RECENT PROGRESS ON UNDERSTANDING THE LARGE SCALE JETS OF POWERFUL QUASARS

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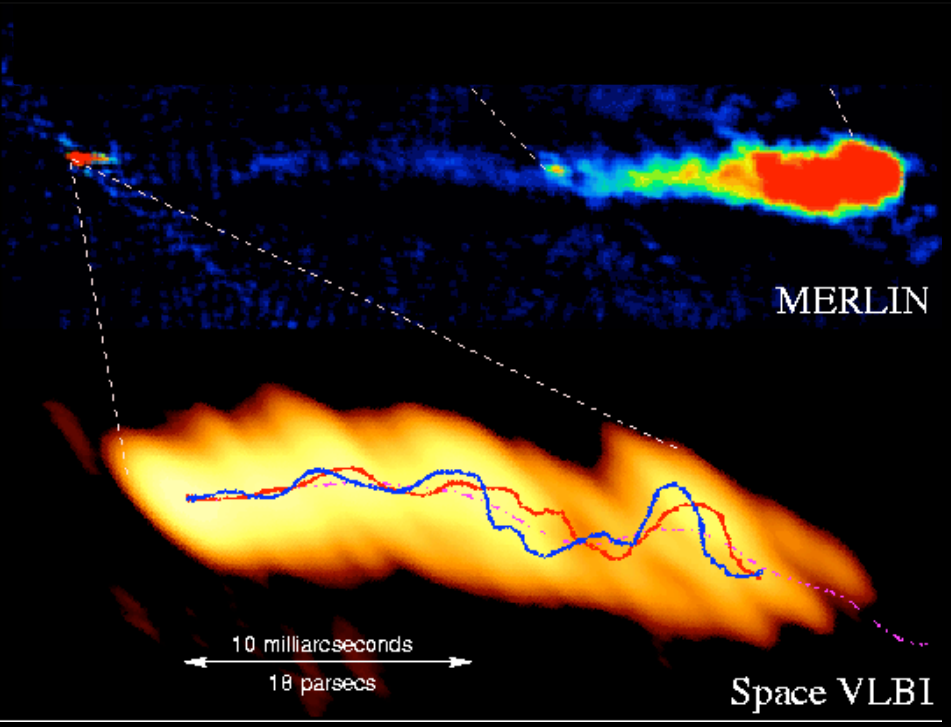
IF WE ONLY HAD RADIO OBSERVATIONS

Polarized radio emission: Synchrotron

Equipartition magnetic field: B~$10^{-4\text{-}5}$ G

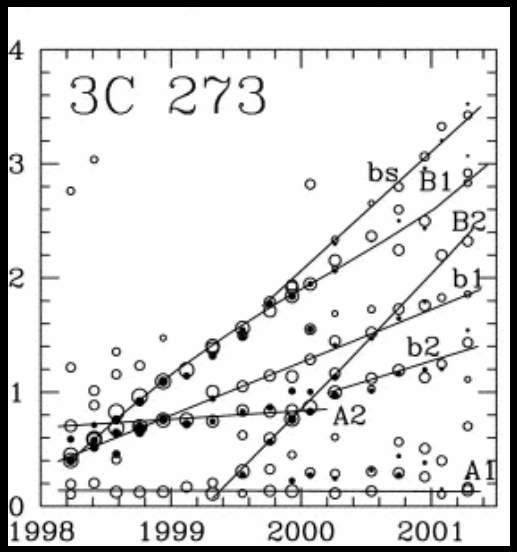
Radio producing electrons: $\gamma \sim$ few 10^3



http://www3.mpifr-bonn.mpg.de/staff/alobanov/3C273-Science/3c273.multiband.gif

Kpc-scale knots:
No in situ e acceleration needed

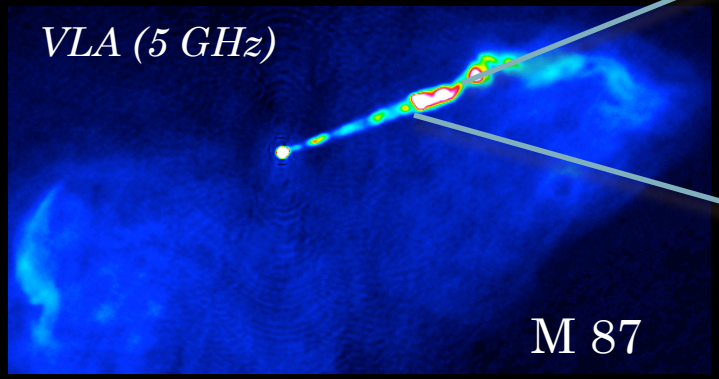
Kpc jet to counter jet flux ratios:
mildly relativistic radio flows at kpc scales *(e.g. Arshakian & Longair 2004)*

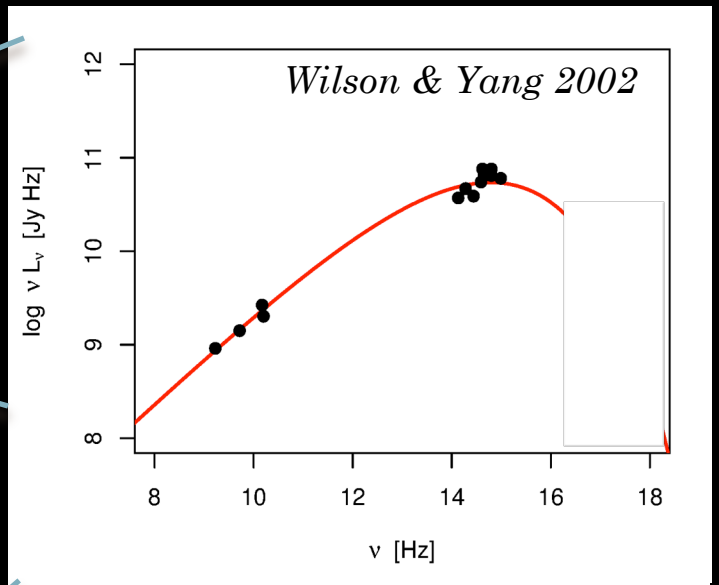


pc-scale superluminal motions:
$\Gamma \sim$few-50
(e.g. Jorstad et al. 2005, Lister et al. 2009)

ADD OPTICAL: SINGLE RADIO-OPTICAL SYNCHROTRON SPECTRUM FOR KPC-SCALE JET KNOTS

Low-power, FR I type jets:

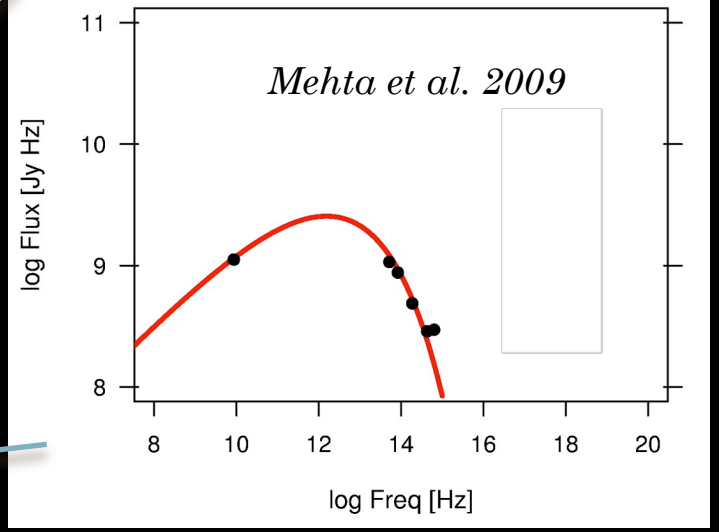




Powerful, "Quasar" jets like PKS 0637-752:

ATCA (15 GHz)

Godfrey et al. 2012



NOW ALSO OPTICAL, MOSTLY HST: SINGLE RADIO-OPTICAL SYNCHROTRON SED FOR KPC-SCALE JET KNOTS

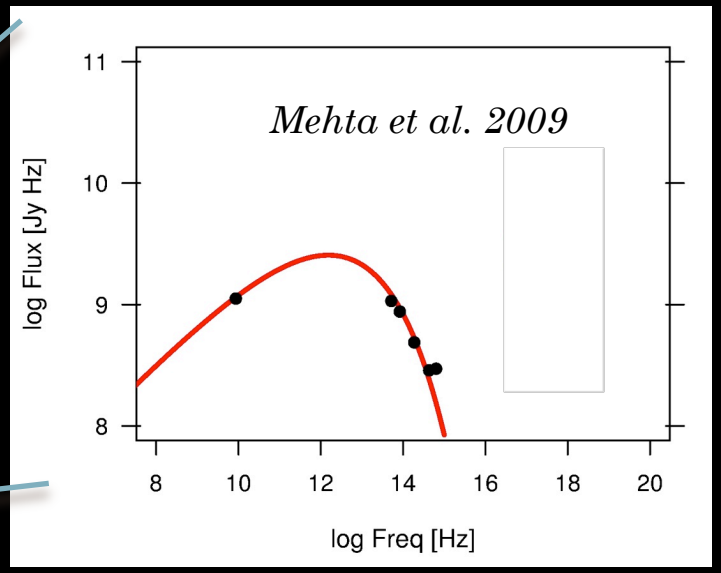
Optical producing electrons: $\gamma \sim 10^{6\text{-}7}$ (TeV energies)

In situ electron re-acceleration at the knots most probably needed

Powerful, "Quasar" Jets like PKS 0637-752:

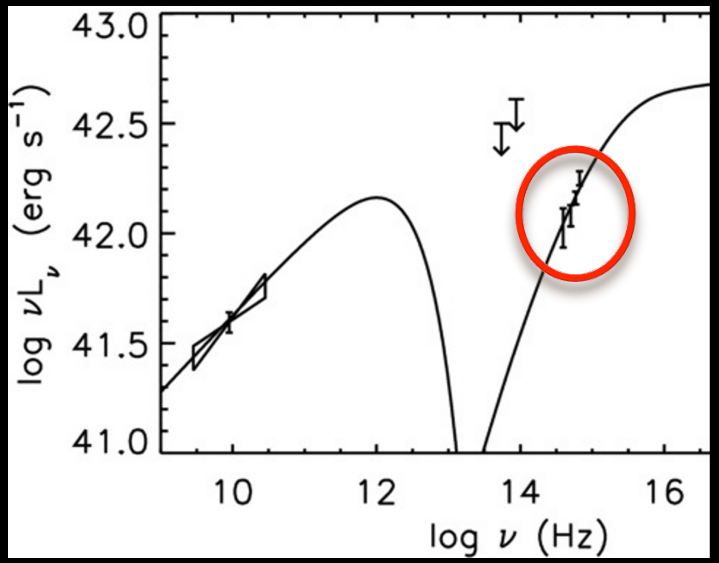
ATCA (15 GHz)

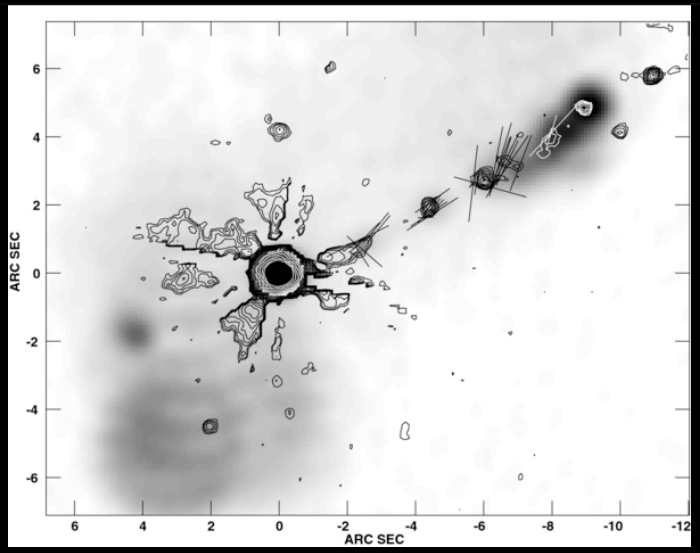
Godfrey et al. 2012



PKS 1136-135 IN THE OPTICAL: A "FREAK OF NATURE" OR ARE WE MISSING SOMETHING?

