Constraining Jet Emission Mechanisms with FERMI

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"Extragalactic Relativistic Jets: Cause and Effect"
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Collaborators

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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... $E = \int P(t)dt$

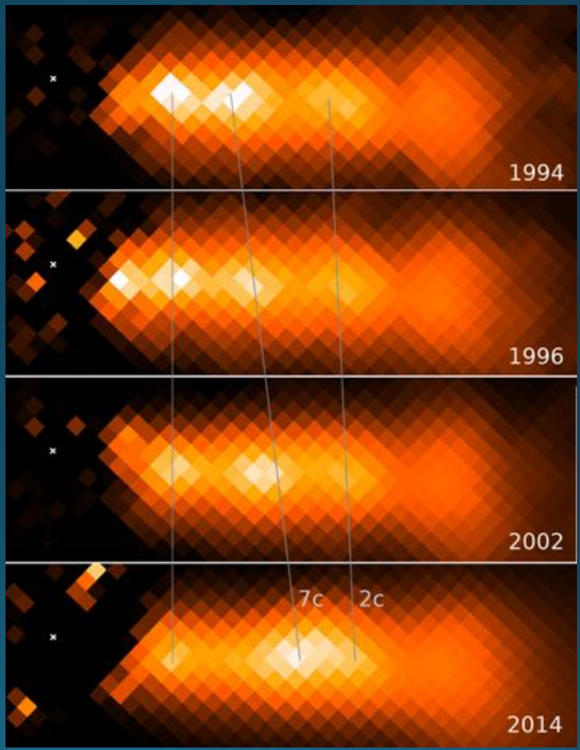
The Unknowns

- Speeds on kiloparsec Scales

Small advertisement: 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.

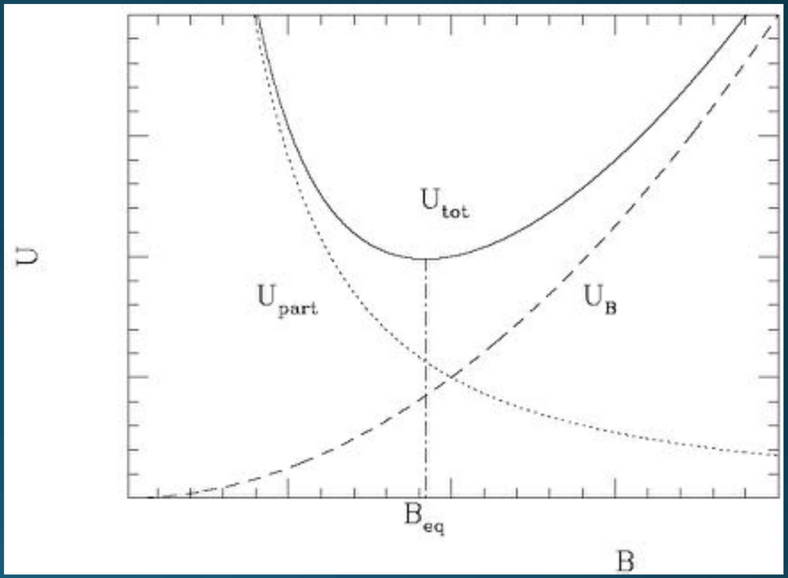
A dozen or so sources currently being tracked with new moderately deep HST observations, there are prospects for more (adaptive optics,



Meyer et al., 2015

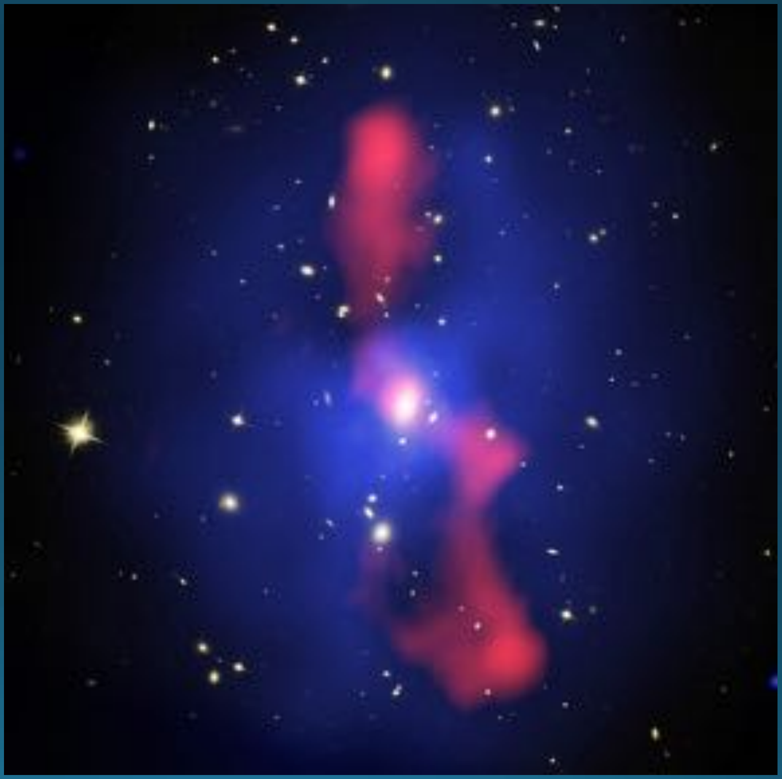
The Unknowns

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



Jets & Wider Impact

- We have seen obvious evidence of feedback in action in clusters
- See work of Birzan, McNamara, Hardcastle & many others working on this – PdV work is an extremely valuable measurement, although an ‘average’.



Jets & Wider Impact

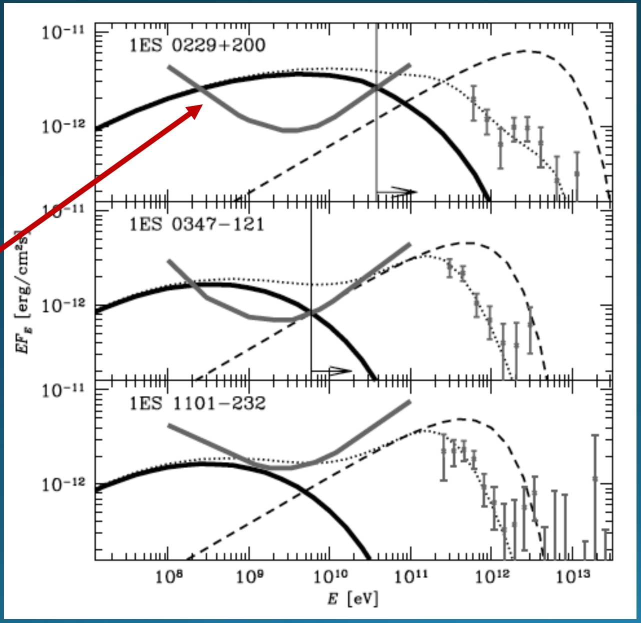
- Heating/Stripping of Galaxy-scale gas
- Mostly ‘negative’ feedback

- But sometimes positive

Jets & Wider Impact

- TeV Heating (recent work by C Pfrommer, A Broderick, P Chang)
  - Motivated in part by the lack of the expected GeV 'halo' around TeV blazars from pair cascades (e.g. Nevonov & Vovk 2010, Aleksic 2010, H.E.S.S 2014)

Fermi limits rule out expected signature



Nevonov & Vovk (2010)

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  - An alternative is plasma beam instabilities (Broderick 2012)
  - May also explain missing dwarf satellites compared to simulations (leads to suppression of dwarfs) , alleviates need for a very differently evolved population, may also explain inverted IGM temperature-density profile at low densities (Chang 2012).

