Extended jets, radio lobes, Seyferts.
Three case studies and a sneak preview

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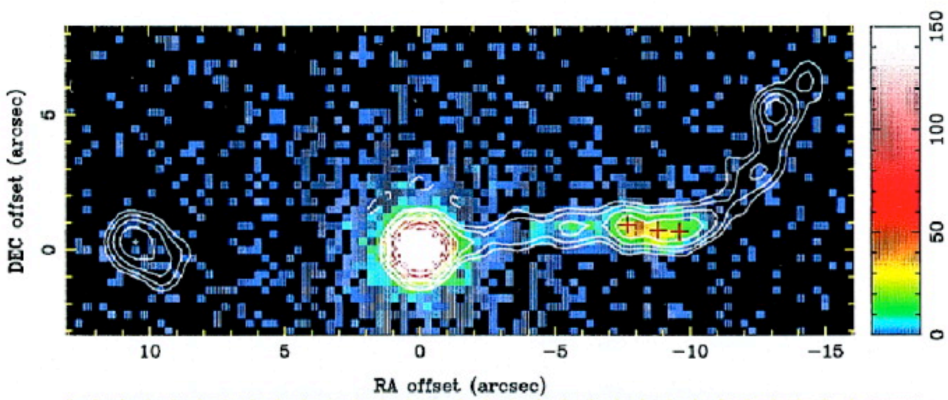
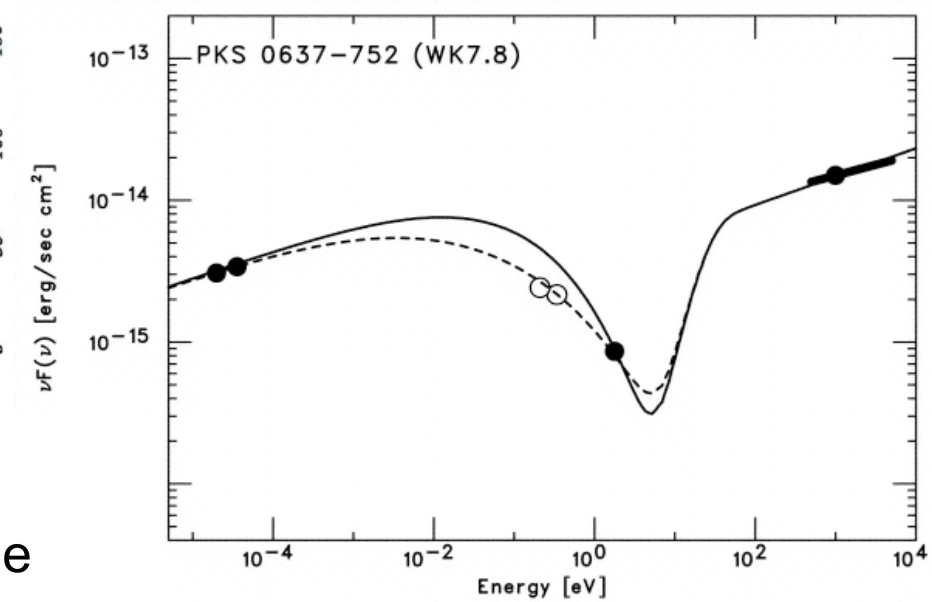
1. A quasar extended jet

Chandra discovers X-ray quasar jets: What is the X-ray emission mechanism?