A second spectral component

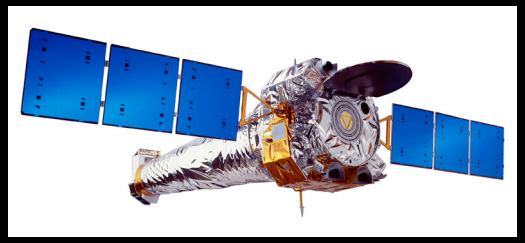




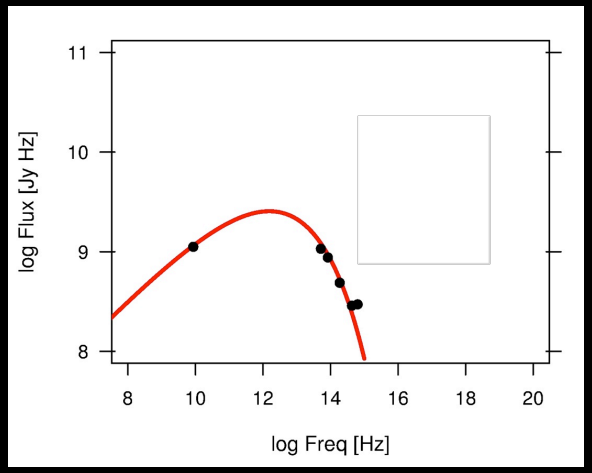
Cara et al. 2013

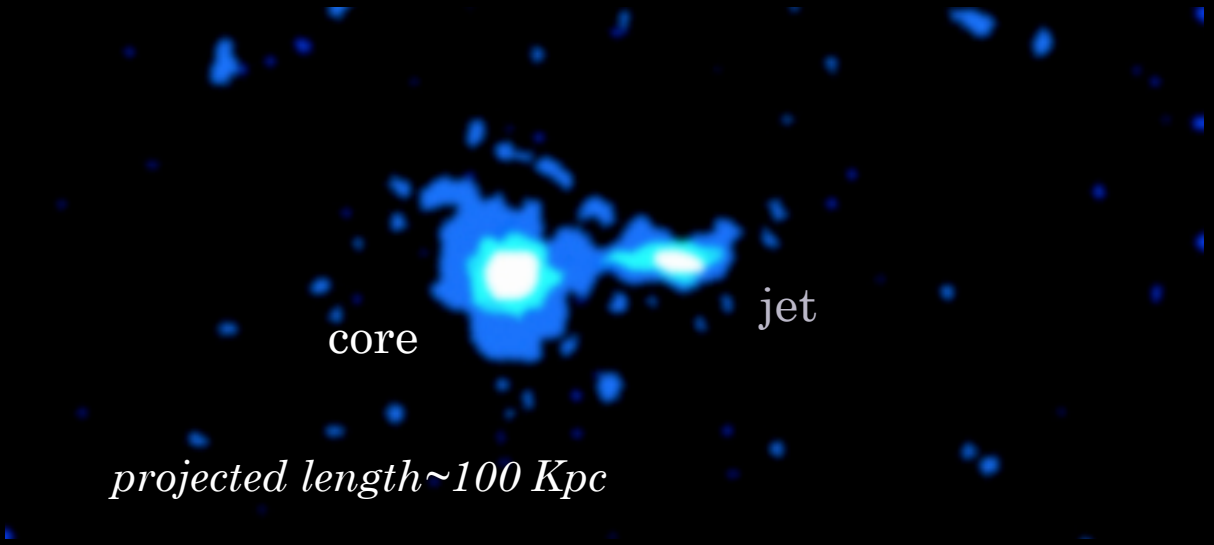
High knot optical polarization (>30%):
Synchrotron emission for the second spectral component

FINALLY X-RAYS: THE QUASAR SURPRISE



August 1999: Trying to focus
Chandra discovers the extended kpc-scale jet of PKS 0637-752





projected length~100 Kpc

Chartas et al. 2000, Schwartz et al. 2000

ANOMALOUSLY BRIGHT QUASAR JETS: A MAJOR CHANDRA DISCOVERY AND AN ONGOING MYSTERY.

Chandra News

Issue 21
Spring 2014

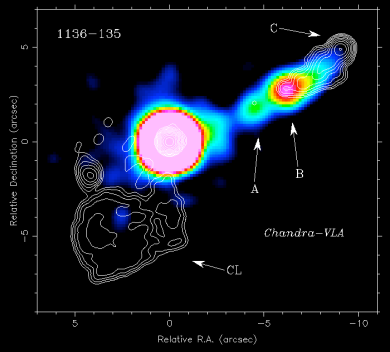
Published by the Chandra X-ray Center (CXC)

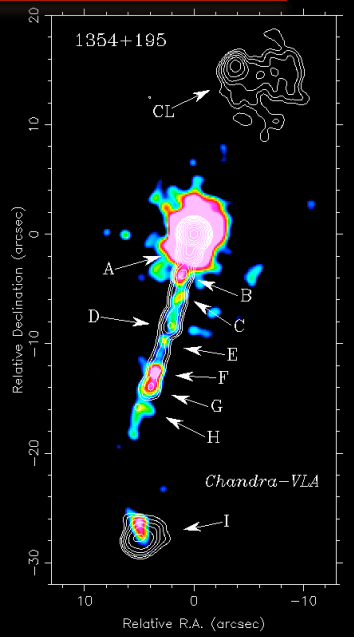
X-ray Jets

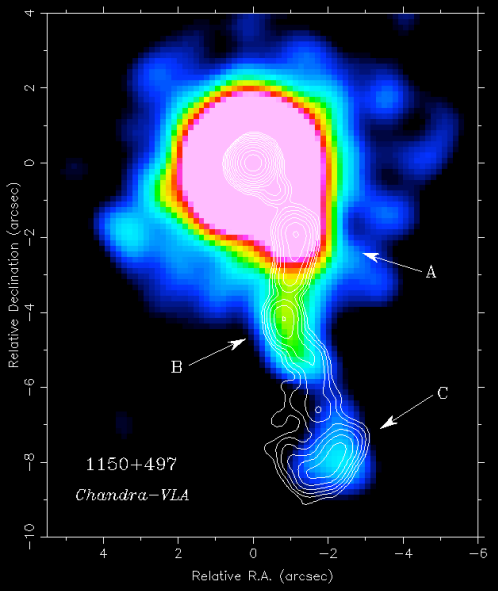
Aneta Siemiginowska

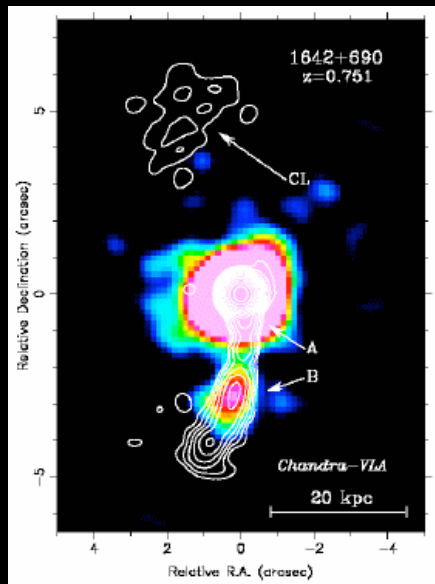
The Active Galaxy 4C+29.30

Credit: X-ray: NASA/CXC/SAO/A.Siemiginowska et al; Optical: NASA/STScI; Radio: NSF/NRAO/VLA







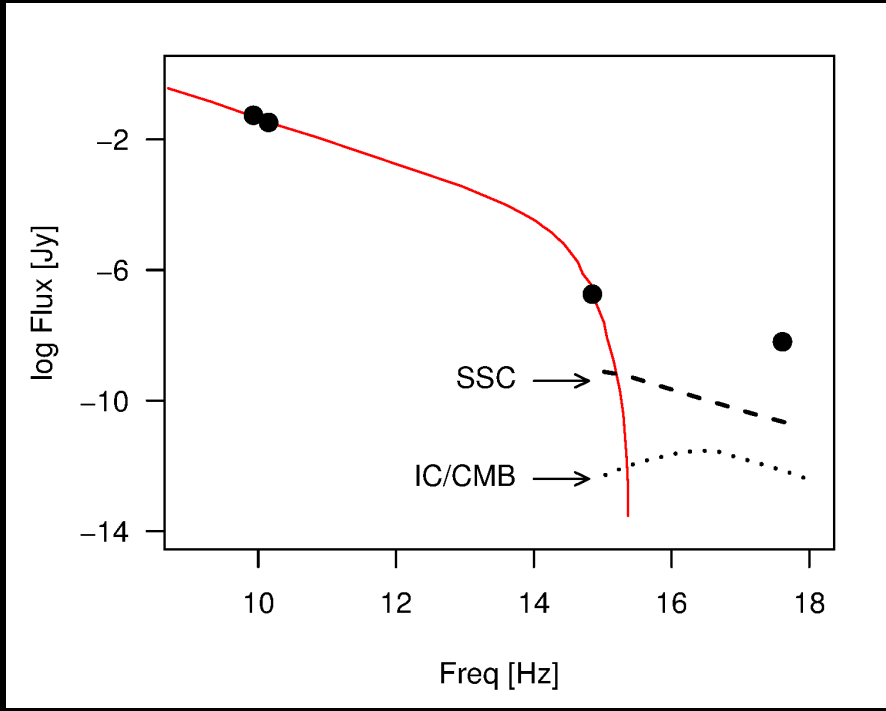


HOW ARE THE X-RAYS PRODUCED?

Inverse Compton scattering?

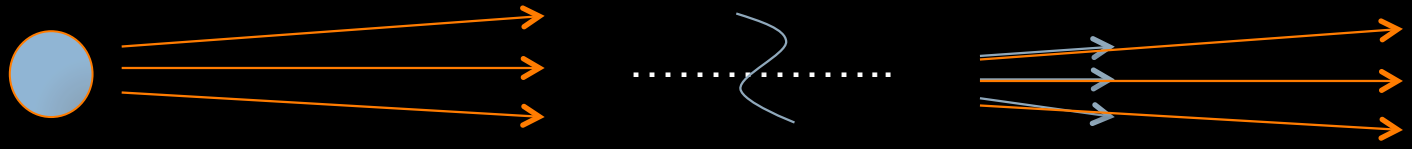
- Synchrotron Self-Compton
- "Inverse" Compton with the CMB photon field (aka "IC/CMB")

<u>both ruled out</u>



Chartas et al. 2000, Assuming equipartition and a non-relativistic large scale jet

JET SPEEDS



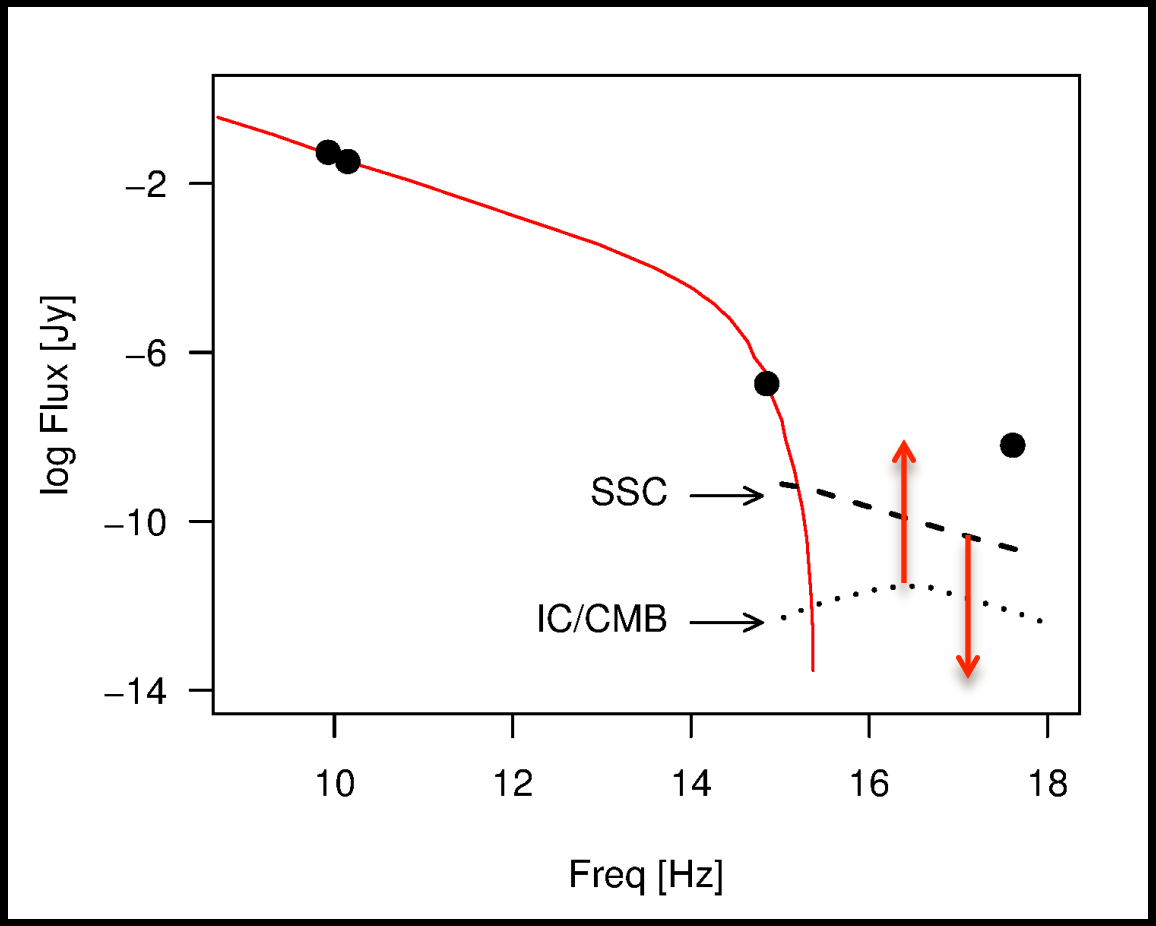
VLBI: quasar jets relativistic on sub-parsec scales with Γ=10-50

Statistical arguments: kpc scale jet mildly relativistic with Γ=1.2-1.5.

