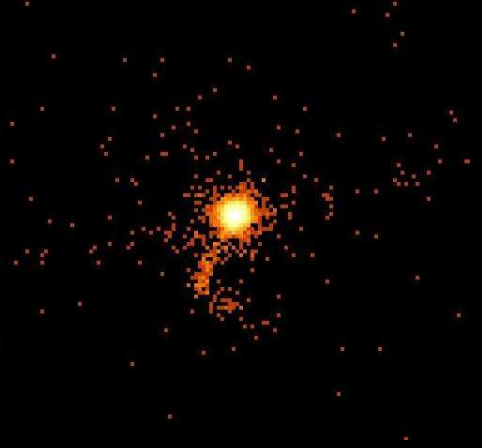
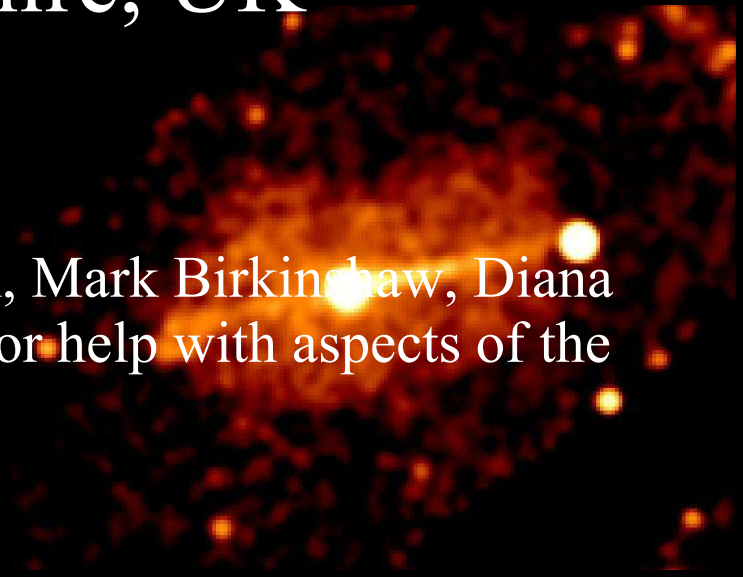


Kiloparsec-scale jets in powerful radio sources – Γ=1.5 or Γ=15?

Martin Hardcastle
University of Hertfordshire, UK



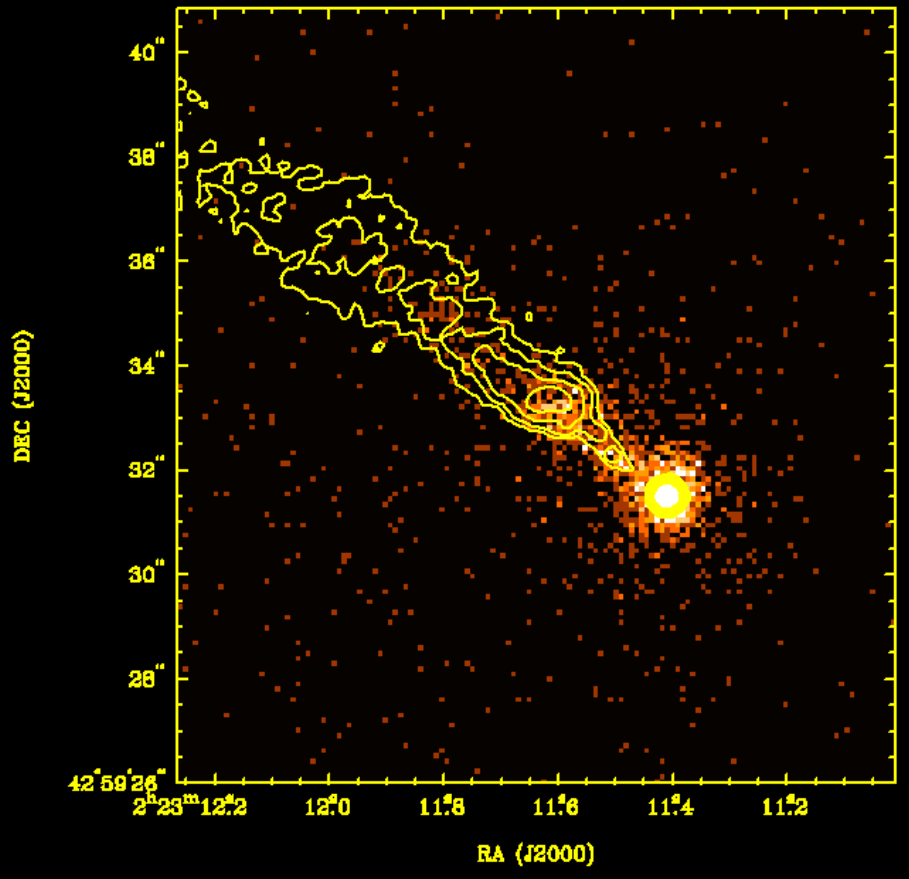
Thanks to Ralph Kraft, Laura Mullin, Judith Croston, Mark Birkinshaw, Diana Worrall, Dan Evans, Dan Harris, Julia Riley, et al., for help with aspects of the work discussed here

Outline

- Introduction
- Implications of high bulk LF
- Problems
- Observational situation
- Tests of the model
- Where are we now?
- See talks by Gelbord, Harris, Schwartz

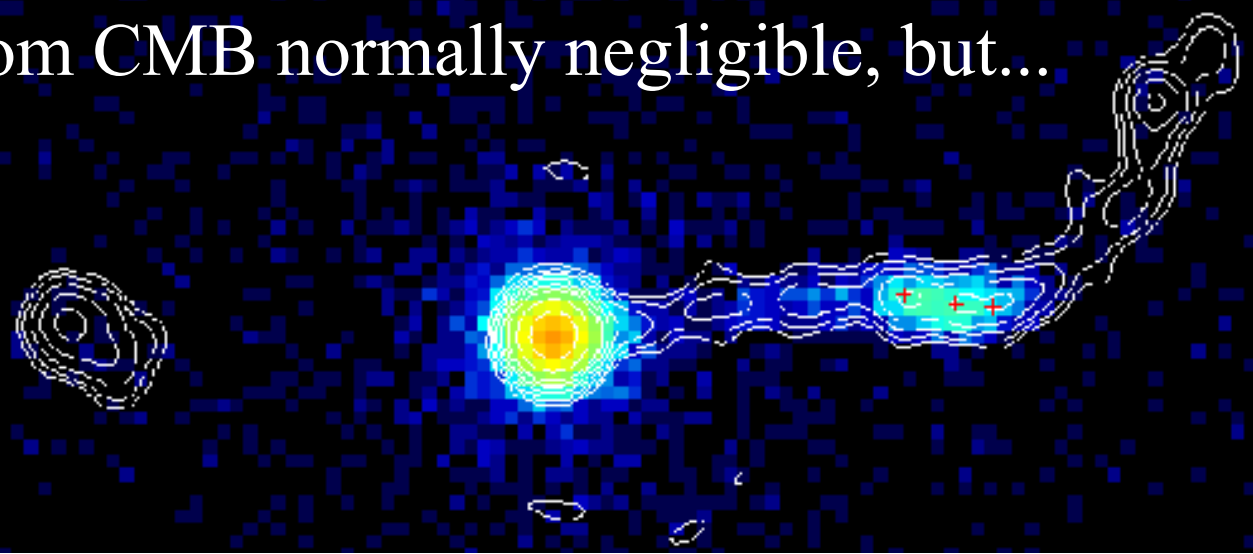
X-ray emission from low-power jets

- Low-power (FRI) sources commonly have kpc-scale X-ray jets
- Overall spectra are consistent with one-zone synchrotron models (with some ad hoc assumptions)
- X-ray emission region associated with bulk deceleration to sub-relativistic speeds (see Robert Laing's talk) in some sources, (but persists to 100-kpc scales in one-sided NGC6251: Evans et al 2005)
- Good consensus on low-power



X-ray emission from high-power jets

- Early *Chandra* discoveries such as PKS 0637 (below: Schwartz et al 2000, Chartas et al 2000): X-ray emission on 100-kpc scales (projected).
- Not consistent with a one-zone synchrotron model or with SSC with fields close to equipartition (preferred model for powerful hotspots, e.g. Hardcastle et al 2004).
- Inverse-Compton from CMB normally negligible, but...