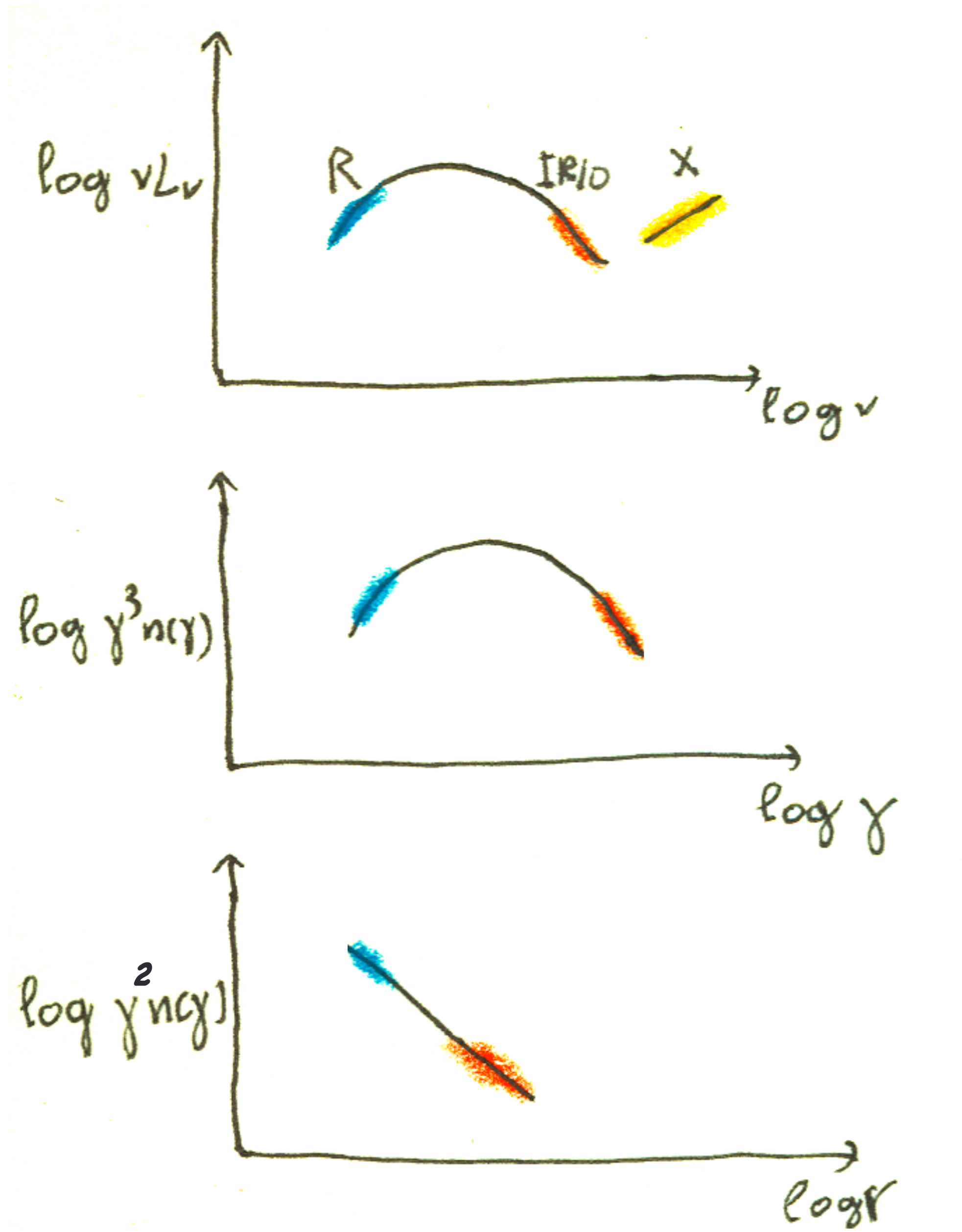


The X-ray emission is too bright to be Synchrotron Self Compton in equipartition.
(Schwartz et al. 2000
Chartas et al. 2001)

