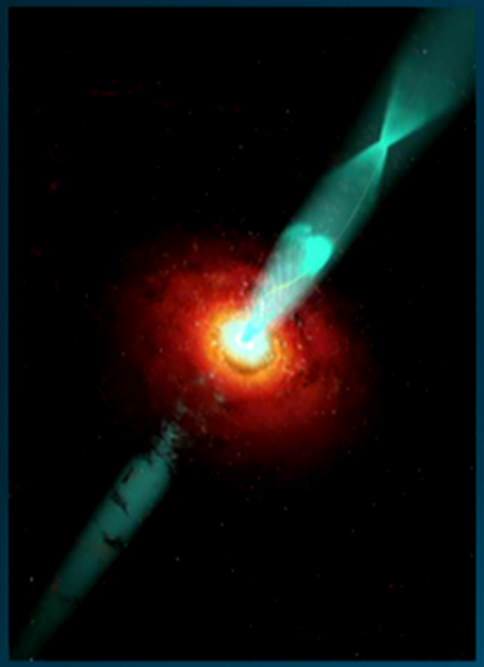
Title: Implications of TeV emission of quasars

Date: Mar 15, 2016 11:00 AM

URL: http://pirsa.org/16030099

Abstract:



Implications of TeV Emission from Quasars

Eileen Meyer
Assistant Professor
University of Maryland, Baltimore County

"Feedback over 44 orders of magnitude: from Gamma-rays to the Universe" Perimeter Institute 14-16 March 2016

University of Maryland, Baltimore County (UMBC)

Suburban Campus just outside Baltimore, ~40 minutes from Washington, DC
~12,000 undergraduates, 3000 graduate students, liberal arts education, STEM-focus, R1 Institution

You may know us for the Meyerhoff Scholarship Program (extremely successful at taking minority students through STEM degrees and on to academic careers)

Physics & Astronomy Department, 25 faculty in Quantum Optics, Condensed Matter, Atmospheric Physics & 5 Astronomers (mainly high-energy, AGN)

Collaborators

Markos Georganopoulos, UMBC
Bill Sparks, STScI
Eric Perlman, FIT
Aneta Siemiginowska, CfA
Leith Godfrey, ASTRON
Jim Lovell, U. Tasmania




Motivation – Why Study Jets?

- Jets as Interesting Physical Laboratories
  - Extreme Physical Environments
  - Black Holes – fundamental physics

- Jets as 'Key Players' in Galaxy Evolution & Feedback
  - Jets clearly heat up and dump energy into their immediate environment
    - Galaxy-scale effects
    - Cluster-scale effects
  - We are still deciding how important jet-mode feedback is, but either way it is generally put in "by hand" in simulations.

→ Quantitative estimates are needed… $E = \int P(t)dt$

The Unknowns

- Speeds on kiloparsec Scales

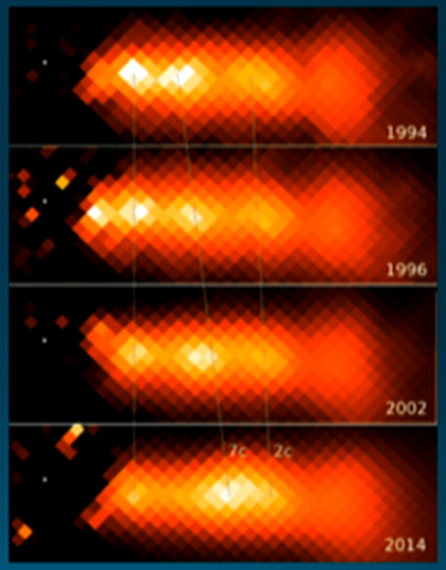
The Unknowns

- Speeds on kiloparsec Scales

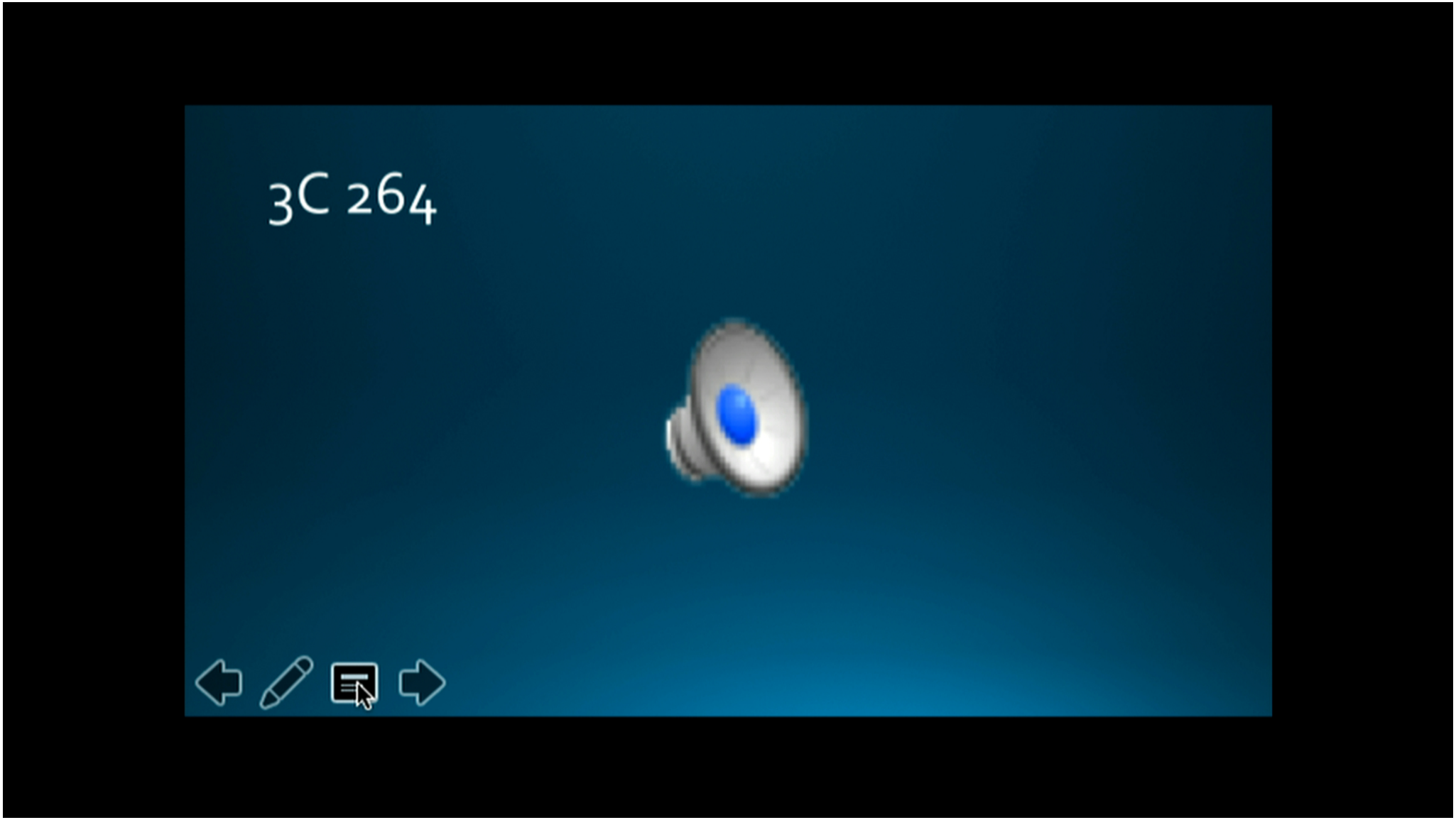
We are getting *some* data using optical proper motions with HST.

