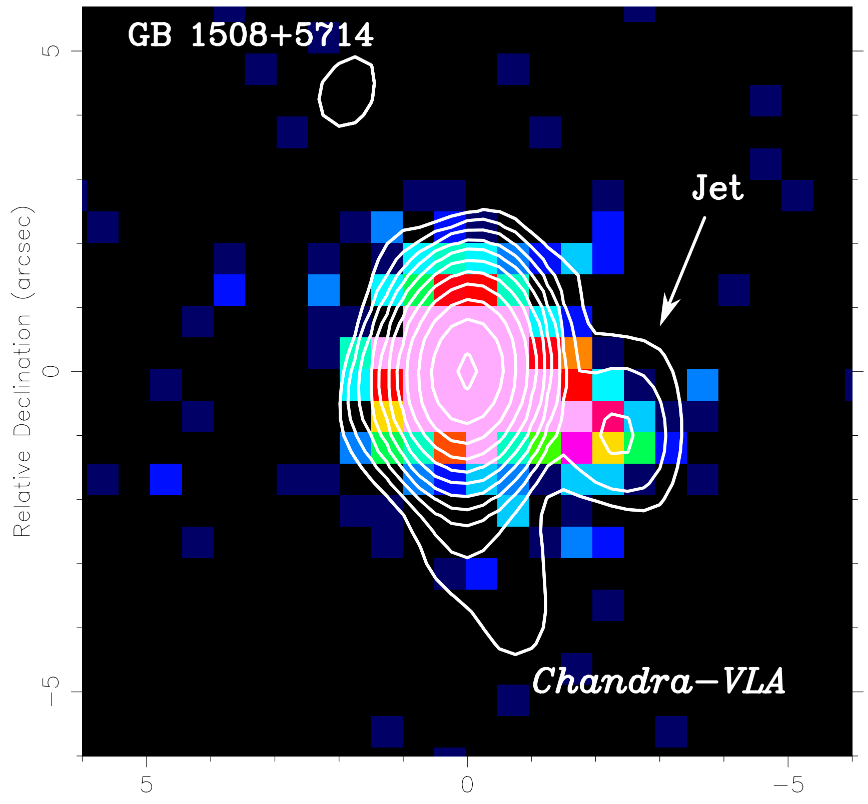


An Einstein and ASCA source



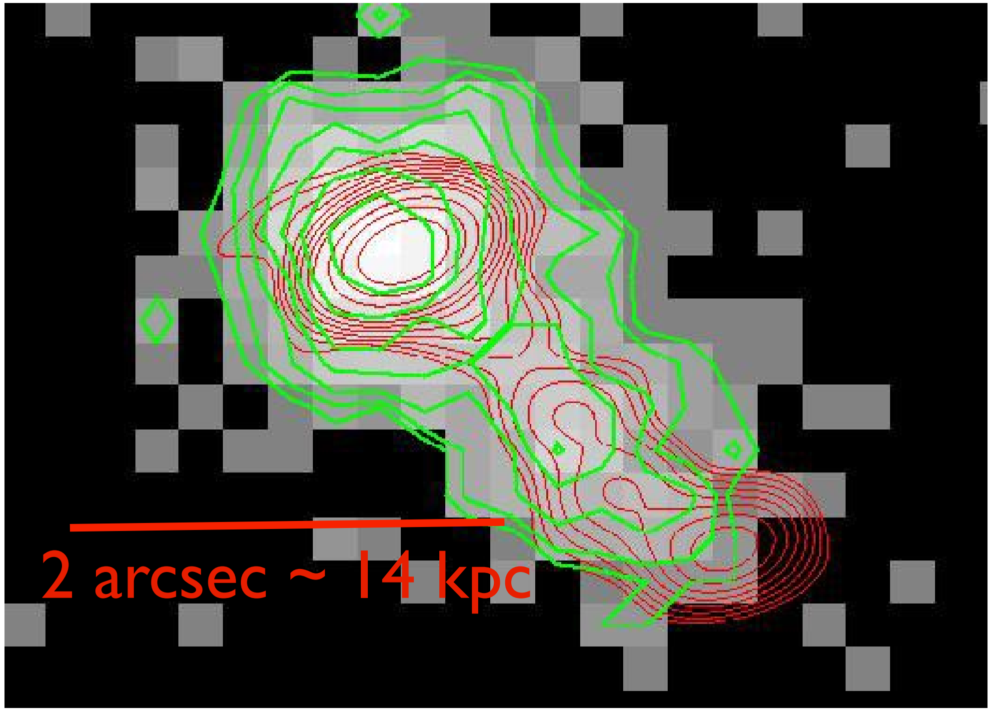


Siemiginowska et al. 2003ApJ...598L..15S