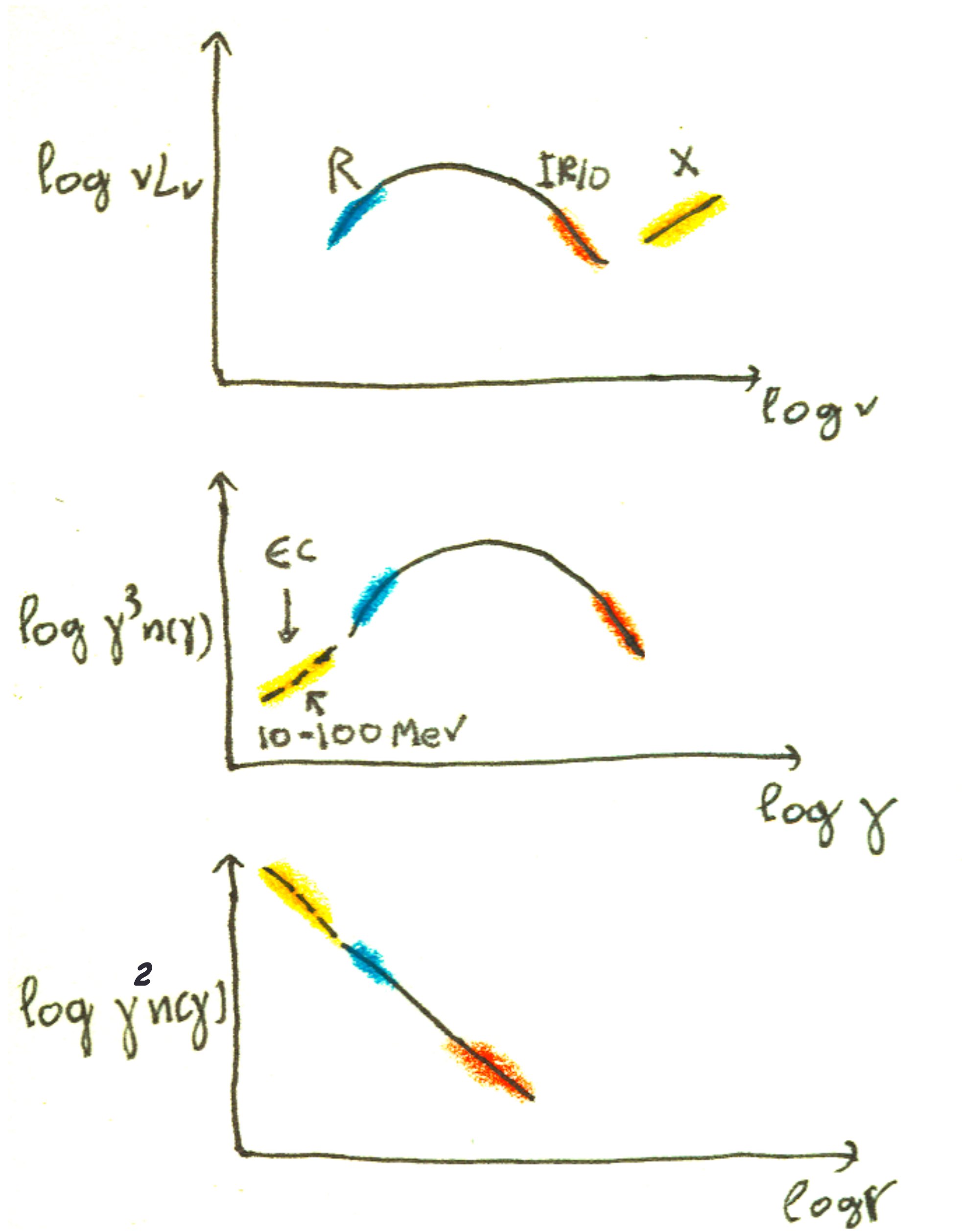


Uchiyama et al. 2005

What is the X-ray emission mechanism?



What is the X-ray emission mechanism?



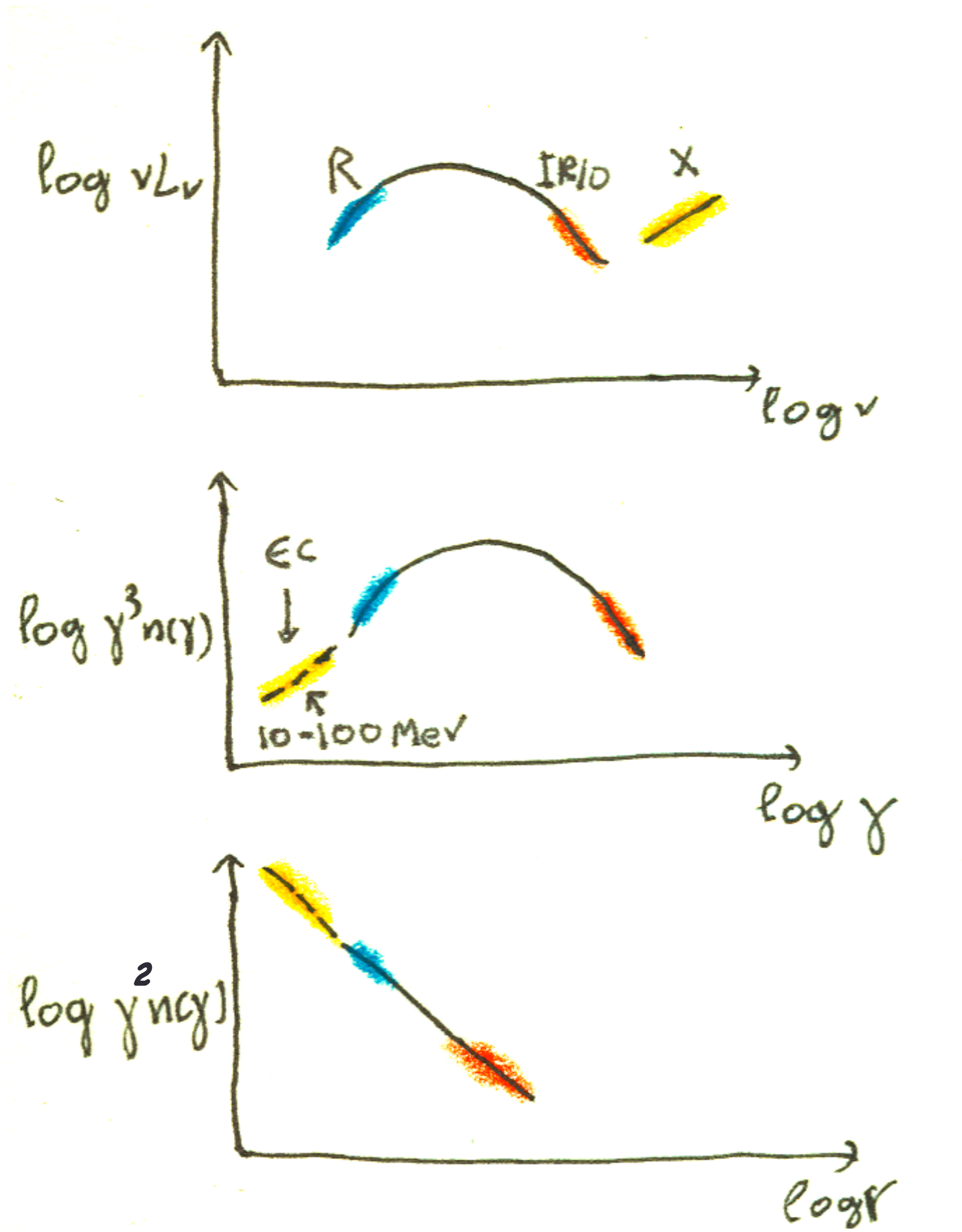
What is the X-ray emission mechanism?

