Japan Aerospace Exploration Agency

Resolved Jets
in Quasars and Radio Galaxies

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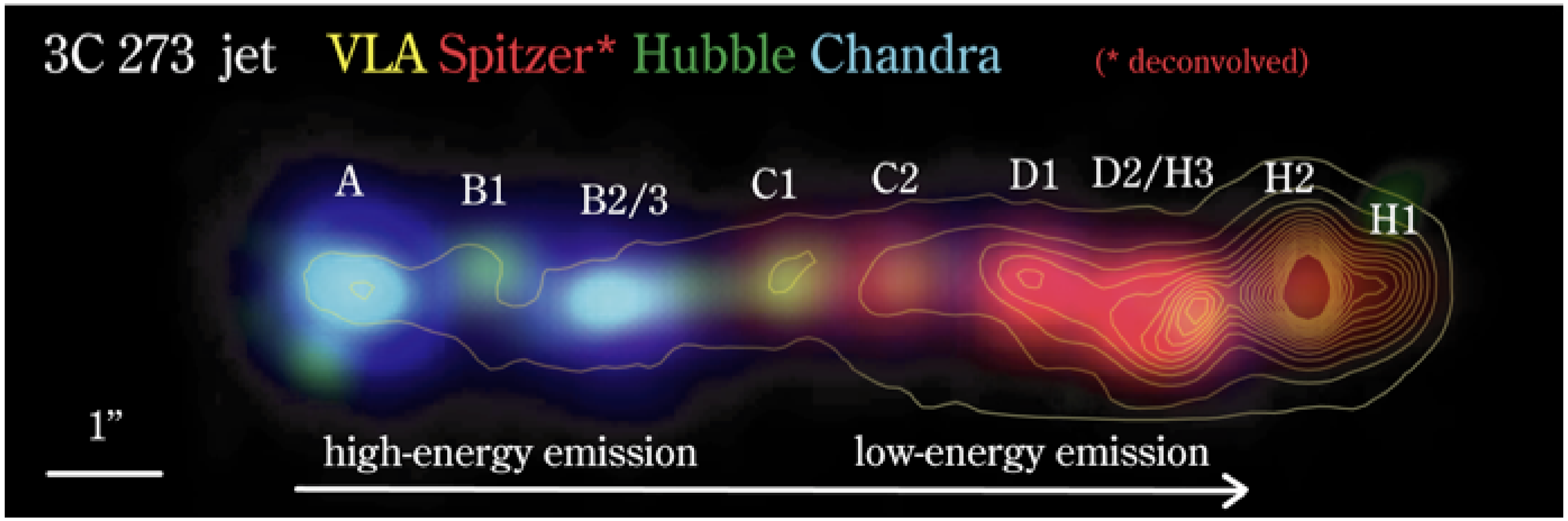
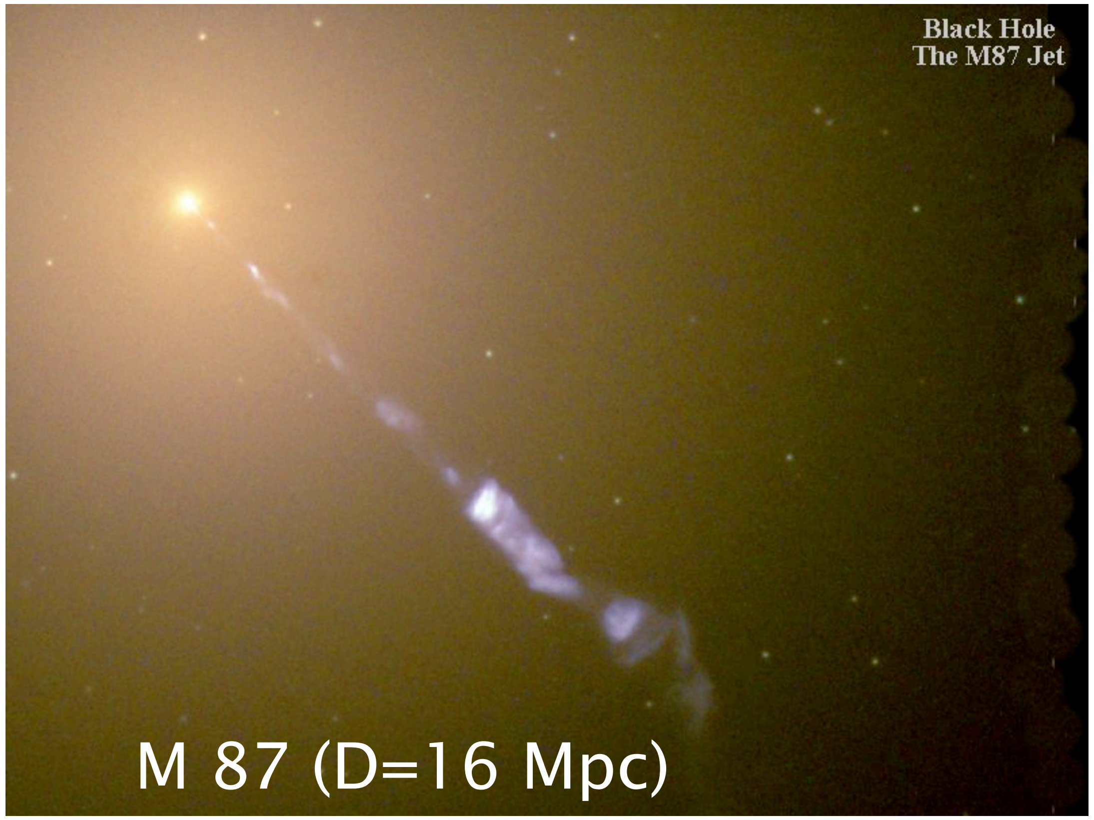
with Meg Urry (Yale), Teddy Cheung (GSFC), ++



AGN relativistic jets on large-scales

- Discovery 89 years ago
  - M 87 jet: H. D. Curtis in 1918
- The Physics of Relativistic Jets
  - [Unresolved parts (sub-pc) Lorentz factor ~10]
  - Resolved parts (kpc-Mpc) Lorentz factor ~2?
- Energy Transport beyond Galaxies
  - Typical Power 10^{46}erg s^{-1}
  - Cooling flow problem in the cluster of galaxies
- The Origin of Ultra-High-Energy-CRs

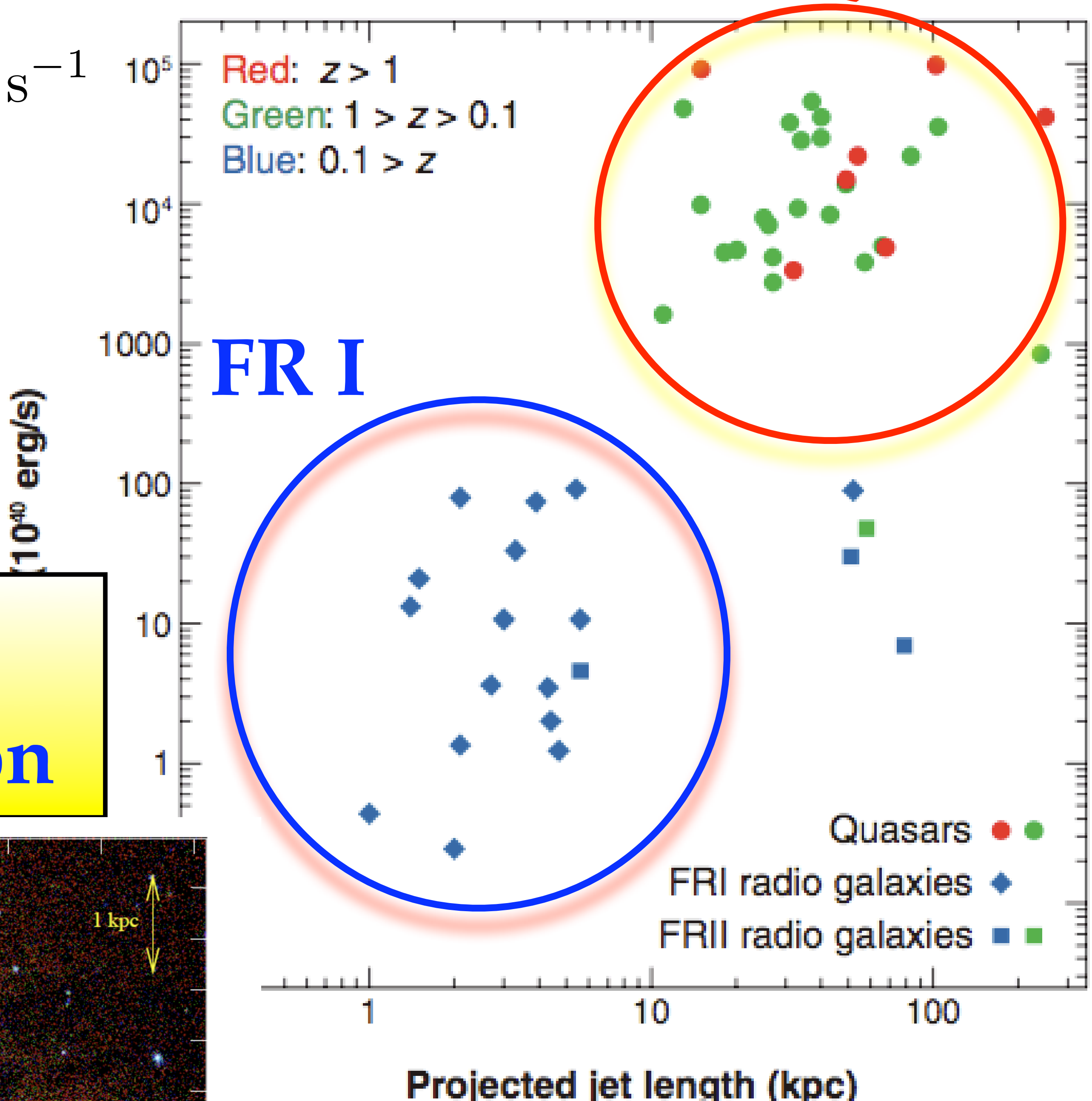


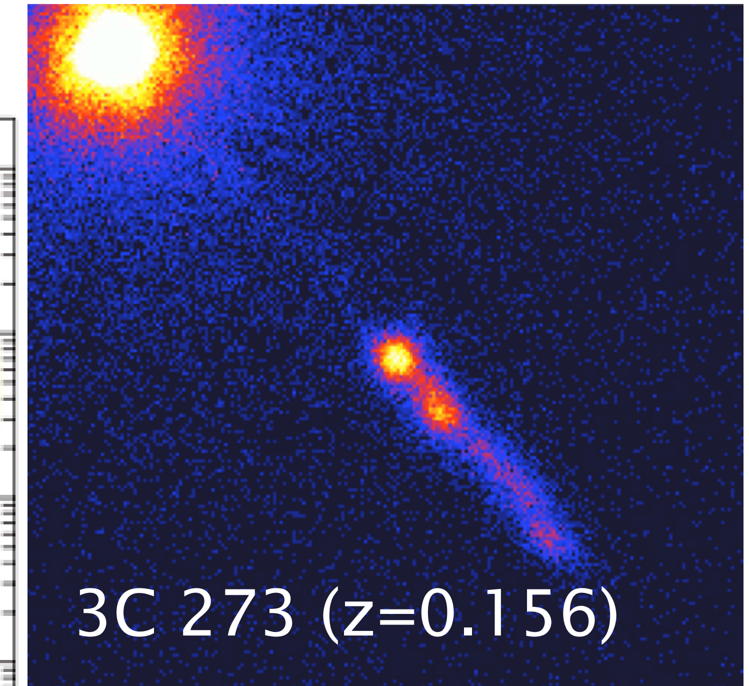
Dramatic improvements in recent years: HST & Chandra

Still, not well understood...

Two classes: low / high power jets

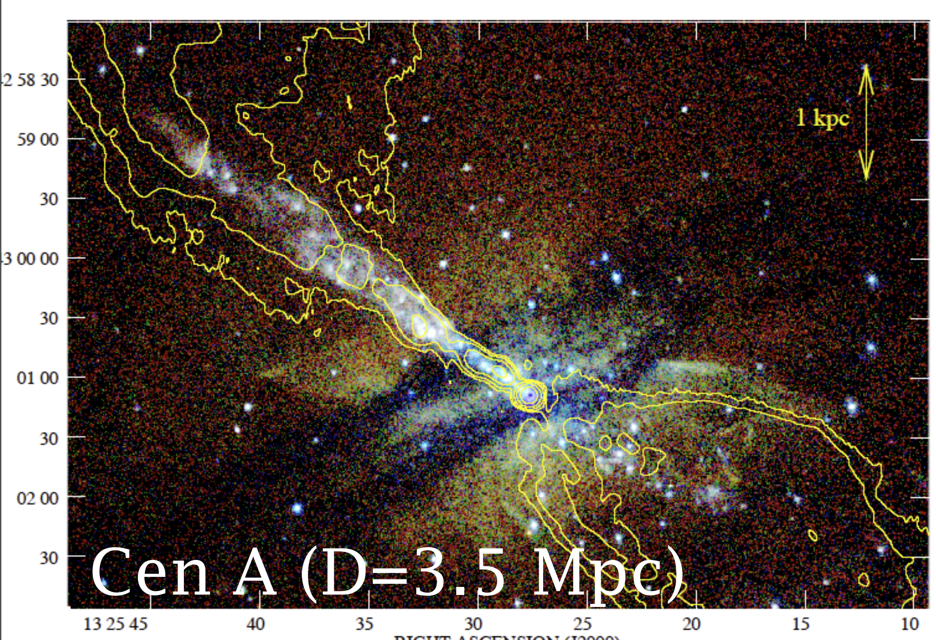
$L_X/10^{40}\mathrm{erg\ s^{-1}}$





X-ray
= Synchrotron

X-ray
= ???



