Inverse Compton Emission as the Origin of 100 kpc-Scale X-ray Jets

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Outline

1. **Arguments for the IC/CMB Mechanism**
    - **Energy densities: Magnetic Field vs. Cosmic Background Photons**
    - **Broadband Spectral Energy Distribution**
    - **Morphology and the X-ray vs. Radio Profiles**
2. **Implications of the IC/CMB Scenario**
    - **Gives B, δ, n_e**
    - **Direct Observation of Kinetic Flux**
    - **Beacons at Large Redshift**
3. **Predictions of the IC/CMB Mechanism**
    - **Detect γ-ray Jets**
    - **X-ray Jet flux dominates at Large Redshift**

Significance of Distinguishing between IC/CMB vs. Synchrotron X-ray Emission.

- **IC/CMB X-Rays are from low energy electrons,**
  $\gamma \sim$ 20 to 1000. Otherwise observable only below 1 MHz.

- **Absence of IC/CMB X-Rays will imply gross deviations from minimum energy.**
  $B >> B_{eq}$

- **If local examples ($z \approx 1$) radiate IC/CMB X-Rays, then X-ray detections or limits may show us the earliest Black Hole activity in the universe.**

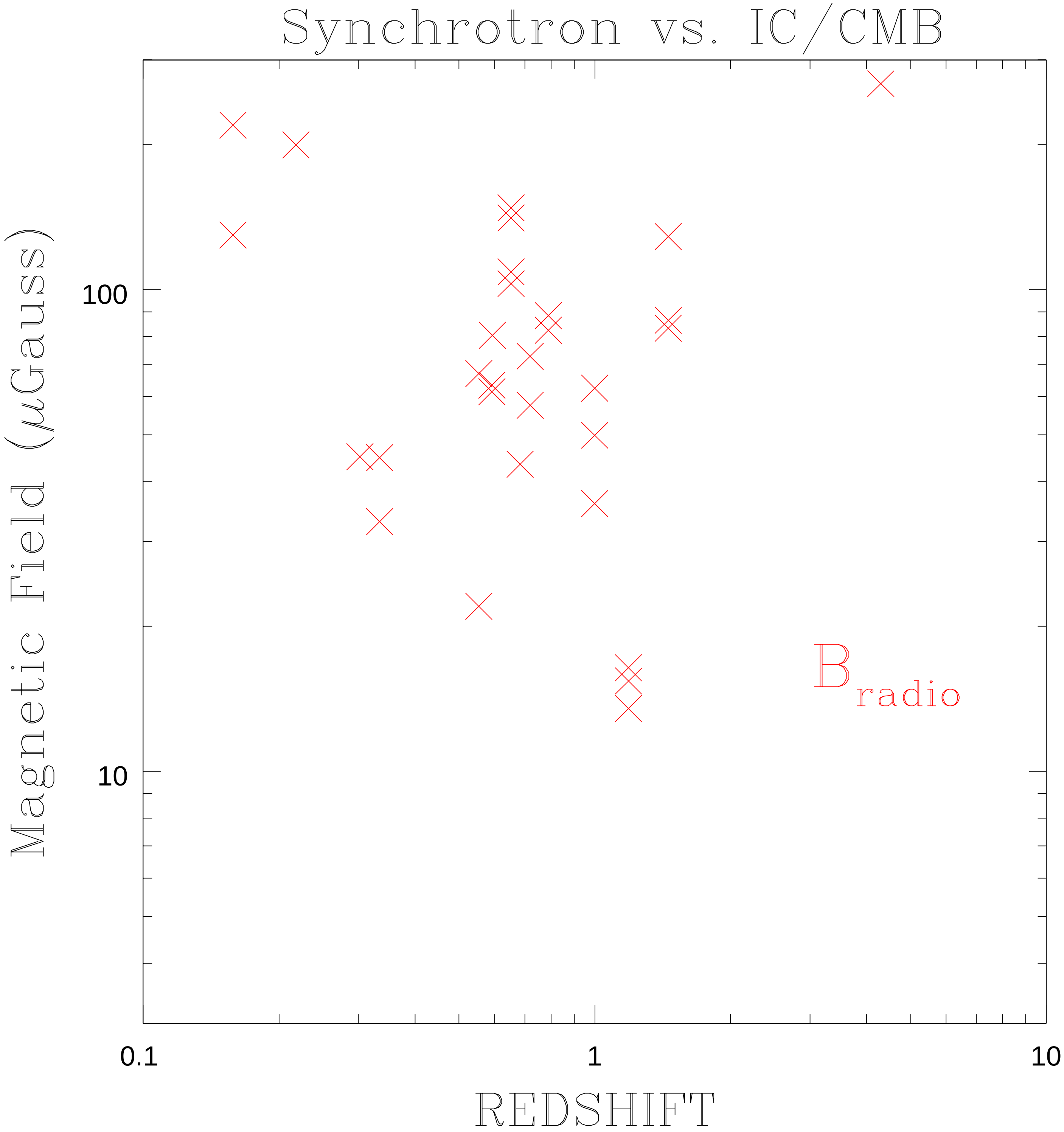
Arguments for the IC/CMB Mechanism

Energy densities:

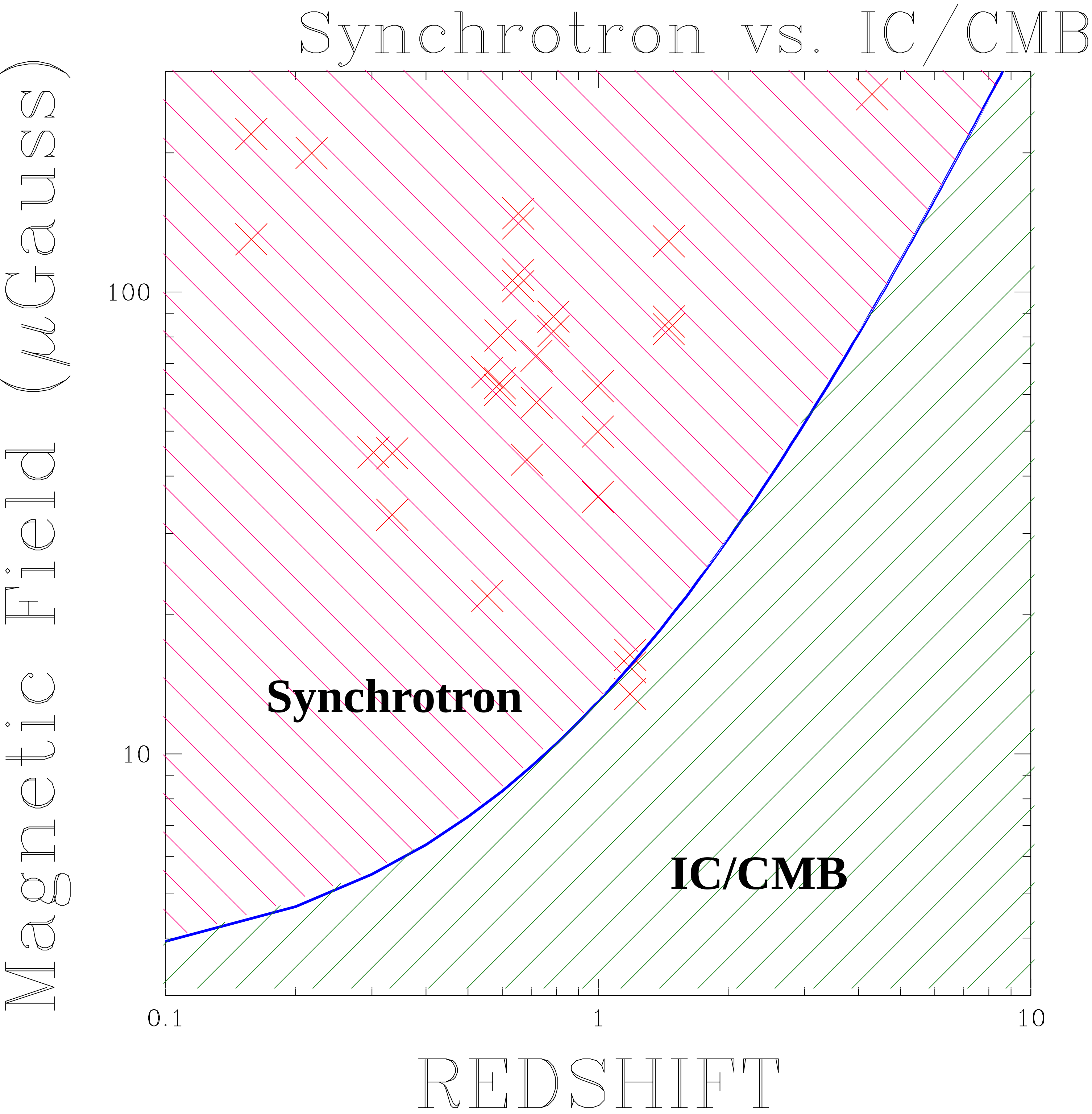
Magnetic Field vs. Cosmic Background Photons

- **Relativistic electrons predominantly lose energy by scattering on the photon (or virtual photon) population with the largest energy density.**

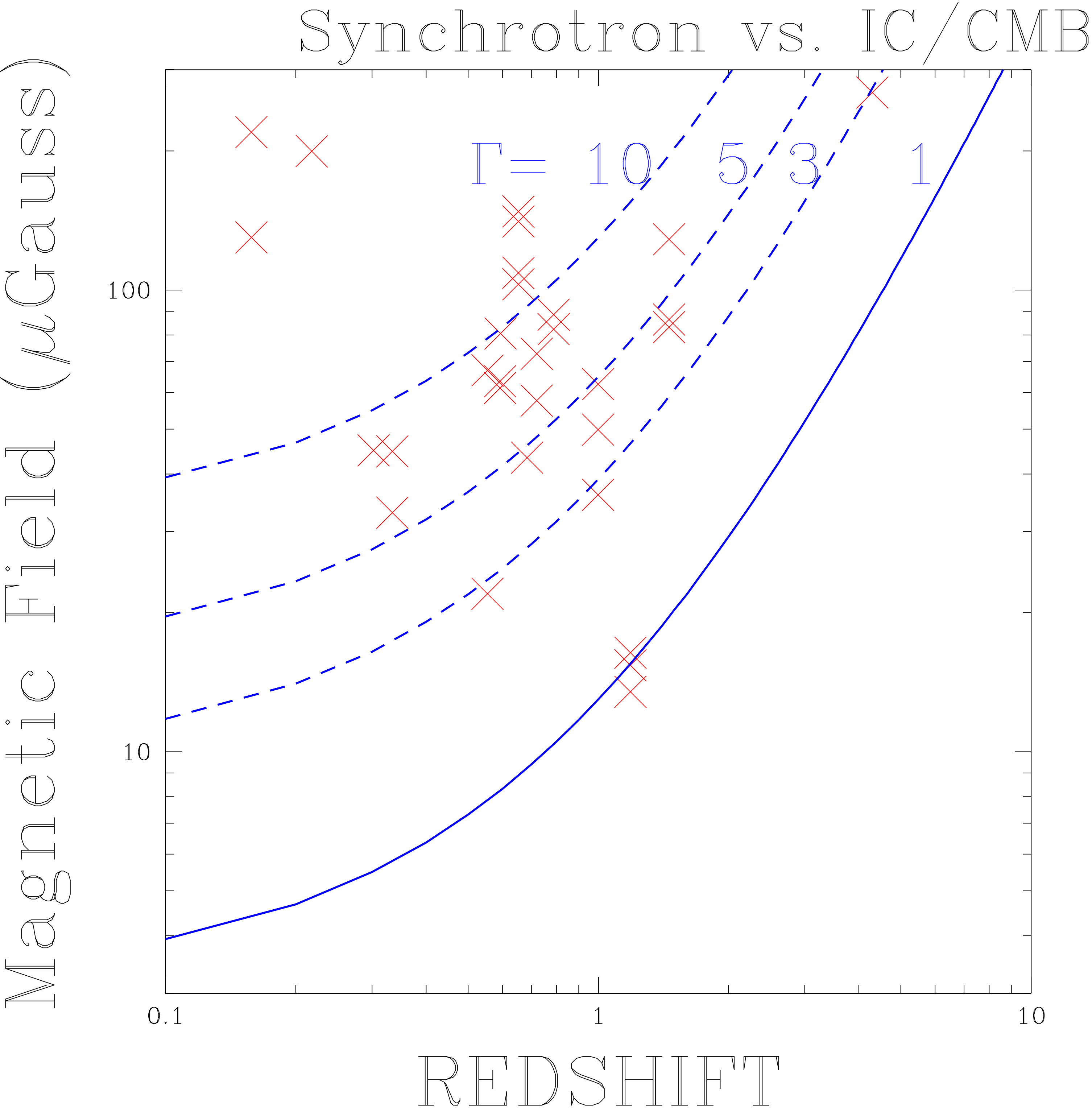
- **If the magnetic field energy density:** $B^2/(8\pi)$
  exceeds the cosmic microwave background energy: $aT_0^4\,\Gamma^2\,(1+z)^4$
  then synchrotron will be the predominant radiation.