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

July 1999: Chandra X-ray Observatory Launched

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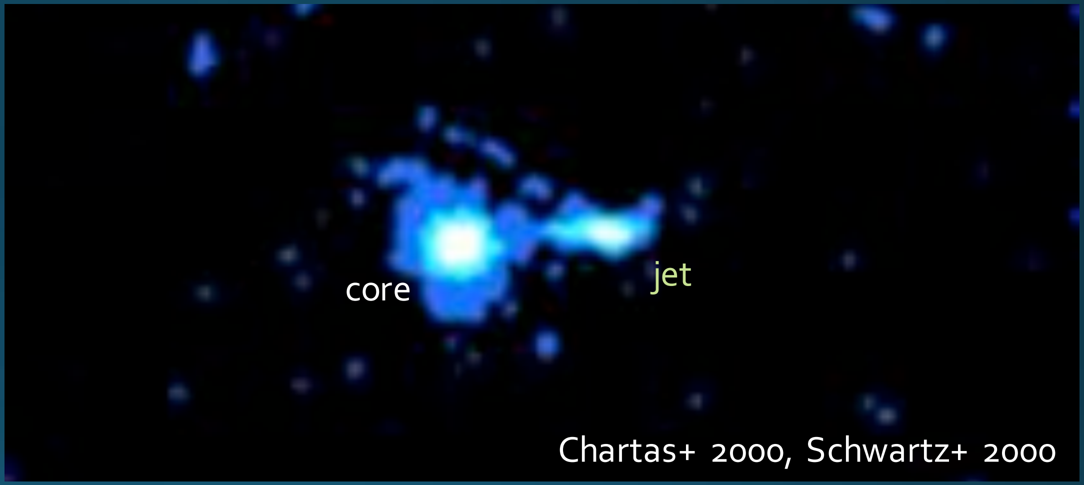
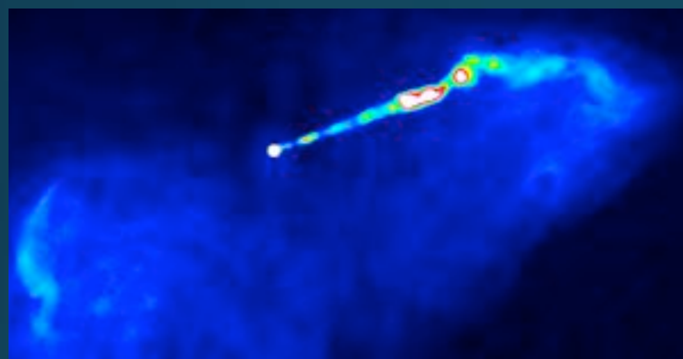
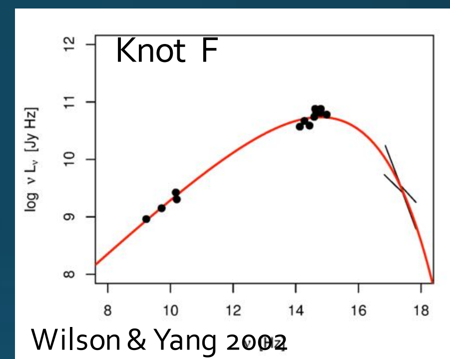
August 1999: Chandra discovers the extended kpc-scale jet of PKS 0637-752 during orbital activation and checkout phase



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

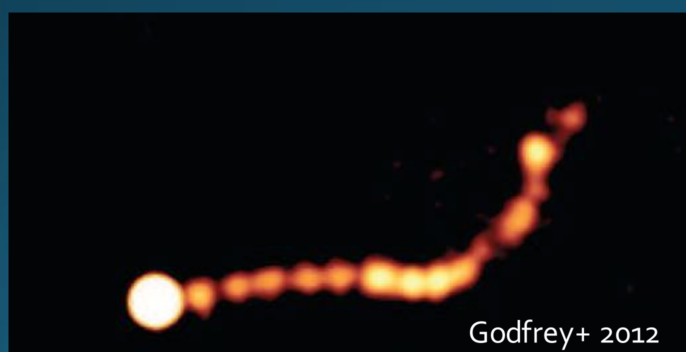
Low-power Jets: synchrotron spectrum producing soft X-rays

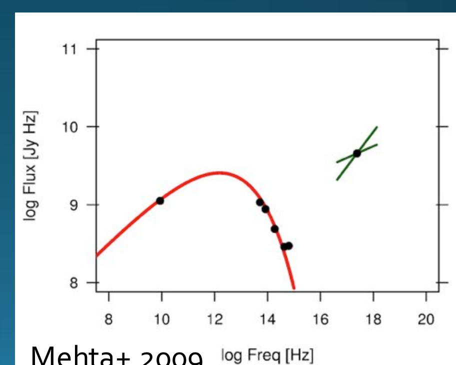




Wilson & Yang 2002

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


Godfrey+ 2012

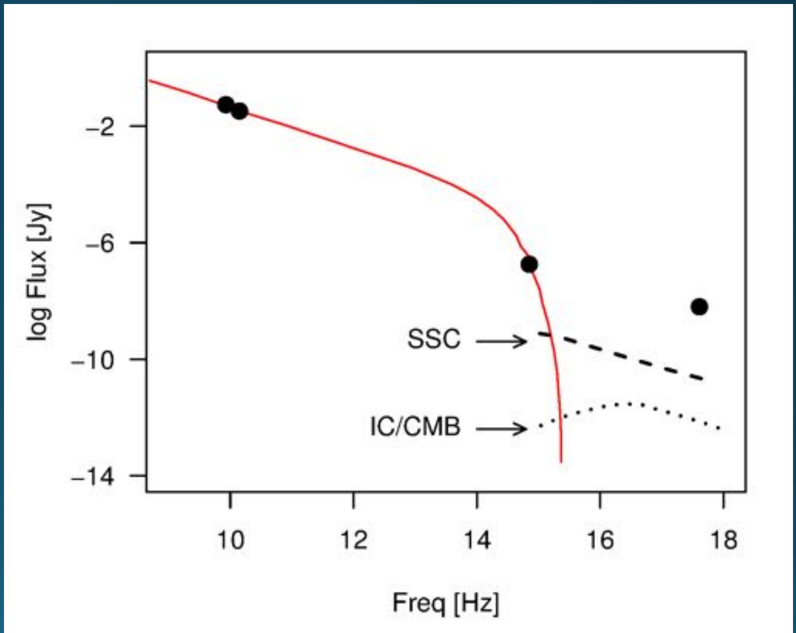


Mehta+ 2009

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

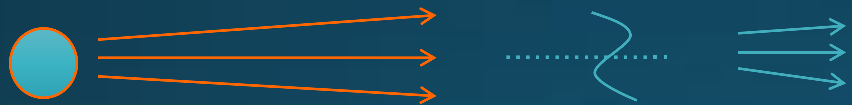
September/October 2000: Chartas et al. & Schwartz et al. discovery & discussion papers on PKS 0637-752 manage to rule out:

- 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)
- A Single Synchrotron Spectrum
- A second, co-spatial synchrotron spectrum was considered, but deemed unlikely because no known reason for it, and co-spatial with first synchrotron component!