Harris & Krawczynski (2006)

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**

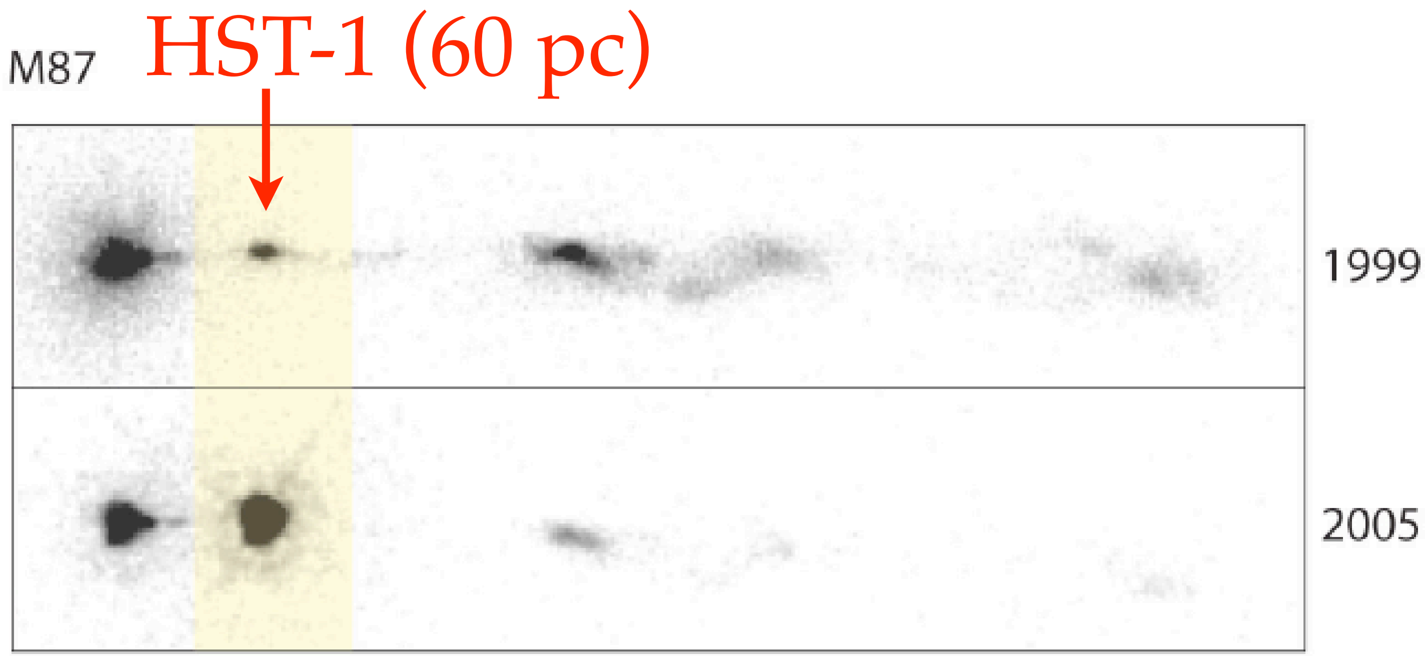
Uchiyama+ (2005, 2006, 2007), Hardcastle+ (2006)

Sub-mm SMA = 2 jet **ALMA coming!** *New!*

Tan+ (2007), This Talk

Low Power Jets

Recent news: M 87 HST-1 flare

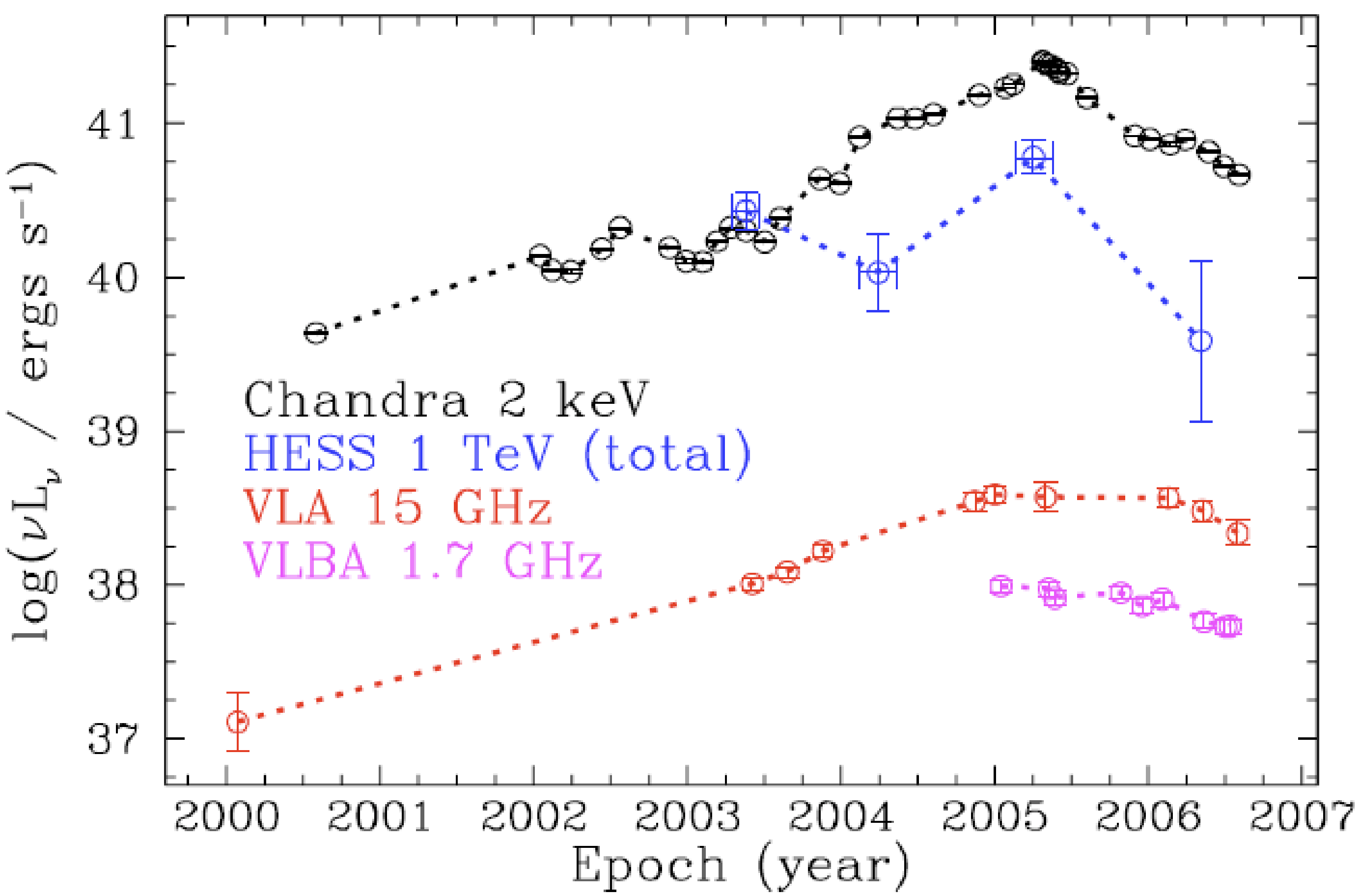


M87 (D=16 Mpc)

HST-1:
a dramatic flare peaked at the year 2005 **Harris et al.**

HST-1:
superluminal motions

Cheung+ (2007)



TeV gamma-ray (HESS) associated with HST-1?

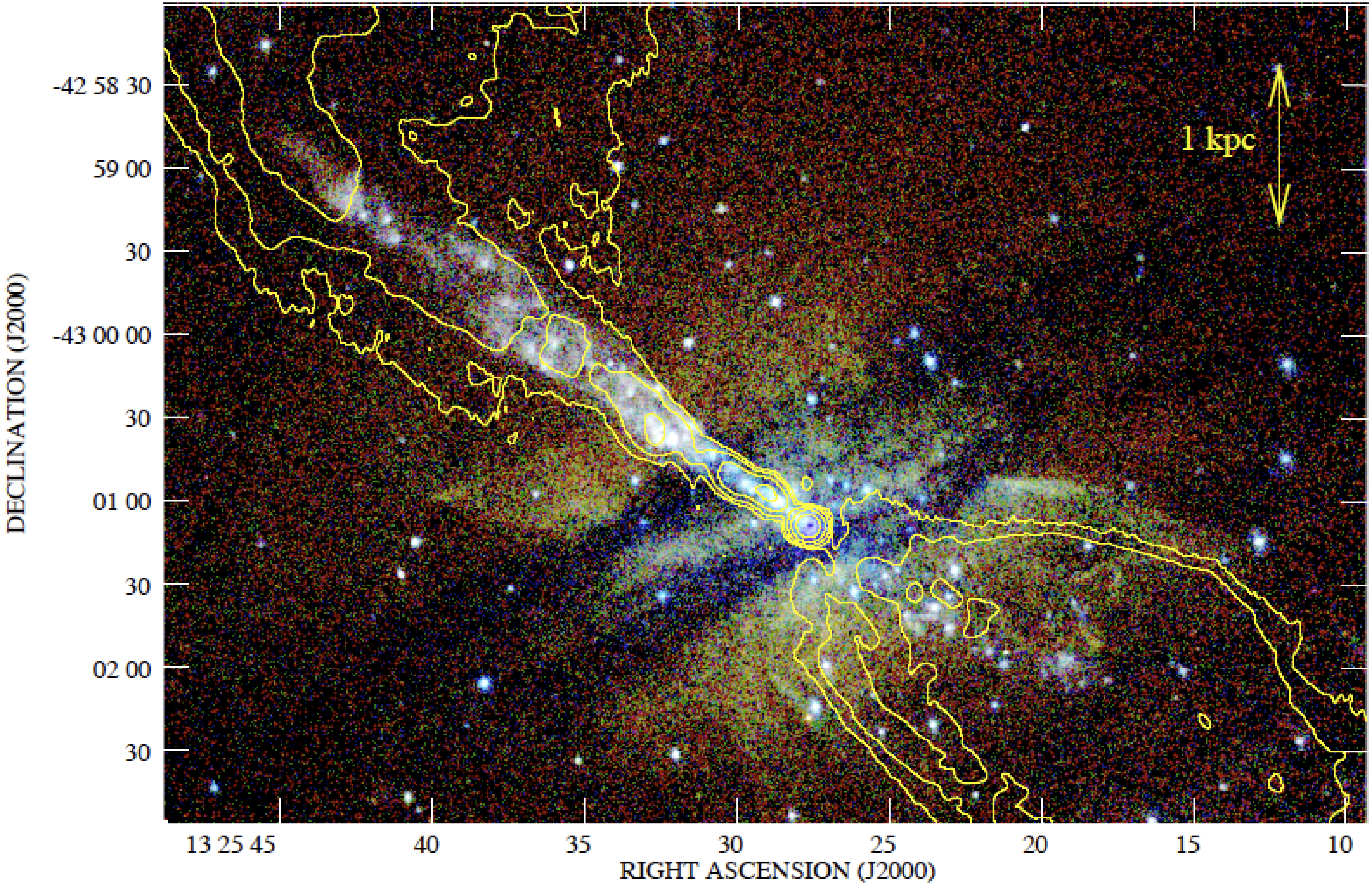
A resolved jet shows “blazar-like” behavior!

Re-confinement shock?

Stawarz (2006)

Recent news: Centaurus A

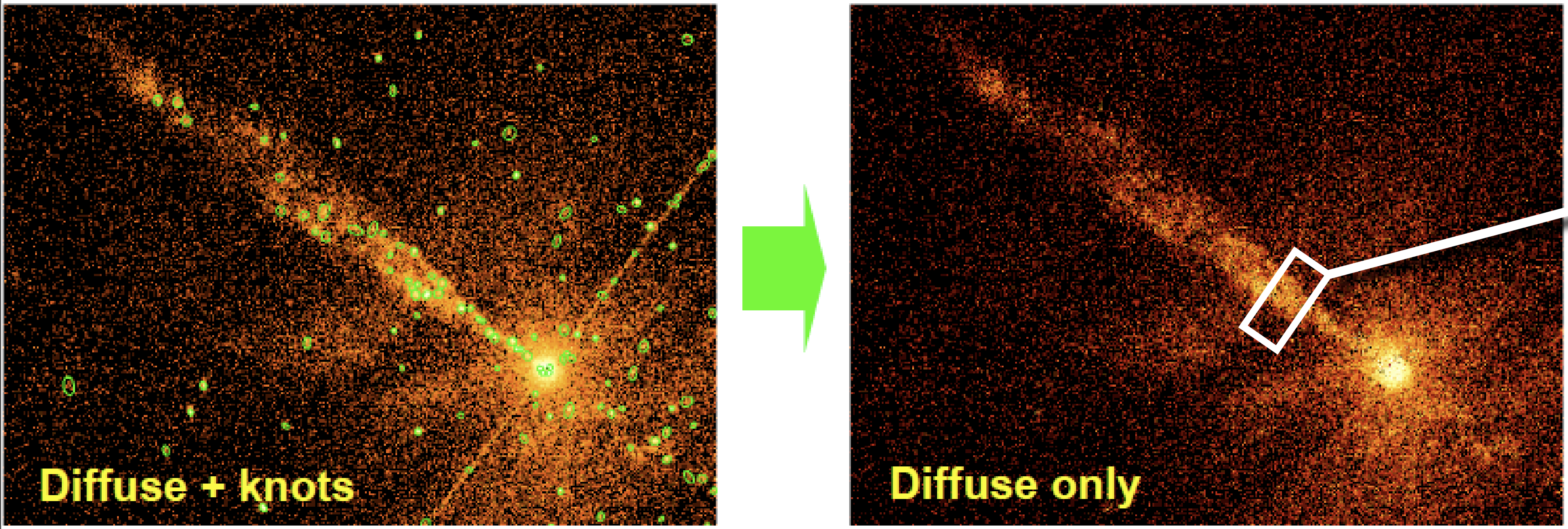
Hardcastle+ (2007)



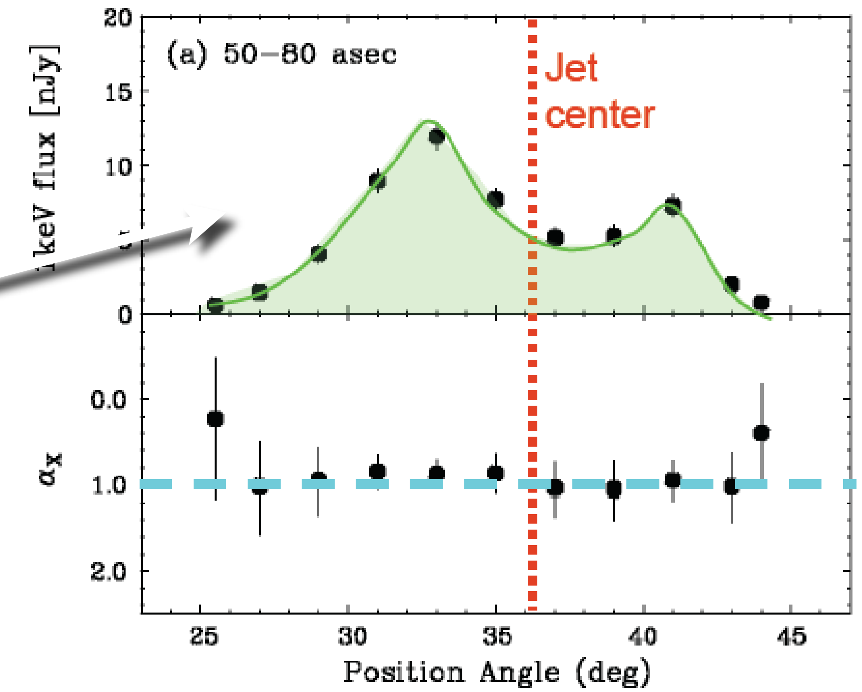
Cen A (D= 3.5 Mpc) deep Chandra image

Recent news: Cen A diffuse X-ray

Cen A Chandra image **Kataoka+ (2006)**



JK+ 06, see also Hardcastle 03



Diffuse X-ray emission:

