High Energy Emission from AGN Jets
活動銀河核の高エネルギー放射

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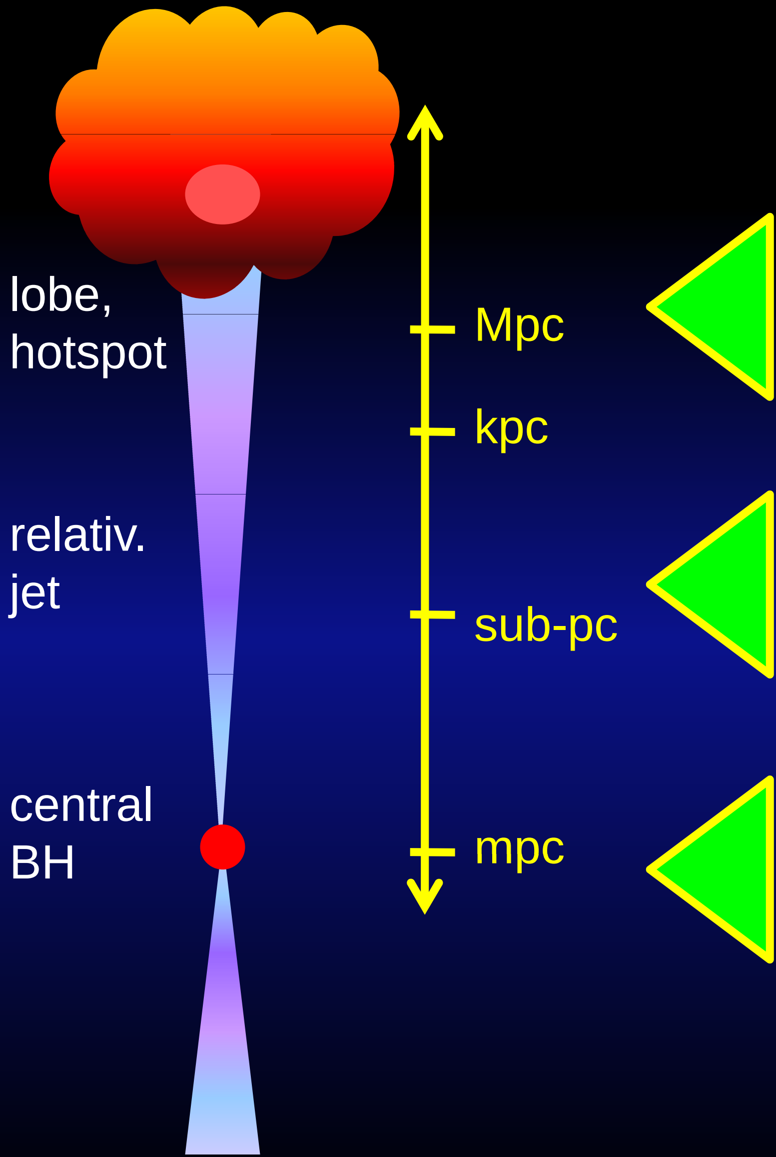
On behalf of the Fermi/LAT collaboration

Outline



AGN jet: on "various scales", across the EM spectrum.

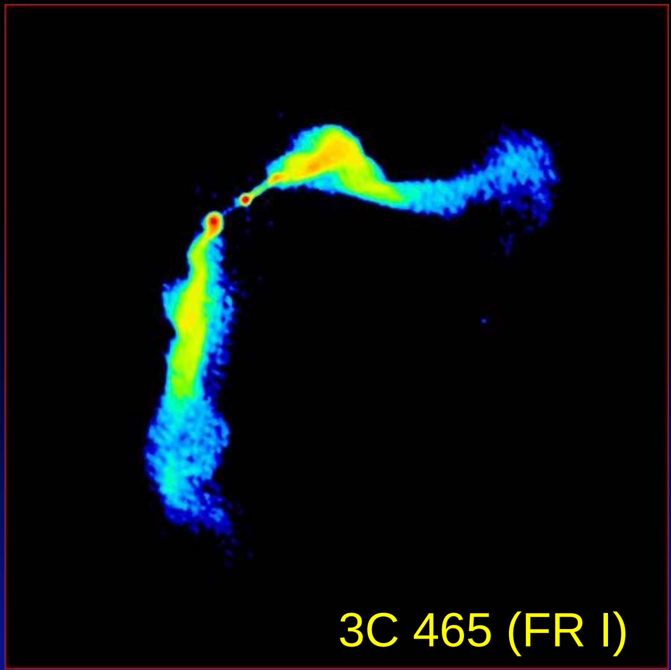
- Large scale jets
  - Physics of FRI jets
  - Physics of FR II jets
- Blazar region
  - Classical view
  - Modern view in Fermi-era
- Jet Launching & particles
  - Disk-jet connection.
  - Long-term monitoring.

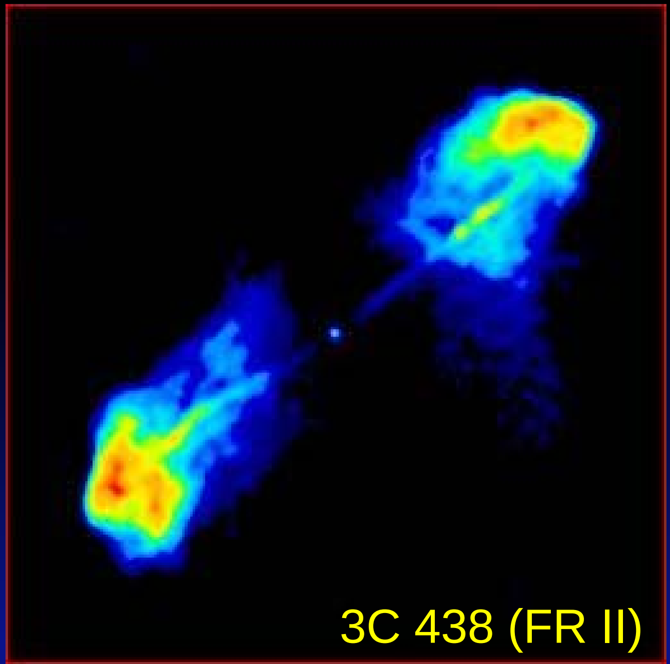
→ *Isobe?*

Jet on kpc-Mpc

3

FR I and FRII

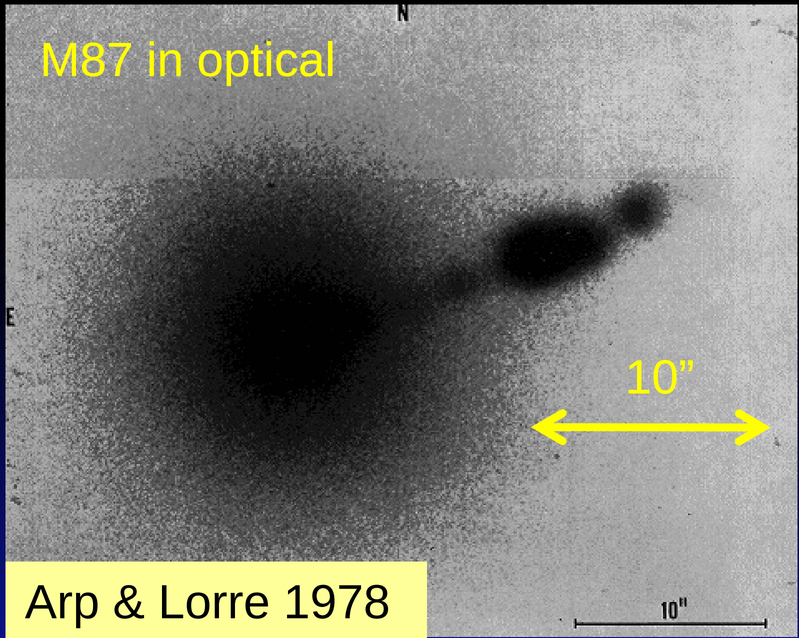


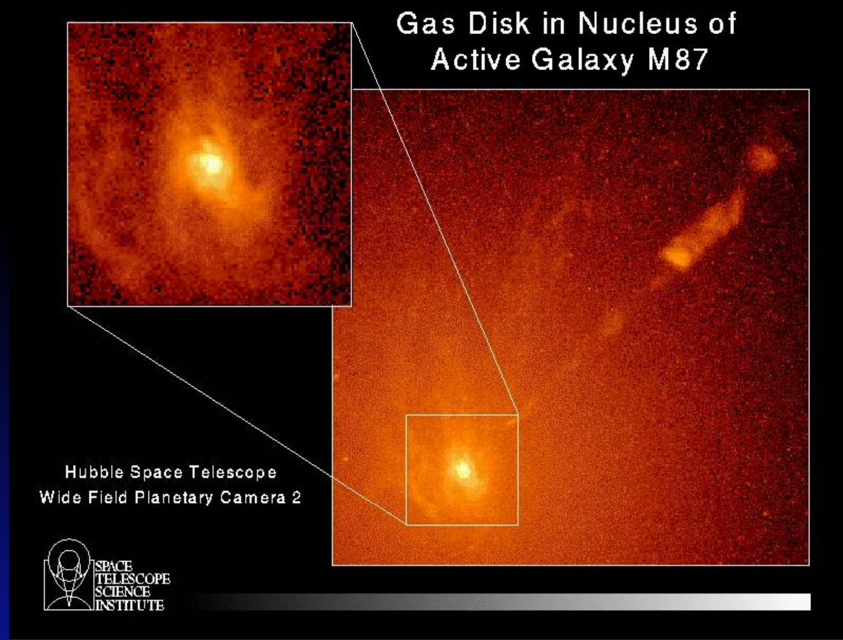


- Low power ($10^{42\text{-}44}$ erg/s)
- Low Γ
- Core brightened
- Bending (ram pressure)
- Decelerating
  (mass entrainment)

- High power ($10^{44\text{-}46}$ erg/s)
- High Γ
- Edge brightened
- Collimated, straight jet
- Deceleration negligible?

AGN Jet =Acceleration Site

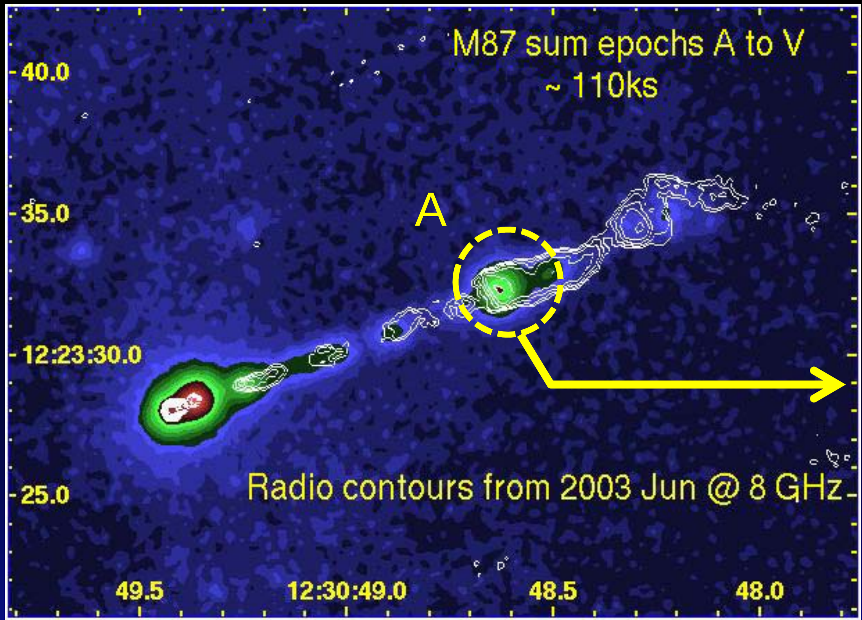




- The jet-like feature in M87 was first reported in Curtis 1918 (!) .
- Electron synchrotron life times in equip fields t_{opt} ~ 100 yr, whilst ,the projected length of jet much larger, D ~ 1.5 kpc.
- This suggests *in situ* acceleration within “knots”.

✓ internal shock due to velocity irregularities in the beam (Rees. 1978)

FR-I: M87 w/ Chandra



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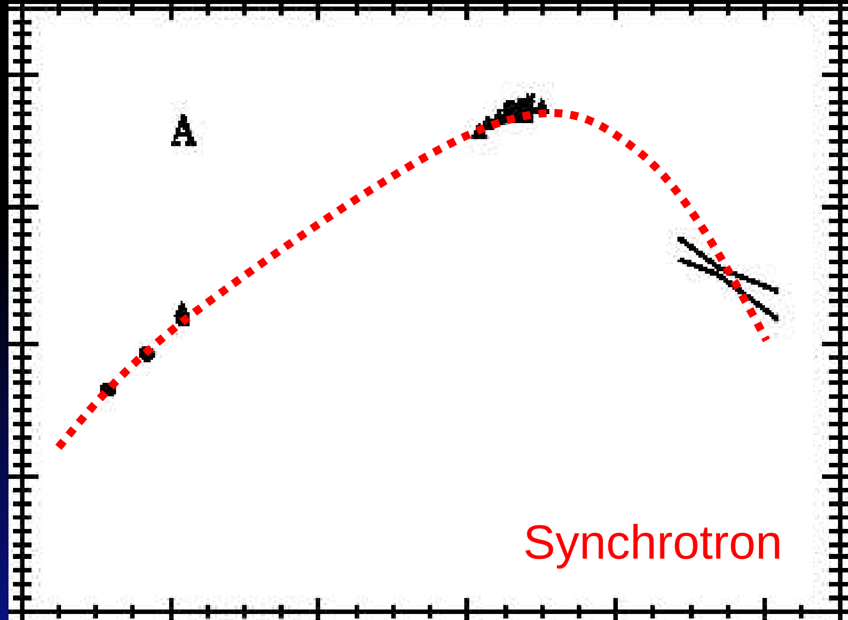
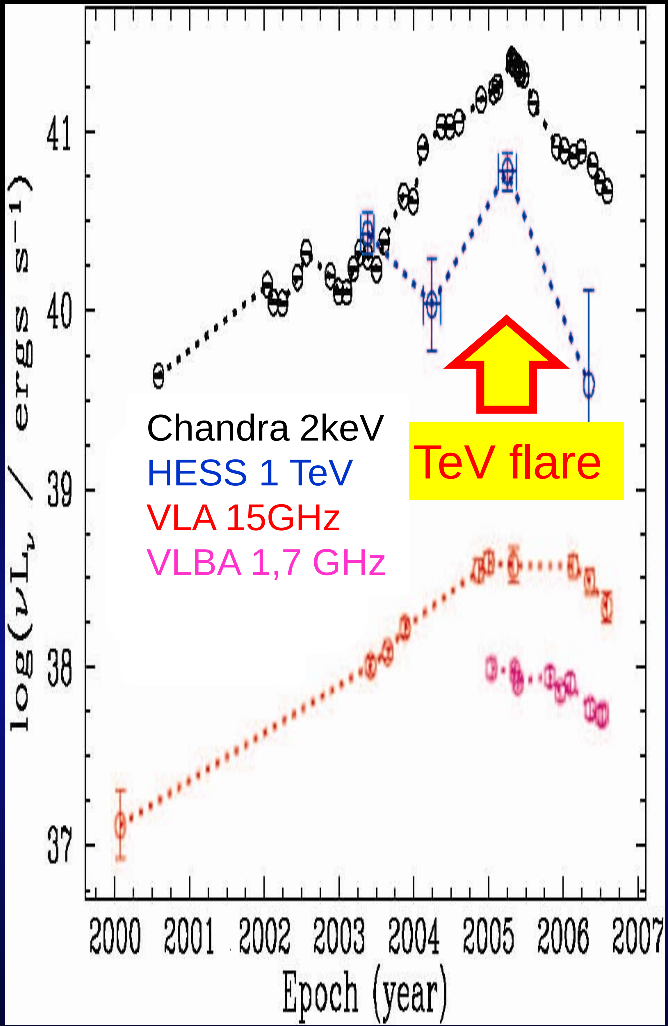


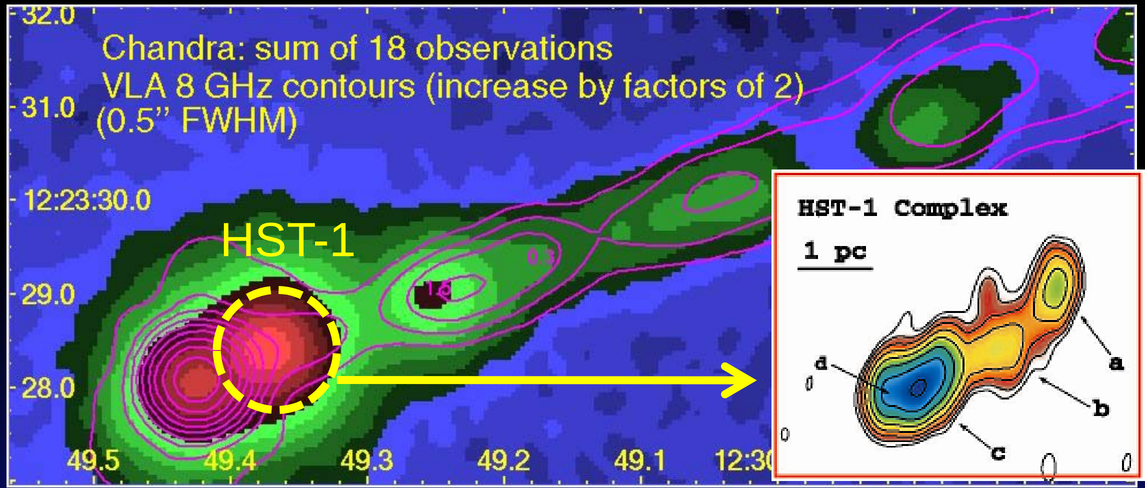
Wilson + 2000

- Single SED can fit radio to X-ray: Electron sync model can work.
  $\rightarrow$ X-ray emitting electrons: E_e = 10~ 100 TeV for B_{eq} ~ 100μG.
- But, we should always keep in mind various assumptions;
  (1) "B ~ B_{eq}" to get various jet parameters.
  (2) emitting volume is "same" for all wavebands.
  (3) filling factor ~ 1 and uniformity… etc