X-ray emission from high-power jets

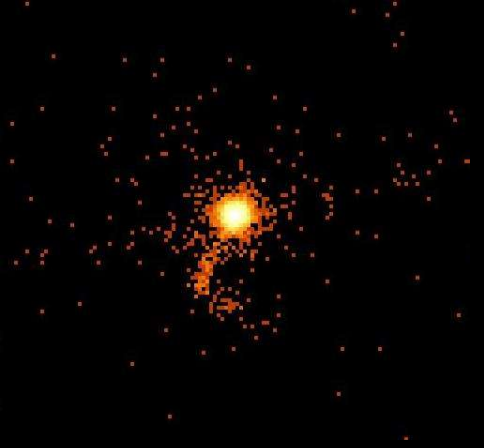
- Tavecchio et al (2000) & Celotti et al (2001): CMB energy density in jet frame goes up as Γ^2.
- In general requires high bulk Γ (but less at high z) and small angle to the line of sight (anisotropic in jet frame, still more so in lab frame).
- For PKS 0637 kpc-scale parameters needed (with equipartition magnetic fields) were in good agreement with pc-scale values => ***no bulk deceleration between pc and kpc scales***.

Implications of CMB/IC

- Essentially constant bulk LF at large distances => little internal dispersion
- Requires population of low-energy electrons ($\gamma \sim 10$) – consistency with hotspot results?
- All sources modelled in this way must have small angles to line of sight ($\lesssim 10°$).
- Most efficient way of transporting energy? (Ghisellini & Celotti 2001).

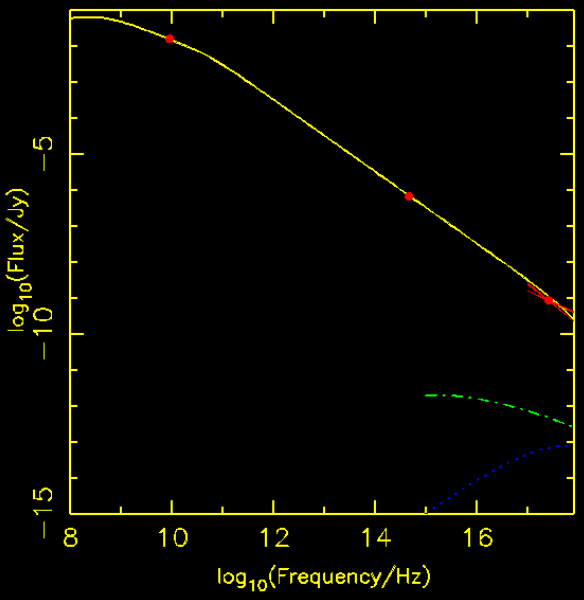
Problems

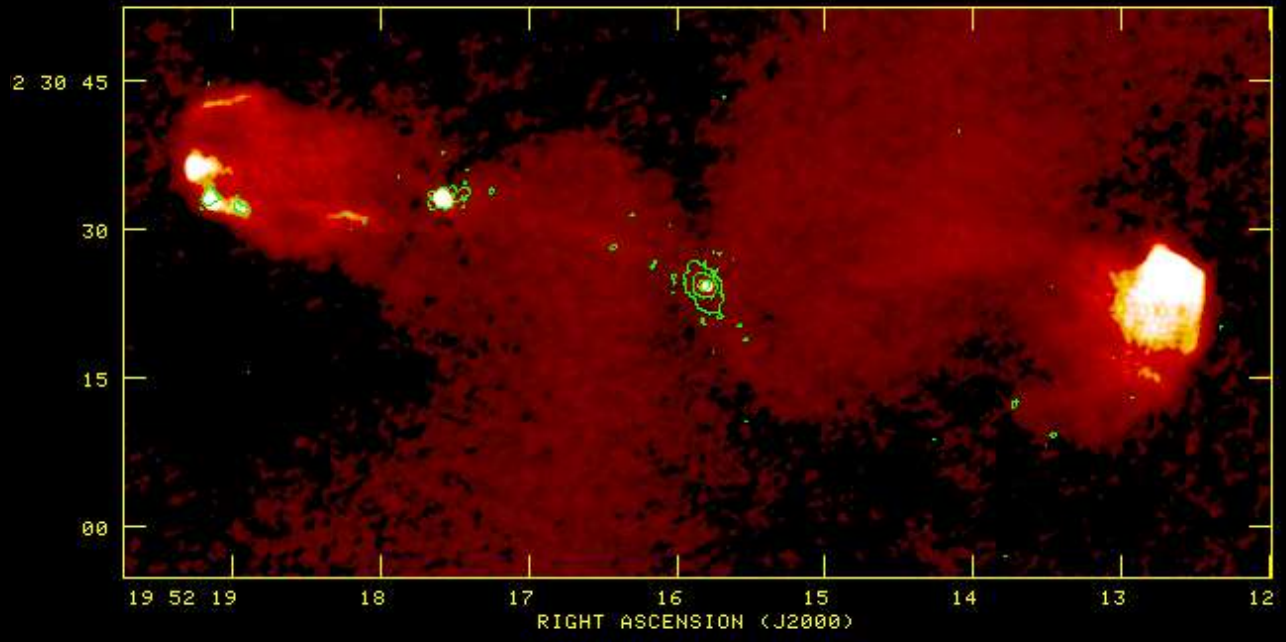
- Speeds inconsistent with best estimates of radio speeds ($v \sim [0.5 – 0.7]c$), see later)
- Jets are knotty in X-ray, optical and radio, though X-ray structure should reflect smooth distribution of cold electrons (Tavecchio et al 2003, Stawarz et al 2004).
- Invoking v. inhomogeneous jets (T. et al) loses minimum-power nature of jets (S. et al) & removes motivation for neglecting SSC.
- Radio/X-ray offsets and ratio variations (see later).



Are all X-ray jets in powerful sources best modelled as CMB/IC?

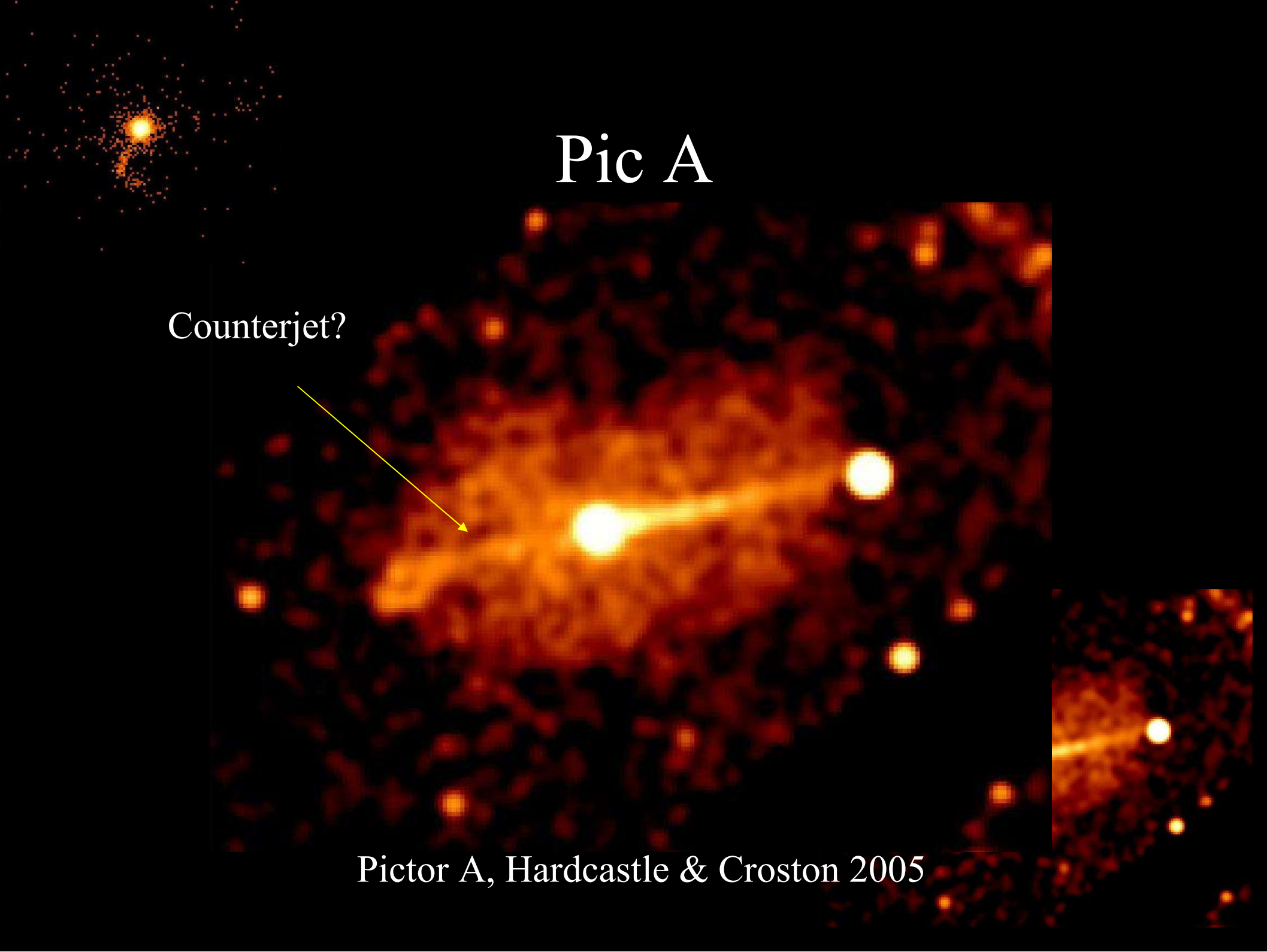
- No!
  - Several examples: 3C403, 3C465, Pic A...