- limb brightened ("spine+sheath" structure?)
- spectral index $\alpha_x \simeq 1$
- synchrotron cooling length ~ 1" : electron production region should be extended (shock-acceleration is unlikely?) **Acceleration sites = extended!**

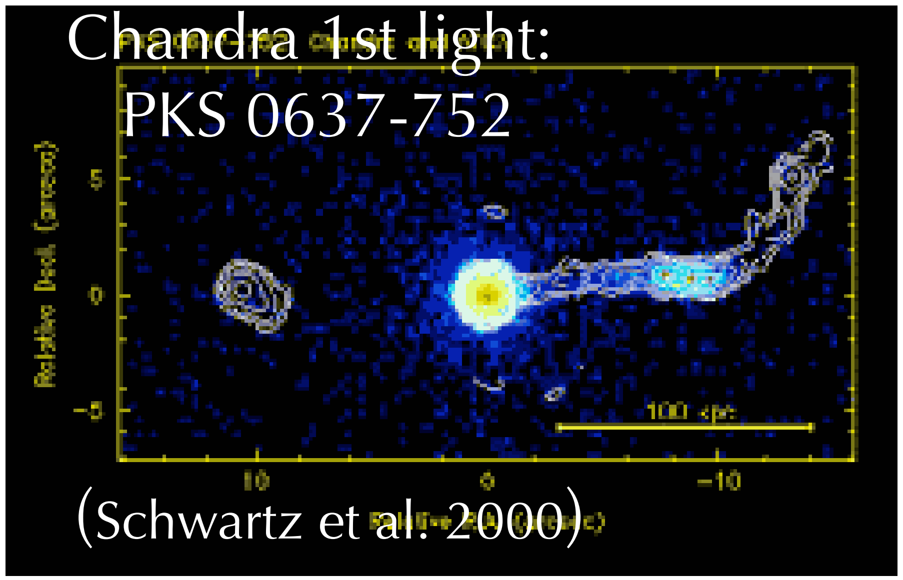
☆ Future "deep" Chandra observations of nearby jets are well deserved.

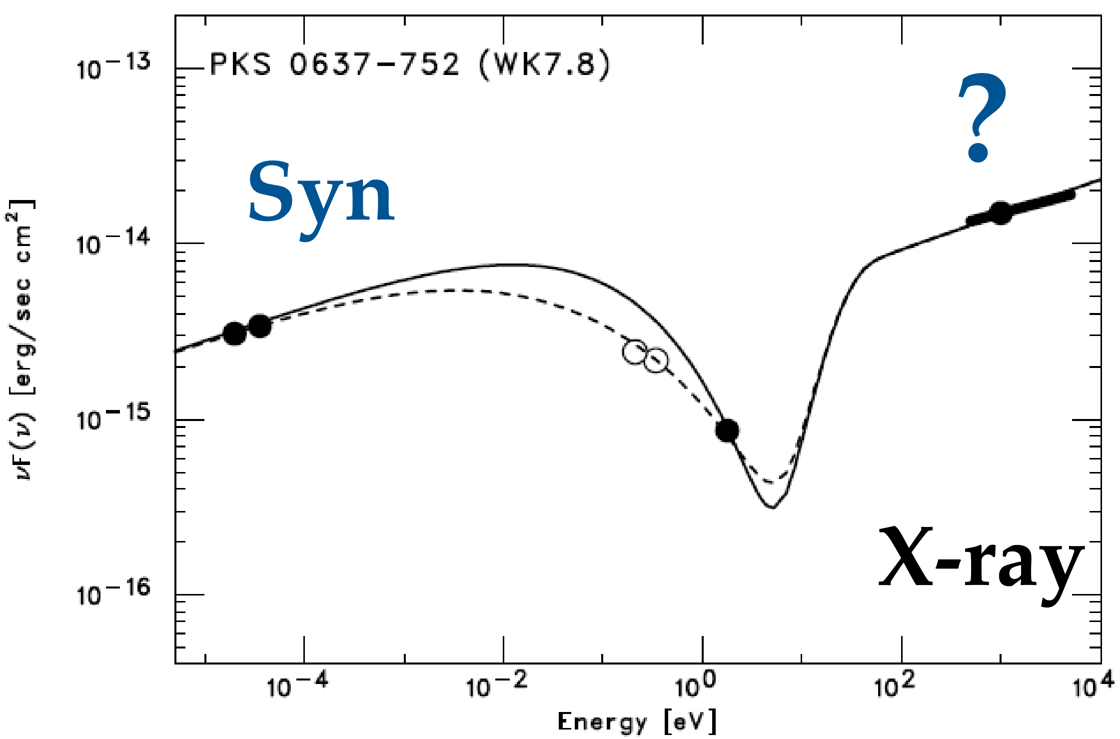
Talk by Kraft 3:35 pm

High Power Jets

Origin of Chandra quasar jets?

Strong X-rays!!





"Beamed IC/CMB" model (popular)

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

Tavecchio+ 00; Celotti+ 01

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

$$\text{for } \delta B = 0.1 \text{ mG}$$

e/p Synchrotron models

(a) 2nd electron synchrotron

e.g., turbulent acceleration

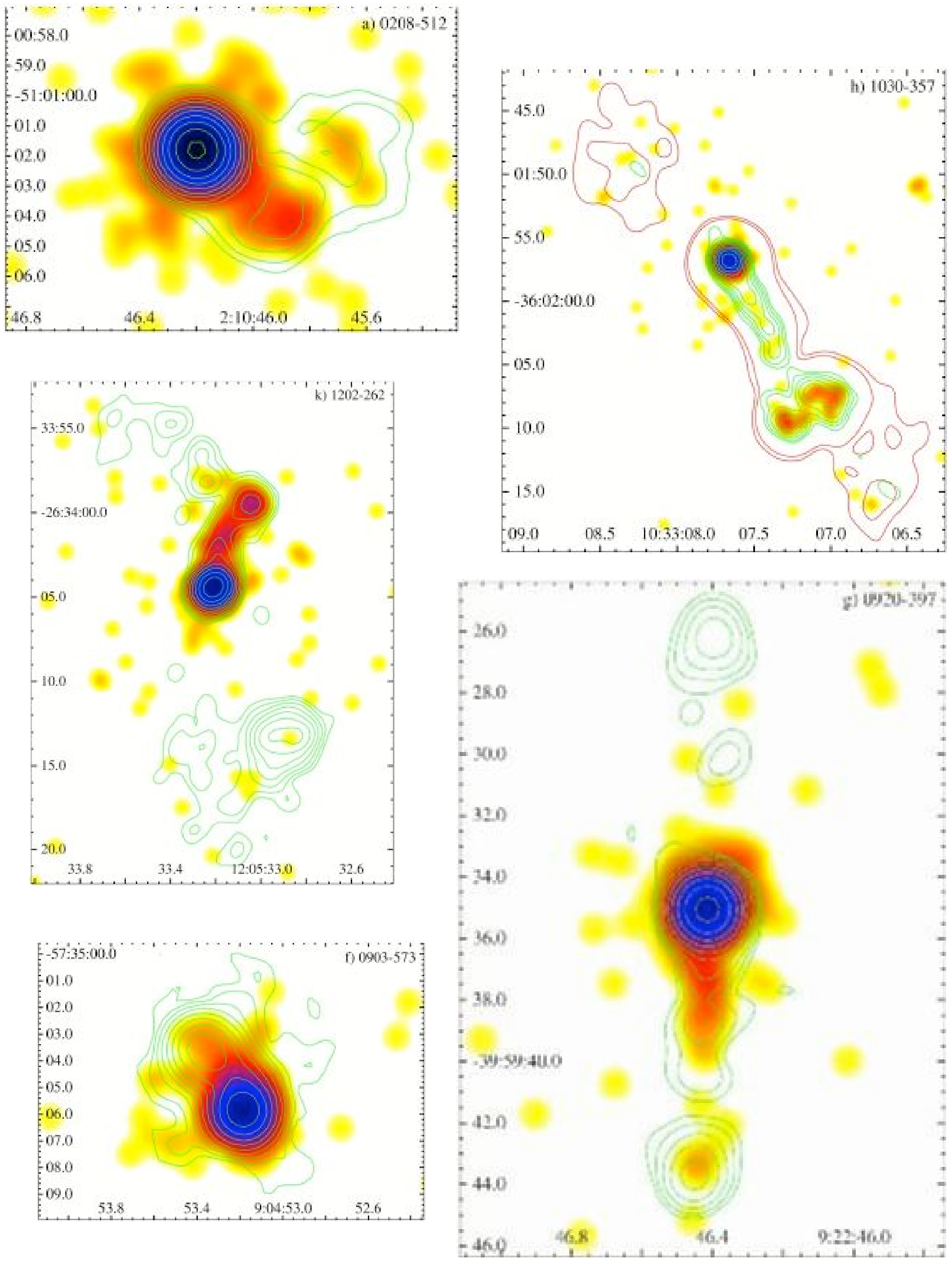
Stawarz&Ostrowski 02

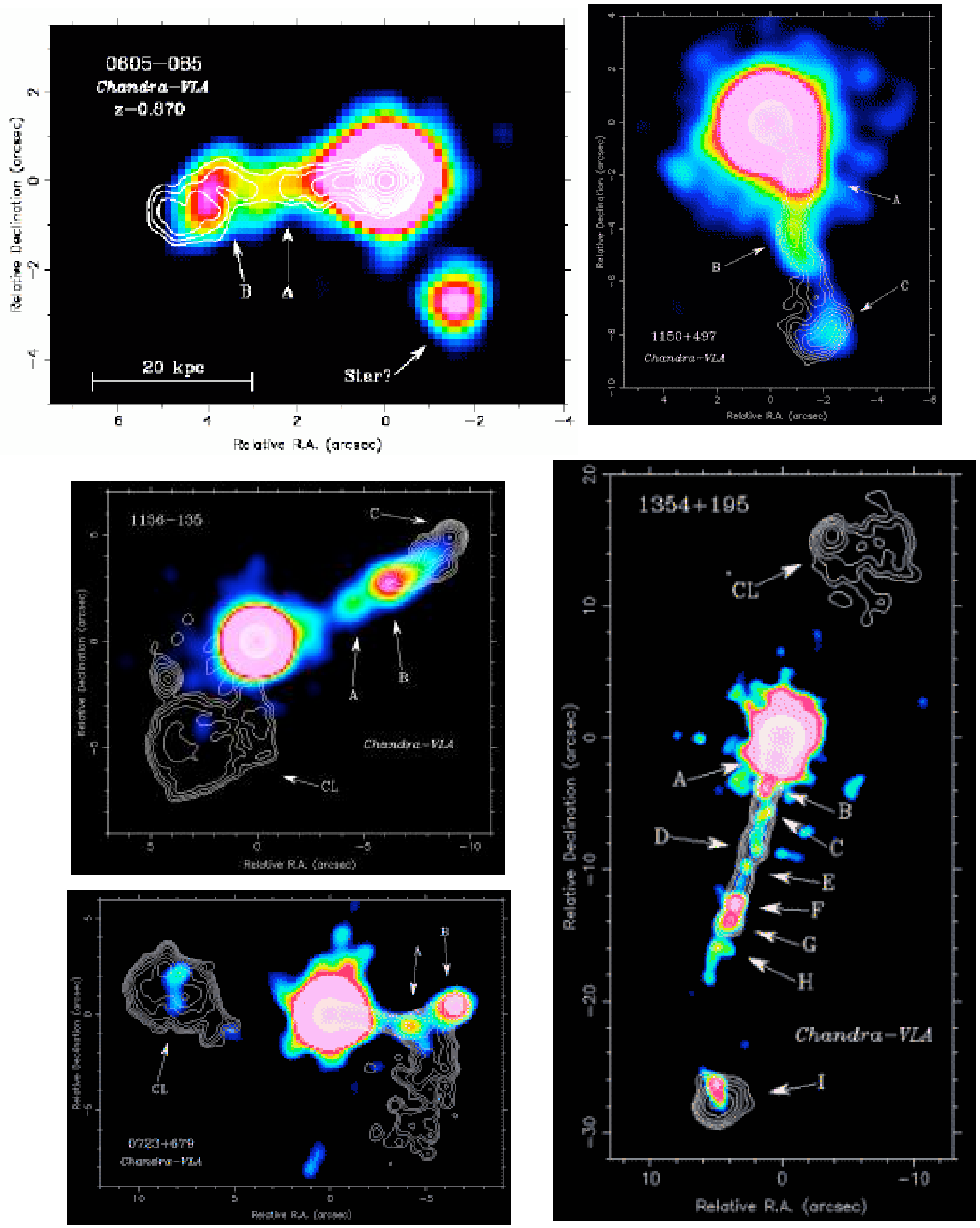
(b) proton synchrotron

Aharonian 02

Chandra snap-shot surveys

Sambruna+ (2004), Marshall+ (2005)