FR-I: X-ray Flare in M87

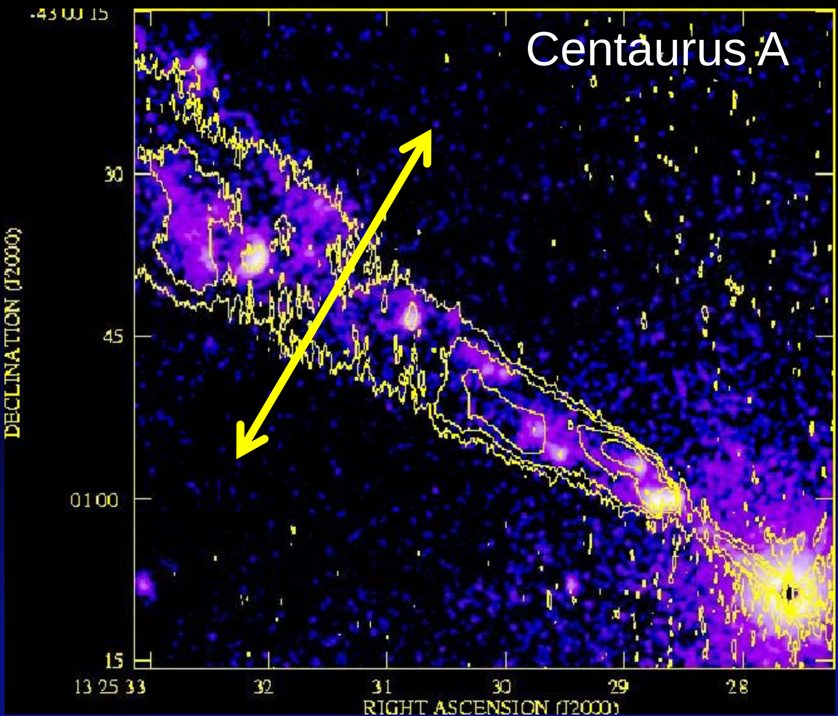


Harris+ 2006, Cheung+ 2007

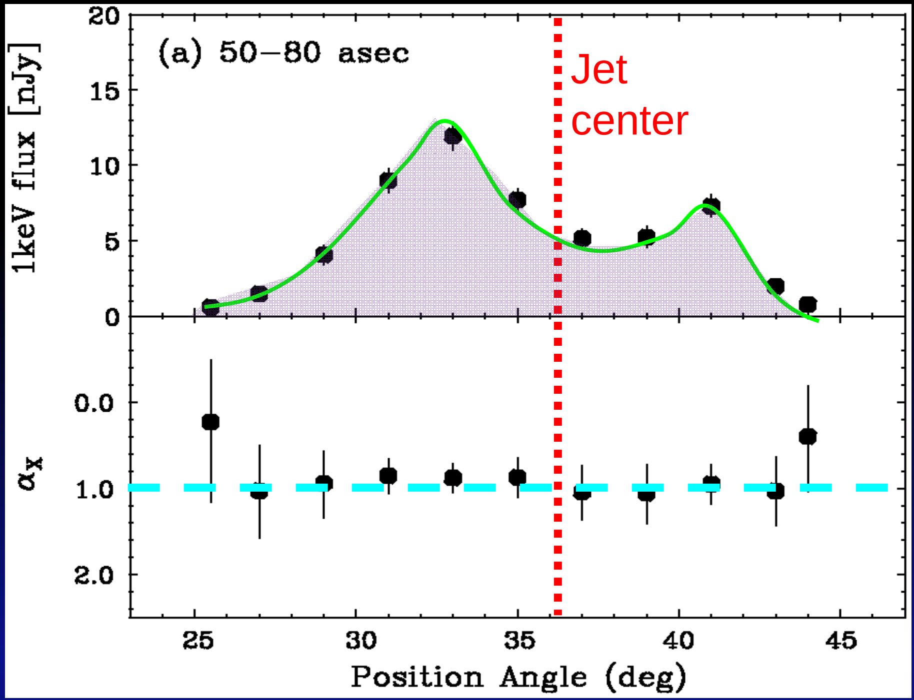


- The outburst of HST-1 was detected, w/ increased X-ray intensity of factor ~50.
- 1" corresponds ~ 77 pc at M87 distance
  - emission region must be very compact or "knotty".
- VLBA observation discovered superluminal radio features within HST-1, that could be associated with excess TeV emission reported by H.E.S.S.

Inner Knot X-ray Emission ?



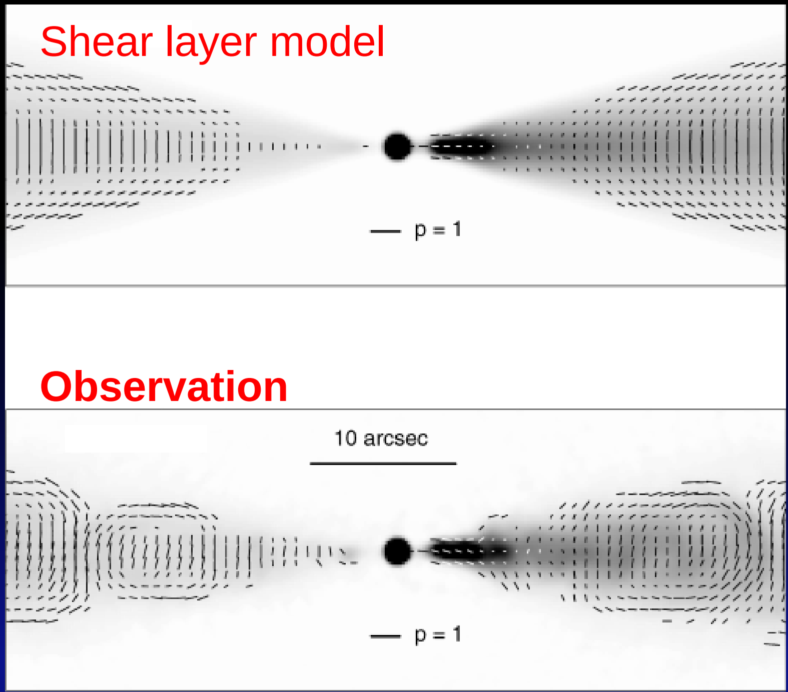
Hardcastle+ 2003

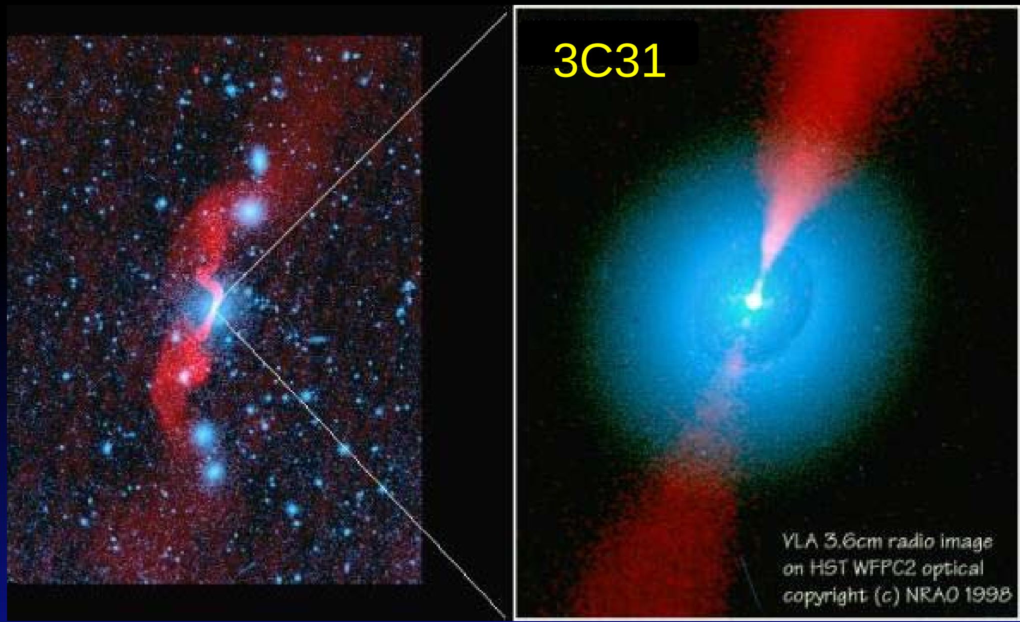


JK + 2006

- Not only bright X-ray knots, but continuous, diffuse emission between knots have been observed.
- For the nearest FR-I Cen-A, "double-horn" profile in trans. direction.
  - ✓ Stratified jet – fast spine & slow sheath ?
  - ✓ Turbulent acceleration (Fermi II) at work over the jet volume ?

FRI: Velocity Shear

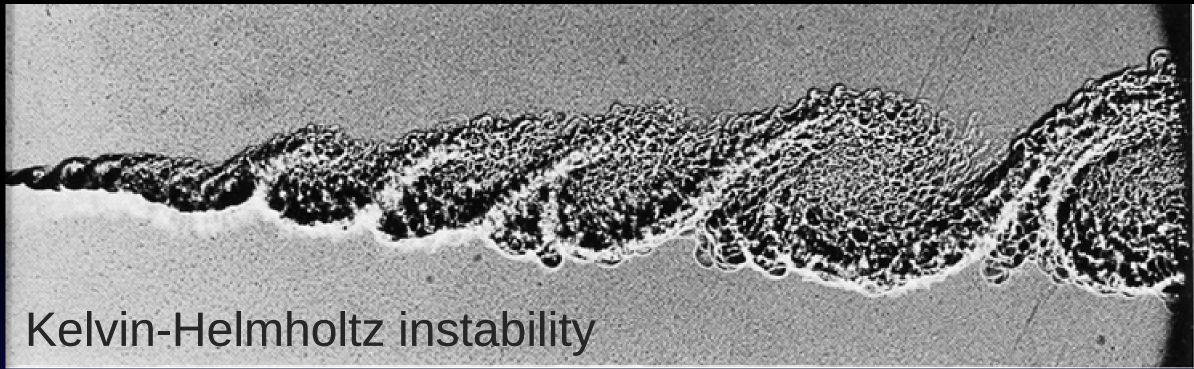


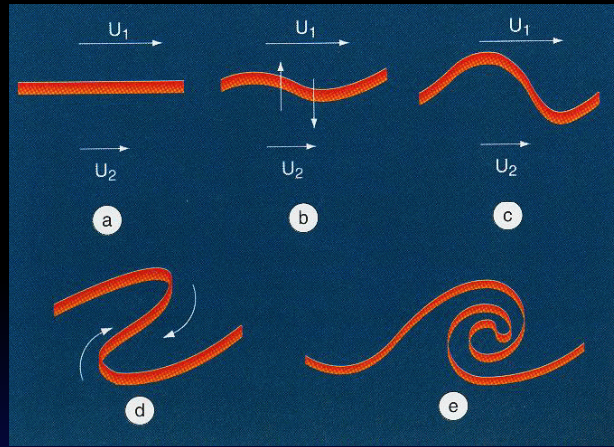


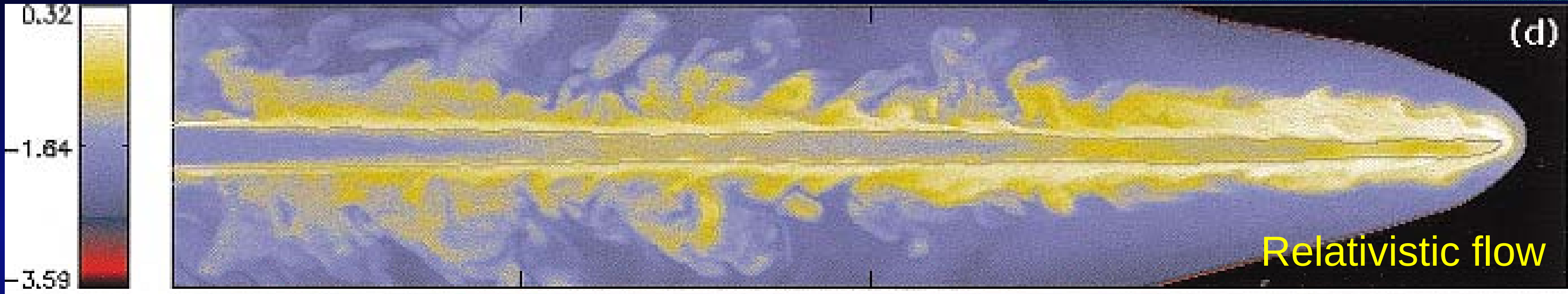
Bridle & Liang 2002

- Decelerated jet modeling w/ shear layers successfully explain observation of 3C 31 and 3C 315..
- "Velocity gradient" is naturally expected via the Jet-Env. interaction.
  - ✓ Entrains ambient medium.
  - ✓ Transfers momentum and energy to ambient medium.
  - ✓ Mixing layer, deceleration of jet …

MHD simulations



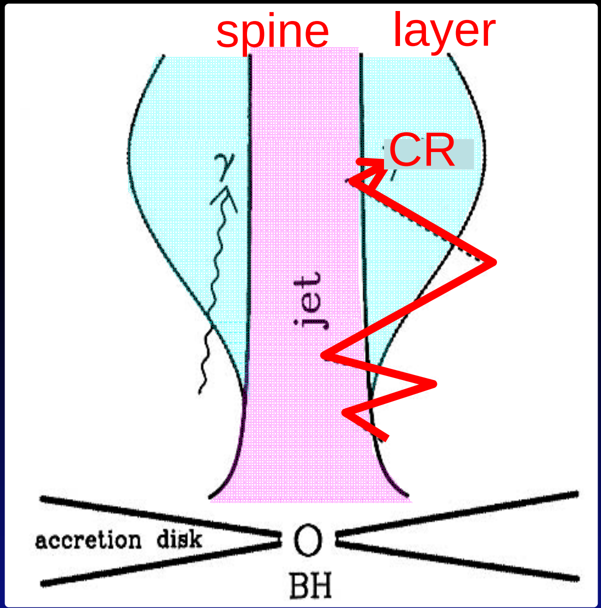


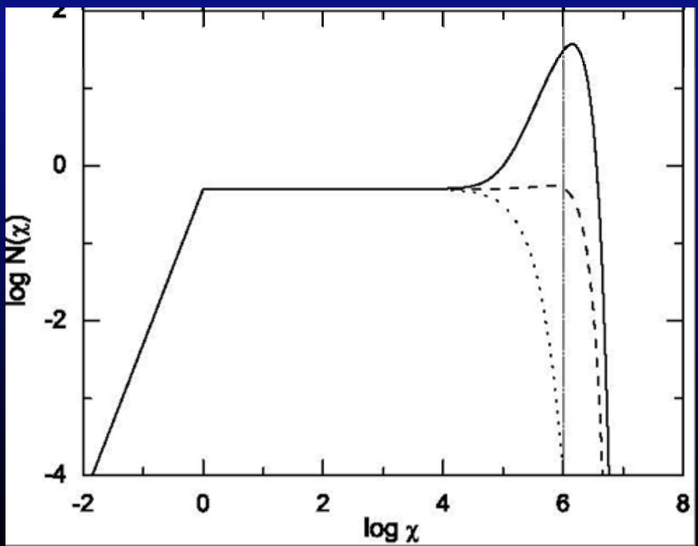


De Young 1986, Aloy+ 1999, Leismann+ 2005, Mizuno+ 2008

- Mass entrainment works very effectively via K-H instability.
- Even in relativistic jets, 3D simulation shows development of shear/mixing layers w/ turbulent B field.

Turbulent Acceleration





- Stratified jet – "spine" + "layer".
- Unlike Fermi-I, turbulent acceleration (Fermi II) can produce very hard electron distribution.
- If field is very turbulent ($\xi \sim 1$), electrons "pile-up" as it never escape from the region.

