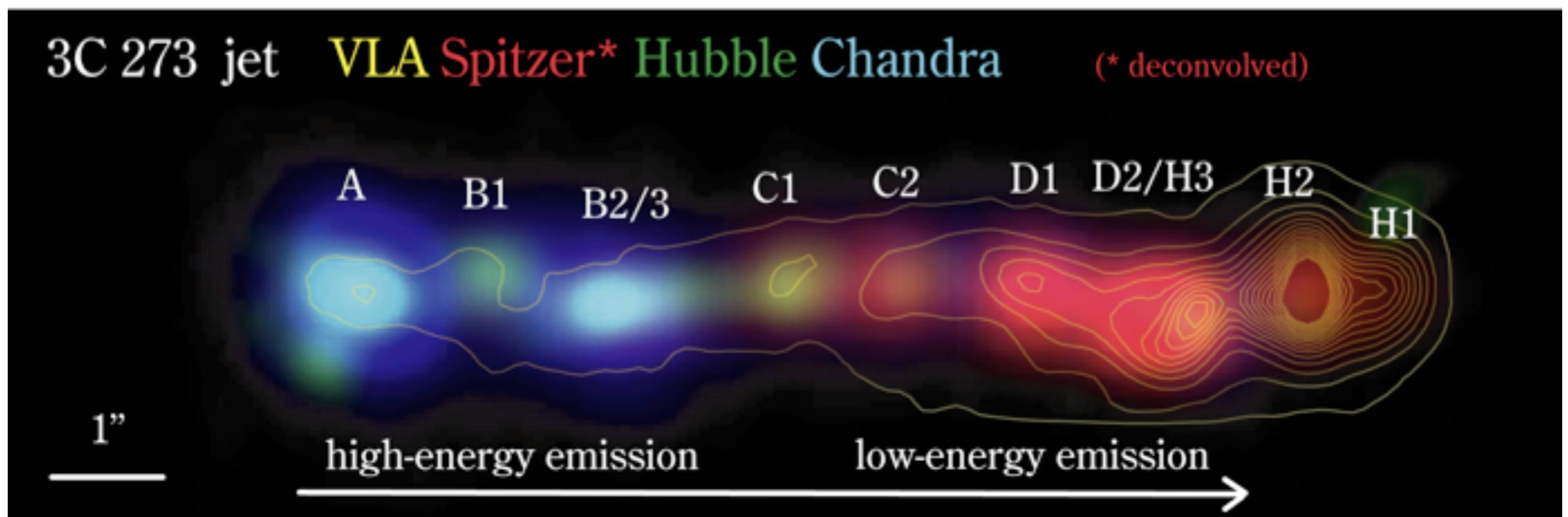
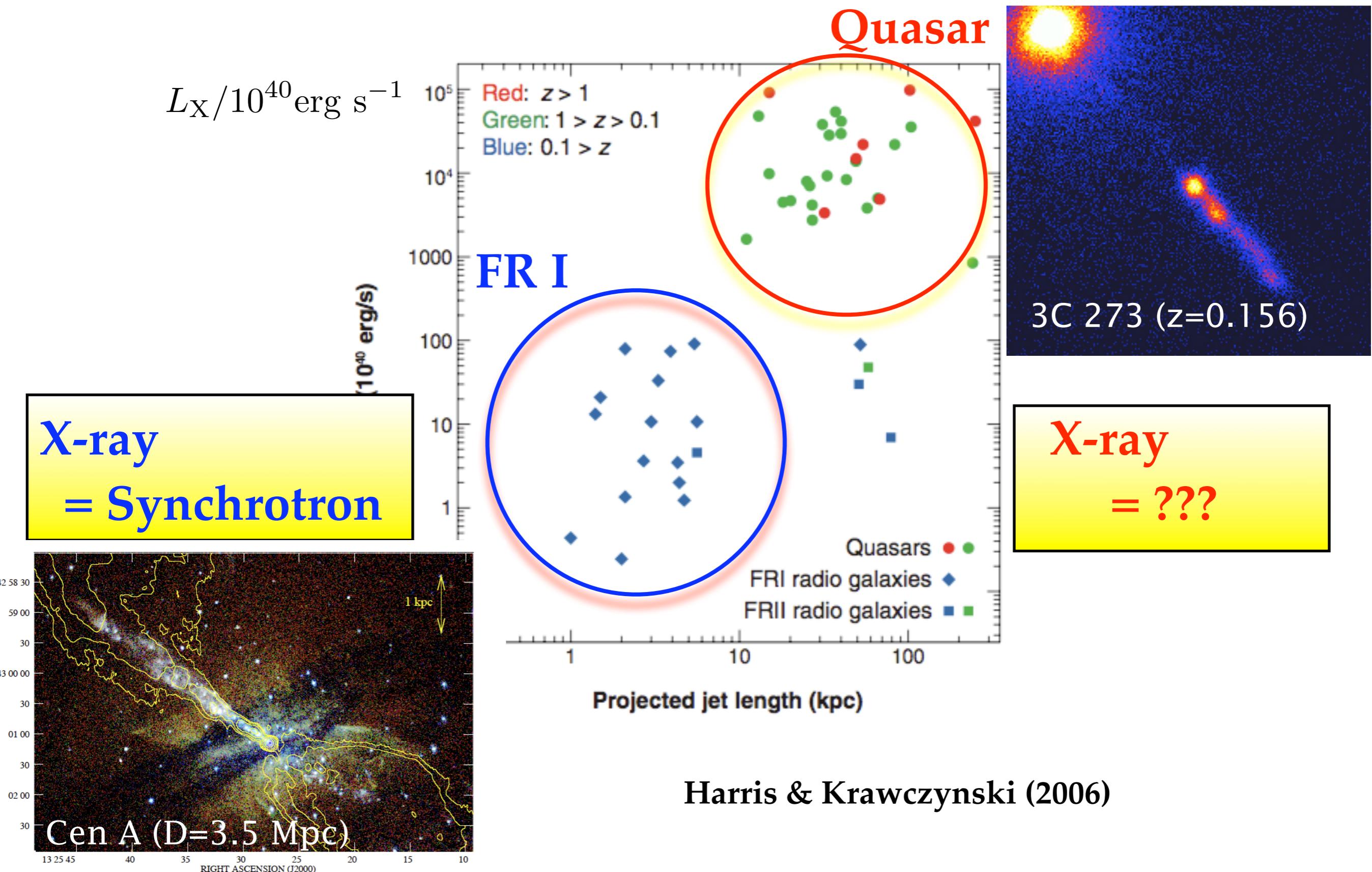


Synchrotron (and IC) jet emission in quasars

Yasunobu Uchiyama (SLAC)

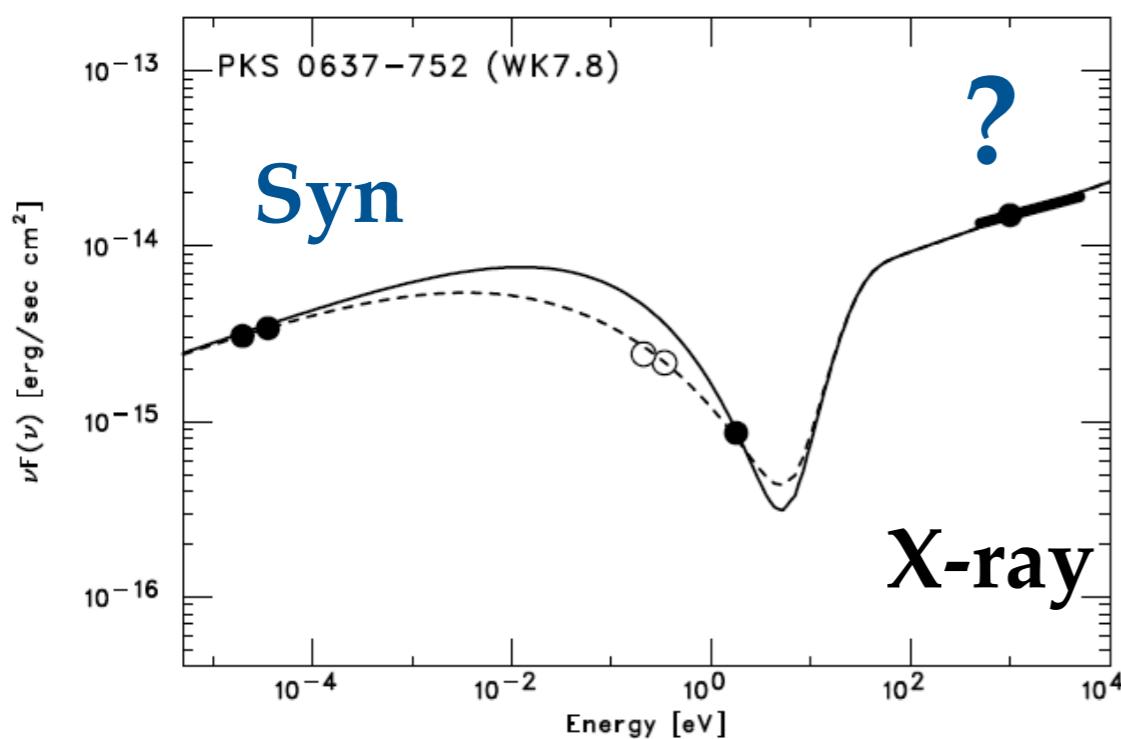
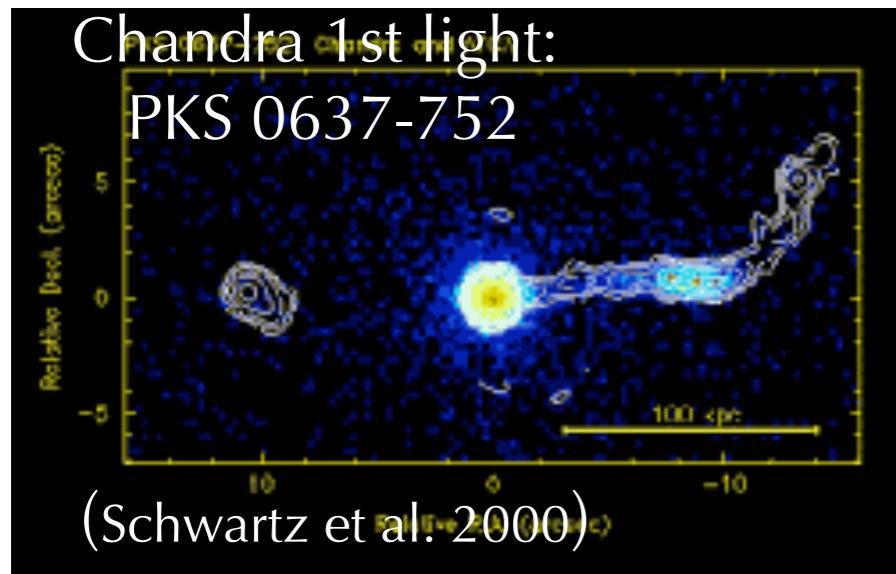


Two classes: low / high power jets



Origin of Chandra quasar jets?

Strong X-rays!!