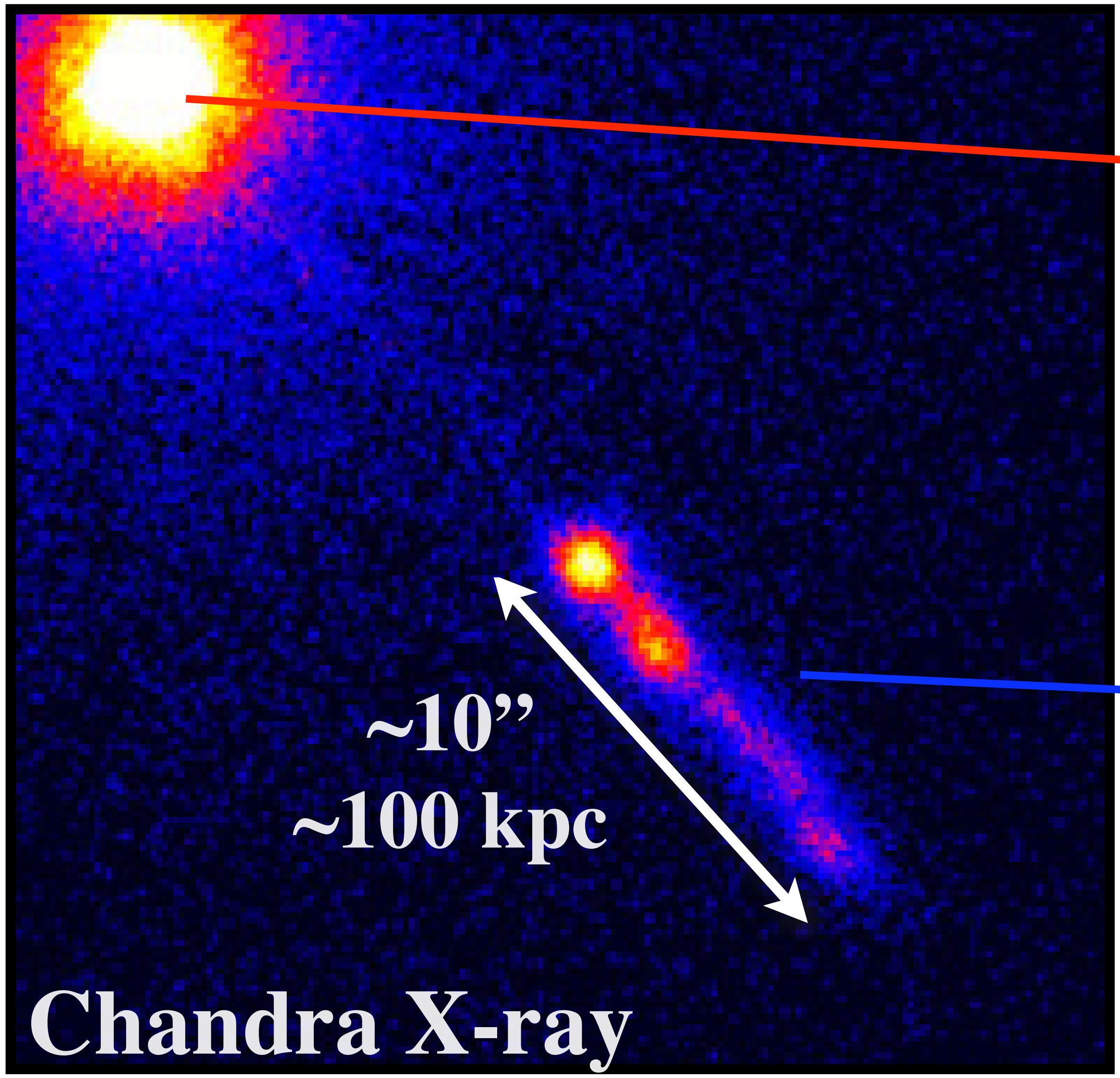


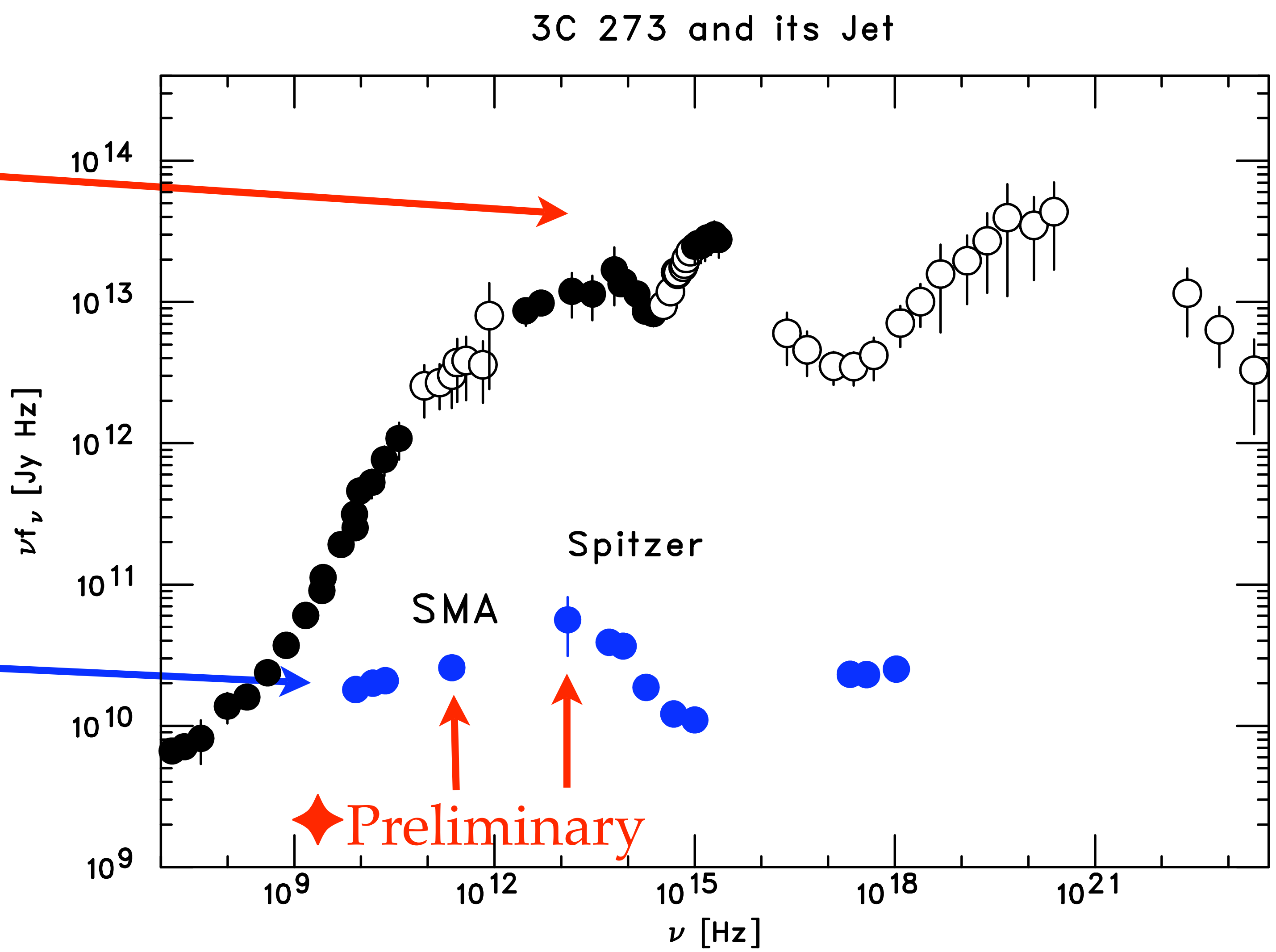
X-ray detection rate is high: about 50%

Quasar 3C 273:
the best example

3C 273 and its jet

Marshall+ 2001





“Blazar Core”
- ✦ Synchrotron + IC
- ✦ Beaming $\delta \sim 10$

Chernyakova+ 2007
Tueler+ 1999, 2006
Kataoka+ 2003

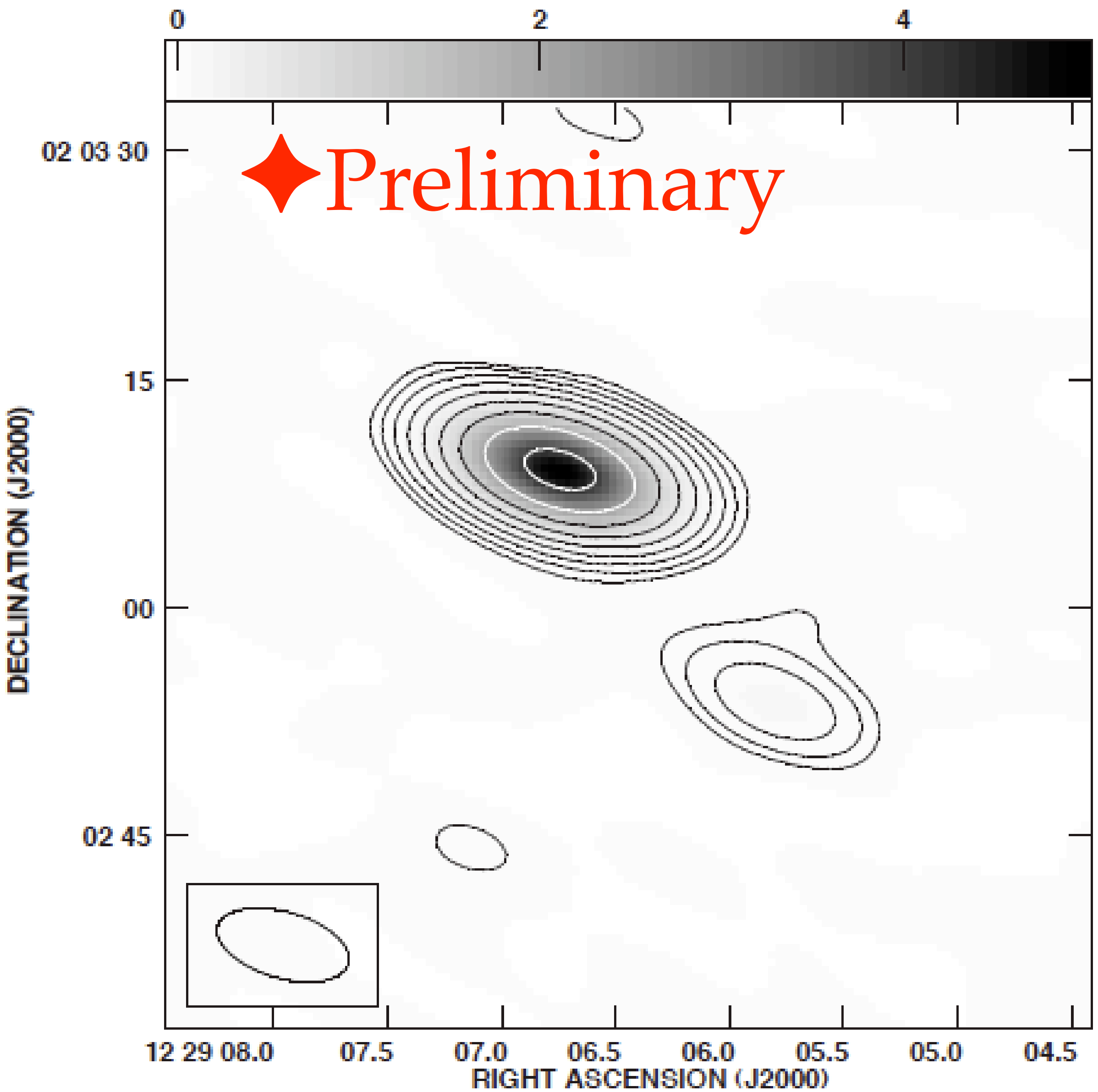
“Extended Jet”
- ✦ Synchrotron + “?”
- ✦ Beaming $\delta \sim ?$

Jester+ 2006, 2007
Uchiyama+ 2006

New! Sub-mm observations of the jet

Asada, Sawada-Sato, Uchiyama, et al.

SMA 230 GHz



sub-compact configuration

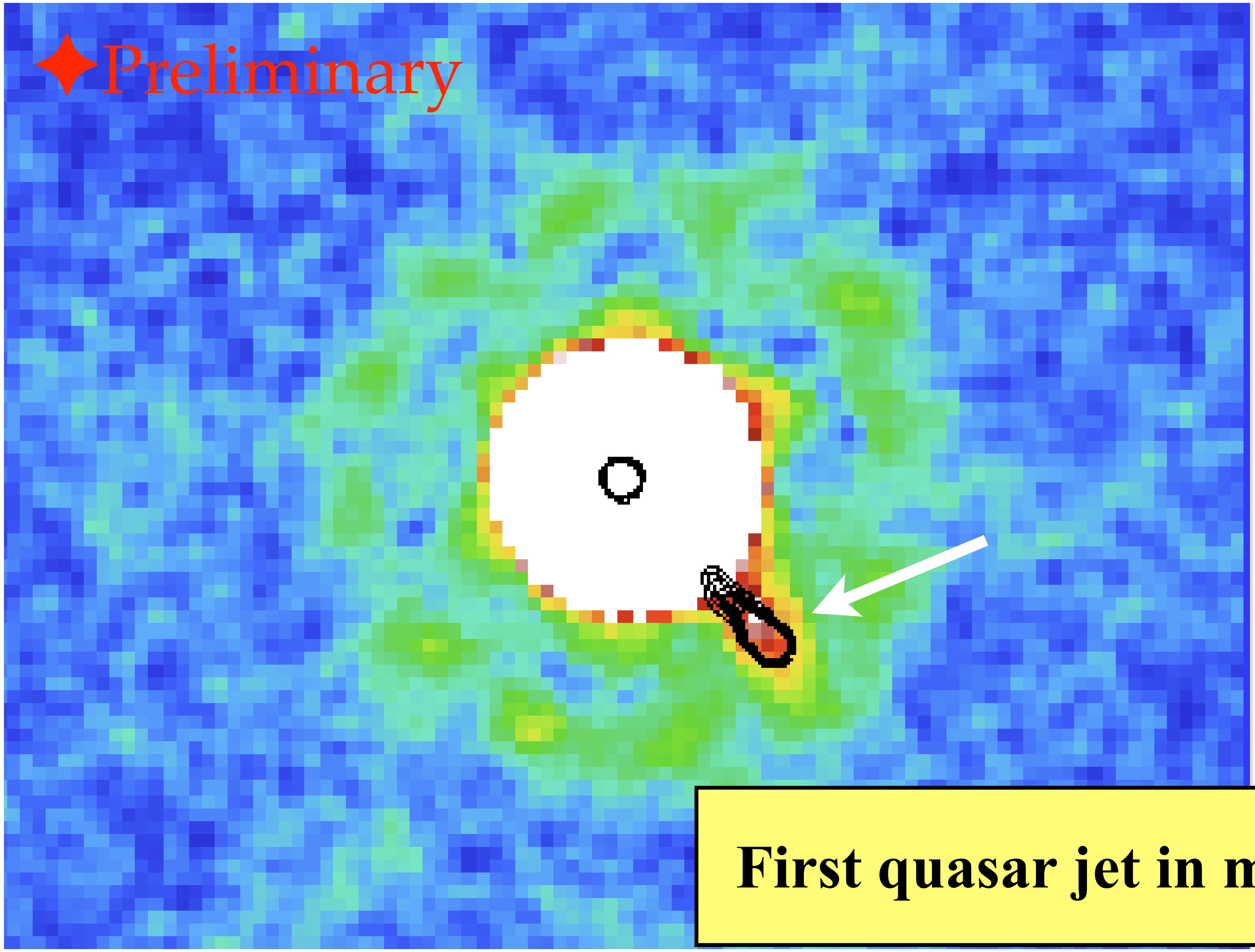
With SMA and PdBI,
<1" resolution imaging will be carried out in this semester

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

First quasar jet in sub-mm!