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

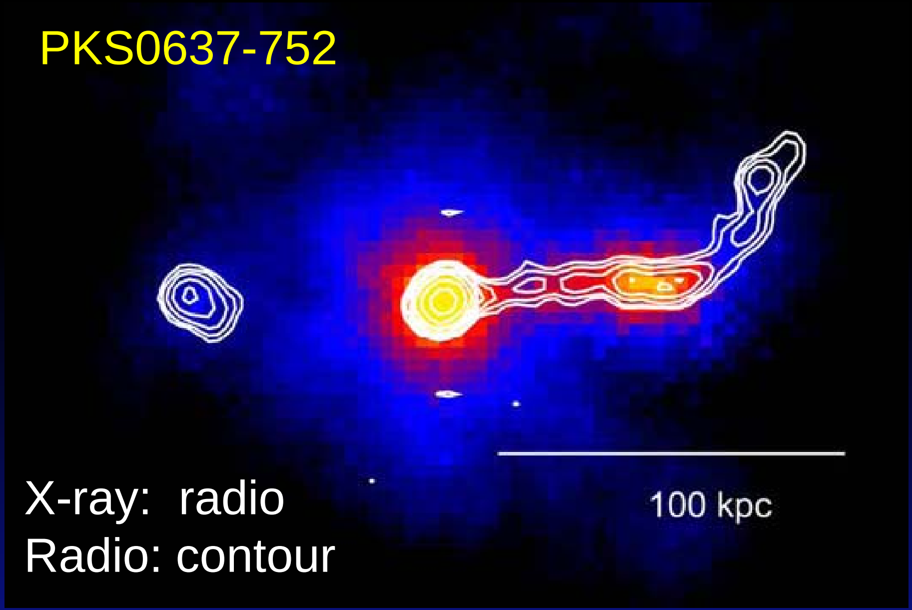
$$t_{esc} \sim 3 \left(\frac{L}{V_A} \right)^2 \frac{c}{l_e} \sim 6\mathrm{x}10^{15} \gamma_8^{-1} B_{100\mu} L^2_{100pc} \ [\mathrm{s}]$$

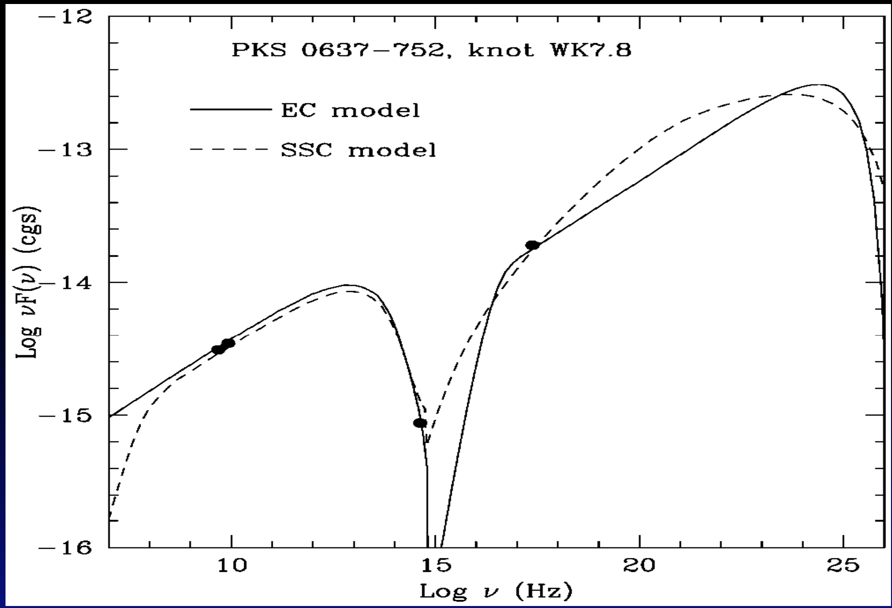
$\Rightarrow$ $t_{esc}/t_{cool} \sim 10^7 \ (B_{100\mu G})^3 (l_{100pc})^2 \xi^{-1}$

where $\xi = U_B/U_T$

Ostrowski 2000, Stawarz & Ostrowski 2002
Stawarz & Petrosian 2008

FR II/QSOs: bright X-ray jet



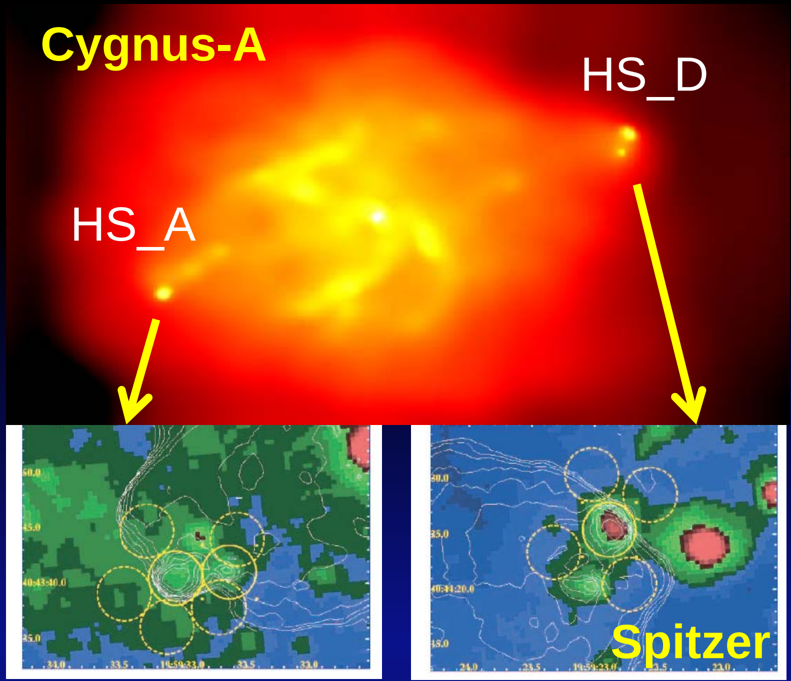


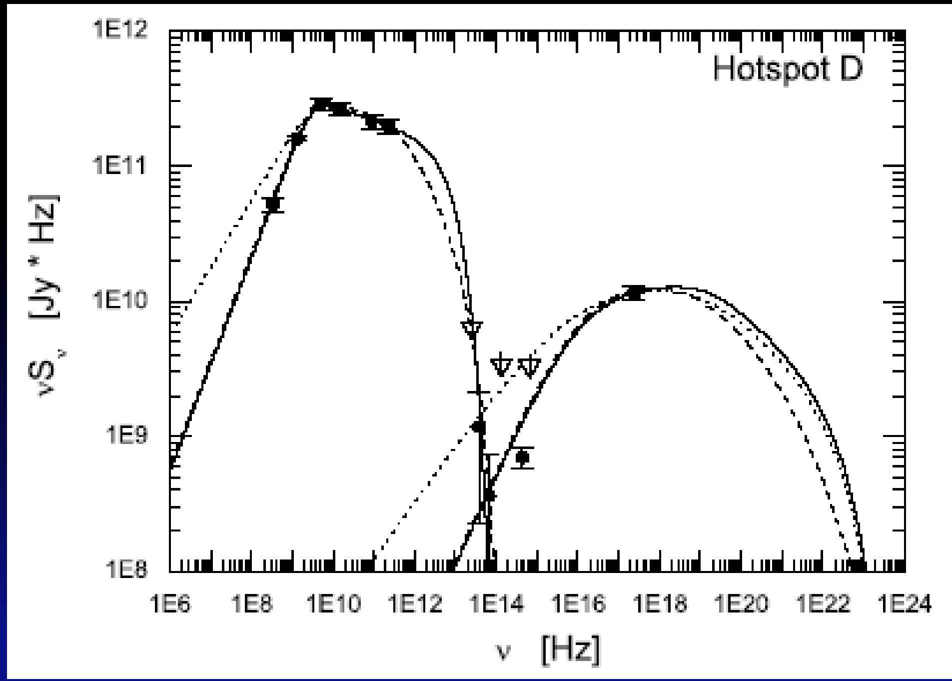
Tavecchio+ 00, also Sambruna+ 2004

- Ultra-luminous X-ray jets:
  - NOT smoothly connecting w/ radio-optical synchroron.
  - IC/CMB is more likely if Γ_{jet} ~10 on Mpc scale ($\propto \Gamma_{jet}^2 U_{CMB}$).
- Consistent w/ VLBI observation (β_{app} ~ 13.3: Edwards+ 06)
- More and more samples: http://hea-www.harvard.edu/XJET/

FR II: Hotspots

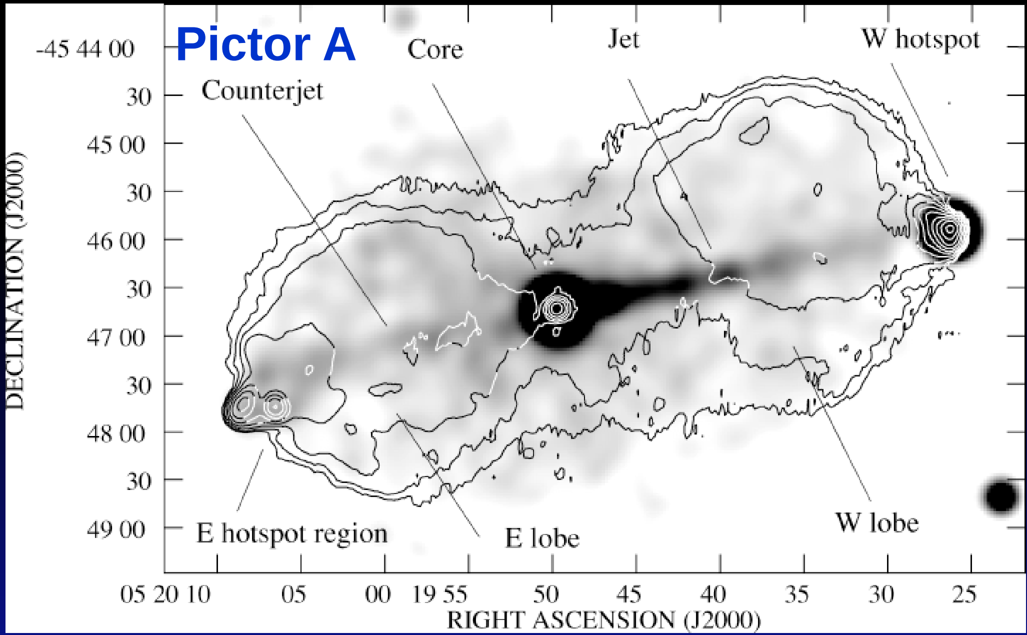
Stawarz+ 2007

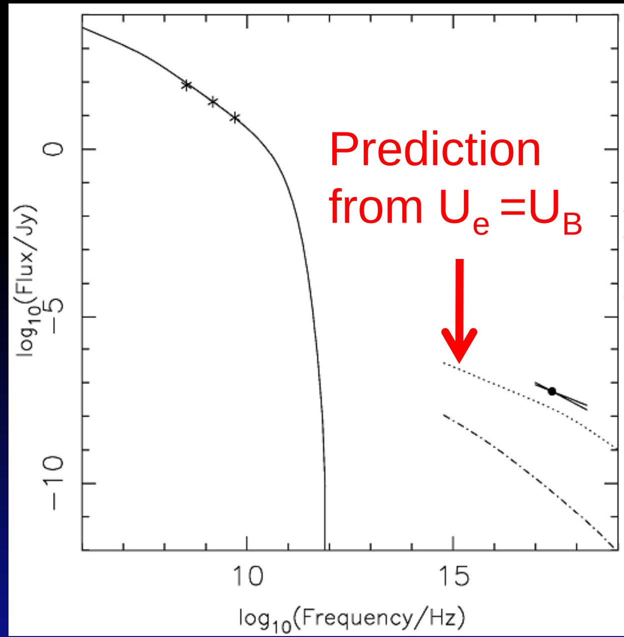




- X-ray emission of hot-spots in high-power FR II jet is consistent w/ synchrotron self-Compton (SSC) model close to $U_e \approx U_B$.
- The hot-spots in low-power jets is too bright in X-ray, suggesting instead synchrotron in origin (Hardcastle et al. 2004).
- Multiple structures often observed; relic? swing of jet-head?

FR II: X-rays from Lobe

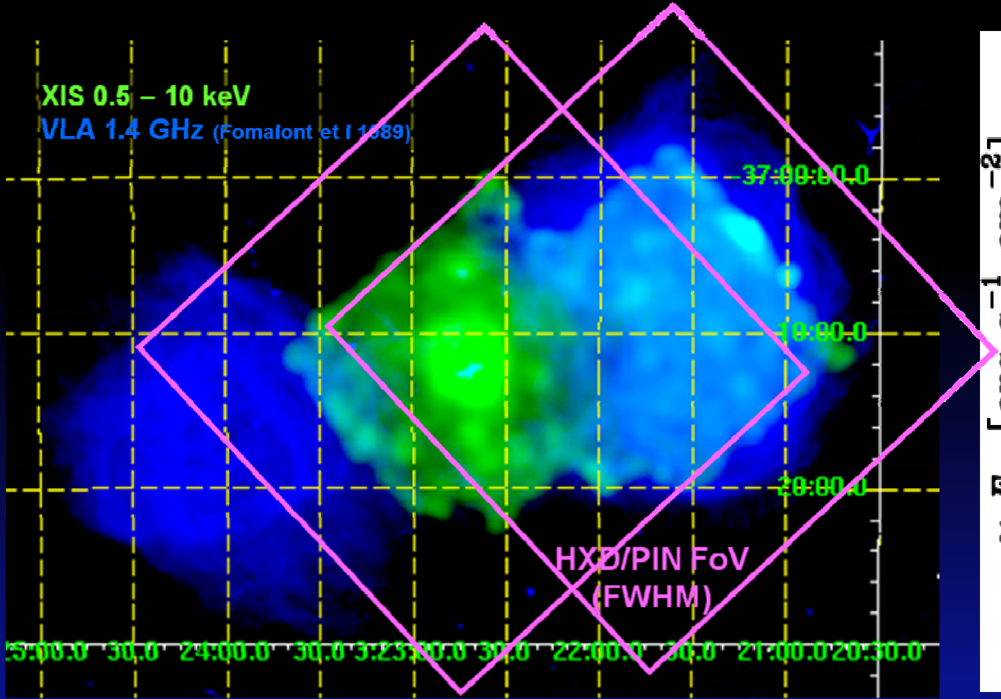


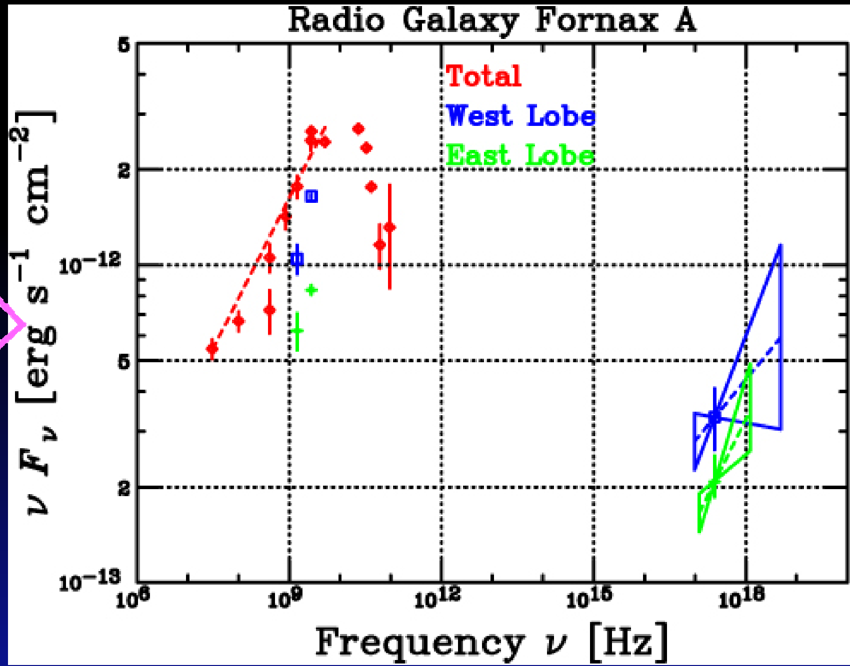


Hardcastle & Croston 2005

- X-ray emission is most likely due to IC/CMB under approximate equipartition between U_e and U_B ($0.3 < B_{IC}/B_{eq} < 1.3$)
- Several “warnings”, however, due to (1) extrapolation of radio spectrum to lower energy, (2) unknown filling factor, (3) contamination of cluster gas (see discussion in Worrall et al. 2009)

