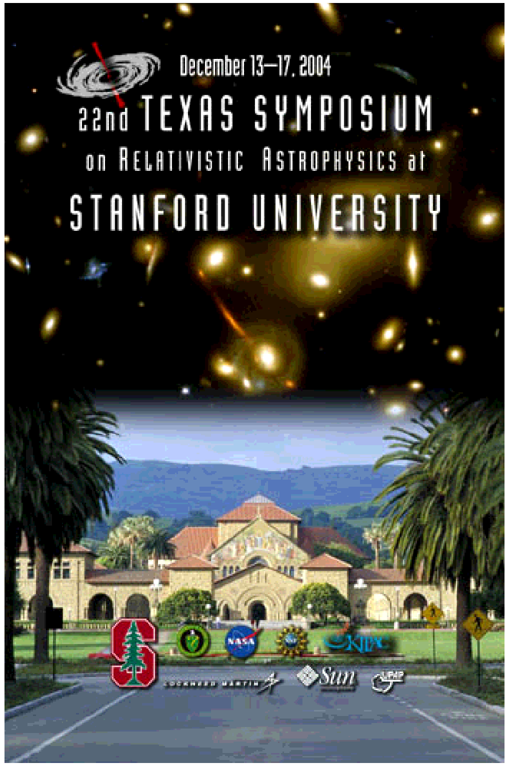
Chandra Observations of Relativistic AGN Jets

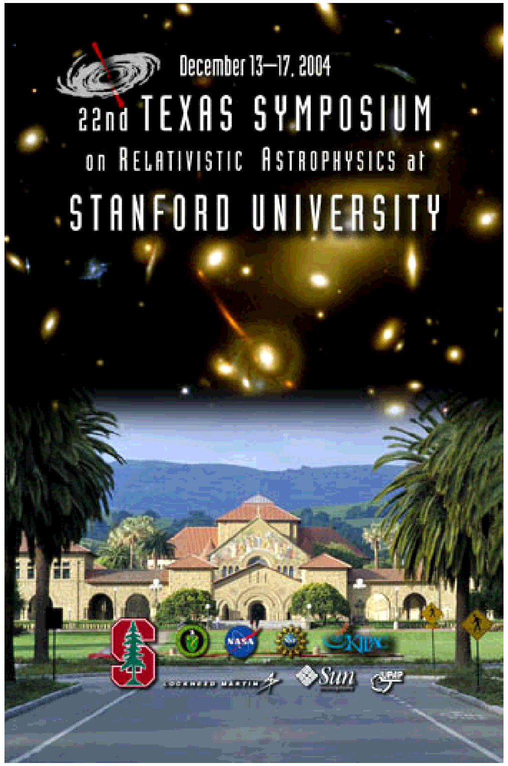
Dan Schwartz

Smithsonian Astrophysical Observatory



TEXAS AT STANFORD

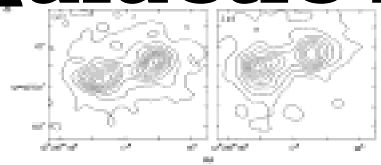
2004 December 15



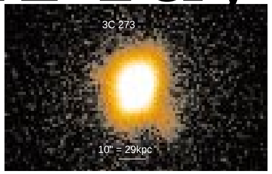
Observations of Extragalactic X-ray Jets

BC: 3 Clear Detections

Cen A: Feigelson et al.



M87: Biretta et al.



Chandra Launched: Jets start rolling in.

CE: 3 Fields of Investigation

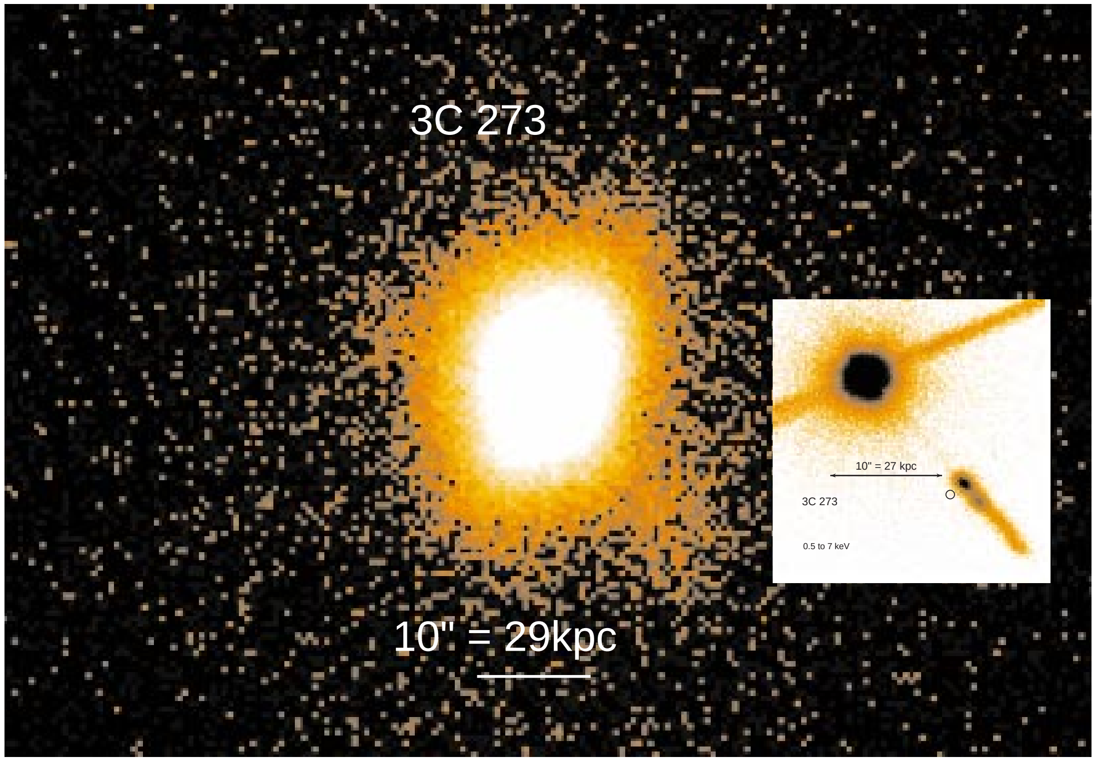
- **Interactions with gas in Seyferts, radio galaxies, clusters.**
- **FR I and BL Lac jets.**
- **Quasars, Powerful Radio Sources, and Cosmology.**

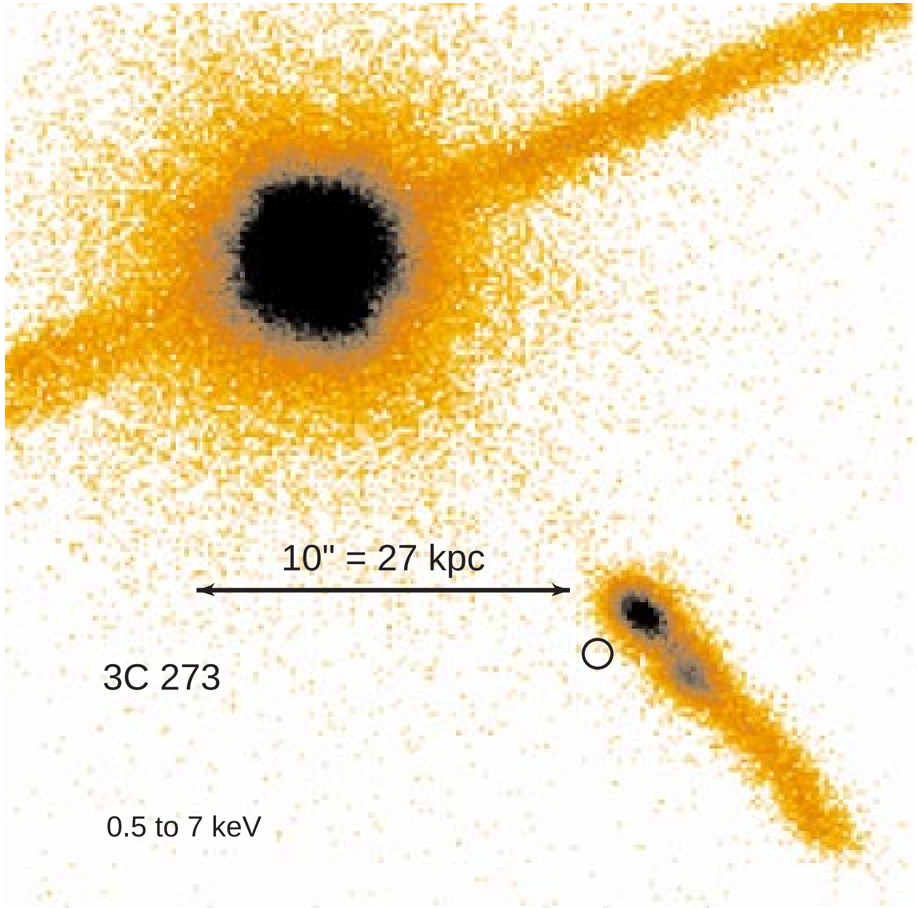
Observations of Extragalactic X-ray Jets

BC: 3 Clear Detections

Chandra Launched: Jets start rolling in. **WHY?**

Angular Resolution!





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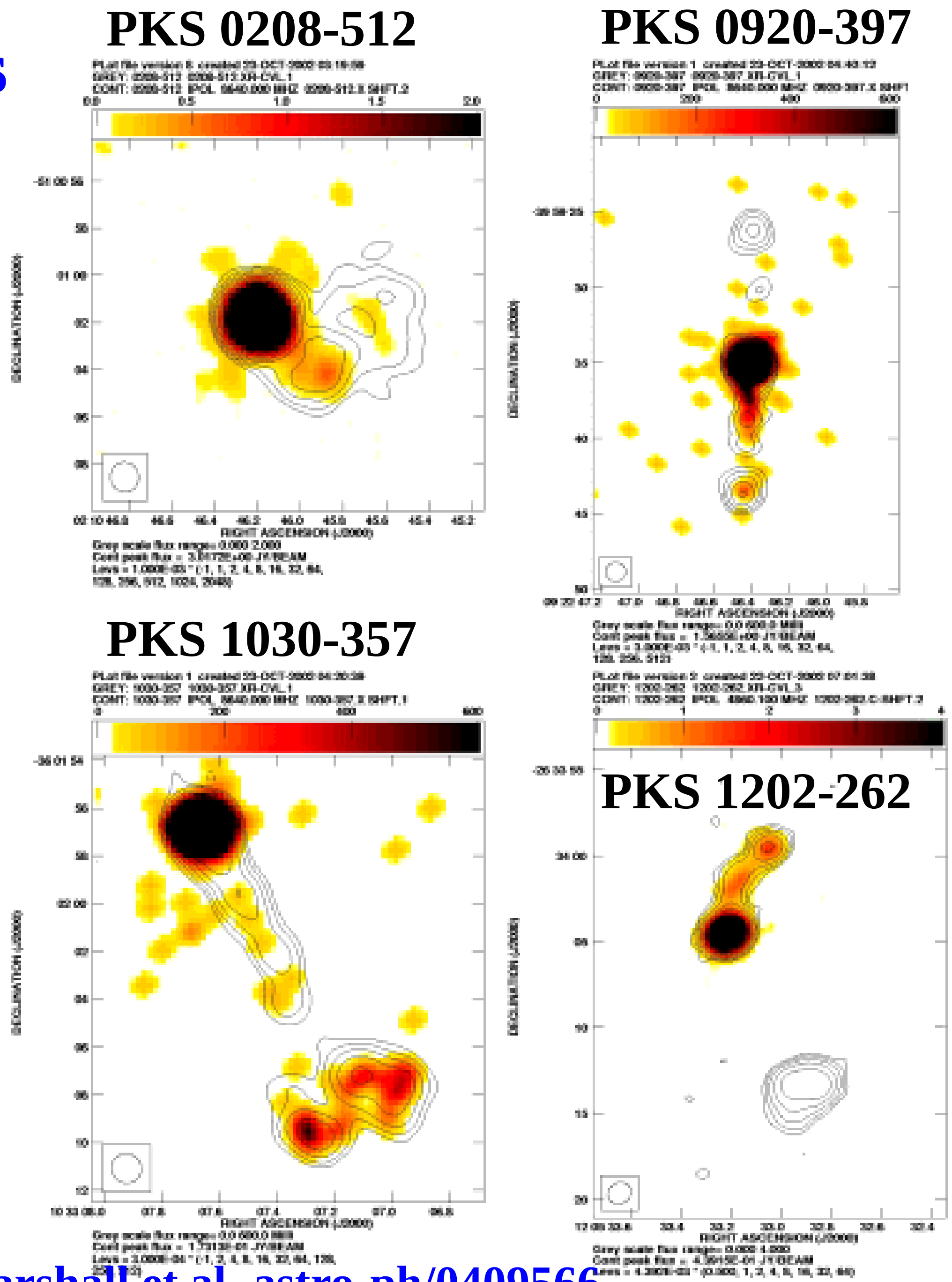
- **What Do We Want to Learn**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**
- **Why Do We Need X-Ray Data?**
  - **Spectral Energy Distribution (SED) gives mechanism**
  - **Particle lifetimes change with observed band**

Outline

1. Spatially resolved analysis

- Broadband SED
- Interpret X-rays as IC/CMB
  - B, δ, γ_{min}
- Kinetic flux and efficiency