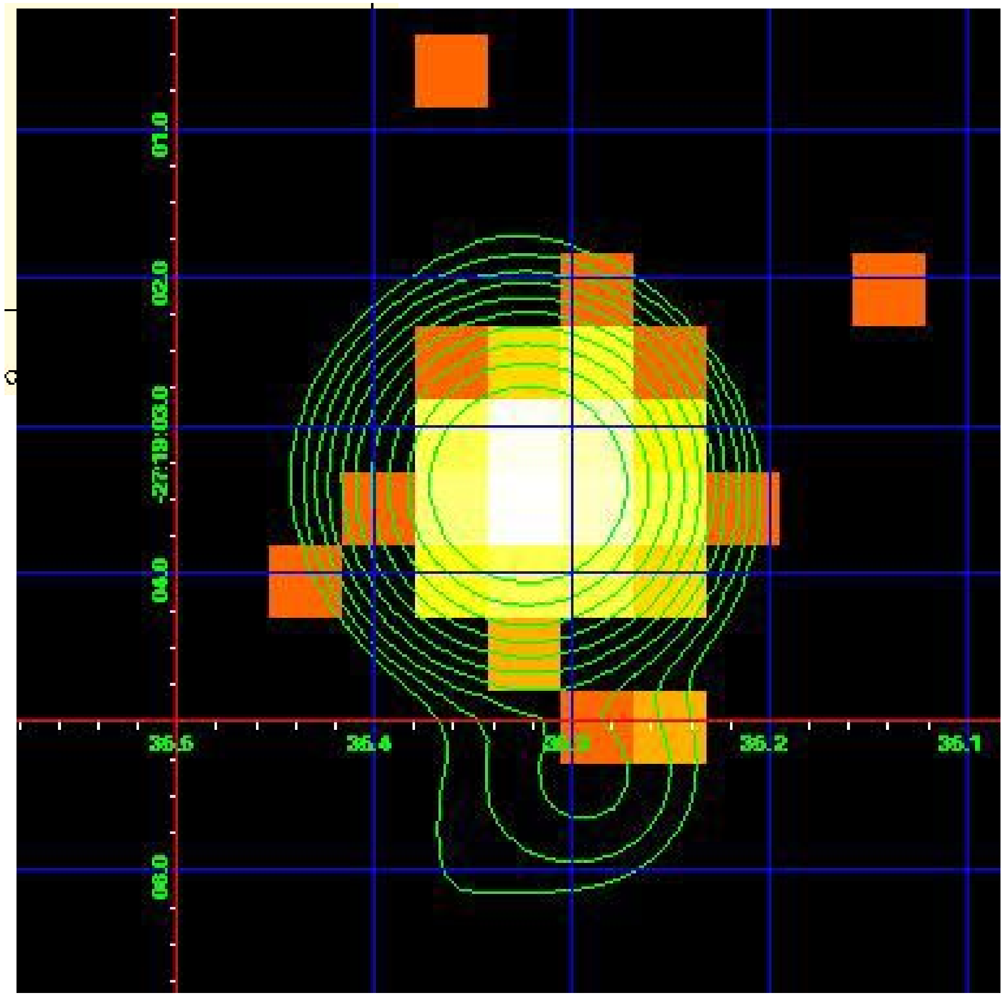


Cheung,2004ApJ...600L..23C

Two more High Redshift X-ray Jets:
Cheung et al. Poster 1613