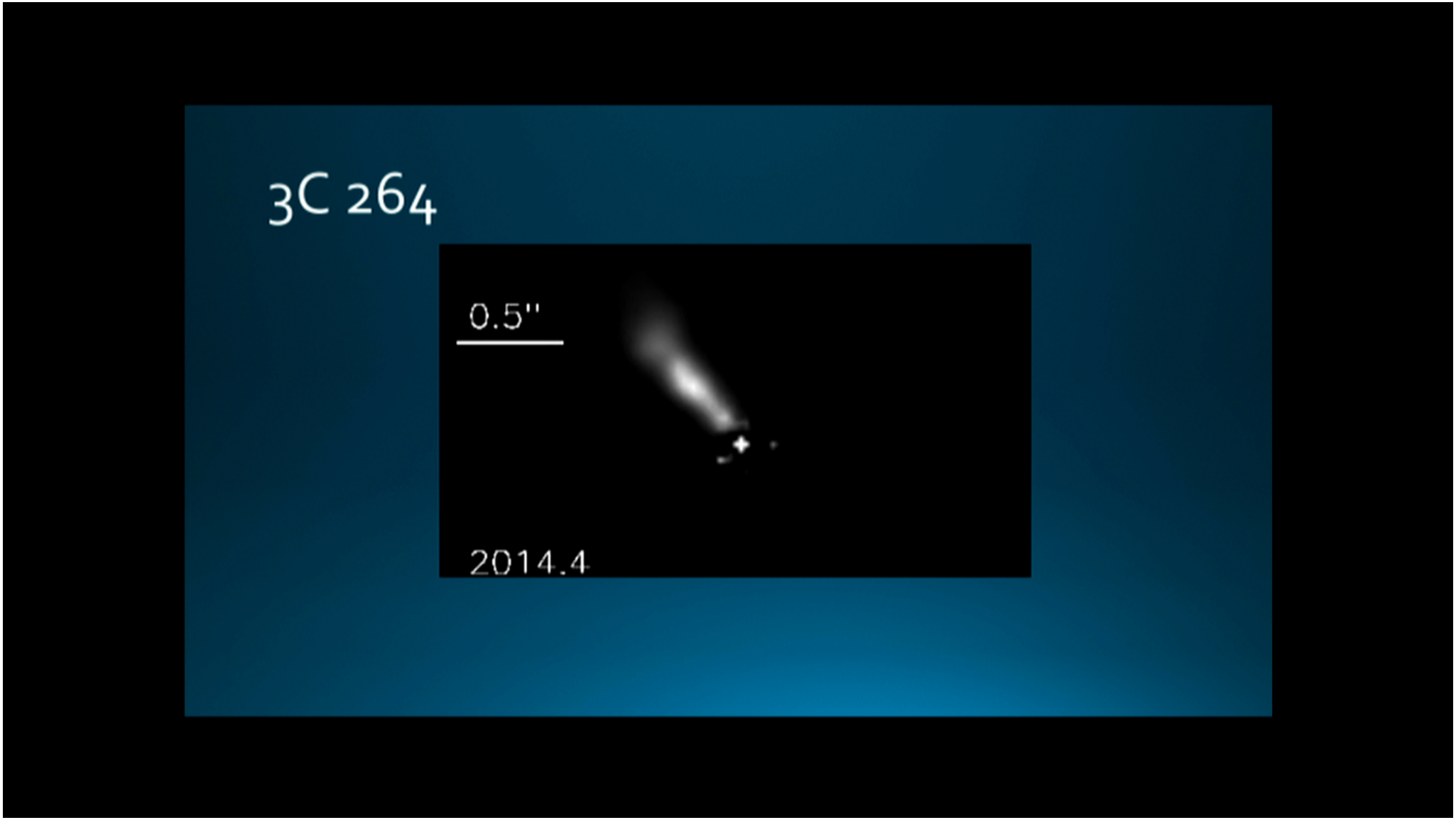
3C 264, at left, has a maximum speed of 7c at ~ 200 pc projected.

A dozen or so sources currently being tracked with new moderately deep HST observations, there are prospects for more



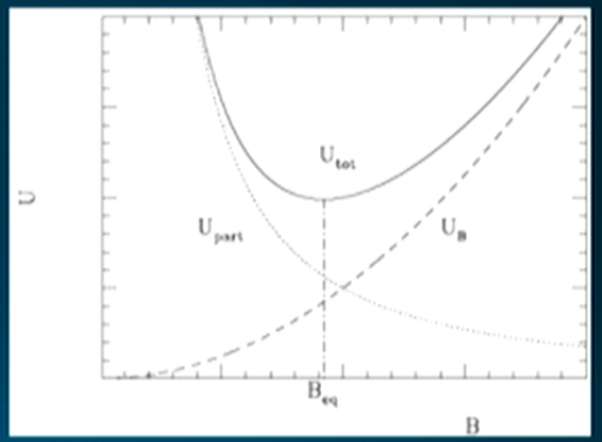
Meyer et al., 2015 Nature


3C 264


3C 264
0.5''
2014.4

The Unknowns

- Speeds on kiloparsec Scales
- Energy partitioning (magnetic field vs particles)
- Matter Content – proton fraction?
- What radiation signature are we even looking at?



FR I -- Low Power, Low Accretion Rate (ADAF)

"BL Lac Objects" when blazars (few degrees)

TeV Blazars or TeV BL Lacs are a subset of these aligned sources

FR II – High Power, High Accretion Rate
(however switch to "high excitation" spectral type occurs *after* switch to FR II morphology, in terms of power).

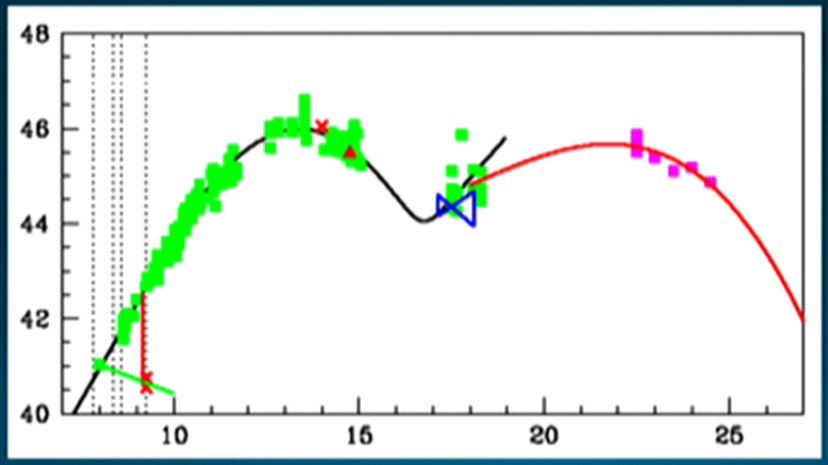
"Broad Lined Radio Galaxies" when more aligned

"Flat Spectrum Radio Quasars" when blazars (few degrees)

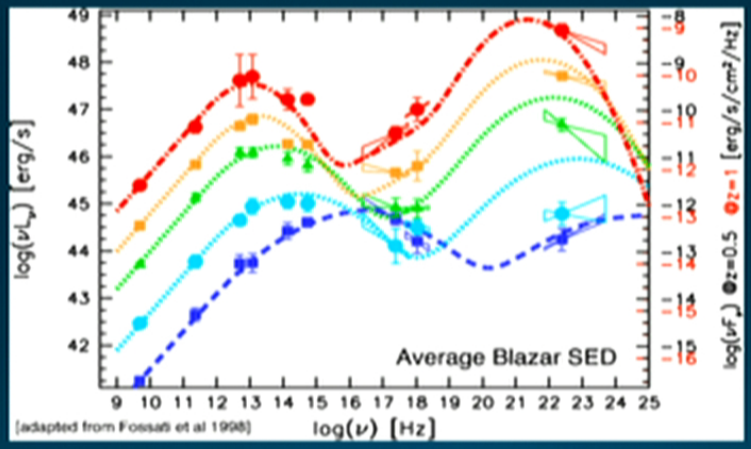
Blazars are often characterized by the frequency of the peak of the synchrotron emission.

This varies from 10^{12} Hz up to 10^{17} Hz (5 orders of magnitude)

Luminosity also can vary by up to 5 orders of magnitude.



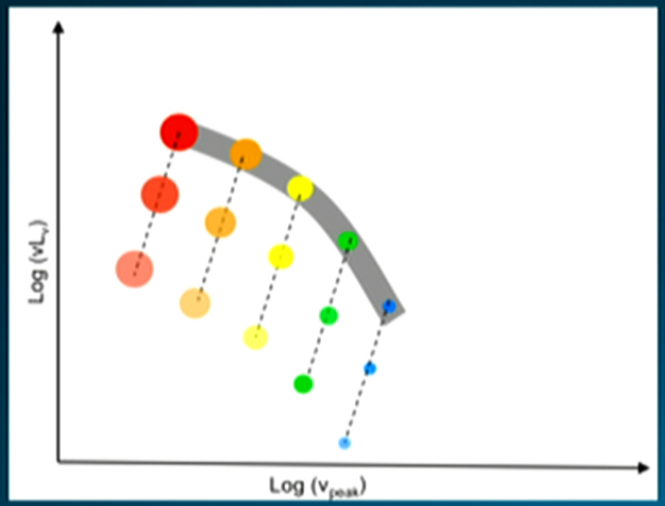
The famous "Blazar Sequence" (Fossati 1998): Note that TeV-emitting blazars are *nearly always high-synchrotron-peak sources* ($\nu_{peak} > 10^{15.5}$ Hz).
These are the lowest-power blazars!