Suzaku Obs. of Fornax A Lobe





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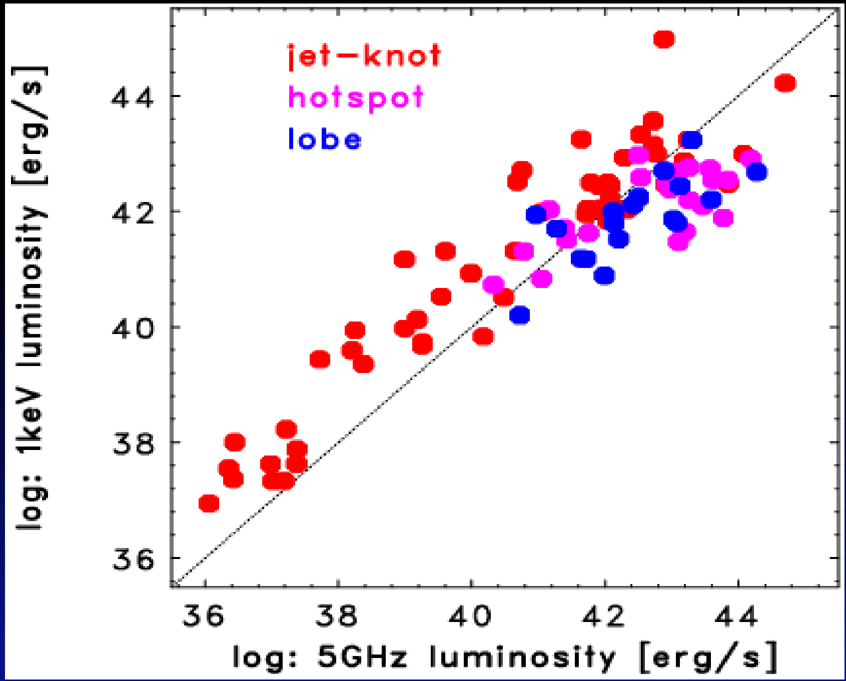
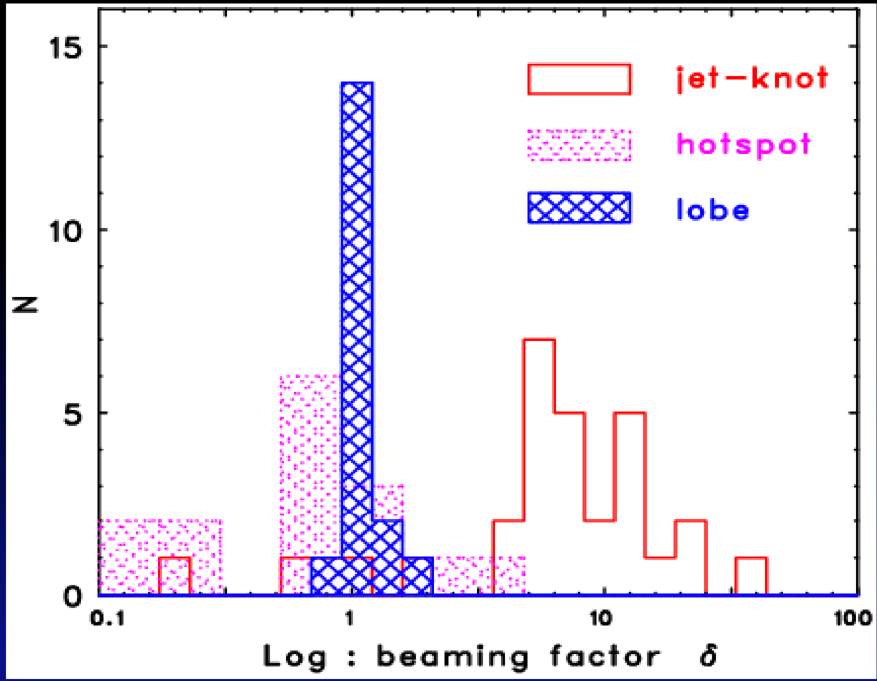
- Hard X-ray signal was successfully detected from the west lobe of Fornax A up to 20 keV. (Tashiro+ 2008)
- Hard X-rays are produced by *same* electrons of γ ~ 5,000 (or E ~ 2.5 GeV) that emit synchrotron in GHz band.
- B_{IC} =1.4 μG, almost consistent w/ equip. B value of B_{eq} =1.6 μG.

Systematic Study

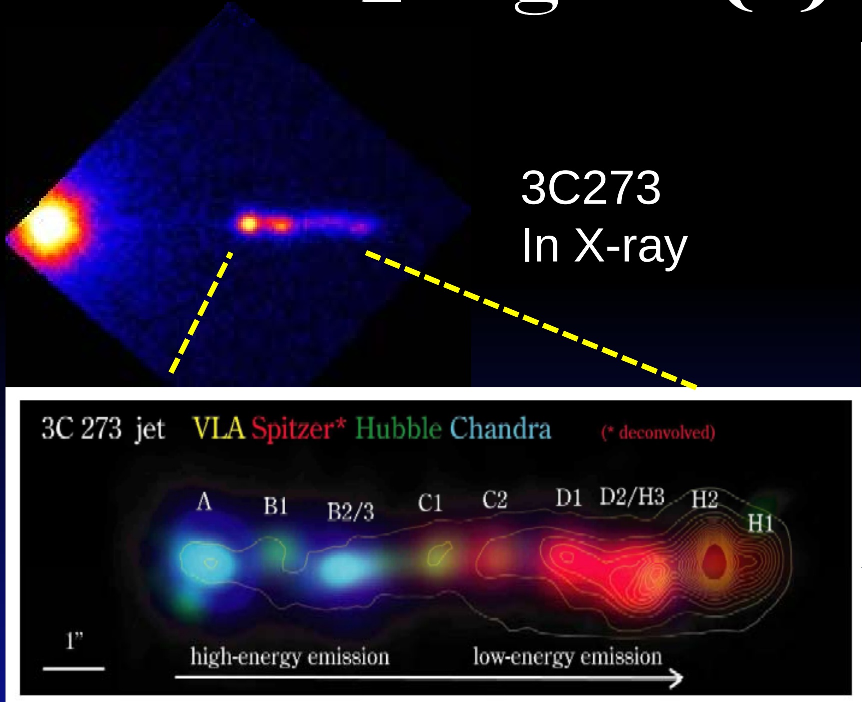
JK & Stawarz 2005



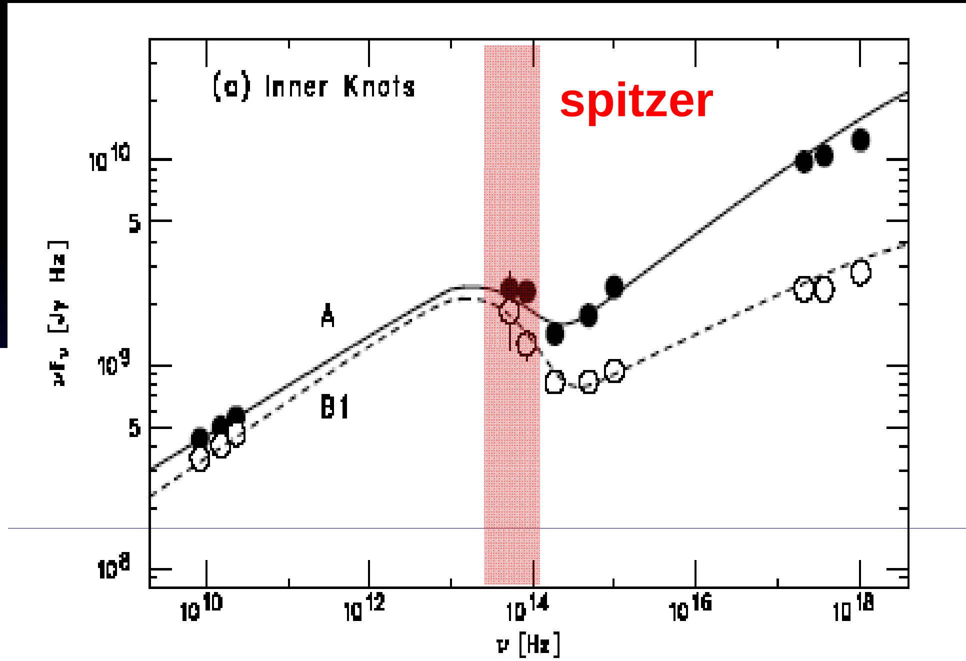


- Distribution of 44 AGNs (56 knots, 24 hotspots, 18 radio lobes).
- A very simple assumption that apparent deviation from equipartition is due to Doppler enhancement, i.e. beaming factor δ.
- Actually, extremely X-ray bright knots can be explained if <u>$\delta \sim 10$</u>, which is consistent w/ PKS0637-752 (classified also as blazars.)

Warning Signal (I)



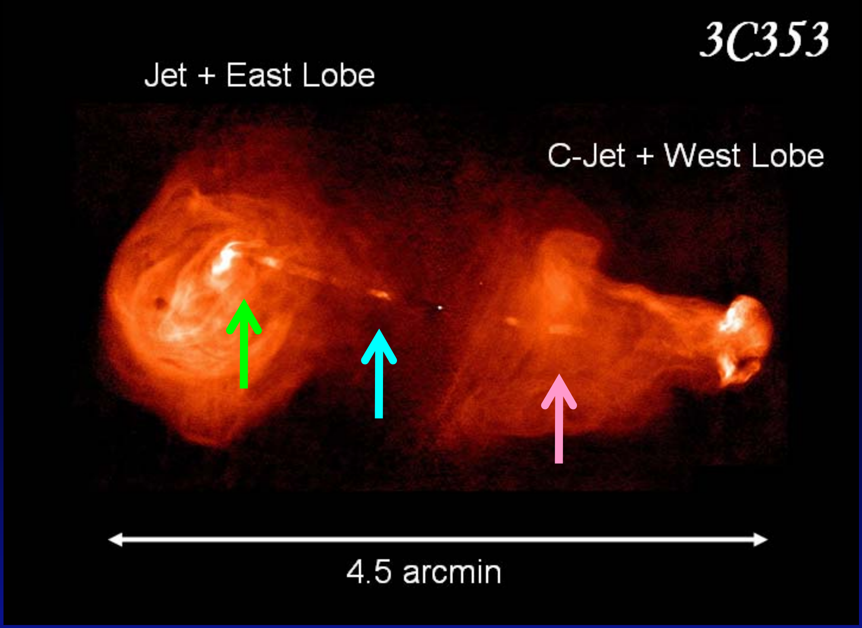
Uchiyama+ 2006, also Jester+ 2006

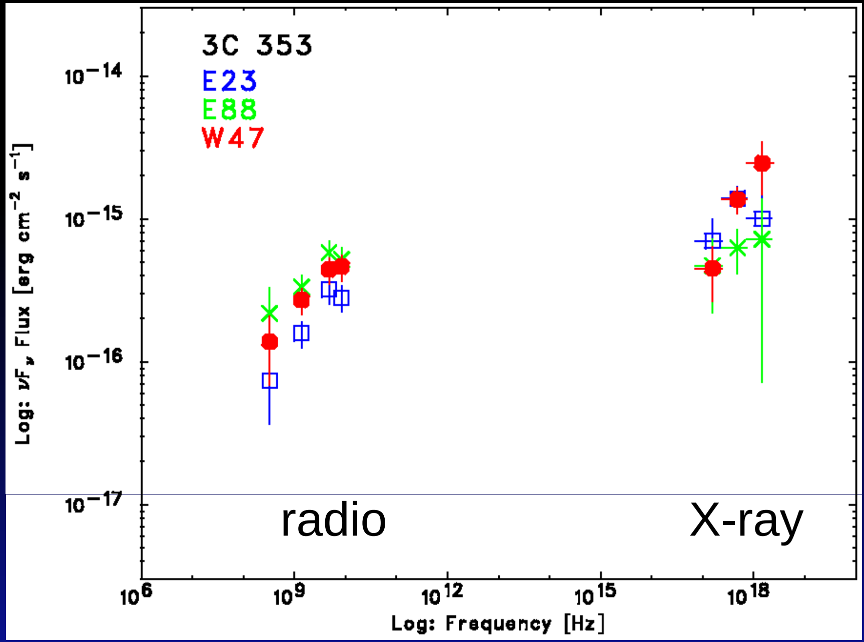


- IR imaging of the jet of 3C 273 by *SPITZER* clearly confirms that optical jet emission is dominated by the 2^{nd}, high E component.
- Both the radio and optical components are linearly polarized to a similar degree of ~ 15% - "double" synchrotron???
- Smooth connection between X-ray and optical: same origin?

Warning Signal (II)

JK+ 08a

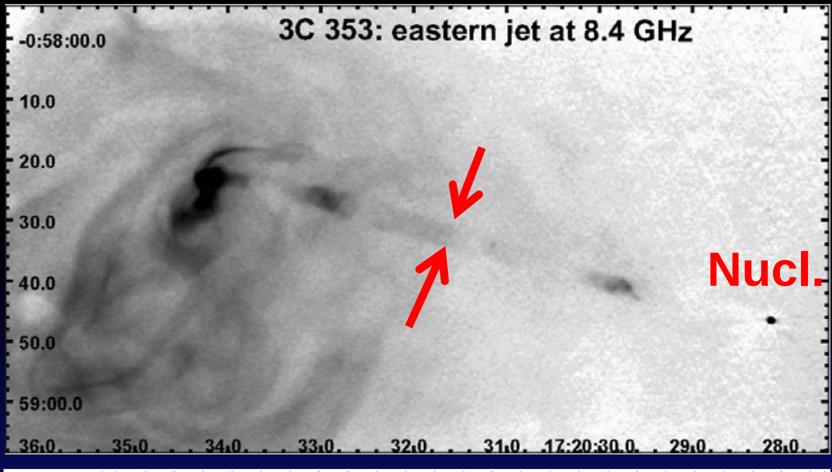


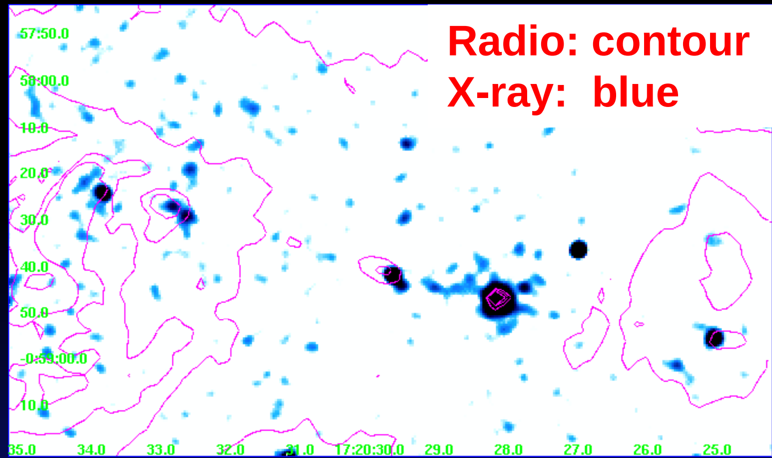


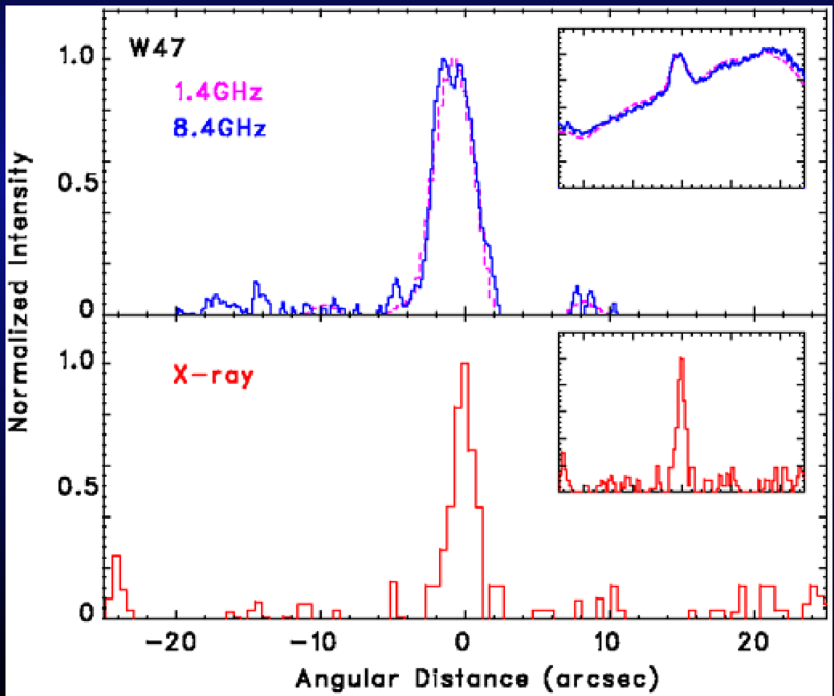
- The 4th strongest FRII radio galaxy in 3C catalog.
- First clear detection of "X-ray counter-jet" by Chandra.
  - ✓ If jet is highly relativistic, $\delta \approx 1/\Gamma_j$, hence Doppler "de-beamed".
- Again, "double Sync" or "Sync tail" more likely?
  - ✓ $E_e \sim 200 \ (\Gamma_j/10)$ TeV ; presence of ultra rela electrons.

