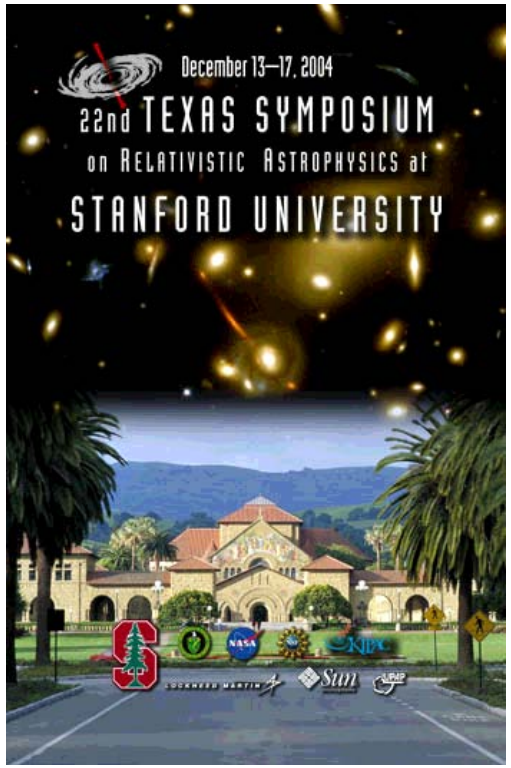
Chandra Observations of Relativistic AGN Jets

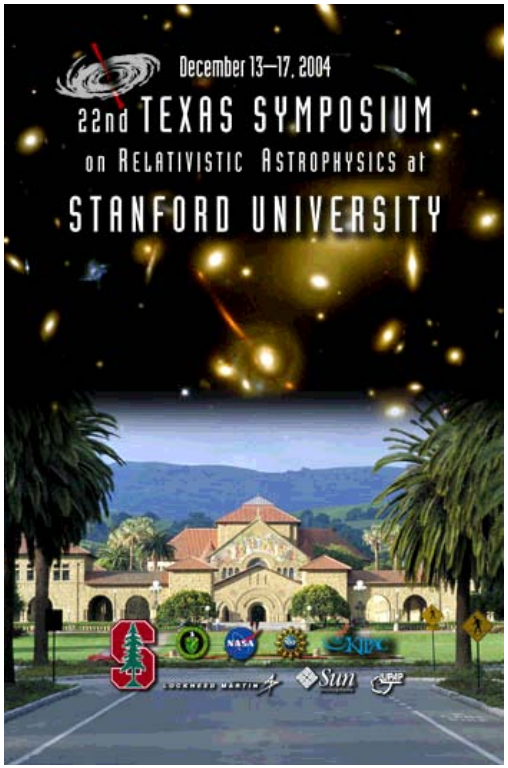
Dan Schwartz

Smithsonian Astrophysical Observatory



TEXAS AT STANFORD

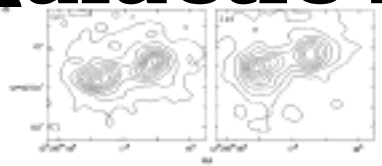
2004 December 15



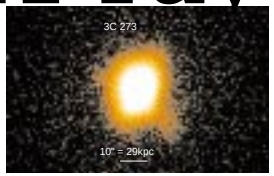
Observations of Extragalactic X-ray Jets

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.**

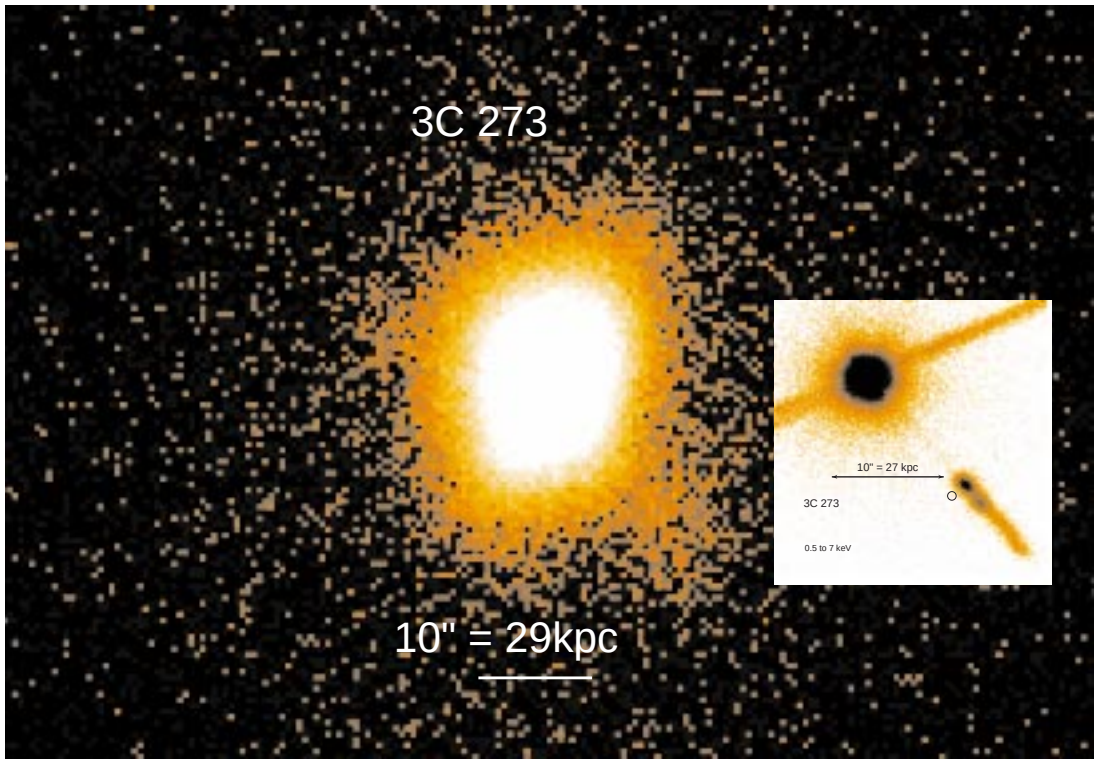
Observations of Extragalactic X-ray Jets

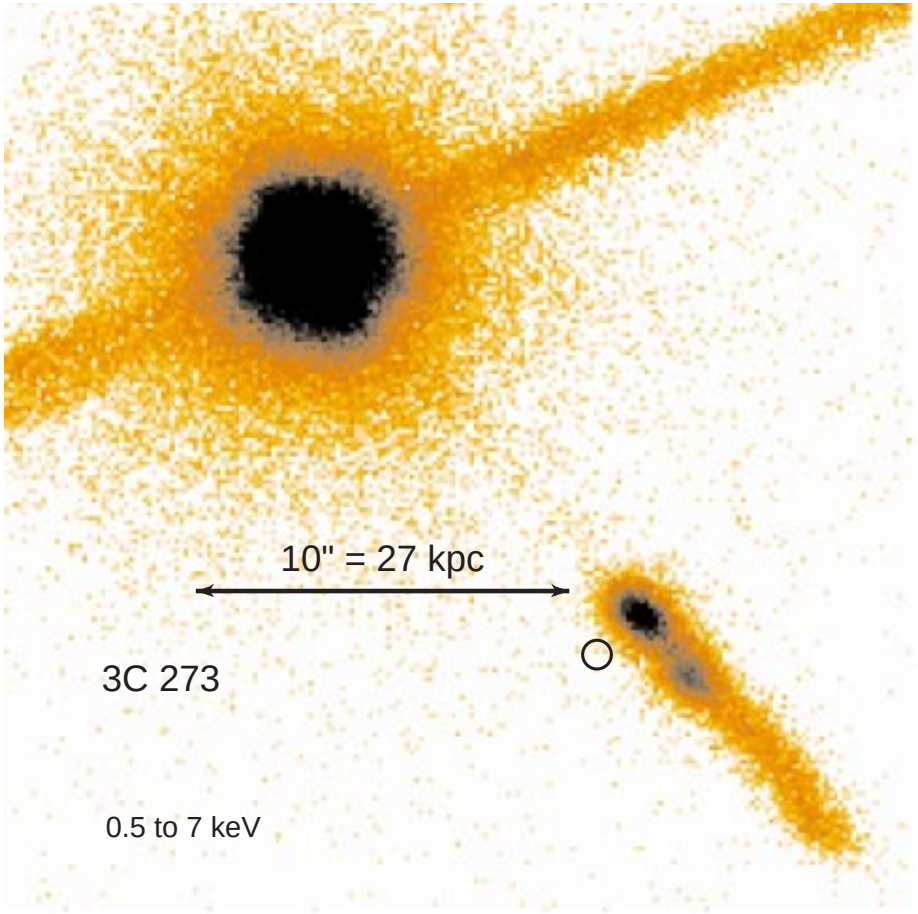
BC: 3 Clear Detections

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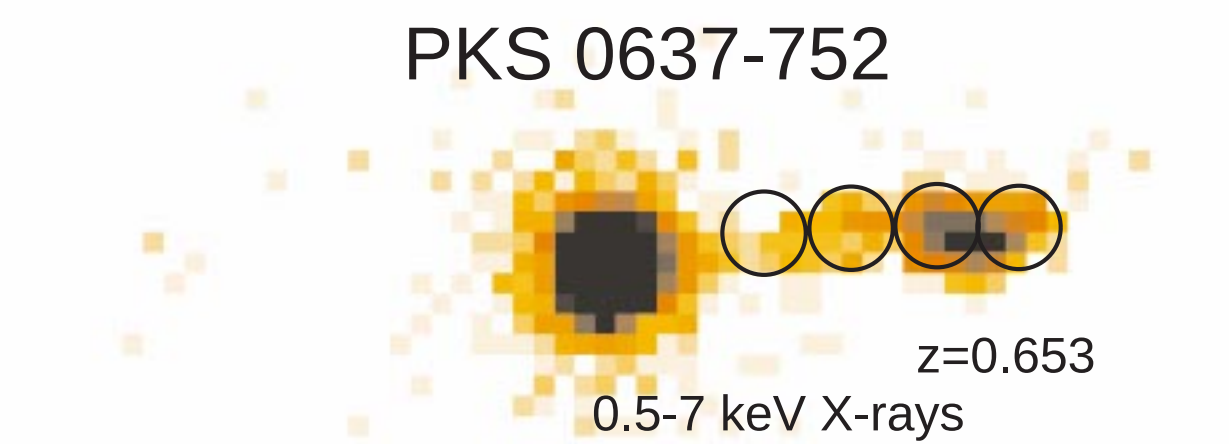
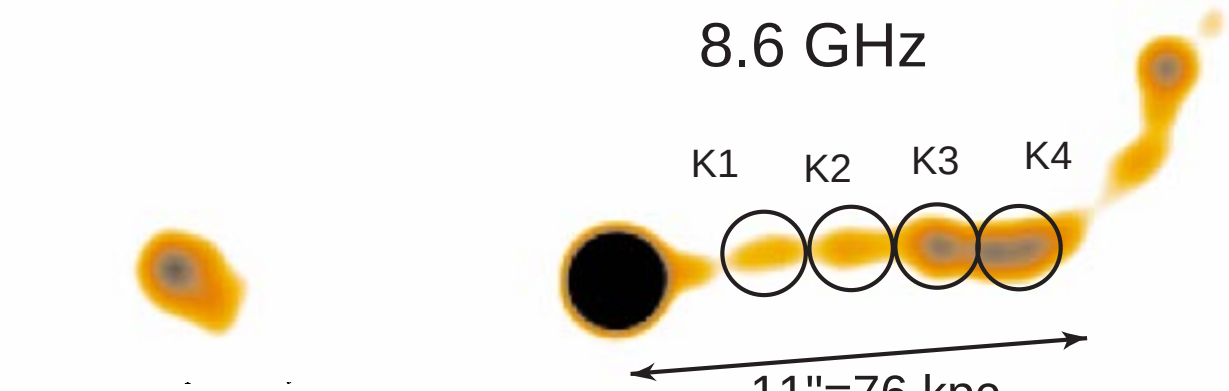
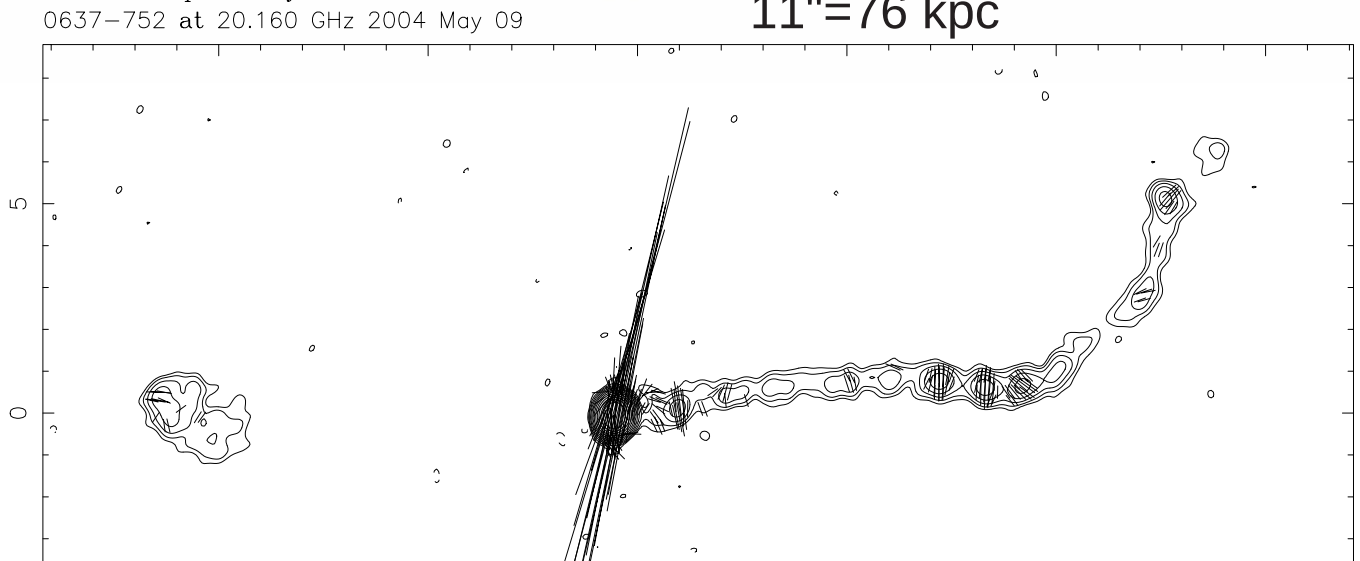
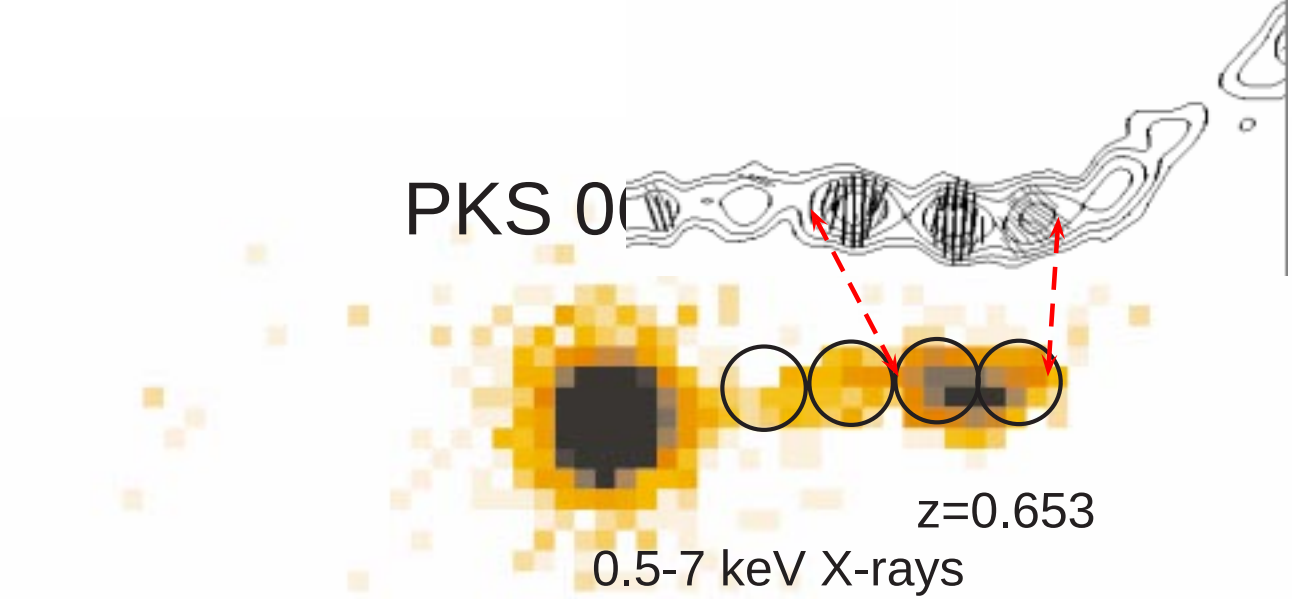
- **What Do We Want to Learn**
  - **Particle composition and acceleration**
  - **Jet acceleration and collimation**
- **Why Do We Need X-Ray Data?**
  - **Spectral Energy Distribution (SED) gives mechanism**
  - **Particle lifetimes change with observed band**