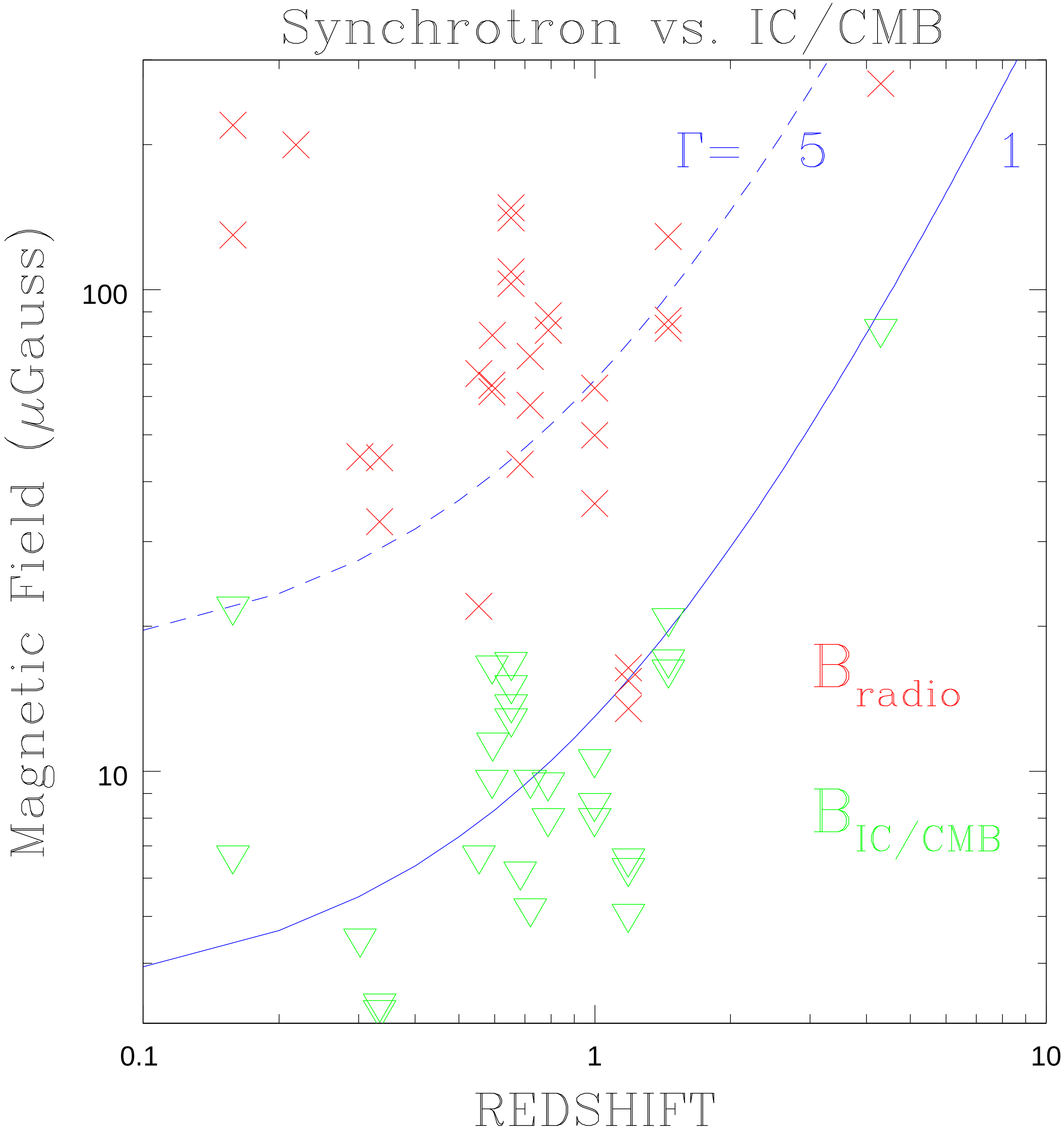
Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B_{radio}



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
100
10
0.1
1
10
REDSHIFT
Magnetic Field (μGauss)



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

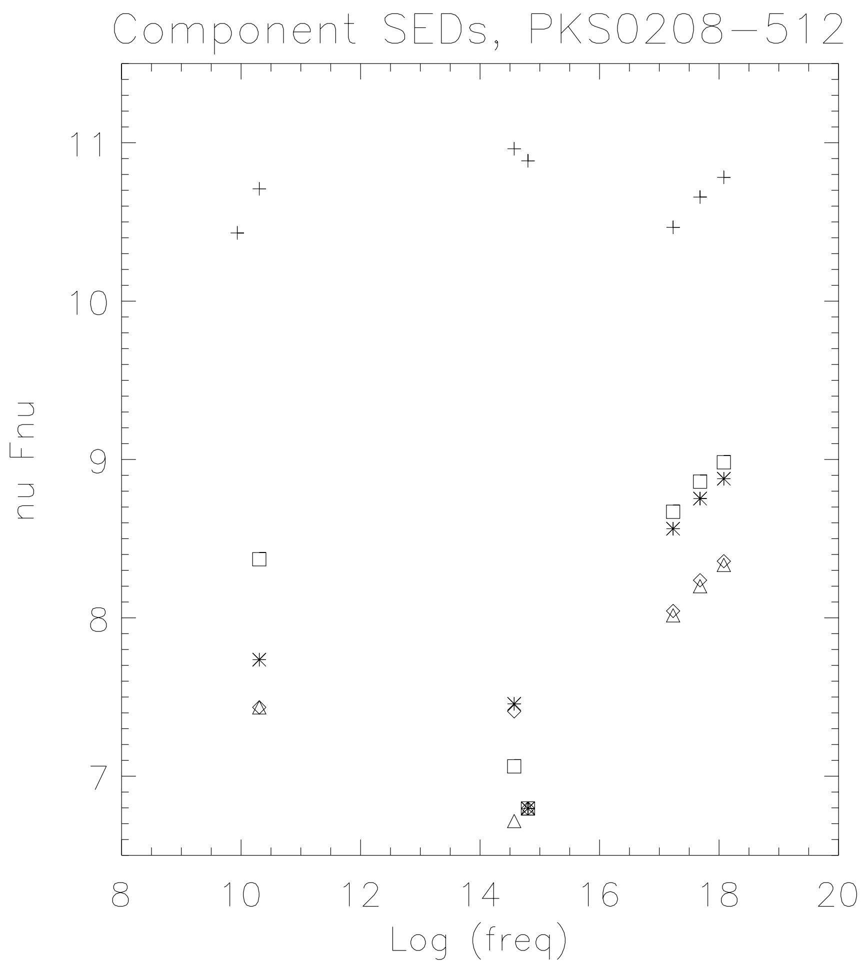
Arguments for the IC/CMB Mechanism

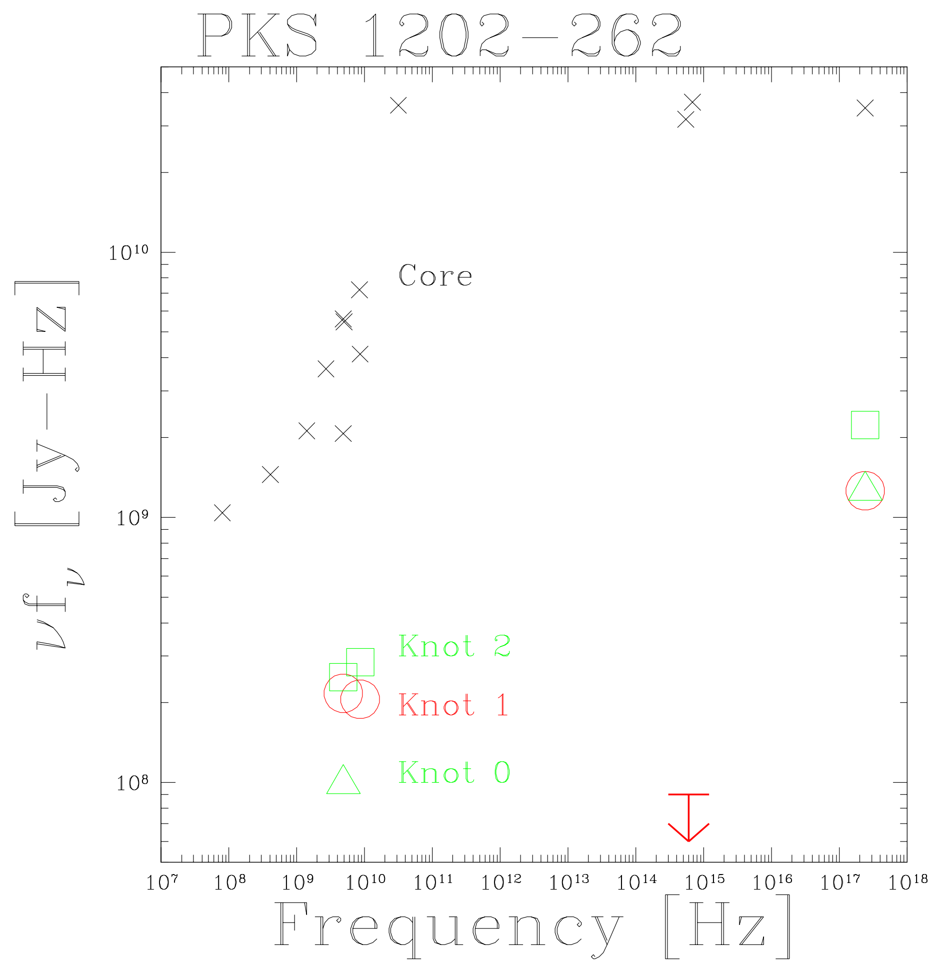
Broadband Spectral Energy Distribution

- **If a single population of electrons produces X-rays via synchrotron emission, then the radio flux density must extrapolate through the optical and connect to the X-ray, possibly with increasing slope.**

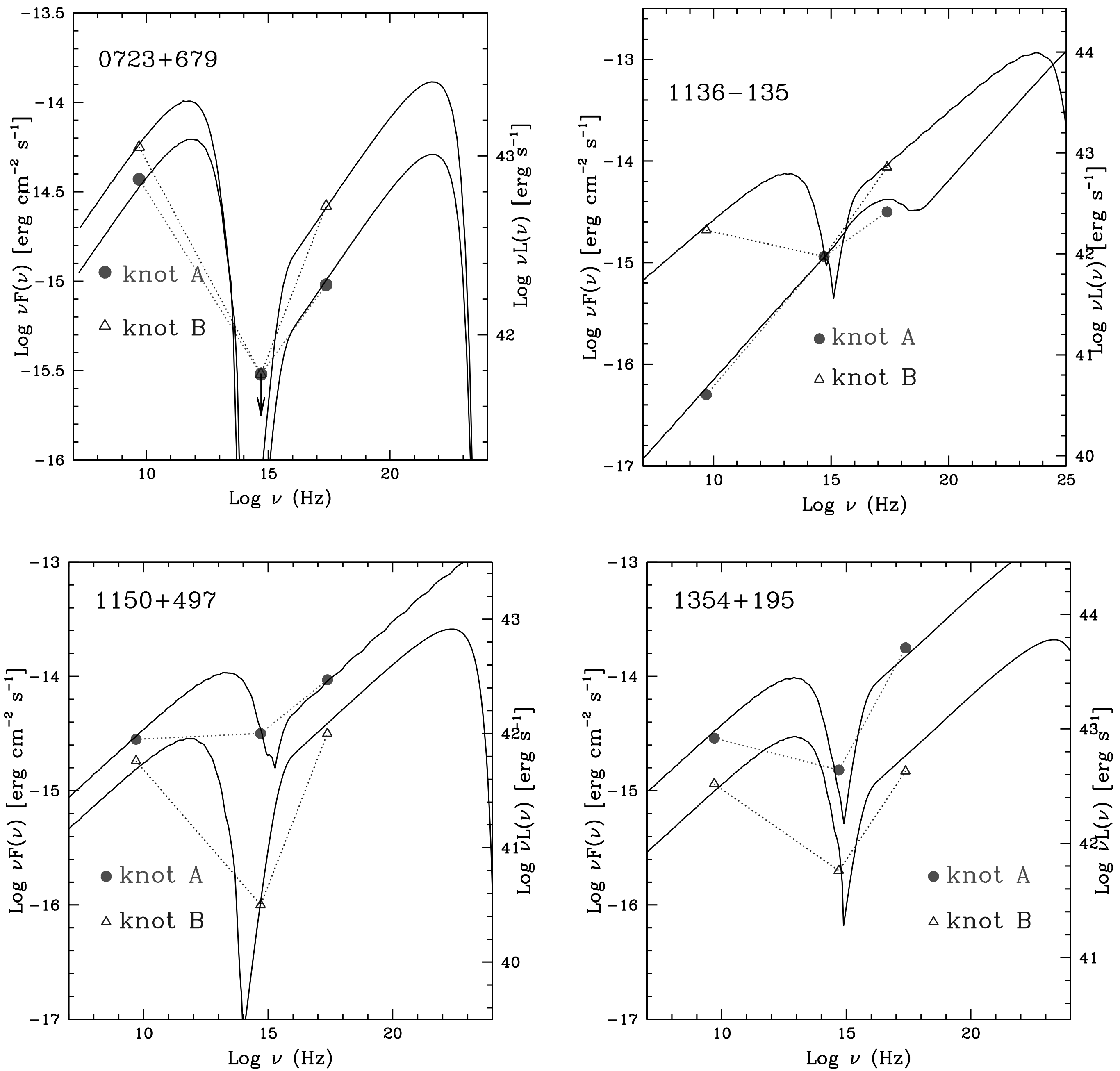
- **Optical upper limits, or detections, below such an extrapolation disallow a single synchrotron emission spectrum.**