2. Morphology
3. Jets at Large Redshift



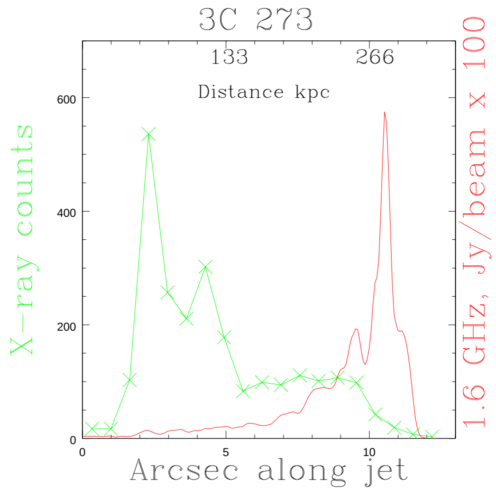
Marshall et al. astro-ph/0409566

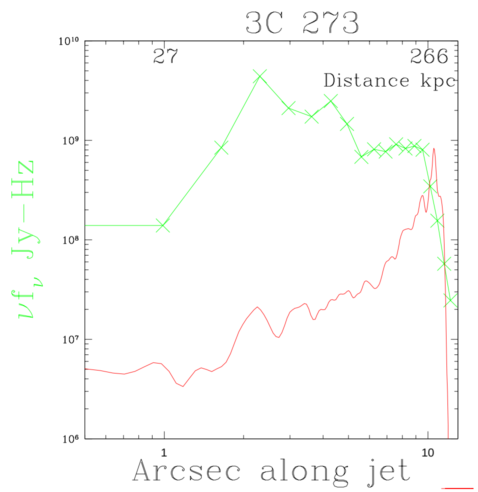
Outline

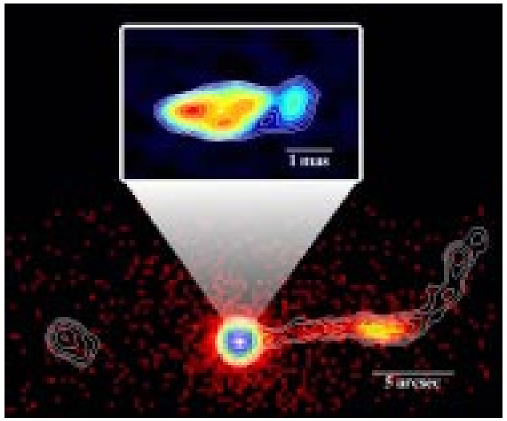
1. Spatially resolved analysis

2. Morphology
   - Profiles
   - X-ray vs Radio Brightness
   - Bends and curvature
   - X-ray vs Radio Polarization

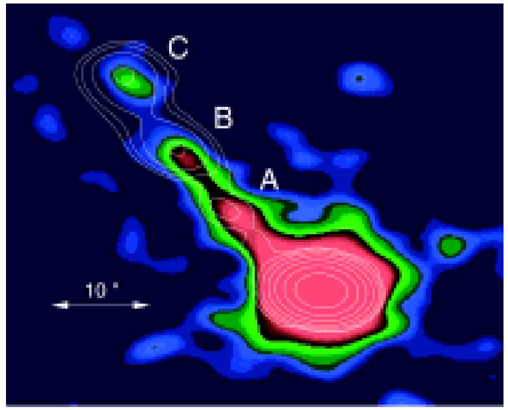
3. Jets at Large Redshift







PKS0637-752 at z=0.653



PKS 1127-145 at z=1.187

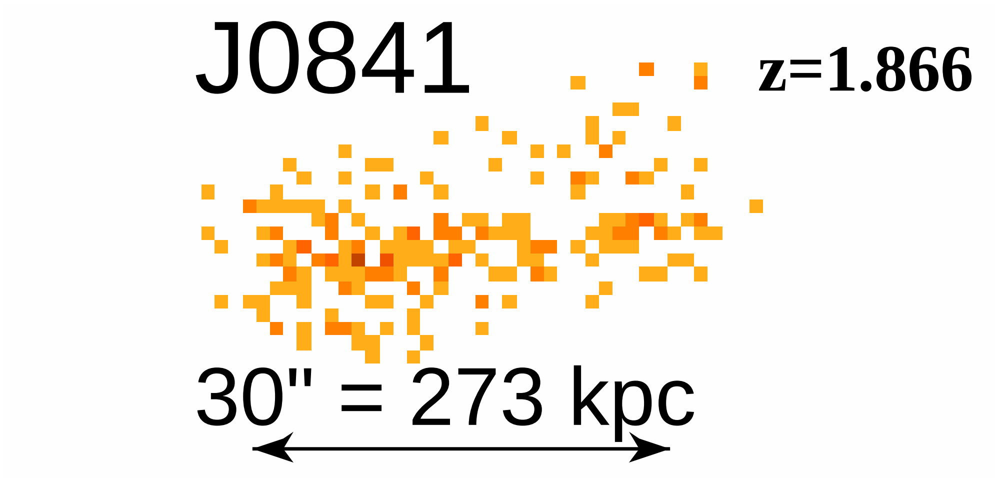
Siemiginowska et al. 2002

Outline

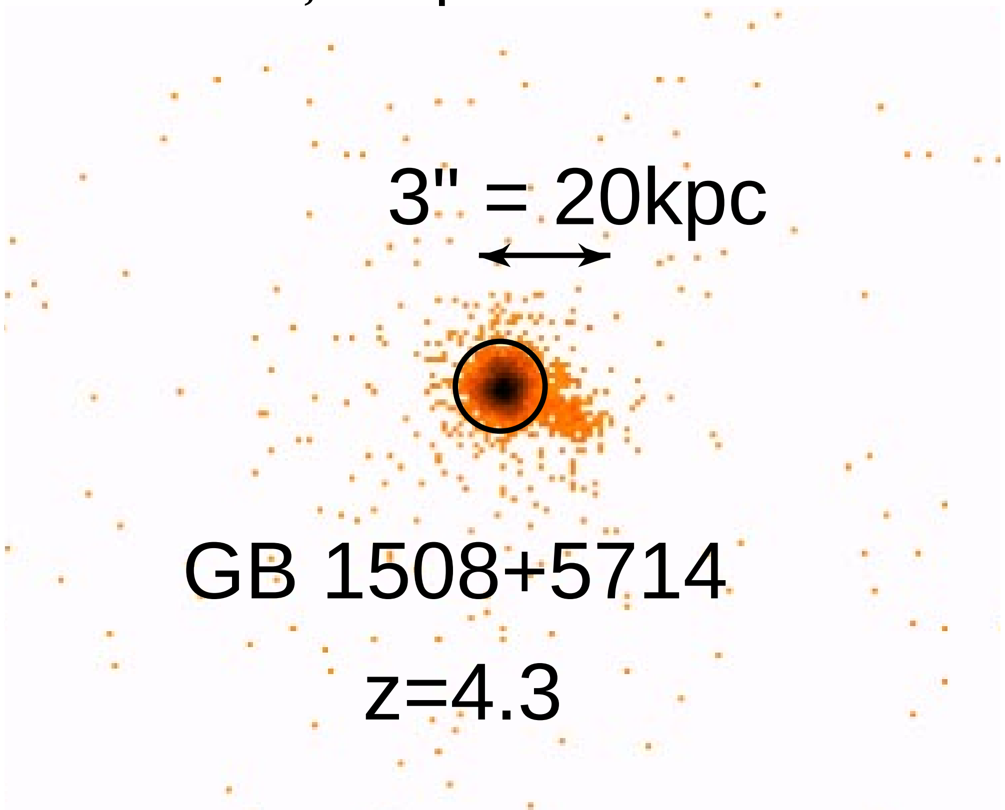
1. Spatially resolved analysis

2. Morphology

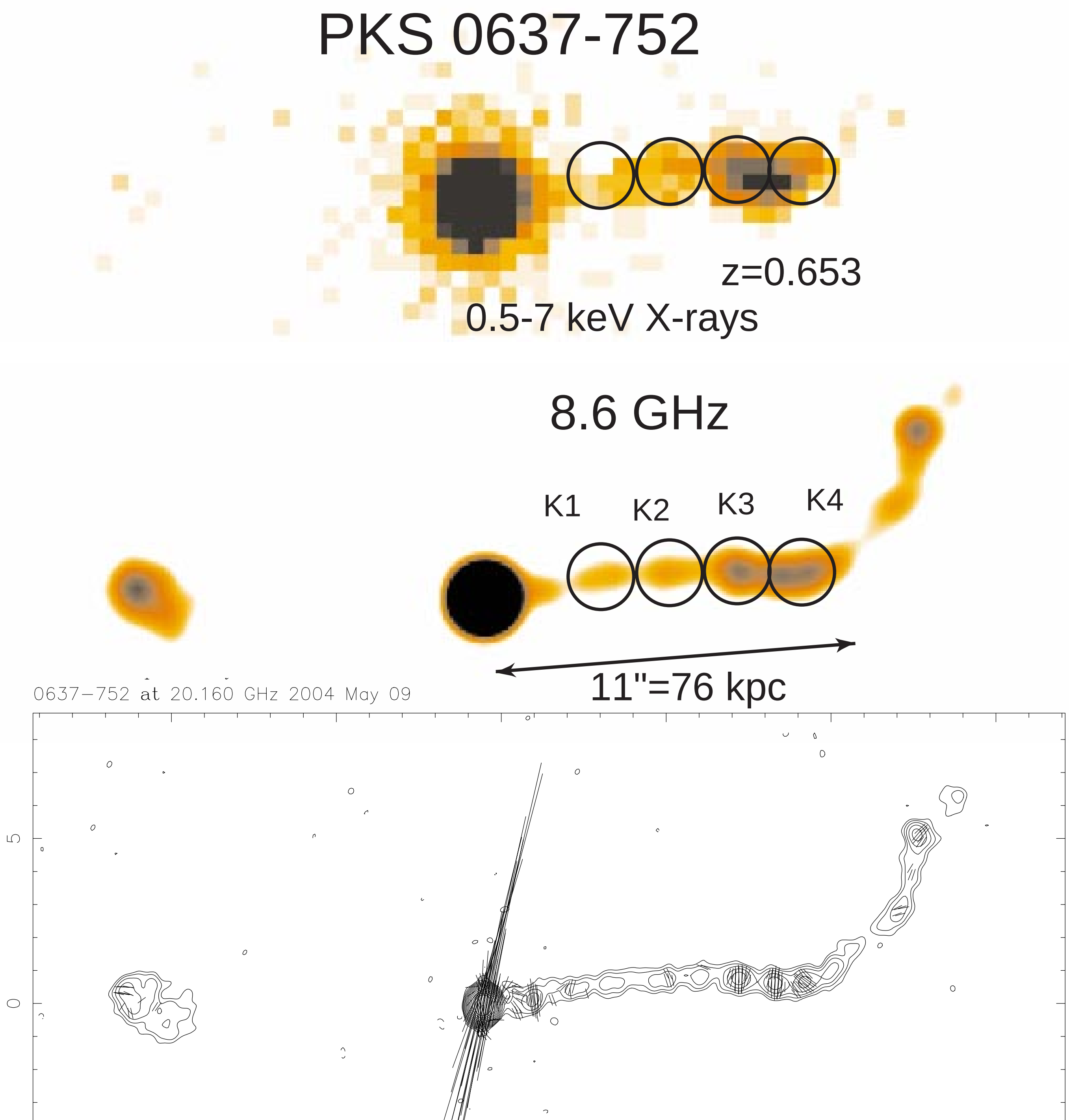
3. Jets at Large Redshift
   - Radio quiet X-ray jets?
   - Beacons to Large Redshift?



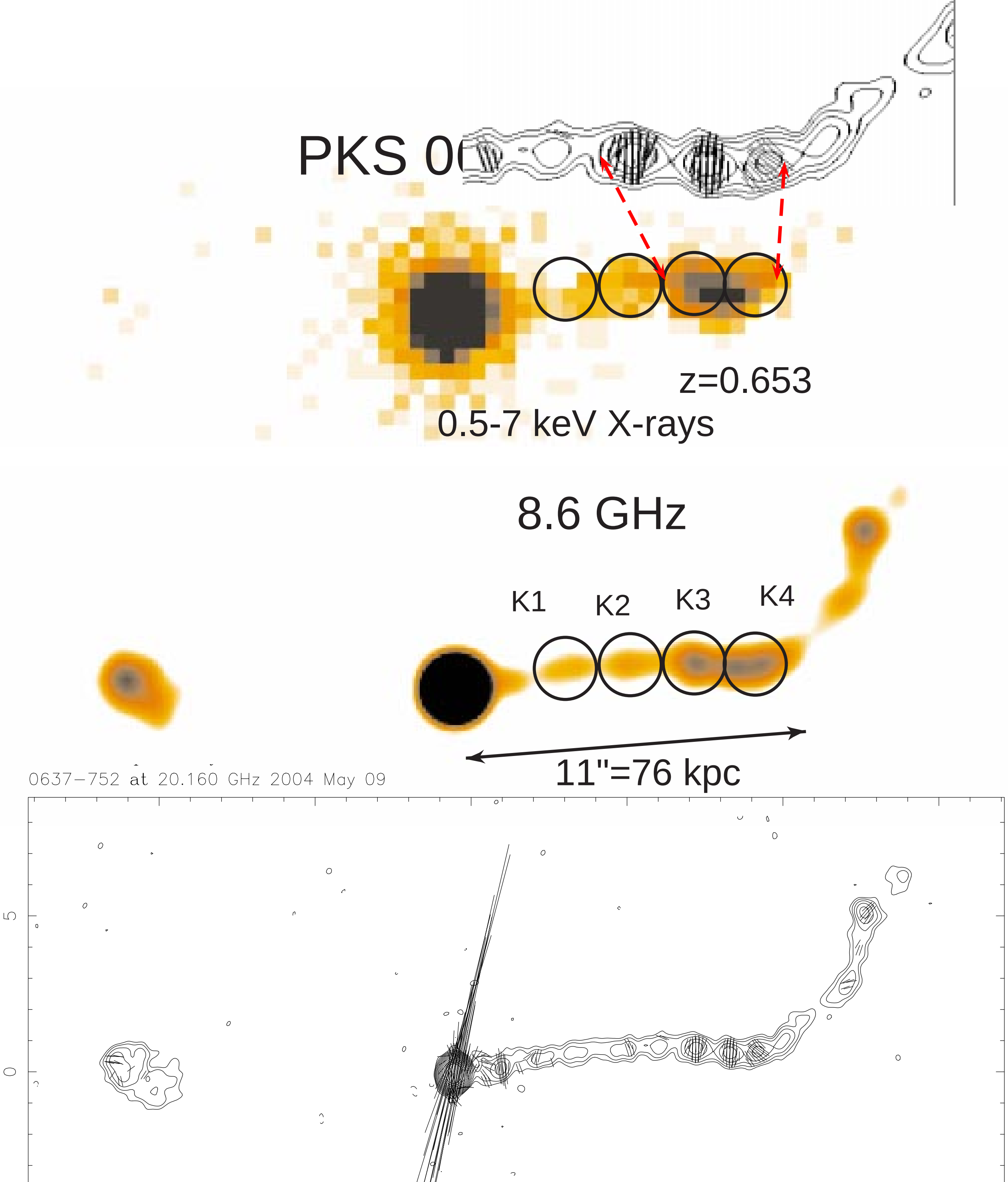
Schwartz et al., 2004ApJ...605L.105S



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



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
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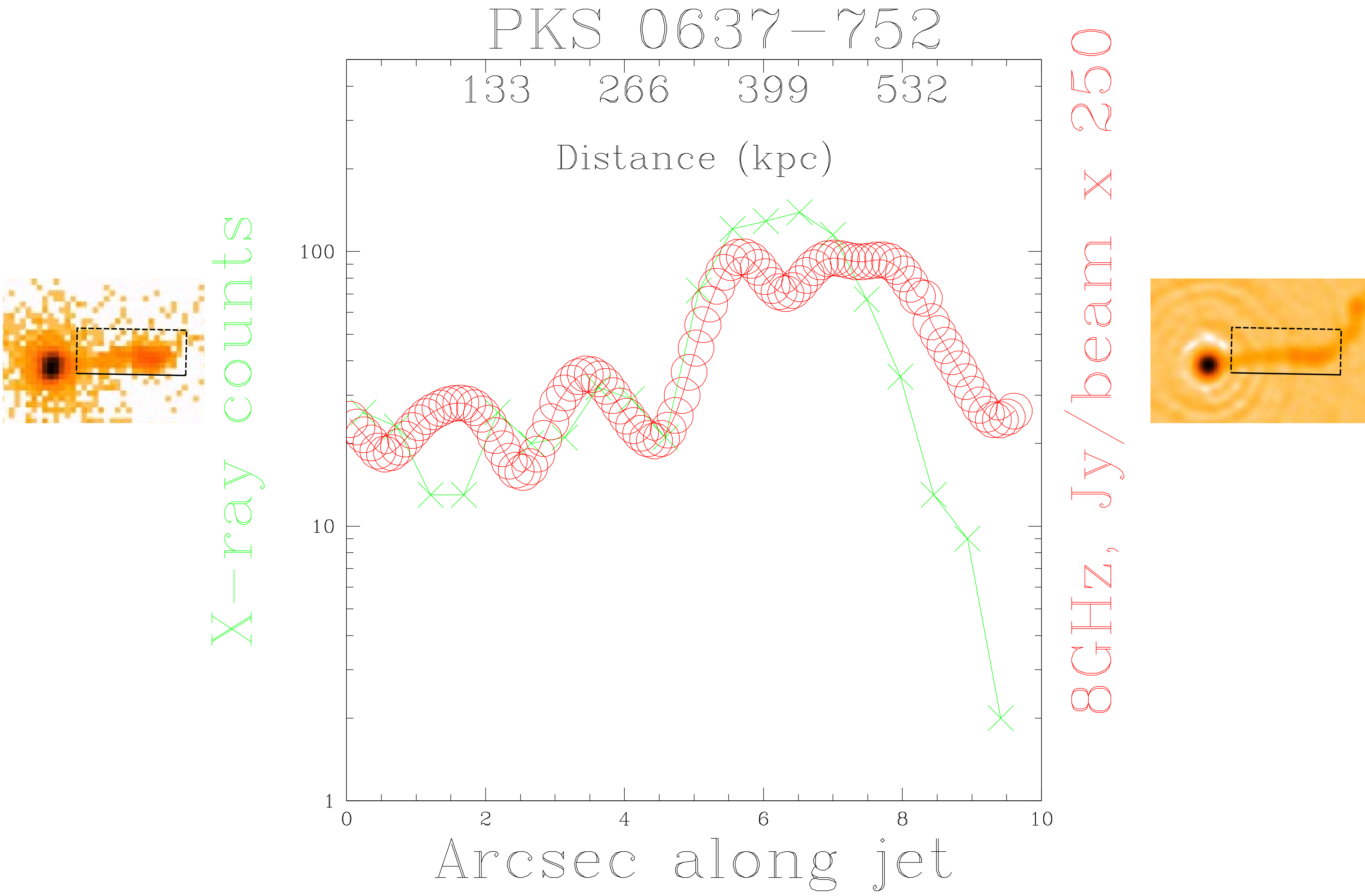
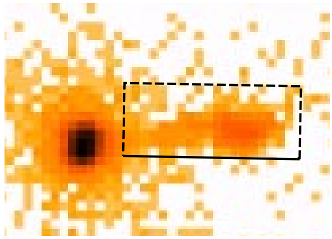
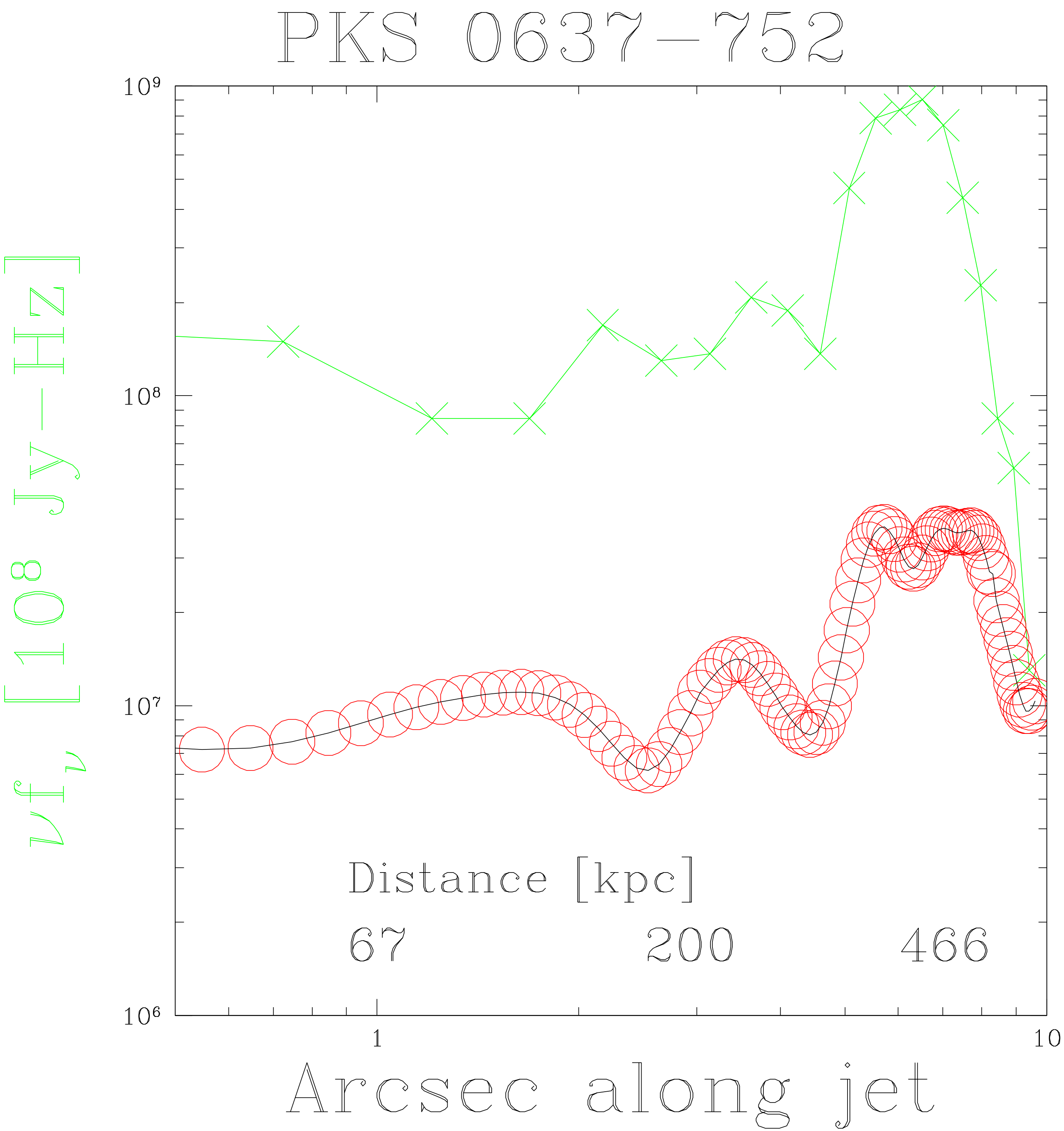
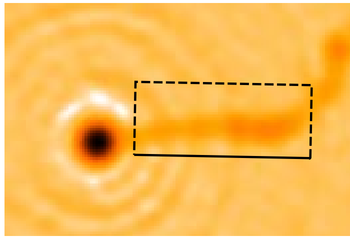


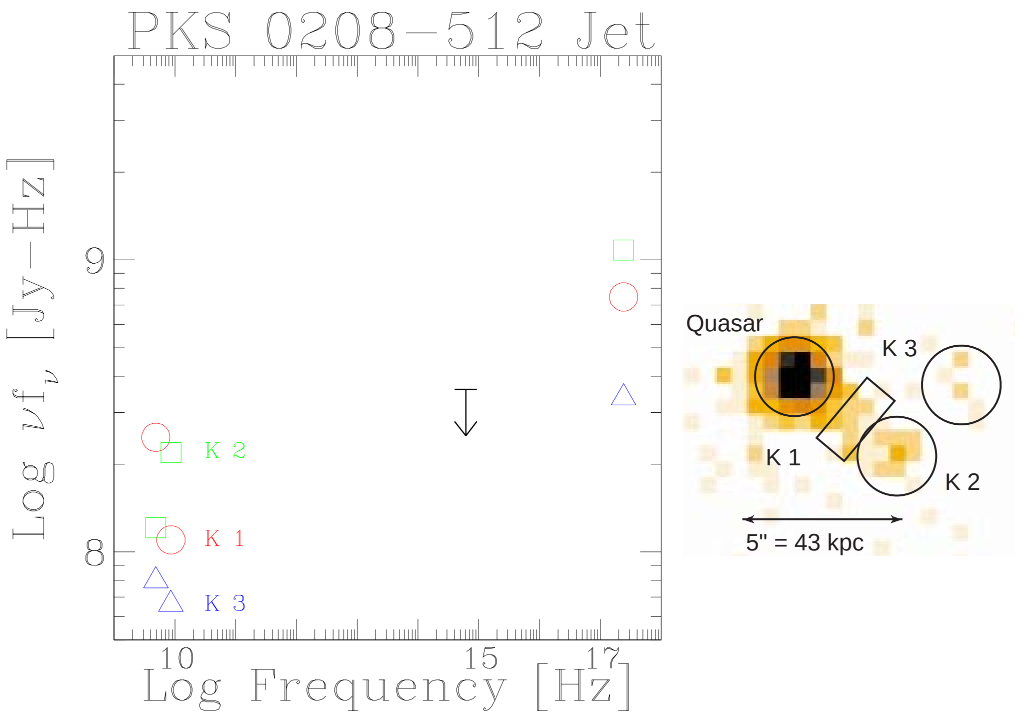
PKS 0637−752
133
266
399
532
Distance (kpc)
100
10
1
0
2
4
6
8
10
Arcsec along jet
X−ray counts
8GHz, Jy/beam x 250