3C403 (Kraft et al 2005)

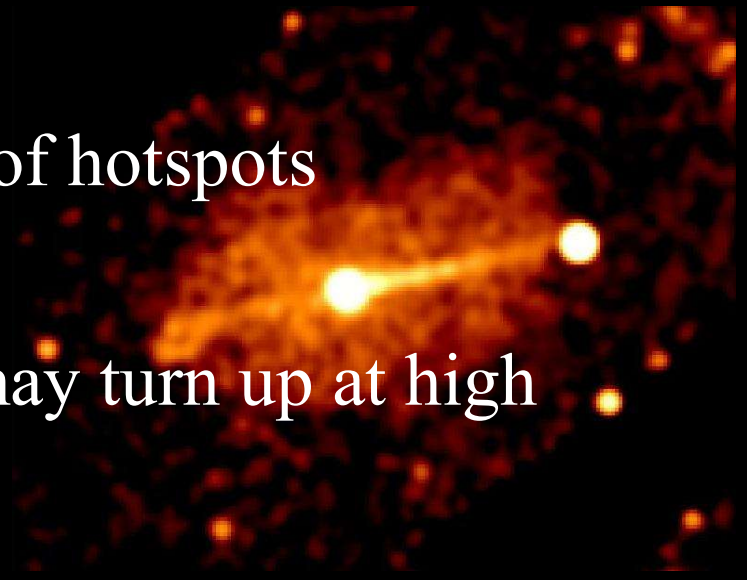
Pic A



Pictor A, Hardcastle & Croston 2005

Synchrotron emission from powerful jets

- Several sources where all jet emission can be modelled as synchrotron
- Synchrotron invoked to explain some components of others (e.g. Sambruna et al 2004)
- Implies possibility of efficient particle acceleration to high energies ($\gamma > 10^7$).
- Consistent with synchrotron models of hotspots (Hardcastle et al 2004).
- Arguments that particle population may turn up at high energies (Atoyan & Dermer)

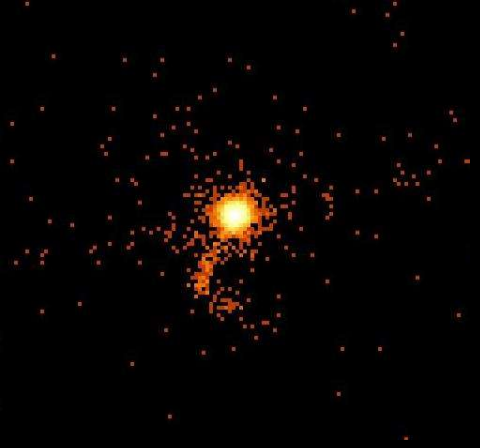


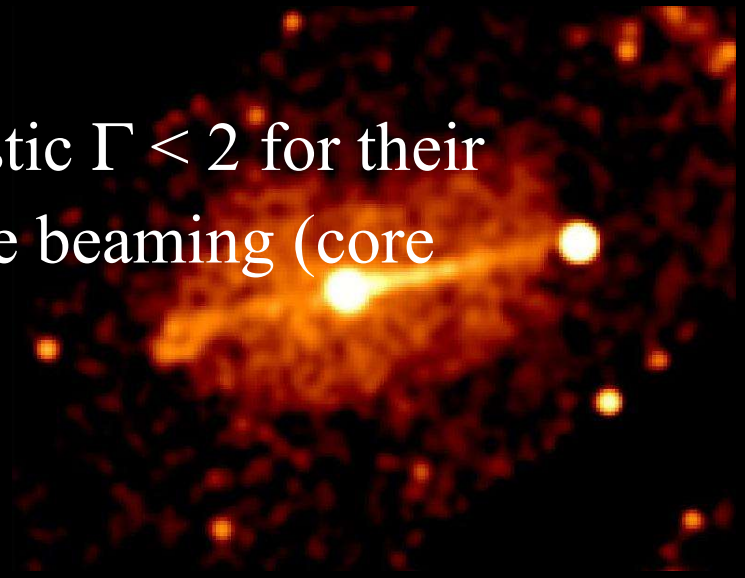
Does incompatibility with one-zone models rule out synchrotron?

- No!
  - Main evidence from detailed studies of FRI jets such as Cen A.
  - No reason to expect a one-zone model to work on scales >> loss spatial scale.
  - *Chandra* spatial resolution at z ~ 1 is ~10^3 times the loss spatial scale.
  - This explains observed 'offsets' in some more distant low-power jets.

Radio results - history

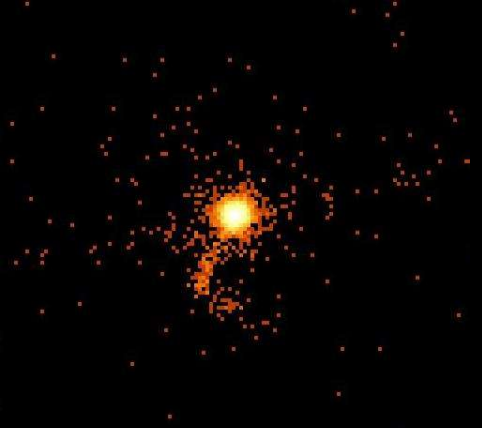
- The idea of constraining jet speed from radio emission dates back 20 years (e.g. Owen & Puschell 1984).
- Laing-Garrington effect (1988) shows that relativistic beaming is important on the kpc scale
- Unified models (Barthel et al 1989) explain the differences between quasar & radio galaxy jets
- Bridle et al (1994) show that characteristic $\Gamma < 2$ for their target objects on assumptions about core beaming (core prom/jet prom plot slopes)