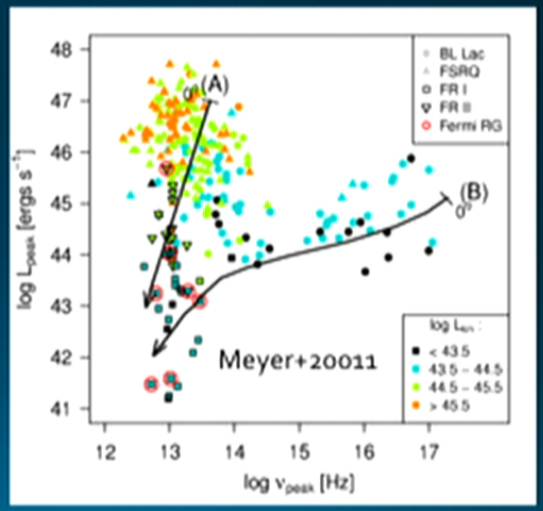


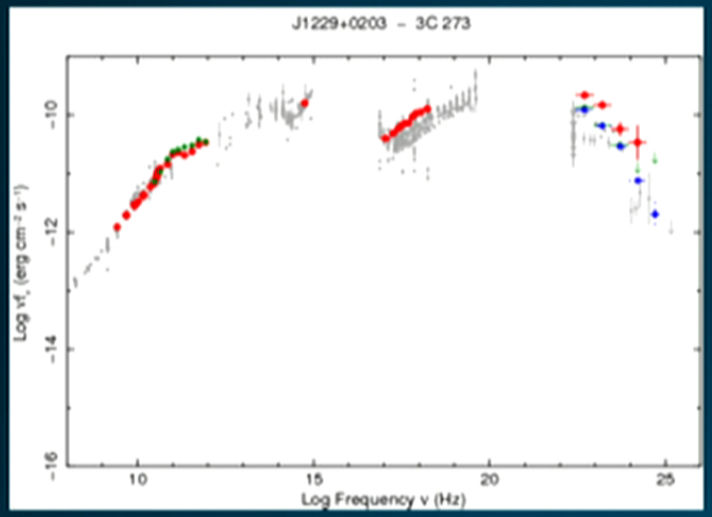
FR Is are non or negatively evolved (e.g., Clewley 2004) .
HSP BL Lacs are also the most negatively evolved population.
(Giommi 1999, Beckmann 2003, Ajello 2014)

Not all BL Lacs are TeV BL Lacs! Many have low-to-moderate synchrotron peaks, and thus lower IC peak values.

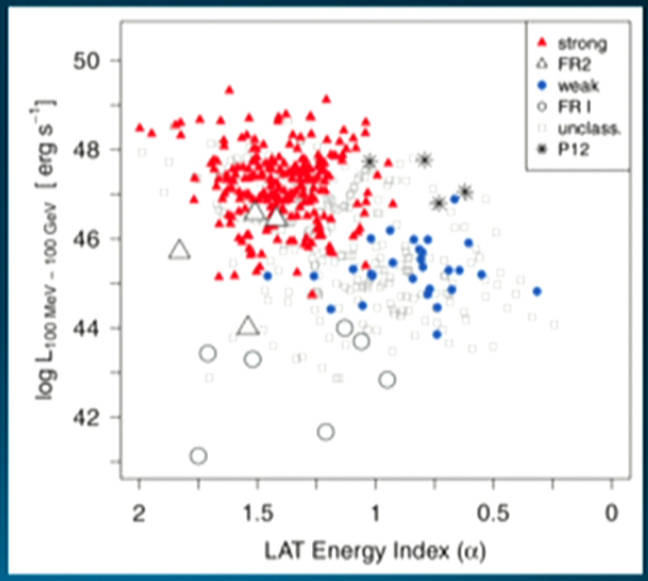
It is not clear if this is an intrinsic difference (higher photon fields, more IC cooling, lower peaks), or if it could be largely an alignment effect + contamination from "hidden" FSRQs.







3C 273: Nuclear Inverse Compton Peak is in MeV range. Extremely Soft in Fermi Band



When LBL/FSRQ types are detected at TeV energies, they tend to be rare, bright objects

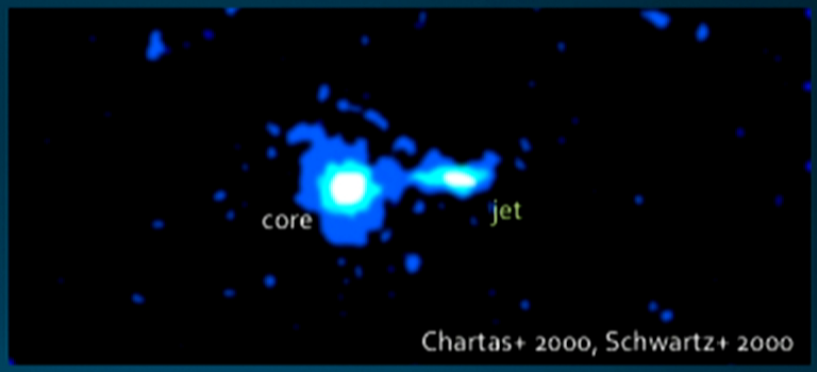
Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

July 1999: Chandra X-ray Observatory Launched

Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

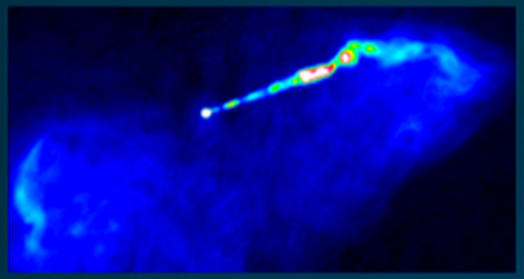
July 1999: Chandra X-ray Observatory Launched

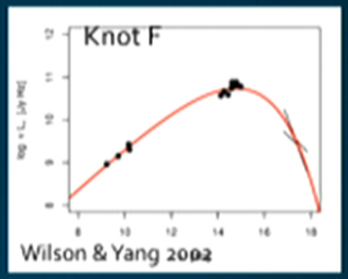
August 1999: Chandra discovers the extended kpc-scale jet of PKS 0637-752 during orbital activation and checkout phase



Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

Low-power Jets:
synchrotron spectrum
producing soft X-rays



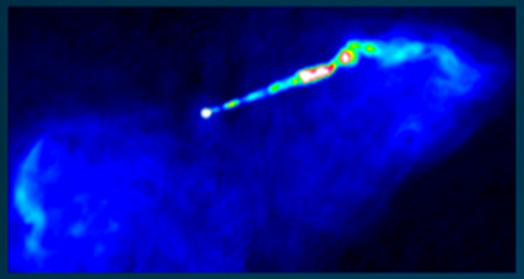


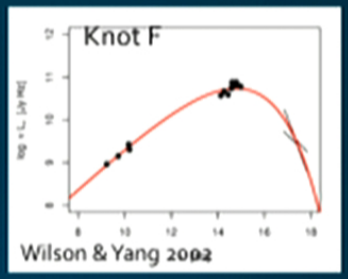
Wilson & Yang 2002

Mehta+ 2009

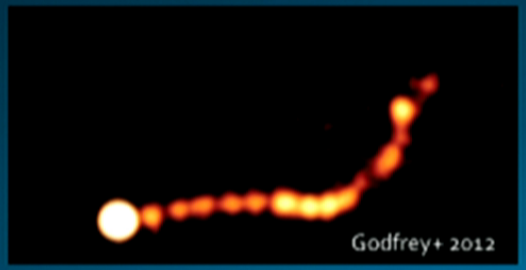
Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

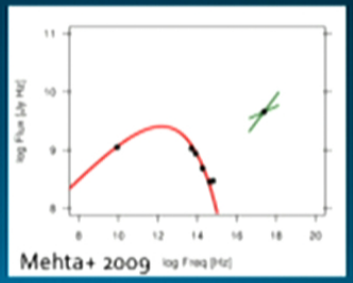
Low-power Jets: synchrotron spectrum producing soft X-rays





High-power Jets: synchrotron spectrum producing no X-rays (turnover is before optical)

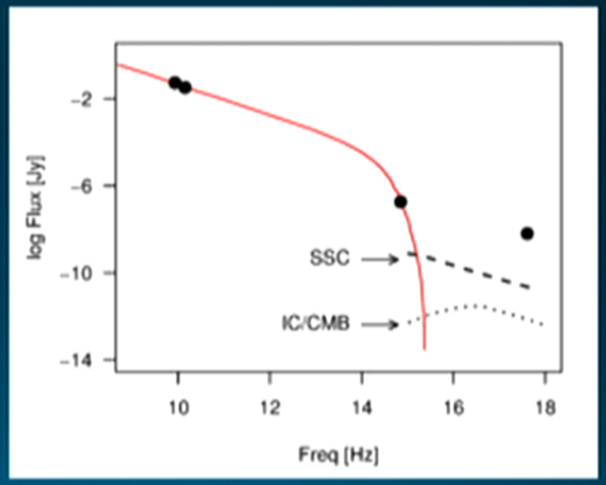




Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

September/October 2000: Chartas et al. & Schwartz et al. discovery & discussion papers on PKS 0637-752 manage to rule out:

- Thermal Bremstrahlung (electron density required far too high)
- Synchrotron self-compton (requires a "gross departure from equipartition)
- Inverse Compton off the CMB (off by orders of magnitude)



Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

November 2000: Tavecchio et al. and **February 2001:** Celotti et al.: is it IC/CMB after all?

Quasar Jets are frequently observed to be highly relativistic on sub-parsec scales probed by VLBI with Γ=10-50

Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

November 2000: Tavecchio et al. and **February 2001:** Celotti et al.: is it IC/CMB after all?