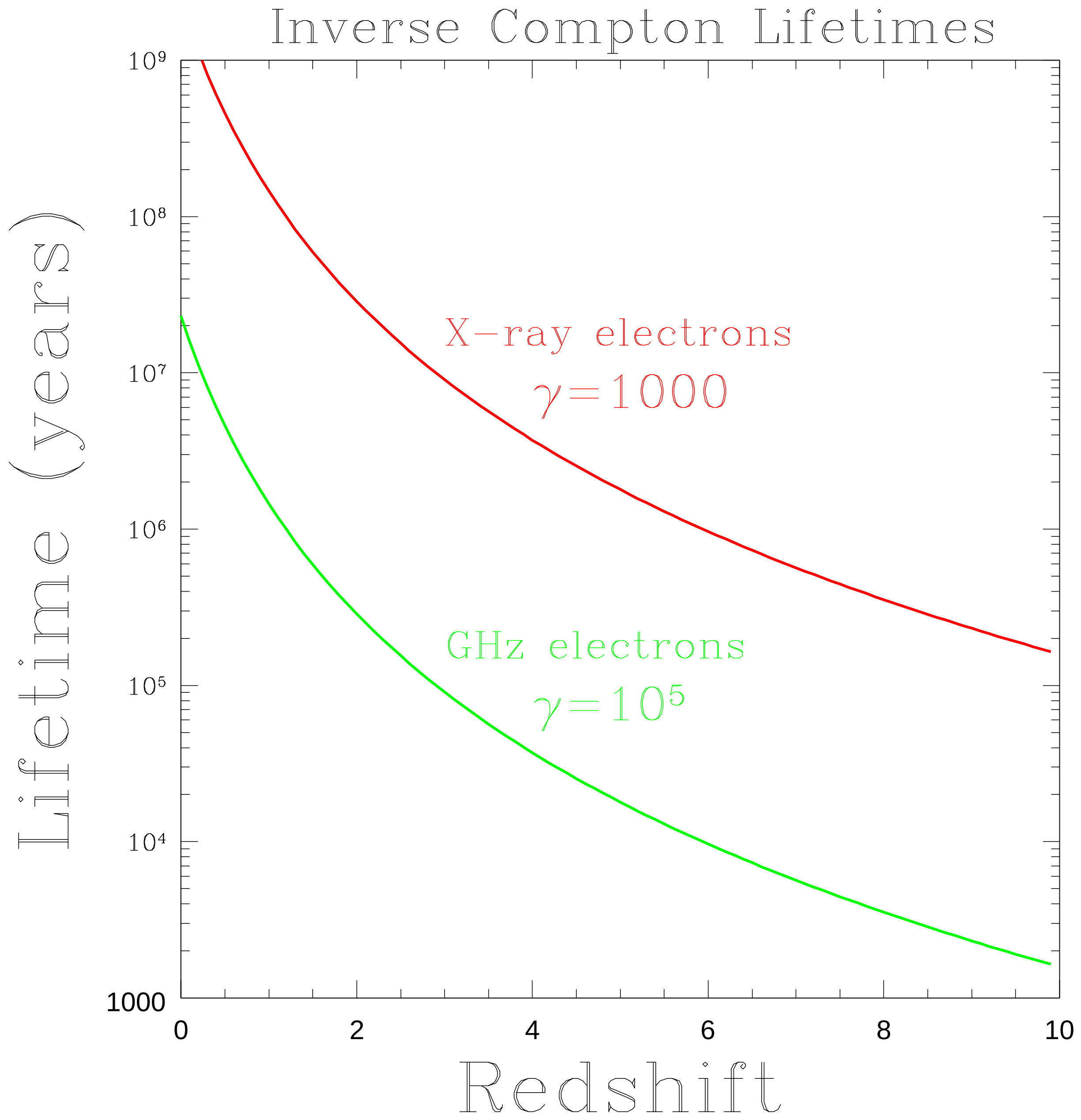
Quasar 1745+624 = 4C +62.29 at z=3.889



PMN J2219-2719 at z=3.634

There Could Be Radio Quiet X-Ray Jets!