History continued

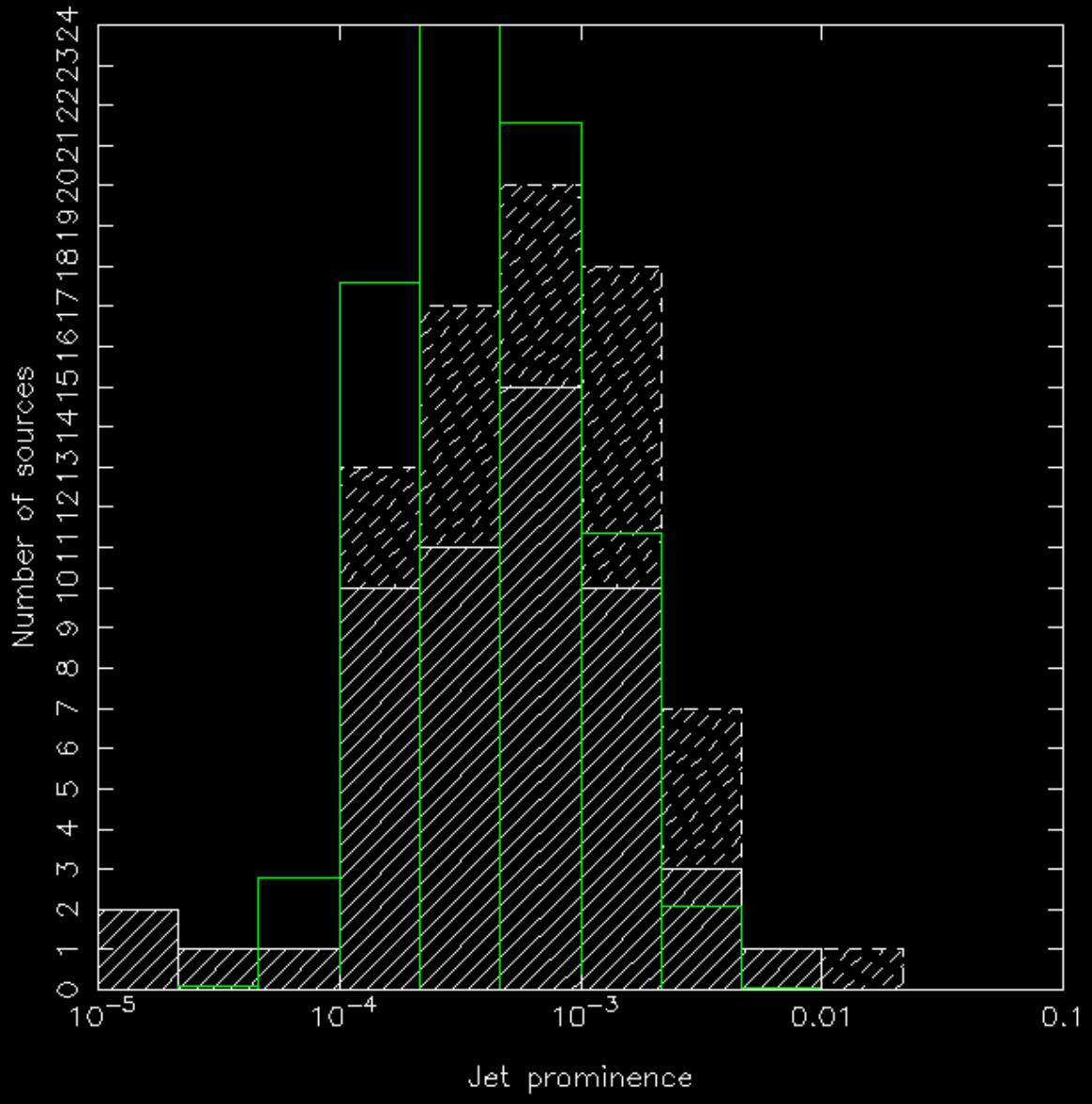
- Wardle & Aaron (1997) find best-fitting jet speeds 0.6-0.7c, with limit $\Gamma < 3.5$ (jet sidedness of Bridle et al quasars)
- Hardcastle et al (1999) find char. speed 0.5-0.7c (jet prominence in unbiased sample).
- Arshakian & Longair (2004) find similar results with a different analysis of Bridle et al quasars & Hardcastle et al radio galaxies (jet sidedness).
- Key result of all of this is that high speeds produce more extreme sidedness/prominence distributions than are observed.

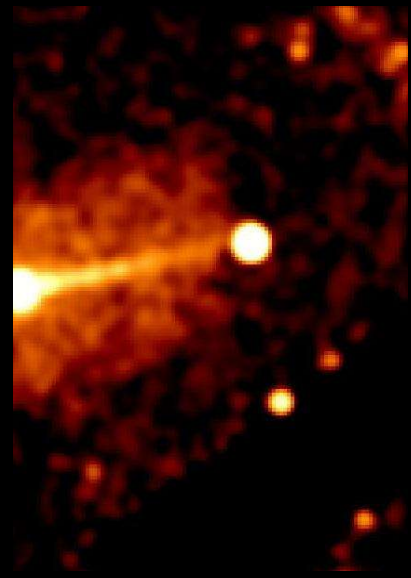



Jet prominences in 3CRR with $z<1.0$

ML fit to data with some intrinsic scatter, $v = 0.6c$.

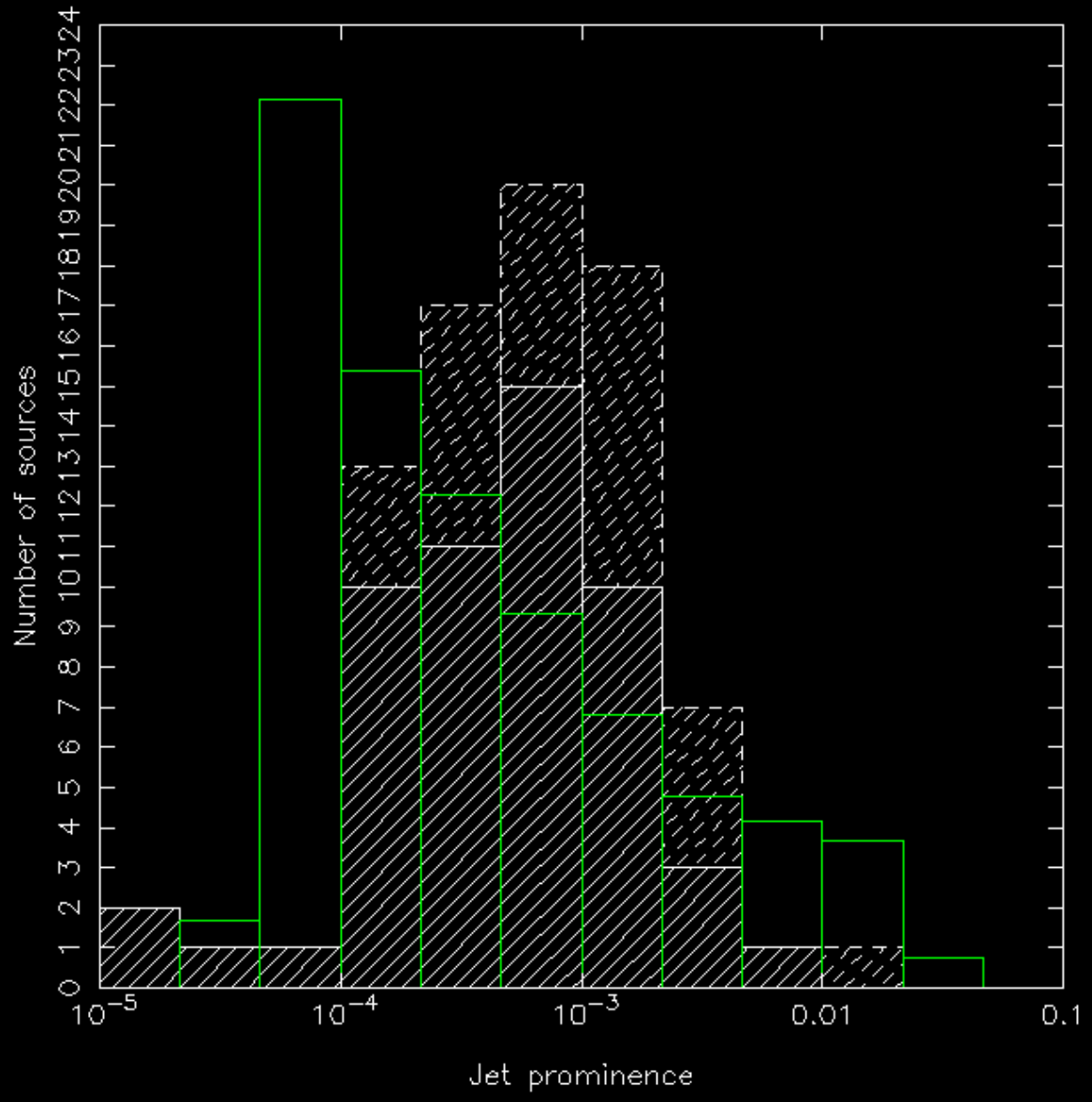
Preliminary results from data of L.M.Mullin et al (in prep.)