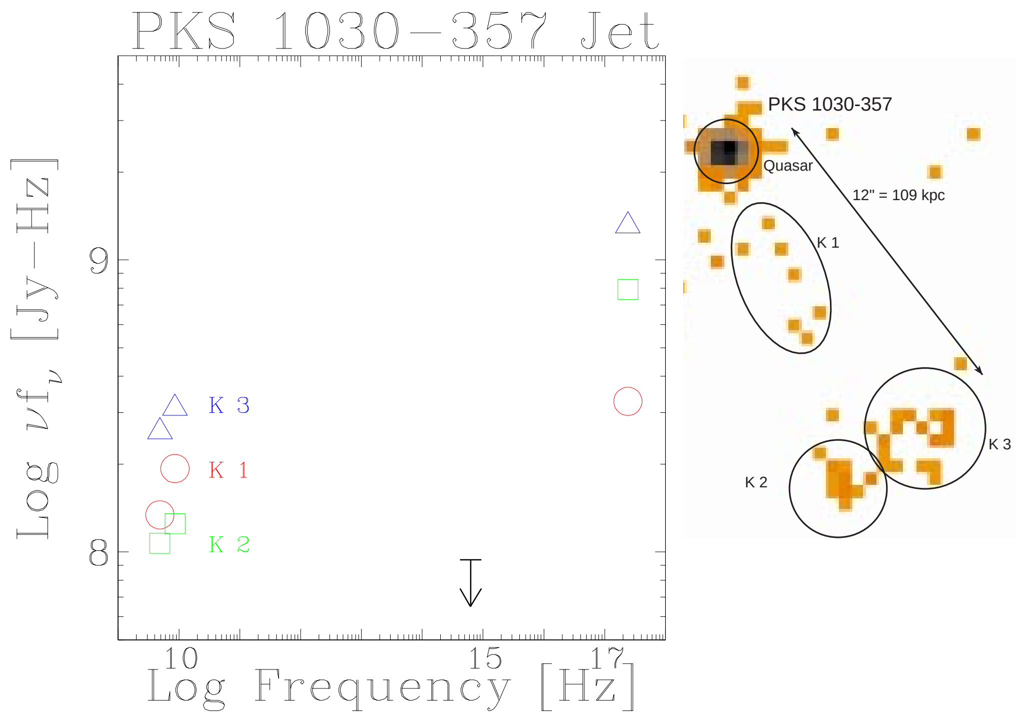


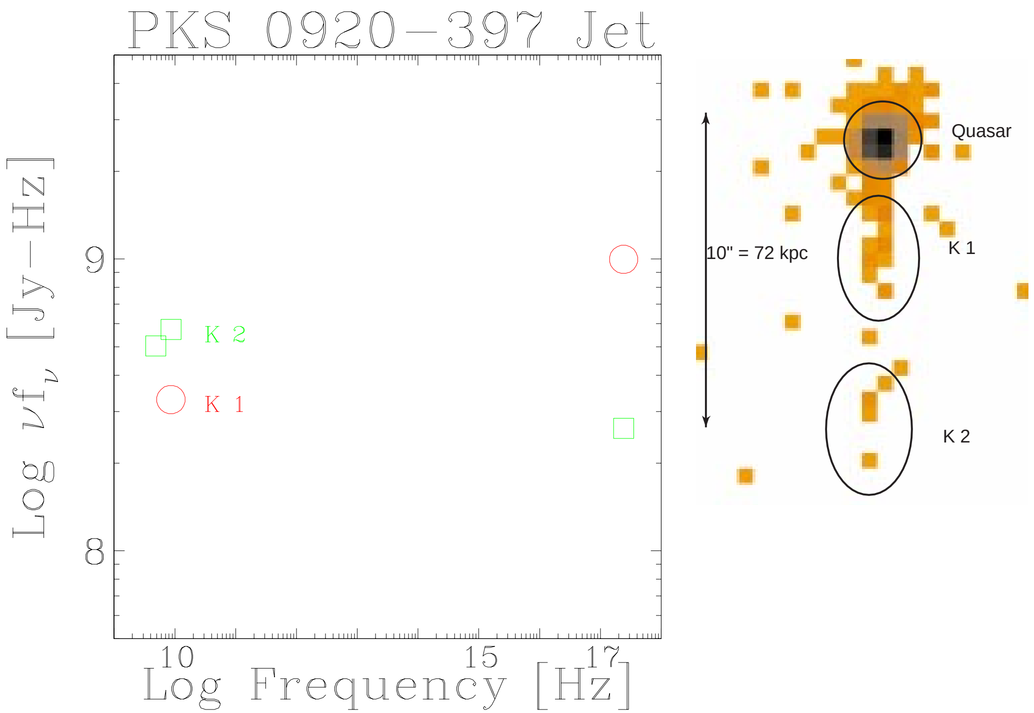

PKS 0637−752
10⁹
10⁸
10⁷
10⁶
νf_ν [10⁸ Jy−Hz]
Distance [kpc]
67
200
466
1
10
Arcsec along jet

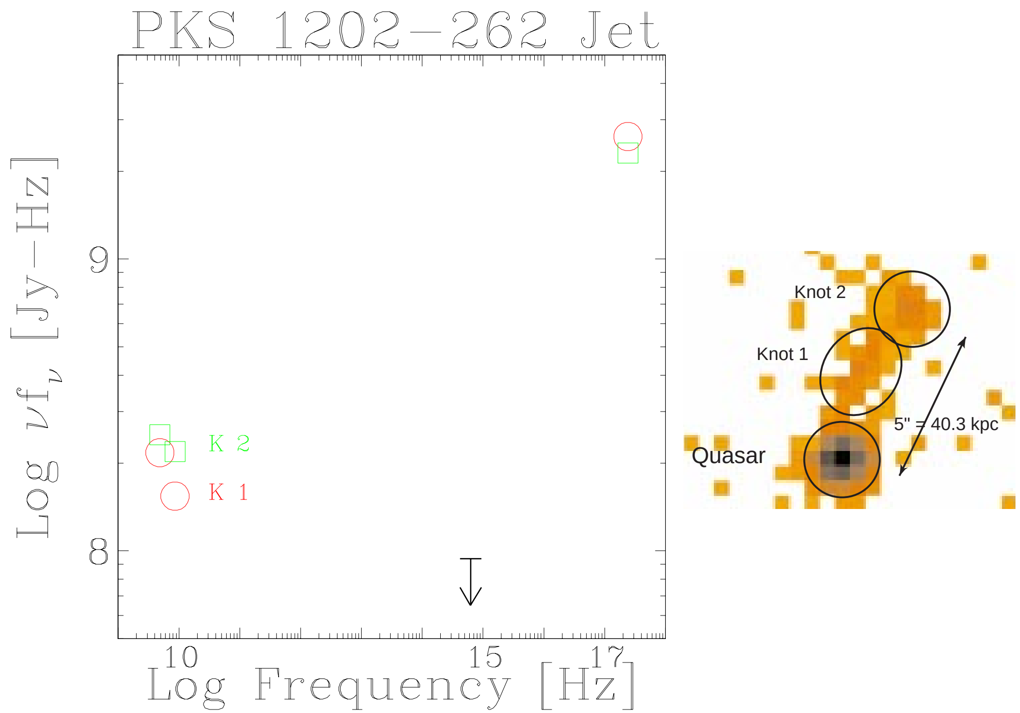


Spectral Energy Distribution often indicates against Synchrotron X-rays









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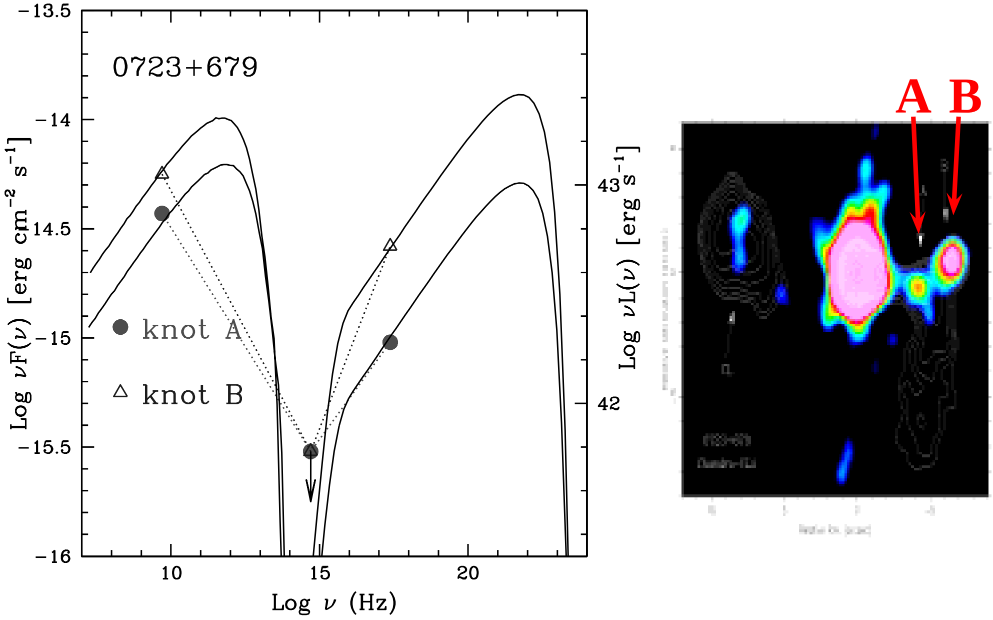

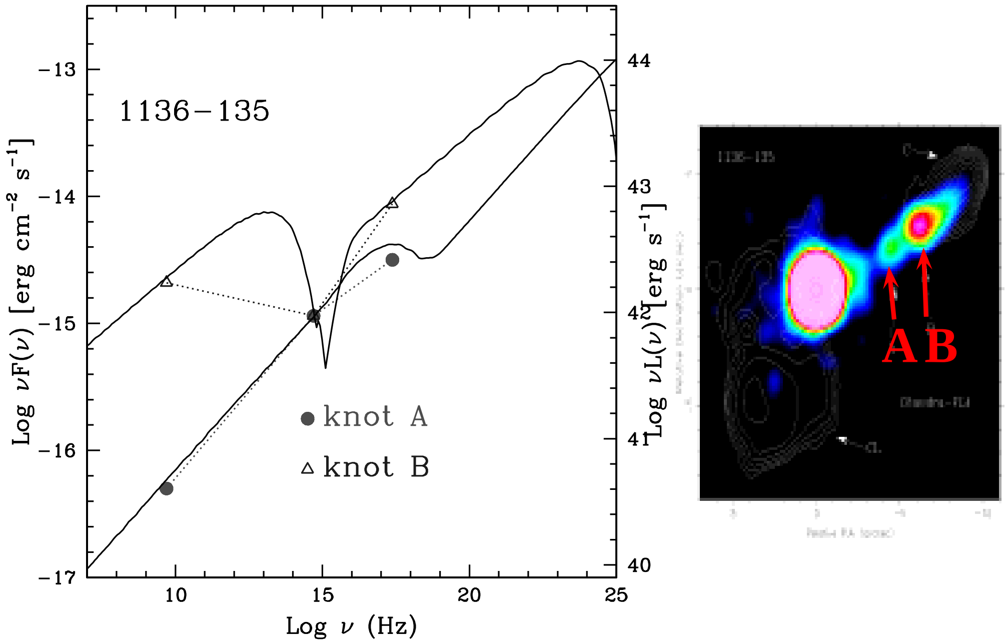

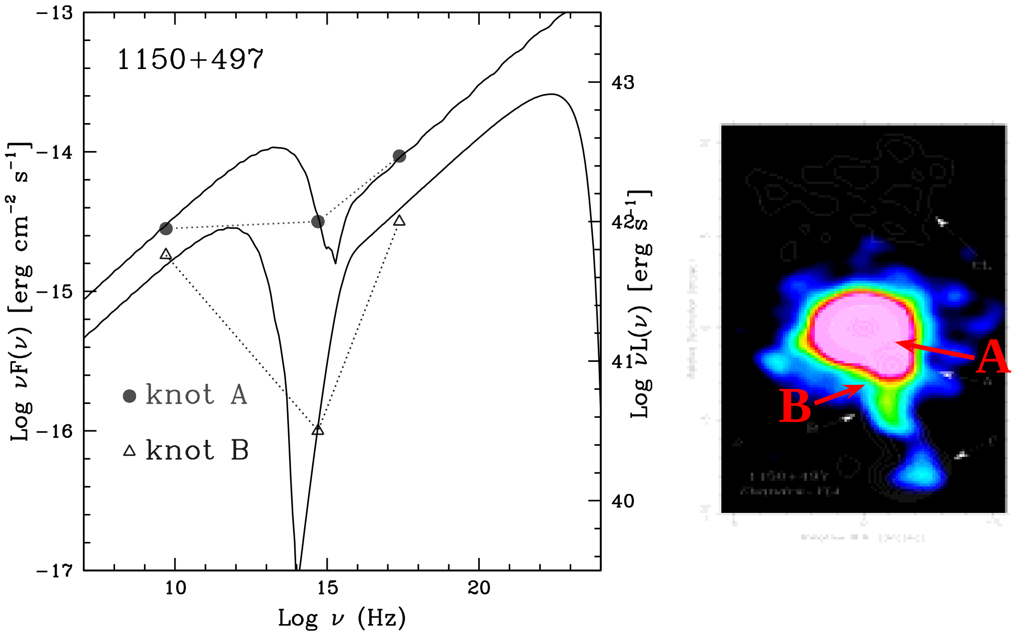

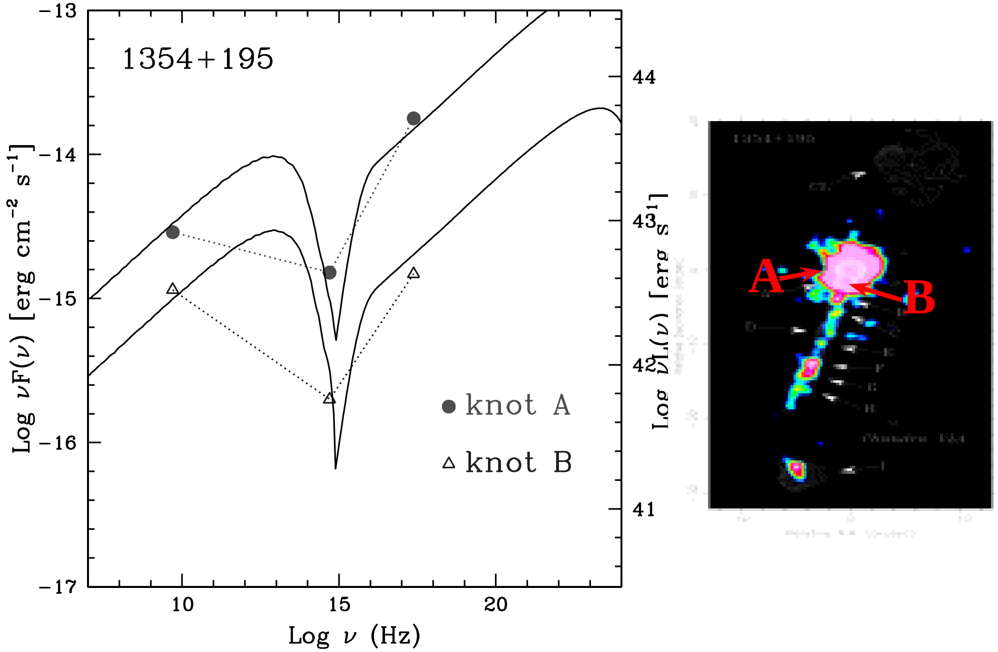

Sambruna et al., 2002ApJ...571..206S

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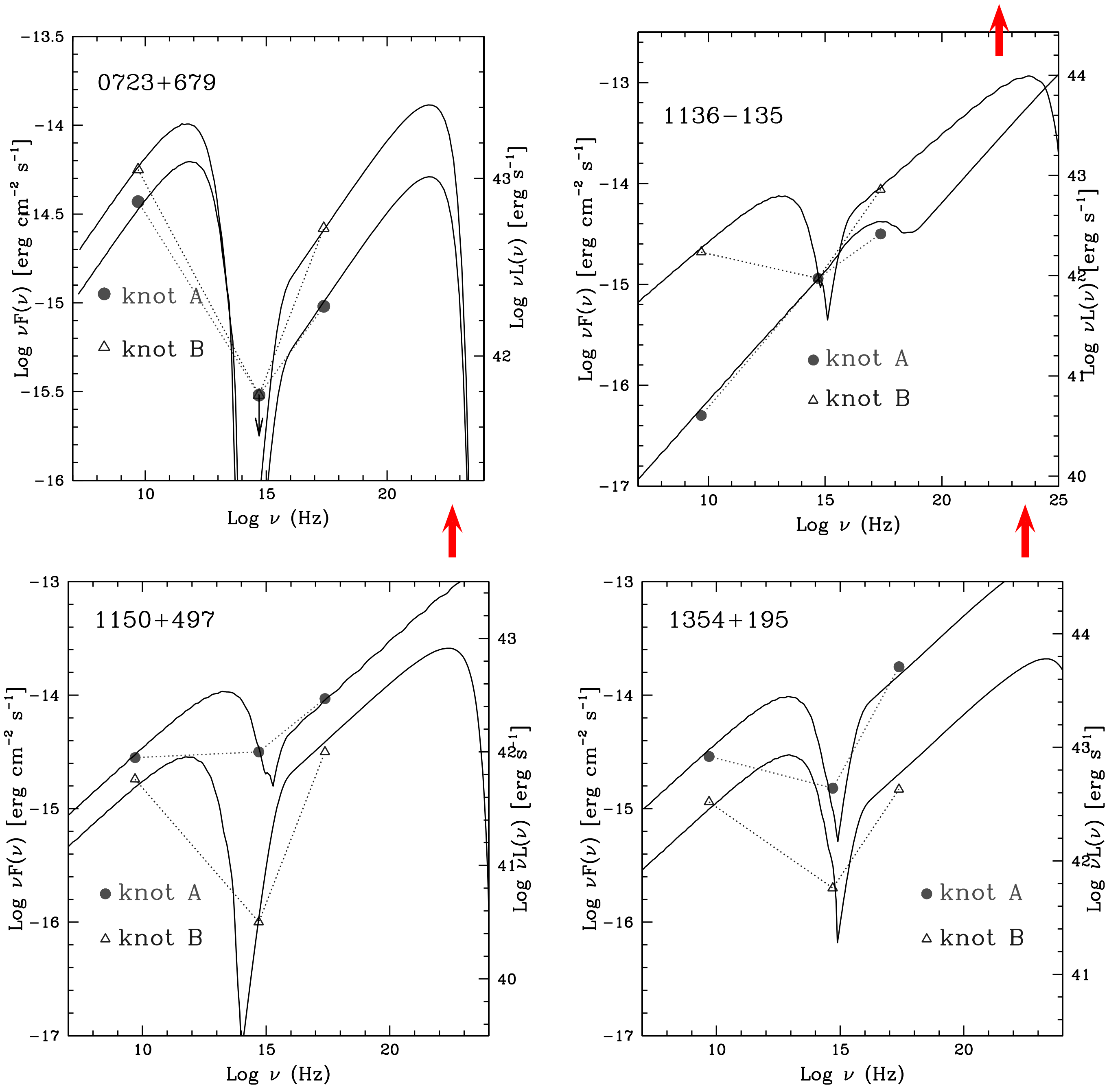


Inverse Compton X-rays from the CMB:

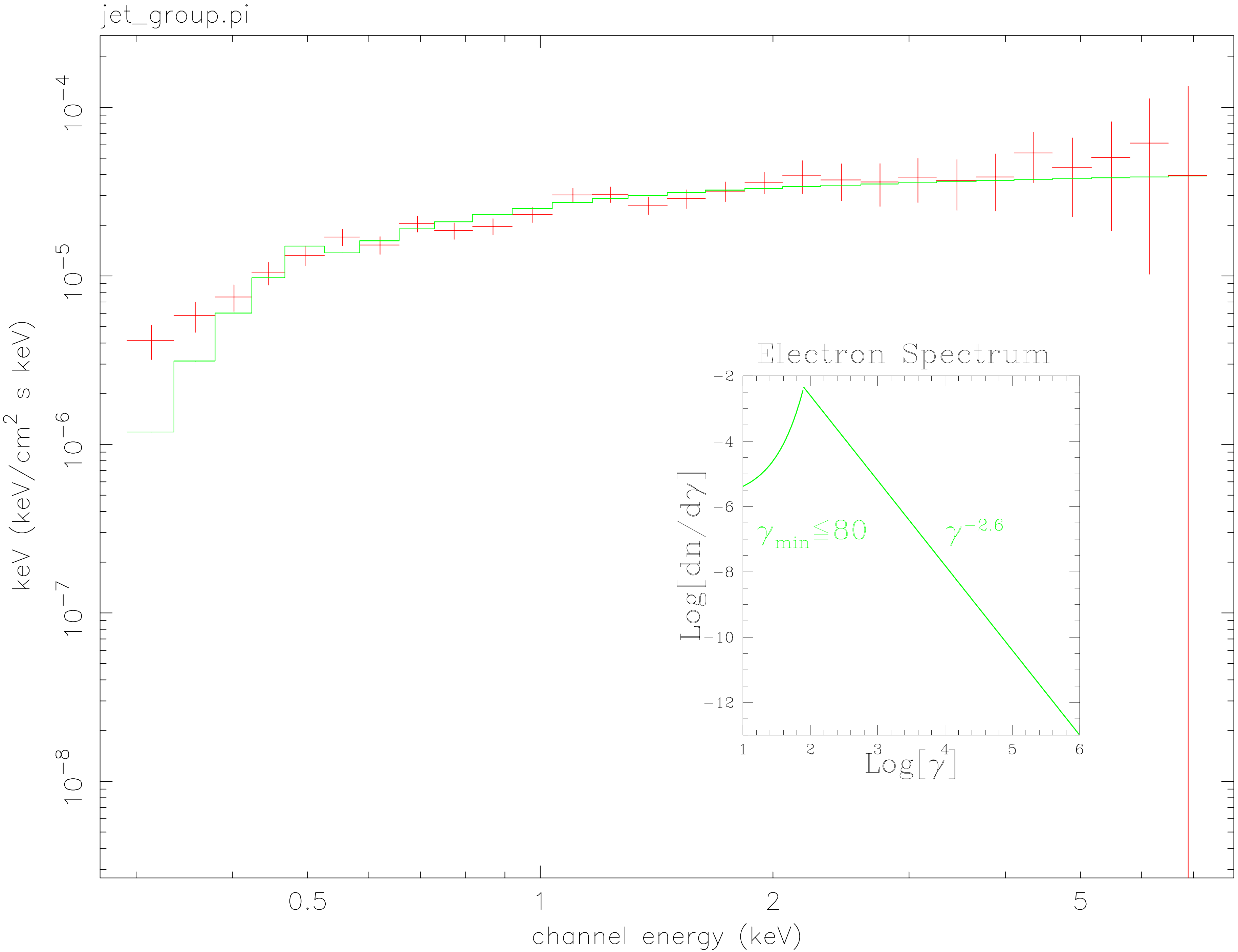
$$\gamma_x \approx 10^{2-3}$$

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

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

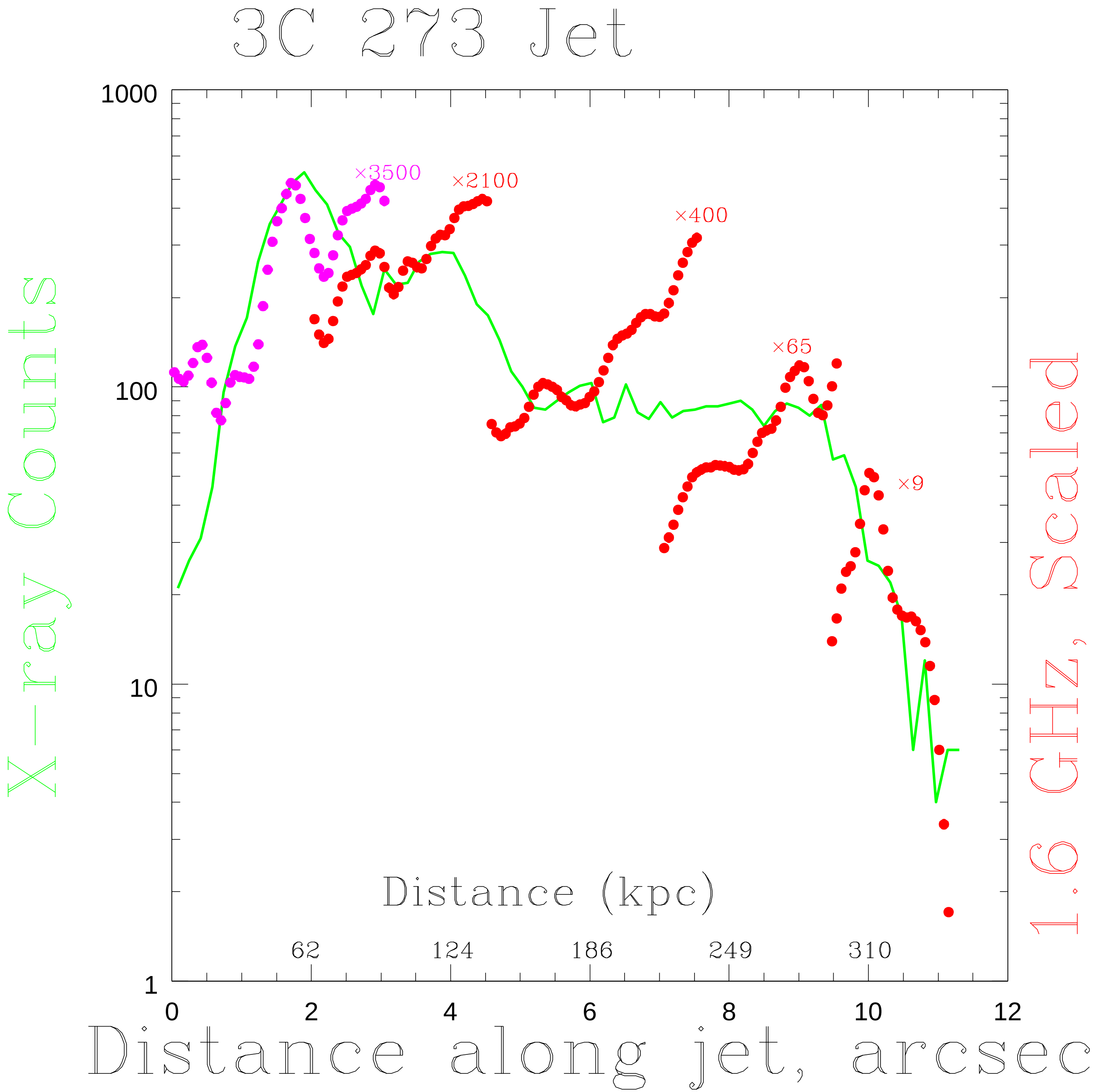
Sambruna et al., 2002ApJ...571..206S

PKS 0637-752 Jet Spectrum



mmueller 4-D

Confront IC/CMB with Morphology



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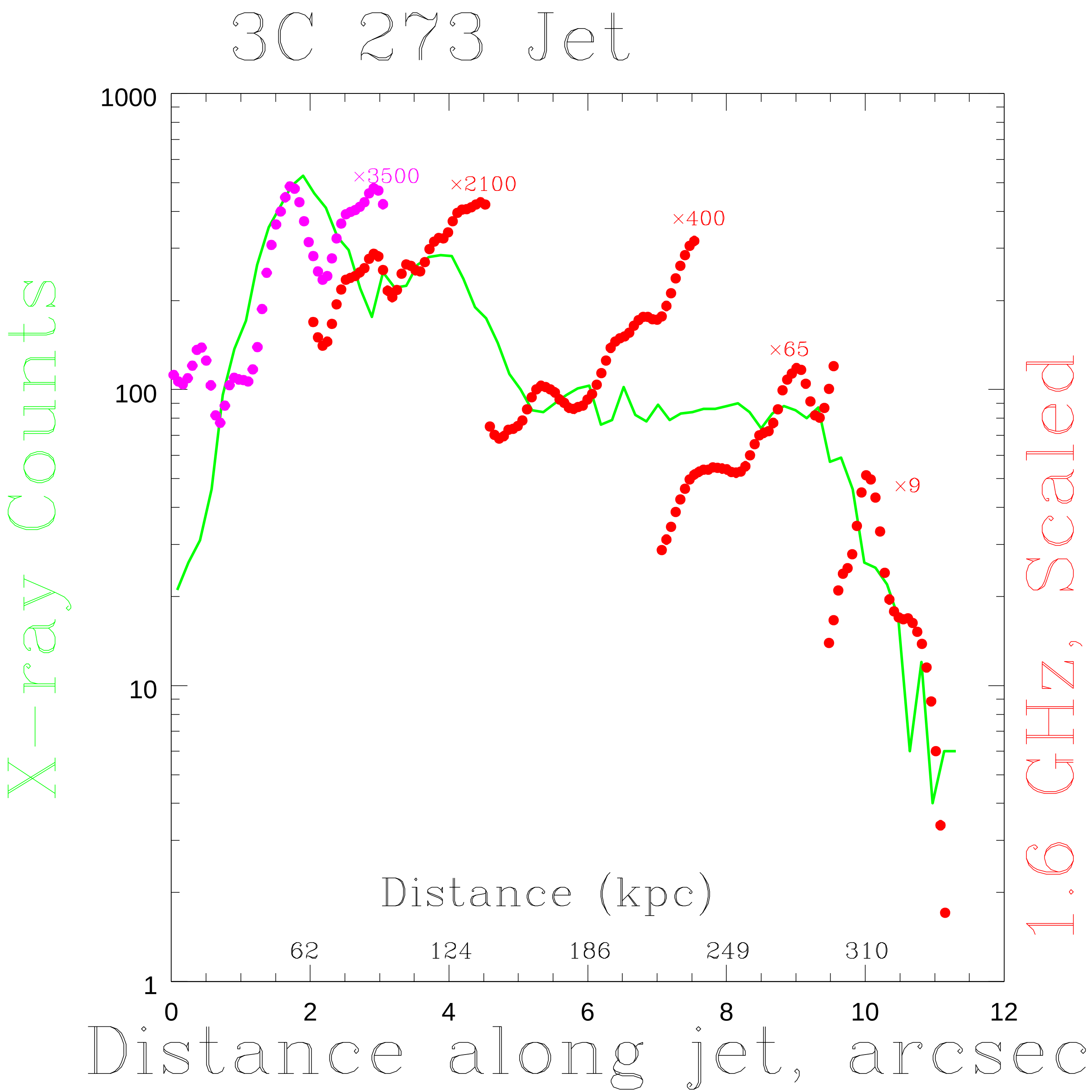
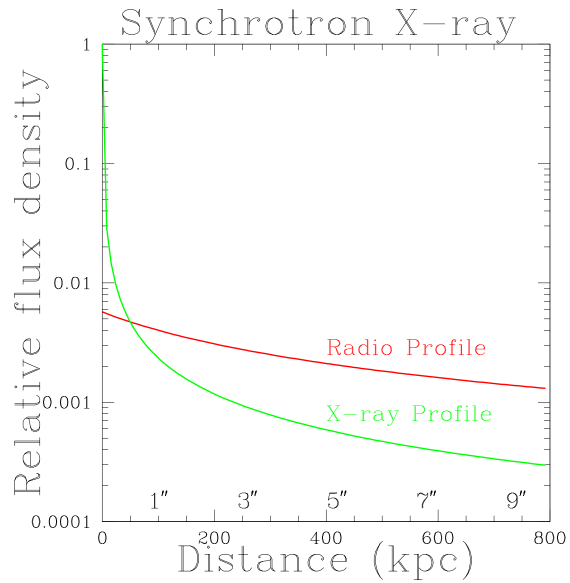
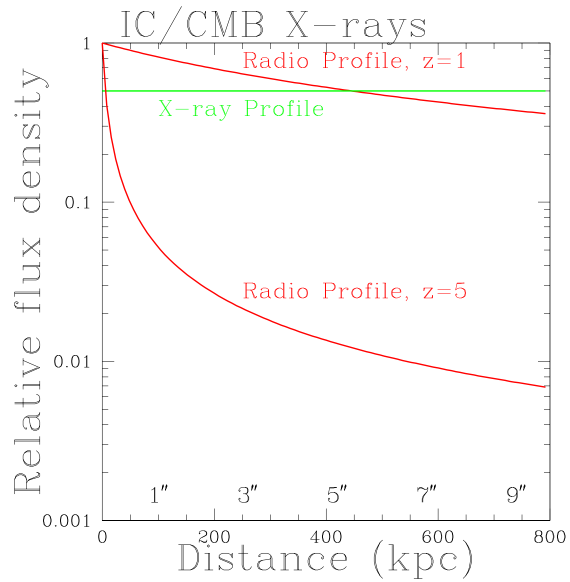


Naive Models





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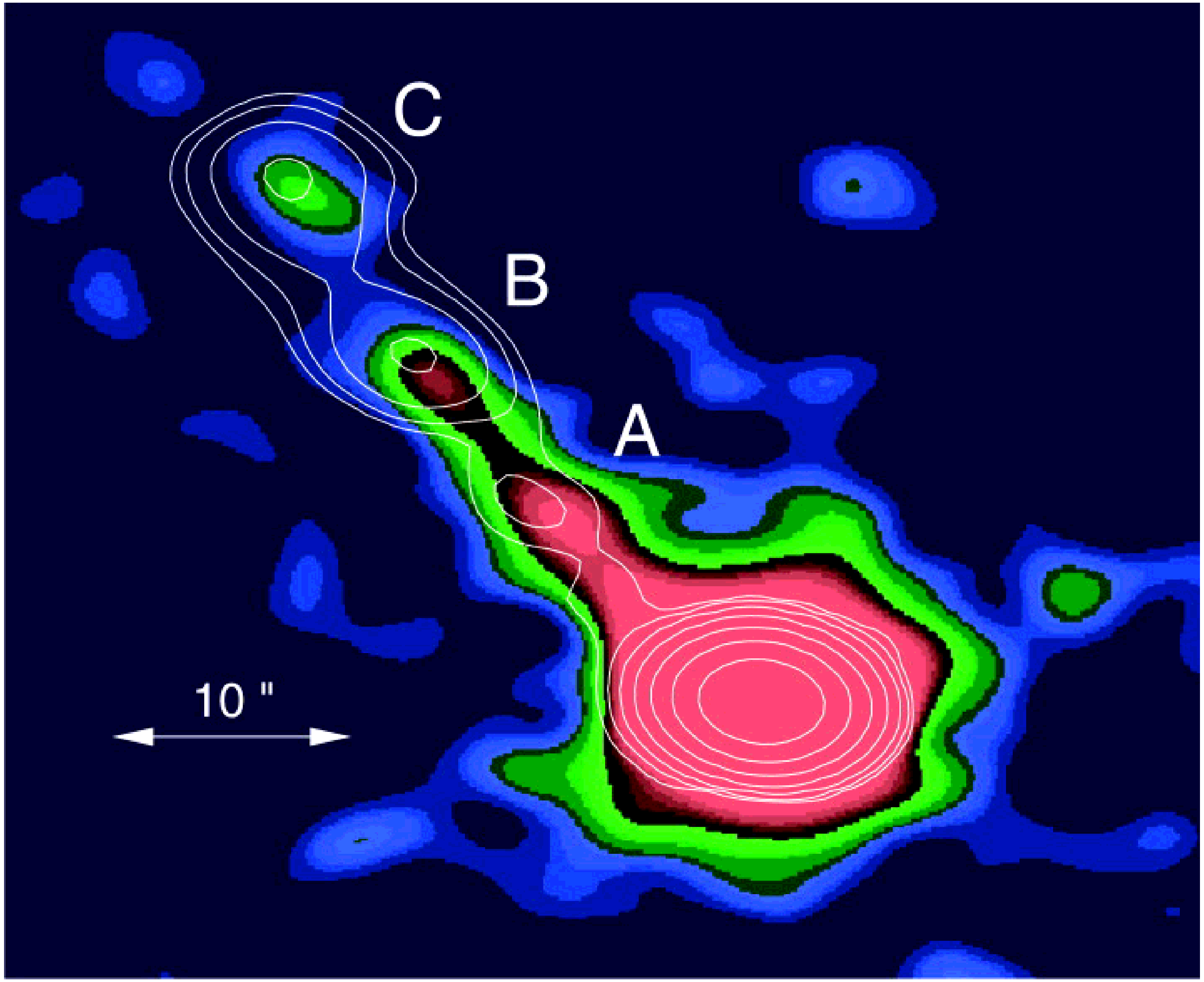
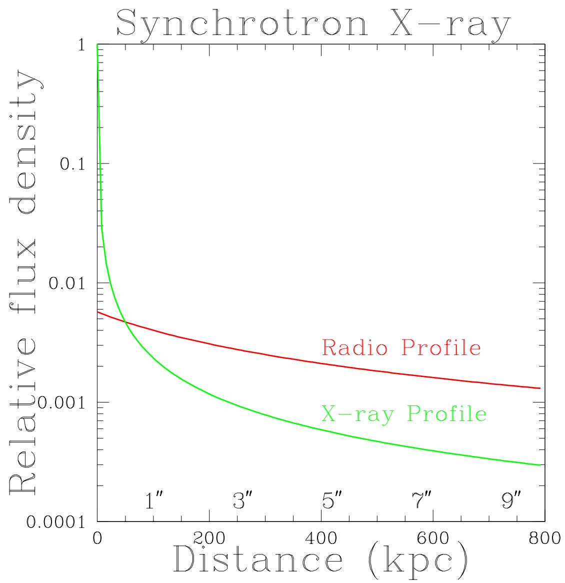
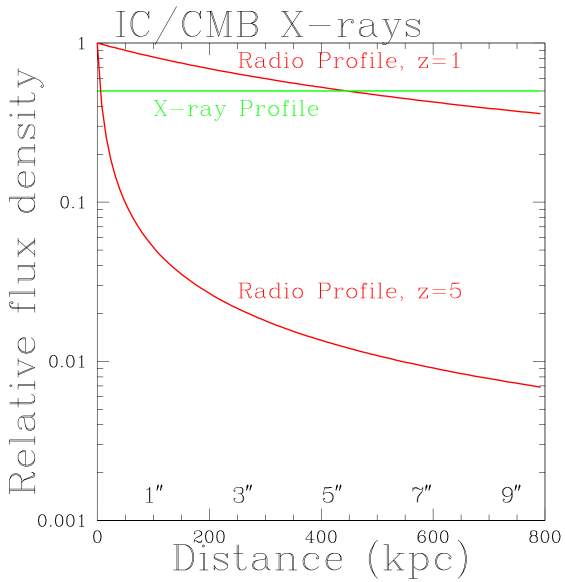