Spectral Energy Distribution often indicates against Synchrotron X-rays



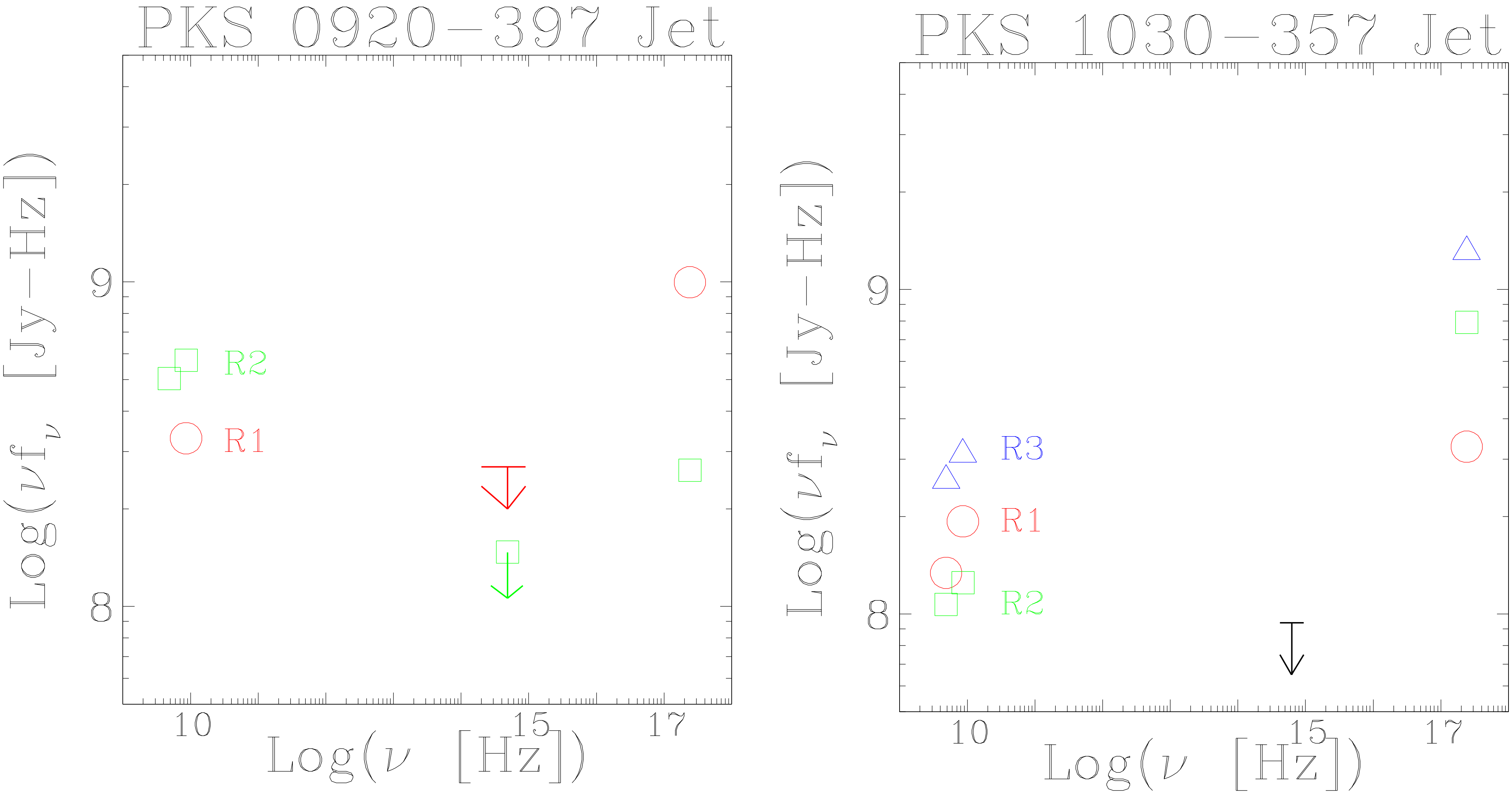


Spectral Energy Distribution often indicates against Synchrotron X-rays



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

Spectral Energy Distribution often indicates against Synchrotron X-rays



Arguments for the IC/CMB Mechanism

Morphology and the X-ray vs. Radio Profiles

- **Lowest energy electrons propagate furthest downstream**

- **Radio emission downstream of synchrotron X-ray emission**

  $\gamma_{x-ray} \approx 10^7; \ \gamma_{radio} \approx 10^{4.5}$

  X-rays decrease rapidly and not well correlated with radio

- **Radio emission upstream of IC/CMB X-ray emission**

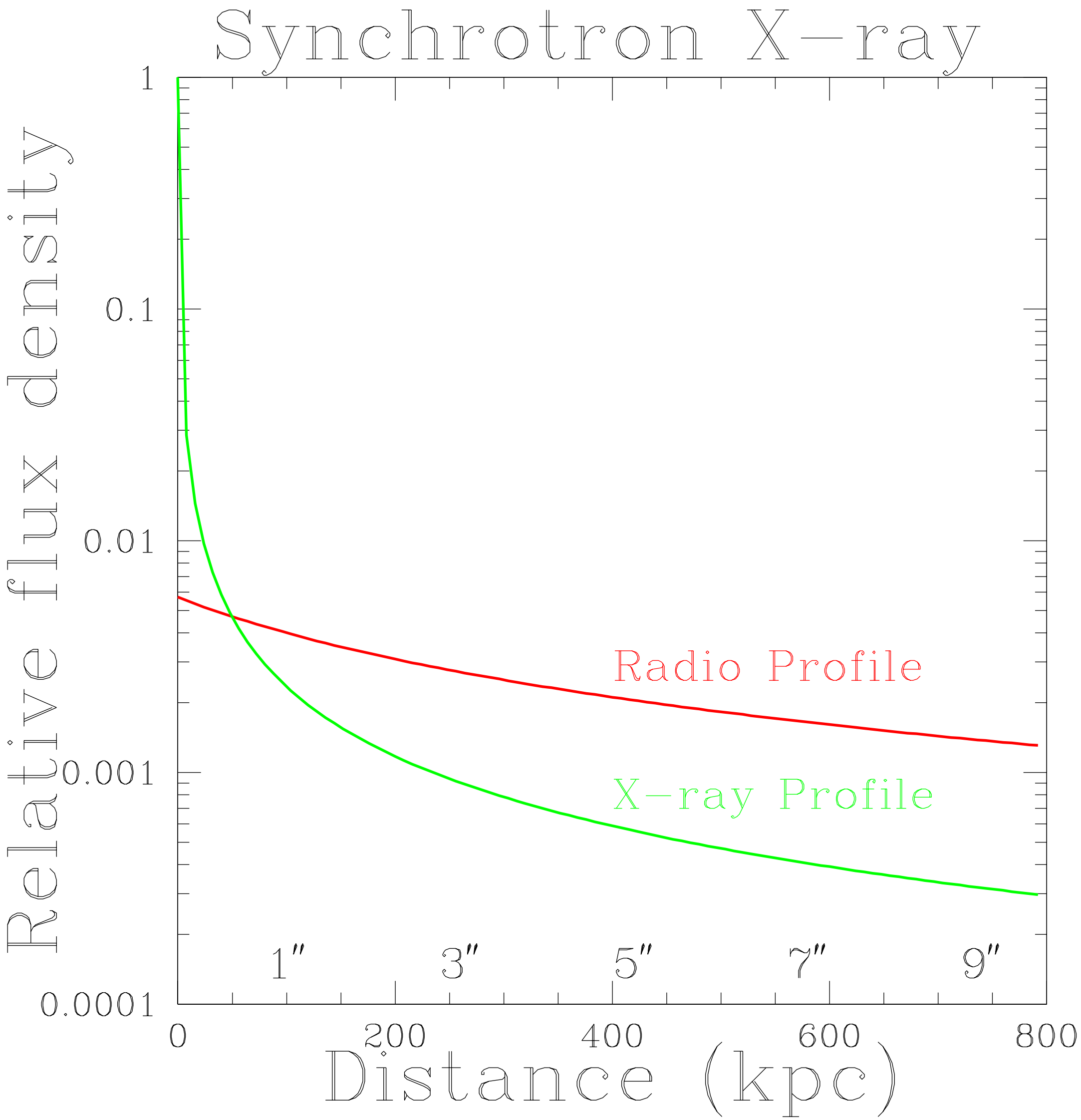
  $\gamma_{x-ray} \approx 10^3; \ \gamma_{radio} \approx 10^{4.5}$

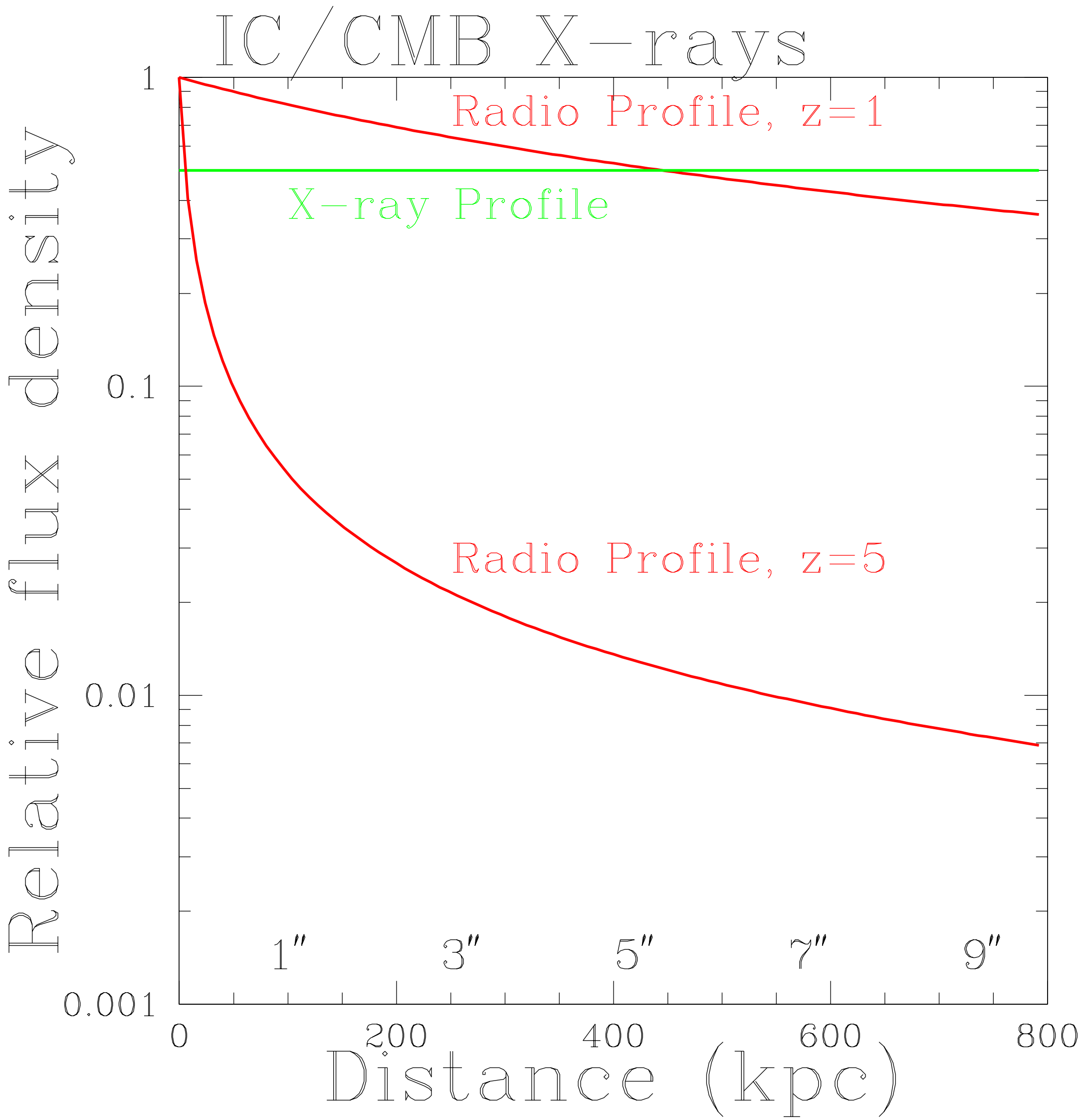
  Radio to X-ray ratio change not as rapid.