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 0
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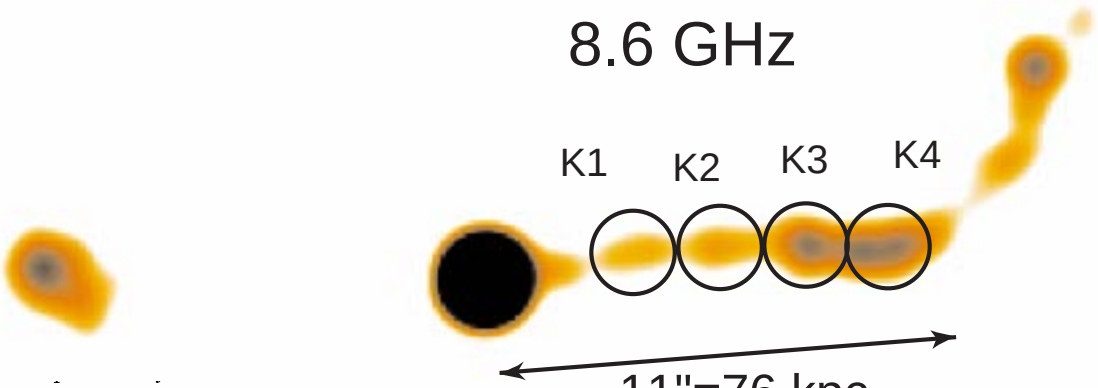
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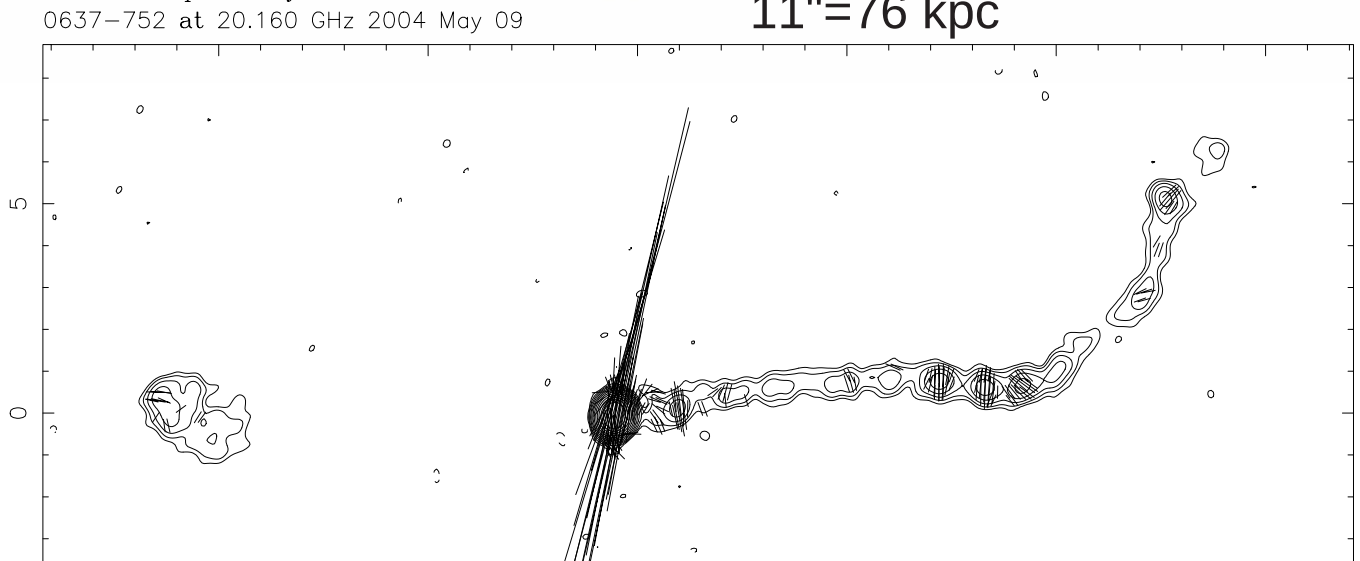
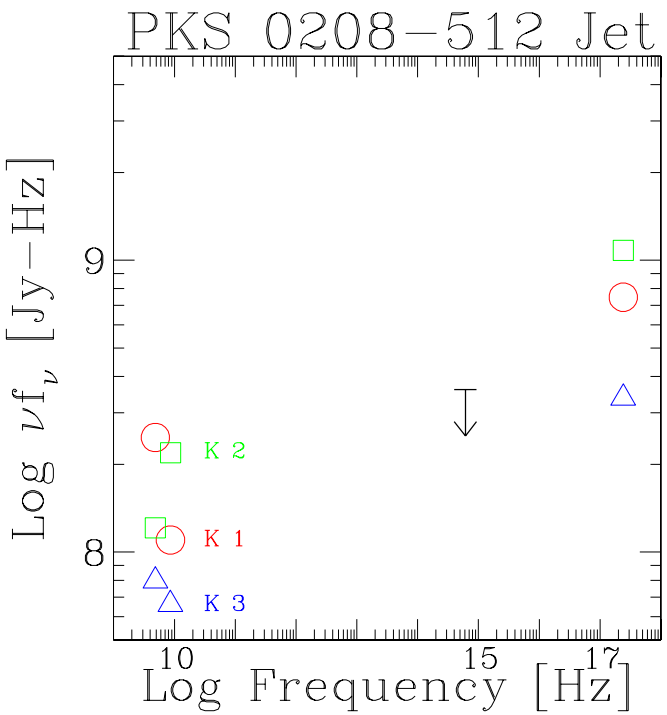
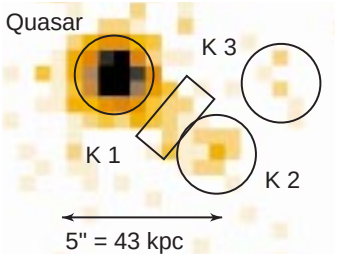
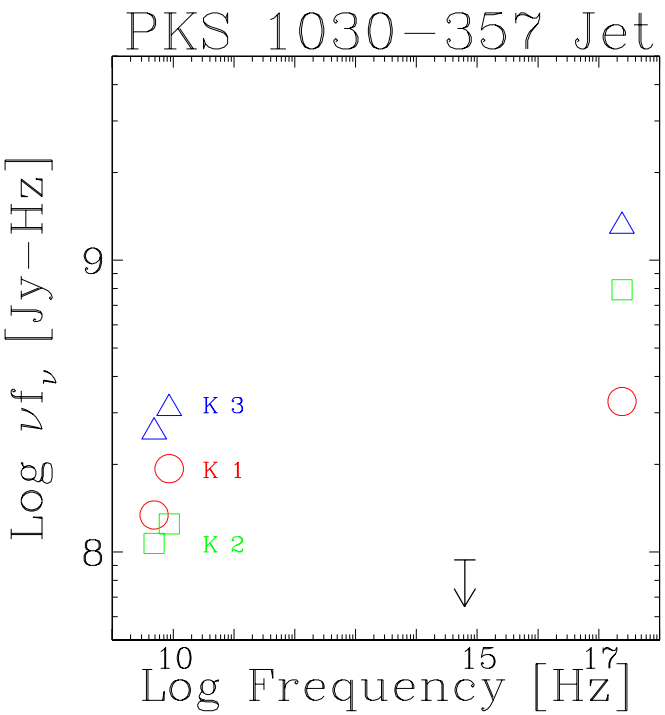
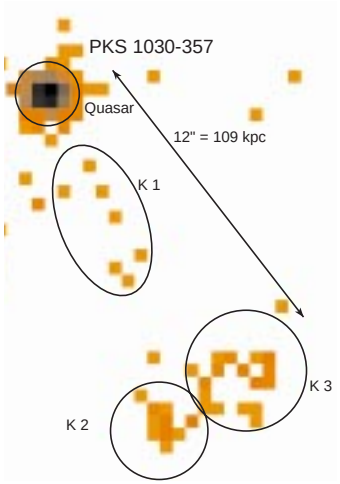

0637−752 at 20.160 GHz 2004 May 09
5
0

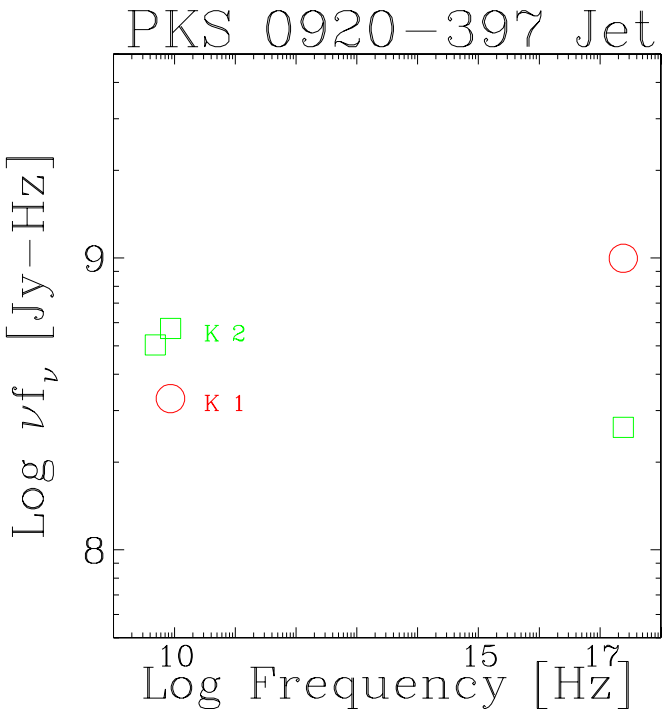
Spectral Energy Distribution often indicates against Synchrotron X-rays

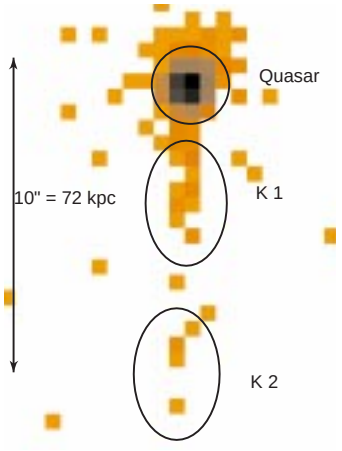


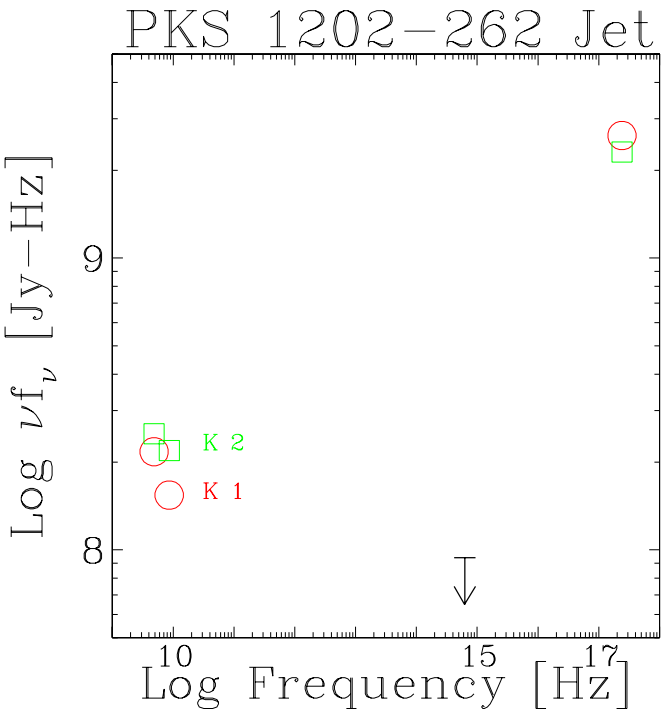


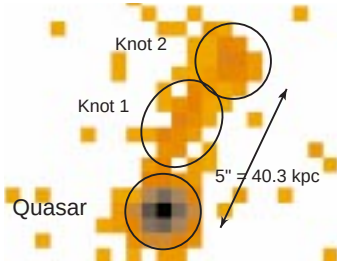












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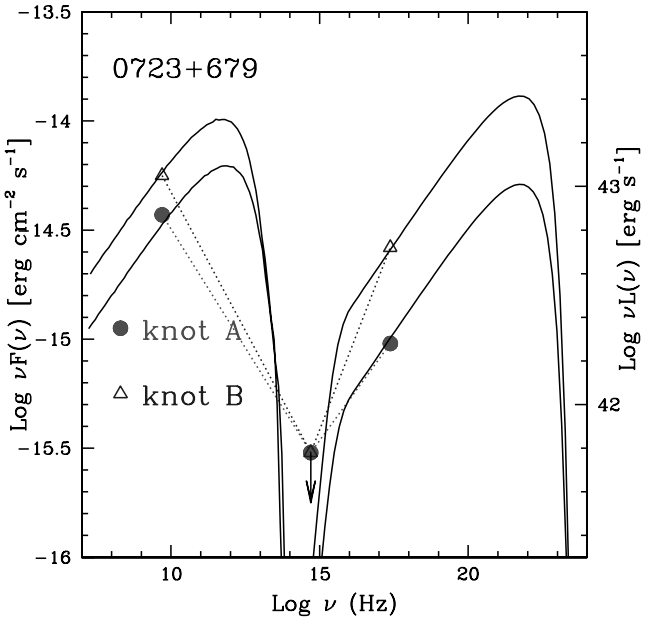

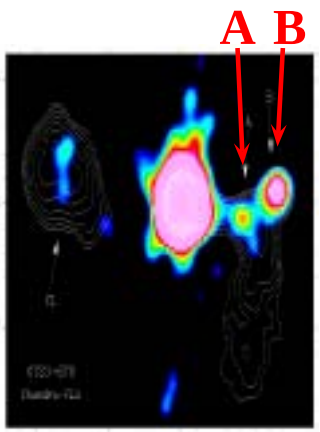

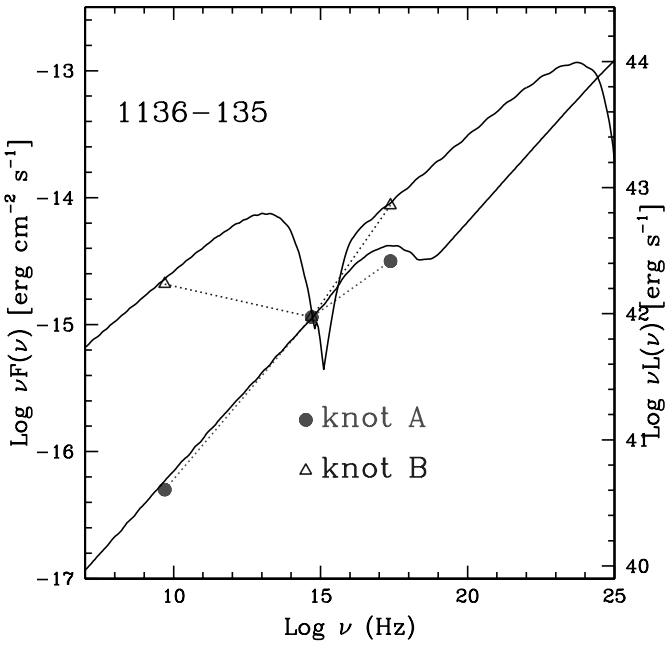

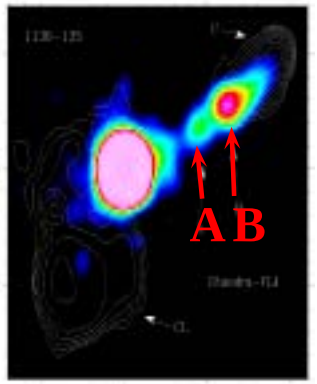

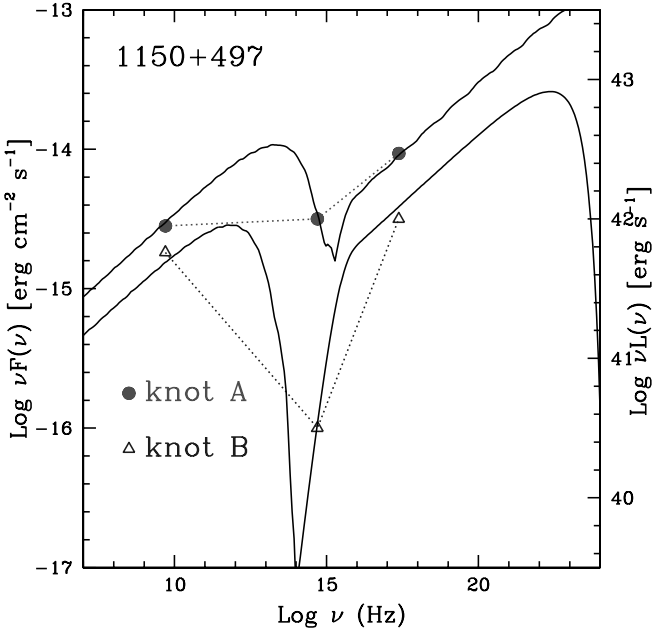

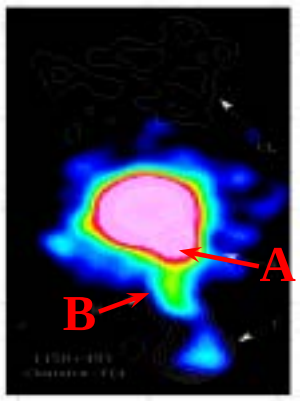

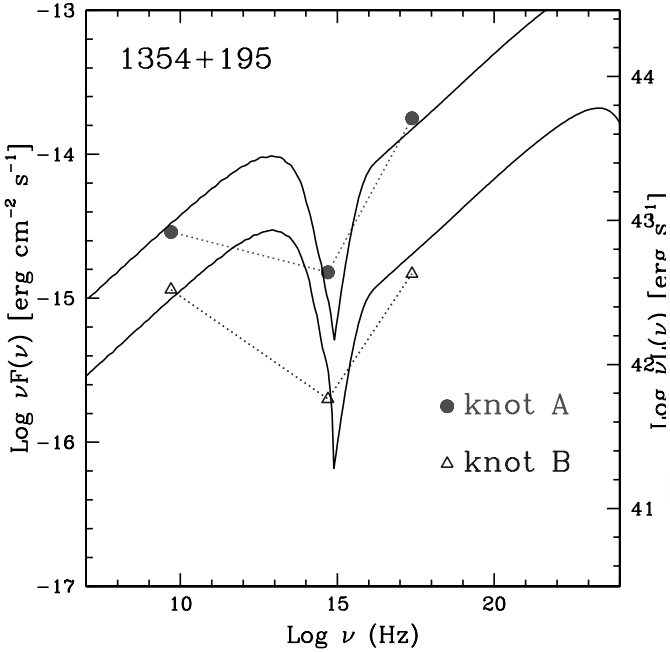

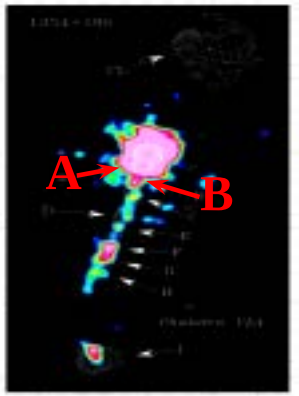

Sambruna et al., 2002ApJ...571..206S

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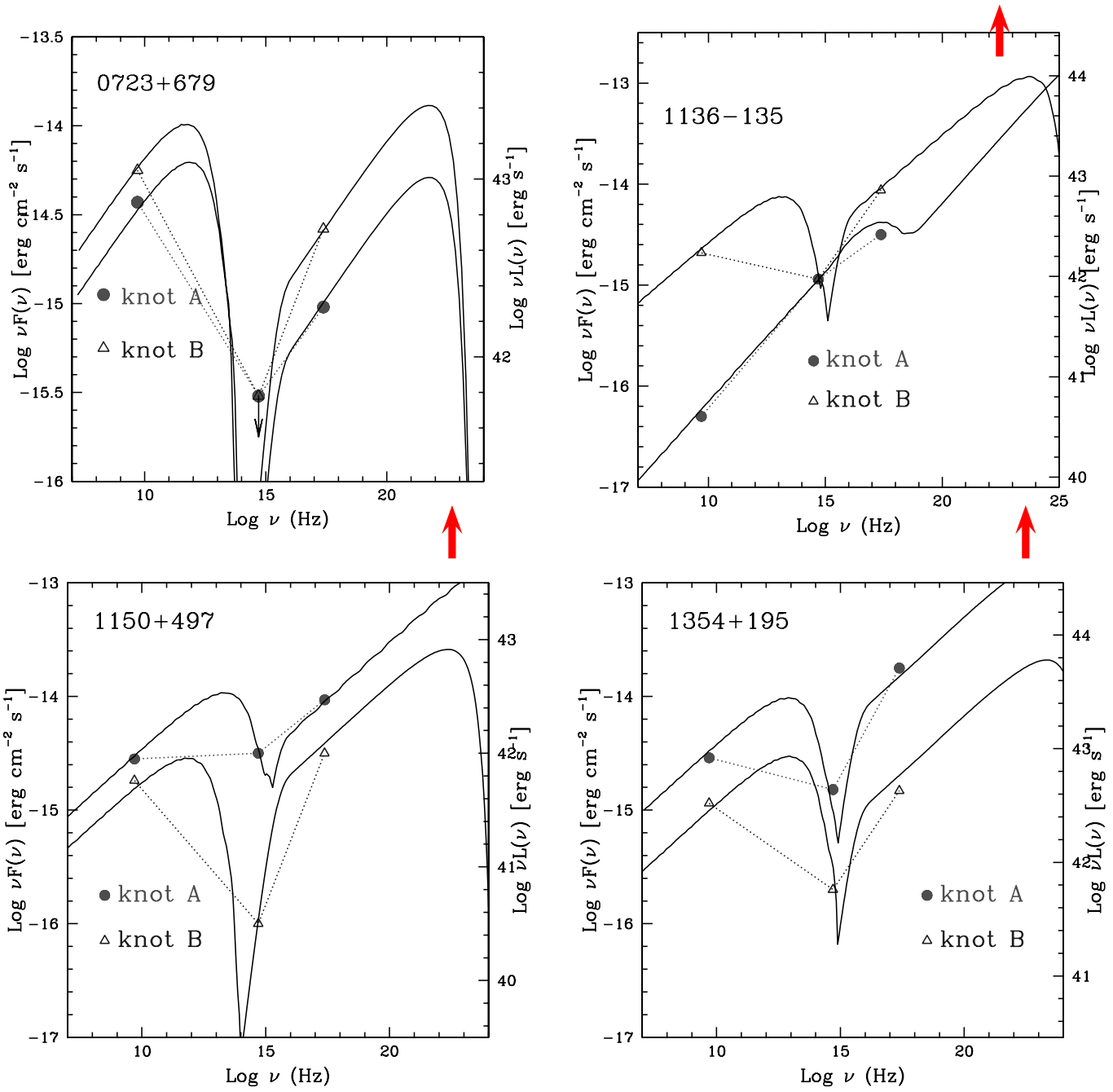


