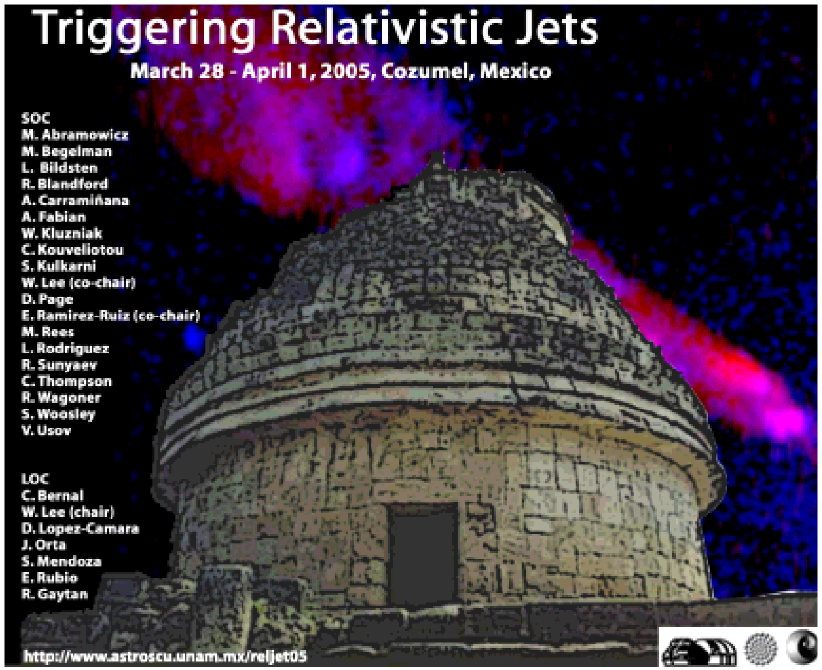
Chandra Observations of Relativistic AGN Jets

Dan Schwartz

Smithsonian Astrophysical Observatory

2005 March 31



Instituto de astronomía

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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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  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**

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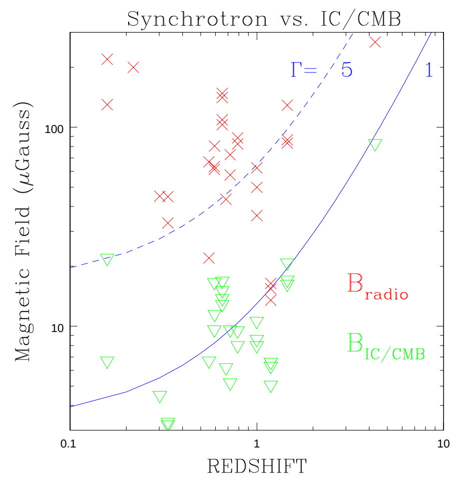
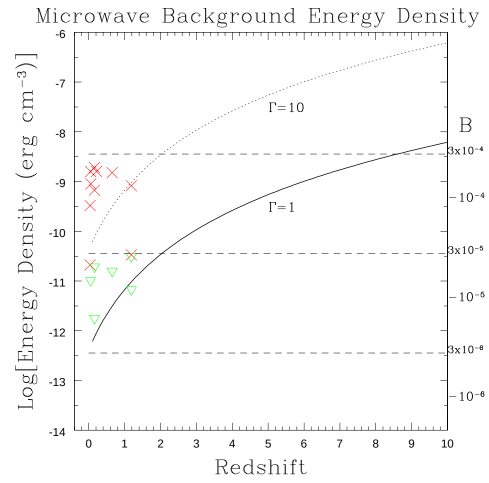
- **What Do We Want to Learn**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**
- **Why Do We Need X-Ray Data?**
  - **Spectral Energy Distribution (SED) gives mechanism**
  - **Particle lifetimes change with observed band**

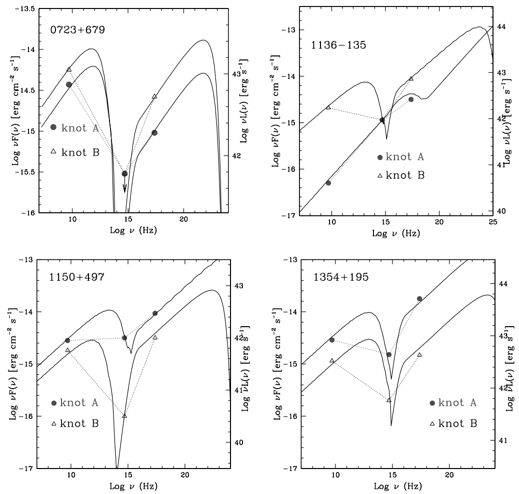
Outline

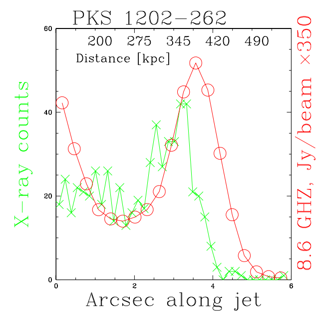
1. **Interpretation as IC/CMB**
   - **Energy densities: B^2 vs. $kT(1+z)^4$**
   - **Broadband SED**
   - **Morphology**
   - **f_x/f_r Profiles**

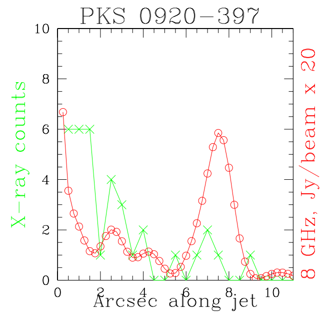
2. **Parameters and Implications**







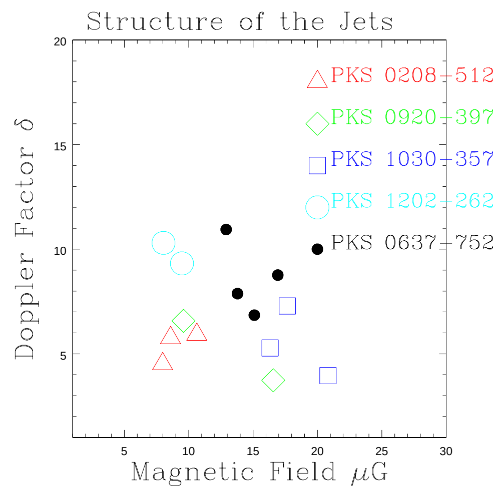


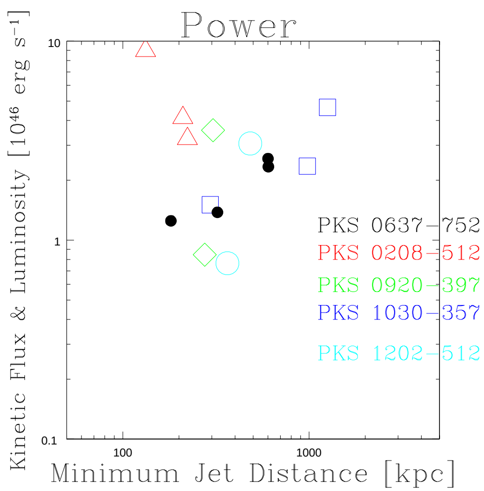


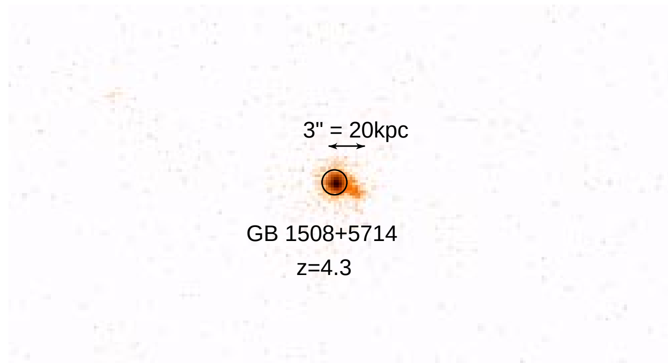
Outline

1. **Interpretation as IC/CMB**

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





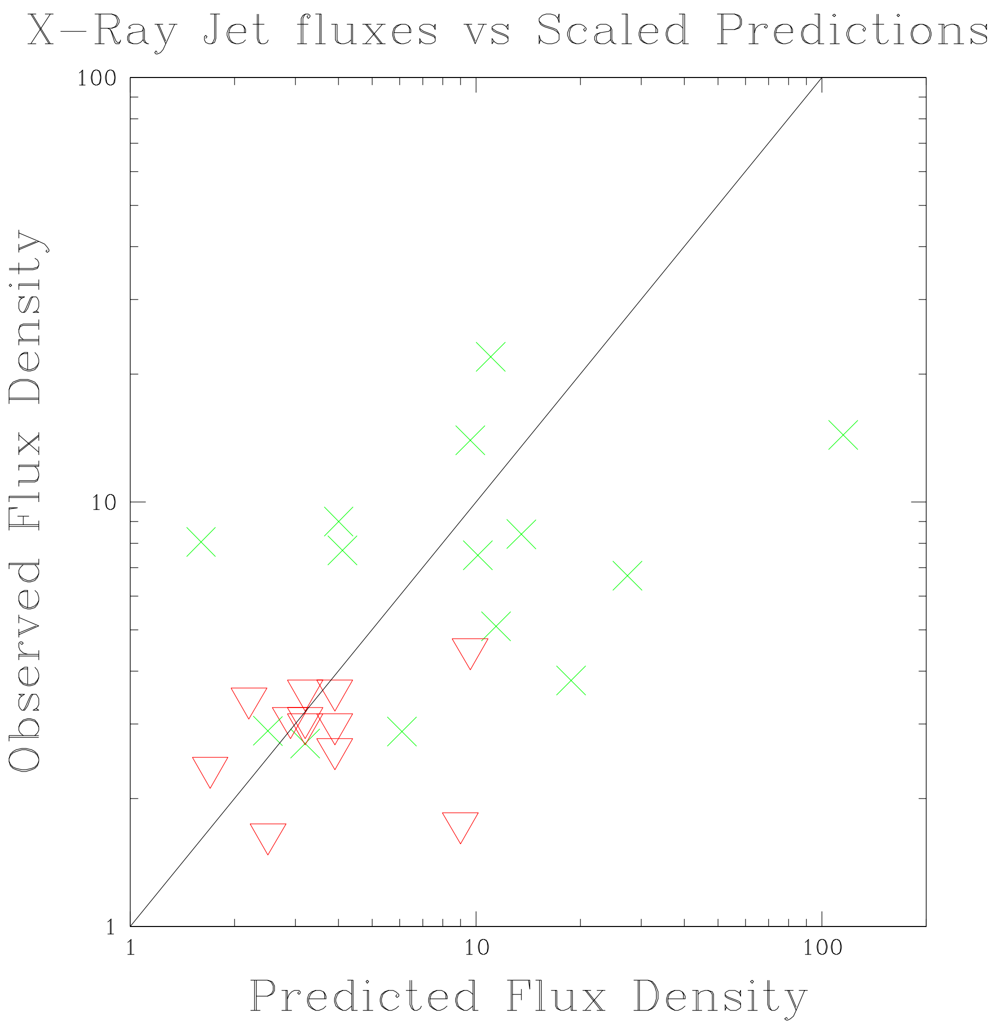


Siemiginowska et al., 2003ApJ...598L..15S

A Radio Selected Jet Sample

Marshall et al. 2005, ApJS, 156, 13

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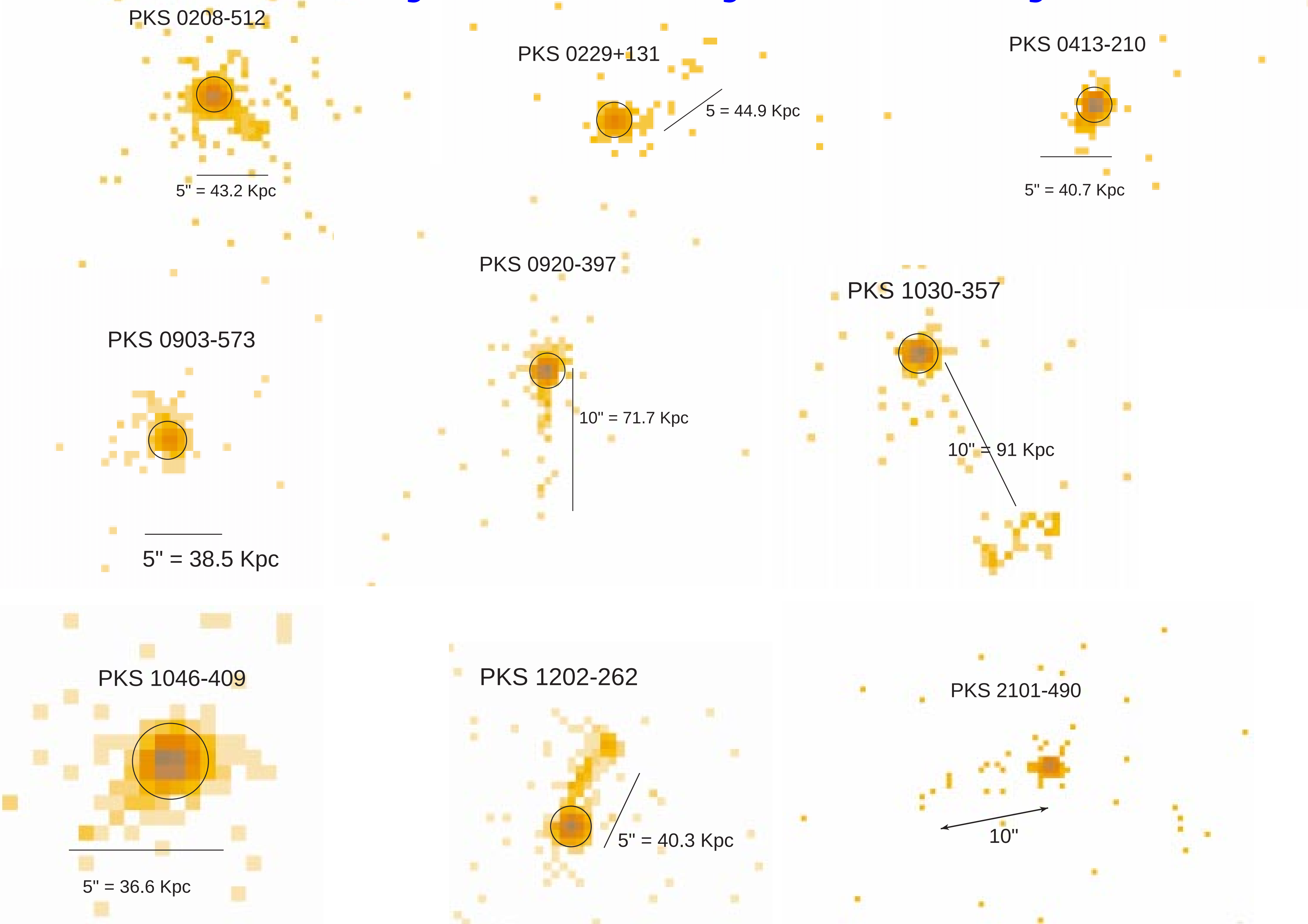
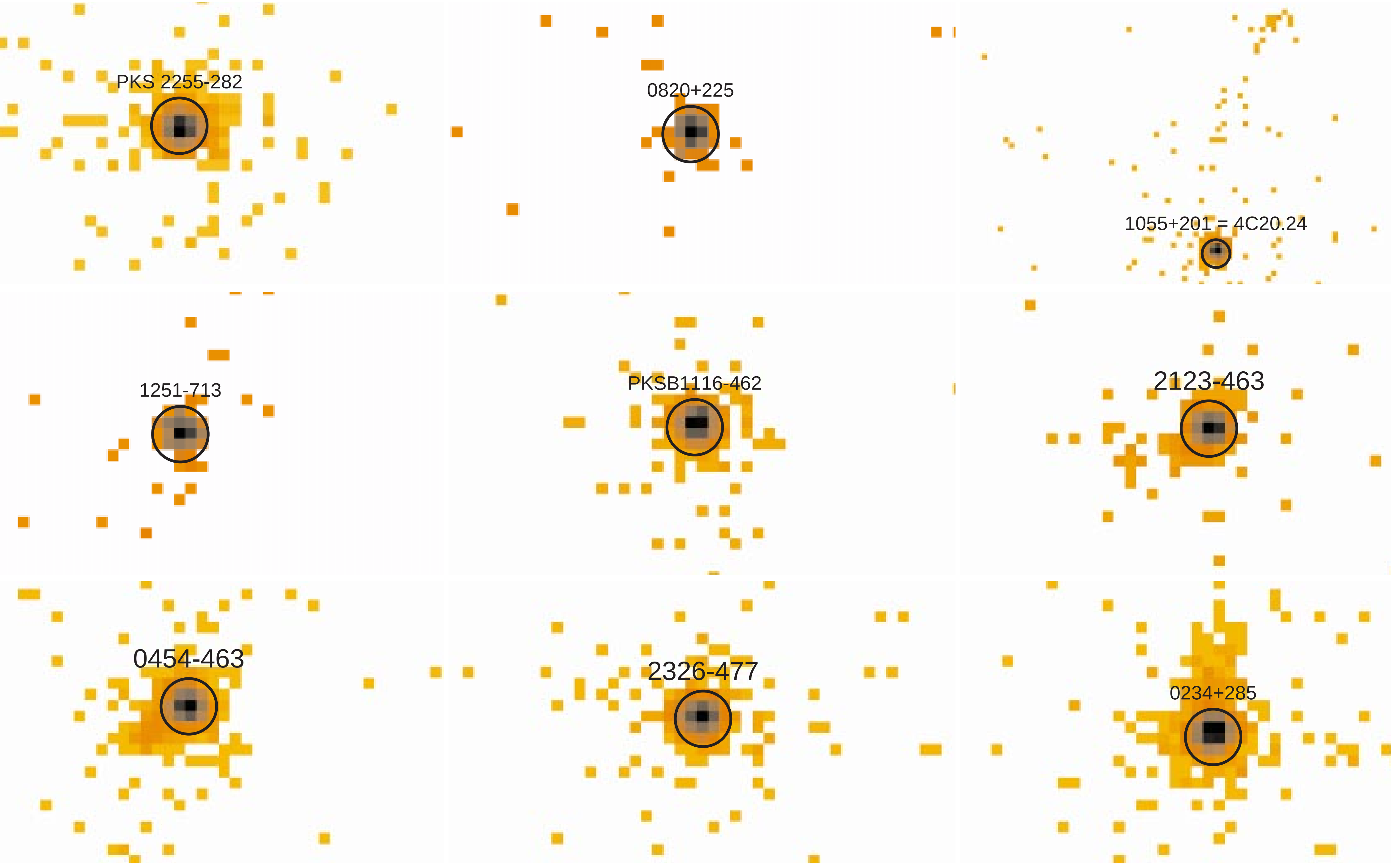
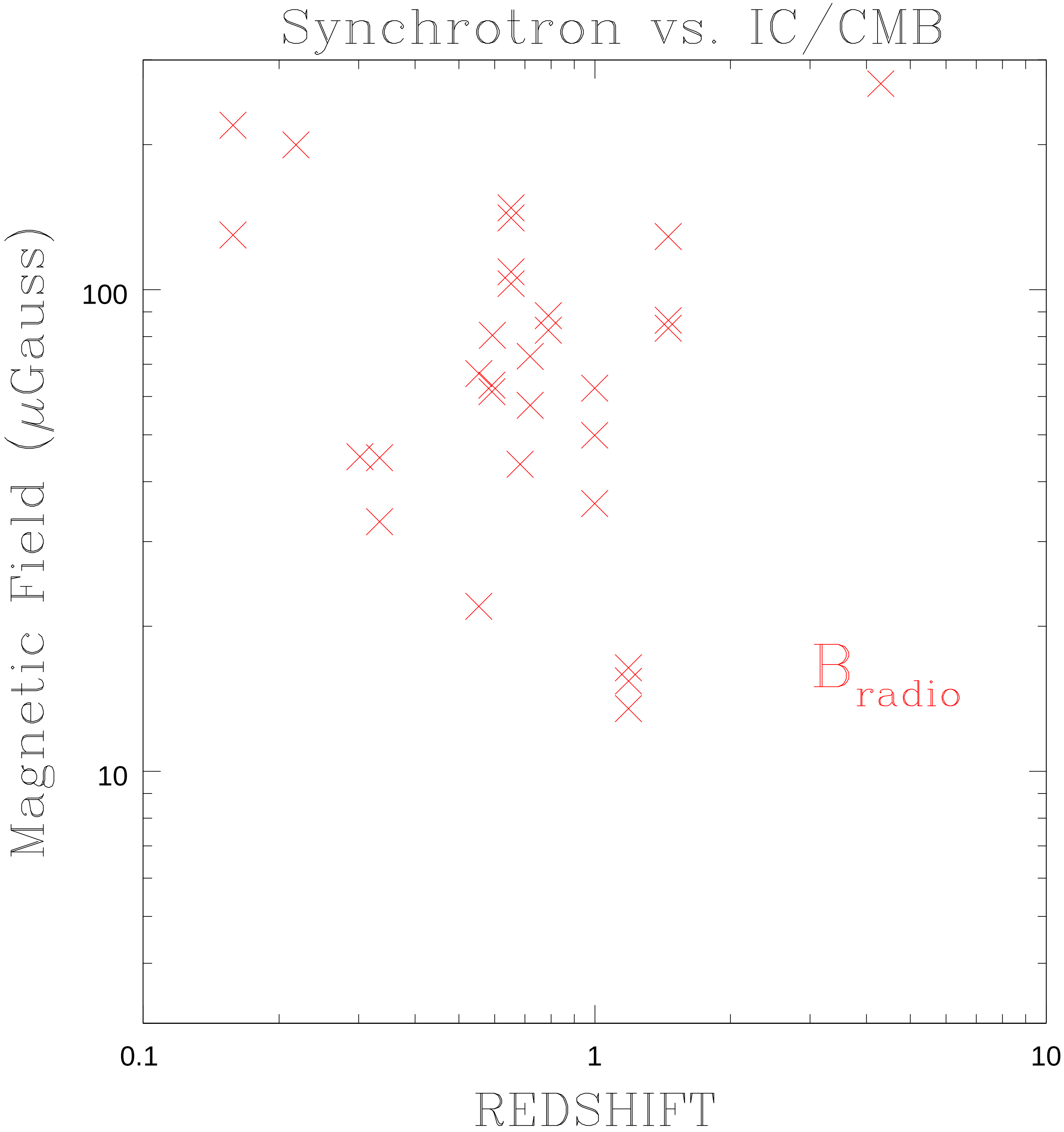
[a]Murphy, Browne & Perley 1993
[b]Lovell 1997