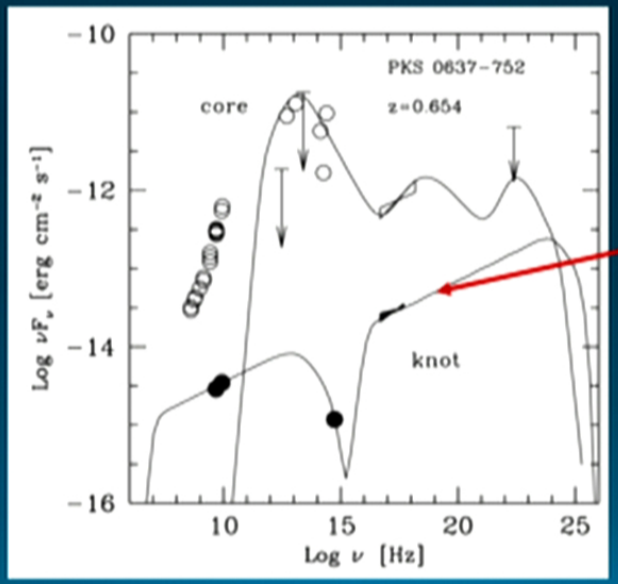
Quasar Jets are frequently observed to be highly relativistic on sub-parsec scales probed by VLBI with Γ=10-50

But Radio surveys have long suggested that on kiloparsec scales the jet is only mildly relativistic with Γ=1.2-1.5 [e.g., Arshakian & Longair 2004, Mullin & Hardcastle 2009]

Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

Celotti et al 2001:

If you simply take $\Gamma \sim 15$, the increased beaming allows the IC/CMB to match the observed X-rays without any other majorly contrived assumptions.

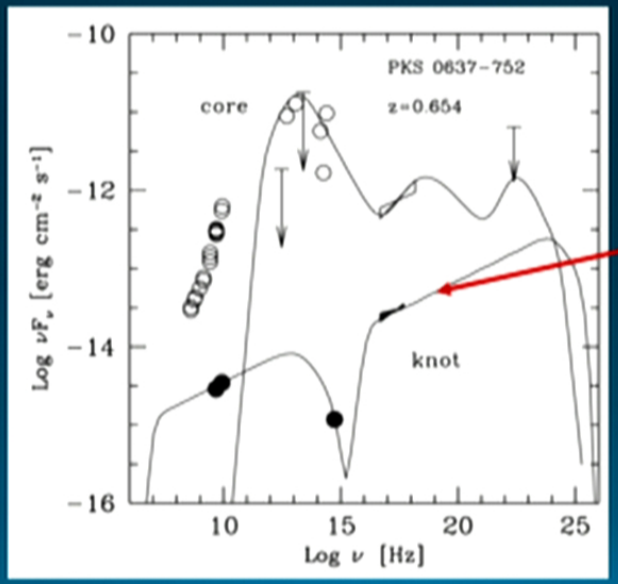


Working IC/CMB model for the knots of PKS 0637-752

Some History: The Rise of the Inverse Compton Model for X-rays from Large-Scale Jets

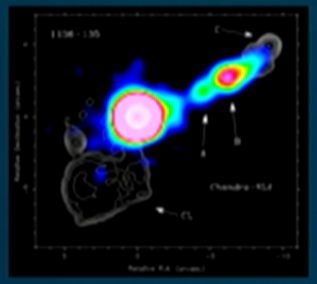
Celotti et al 2001:

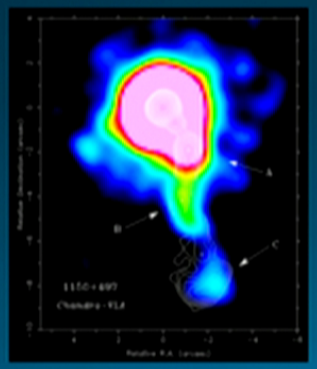
If you simply take Γ~15, the increased beaming allows the IC/CMB to match the observed X-rays without any other majorly contrived assumptions.

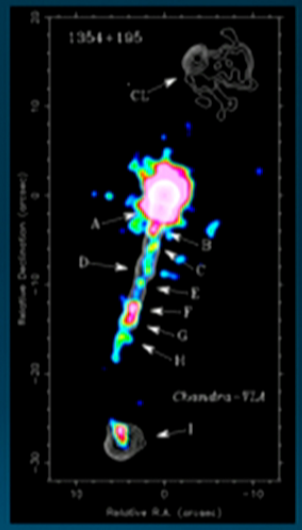


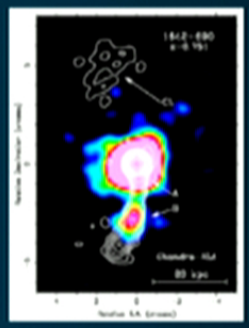
Working IC/CMB model for the knots of PKS 0637-752

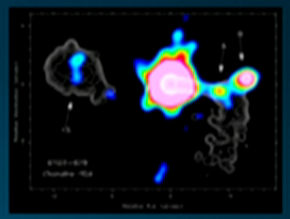
Anomalously Bright Quasar Jets: One of Chandra's major discoveries, and an ongoing **mystery.**









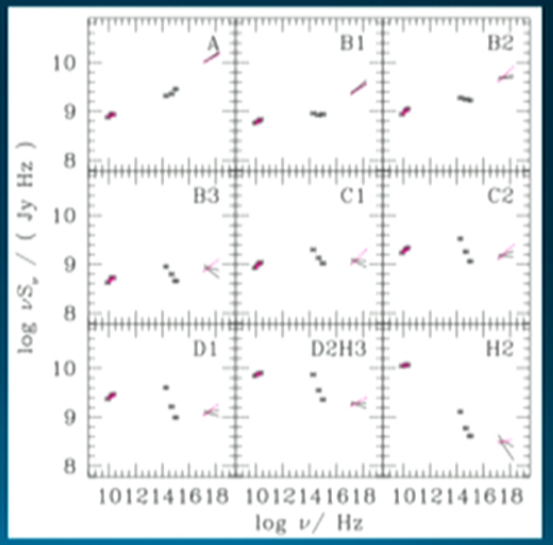


Several dozen now discovered (see review by Harris & Krawczynski 2006, Also papers by Marshall, Sambruna, Jorstad & Marscher, Kharb, Godfrey, Siemiginowska, and many more...

Doubts about the IC/CMB model

- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)

Frequently observed decrease in X-rays rel. to radio, shown at left for 3C 273 Only makes sense if you have a gradual deceleration of the flow through the kpc-scale jet.



Doubts about the IC/CMB model

- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases

Doubts about the IC/CMB model

- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases
- Small beaming angle sometimes implies jet lengths > 1 Mpc (longer than the very longest in the plane of the sky)

Doubts about the IC/CMB model

- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases
- Small beaming angle sometimes implies jet lengths > 1 Mpc (longer than the very longest in the plane of the sky)
- In many cases the IC/CMB fit is an "uncomfortable" one

Doubts about the IC/CMB model

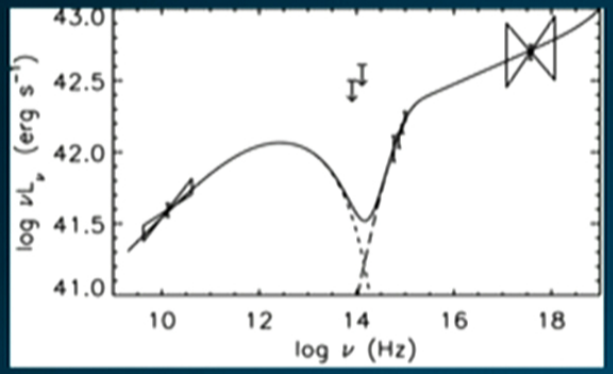
- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases
- Small beaming angle sometimes implies jet lengths > 1 Mpc (longer than the very longest in the plane of the sky)
- In many cases the IC/CMB fit is an "uncomfortable" one
- Jester 2006, Uchiyama 2006, Hardcastle 2006: All suggest (leptonic) synchrotron models very much alive

Doubts about the IC/CMB model

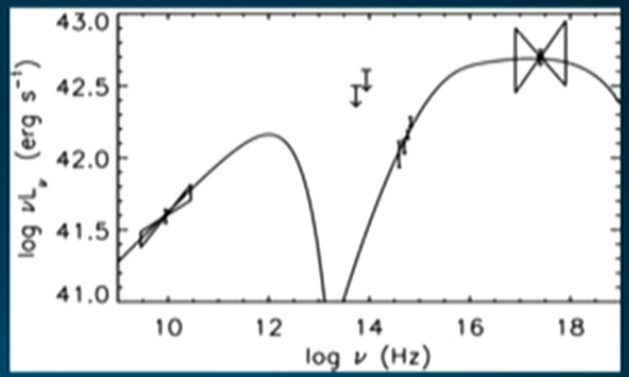
- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases
- Small beaming angle sometimes implies jet lengths > 1 Mpc (longer than the very longest in the plane of the sky)
- In many cases the IC/CMB fit is an "uncomfortable" one
- Jester 2006, Uchiyama 2006, Hardcastle 2006: All suggest (leptonic) synchrotron models very much alive
- Hadronic models also a rather under-explored possibility (Aharonian 2002)

The Essential Problem

Second-synchrotron and IC/CMB fit radio-optical-Xray equally well.



