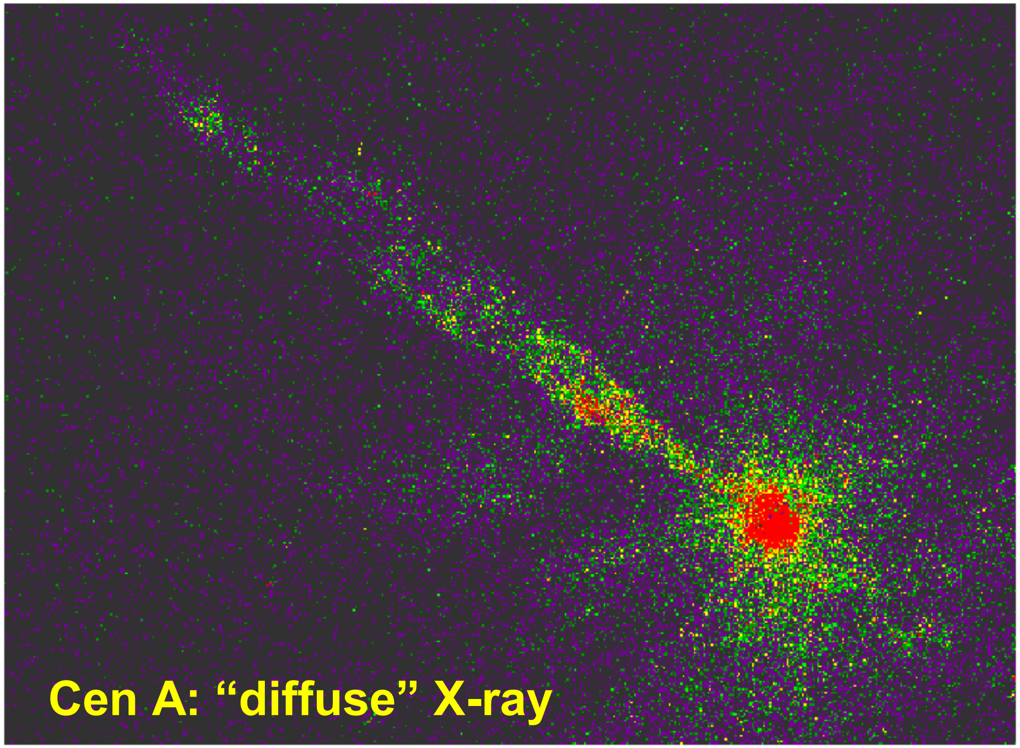
Broad-Band Observations of Large Scale Jets in AGNs



Jun KATAOKA

(Tokyo Inst. of Tech.)

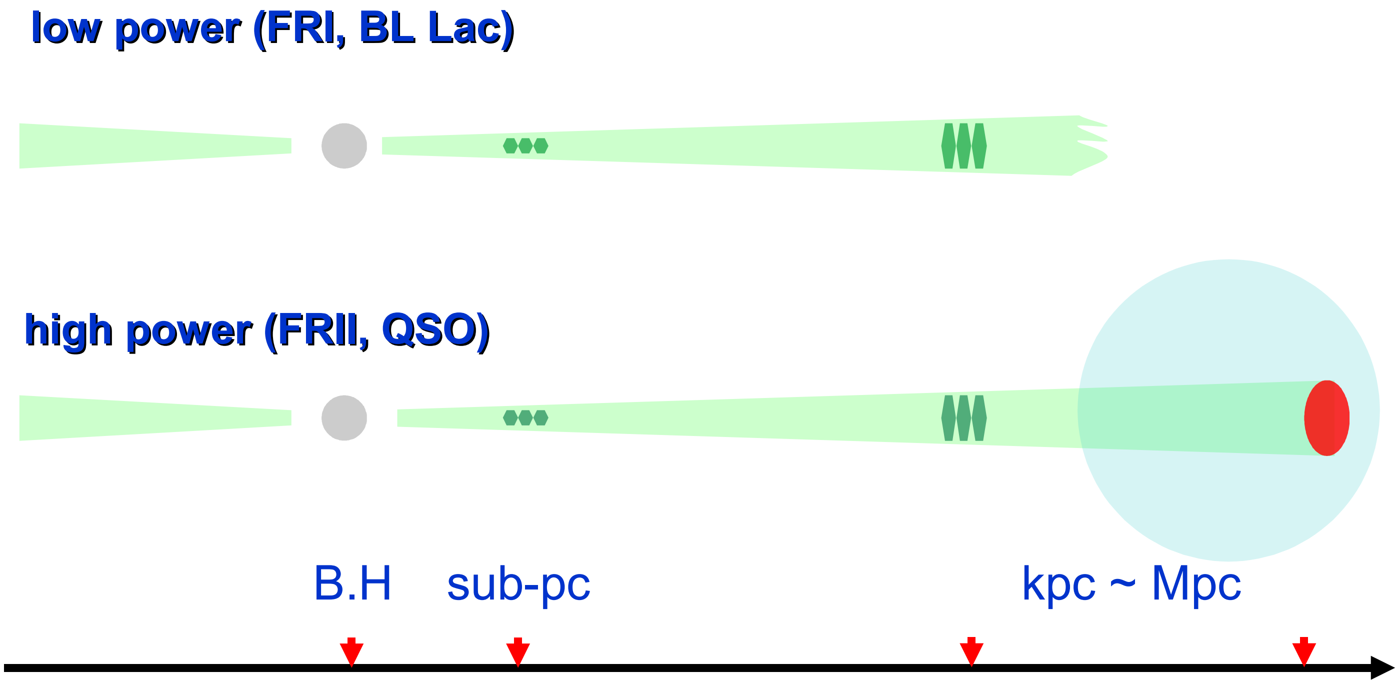
Outline

- Brief introduction
  - ✓ Sub-pc to Mpc connection (from “blazars” to “Rad Gal”)

- Multiband study of large-scale jets.
  - ✓ Comparative study of knots, hotsopts, and lobes
  - ✓ Merits/demerits of beamed IC/CMB

- Toward nature of *“bright”* X-ray jets
  - ✓ Non-standard Sync emission and acceleration
  - ✓ Observation of jet structures
  - ✓ Jet contents

AGN Jet: introduction



- Viewing angle is a key to identify various classes in AGNs.
- Blazars' emission come from the most inner part of the jet, via the internal-shock in sub-pc jet.
- Large scale jets in powerful radio galaxies (FR II/QSO) extend to Mpc scale: internal and/or external-shock ?

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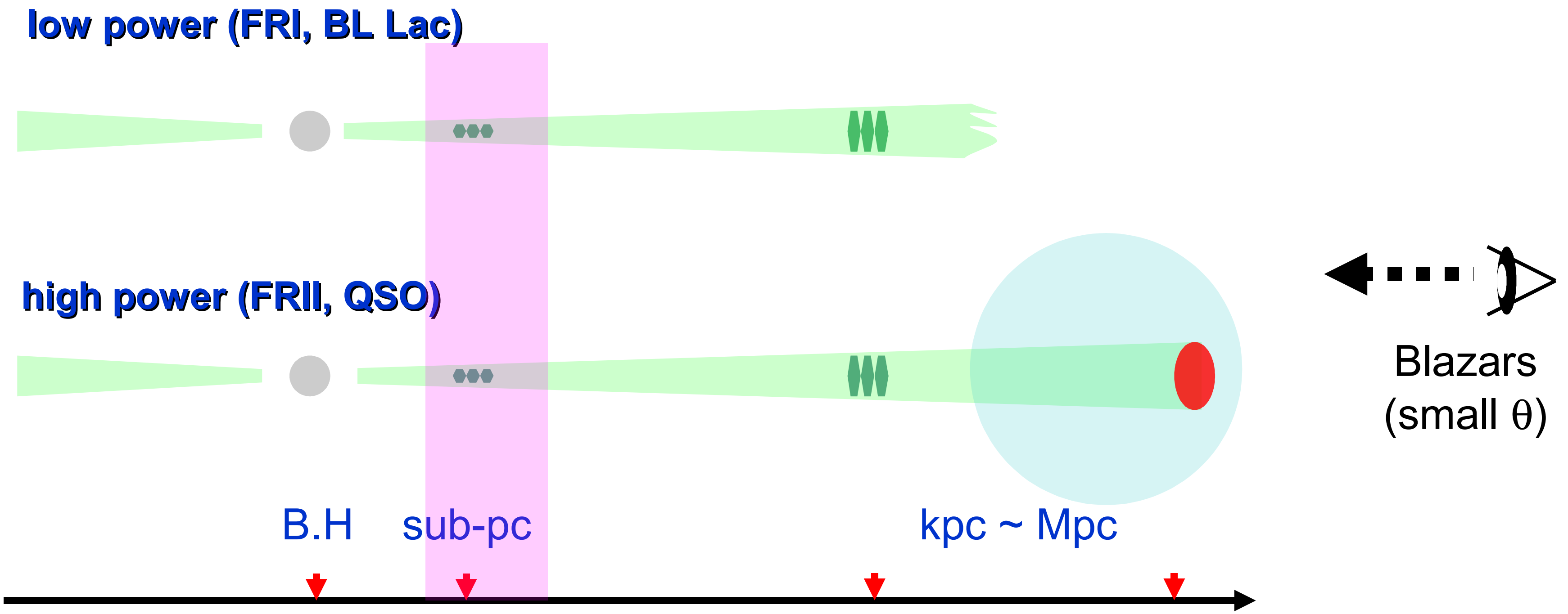

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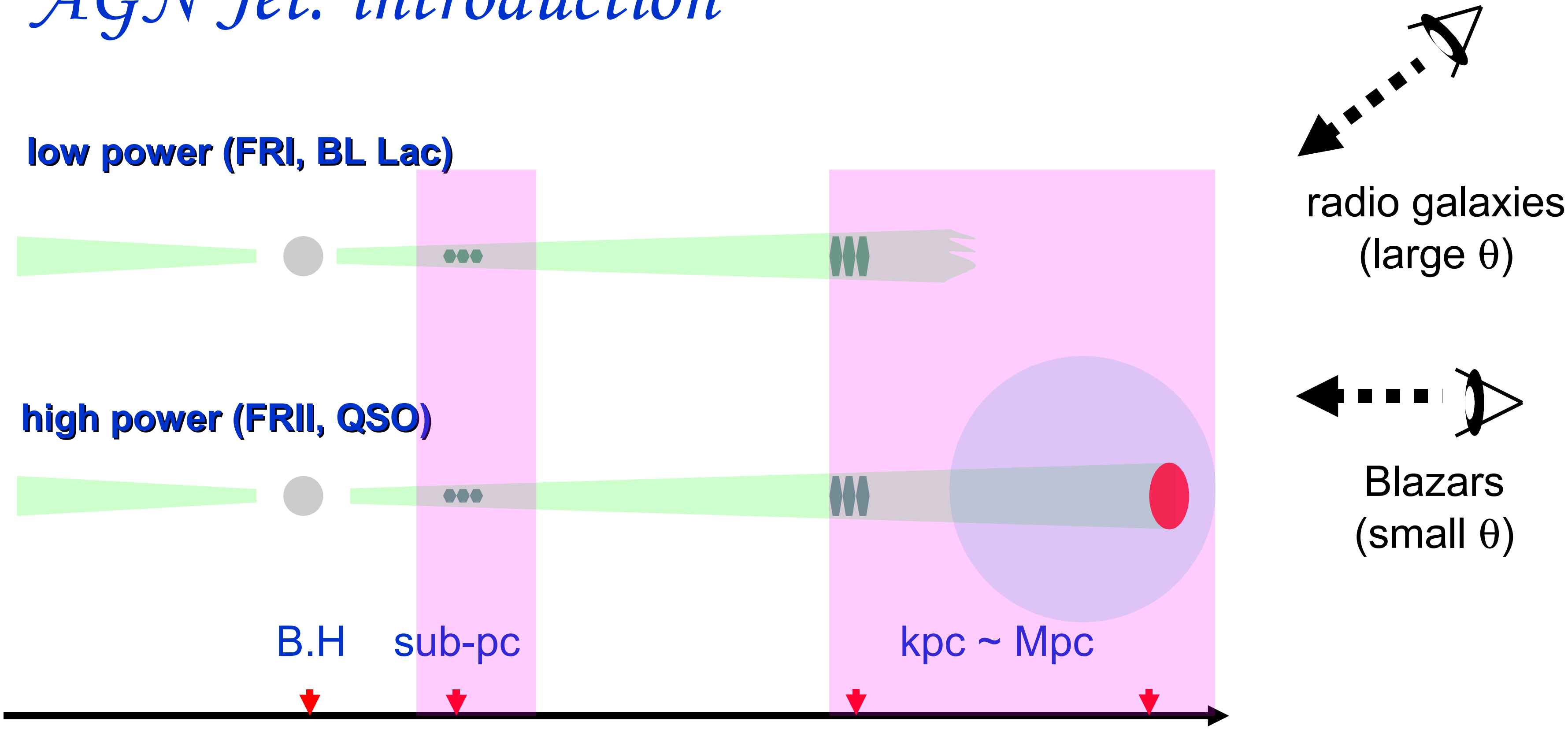

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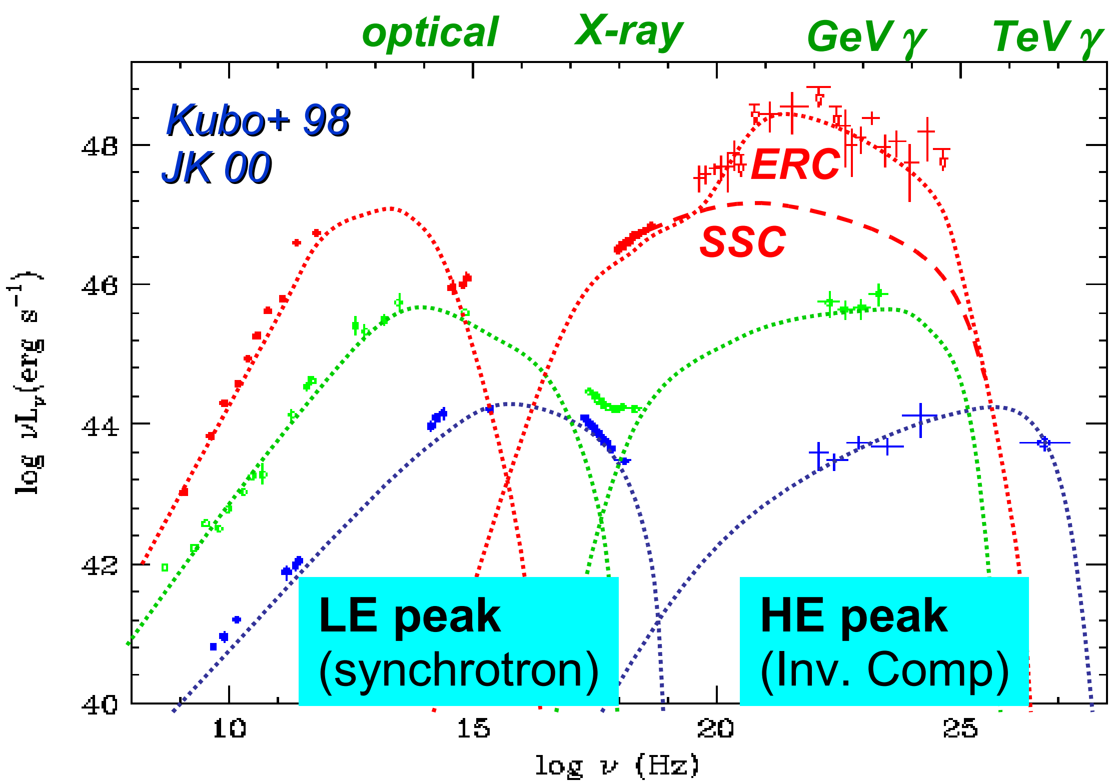
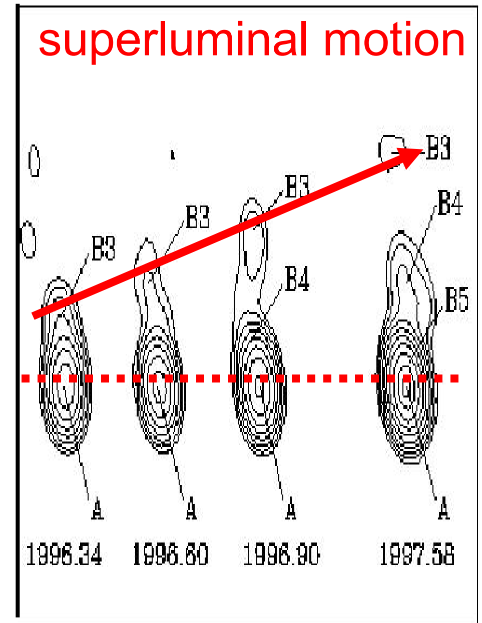
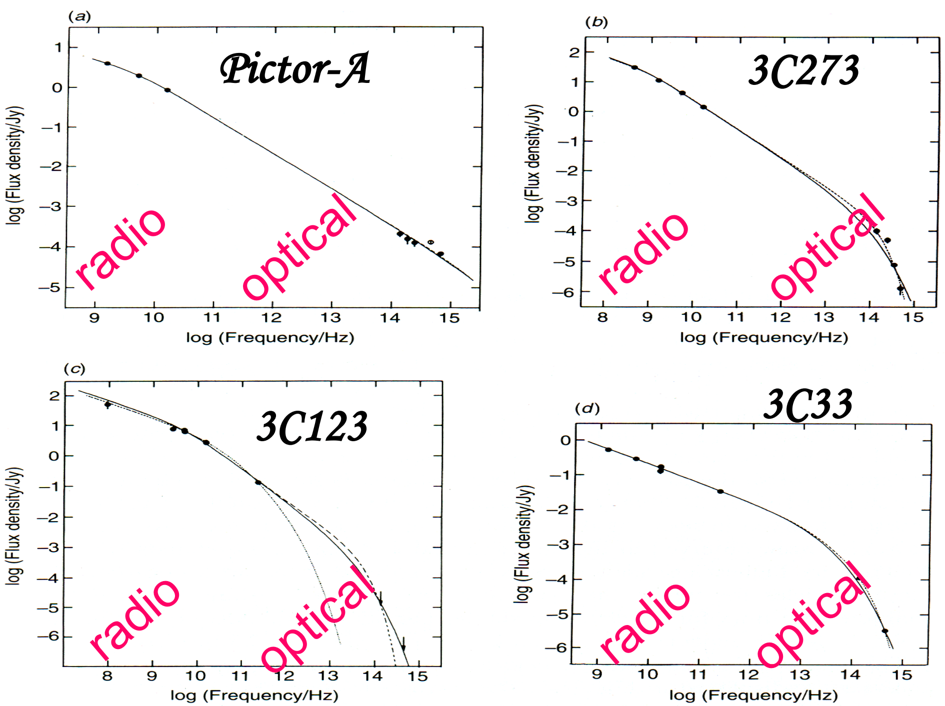
"Blazar" region (sub-pc~ pc jet)