“Beamed IC/CMB” model

Inverse-Compton by MeV electrons
significant beaming (at ~ 100 kpc)
with a Doppler factor $\delta \sim 10$

Tavecchio+ 00; Celotti+ 01

$$\frac{L_{\text{IC}}}{L_{\text{syn}}} \simeq 1.4 \times 10^{-3} (1+z)^4 \delta^4$$

for $\delta B = 0.1$ mG

e/p Synchrotron models

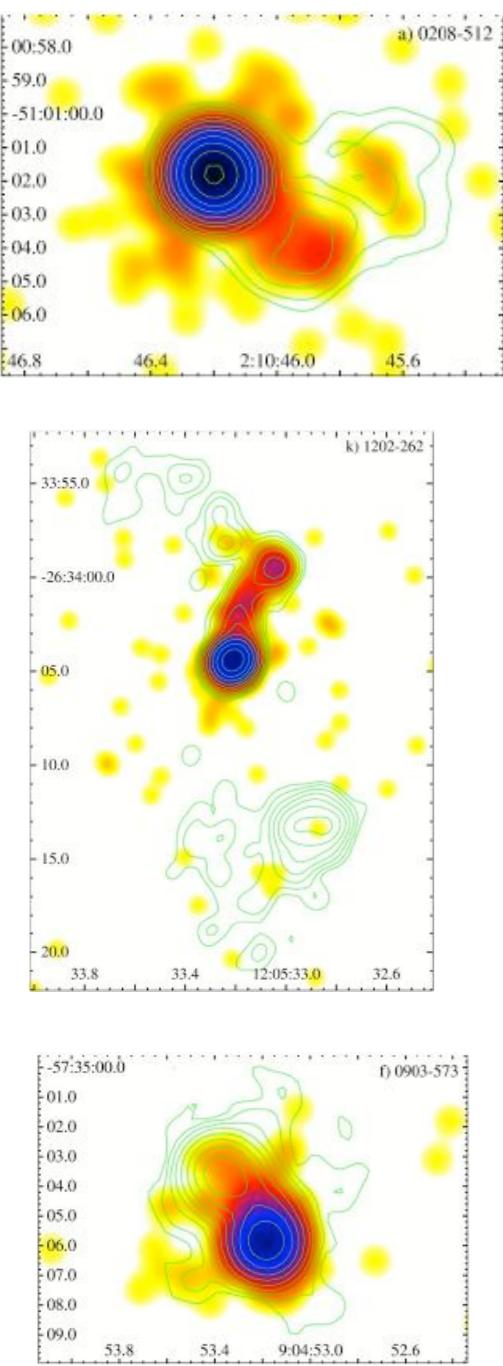
(a) 2nd electron synchrotron
e.g., turbulent acceleration

Stawarz&Ostrowski 02

(b) proton synchrotron

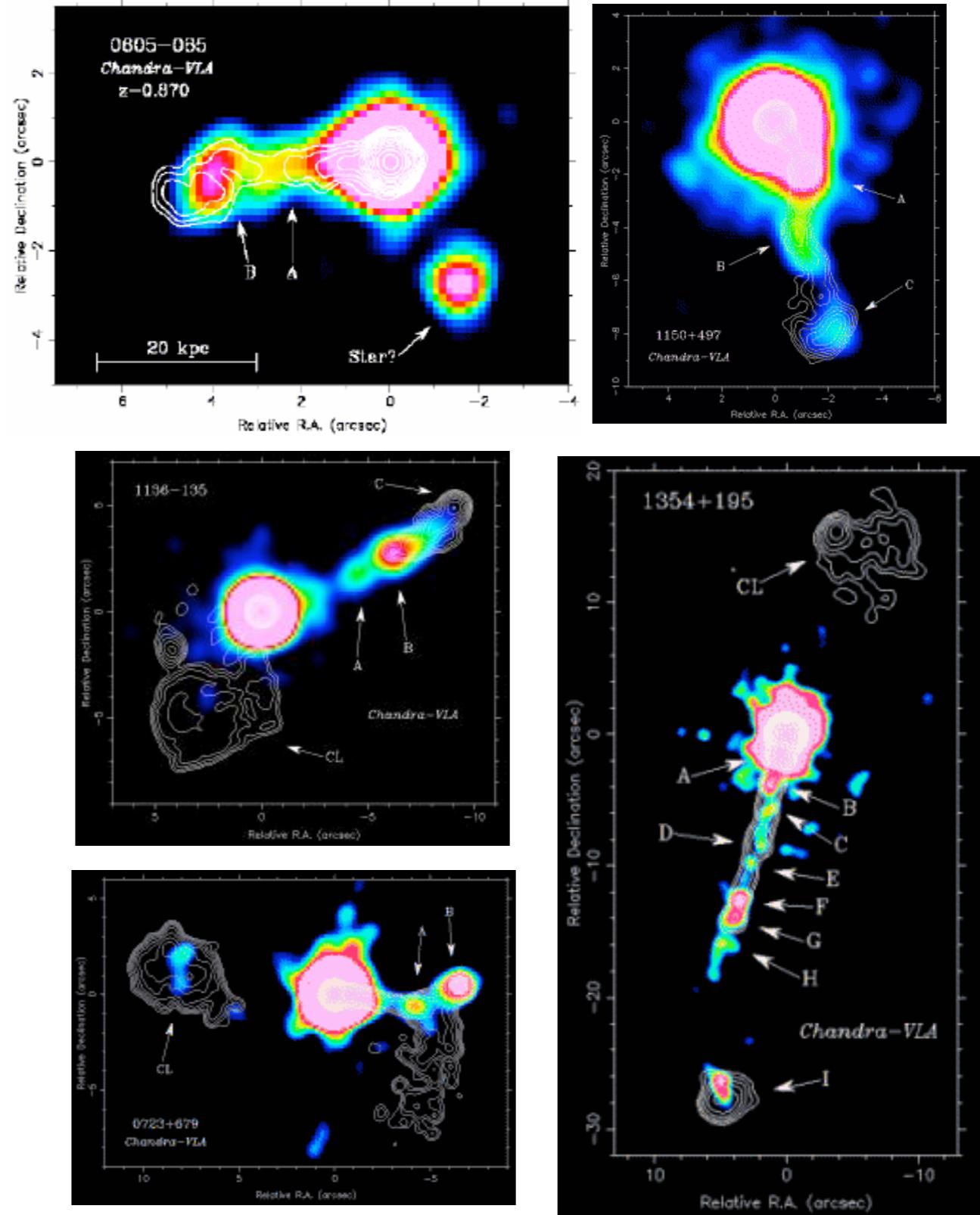
Aharonian 02

Chandra snap-shot surveys



Marshall+ (2005)

Sambruna+ (2004)



X-ray detection rate is high: about 50%

Observational windows

- ★ We need “arcsecond” (or better) resolution

GHz VLA etc

Optical Hubble Space Telescope **> 30 jets**
Crane et al. (1993), Bahcall et al. (1995),

X-ray Chandra Observatory **> 70 jets**
Chartas+ (2000), Schwartz+ (2000), Sambruna+ (2004), ...

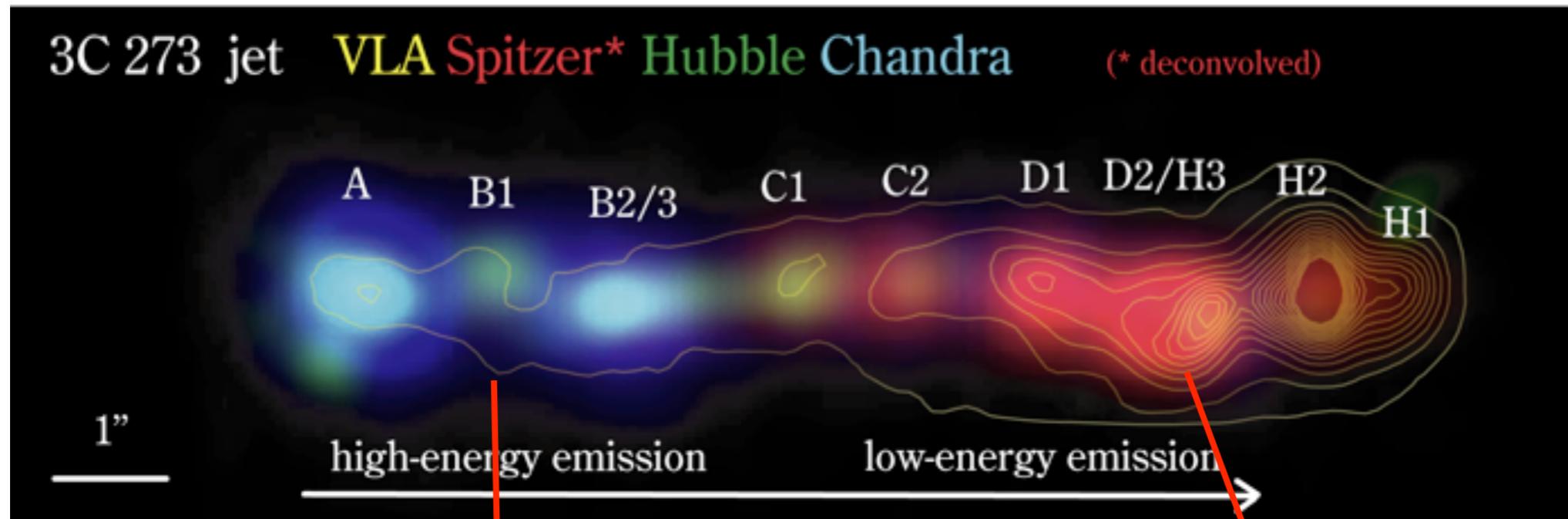
IR Spitzer Space Telescope = **5 jets**
Uchiyama+ (2005, 2006, 2007), Hardcastle+ (2006)

