Quasar large scale jets: Fast and powerful or weak and slow, but efficient accelerators?

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Talk overview

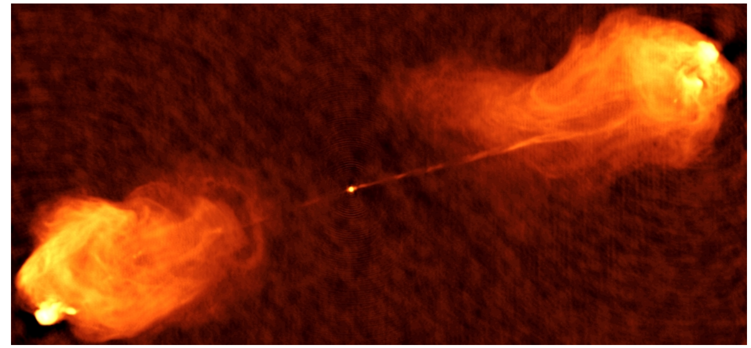
- The situation before Chandra
- Chandra X-ray emission: Synchrotron of Inverse Compton?
- PKS 1136-135: HST polarimetry corners the IC model
- 3C 273: Fermi analysis rules out the IC model
- Where do we want to go from here

Equipartition, the most efficient way for producing a given synchrotron spectrum

Minimum source energy content when:

Magnetic field energy density= radiating electrons energy density

Deviations from equipartition are energetically very expensive



> $L_s \propto n \gamma^2 B^2 \propto \gamma U_p U_B$

> $U = U_p + U_B = U_p + \frac{C}{U_p}$

> $\frac{\partial U}{\partial U_p} = 0 \Rightarrow U_p^2 = C \Rightarrow \boxed{U_p = U_B}$

Equipartition, the most efficient way for producing a given synchrotron spectrum

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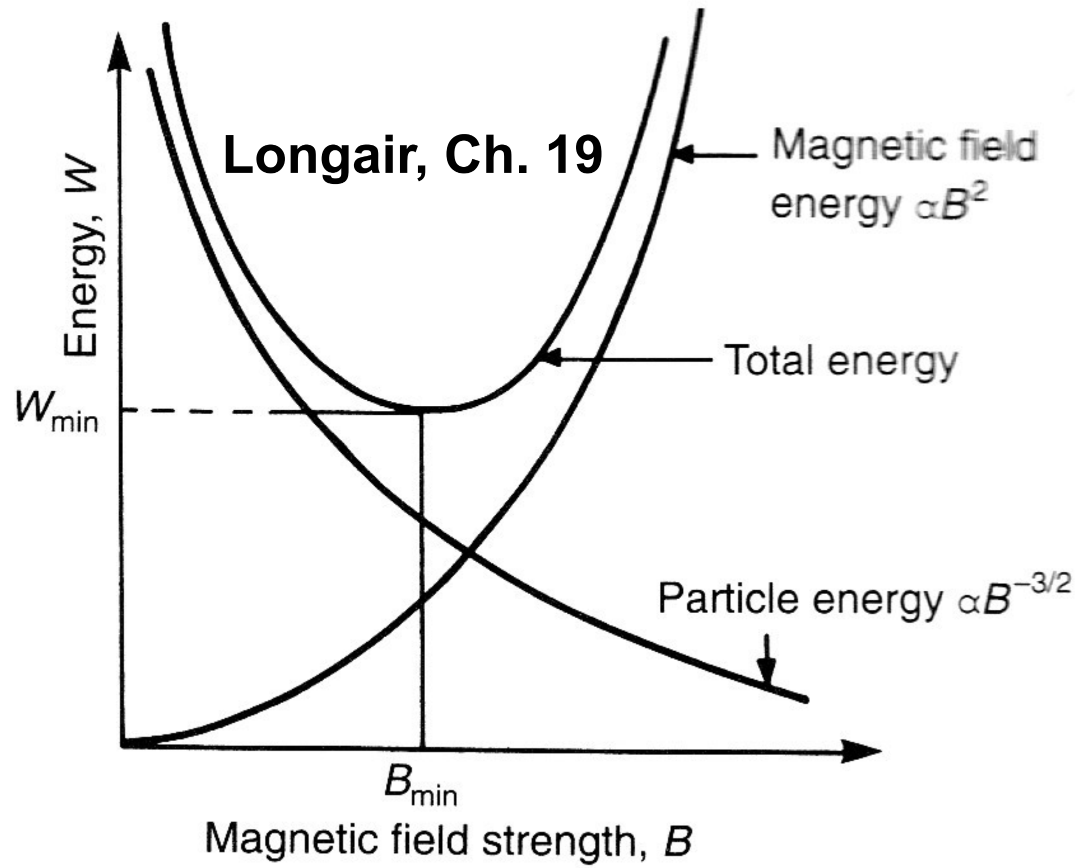
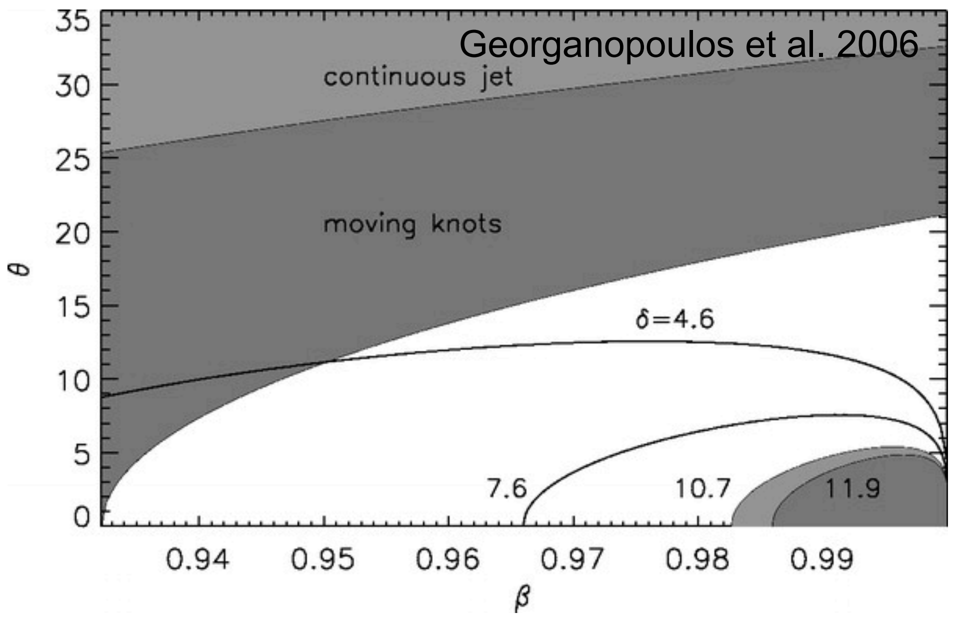


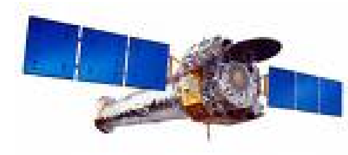
Can we estimate how fast the large scale jets flow?



We can only exclude parts of the β-θ plane from jet to counter-jet flux ratio.

A statistical treatment gives $\beta > \sim 0.6$ for powerful radio galaxies and quasars (Arshakian & Longair 2004)

Just before Chandra



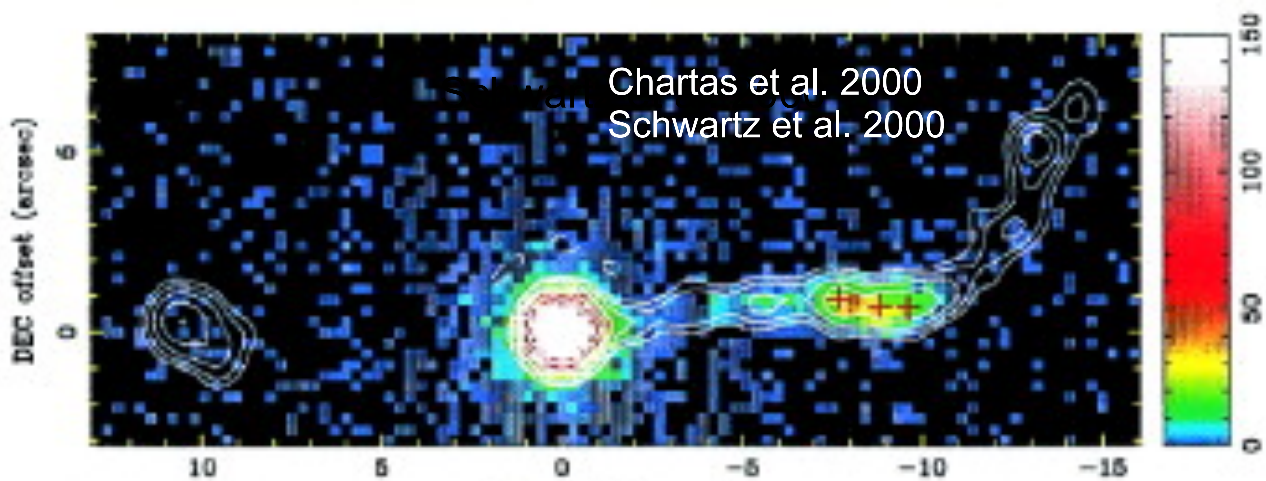
>In equipartition, the level of X-ray emission expected from the jets is very weak.

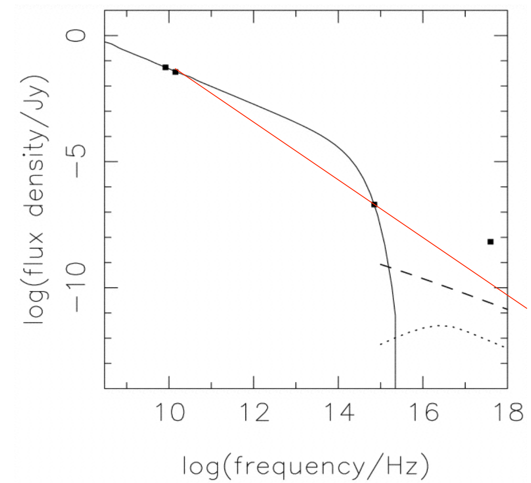
>No significant X-ray emission was expected from the jets of Quasars.

>People were so sure, that they decided to focus the scope using PKS 0637-752, a bright quasar, they thought it would be just a point source.

In an attempt to focus,
Chandra detects the superluminal quasar PKS 0637-752.

projected length~100 Kpc





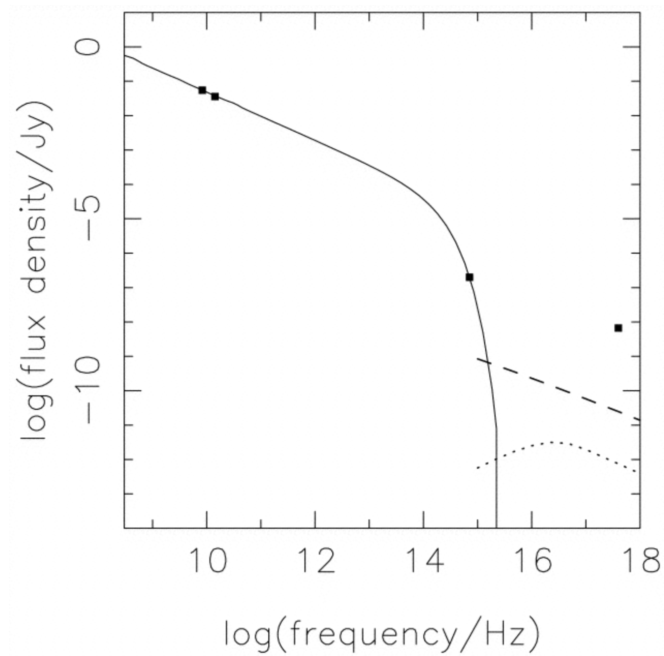
The Knot X-ray emission is not an extension of the radio-optical spectrum, it is a separate component.

What is the X-ray emission?

It is neither SSC (dashed line), nor EC off the CMB (dotted line)

In equipartition and no beaming they both under-produce the X-ray flux by 2-4 orders of magnitude.

Then what is it?



Hint:

Apparent superluminal (u>c) velocities (Lovell et al. 2000):

Relativistic flow (Γ~15) in pc-scale jet pointing close to the observer.

What if the flow remains relativistic at the X-ray knots?