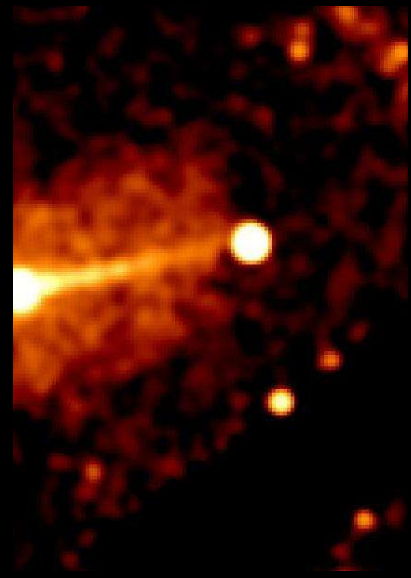


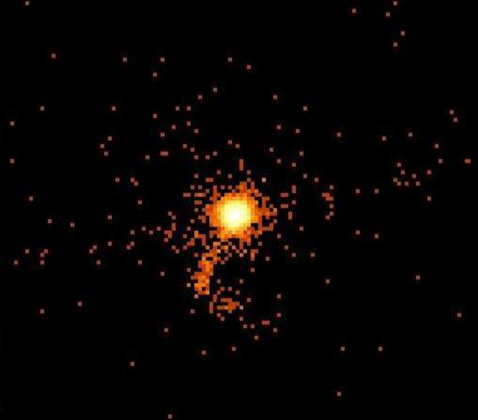


Jet prominences in 3CRR with $z<1.0$

No intrinsic scatter, $v = 0.9c$ ($\Gamma = 2.3$).

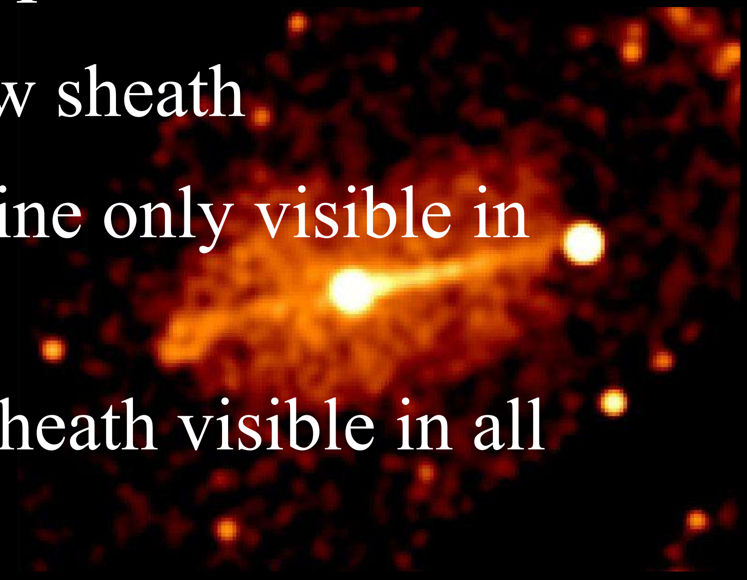






Get-outs for CMB/IC

- Radio data not matched to X-ray? – not really true now radio sample extends to $z = 1$.
- Radio objects not matched to X-ray objects? – not true unless CDQ not in standard unified models
- Jet velocity structure? – entirely possible!
  - requires high-speed spine and slow sheath
  - radio and X-ray emission from spine only visible in CDQ.
  - synchrotron radio & X-ray from sheath visible in all sources...

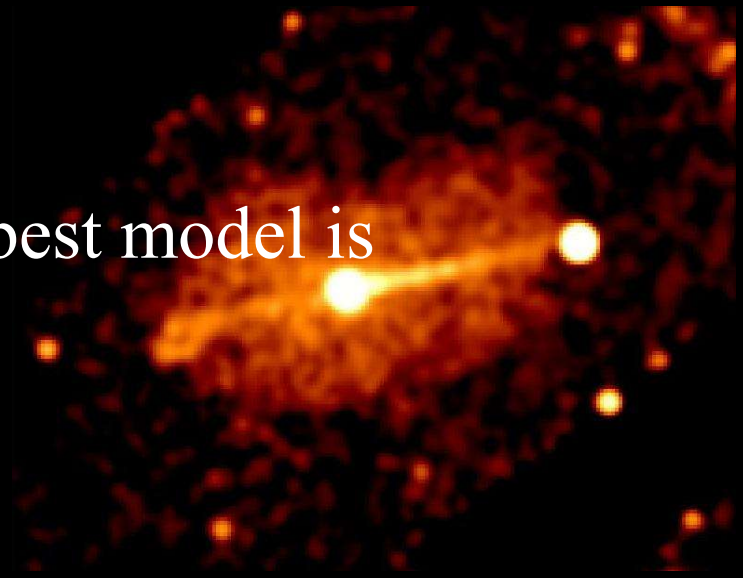


Testing the model

- Models in which *all* FRII jets are CMB/IC are ruled out by observations.
- Little to rule out synchrotron with a multi-component model in most objects (very few sources have $\alpha_{ox} < 0.5$).
- Since jet velocity structure is *required* hard to test beaming models statistically (need v large unbiased sample to get significant CDQs).
- How can we subject CMB/IC to a critical test?

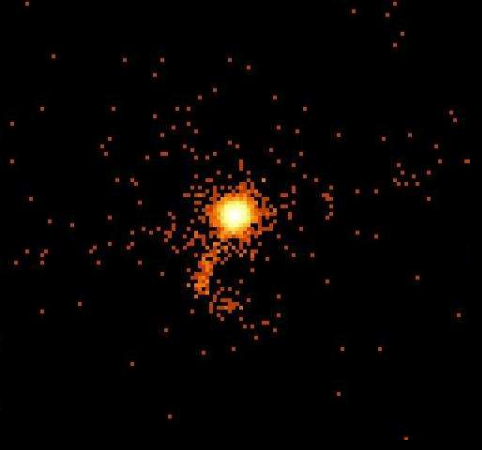
Testing, testing

- Are all the X-ray jets modelled as CMB/IC consistent with the idea of no deceleration on the pc scale?
- Particularly interesting in this case are the jets with multiple X-ray/radio components.
- I selected all the FRII sources with extended jets from the XJET pages (http://hea-www.harvard.edu/XJET/)
- Pic A used as a control even though best model is synchrotron.