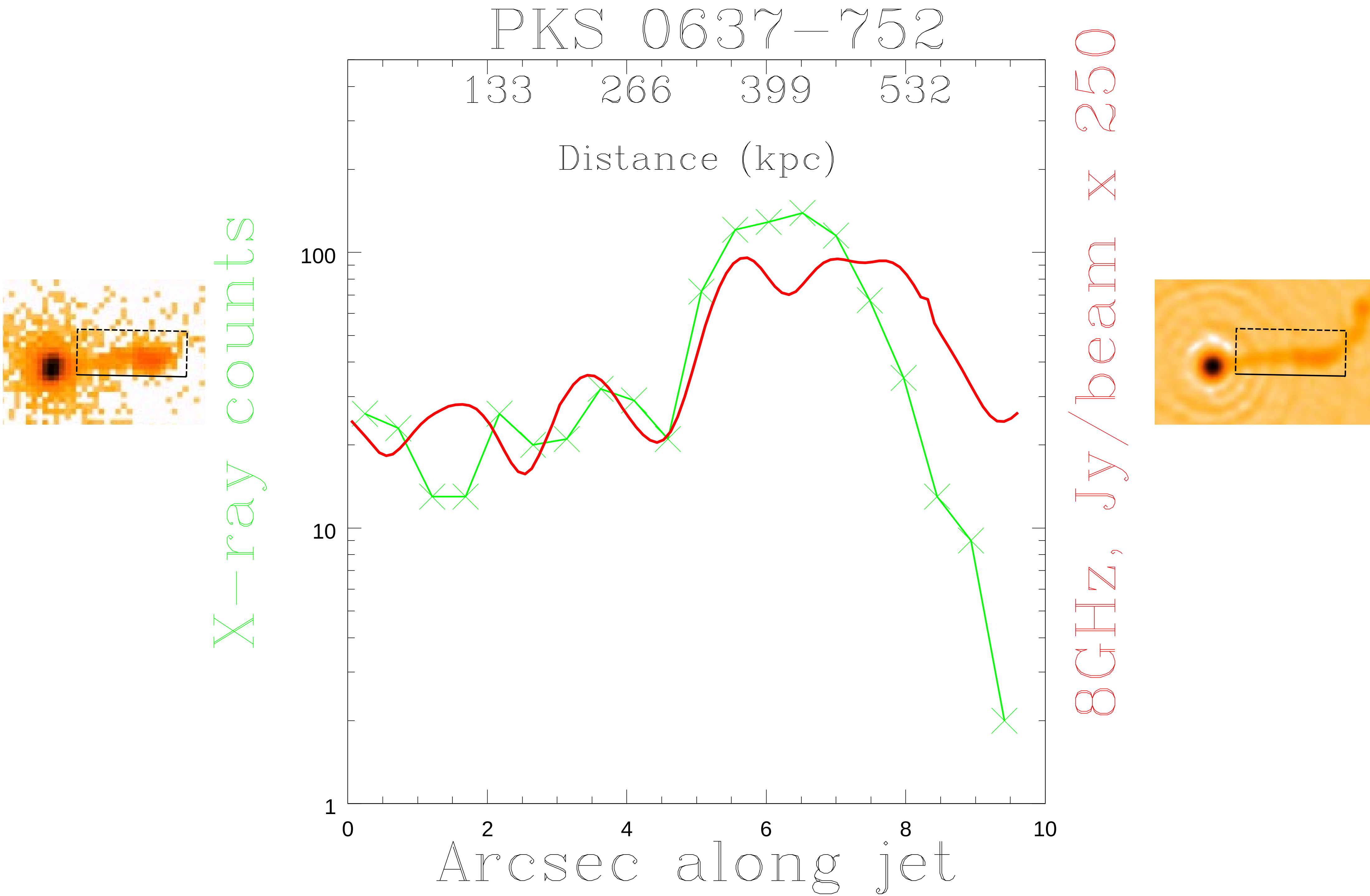
Confront IC/CMB with Morphology

Naive Models

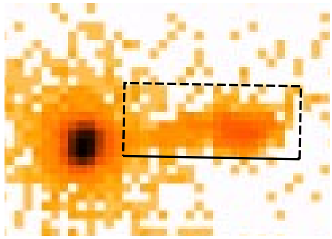
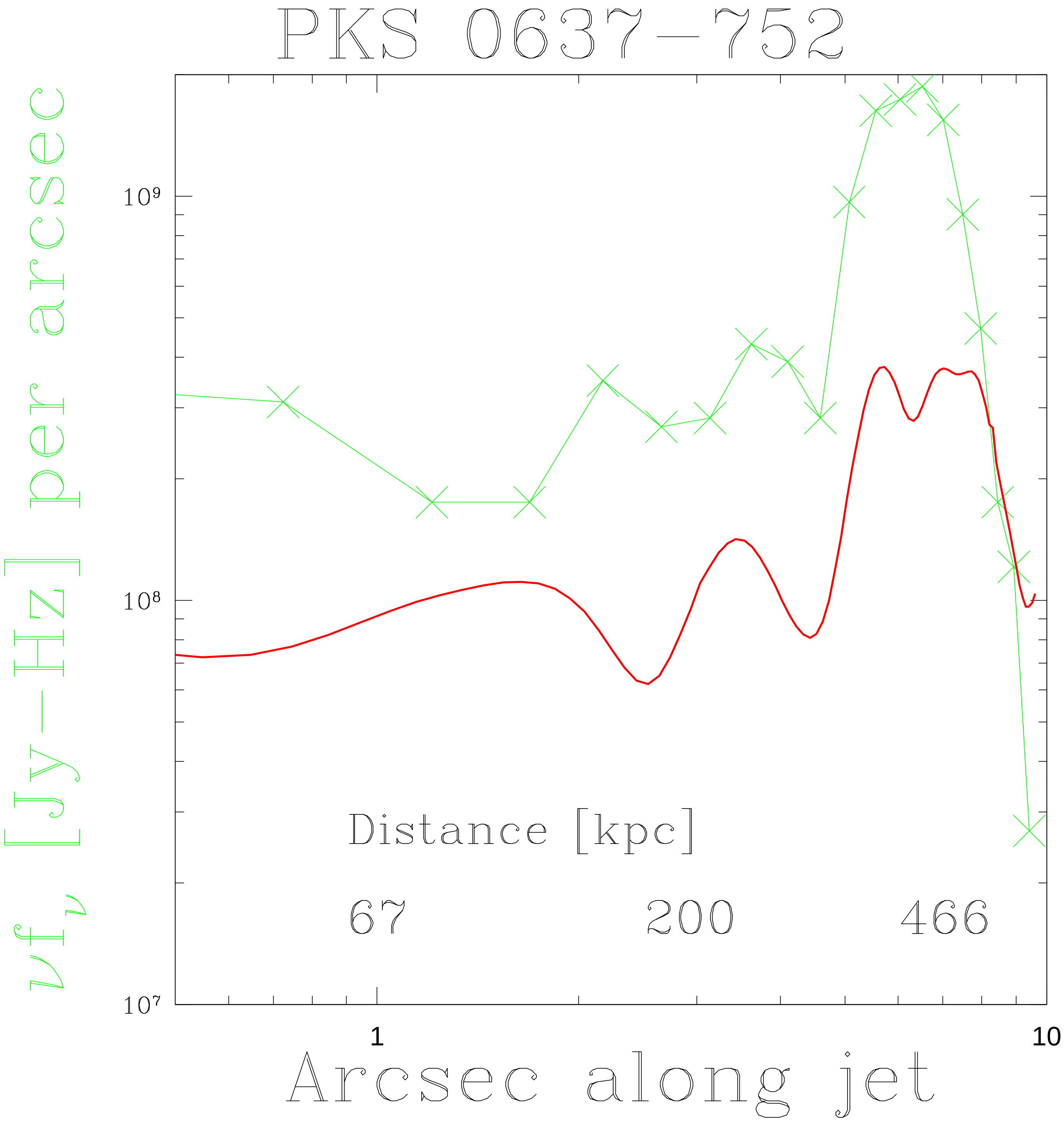
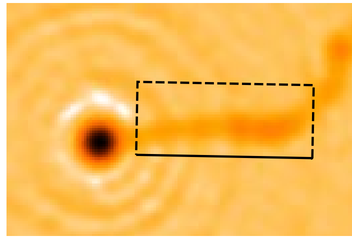
(z=1; Γ=10; θ=0.1 radian; B=10μG)

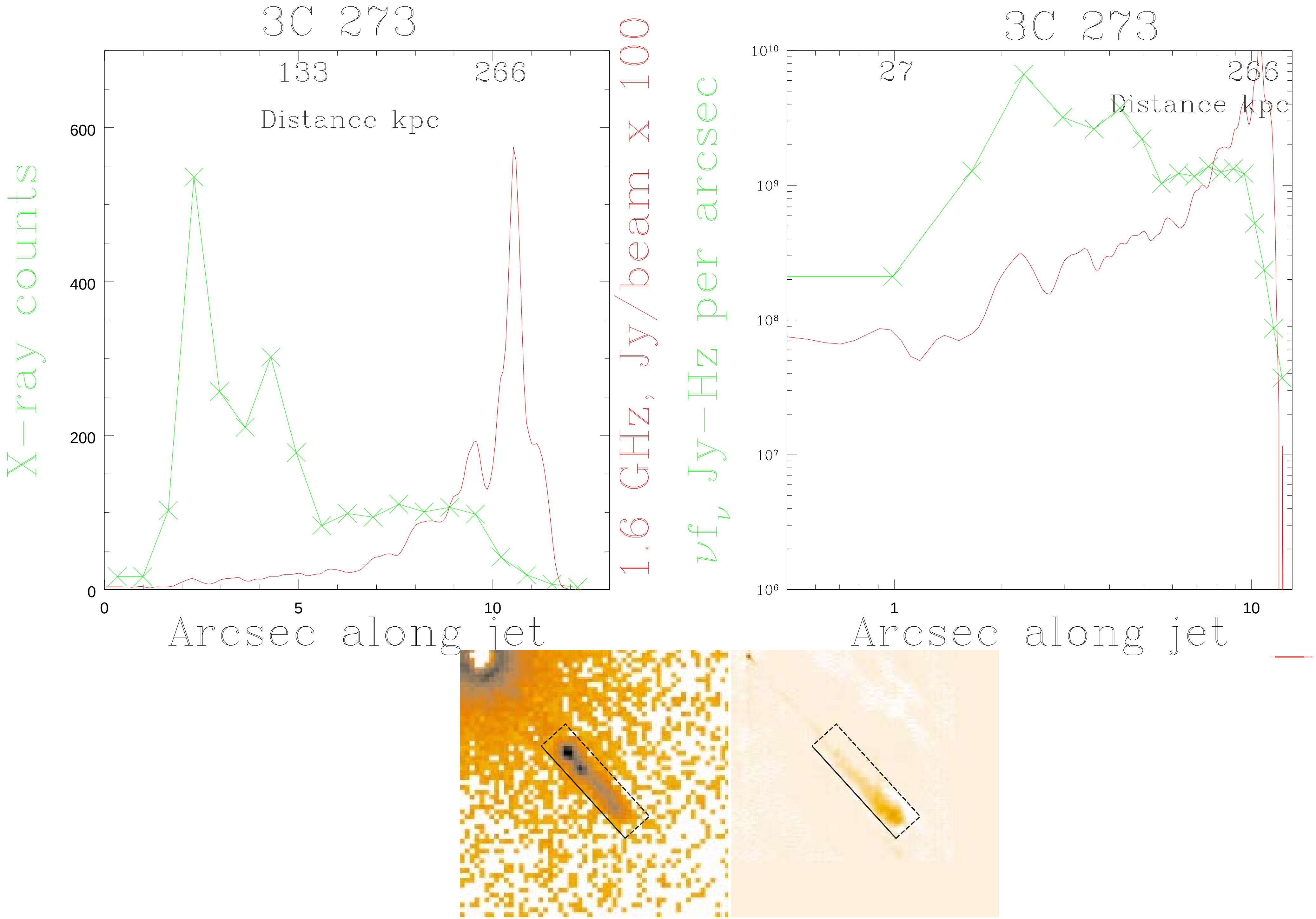


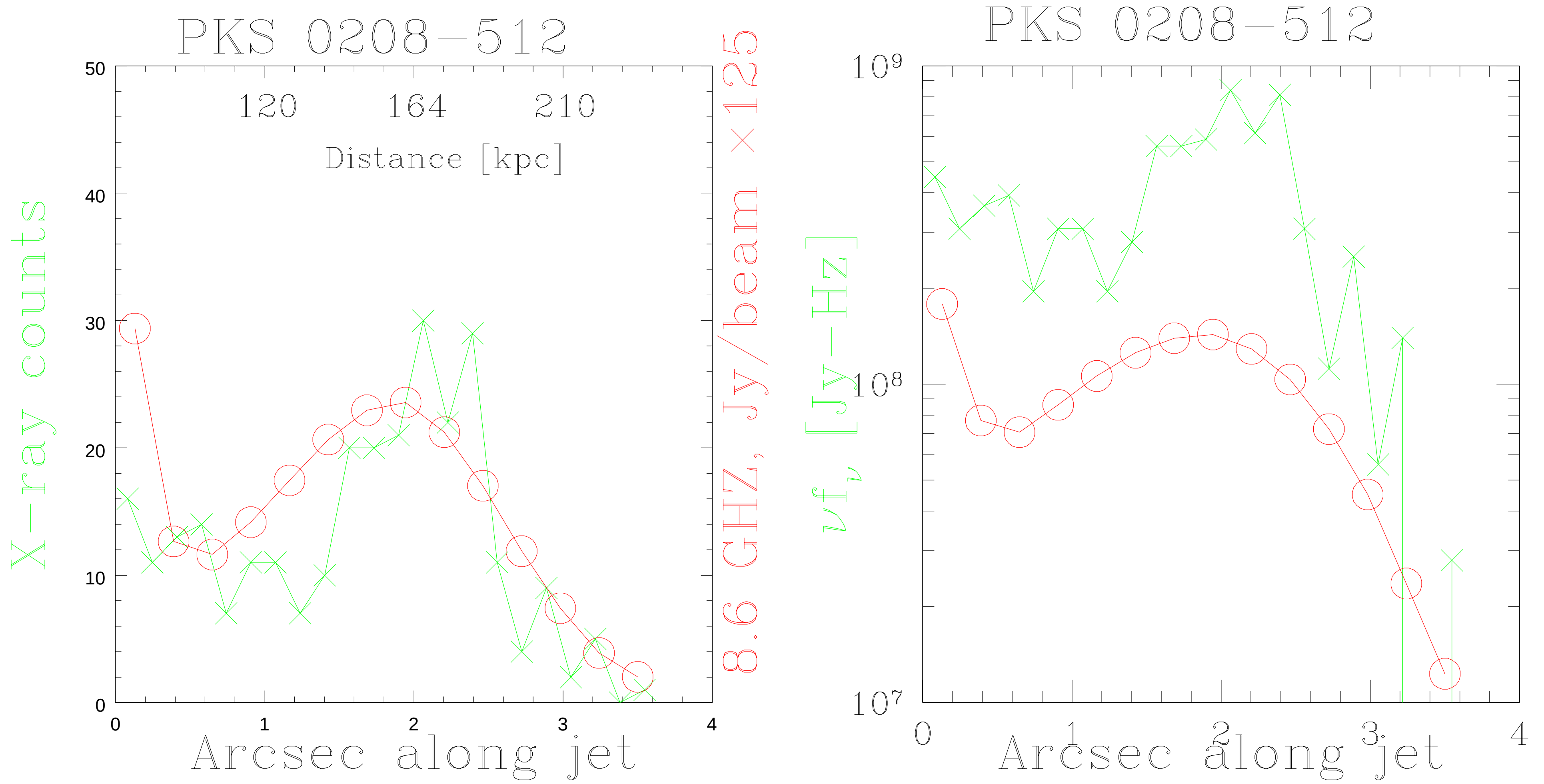


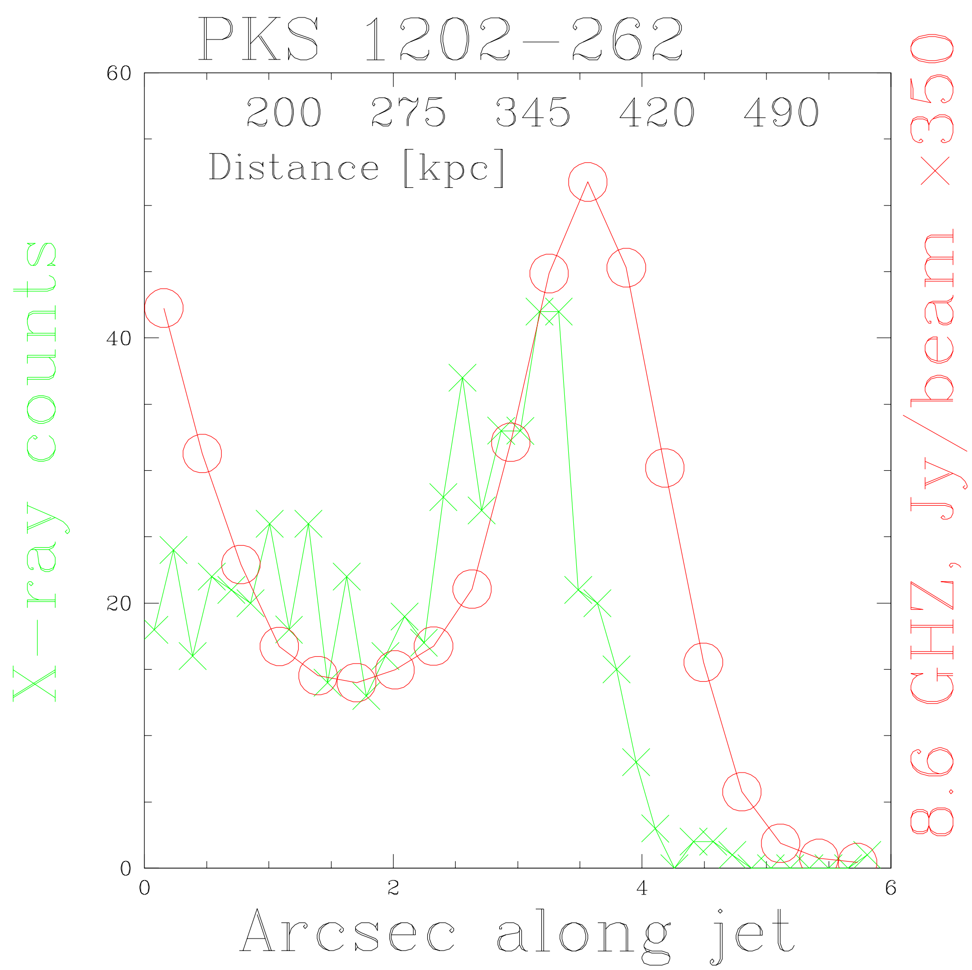


PKS 0637−752
133
266
399
532
Distance (kpc)
100
10
1
0
2
4
6
8
10
Arcsec along jet
X−ray counts
8GHz, Jy/beam x 250