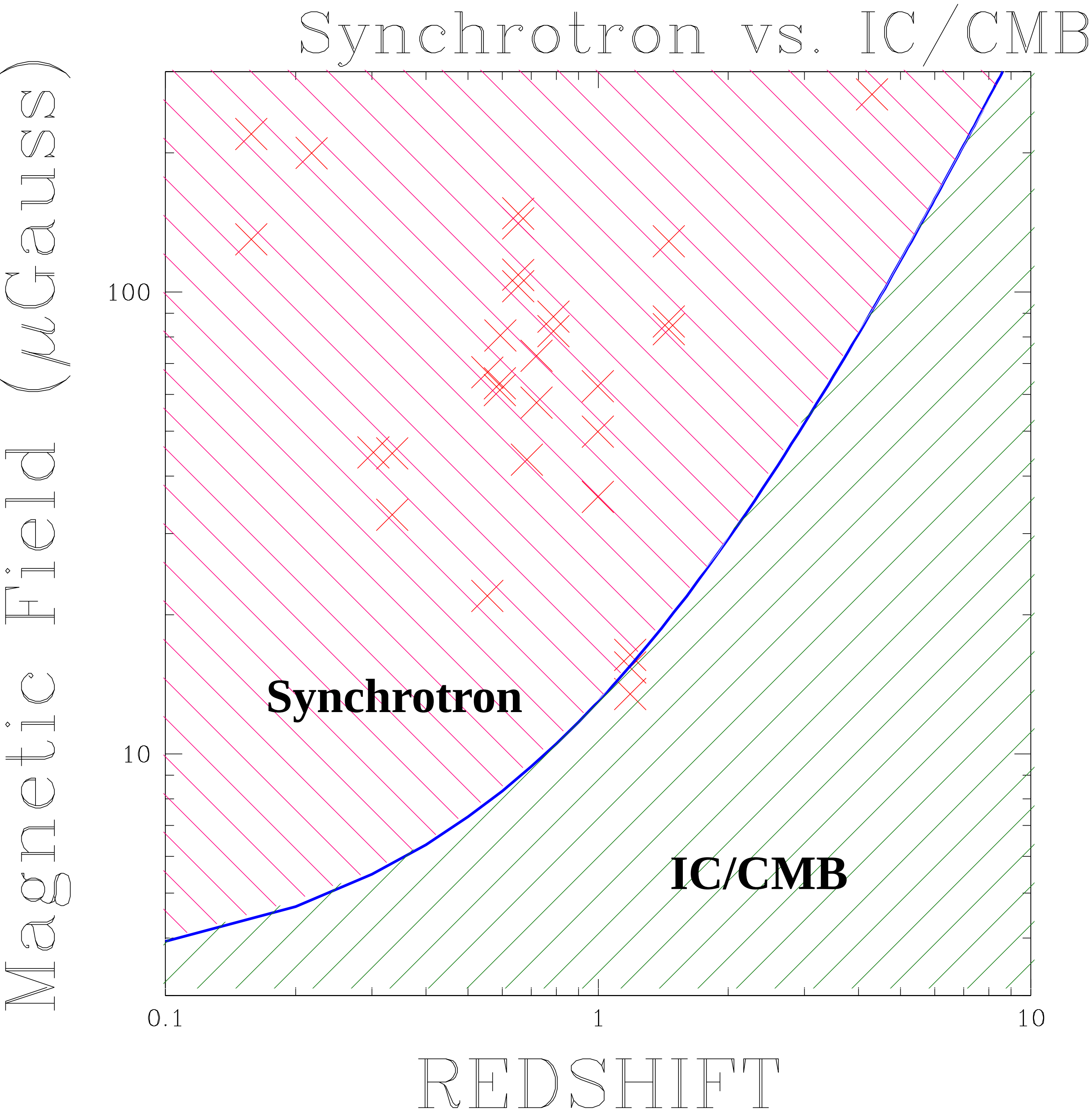
A Survey for X-ray Jets – Cycle 3

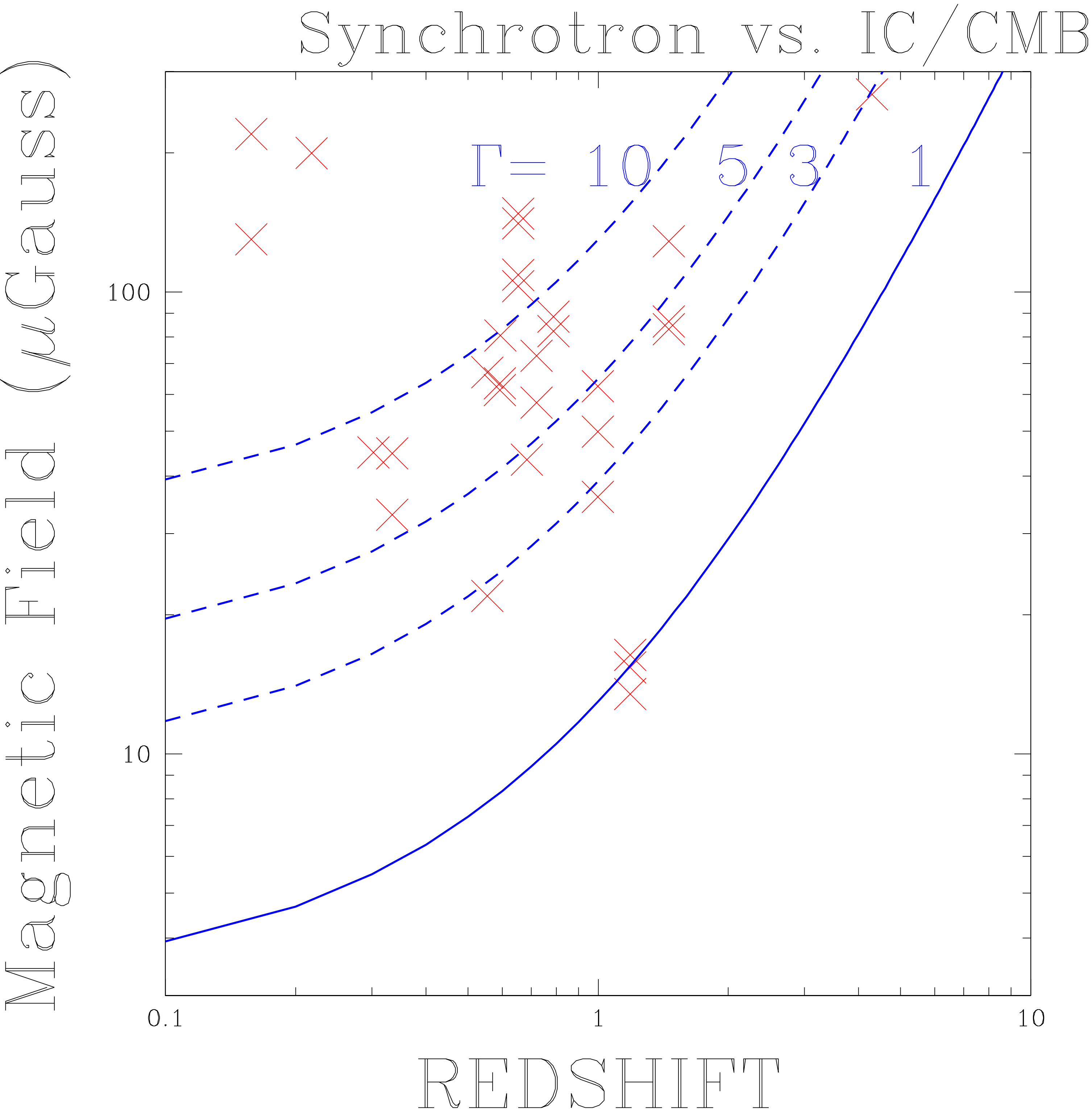


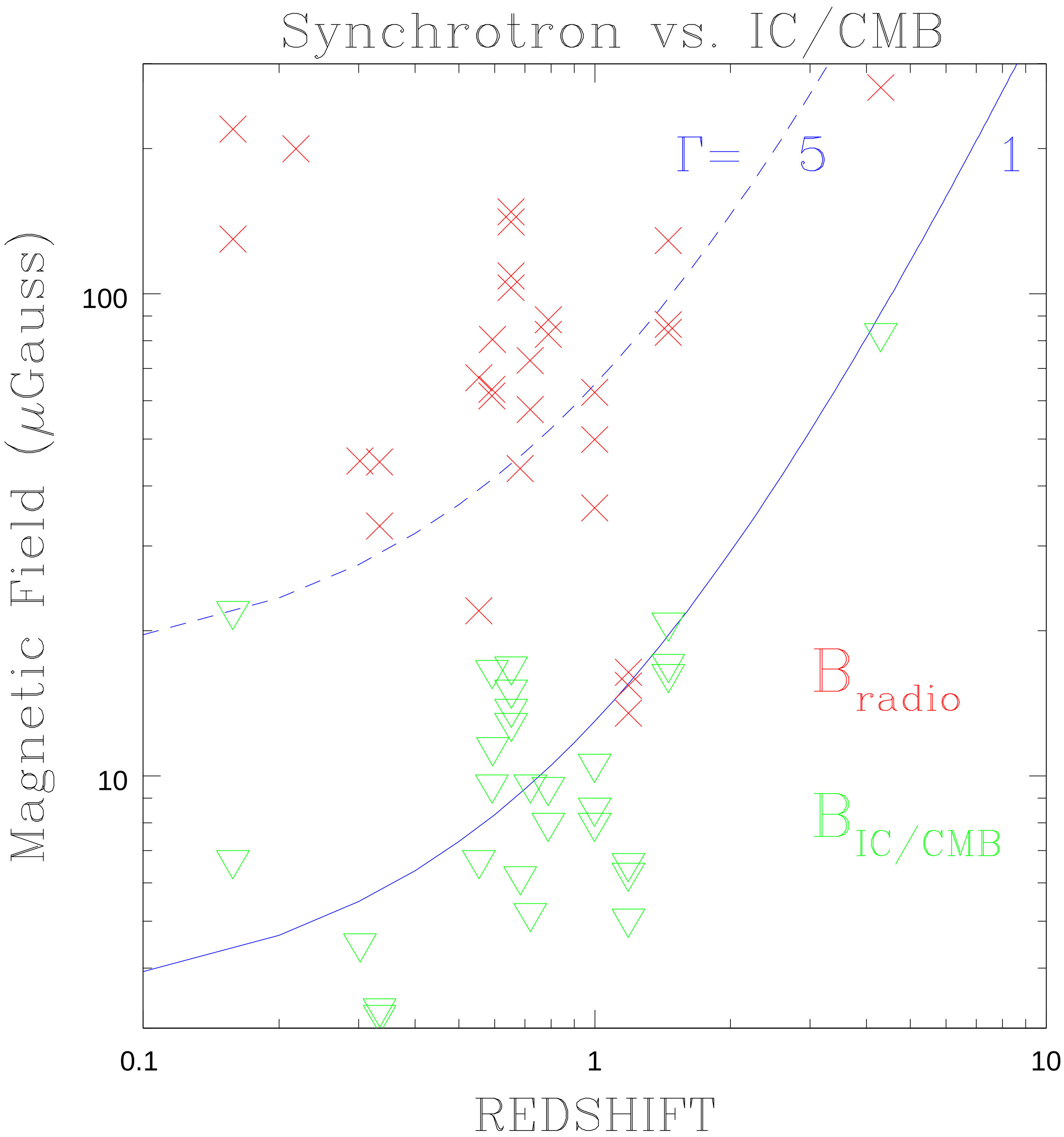
A Survey for X-ray Jets – Cycle 5




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

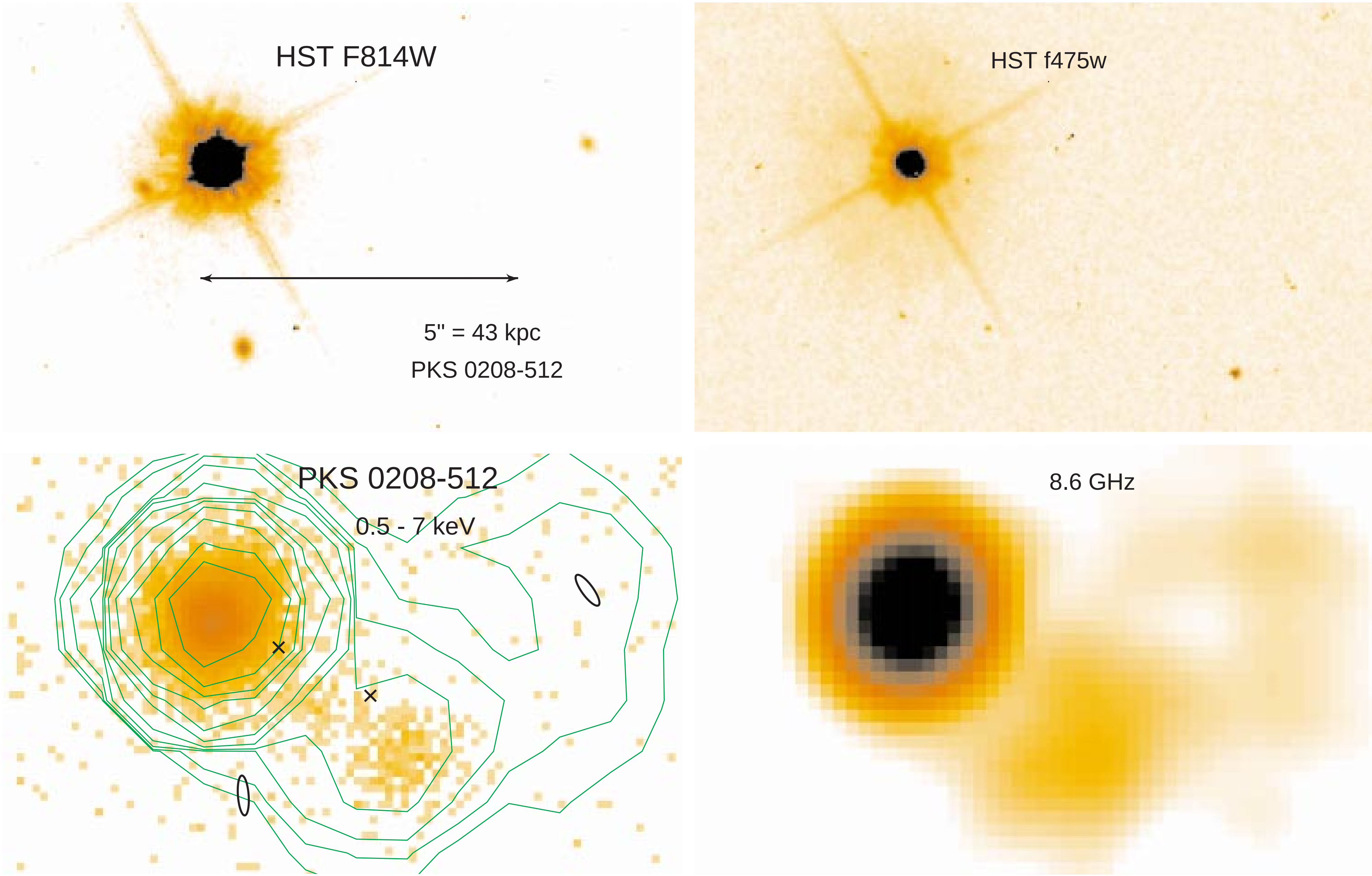

Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
Synchrotron
IC/CMB


Synchrotron vs. IC/CMB
Γ= 10 5 3 1
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT



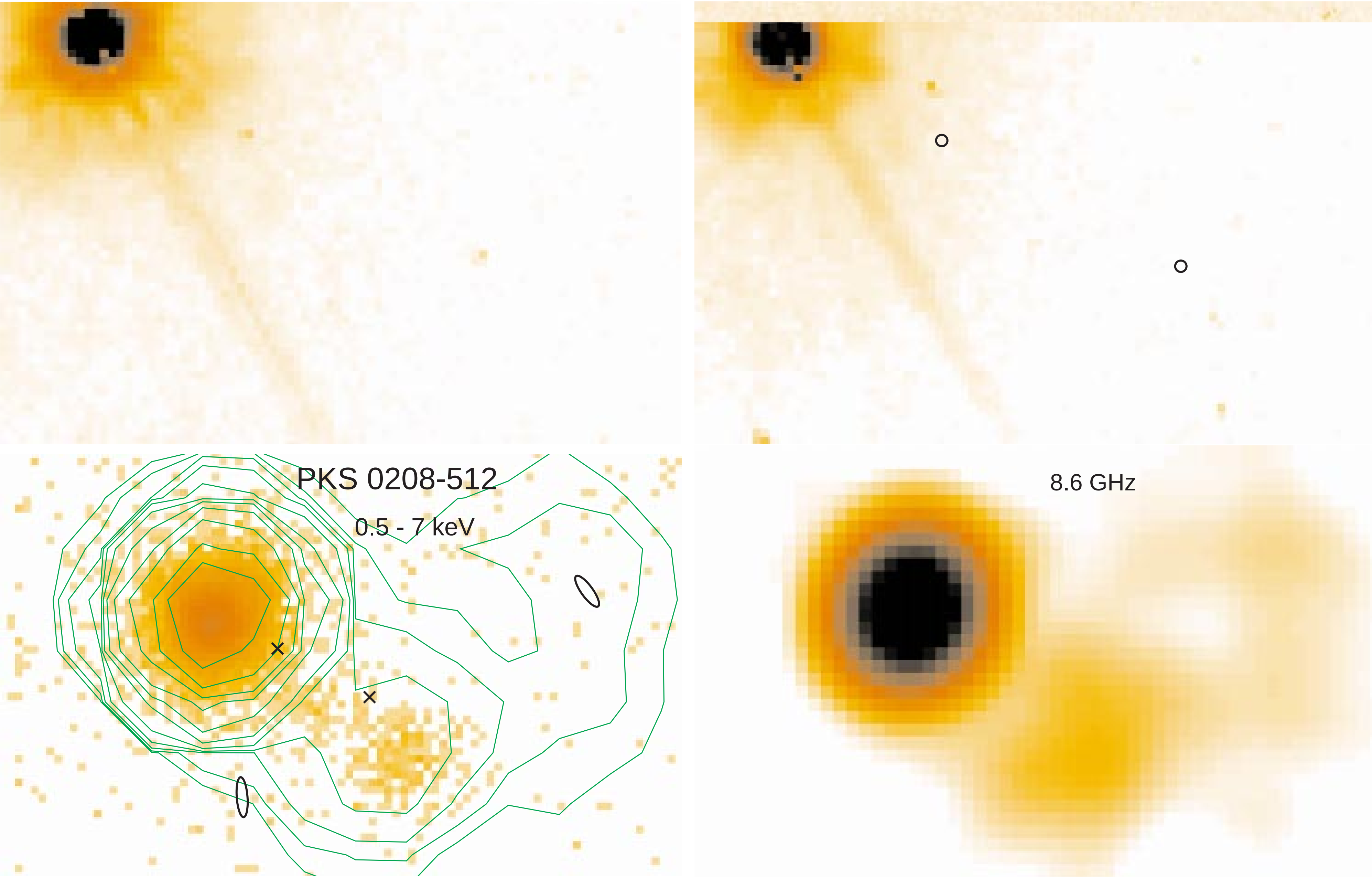
Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
Γ= 5
1
B radio
B IC/CMB

PKS 0208-512

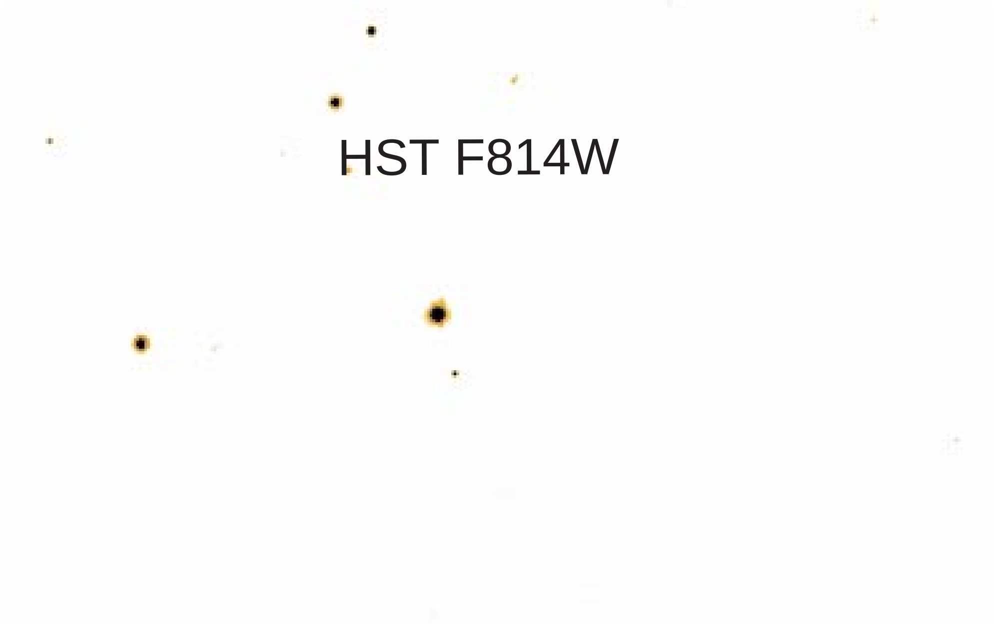


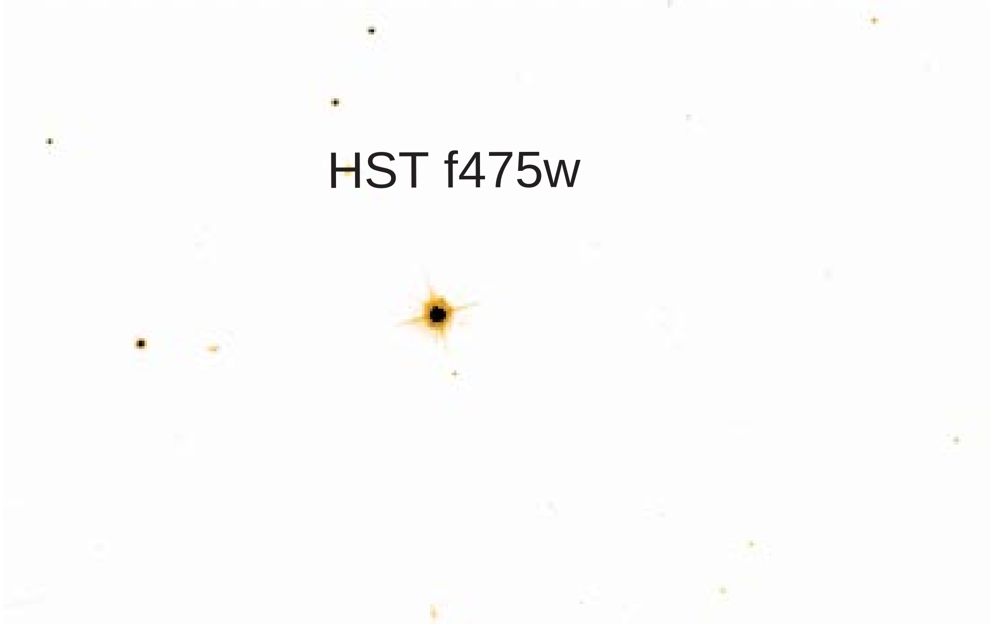
HST F814W
5" = 43 kpc
PKS 0208-512
HST f475w
PKS 0208-512
0.5 - 7 keV
8.6 GHz