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

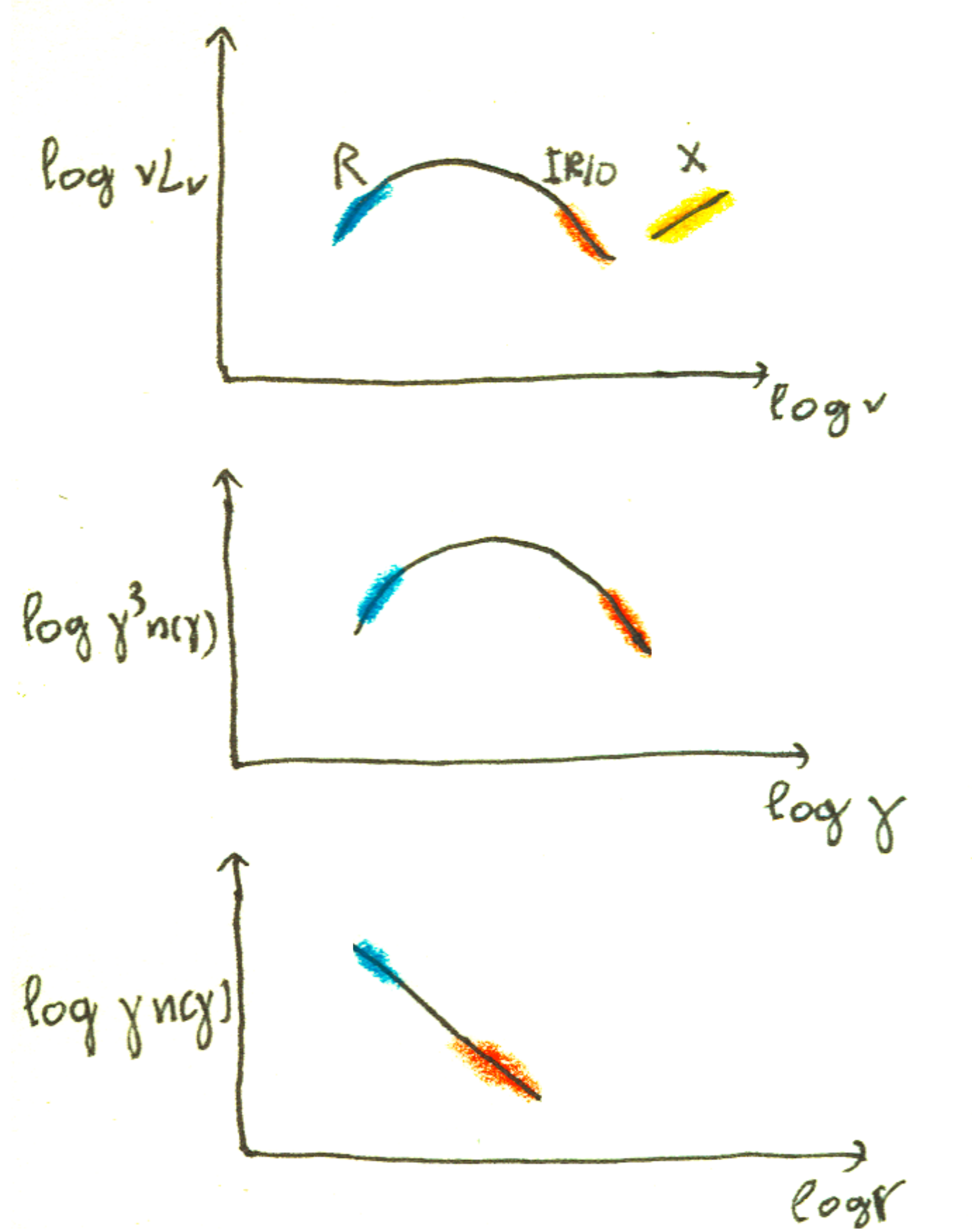
Extends the electron energy distribution (EED) down to 10 -100 MeV energies

Requires relativistic large scale jets (δ~10)