What if jets actually remain highly relativistic on kpc scales? *(Tavecchio et al 2000, Celotti et al. 2001)*

JET SPEEDS

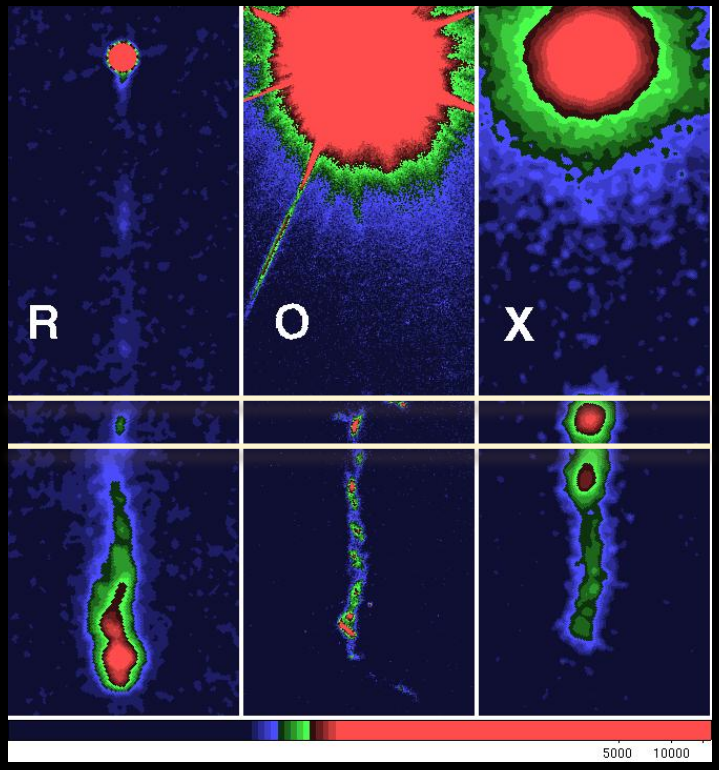
What if jets actually remain highly relativistic on kpc scales?
(Tavecchio et al 2000, Celotti et al. 2001)



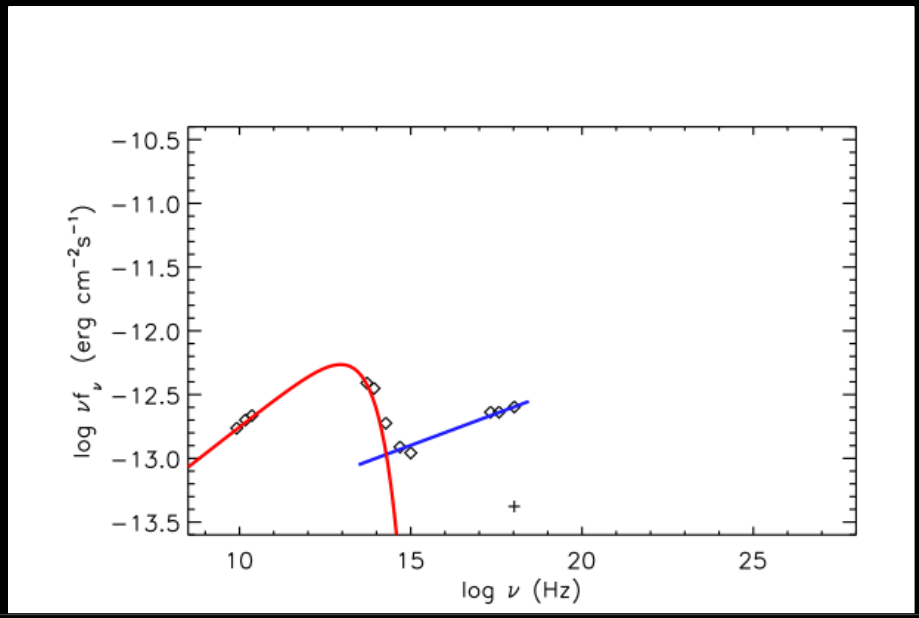
THE IC/CMB X-RAY INTERPRETATION

If the Kpc scale jet retains the pc-scale relativistic speeds, then the X-ray emission can be modeled as IC/CMB

(Tavecchio et al 2000, Celotti et al. 2001)



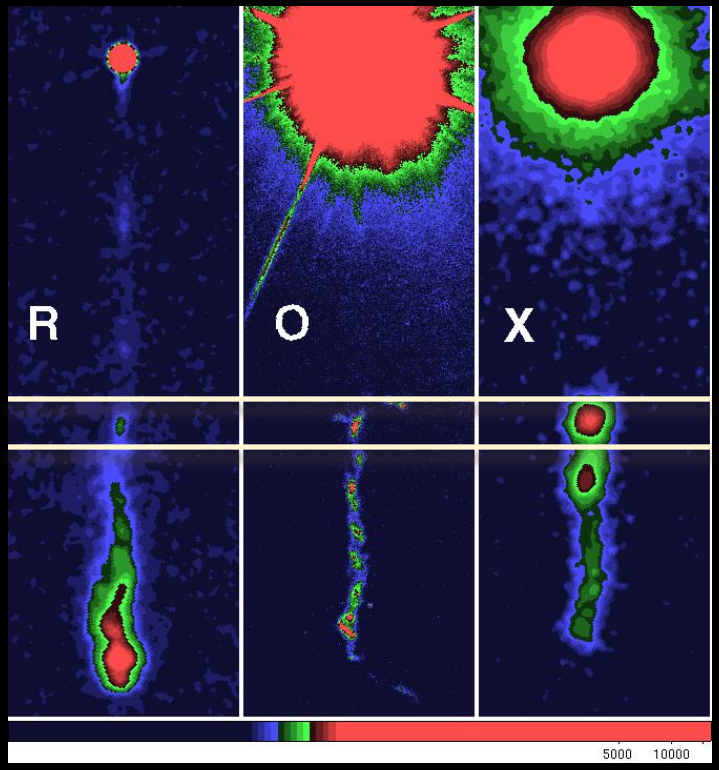
(3C 273 Marshall et al. 2005)

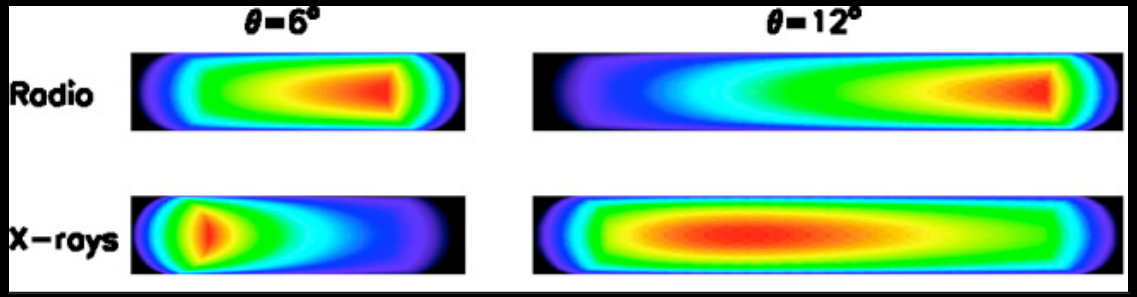


THE IC/CMB X-RAY INTERPRETATION

In agreement with the argument that powerful jets reach the terminal hotspots with relativistic speeds (Γ~2-3) *(Georganopoulos et al. 2003)*.

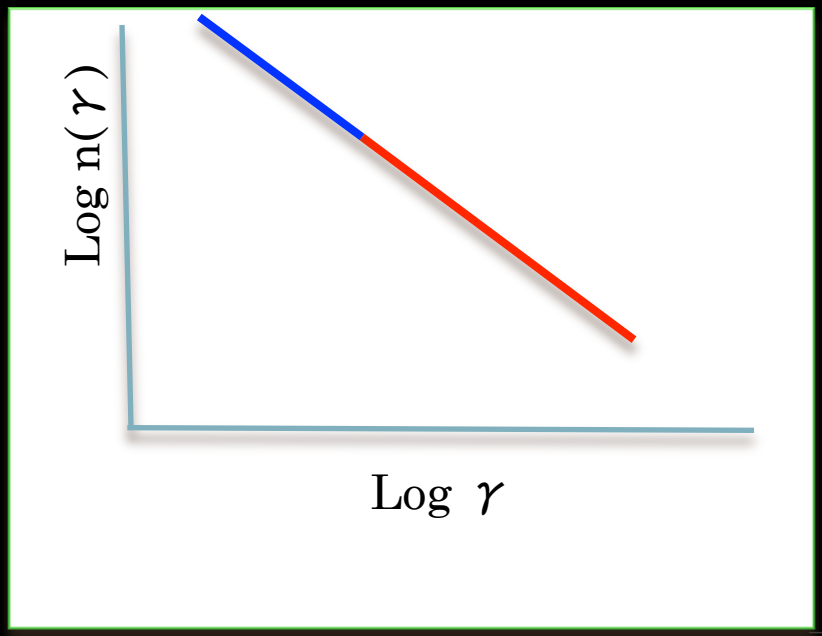
Can explain the gradual brightening (dimming) of the radio (X-ray) jet as resulting from a gradual deceleration of the flow *(Georganopoulos et al. 2004)*.

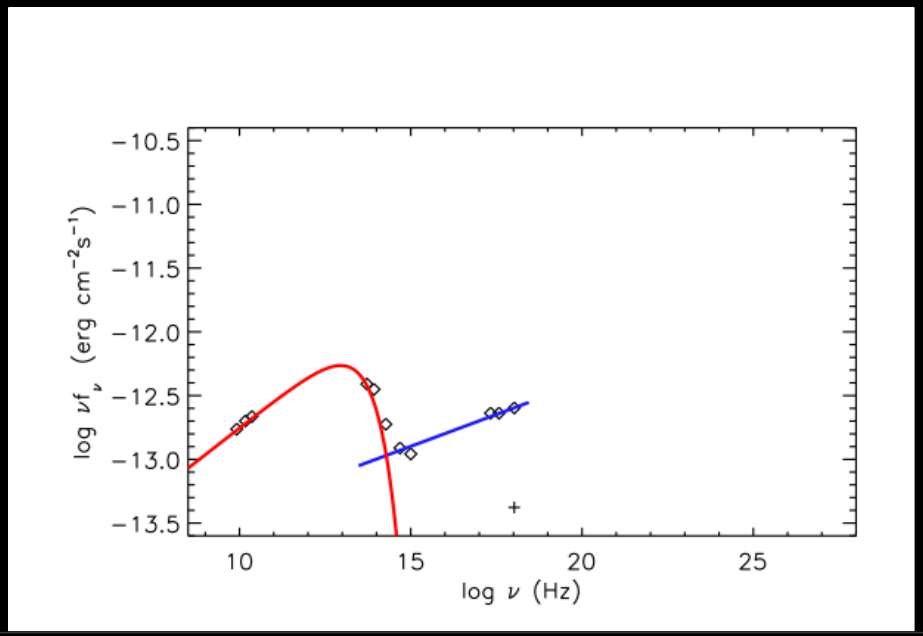




THE IC/CMB X-RAY INTERPRETATION.

- Extends the electron energy distribution down to γ ~1-100 from γ ~few 10^3 required by the radio.
- Requires relativistic large scale jets (Γ ~10-20)
- Requires powerful (sometimes super Eddington) jets *(Dermer & Atoyan 02, 04)*
- Requires propagating knots and not standing shocks, due to the long radiative cooling length of the γ ~ 100 electrons and the knotty X-ray jet morphology





GAMMA-RAY EMISSION PREDICTED BY THE IC/CMB MODEL

The γ-ray SED depends on a single parameter (B/δ) or δ in equipartition.

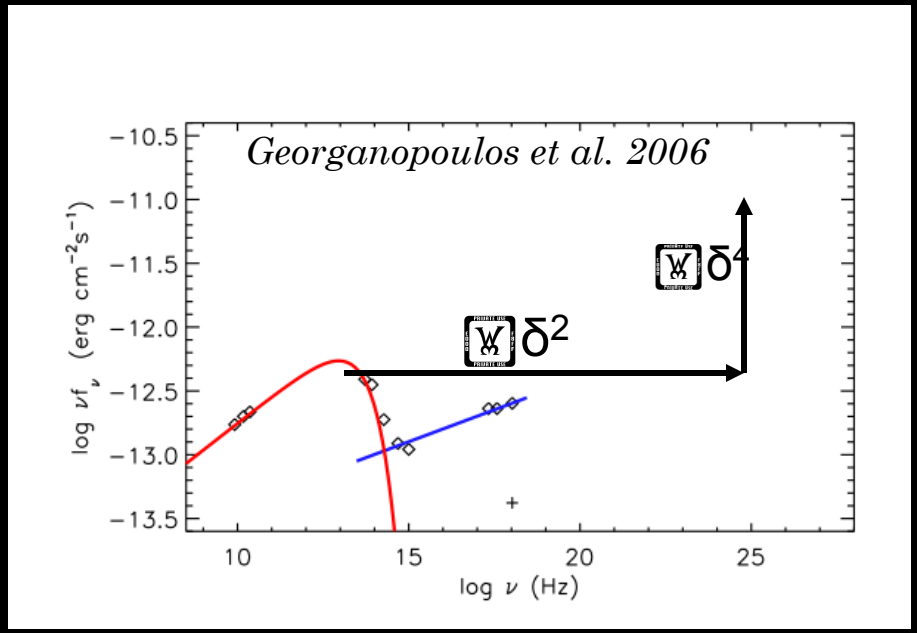
$$\frac{\nu_c}{\nu_s} = 6.6\times10^{4}(B/\delta)^{-1} = 6.6\times10^{8}\delta^{2}$$

B/δ (δ in equipartition) is fixed by the requirement to fit the radio-optical and X-ray observations.