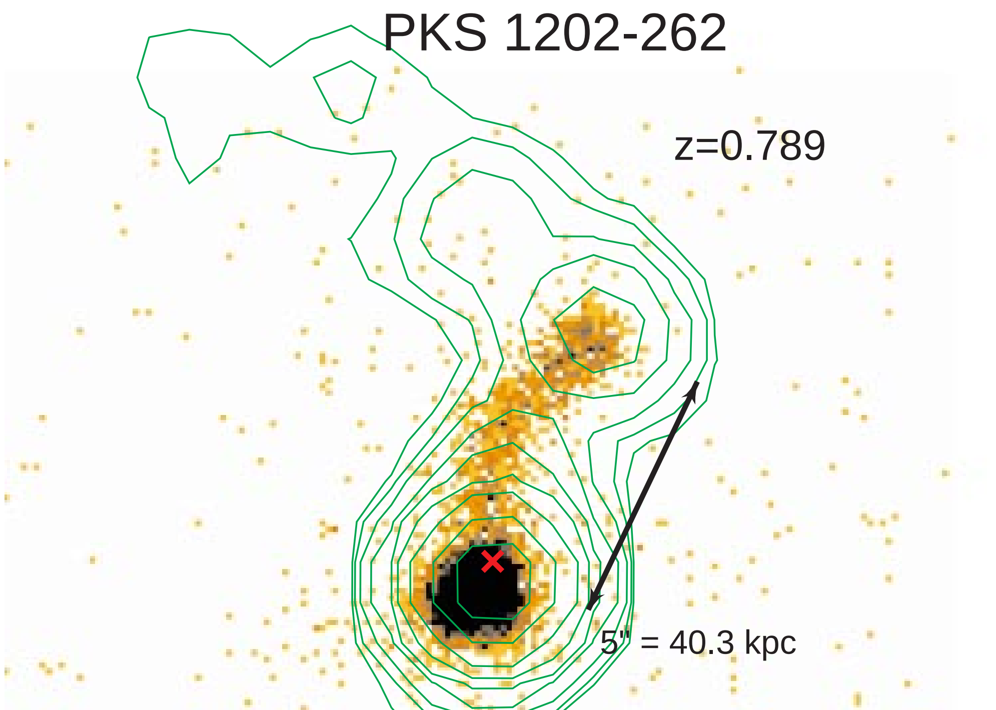
PKS 0208-512

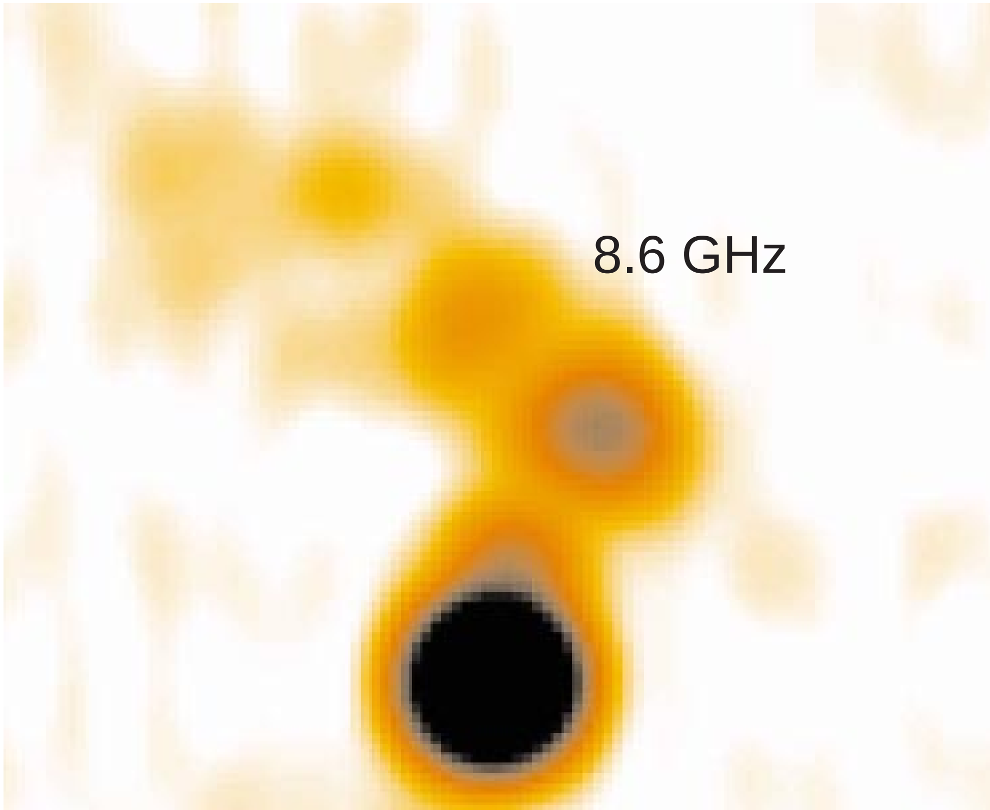


PKS 1202-262

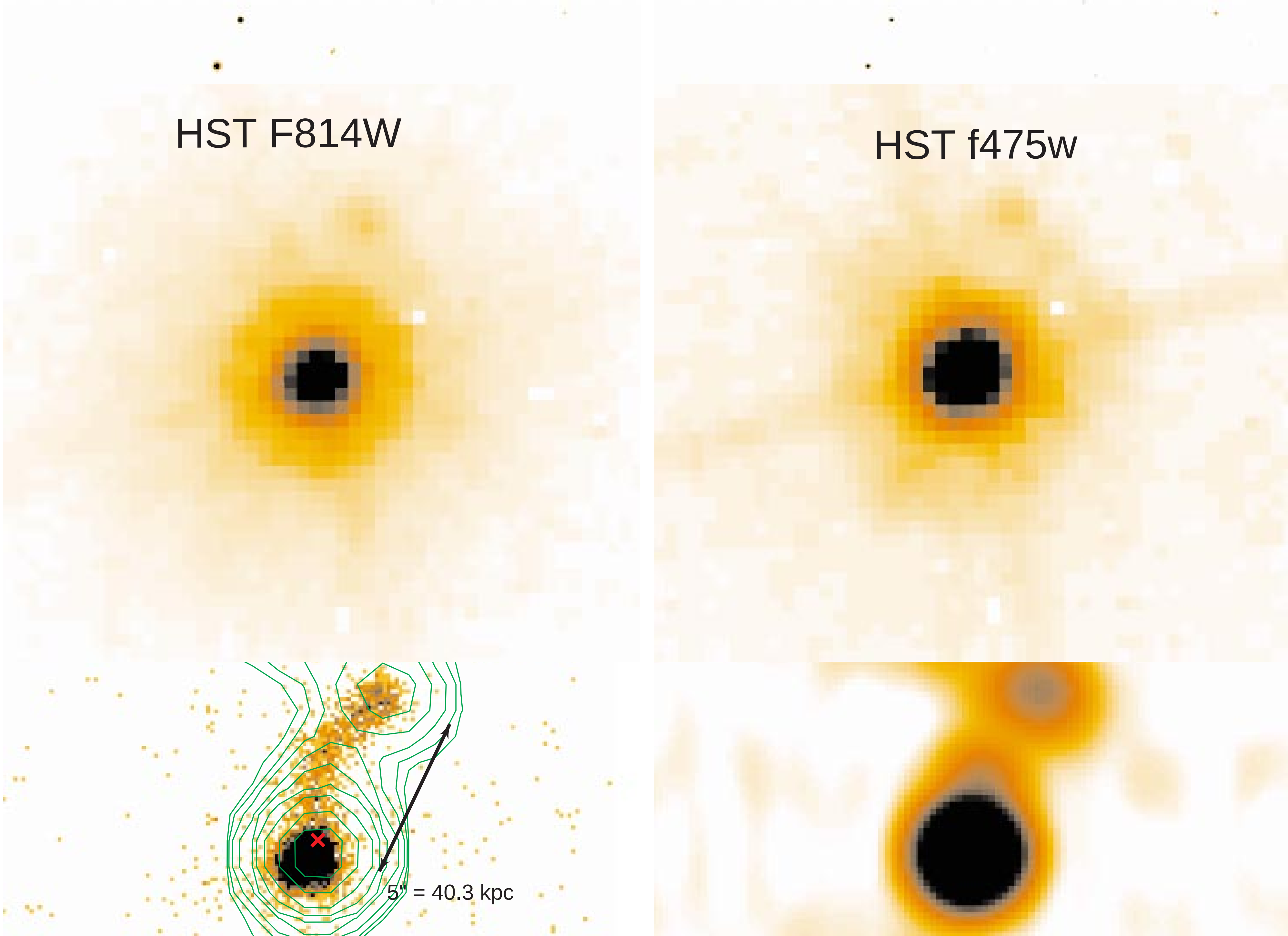




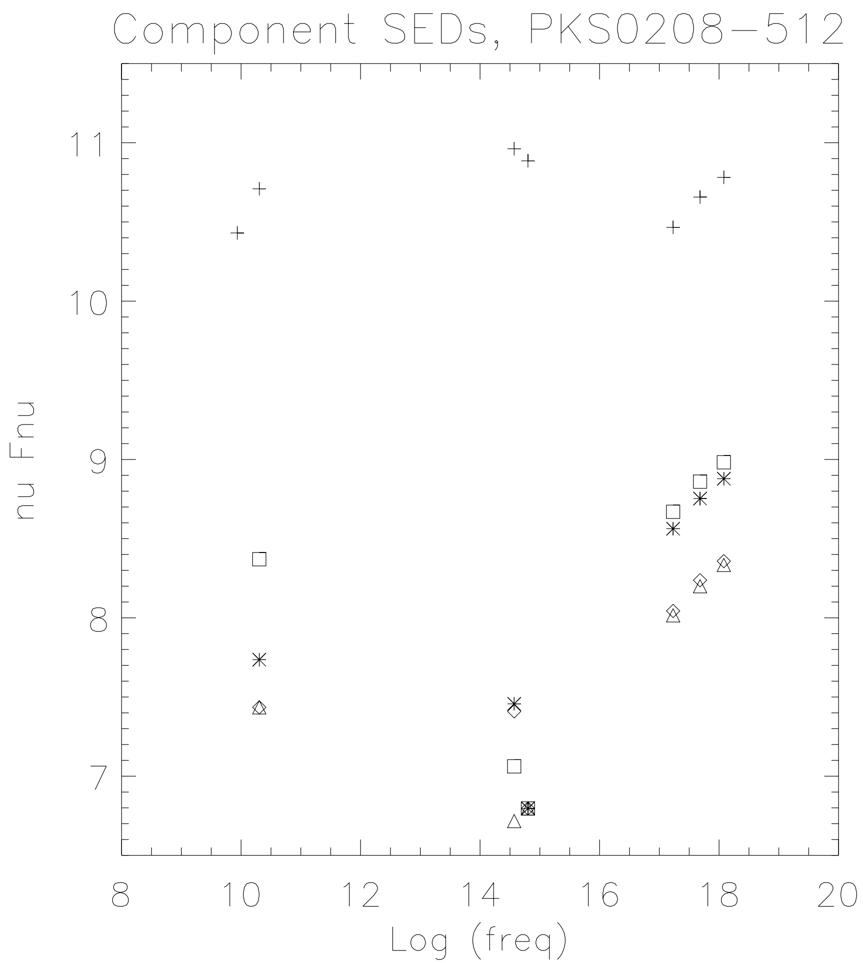


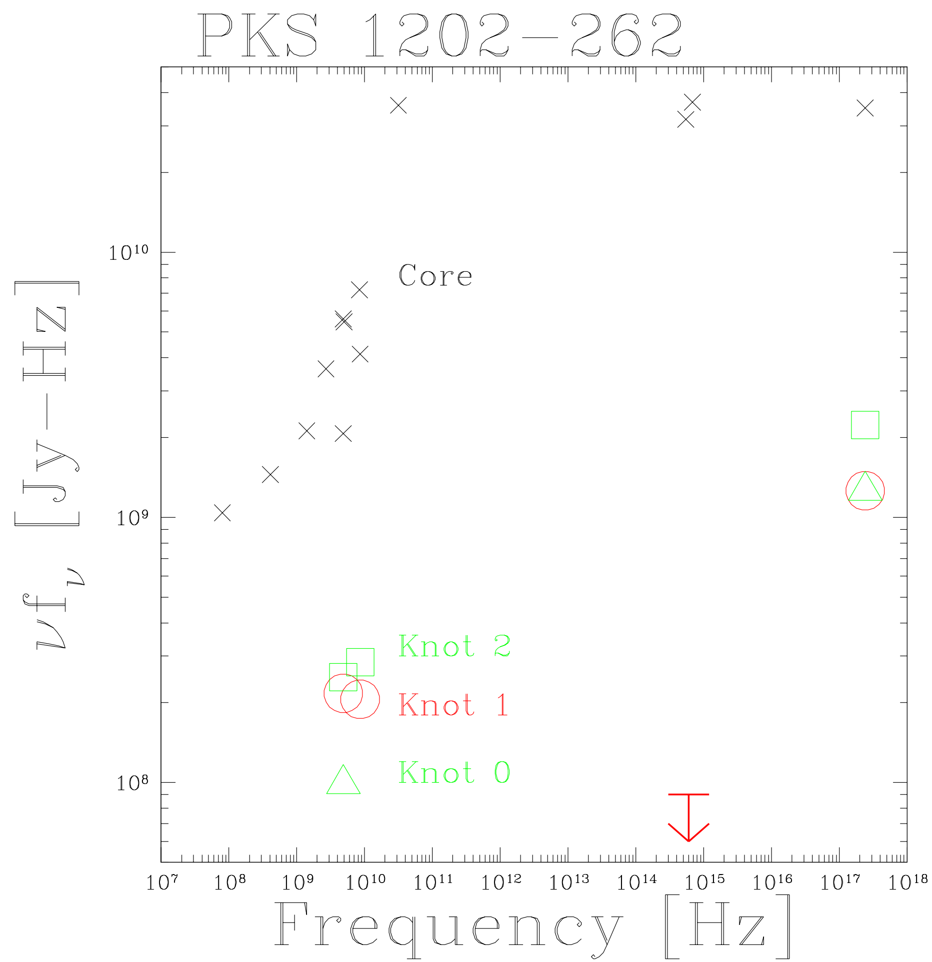


PKS 1202-262



Spectral Energy Distribution often indicates against Synchrotron X-rays





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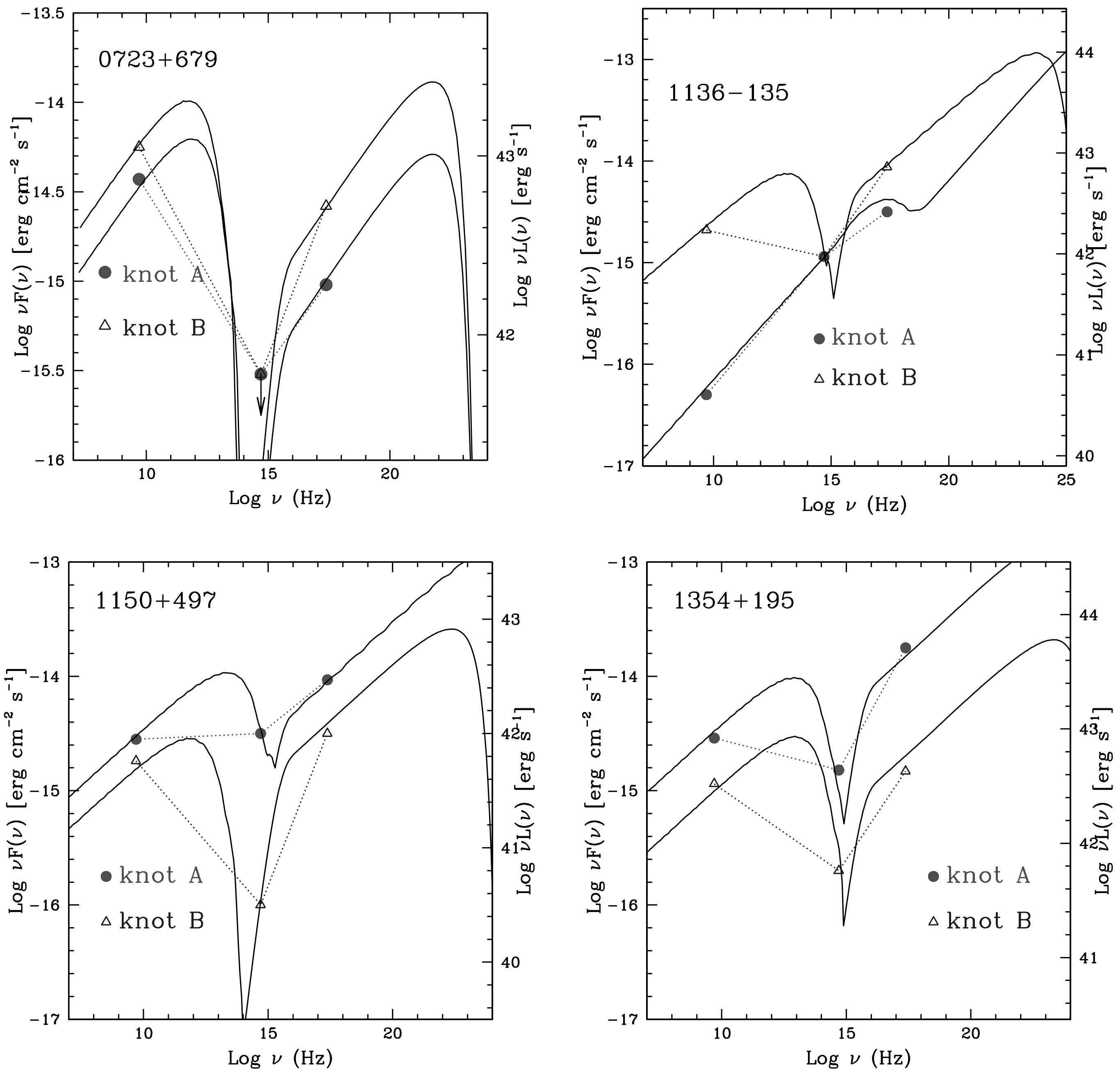
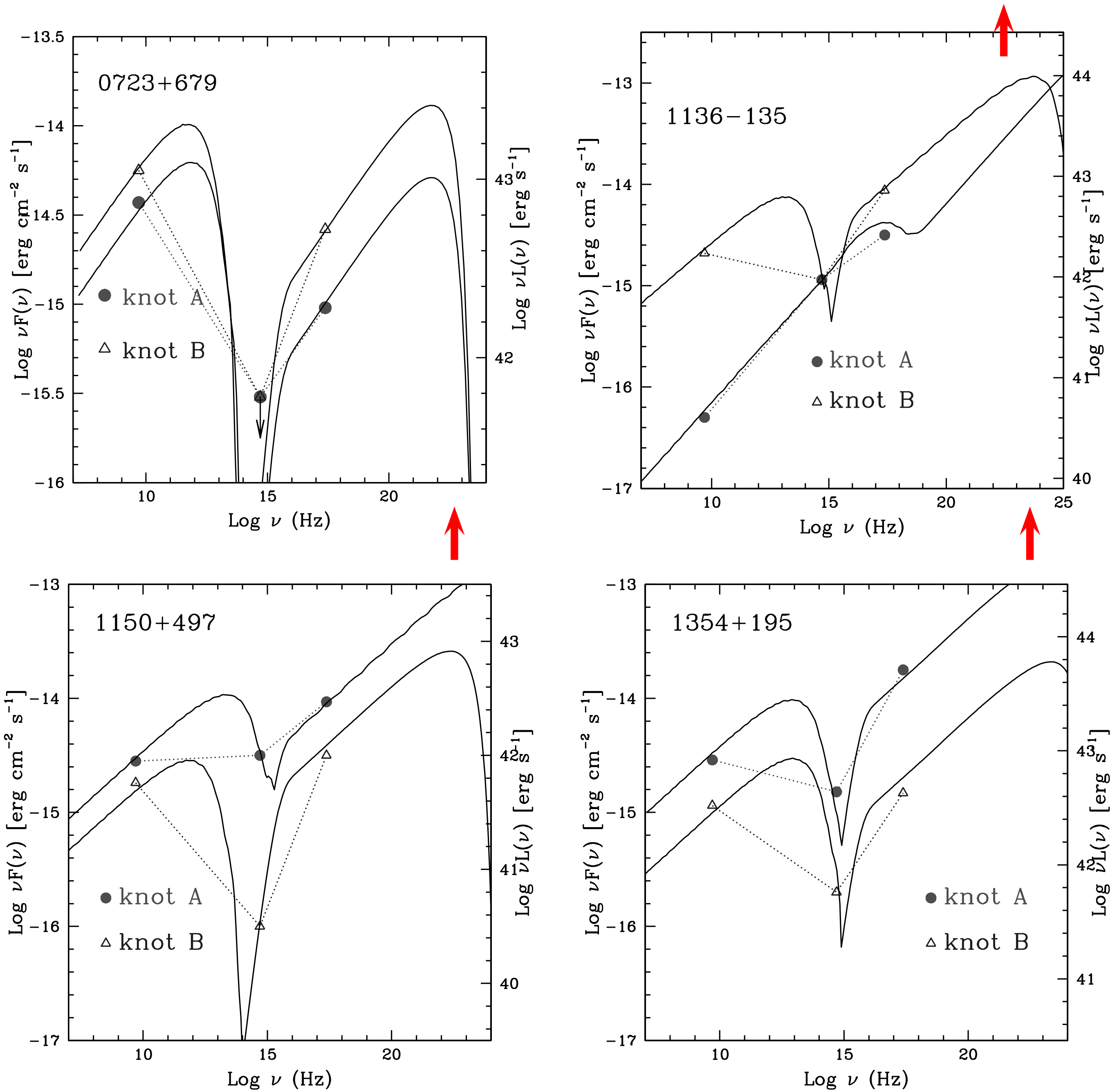


Sambruna et al., 2002ApJ...571..206S

Spectral Energy Distribution often indicates against Synchrotron X-rays



Inverse Compton X-rays from the CMB:

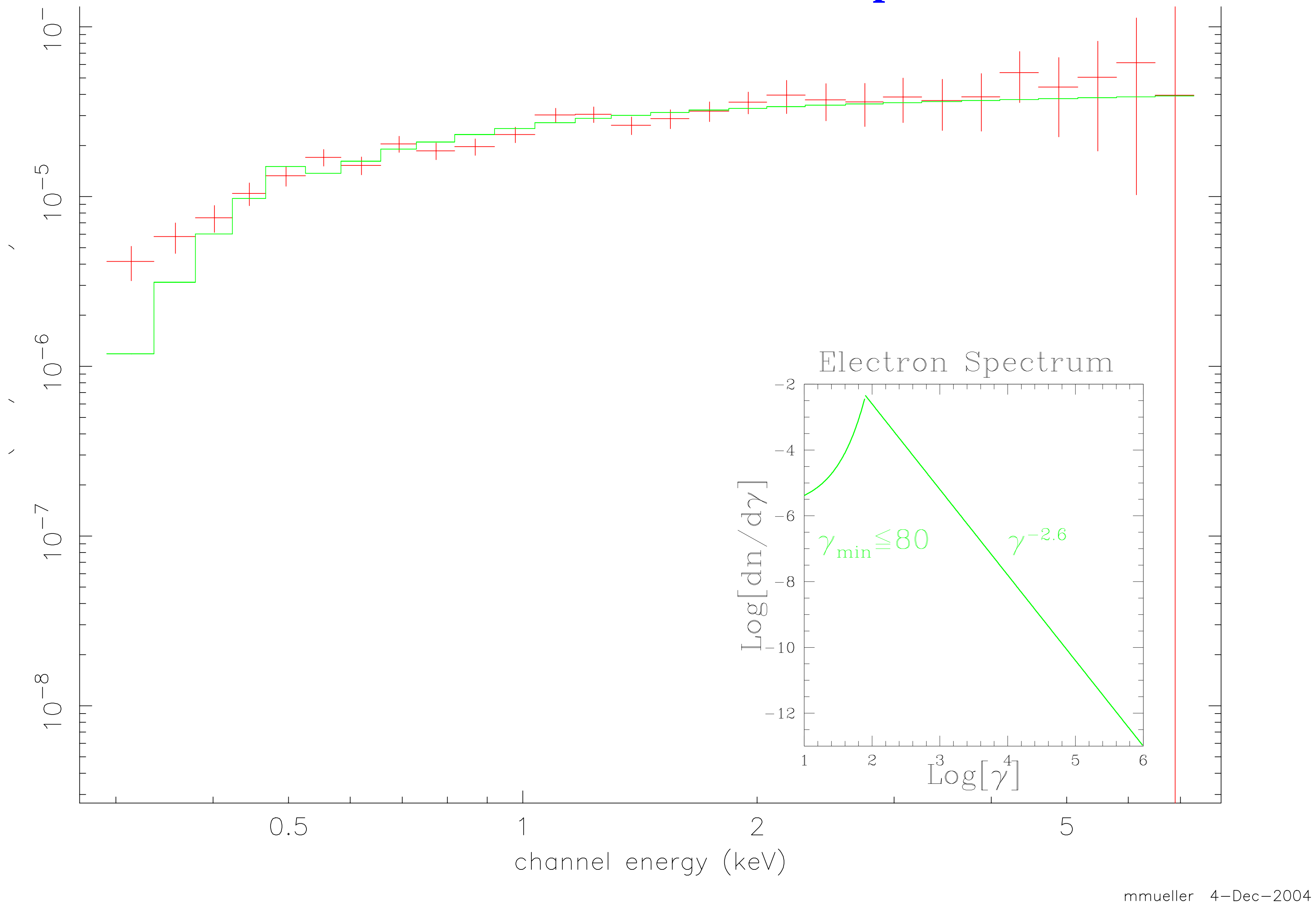
$$\gamma_x \approx 10^{2-3}$$

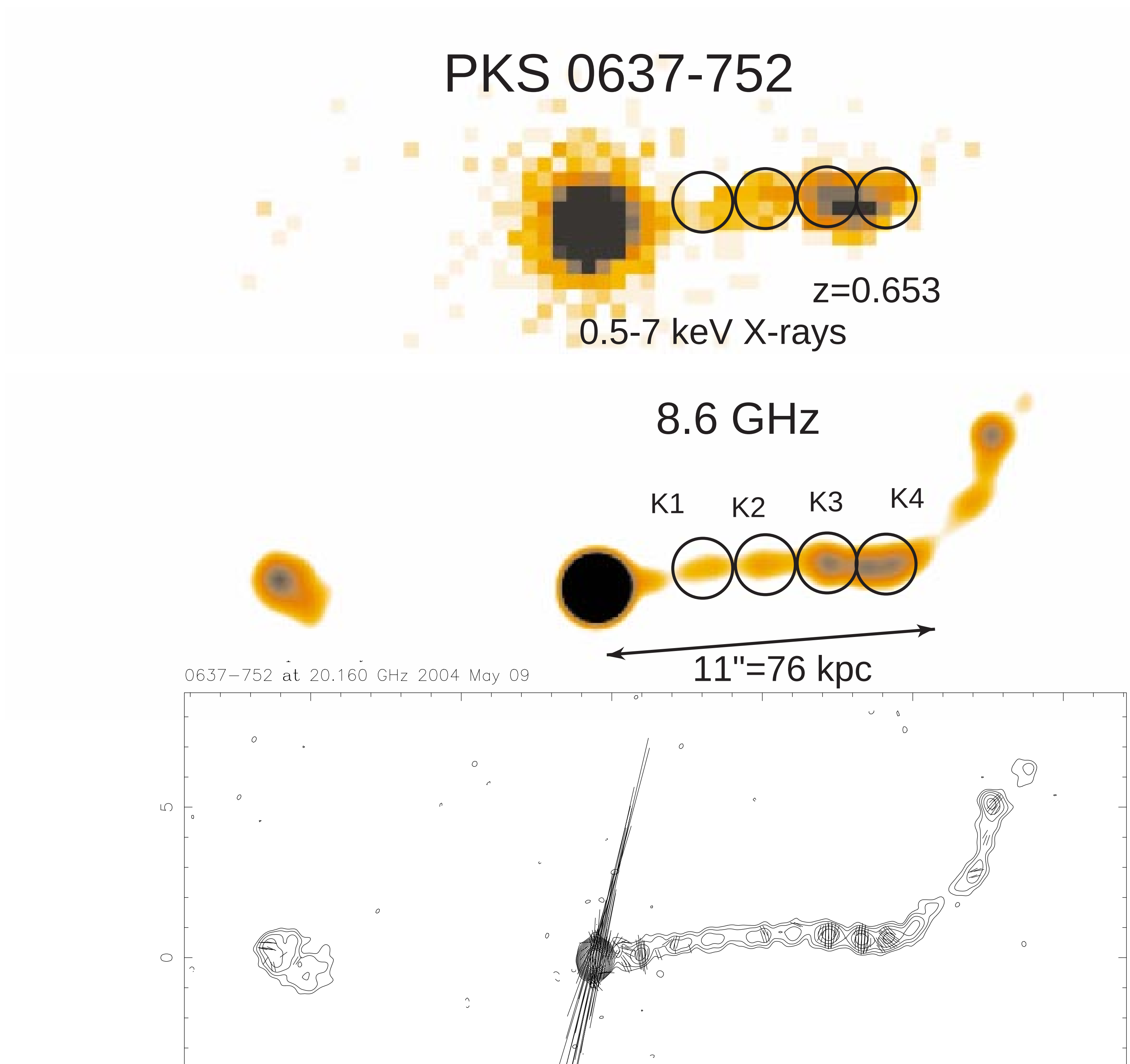
$$\gamma_r \approx 10^{4-5}$$

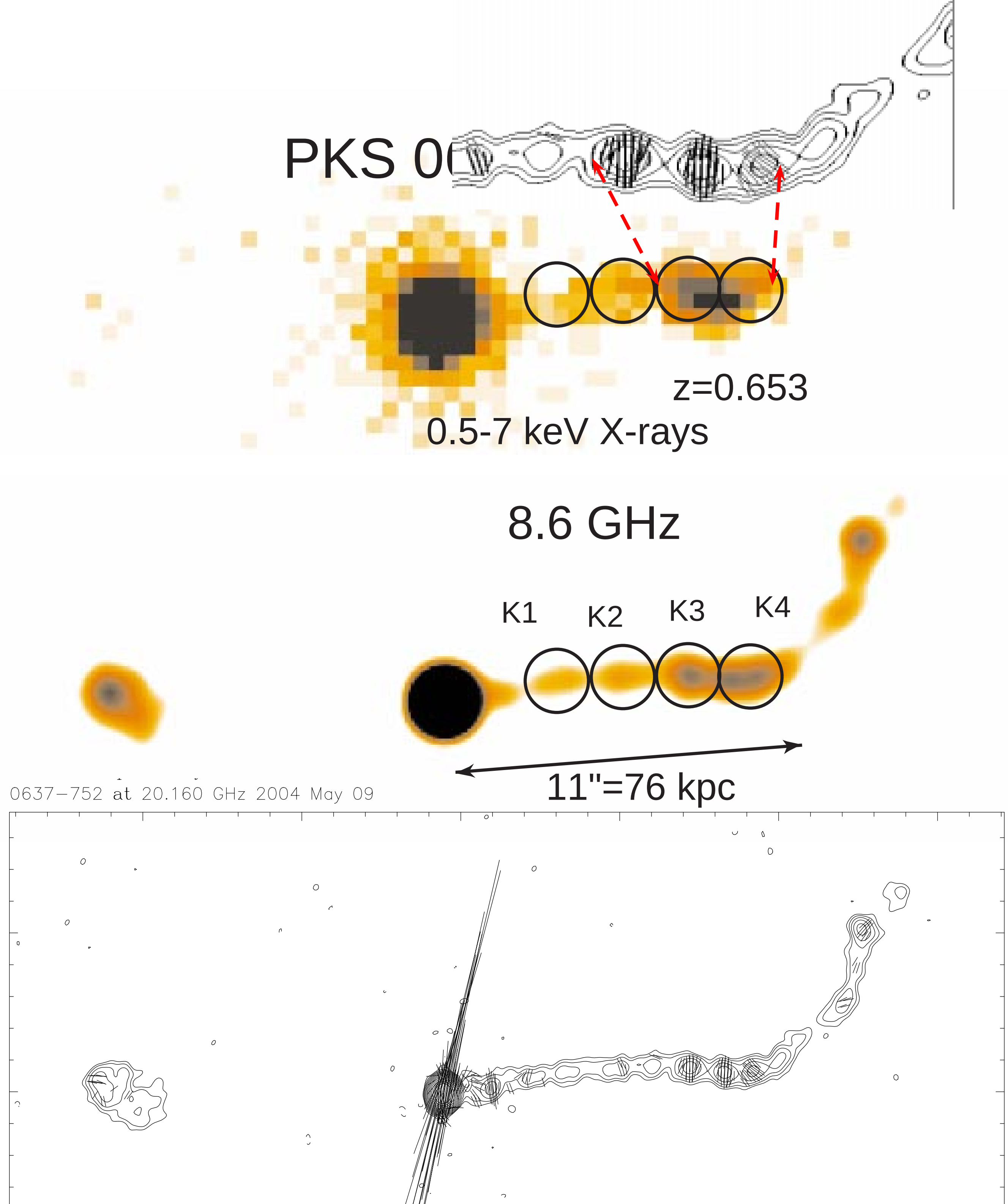
Some kpc scale jets may be detectable by GLAST, at 10^{-13} to 10^{-12} ergs cm^{-2} s^{-1}

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

PKS 0637-752 Jet Spectrum




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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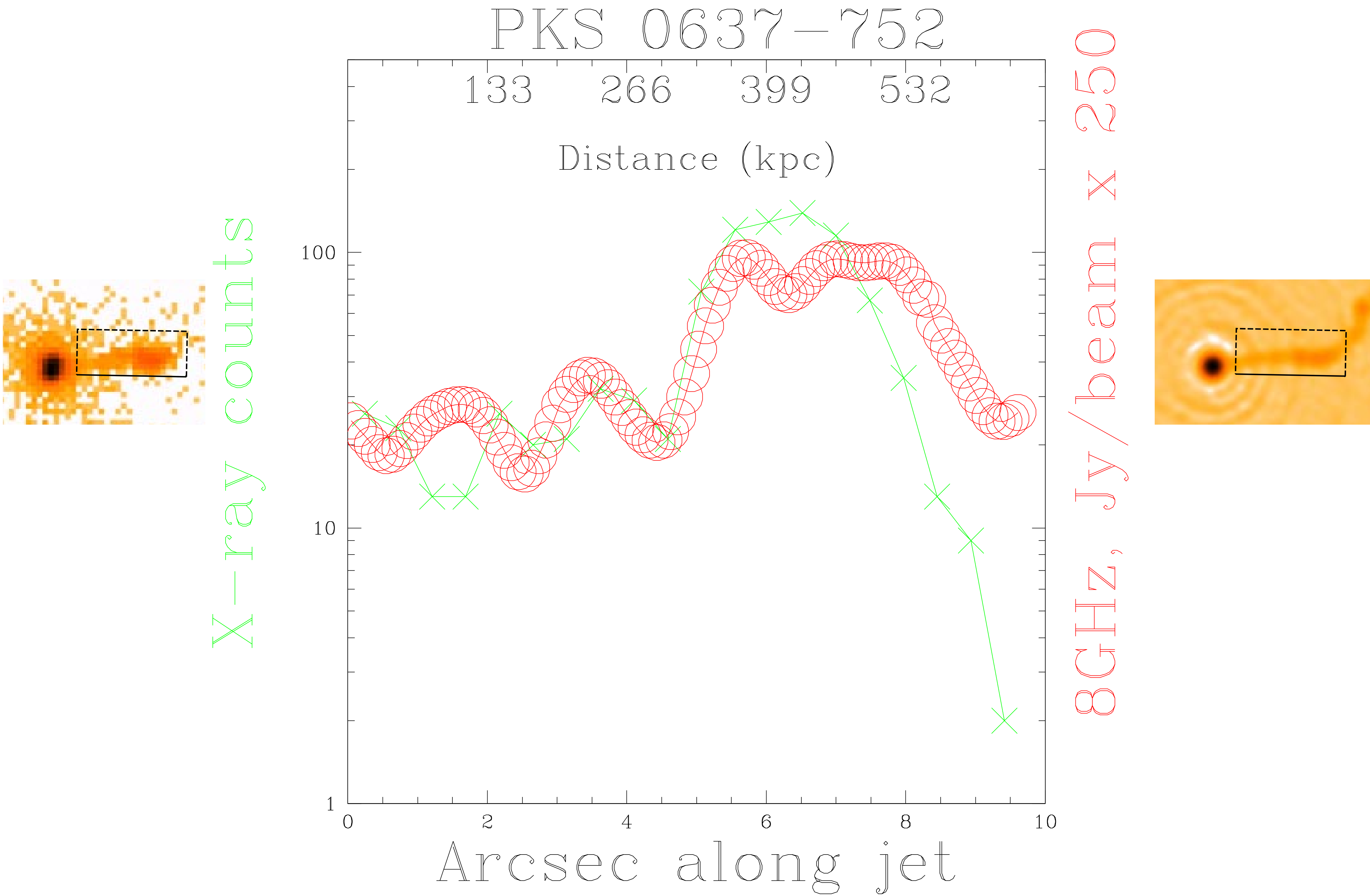
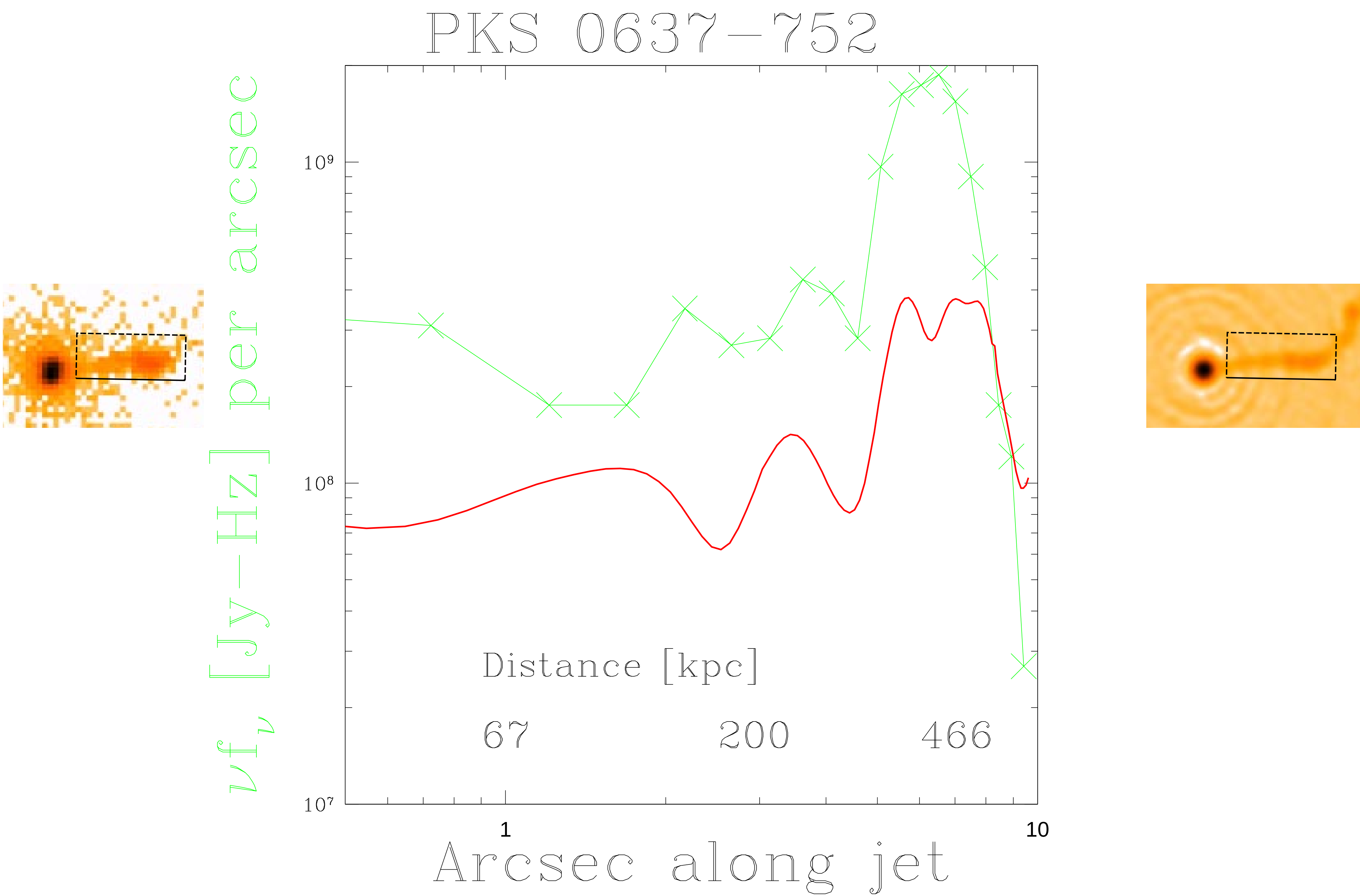
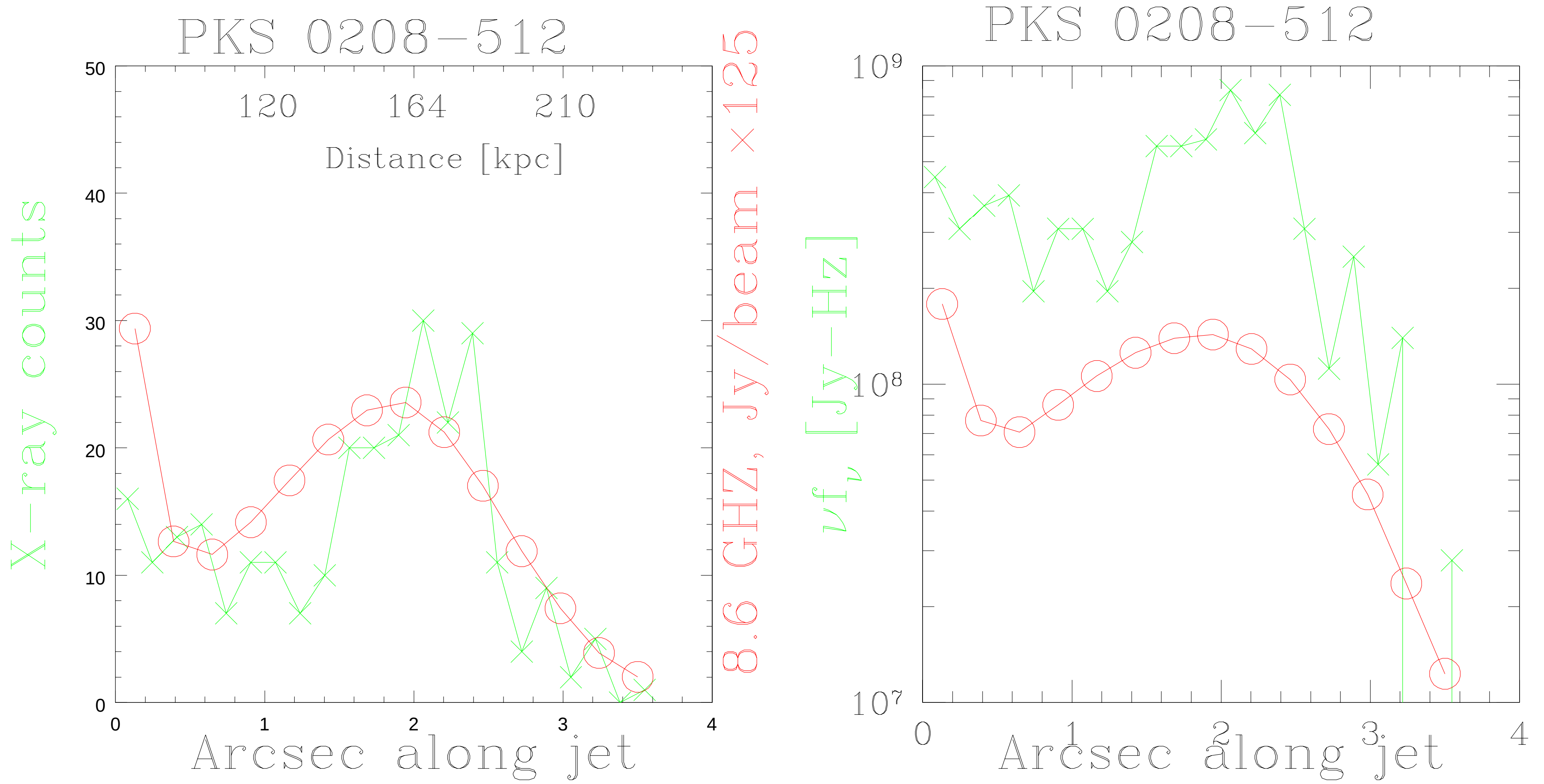
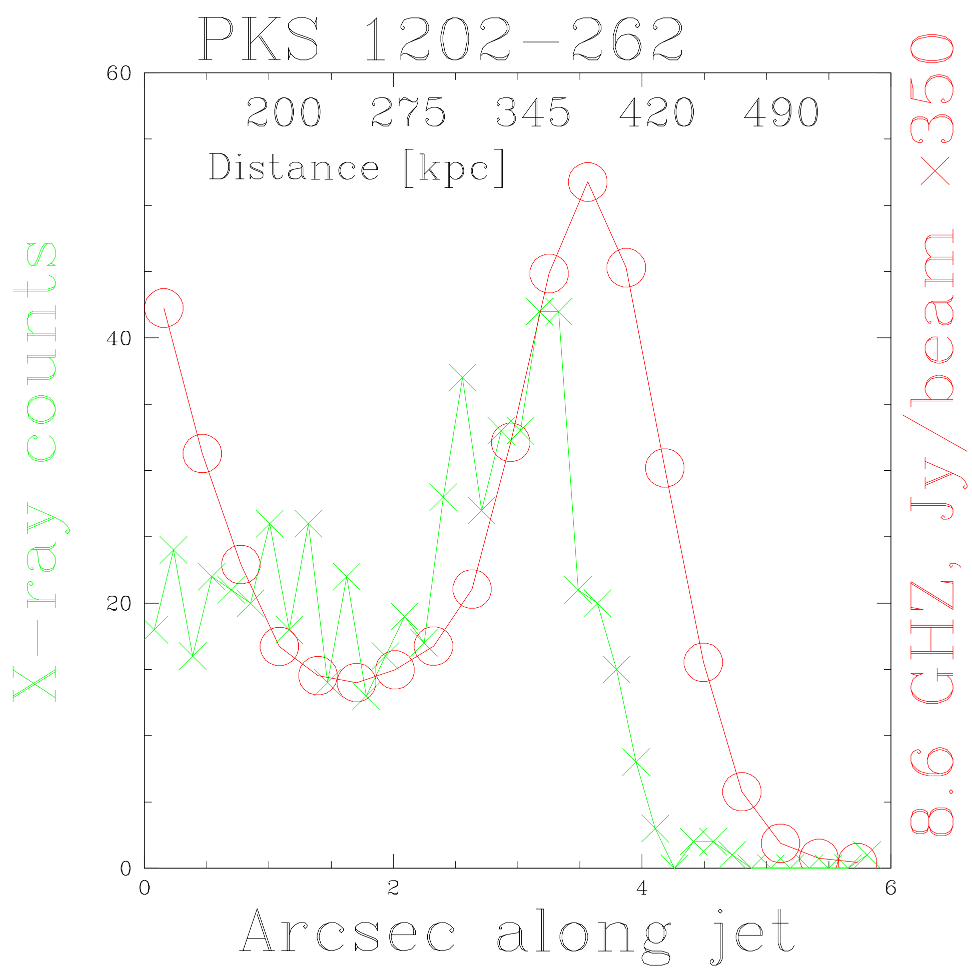


PKS 0637−752
133
266
399
532
Distance (kpc)
100
10
1
0
2
4
6
8
10
Arcsec along jet
X−ray counts
8GHz, Jy/beam x 250

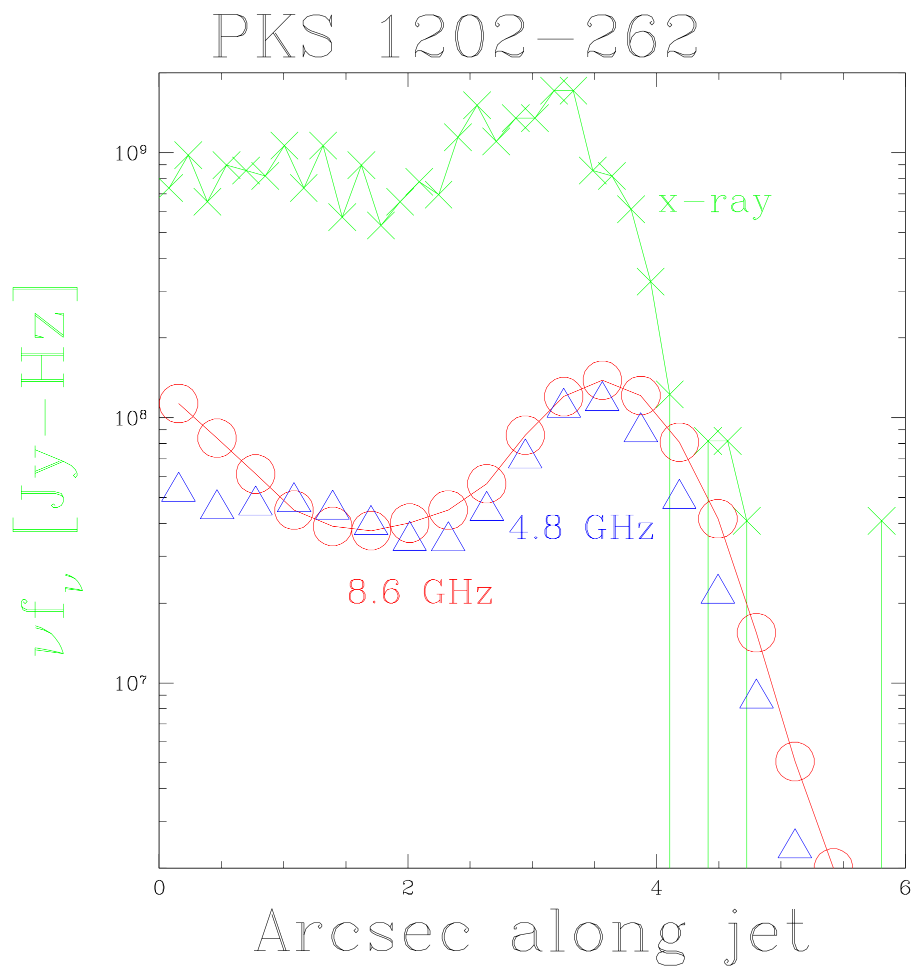

PKS 0637−752
νf_ν [Jy−Hz] per arcsec
10^9
10^8
10^7
1
10
Distance [kpc]
67
200
466
Arcsec along jet



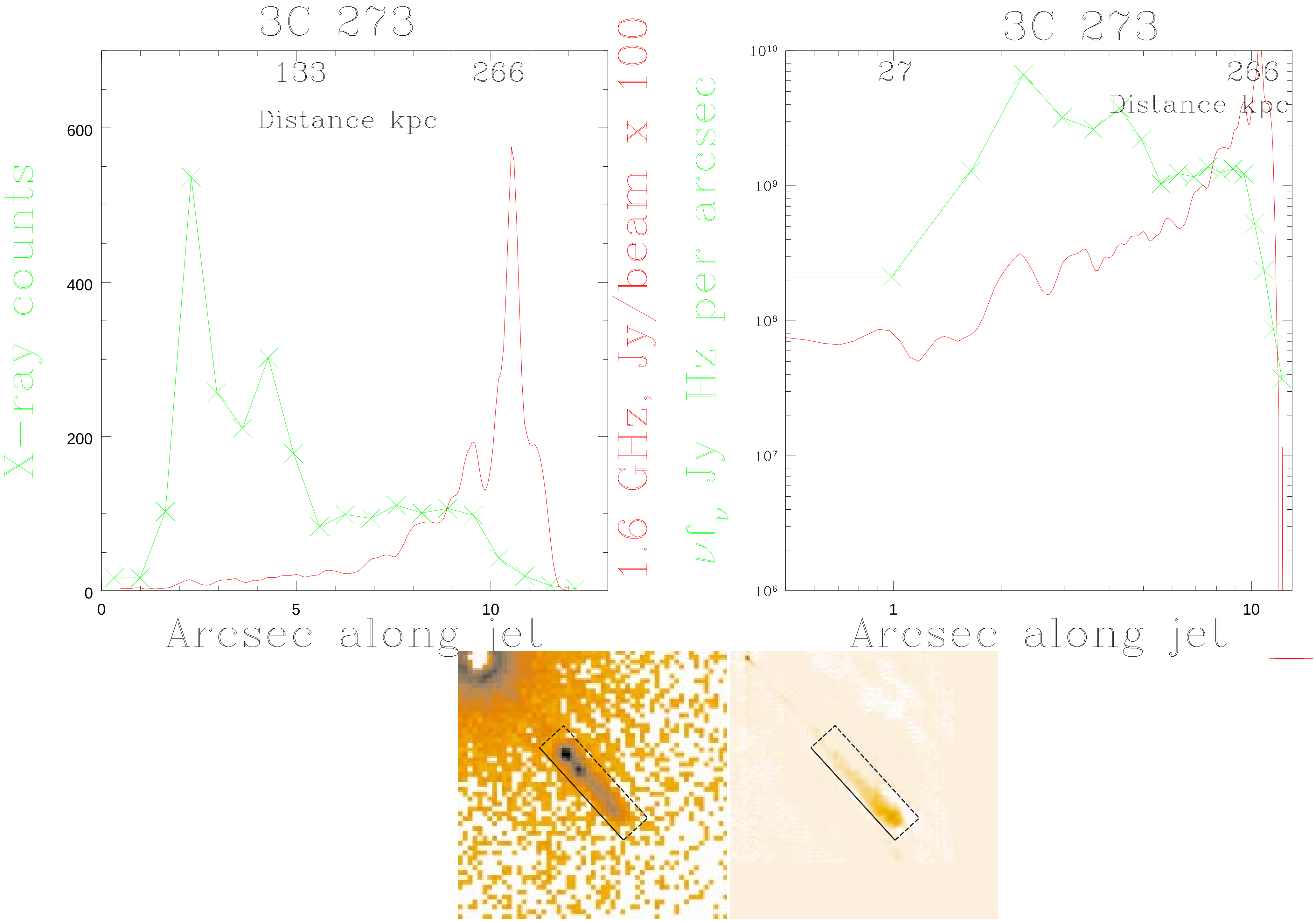
PKS 0208−512
X-ray counts
8.6 GHZ, Jy/beam ×125
Distance [kpc]
120
164
210
0
10
20
30
40
50
0
1
2
3
4
Arcsec along jet
PKS 0208−512
νf_ν [Jy-Hz]
10^9
10^8
10^7
0
1
2
3
4
Arcsec along jet