Beamed SSC luminosity in equipartition

- $L_{S,obs} \propto L_S \delta^4$
- $L_S \propto U_p U_B = U_p^2 = U_B^2$

→ $U_B = U_p \propto \delta^{-2}$

- $L_{SSC} \propto U_p U_S$
- $U_S \propto \frac{L_S}{R^2} = \frac{U_p U_B}{R^2}$

→ $L_{SSC} \propto U_p^2 U_B$

→ $L_{SSC,obs} = L_{SSC} \delta^4$

$$L_{SSC,obs} \propto \delta^{-2}$$

For a given synchrotron luminosity, beaming decreases the level of SSC luminosity in equipartition

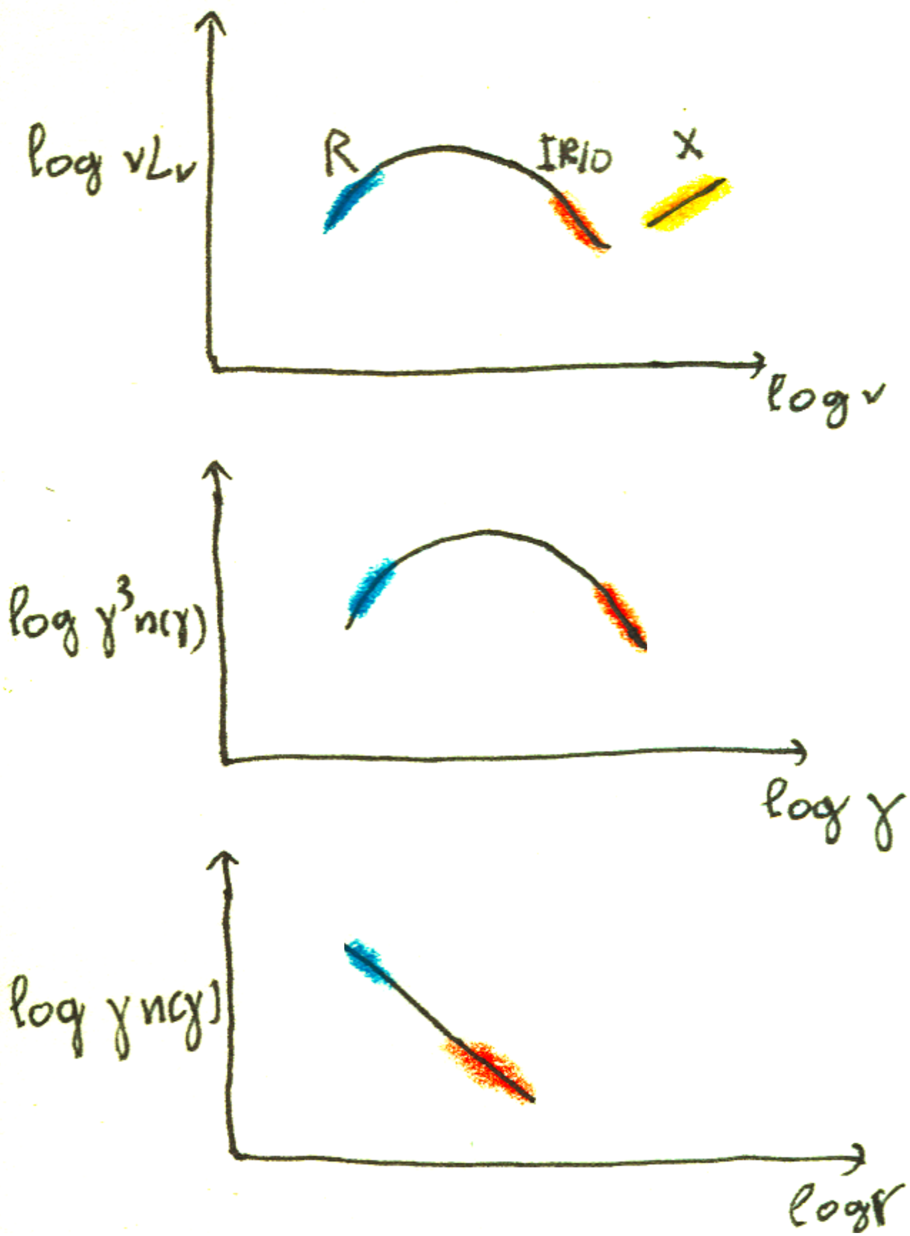
Beamed EC luminosity in equipartition

- $L_{EC} \propto U_p \, \Gamma^2 U_{ext}$
- $L_{EC,obs} = L_{EC} \frac{\delta^6}{\Gamma^2}$
- $U_p \propto \delta^{-2}$

$$L_{EC,obs} \propto \delta^4$$

For a given synchrotron luminosity, beaming increases the level of EC luminosity in equipartition

What is the X-ray emission mechanism?



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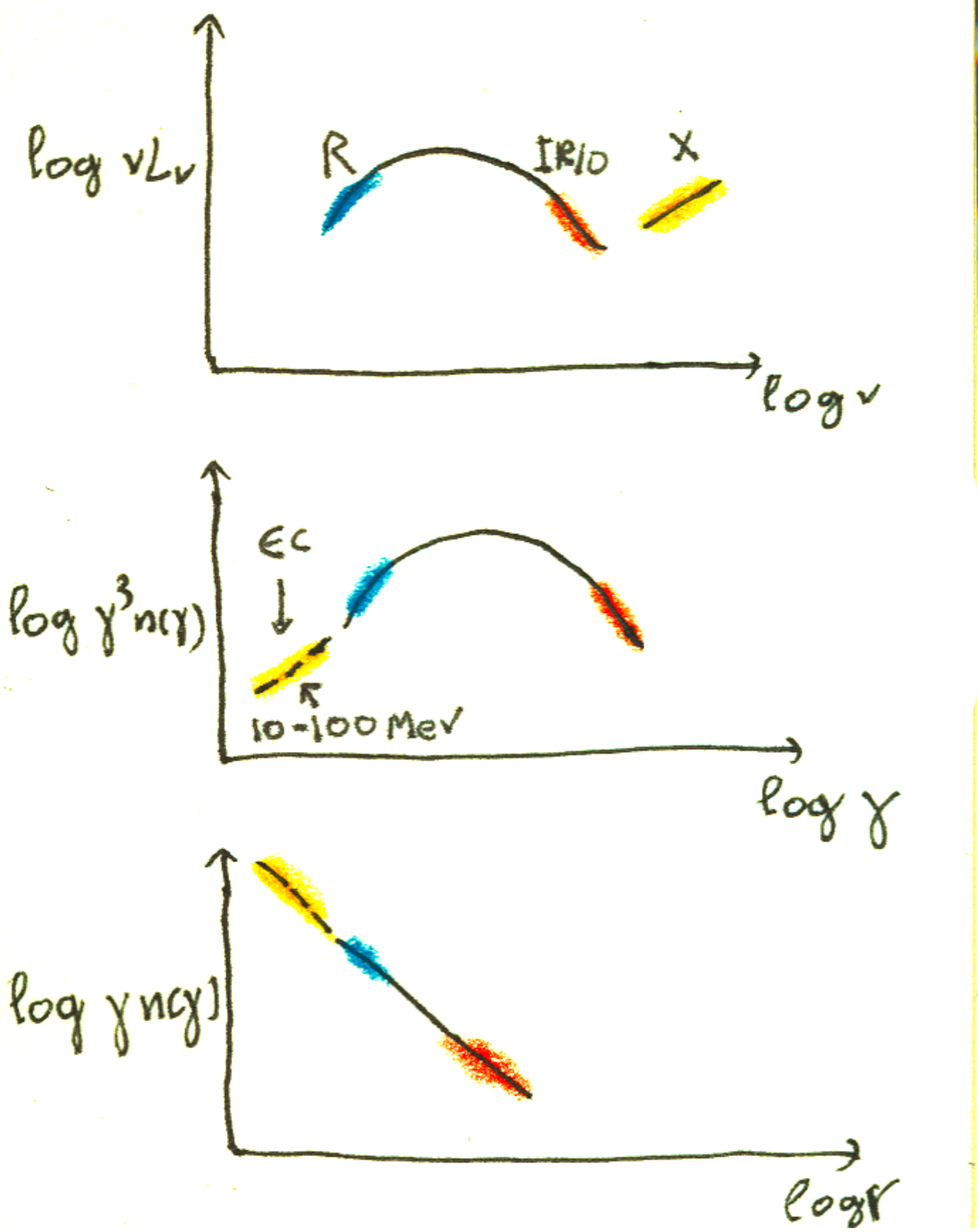


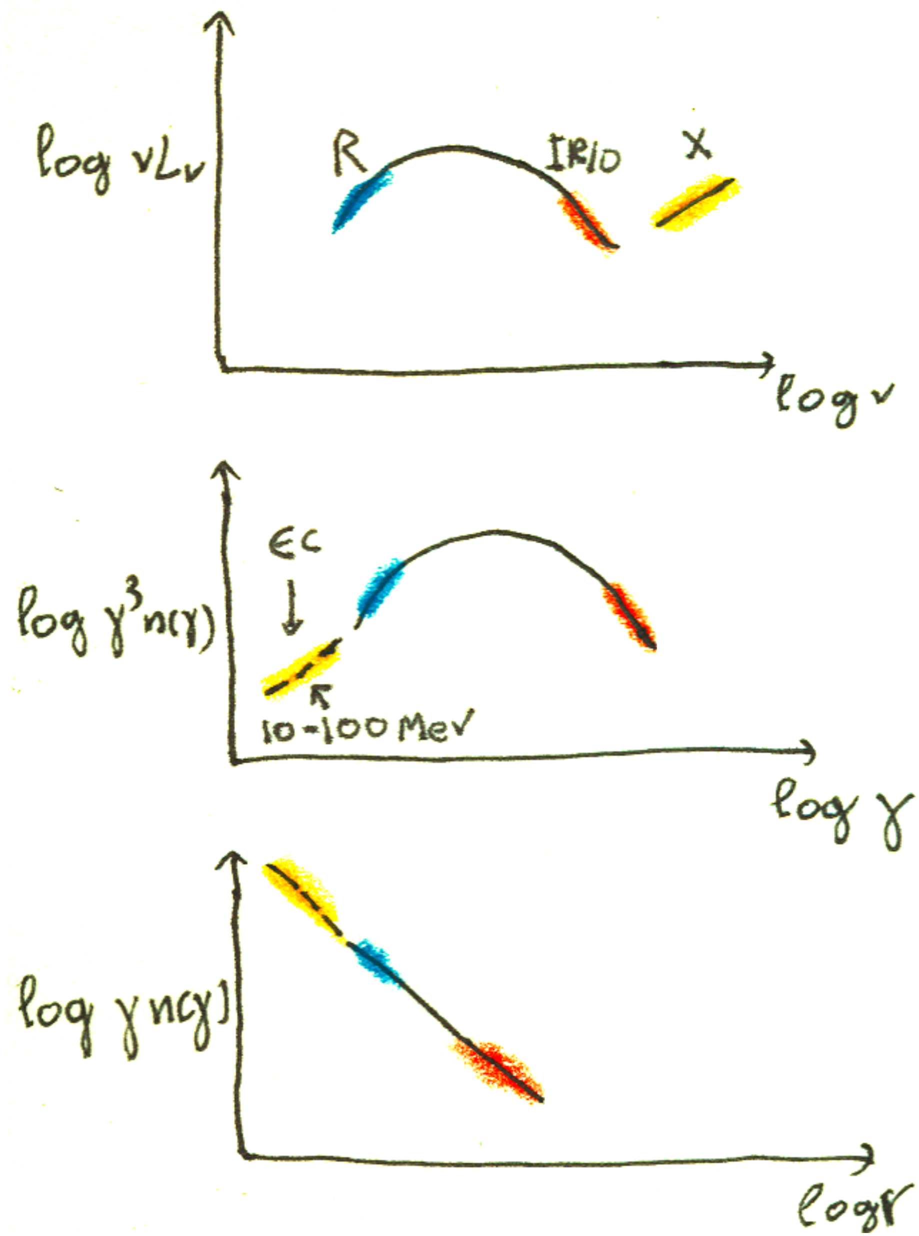
What is the X-ray emission mechanism?

Inverse Compton scattering off the CMB (EC/CMB)
(Tavecchio et al. 2000, Celotti et al. 2001)

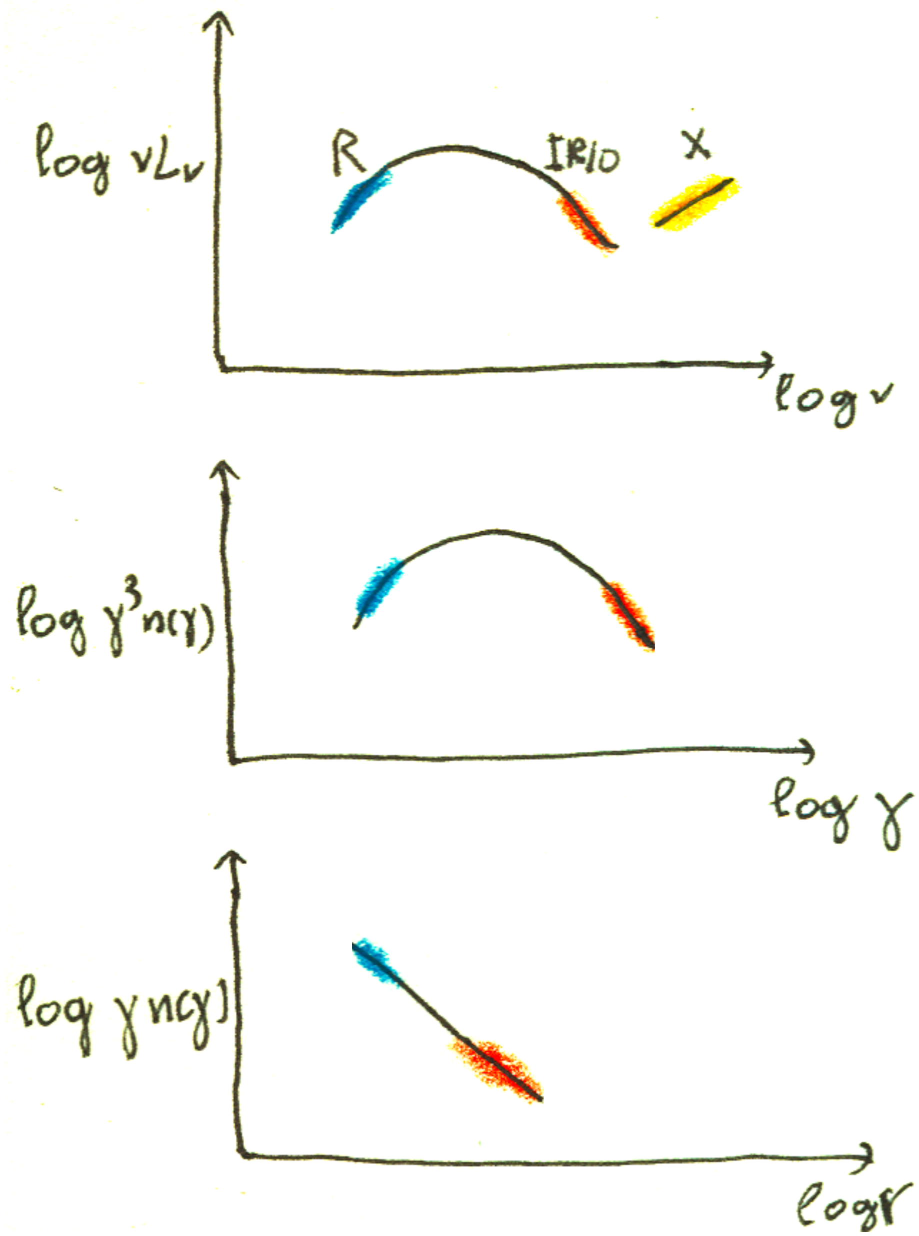
Extends the electron energy distribution (EED) down to 10 -100 MeV energies

Requires relativistic large scale jets (δ~10)

Increased jet power requirements, radiatively inefficient (Dermer & Atoyan 2002, 2004)



What is the X-ray emission mechanism?