Upcoming ALMA
will detect many jets

Spitzer MIPS data



First quasar jet in mid-IR

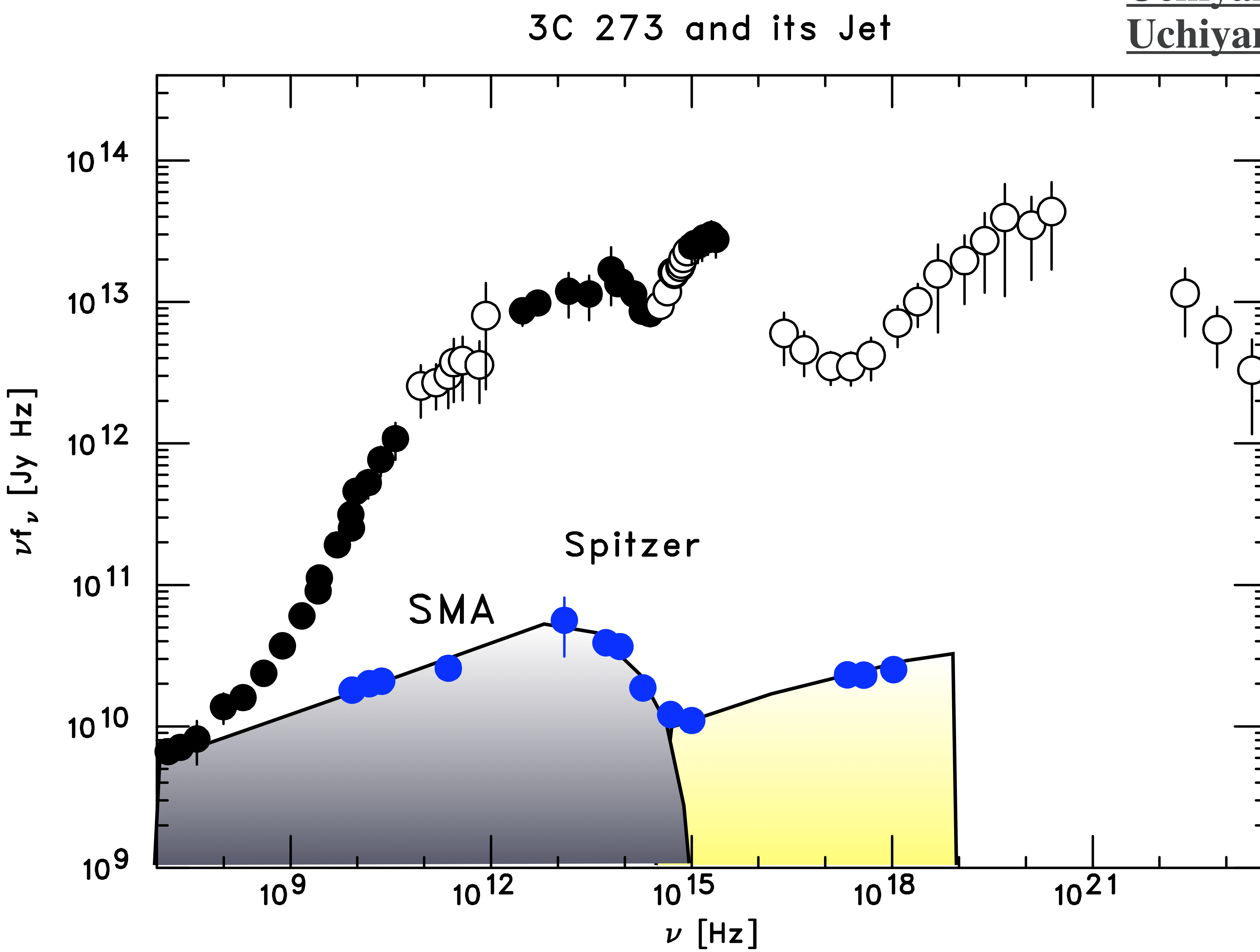
Spitzer MIPS 24 microns

(2004 June: historical core-jet minimum)

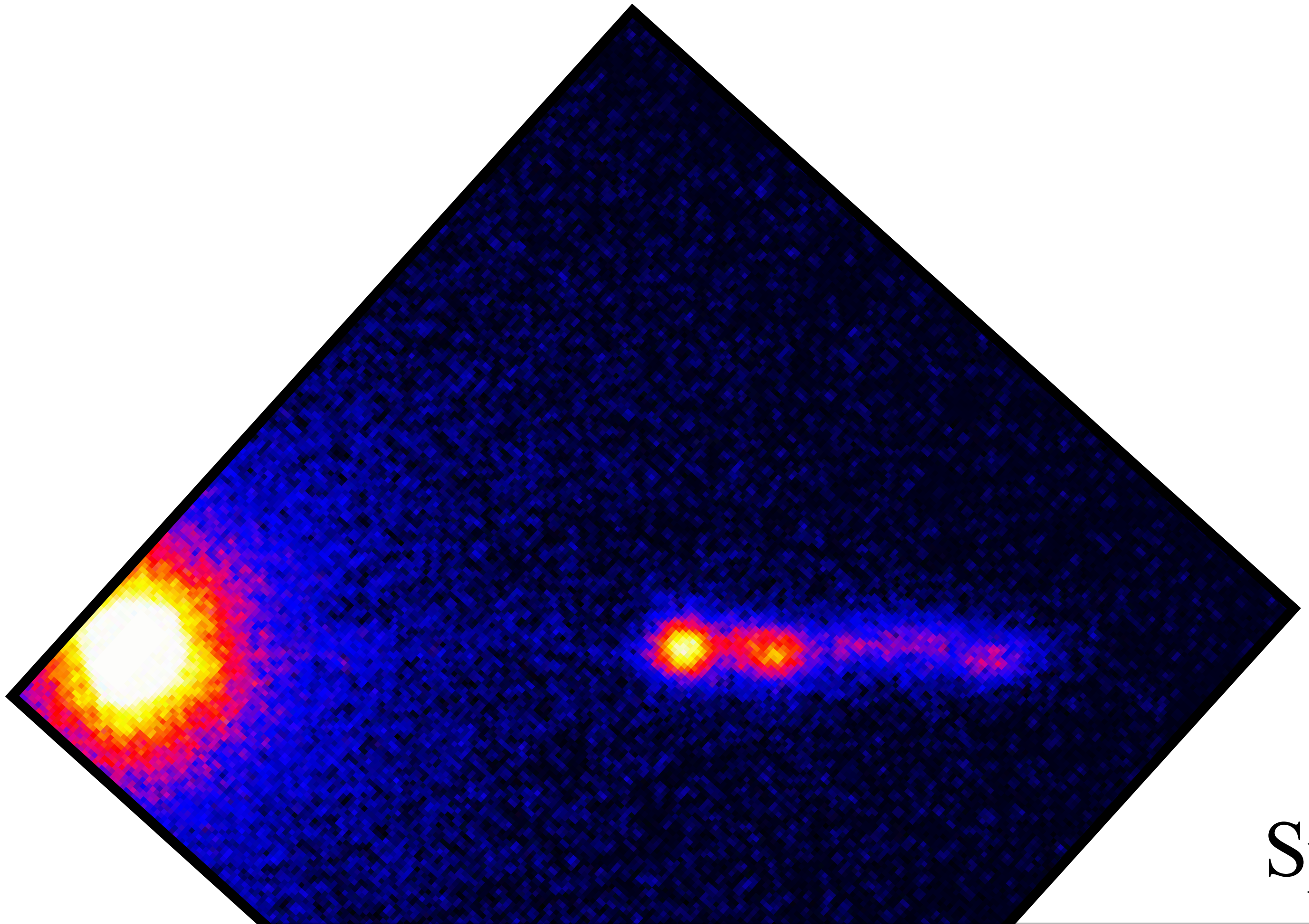
Added to Uchiyama+ (2006):
Spitzer IRAC 3.6 & 5.8 microns

2-component SED revealed thanks to SMA and Spitzer

Uchiyama+ 2006
Uchiyama+ in prep



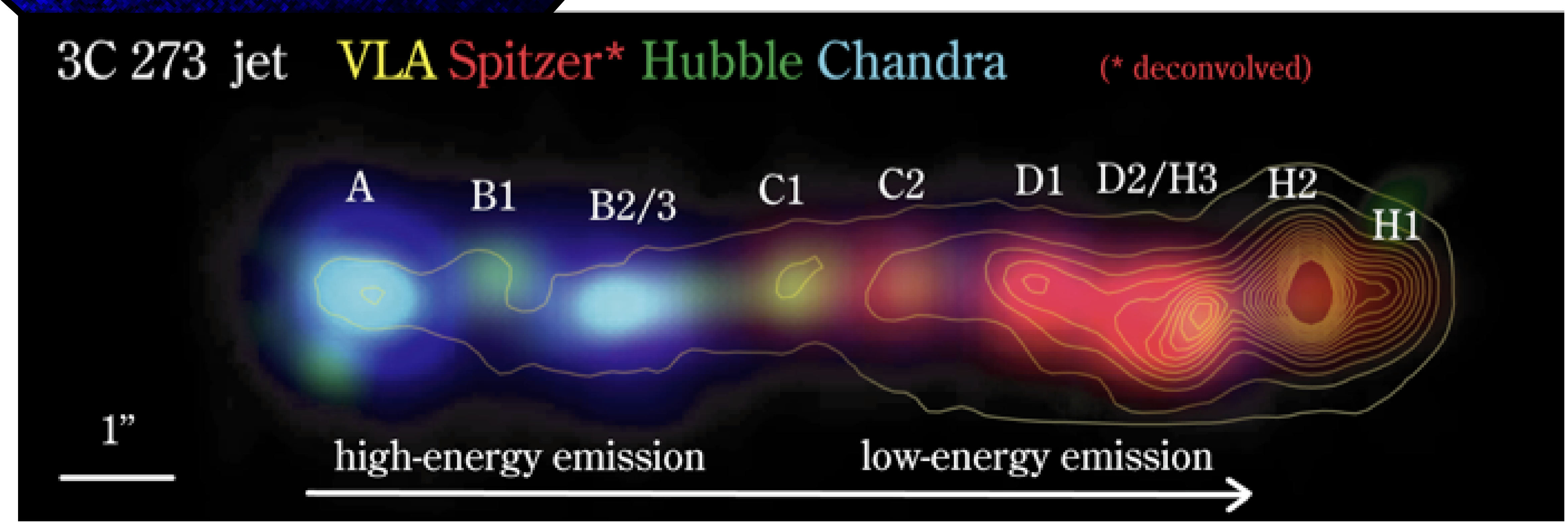
Problem: the origin of the high-energy component



Jet Knots

- knot by knot analysis
- r ~ 0.3” ~ 1 kpc
- B ~ 0.1 mG (eq)