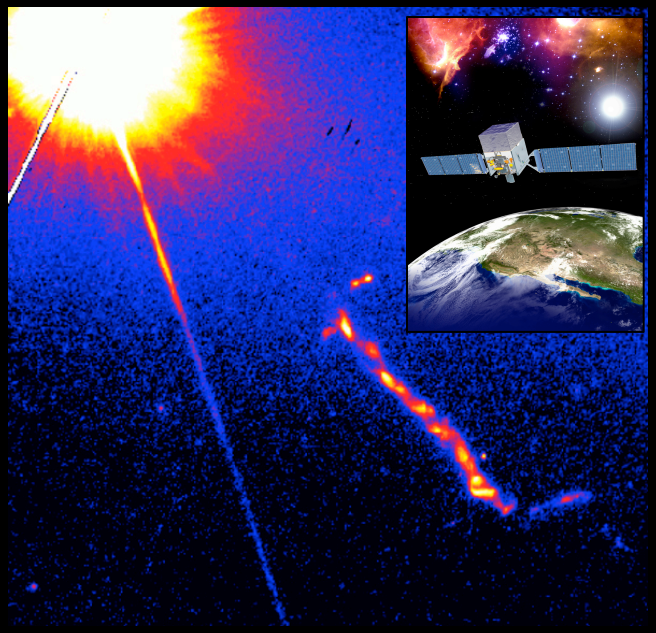
$$\frac{L_c}{L_s} = 2.5\times10^{-11}(B/\delta)^{-2} = 2.5\times10^{-3}\delta^{4}$$

The γ-ray SED is predicted with no freedom.

Test of the EC/CMB model:
The level of the *Fermi* emission



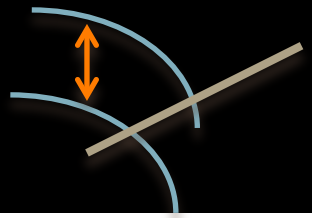
CASE 1: WAITING 3 YEARS FOR A 3C 273 FERMI LOW STATE



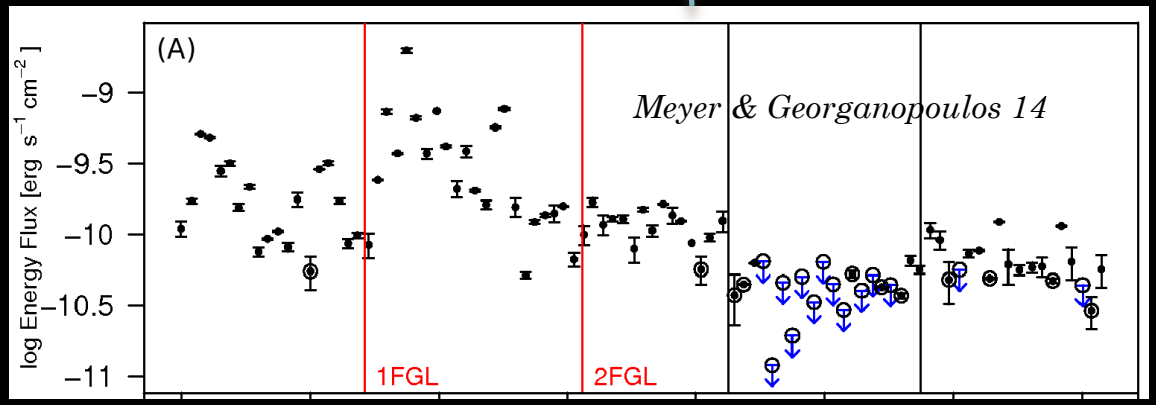
Resolution Issue: Fermi sees core and large scale jet as a point source

<u>However:</u>

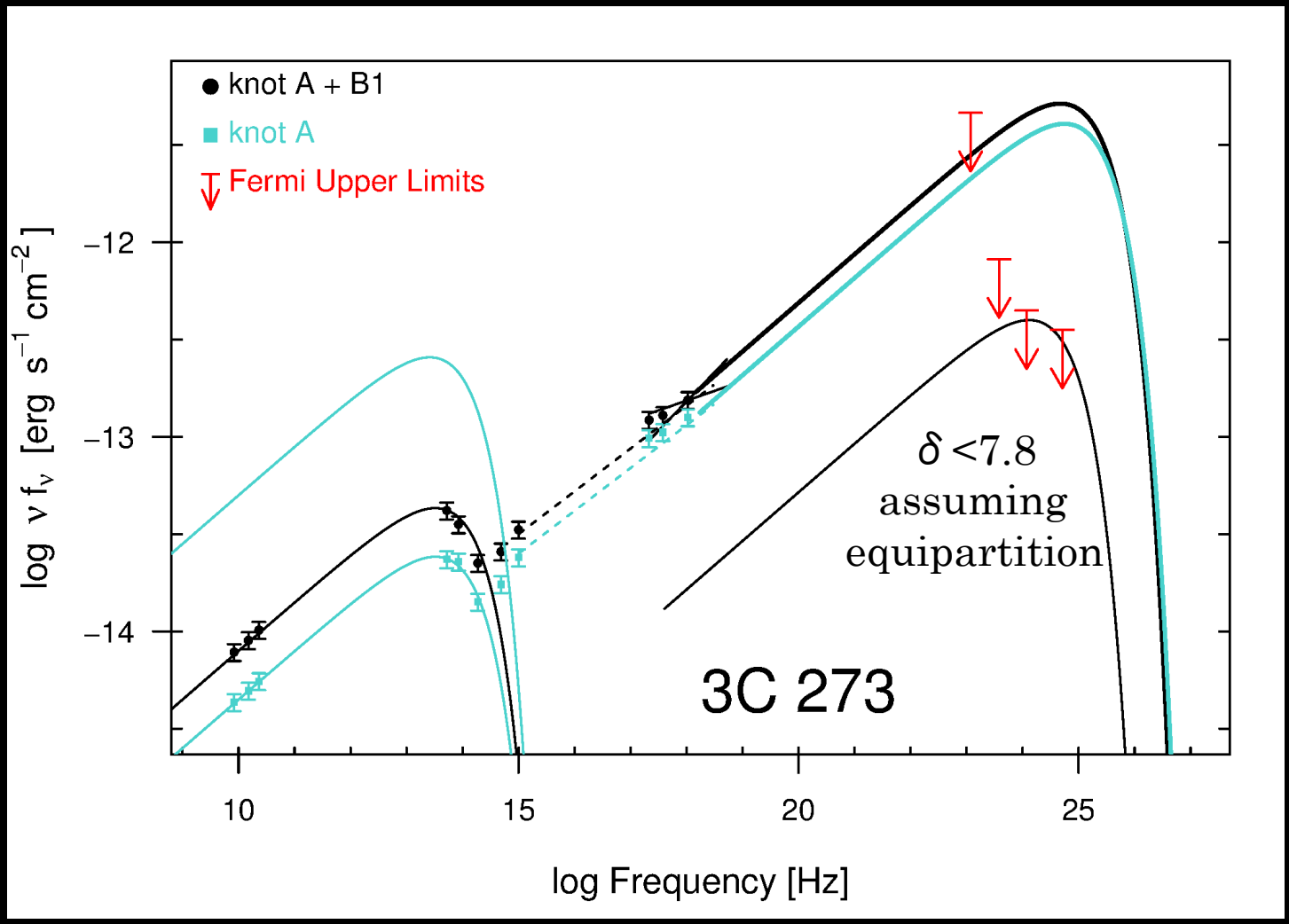
- IC/CMB emission should be **steady**.
- The core is known to be **variable**.



Stack the parts of the light curve when the blazar is low to get the lowest upper limit, which applies to both the core + the jet.