Sambruna et al., 2002ApJ...571..206S

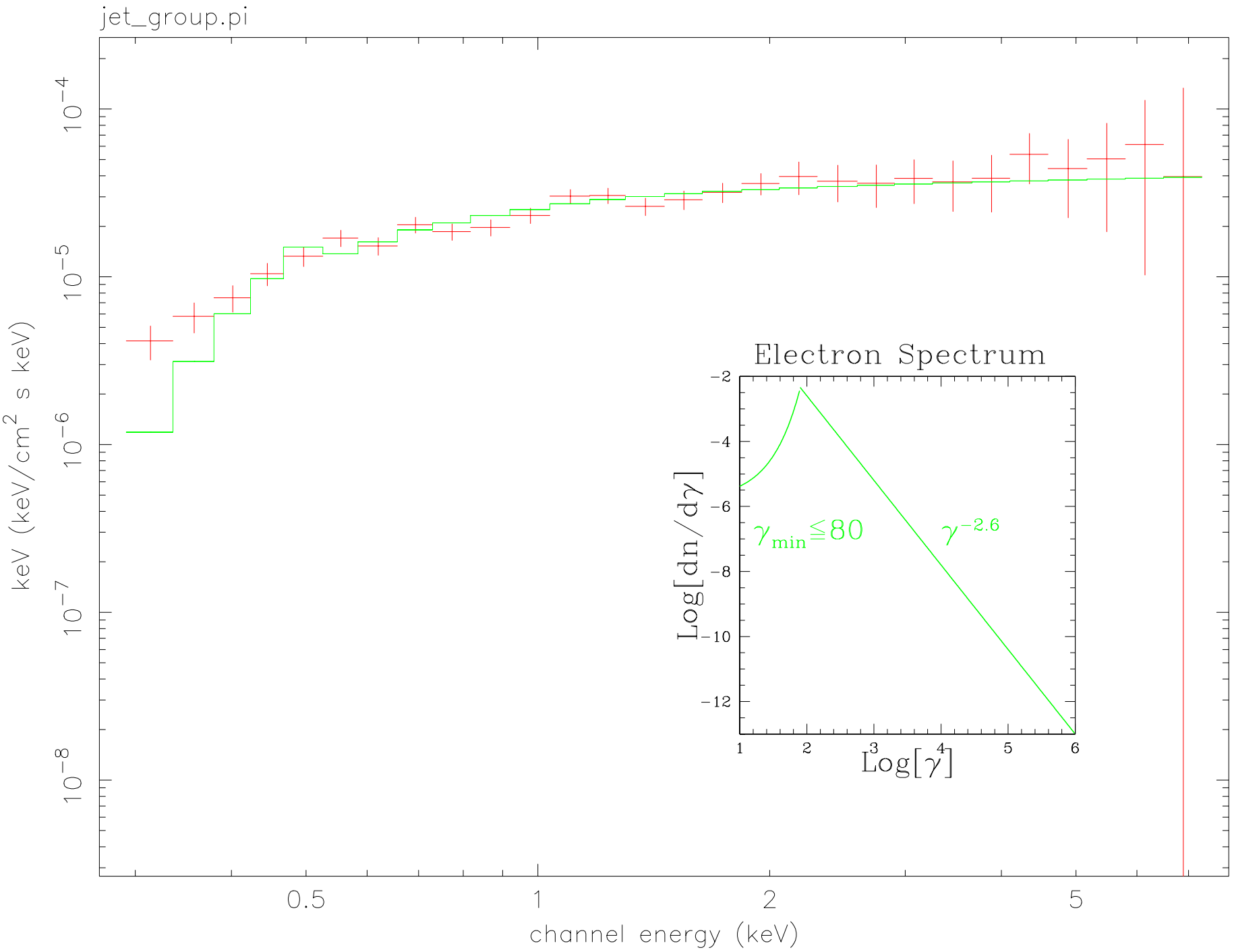
Inverse Compton X-rays from the CMB:

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

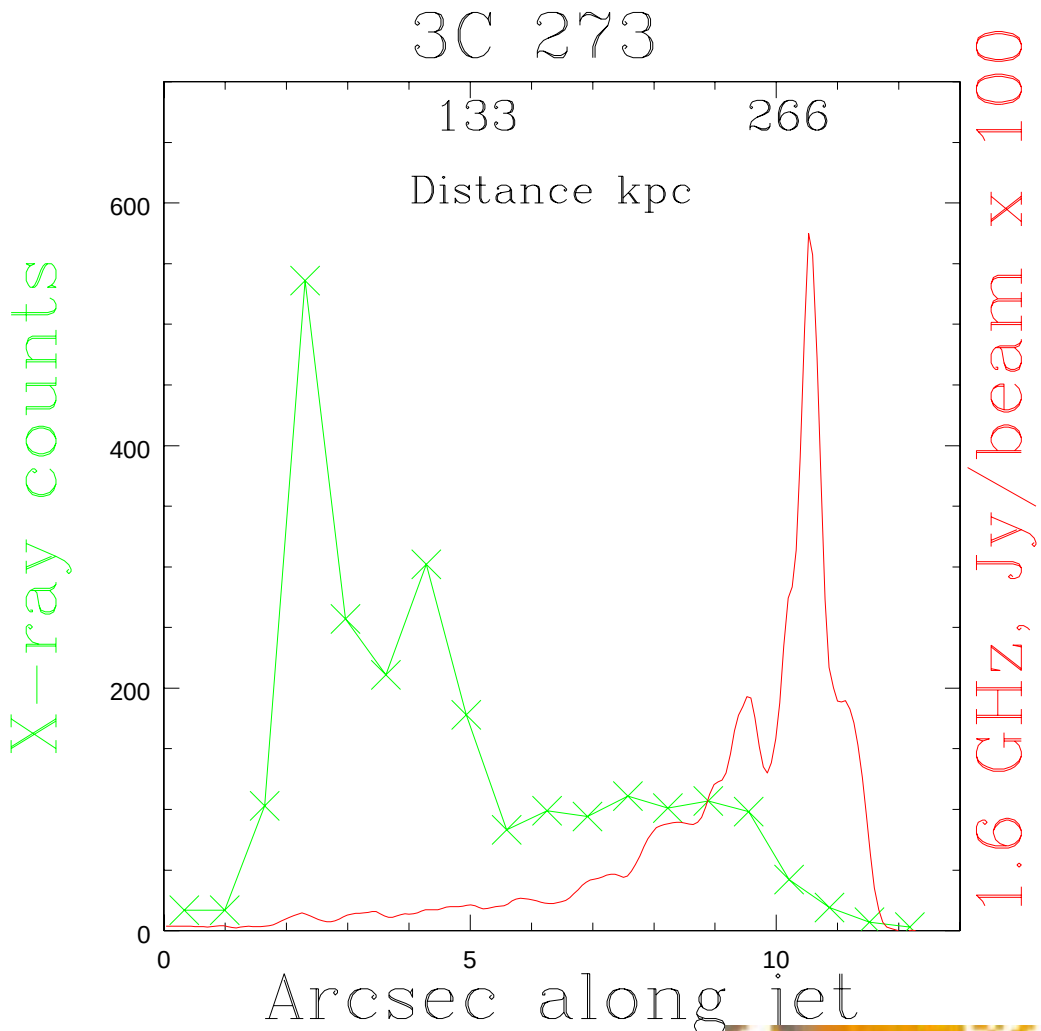
$$\gamma_r \approx 10^{4-5}$$

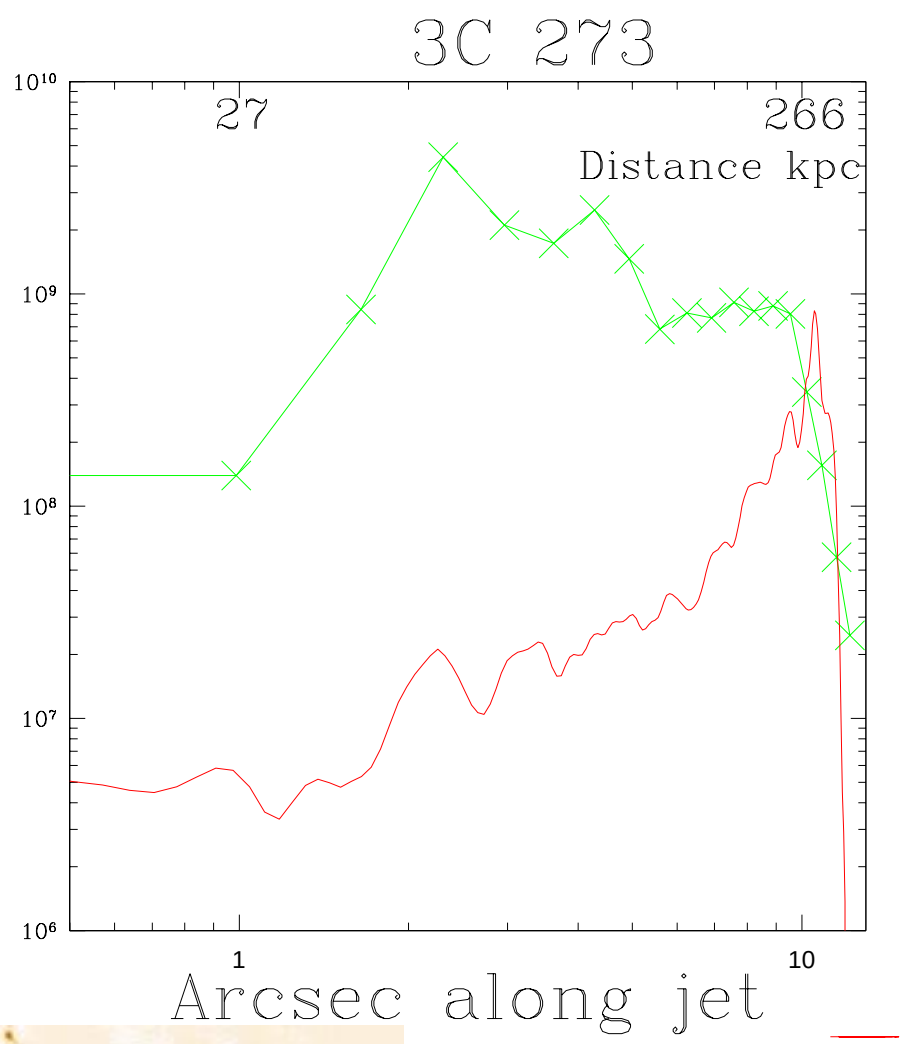
Some jets may be detectable by GLAST, at 10^{-13} to 10^{-12} ergs cm^{-2} s^{-1}

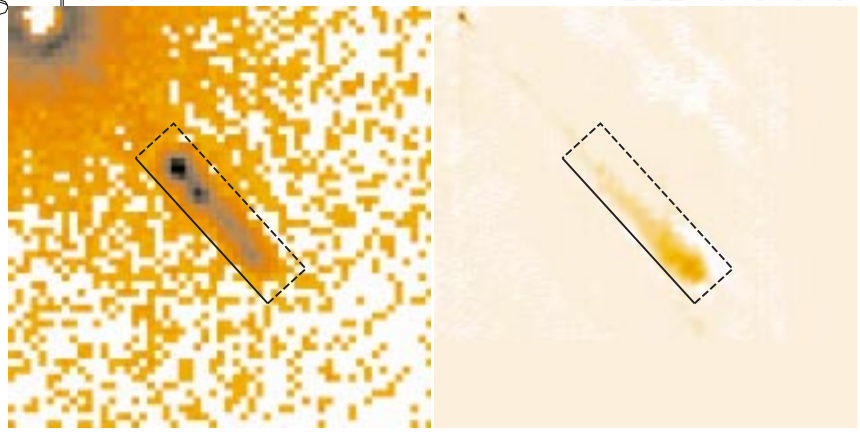
PKS 0637-752 Jet Spectrum



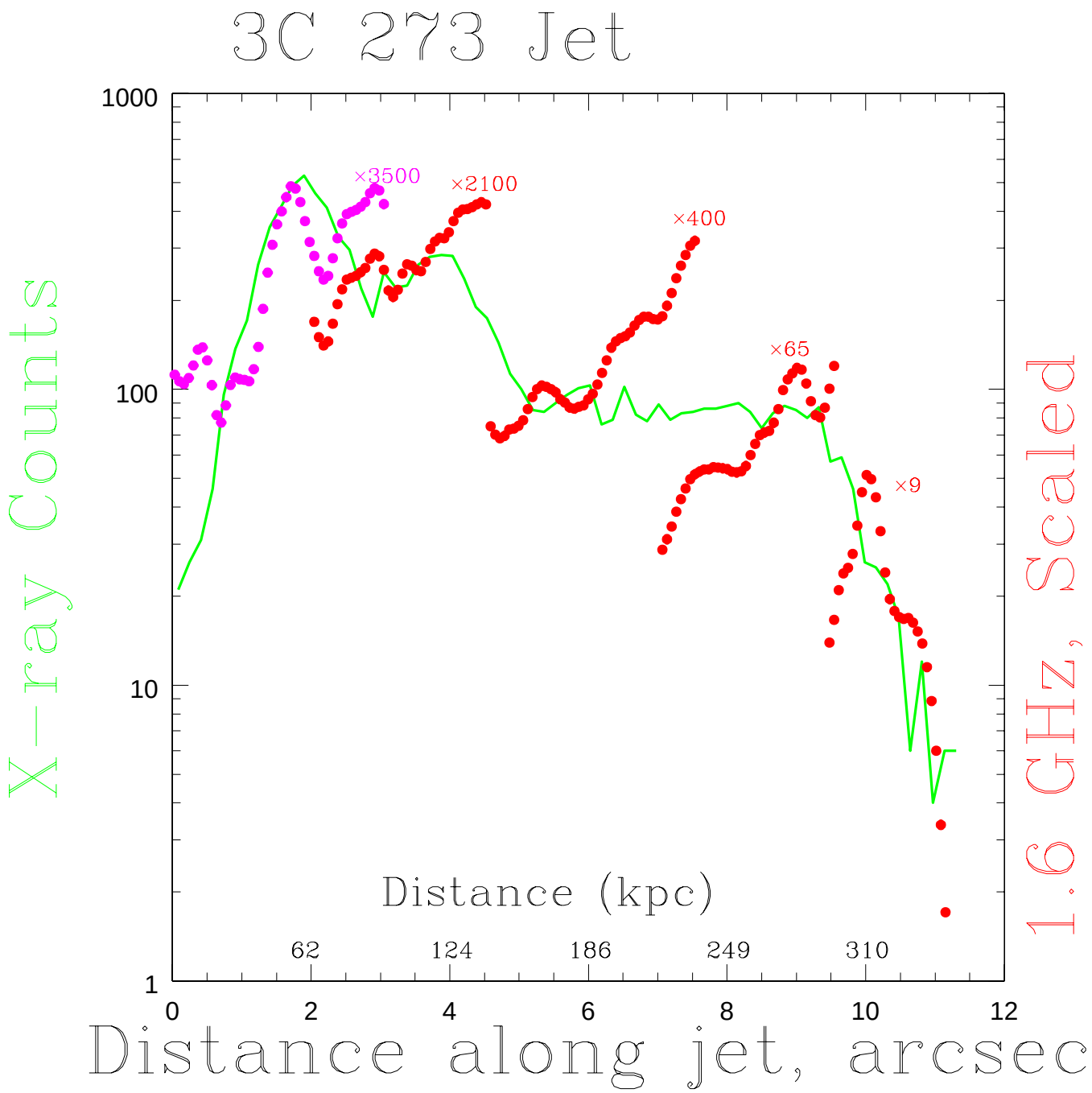
mmueller 4−D


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}
1
10
νf_ν, Jy−Hz
Arcsec along jet