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



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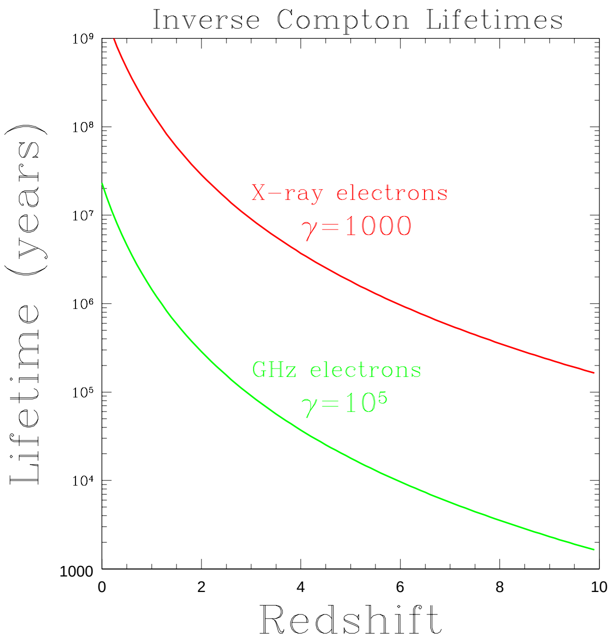