PKS 1136-135, IC/CMB Model



PKS 1136-135, synchrotron Model

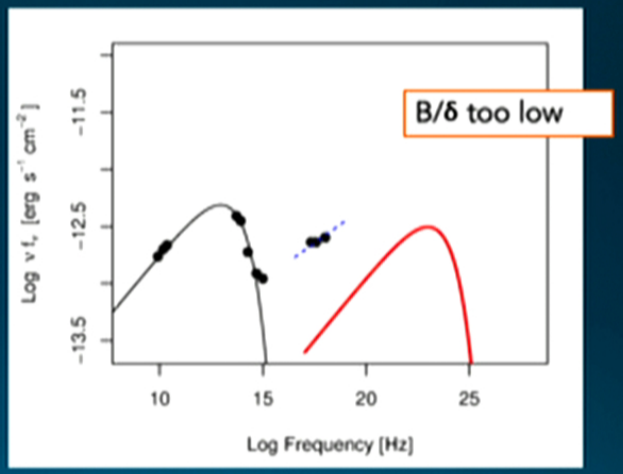
Cara+ 2013 – Showing that X-rays of PKS 1136-135 are synchrotron due to high UV polarization

The Test: How to Rule out IC/CMB

The IC Component is a copy of the synchrotron, shifted in frequency and luminosity.

That shift is parameterized ONLY by B/δ, no other free parameters.

[Georganopoulos+ 2006]

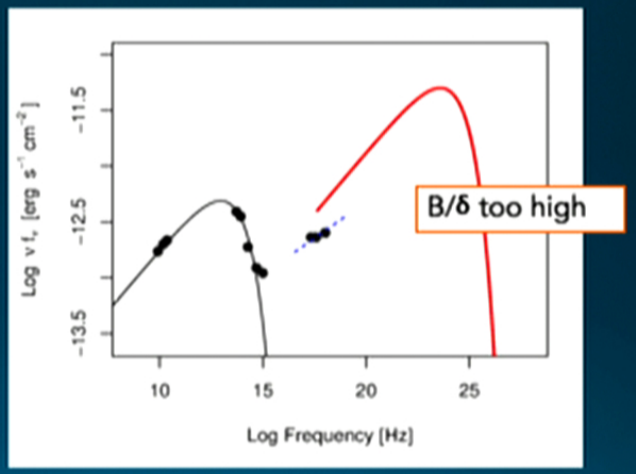


The Test: How to Rule out IC/CMB

The IC Component is a copy of the synchrotron, shifted in frequency and luminosity.

That shift is parameterized ONLY by B/δ, no other free parameters.

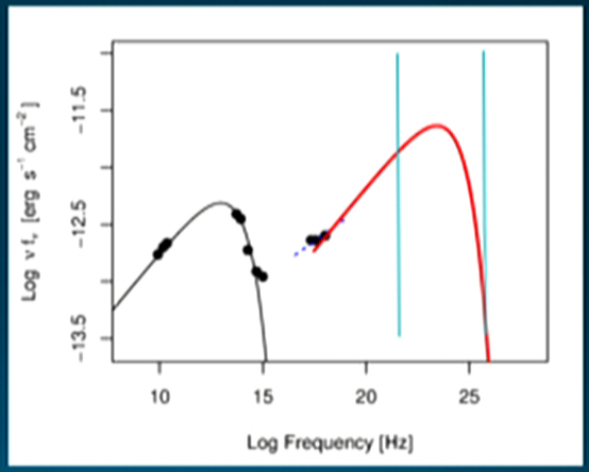
[Georganopoulos+ 2006]



The Test: How to Rule out IC/CMB

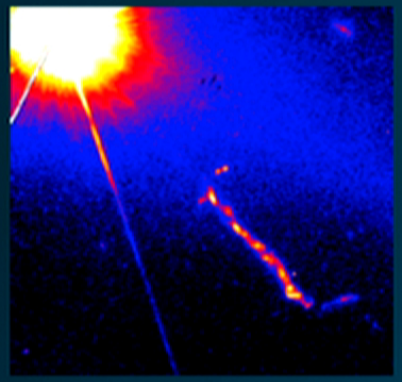
The IC Component is a copy of the synchrotron, shifted in frequency and luminosity.

That shift is parameterized ONLY by B/δ, no other free parameters.



Getting the X-rays just right means fixing B/δ and consequently implies a high level of gamma-ray emission which should be detectable with Fermi

The case of 3C 273

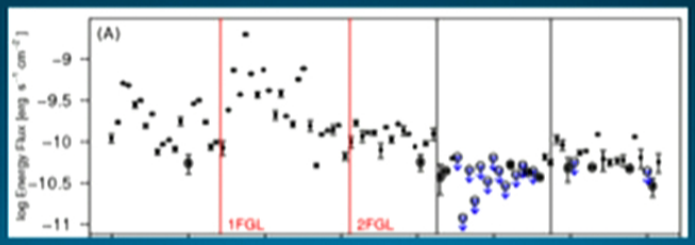


Resolution Issue: From core to end of the jet is ~ 24" - even the 68% PSF at 3 GeV is >10x this scale (few tenths of a degree)

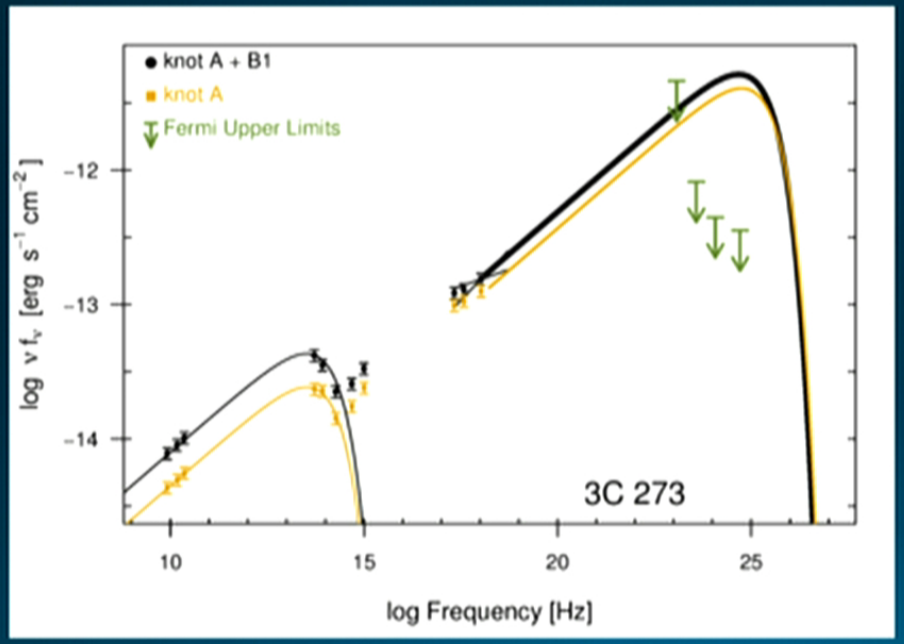
<u>However:</u>

- IC/CMB emission of the 3C273 should be quite **hard and completely non-variable**.
- The core is known to be soft (Γ~2.7), and **variable**.

We can thus stack the parts of the 3C 273 lightcurve when the blazar is low to get the lowest upper limit, which applies to both the core + the jet.



The case of 3C 273

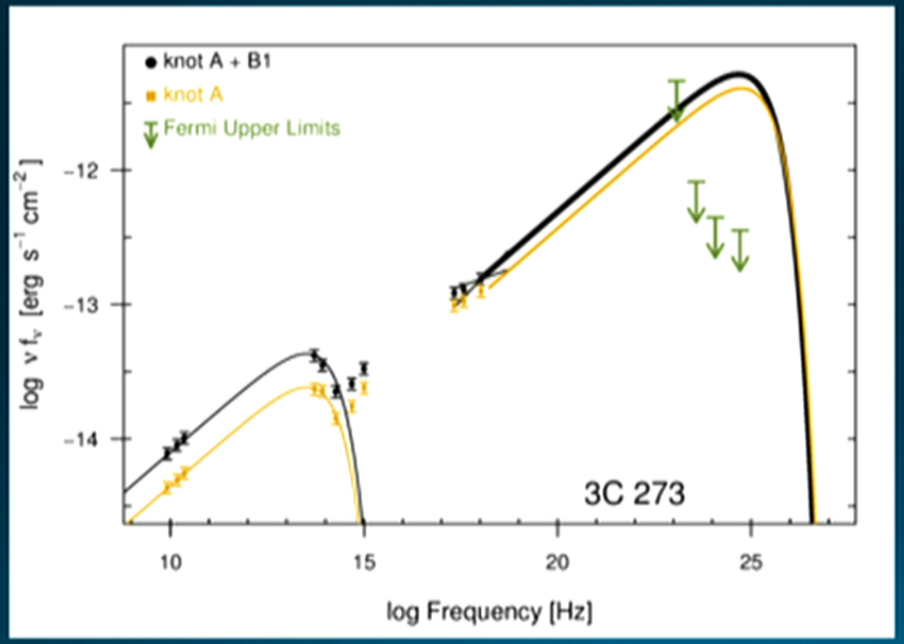


IC/CMB clearly ruled out at the > 99.99% level

You cannot satisfy producing the X-rays and the gamma-ray limits.