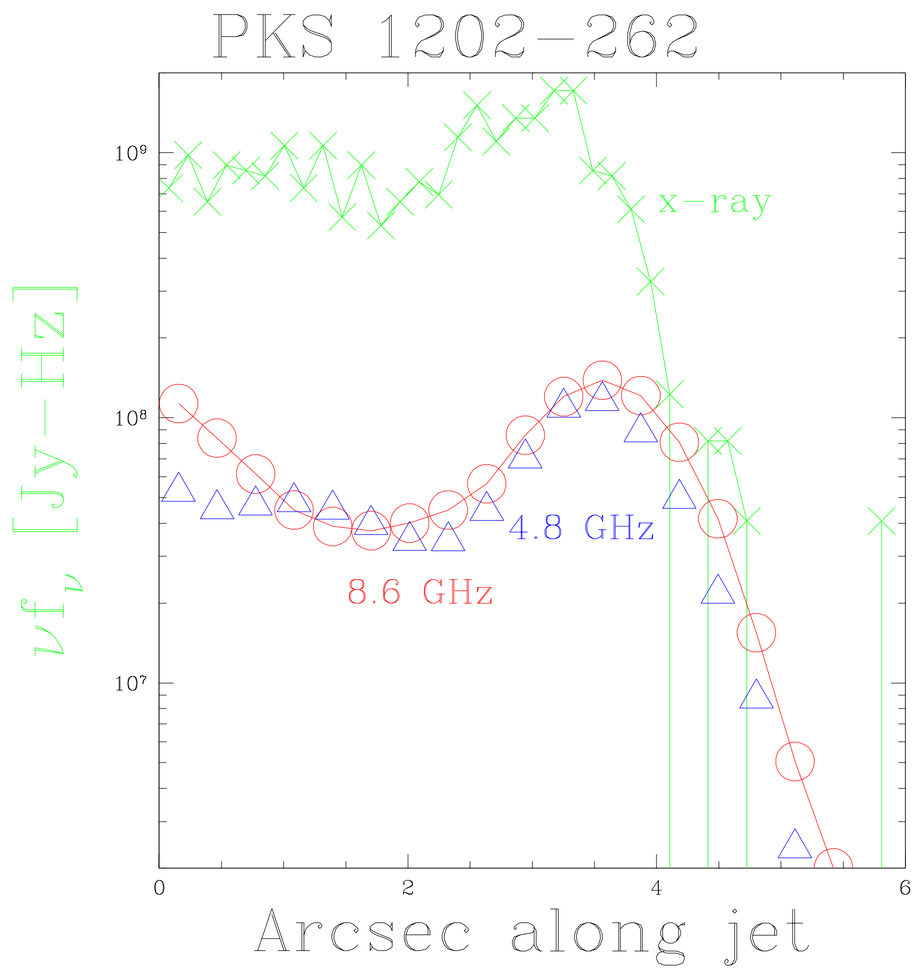


PKS 0637−752
νf_ν [Jy−Hz] per arcsec
10^9
10^8
10^7
Distance [kpc]
67
200
466
1
10
Arcsec along jet



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

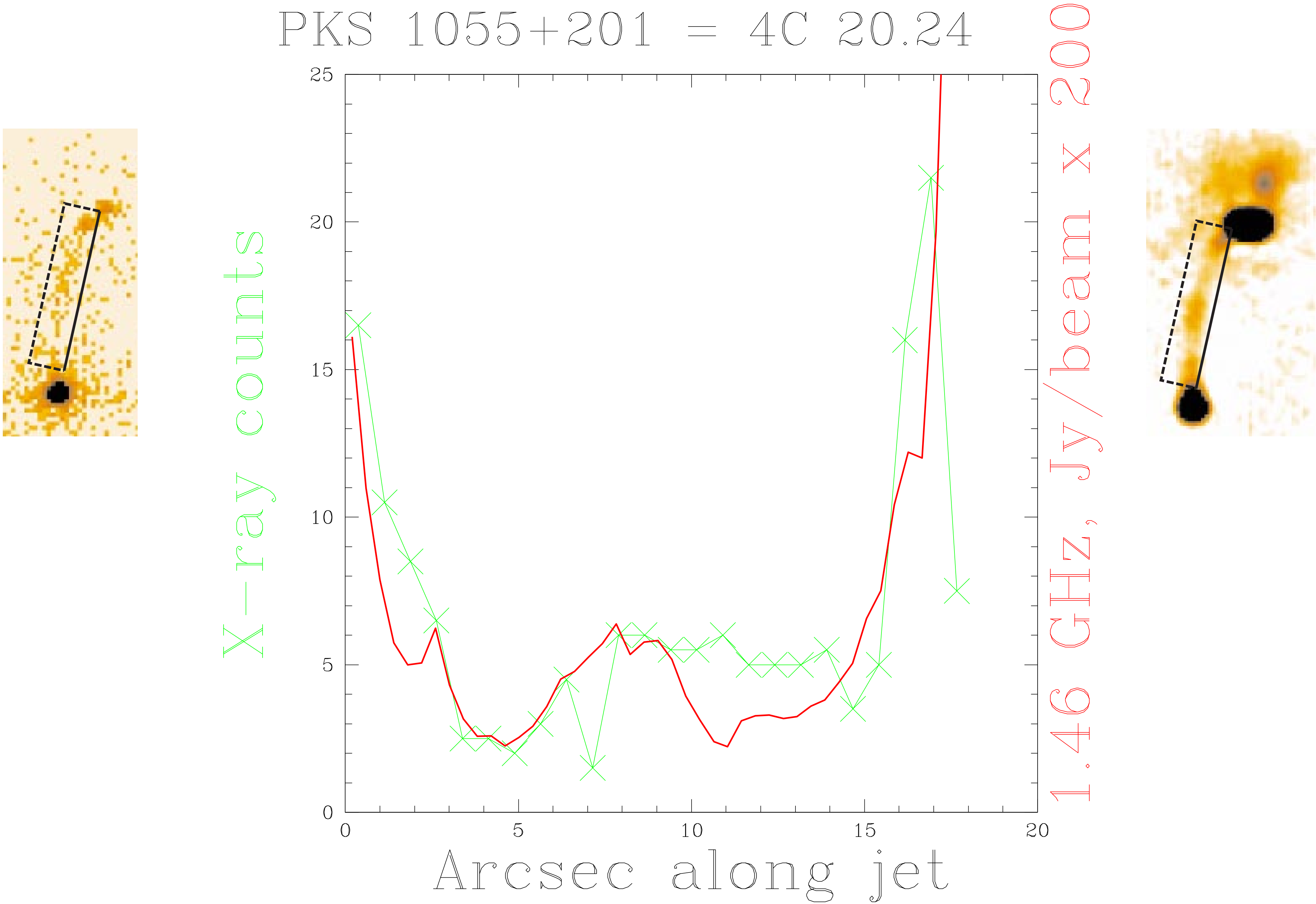

PKS 0208−512
120
164
210
Distance [kpc]
X-ray counts
8.6 GHZ, Jy/beam ×125
Arcsec along jet
PKS 0208−512
10^9
10^8
10^7
νf_ν [Jy−Hz]
Arcsec along jet

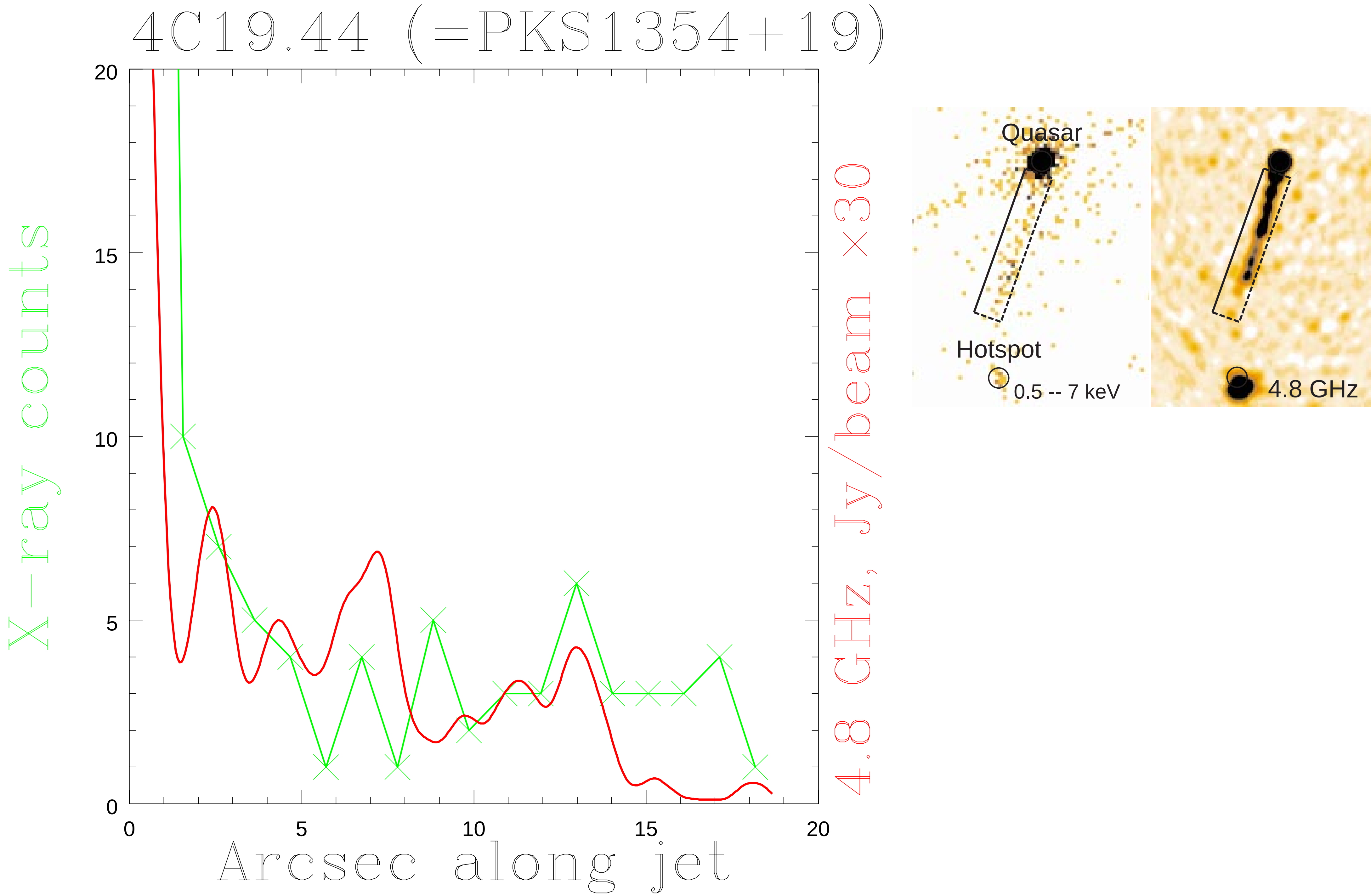


PKS 1202−262
200
275
345
420
490
Distance [kpc]
X−ray counts
8.6 GHZ, Jy/beam ×350
60
40
20
0
0
2
4
6
Arcsec along jet



PKS 1202−262
10^9
10^8
10^7
x−ray
4.8 GHz
8.6 GHz
νf_ν [Jy−Hz]
0
2
4
6
Arcsec along jet


PKS 1055+201 = 4C 20.24
X-ray counts
1.46 GHz, Jy/beam x 200
Arcsec along jet
0
5
10
15
20
25
0
5
10
15
20



4C19.44 (=PKS1354+19)
X−ray counts
4.8 GHz, Jy/beam ×30
Arcsec along jet
0
5
10
15
20
Quasar
Hotspot
0.5 -- 7 keV
4.8 GHz

Morphology Summary

- **Roughly constant f_x/f_r (within $\times 2$).**
  X-rays end when radio makes sharp bend.
  IC/CMB: Strong Beaming Dependence

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

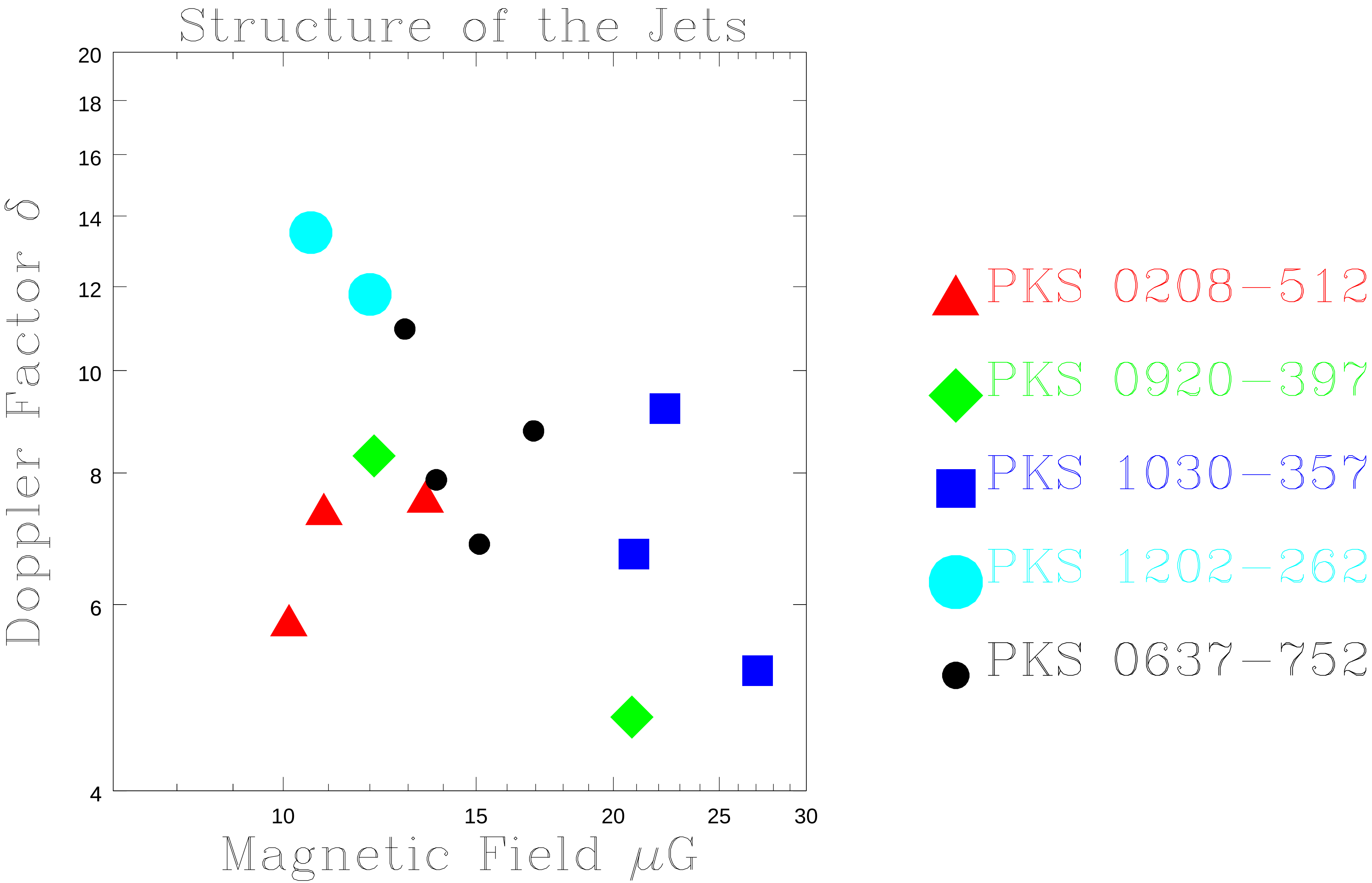
- **Roughly constant f_x/f_r (within $\times 2$).**
  X-rays persist beyond radio.
  IC/CMB: Longer Lived Low Energy Electrons