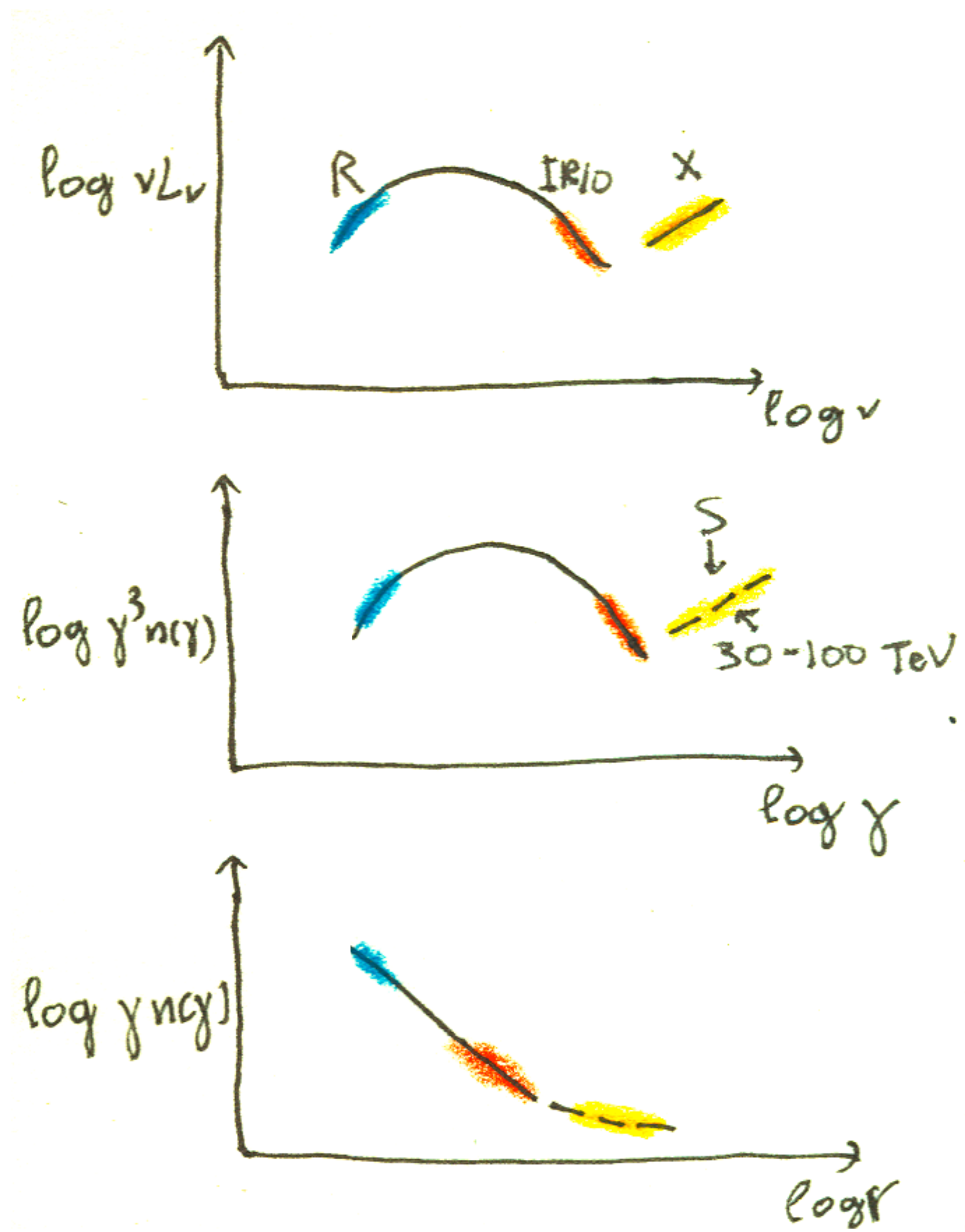
Increased jet power requirements, radiatively inefficient



What is the X-ray emission mechanism?



What is the X-ray emission mechanism?