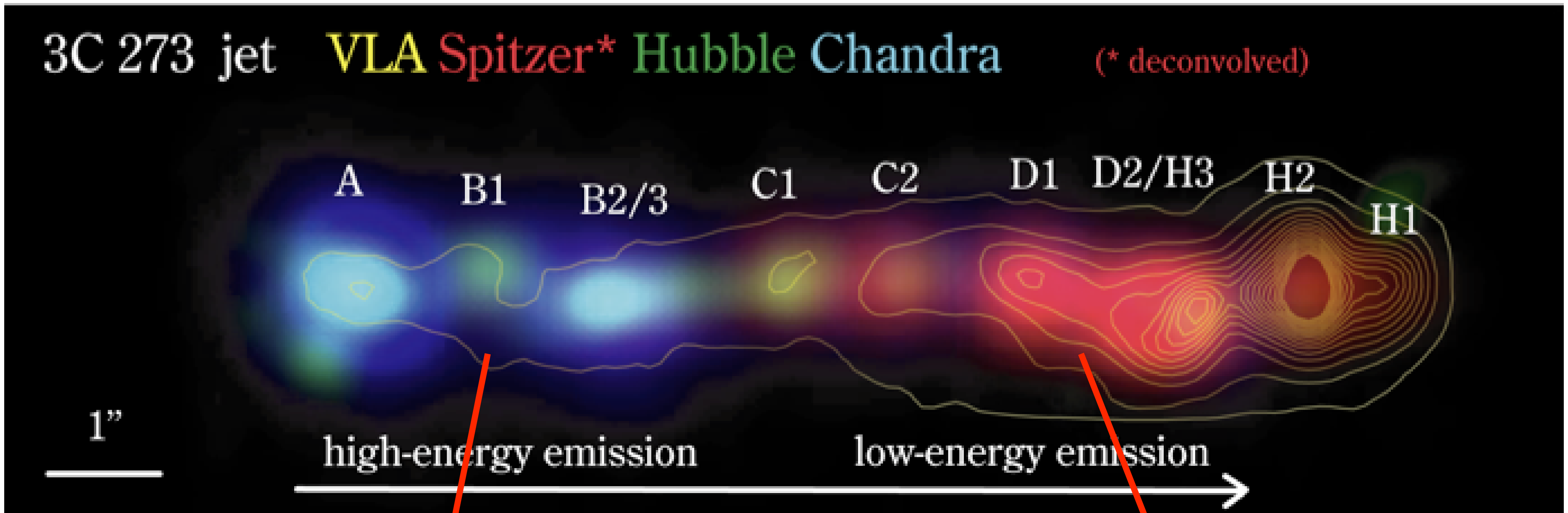
Spectral evolution along the jet

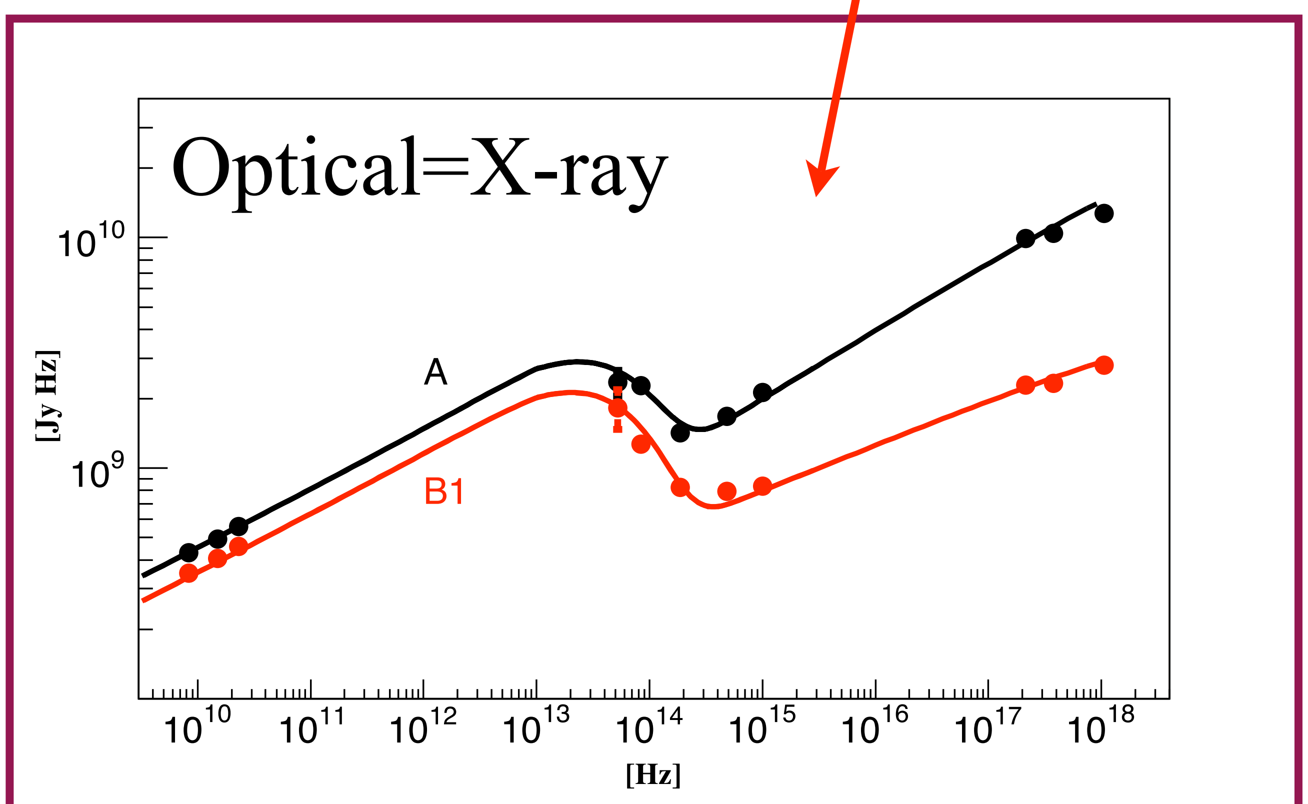


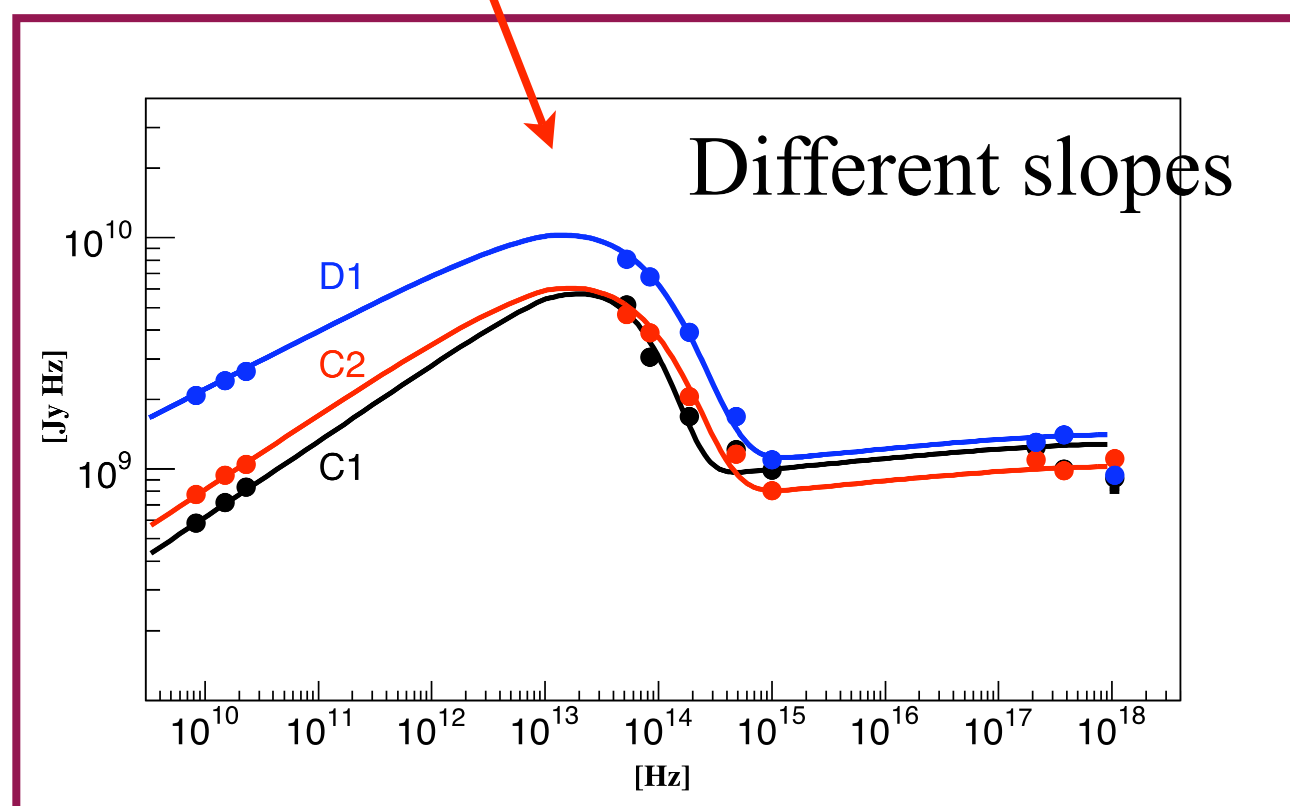
Uchiyama+ 2006
(see also Jester+ 2006)

Knot SEDs: 2 components

Uchiyama+ 2006
(see also Jester+ 2006)







Recent HST Far-UV

Jester+ 2007

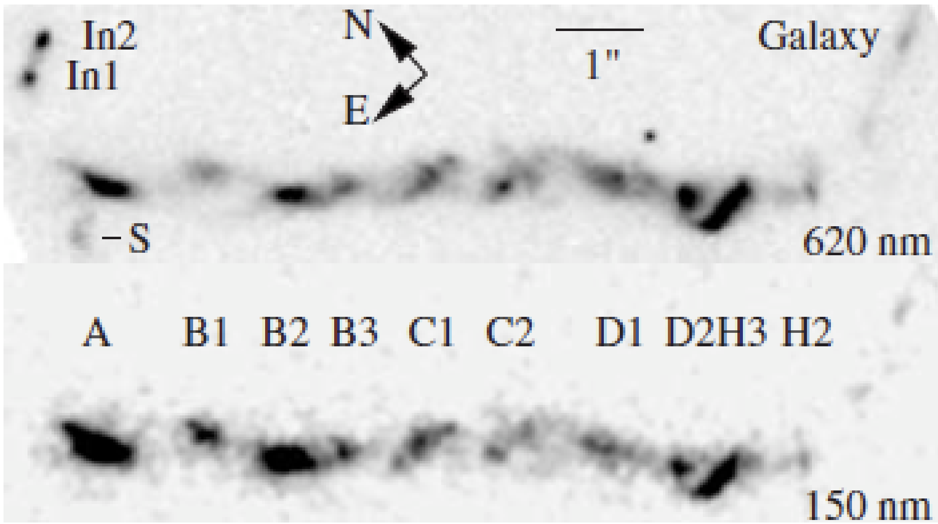
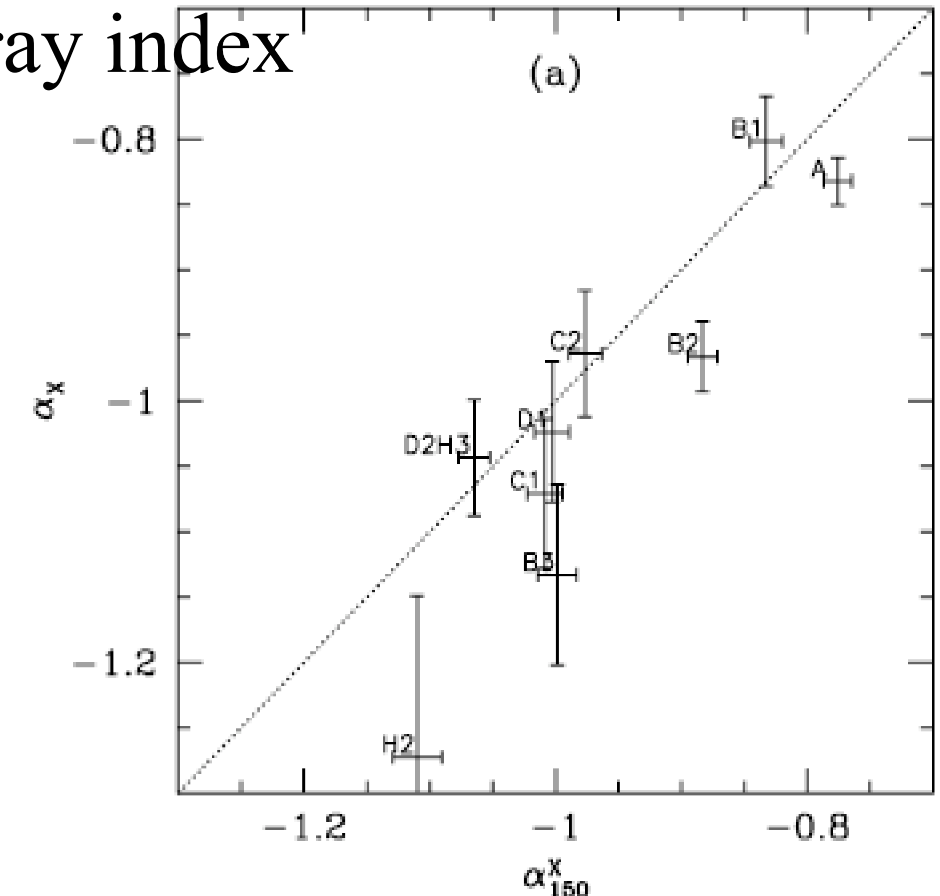
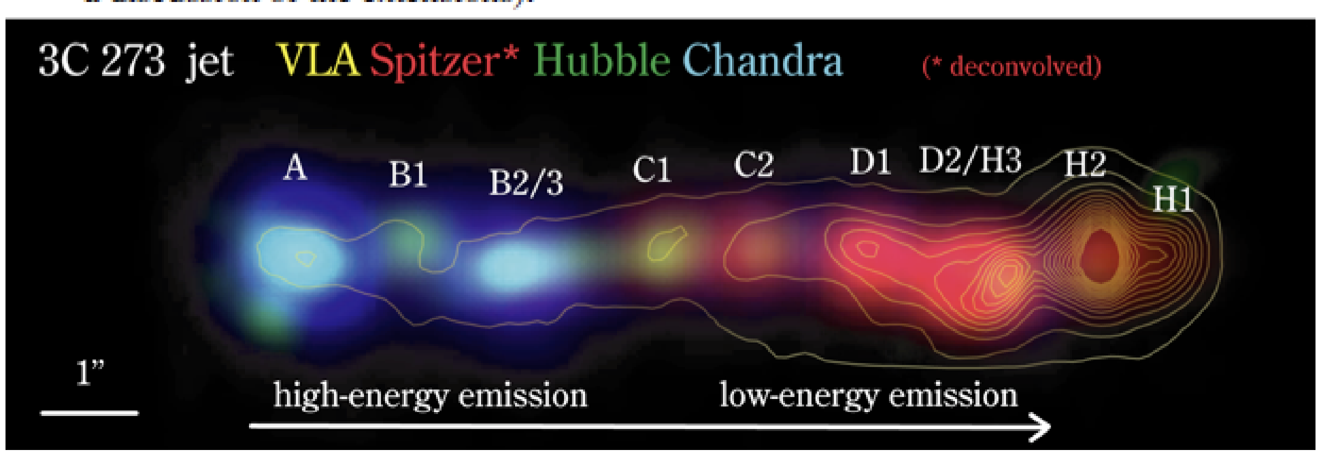


Figure 1. Map of surface brightness (linear grey-scale) of the jet of 3C 273 at 150 nm with *HST*/ACS/SBC/F150LP (bottom), and for comparison, at 620 nm with *HST*/WFPC2/PC1/F622W (top; data from Jester et al. 2001). The images have been rotated to place a position angle of 222° along the horizontal. 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 µm to 300 nm, but not at 150 nm (see Section 4.4 for a discussion of the extensions).