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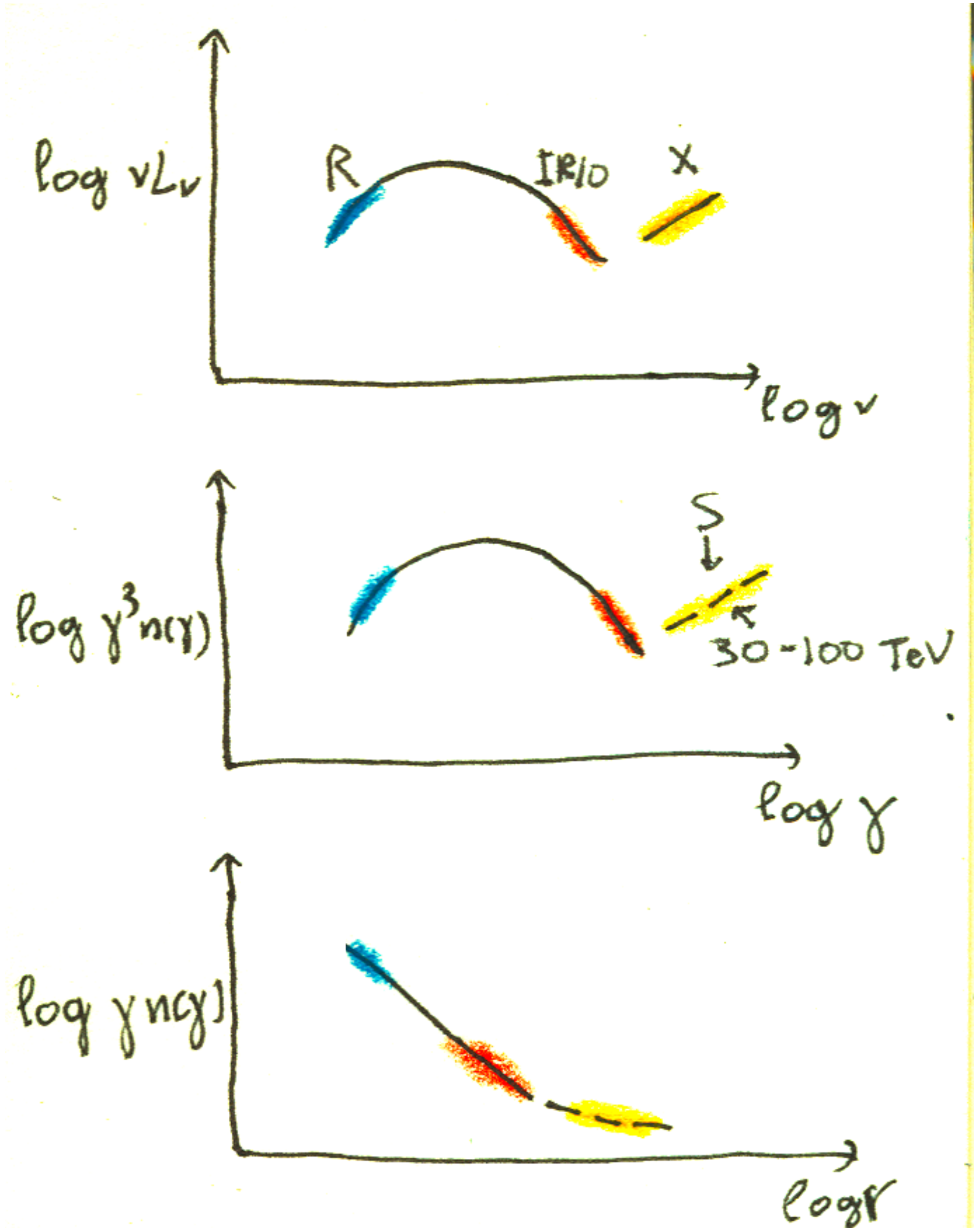


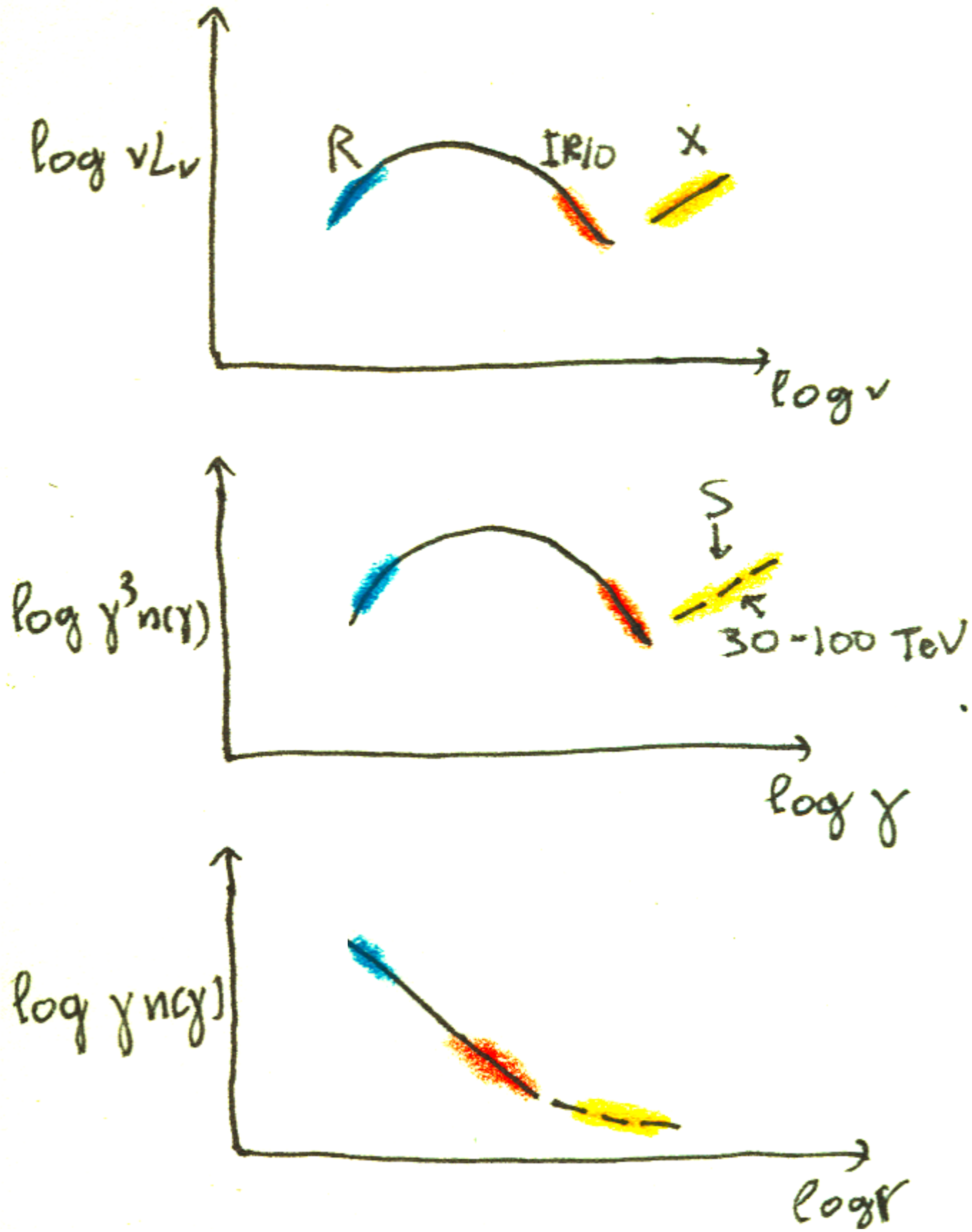
What is the X-ray emission mechanism?

Synchrotron
(e.g. Harris et al. 2004, Hardcastle 2006)

Additional EED component at ~1-100 TeV energies

No need for highly relativistic large scale jet

More economical in jet power, radiatively efficient

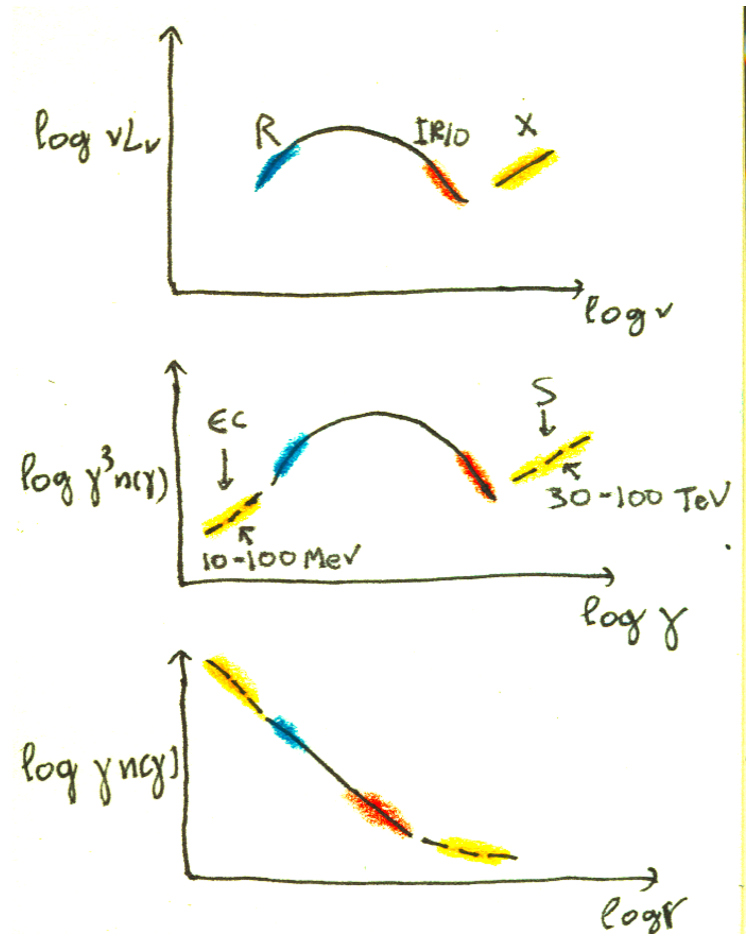


1. The EED in EC/CMB model cuts off of at sub-TeV energies. The EED in the synchrotron model extends to 30-100 TeV.

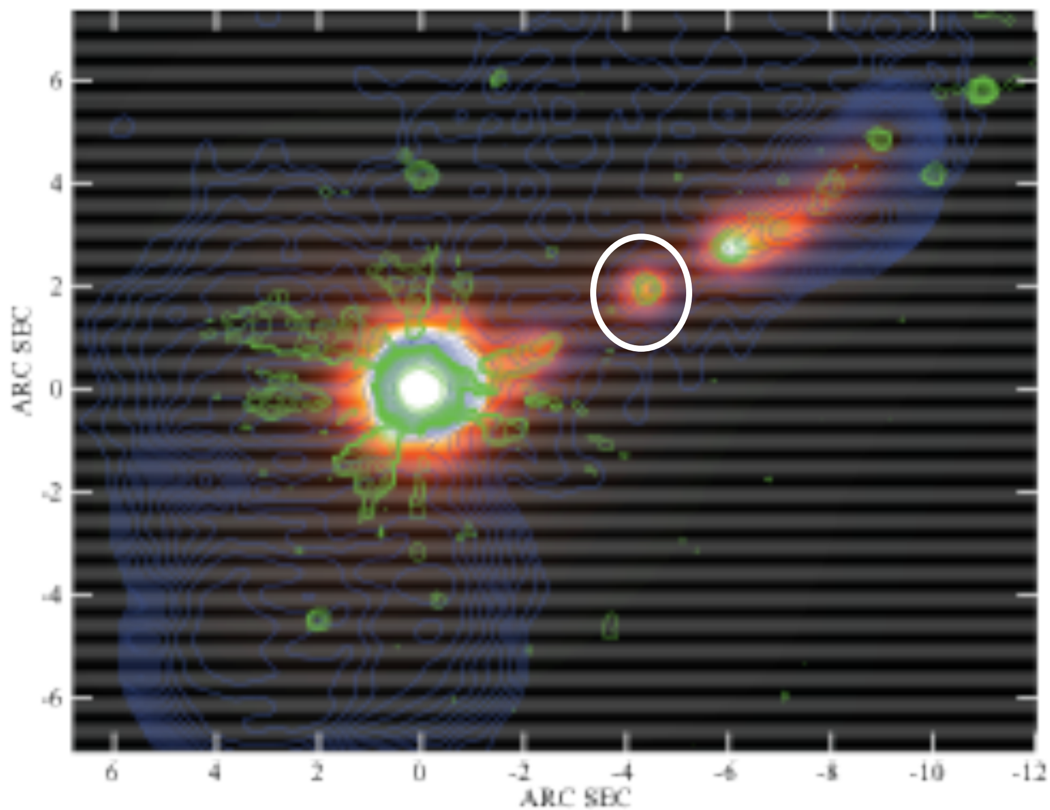
2. The EED in the EC/CMB model has to be extended to very low energies.