Siemiginowska et al. 2002 ApJ...570..543S

PKS 1127-145 at z=1.187

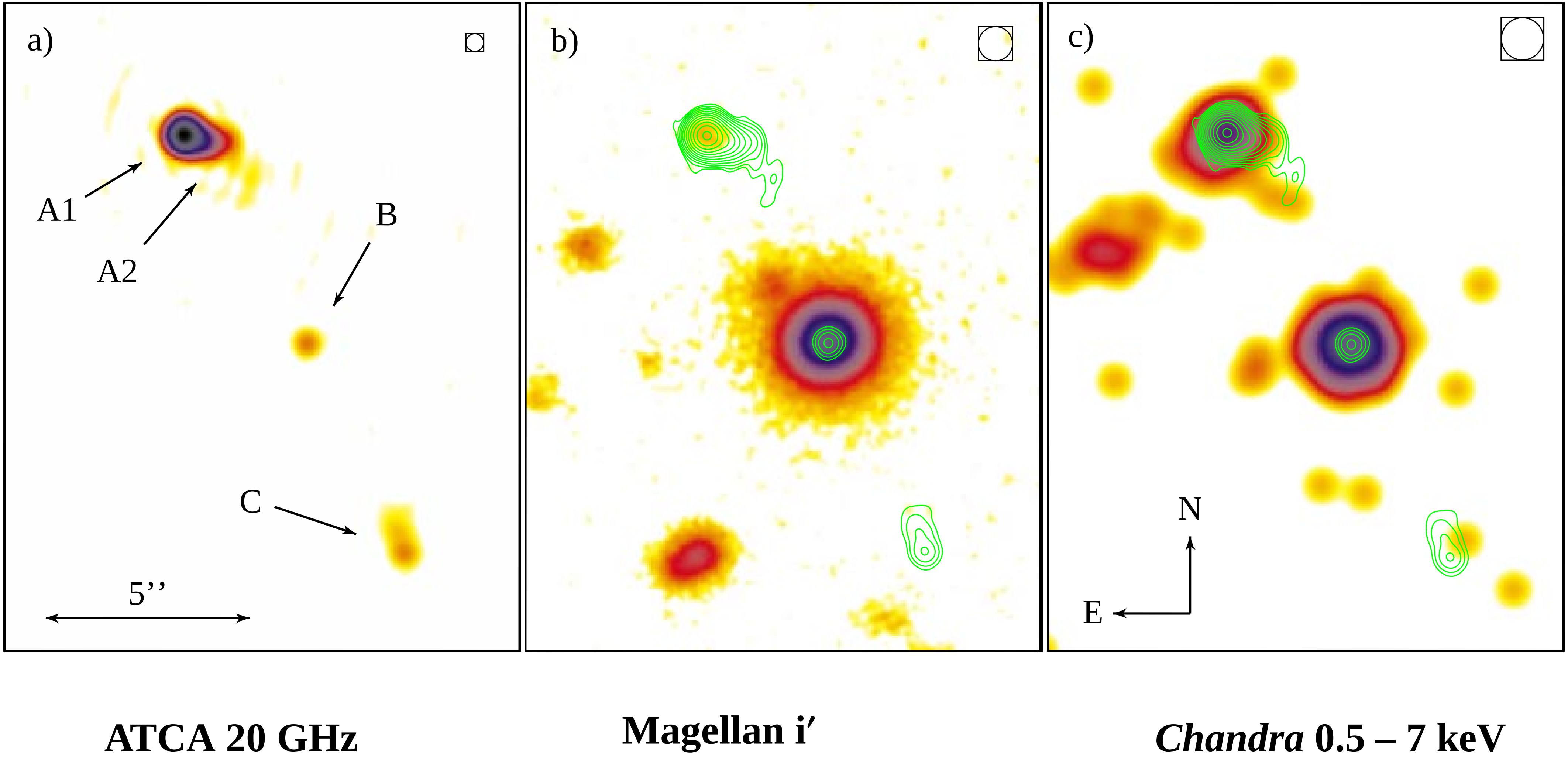
Naive Models





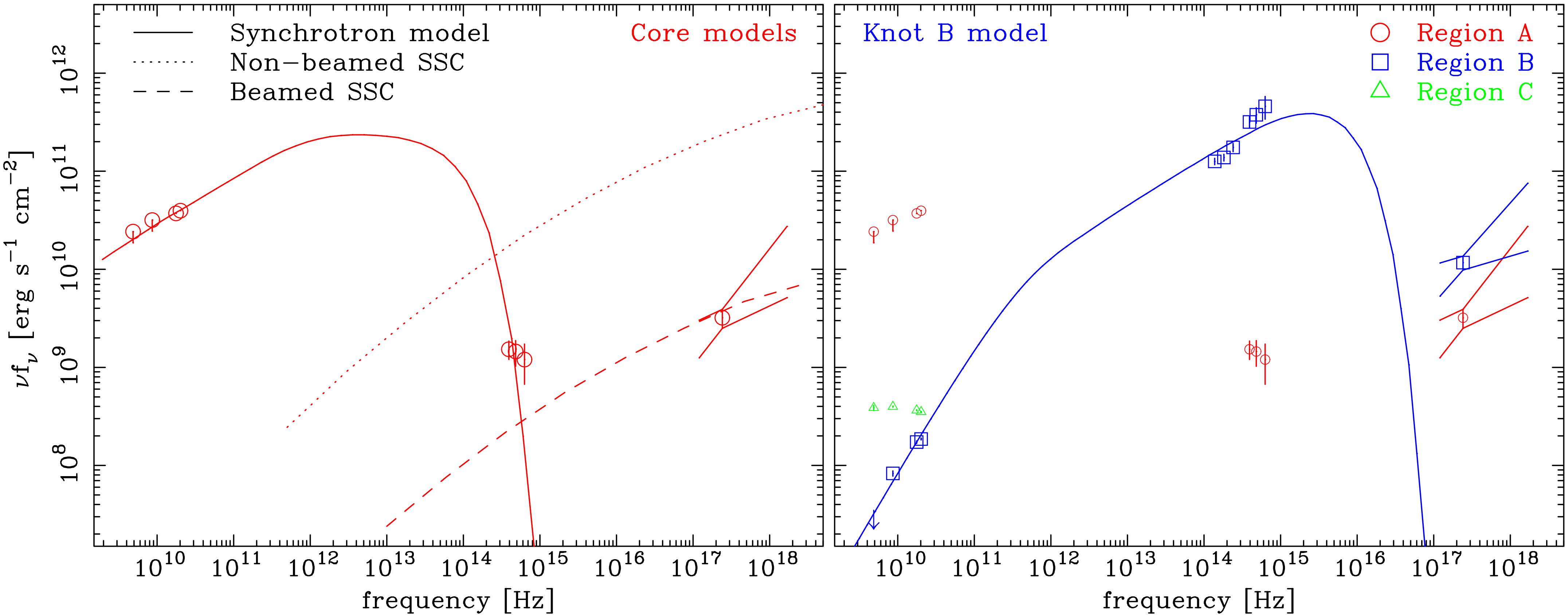
PKS 1421-490 Images

Gelbord et al.



PKS 1421-490 Spectra

Gelbord et al.



Core Model

Radio–Optical: Synchrotron

Equipartition

B=13mG, Γ=20, θ=2.9°

20$\leq \gamma \leq 10^4$

$\gamma_{break} = 10^3$

X-ray: SSC

Jet Model

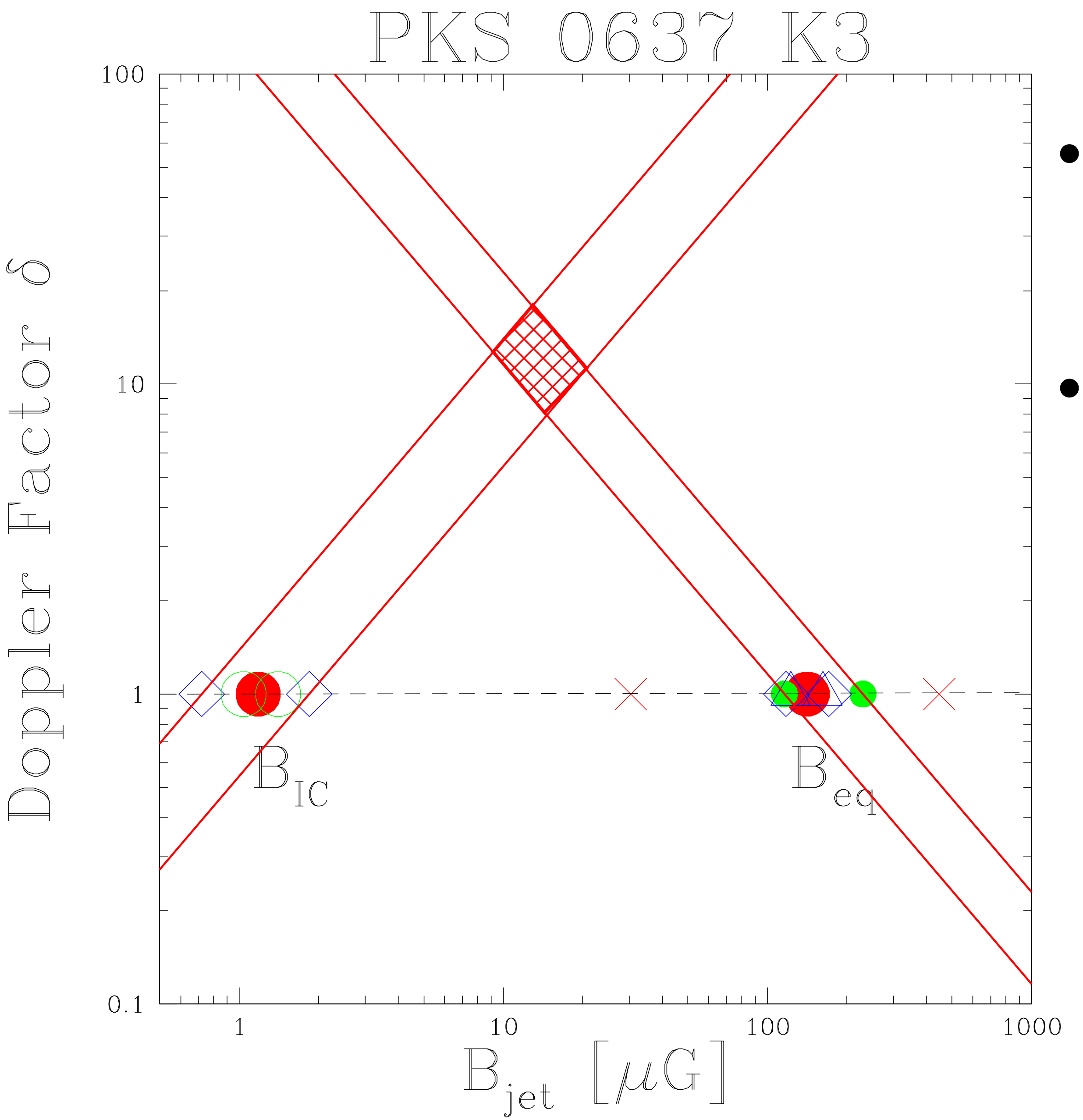
Radio–Optical: Synchrotron

Equipartition

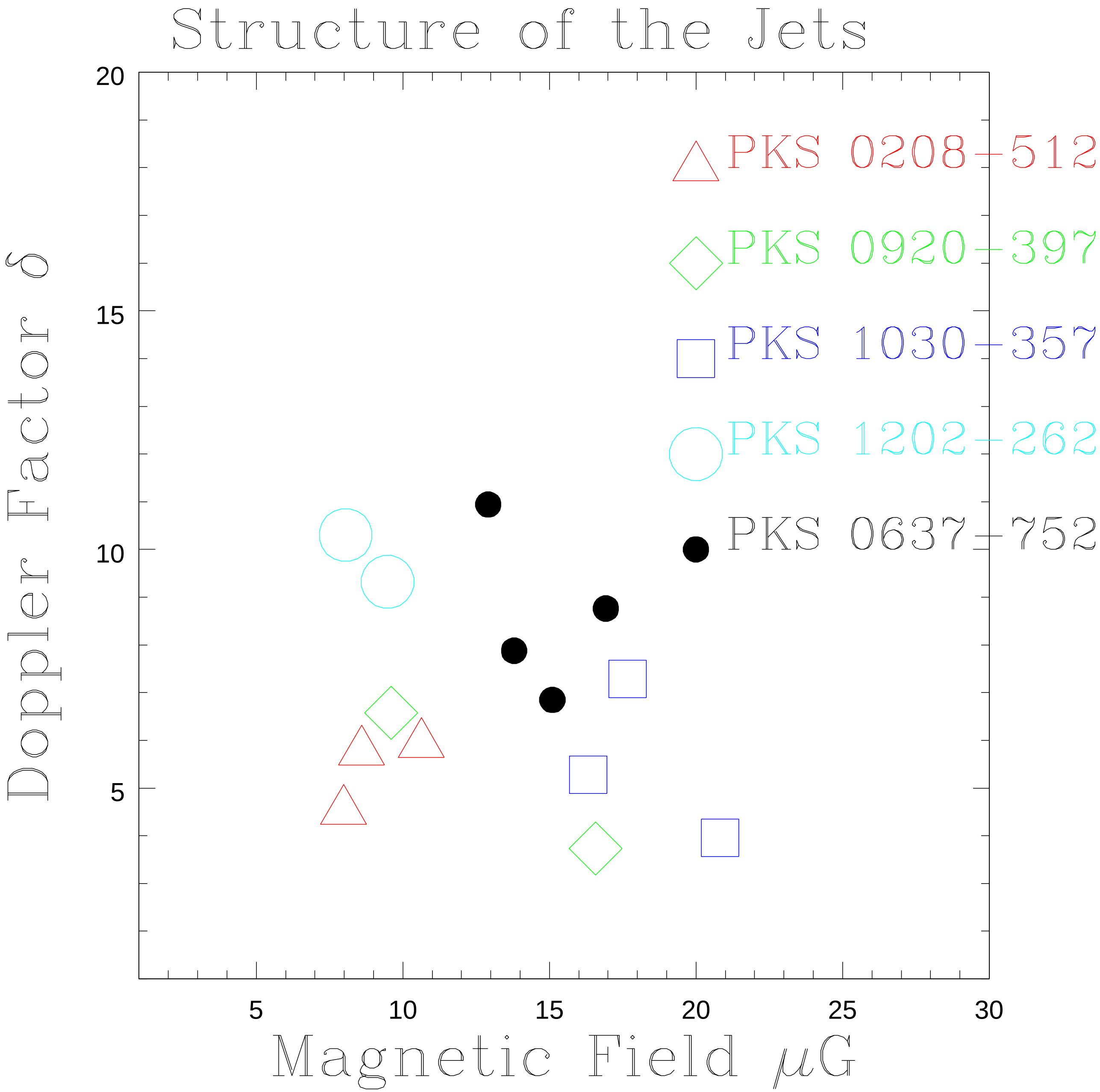
B=85mG

$10^4 \leq \gamma \leq 2 \times 10^6$

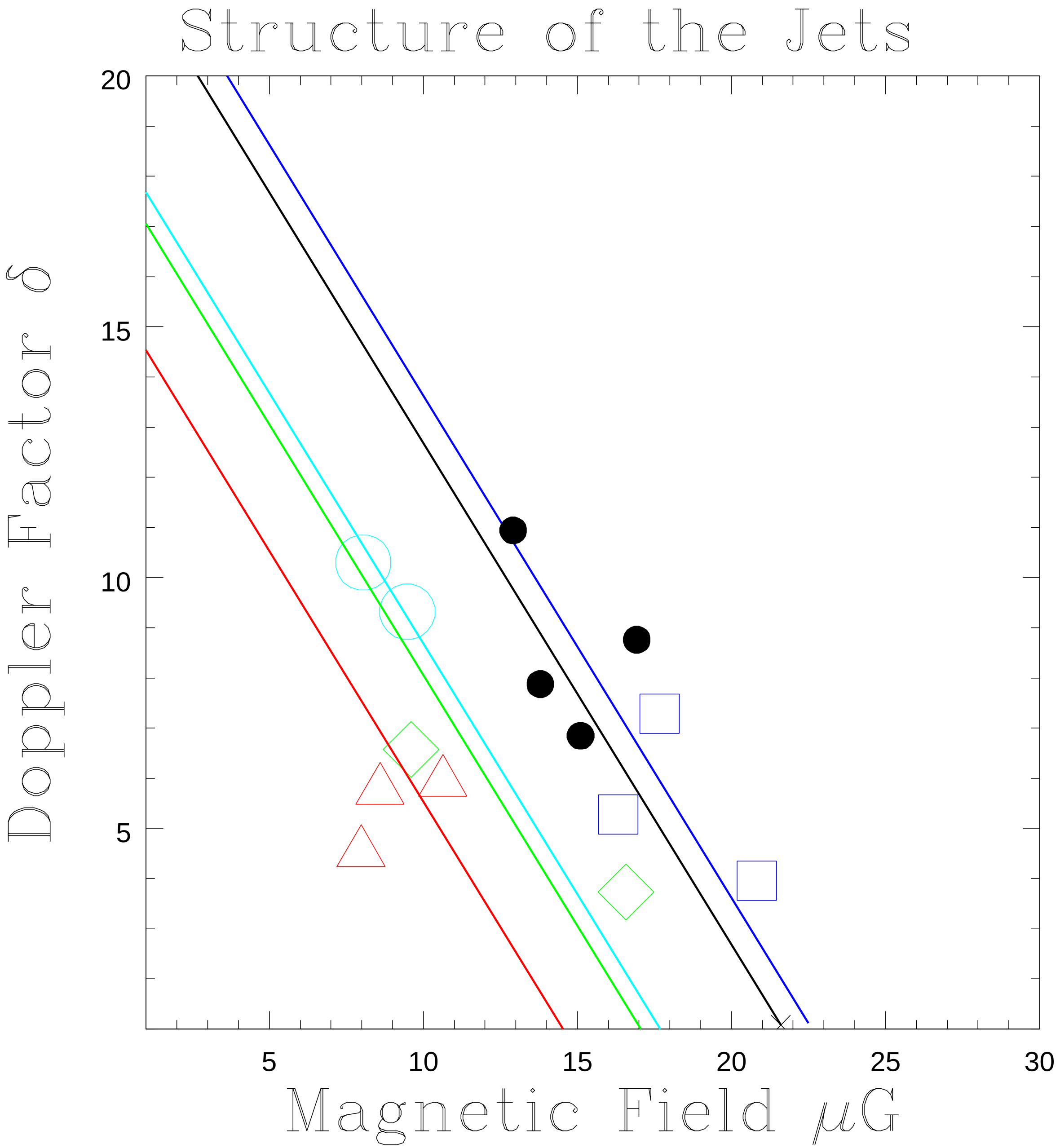
X-ray: Upstream Comptonization?