Sub-mm SMA = 2 jet **ALMA coming!**
Tan+ (2007), This Talk  **New!**

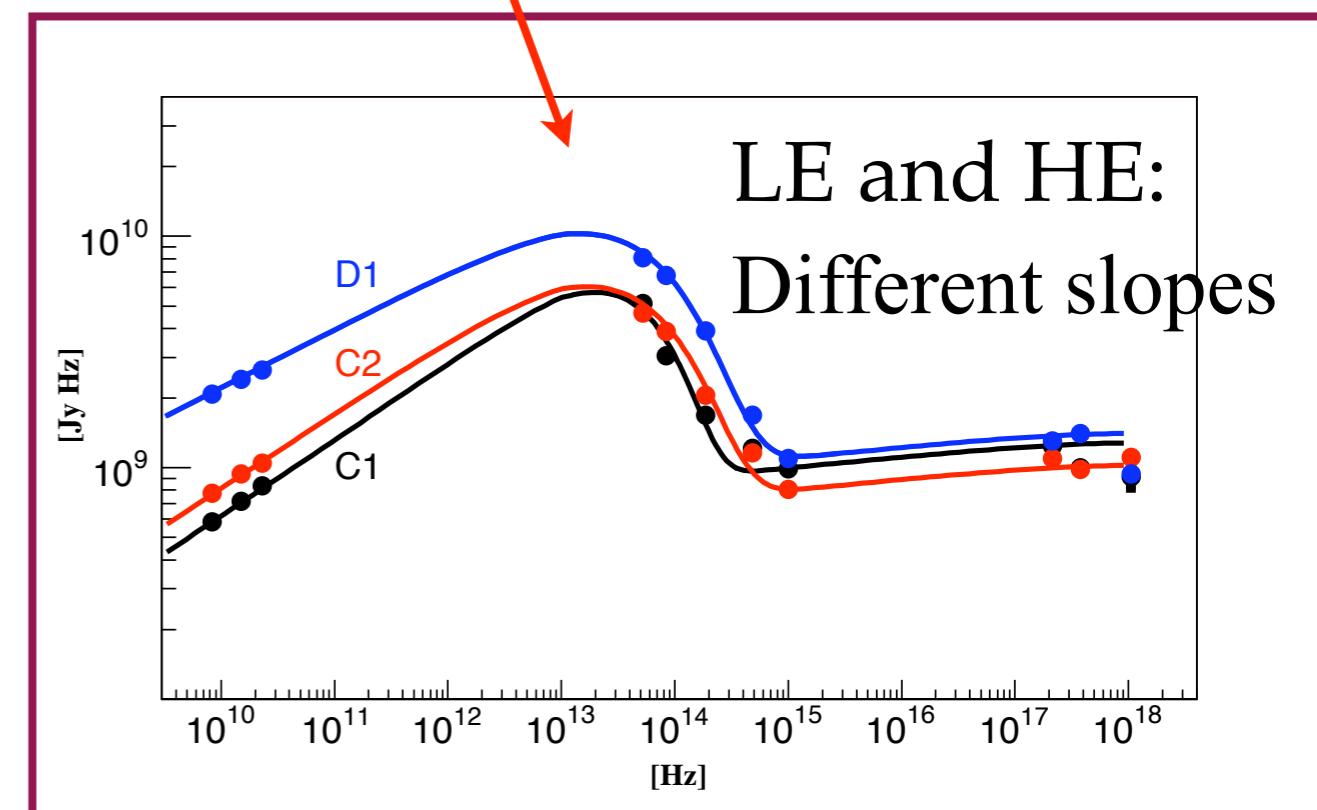
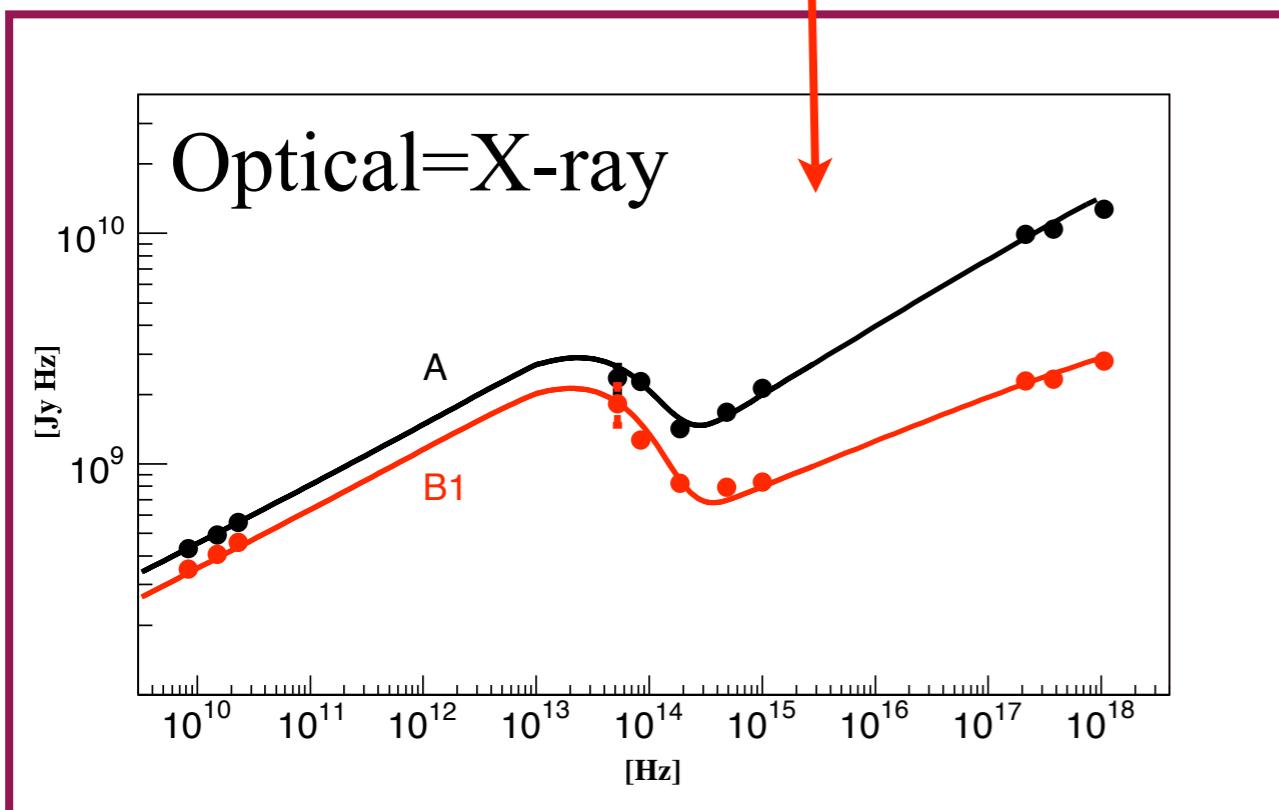
Quasar 3C 273: the brightest one

Knot SEDs: 2 components

Uchiyama+ 2006
(see also Jester+ 2006)



- knot size: $\sim 0.3'' \sim 1$ kpc
- $B \sim 0.1$ mG (eq)



HST Far-UV Jester+ 2007

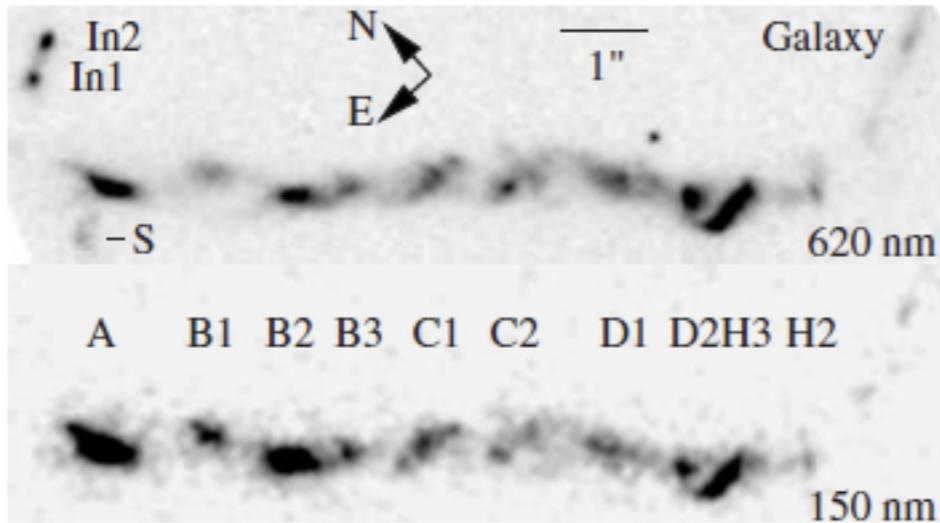
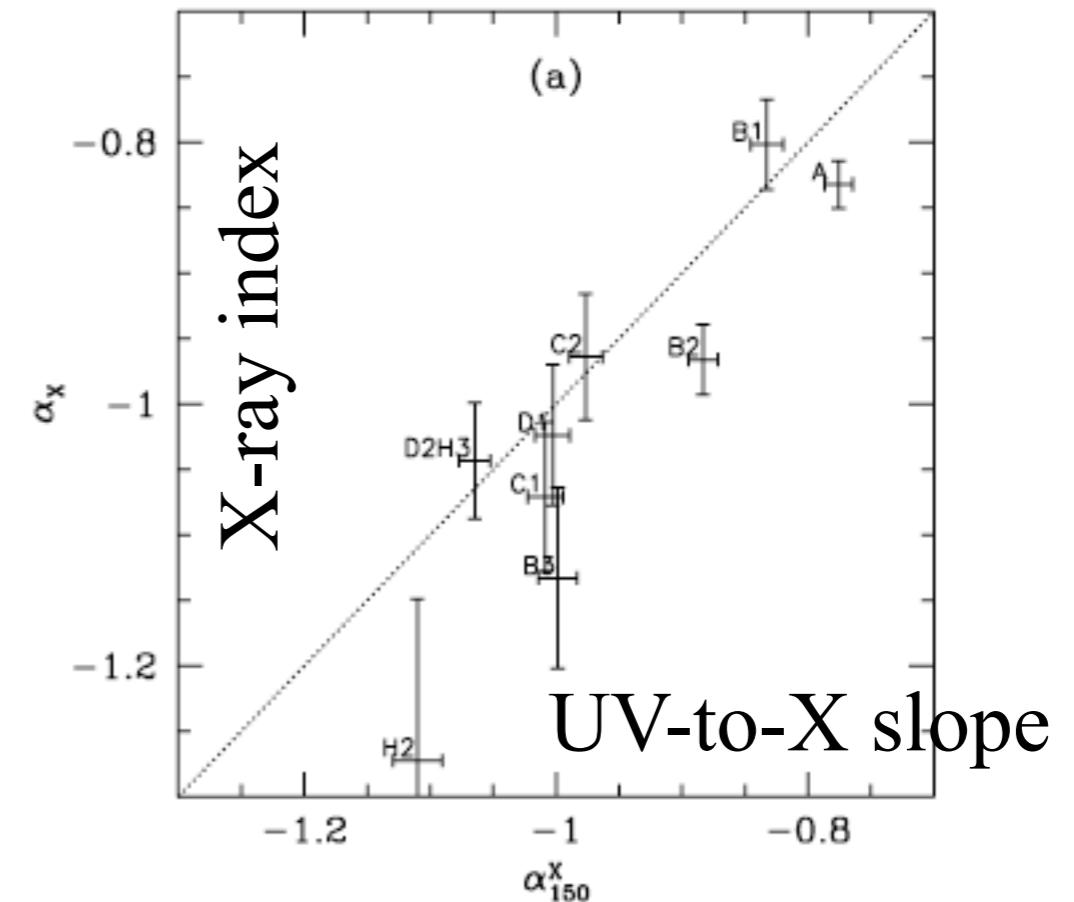
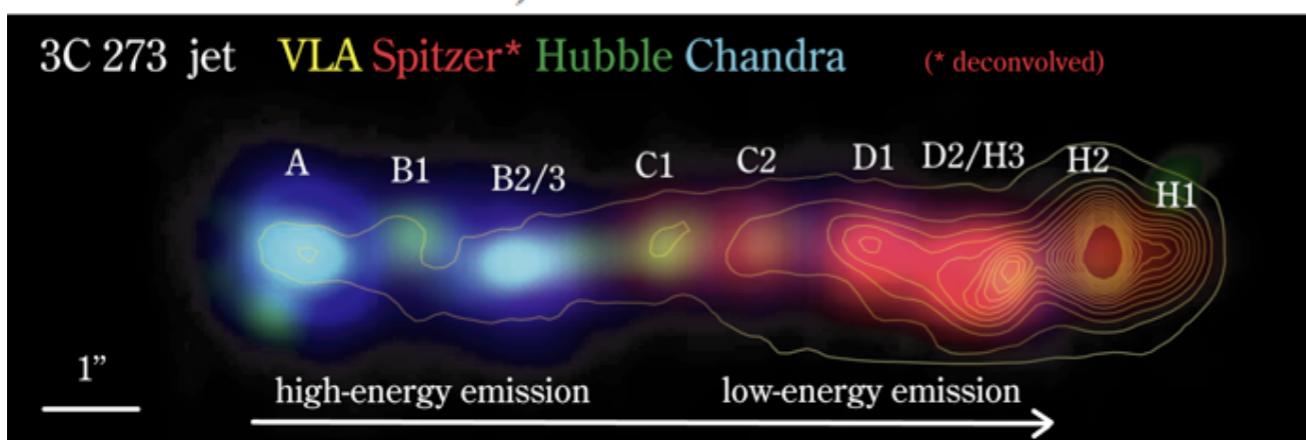
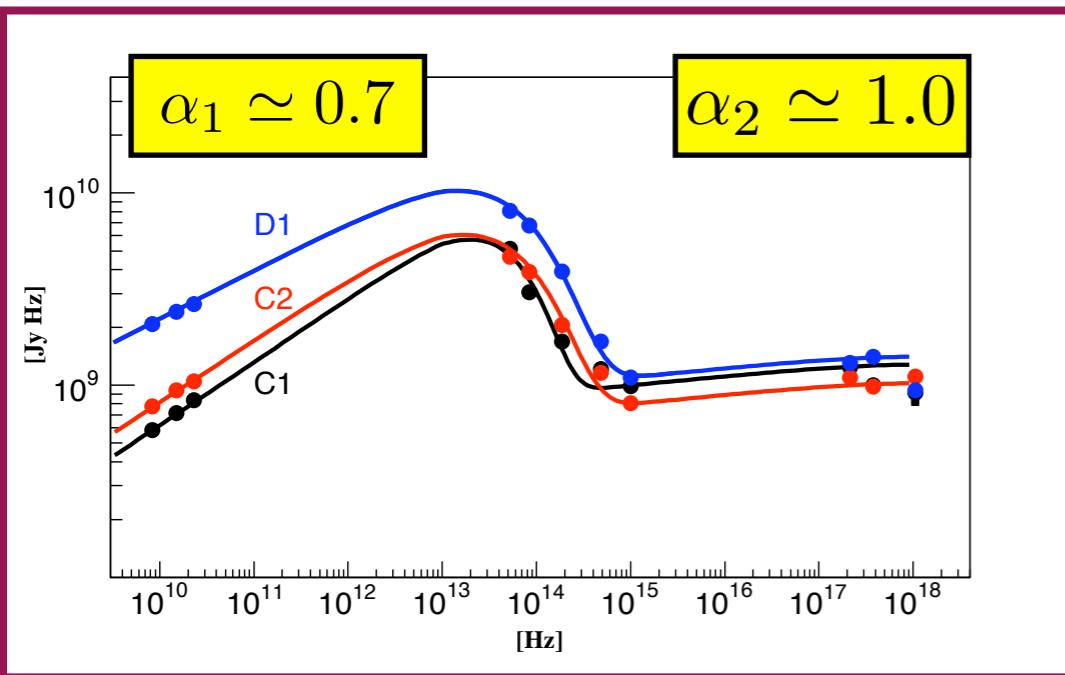


Figure 1. Map of surface brightness (linear grey-scale) of the jet of 3C 273 at 150 nm with *HST*/ACS/SBC/F150LP (bottom), and for comparison, at 620 nm with *HST*/WFPC2/PC1/F622W (top; data from Jester et al. 2001). The images have been rotated to place a position angle of 222° along the horizontal. The quasar lies 12 arcsec to the north-east of knot A. The names of the regions used in the following figures are indicated. On the 620-nm map, S, In1 and In2 label the ‘optical extensions’ that are visible at all wavelengths from $1.4\ \mu\text{m}$ to 300 nm, but not at 150 nm (see Section 4.4 for a discussion of the extensions).