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

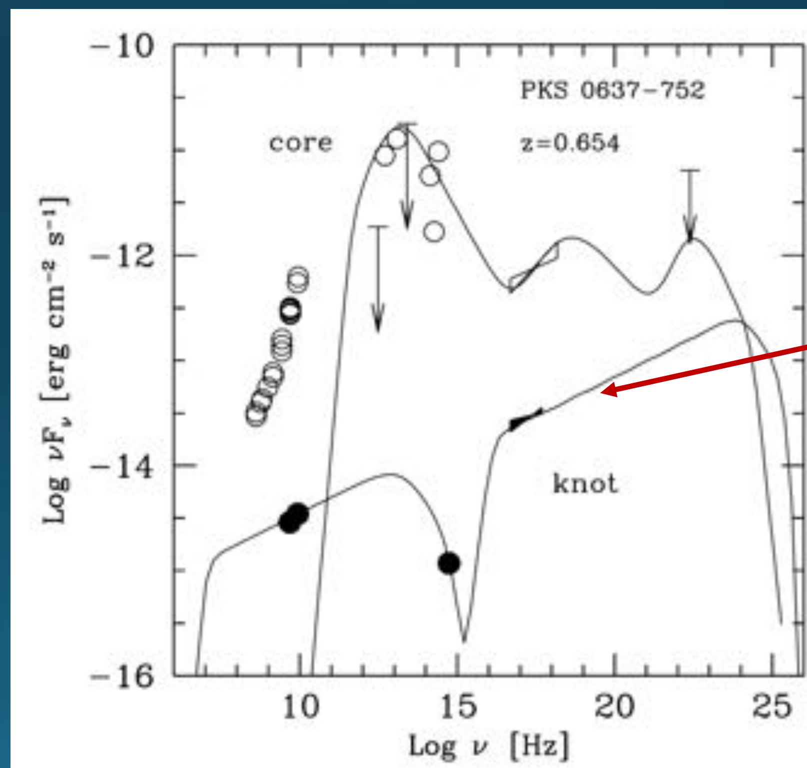
But Radio surveys have long suggested that on kiloparsec scales the jet is only mildly relativistic with Γ=1.2-1.5 [e.g., Arshakian & Longair 2004]

However, if you assume that powerful quasar jets remain highly relativistic on kpc scales, then IC/CMB works.

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.

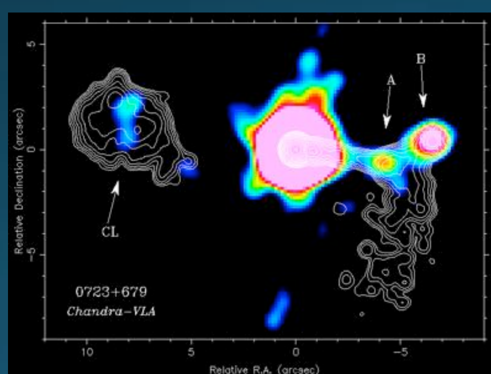


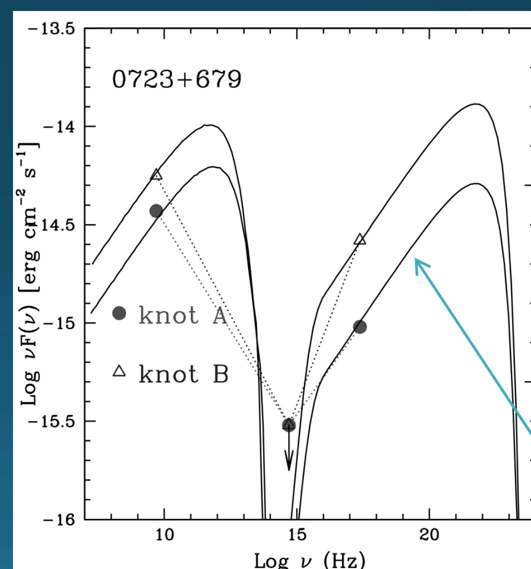
Working IC/CMB model for the knots of PKS 0637-752

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

- Over the past 15 years, the IC/CMB model is the most popular, though technically unconfirmed explanation for the anomalous X-ray jets.

PKS 0723+679

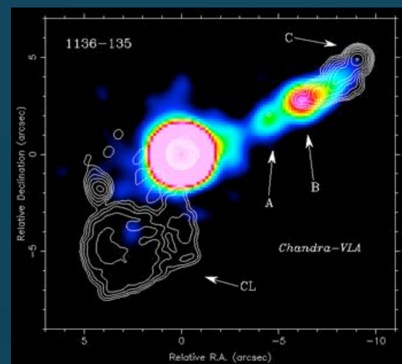


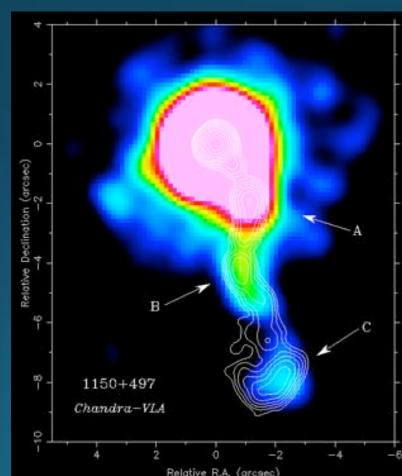


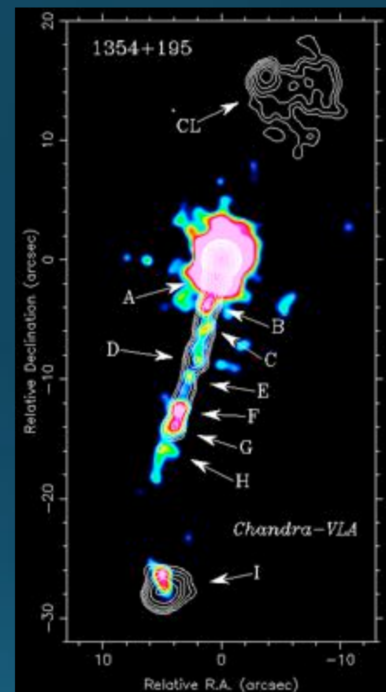
Working IC/CMB model assuming fast jet

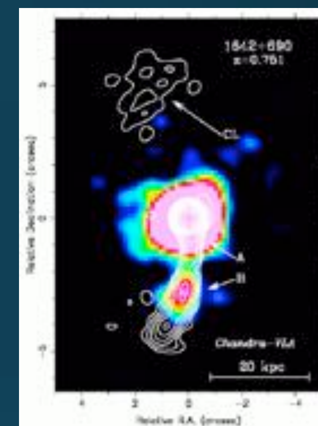
Sambruna+ 2002

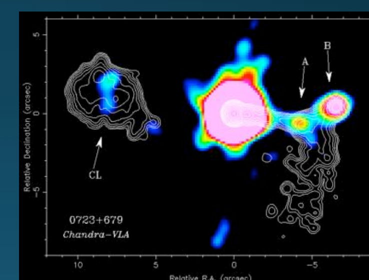
Anomalously Bright Quasar Jets: One of Chandra’s major discoveries, and an ongoing **mystery.**









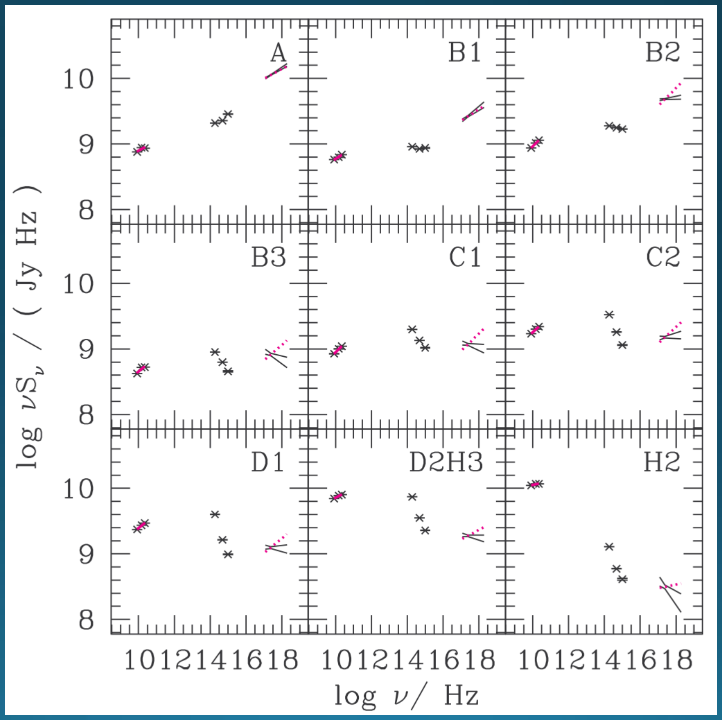


Several dozen now discovered (see review by Harris & Krawczynski 2006, Also papers by Marshall, Sambruna, Jorstad & Marscher, Kharb, Godfrey, Siemiginowska, and many more…

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.