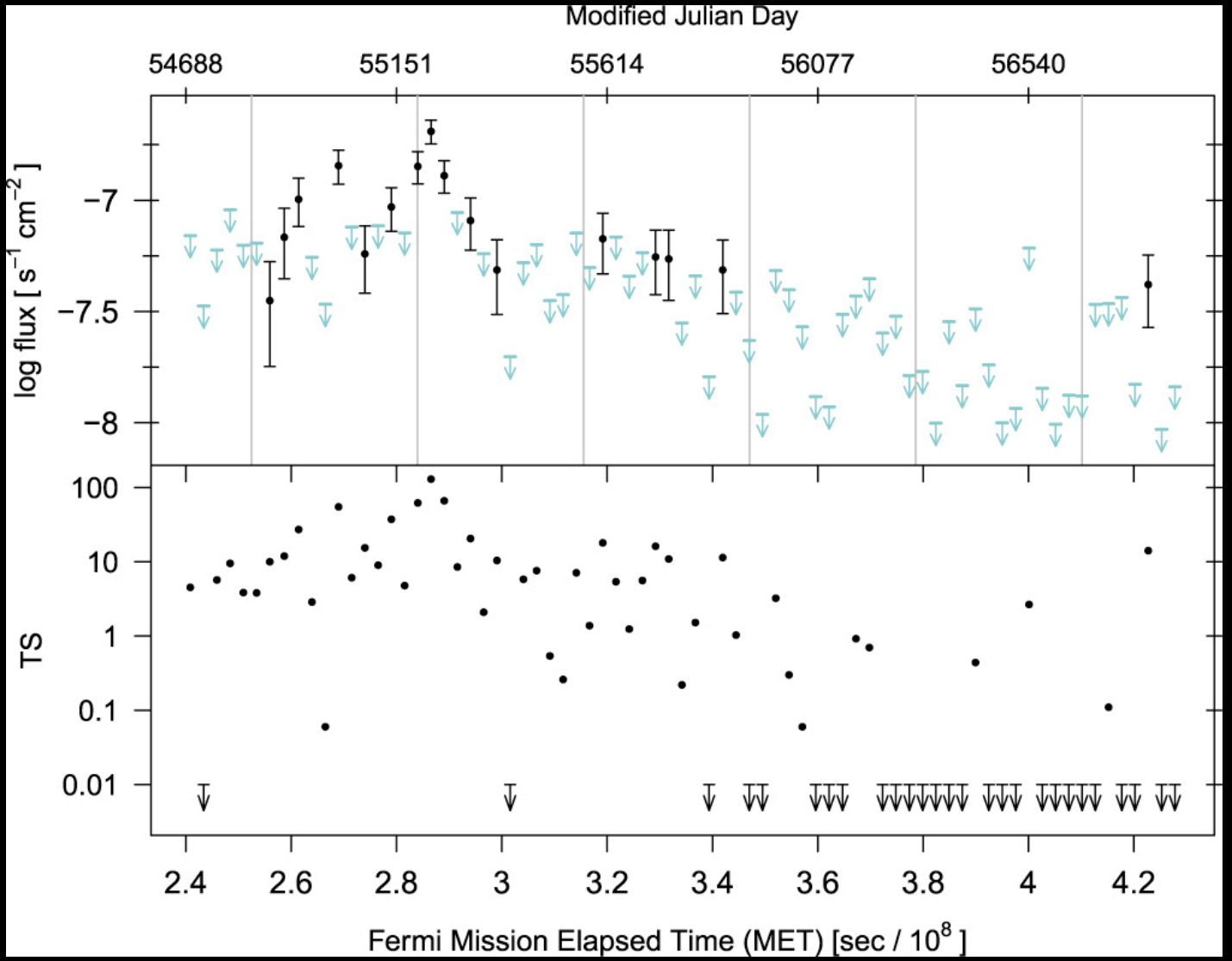


3C 273: IC/CMB IS RULED OUT

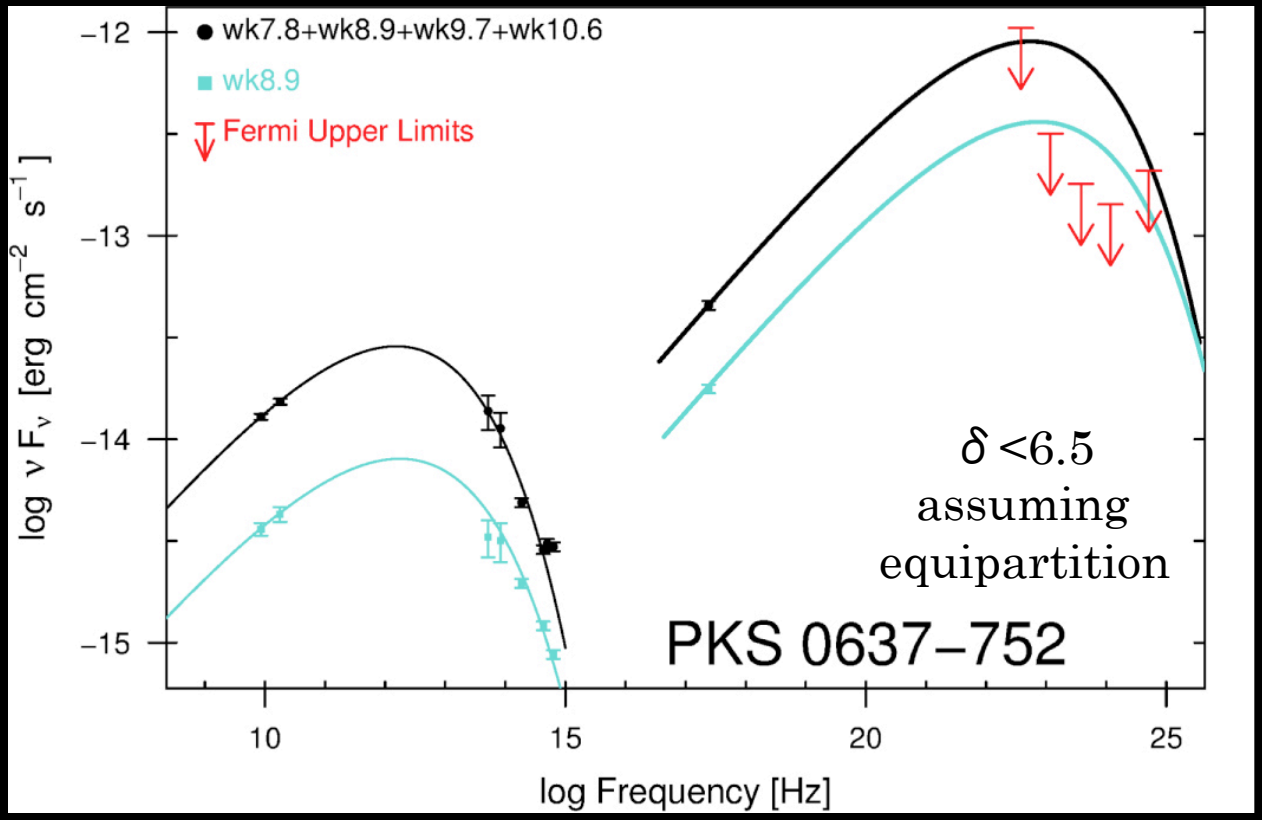


Meyer & Georganopoulos 2014

CASE 2: PKS 0637-752

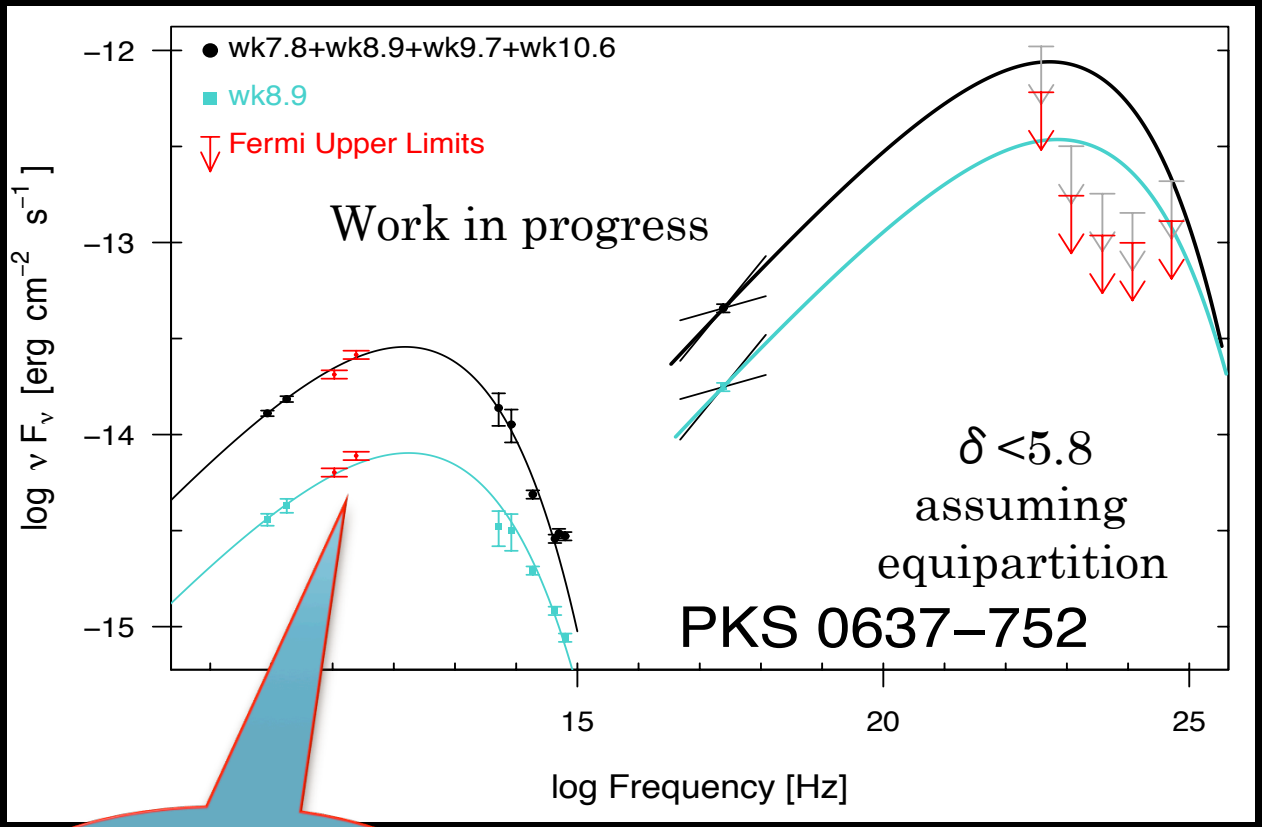


PKS 0637: IC/CMB IS RULED OUT



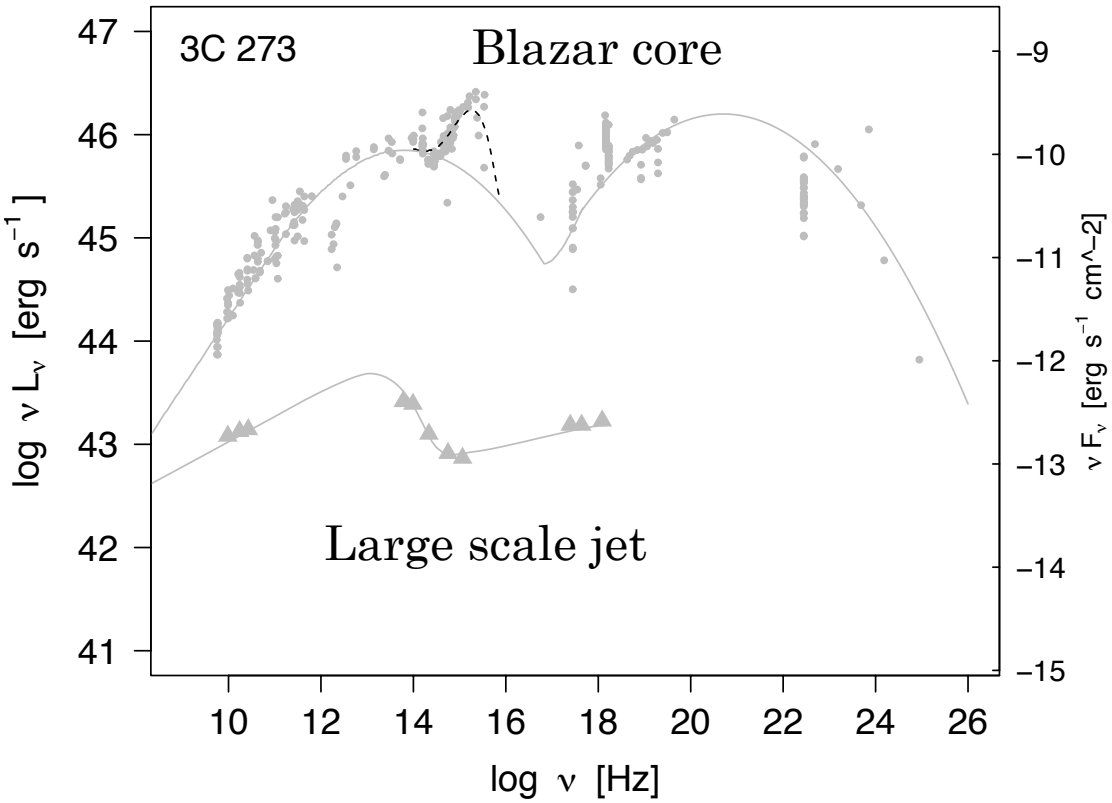
Meyer et al. 2015

PKS 0637: ADDING THE LATEST LOW STATE



ALMA
observations
PI E. Meyer

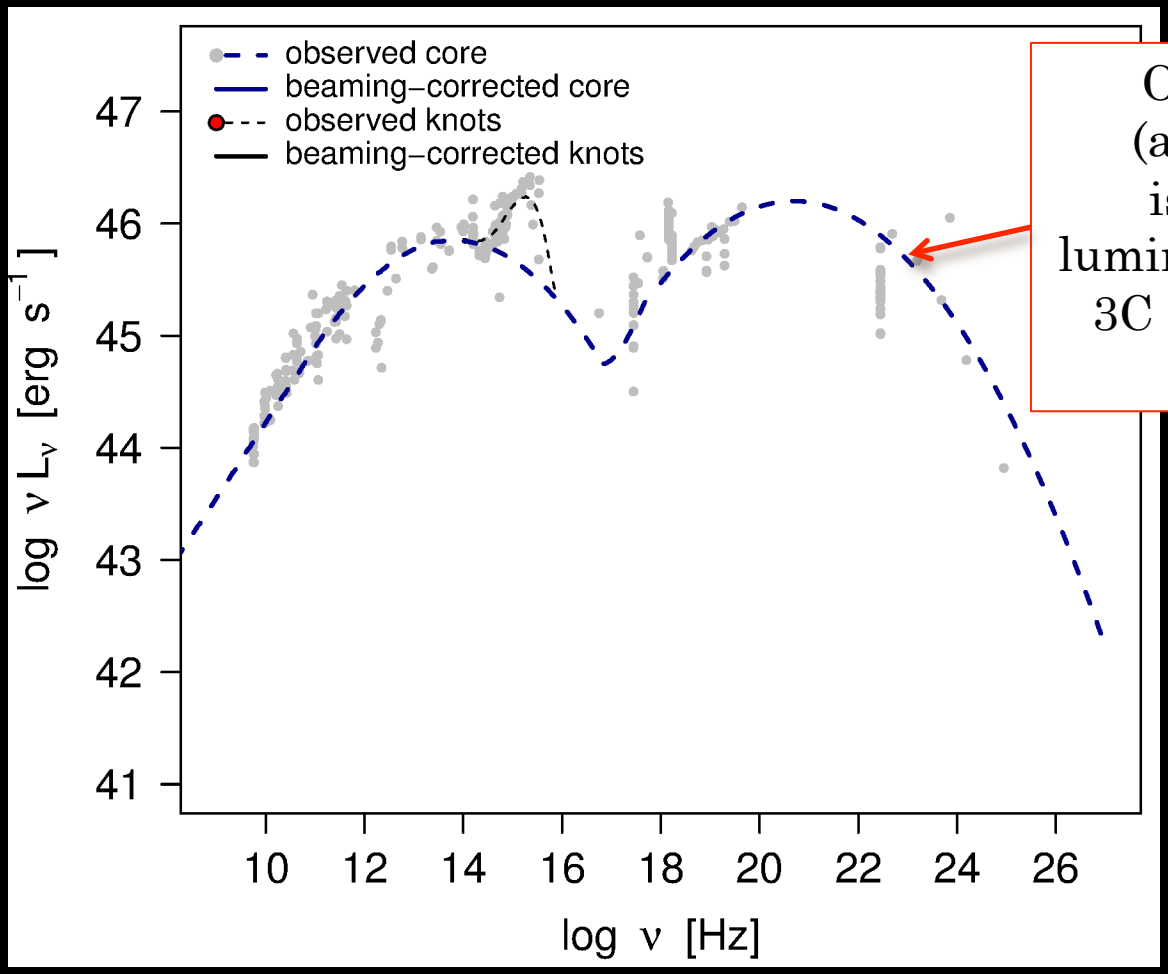
A SIMPLE THING THAT WENT UNNOTICED



The blazar appears much brighter than the jet in all energies.

But does it dominate the radiative output?

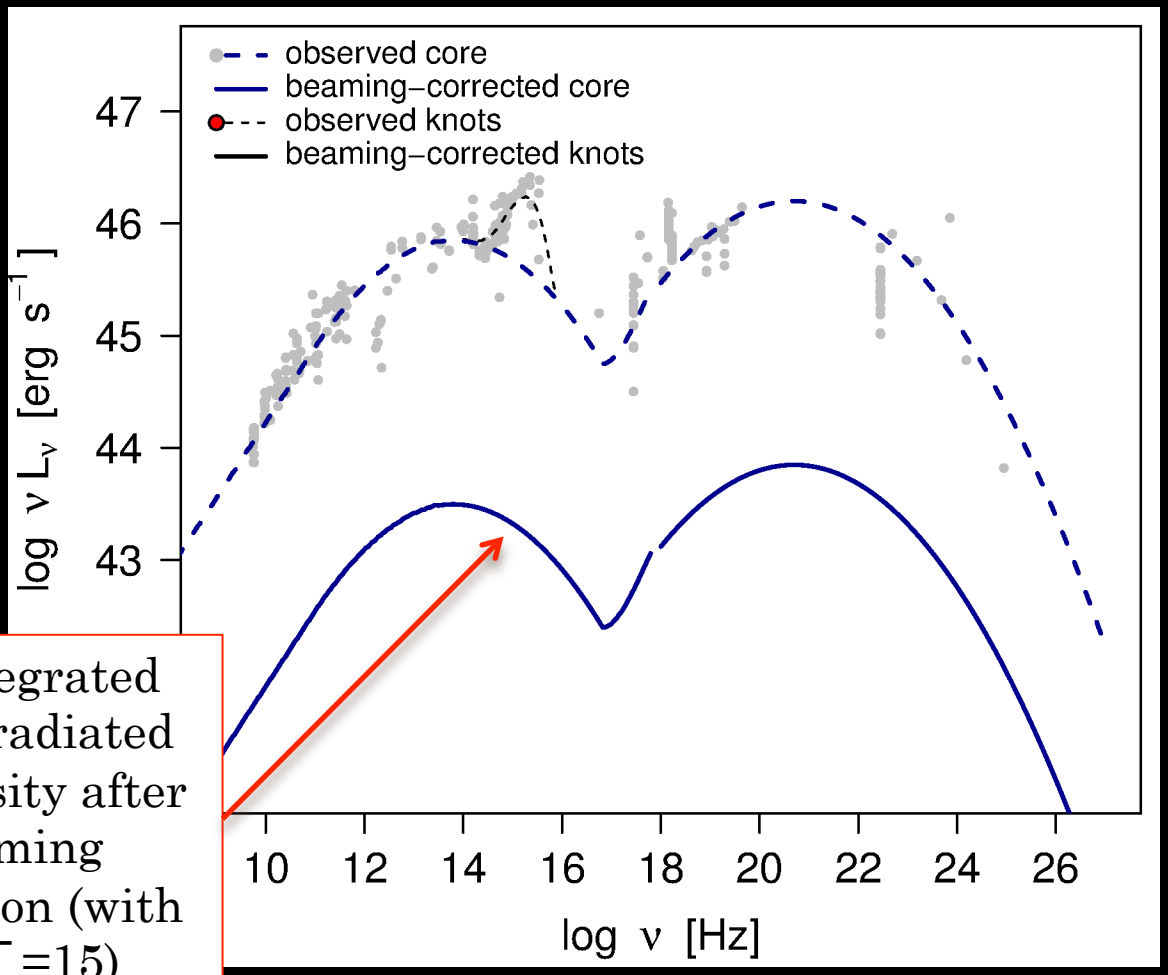
THE RADIATIVE OUTPUT OF THE JETS



Observed (assuming isotropy) luminosity of the 3C 273 blazar (core)