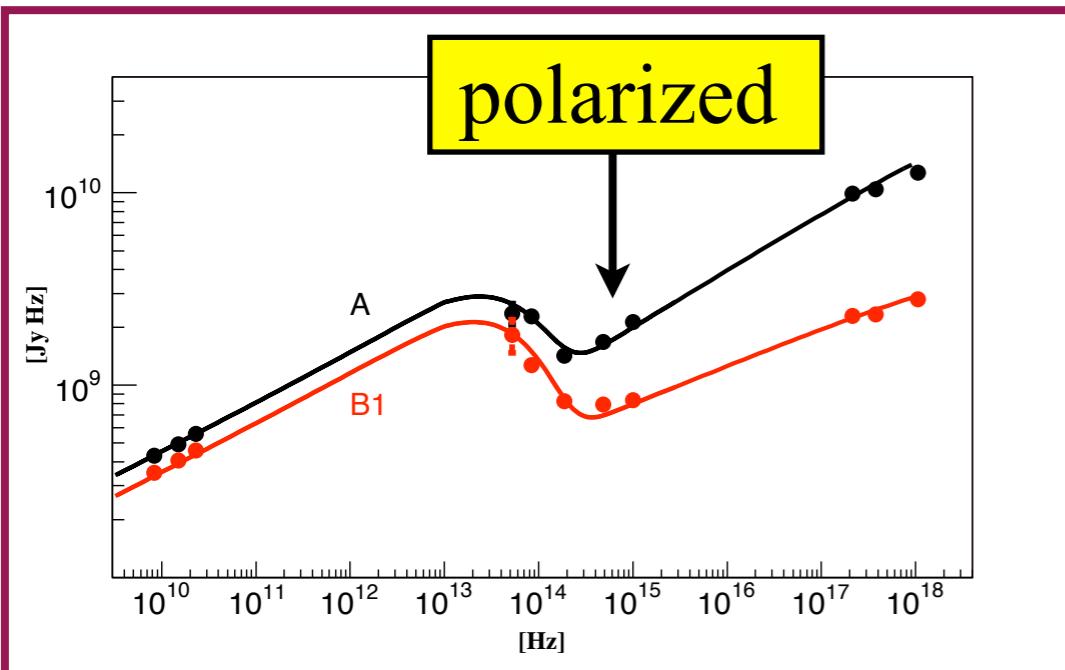
UV confirms the optical-X-ray connection

Popular “Beamed IC/CMB” model fails?



Steeper spectral slopes of the 2nd components argue against “beamed IC”.

Jester+ 2006



Optical polarization (if confirmed) argues against “beamed IC”.

Uchiyama+ 2006

Simple “beamed IC” faces difficulties.

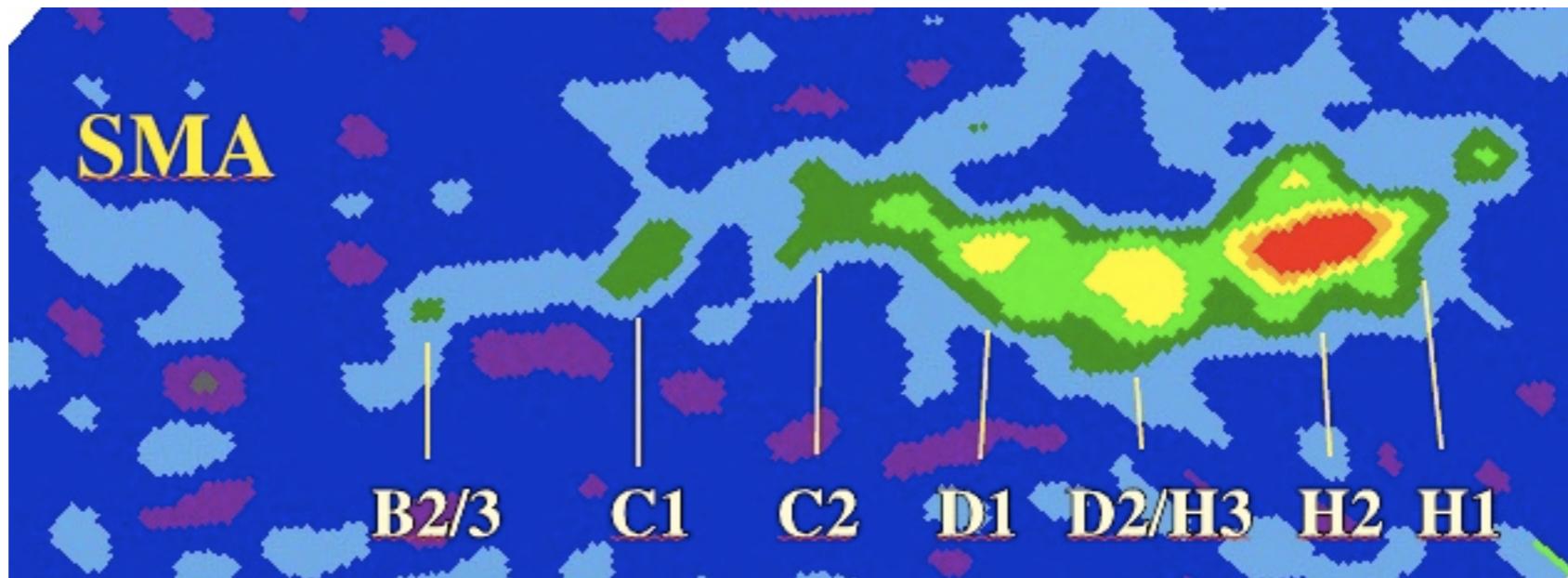
New!