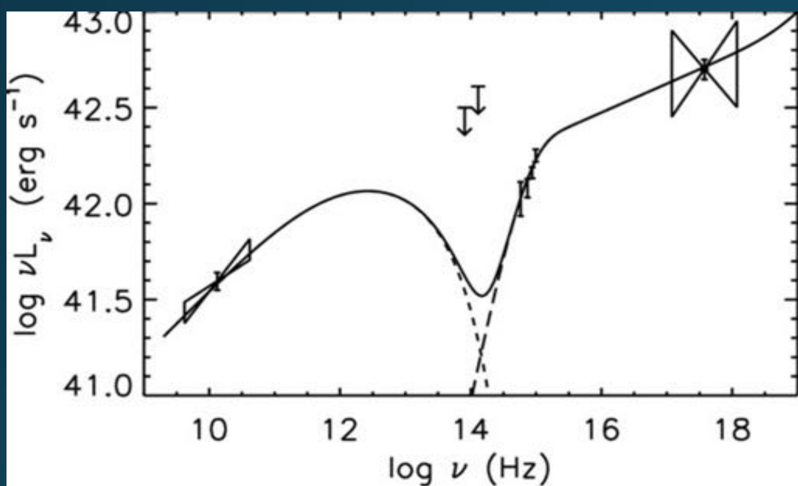


Doubts about the IC/CMB model

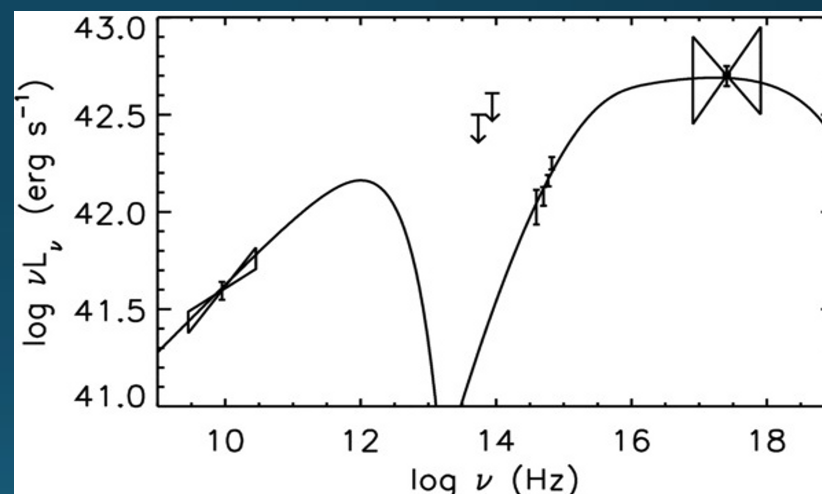
- IC/CMB only works with deceleration (Georganopoulos & Kazanas 2004, Hardcastle 2006)
- IC/CMB requires near or super-Eddington jets in some cases
- Small beaming angle sometimes implies jet lengths > 1 Mpc (longer than the very longest in the plane of the sky)
- In many cases the IC/CMB fit is an "uncomfortable"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

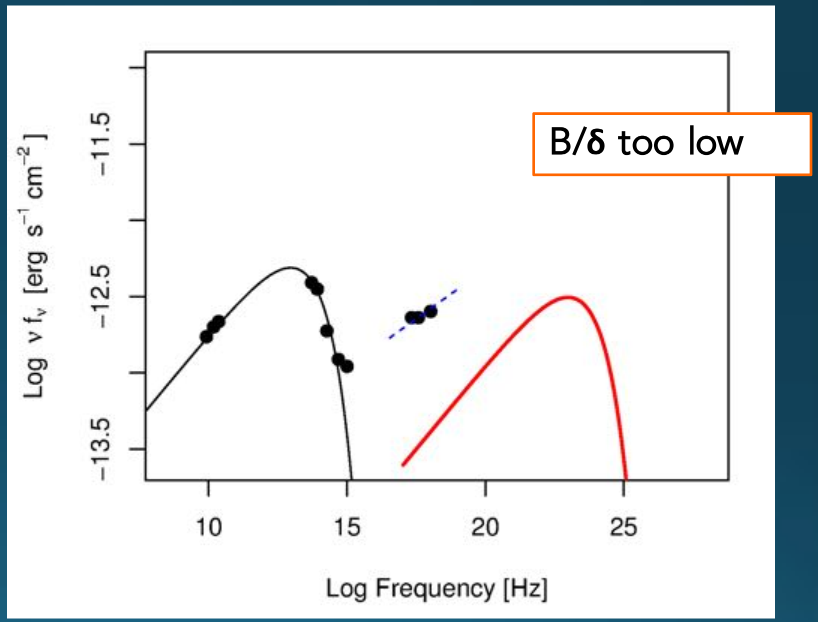
Cara+ 2013 – Showing that X-rays of PKS 1136-135 are synchrotron due to high UV polarization

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]



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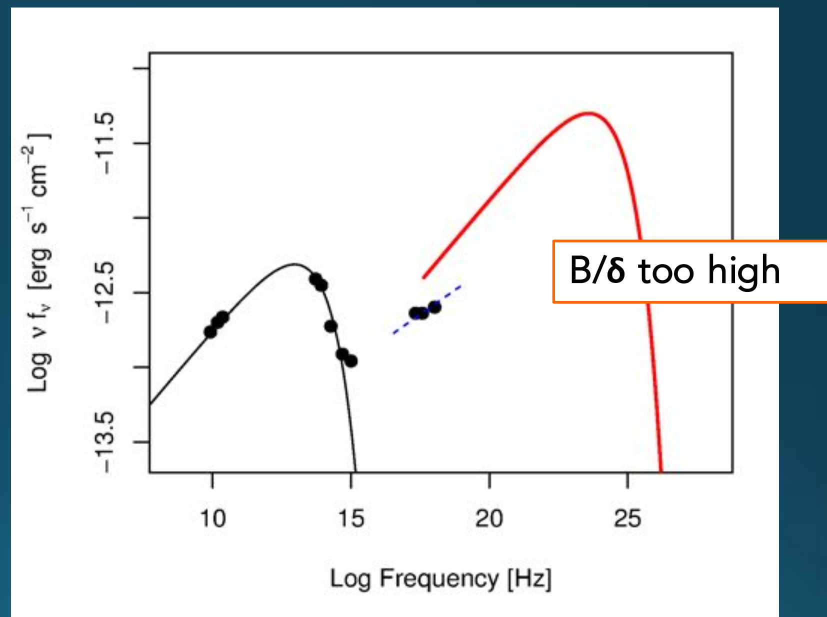