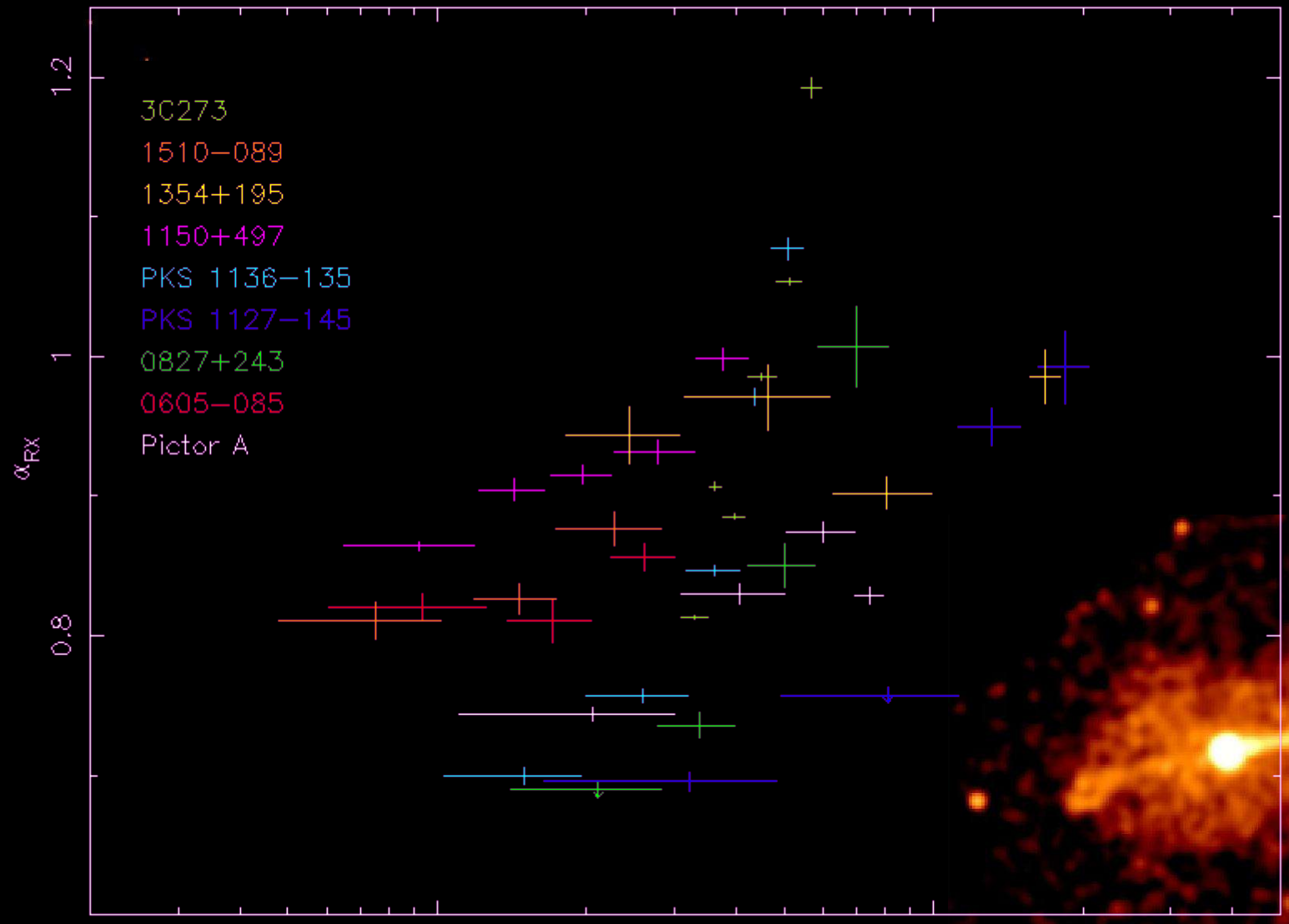


A sample of jets

- X-ray data from *Chandra* archive, radio from VLA
- Jets broken down into regions with suitable X-ray/radio statistics for measurements.
- Model fitting using numerical code that directly integrates the anisotropic IC results of Brunetti et al (2000) and transforms to lab frame => takes into account realistic electron distn, CMB spectrum, etc. $\gamma_{min} = 10$.
- Projection taken into account => not purely a function of Doppler factor: small angles have big advantage
- Assume equipartition.
- Largest uncertainty in modelling is size measurements.