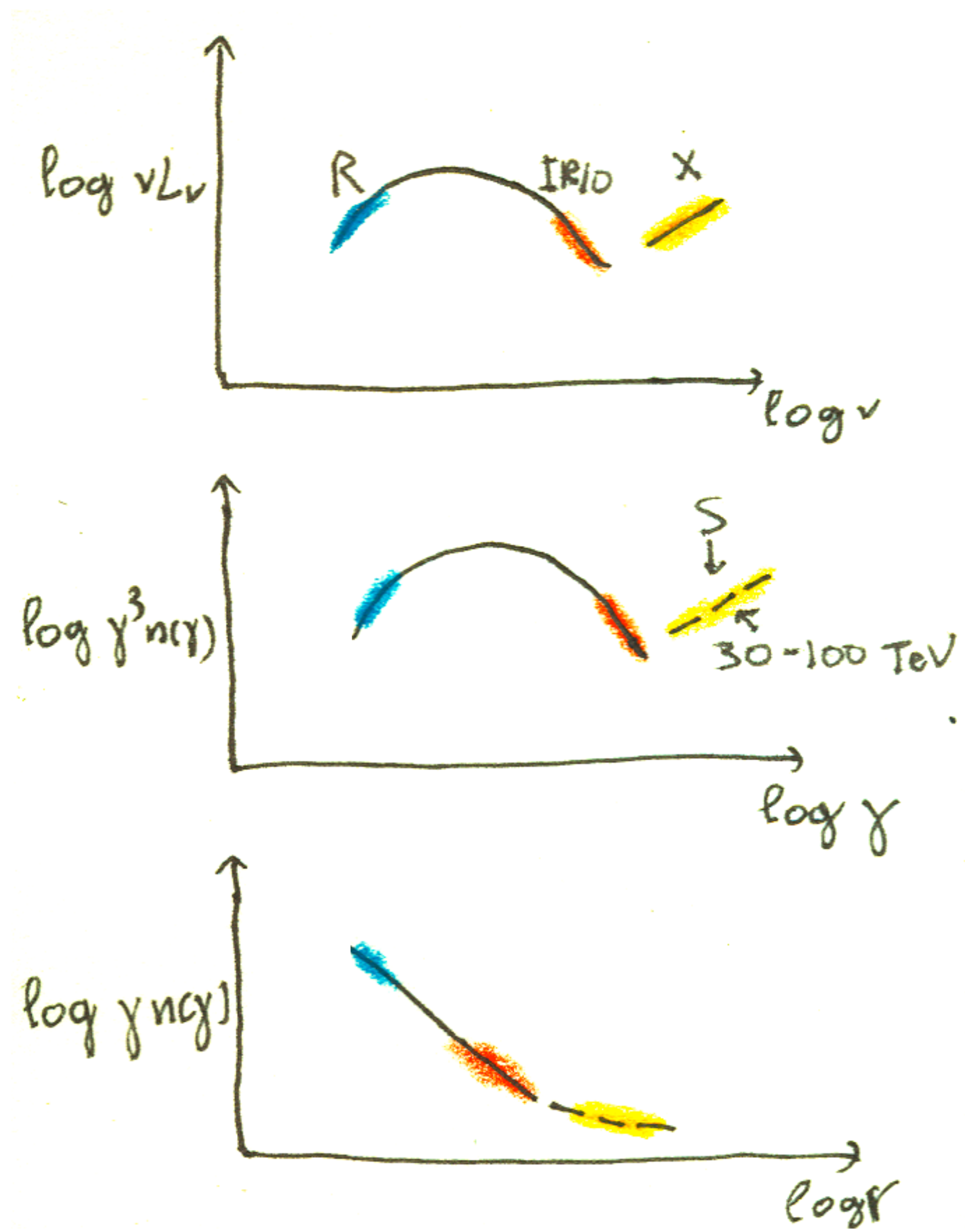
What is the X-ray emission mechanism?

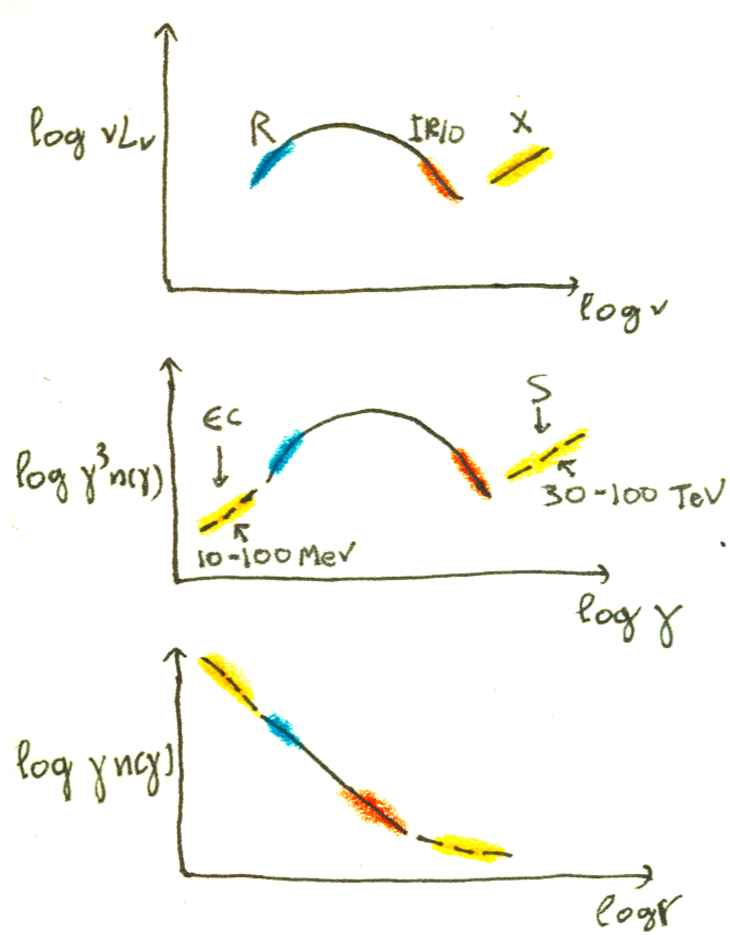
Synchrotron
(e.g. Harris et al. 2004, Hardcastle 2006)

Additional EED component at ~1-100 TeV energies

No need for highly relativistic large scale jet

More economical in jet power, radiatively efficient





<u>BIG DIFFERENCE</u>: The EED in EC/CMB model cuts off of at **sub-TeV energies**
The EED in the synchrotron model goes up to **30-100 TeV.**