3. The jet in the EC/CMB case has to remain highly relativistic (Γ~10-20) at kpc scales.

2,3 => The EC/CMB requires a high jet power (Dermer & Atoyan 2004)



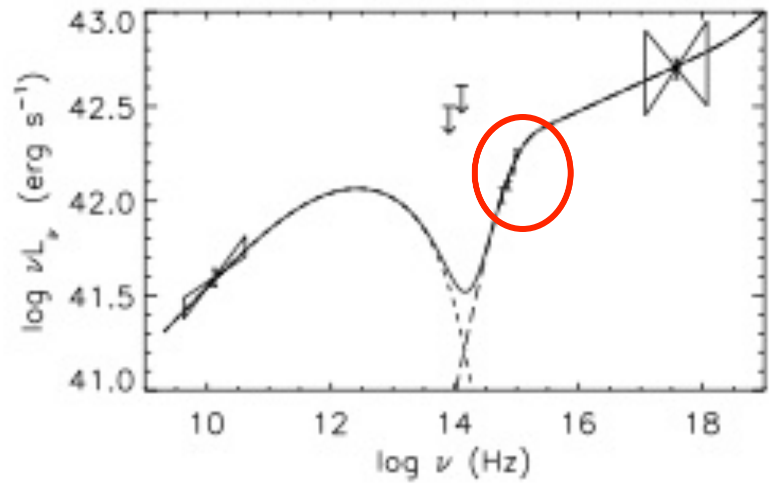
PKS 1136-135



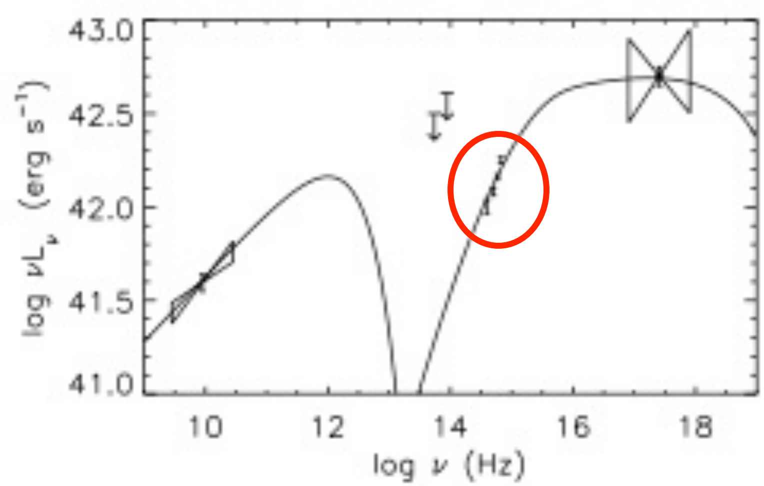
VLA (blue contours) and HST F555W (Green contours) on the Chandra image (color). Cara et al. 2013

PKS 1136-135

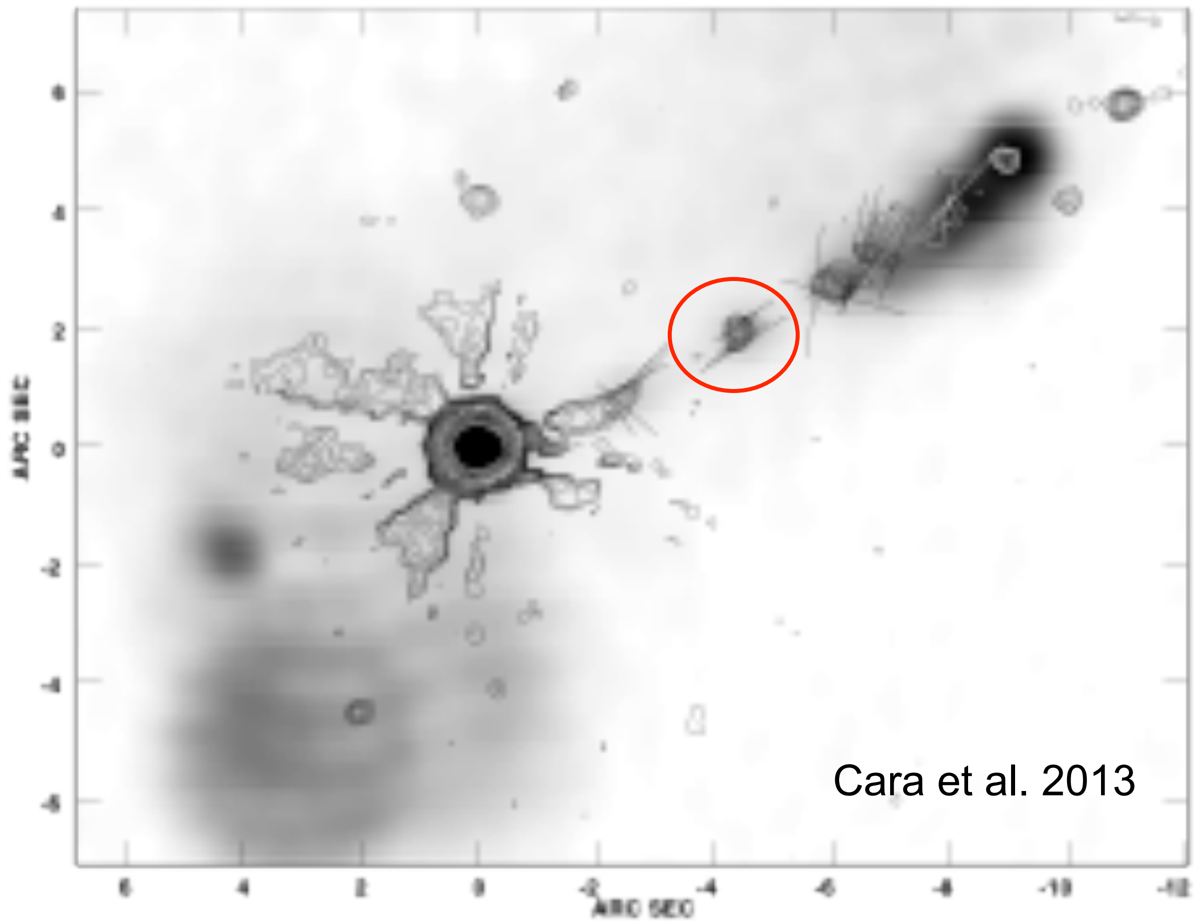
Modeling of knot A: Both EC/CMB and Synchrotron models can reproduce the SED (Cara et al. 2013).



<u>Important:</u> The optical emission is the tail of the high energy component.

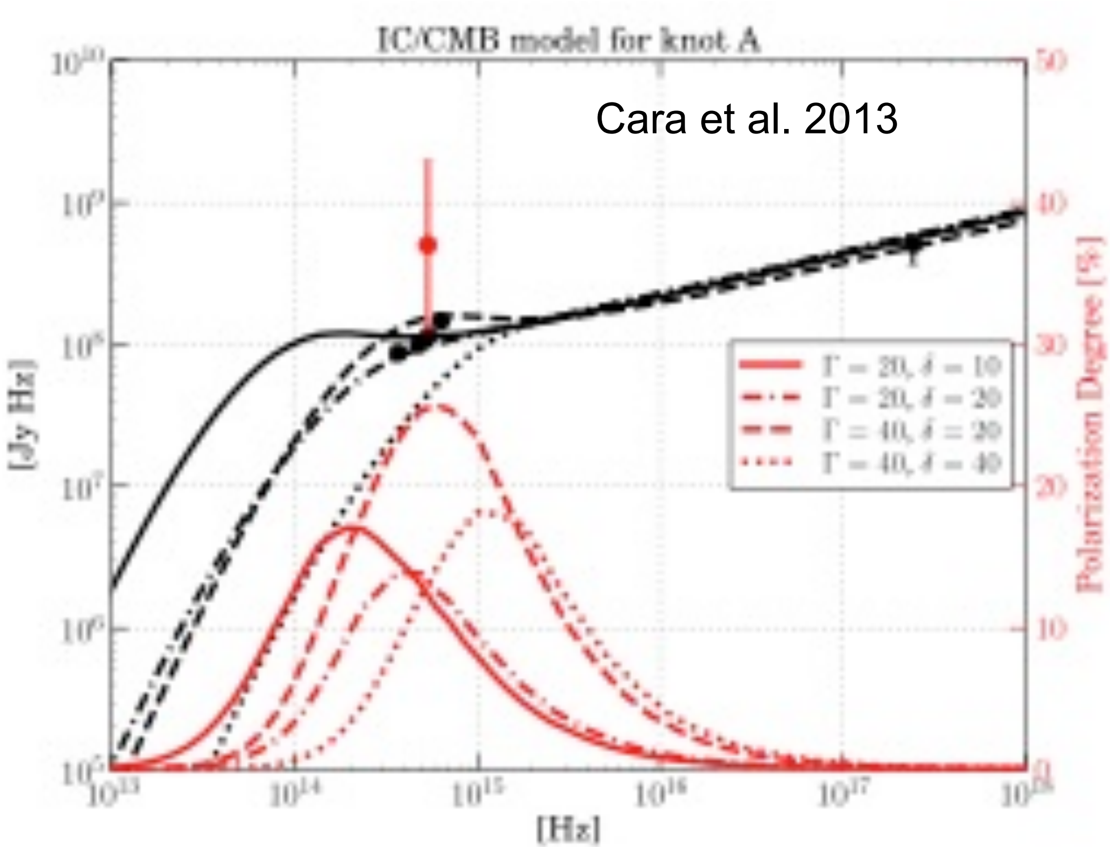


PKS 1136-135



The HST F555W flux of knot A is 37±6 % polarized.

PKS 1136-135

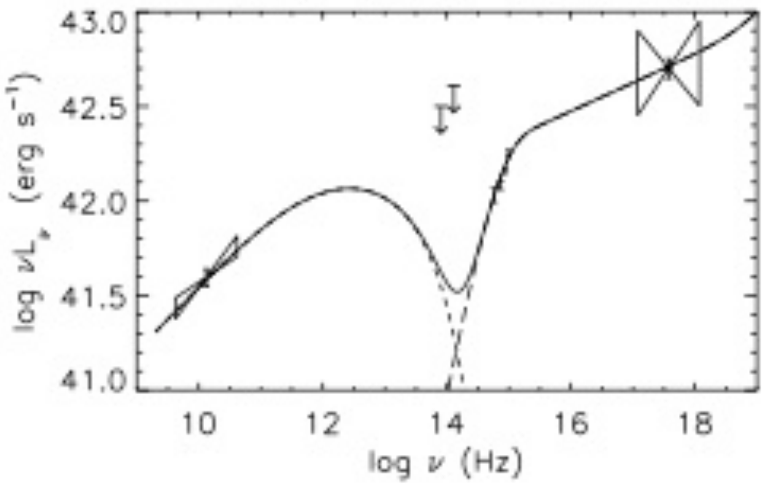


Best case for EC/CMB
Γ=40,
δ=20,
γ_{min}=1.2
In 2σ agreement
with the observations

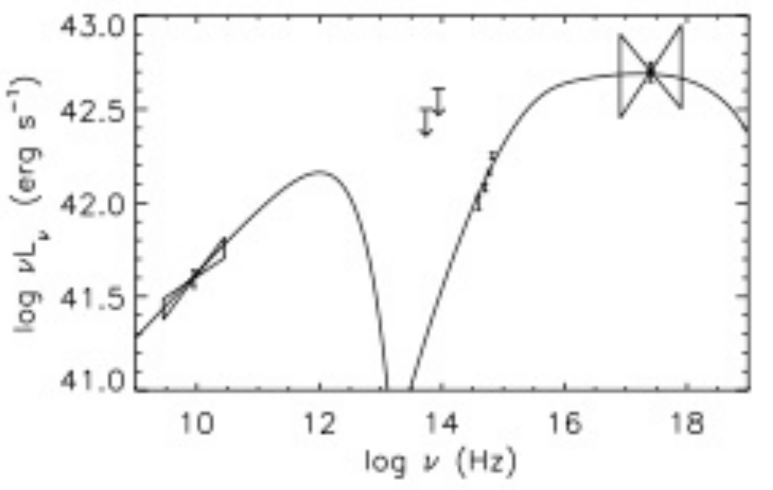
To reproduce this as EC/CMB, the low energy cutoff of the EED has to be very low and the flow very fast (Uchiyama & Coppi in prep).

PKS 1136-135

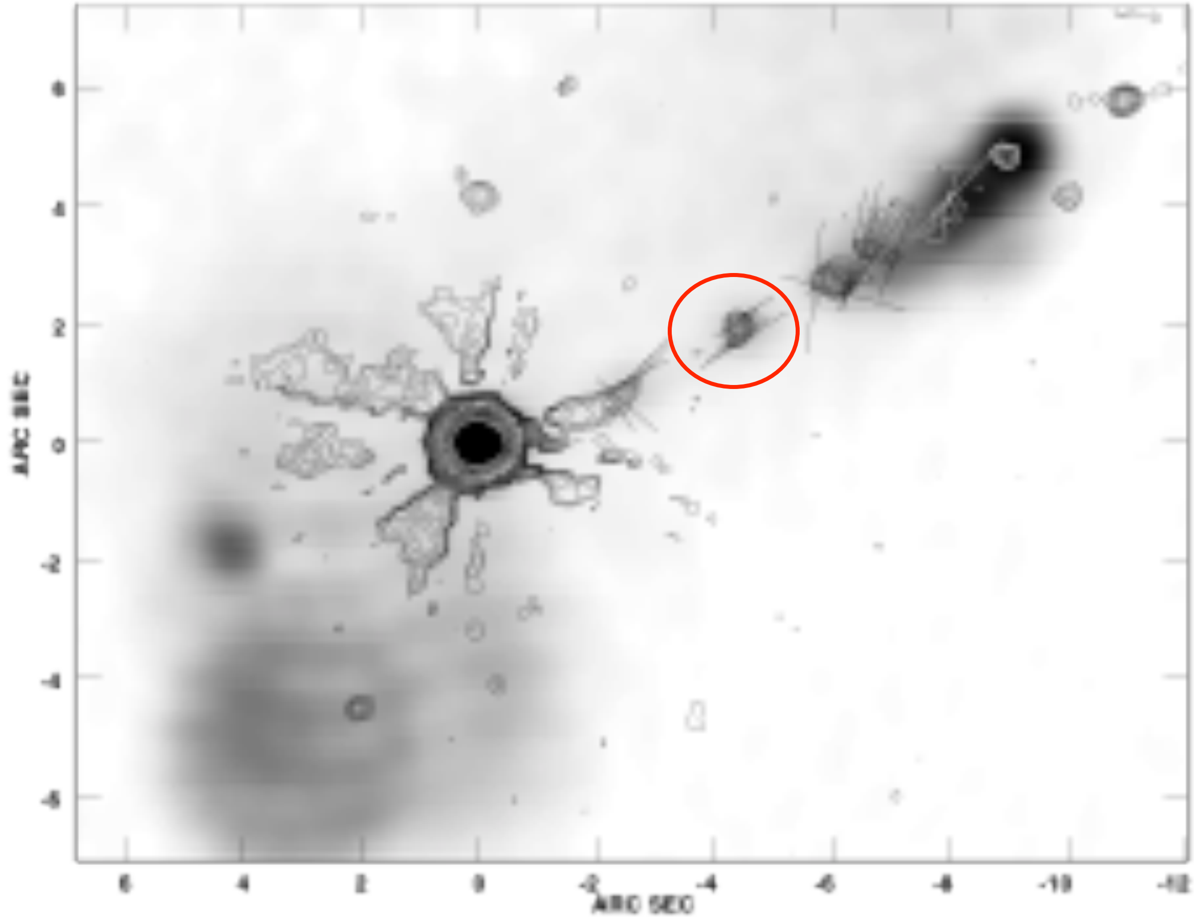
EC/CMB:
$\Gamma=40, \delta=20, \theta=2.48^{o.}$
$\gamma_{max}=3\times10^5$
De-projected length=1.6 Mpc,
Jet power: $L_{jet}=34 \times L_{edd,9}$



Synchrotron model:
$\Gamma=\delta=2, \theta=30^{o.}$
$\gamma_{max}=2\times10^8$
De-projected length=140 kpc,
Jet power: $L_{jet}=0.07 \times L_{edd,9}$