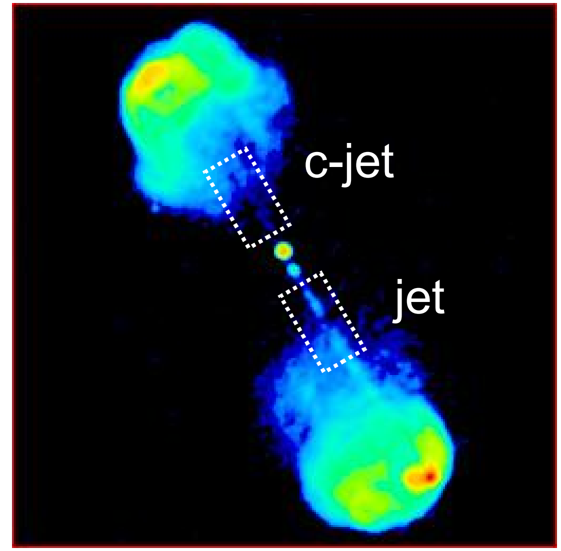




- "Well-defined" double peaks over two decades in freq.
  - ➡ u_e and u_B can be determined uniquely, by comparing LE/HE
- Direct measurement via superluminal motion **$\Gamma_{jet} > (\beta^2_{app} + 1)^{1/2}$**
- Rapid time variability as short as 1 day: **$R \sim ct_{var}\,\delta$**
  - ➡ **$B \sim 0.1$ G, $R \sim 0.01$ pc, $\Gamma_{jet} \sim 10$, $u_e \sim 10\, u_B$**

Radio Gal. (kpc~Mpc jet)





$$R = \left[\frac{1 + \beta \cos\theta}{1 - \beta \cos\theta} \right]^{2+\alpha}$$

where $\alpha \sim 0.5\text{-}1$

- Smooth Sync between radio and optical.
  - ➡ Parameters degenerate as $L_{sync} \propto u_e\, u_B\, V$.
- Proper motions are often difficult to observe.
  - ➡ Jet/c-jet provides only weak constraint (e.g., $\Gamma_{jet} \sim 2$ for M87).
- Lack of variability prevent us imagine size of distant sources.
  - ➡ ***Physics of kpc/Mpc jets are much more unclear!***

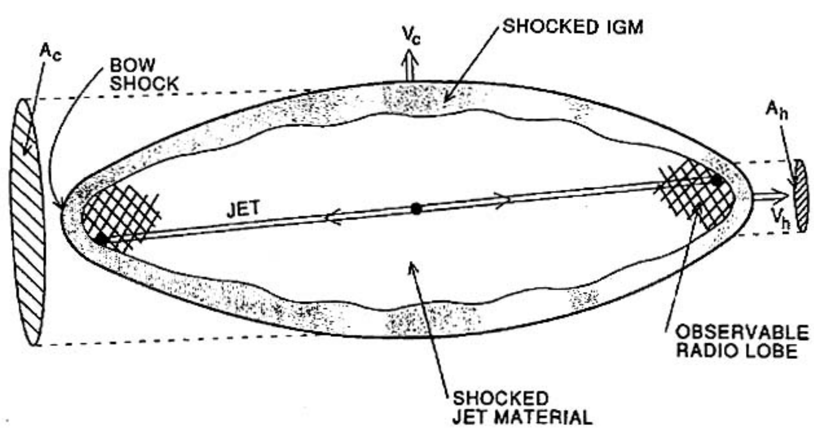
Why large scale jets important?

- Only ~ 1% of kinetic energy would be converted into radiation in sub-pc jet, as also implied from an internal shock scenario.

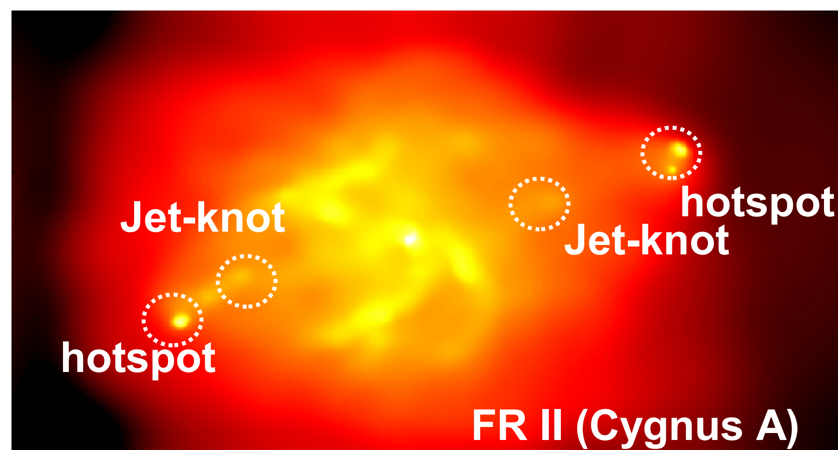
$$\begin{cases} L_{kin} \sim \pi R^2 c\, \Gamma^2_{jet} (u_e + u_B) \\ L_{rad} \sim 4\pi R^2 c\, (u_B + u_{rad}) \end{cases} \Rightarrow \frac{L_{rad}}{L_{kin}} \sim \frac{1}{\Gamma^2_{BLK}} \sim \frac{1}{100}$$

- An ideal laboratory for jet interaction, heating, and large-scale structure formation of hotspots and lobes.

  ➡ Recent X-ray observations adds NEW clues to jet physics!

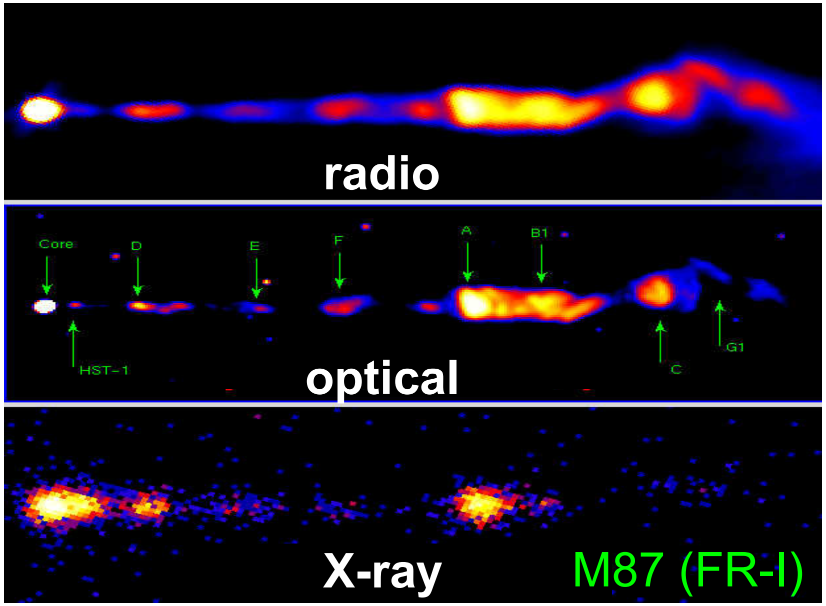


Jet model : Begelman & Cioffi 89

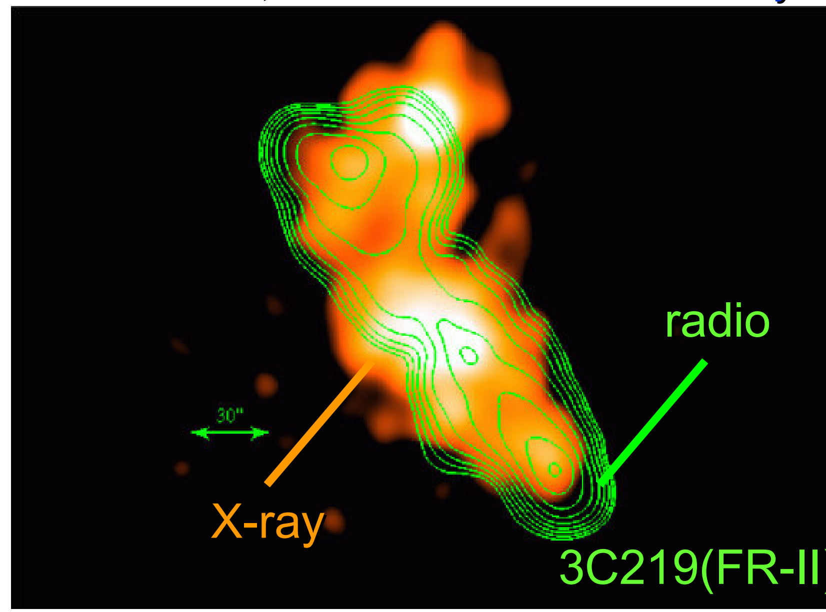


Chandra : Wilson+ 00

X-ray jets: Data Sample

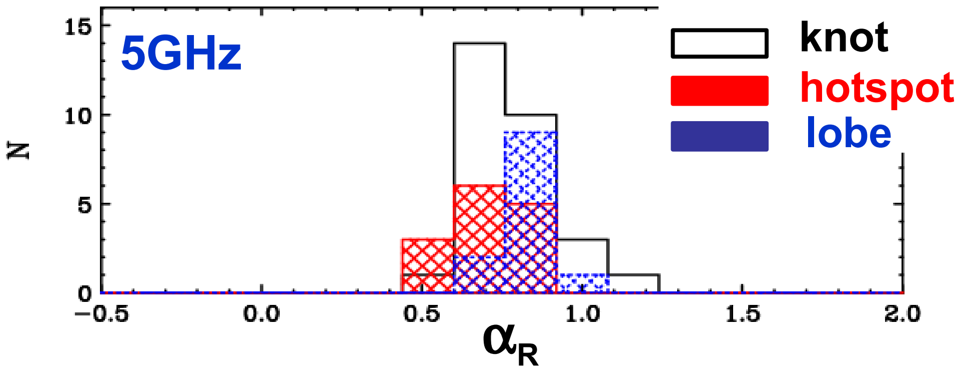


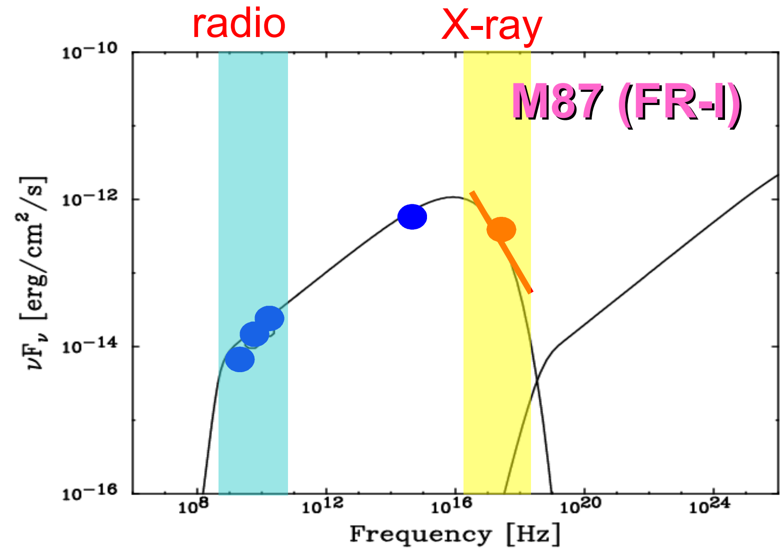
Marshall+ 02; Comastri+ 03 ... and many !

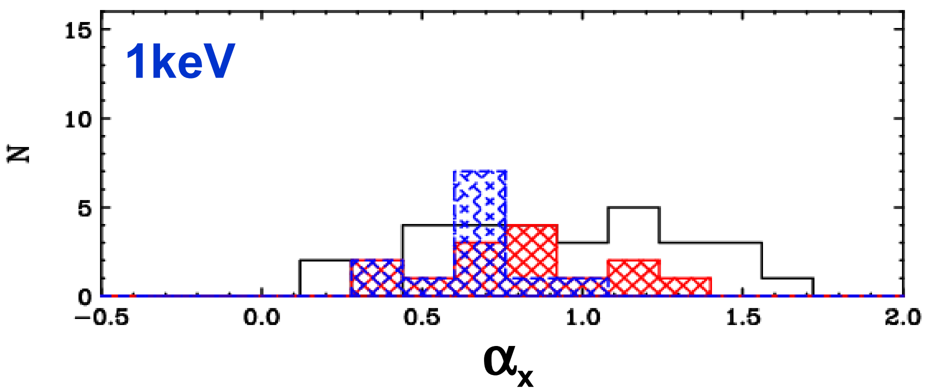


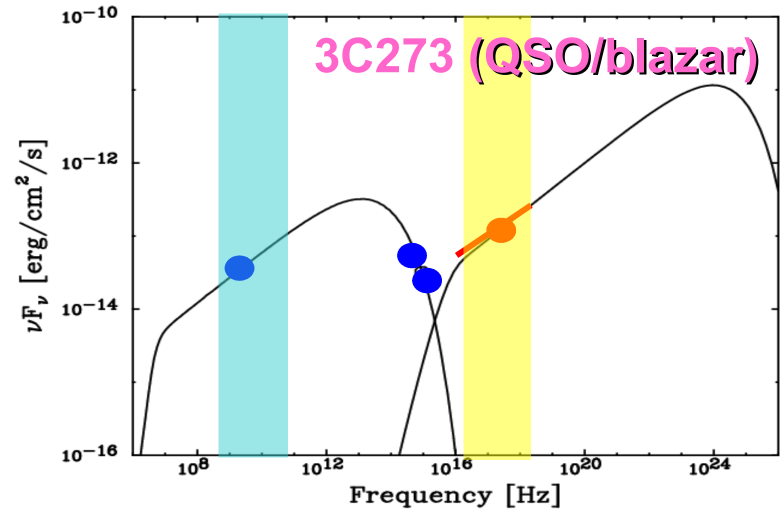
- 44 radio galaxies detected with Chandra/XMM by Dec.2004.
  (see http://hea-www.harvard.edu/XJET/index.cgi by D.Harris for most recent information. # of detected source reached to 75 as of June 2006!)
- 56 jet-knots, 24 hotspots, 18 radio lobes (ASCA+SAX).
- 13 FR-I, 13 FR-II, 14 QSOs, 4 blazars.
- Nearest: Cen A (z = 0.00183), Farthest: GB1508 (z = 4.3)

Radio-to-X-ray Comparison









- 5GHz spectral index $\alpha_R \approx 0.5\text{-}1.0$
  - ➡ A “canonical” Sync. spectrum.
- 1keV spectral index $\alpha_x \approx 0.2\text{-}1.7$
  - ➡ High-E end of Synchrotron (FR-I)
  - ➡ “beamed “IC/CMB” or SSC? *e.g., Tavecchio+ 00, Celotti+01*

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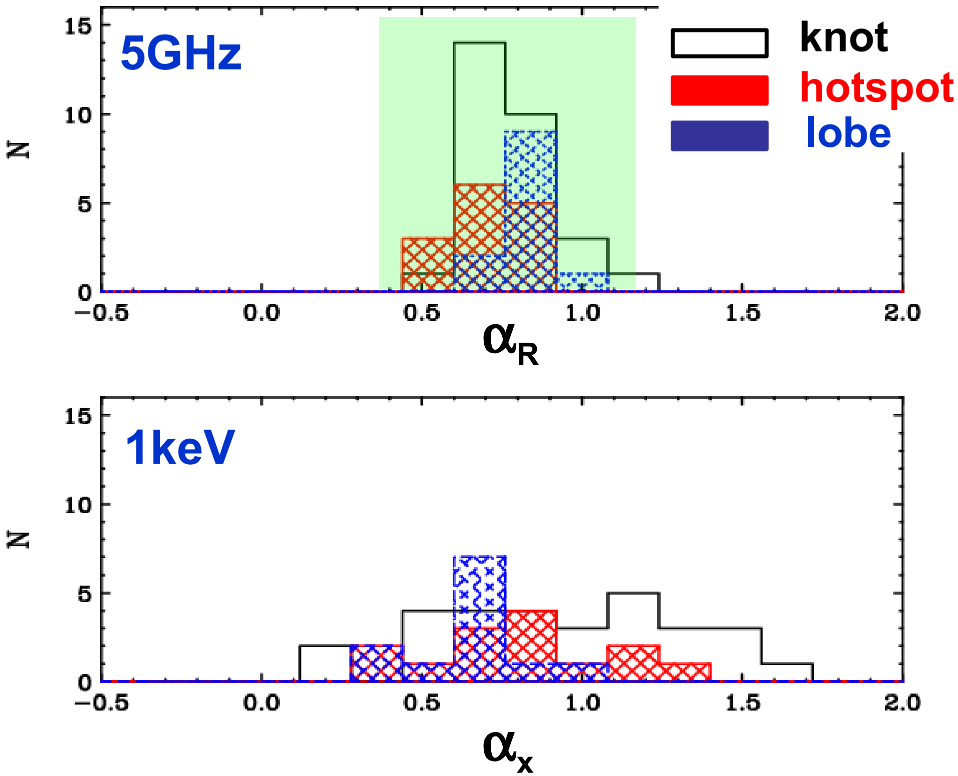