Warning Signal (III)

JK+ 08a





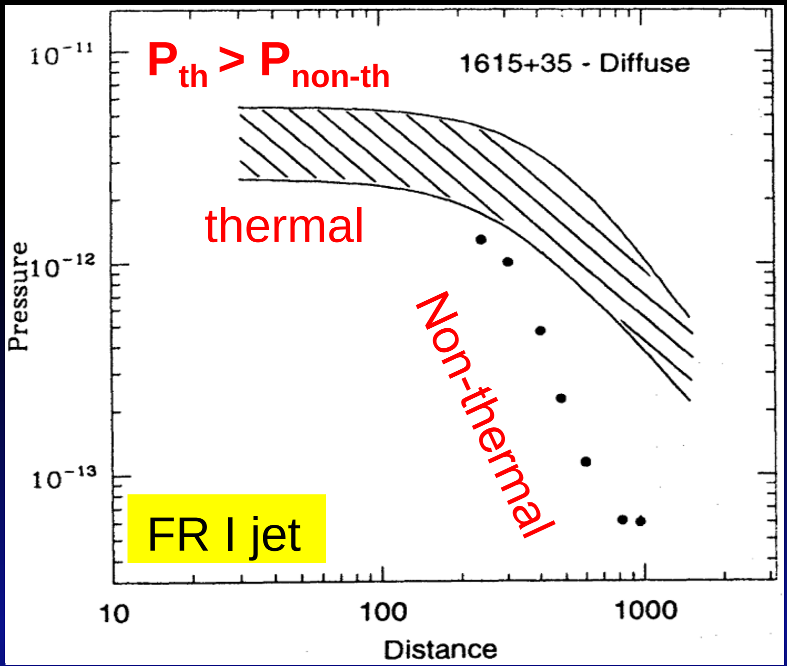


- Various jet structure visble:
  - transversal
    - ✓ narrow X-ray jet.
    - ✓ spine vs sheath visible ?
  - longitudial
    - ✓ peak offset: ~ 5 kpc.
    - ✓ sync cooling? NO!

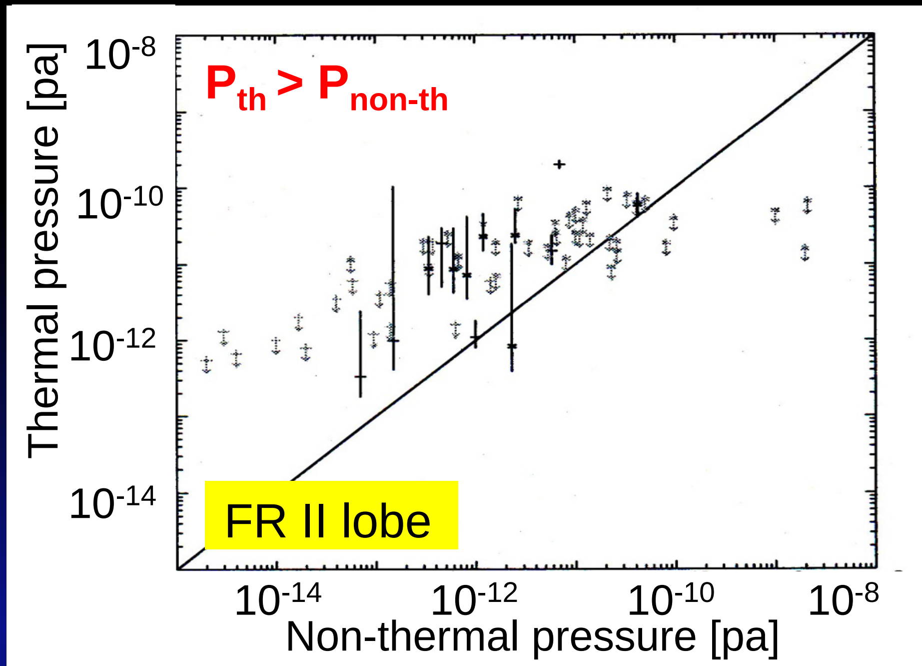
Much more complicated than we have originally thought …

Calorimetry & Jet Content

Feretti+ 1995



Hardcastle & Worrall 2000

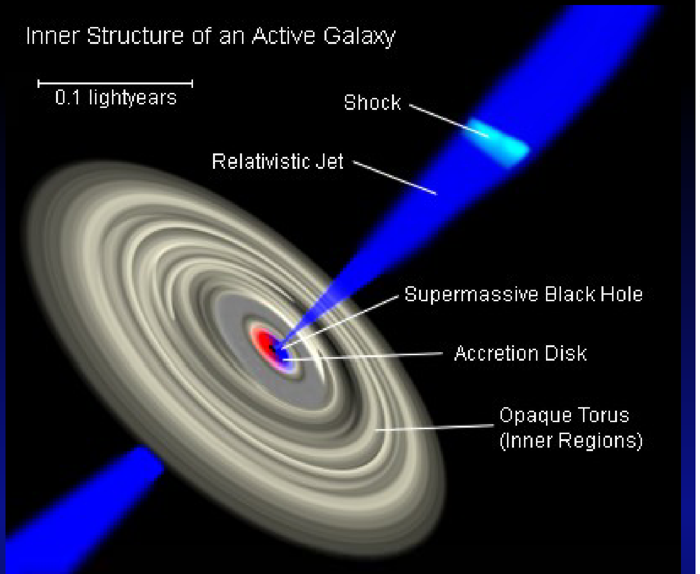


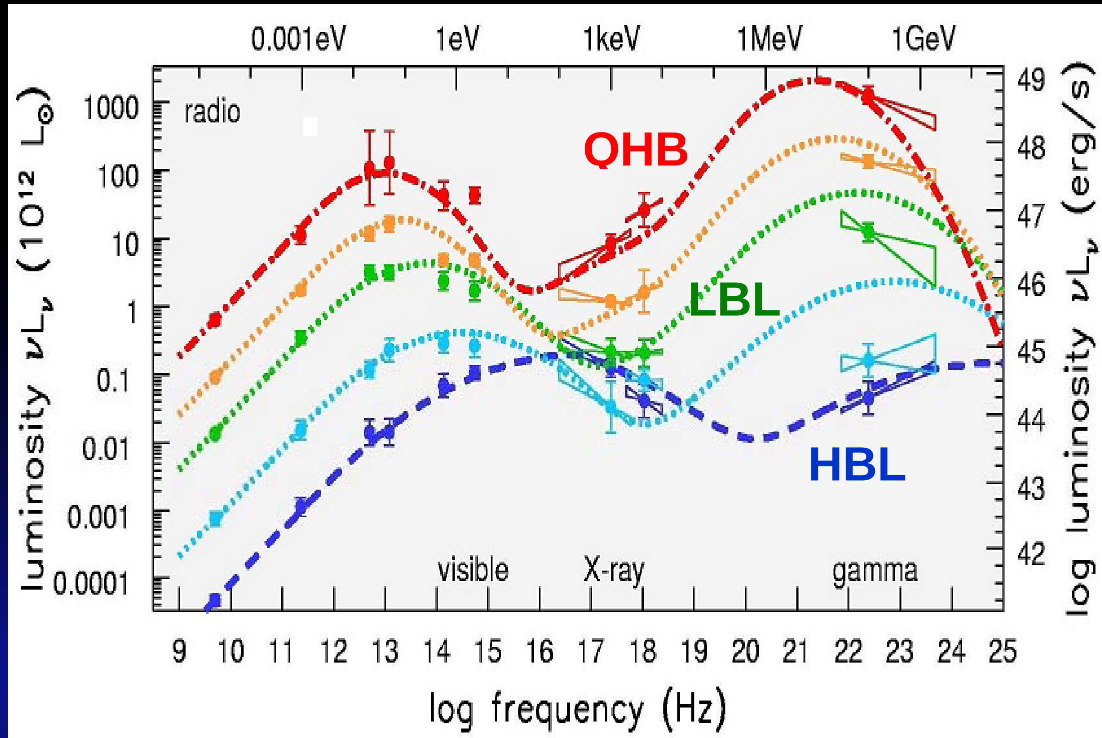
- It has oftern been suggested that min. pressure in FRI /FRII jets is normally below that of external X-ray emitting medium.
- Maybe significant contribution from protons and/or thermal electrons, but still premature (e.g., Croston+ 08).
- Independent approach from “cocoon-dynamics” also suggests invisible matter in FR II jets (e.g., Ito+ 08).

Jet on sub-pc

Blazars

Fossati+ 98, Kubo+98

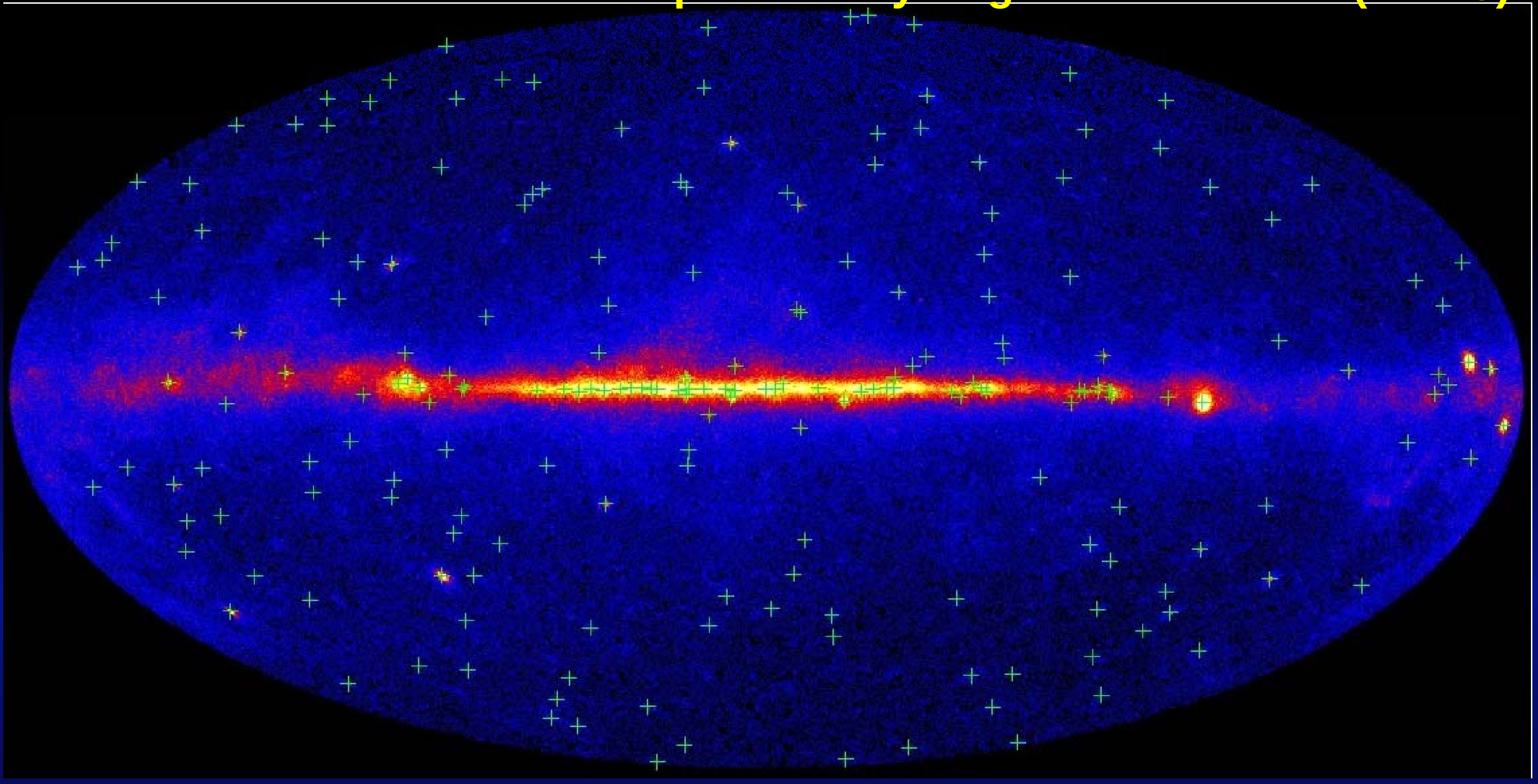




- Blazars: jet closely aligned to our line of sight.
  - SL motion, one-sided jet ➡ β_{jet} ~ 0.99 c or $\Gamma_{jet} \gtrsim 10$
- "Double peaks" over two decades in ν.
  - Sync + Inv. Compton, but wide variety ➡ HBL, LBL, QHB
  - Most powerful objects peaks at low ν ➡ "Blazar Sequence"

Now We have Fermi !

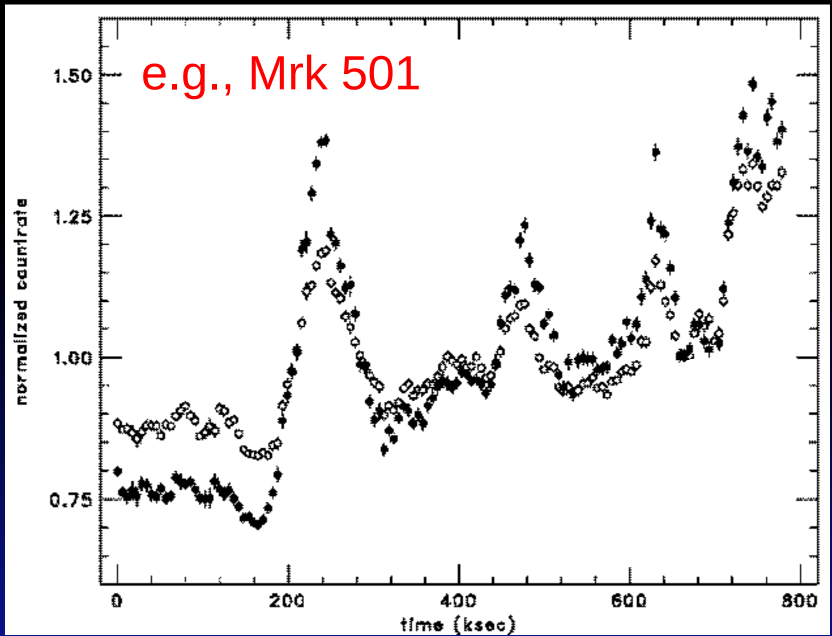
205 preliminary bright LAT sources (>10 σ)

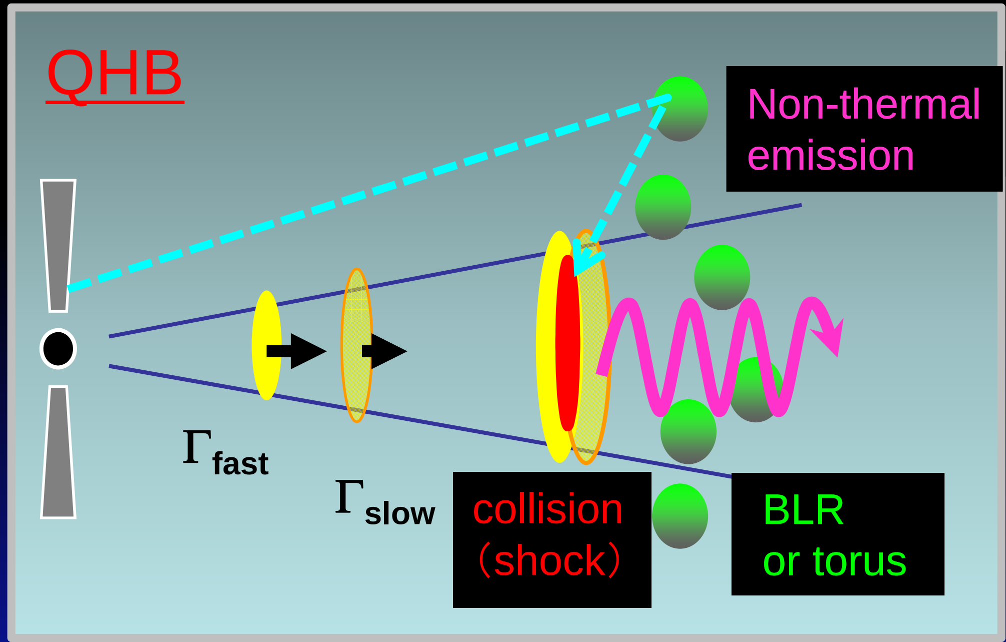


- 57 QHBs, 42 BL Lac (HBL+LBL), 6 unID, and 2 radio galaxies.
- Note, EGRET found fewer than 30 sources above 10 σ in its lifetime.
- Typical 95 % error is less than 10' .