Confront IC/CMB with Morphology



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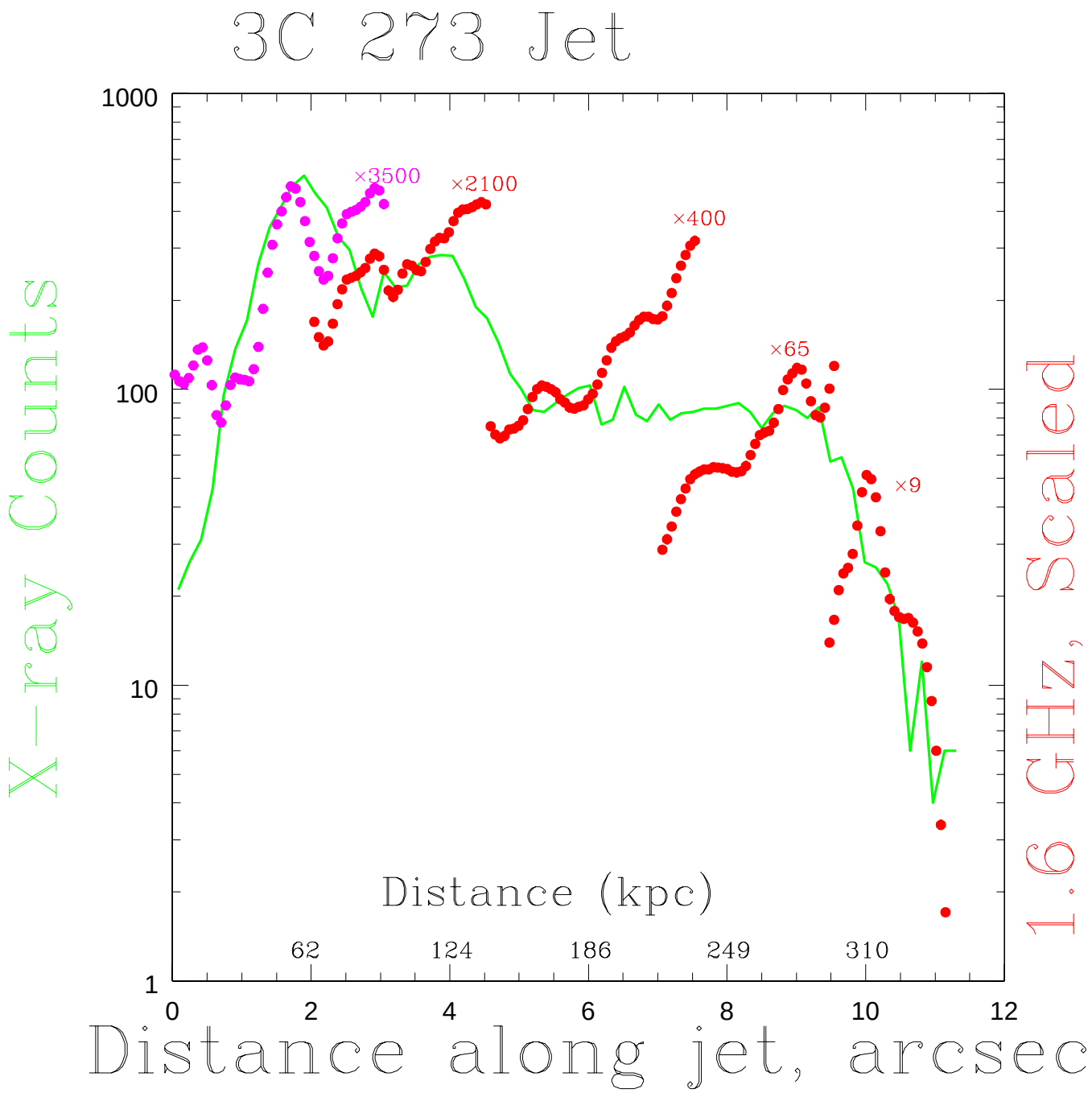
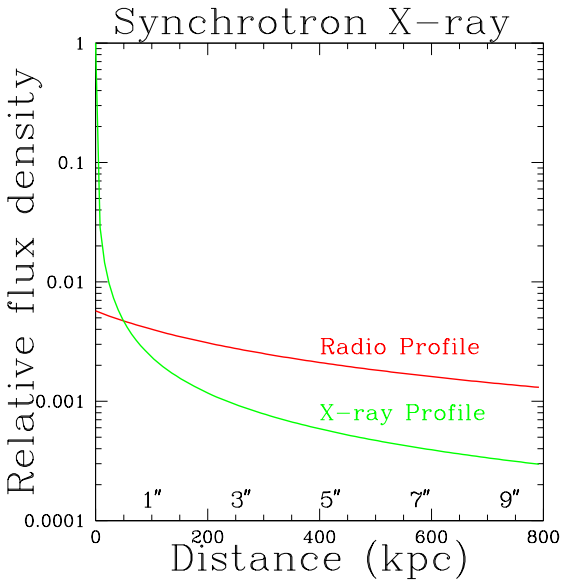
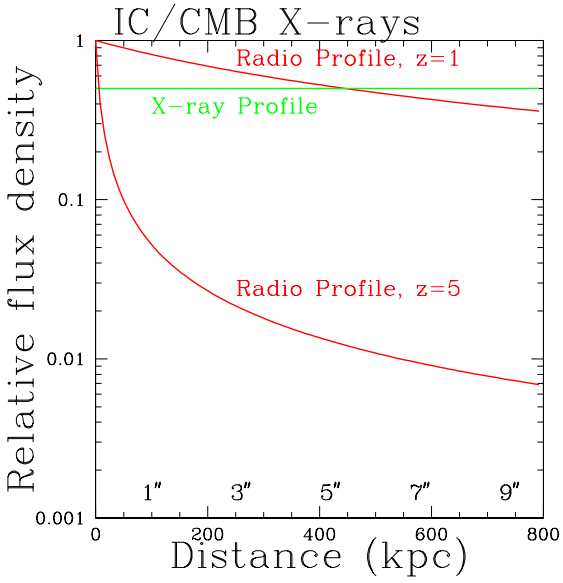
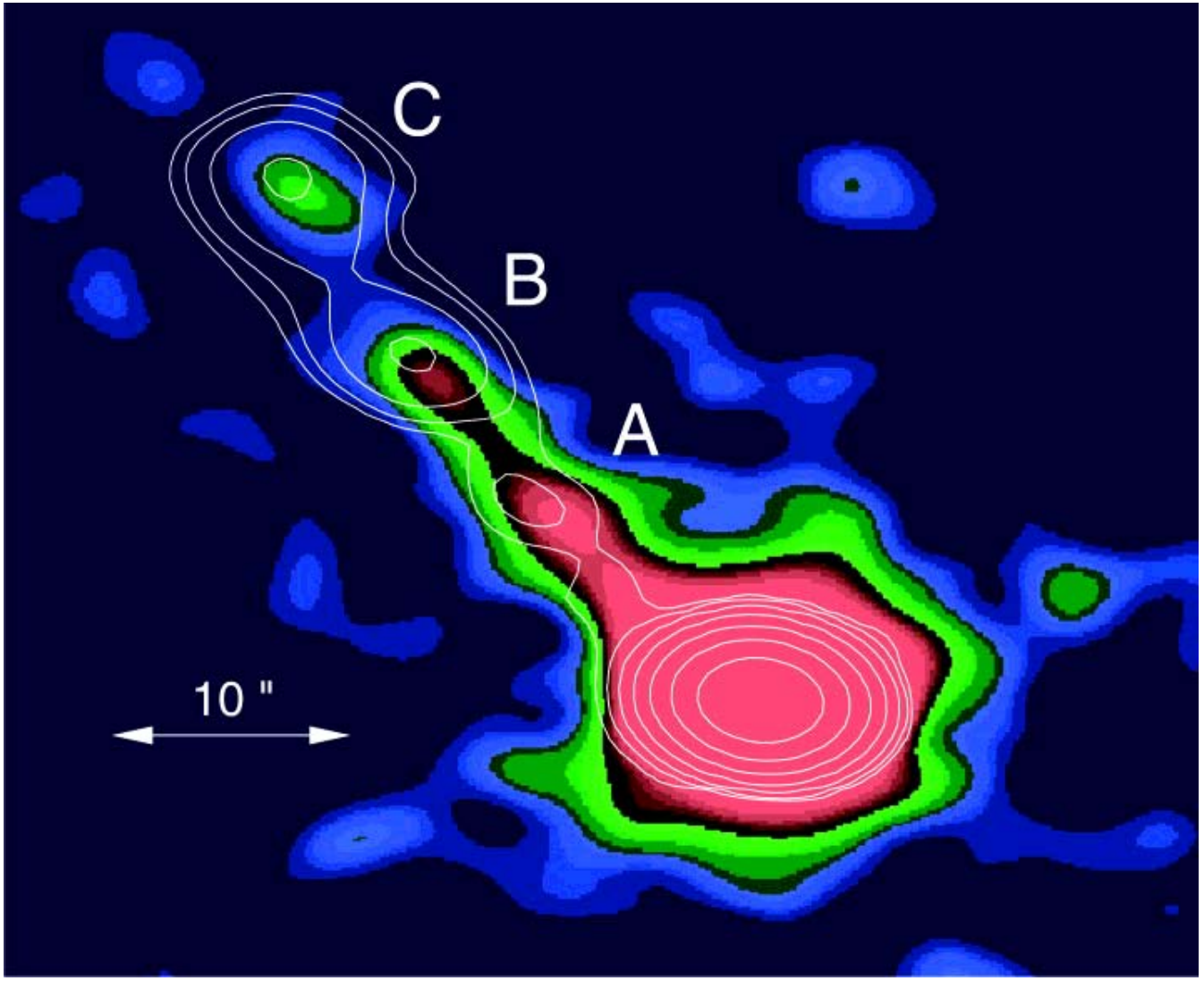


Naive Models





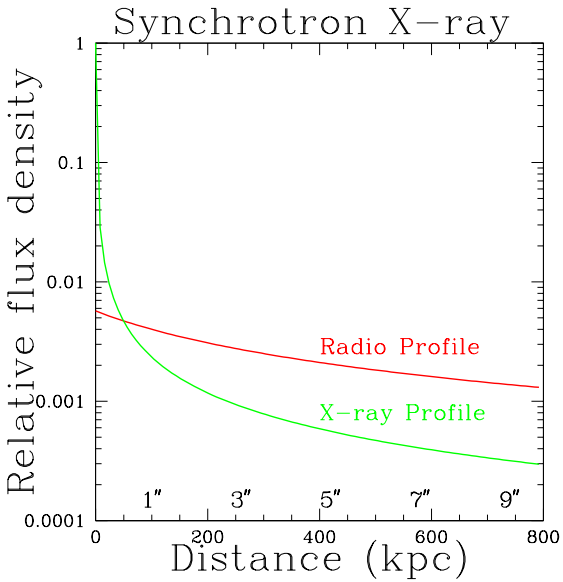
Confront IC/CMB with Morphology

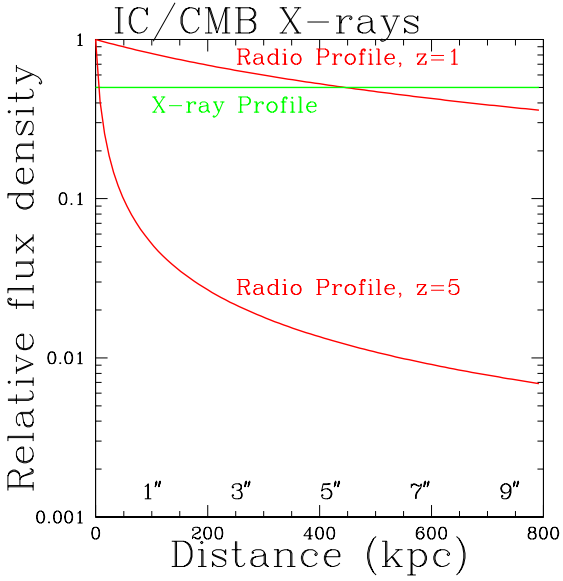


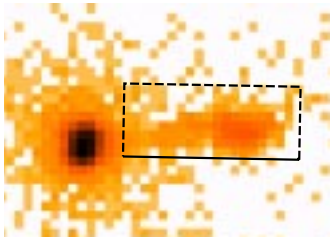
Siemiginowska et al. 2002 ApJ...570..543S

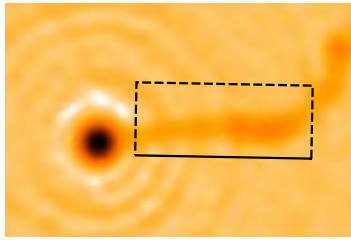
PKS 1127-145 at z=1.187

Naive Models



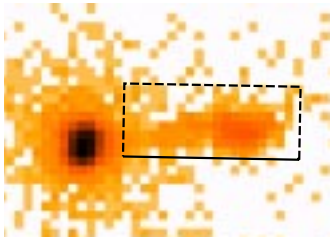


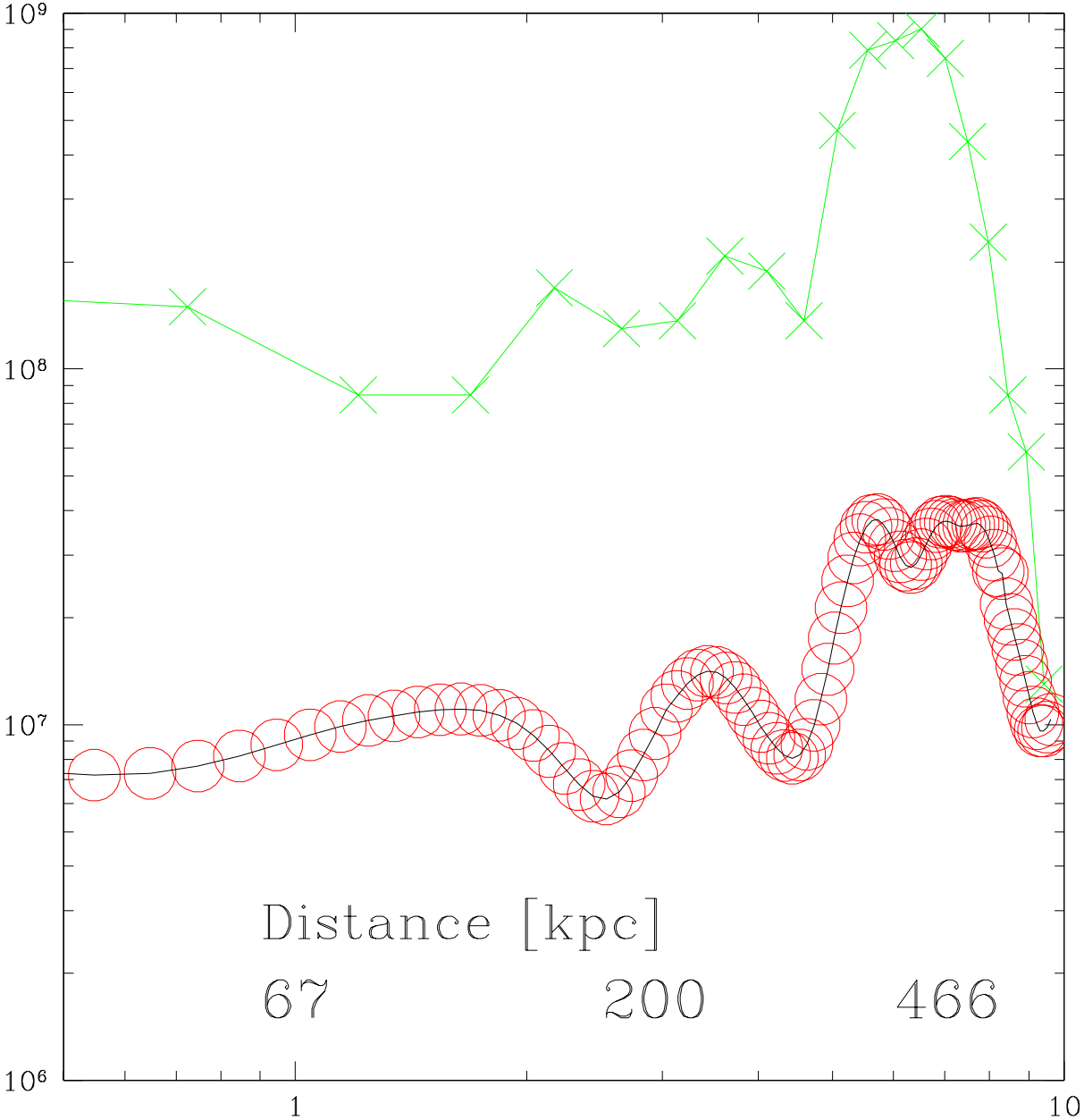


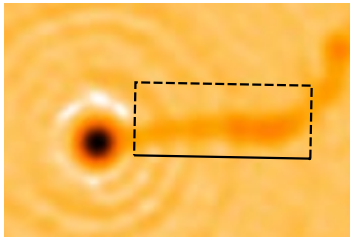


PKS 0637−752
133
266
399
532
Distance (kpc)
100
10
1
0
2
4
6
8
10
Arcsec along jet
X−ray counts
8GHz, Jy/beam x 250

PKS 0637−752

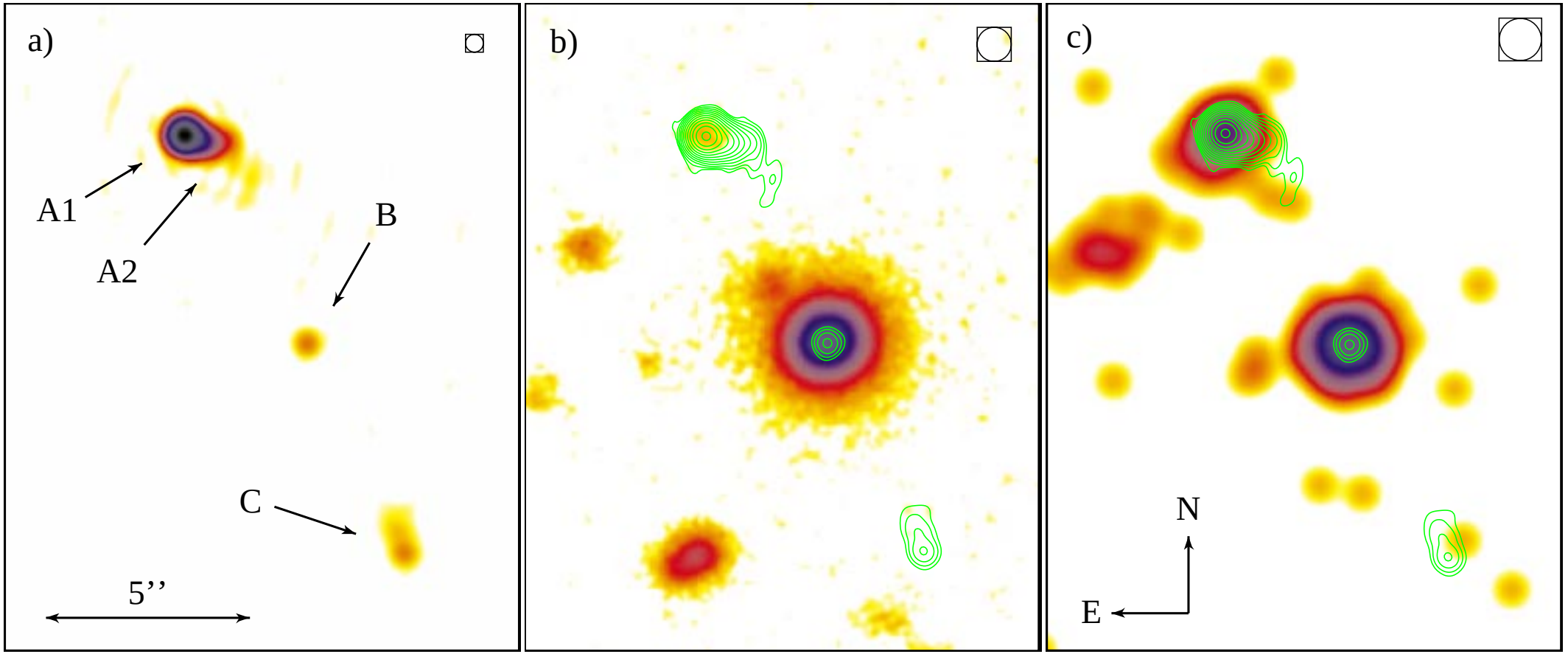



10^9
10^8
10^7
10^6
νf_ν [10^8 Jy−Hz]
Distance [kpc]
67
200
466
1
10
Arcsec along jet