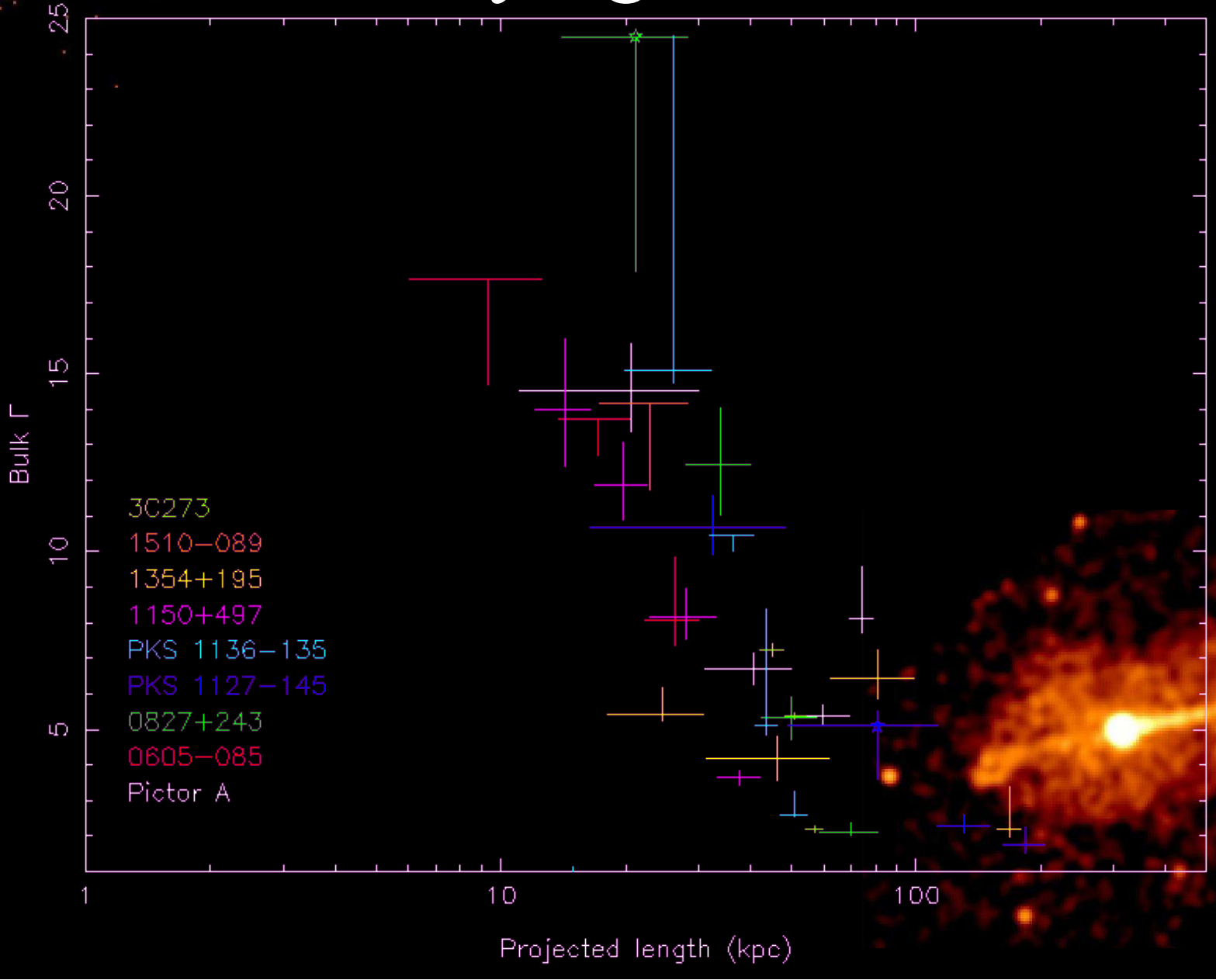
X-ray/radio ratio



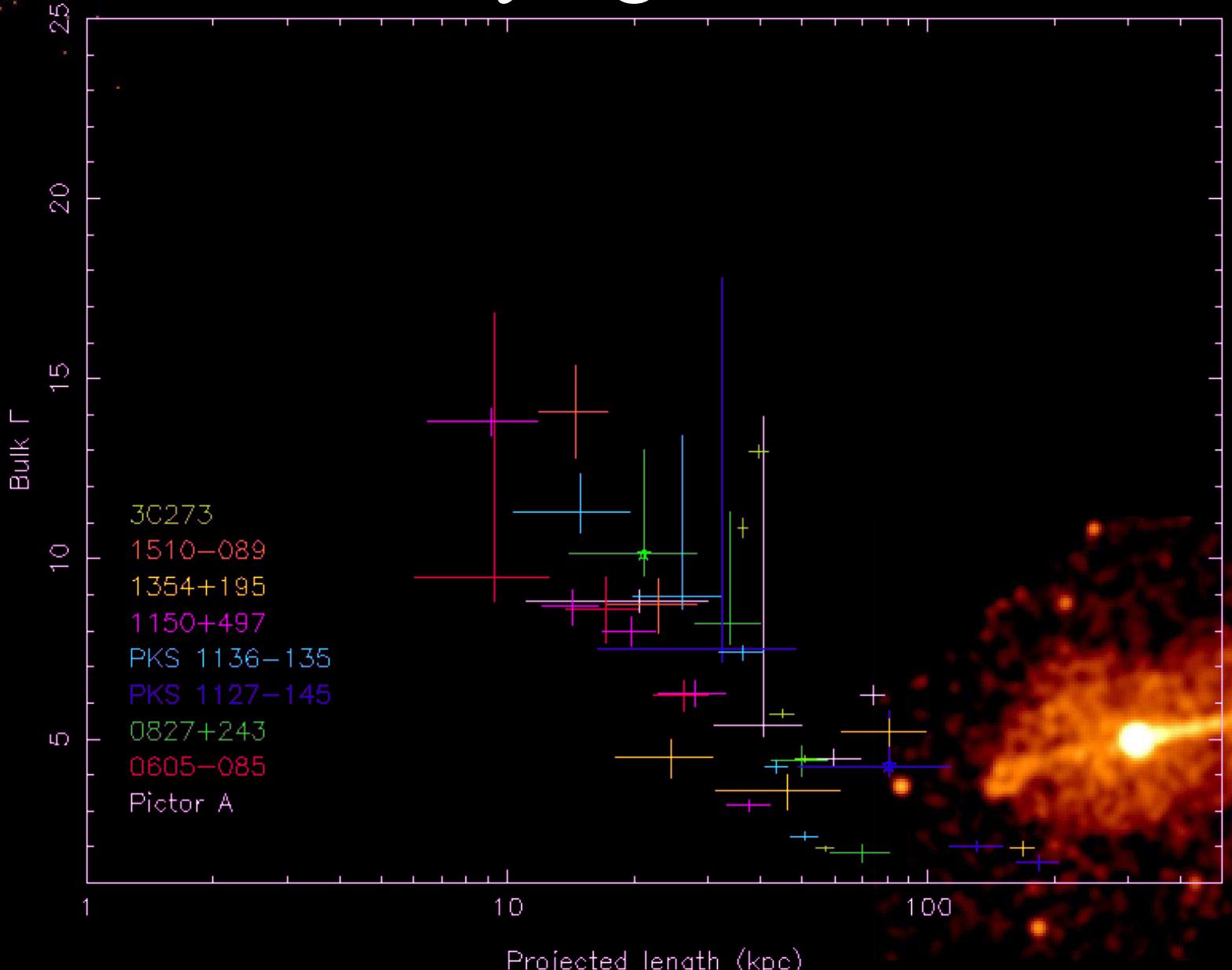
Varying α_{RX}

- Previously commented on, e.g. by Sambruna et al (2004), but this sample (w/ all resolved jets) shows it particularly clearly.
- In CMB/IC model some of this due to jet spatial structure, but most due to varying θ or varying Γ.
- Varying θ requires large changes which often do not correspond to changes in plane of sky (though some sources are bent, e.g. 0827+243).
- Varying Γ requires deceleration.

Varying Γ (4°)

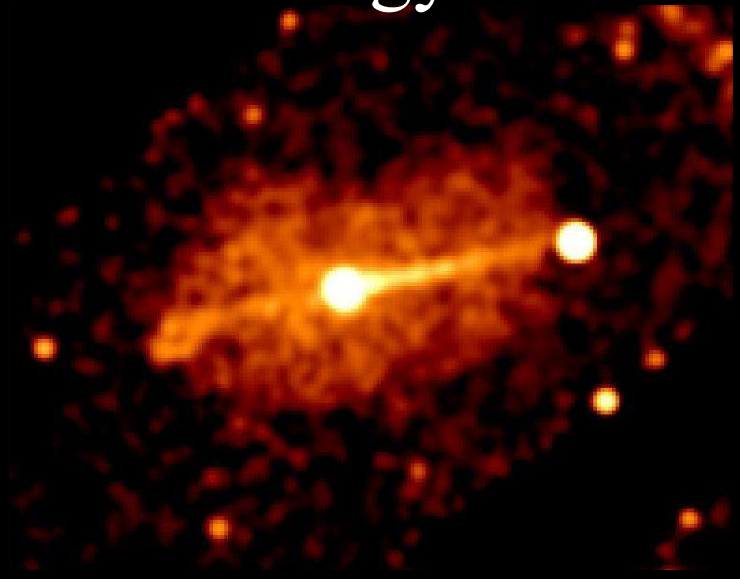

Bulk Γ
25
20
15
10
5
1
10
100
Projected length (kpc)
3C273
1510−089
1354+195
1150+497
PKS 1136−135
PKS 1127−145
0827+243
0605−085
Pictor A

Varying Γ (2°)

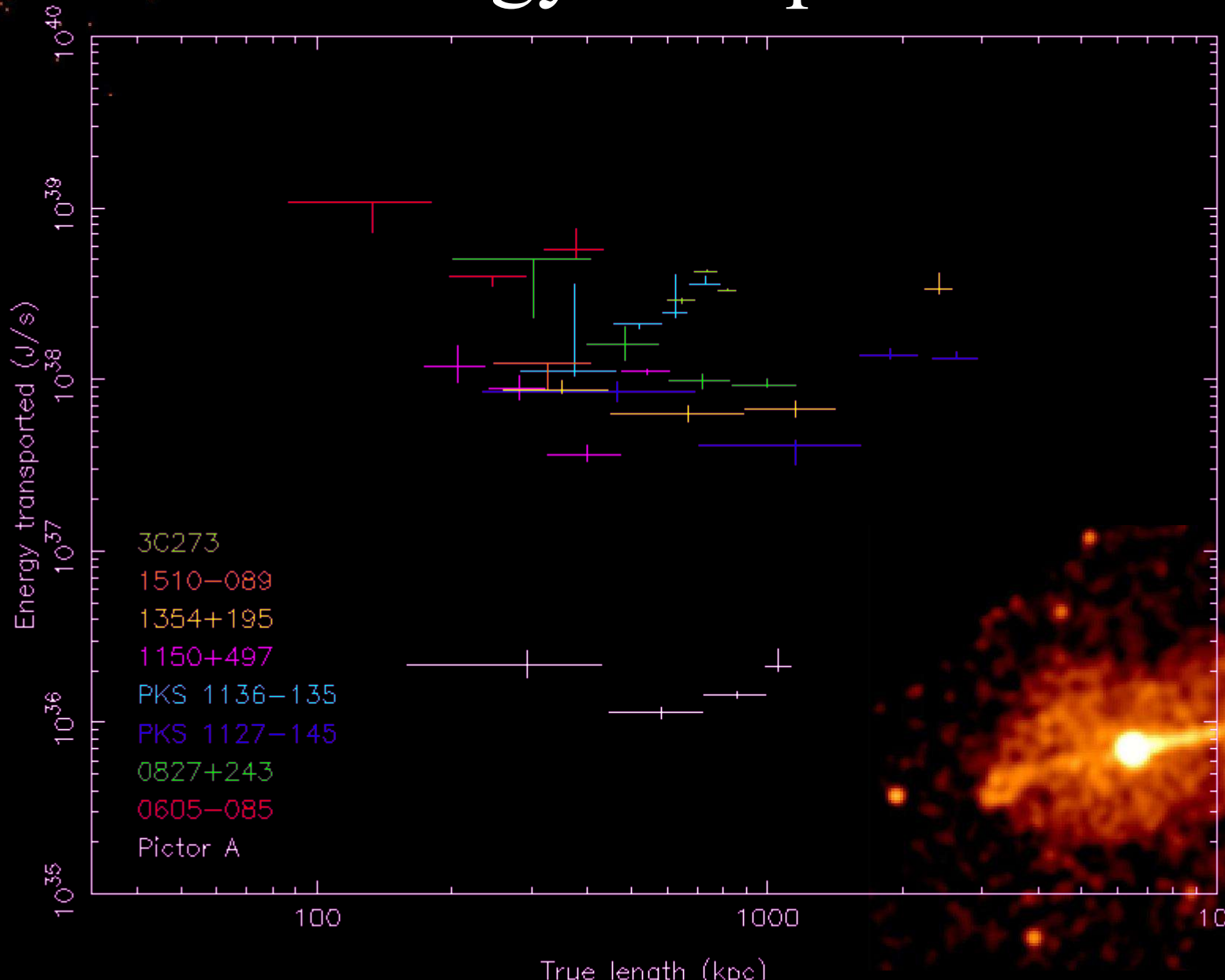

Bulk Γ
25
20
15
10
5
1
10
100
Projected length (kpc)
3C273
1510−089
1354+195
1150+497
PKS 1136−135
PKS 1127−145
0827+243
0605−085
Pictor A

Varying parameters

- Magnitude of effect depends on choice of angle to l.o.s., but direction of effect is always present.
- Clear trend for required LF to decrease with distance.
- We can ask what effect this has on the energy transported by the jet...