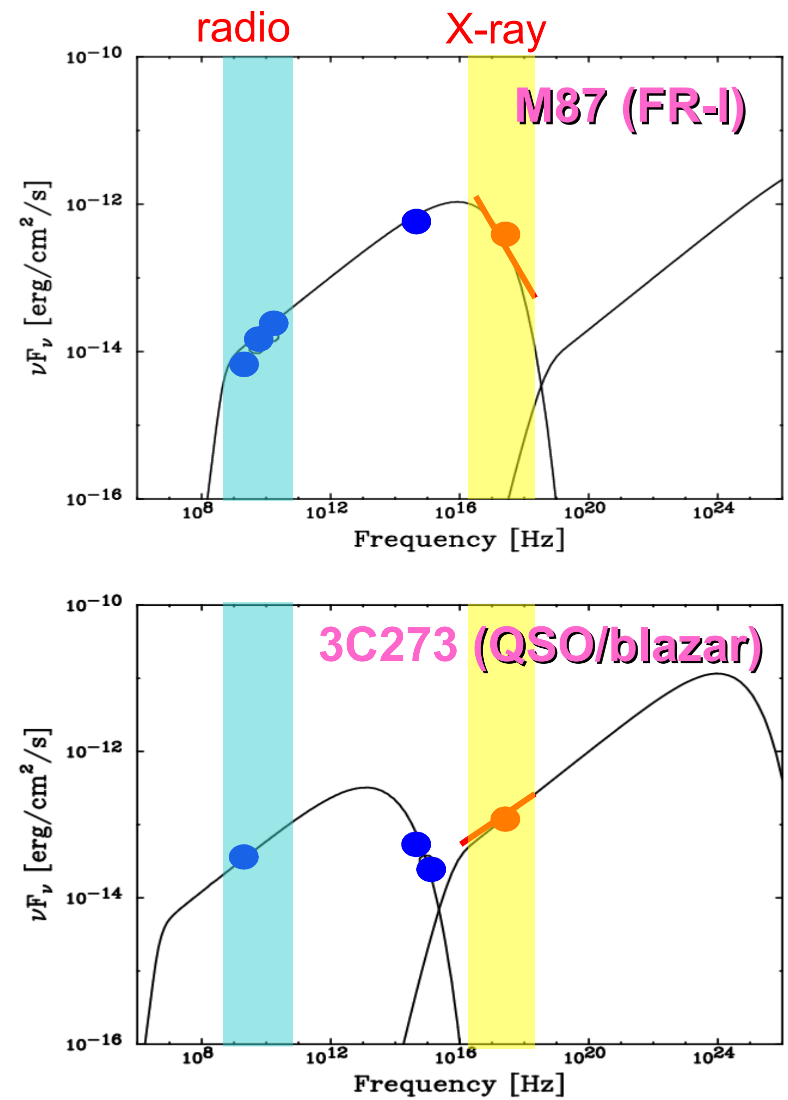

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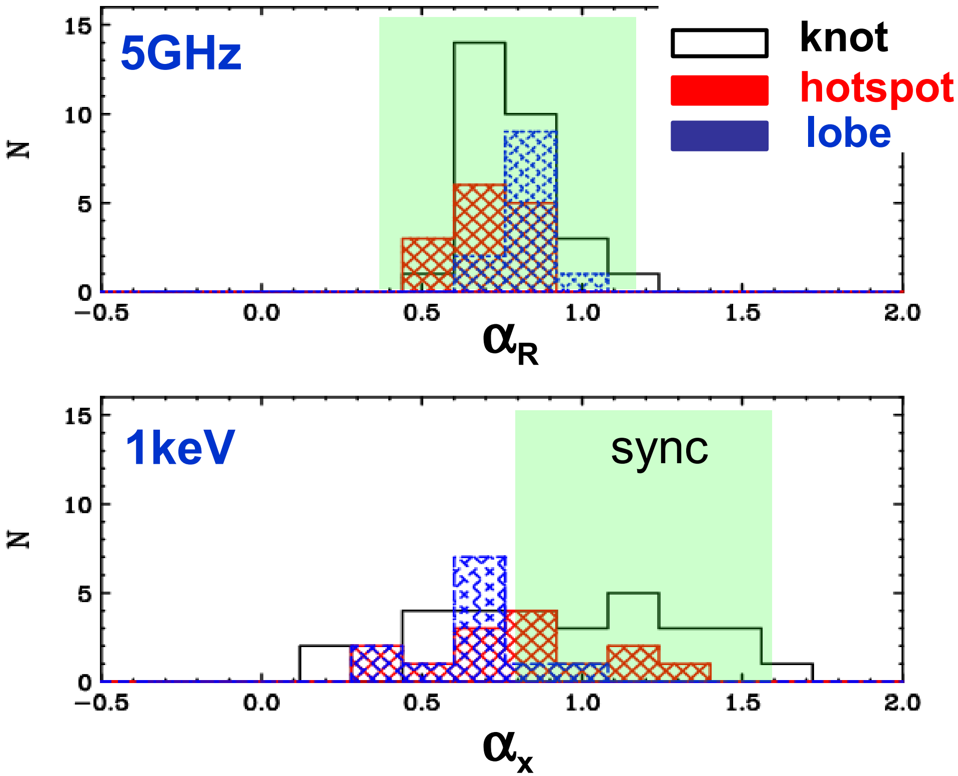

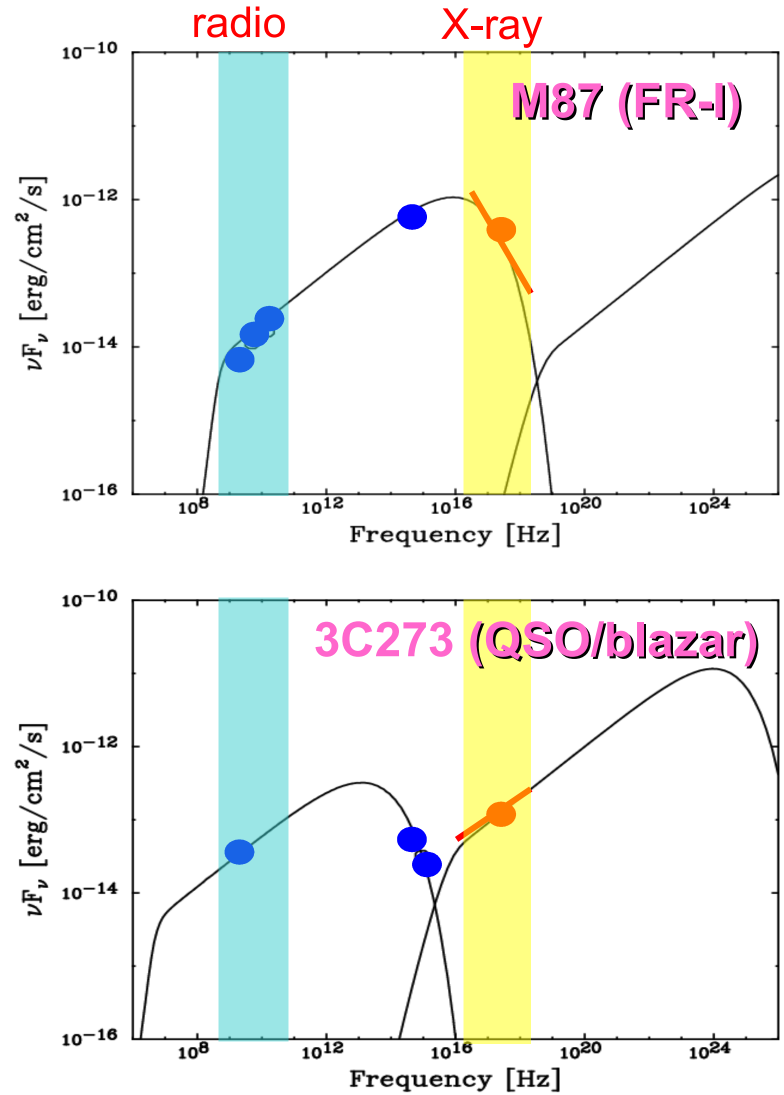

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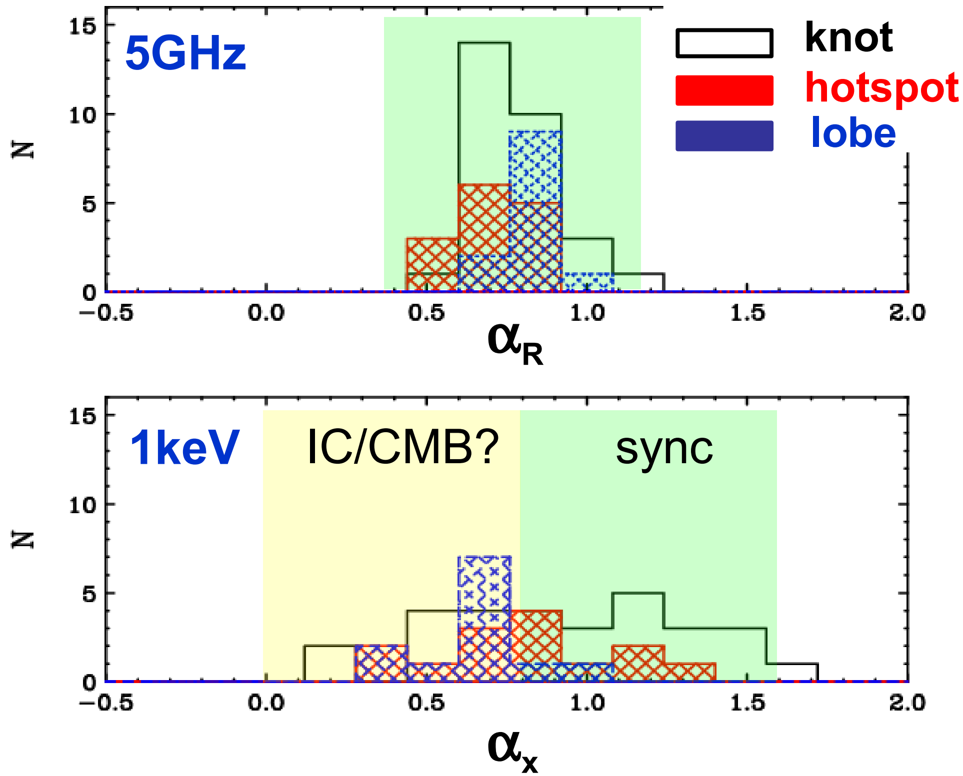

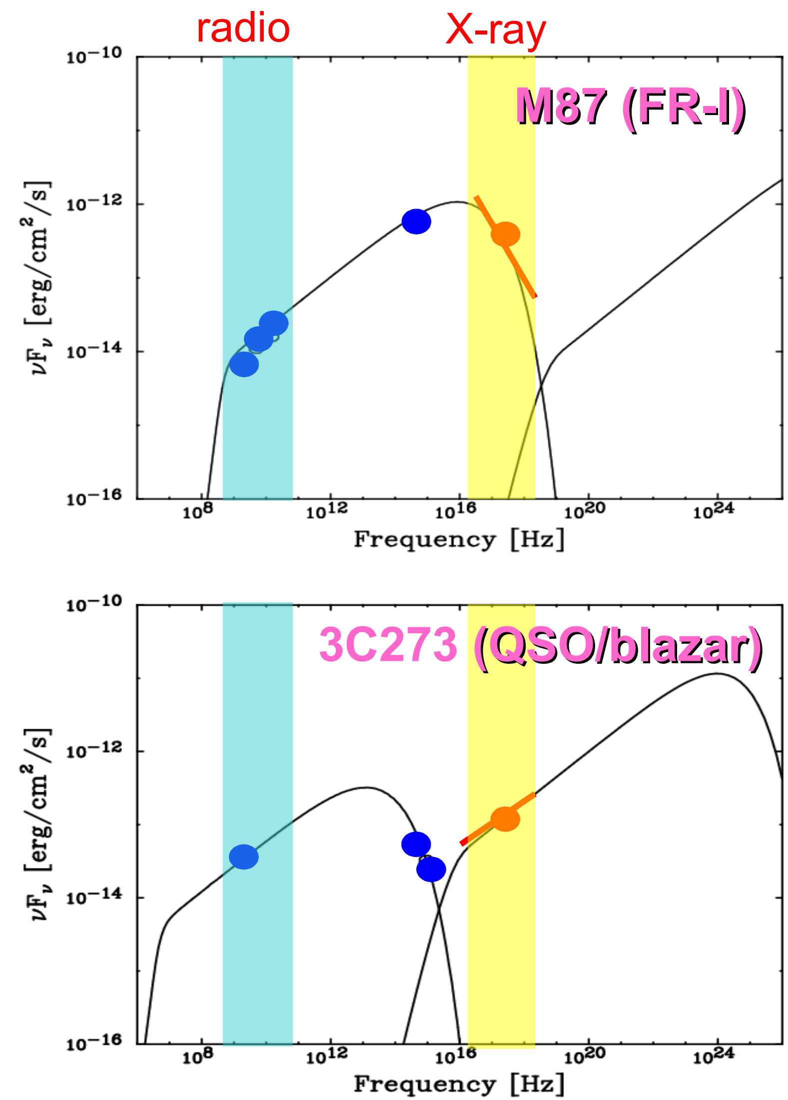

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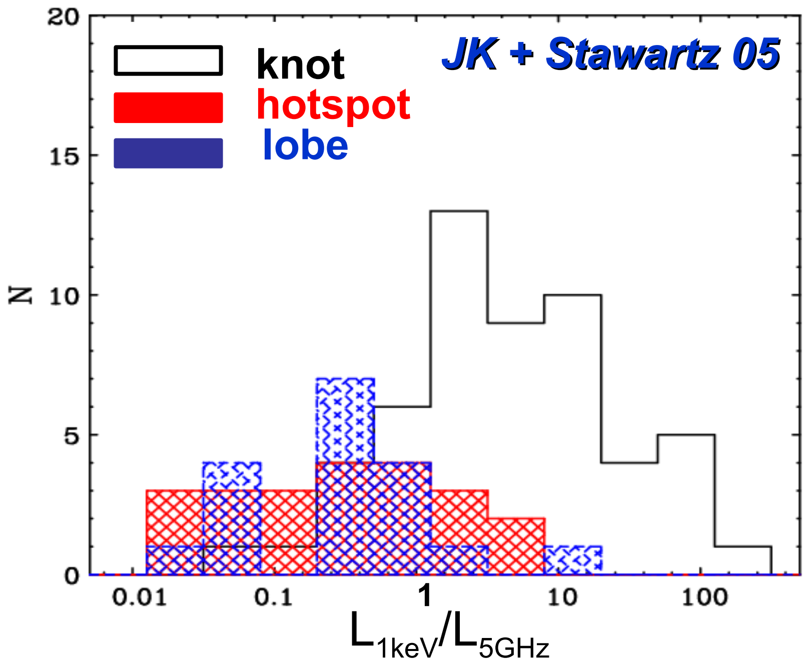
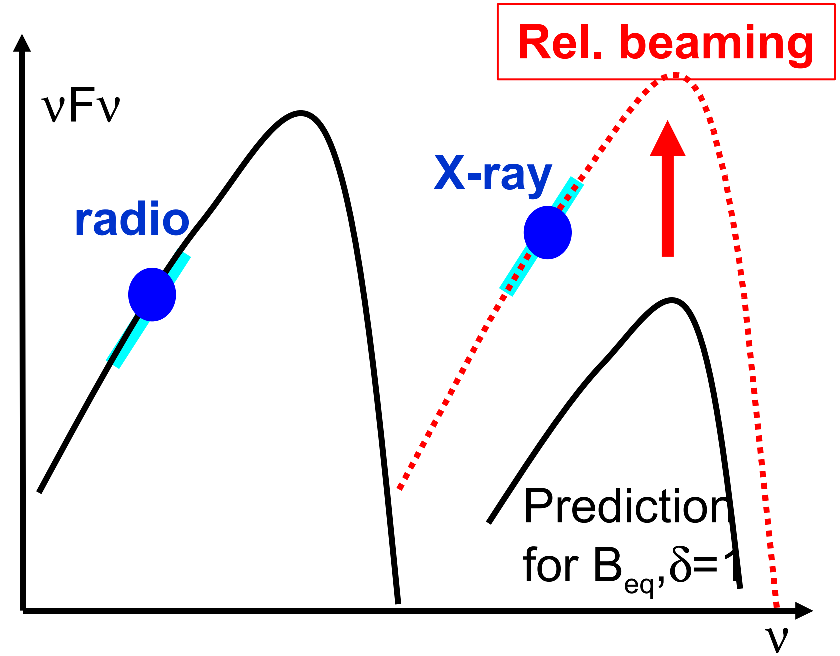
"Beamed" IC/CMB : Method