Two competing models, two γ-ray bands, and a helpful source

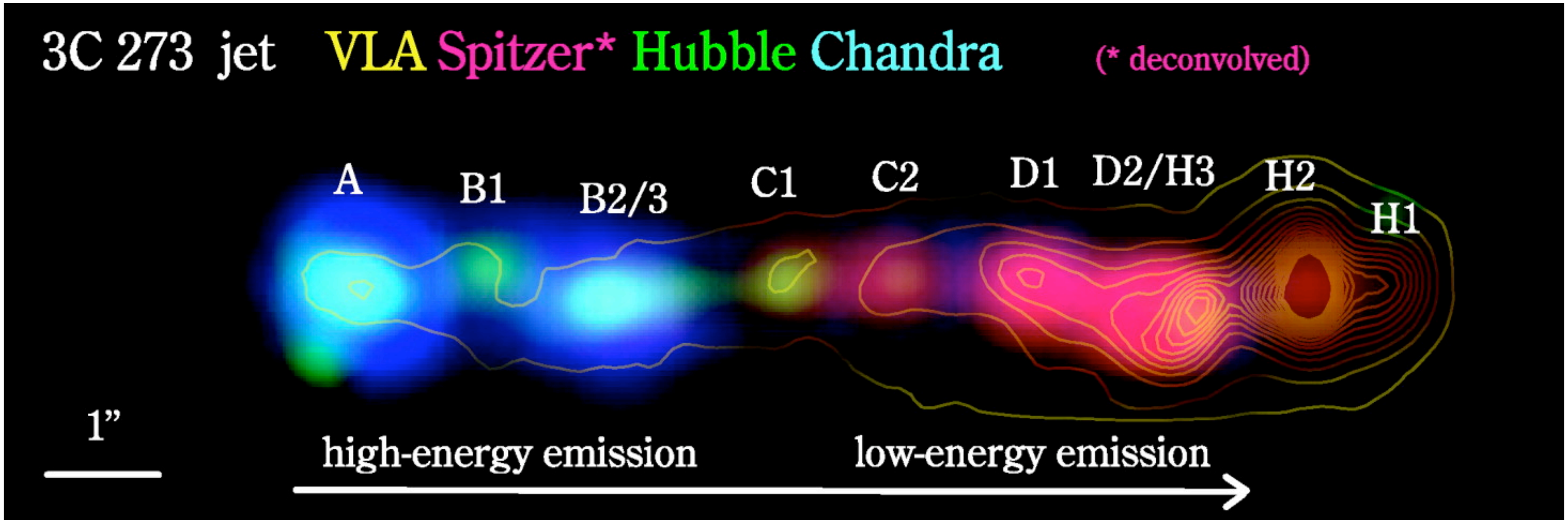
• The EED in both models have sub-TeV electrons:
Sub-TeV electrons + CMB-> ***GeV emission from both models***

•The EED of the synchrotron model has multi-TeV electrons
Multi-TeV electrons +CMB-> ***TeV emission only from the synchrotron model***

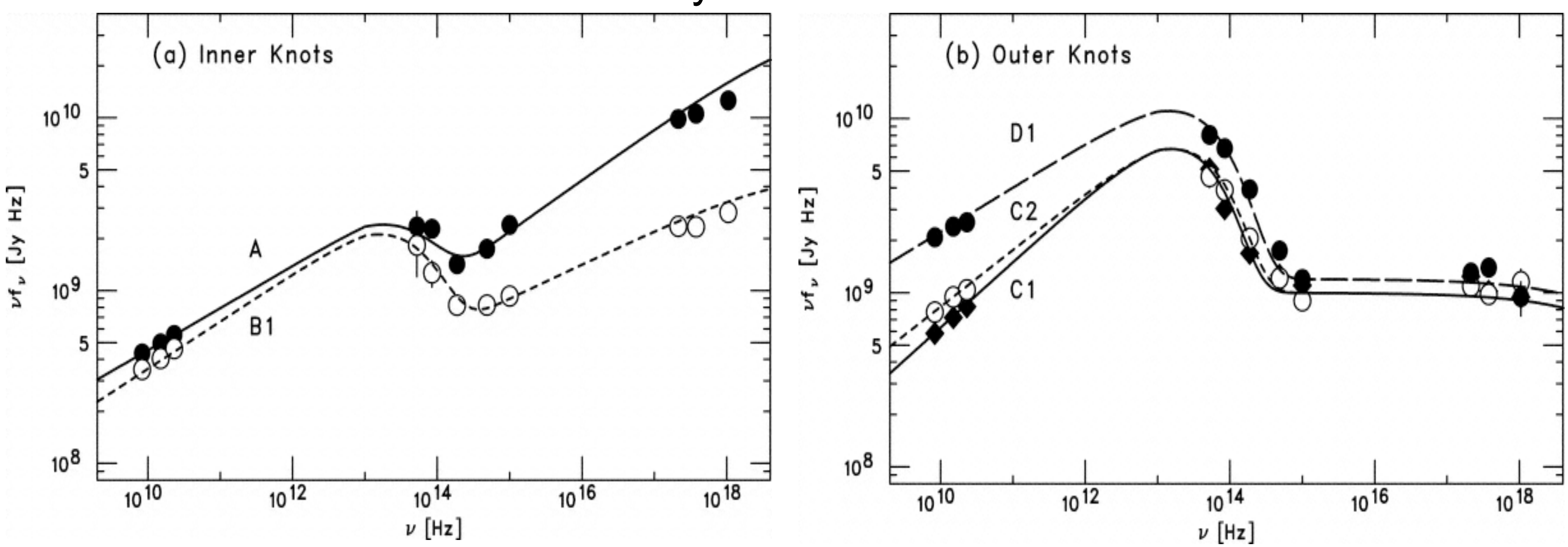
Let's apply these to a bright, nearby source: 3C 273 at z=0.158