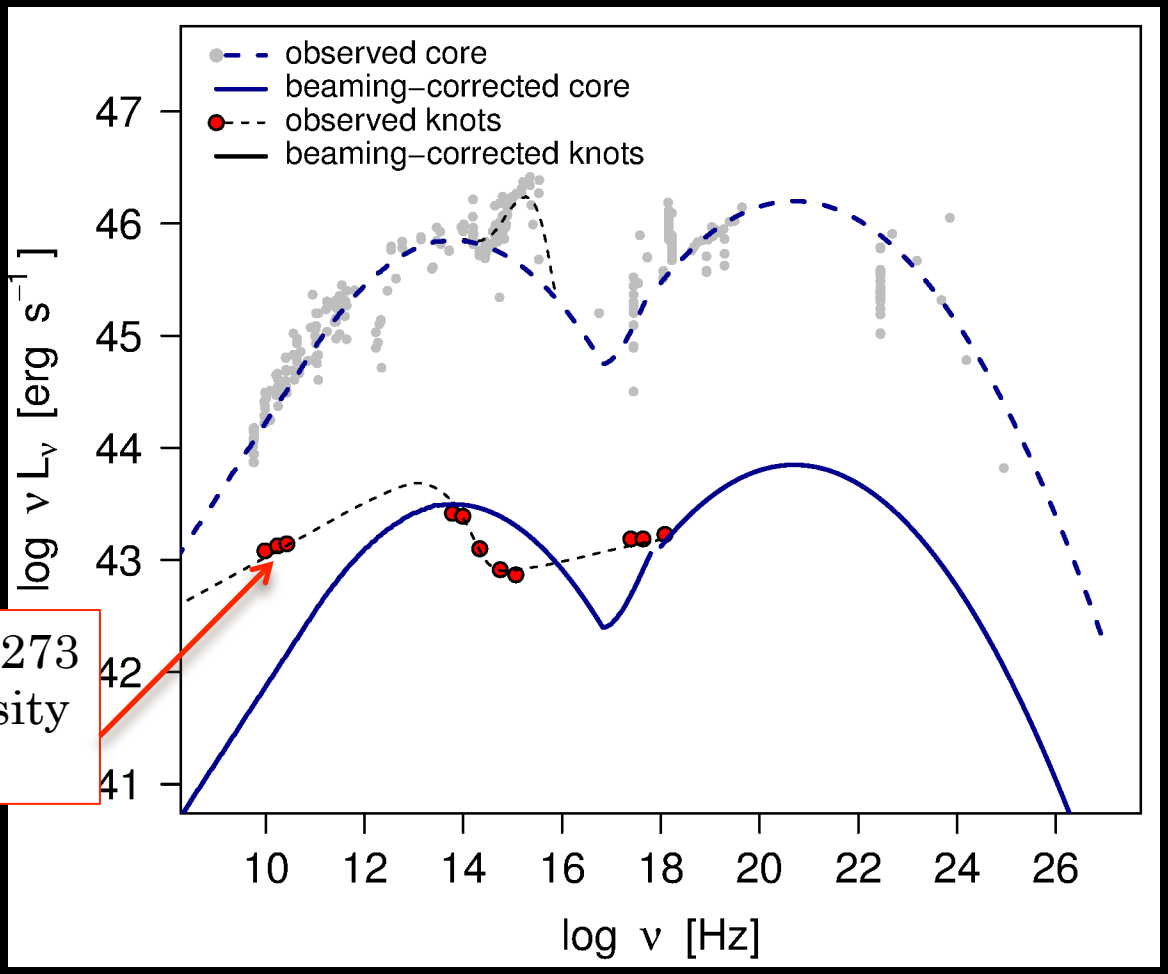
THE RADIATIVE OUTPUT OF THE JETS

$L \sim L_{iso} / \Gamma^2$



4π-integrated "true" radiated luminosity after beaming correction (with $\delta = \Gamma = 15$)

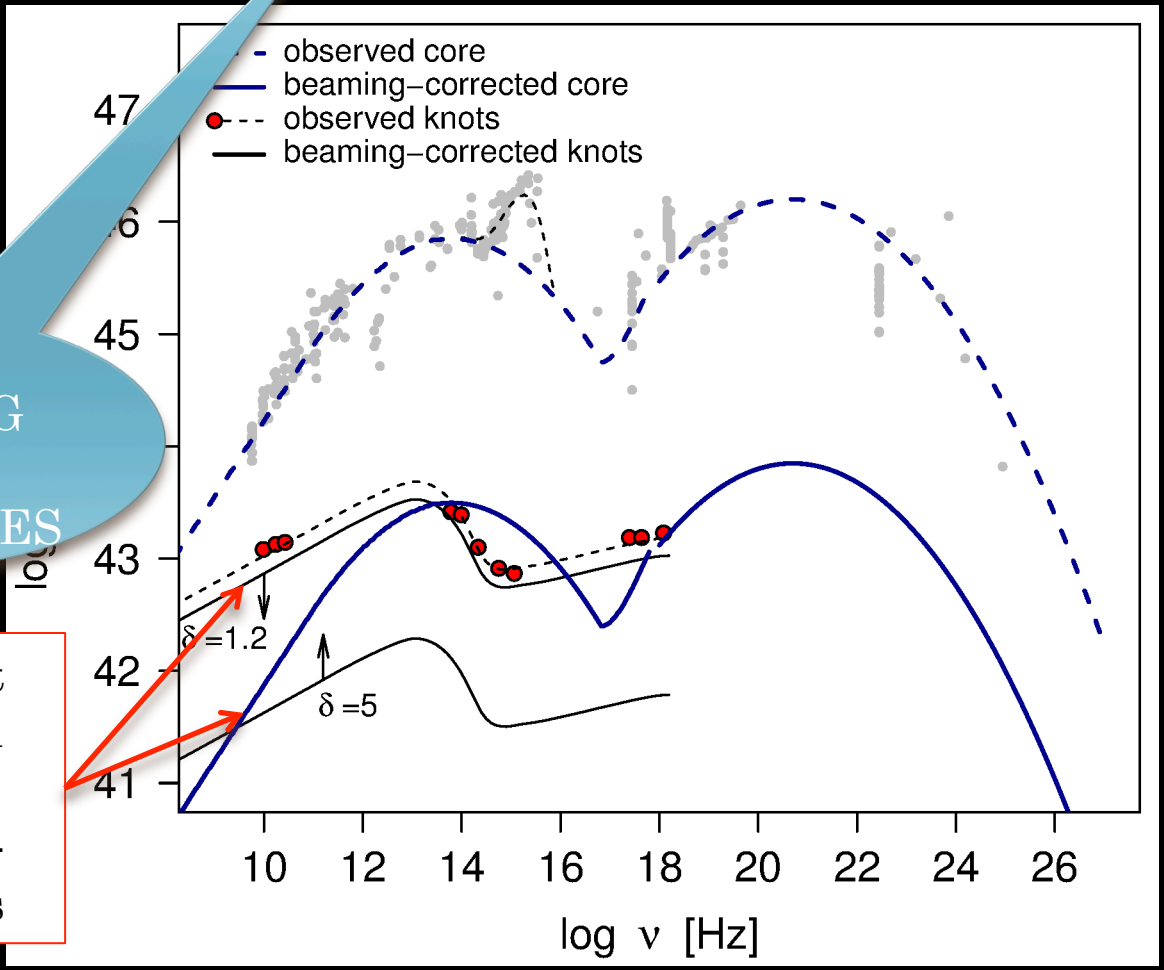
THE RADIATIVE OUTPUT OF THE JETS



"observed" 3C273 knot Luminosity (total)