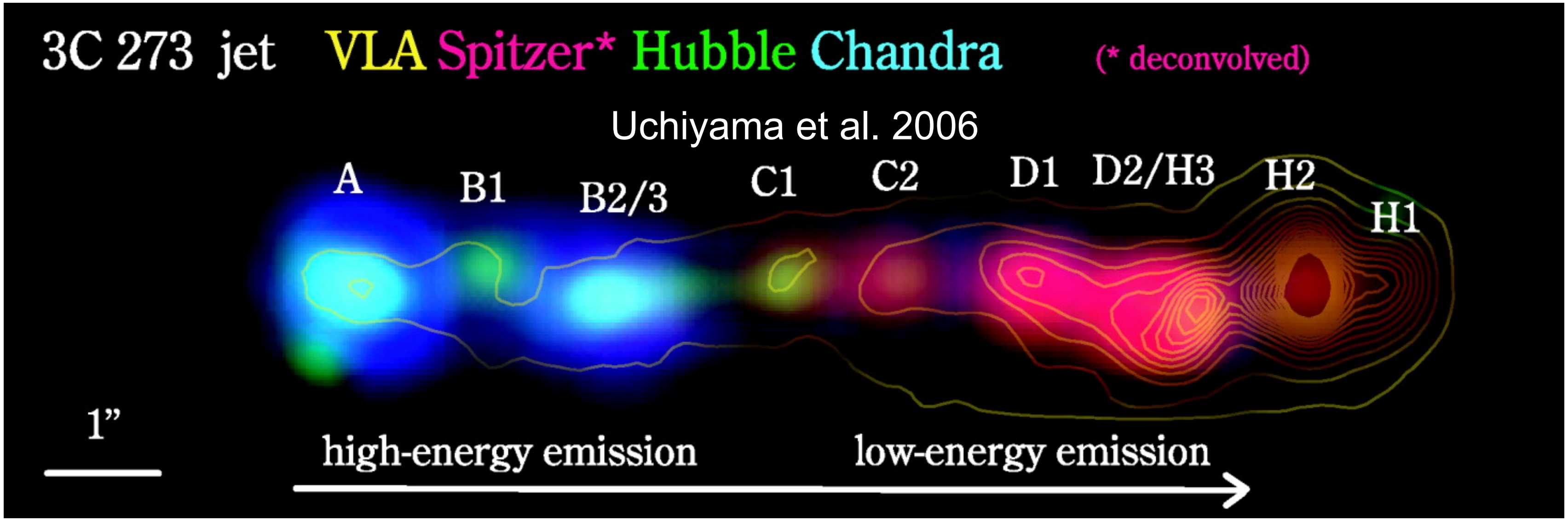
PKS 1136-135



EC/CMB IS DISFAVORED BUT NOT YET REJECTED

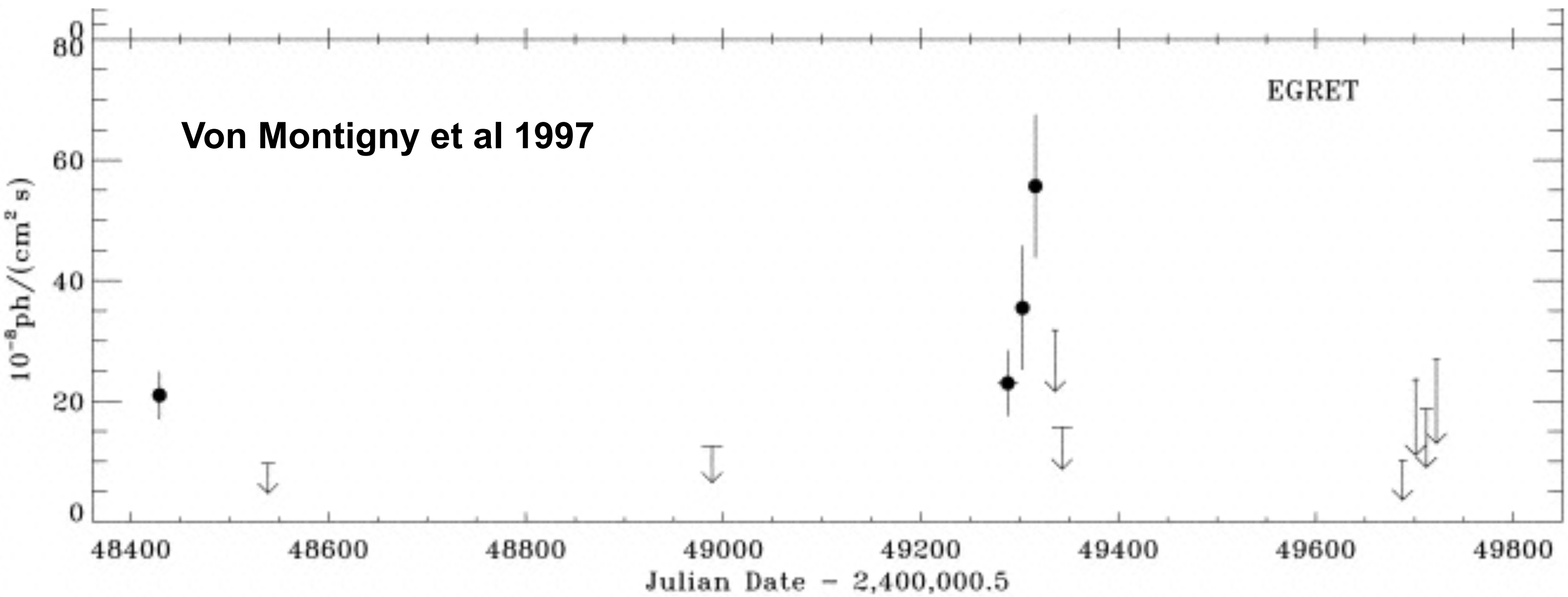
3C 273

The γ-ray observed emission is the sum of the variable blazar component and the steady large scale jet emission.

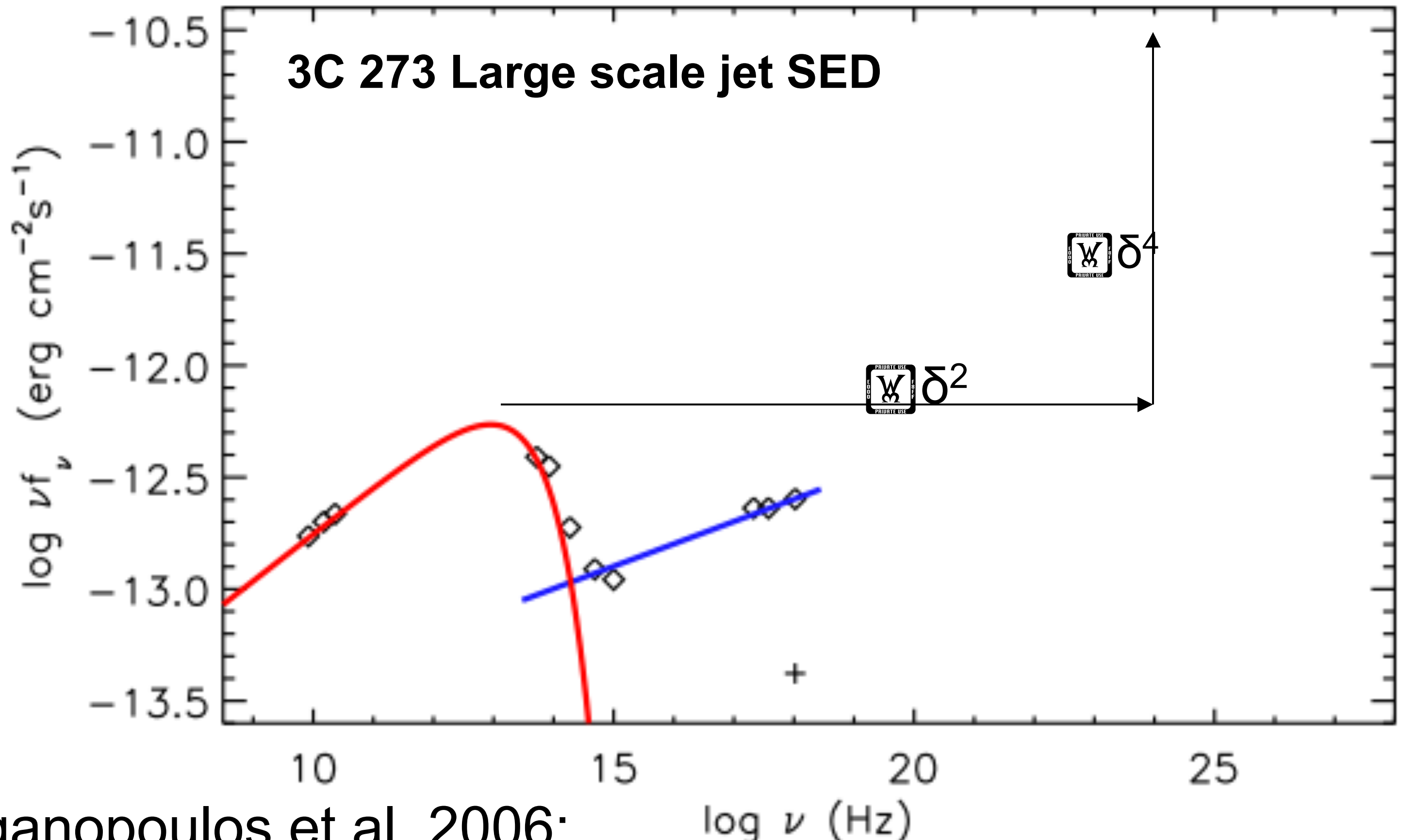


3C 273 was below the EGRET sensitivity limit for more than half of the times it was observed.

The lowest GeV flux observed is an upper limit for the large scale jet flux.

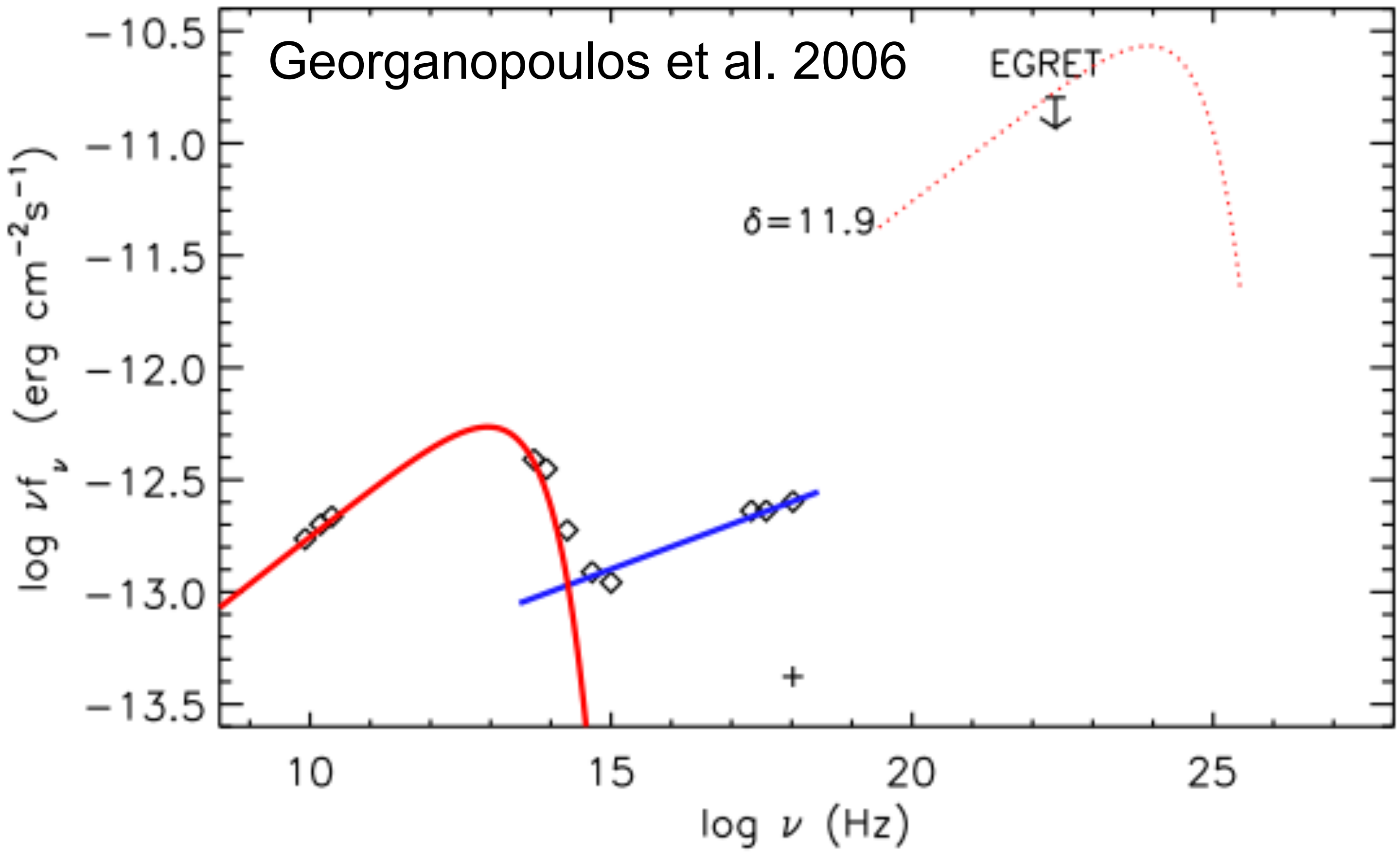


What γ-ray emission do we expect from the large scale jet radio to optically emitting electrons?