PKS 1421-490 Images

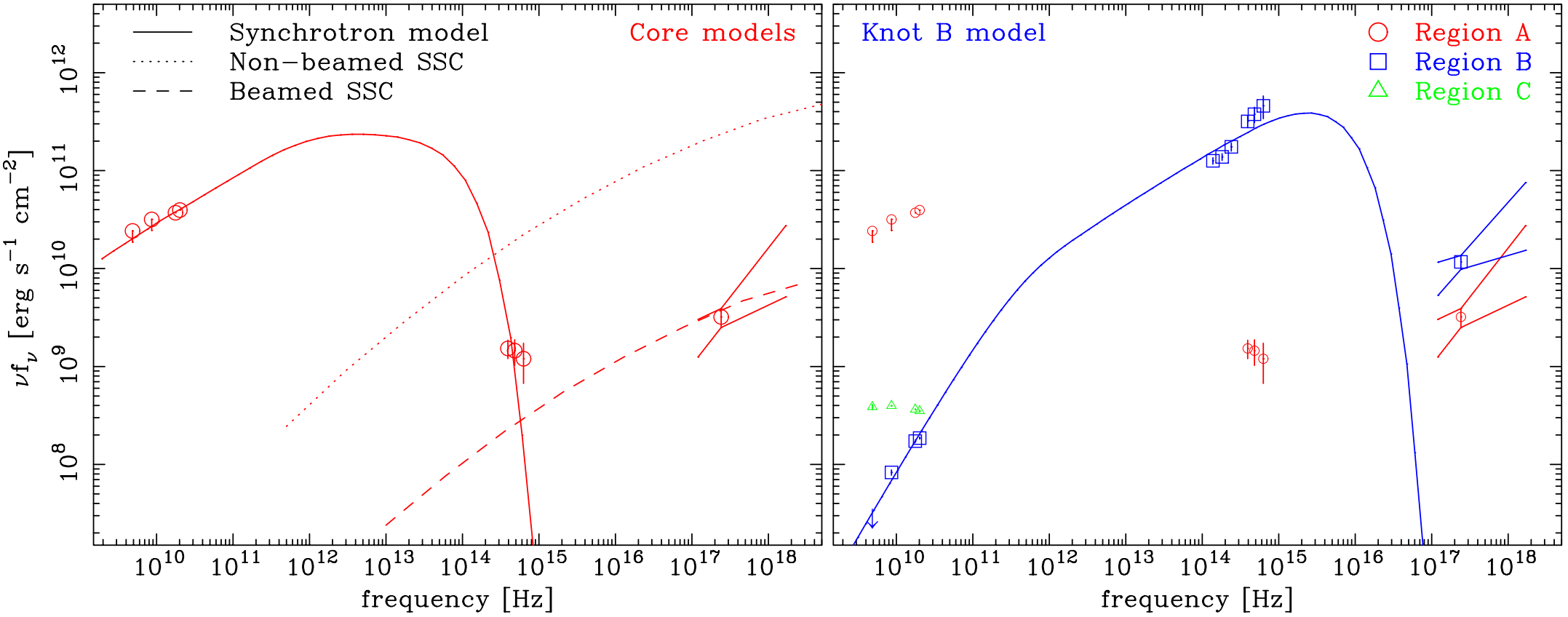
Gelbord et al.



ATCA 20 GHz | **Magellan i′** | ***Chandra* 0.5 – 7 keV**

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

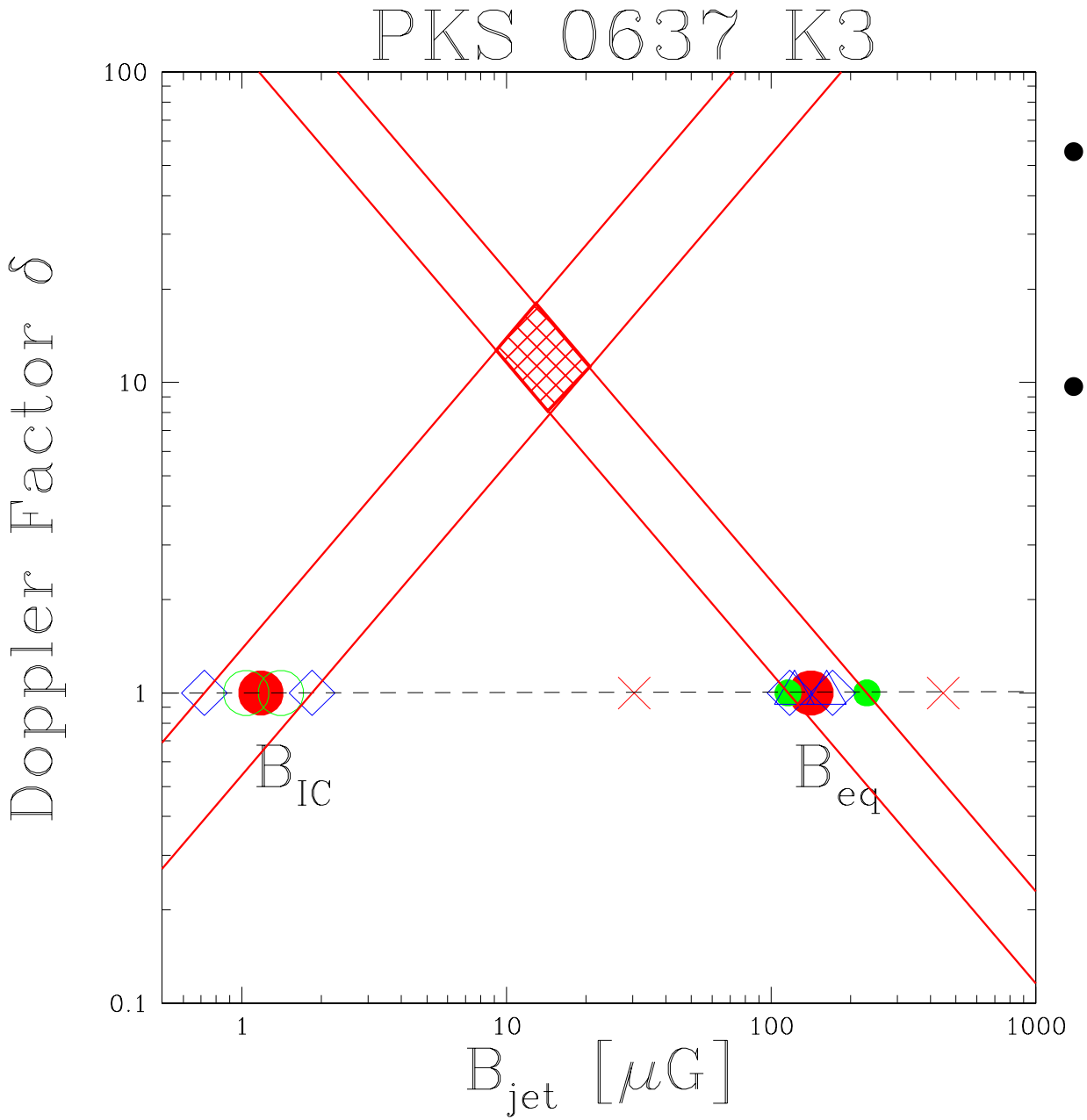
Radio–Optical: Synchrotron

Equipartition

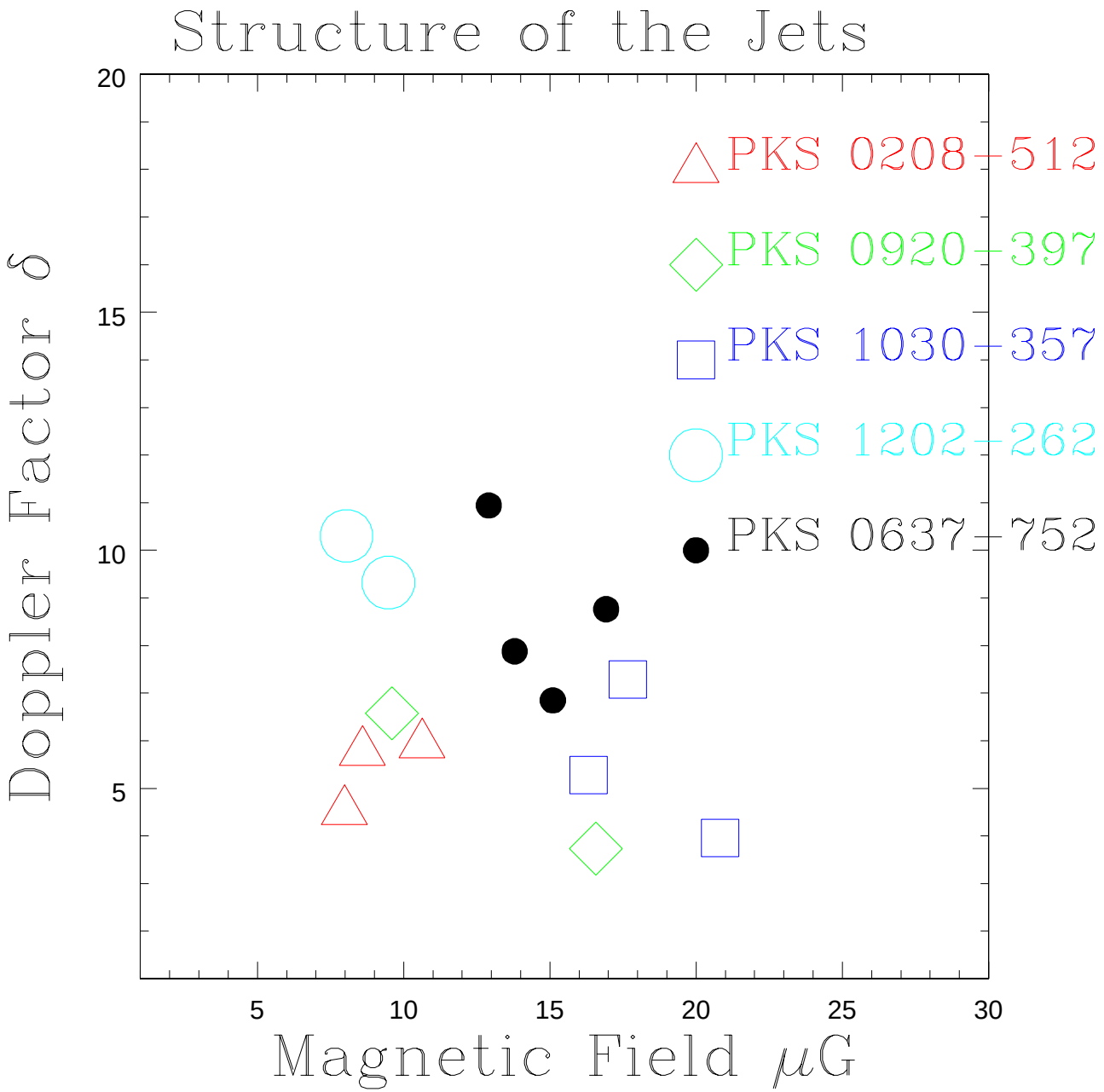
B=85mG

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

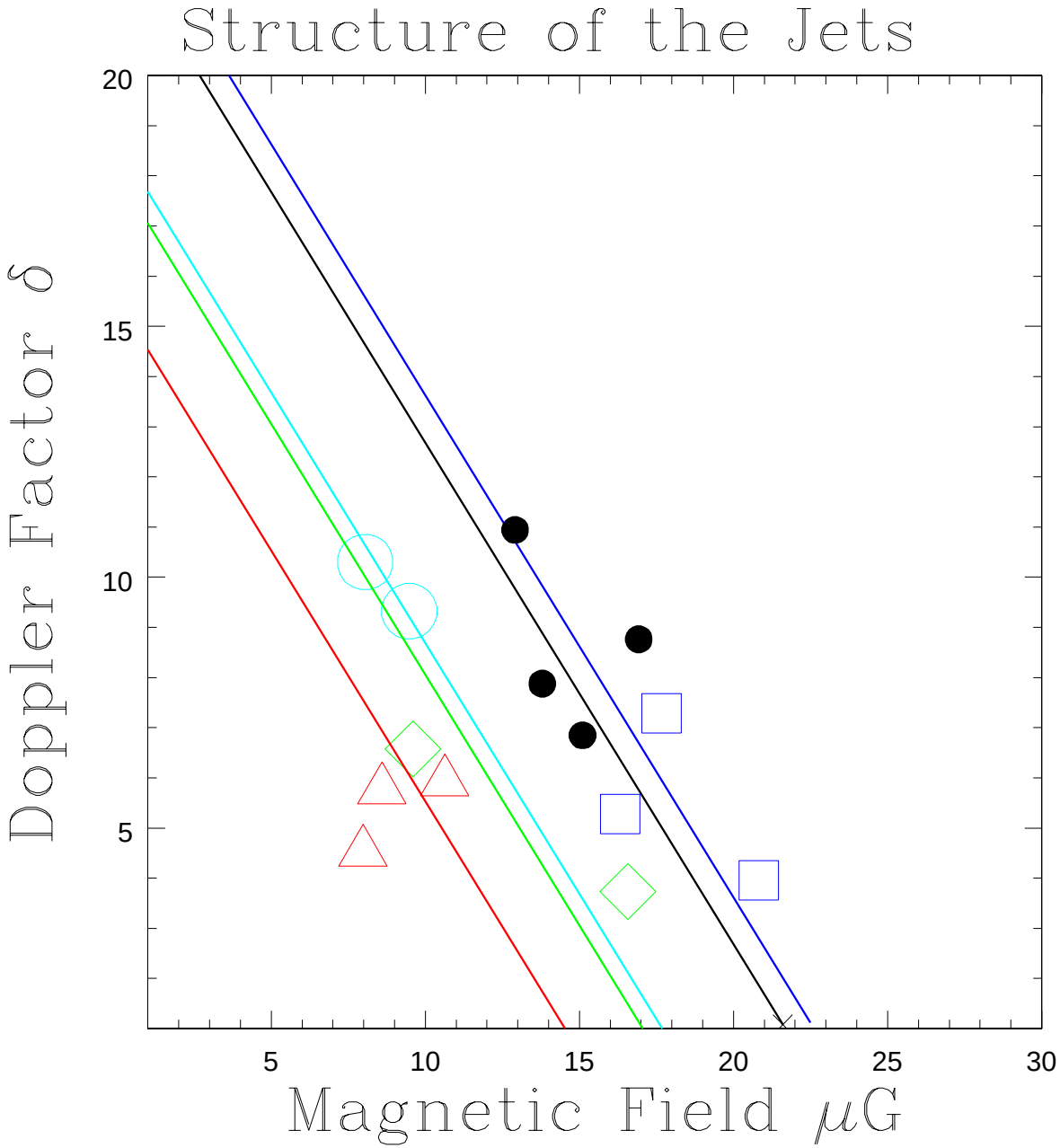
X-ray: Upstream Comptonization?



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

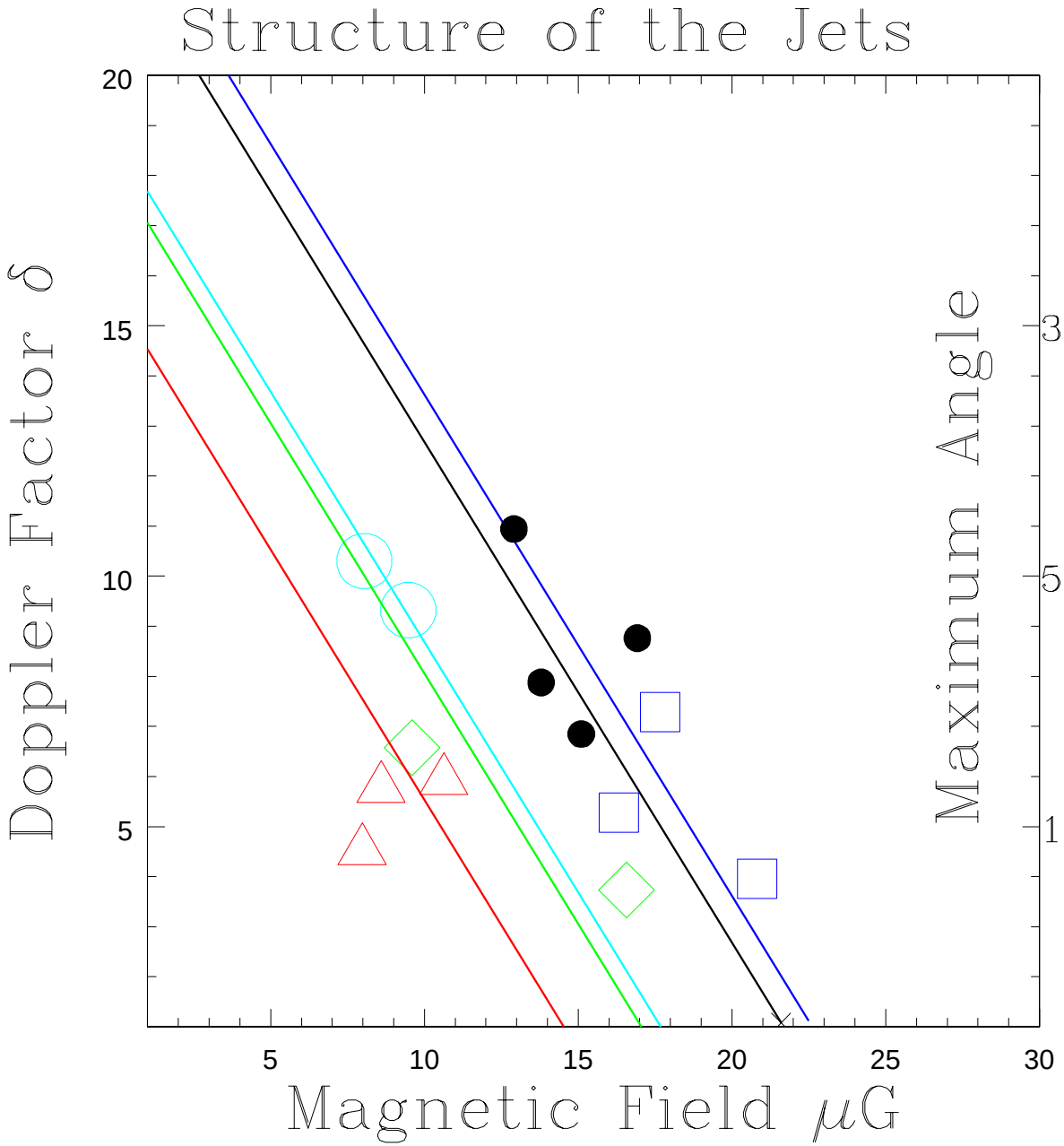

Structure of the Jets
Doppler Factor δ
Magnetic Field μG
20
15
10
5
5
10
15
20
25
30
PKS 0208−512
PKS 0920−397
PKS 1030−357
PKS 1202−262
PKS 0637−752