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

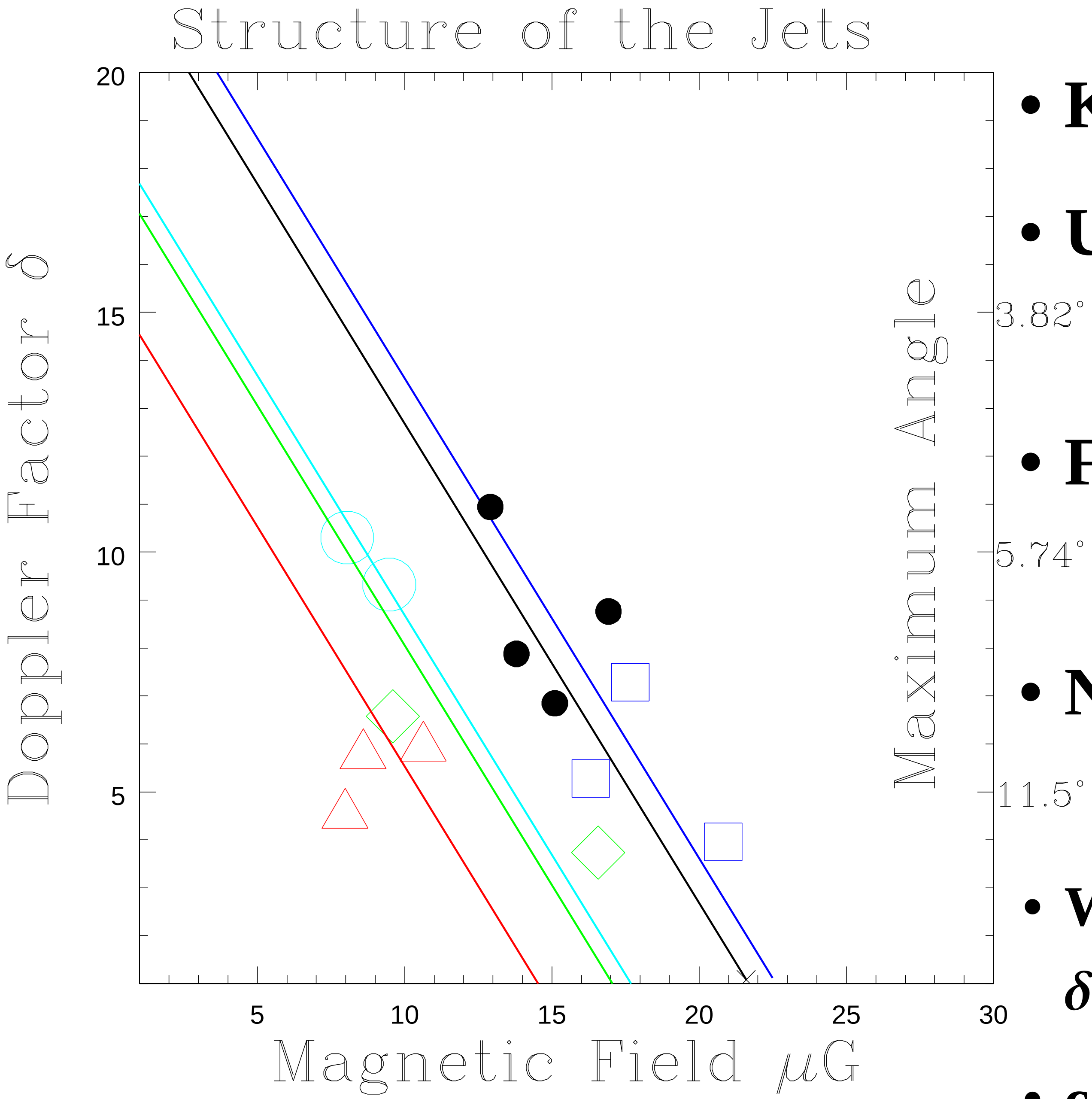


Structure of the Jets
Doppler Factor δ
Magnetic Field μG
PKS 0208−512
PKS 0920−397
PKS 1030−357
PKS 1202−262
PKS 0637−752
20
15
10
5
5
10
15
20
25
30



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



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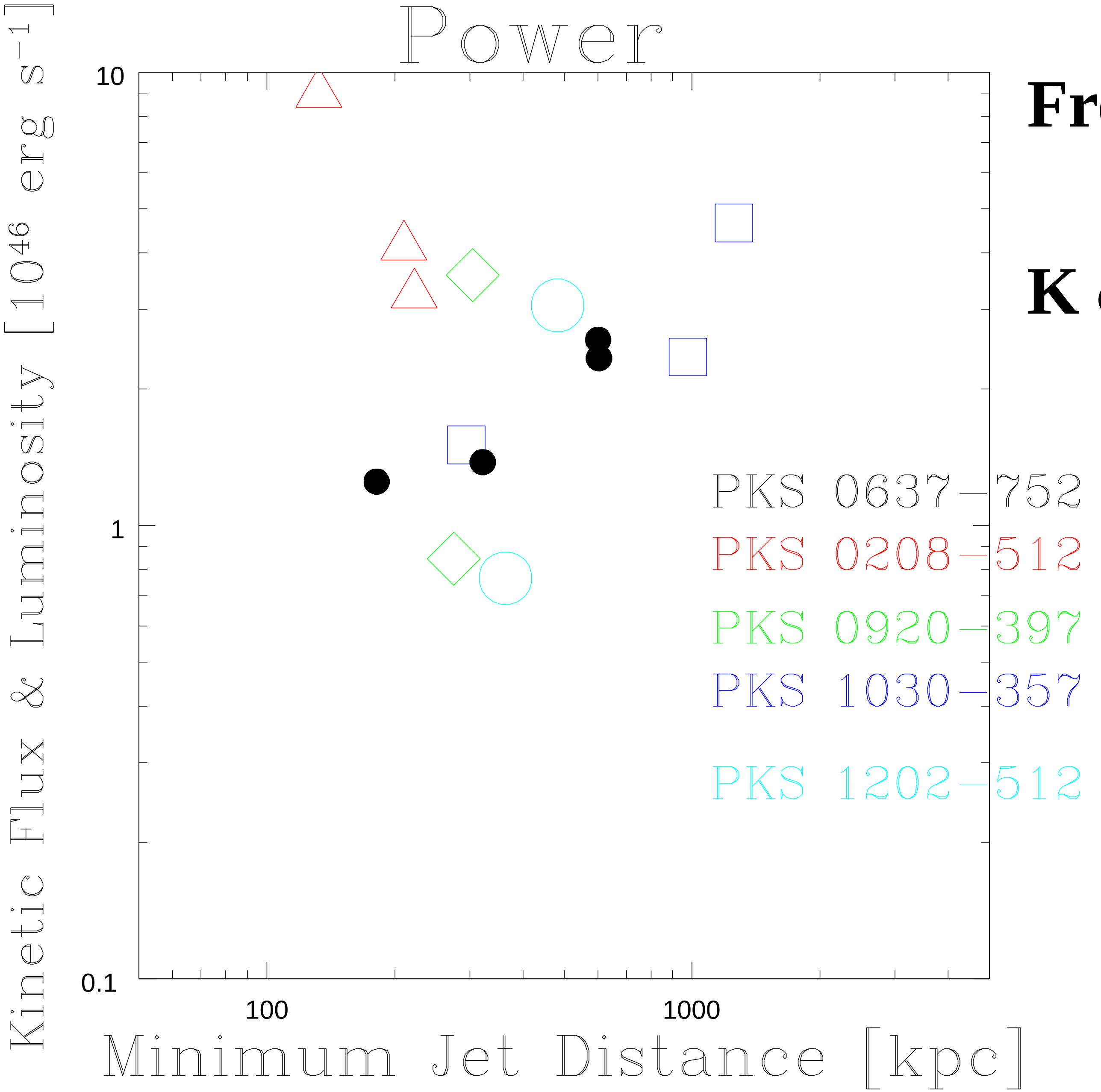
- U is total internal energy density, $U_B + U_e + U_p$
- For equipartition, $U = \frac{B^2}{8\pi}(2 + k)$
- NOTE: K constant $\Rightarrow$ $(B\,\Gamma)^2$ = constant
- We take $\Gamma \approx \delta$
  $\delta = (\Gamma(1 - \beta\cos(\theta)))^{-1}$
- $\cos(\theta_{max}) = \frac{\delta - 1/\delta}{\sqrt{(\delta^2 - 1)}}$

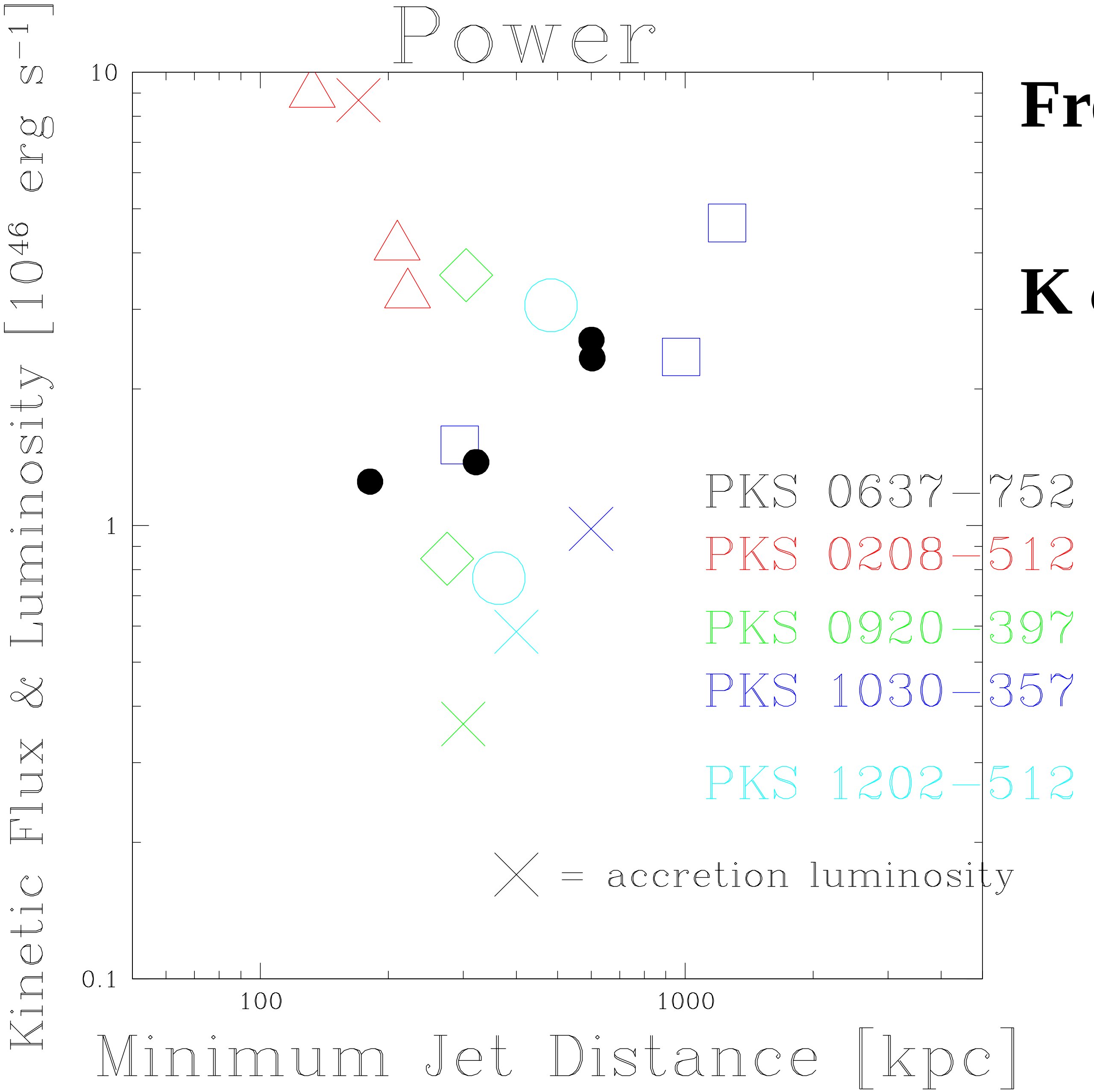
Kinetic Flux



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

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

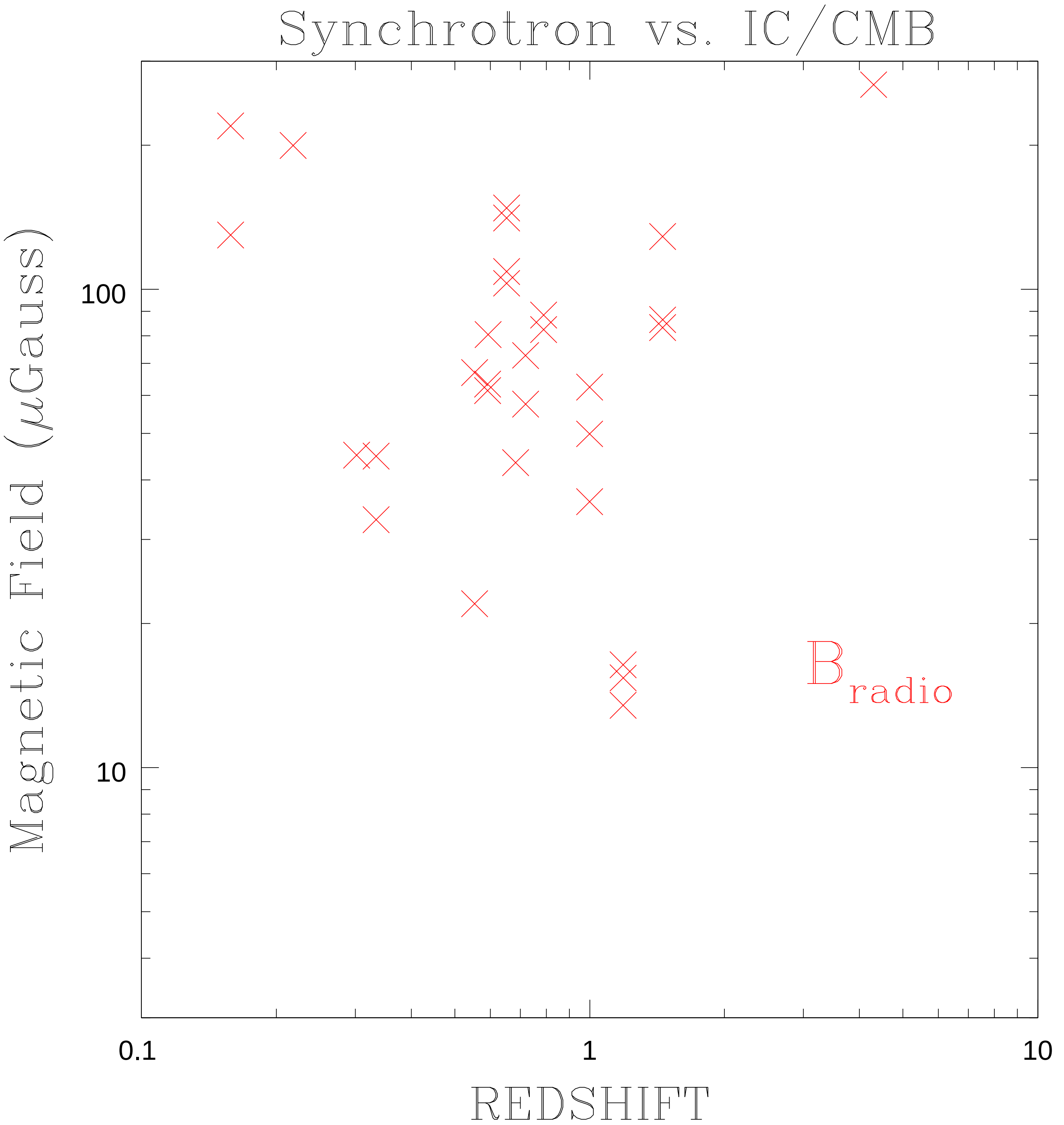
Kinetic flux is a significant, even dominant, portion of the accretion energy budget.

Implications of the AGN Jets

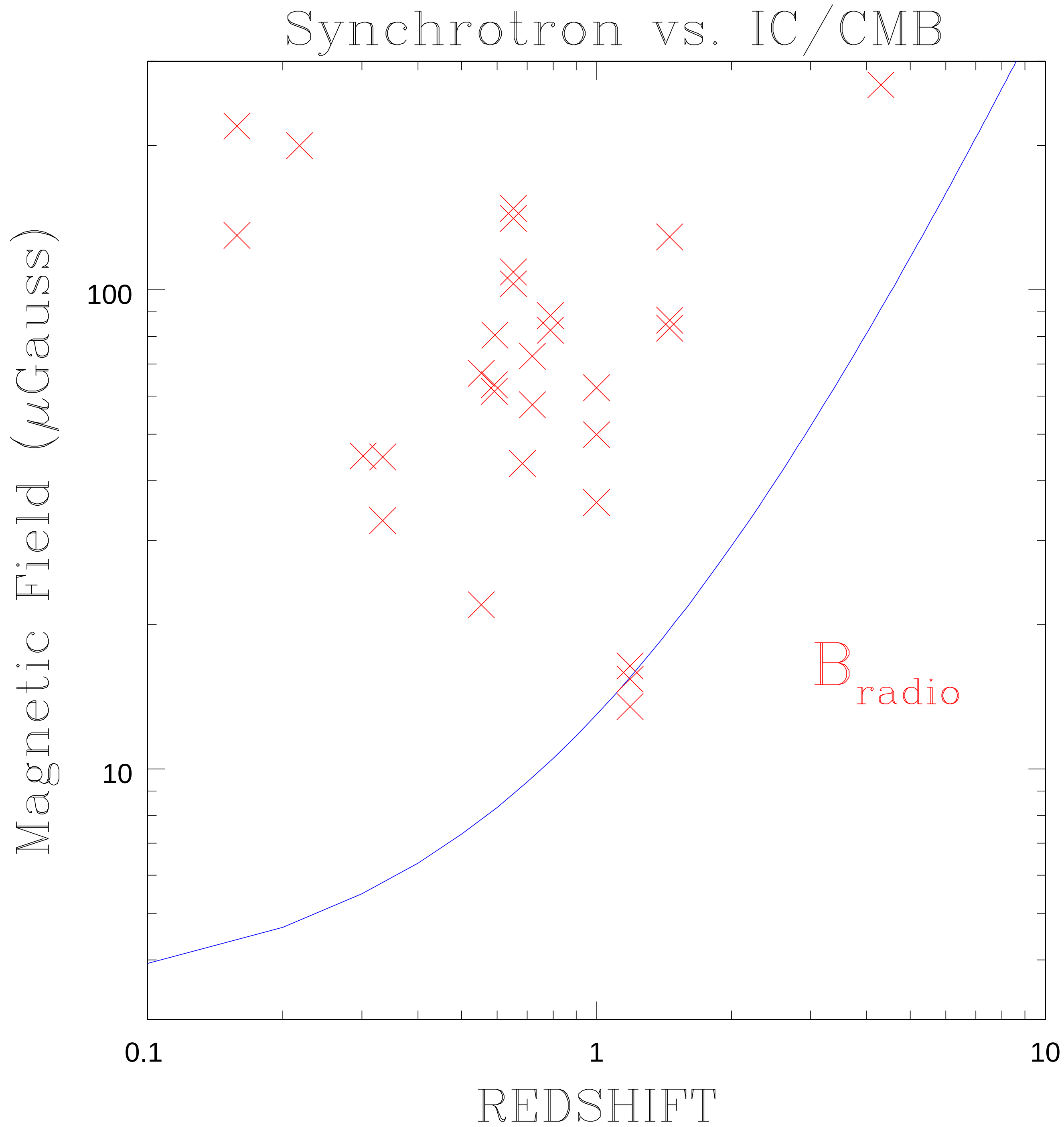
- **Eddington Luminosity might not limit Accretion Rate**