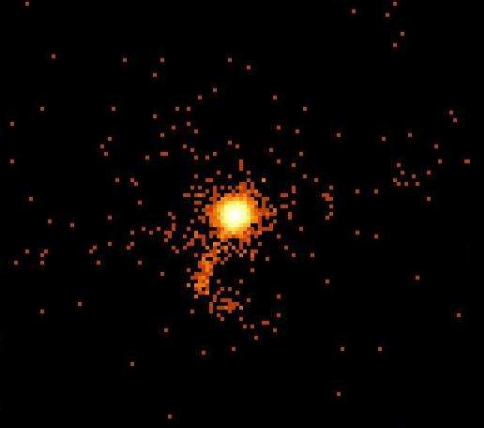


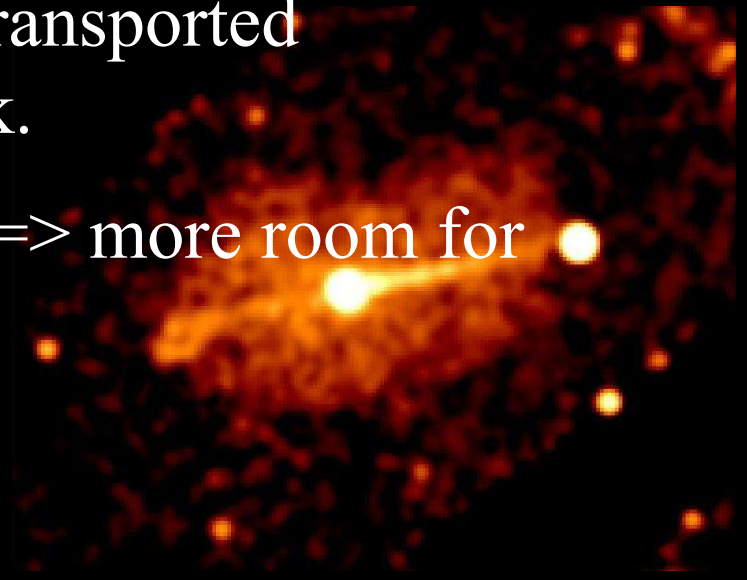
Energy transport



Energy transport

- No clear trend with energy transport, but
- Model fails a consistency check in the sense that we would expect a constant or decreasing energy carried by the jet.
- Not clear whether a value of angle to l.o.s. could be determined that would keep energy transported approximately constant – future work.
- More sensitive to spatial parameters => more room for error.



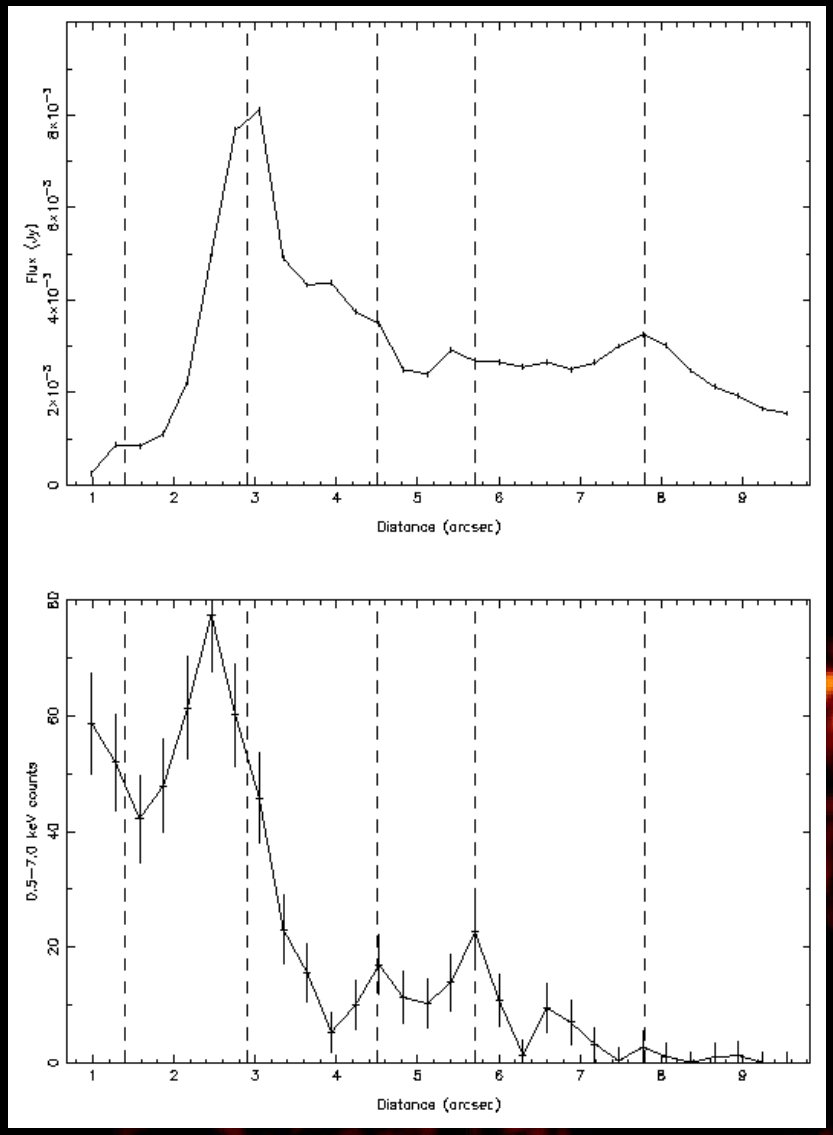


Consequences of varying Γ

- If LF varies on these scales we might expect to see some radio evidence (in terms of more two-sided jets at large distances), but no such evidence exists (e.g. Mullin et al.)
- True even if jet has velocity structure.
- If jets in general decelerate then the good agreement between pc-scale and kpc-scale numbers in PKS 0637 must be coincidental.
- => We lose another good feature of the CMB/IC model, the *prediction* of kpc-scale properties based on pc-scale measurements.

Alternatives

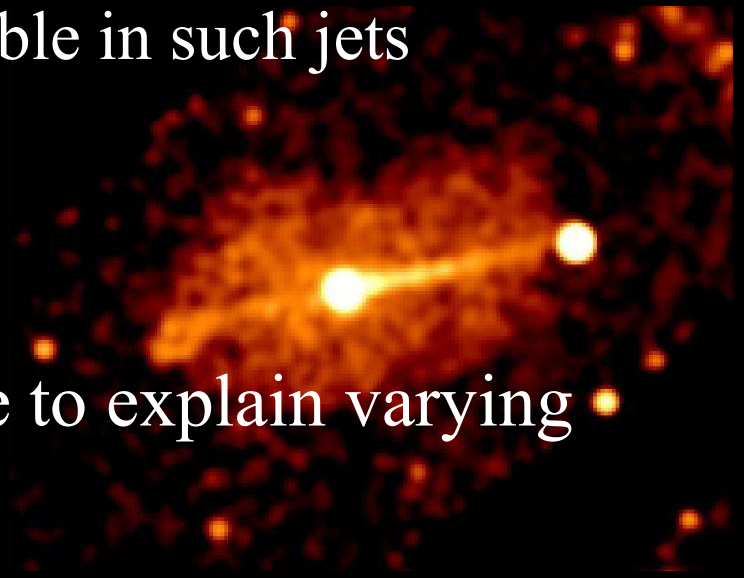
- Systematically decreasing X-ray to radio ratio is also seen in FRI jets (synchrotron), albeit on smaller spatial scales
- Jet is less able to accelerate high-energy particles?
- We seem to be trying to explain the *same* observational phenomenon in terms of radically different physical processes!



Radio and X-ray profiles of 3C66B jet (Hardcastle et al 2001)

Alternatives

- Can (some of the) emission of powerful jets be synchrotron?
  - requires a second synchrotron component – ad hoc
  - but we know a second component of some kind is required in 3C273 (Jester et al 2005)
  - synchrotron emission certainly possible in such jets
- Would unify FRI and FRII jets
- Offsets would be explained.
- If both processes operate may be able to explain varying α_{RX} without deceleration.



Jet speeds: summary

- Radio data show clearly that at least some part of the jets is not highly relativistic on kpc scales ($\Gamma \sim 1.5$)
- If the X-ray is from the CMB/IC process then
  - jets must have velocity structure on 100-kpc scales
  - 'spine' of jet must have relativistic speeds ($\Gamma \sim 15$)
  - spine must decelerate on 100-kpc scales without any evident deceleration of slower sheath.
- If X-ray is synchrotron none of this is required...