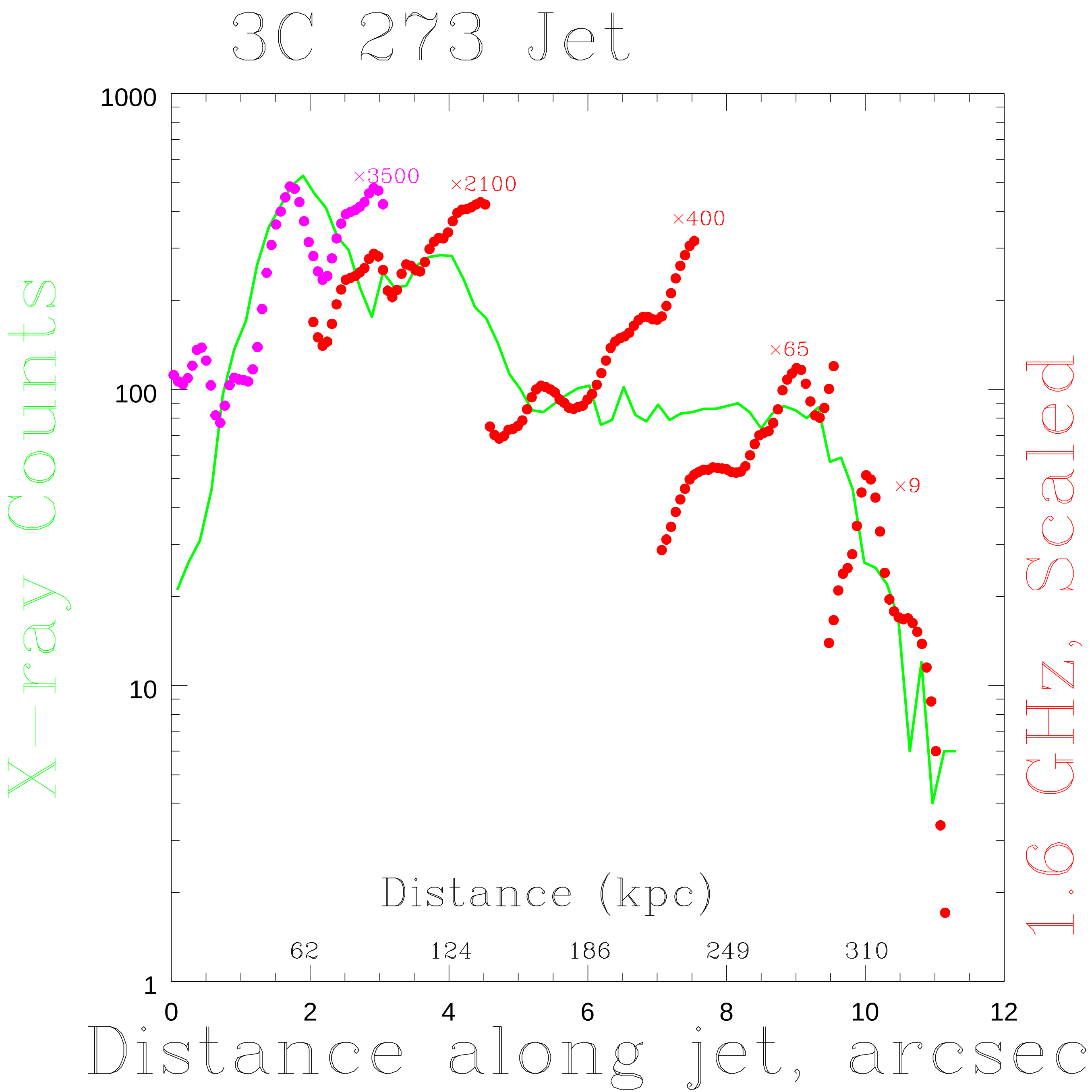
PKS 1202−262
200 275 345 420 490
Distance [kpc]
X−ray counts
8.6 GHZ, Jy/beam ×350
Arcsec along jet



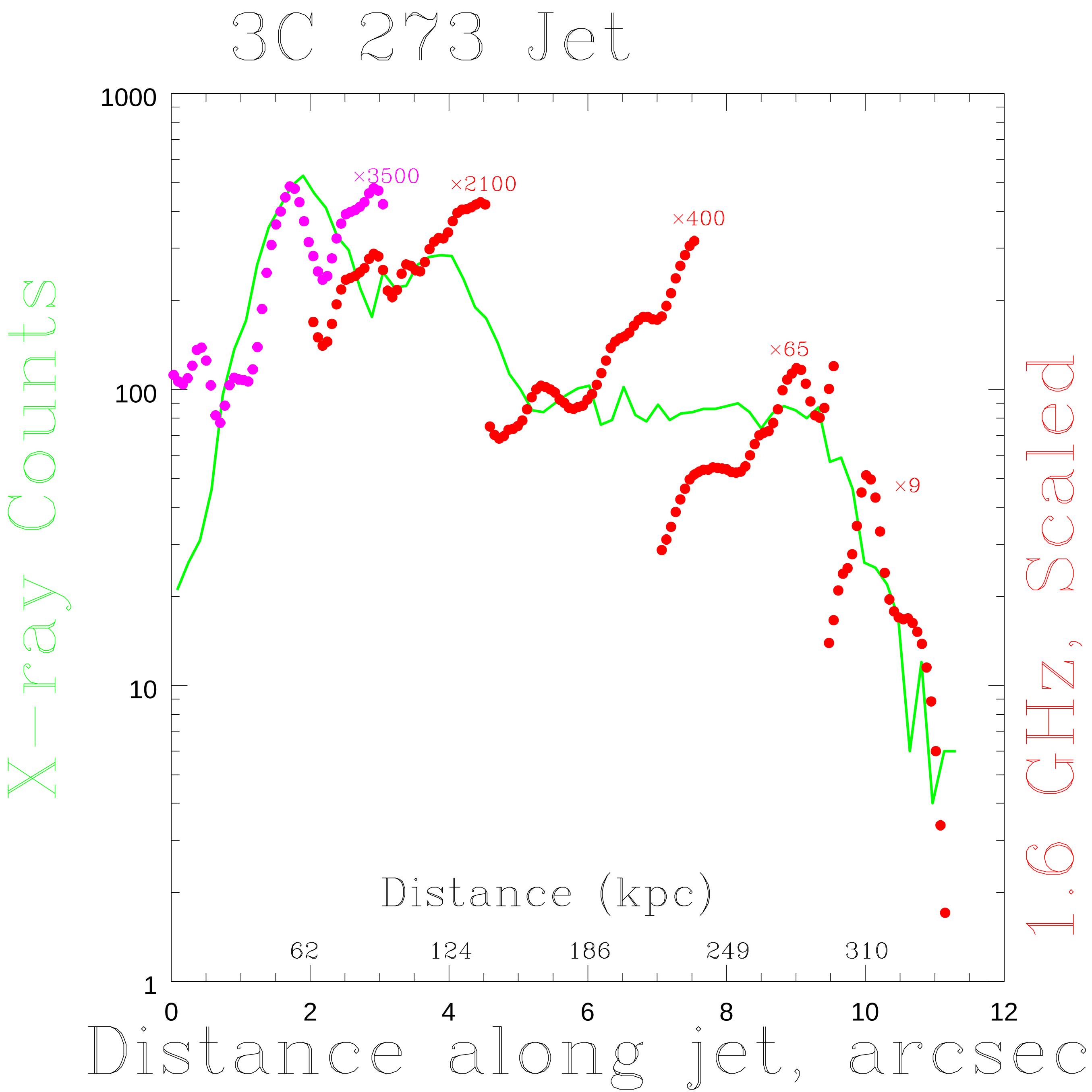
PKS 1202−262
x−ray
4.8 GHz
8.6 GHz
νf_ν [Jy−Hz]
Arcsec along jet


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

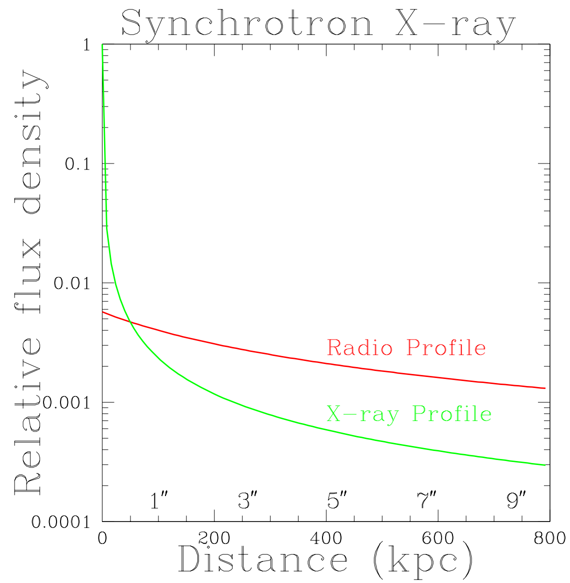
Confront IC/CMB with Morphology

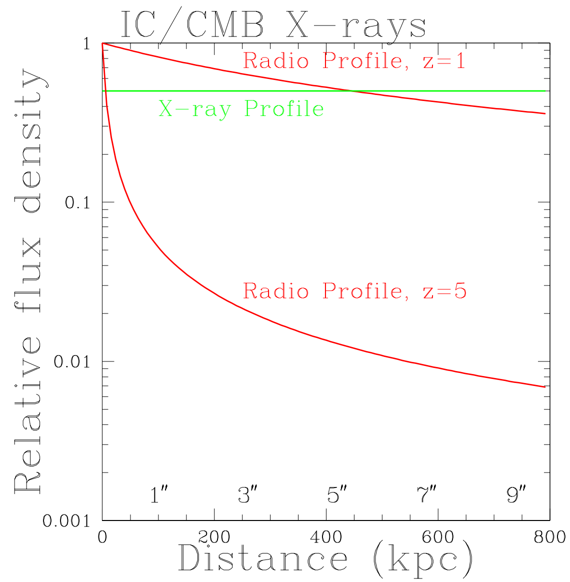


Confront IC/CMB with Morphology

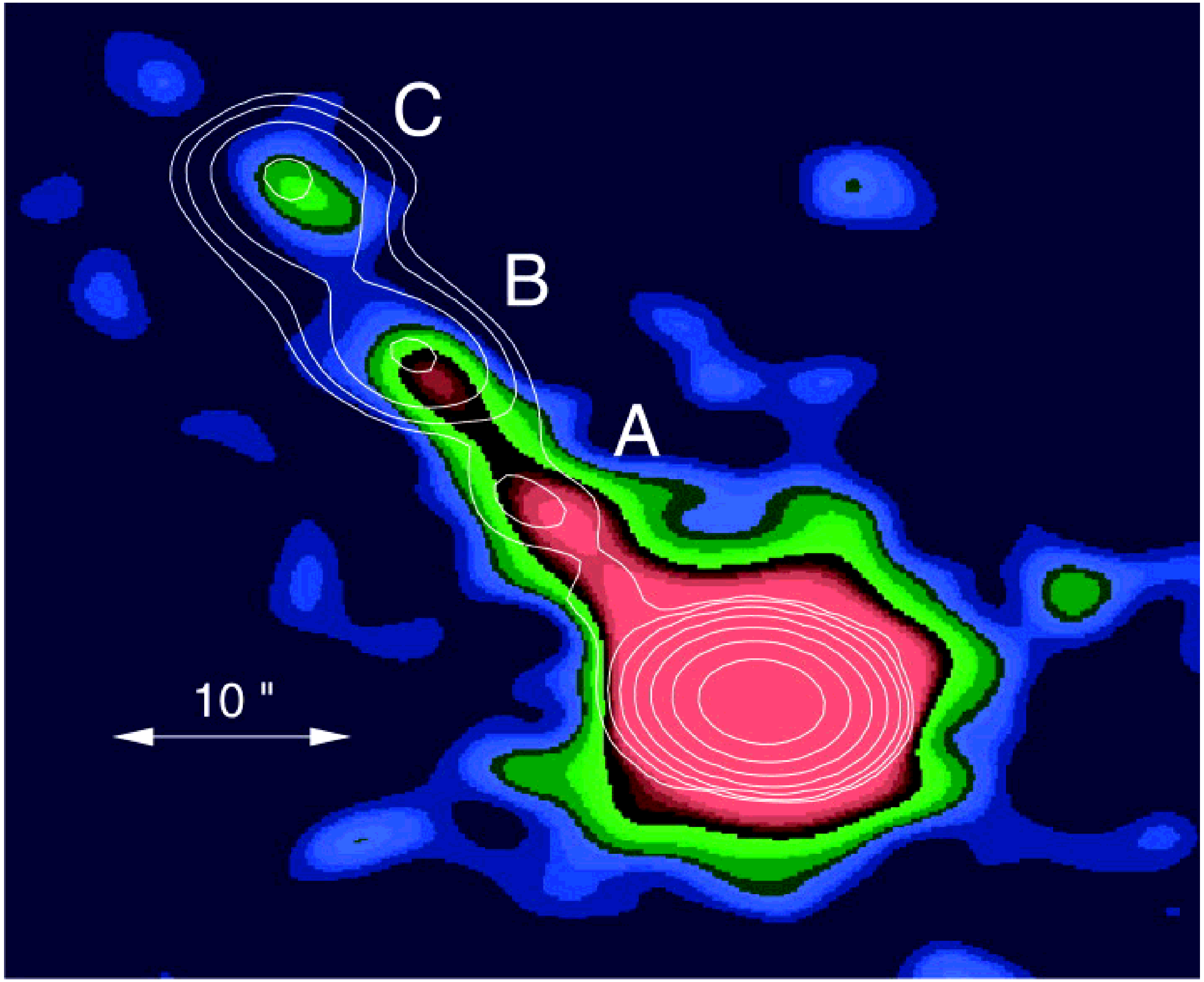


Naive Models





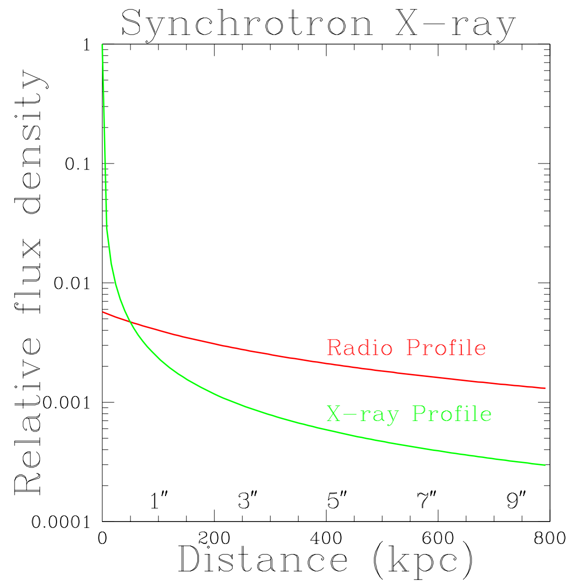
Confront IC/CMB with Morphology

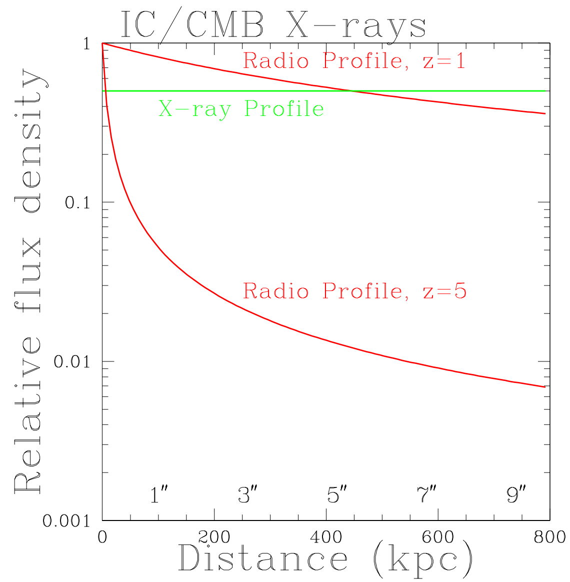


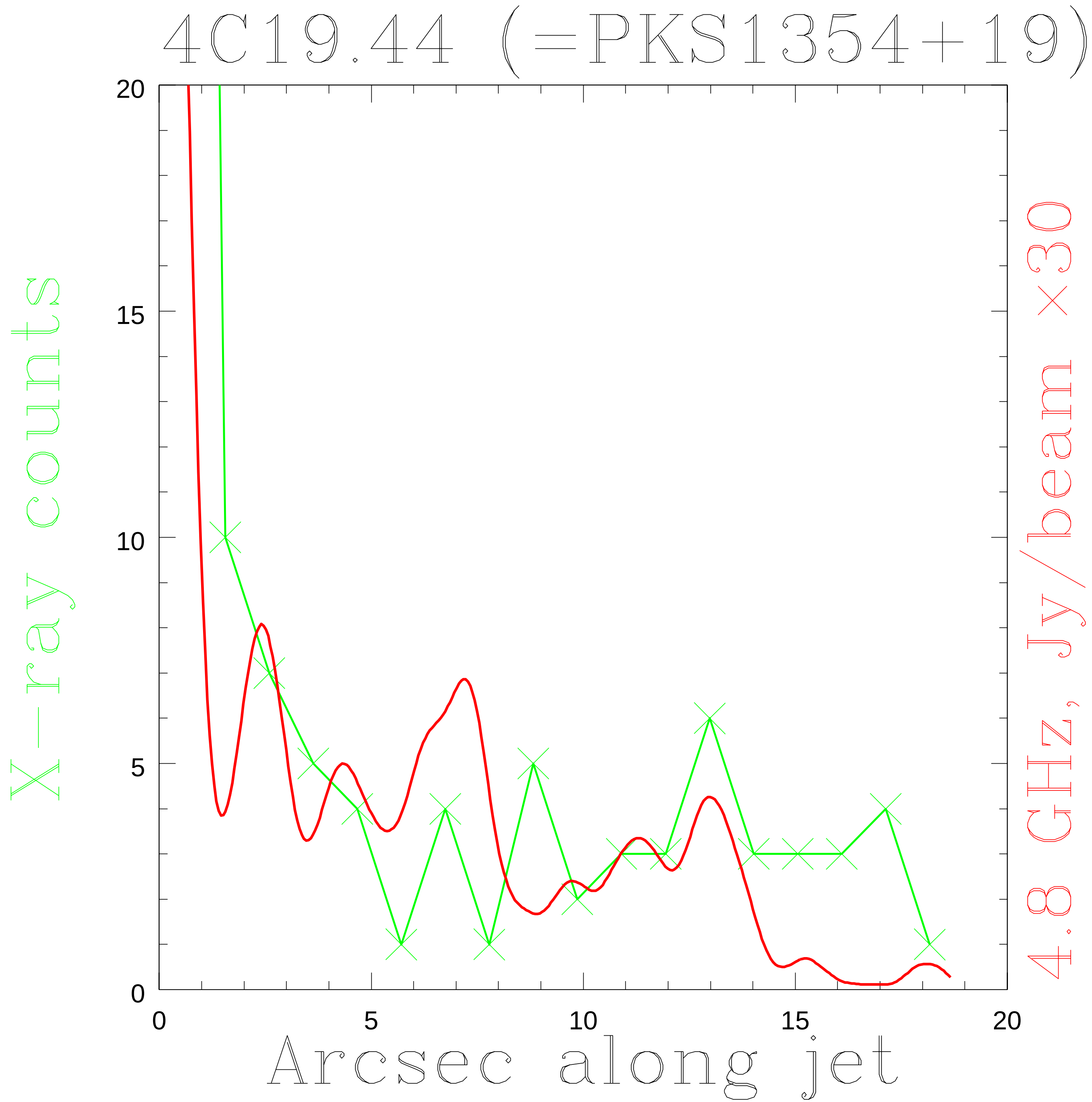
Siemiginowska et al. 2002 ApJ...570..543S

PKS 1127-145 at z=1.187

Naive Models







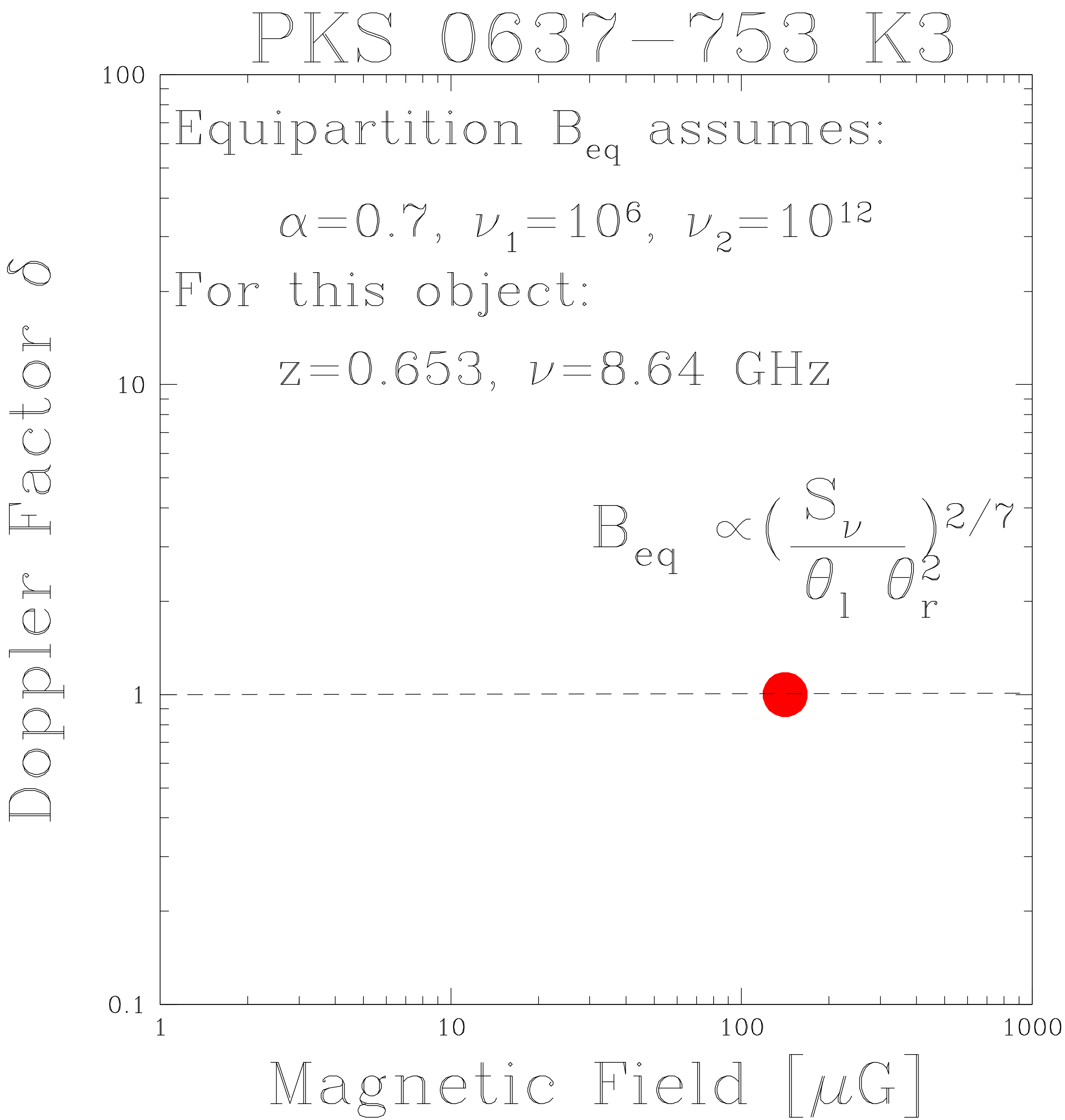
4C19.44 (=PKS1354+19)
X-ray counts
4.8 GHz, Jy/beam ×30
Arcsec along jet
0
5
10
15
20

Morphology Summary

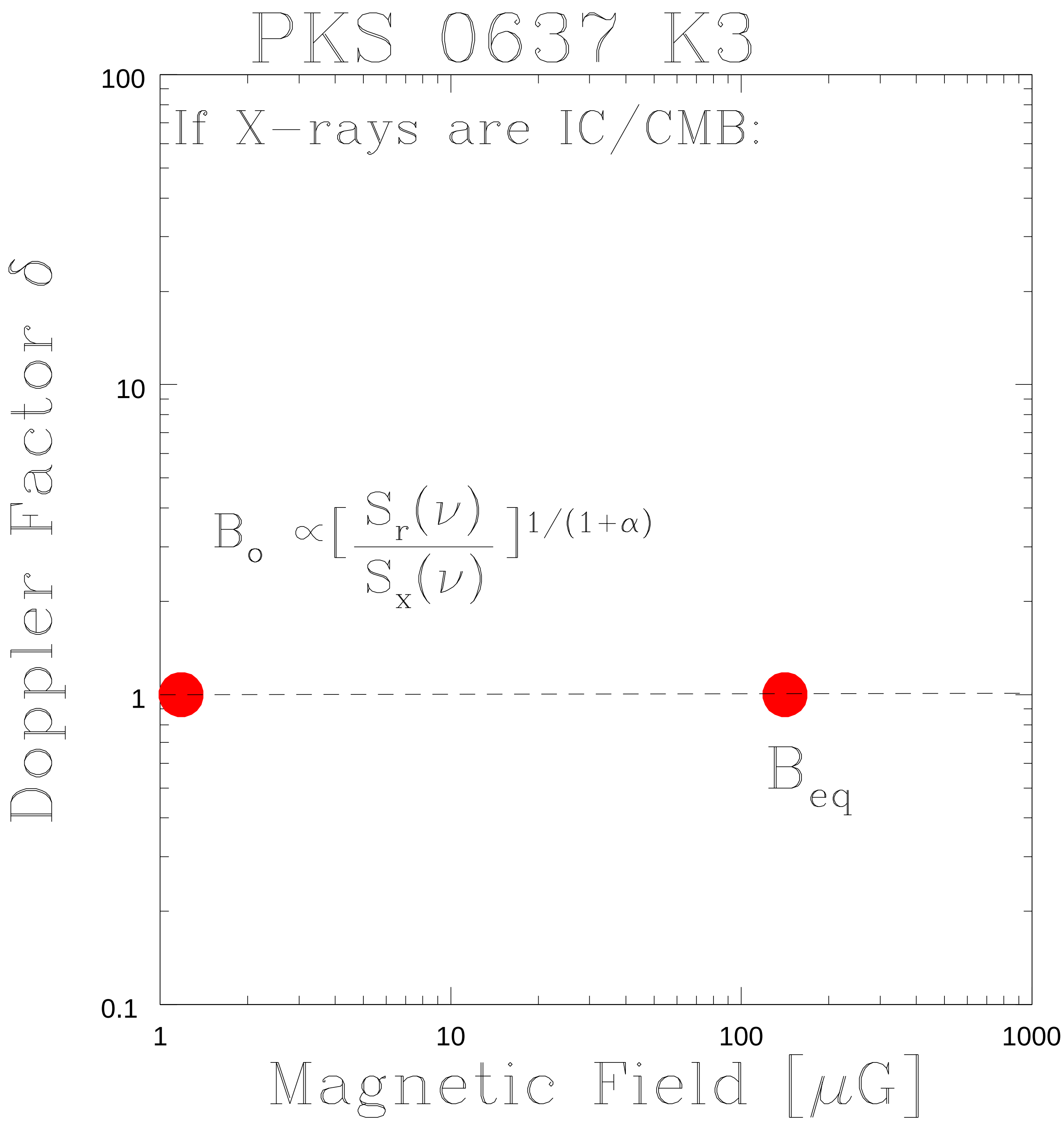
- **Roughly constant f_x/f_r (within $\times 2$).**
  X-rays end when radio makes sharp bend.