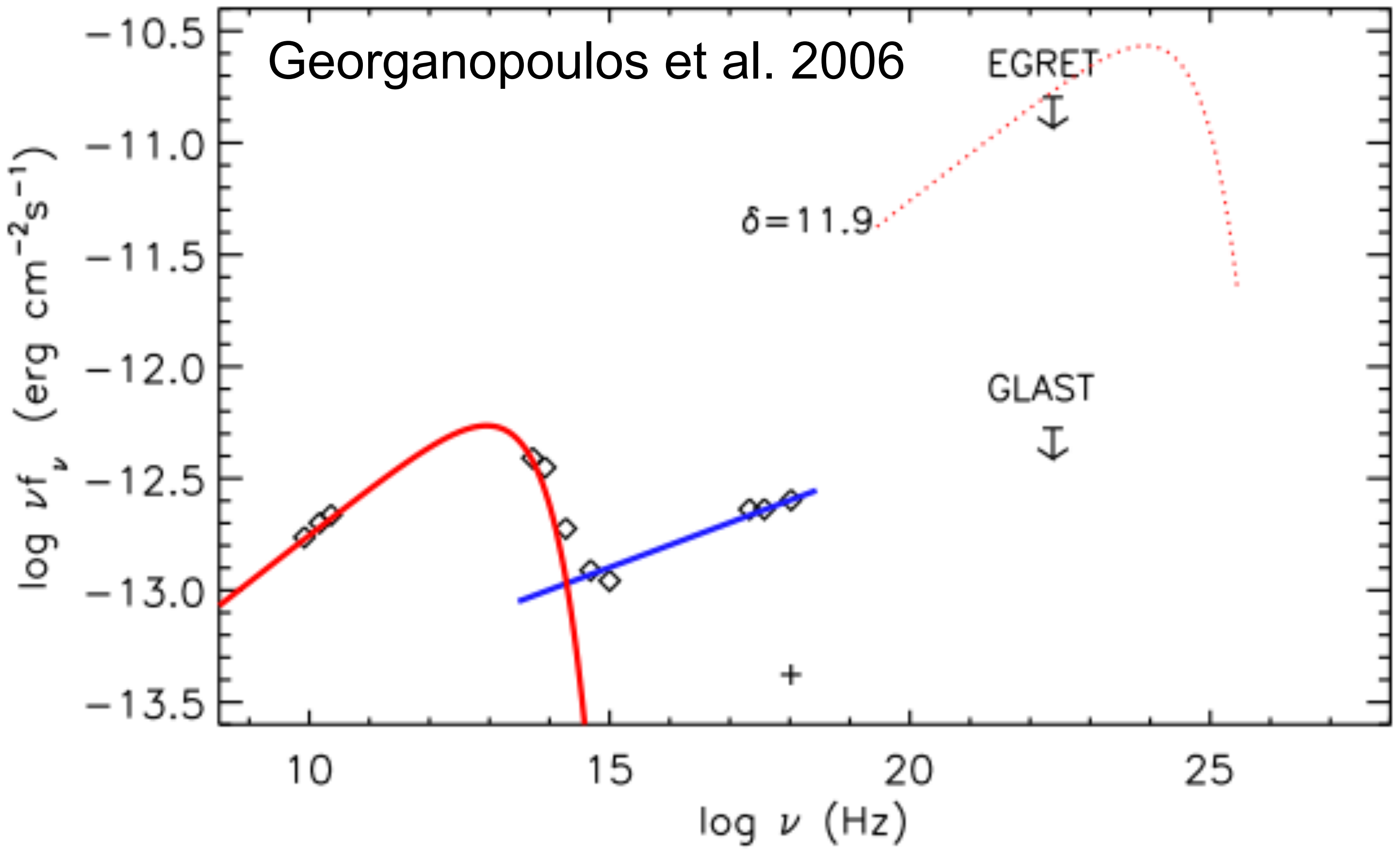


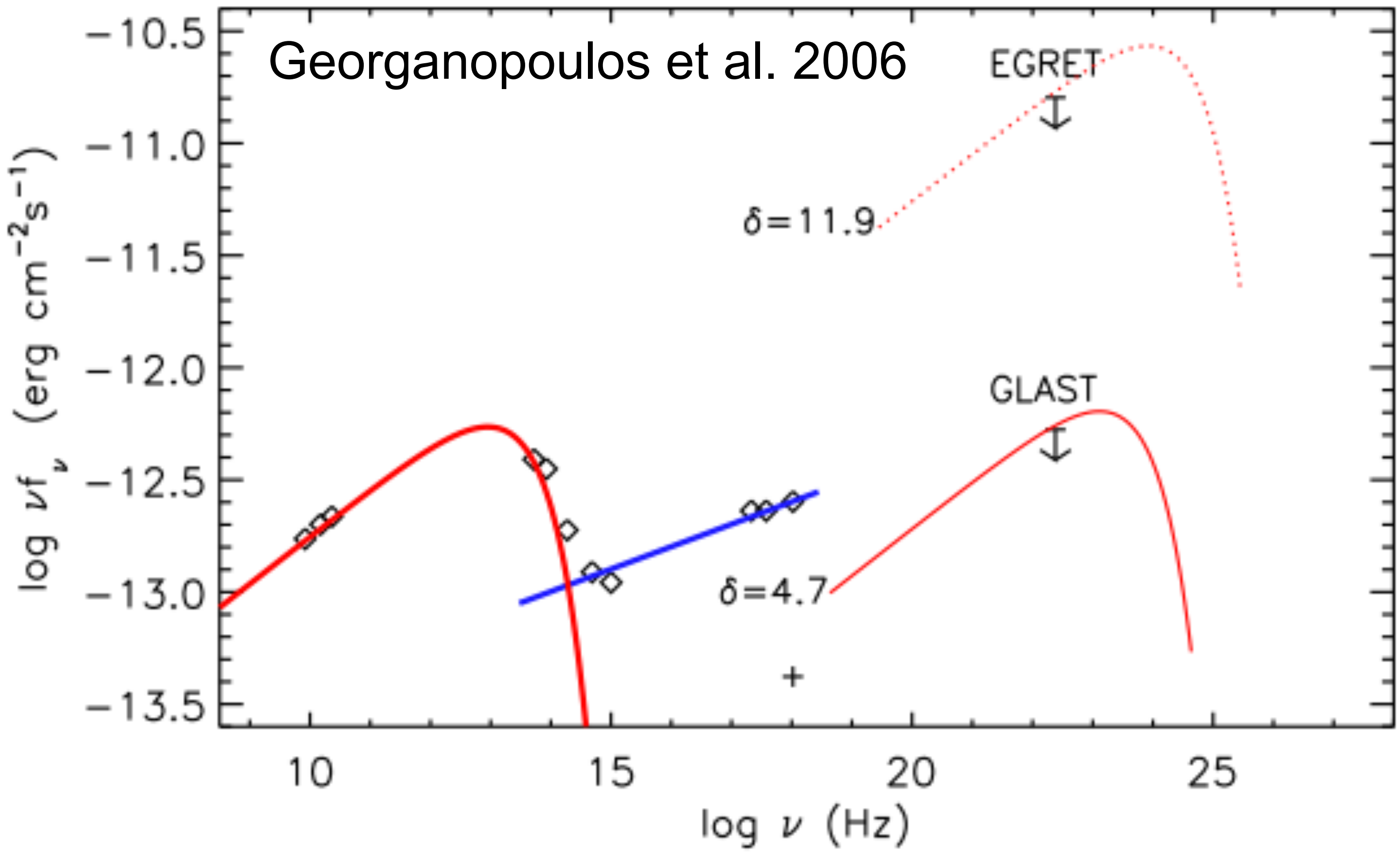
Georganopoulos et al. 2006:

The radio to optical synchrotron emitting electrons will unavoidably upscatter the CMB. In equipartition, this will produce an EC/CMB component shifted by δ^2 in frequency and δ^4 in power.



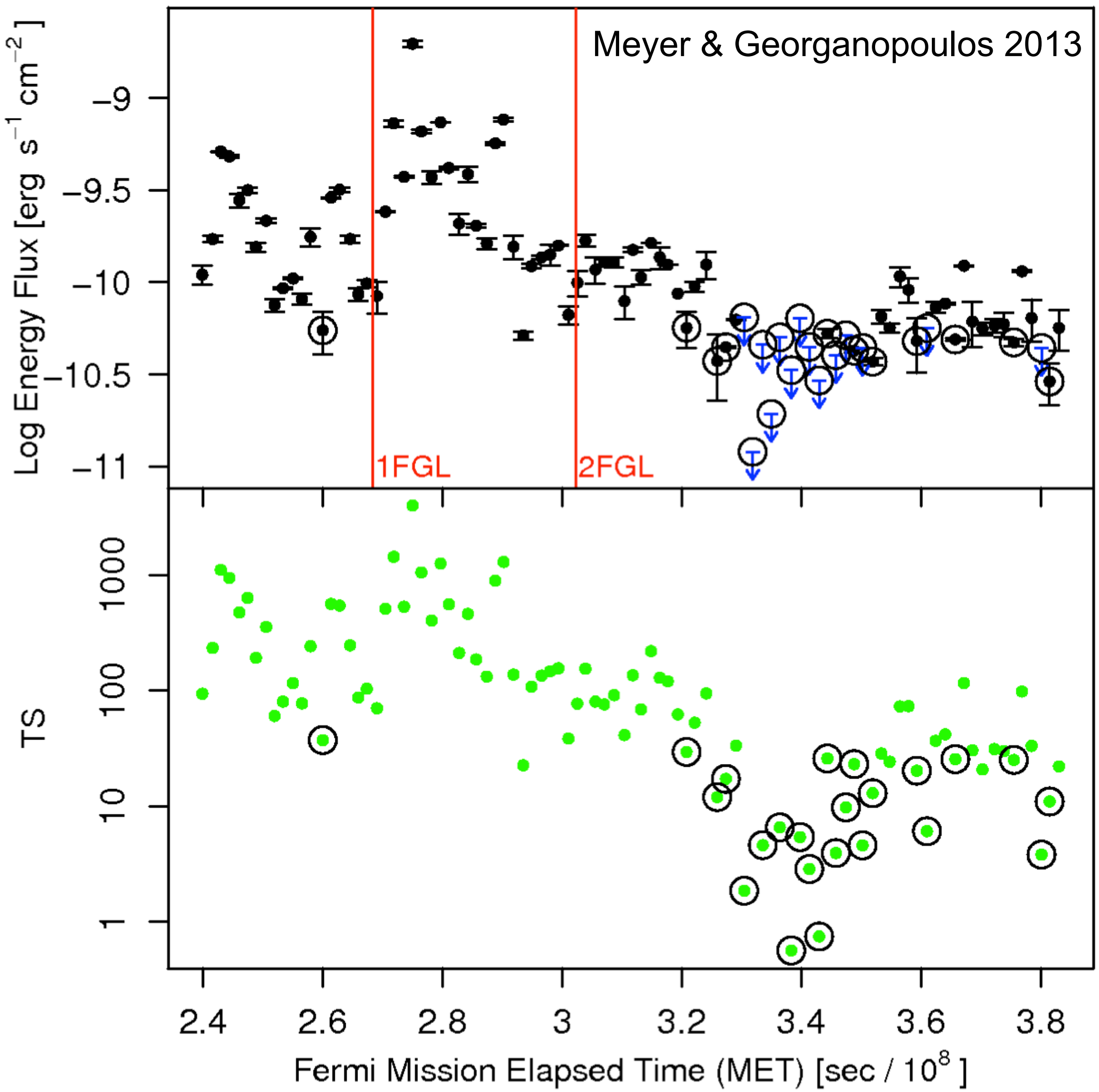
EGRET limits require δ<11.9, assuming equipartition.


Georganopoulos et al. 2006
EGRET
δ=11.9
GLAST
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
−13.5
log νf_ν (erg cm^-2 s^-1)
10
15
20
25
log ν (Hz)



GLAST can push this down to $\delta<4.7$, assuming equipartition.

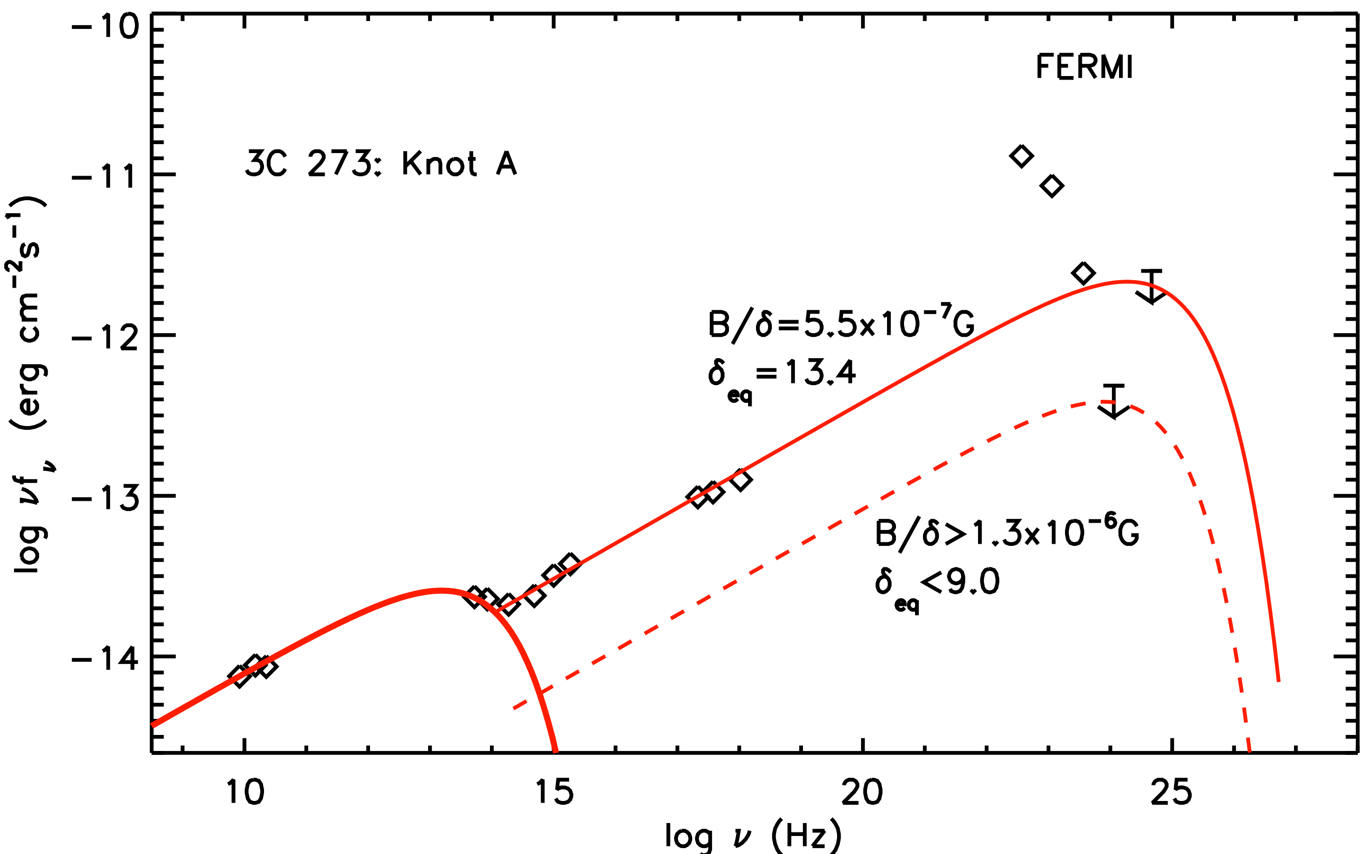
7 years later…



EC/CMB peak frequency and peak luminosity, without assuming equipartition:

$$\frac{\nu_c}{\nu_s} = \frac{2\pi m_e c(1+z)\nu_0}{e(B/\delta)} = 6.6\times10^4 (B/\delta)^{-1}$$