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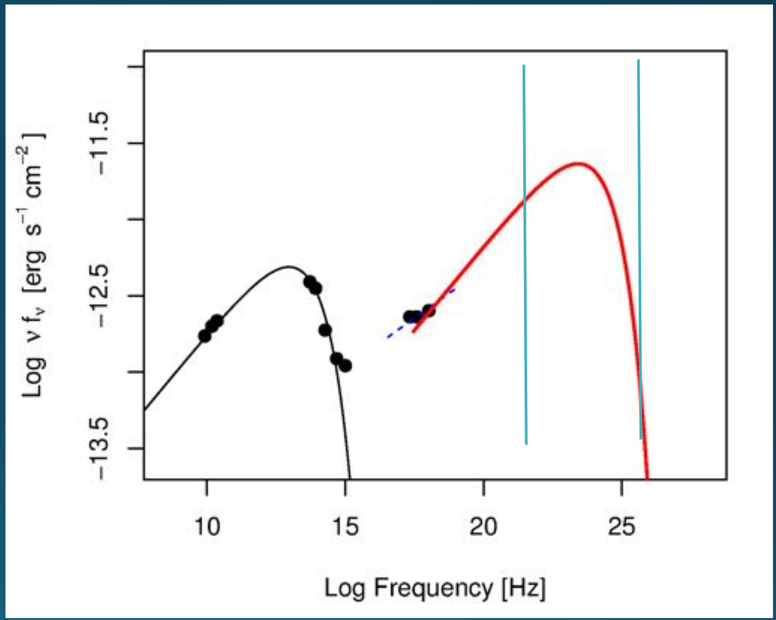
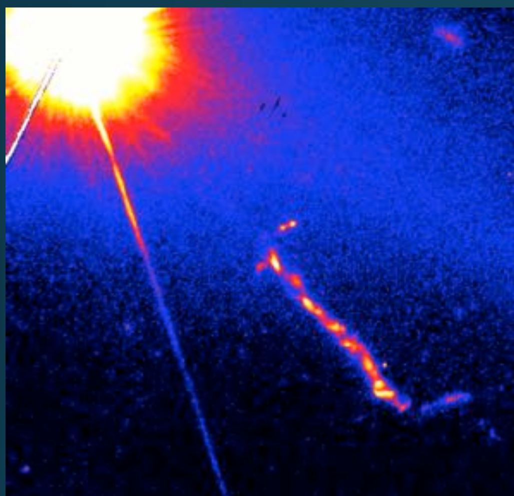


Getting the X-rays just right means fixing B/δ and consequently implies a high level of gamma-ray emission which should be detectable with Fermi

The case of 3C 273

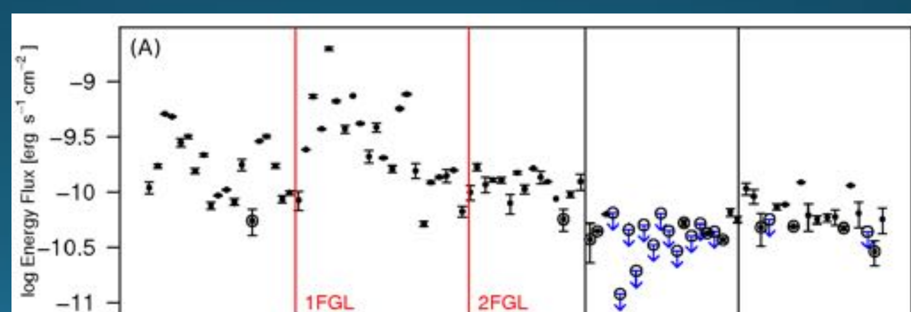


Resolution Issue: From core to end of the jet is ~ 24" - even the 68% PSF at 3 GeV is >10x this scale (few tenths of a degree)

<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.



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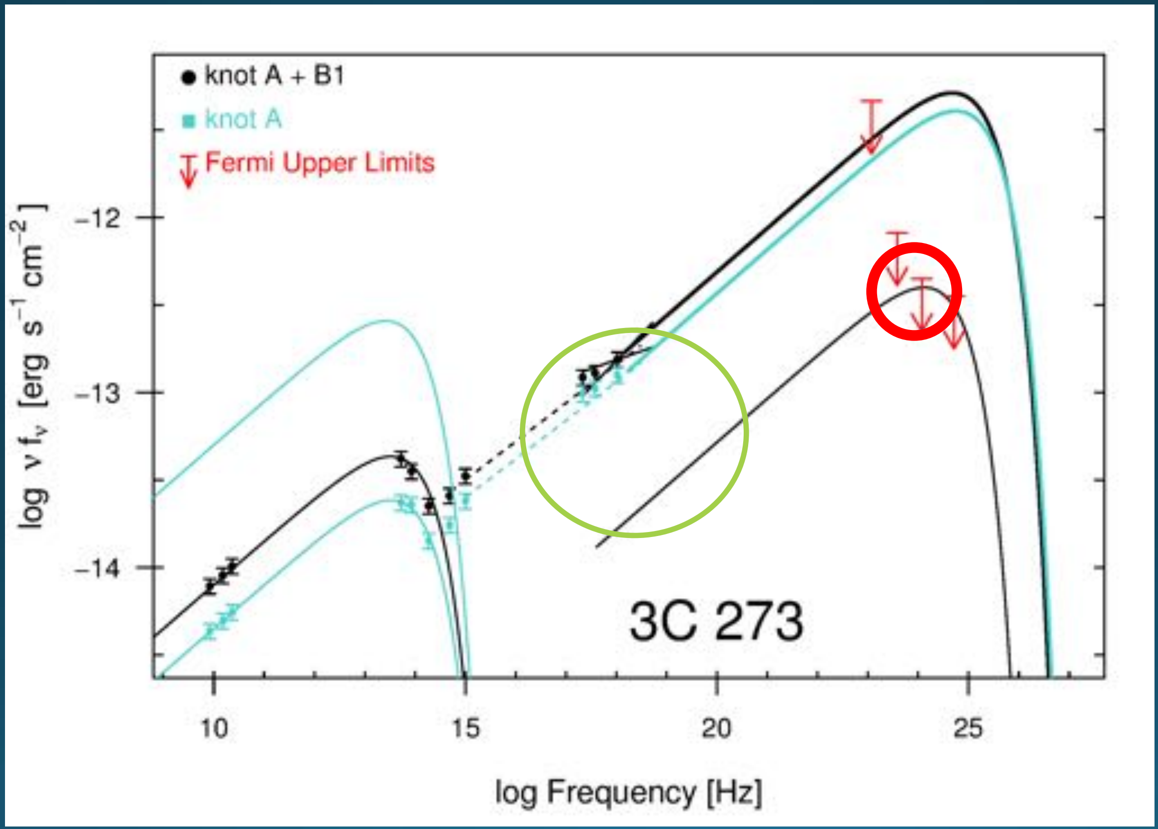
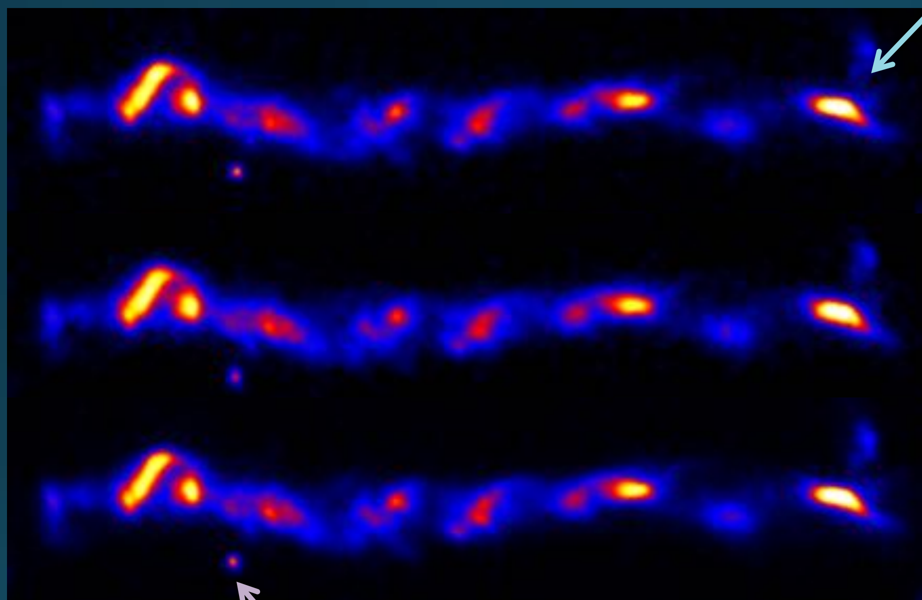