RADIATIVE OUTPUT OF BLAZAR AND LARGE SCALE JET: COMPARABLE

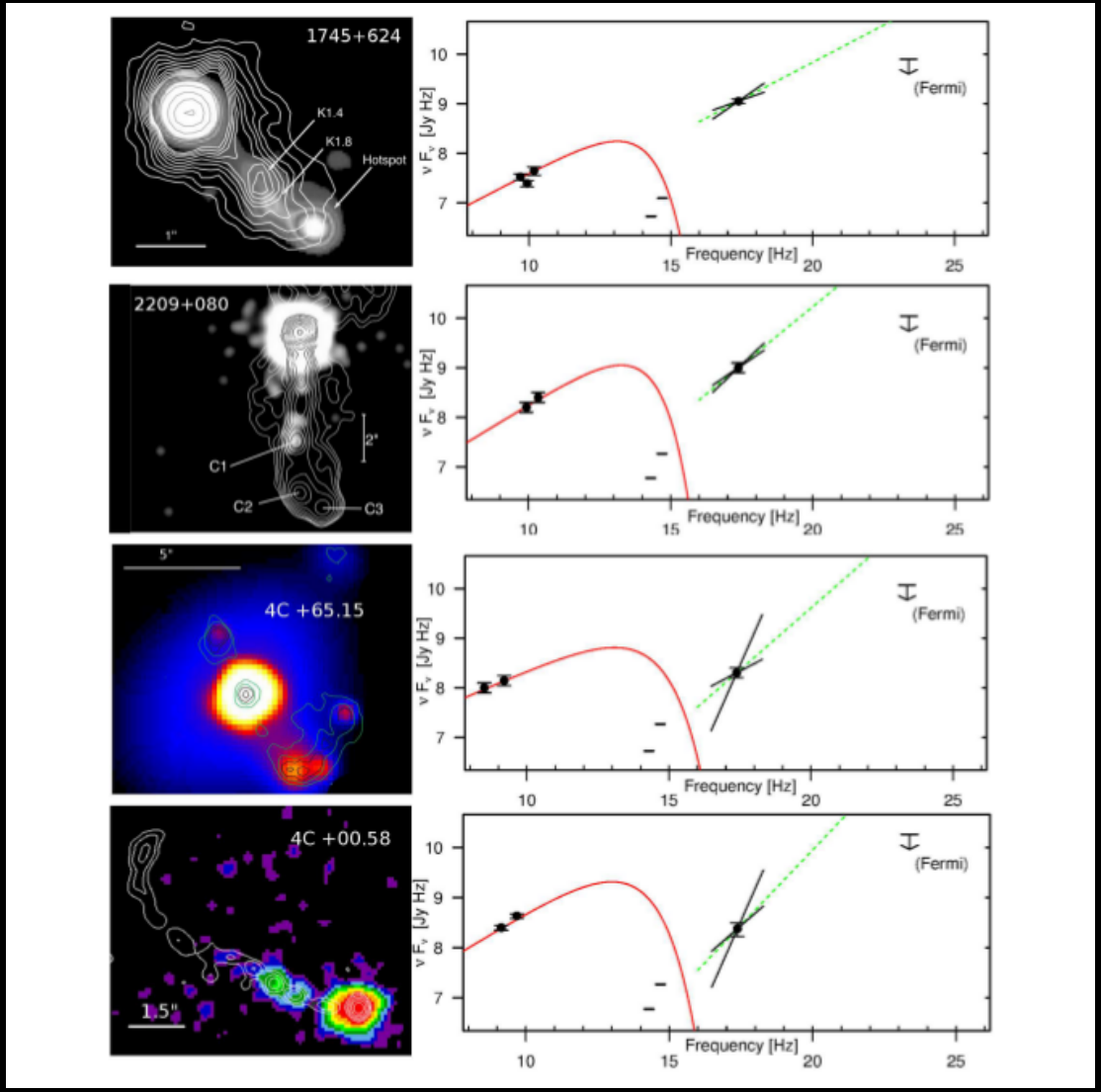
START THINKING ALONG THESE LINES



Range of knot 4π-integrated luminosity within Fermi-derived limits

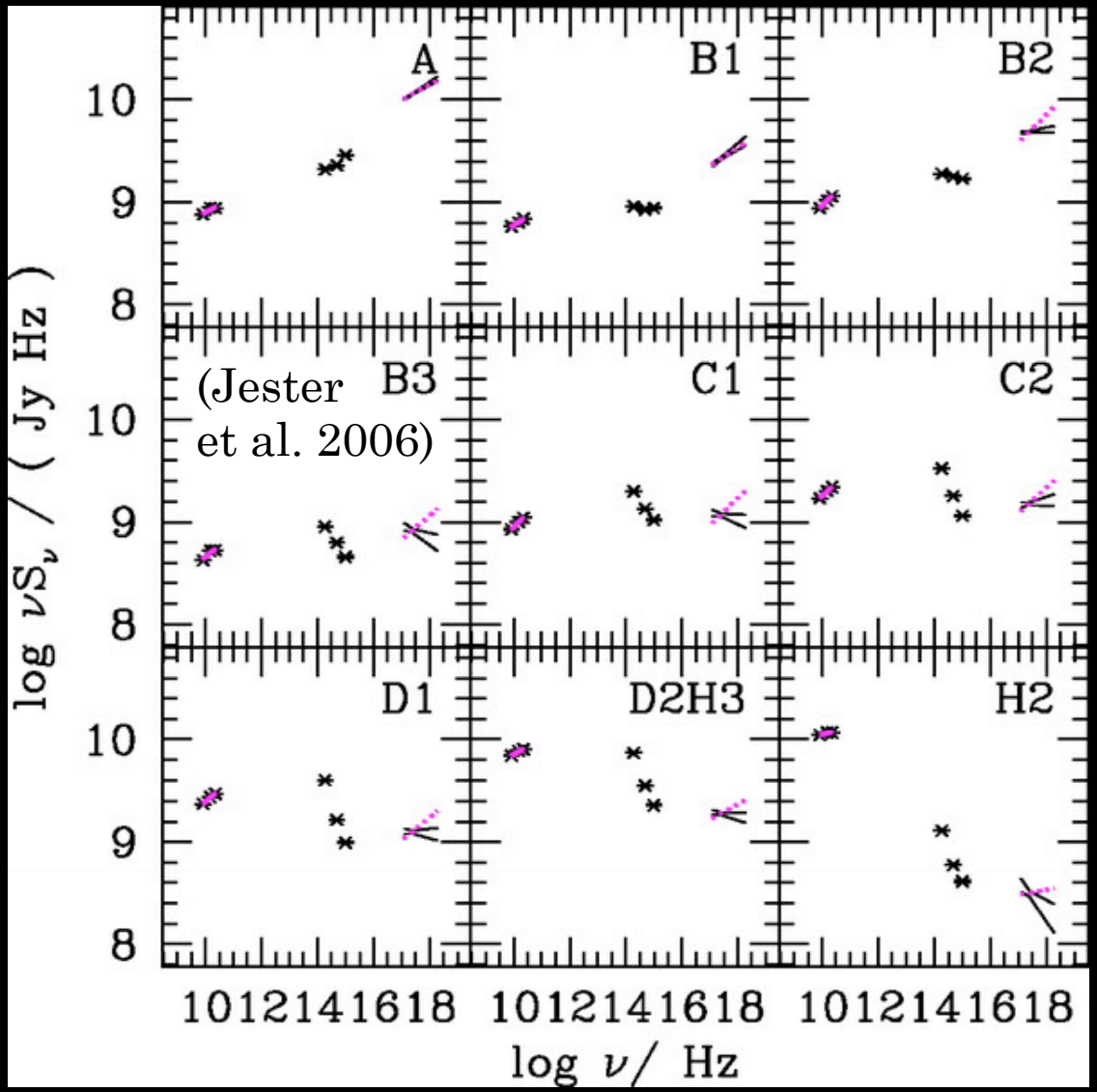
EXTENDING THE FERMI TEST

Current work (Peter Breiding PhD thesis): the Fermi test on more jets with new VLA, ALMA, Chandra, and HST observations

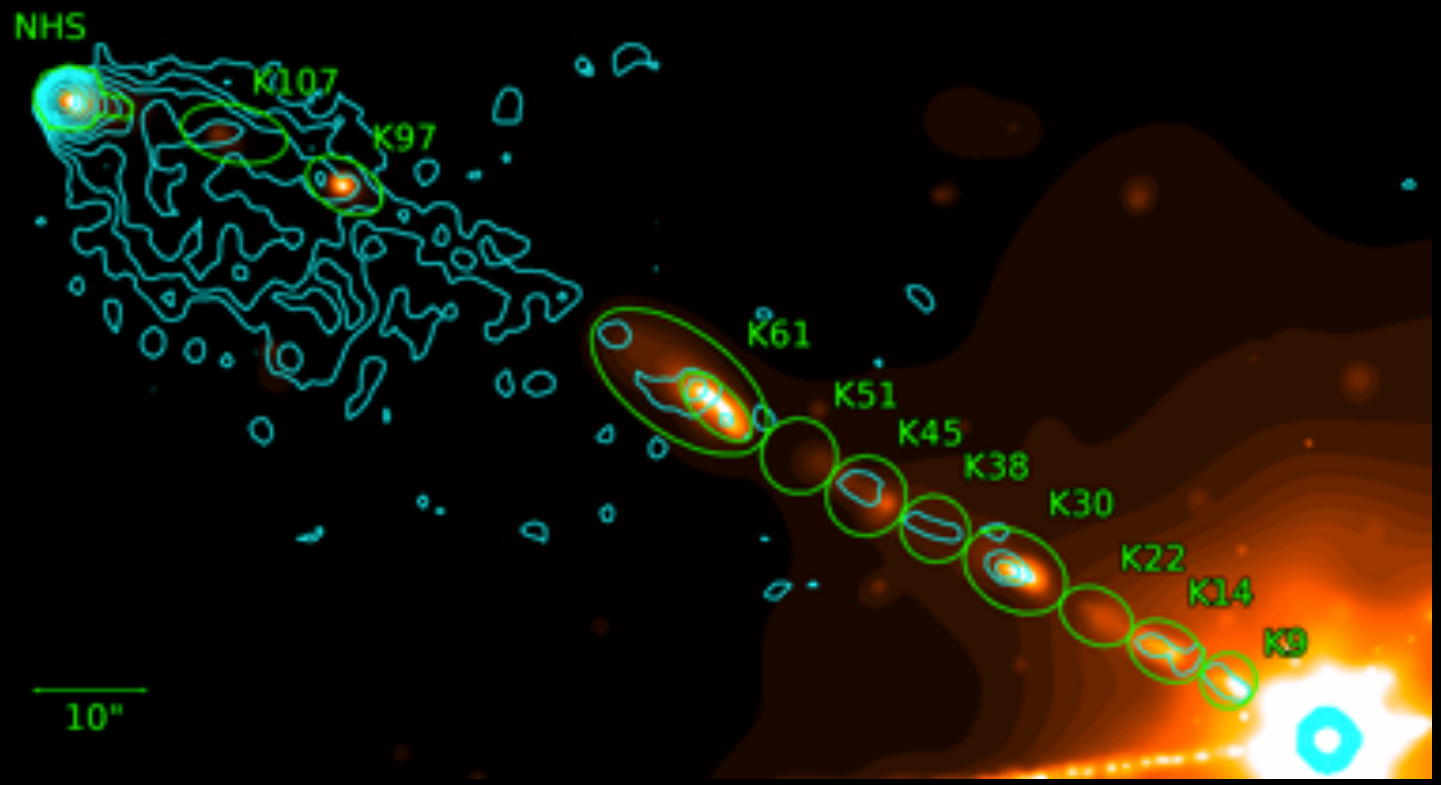


IN RETROSPECT: AN EARLY PROBLEM WITH EC/CMB

3C 273: The X-ray spectral index is softer than the radio in all knots except A and B1 (Jester et al. 2006).



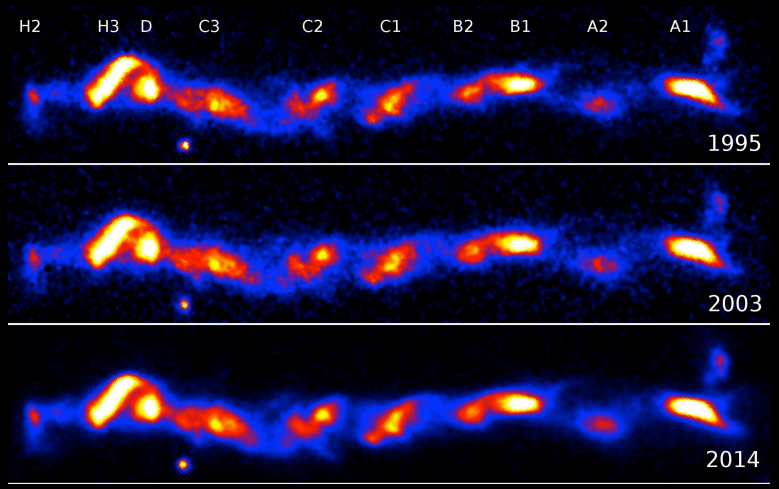
ADDITIONAL CONSTRAINTS FOR EC/CMB OR ANY OTHER INTERPRETATION: X-RAYS DISPLACED UPSTREAM OF THE RADIO

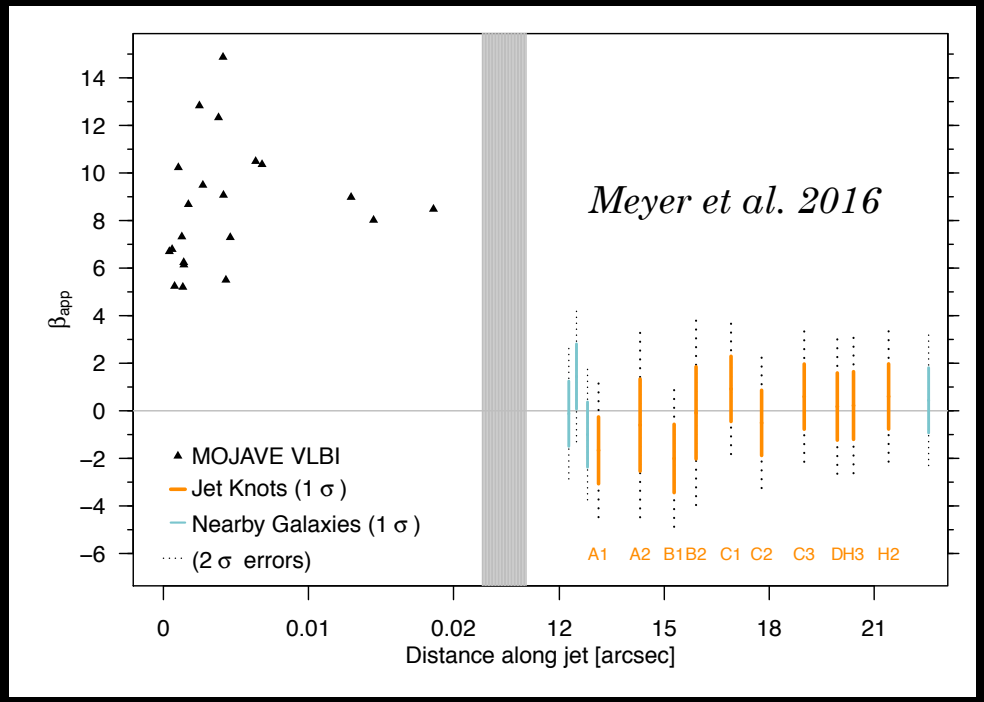


3C 111: X-ray knots peak upstream the radio knots (Clautice et al. 2016).

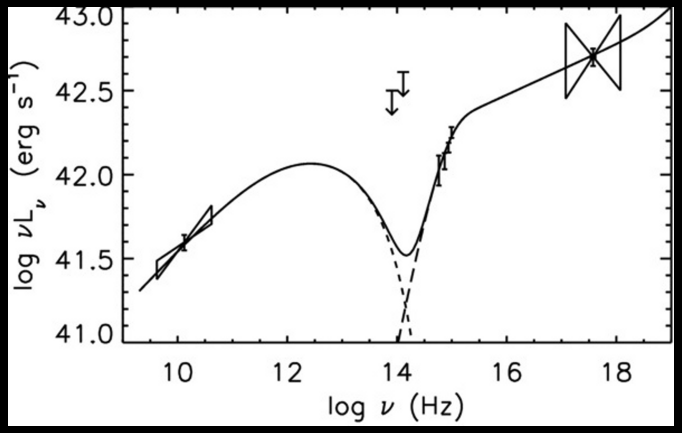
HST ASTROMETRIC CONSTRAINTS ON THE IC/CMB X-RAY INTERPRETATION.

3C 273 HST kpc-scale astrometric proper motion studies:
knot advance speed compatible with zero, upper limit $\Gamma < 2.9$
This is slow for explaining the X-rays with IC/CMB.

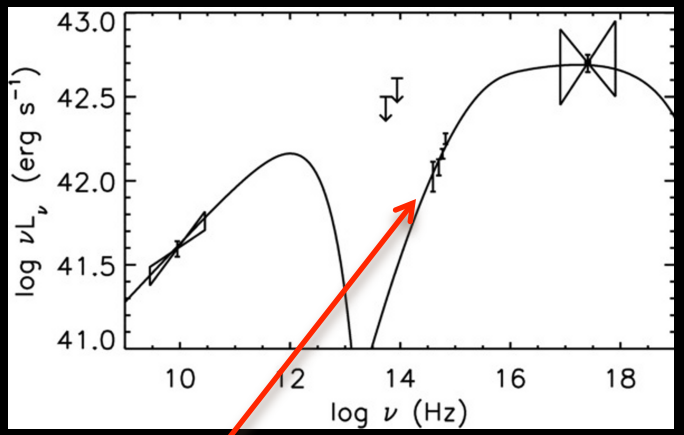




X-RAYS: SYNCHROTRON FROM A SECOND POPULATION OF ENERGETIC ELECTRONS?