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 ⇒ $(B\,\Gamma)^2$ = constant

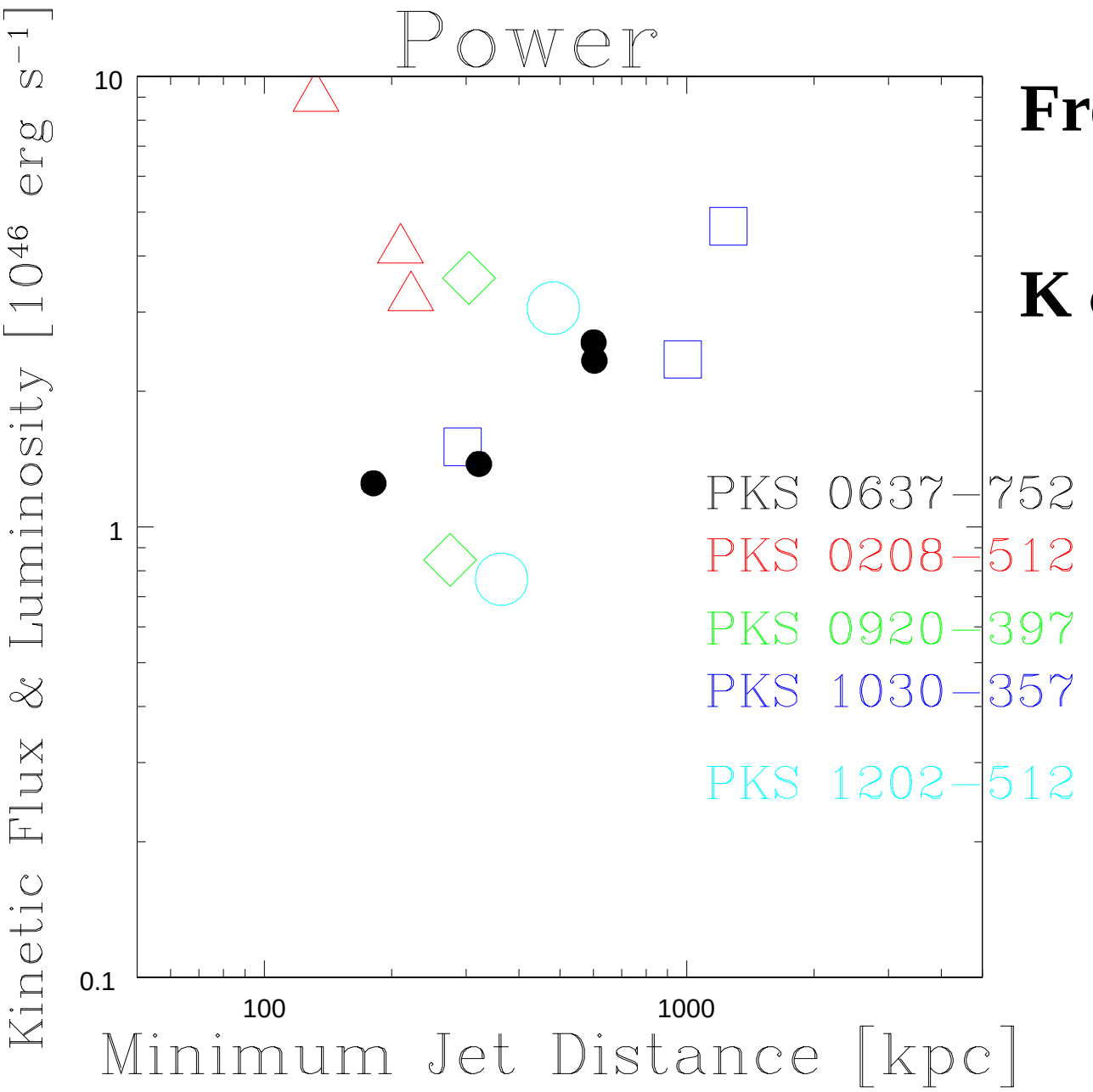
Kinetic Flux



- $K = \Gamma^2 \pi\, r^2 \beta\, c\, U$
- 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 ⇒ $(B\,\Gamma)^2 = \text{constant}$
- We take $\Gamma \approx \delta$

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

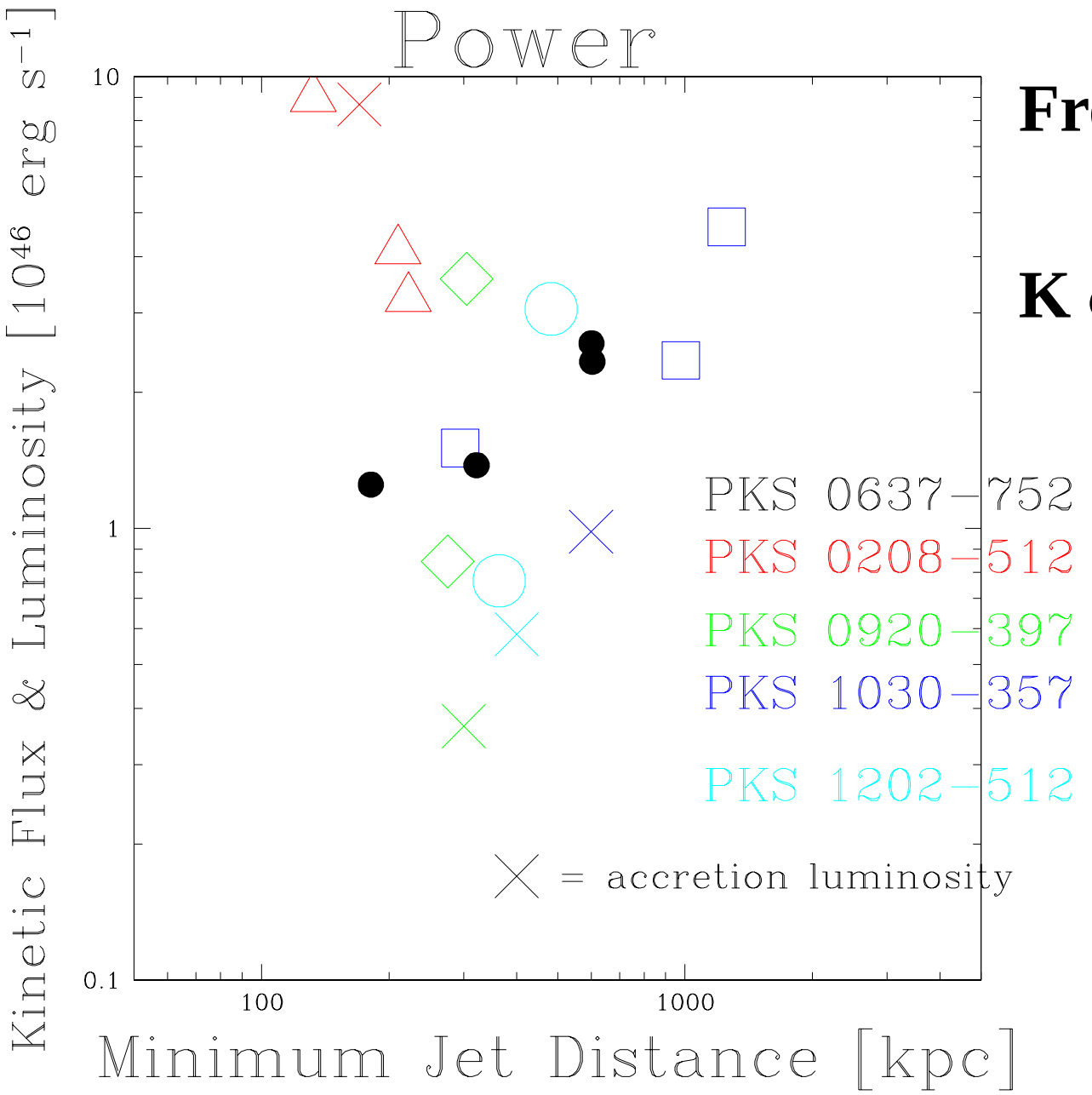
Kinetic Flux



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

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

Kinetic Flux



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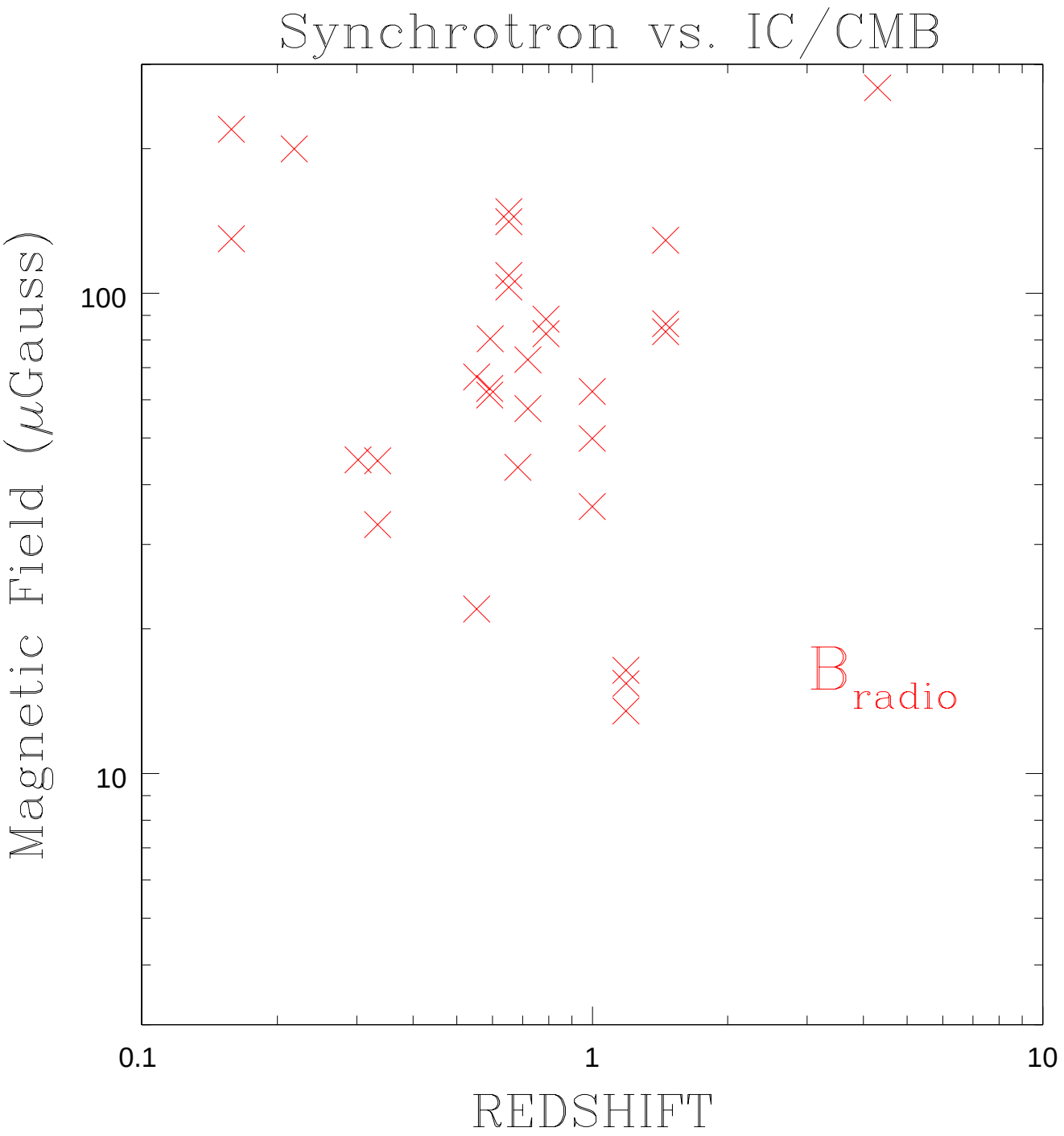
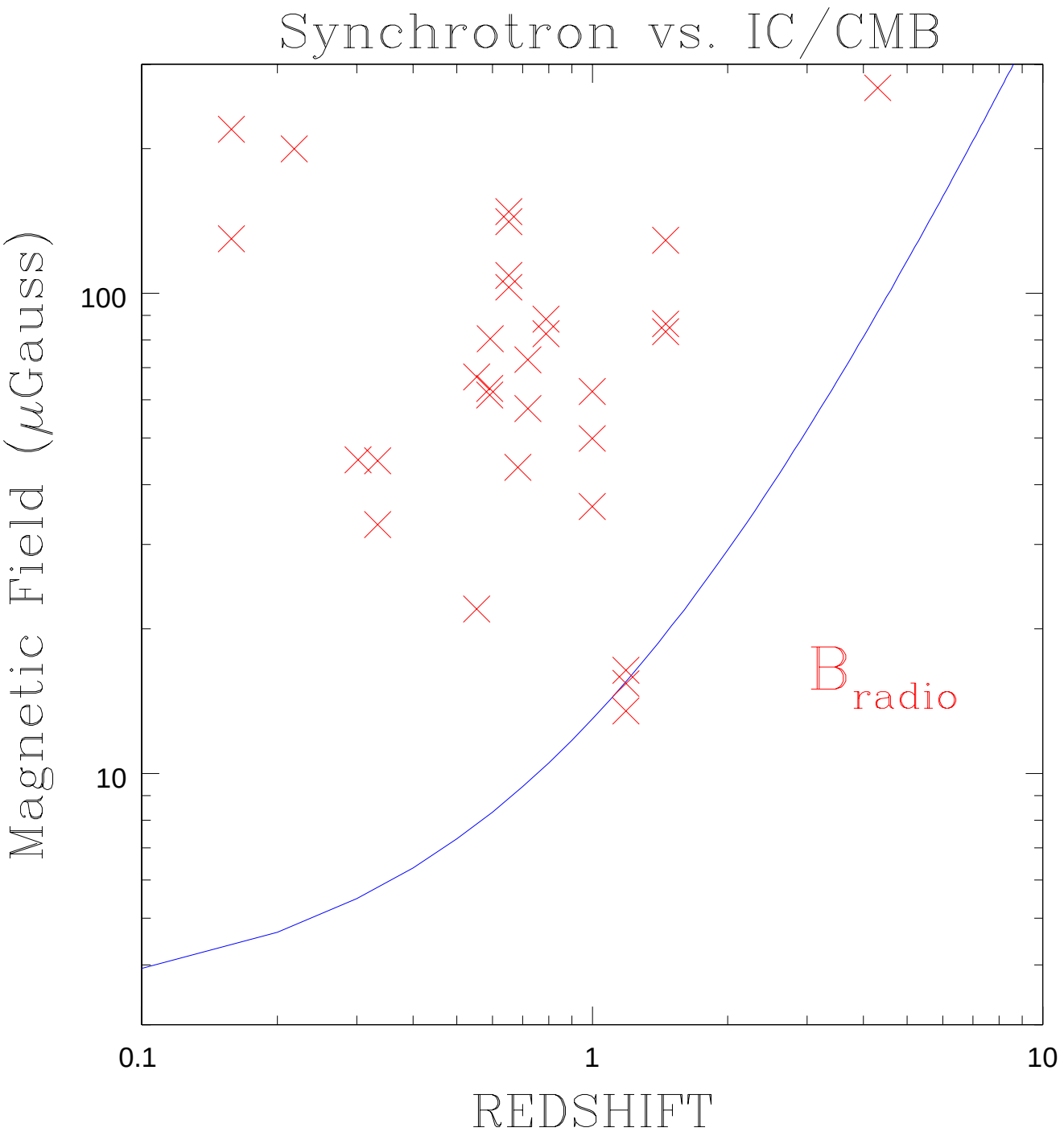
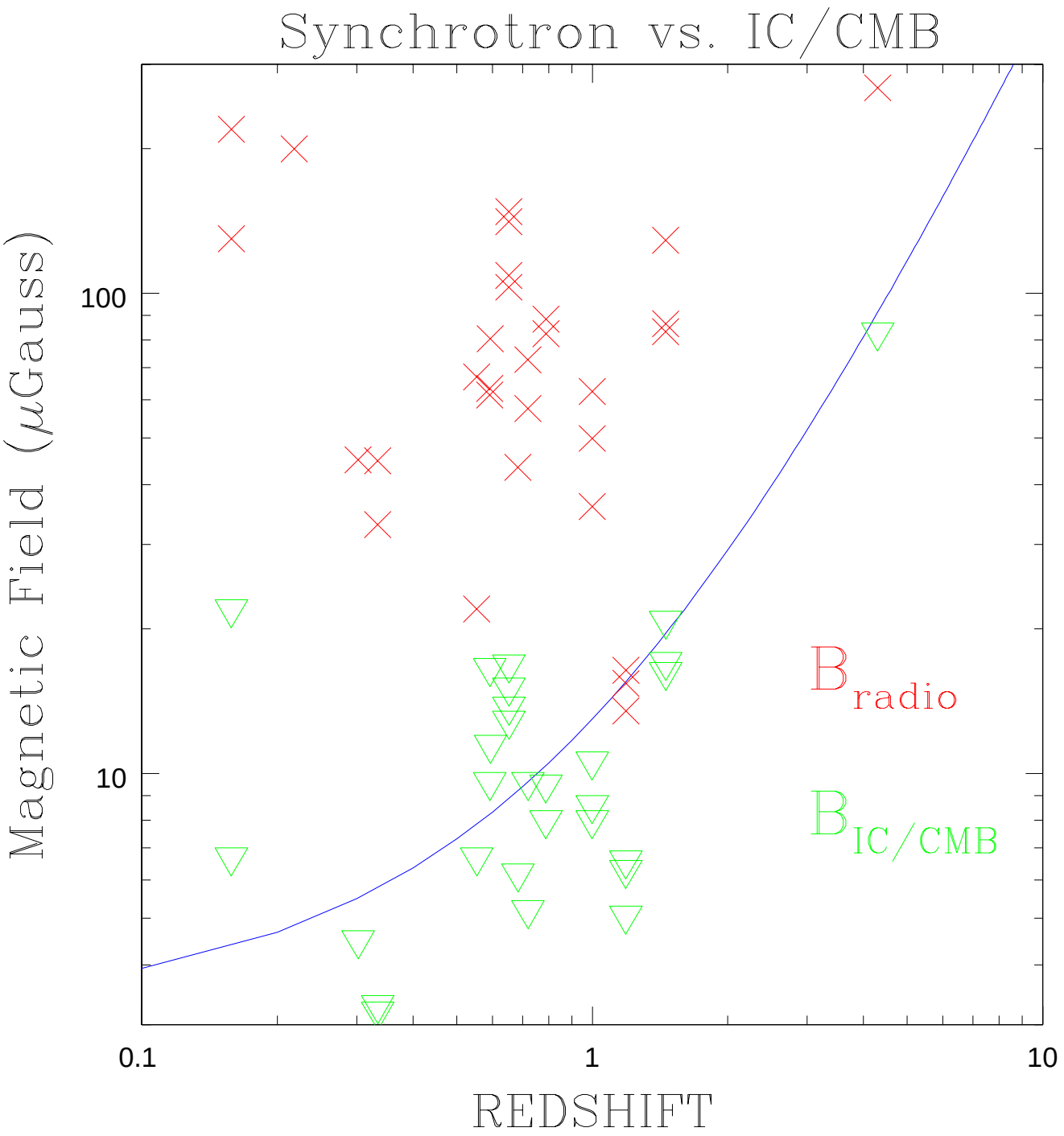
Kinetic flux is a significant, even dominant, portion of the accretion energy budget.