IC/CMB clearly ruled out at the > 99.99% level

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

original result in Meyer & Georganopoulos 2014 ApJ 780, 27

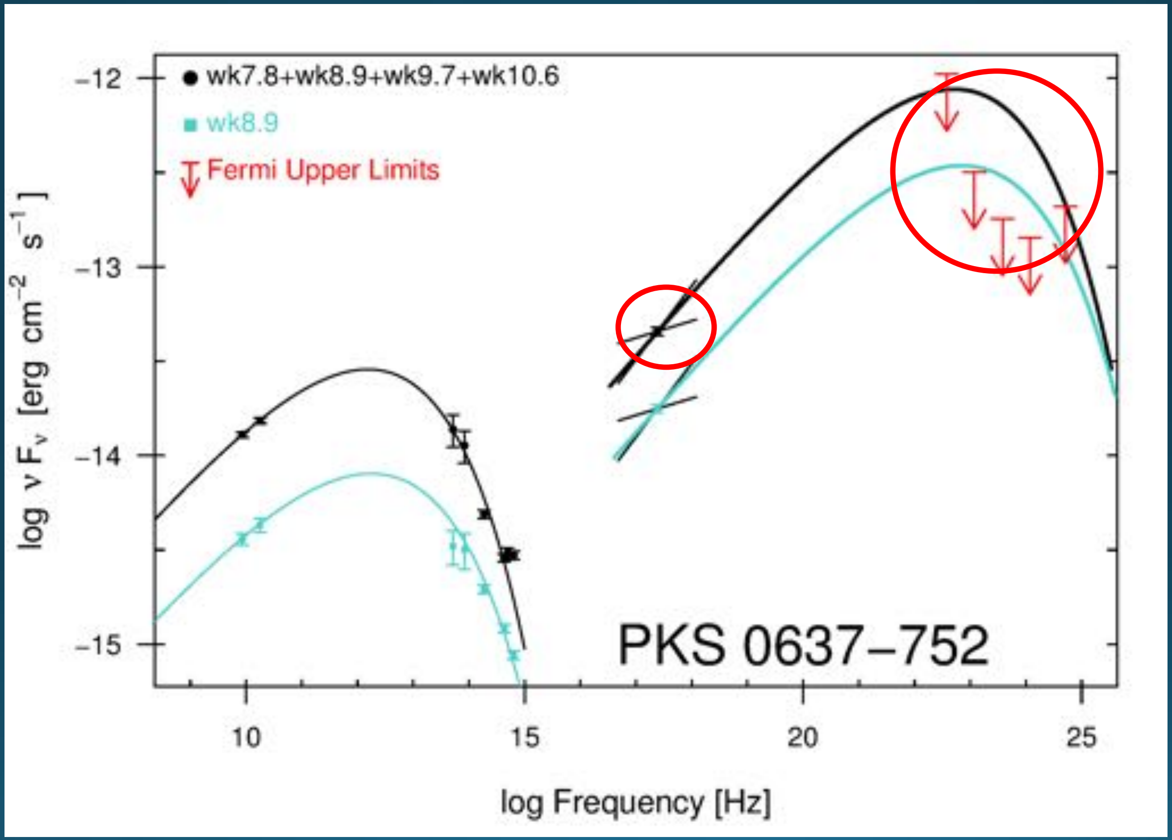
3C 273 another way



Results: no apparent proper motions in any knots.
no flux changes (compare to Pictor A, M87, ...)
Knot A speed limit of < 1c

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

The case of PKS 0637-752

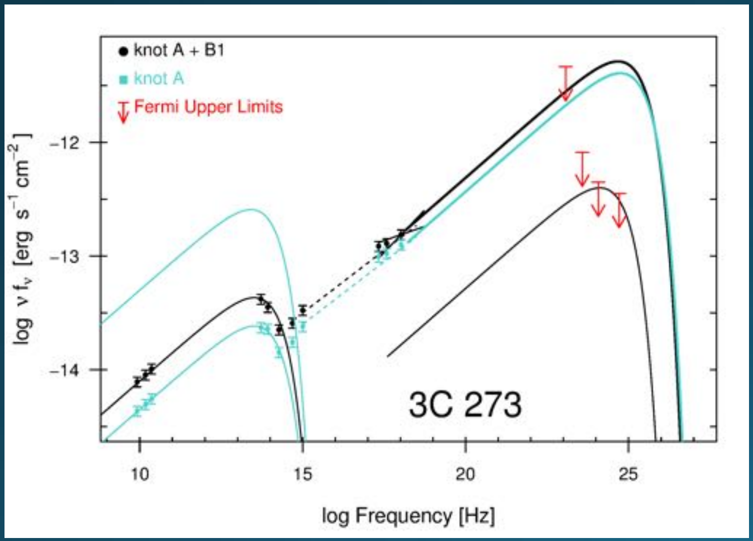


IC/CMB is now ruled out at the > 99.99% level for the original jet for which the model was first proposed!

(Meyer et al. 2015)