Katagiri's talk

Internal shock in blazars





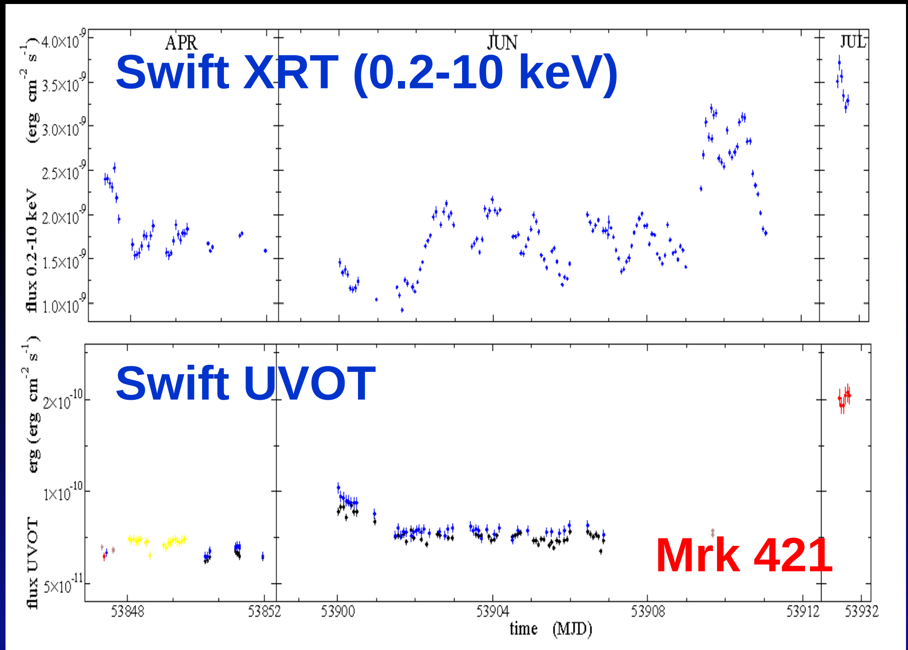
JK+ 2001, Tanihata+ 2001, 2003

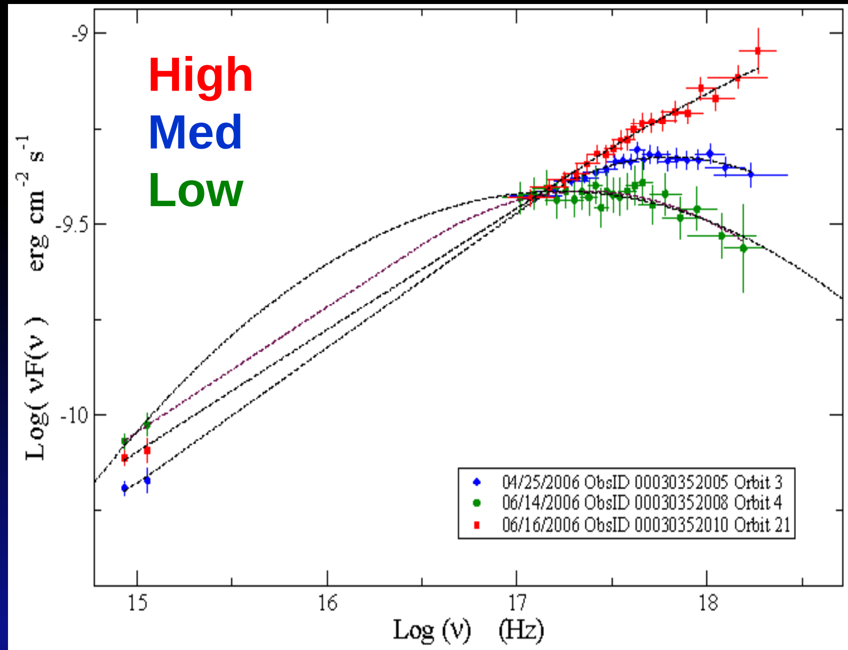
- Rapid variability suggests: $R \sim c\, t_{var}\, \delta \sim 10^{-3}$ pc.
- Only little variability below $t_{var} \ll 1$d : "Internal shock"
  - Modulation of relativistic outflows : $D \sim 10\, \Gamma_{jet}^{\ 2} R_g \sim 0.01$ pc

    ⇨ sub-pc jet (the first site of E-dissipation)
  - "Jet power" & "seed photons" control the blazar sequence.

Spectral Evolution of HBL

Tramacere+ 2009 (also Tanitaha+ 2004 etc)



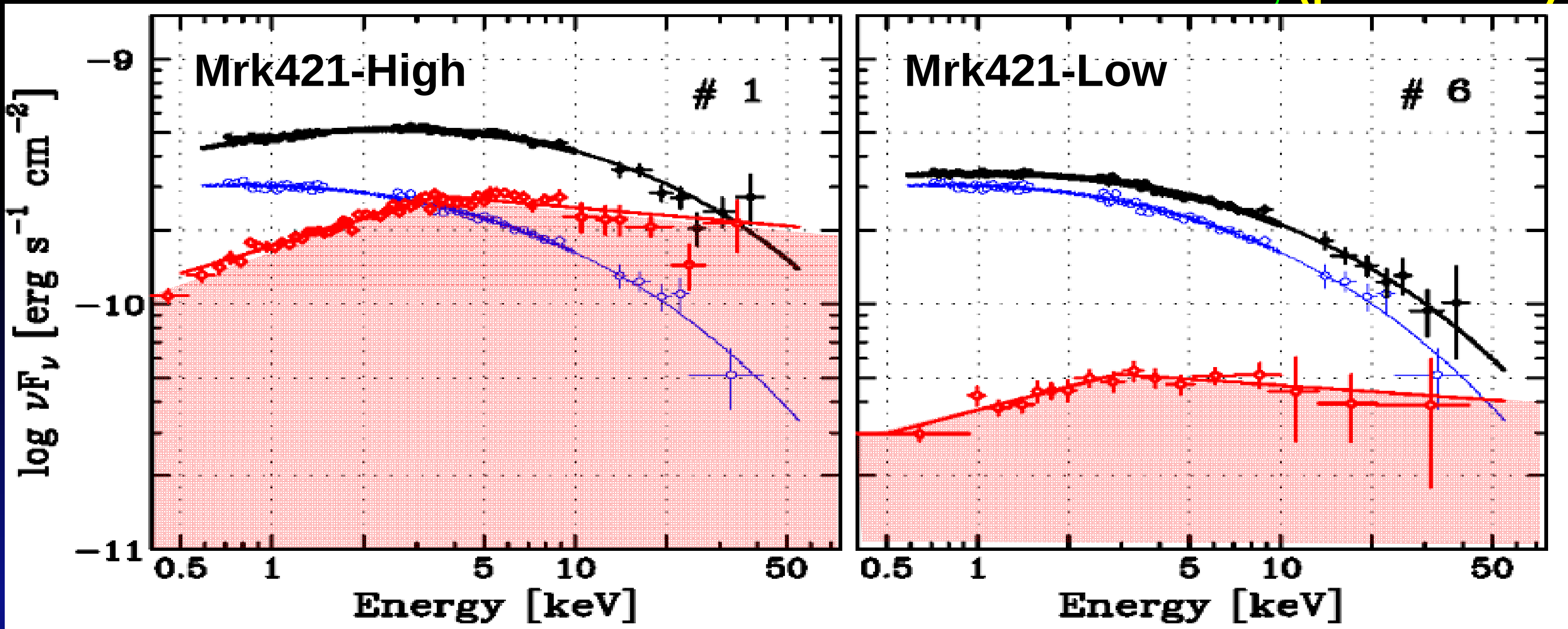


- Significant evolution *only* at X-rays, i.e., no significant variation at UV-optical: $E_p \sim 1$ keV $\rightarrow$ 10 keV.
- Usually, this has been argued as sudden increase of electron γ_{max} .
  (e.g., Takahashi + 1996, 2000, JK+ 1999, 2000)
- $\nu_{max} \propto \xi^{-1} \delta \, v_s^2$ (ξ: gyro factor, δ: beaming factor, v_s: shock speed)

Is it really expected???

Revealing "Variable" Component

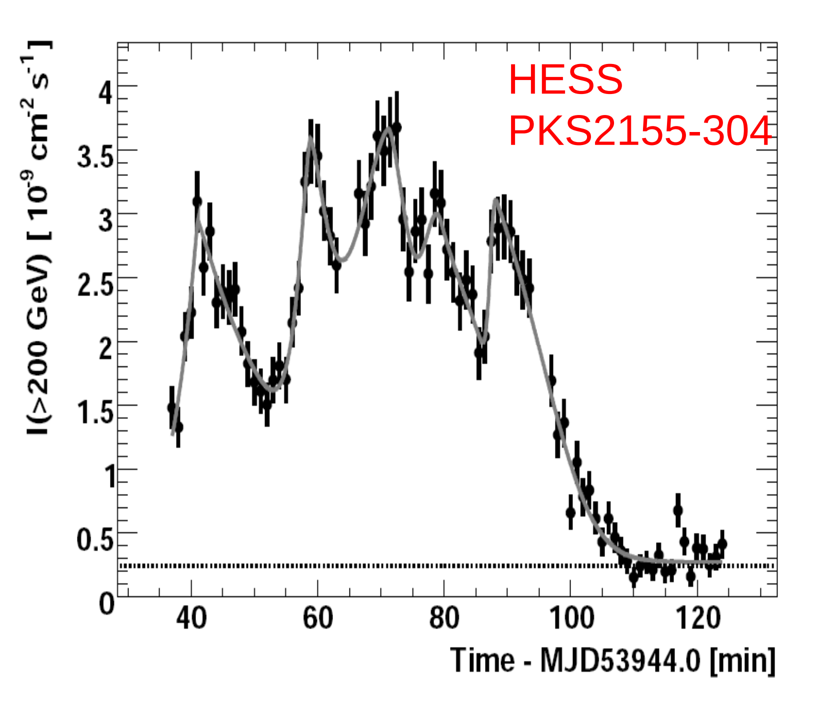
Ushio+ 2009 submitted, **(poster #P6)**

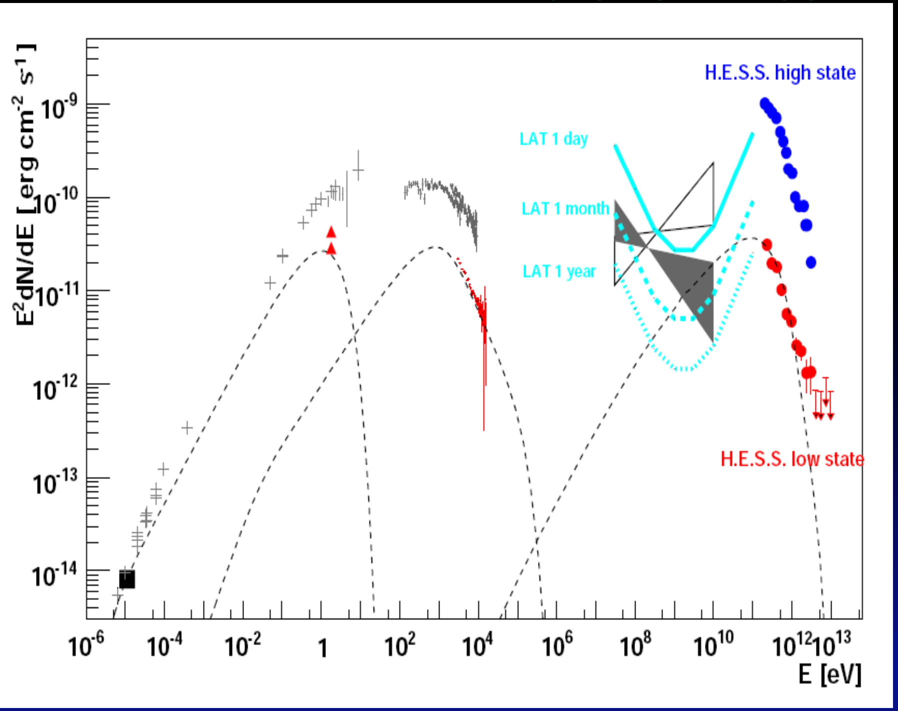


- "Variable component": $\Gamma_1 = 1.6$, $\Gamma_2 = 2.1$, $E_{brk} \sim 3$ keV
  - ✓ Fresh electrons "being accelerated" .
  - ✓ Innermost ($D \sim 10^{3\text{-}4}\ r_g$) region of the jet.
- "Steady component": $\Gamma \sim 2.0$, $E_p << 1$ keV (exp cutoff)
  - ✓ Already cooled electrons at large distance.
  - ✓ Fermi II (stochastic acceleration) at work ?

Ultra Fast Variability of HBL

Aharonian+ 2007





- PKS 2155-304: HBL, z=0.116
  - July 2006 flare: ~7 Crab, VHE strongly correlated with X-rays.
  - Ultra-fast variability as short as min scale by H.E.S.S.
- Fermi Campaign:
  - 11 nightly obs. using HESS, ATOM, RXTE (+ Swift)
  - Constraints on spectral shape, especially EIRB.

Fermi Observation of HBL

Submitted to ApJ

- <u>SSC model fitting</u>

  VHE: ~0.2 Crab, $\Gamma_{int} \approx 2.5$

  HE: Γ_L=1.61±0.16, Γ_h=1.96±0.08, E_b=1.0±0.3 GeV

  X-ray: Γ_L=2.36±0.01, Γ_h=2.67±0.01, E_b=4.4±0.5 keV

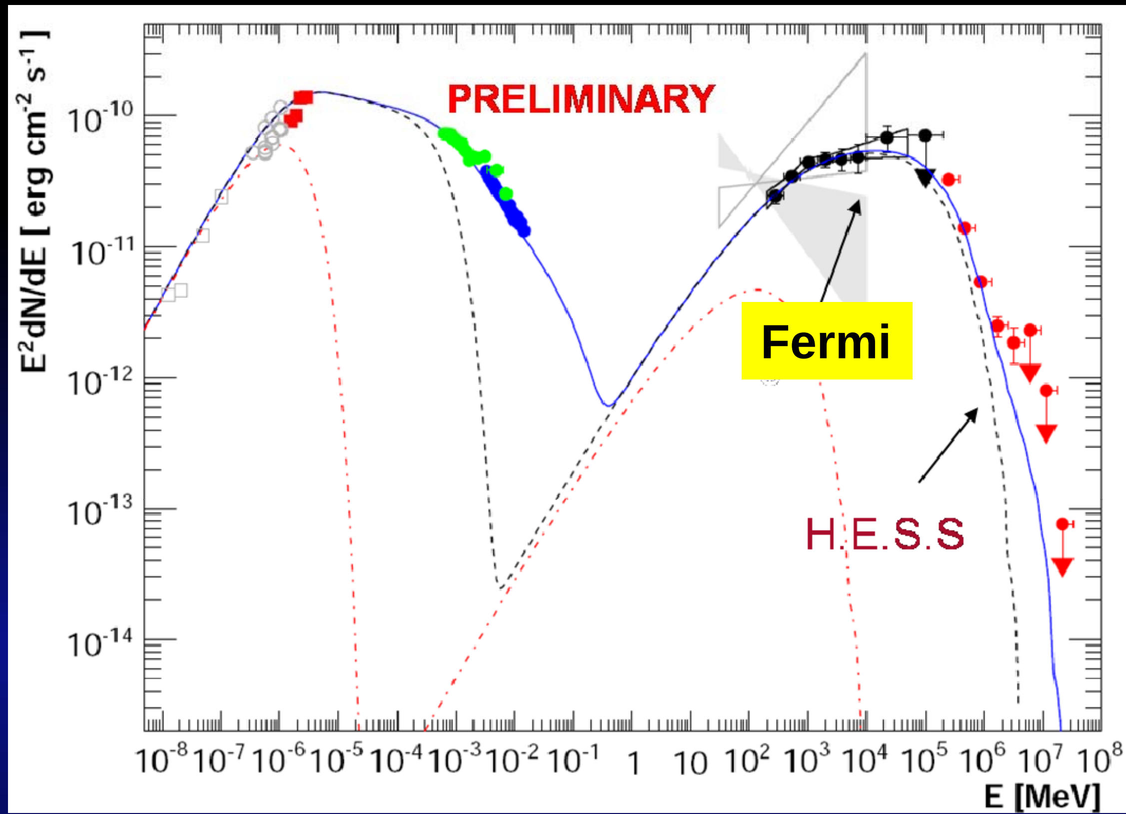
<u>Model parameters</u>

(3-component power-law):

p_0=1.3, p_1=3.2, p_2=4.3 where $dn/d\varepsilon \propto \varepsilon^{-p}$

break energies: ε_1=7.4GeV, ε_2=120GeV

R=1.5×10^{17}cm, δ=32, B=0.02G

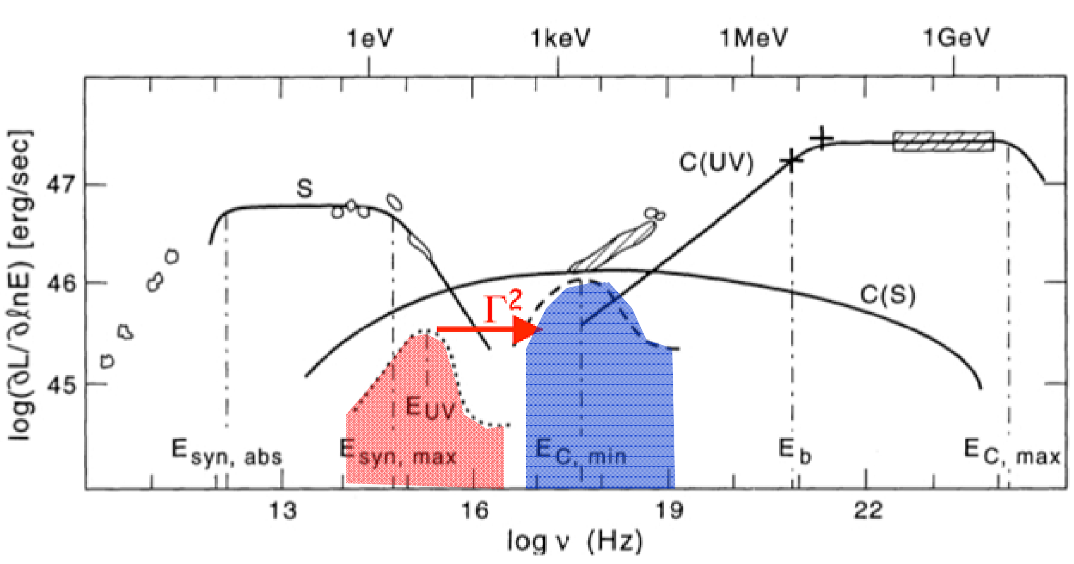


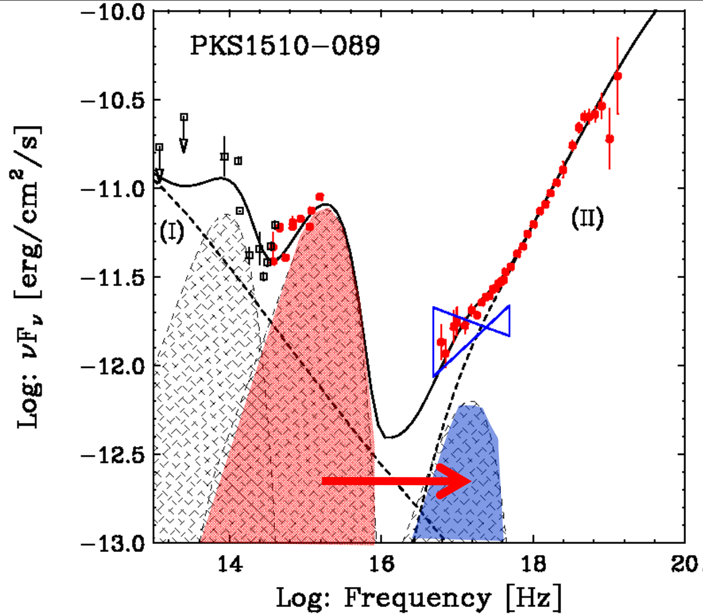
- Some thought…
  - X-rays are produced by highest energy electrons, $\varepsilon > \varepsilon_2$
  - HE and VHE are produced by electrons with $\varepsilon_1 < \varepsilon < \varepsilon_2$
  - X-rays can vary independently of VHE emission (cf. July 2006 flare)