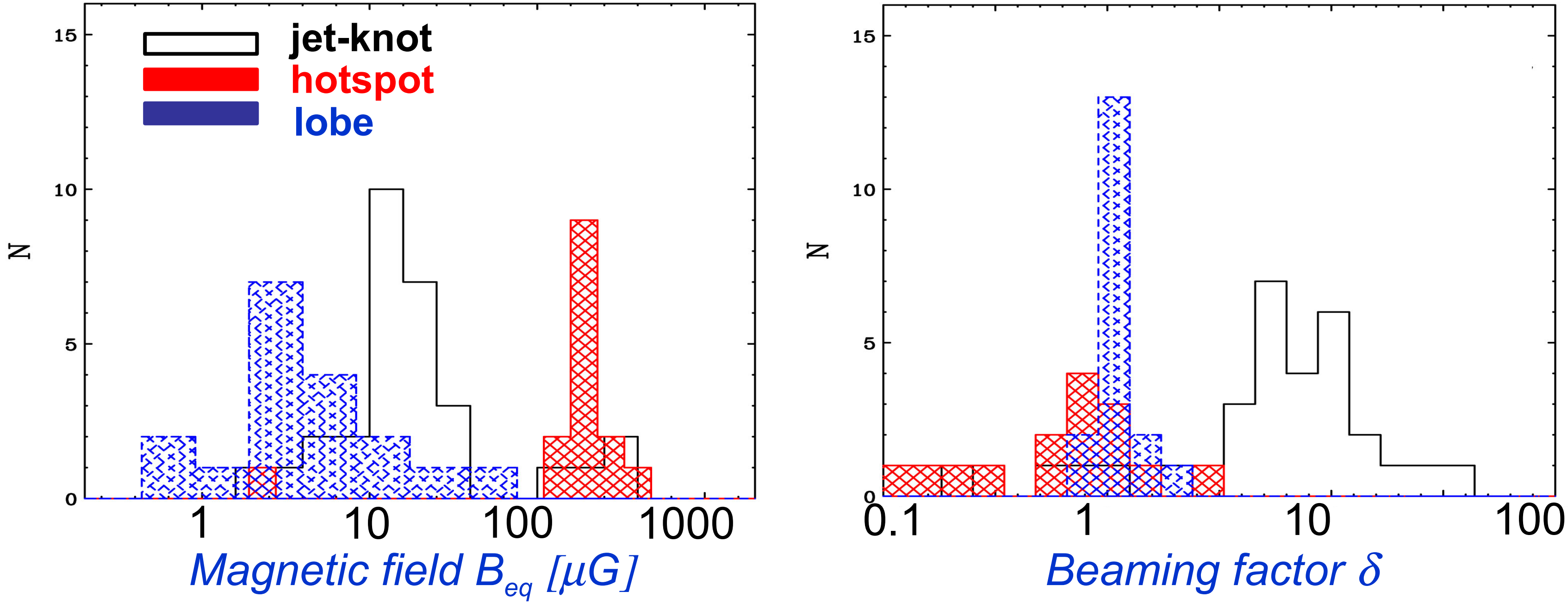
- Only jet-knots are bright in X-rays, in the sense $L_{1keV}/L_{5GHz} > 1$.
- Calculate "expected" X-ray fluxes for IC/CMB (or SSC for hotspots) production of X-rays in a homogenous region, under $u_e = u_B$.

We expect that...

- Too bright X-ray jet-knots could be explained by considering an appropriate beaming factor as $L_{IC/CMB} \propto \delta^3$ or $L_{SSC} \propto \delta^{-5/2}$.

Beamed IC/CMB : Results

JK+Stawartz 05 (also Hardcastle+04, Croston+05)



- Distribution of B_{eq} that can reproduce the radio/X-ray luminosities.
  - ➡ B-field is significantly enhanced in the hotspot?
- For the hotspots and radio lobe, $\delta \sim 1$ is expected, as expected from the "terminal point" of the jet. (assumption of $u_e = u_B$ is valid.)
- ***$\delta \sim$ 10 required*** for most of the jet-knots.
  - ➡ **Maybe jets are relativistic even on kpc-Mpc scales?**

also see, Sambruna+04

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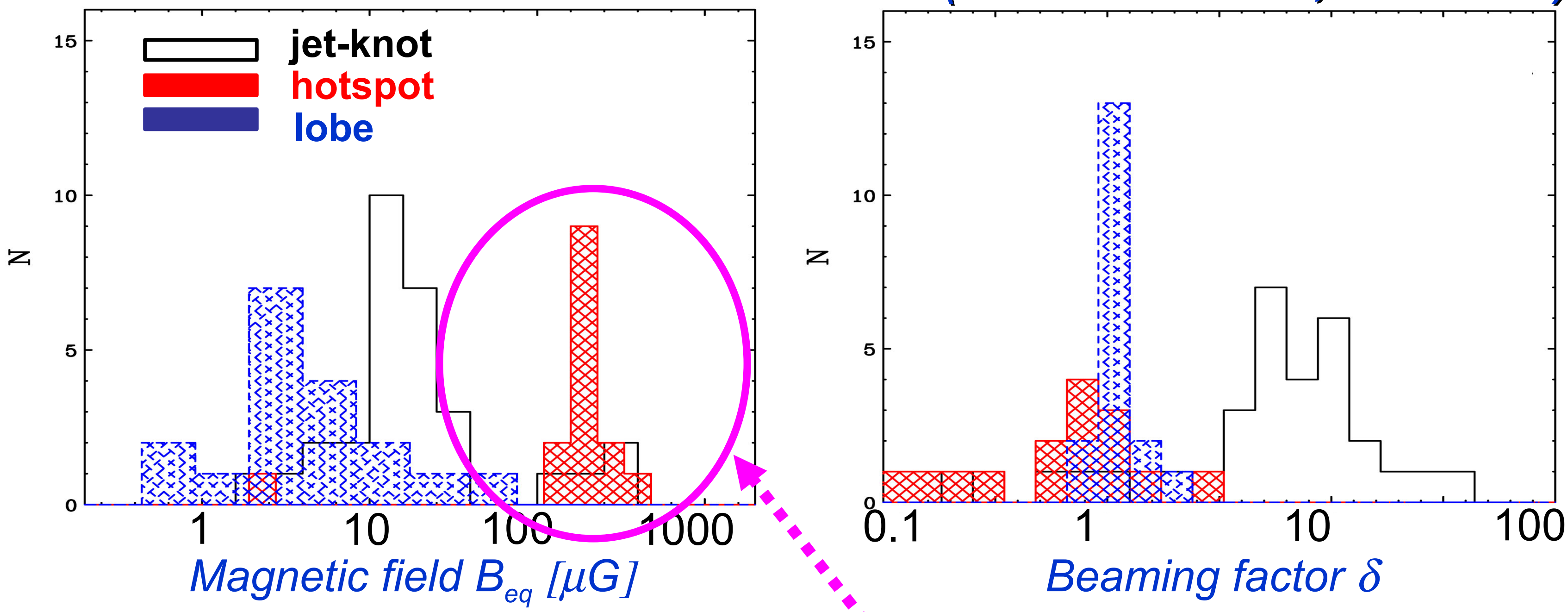

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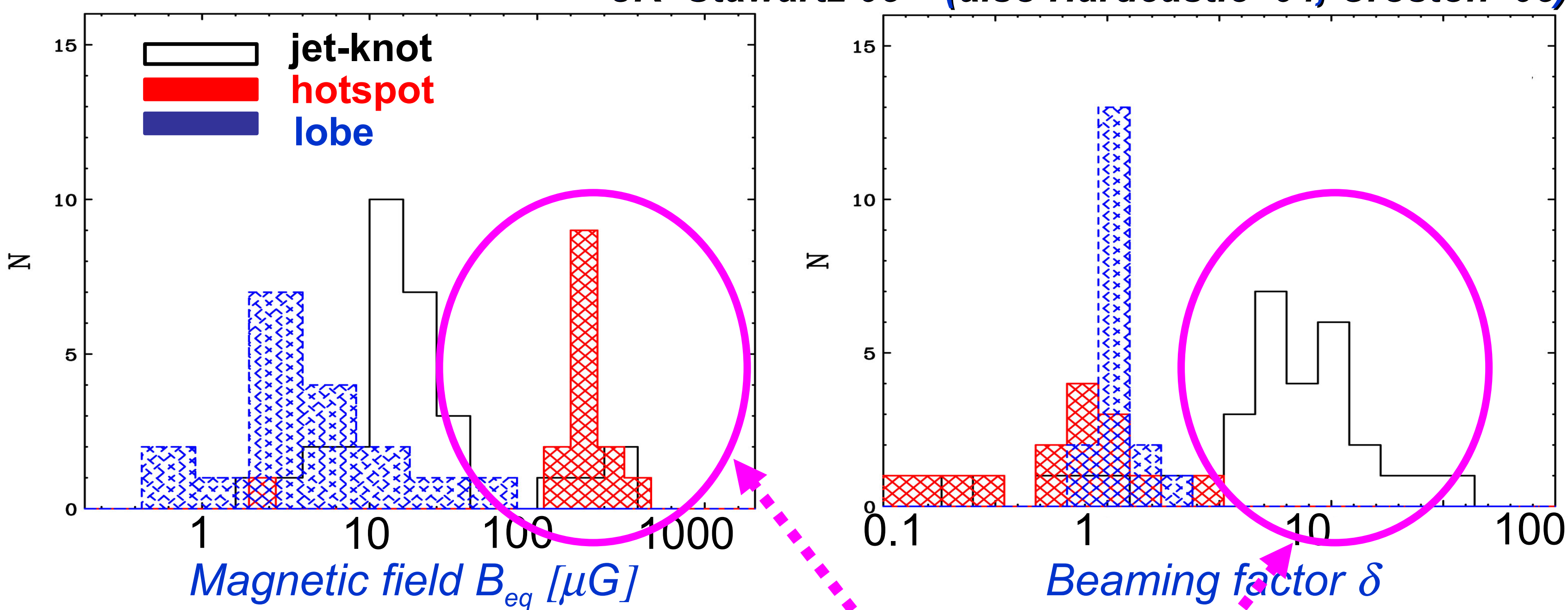

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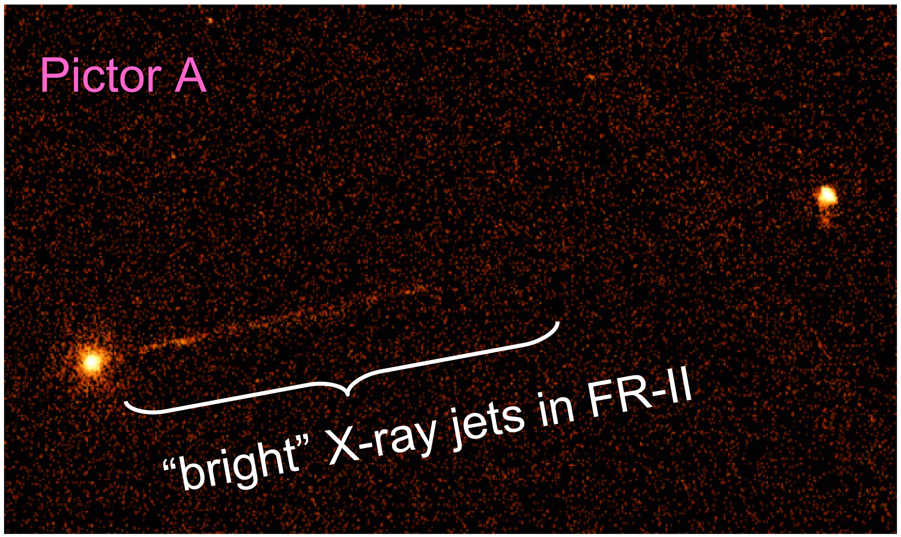
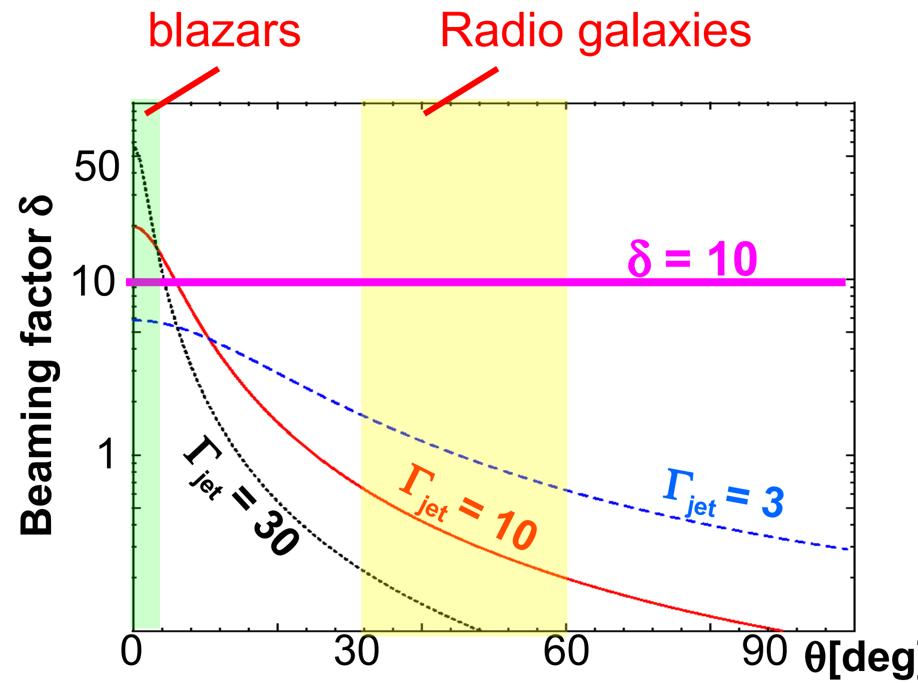
Warning Signal (1) : beaming?

Wilson+ 01



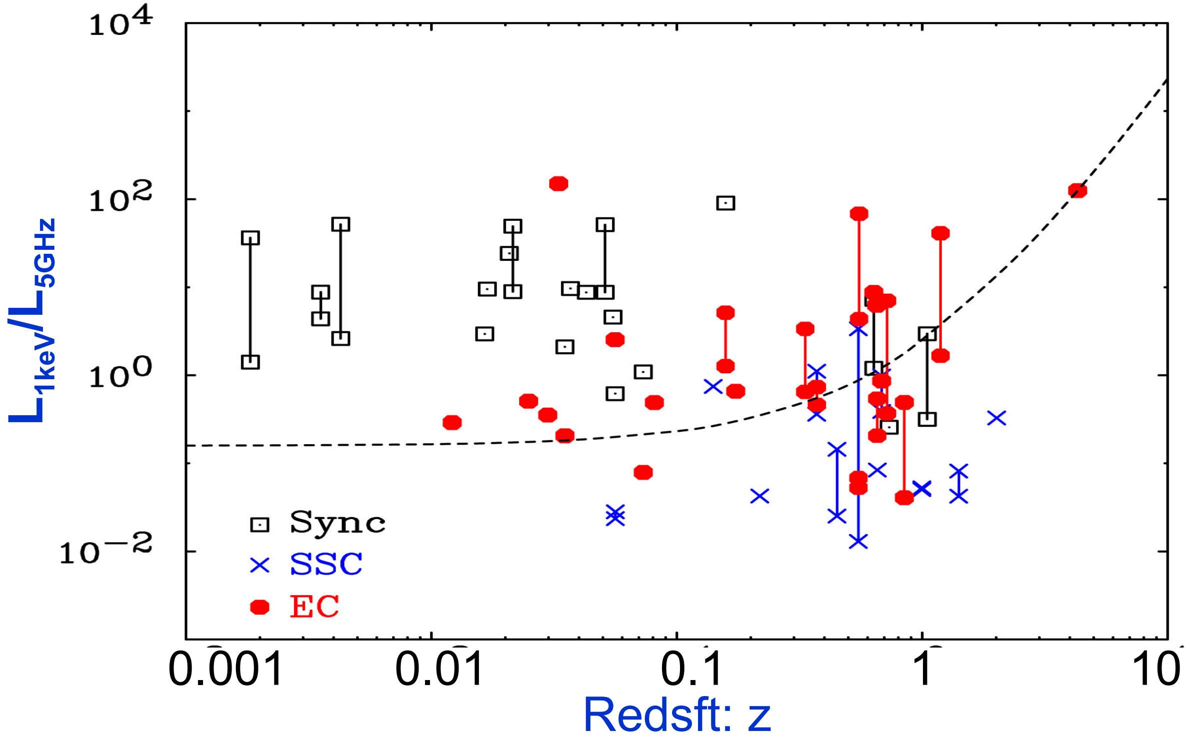


- Not only powerful QSOs (e.g.,PKS0637, 3C273), but also several FR-II jets are "bright" in X-rays (Pictor A; *Wilson+ 01*, 3C303; *JK+ 03 etc* …).

- The X-ray enhancement due to relativistic beaming is **hardly expected**, as viewing angles of FR II are generally large!

- If we give up "$u_e \sim u_B$" assumption, the magnetic field must be as small as **$B \sim 0.01\ B_{eq}$**, meaning that **$u_e \sim 10^8\ u_B$** for extreme cases!.