- **X-ray profile decreases, Radio profile increases,**
  f_x/f_r changes more than $\times 10$.

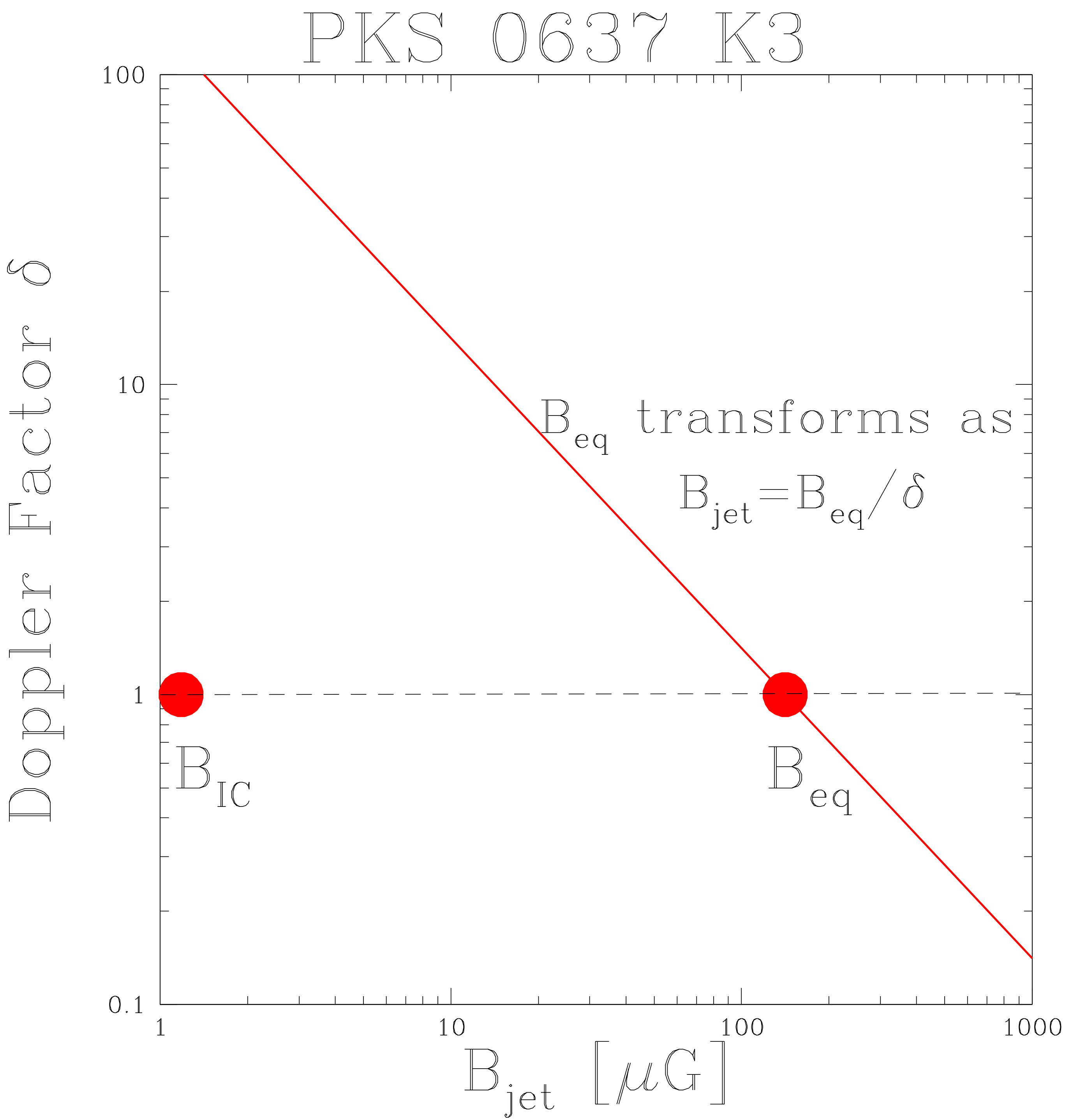
- **Roughly constant f_x/f_r (within $\times 2$).**
  X-rays persist beyond radio.

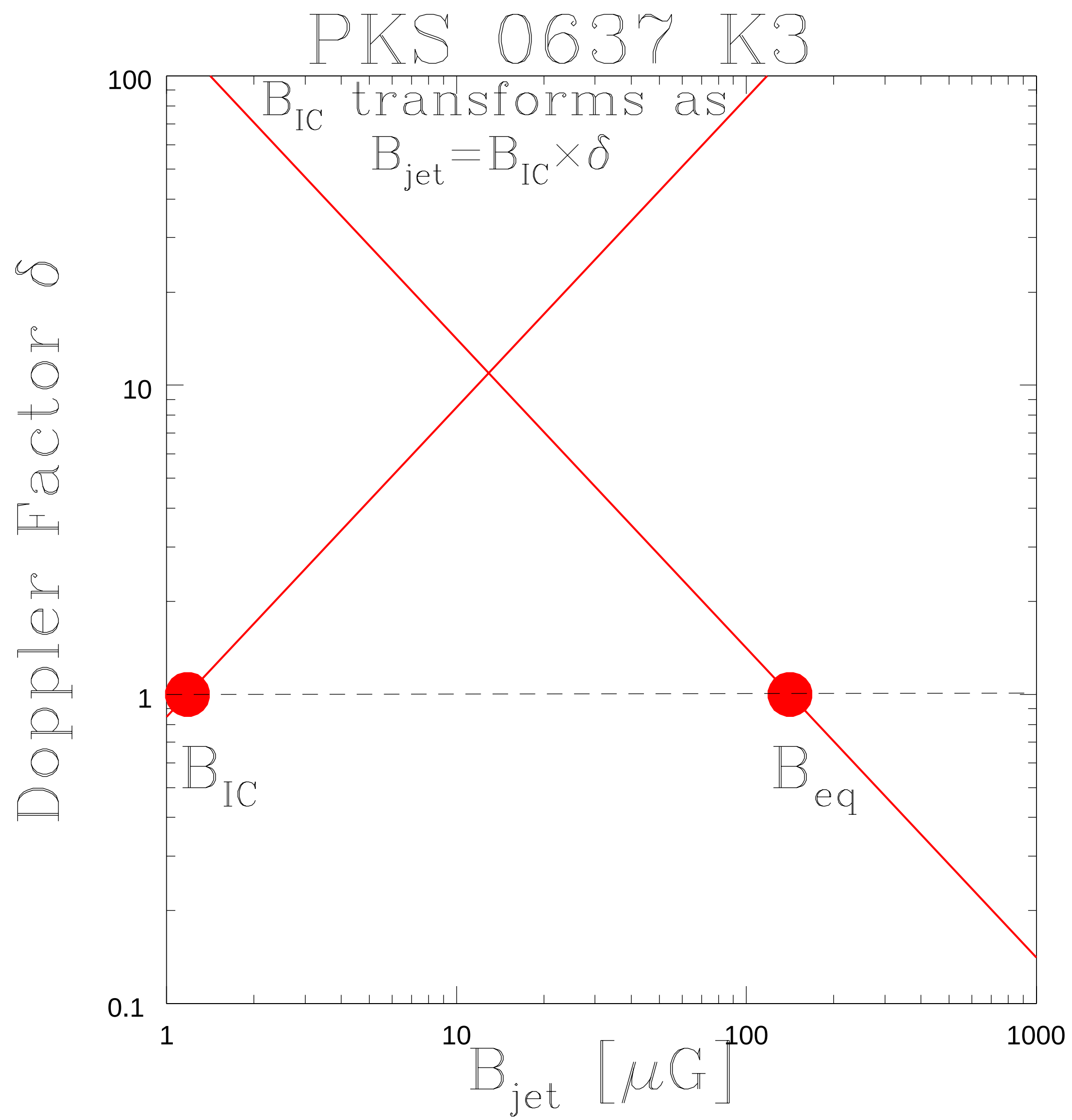


PKS 0637−753 K3
Equipartition B_{eq} assumes:
$\alpha=0.7,\ \nu_1=10^6,\ \nu_2=10^{12}$
For this object:
$z=0.653,\ \nu=8.64$ GHz
$B_{eq} \propto \left(\frac{S_\nu}{\theta_l\ \theta_r^2}\right)^{2/7}$
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000

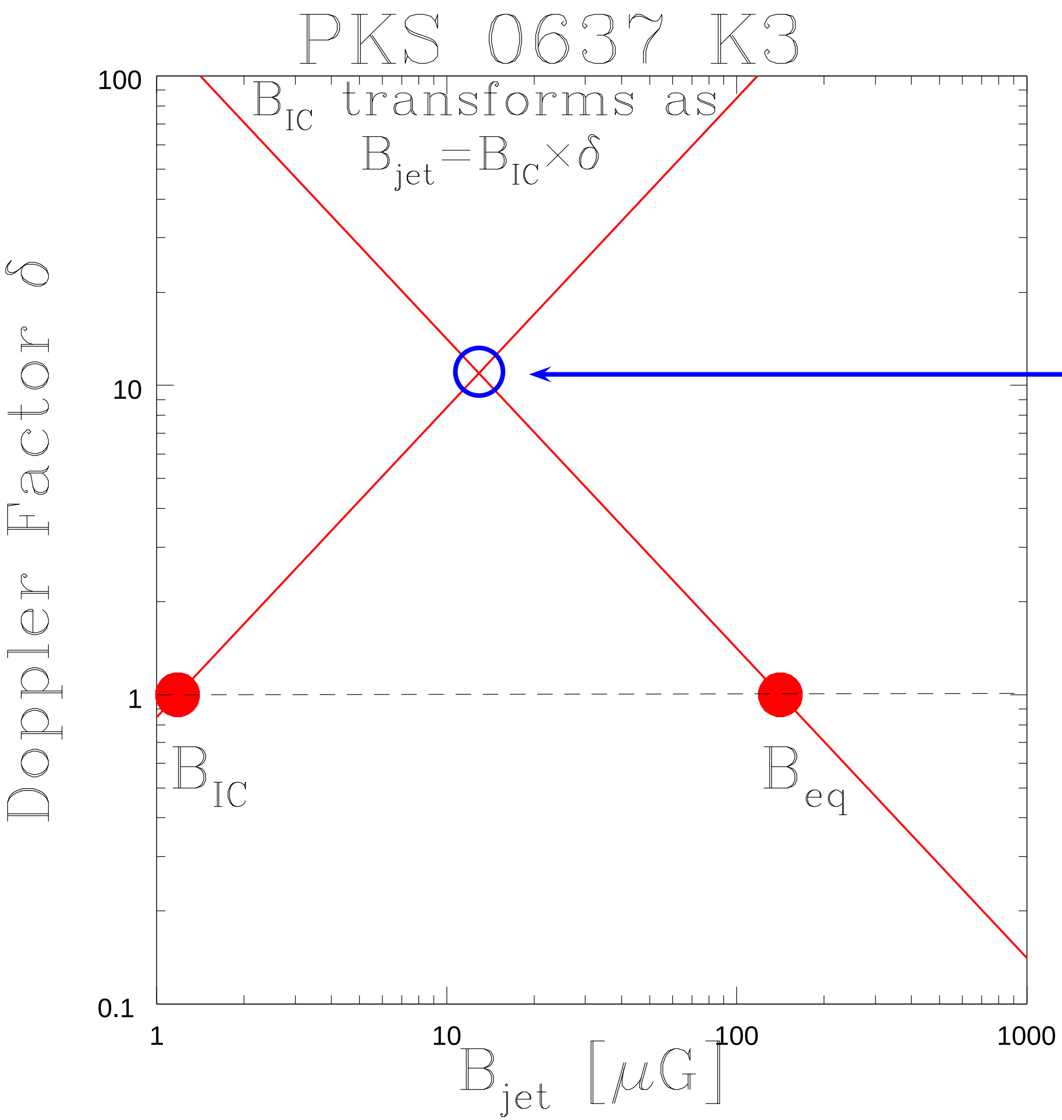


PKS 0637 K3
If X-rays are IC/CMB:
$B_o \propto \left[\frac{S_r(\nu)}{S_x(\nu)}\right]^{1/(1+\alpha)}$
B_{eq}
Doppler Factor δ
Magnetic Field [μG]
100
10
1
0.1
1
10
100
1000


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

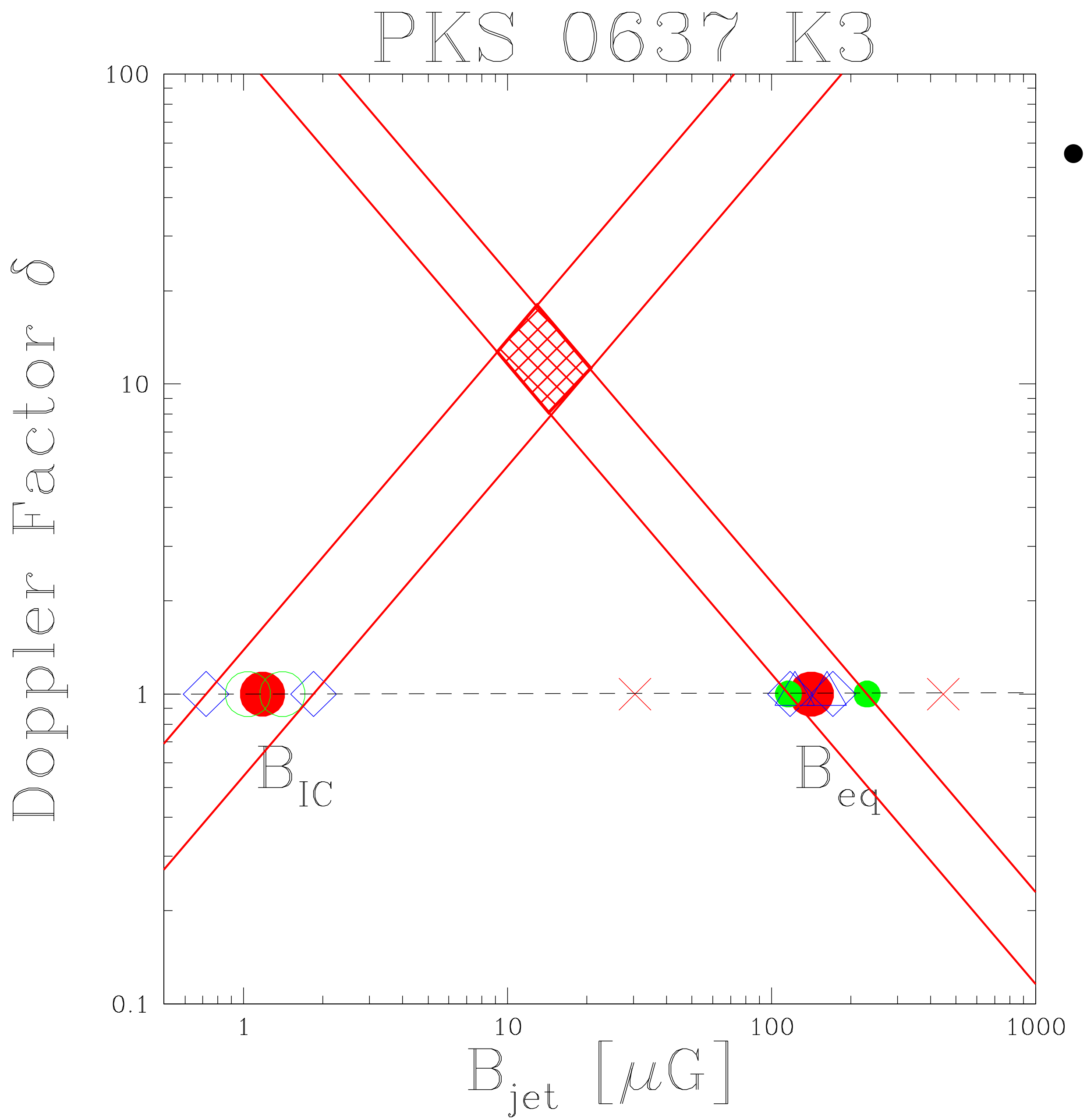


PKS 0637 K3
B_IC transforms as
B_jet=B_IC×δ
Doppler Factor δ
B_jet [μG]
B_IC
B_eq
100
10
1
0.1
1
10
100
1000

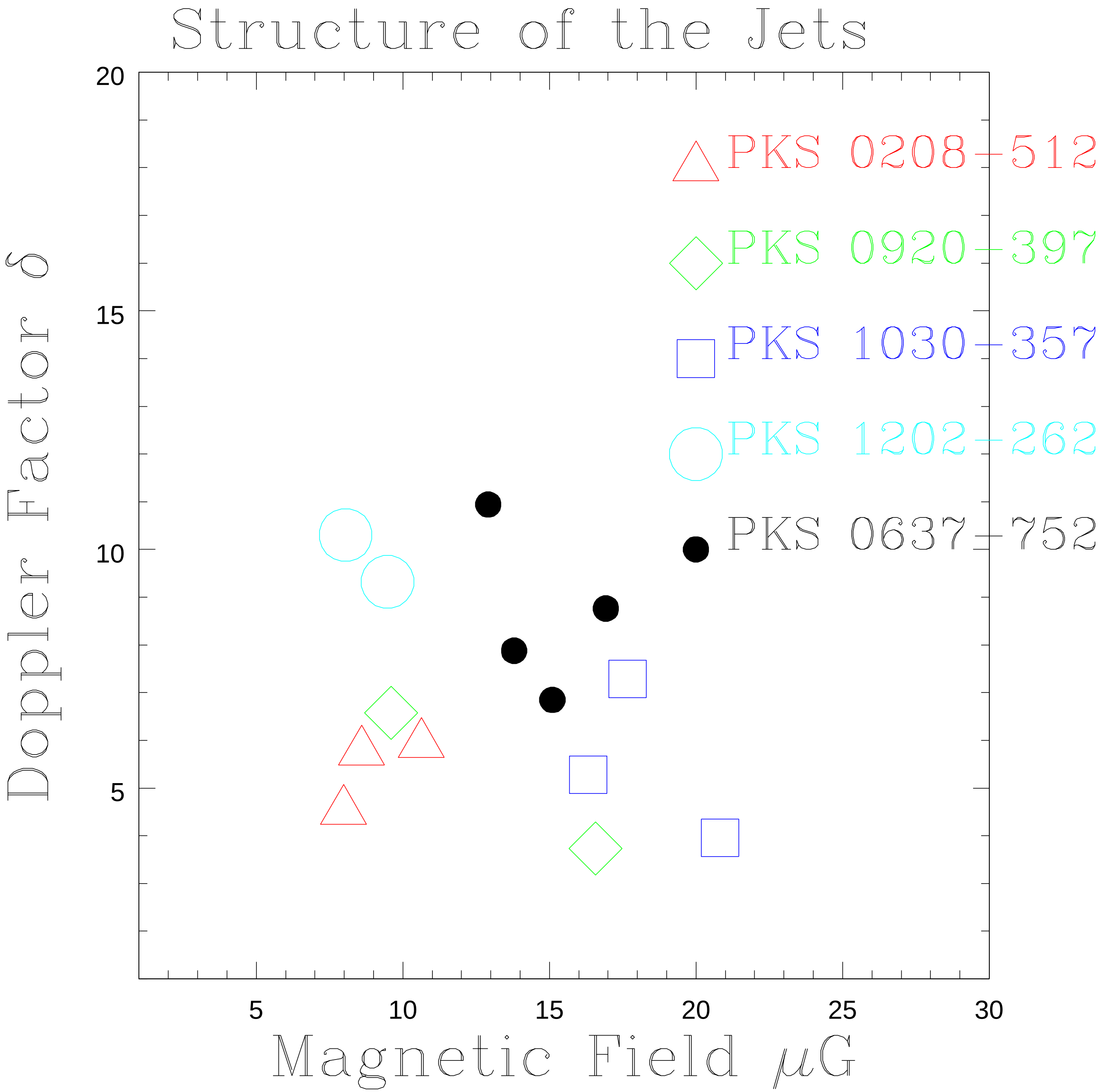


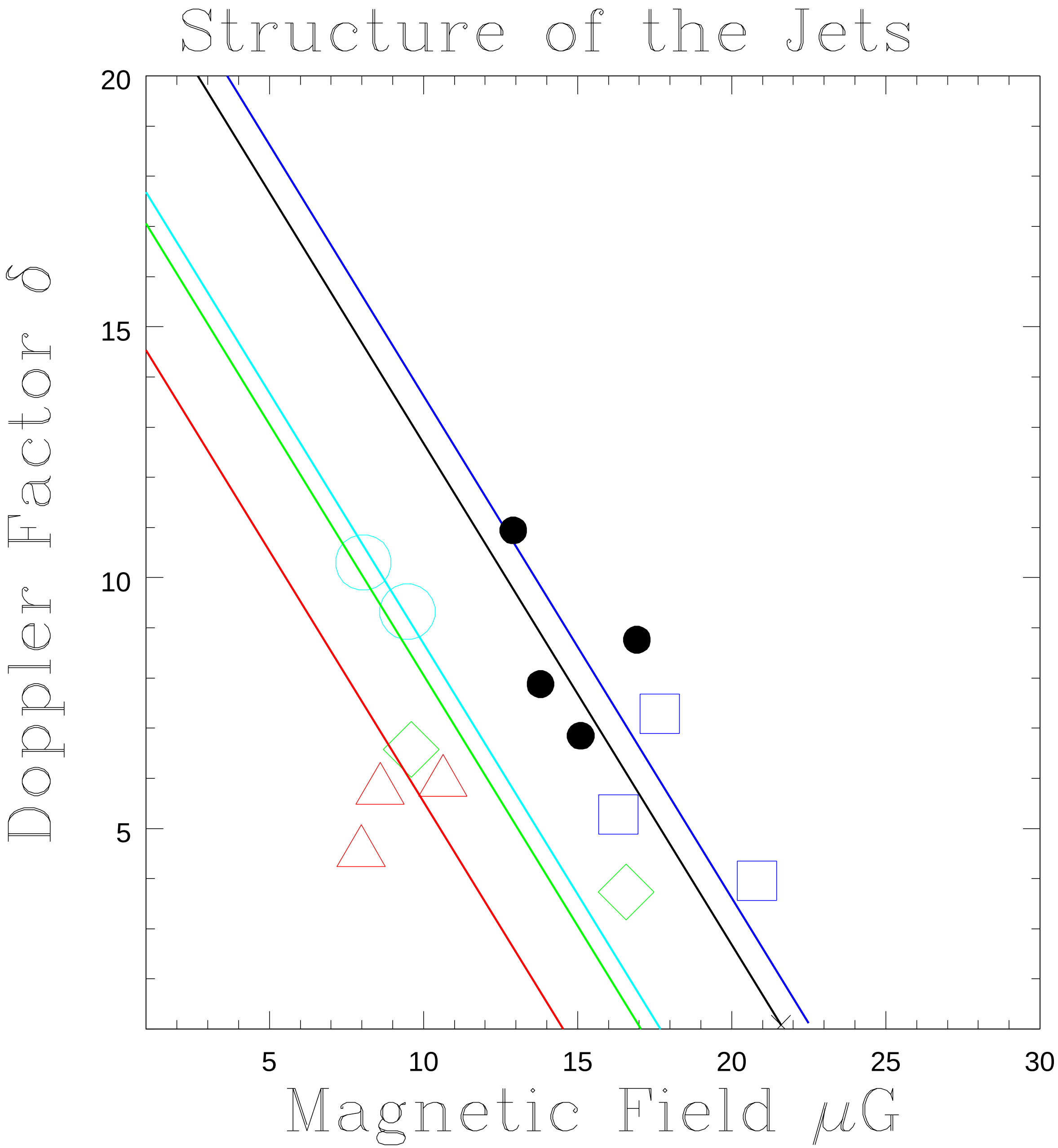
The intersection gives a solution for the magnetic field, B, in the rest frame, and for the apparent Doppler factor,