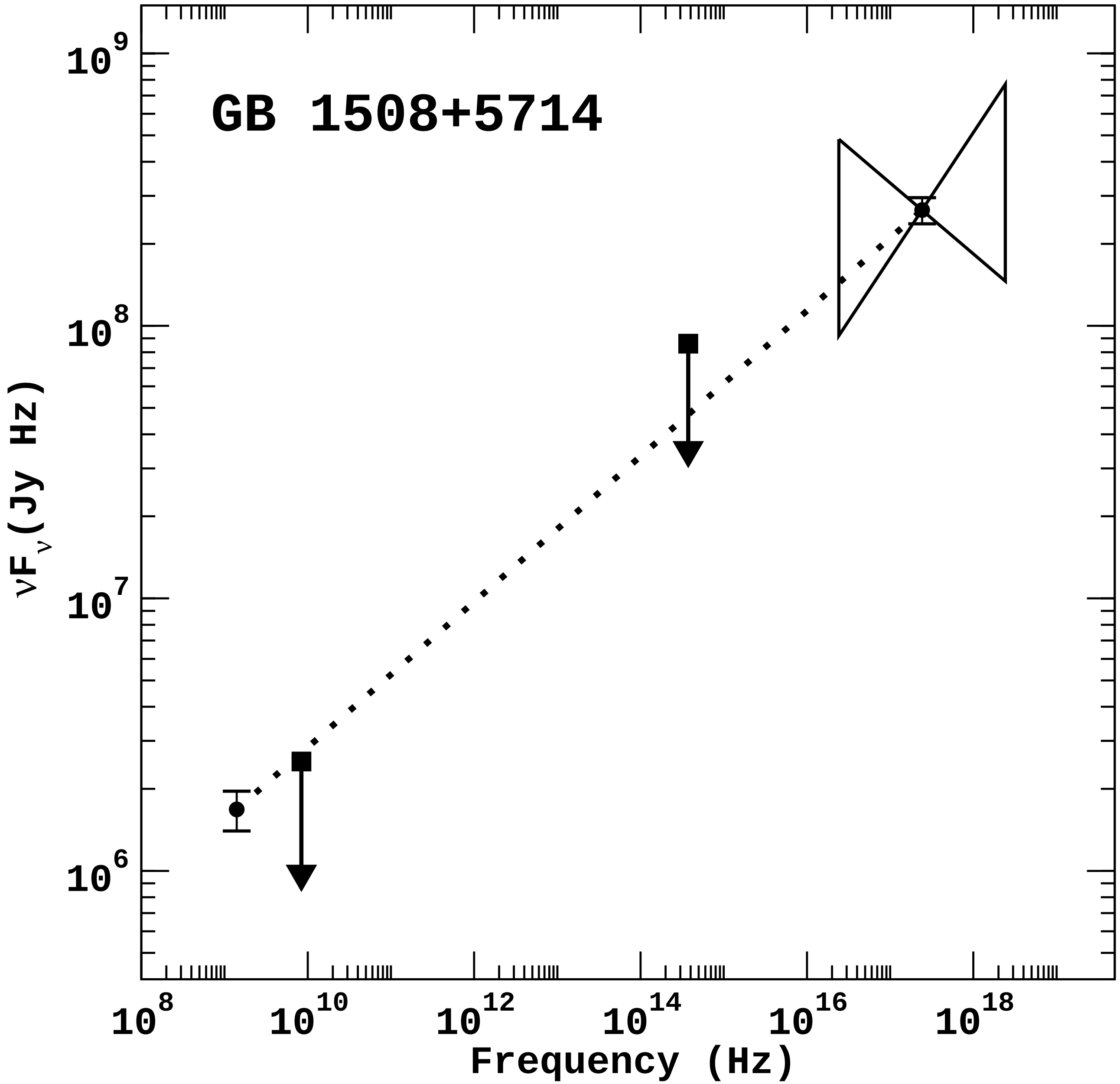
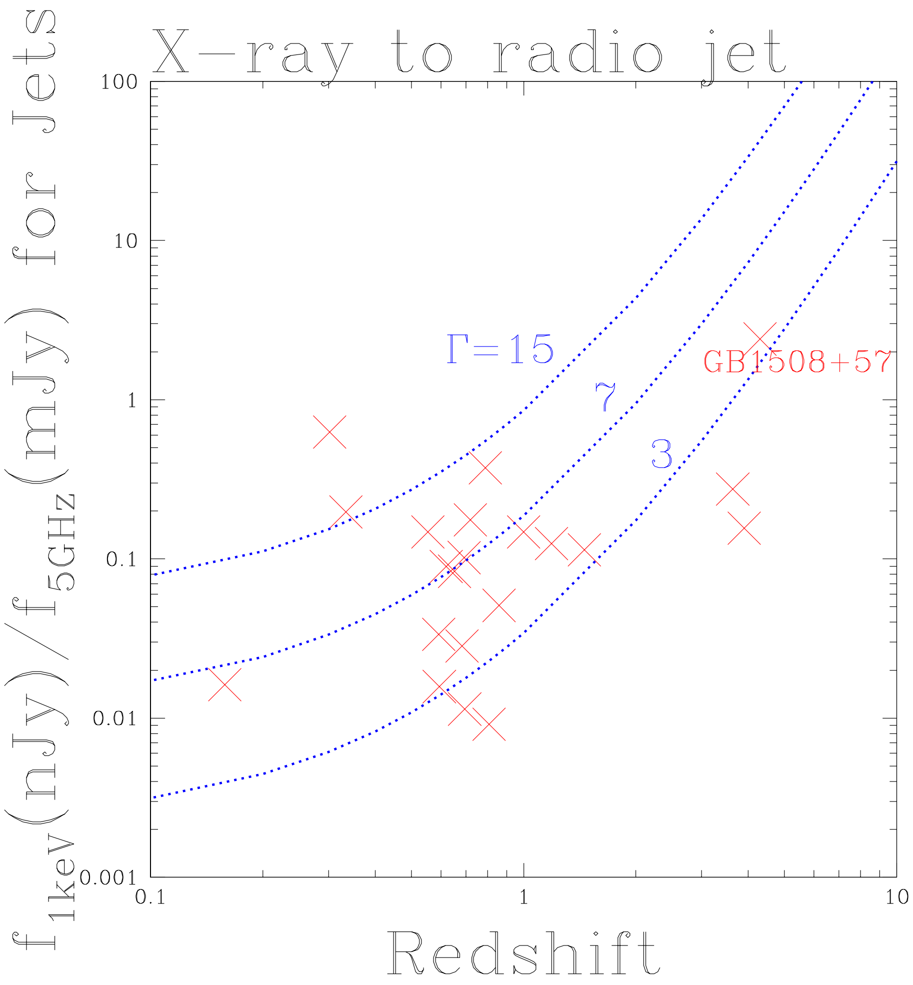
- **$\nu = 4.2 \times 10^{-6} \gamma^2$ H[μG] $\approx$ 10 MHz**
- **Age $\approx 3 \times 10^4$ years?**