Limits on Doppler factor/Magnetic Field

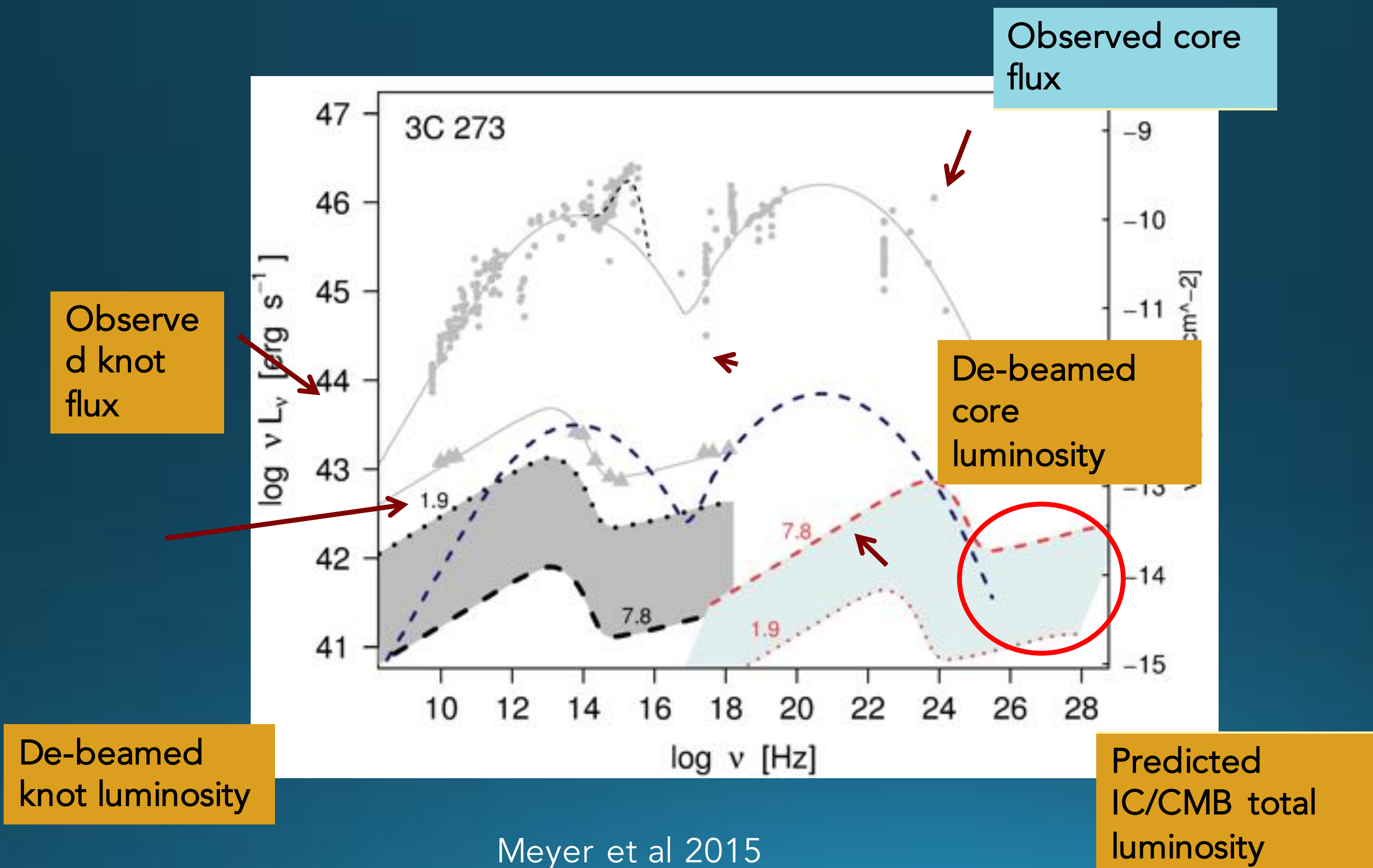
Fermi observations not only rule out IC/CMB X-rays, they put limits on the Doppler beaming factor of jets on kpc scales.



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

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

Consolation Prize: Slow Jets = TeV Emission



Meyer et al 2015

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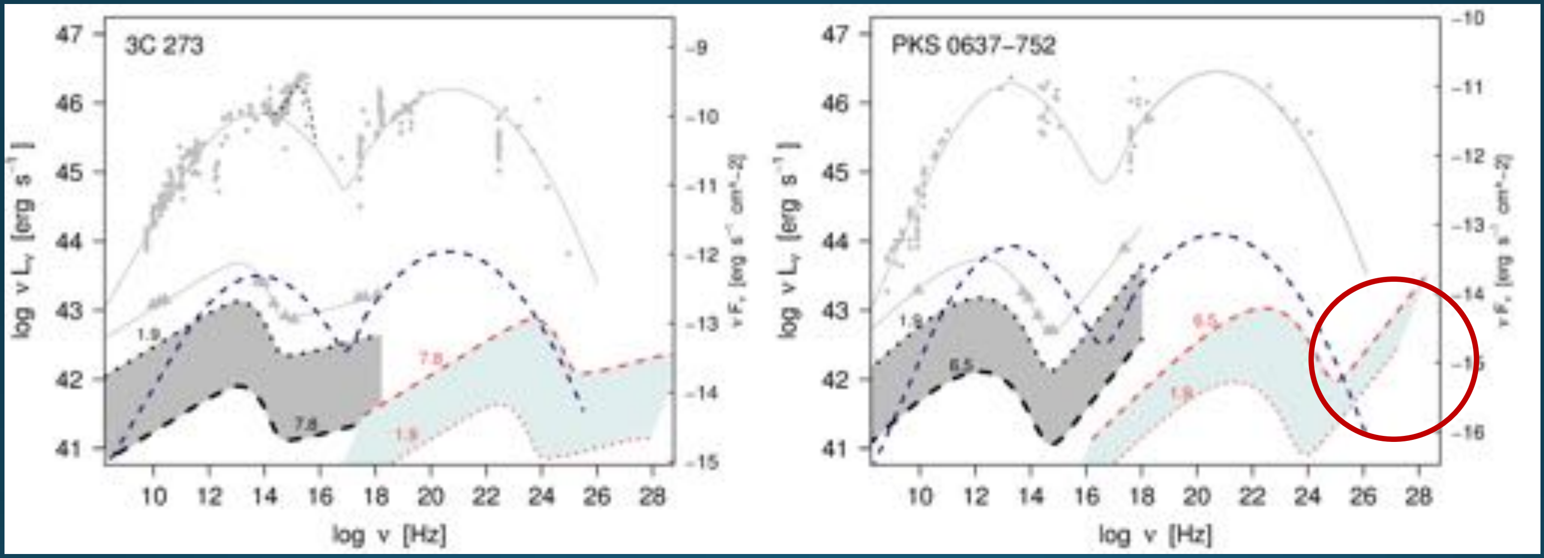
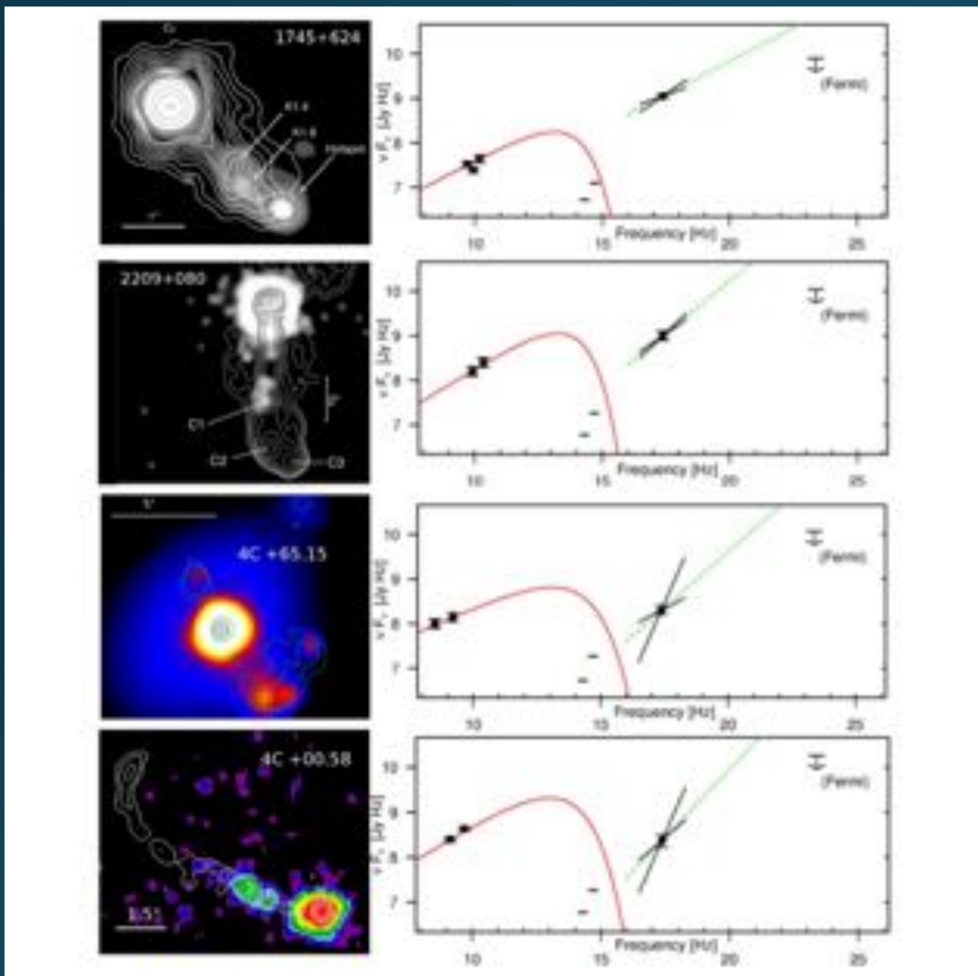