Meyer & Georganopoulos 2014 ApJ 780, 27

The case of 3C 273

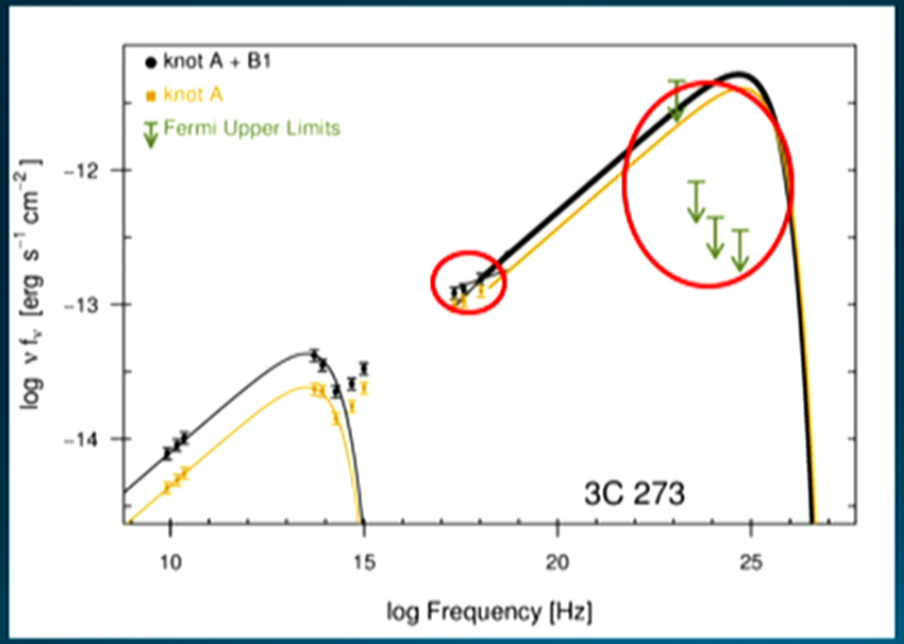


IC/CMB clearly ruled out at the > 99.99% level

You cannot satisfy producing the X-rays and the gamma-ray limits.

Meyer & Georganopoulos 2014 ApJ 780, 27

The case of 3C 273

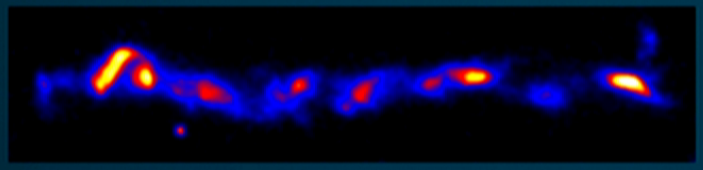


IC/CMB clearly ruled out at the > 99.99% level

You cannot satisfy producing the X-rays and the gamma-ray limits.

Meyer & Georganopoulos 2014 ApJ 780, 27

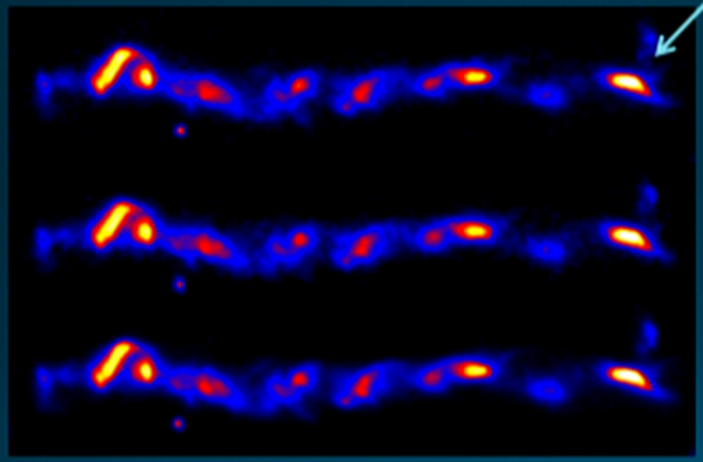
3C 273 another way



The Jet in 1995

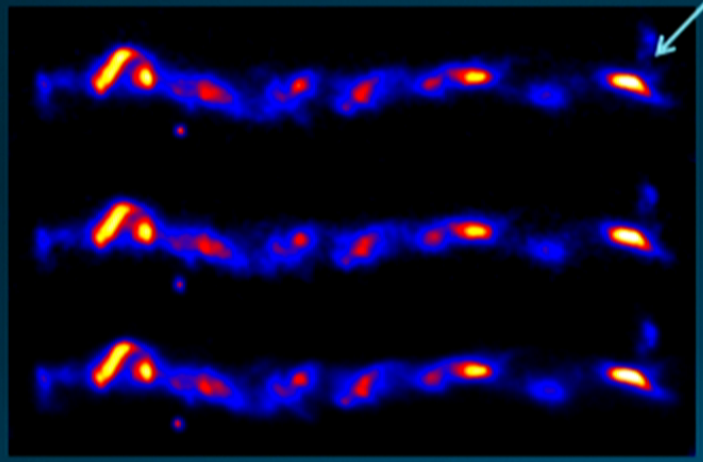
(Meyer et al., 2015,
submitted to ApJ)

3C 273 another way



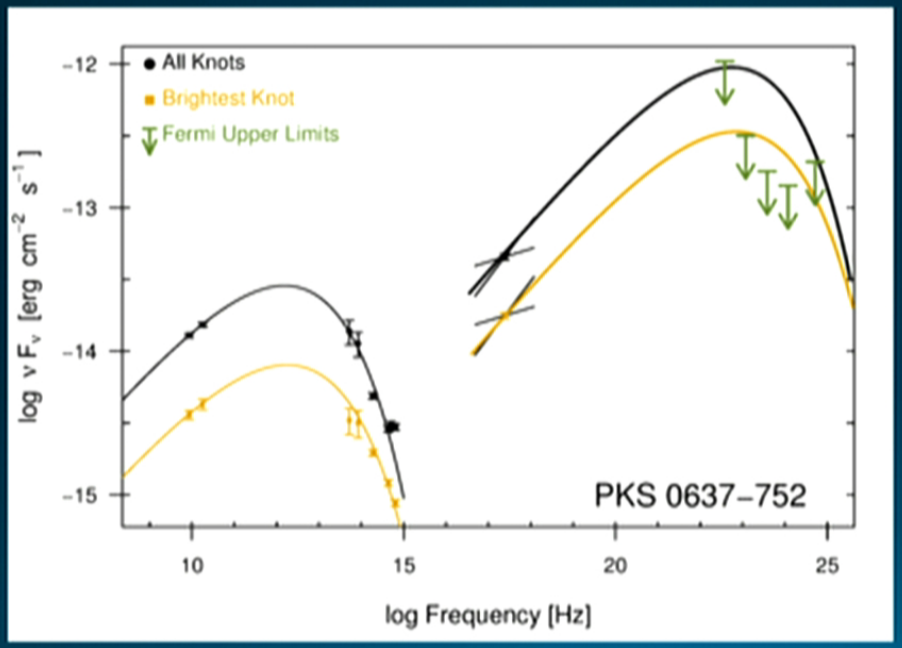
(Meyer et al., 2015, submitted to ApJ)

3C 273 another way



(Meyer et al., 2015, submitted to ApJ)

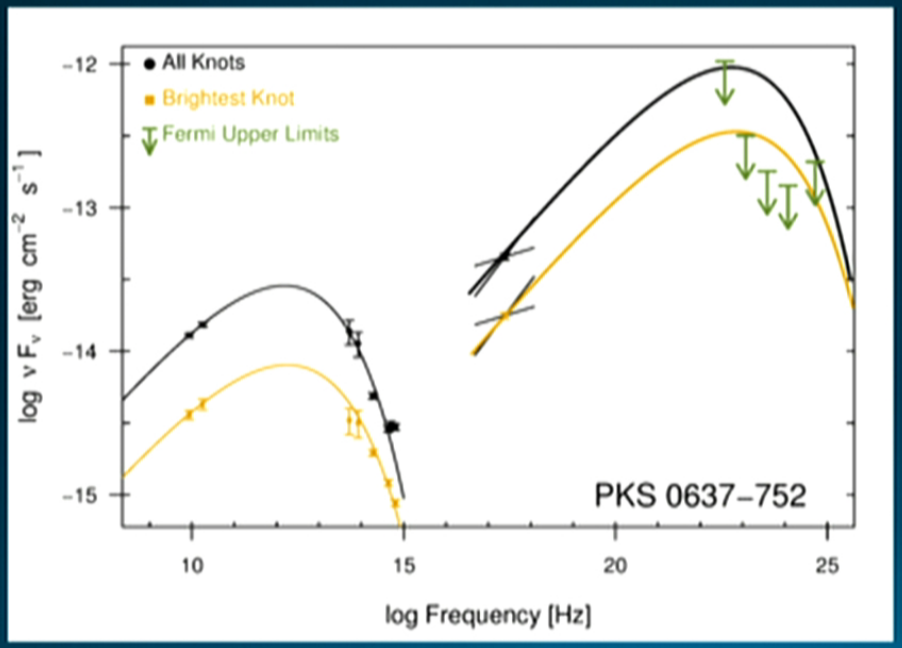
The case of PKS 0637-752



(Meyer et al. 2015 ApJ 805 154)

IC/CMB is now ruled out at the > 99.99% level for the original jet for which the model was first proposed!