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



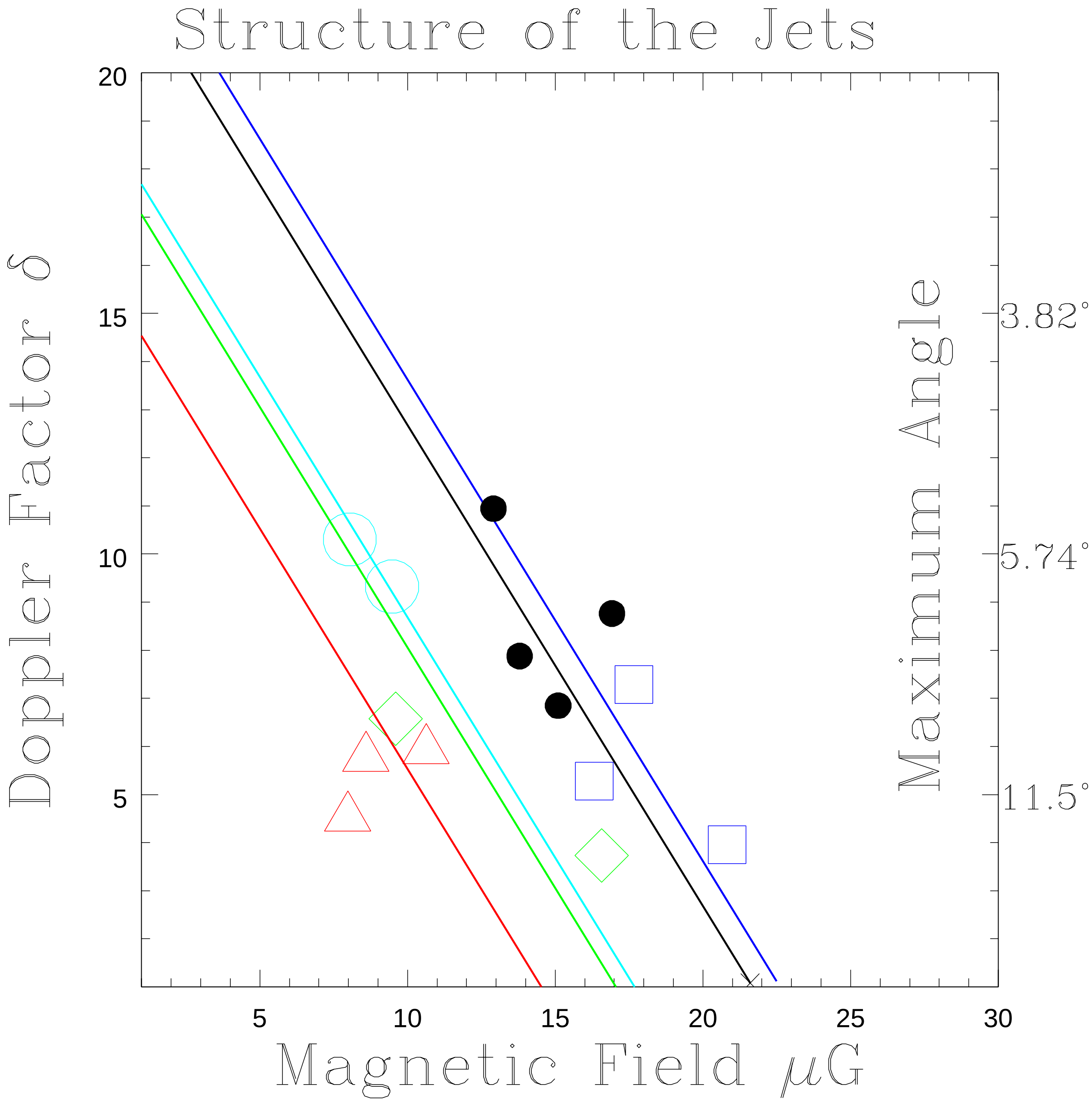
- **Determined B and δ within a factor of 2**


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



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**

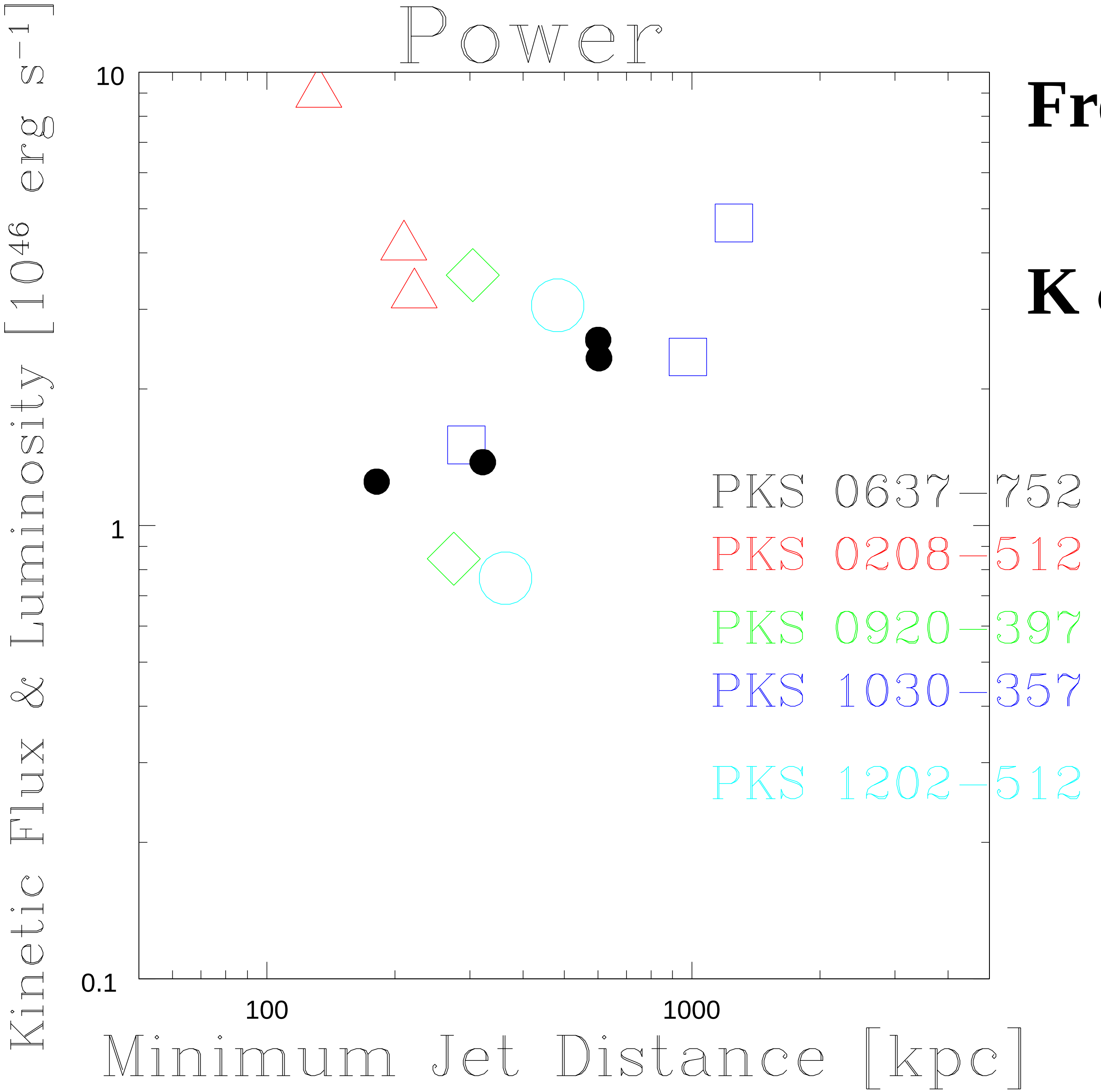


Kinetic Flux

- $\mathbf{K} = \Gamma^2 \pi\, r^2 \beta\, c\, U$
- **We take** $\Gamma \approx \delta$

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

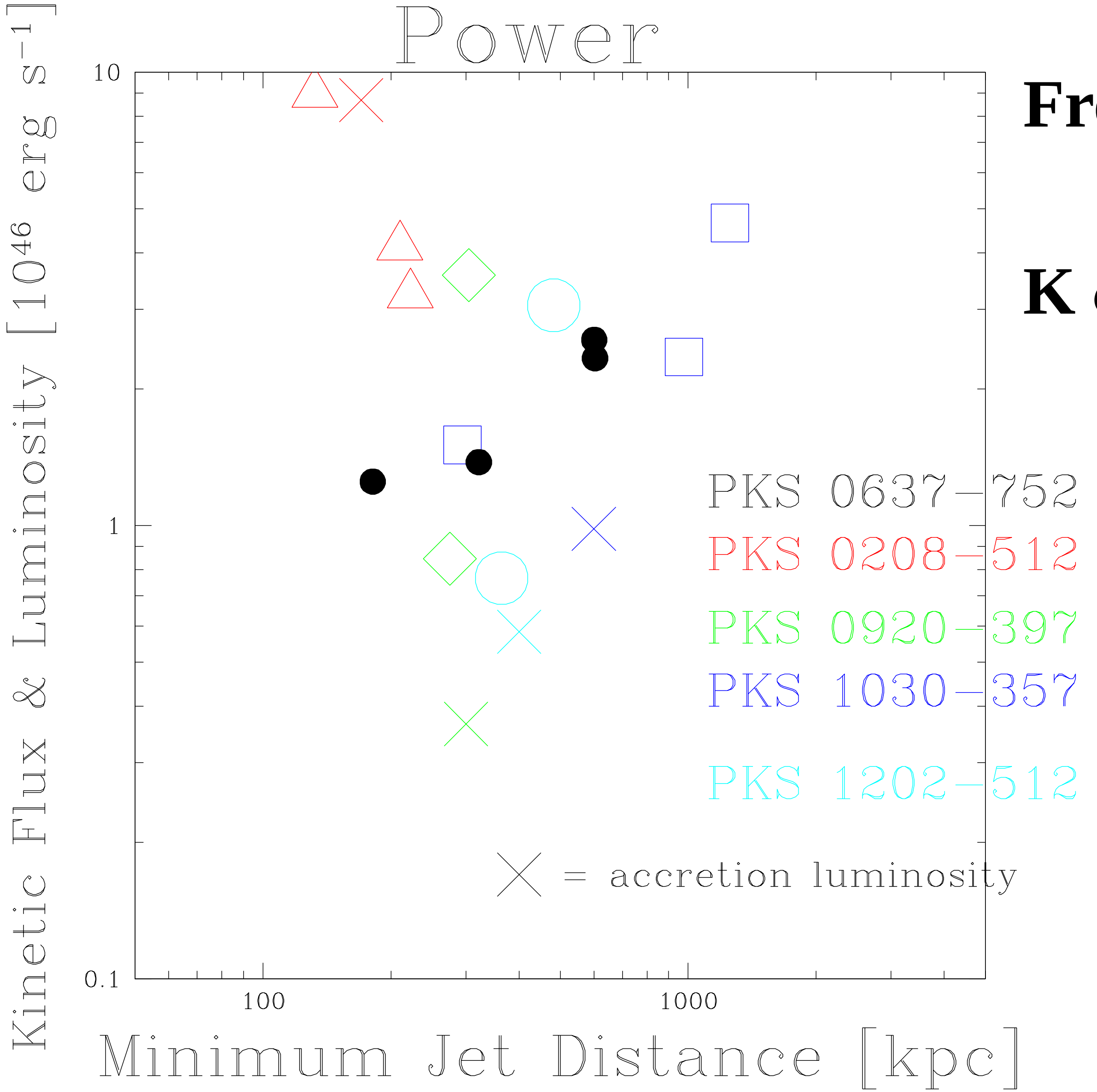
Kinetic Flux



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

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

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

Implications of the AGN Jets

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

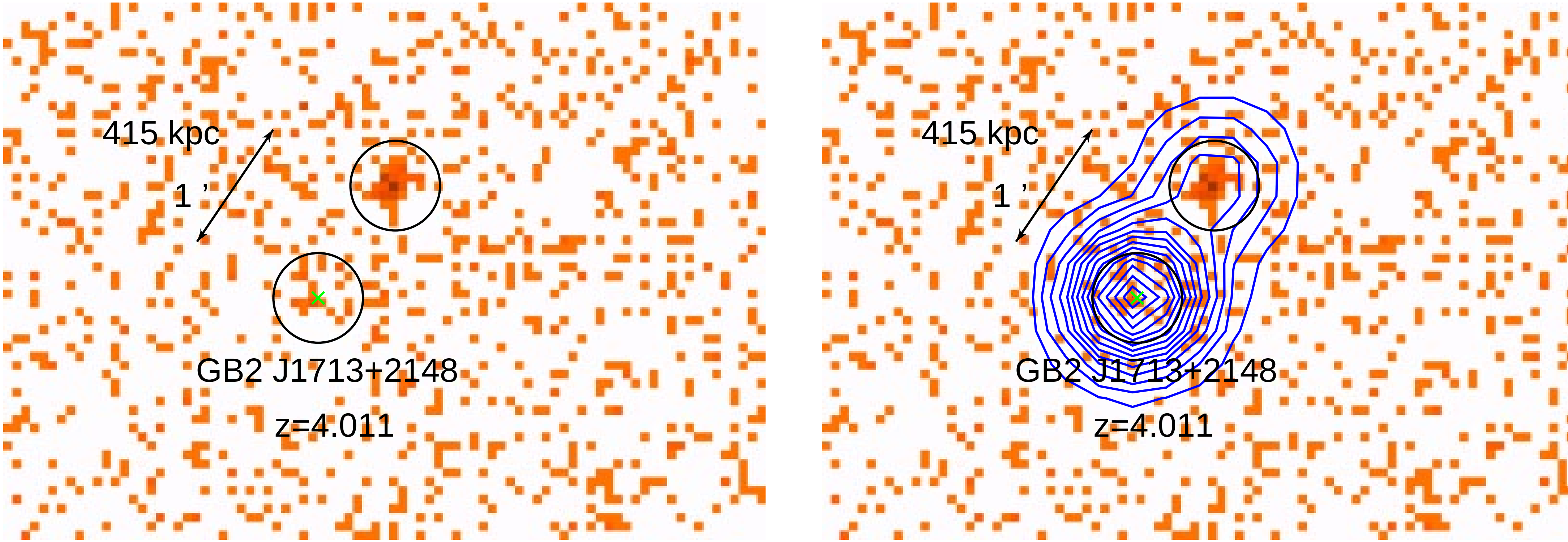
- **Jets may Power Cluster Cavities – Stop Cooling Flows**

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

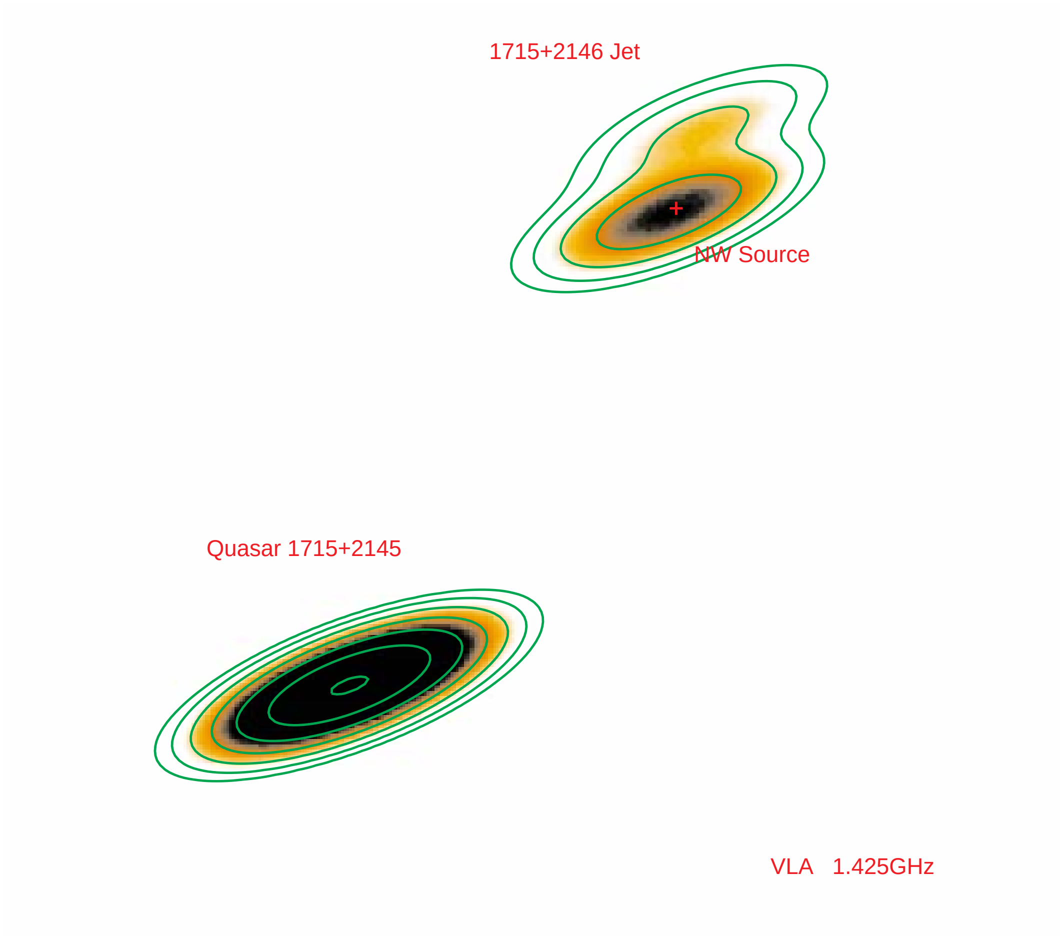
Where ARE the bright X-ray Jets at High Redshift?

- **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



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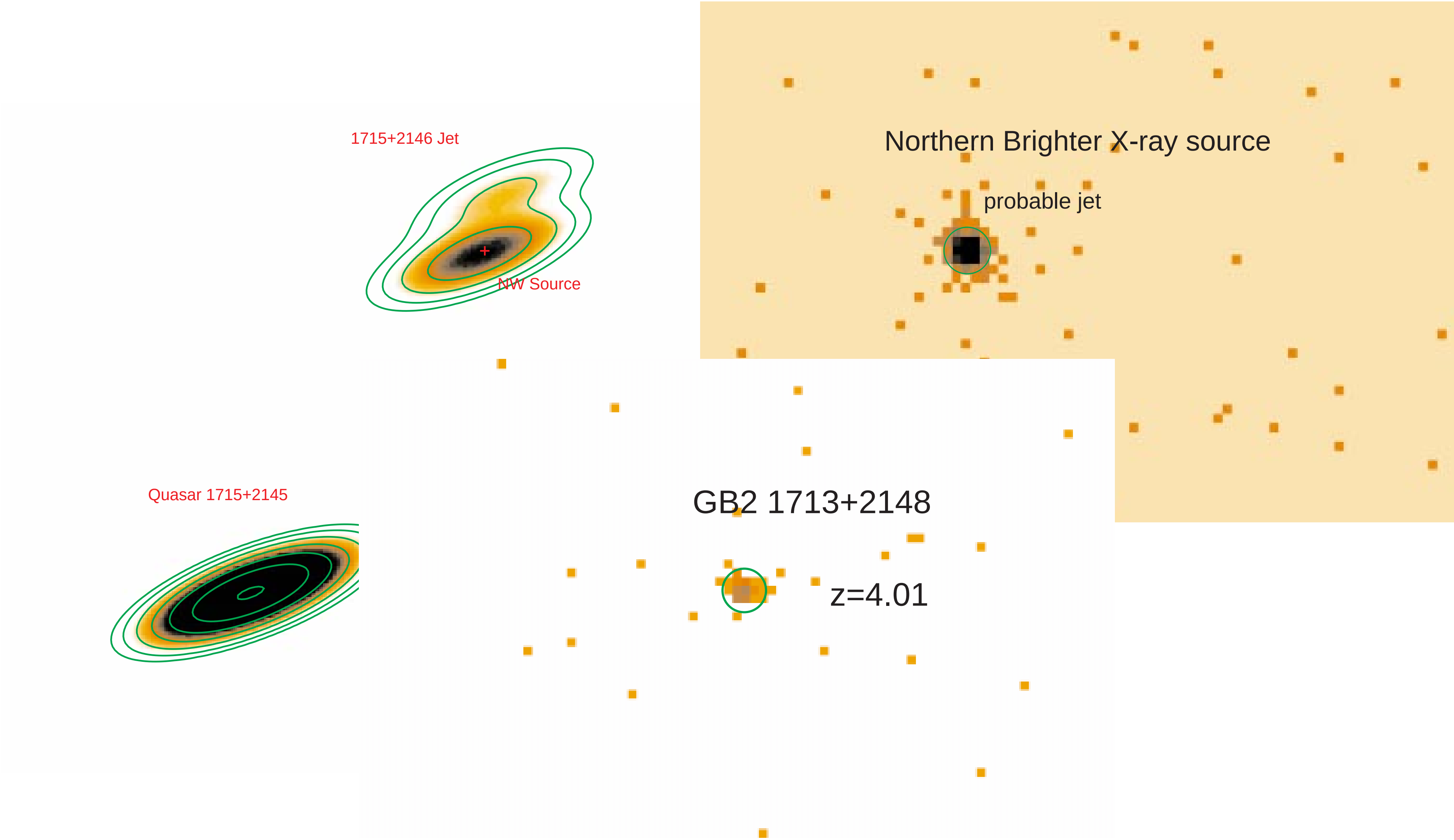
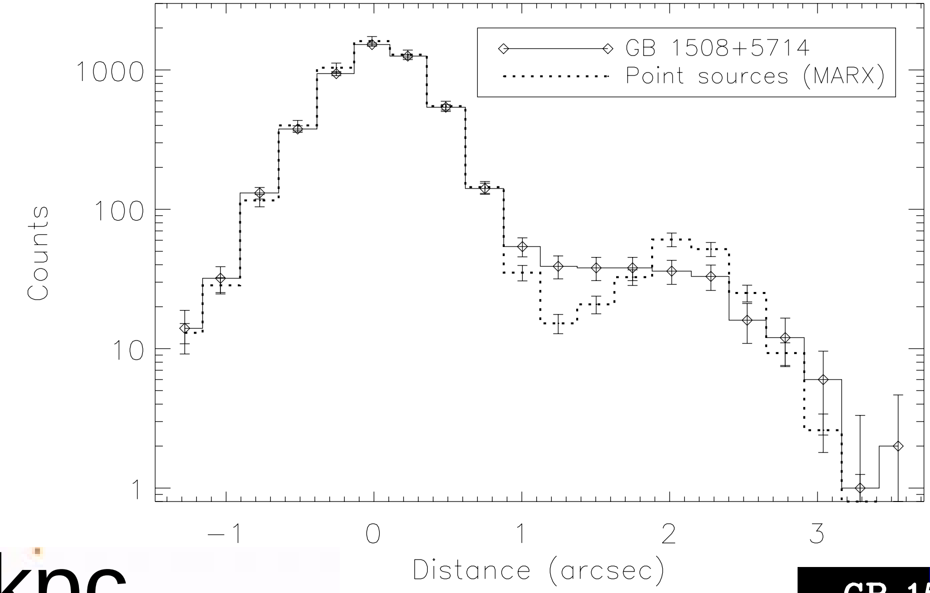
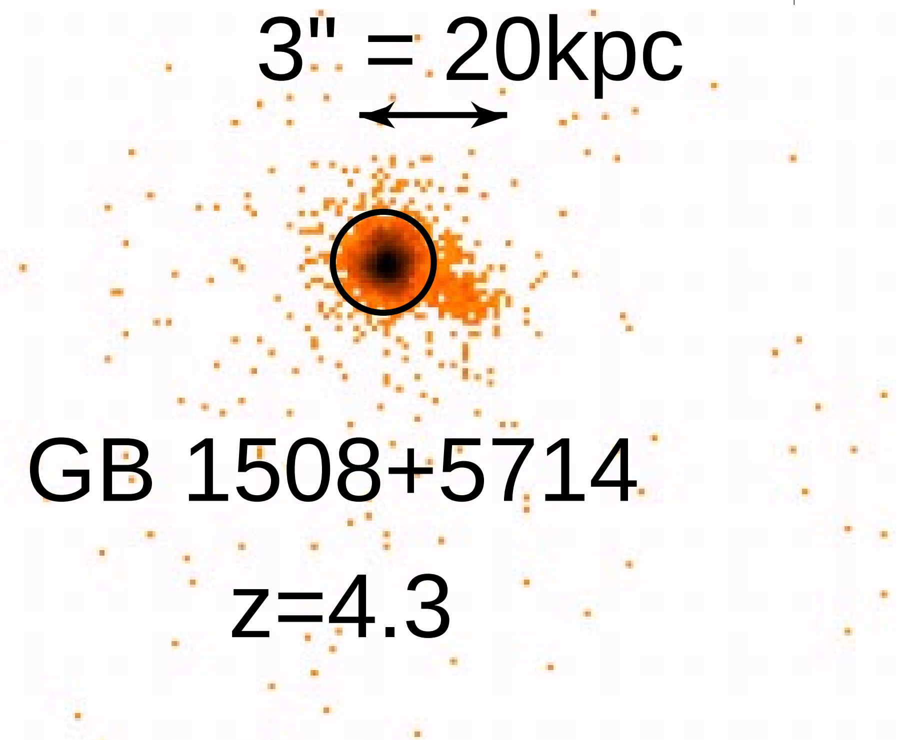
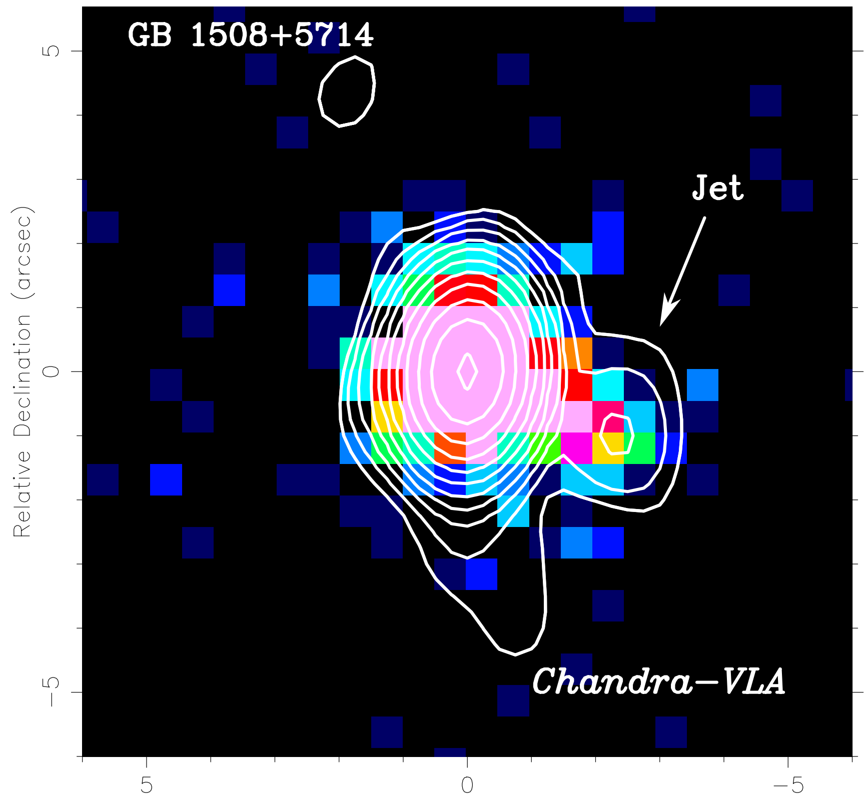