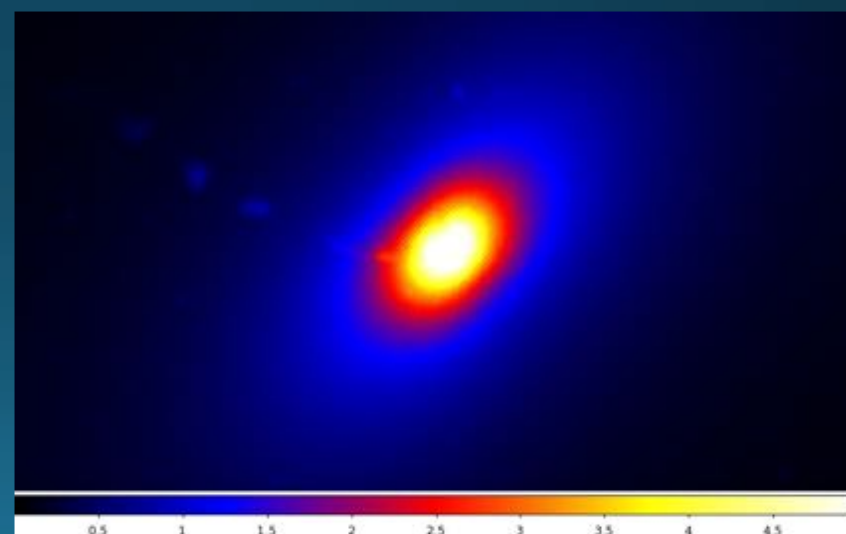
Both 3C 273 and PKS 0637-752 already have predicted IC/CMB TeV emission which is far above the isotropic output of a 'typical' TeV Blazar.

Consolation Prize: Slow Jets = TeV Emission

- TeV heating no longer limited to the relatively low number density (and possibly negatively evolving) TeV BL Lac class.
- Even if the plasma beam instabilities not as efficient as calculated by the Pfrommer et al group (see e.g., Sironi & Giannios 2014), the cumulative effect of all quasar jets may compensate → interesting to study the population effects for input into galaxy evolution simulations.
- TeV heating at high redshifts? → IC/CMB goes up as $(1+z)^4$ (effects on the early Universe?)



What is next? We will be using the Fermi test on at least 8 more jets this year (new Chandra and HST observations)



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

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.

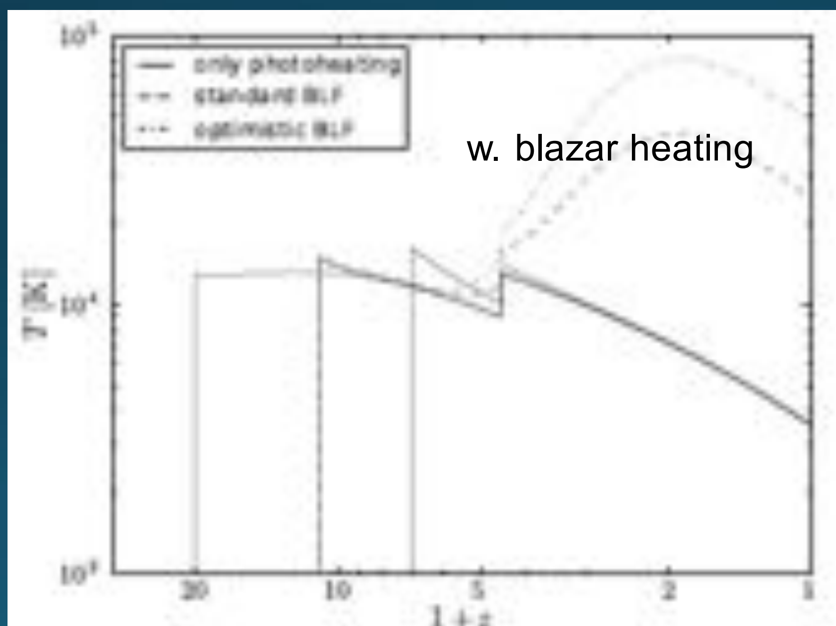
7. Prediction: Either Fermi or CTA will finally detect this component, ultimate proof that the X-rays are synchrotron.

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
- Population study of Anomalous X-ray Jets to estimate TeV heating potential (initial idea paper should be out in a few months, until then see Meyer & Georganopoulos 2015).

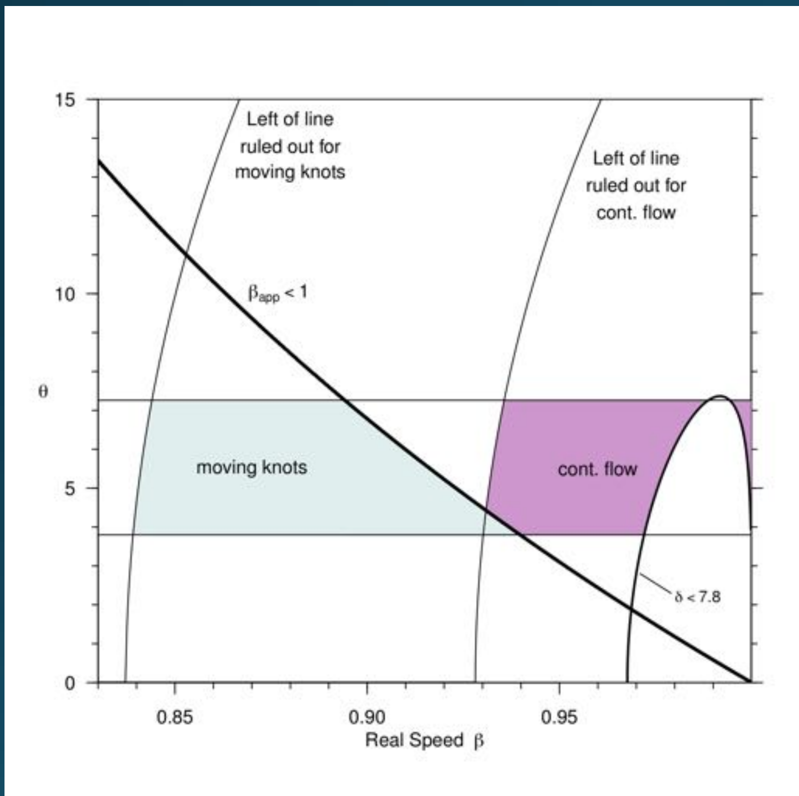
TeV Heating

- Issues that could be solved by Jet Heating:
  - Inverted temperature-density relation in under-dense regions of the IGM



PC, Broderick & Pfrommer (2012)

3C 273 another way



The colored zones at left give the remaining 'allowed' zones given the following constraints:

Bapp = 15 c on parsec-scale (Lister et al 2009)
Jet length < 1 Mpc
Bapp < 1c on kpc scale