Sub-mm observations of the jet

SMA+PdBI 230 GHz

◆ Preliminary

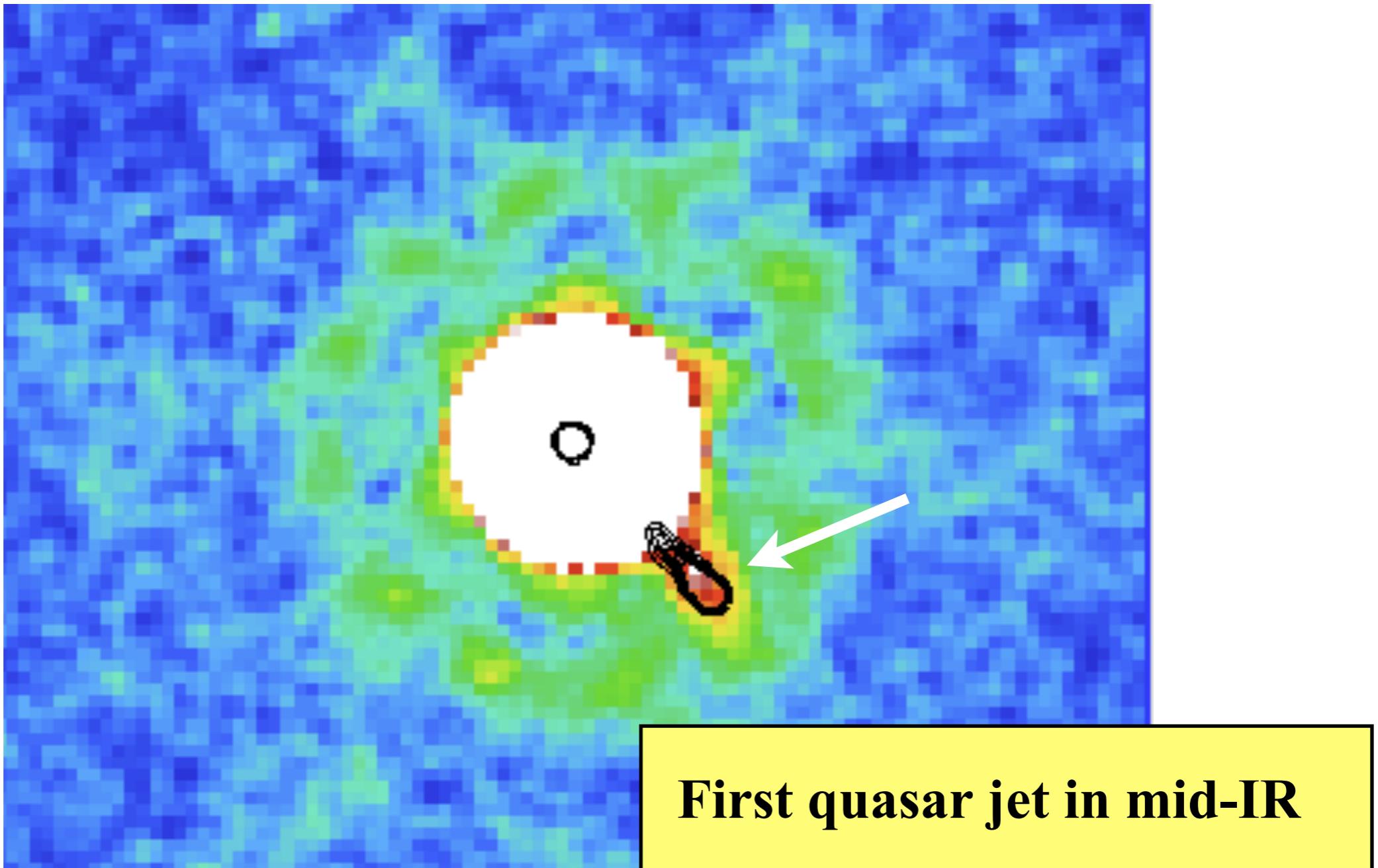
First quasar jet in sub-mm



With the sensitivity of SMA and PdBI,
only 3C 273 can be fully explored

Upcoming ALMA is capable of detecting many jets

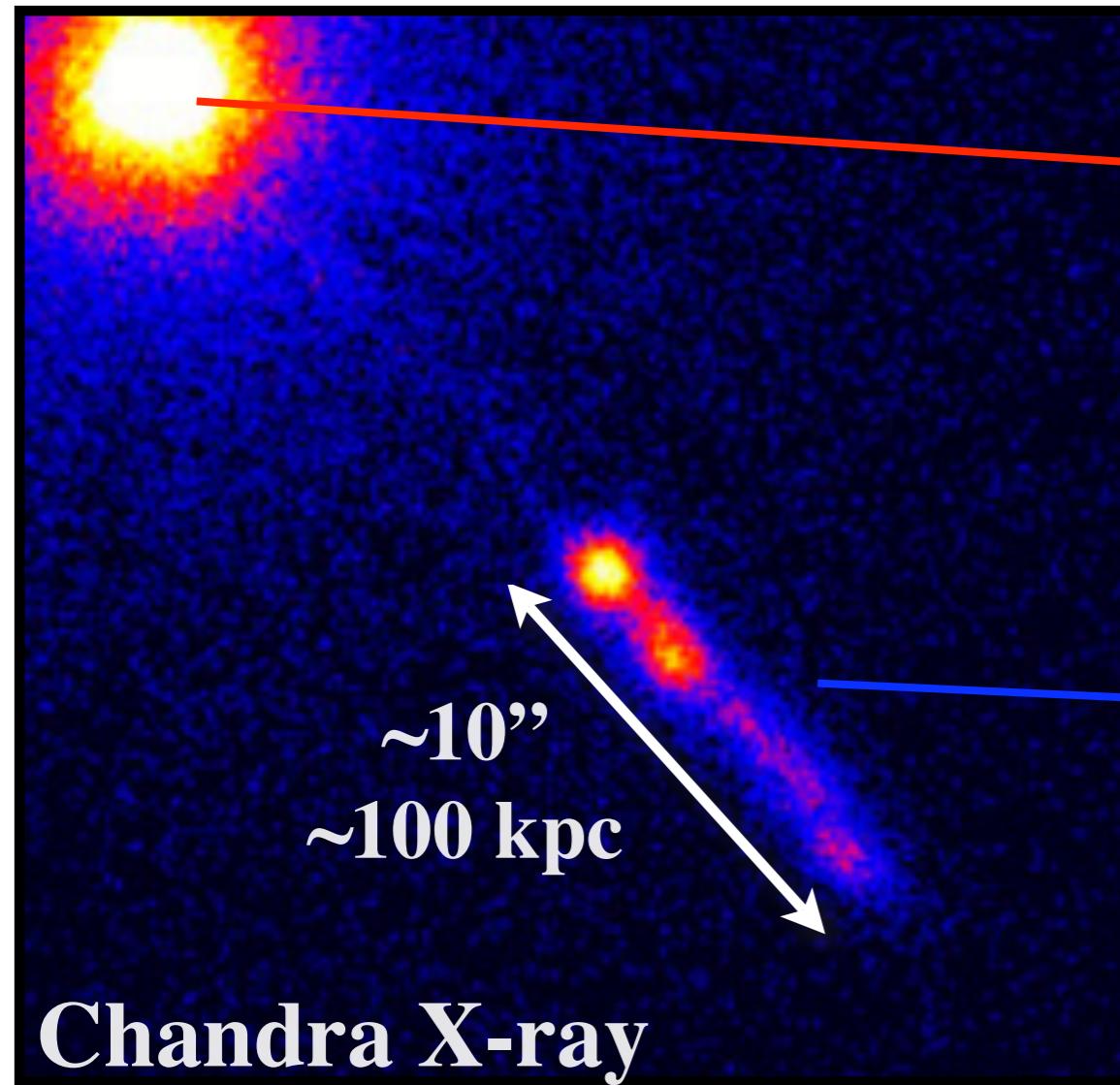
Mid-infrared: Spitzer MIPS



Spitzer MIPS 24 microns
(2004 June: historical core-jet minimum)

Core and Extended Jet

Marshall+ 2001



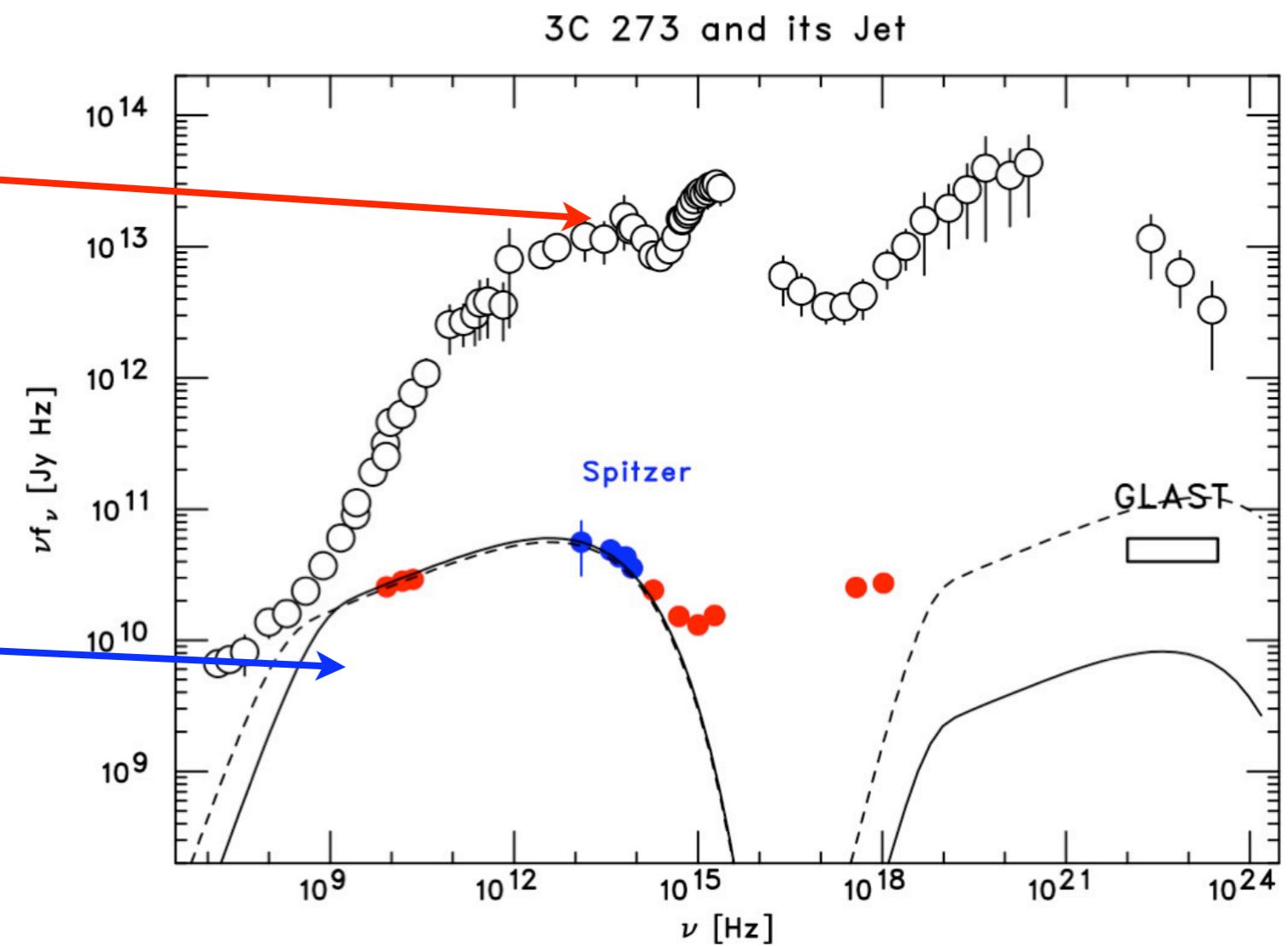
Chandra X-ray

“Blazar Core”

◆ Synchrotron + IC

◆ Beaming $\delta \sim 10$

Chernyakova+ 2007
Tueler+ 1999, 2006
Kataoka+ 2003



“Extended Jet”

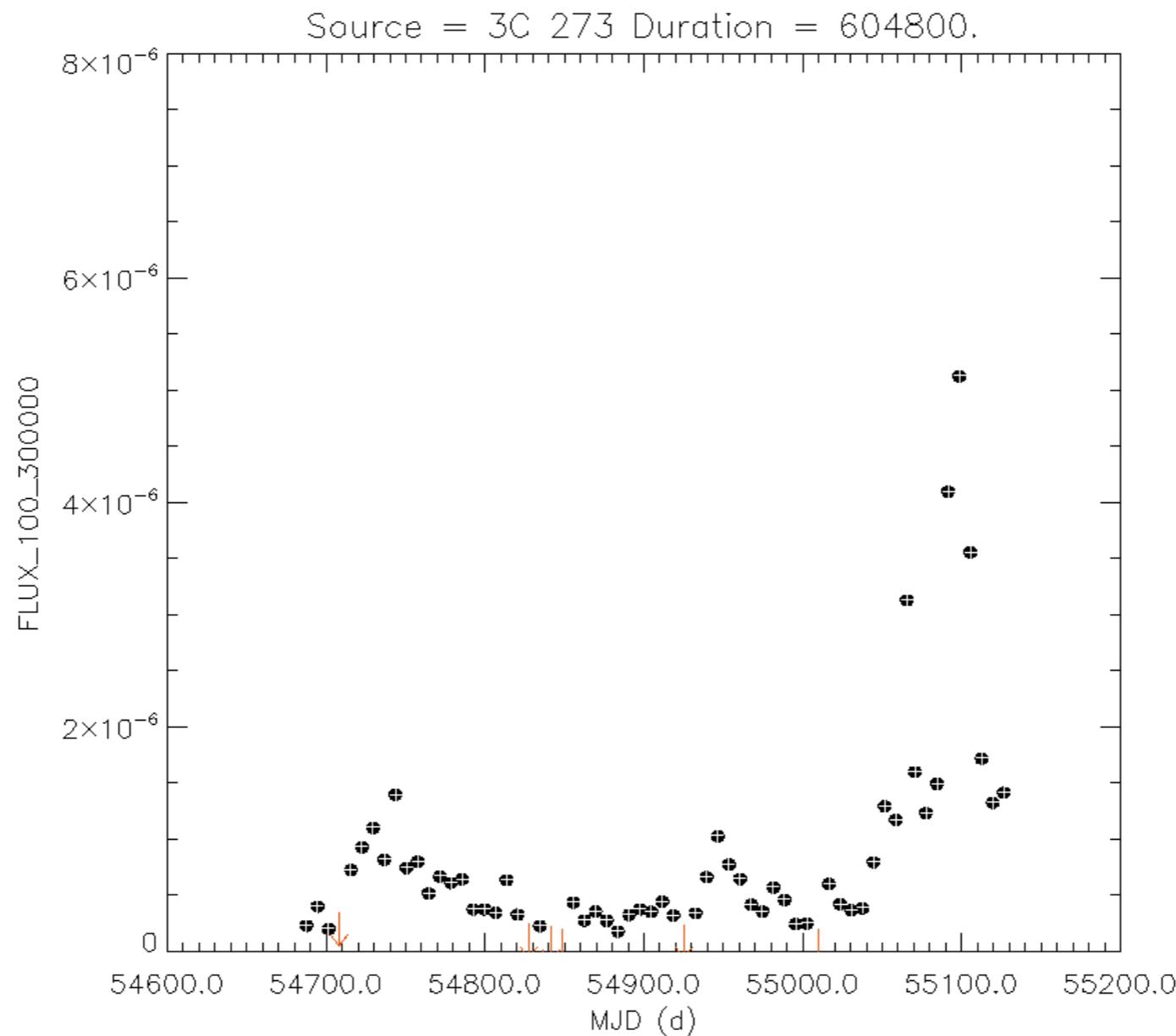
◆ Synchrotron + “?”