IC/CMB Implications for AGN Jets

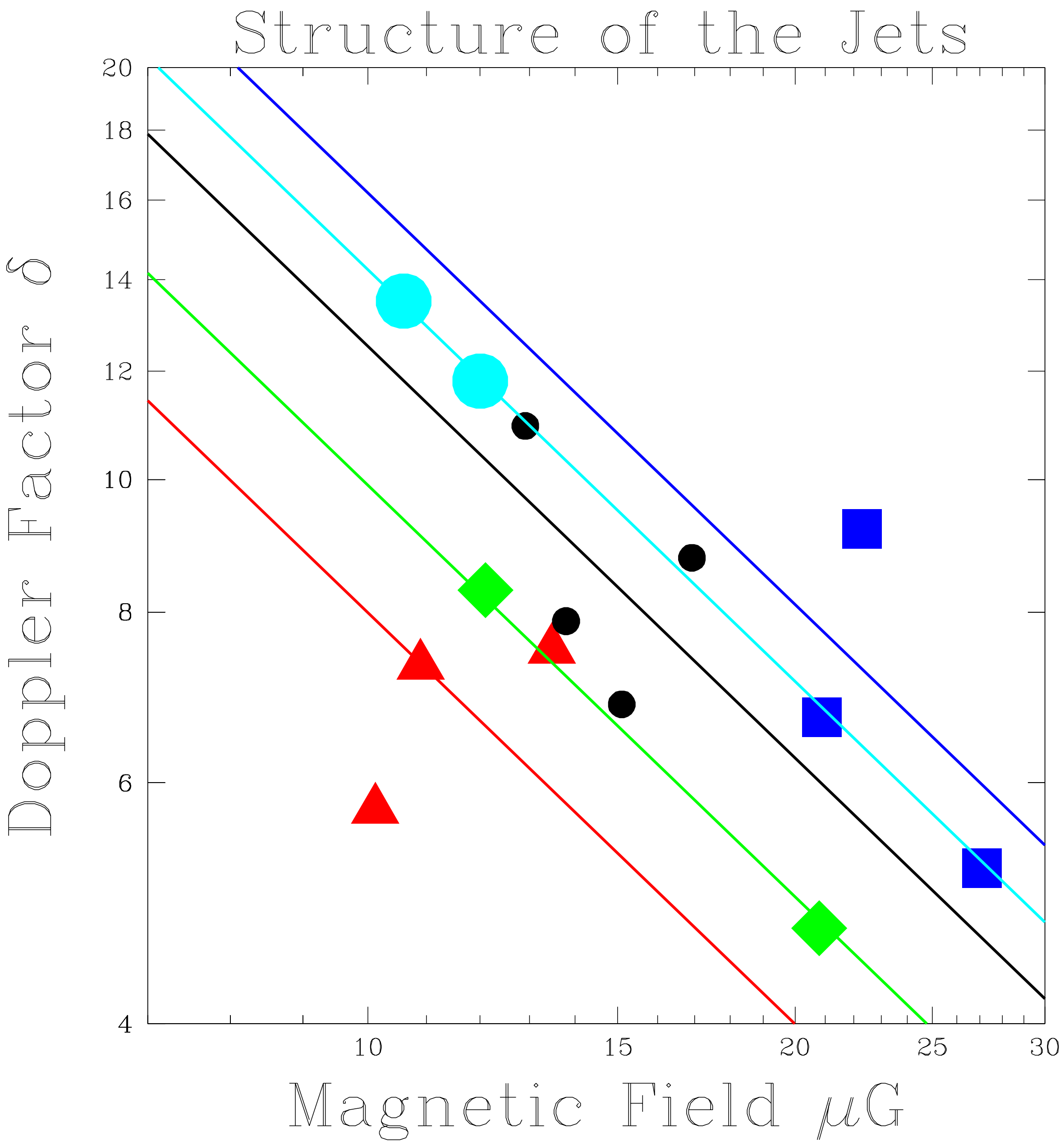
- **Eddington Luminosity might not limit Accretion Rate – Black Holes may Grow more rapidly than expected.**

- **We observe sufficient Jet Power to inflate Cavities in Clusters of Galaxies & Stop Cooling Flows**
  10^{61} ergs in 30 Myrs.

- **IC/CMB X-ray jets Maintain Constant Surface Brightness vs. z.**
  Can detect their X-rays at any Redshift.

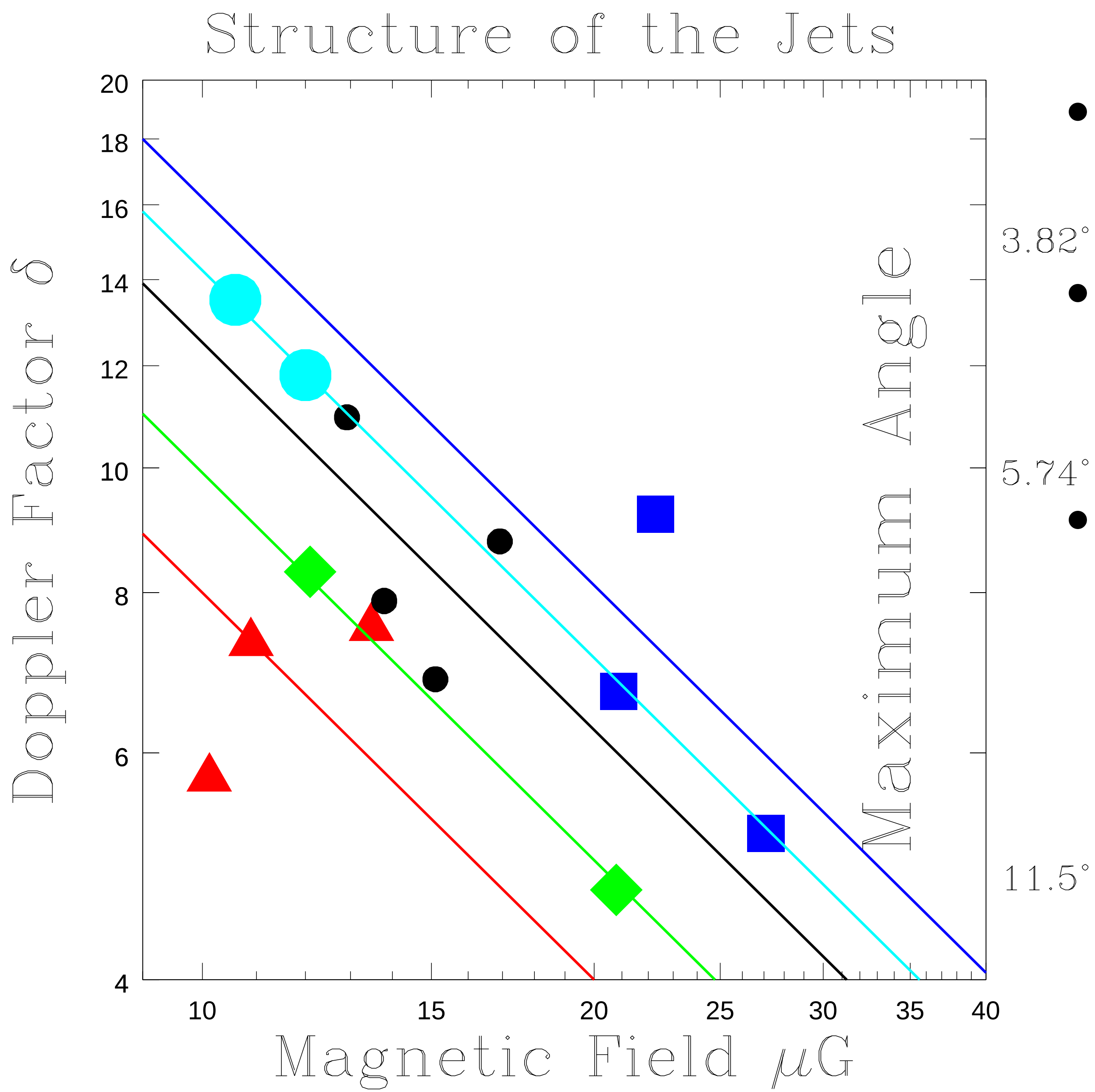


Structure of the Jets
Doppler Factor δ
Magnetic Field μG
20
18
16
14
12
10
8
6
4
10
15
20
25
30
PKS 0208−512
PKS 0920−397
PKS 1030−357
PKS 1202−262
PKS 0637−752



Kinetic Flux

- $P_{jet} = \Gamma^2 \pi\, r^2 \beta\, c\, (w - \rho_0\, c^2 / \Gamma)$
- w is enthalpy density, ρ_0 the mass density
- For equipartition, $w = \frac{B^2}{6\pi}(2 + \chi)$
- NOTE: P_{jet} constant $\Rightarrow$ $(B\,\Gamma)^2$ = constant



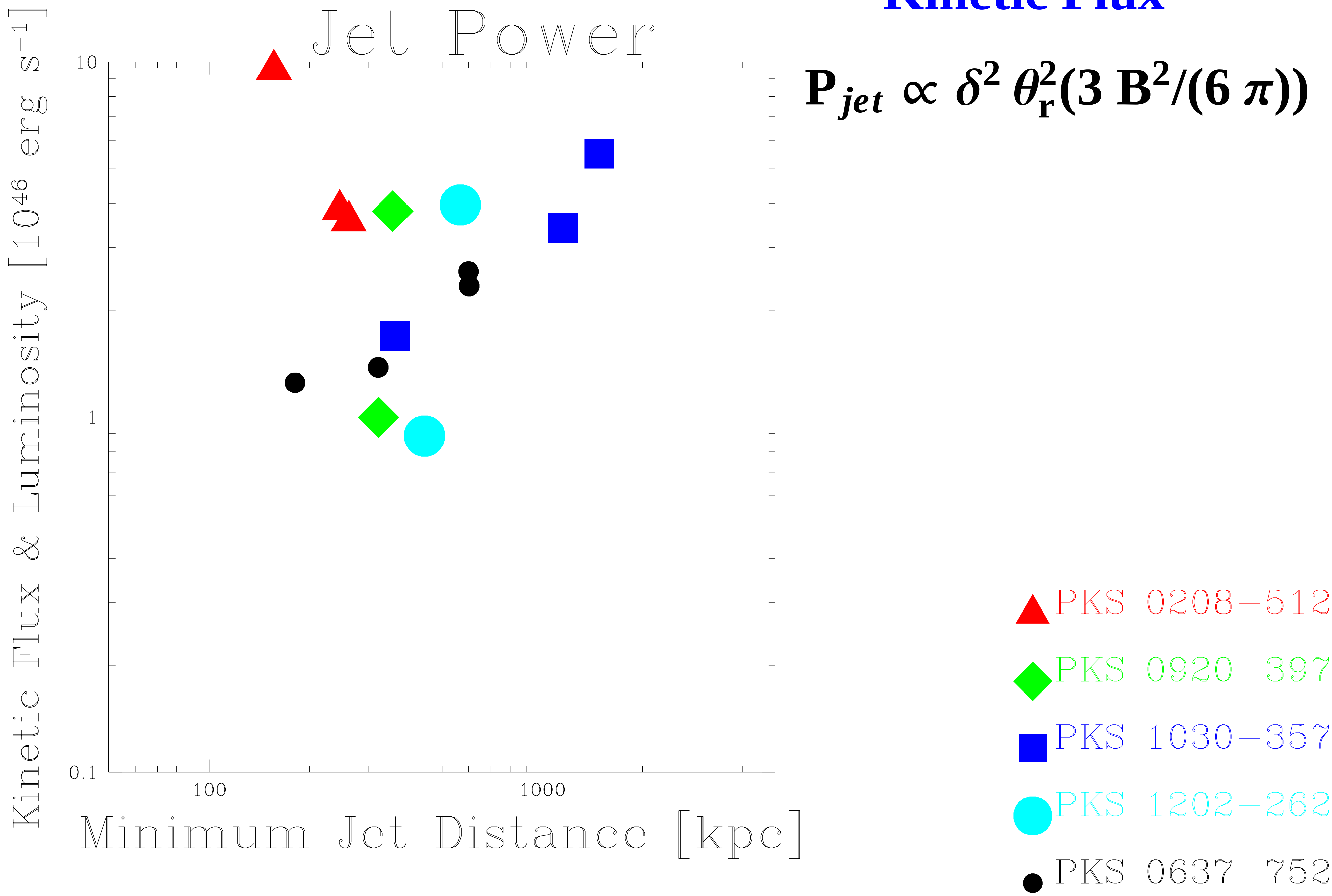
Kinetic Flux

- $P_{jet} = \Gamma^2 \pi r^2 \beta c (w - \rho_0 c^2 / \Gamma)$
- **We take** $\Gamma \approx \delta$