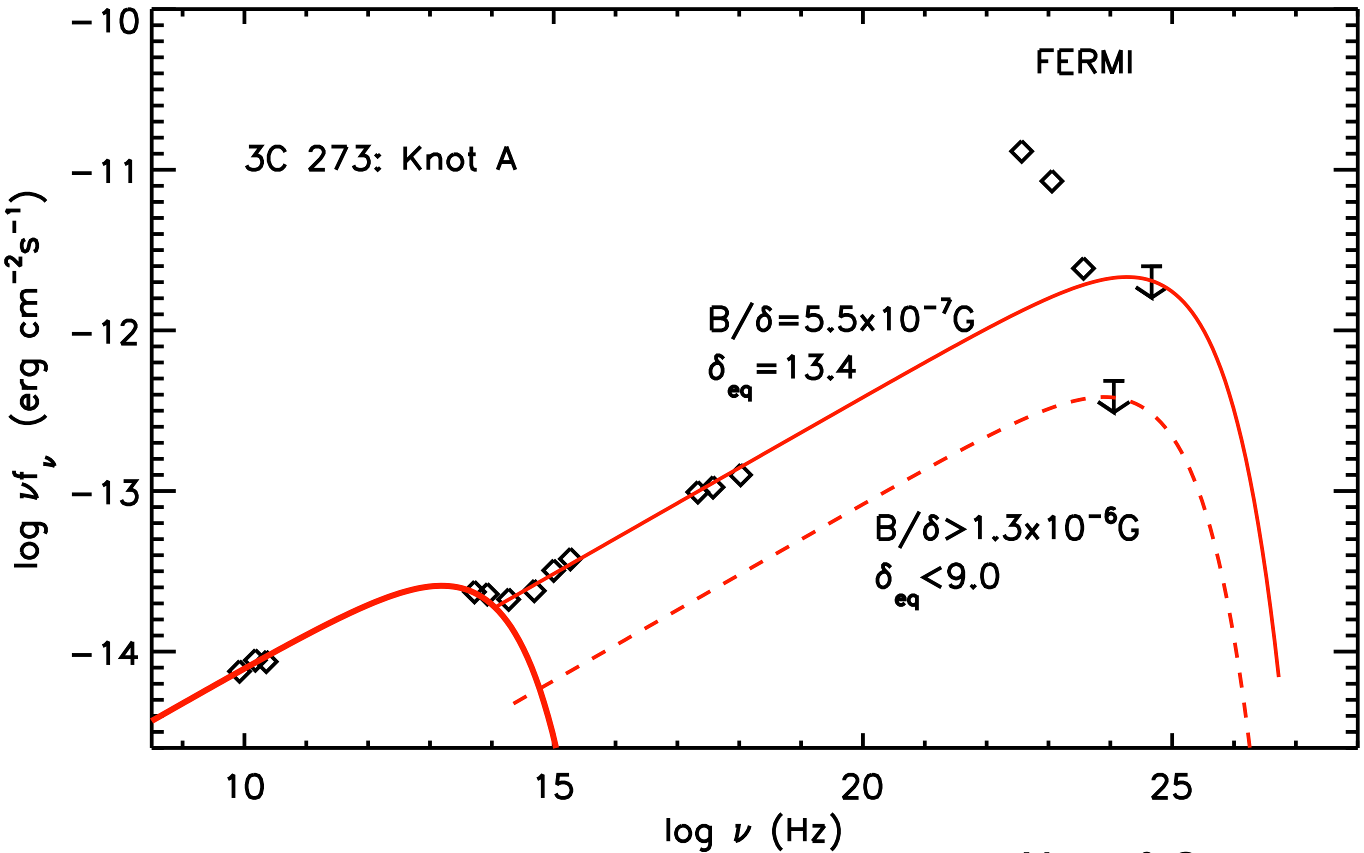
$$\frac{L_c}{L_s} = \frac{32\pi U_0(1+z)^4}{3(B/\delta)^2} = 2.5\times10^{-11} (B/\delta)^{-2}$$



Meyer & Georganopoulos 2013

To reproduce the UV-X-ray SED of knot A we require $B/\delta = 5.5 \times 10^{-7}$ G (or $\delta_{eq}=13.4$) which **overproduces** the Fermi upper limit.

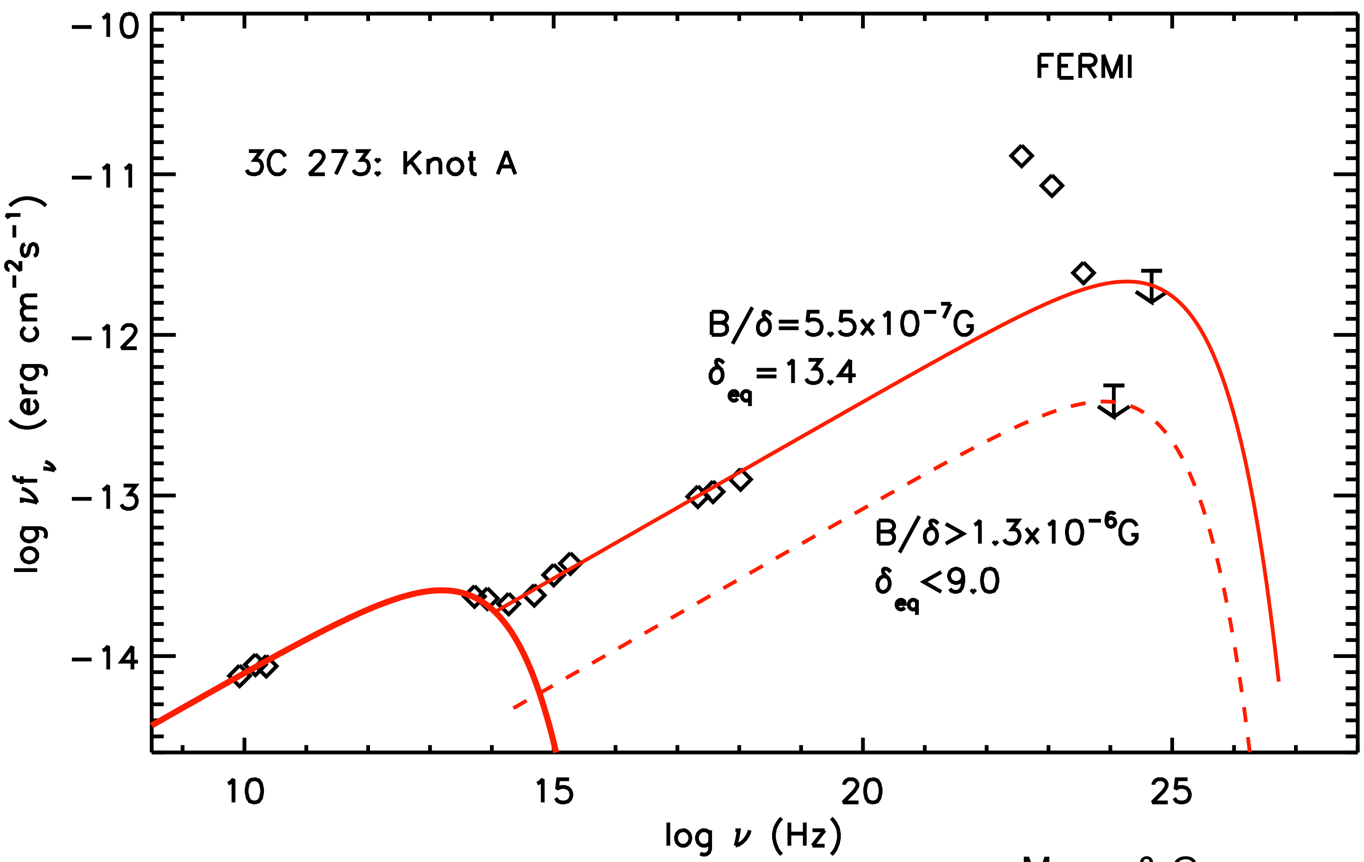
This **eliminates** EC/CMB for the X-ray emission of knot A.



Meyer & Georganopoulos 2013

To satisfy the Fermi upper limit we require

$B/\delta > 1.3 \times 10^{-6}$ G (or $\delta_{eq} < 9.0$).



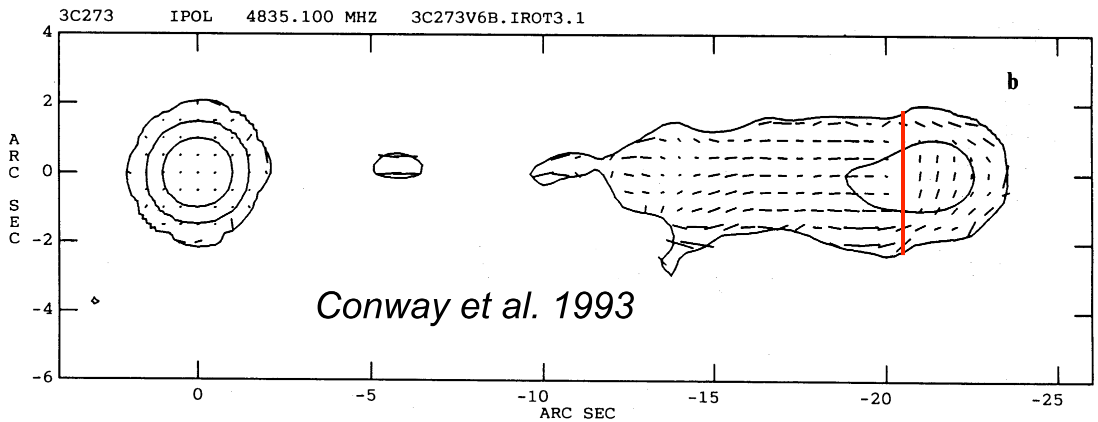
Meyer & Georganopoulos 2013

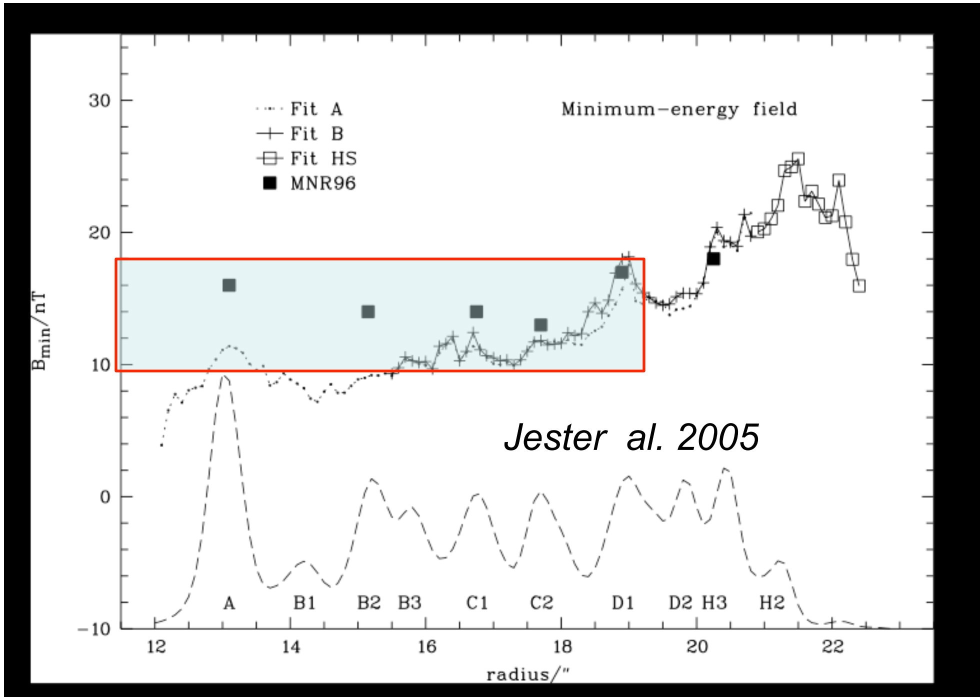
Can we do better? Sum up the flux of many knots

The jet polarization direction up to knot D1 is parallel to the jet, then abruptly turns by 90°, possibly by strong deceleration.

The equipartition magnetic field varies by less than a factor of 2 along the A to D1 knots

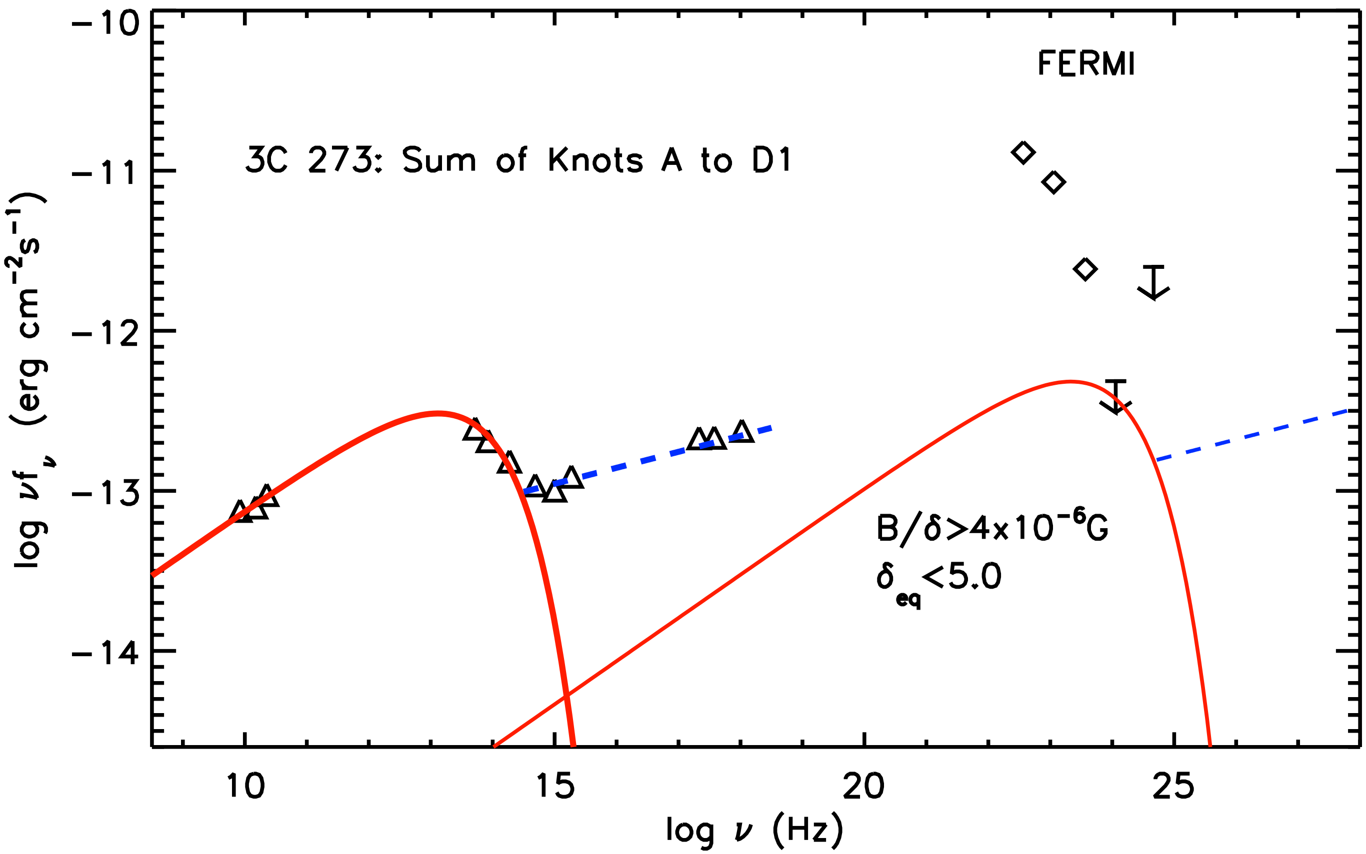
Assumption:
A single δ and B characterize all the knots from A to D1.