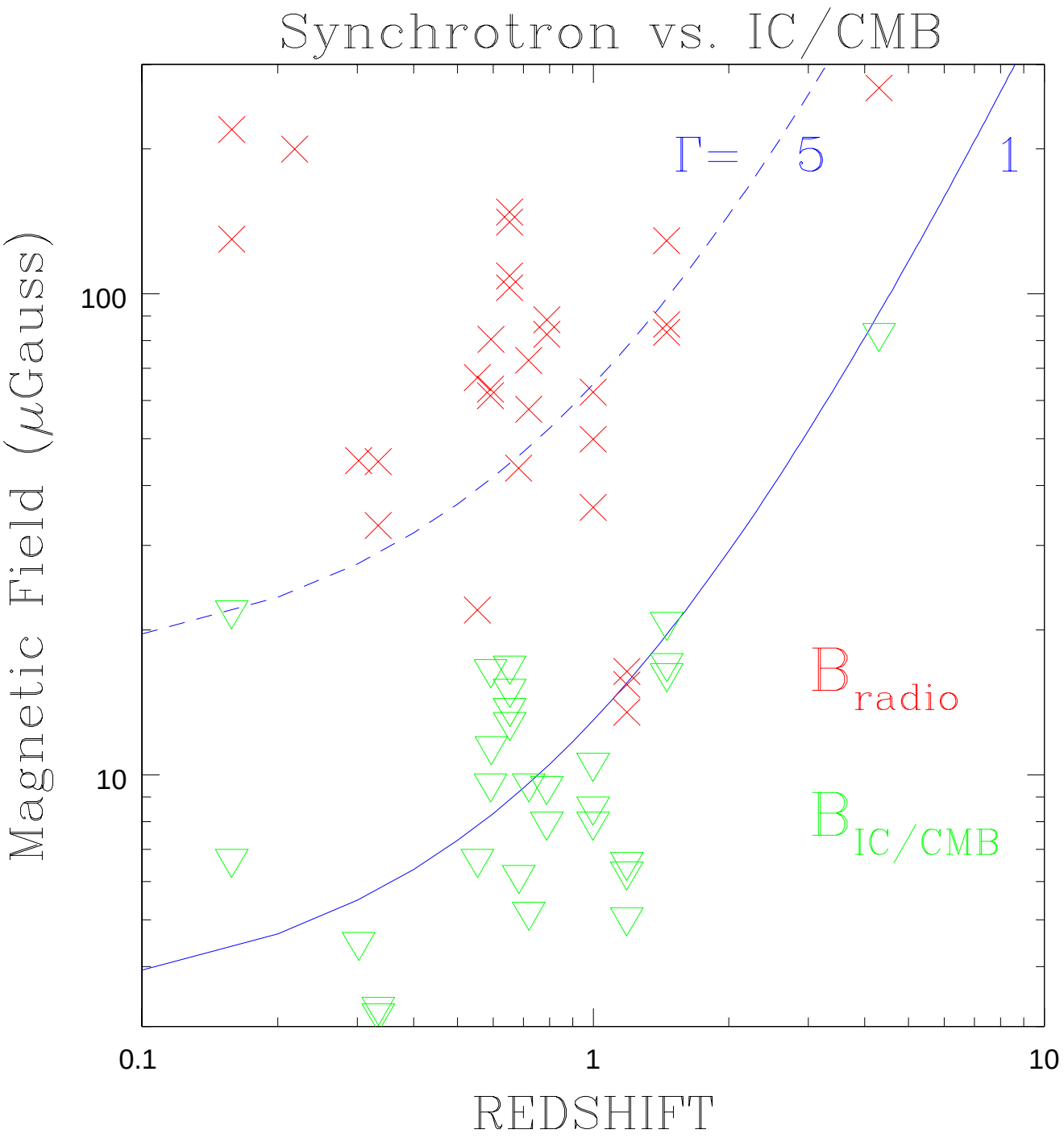
Implications of the AGN Jets

- **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}

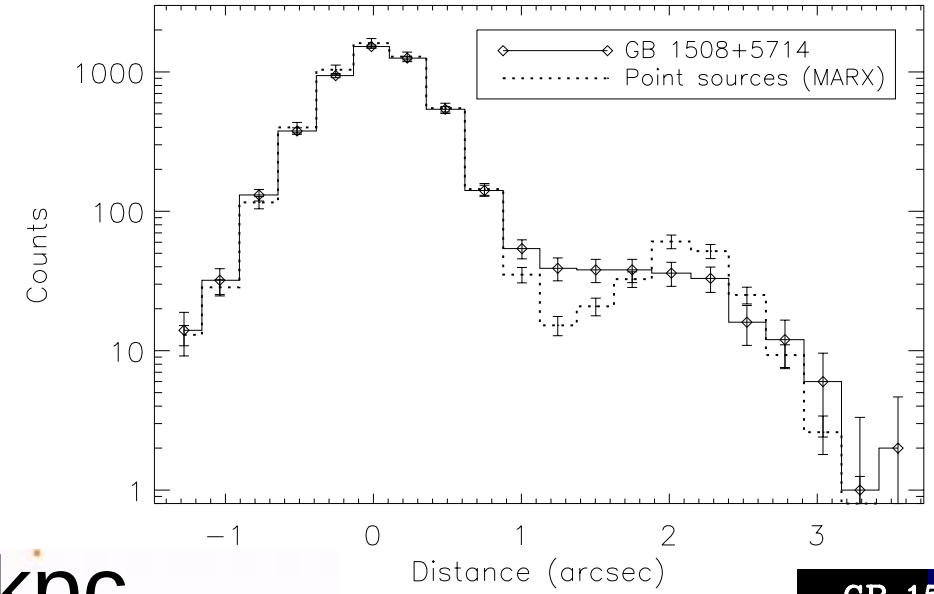

Synchrotron vs. IC/CMB
Magnetic Field (μGauss)
100
10
0.1
1
10
REDSHIFT
B_{radio}
$B_{IC/CMB}$

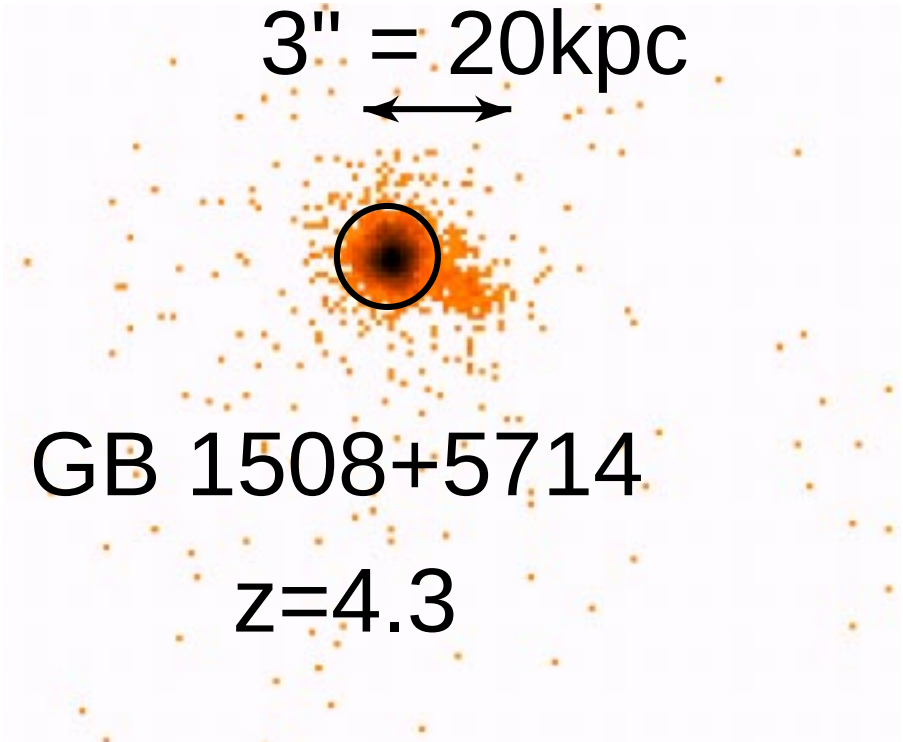

Synchrotron vs. IC/CMB
Γ= 5
1
100
10
0.1
1
10
Magnetic Field (μGauss)
REDSHIFT
B radio
B IC/CMB

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

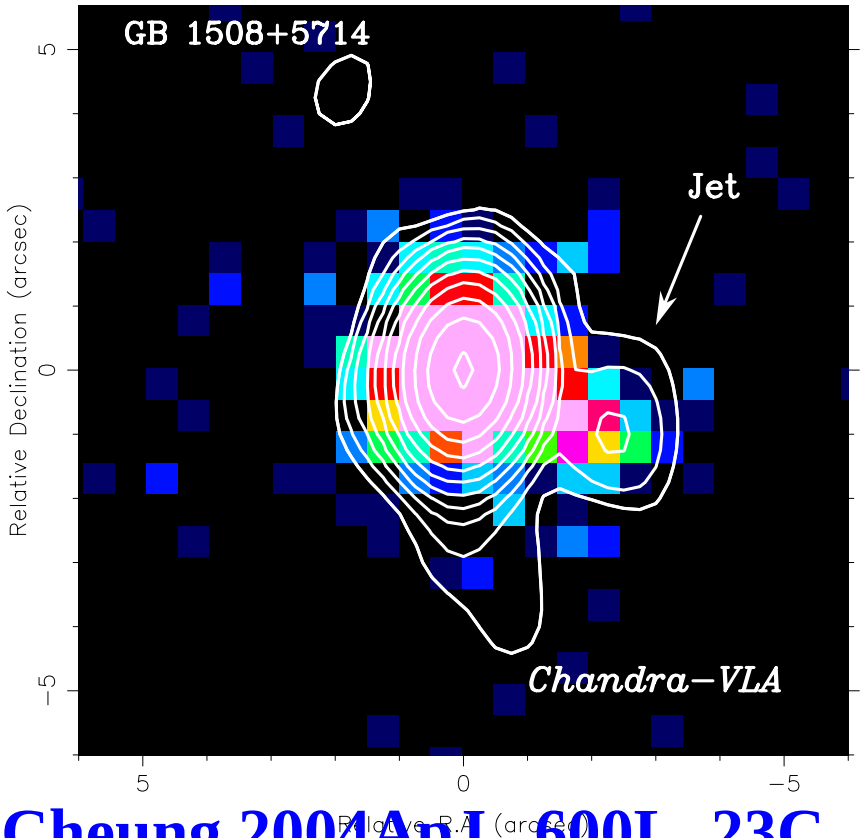
- **Unidentified ROSAT sources?**
- **Bright ROSAT, ASCA, EINSTEIN quasar identifications?**
- **Extreme X-ray/Optical sources (Koekemoer et al. 2004ApJ...600L.123K) in Chandra Deep Surveys?**