Contact Author: J.Chiang

Suzaku observation of QHB (I)

JK+ 08b



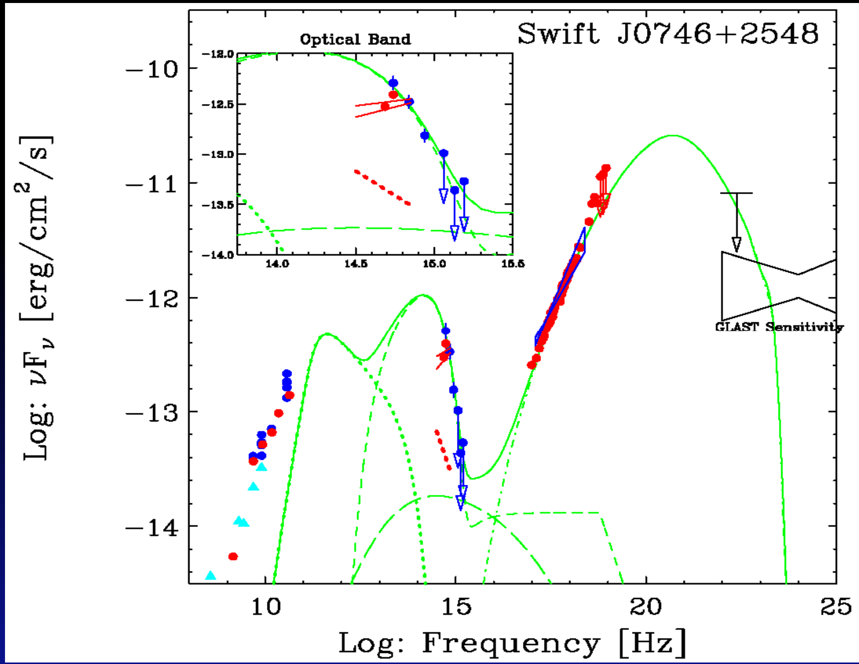


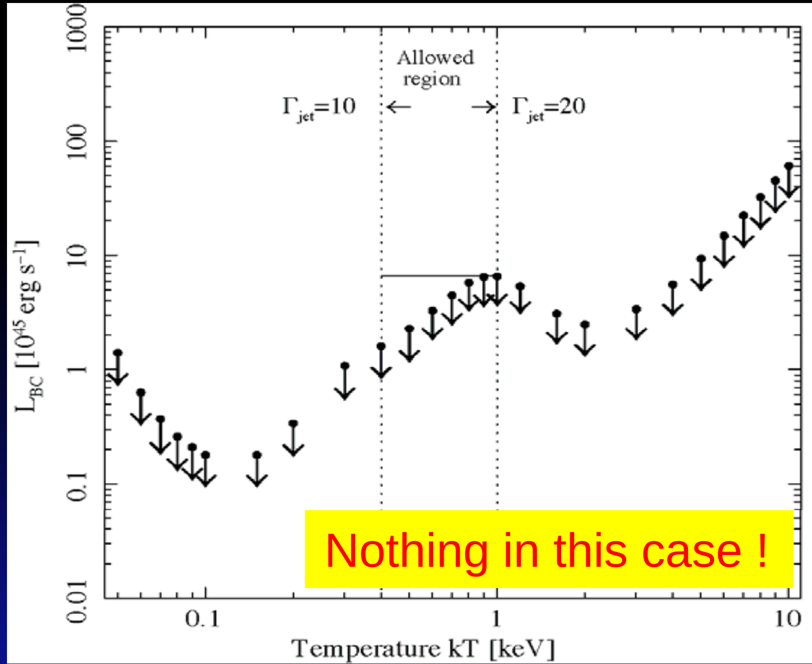
- "Seed" for the ERC process is UV photons reflected by the BLR. E_{diff} ~ 10 eV, $L_{diff} \sim 10^{46}$ erg/s
- Before the "blazar zone", fast /slow shells up-scatter UV via the "bulk-Comptonization" to $E_{BC} \sim \Gamma_{BLK}^2 E_{diff}$ ~ 1 keV.
- BC luminosity depends on the jet composition : $L_{BC} \propto (n_e/n_p) L_{jet}$

⇨ $\boxed{\Gamma \sim 20,\ r \sim 1\text{pc},\ n_e/n_p \sim 10,\ B \sim 0.6\ \text{G},\ L_e/L_p \sim 0.05}$

Suzaku observation of QHB (2)

Watanabe+ 09



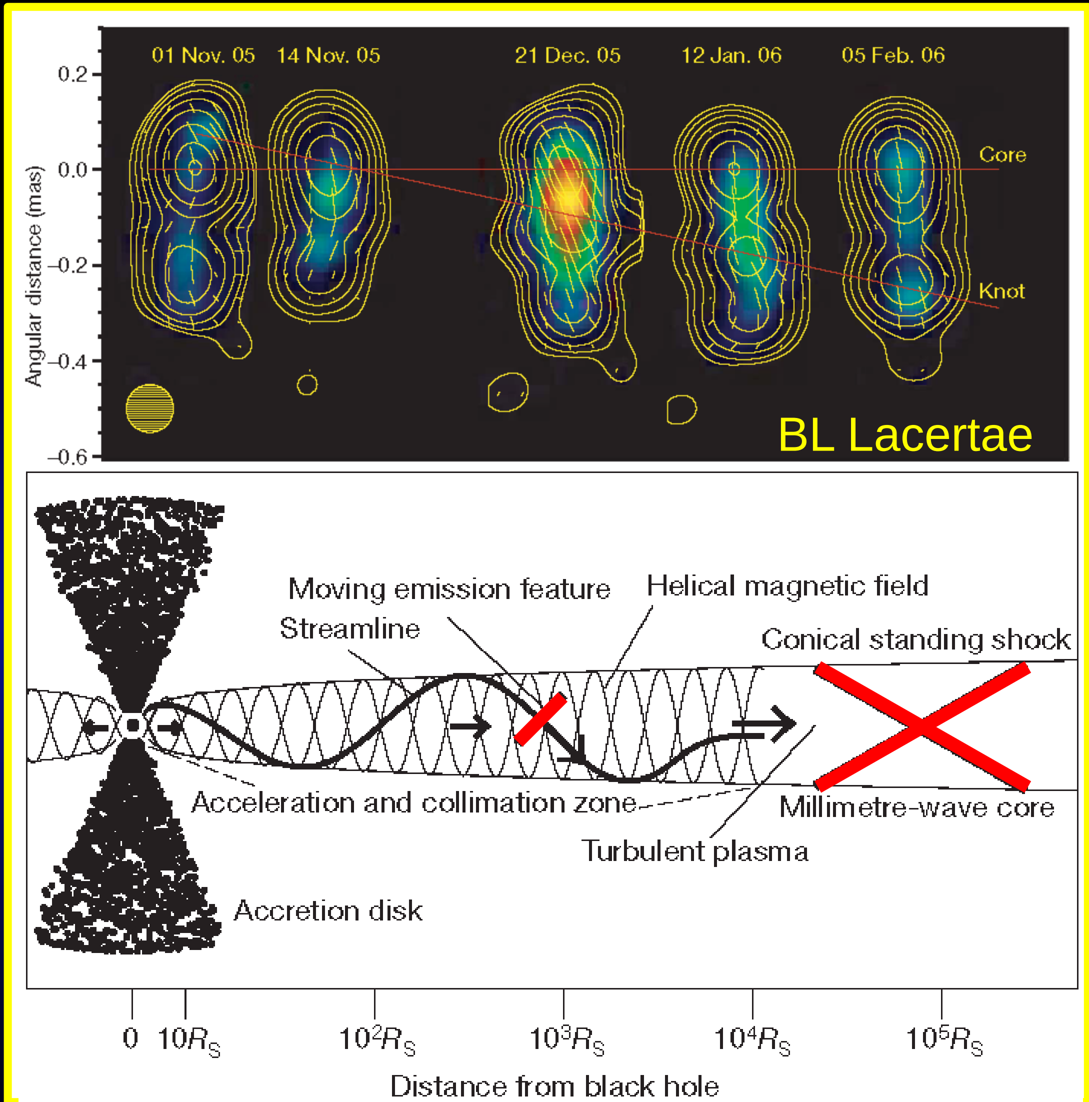


- A distant QHB at z = 2.98 (Sambruna+ 06)
- Non detection of BC component , but useful UL on particle contents in jets: $n_e/n_p \lesssim 7.3$.

But, still mystery…the lack of BC emission in general may mean:
(1) jets cannot be fully formed/accelerated too close to the BH?
(2) cold electrons cannot carry bulk of the jet power?

Note on the Blazar region ?

Marscher+ 2008



- Bright feature in the jet causes a "double flare":
  (1) optical to TeV flare w/ 240º PA rotation.
  (2) delayed radio flare.
- First flare: plasma passing through the helical B field, (towards the observer)
  Second flare: plasma crosses a standing shock ?

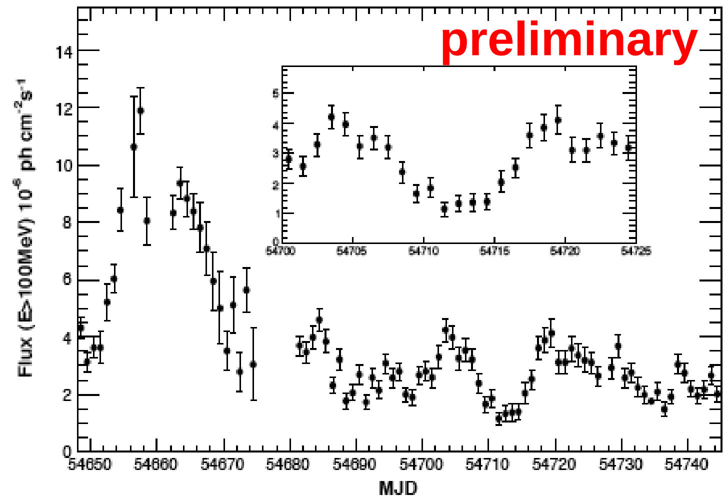
  Jet may not fully be formed/accelerarted in blazar zone?

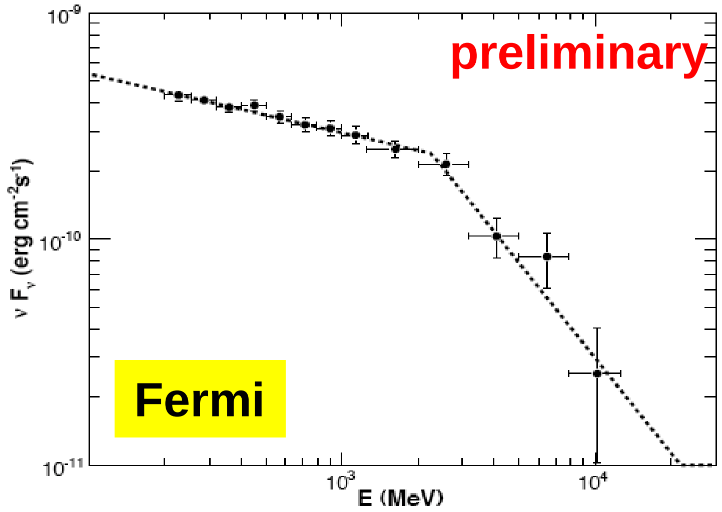
Fermi Observation of QHB

Submitted to ApJ

- <u>3C454.3 at z = 0.859</u>
  Detected by EGRET, AGILE.
  Very active since 2000.
- Fermi-LAT data show rapid, quasi-symmetric, flares on a time scale of ~3 days.
- First observation of a <u>spectral break</u> above 100MeV.

<u>A possible interpretattion:</u>
Direct signature of an intrinsic break in the energy distribution of the radiating particles?

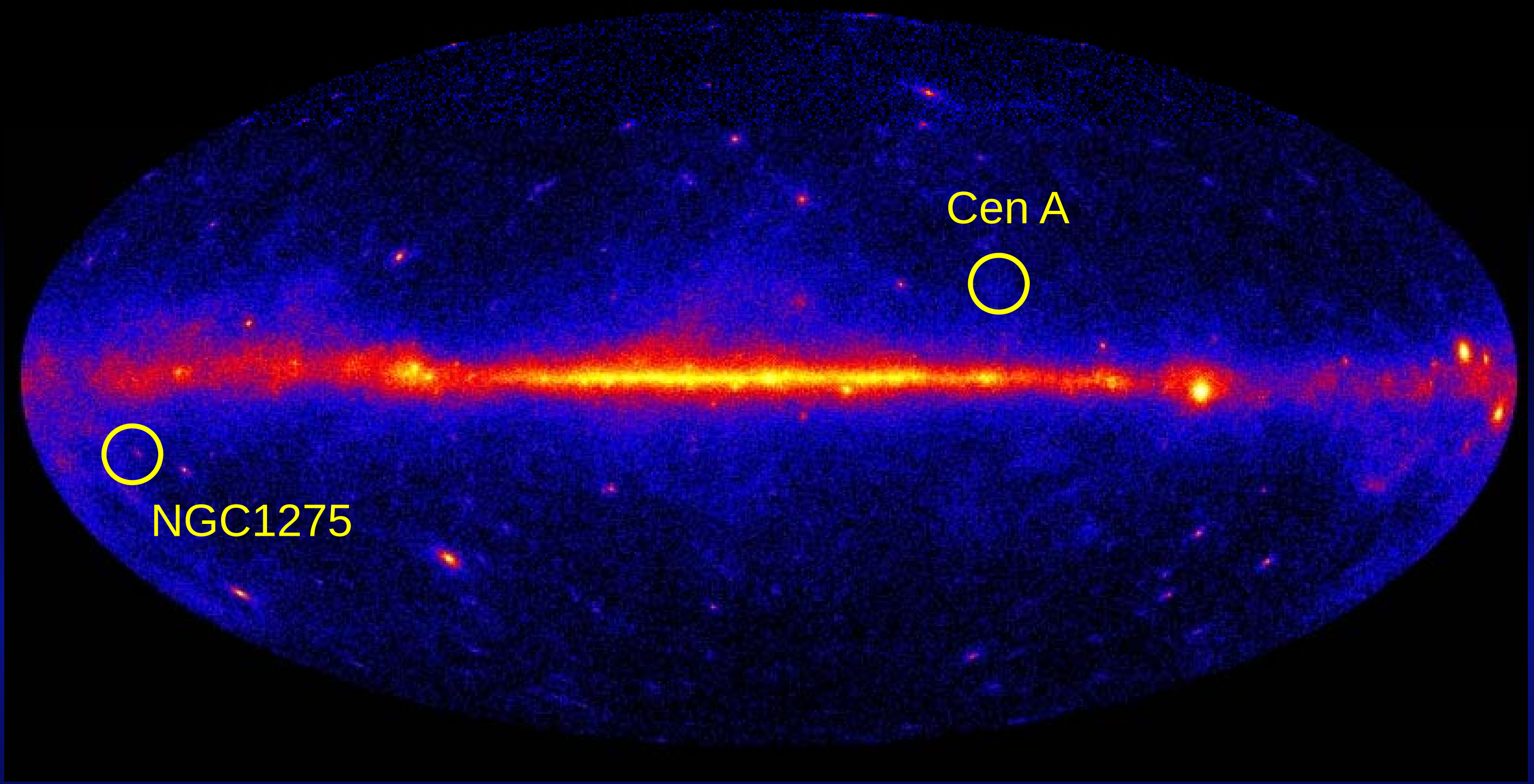




Contact Author: G.Madejski & B.Lott

Non-blazar type AGN?