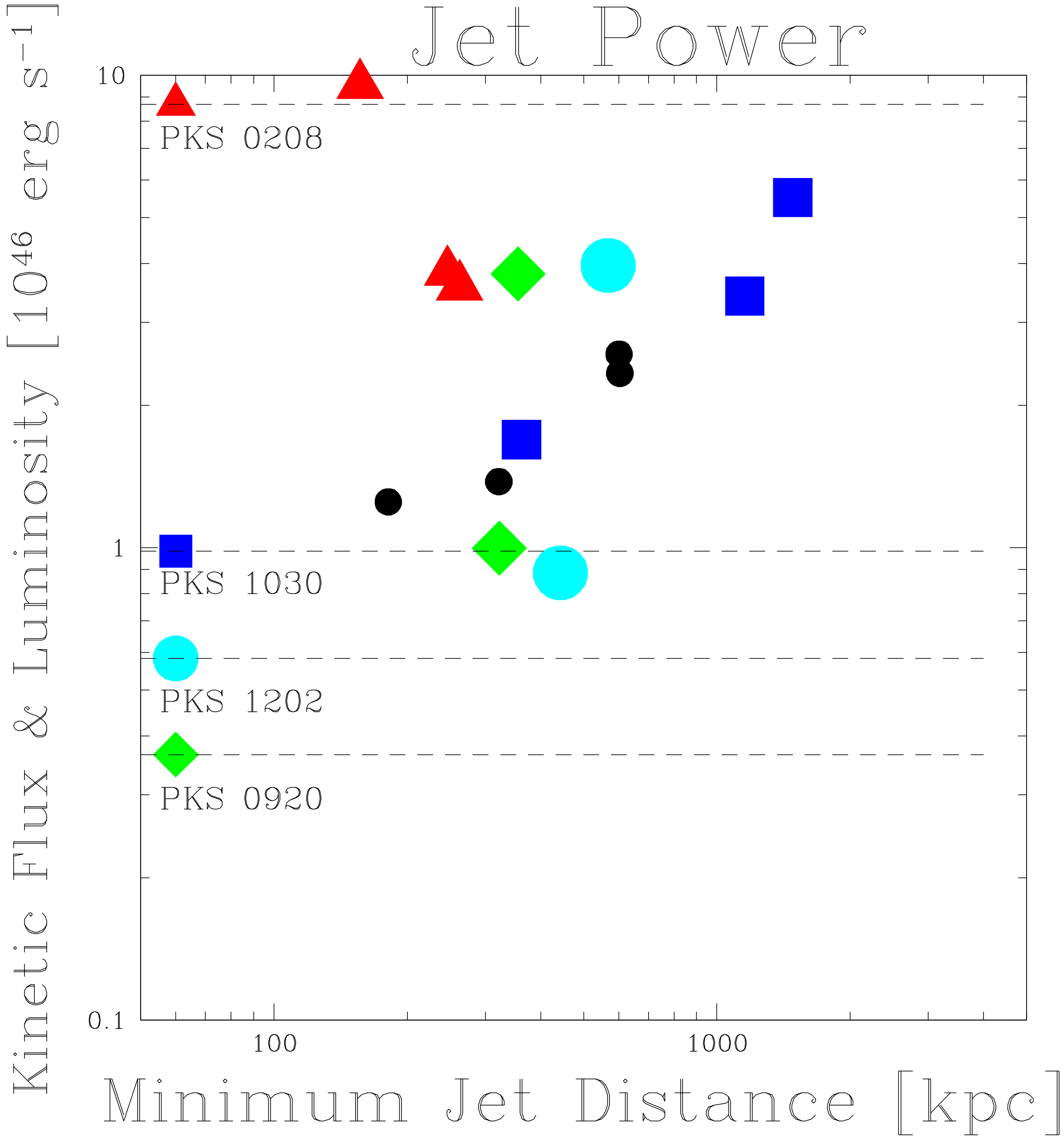
  $\delta = (\Gamma(1 - \beta \cos(\theta)))^{-1}$
- $\cos(\theta_{max}) = \sqrt{(\delta^2 - 1)}/\delta$

Kinetic Flux

$$P_{jet} \propto \delta^2 \theta_r^2 (3 B^2/(6\pi))$$



Kinetic Flux



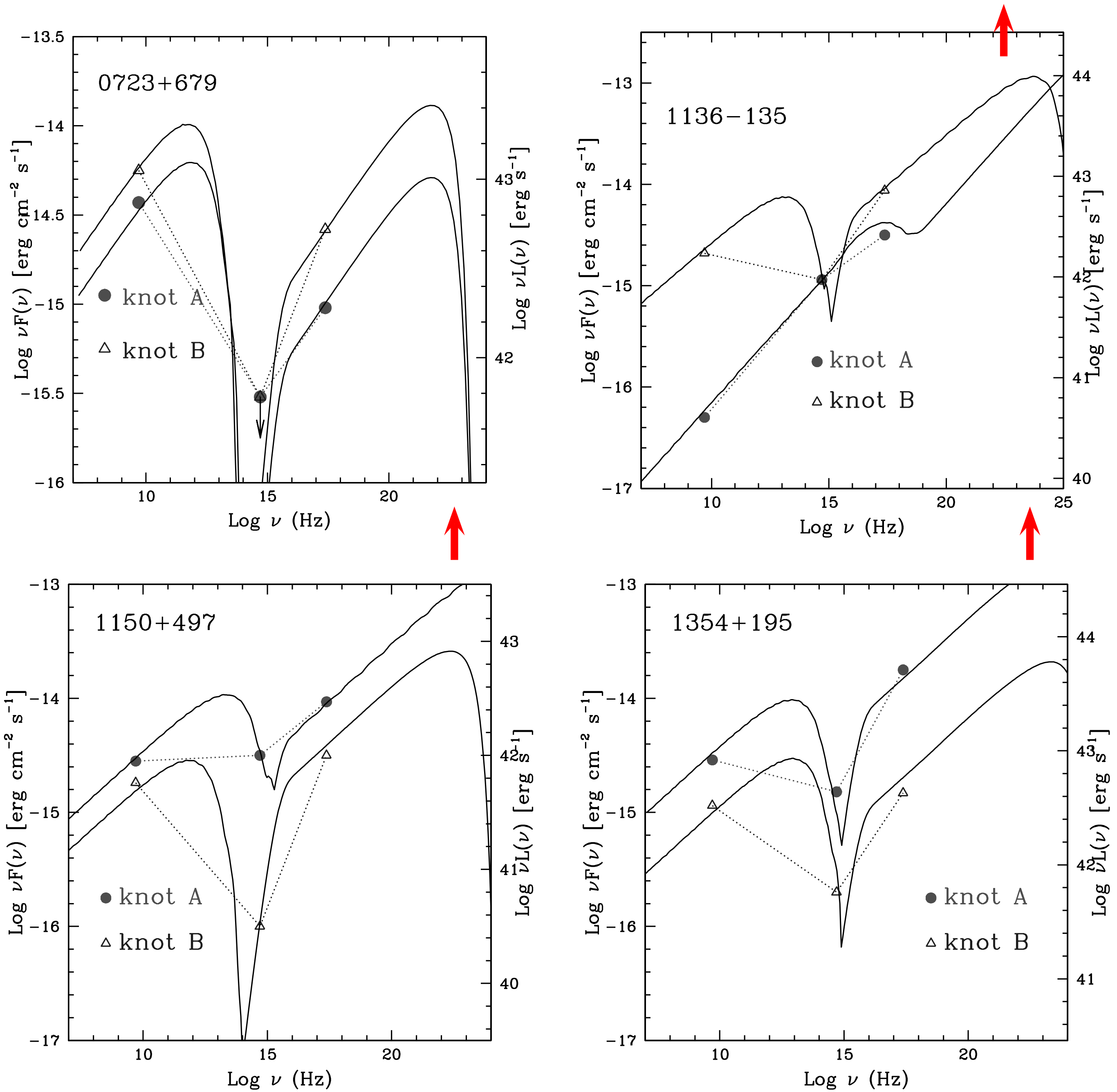
From $\mathbf{K = \Gamma^2 \pi\, r^2 \beta\, c\, U}$**,**

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

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

Predictions of the IC/CMB Mechanism

- **Must have IC/CMB γ-ray Jets**
- **X-ray to radio flux ratio of jet must increase with redshift**
- **X-ray jet to X-ray quasar flux must increase with redshift**
- **There may be radio quiet jets**
- **X-ray jet flux density index equal or flatter than radio**



Inverse Compton X-rays from the CMB:

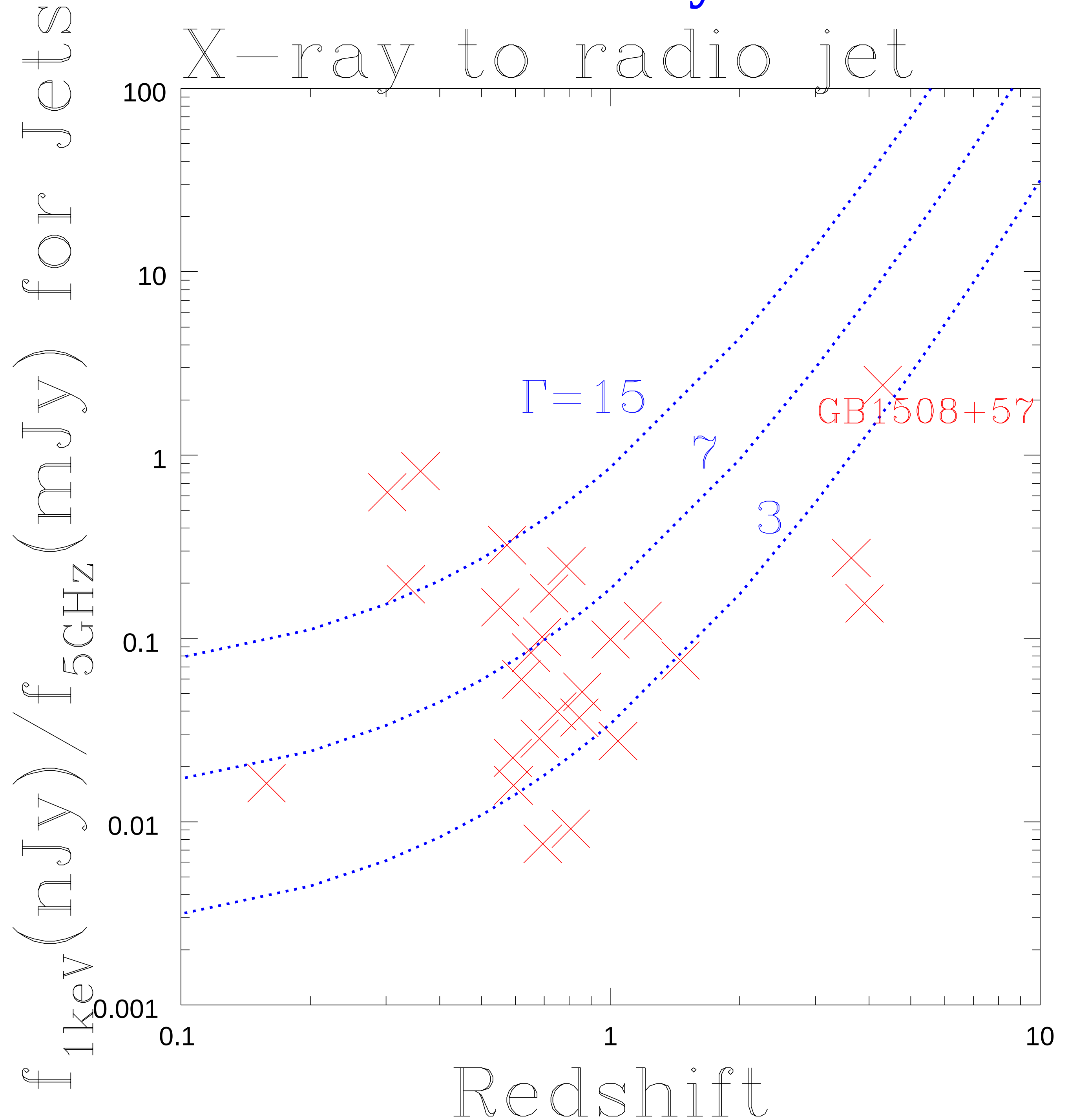
$\gamma_x \approx 10^{2-3}$

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

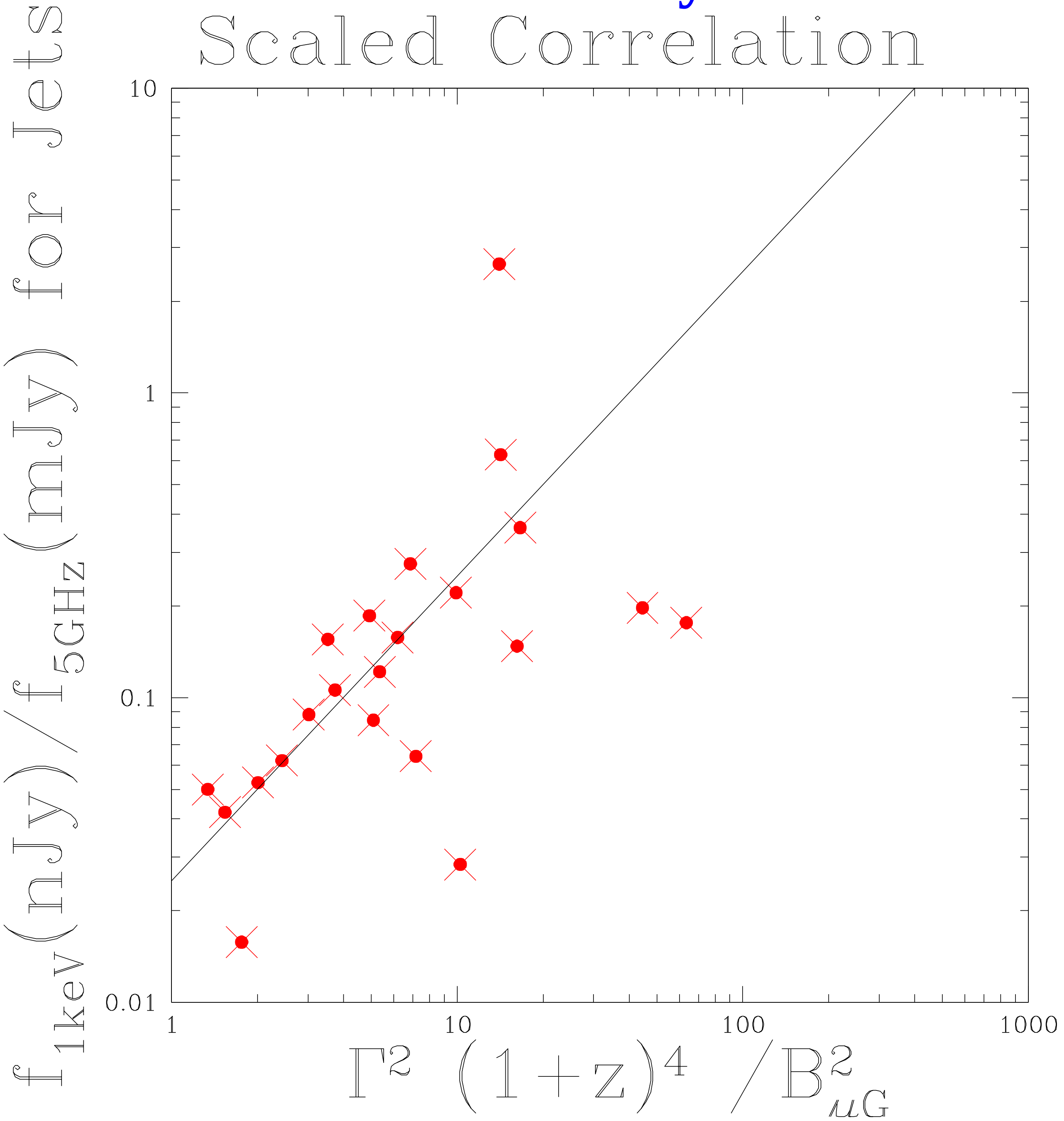
Some kpc scale jets may be detectable by GLAST, at 10^{-13} to 10^{-12} ergs cm^{-2} s^{-1}