X-ray index



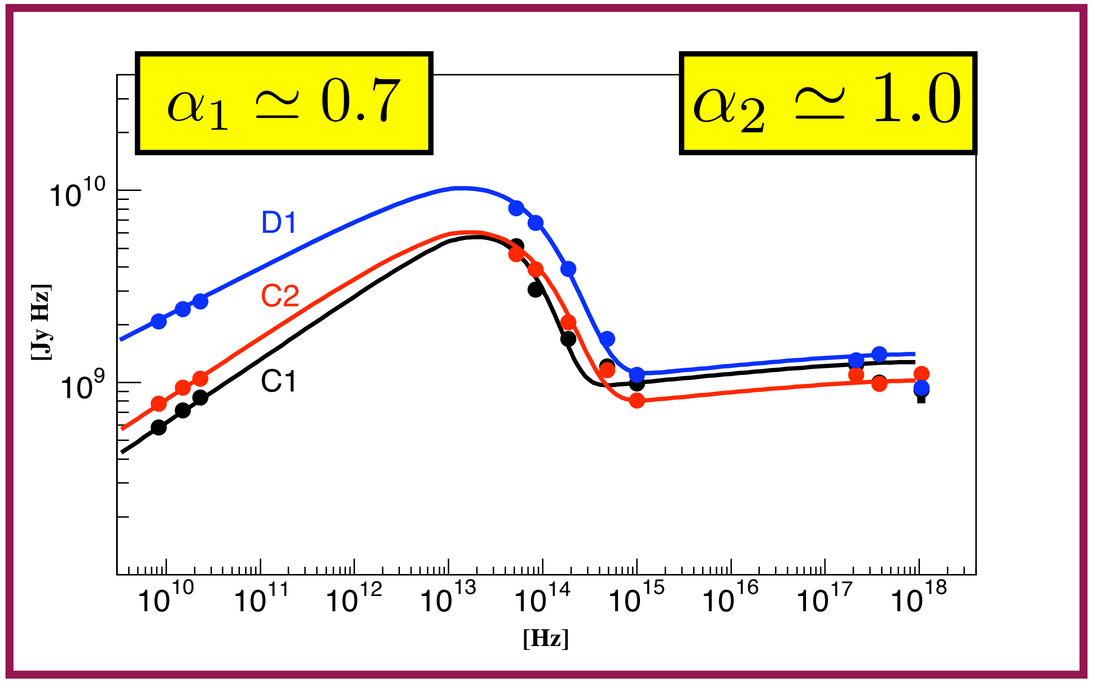
UV-to-X slope



verifying the optical-X-ray connection

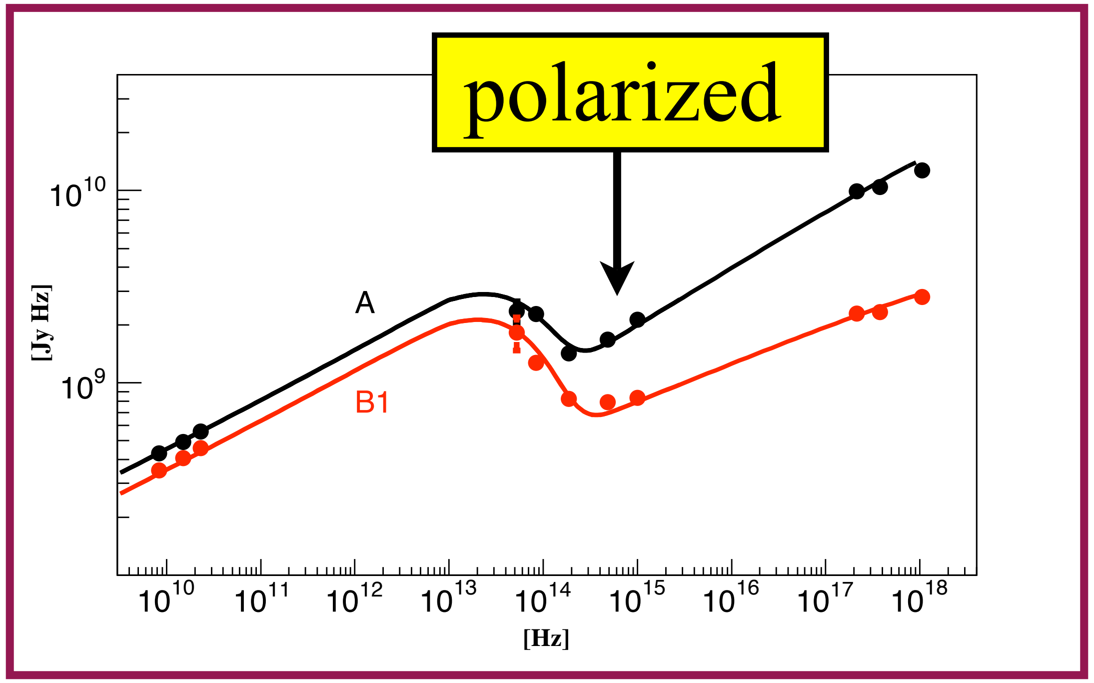
✦ Far-UV (150 nm) data confirm our SED modeling.

Popular "Beamed IC/CMB" model works?



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

Jester+ 2006



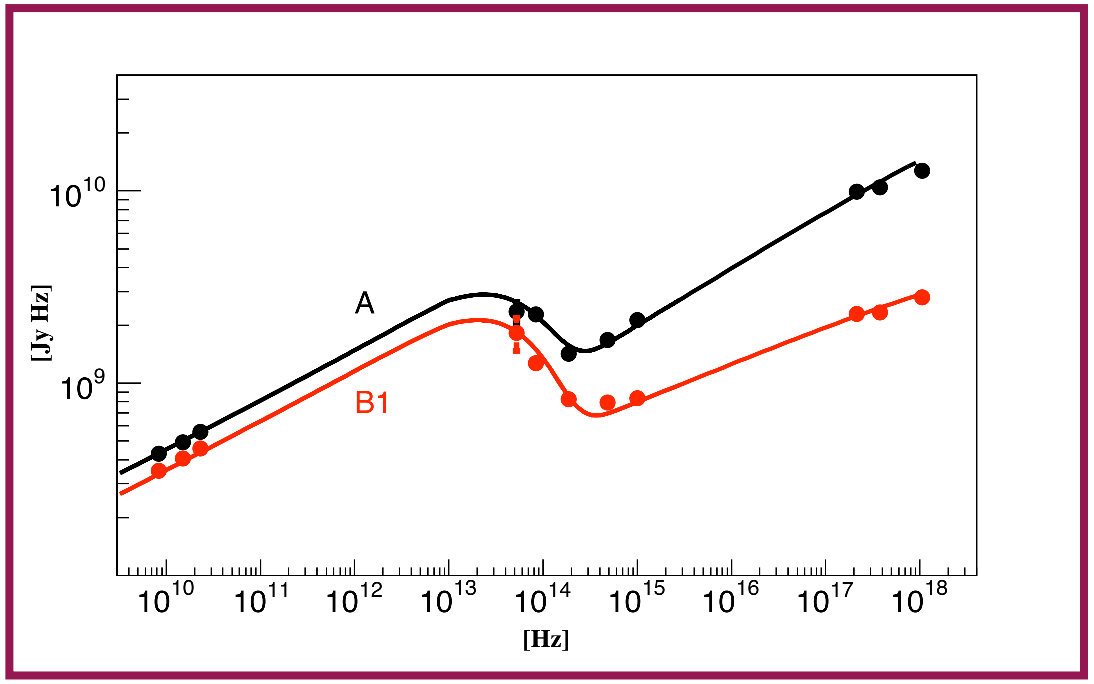
Optical polarization (if confirmed) argues against "beamed IC".

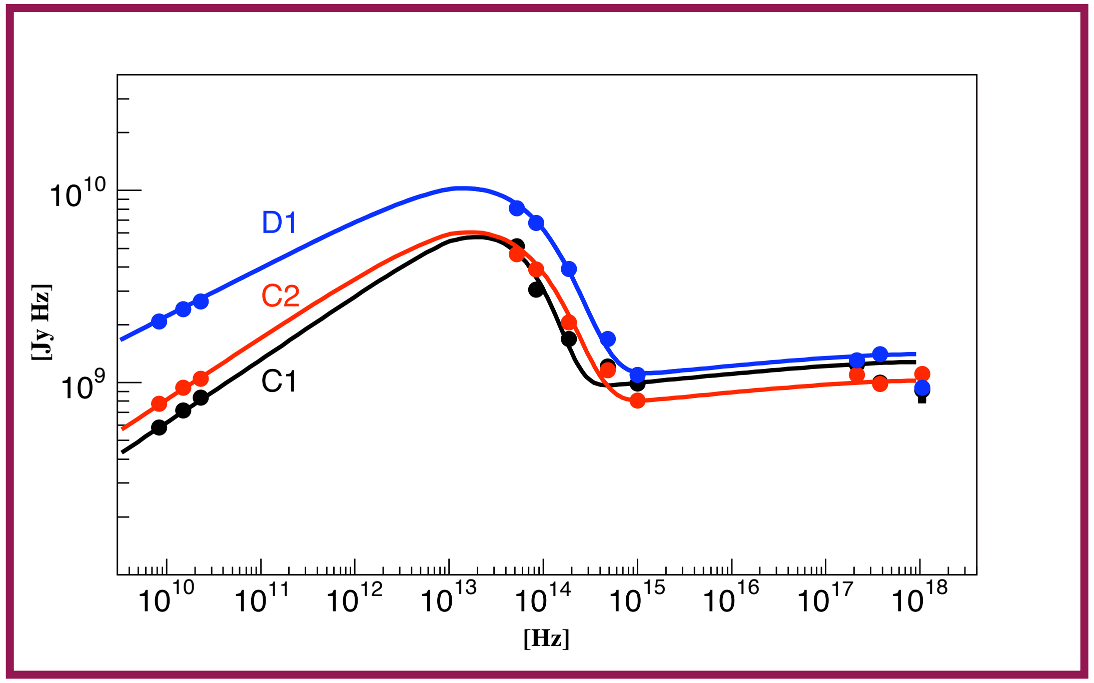
Uchiyama+ 2006

Perlman's talk (the next speaker)

Simple "beamed IC" faces difficulties.

"Double-Synchrotron" Model





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

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

frequency-independent knots?
steep spectra can be explained?

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

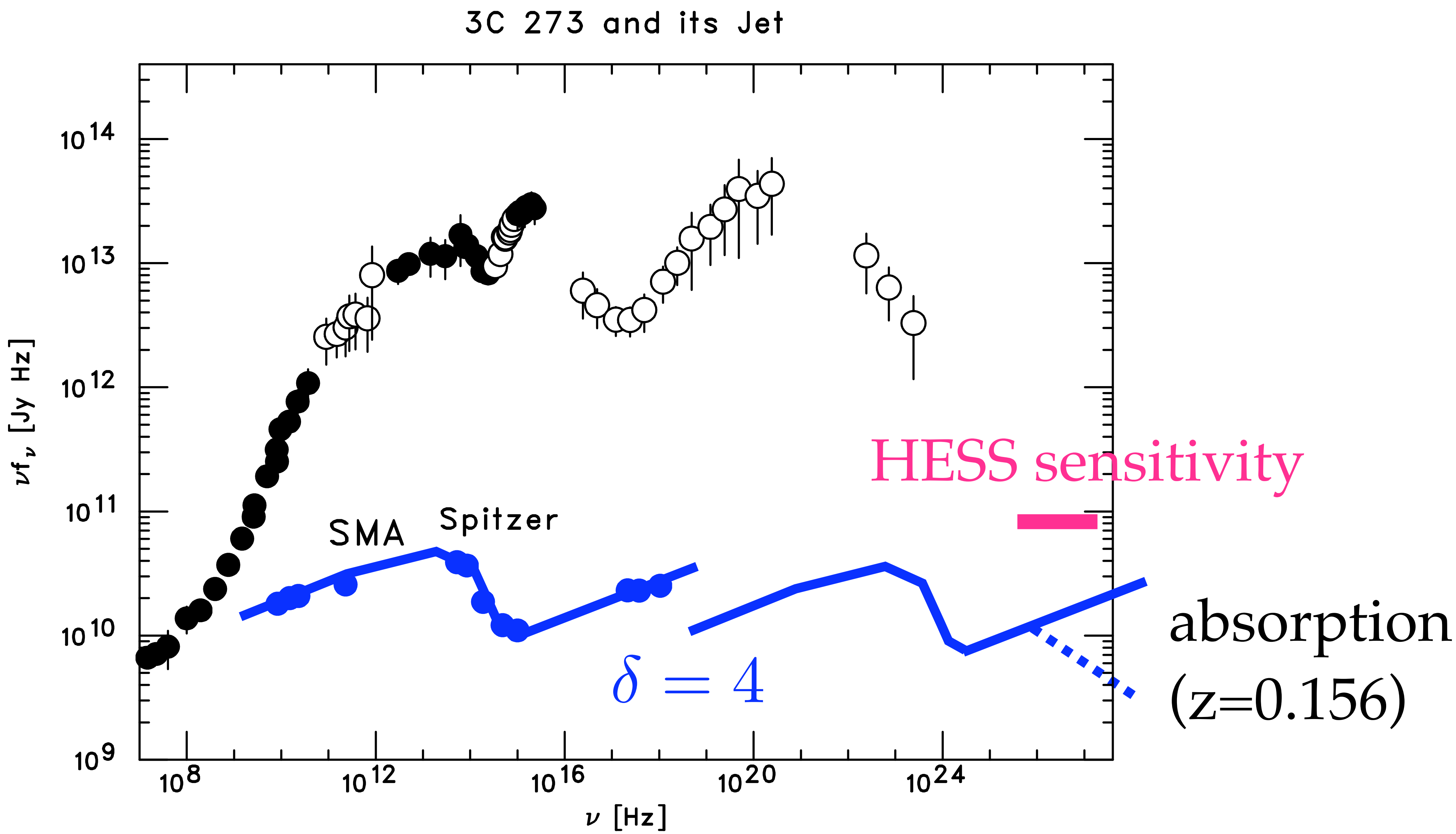
$$\nu_c \sim 2 \times 10^{18} \; B_{\rm mG} \; E_{18}^2 \; [\mathrm{Hz}]$$

$$L_X \sim 0.1 \frac{W_p}{t_{\rm syn}} \sim 0.4 \times 10^{42} \; B_{\rm mG}^4 \; \mathrm{erg \; s^{-1}}$$

$$E_p \sim 10^{18} \; \mathrm{eV}, \quad \mathrm{B} \sim \mathrm{mG}$$

B-field would be too large?

2nd Synch: Electron or Proton?



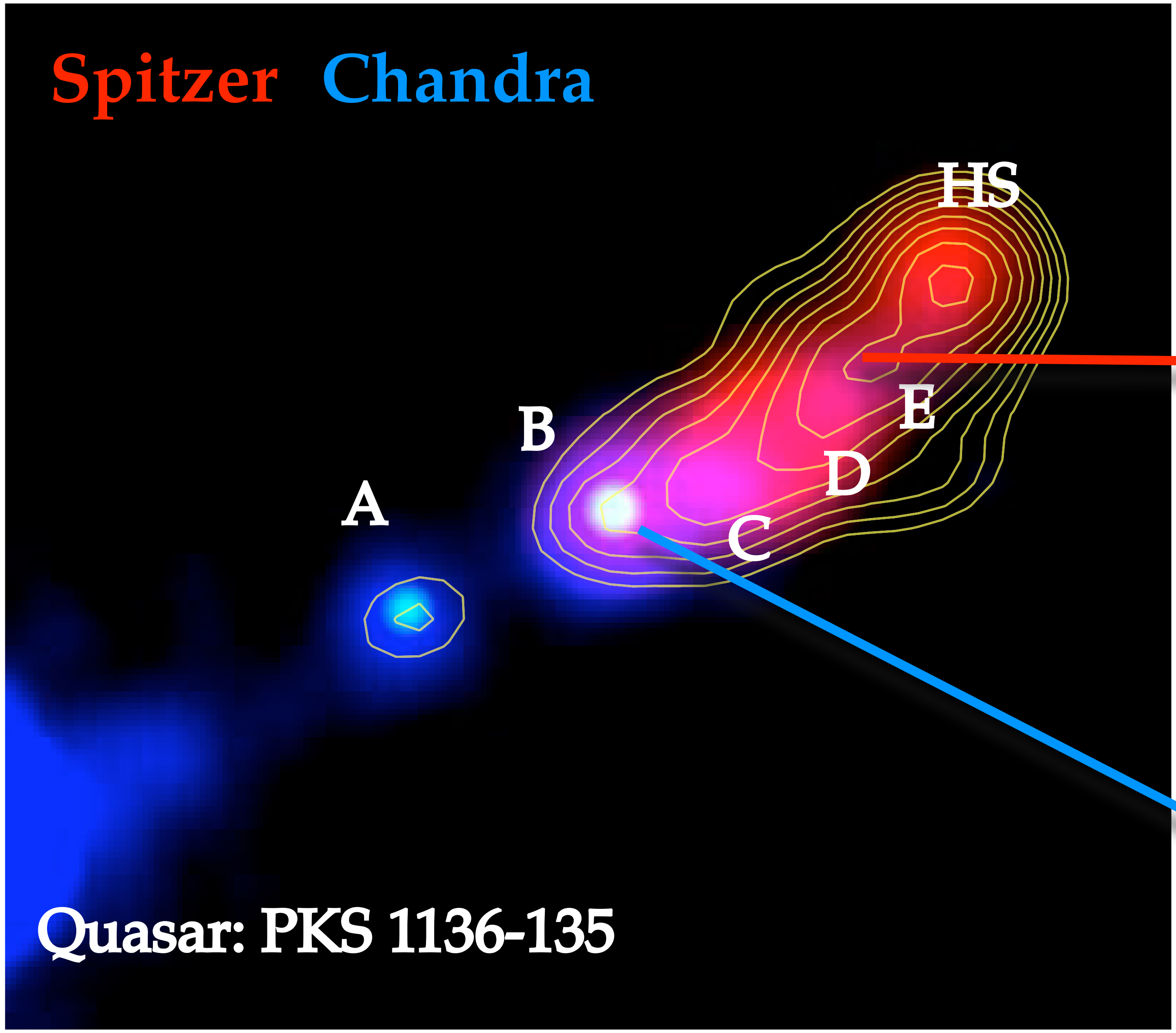
If the 2nd synchrotron is due to electrons, there must be its IC counterpart in TeV range. **Georganopoulos+ 2007**