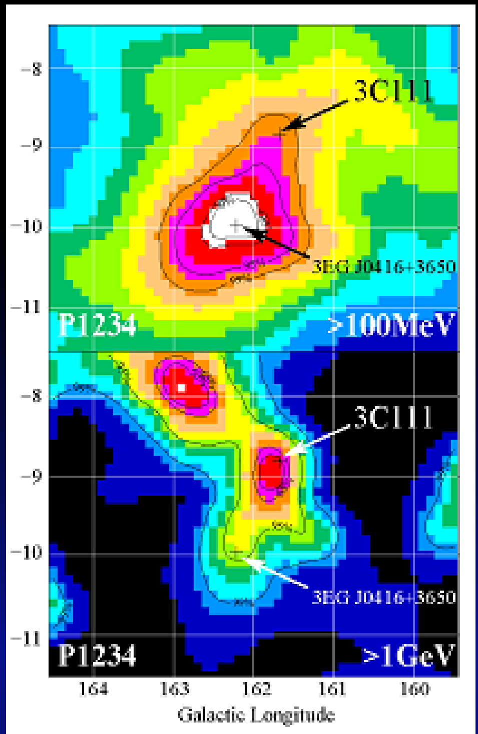
3 month image (2008.8-10)

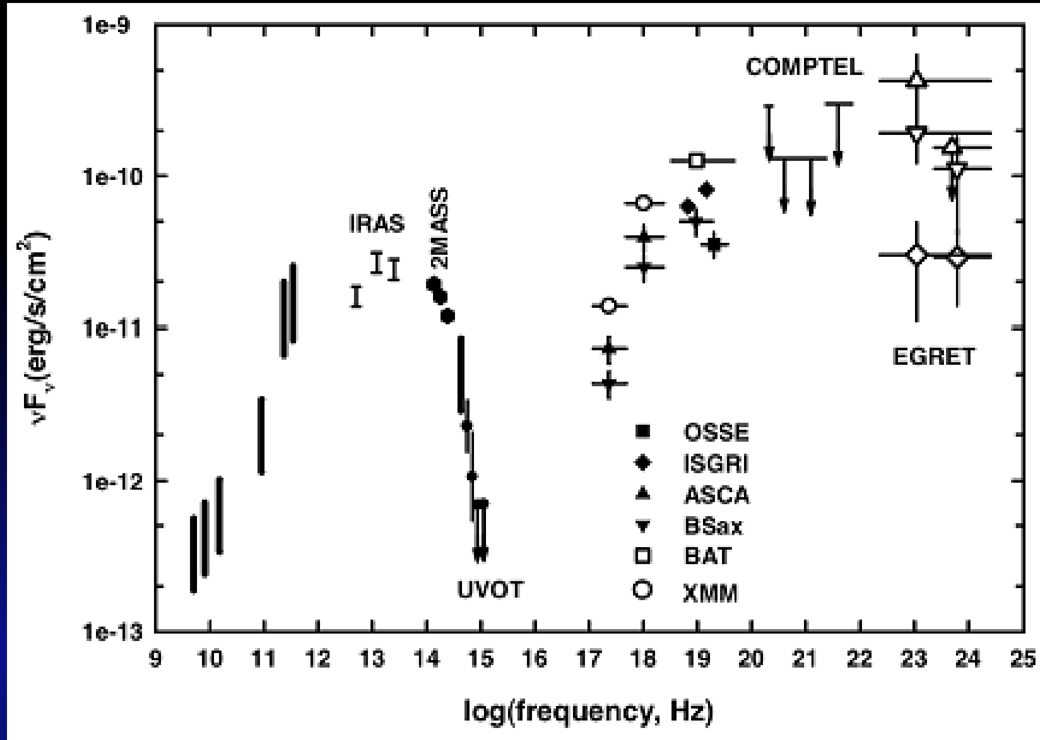


- 2 radio galaxies, NGC 1275 and Cen A have already been detected above 10 σ level.
- Not surprising – detections of several RGs reported by EGRET.

EGRET Detection of RGs

Hartman+ 2008

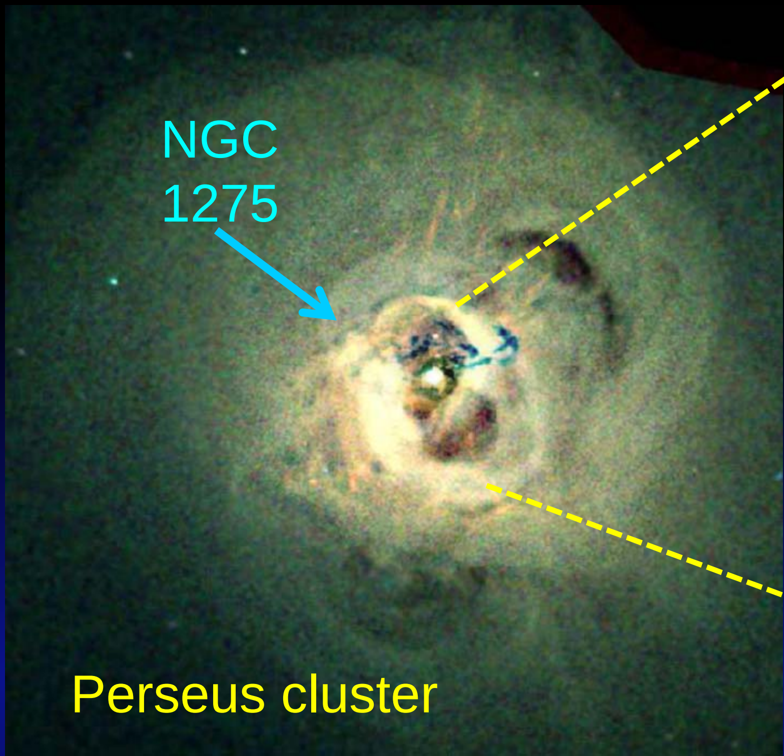


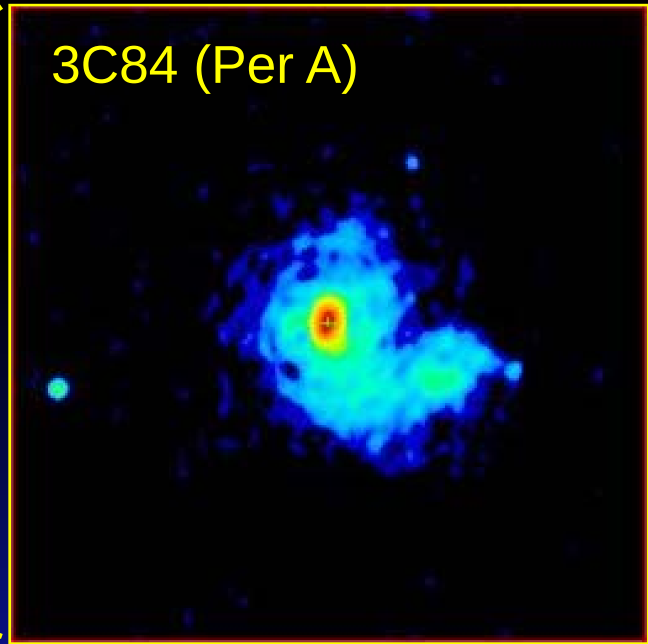


- Reanalysis of EGRET data significantly increases the number of AGNs detected at > 100 MeV (Nandikotkur+ 07, but see Casandjian & Isabelle 08)
- Centaurus A, 3C 111, NGC 6251 were detected, indicating close similarity of the SED w/ blazars.

(Hartman+ 08; Mukhergee+ 02; Sreekumar+ 99)

New Comer: NGC 1275 ?





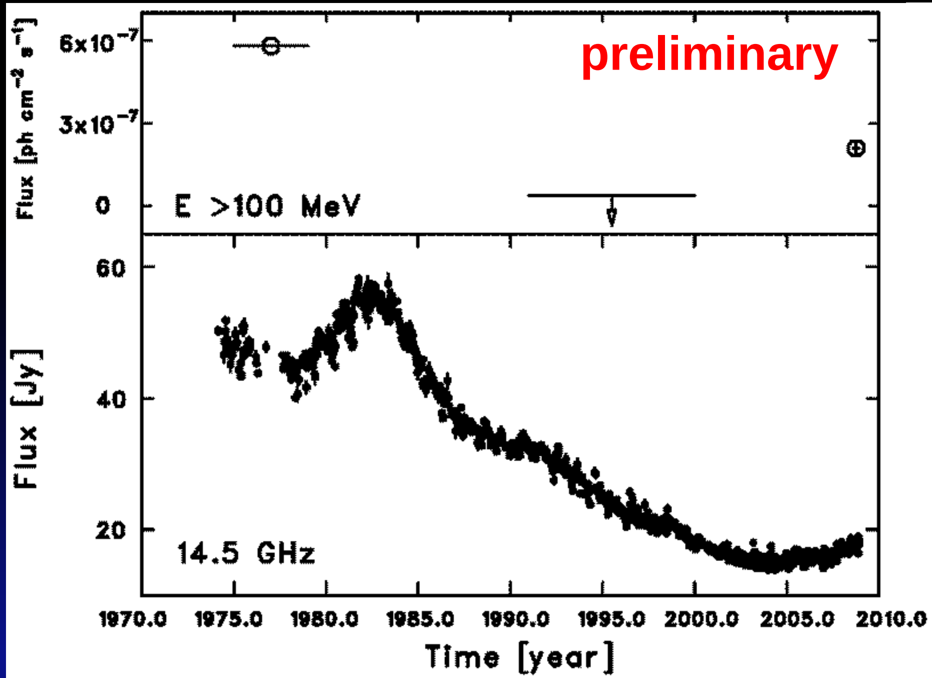
e.g., X-ray: Fabian+ 03
Radio: Pedlar+ 90, Asada +06

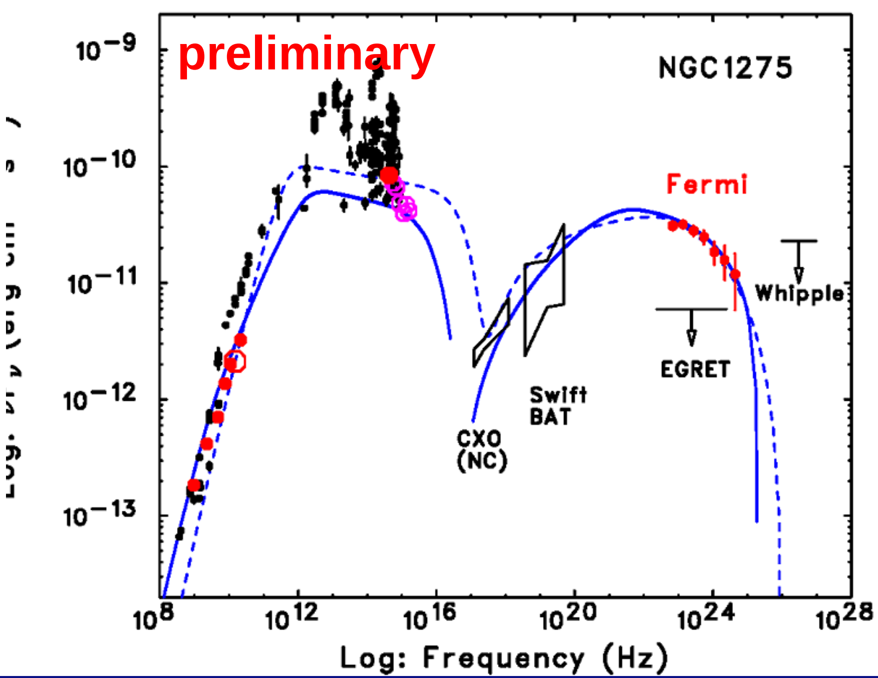
- Perseus cluster hosts the giant elliptical galaxy NGC 1275 at its center. Shocks and ripples are clearly evident in deep Chandra image.
- In radio, NGC 1275 hosts the exceptionally bright radio source Per A, also known as 3C 84.

AGN, or dark matter annihilation ?

SED and Long-term Trend

Submitted to ApJ





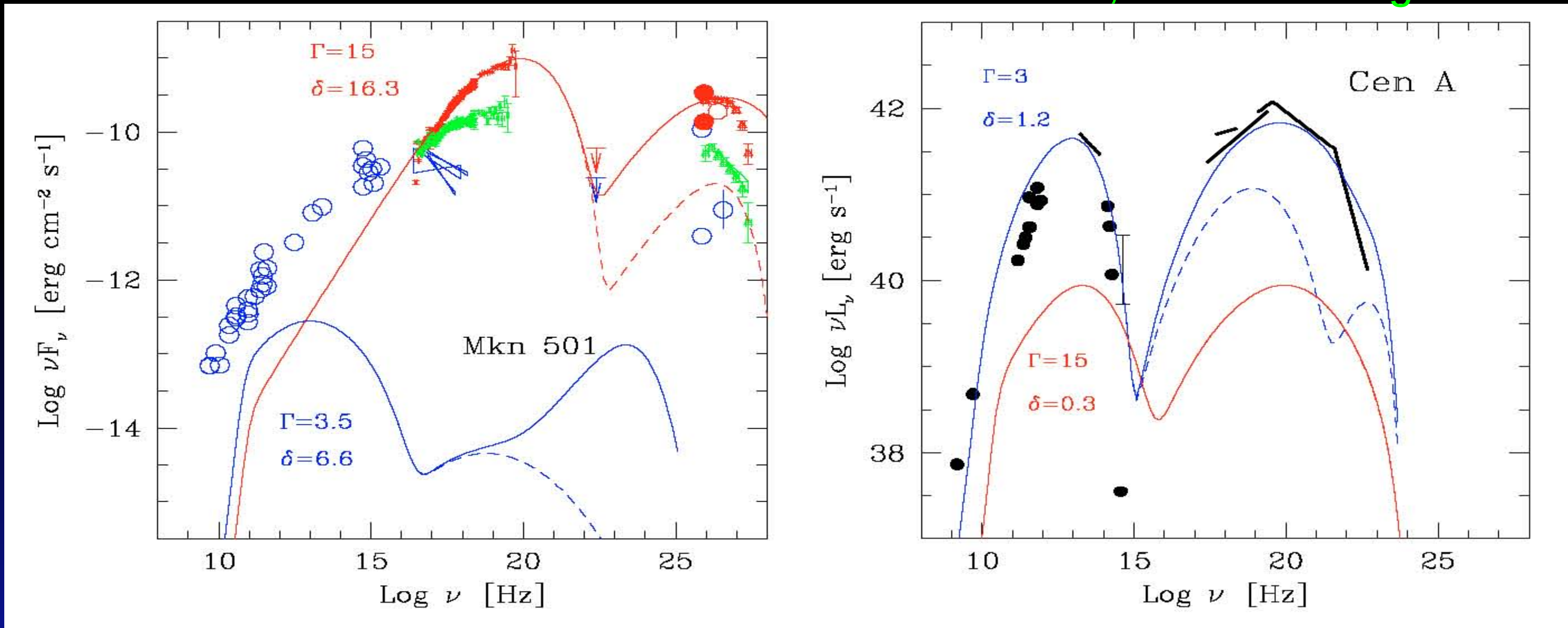
- Clear detection but Fermi LAT, but tight UL given by EGRET.
  → significant variability on time-scale of years to decades.
  → could be associated with ejection of new radio knot?

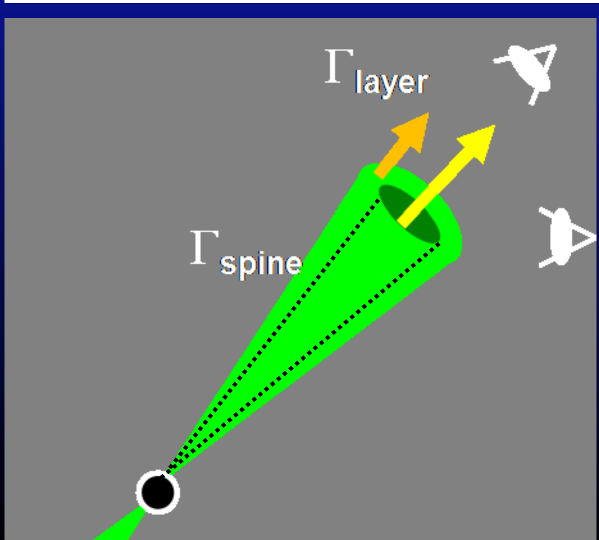
- Either one-zone SSC (Γ_j = 1.8) or decelerating jet flow (Γ_j = 10 → 2) model represent s the data well.

Contact Author: J.Kataoka

RGs as a Gamma-ray Emitter

Ghisellini+ 05, also Chiaberge+ 2000





- RGs may/should be "mis-aligned" blazars
  - low power FR I ⟷ BL Lacs
  - high power FR II ⟷ QHBs
- SED modeling on-going

Spine dominated ….. Blazars
Layer dominated ….. RGs

Summary

I have reviewed most recent observational highlights from large scale jets & blazars viewed at high energies.

- Recent survey of large-scale jets with CXO have brought us new insights on the kpc/Mpc scale jet - jet structures, turbulent acceleration, ultra relativistic electrons above 100 TeV.

- Unprecedented sensitivity of Fermi/Suzaku provides new challenges to the blazar physics - Unification of blazars and radio galaxies are being more common.

More will come soon w/ Fermi!