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

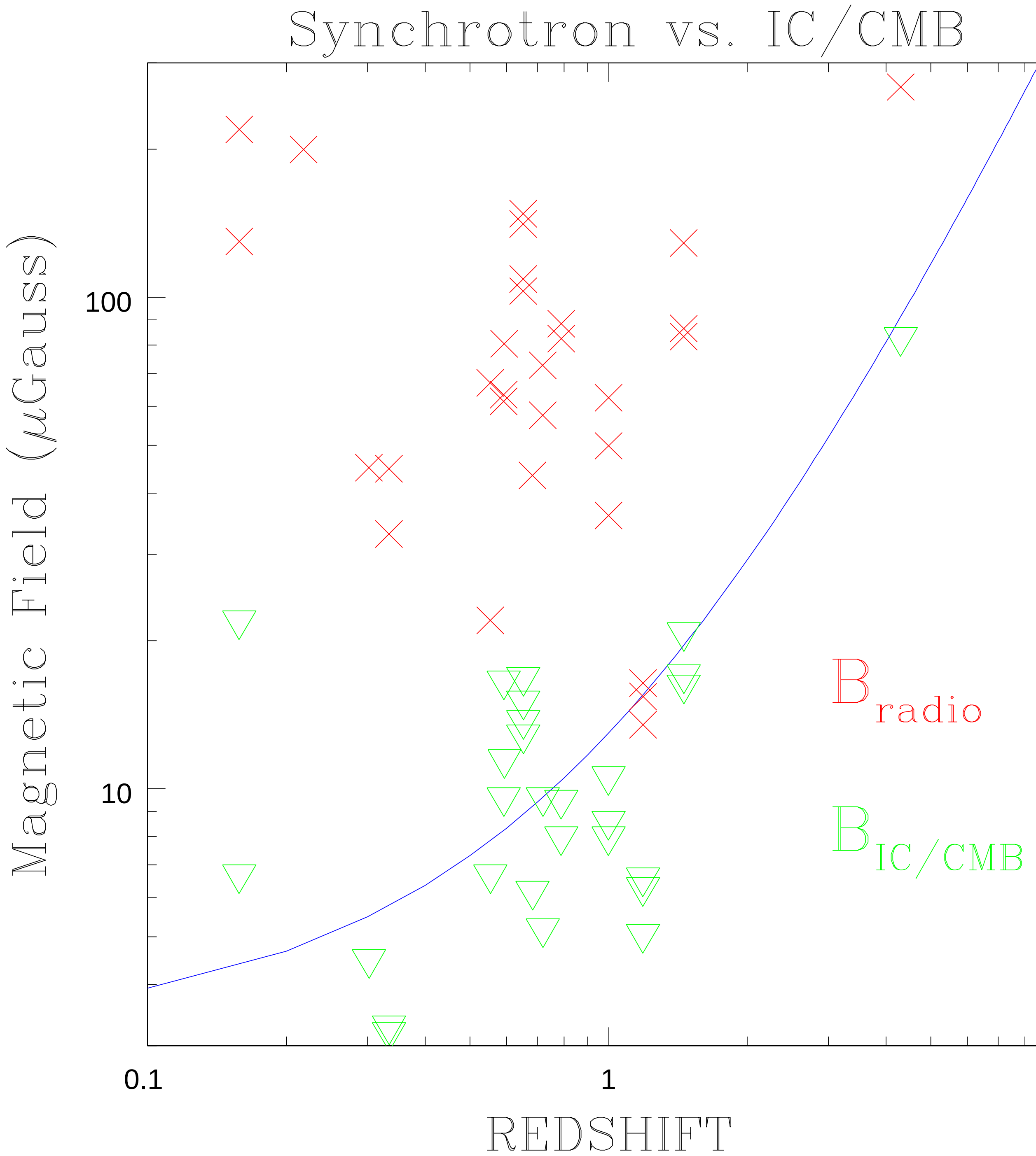
- **IC/CMB X-ray jets Maintain Constant Surface Brightness vs. z. We will detect them at Arbitrarily Large Redshift.**



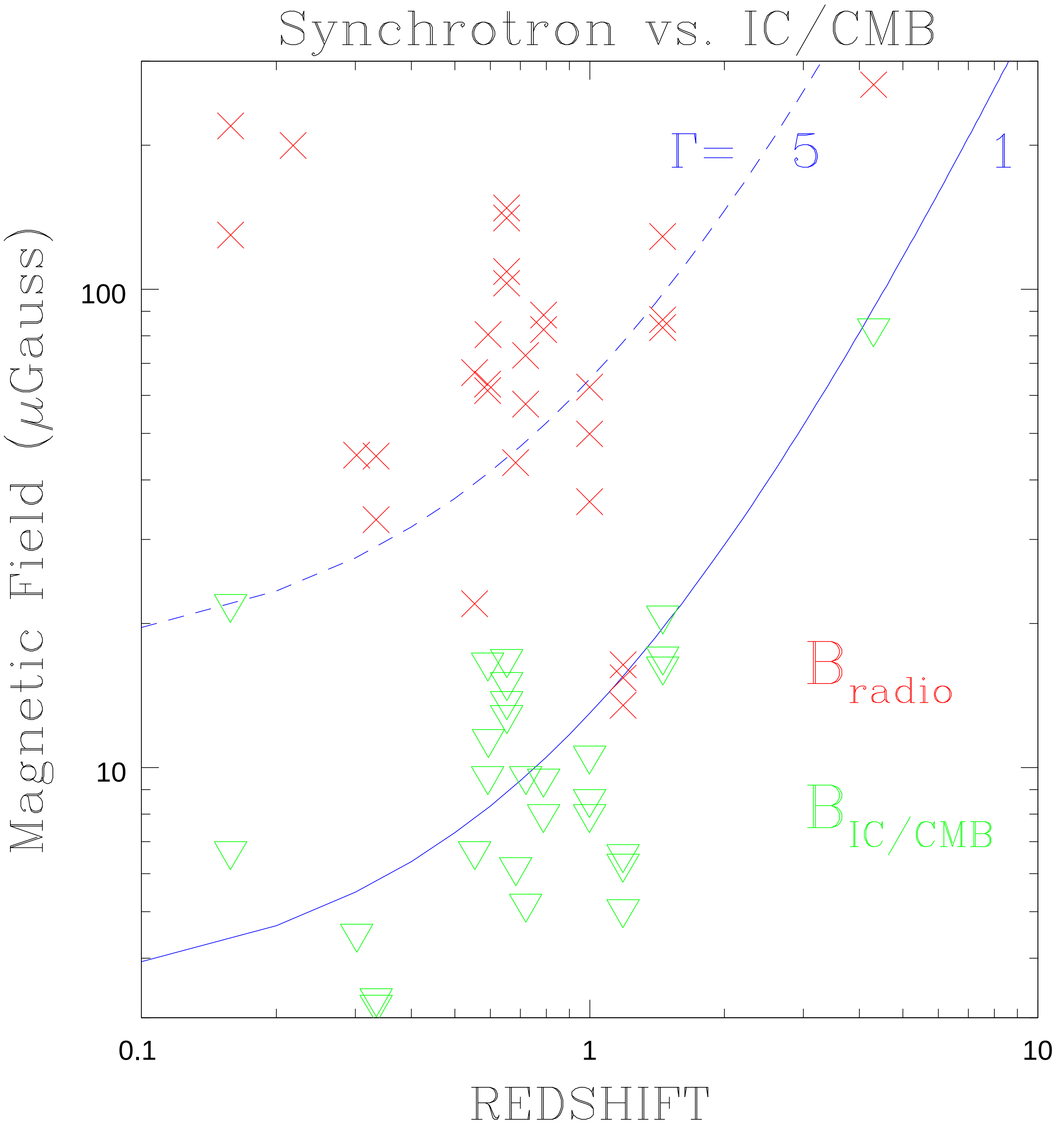
Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B radio



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



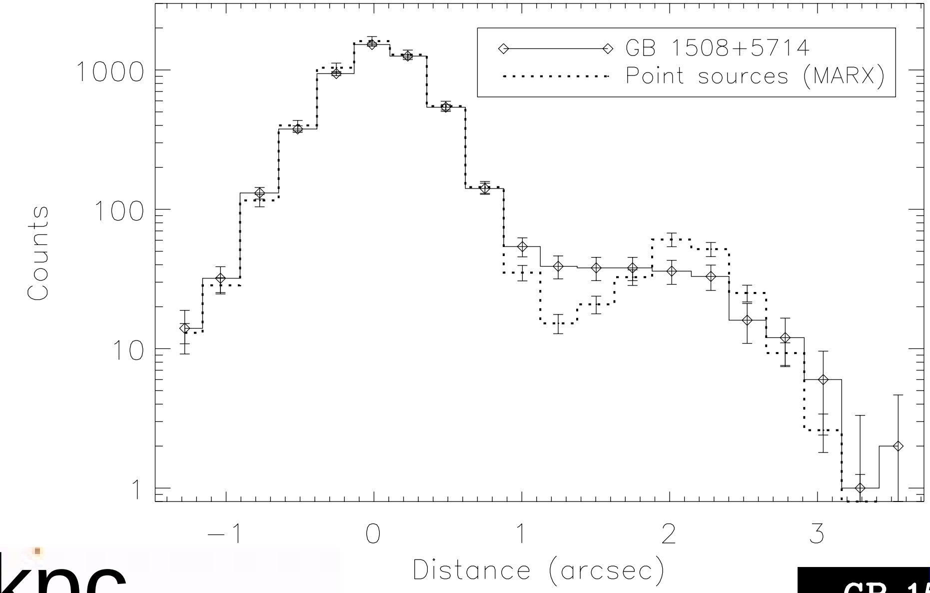
Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B_{radio}
$B_{IC/CMB}$

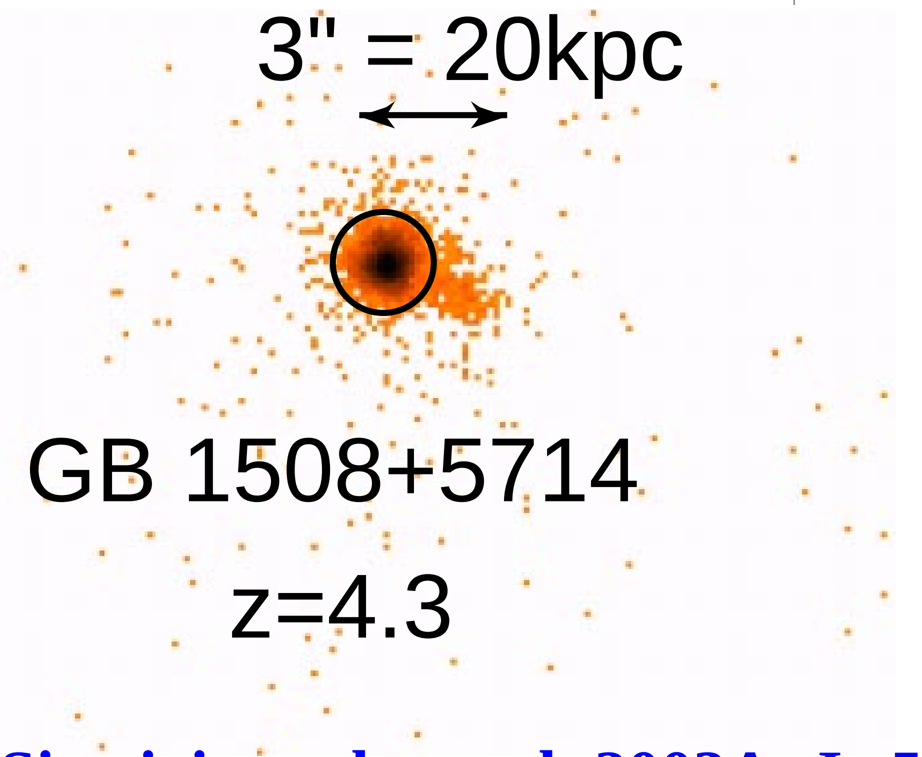

Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
REDSHIFT
100
10
0.1
1
10
Γ= 5
1
B_{radio}
$B_{IC/CMB}$

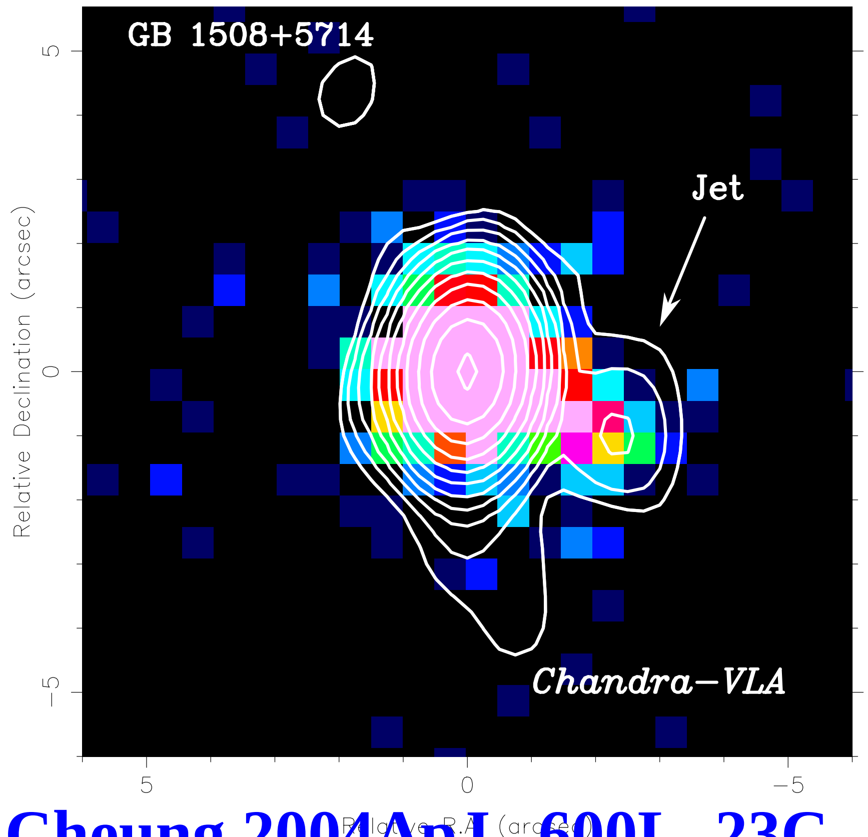
Where ARE the bright X-ray Jets at High Redshift?

- **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?



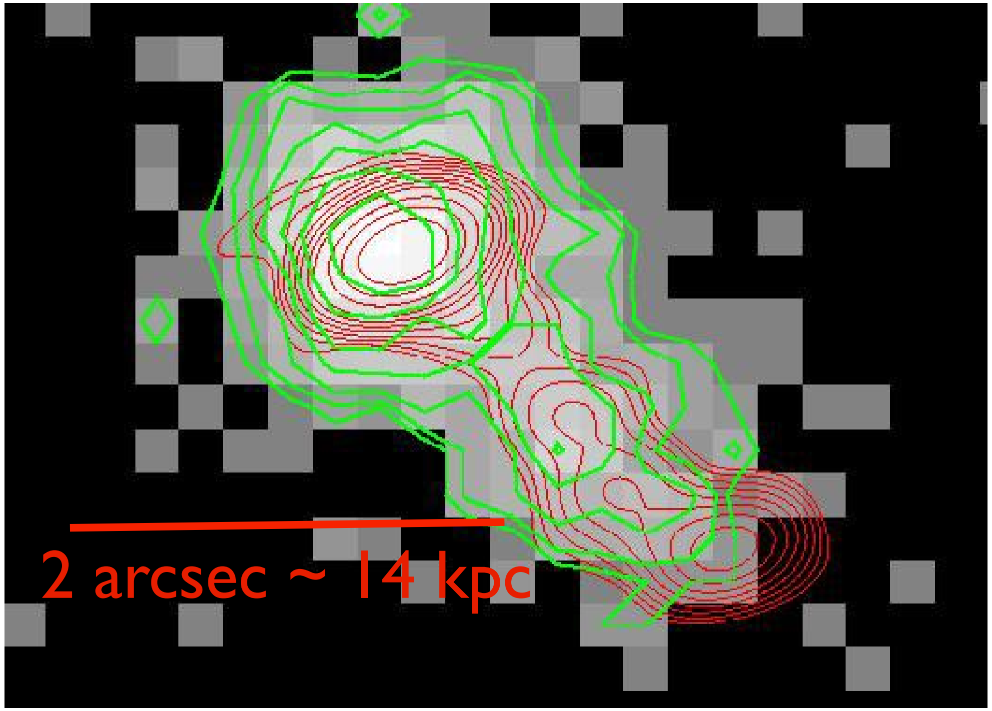




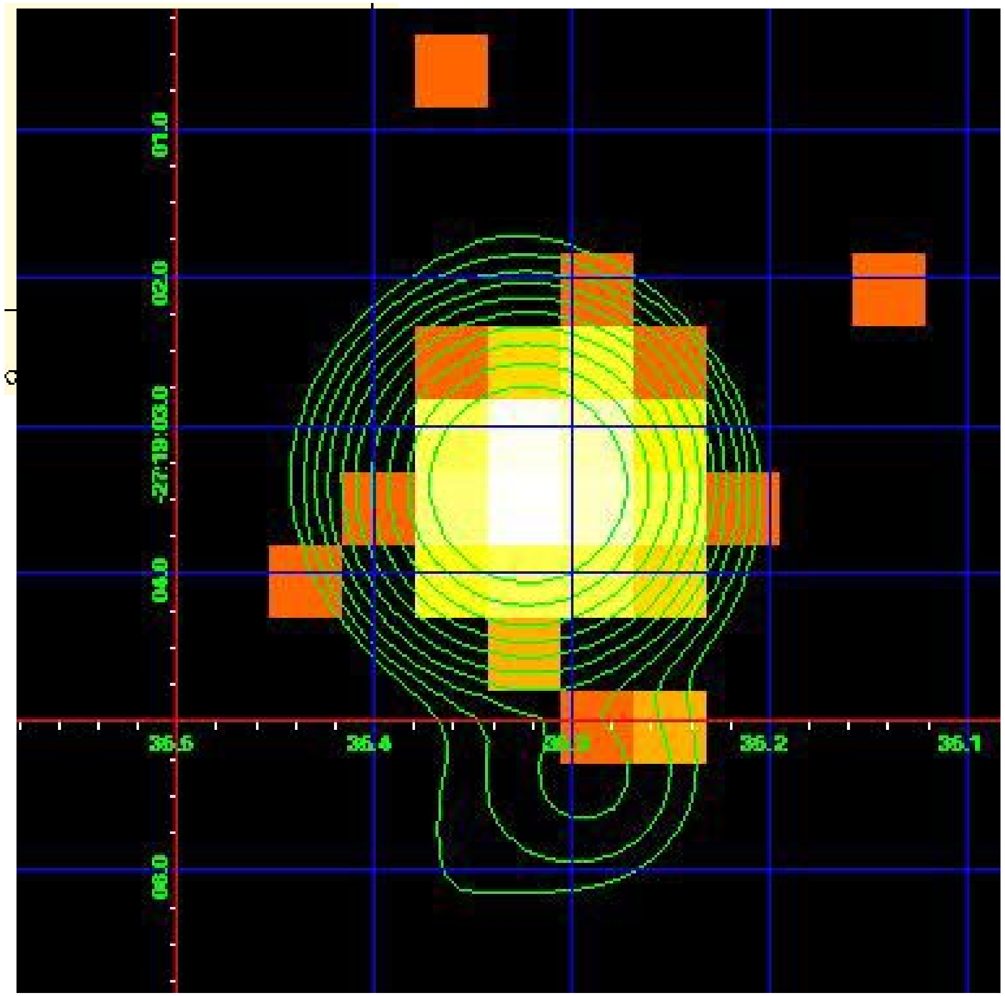
Siemiginowska et al. 2003ApJ...598L..15S