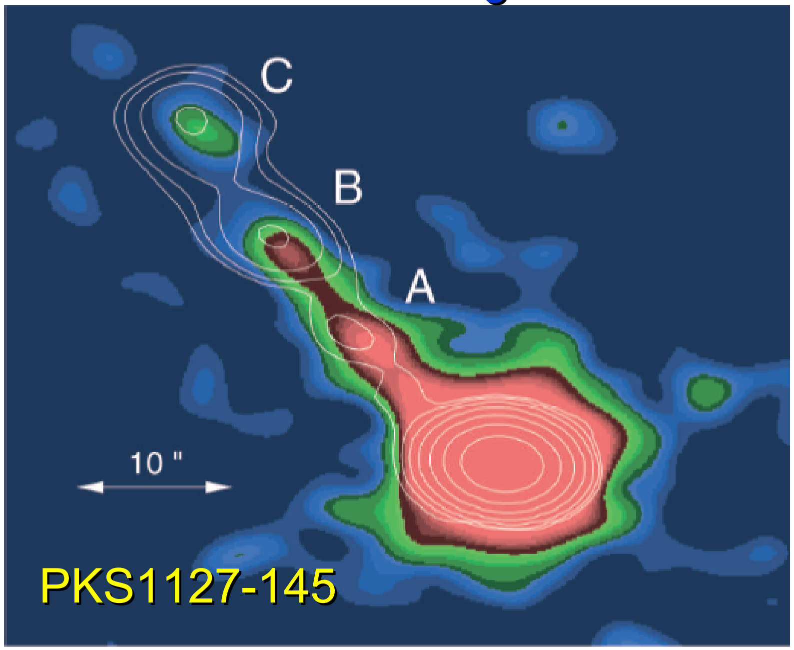
Warning Signal (2) : z-dependence?

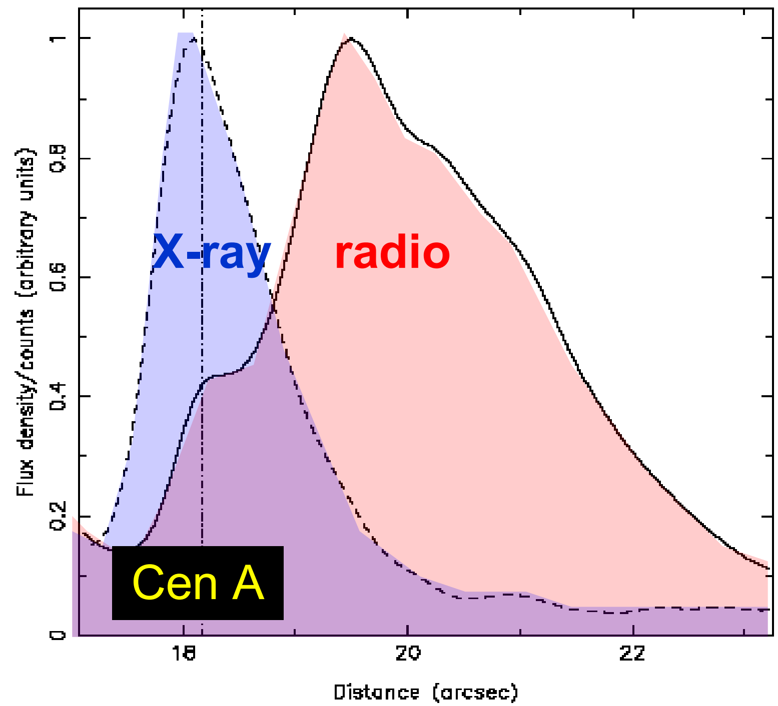


JK & Stawarz 05, see also Marshall+ 05

- prediction from IC/CMB: $\frac{L_X}{L_R} \propto u_{CMB} (1+z)^4 \delta^2$
  - "Distant jets should be brighter in X-rays"
- No such trend ?… large variations even in same objects.
  - "deceleration" ?, but many difficulties! *(e.g., Hardcastle 06)*

Warning Signal (3) : offset?

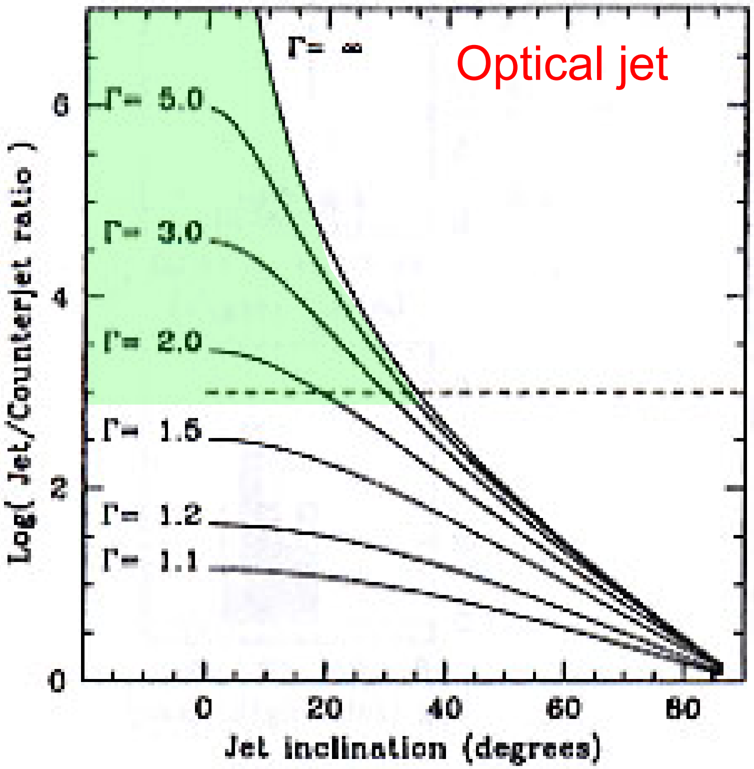




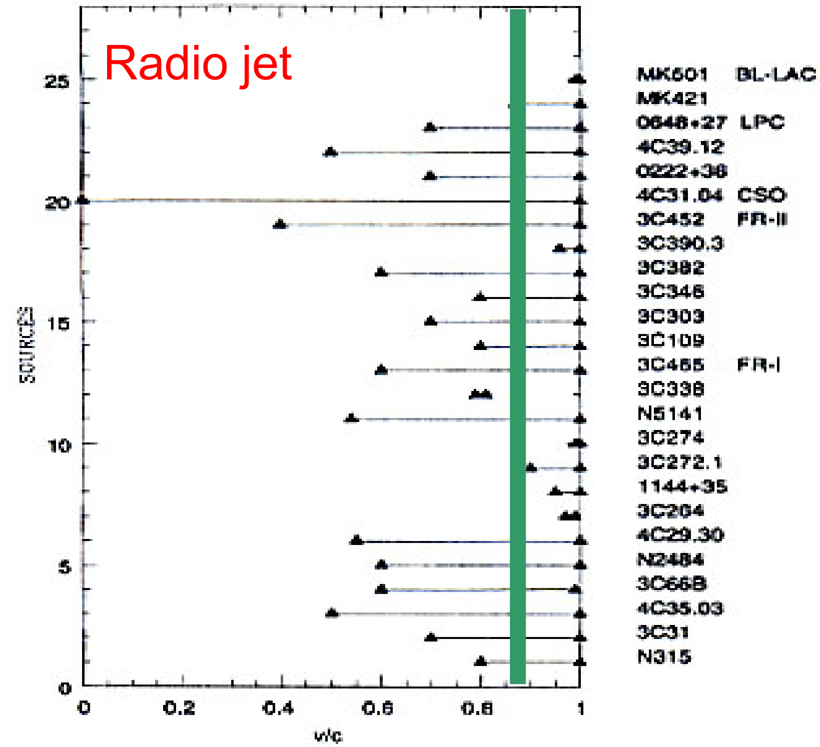
- Many jet sources show "offsets" between radio and X-ray peaks, in most cases, X-ray peak intensities "precede" the radio.
  - ➡ Reality of one-zone model? (different jet structure?)
  - ➡ X-rays emission process other than IC/CMB?

Warning Signal (4) : jet speed?

Scarpa & Urry 02



Wardle & Aaron 97, Giovannini+ 01

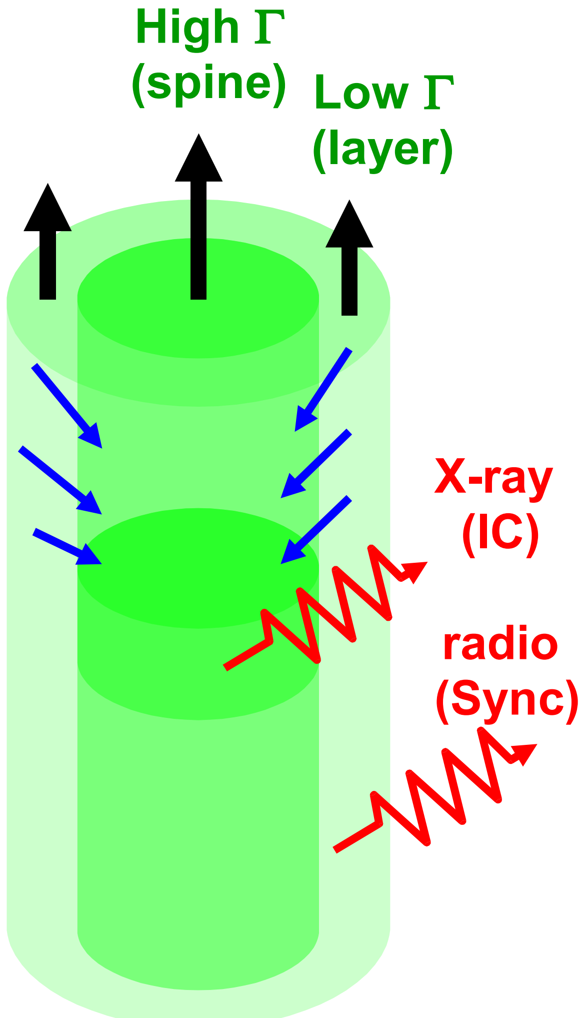


- From the optical/radio measurements of jet/c-jet ratios in sub-pc/kpc scale jet, most probable values for the jet speed and inclination are:

  β = 0.90-0.99, $\theta \sim$ 20 deg ➡ **$\Gamma_{jet} \lesssim$ 5 , $\delta \sim$ a few**

- Even powerful QSO jets may NOT so fast on kpc-Mpc scales!

Stratified Jet? : IC/CMB Model

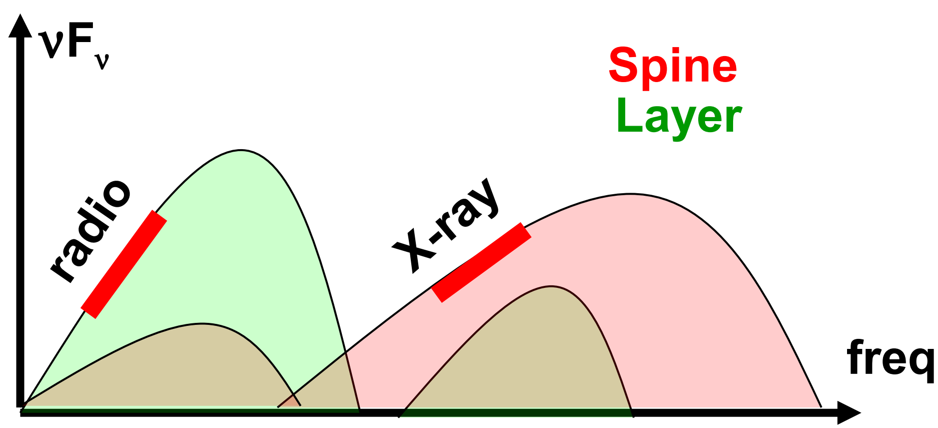


- Two-zone jet models (e.g., Celotti+ 01):

✓ "fast spine" + "slow layer (sheath)".
✓ Not only CMB, but emission from slow layer contributes as "seed photons".

■ Basic idea:

✓ slow layer ➡ Radio (sync)
✓ fast spine ➡ X-ray (inv Comp)

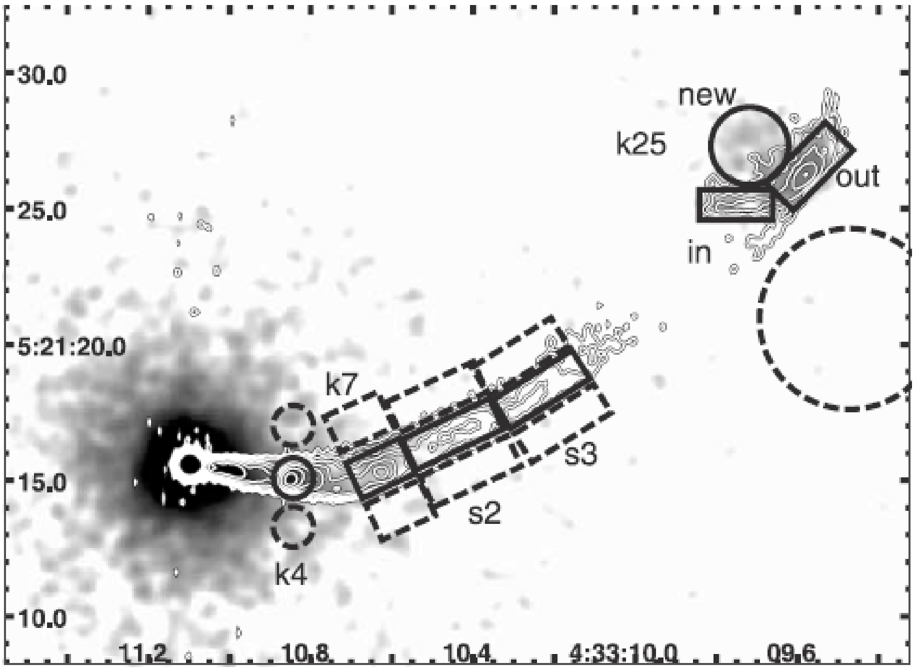


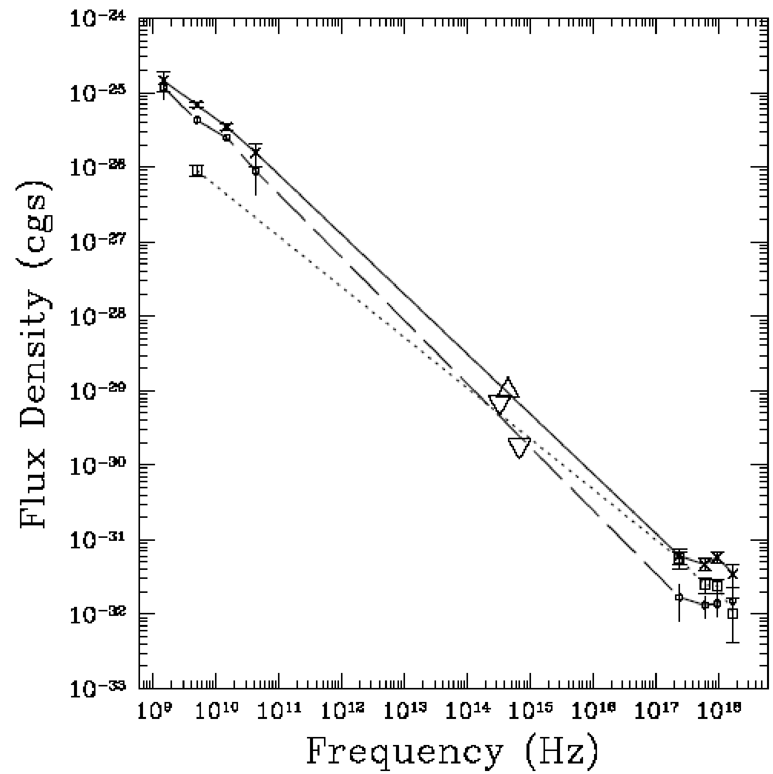
■ However….

✓ X-ray spectra significantly softer than radio.
✓ in order to reproduce 3C273 knot-A,
Γ_{spine} ~ 50-100 ! (see, Jester+ 06)

3C120: "Non-standard" Sync ?