◆ Beaming $\delta \sim ?$

Jester+ 2006, 2007
Uchiyama+ 2006

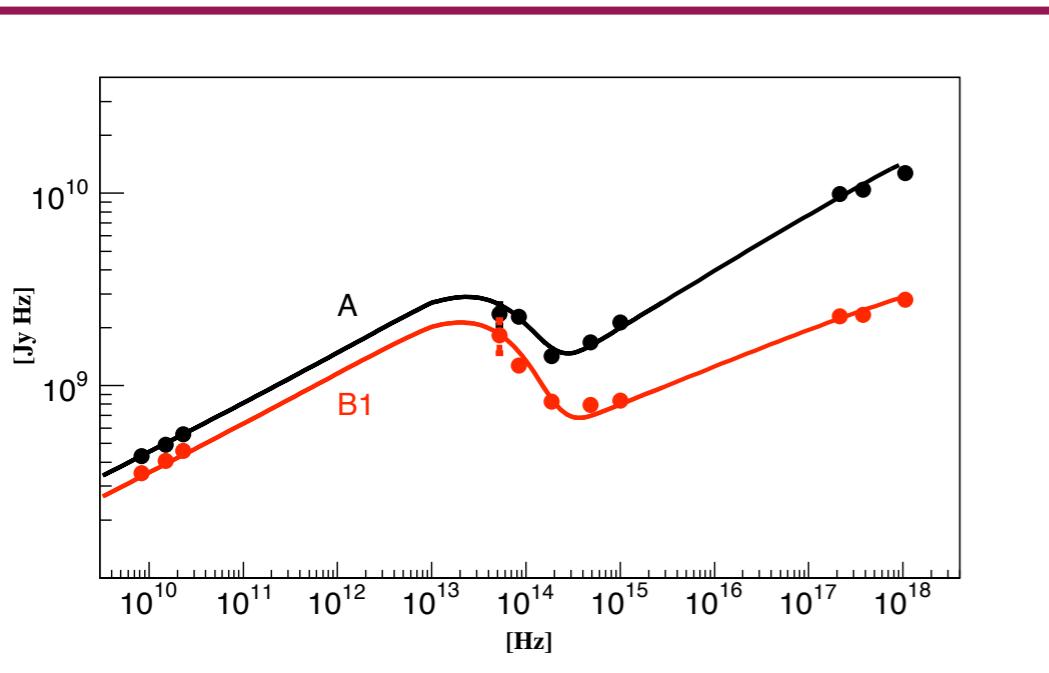
Fermi-LAT Observations

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/



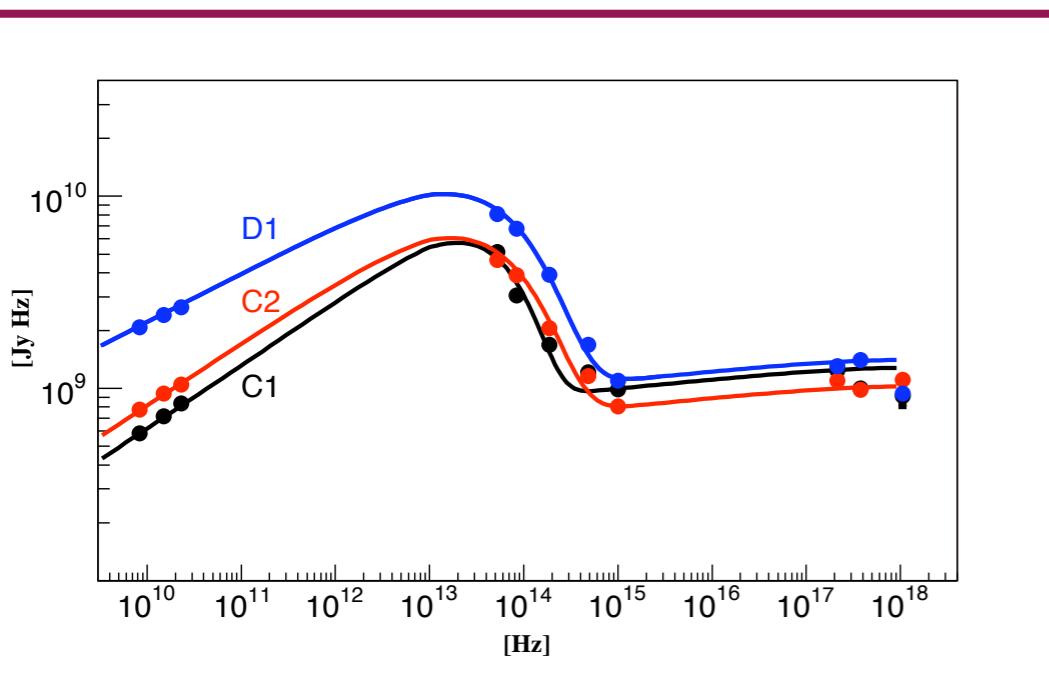
Gamma-ray light curve (>100 MeV)
1 bin = 1 week

Two synchrotron components



(Option 1) Stawarz&Ostrowski 02
The 2nd synchrotron formed by
electrons (e.g. turbulent acceleration).

X-ray : 10-100 TeV electrons



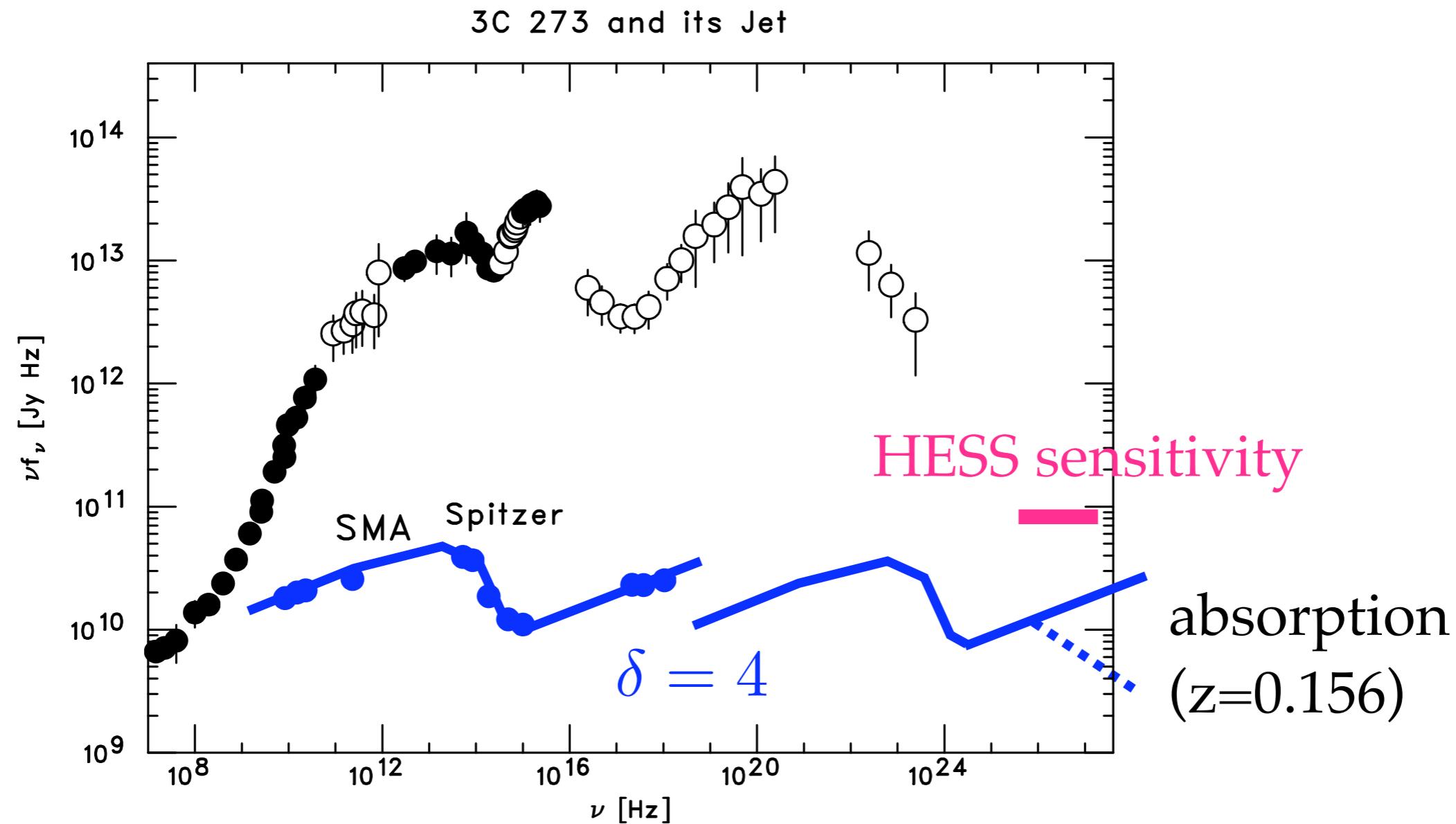
(Option 2) Aharonian 02
The 2nd synchrotron formed by
protons (proton-synchrotron)

$$\nu_c \sim 2 \times 10^{18} B_{\text{mG}} E_{18}^2 \text{ Hz}$$
$$L_X \sim 0.1 \frac{W_p}{t_{\text{syn}}} \sim 0.4 \times 10^{42} B_{\text{mG}}^4 \text{ erg s}^{-1}$$
$$E_p \sim 10^{18} \text{ eV}, \quad B \sim \text{mG}$$

- ◆ Sync 1 : radio-optical
- ◆ Sync 2 : optical-X-ray

B-field would be too large?

HE Synch: Electron or Proton?

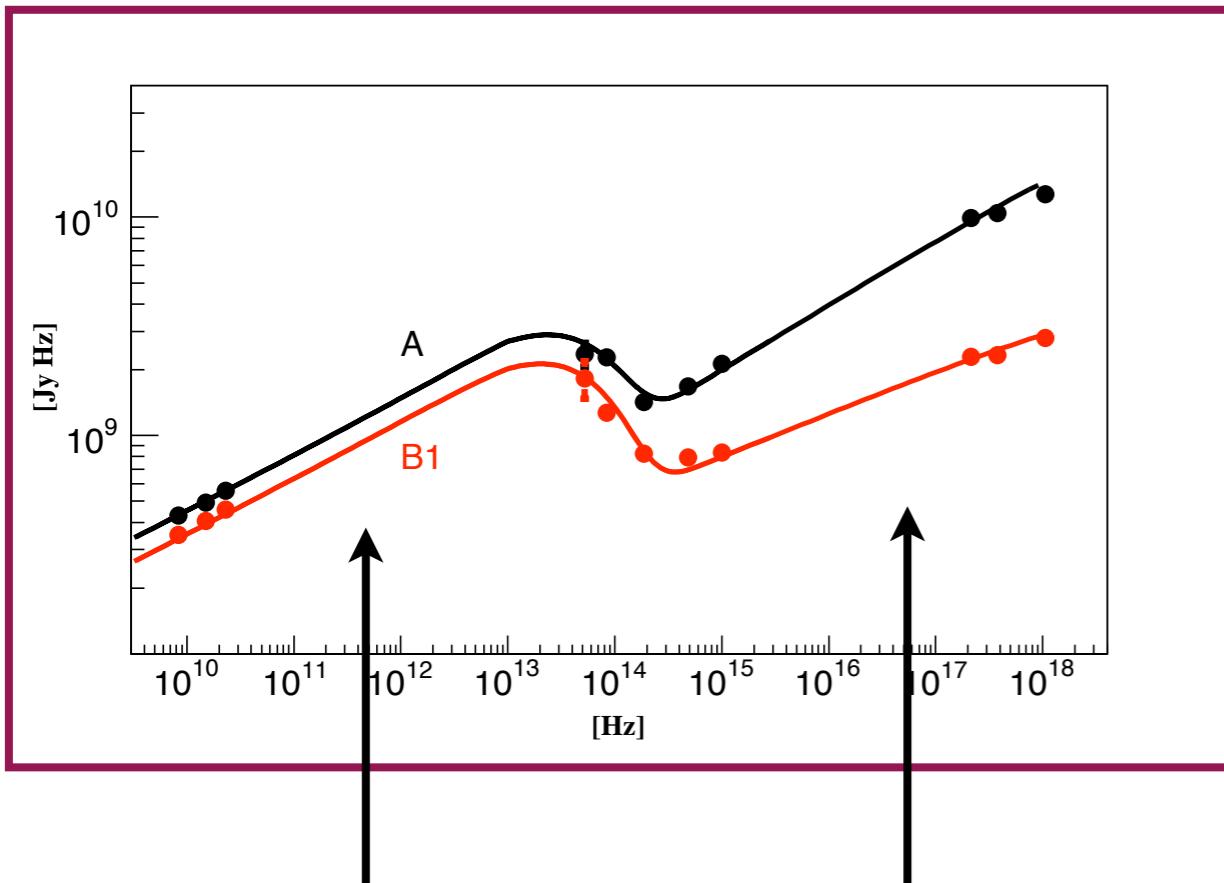


If the 2nd synchrotron is due to electrons, there must be its IC counterpart in TeV range. **Georganopoulos+ 2007**

Planned TeV telescopes (CTA/AGIS) may answer this question.

(Option 3?)