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

Correlation of X-ray and Radio Flux Densities

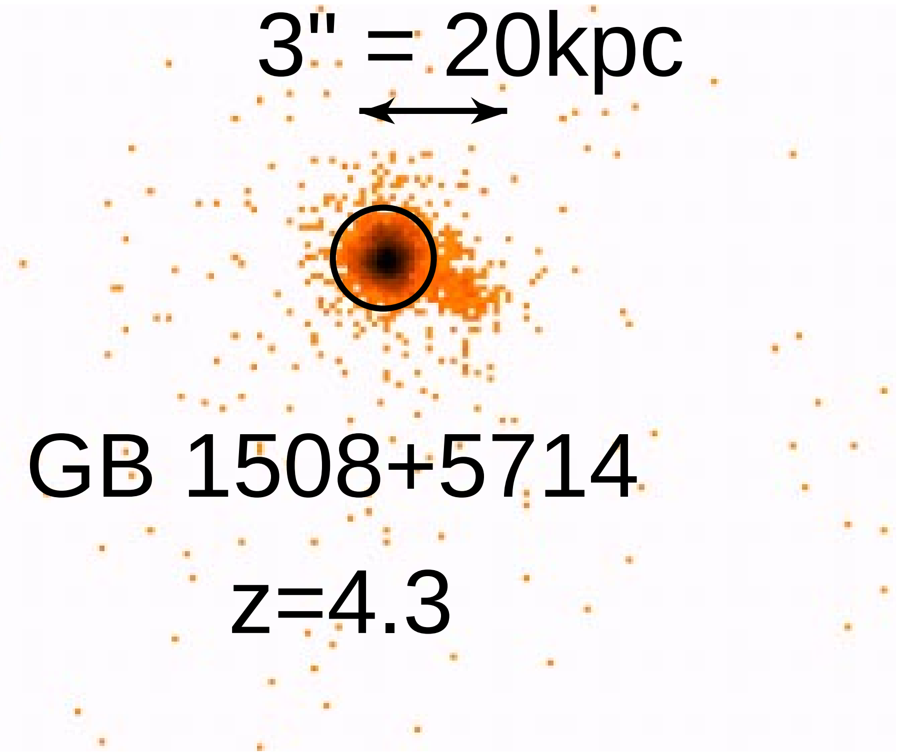


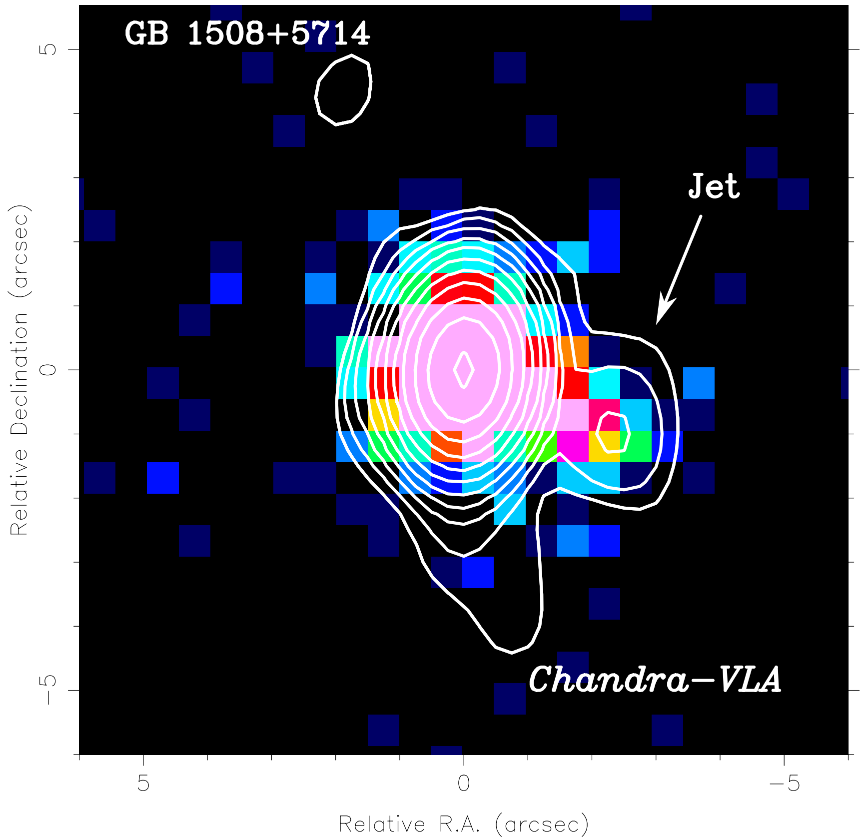
Correlation of X-ray and Radio Flux Densities



An X-ray Jet at High Redshift

An Einstein and ASCA source



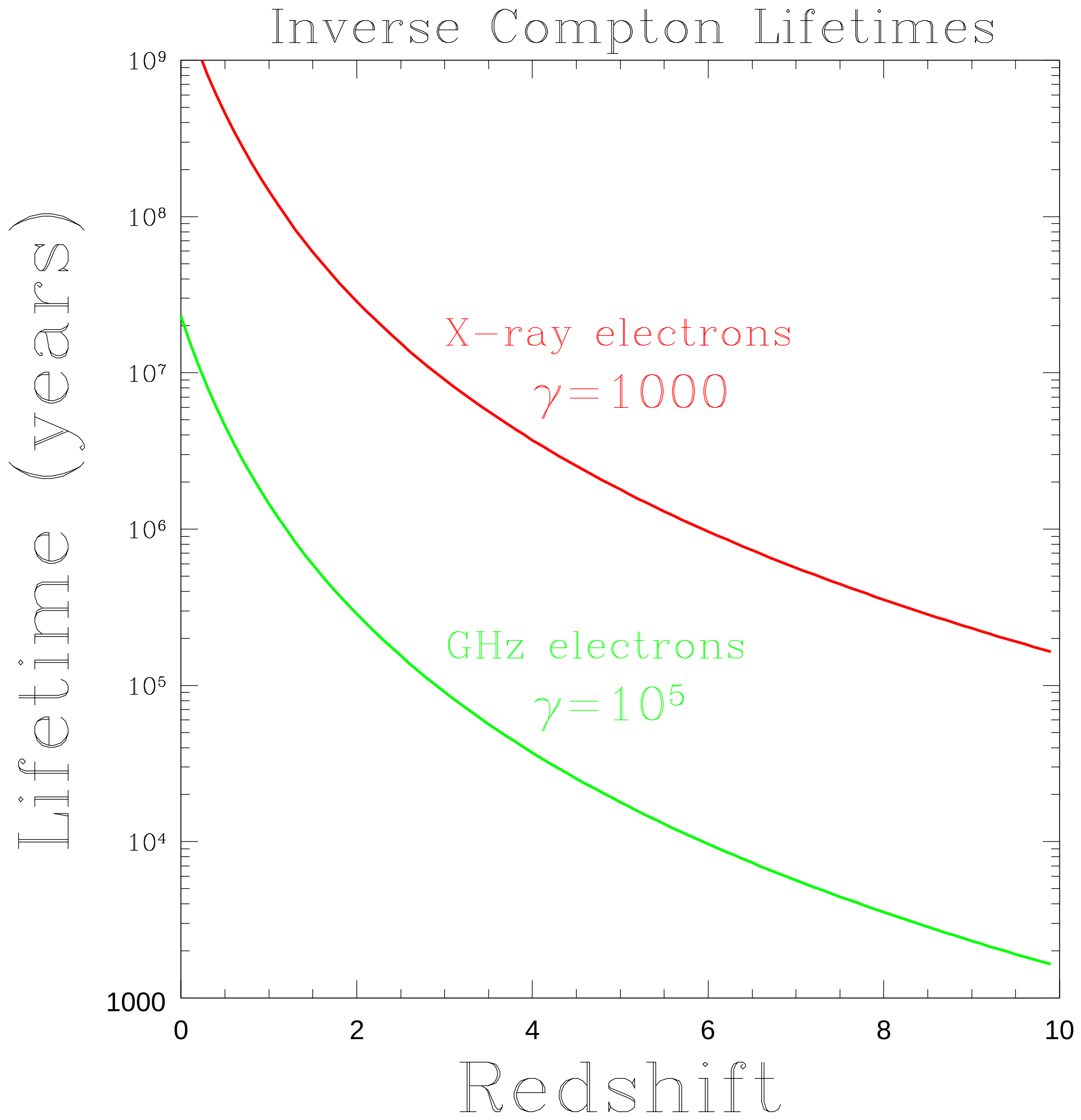


Siemiginowska et al. 2003ApJ...598L..15S

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

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[μG] $\approx$ 10 MHz**



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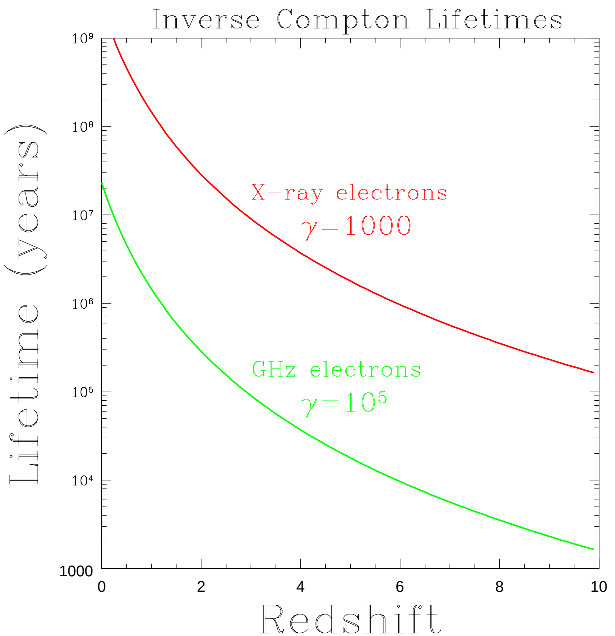
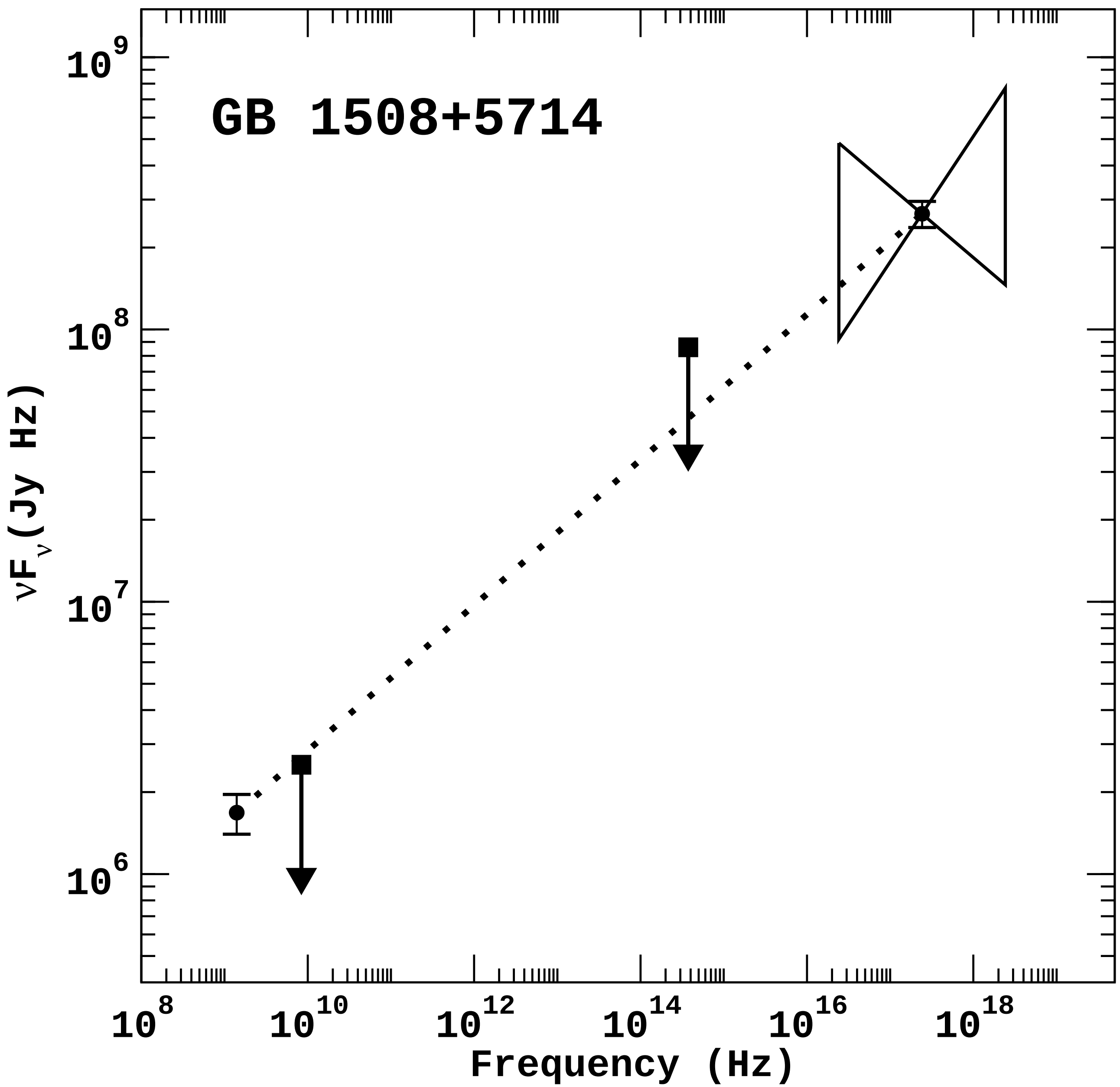
- **1 keV X-rays produced by $\gamma \approx 1000/\Gamma$**
- **$\nu = 4.2 \times 10^{-6} \gamma^2$ H[μG] $\approx$ 10 MHz**
- **Age $\approx 3 \times 10^4$ years?**





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

Significance of Jet X-ray Emission

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

Significance of IC/CMB X-ray Emission

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

4. **X-ray jets will be easily detected at large redshift!**
   May signal the first Massive Black Holes in the Universe