An Einstein and ASCA source



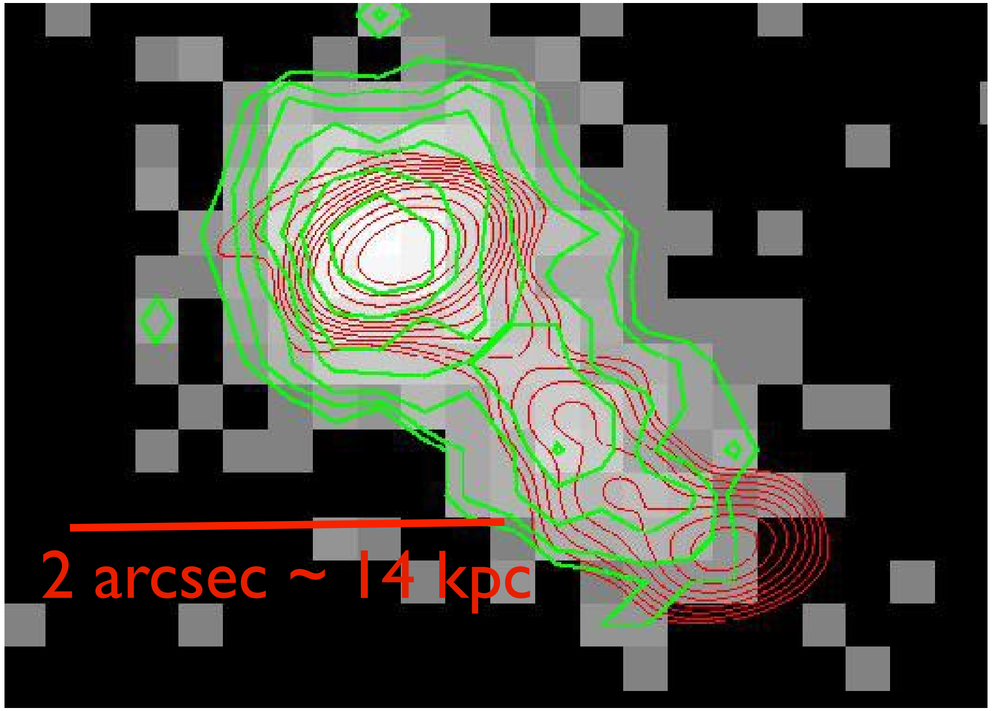




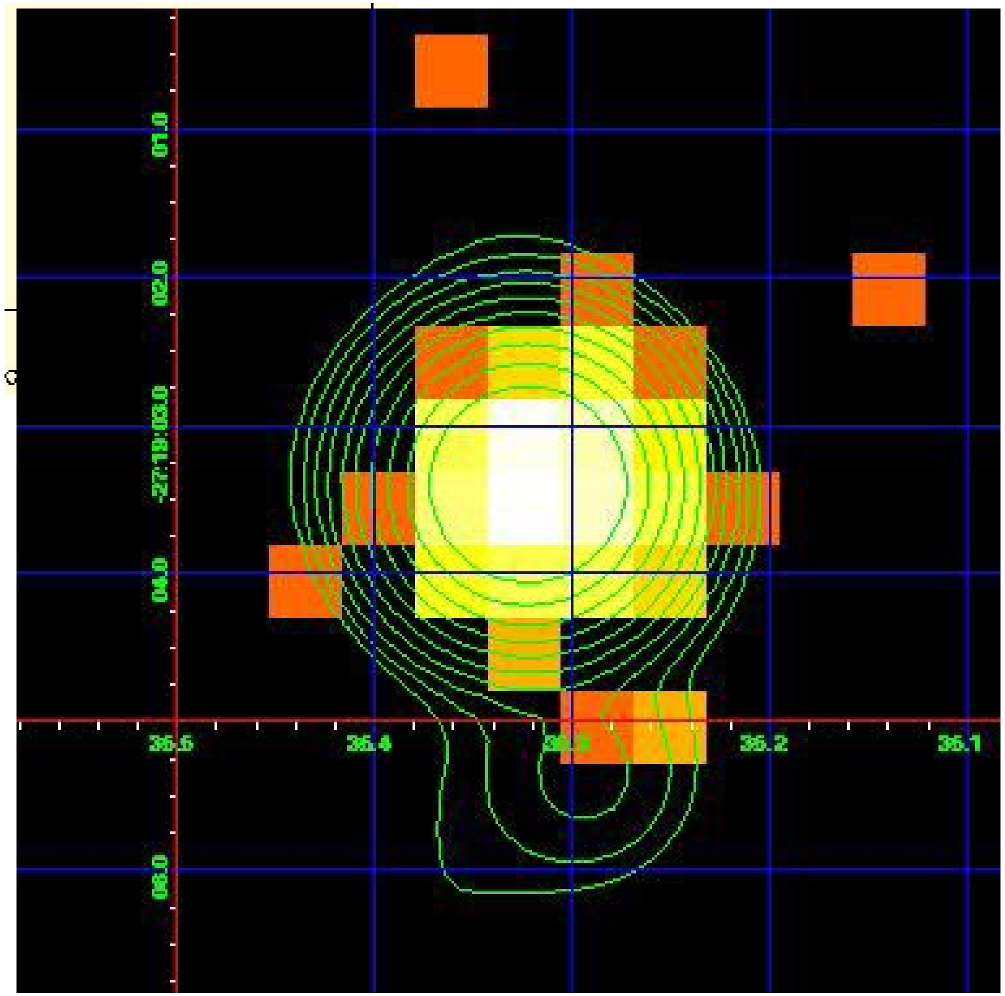
Siemiginowska et al. 2003ApJ...598L..15S

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

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



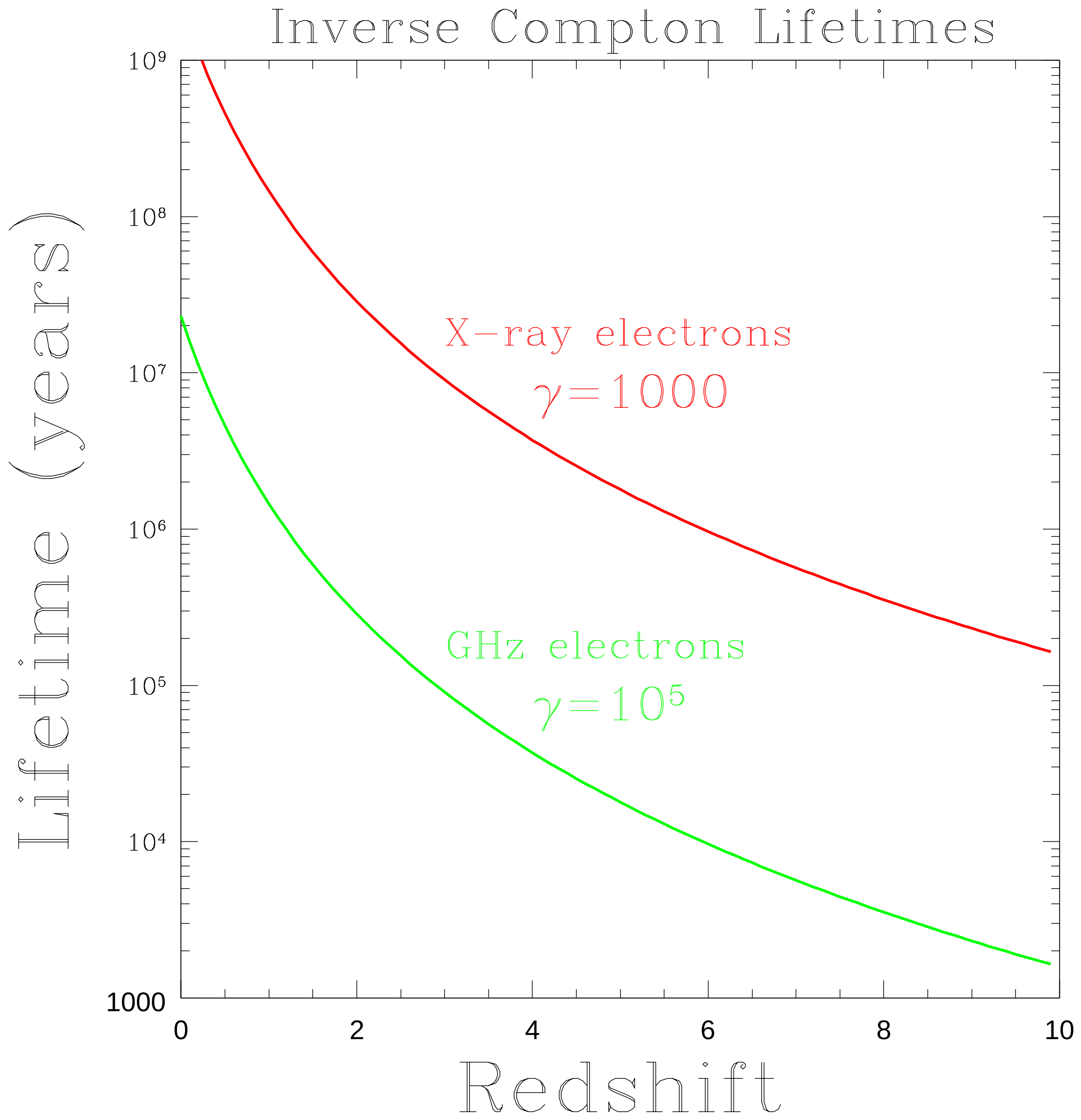
Quasar 1745+624 = 4C +62.29 at z=3.889



PMN J2219-2719 at z=3.634

There Could Be Radio Quiet X-Ray Jets!

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



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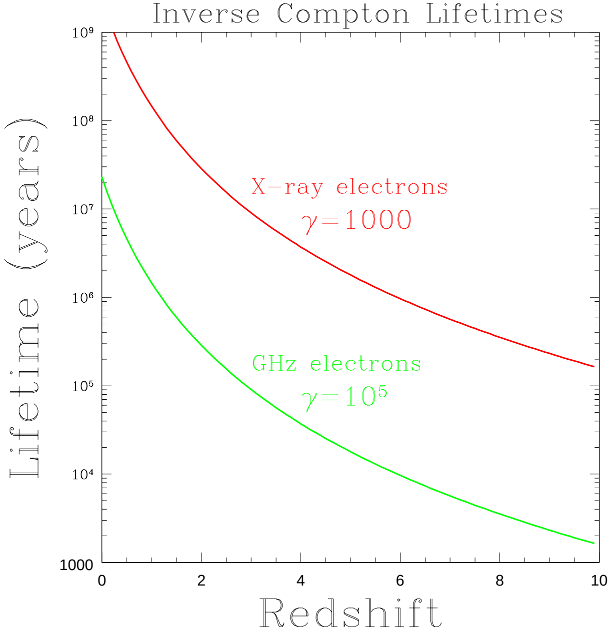
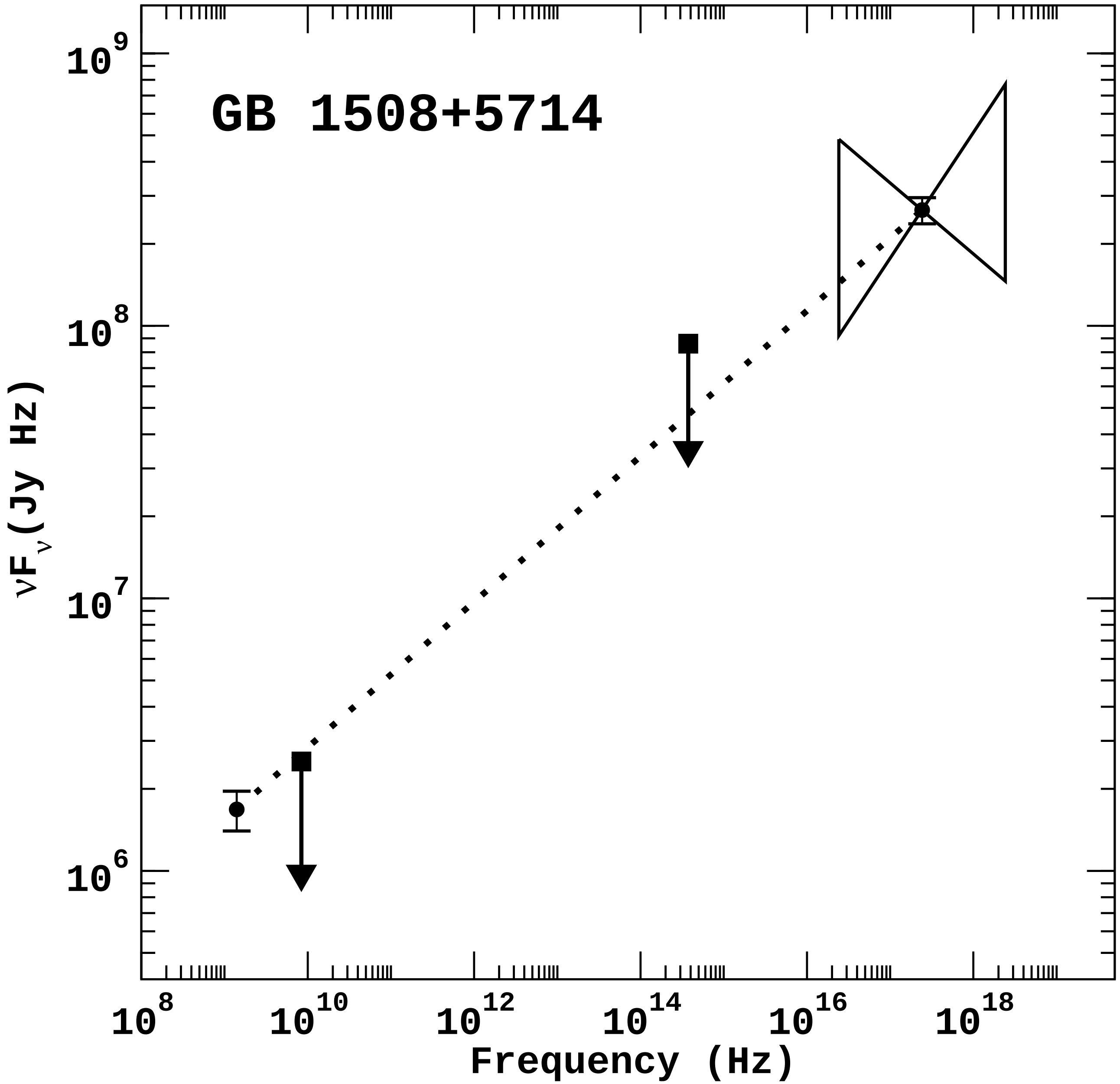
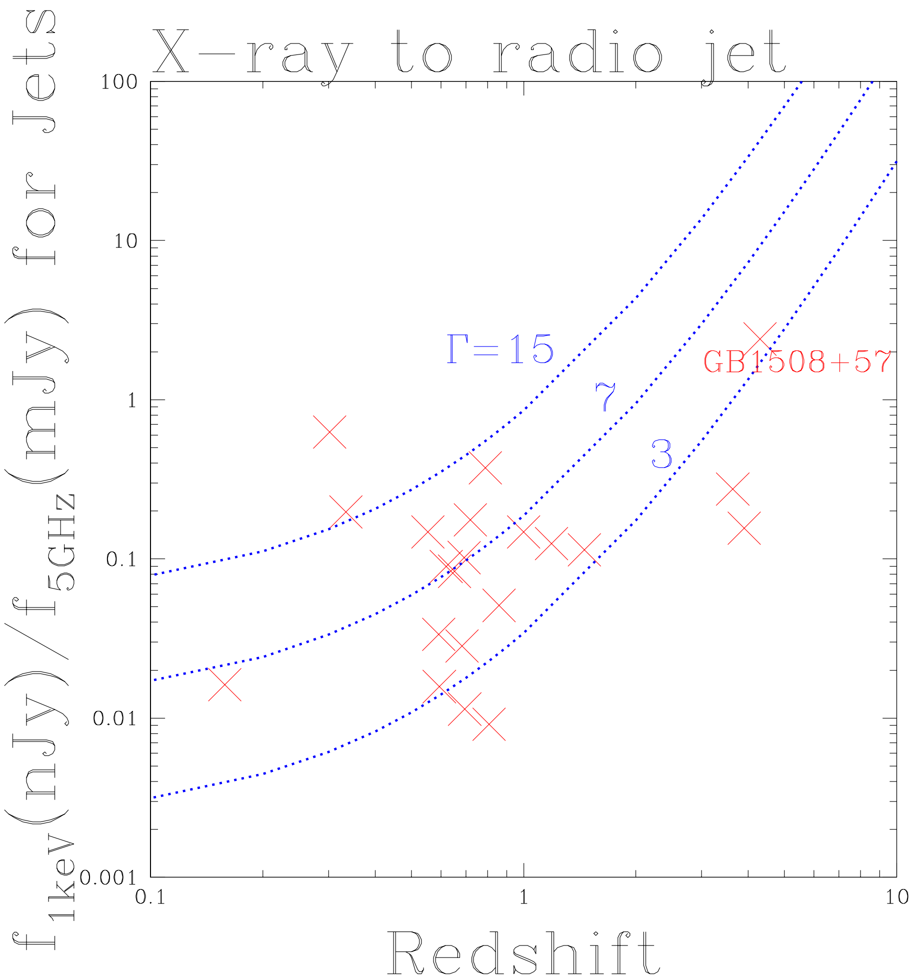
- **Age $\approx 3 \times 10^4$ years?**

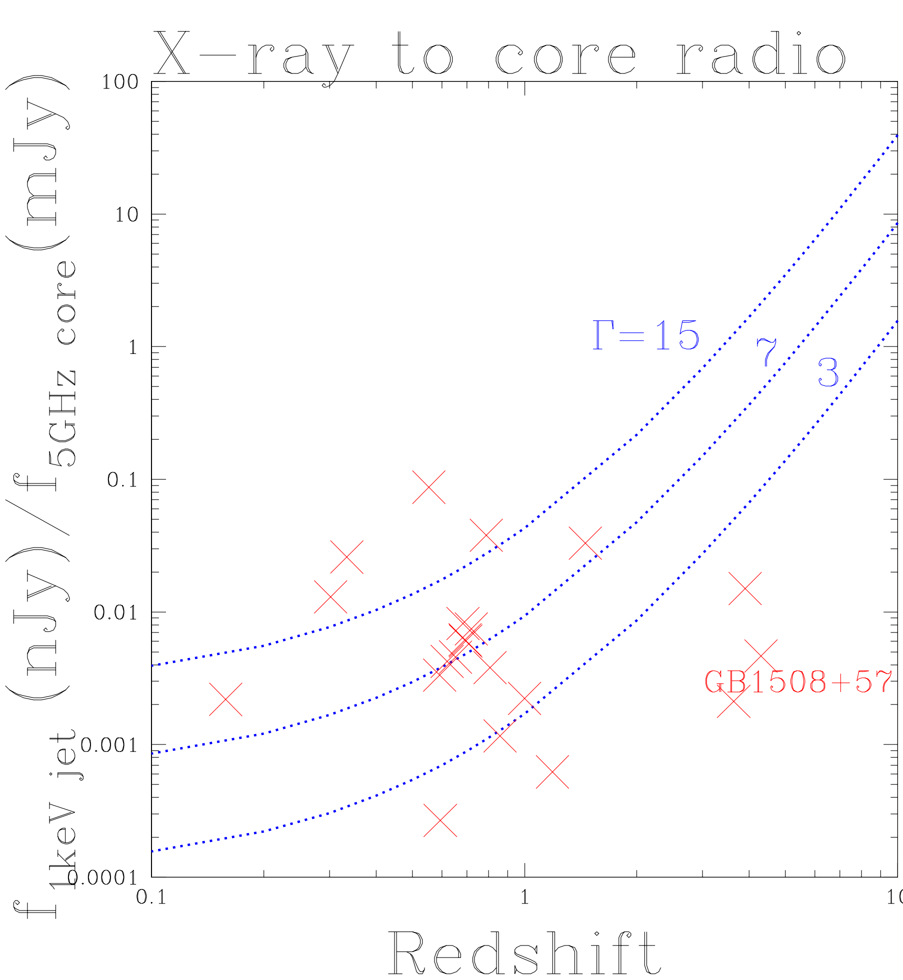




Cheung,2004ApJ...600L..23C

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!