PKS 1136-135, IC/CMB Model

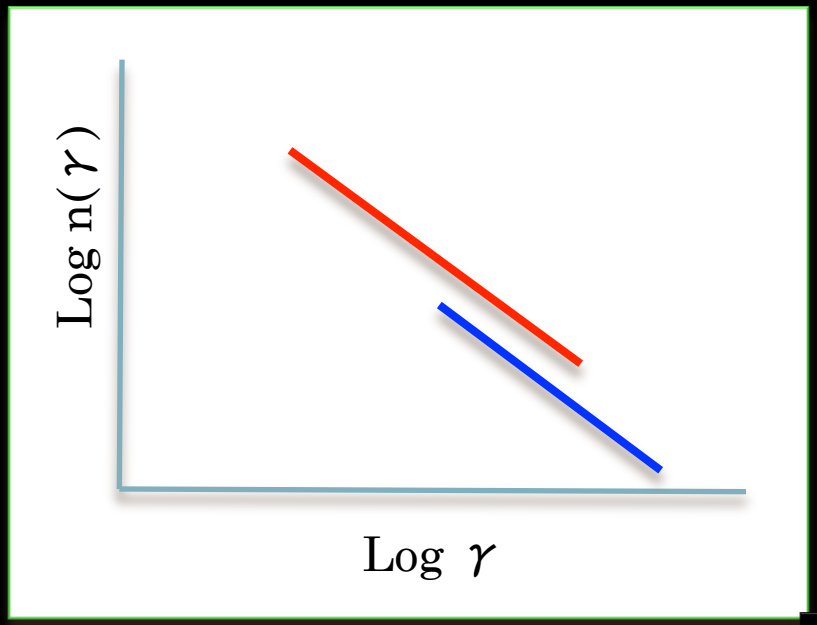


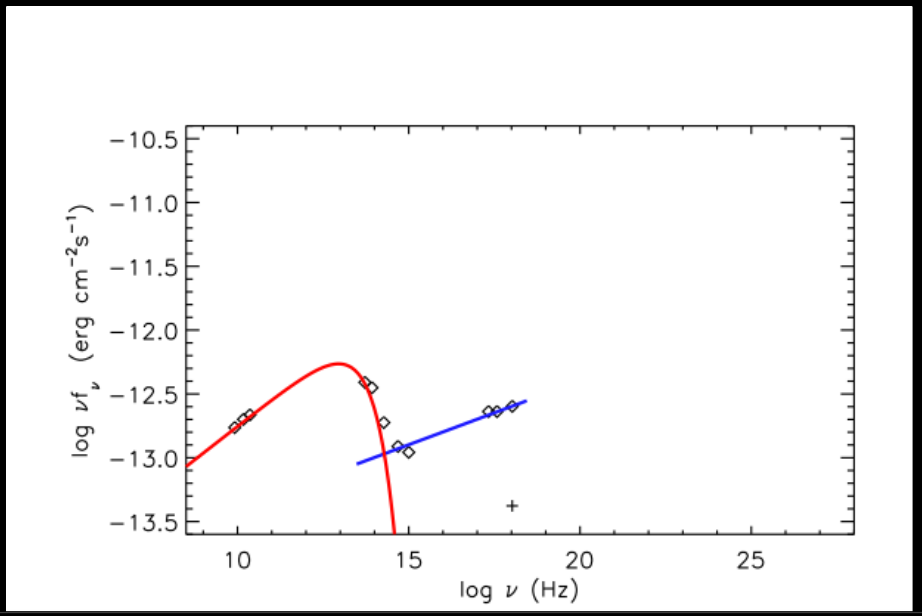
PKS 1136-135, synchrotron Model

Cara+ 2013:
Synchrotron because of the high UV polarization

WHAT CAN THE X-RAY EMISSION MECHANISM BE?

- Leptonic synchrotron (*e.g. Harris et al. 2004, Hardcastle 2006*)
- In situ electron acceleration at least up to 100 TeV energies
  - What explains the displacements?
- No need for highly relativistic large scale jet, easily sub-Eddington
- What physical situation produces this double power law?

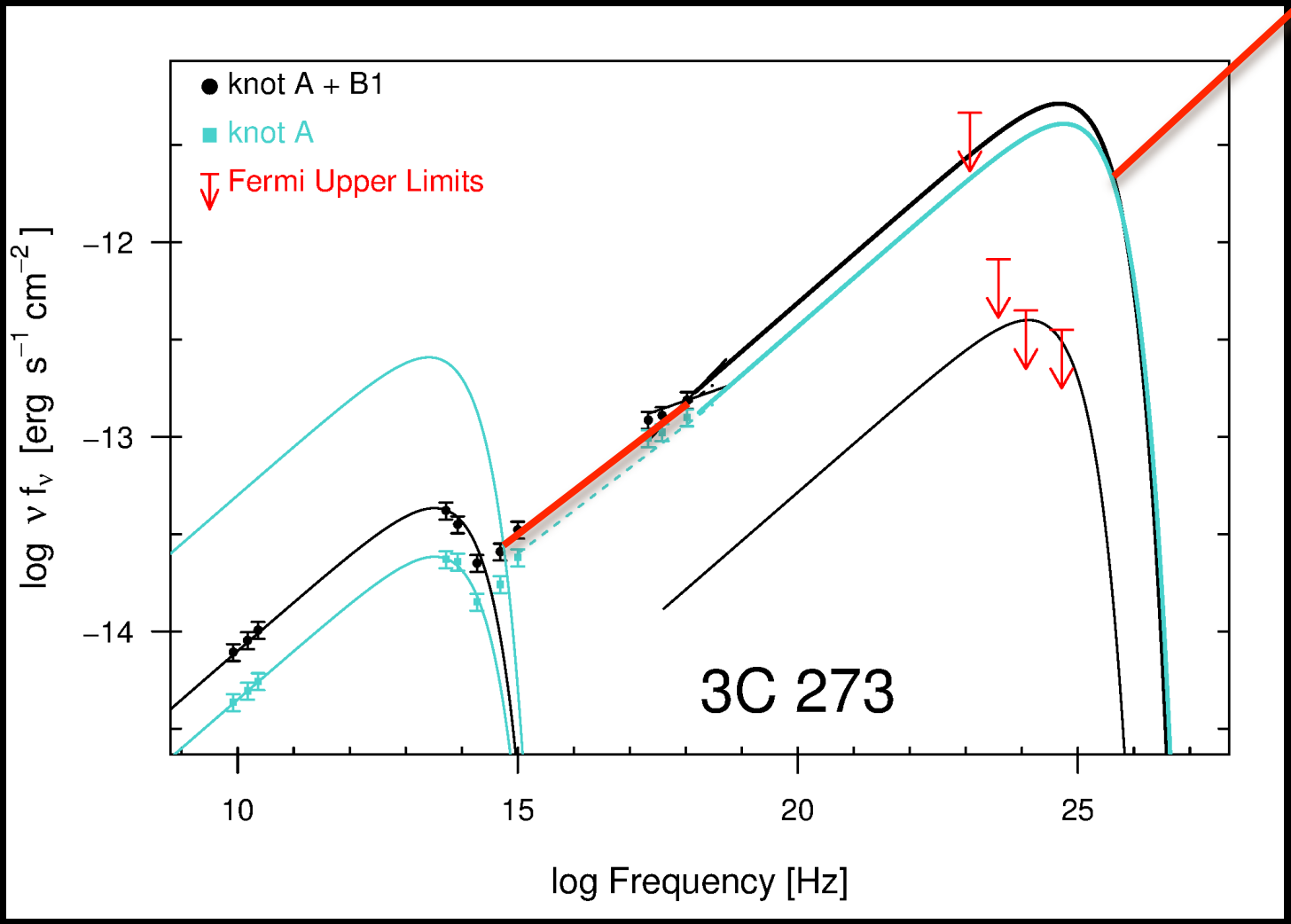




WHAT CAN THE X-RAY EMISSION MECHANISM BE?

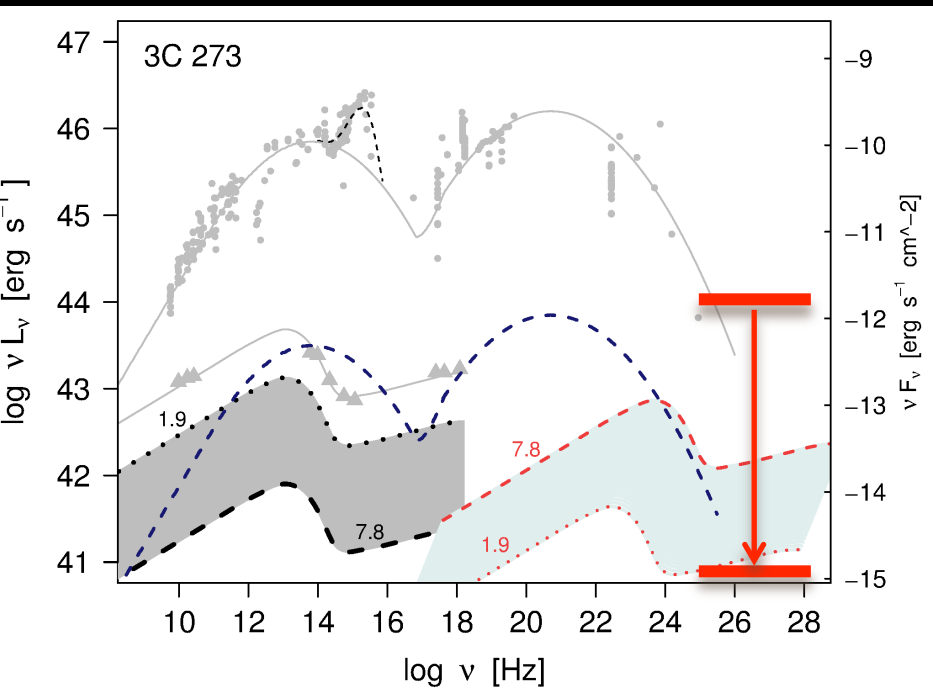
- Proton synchrotron (*Aharonian 2002*)
- Protons need to be accelerated to ~10^{18} eV
- Transport time from the core to the knots ~ radiative loss time: no need for in situ acceleration. But how is the knot structure explained?
- Larger magnetic field (B~0.001 G) and power (~Eddington) requirements
- But what explains the displacements?
- And how can we discriminate observationally?

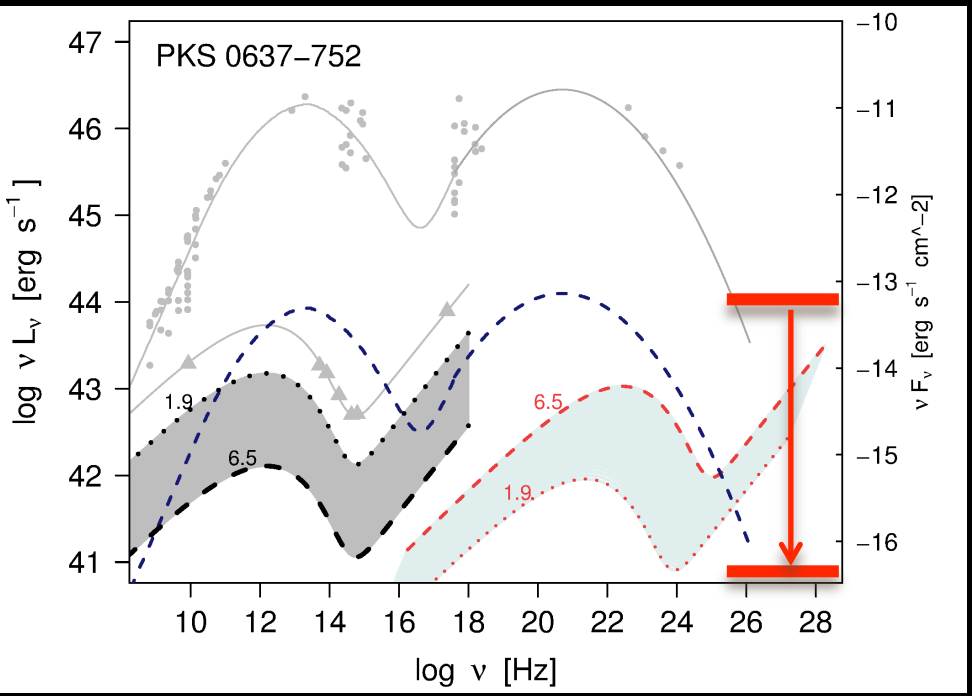
A TEV DISCRIMINANT BETWEEN LEPTONIC AND HADRONIC MODELS?



4π TEV OUTPUT OF A LARGE SCALE JET: LARGER THAN THAT OF A TEV BLAZAR!

Both 3C 273 and PKS 0637-752 have predicted IC/CMB TeV 4π power higher than the 4π-integrated output of a 'typical' TeV Blazar.





CONCLUSIONS

3 OUT OF 3 sources:
IC/CMB does not work.

NOT SO FAST:
Our sources are not highly relativistic, $\Gamma <$ ~few

A LOSSY PIPELINE:
The 4π-integrated luminosity of large scale jets
may be comparable to that of their blazar core.

MORE ROYAL THAN THE KING:
If the X-rays are leptonic synchrotron, the 4π-integrated TeV luminosity of large scale jets is higher than that of TeV blazars

LEPTONIC OR HADRONIC?
TeV observations with CTA could distinguish between the two.

EL

FIN