Harris+ 04

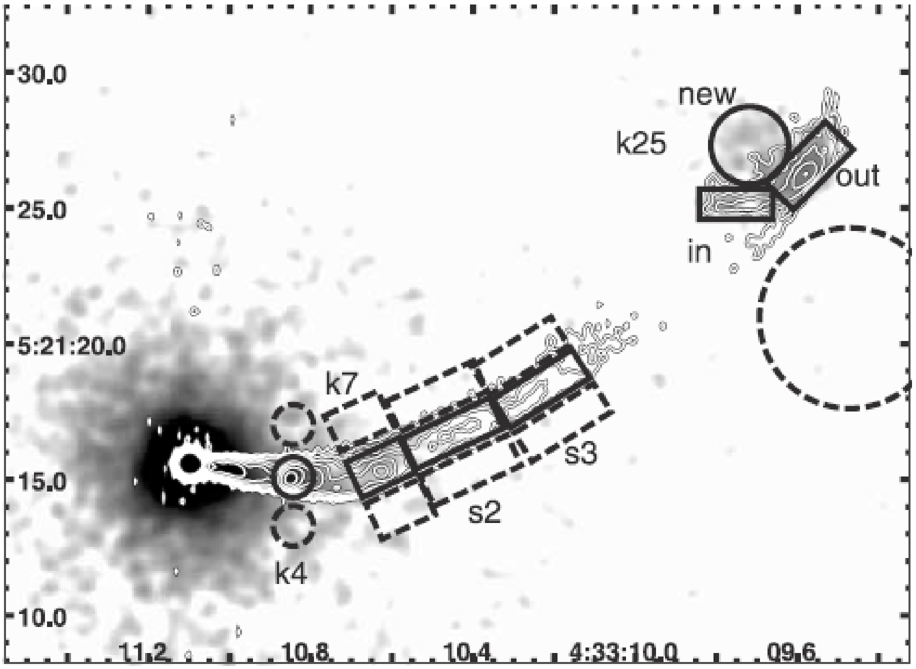


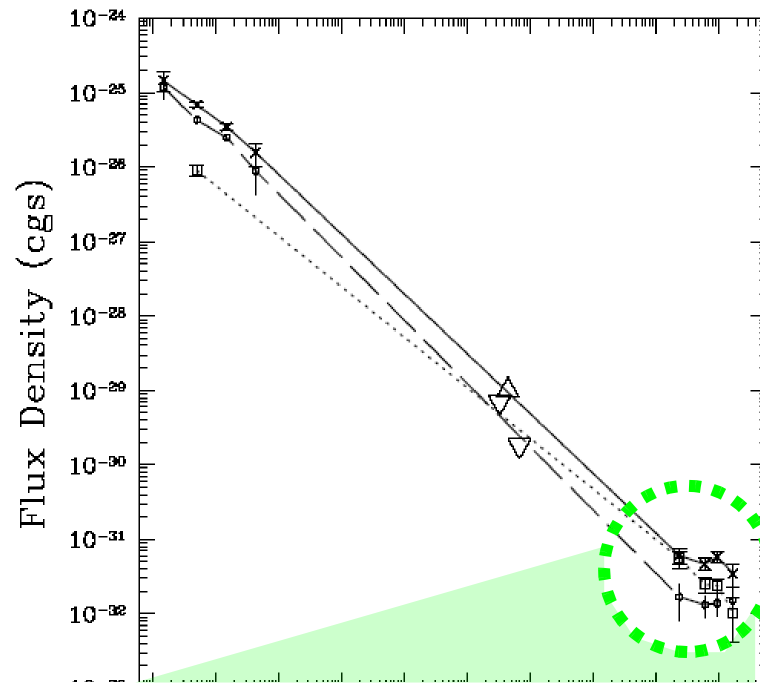


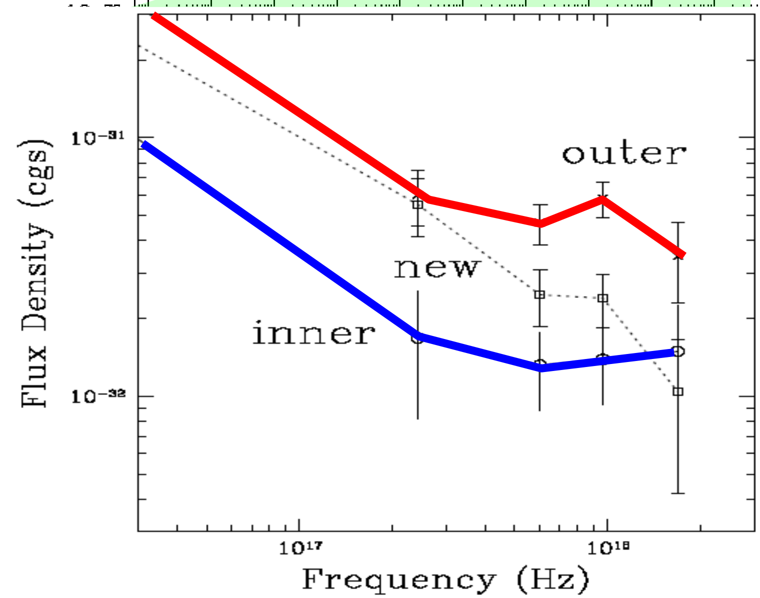
- Convex X-ray spectrum for k25.
- Difficult to explain either by conventional Sync or IC/CMB model! *(Harris, Mossman, Walker 04)*

3C120: “Non-standard” Sync ?

Harris+ 04







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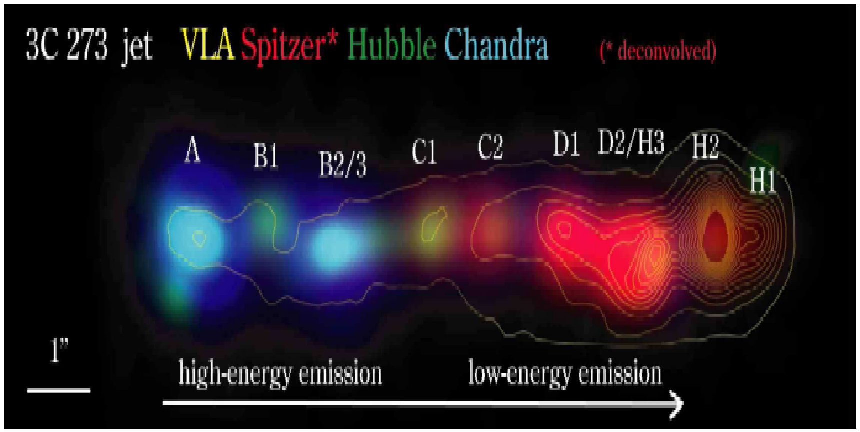
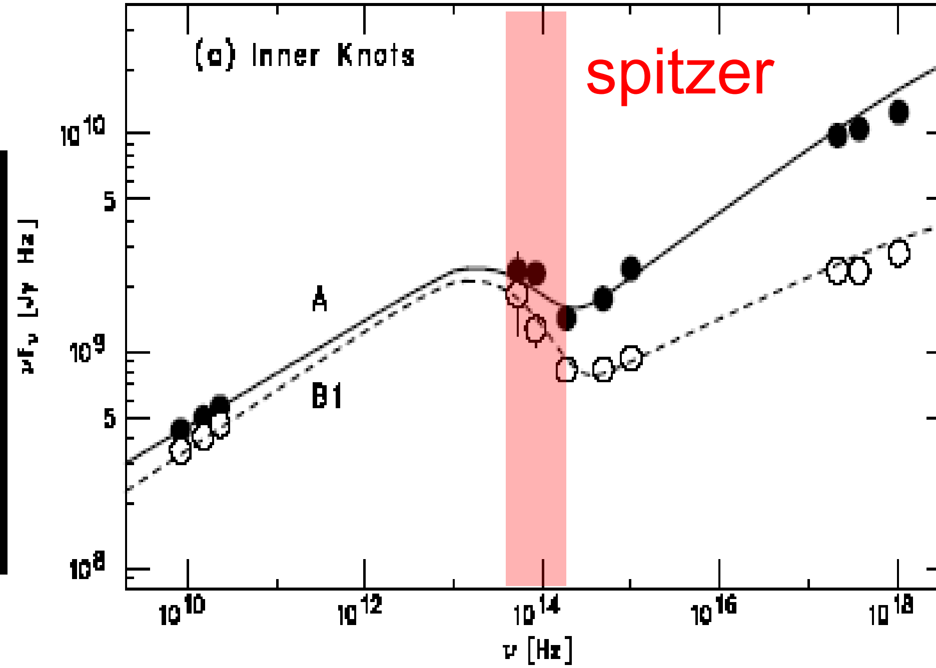
"New" Evidence for "Sync X-ray Jet"

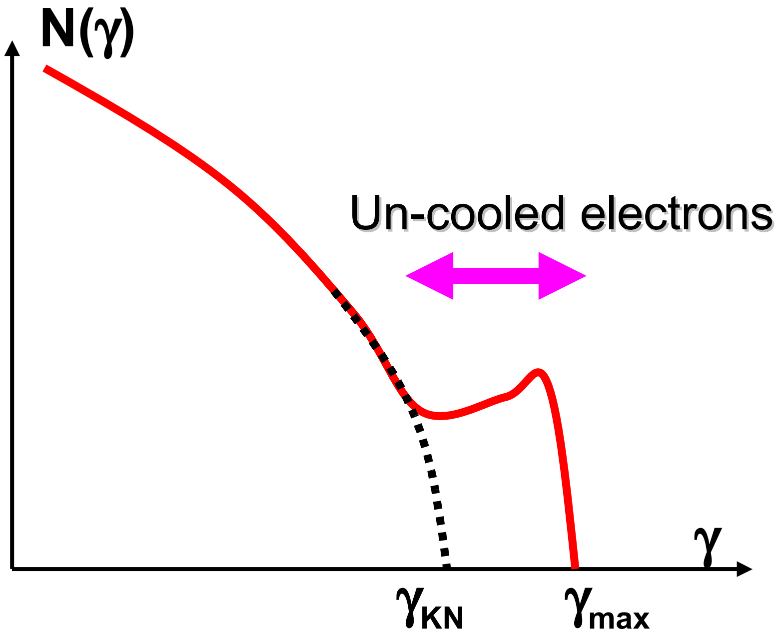
Uchiyama+ 06, poster #49



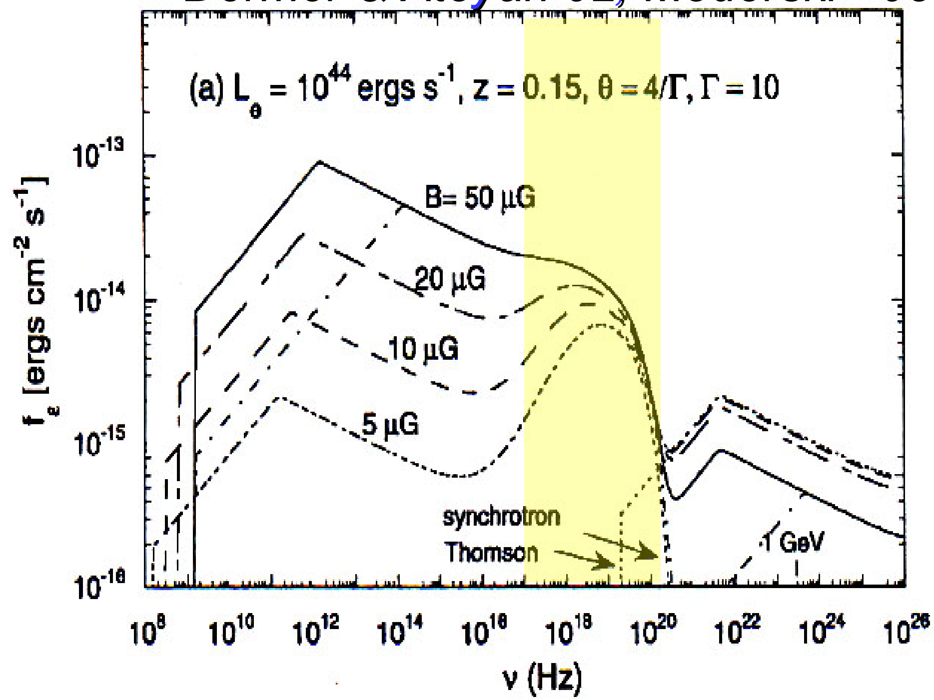


- IR imaging of the jet of 3C 273 by *SPITZER* clearly confirms that the optical jet emission is dominated by the 2nd, high E component.
- Both the radio and optical components are linearly polarized to a similar degree of ~ 15%, most likely Sync in origin.
- Due to a smooth connection between optical and X-rays, X-ray jet is possibly Sync in nature (leptonic? hardronic? still under debate!)

Sync X-ray bump in KN regime?

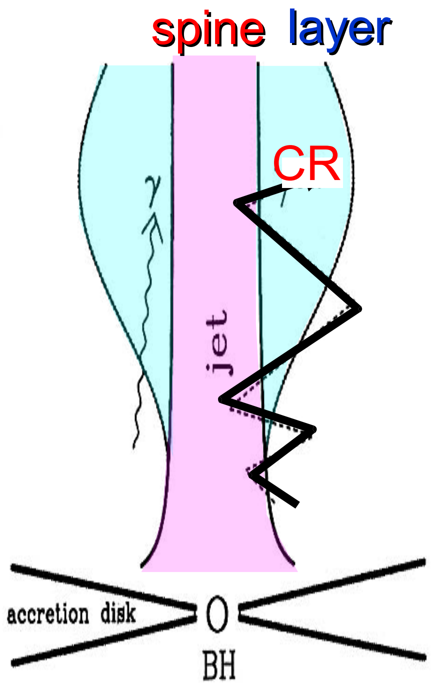


Dermer & Atoyan 02, Moderski+ 05



- Assuming electrons lose energy predominantly due to IC radiation.
  - ➡ IC cross section reduces significantly in the KN regime compared to a canonical **$d\gamma/dt \propto \gamma^{-2}$** relation.
  - ➡ Very high energy electrons, $\gamma_{KN} < \gamma < \gamma_{max}$, do not cool effectively, that may result in a “characteristic bump” observed in X-rays.

Turbulent Acceleration?



- Again, stratified jet! – "spine" + "layer".
- Accel. process in layer is quite different.

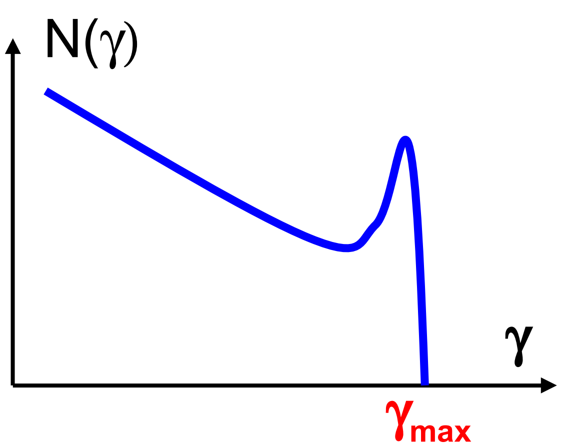
$$t_{acc} \sim \frac{3\lambda_e}{c}\left[\frac{c}{V_A}\right]^2 \sim 5\mathrm{x}10^9\,\gamma_8\,B^{-1}_{100\mu}V^{-2}_{A,8}\ \ [s]$$

$$t_{esc} \sim 3\left[\frac{L}{V_A}\right]^2\frac{c}{\lambda_e} \sim 6\mathrm{x}10^{15}\,\gamma_8^{-1}\,B_{100\mu}L^2_{100pc}\ [s]$$

➡ $t_{esc}/t_{cool} \sim 10^7\ (B_{100\mu G})^3\,(l_{100pc})^2\,\zeta^{-1}$

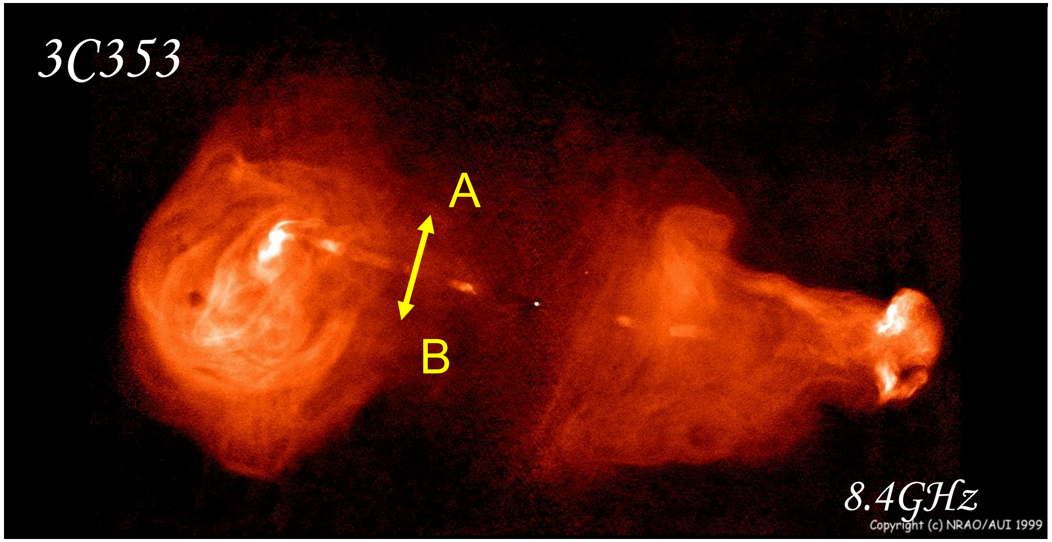
where $\zeta = U_B/U_T$

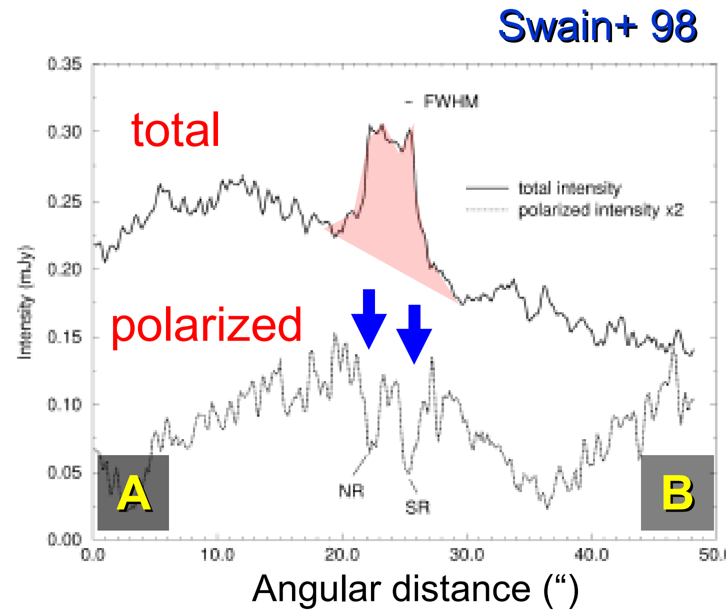
- If field is very turbulent ($\zeta \sim 1$), electrons "pile-up" as it never escape from the region.
  - ➡ different spectra in spine/layer.
  - ➡ observed hump in X-rays?