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

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



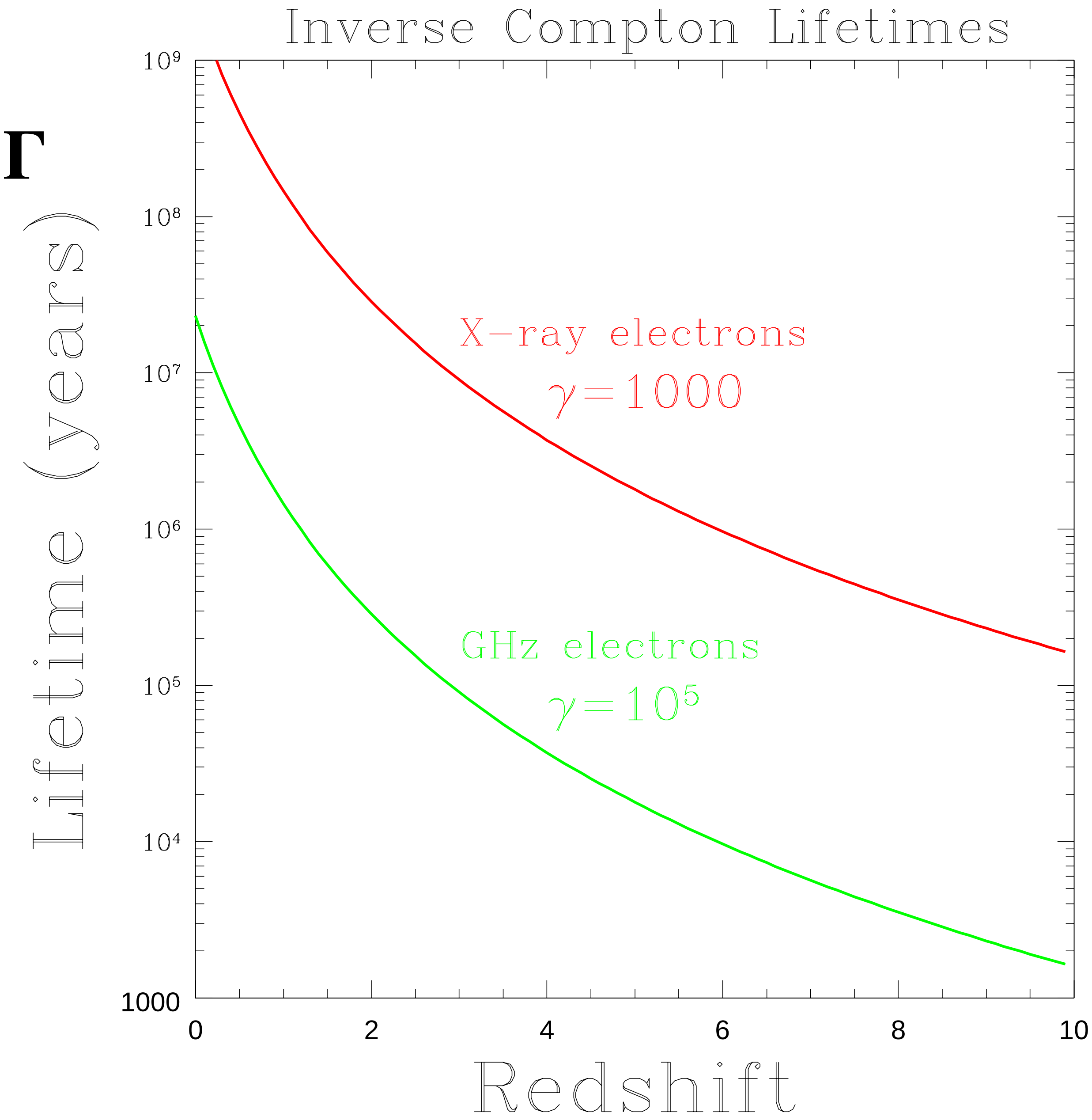
Quasar 1745+624 = 4C +62.29 at z=3.889



PMN J2219-2719 at z=3.634

There Could Be Radio Quiet X-Ray Jets!

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



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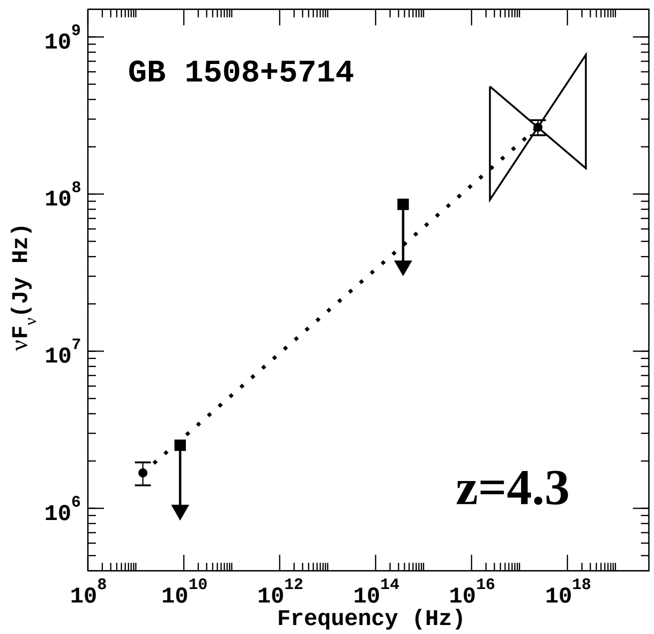
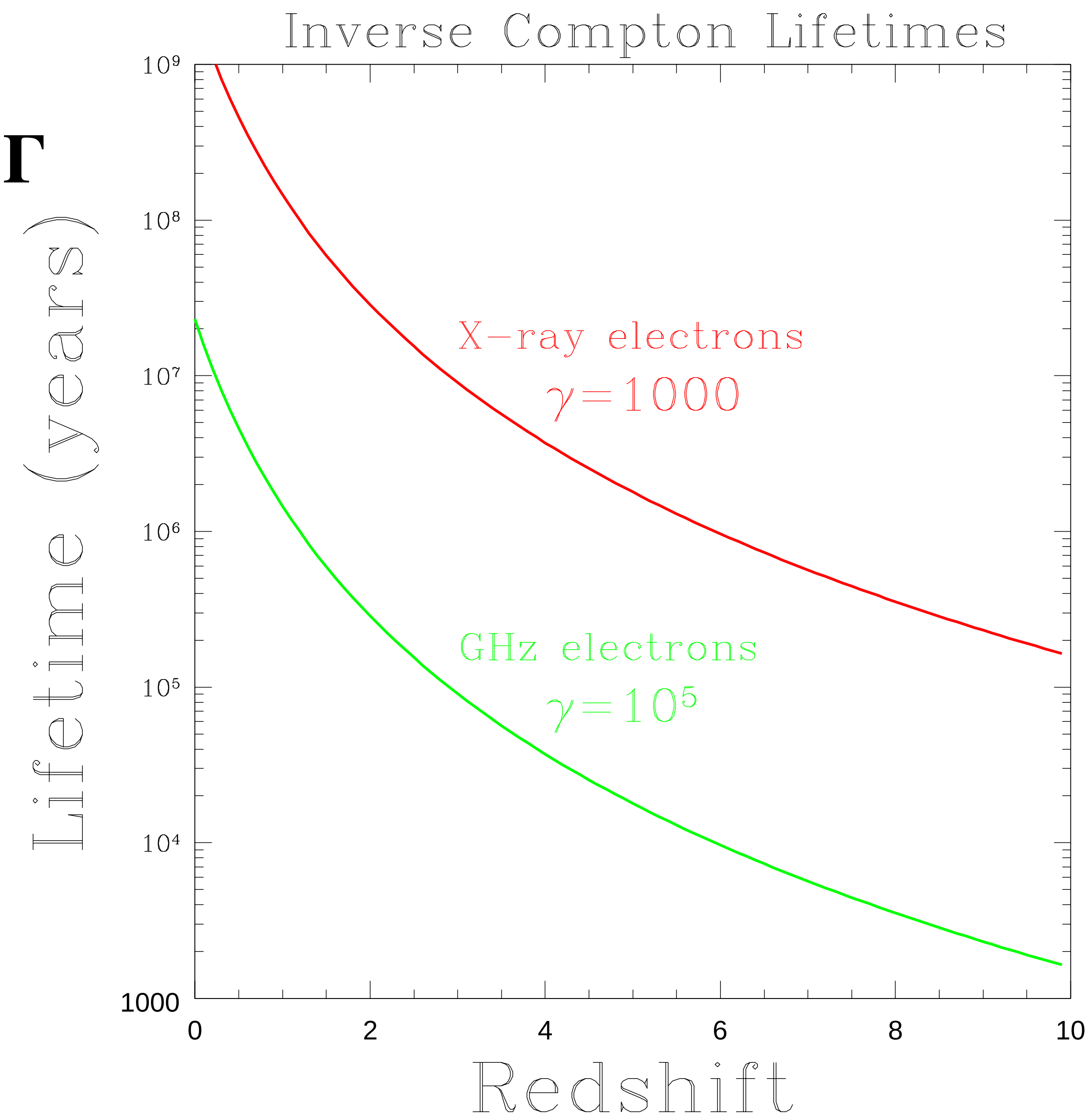
- **1 keV X-rays produced by $\gamma \approx 1000/\Gamma$**
- **$\nu = 4.2 \times 10^{-6} \gamma^2$ H[μG] $\approx$ 10 MHz**

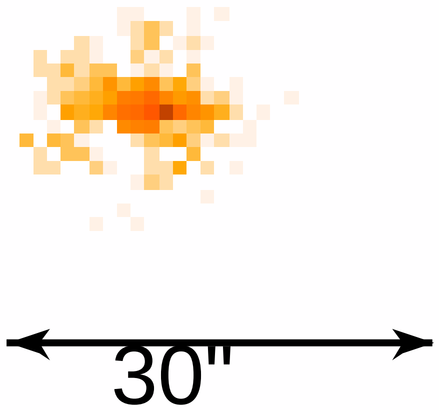


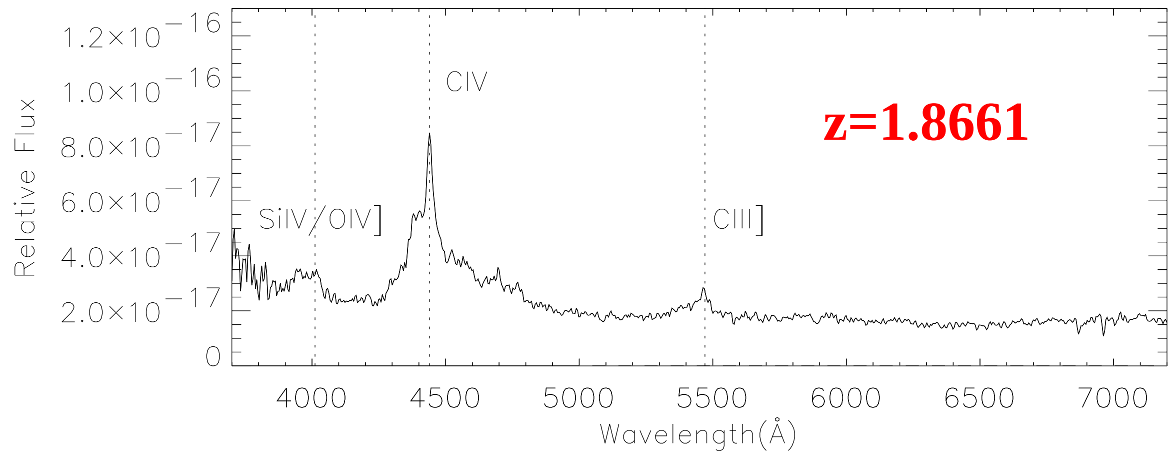
Cheung,2004ApJ...600L..23C

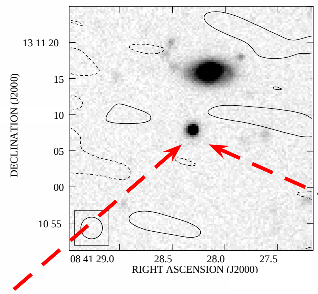


A Radio Quiet X-Ray Jet?

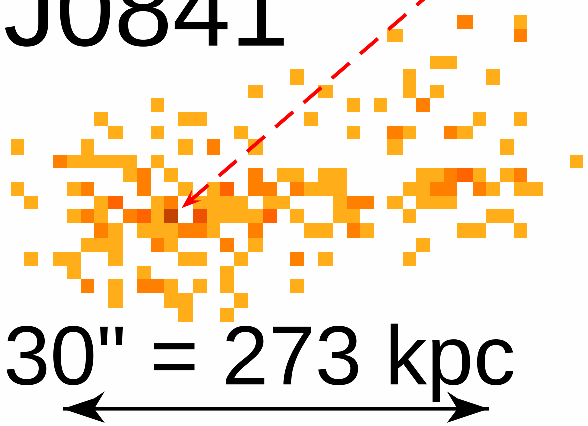
EMSS 0841+1314

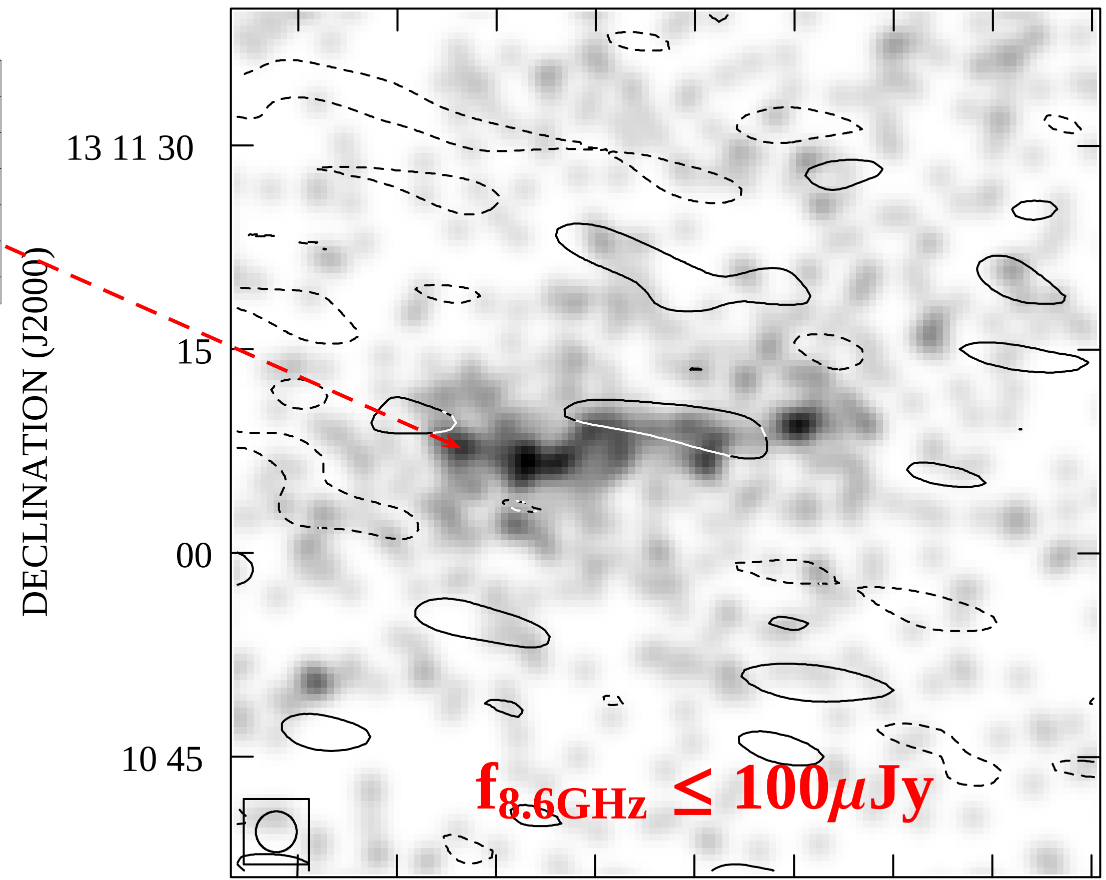




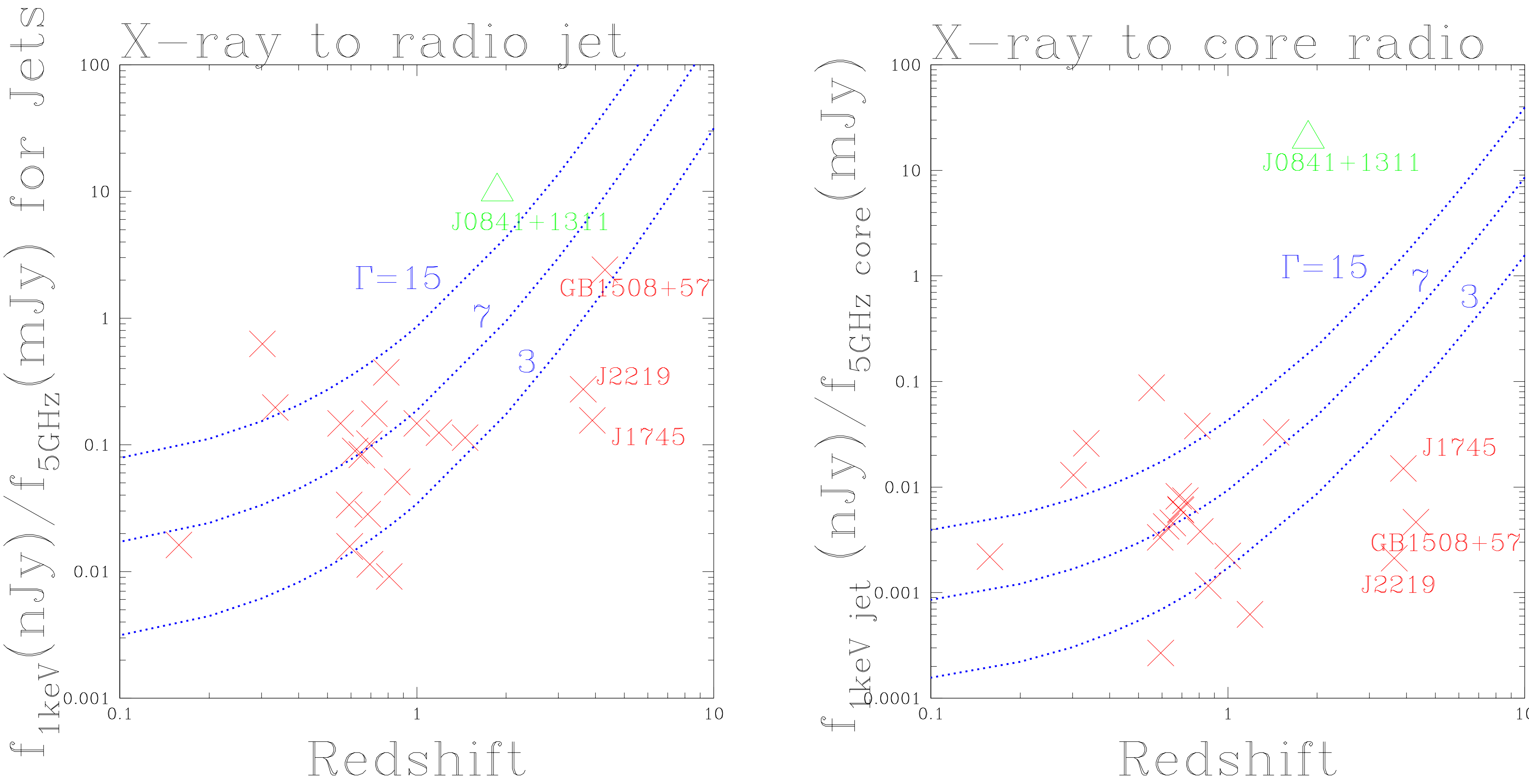


J0841





Correlation of X-ray Jet and Radio Flux Densities



Significance of the X-ray Emission

1. **Jet radiated power dominated by X-rays.**
2. **SED through X-ray band provides clues to structure.**
   - **Acceleration sites**
   - **Deceleration of bulk motion**
   - **Low energy electron cutoff**
   - **Hadron content**

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**