Jitter Radiation



Synchrotron

Jitter Radiation

Microscopic magnetic field fluctuation smaller than r_g/γ

$$k_B > eB/(m_e c^2)$$

Emitted photon energy:

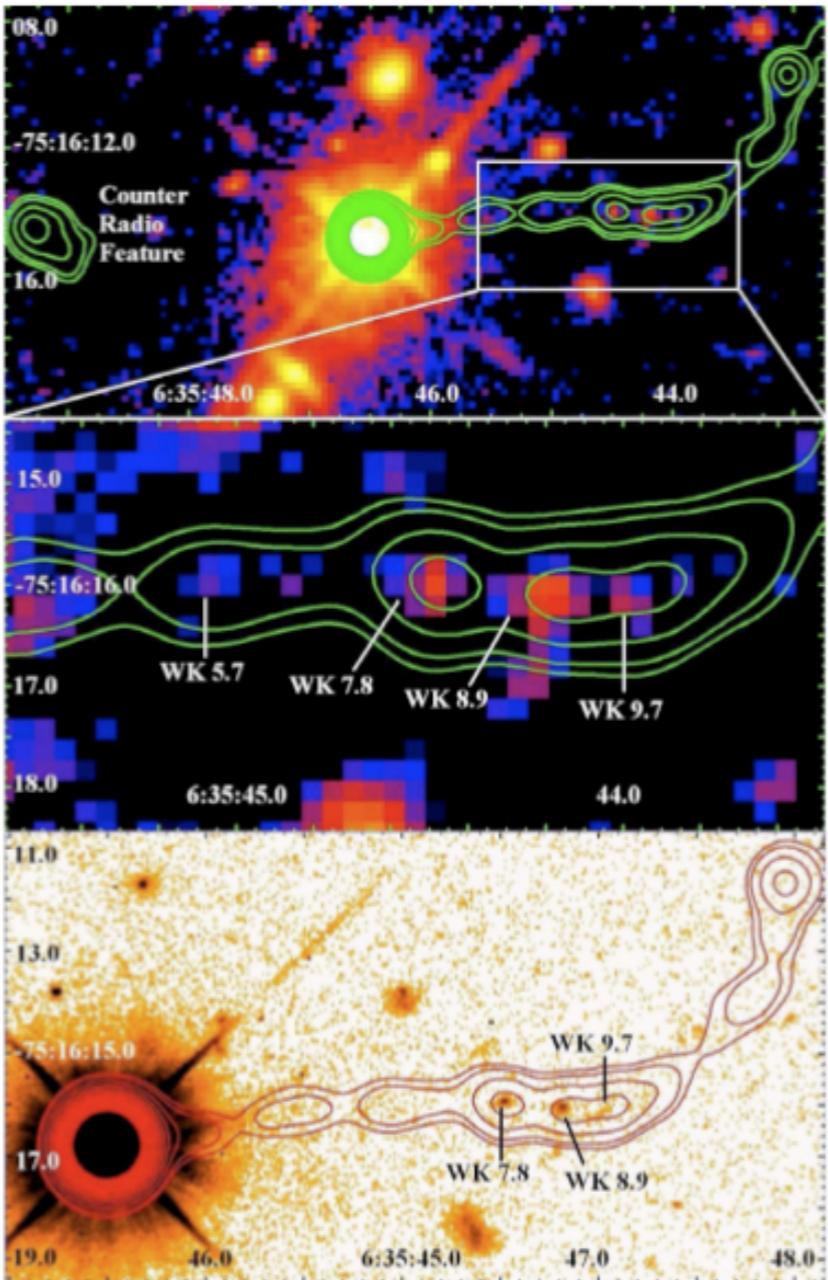
$$\begin{aligned}\epsilon_{\text{jitter}} &\sim \hbar k_B c \gamma^2 \\ &> \epsilon_{\text{syn}}\end{aligned}$$

$$\epsilon f(\epsilon) \propto \epsilon^{-\mu} \quad \longleftarrow \quad k P_B(k) \propto k^{-\mu}$$

magnetic power spectrum

Quasar PKS 0637-752: First Chandra Jet

Mehta+ 2009



NICMOS

ACS

New Hubble NICMOS+ACS data indicate spectral hardening in the optical band:

$$\alpha_{\text{NICMOS-WFPC2}} = 0.91 \pm 0.06$$

$$\alpha_{\text{WFPC2-ACS}} = 0.35 \pm 0.12$$

The onset of the HE component can be seen in “blue” light.

Figure 1. The NICMOS and ACS images with the radio contours for PKS 0637-752 overlaid. The top panel is the NICMOS image of the whole jet with green radio contours. The middle panel is a zoomed image of the white box in the top panel. The bottom panel shows the ACS image with radio contours in red.

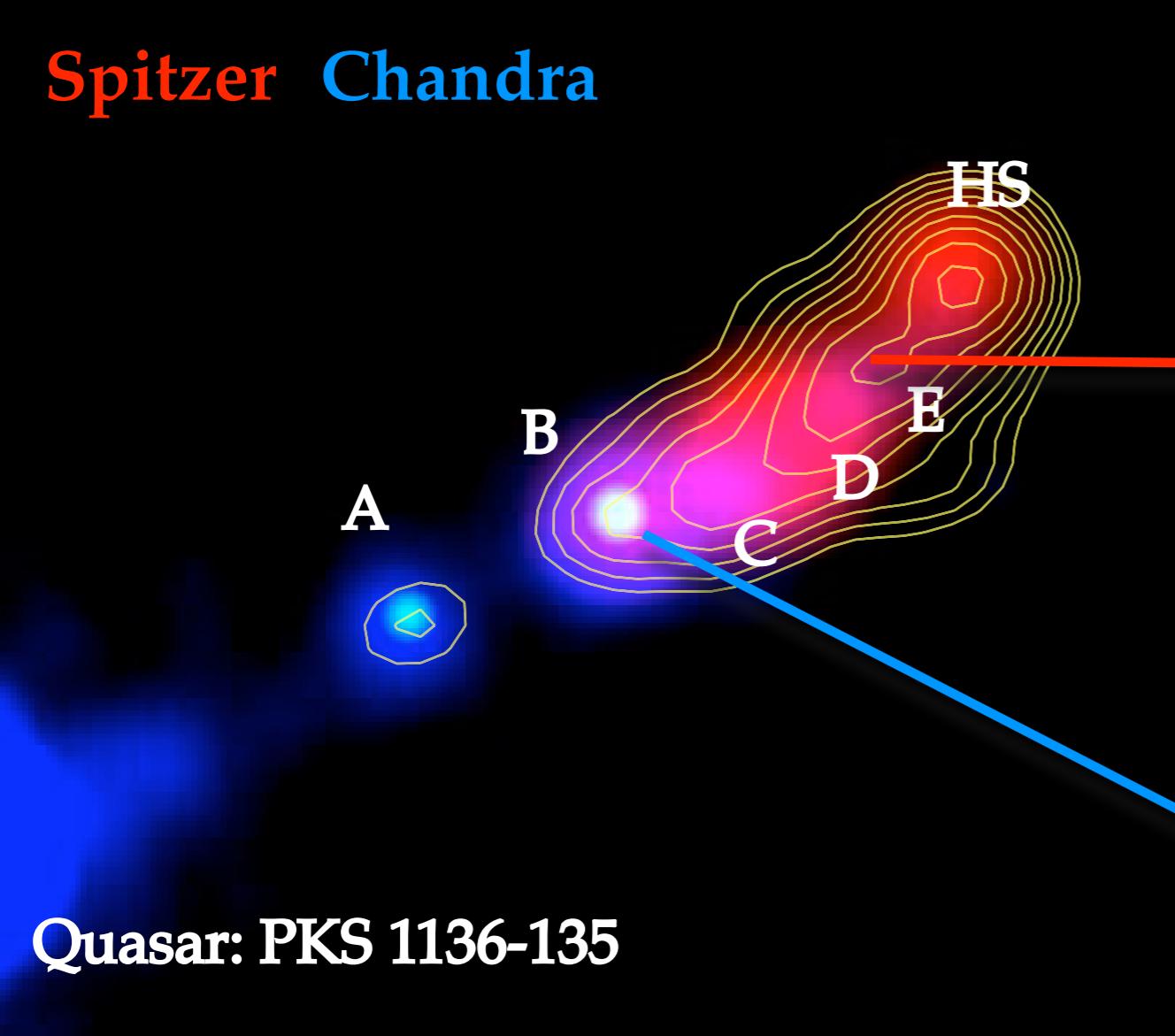
Quasar PKS 1136-135: HST polarimetry

PKS 1136-135 (z=0.55)

Uchiyama+ (2007)

Lobe-dominated quasar

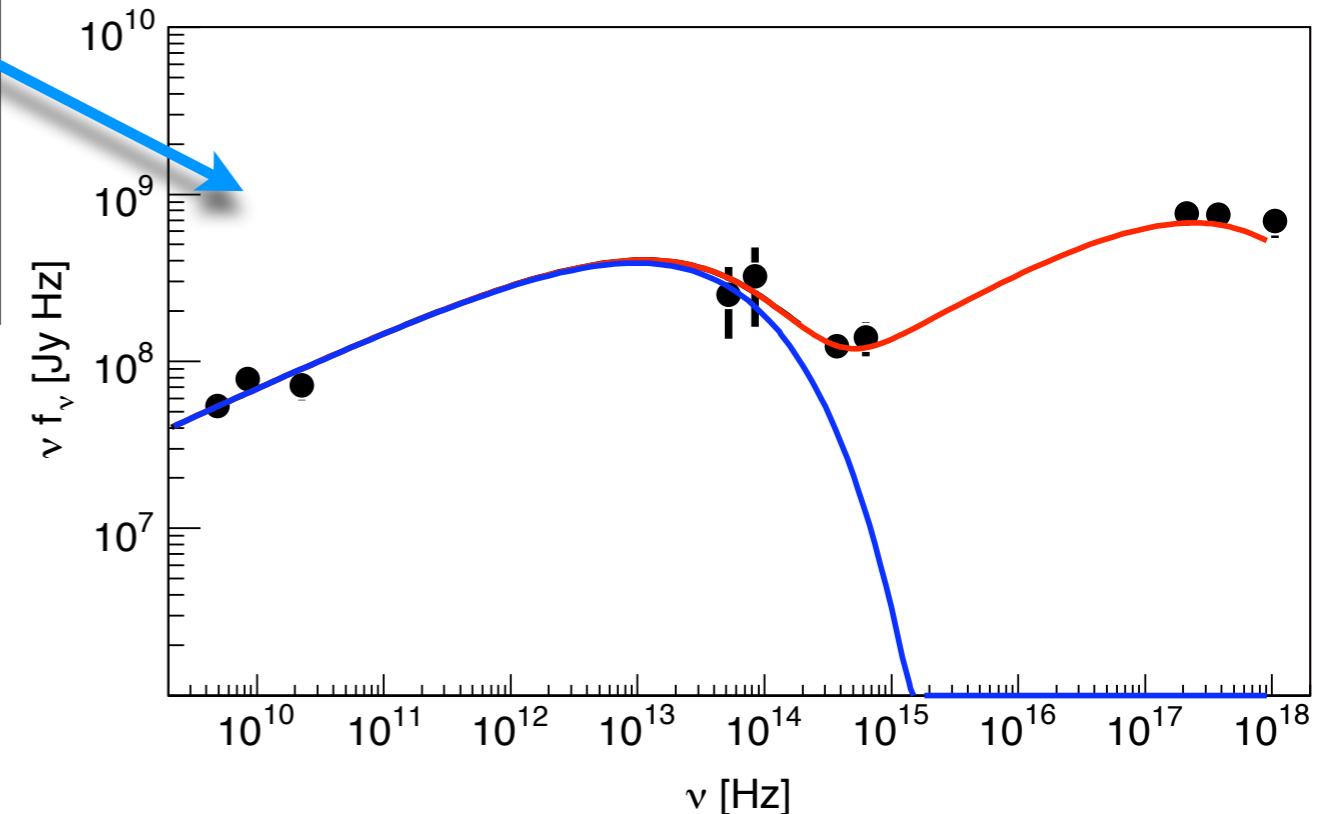
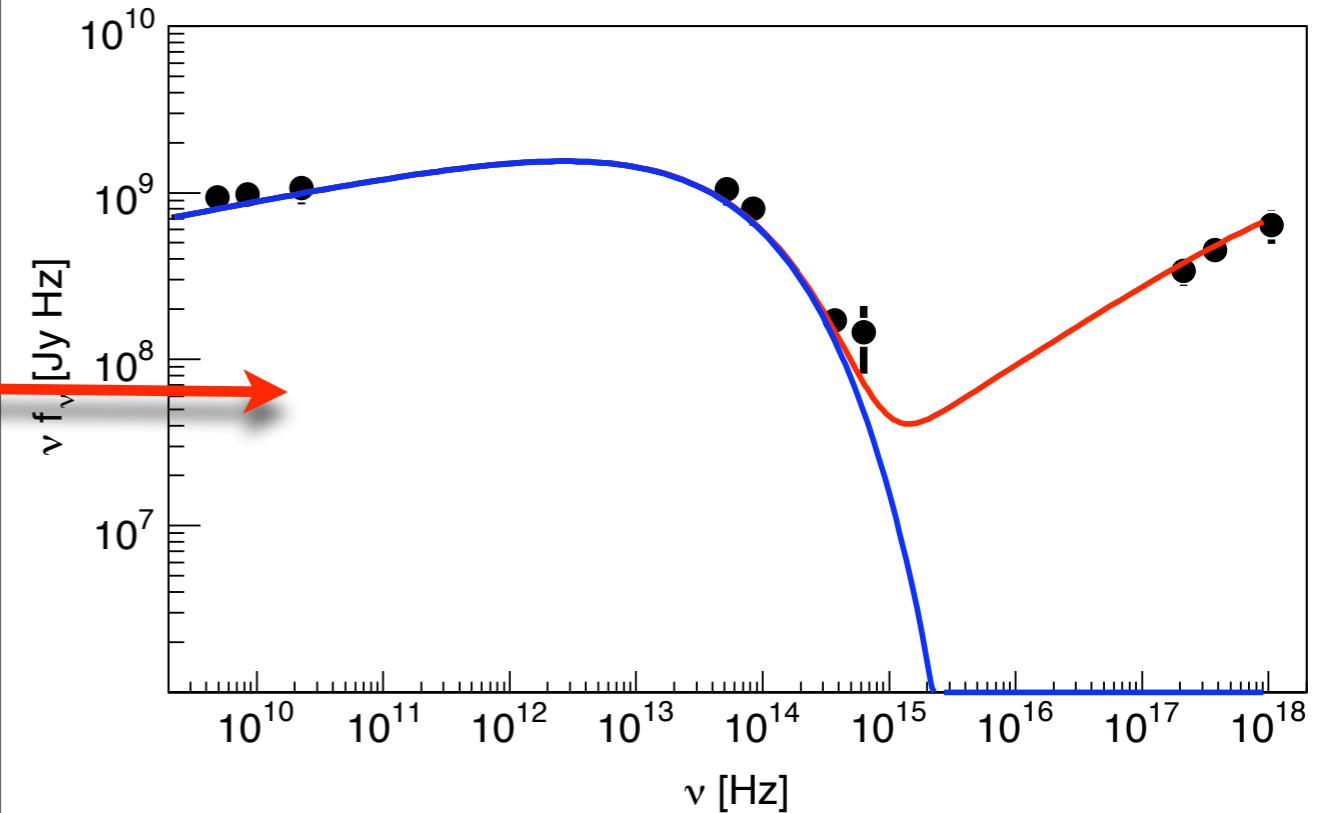
Spitzer Chandra