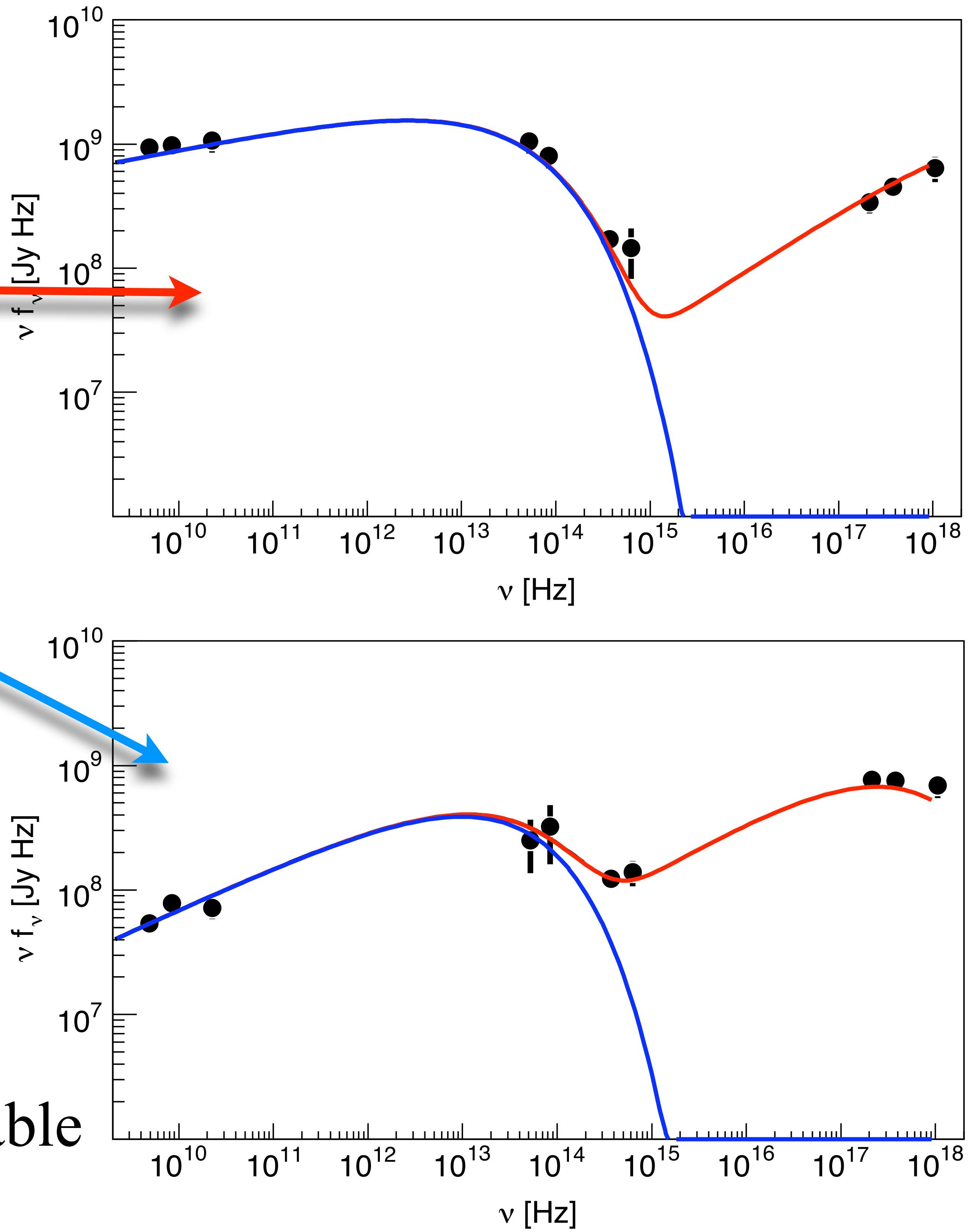
Future TeV telescopes may solve this problem.

PKS 1136-135 (z=0.55)

Uchiyama+ (2007)

Lobe-dominated quasar





SEDs similar to 3C 273

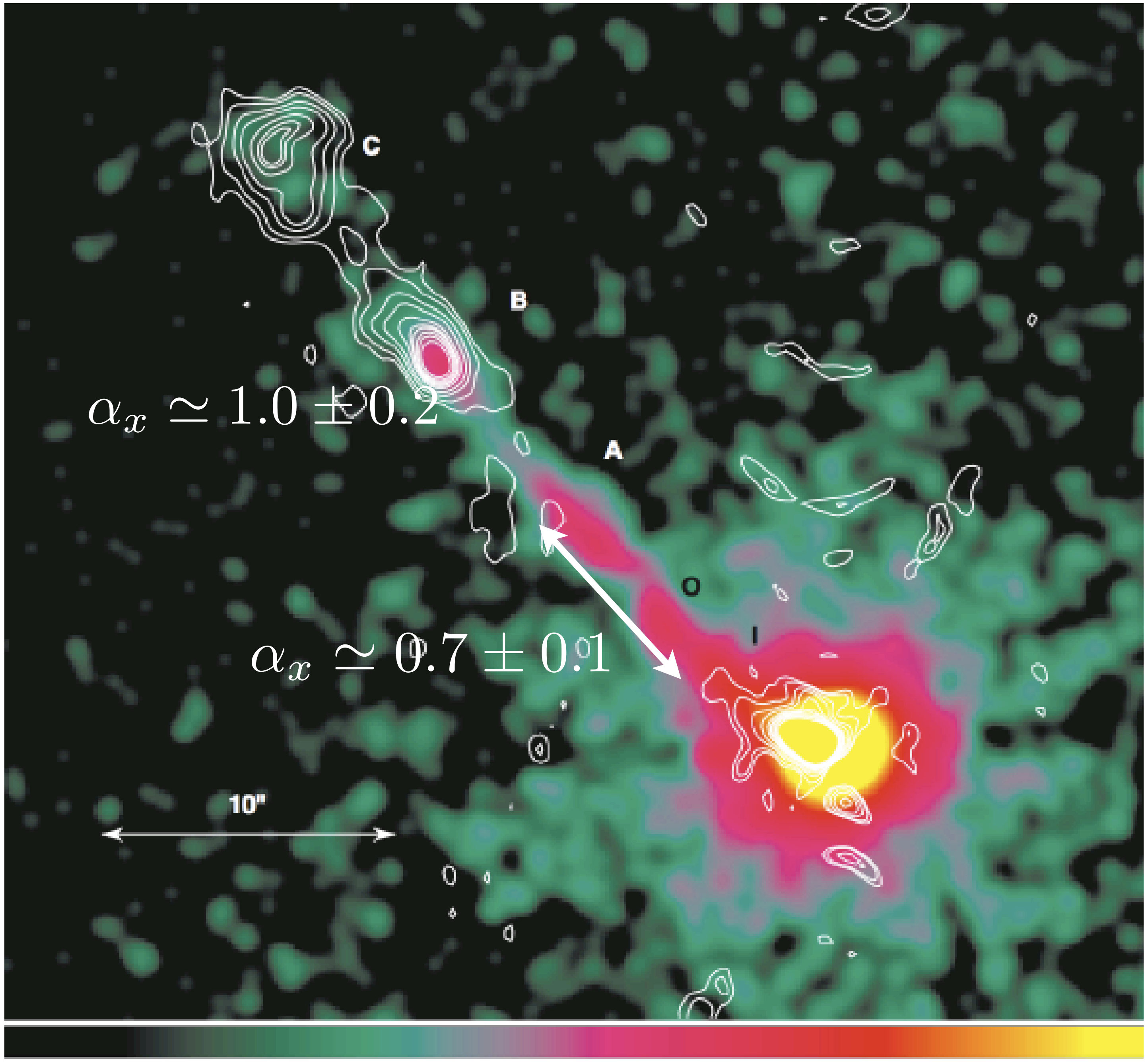
Viewing angle would not be very small

--- Beamed IC/CMB model unfavorable

PKS 1127-145 (z=1.18)

Siemiginowska+ (2007)

100 ks observation



- Again, similar to 3C 273
- Flatter X-ray spectra in inner parts.
- Simple "one-zone" IC models fail.

Knot B has ~100 photons.

Origin of quasar X-ray jets: current status

- Beamed IC/CMB model
  - Unlikely for some well-studied jets
  - Optical polarimetry is key to get a definitive answer
  - High-z jets can be used to check this model
  - GLAST will shed new light
- Electron/proton synchrotron model
  - Theoretical studies are necessary
  - Future TeV observations will discriminate e/p
  - Diffuse X-ray in Centaurus A has a similar origin?

Summary

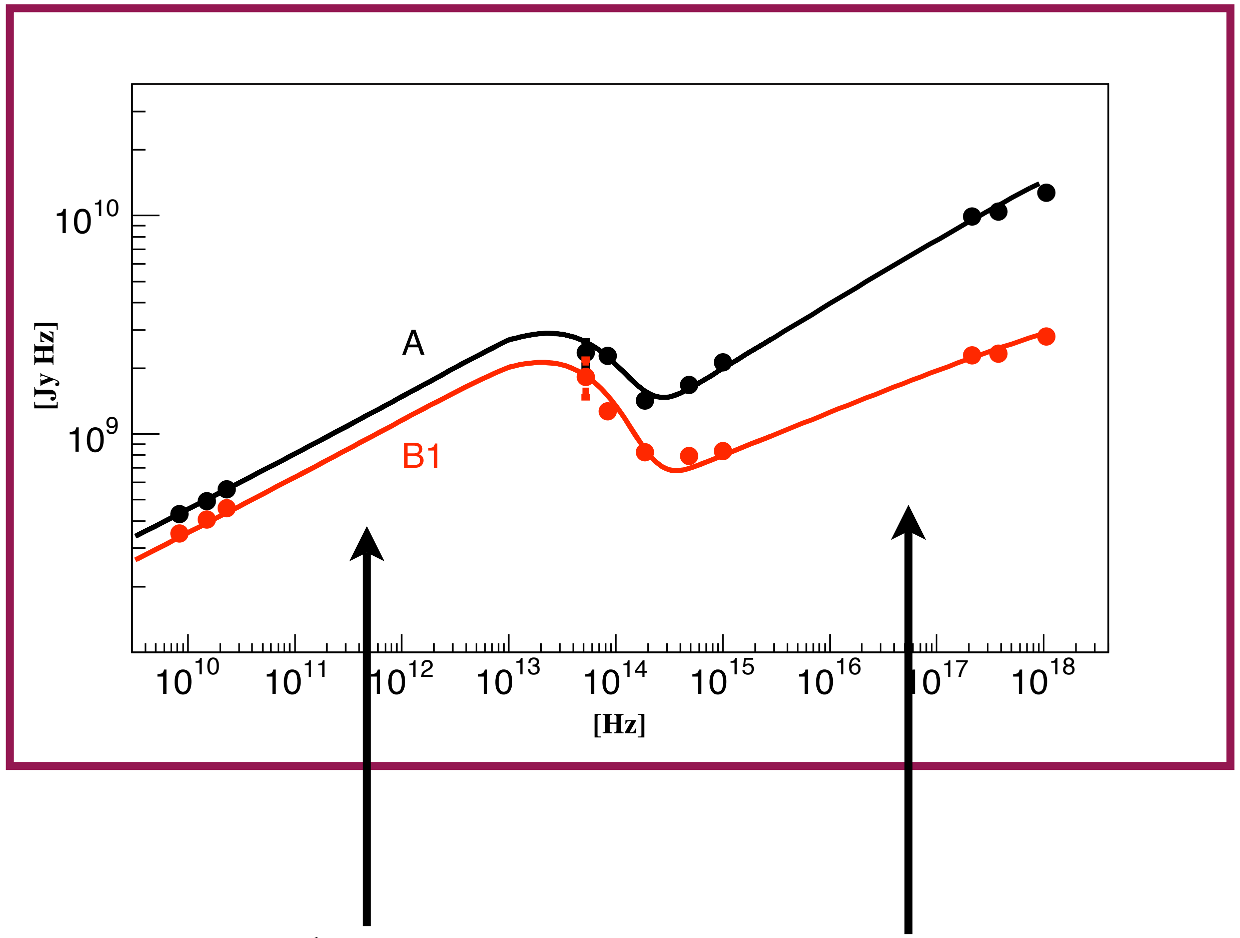
- Low power jets (FR I radio galaxies)
  - Recent news from M 87: HST-1 flare, TeV gamma-rays
  - Recent news from Cen A: diffuse X-ray emission
- High power jets (quasars)
  - New observational windows: sub-mm, IR
  - The most-detailed object: 3C 273
    - 2-component SED: “sync + sync”
  - Various diagnostic tools
  - Understanding of the X-ray emission is crucial to deepen the jet physics
- Future
  - X-ray: Chandra!! (XEUS, Con-X do not have 1” resolution)
  - ALMA & JWST !

Beyond the standard picture of jets

(Option 3)

Diffusive Synchrotron

(a.k.a. Jitter radiation)



Synchrotron   Diffusive Synch.

Microscopic magnetic field fluctuation smaller than r_g/γ

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

Emitted photon energy:

$$\epsilon_{\rm jitter} \sim \hbar k_B c \gamma^2$$
$$> \epsilon_{\rm syn}$$

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

magnetic power spectrum

Optical polarization is crucial.

Core and extended jet

Tavecchio+ 07