Ostrowski 00, Stawarz & Ostrowski 02

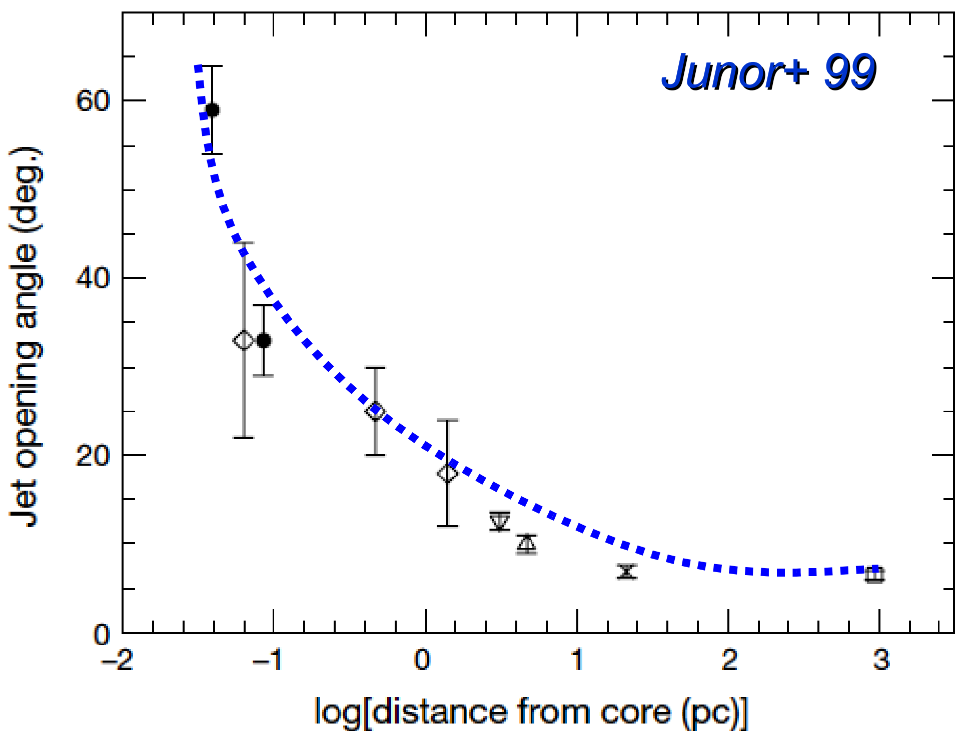
Stratified Jet : Radio Observation of 3C353

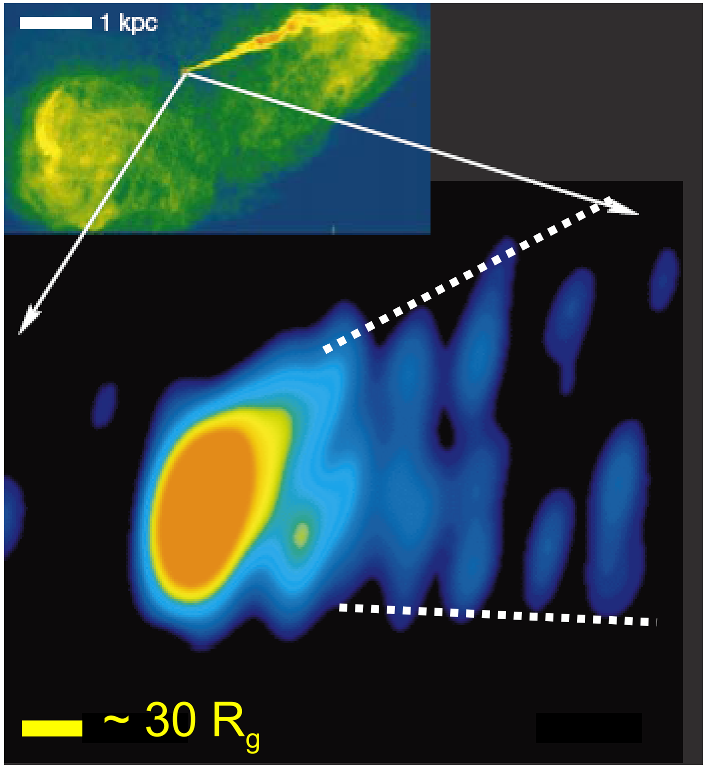




- VLA observation of FR-II radio galaxy 3C353 at 8.4 GHz.
  - **“Flat topped”** total intensity profile.
  - The polarization **“rails”** at the edges of jets.
    (result from vector cancellation between polarized jet emission and orthogonally polarized lobe emission?)
- Most of the jet emission comes from a thick outer layer, rather than the fast spine?

M87 : Jet Launching Site





- VLBI observations of M87:

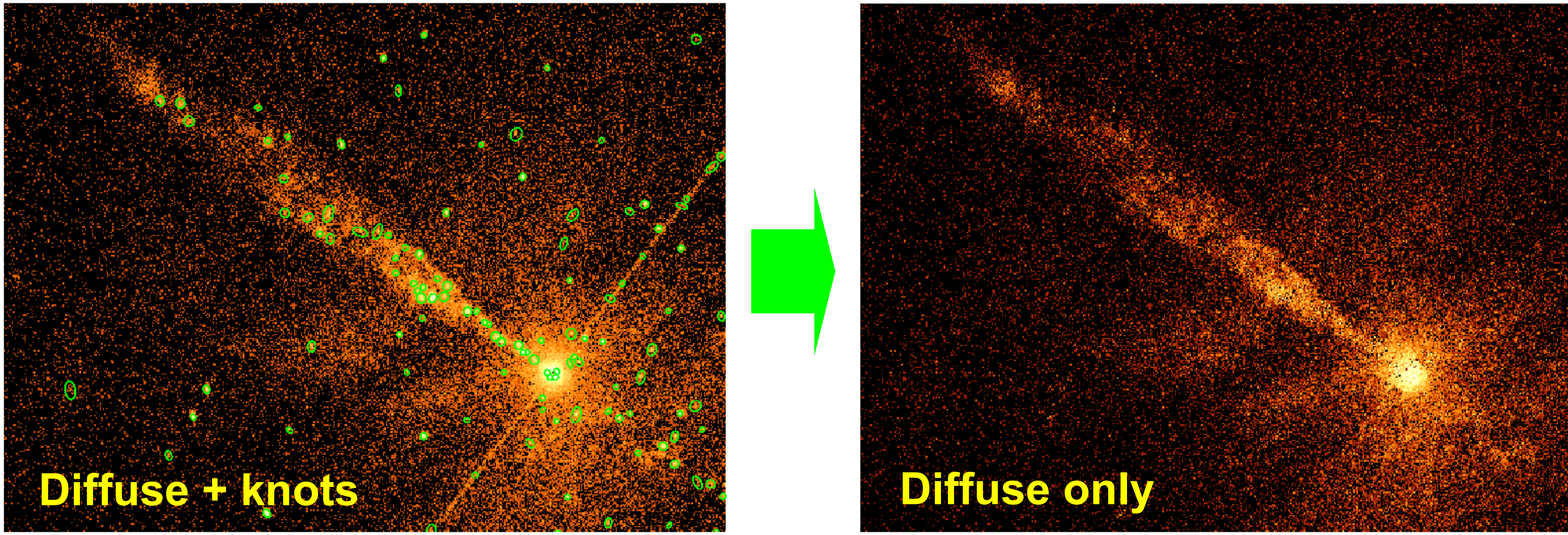
✓ evidence for Jet formation, and collimation at ~ 30-100 R_g scales.

➡ Jet are formed by an accretion disk?

- Another important discovery:

✓ evidence for "limb-brightening" in jets even at sub-pc scale.

Diffuse X-ray Emission of Cen-A Jet



JK+ 06, see also Hardcastle 03

- A deep Chandra observation of Centaurus A.
  - Nearest AGN (d_L = 3.4Mpc, 1" = 18 pc).
  - An ideal laboratory for investigating the transverse jet structure.

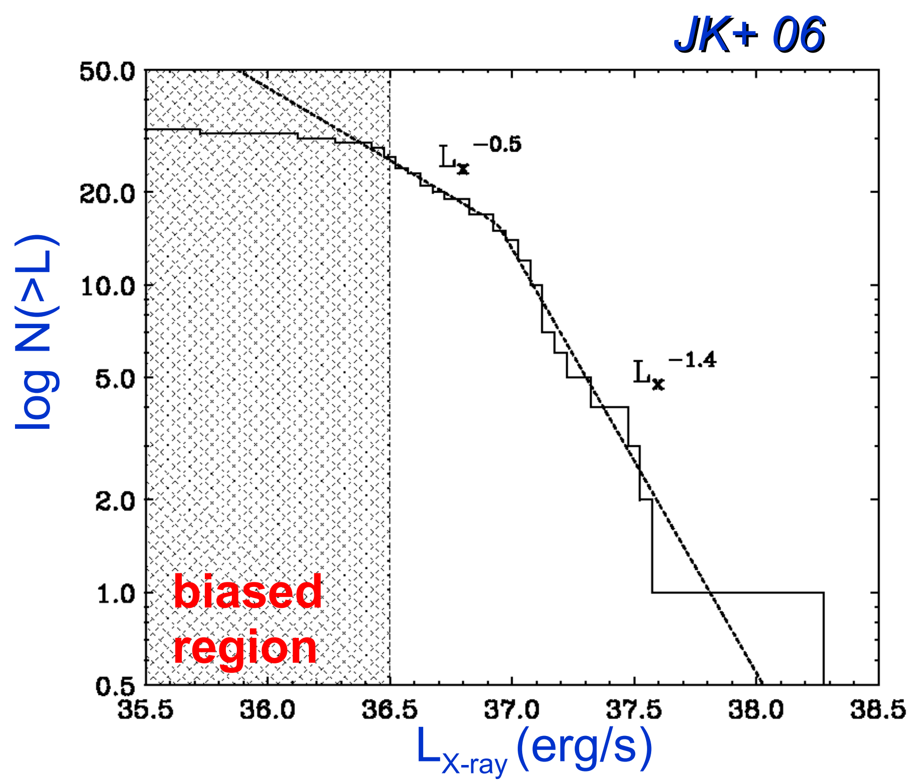
- 41 jet-knots of 0.5"~4" size were detected and REMOVED. "Holes" after removing the jet-knots were interpolated by surrounding pixels.
  - Finally obtain an X-ray jet image for **DIFFUSE emission only.**

Diffuse or Unresolved?

- Some fraction of extended emission may be explained by the pile-up of small scale knots.

Need Log-N/Log-S study!

$$N(>L) \propto \begin{cases} L^{-0.5} & (L < L_{brk}) \\ L^{-1.4} & (L > L_{brk}) \end{cases}$$



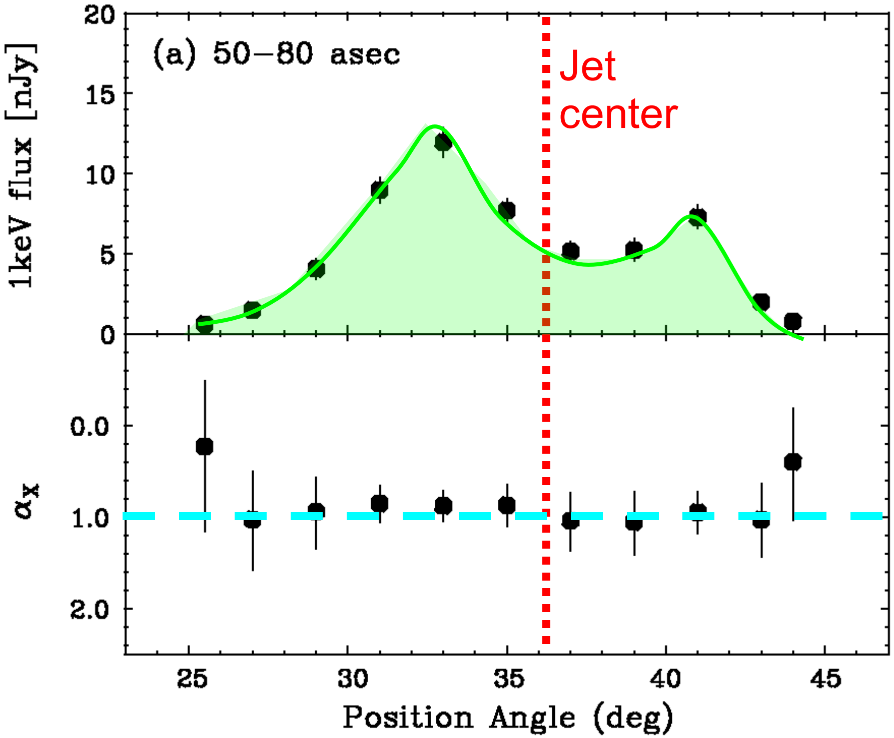
$$L_{total} = \int_{L_{min}}^{L_{max}} N(>L)\, dL \quad \cdots\cdots \quad L_{total} < 8.1\times10^{38}\ \text{erg/s}$$

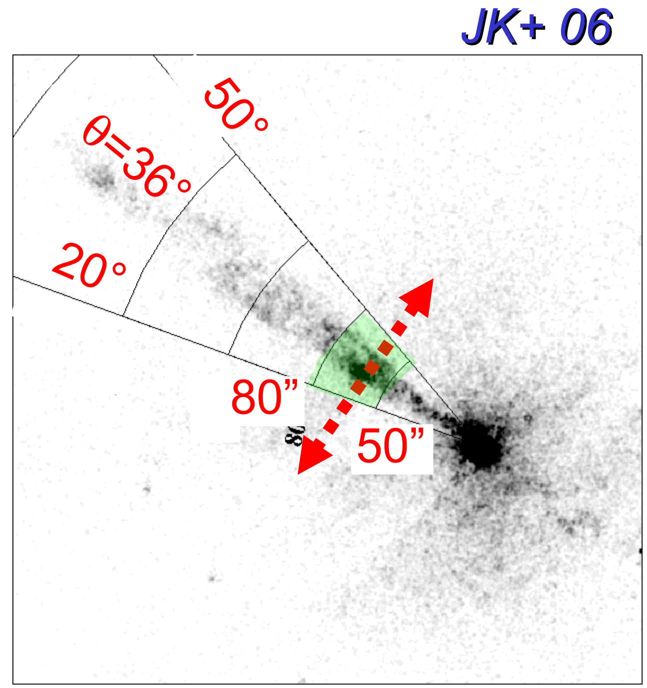
vs. X-ray Jet total : $L_{jet} = 1.6\times10^{39}$ erg/s

✓ "Really diffuse" emission accounts for ~50% of total luminosity.

✓ Unresolved small scale knots should be < 20 %.

Transverse Profile of X-ray Jet

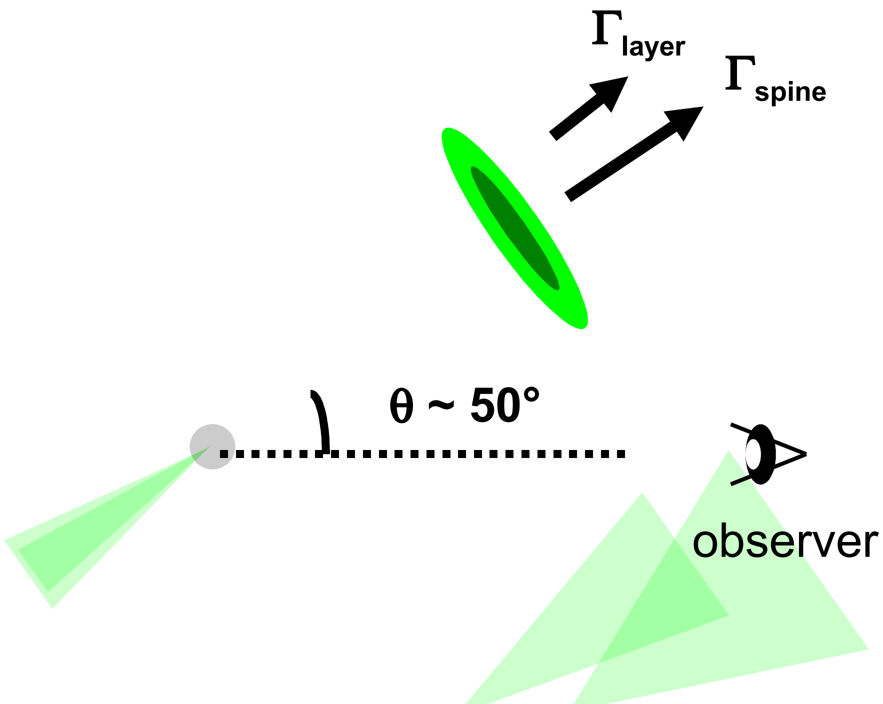


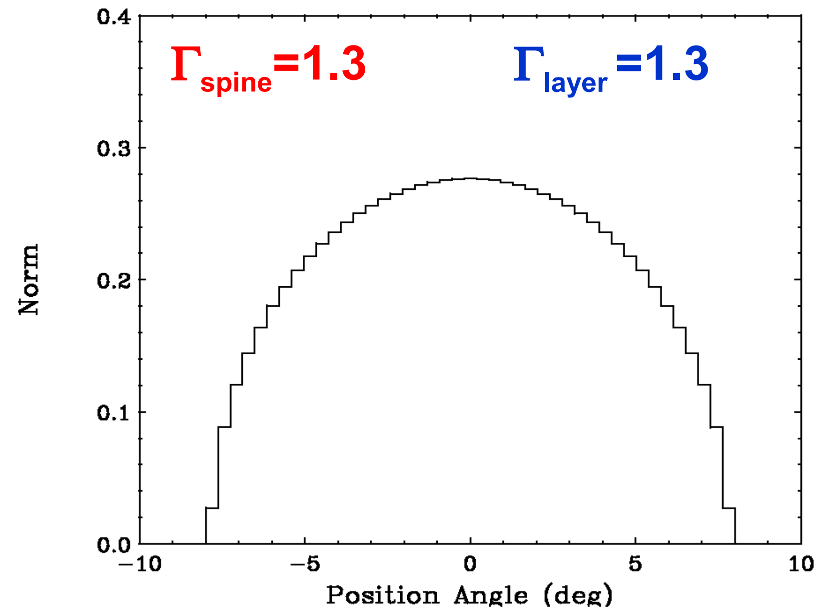


- Clear detection of "double-horn" structure in the transverse direction.
- Spectral index is almost uniform across/along the jet, $\alpha_X \sim 1$.
  - ➡ already modified by sync loss, while cooling time is very short;

  $t_{syn} \sim 20\ B_{100\mu}^{-3/2} E_{10keV}^{-1/2}$ [yr] ➡ **Need for cont. accel. over jet volume!**
- Hints of extremely hard spectra at very edges of the jet?