Quasar: PKS 1136-135

SEDs similar to 3C 273

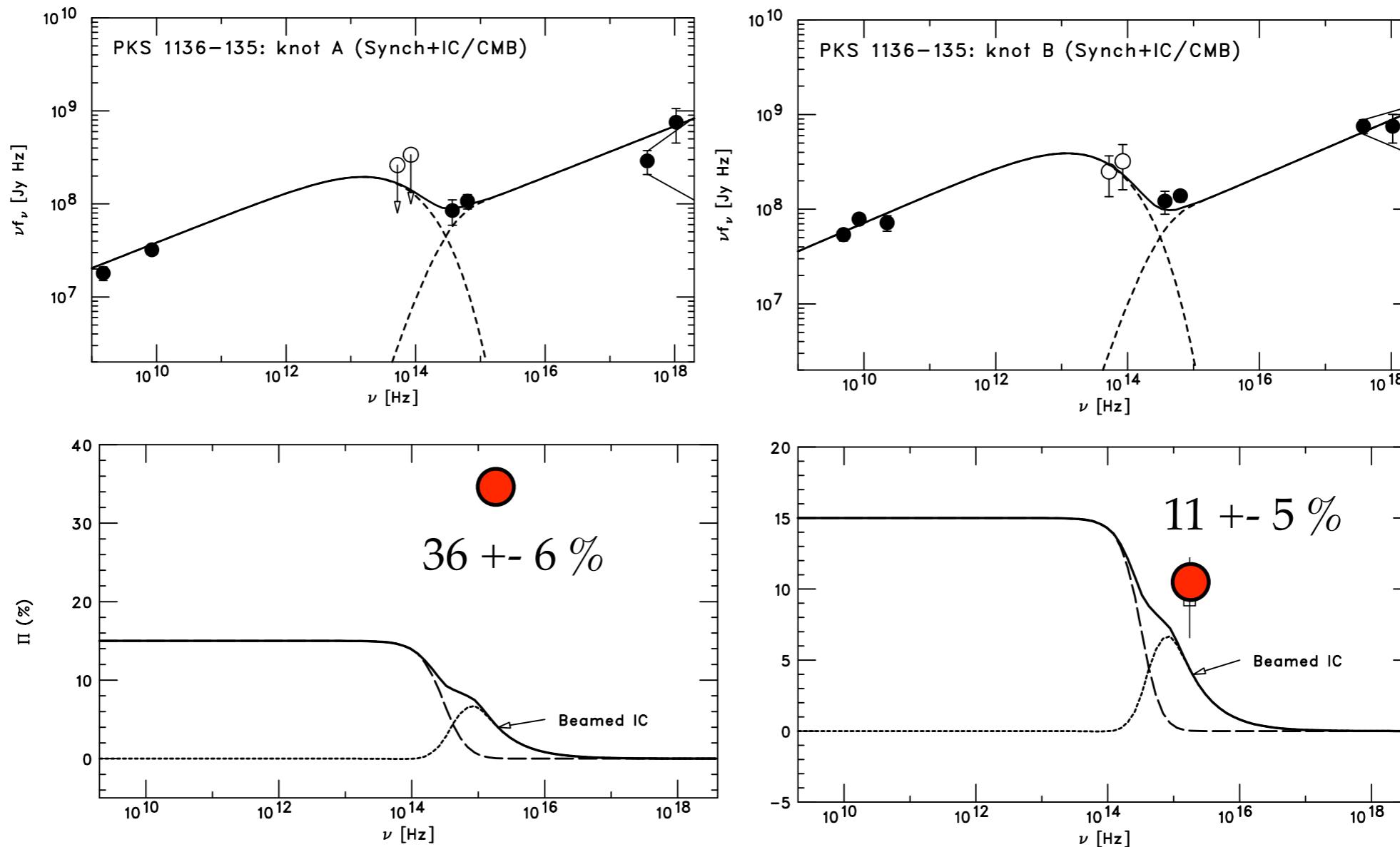
Viewing angle would not be very small
--- Beamed IC/CMB model unfavorable



New!

HST Polarimetry

Cara+ (2009)

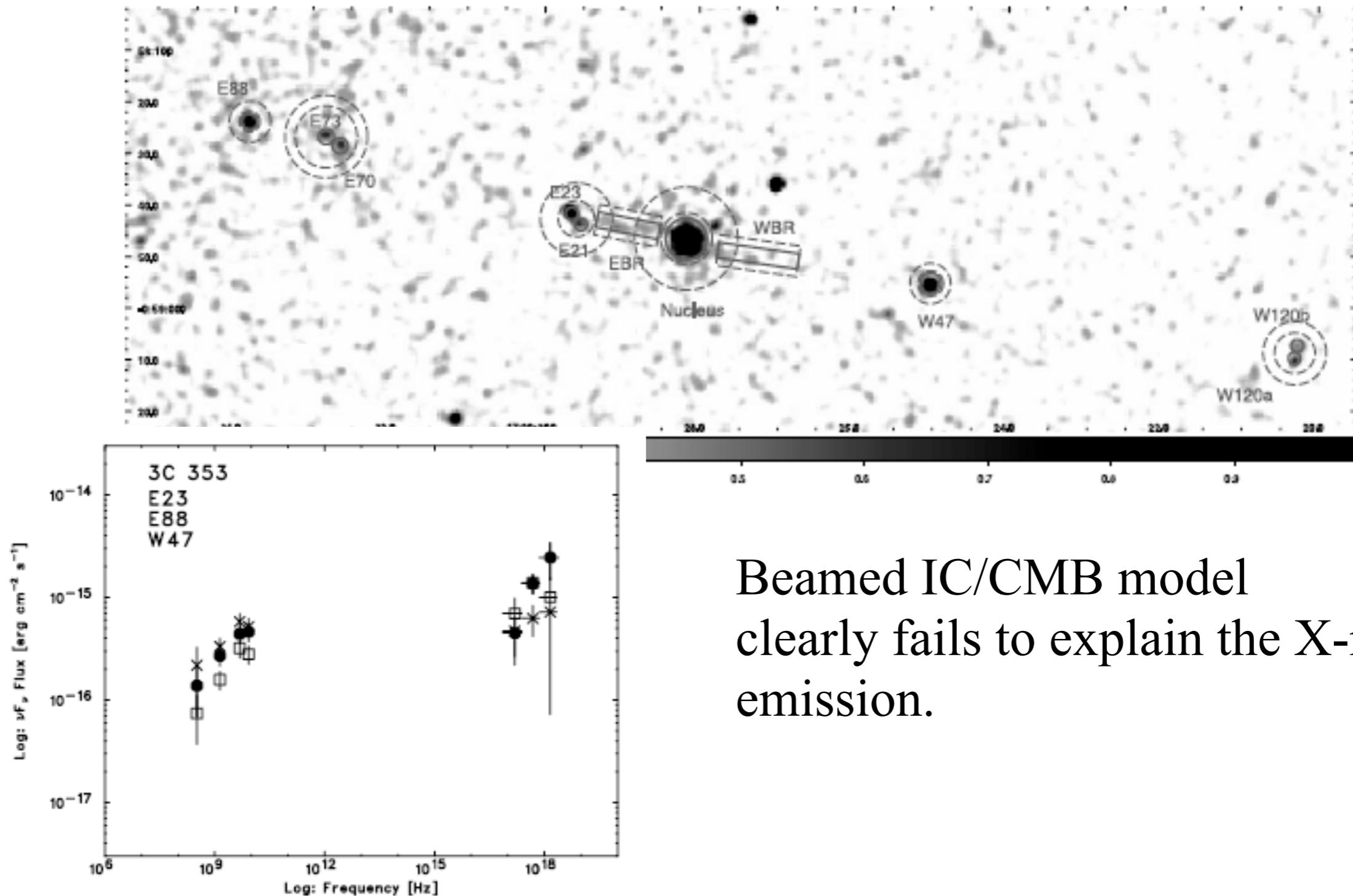


Highly polarized optical emission is detected.

- The degree of polarization is larger than that predicted for beamed IC/CMB
- Beamed IC/CMB model unfavorable
- Confirms synchrotron origin of HE component

FRII 3C353: Counter-jet detection with Chandra

Kataoka+ 2008



Summary

Extended quasar jets have 2 spectral components:

- Recent studies indicate high-energy component (optical-X-ray) is also likely to be of synchrotron origin:
 - Spectral shapes and energetics (3C273)
 - Optical polarization (PKS 1136-135)
 - Counter-jet detection (3C353) Kataoka+ 2008
- ✓ Electrons of 10-100 TeV can be accelerated in kpc knots despite severe synchrotron cooling