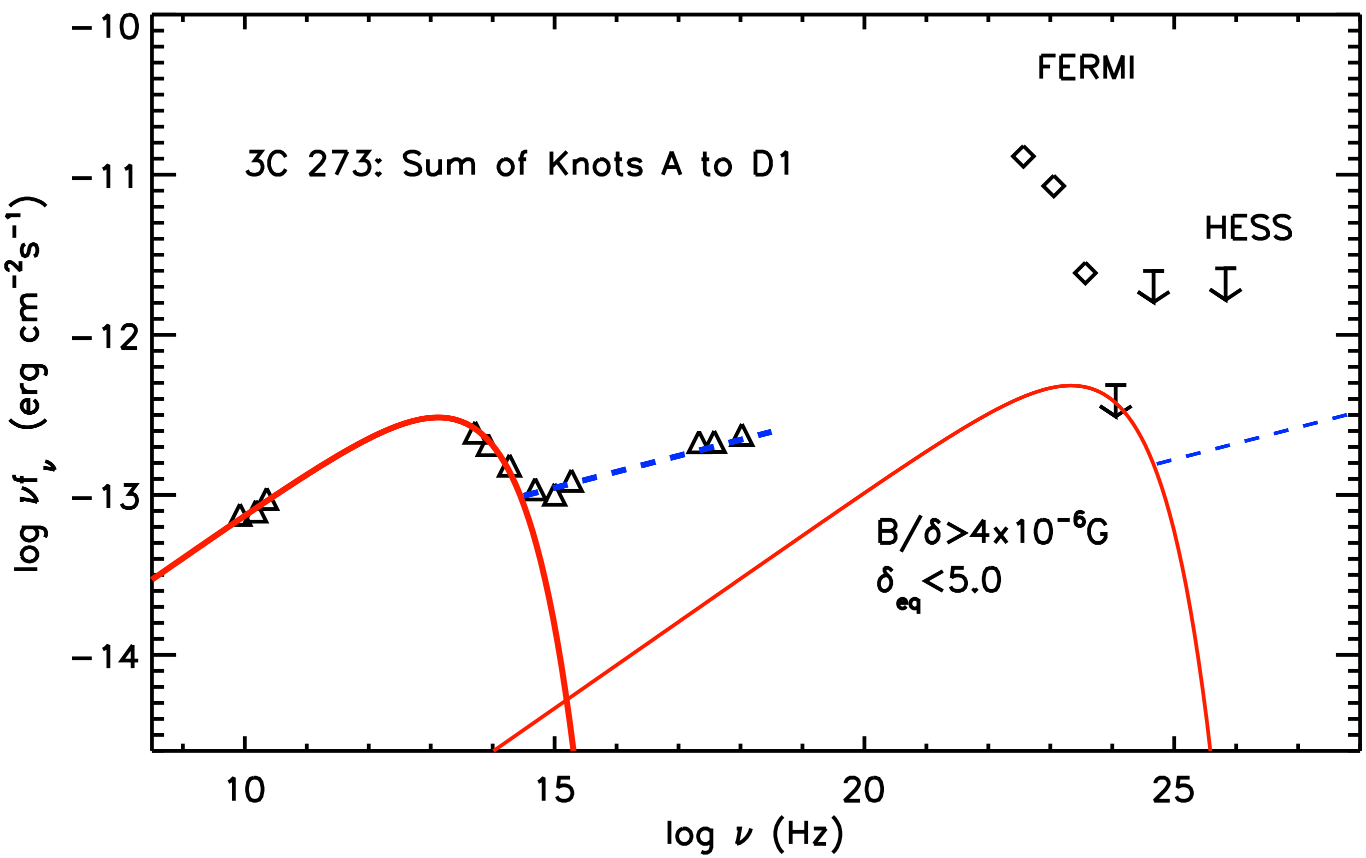
SED of the sum of knots A to D1: To satisfy the Fermi upper limit we require

$B/\delta > 4 \times 10^{-6}$ G (or $\delta_{eq} < 5.0$).



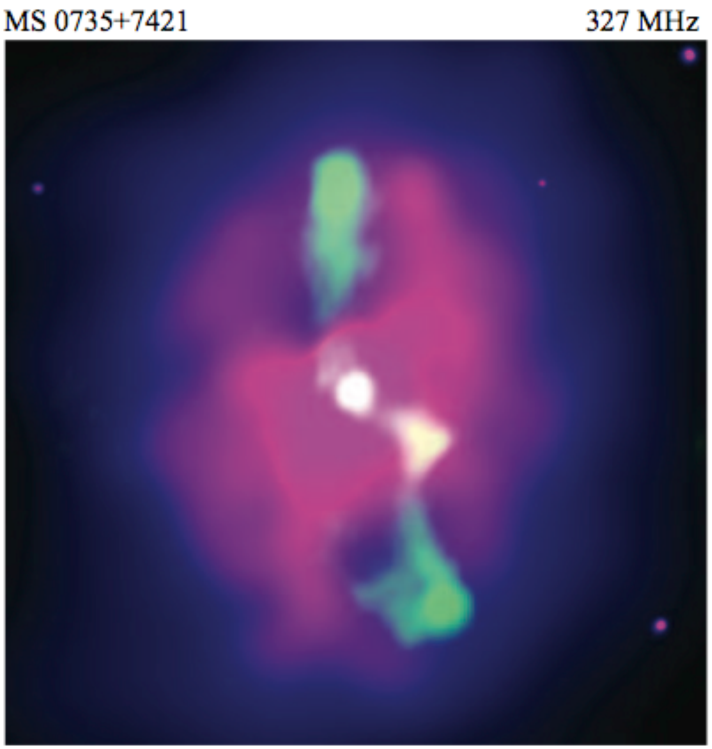
Meyer & Georganopoulos 2013

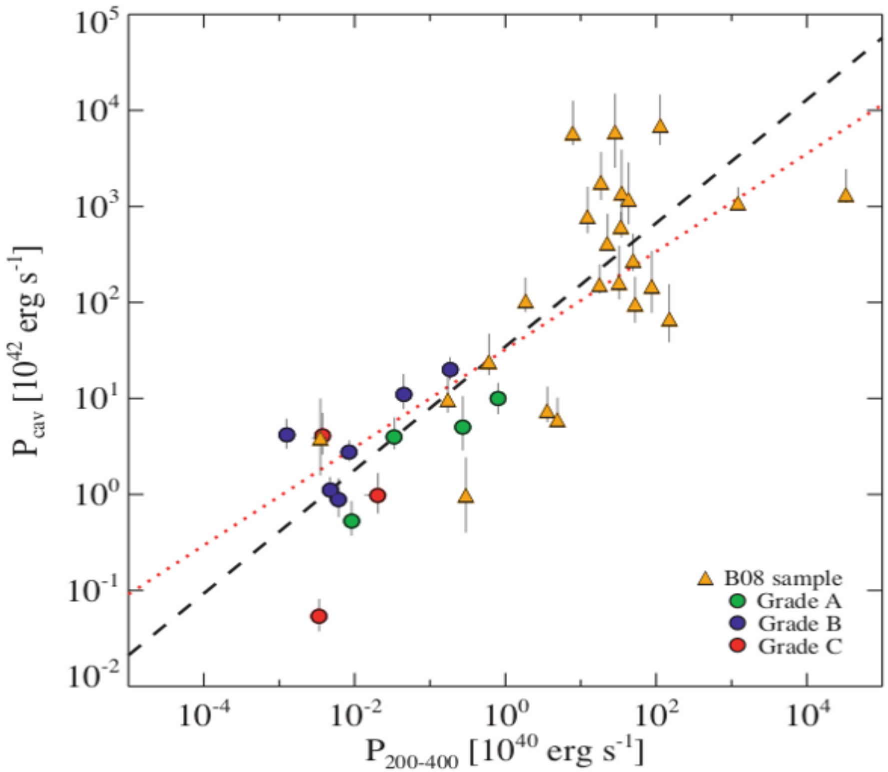
Constraint on the bulk motion Lorentz factor Γ:
Require that the cooling break in the synchrotron emission is at $\sim 10^{13.5}$ Hz



Constraint on the bulk motion Lorentz factor Γ:
Require that the cooling break in the synchrotron emission is at $\sim 10^{13.5}$ Hz

Adopt jet power $L_{jet}=10^{35.5\pm0.7}$ erg/s from the X-ray cavity method





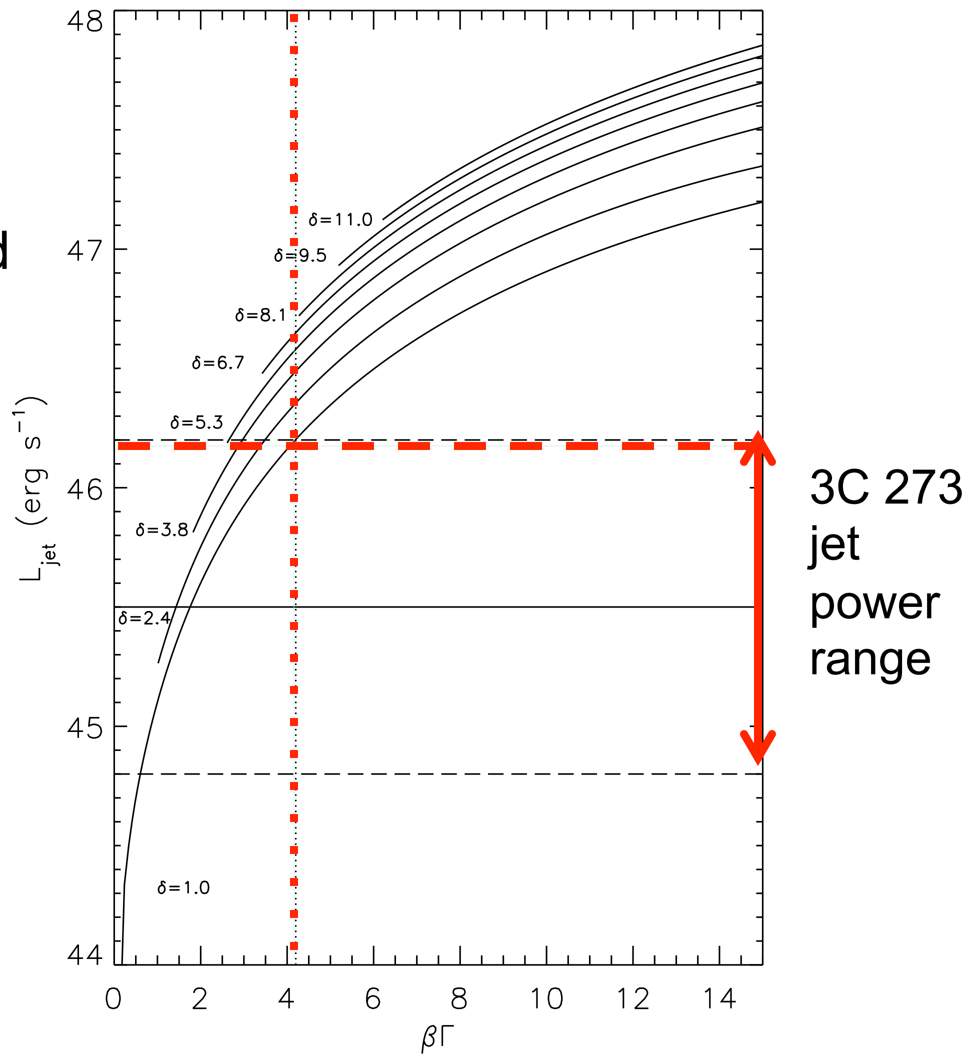
Cavagnolo et al 2010,
Also Shabala & Godfrey 2013

Constraint on the bulk motion Lorentz factor Γ:
Require that the cooling break in the synchrotron emission is at $\sim 10^{13.5}$ Hz
Adopt jet power from the X-ray cavity method

For a given **δ** and **Γ** find **B** that gives a cooling break at $10^{13.5}$ Hz, calculate the electron energy distribution to produce the observed radio emission and from these, calculate the jet power.

Not to overproduce the jet power:

βΓ<~4.2
δ<~5.3



What is next?

- Produce Fermi light curves of quasars with X-ray jets and use any deep minima we may locate to rule out EC/CMB and constrain the speed of the jet.

- What are the characteristics of the multi TeV electron synchrotron emitting region? How can we constrain its physical description?

Conclusions

HST polarimetry of PKS 1136-135 disfavor an EC/CMB origin of the jet X-rays.

Fermi upper limits on 3C 273 jet <u>**rule out**</u> an EC/CMB origin of the jet X-rays.

The jet of 3C 273 is relatively slow (Γ<~4)