Stratified X-ray Jet in Cen A?



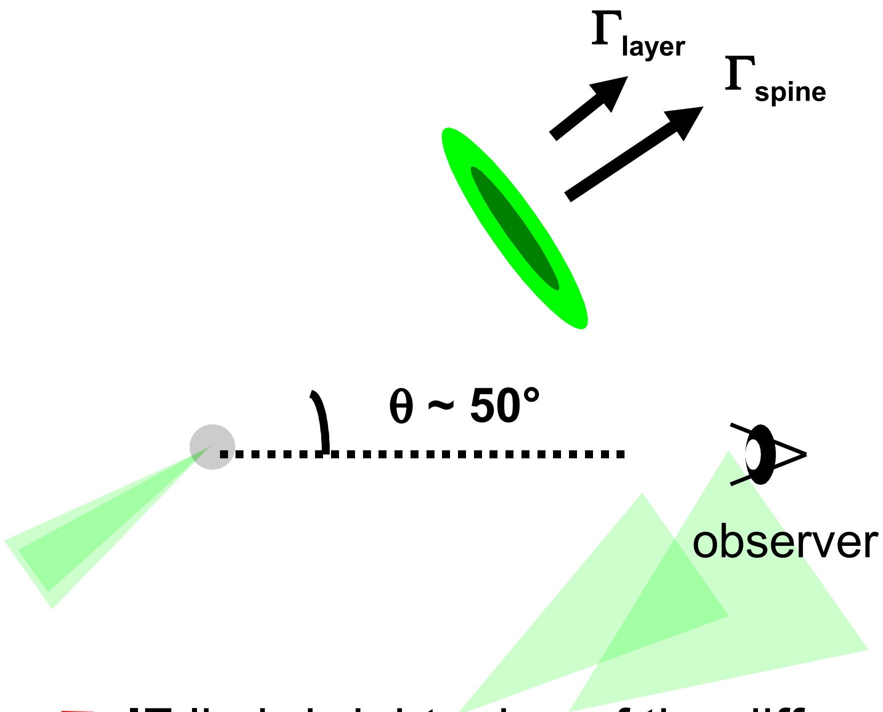


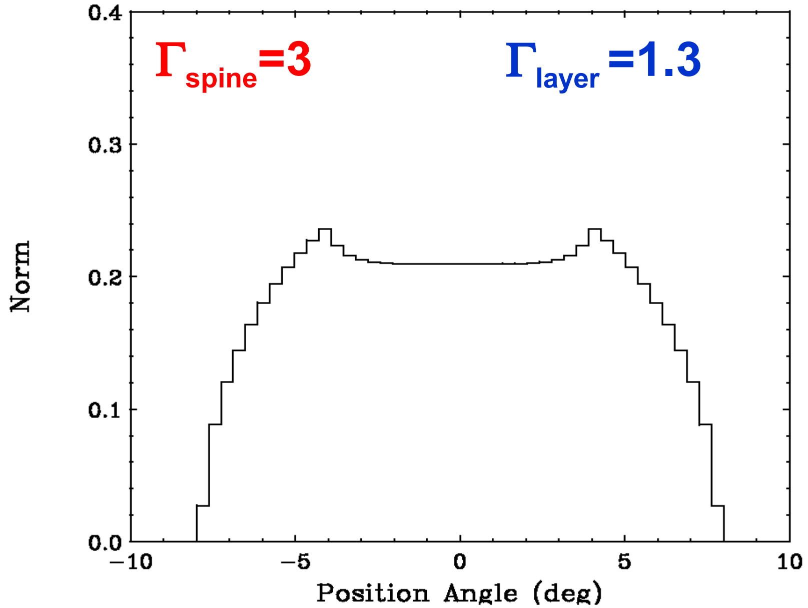
- **IF** limb-brightening of the diffuse X-ray emission is
  (1) due to the varying Doppler enhancements, and
  (2) emissivity is uniform along the jet, we obtain

  Γ_{layer} ~ 1/sinα ~ 1.3, where α ~ 50deg is the jet viewing angle.

- To reproduce the observed "double-horn" structure, **Γ_{spine} > 3**
- Oversimplified assumption, but consistent with stratified jet scenario.

Stratified X-ray Jet in Cen A?





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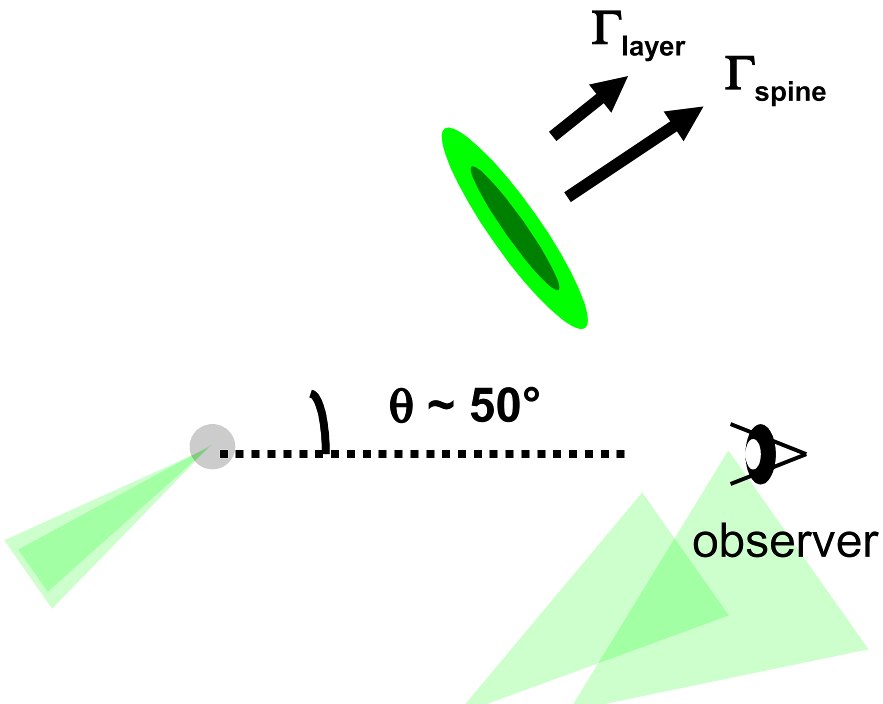

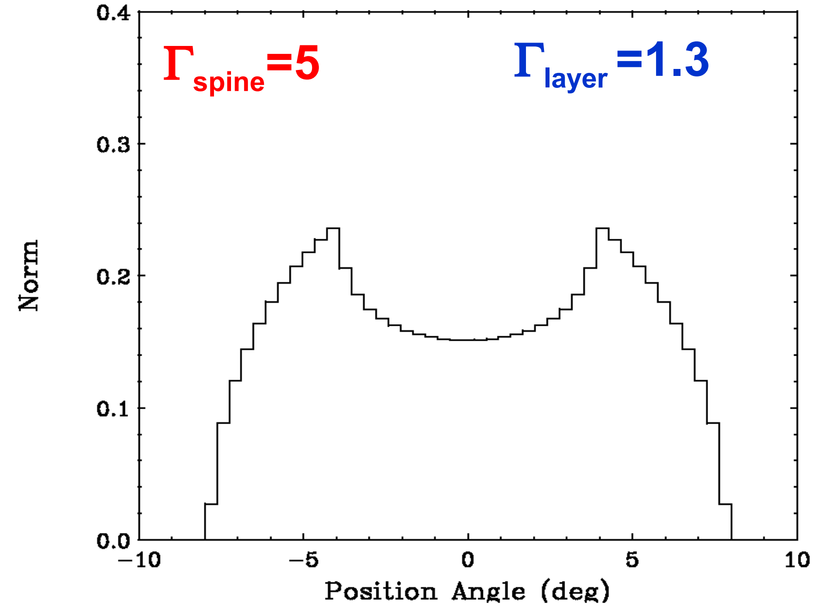

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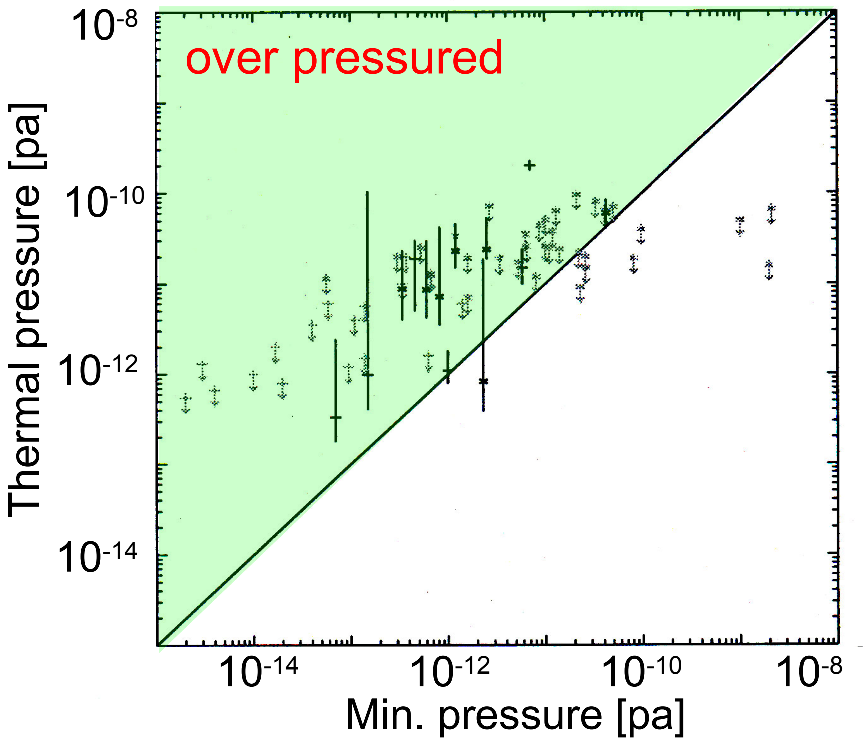
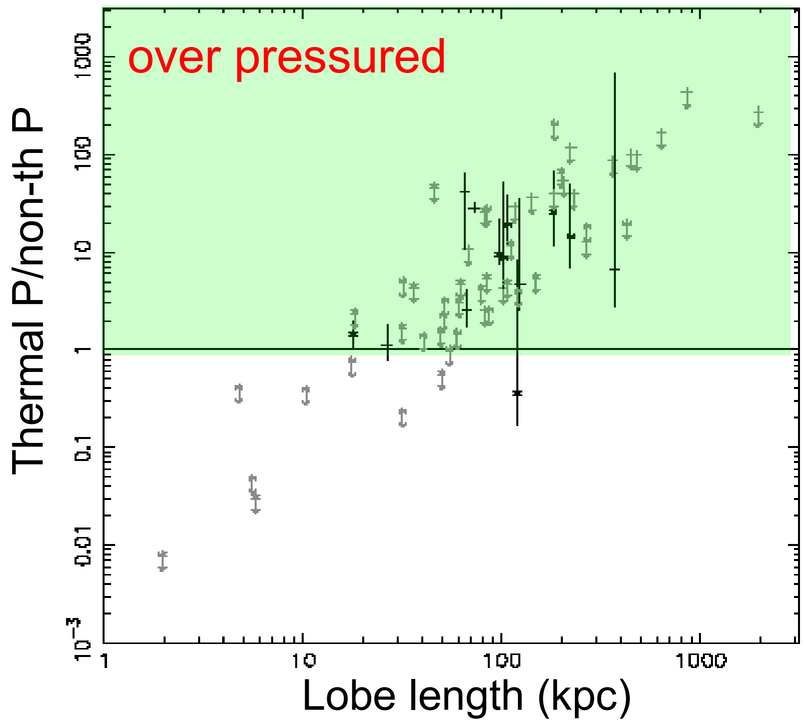
Jet Content (1)

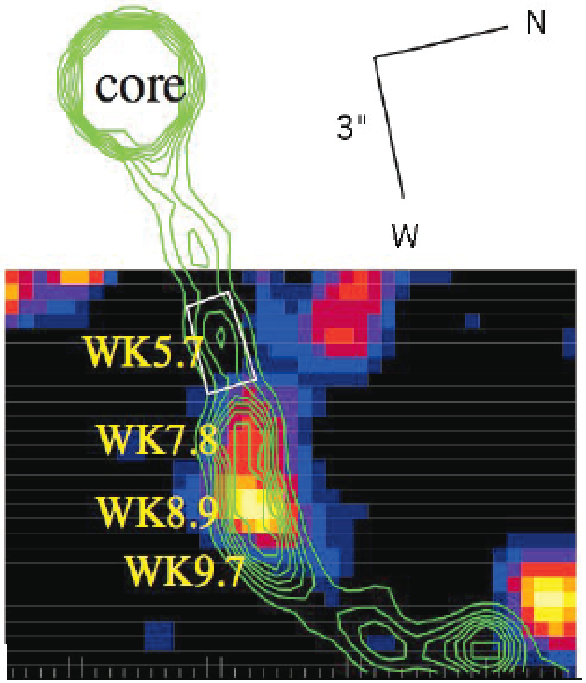
Hardcastle & Worrall 00



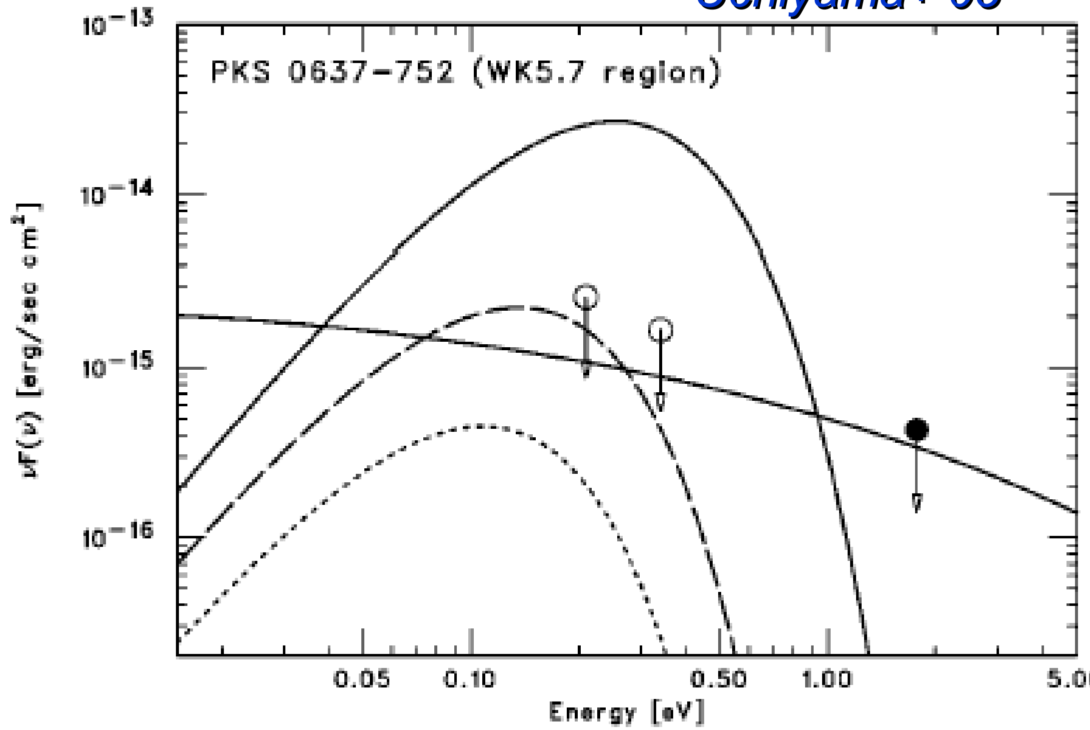


- In both hotspots & lobes, we expect $u_e \sim u_B$. Even for jet-knots, $u_e \gg u_B$ is NOT required, as long as giving up IC/CMB scenario.
  ➡ This is, however, NOT exclusively to leptonic jet!
- Indeed. studies of pressure balance within the lobes suggest **$P_{thermal} > P_{non\text{-}th}$**, meaning significant contribution of hidden protons.

Jet Content (2)



Uchiyama+ 05



- IF jets are moving with relativistic speed at kpc-Mpc scale (Γ_{BLK} ~ 10) "bulk-Comp" of CMB photons is expected just in IR band.
  - ✓ NOT observed for PKS0637-752 …
  - ✓ Beamed IC/CMB invalid? pure e^-e^+ jet unfavorable?

(see the discussion in *Sikora & Madejski 00* for Blazars)

Summary

- Recent observations confirm that almost all jet structures (jet-knots, hotspots, lobes) are strong “X-ray emitters”.
- Lobes and hotspots well support an assumption of $u_e \sim u_B$, whereas “too bright” X-ray jets challenge a conventional, one-zone IC/CMB. Indeed, various evidence for “non-standard” spectra and “stratified jets” are being obtained very recently.
- These observations more strongly favor Sync origin of X-ray emission, and these may be related with an “exotic” particle acceleration in jet boundary shear layer.