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



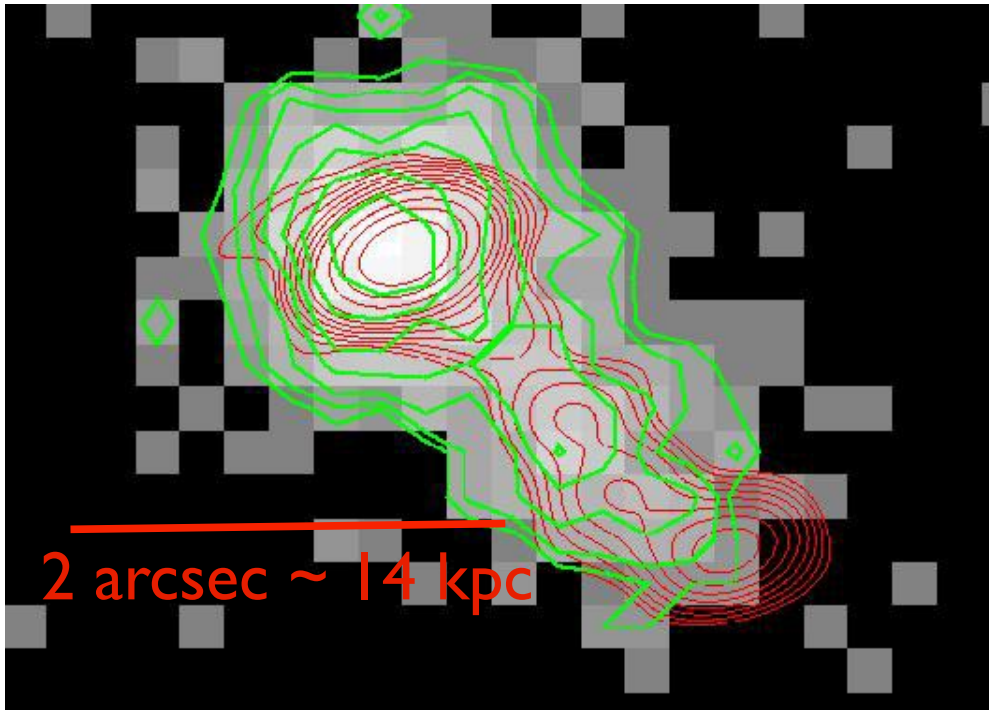


Siemiginowska et al. 2003ApJ...598L..15S

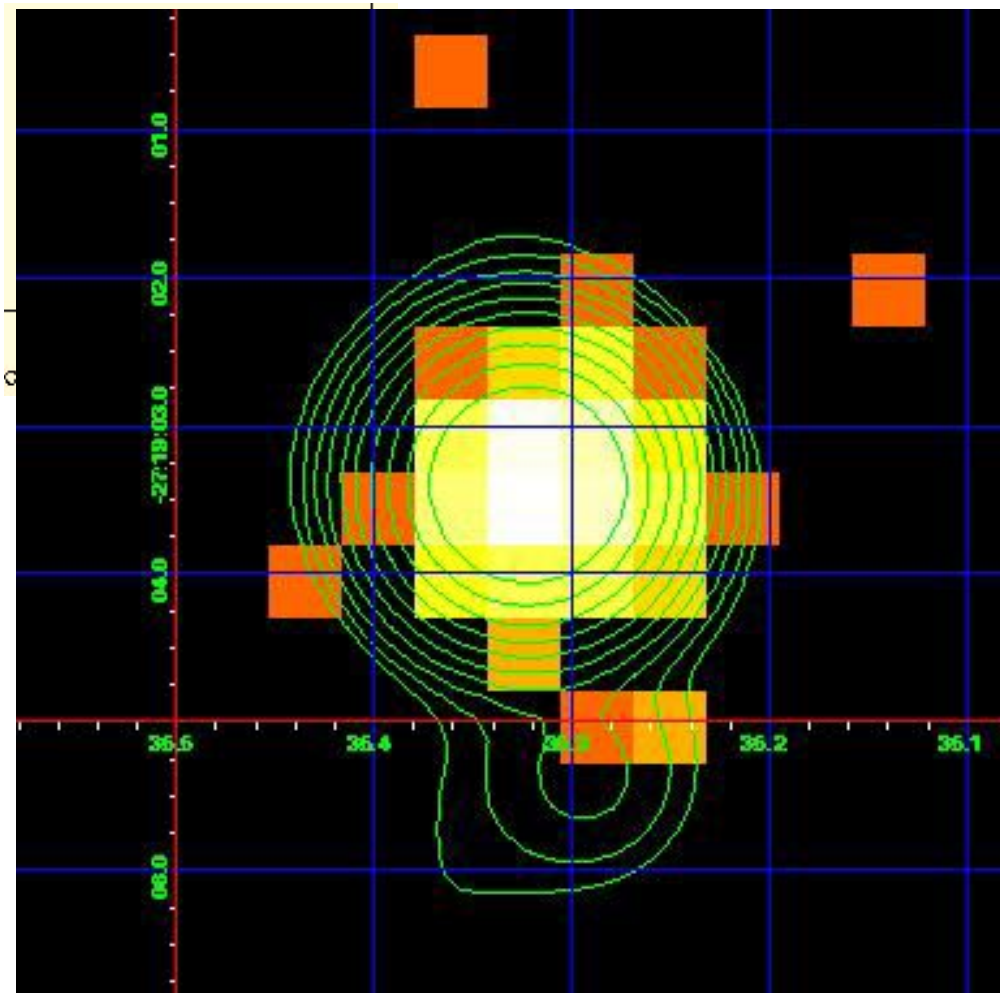


Cheung,2004ApJ...600L..23C

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



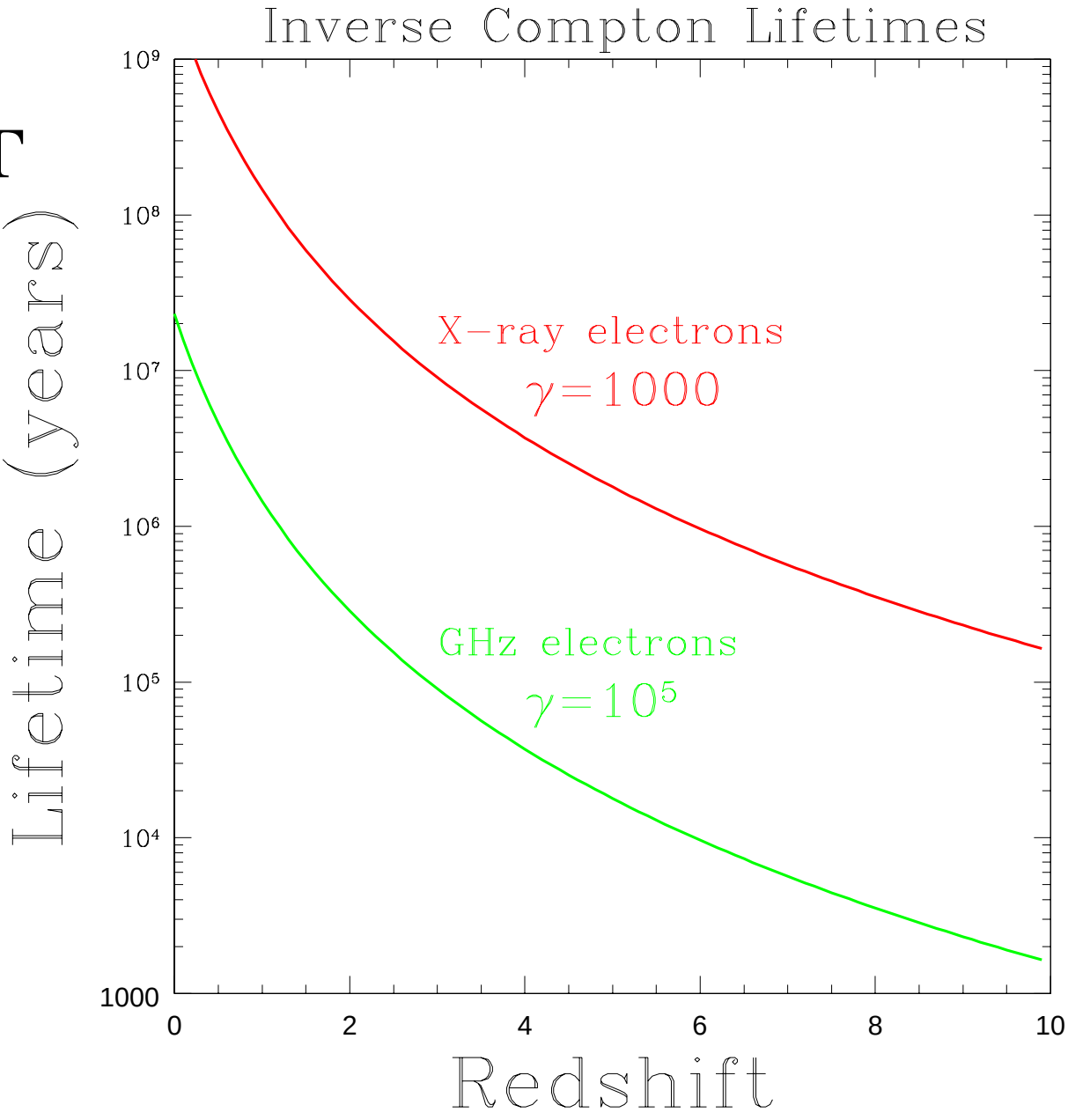
Quasar 1745+624 = 4C +62.29 at z=3.889



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[μG] $\approx$ 10 MHz**



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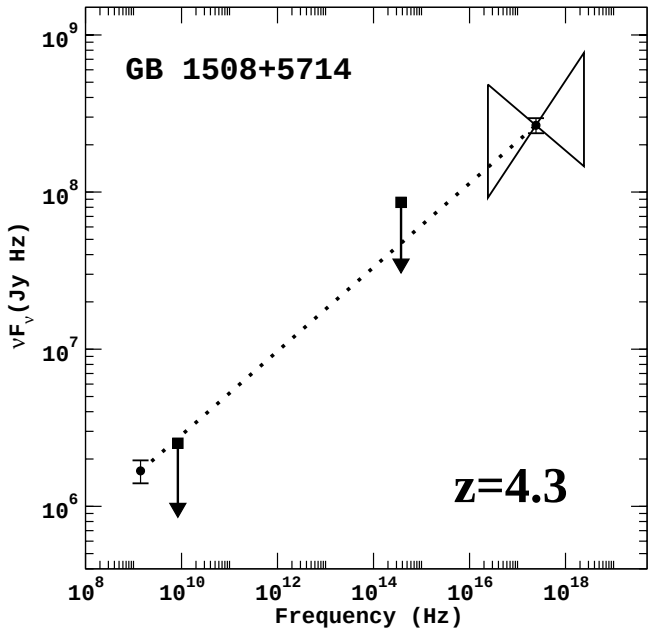
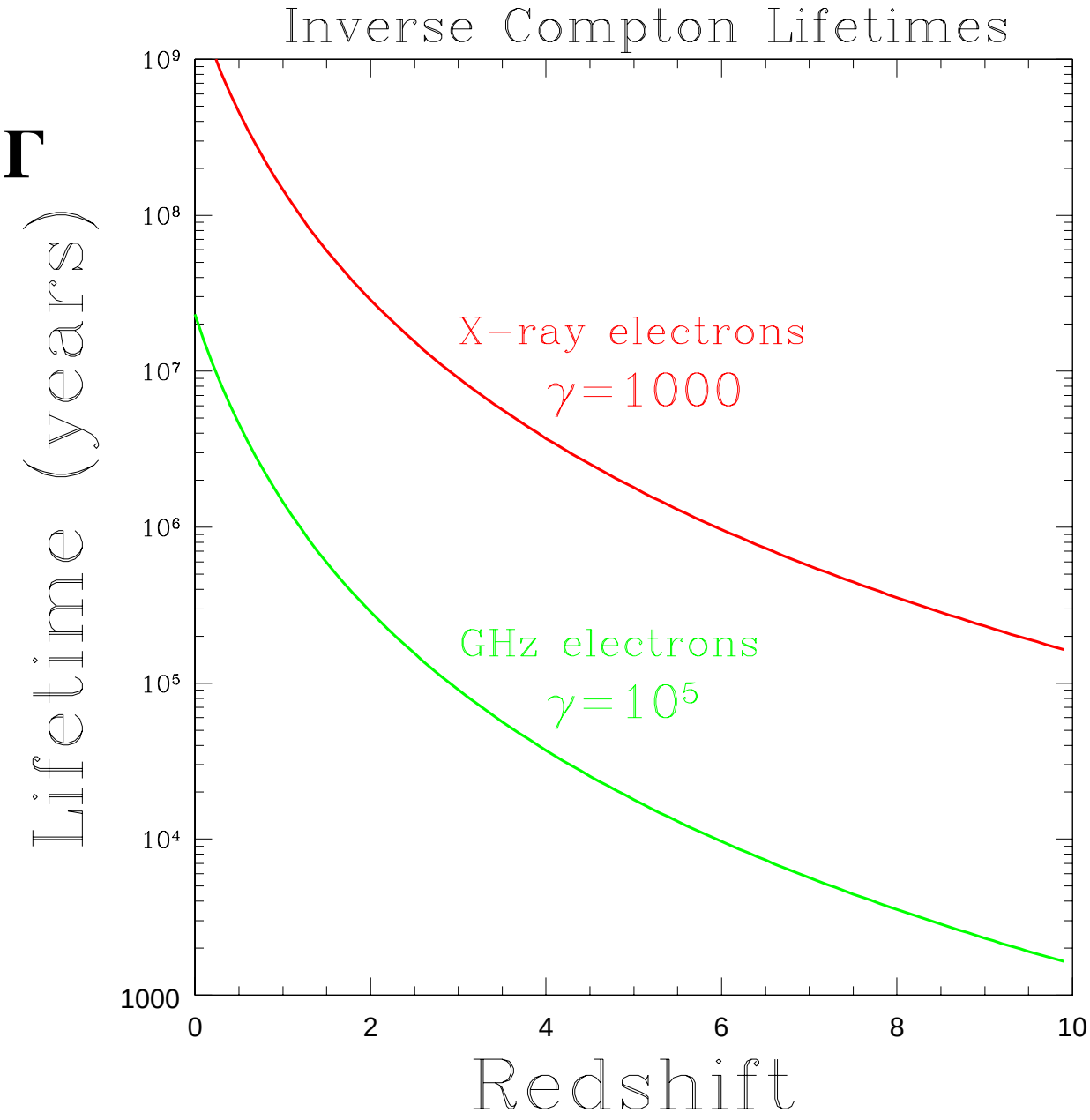
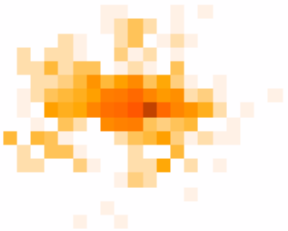


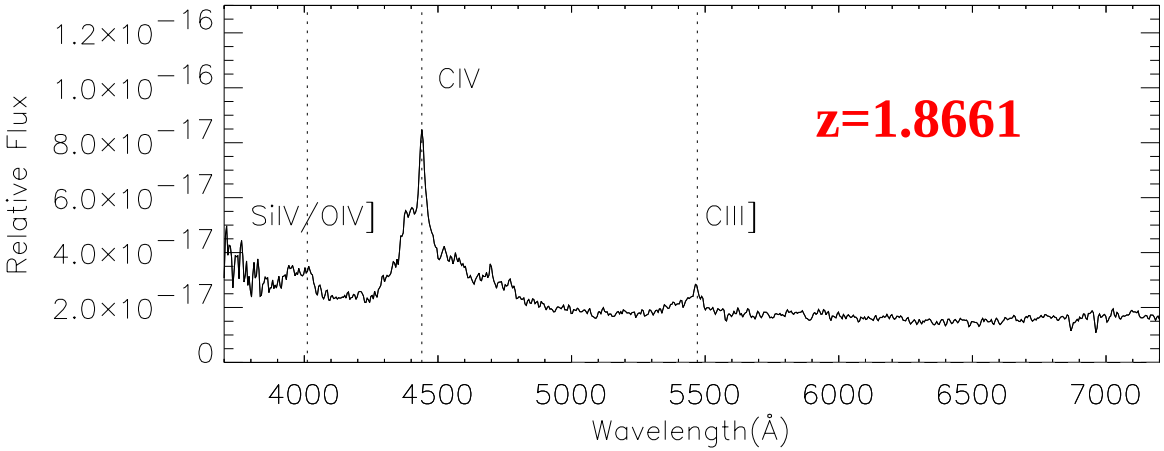
Cheung,2004ApJ...600L..23C



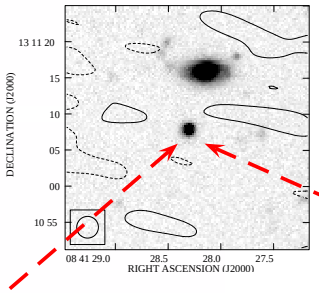
A Radio Quiet X-Ray Jet?

EMSS 0841+1314

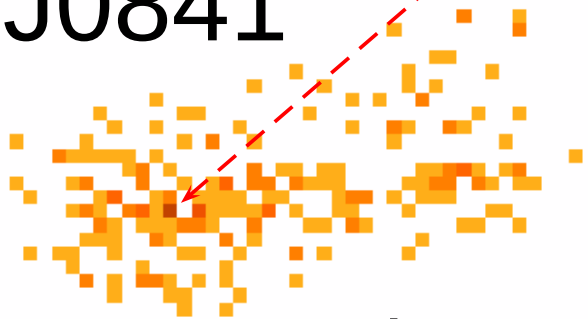




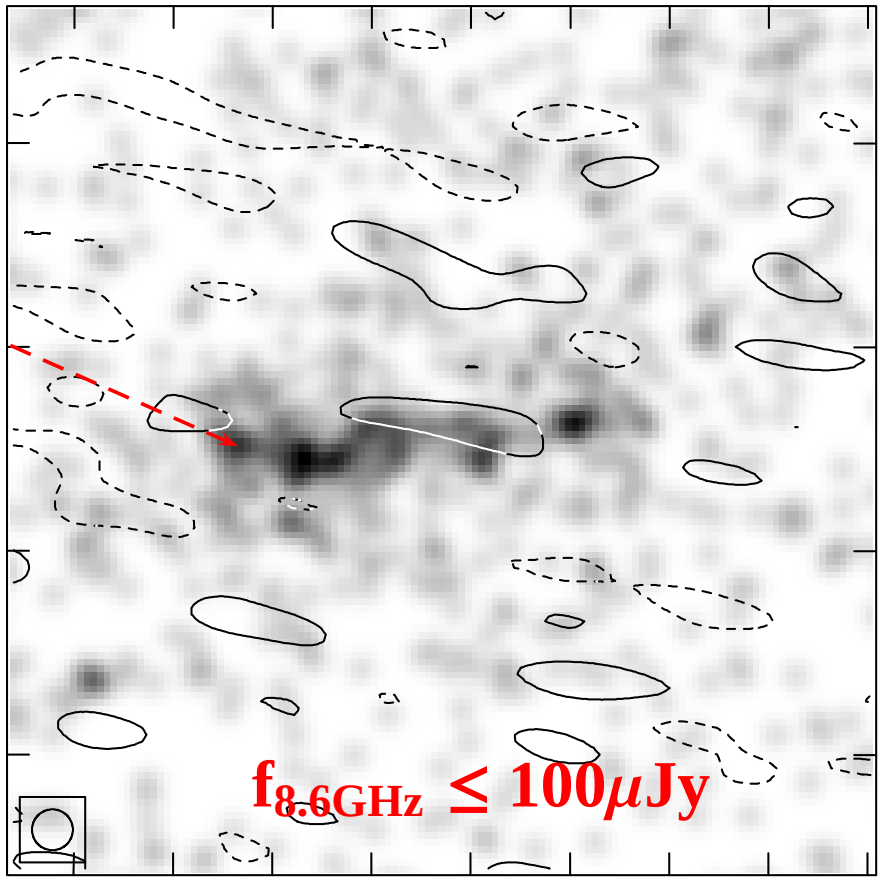
30"



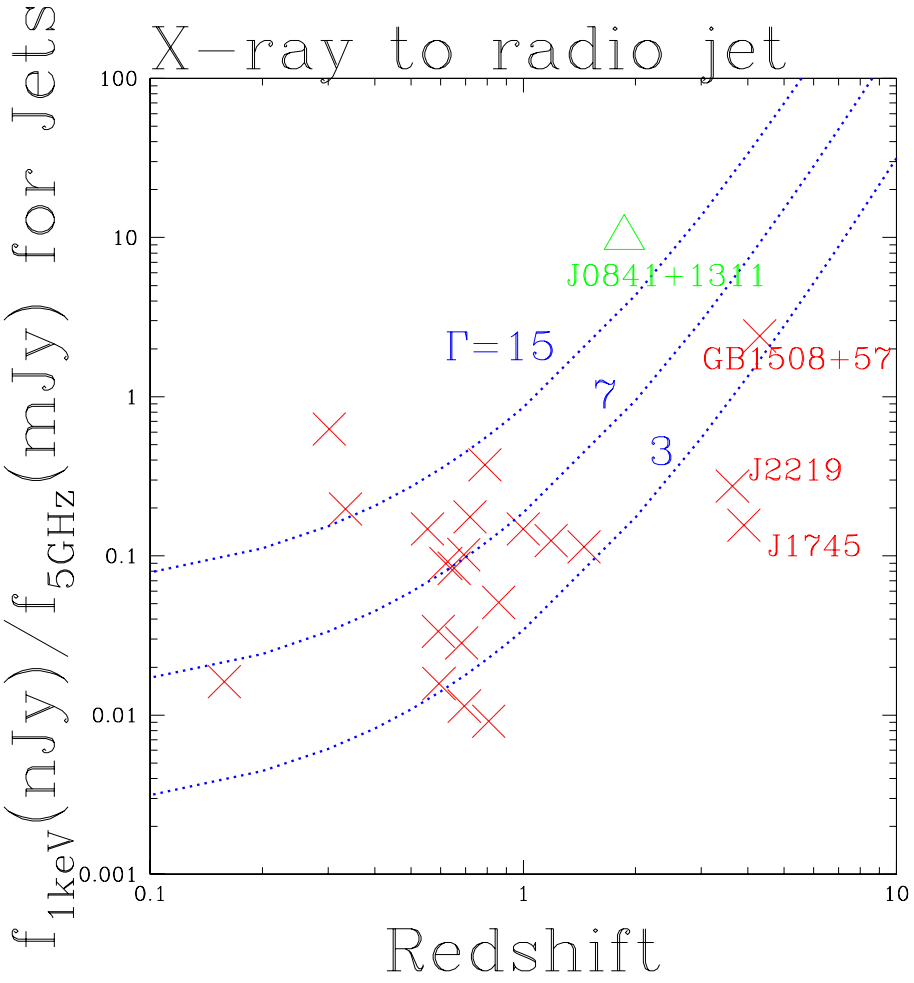
J0841

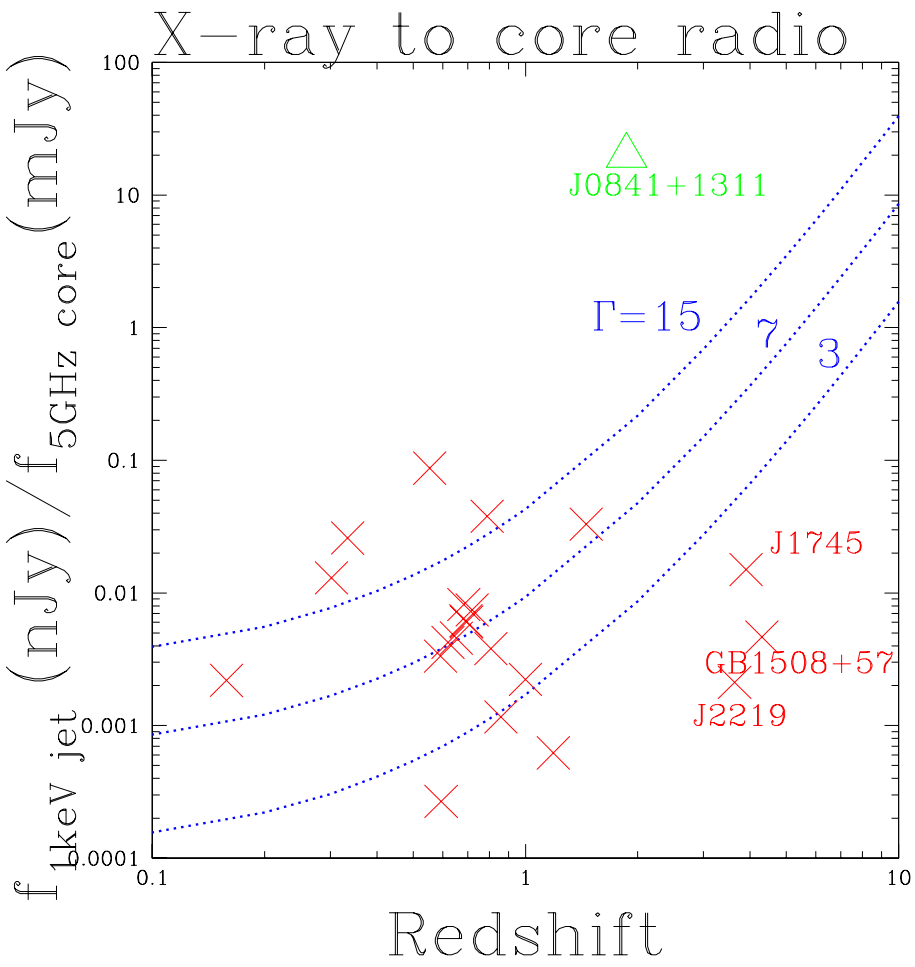


30" = 273 kpc



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!