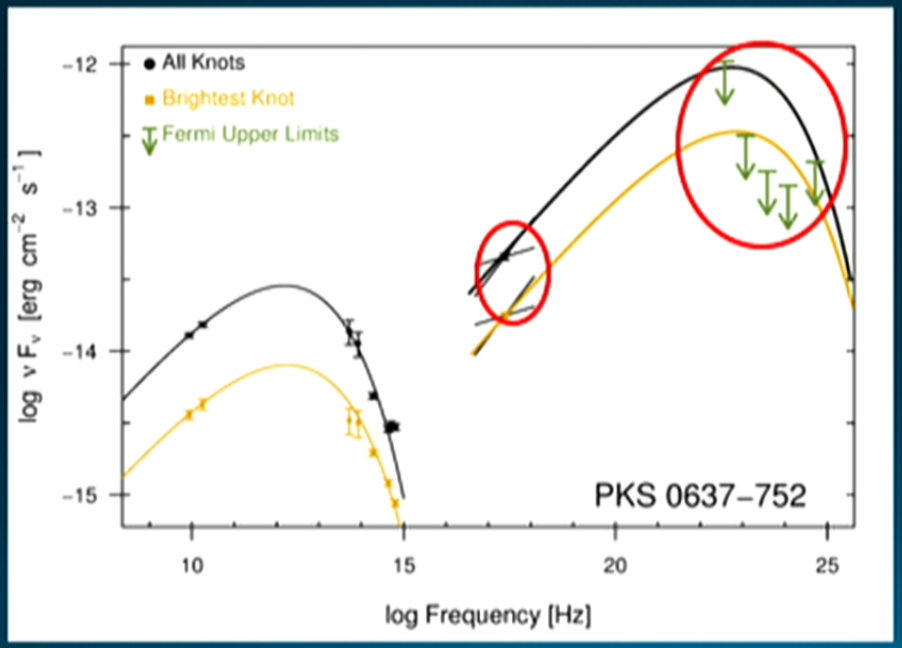
The case of PKS 0637-752



IC/CMB is now ruled out at the > 99.99% level for the original jet for which the model was first proposed!

(Meyer et al. 2015 ApJ 805 154)

The case of PKS 0637-752

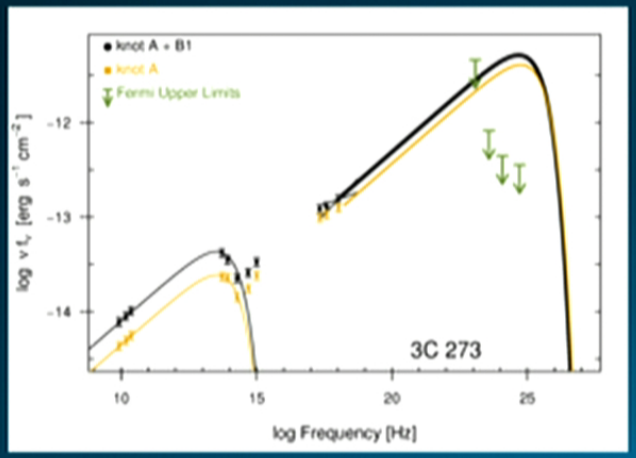


(Meyer et al. 2015 ApJ 805 154)

IC/CMB is now ruled out at the > 99.99% level for the original jet for which the model was first proposed!

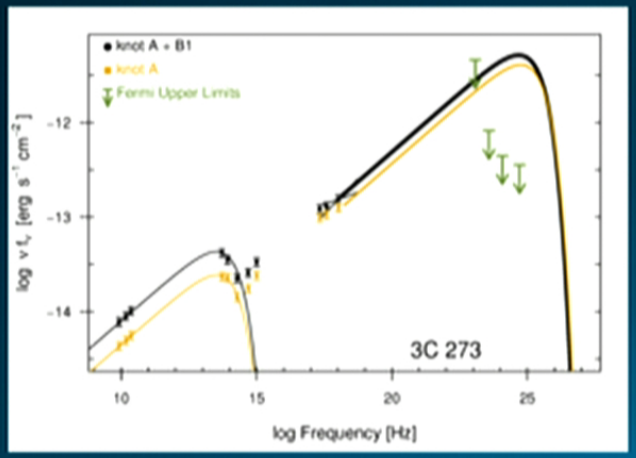
Limits on Doppler factor/Magnetic Field

Fermi observations not only rule out IC/CMB X-rays, they put limits on the Doppler beaming factor of jets on kpc scales.



Limits on Doppler factor/Magnetic Field

Fermi observations not only rule out IC/CMB X-rays, they put limits on the Doppler beaming factor of jets on kpc scales.



Assuming equipartition fields, $\delta < 7.8$ in 3C 273 (based solely on knots A and B1)

For PKS 0637-752, $\delta < 6.5$

Take-away #1: The IC/CMB Model is in trouble.

Take-away #1: The IC/CMB Model is in trouble.

IC/CMB has been conclusively ruled out by lack of gamma-rays on 2 sources
(Meyer & Georganopoulos 2014, Meyer et al., 2015)

Take-away #1: The IC/CMB Model is in trouble.

IC/CMB has been conclusively ruled out by lack of gamma-rays on 2 sources
(Meyer & Georganopoulos 2014, Meyer et al., 2015)

IC/CMB has also been ruled out by lack of proper motions In 3C 273
(Meyer et al., 2015, submitted)

Take-away #1: The IC/CMB Model is in trouble.

IC/CMB has been conclusively ruled out by lack of gamma-rays on 2 sources
(Meyer & Georganopoulos 2014, Meyer et al., 2015)

IC/CMB has also been ruled out by lack of proper motions In 3C 273
(Meyer et al., 2015, submitted)

IC/CMB has been ruled out in a third case because the second component is highly polarized (35%, unexpected since the CMB has low polarization)
(Cara et al., 2013)

Take-away #1: The IC/CMB Model is in trouble.

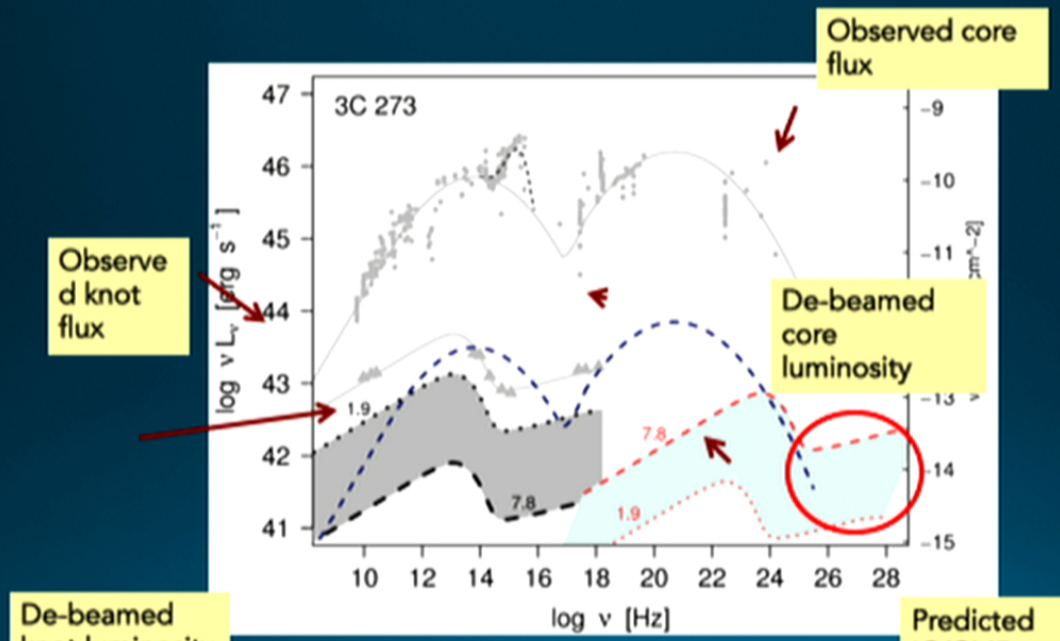
IC/CMB has been conclusively ruled out by lack of gamma-rays on 2 sources
(Meyer & Georganopoulos 2014, Meyer et al., 2015)