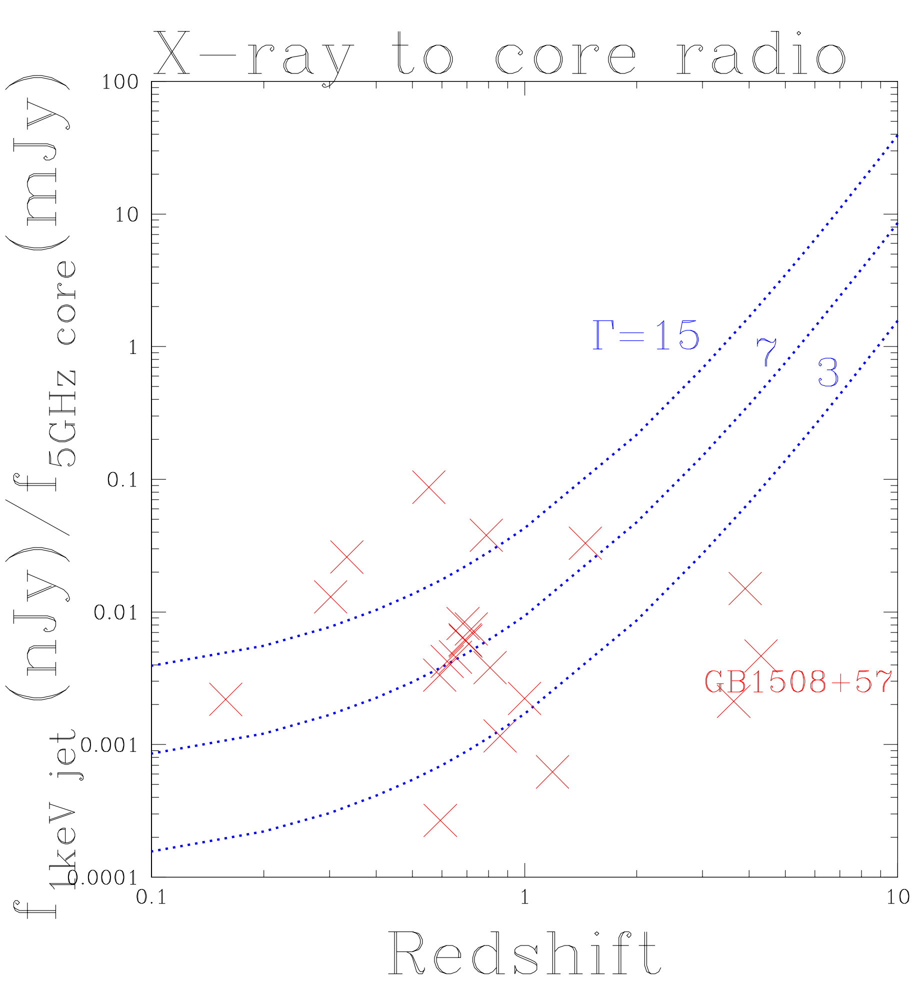




Cheung,2004ApJ...600L..23C

Correlation of X-ray Jet and Radio Flux Densities





Significance of the X-ray Emission

1. **X-rays dominate power radiated by jet**
2. **SED through X-ray band provides clues to structure.**
   - **Acceleration sites**
   - **Deceleration of bulk motion**
   - **Proton content**

Significance of the X-ray Emission

If emission is inverse Compton on the Cosmic Microwave Background

3. X-rays give the effective Doppler factor, rest frame B, and electron γ_{min}

4. X-ray jets will be detectable at arbitrarily large redshift!