IC/CMB has also been ruled out by lack of proper motions In 3C 273
(Meyer et al., 2015, submitted)

IC/CMB has been ruled out in a third case because the second component is highly polarized (35%, unexpected since the CMB has low polarization)
(Cara et al., 2013)

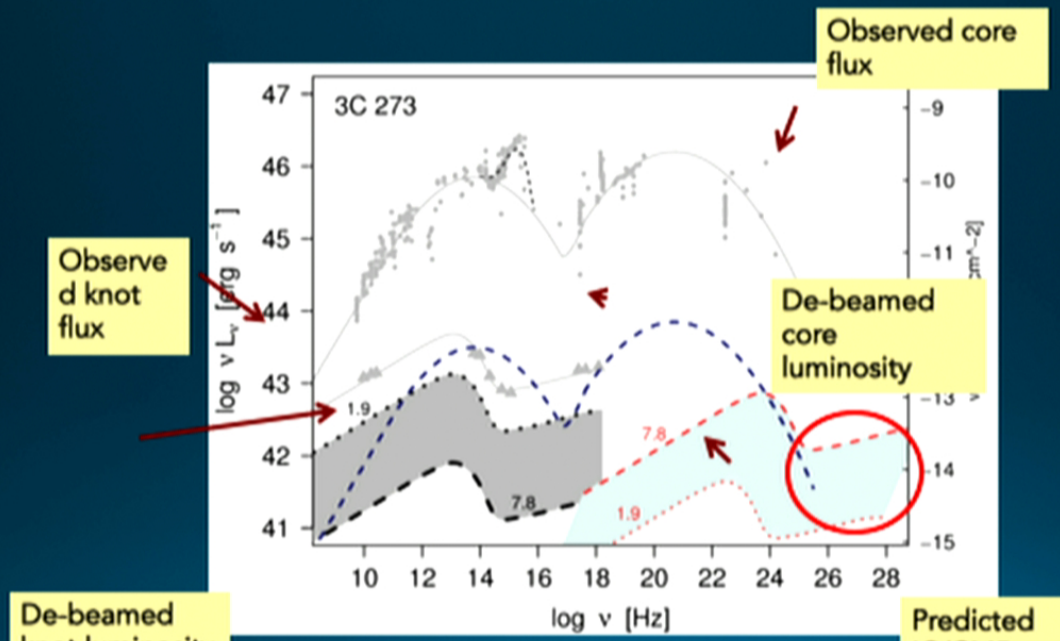
Take-away #2: The only alternative is a second synchrotron component
Theorists: what is this and why is it there?

Consolation Prize: Slow Jets = TeV Emission



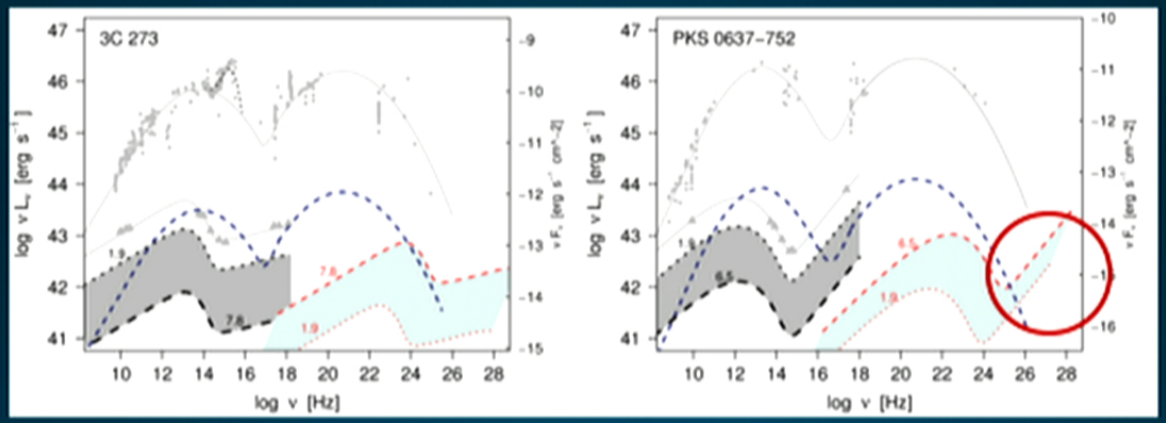
Meyer et al 2015

Consolation Prize: Slow Jets = TeV Emission



Meyer et al 2015

Consolation Prize: Slow Jets = TeV Emission



Both 3C 273 and PKS 0637-752 already have predicted IC/CMB TeV emission which is far above the isotropic output of a 'typical' TeV Blazar.

Take-aways

1. IC/CMB is not the cause of the anomalously high X-rays in 3C 273, PKS 0637-752, and PKS 1136-135

Take-aways

1. IC/CMB is not the cause of the anomalously high X-rays in 3C 273, PKS 0637-752, and PKS 1136-135
2. I think it likely that this will turn out to be true for most of our anomalous X-ray sources (maybe not at high z?)

Take-aways

1. IC/CMB is not the cause of the anomalously high X-rays in 3C 273, PKS 0637-752, and PKS 1136-135
2. I think it likely that this will turn out to be true for most of our anomalous X-ray sources (maybe not at high z?)
3. We still have a mystery: what is the source of the second synchrotron component? Why does it appear co-spatial? Why does it (usually) decrease as you go down the jet? → theorists!

Take-aways

1. IC/CMB is not the cause of the anomalously high X-rays in 3C 273, PKS 0637-752, and PKS 1136-135
2. I think it likely that this will turn out to be true for most of our anomalous X-ray sources (maybe not at high z?)
3. We still have a mystery: what is the source of the second synchrotron component? Why does it appear co-spatial? Why does it (usually) decrease as you go down the jet? → theorists!
4. Kpc-scale jets are not, after all, super-fast. They are mildly relativistic (one-sided jets, hotspots are also somewhat beamed).

Take-aways

5. Prediction: Fermi will detect IC/CMB before the 10 year mission is up. It must be there at some level even if it doesn't produce the X-rays. This gives us a direct measurement of B/δ

Take-aways

5. Prediction: Fermi will detect IC/CMB before the 10 year mission is up. It must be there at some level even if it doesn't produce the X-rays. This gives us a direct measurement of B/δ

6. The synchrotron X-rays should give us lots of TeV emission, almost certainly more than 'TeV blazar's in total luminosity. This may turn out to be Really Important.

Take-aways

5. Prediction: Fermi will detect IC/CMB before the 10 year mission is up. It must be there at some level even if it doesn't produce the X-rays. This gives us a direct measurement of B/δ

6. The synchrotron X-rays should give us lots of TeV emission, almost certainly more than 'TeV blazar's in total luminosity. This may turn out to be Really Important.

7. Prediction: Either Fermi or CTA will finally detect this component, ultimate proof that the X-rays are synchrotron.

Implications for TeV Heating?

-FSRQ are more likely the positively evolving population, dominant at high z
-Total (4pi) TeV power is 1-2 orders of magnitude higher than "TeV" BL Lacs
Subject to uncertainties in (a) Magnetic Field Strength and (b) Speed on kpc scales

However…

-Not clear how beamed these TeV photons are – critical density?
-If the X-rays are hadronic, we may not be see TeV emission at all from these sources (however, qualitatively, I would be on forward-reverse shocks producing dual synchrotron spectra).

Implications for TeV Heating?

-FSRQ are more likely the positively evolving population, dominant at high z
-Total (4pi) TeV power is 1-2 orders of magnitude higher than "TeV" BL Lacs
Subject to uncertainties in (a) Magnetic Field Strength and (b) Speed on kpc scales

However…

-Not clear how beamed these TeV photons are – critical density?
-If the X-rays are hadronic, we may not be see TeV emission at all from these sources (however, qualitatively, I would be on forward-reverse shocks producing dual synchrotron spectra).

Follow-up & Current Work

- New data on 8 sources + archival effort on about 2 dozen total jets should give us a good test of IC/CMB overall with Fermi
- Variability study for Chandra X-ray jets: variability not expected in IC/CMB
- Ongoing look for the TeV 'upturn' at the highest Fermi energies to confirm synchrotron origin of X-rays, possible CTA detections
- Population study of Anomalous X-ray Jets to estimate TeV heating potential -→ RESULTS SOON

Follow-up & Current Work

- New data on 8 sources + archival effort on about 2 dozen total jets should give us a good test of IC/CMB overall with Fermi
- Variability study for Chandra X-ray jets: variability not expected in IC/CMB
- Ongoing look for the TeV 'upturn' at the highest Fermi energies to confirm synchrotron origin of X-rays, possible CTA detections
- Population study of Anomalous X-ray Jets to estimate TeV heating potential -→ RESULTS SOON