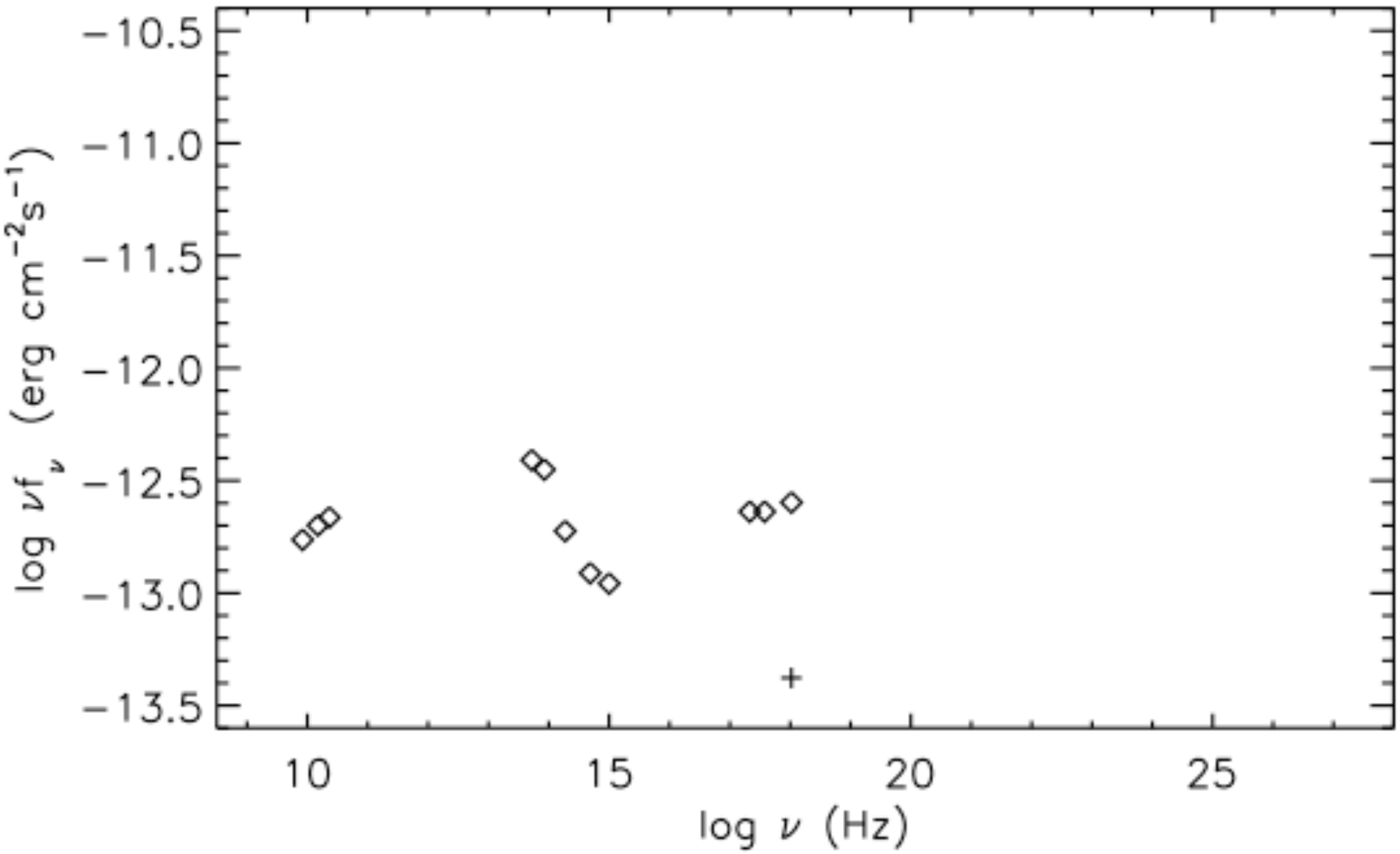
Q: Is it close enough for TeV photons to go through the extragalactic background light?

A: Yes, it is. The Universe is transparent enough (Aharonian et al. 2006, HESS detection of z=0.186, z=0.165 blazars).

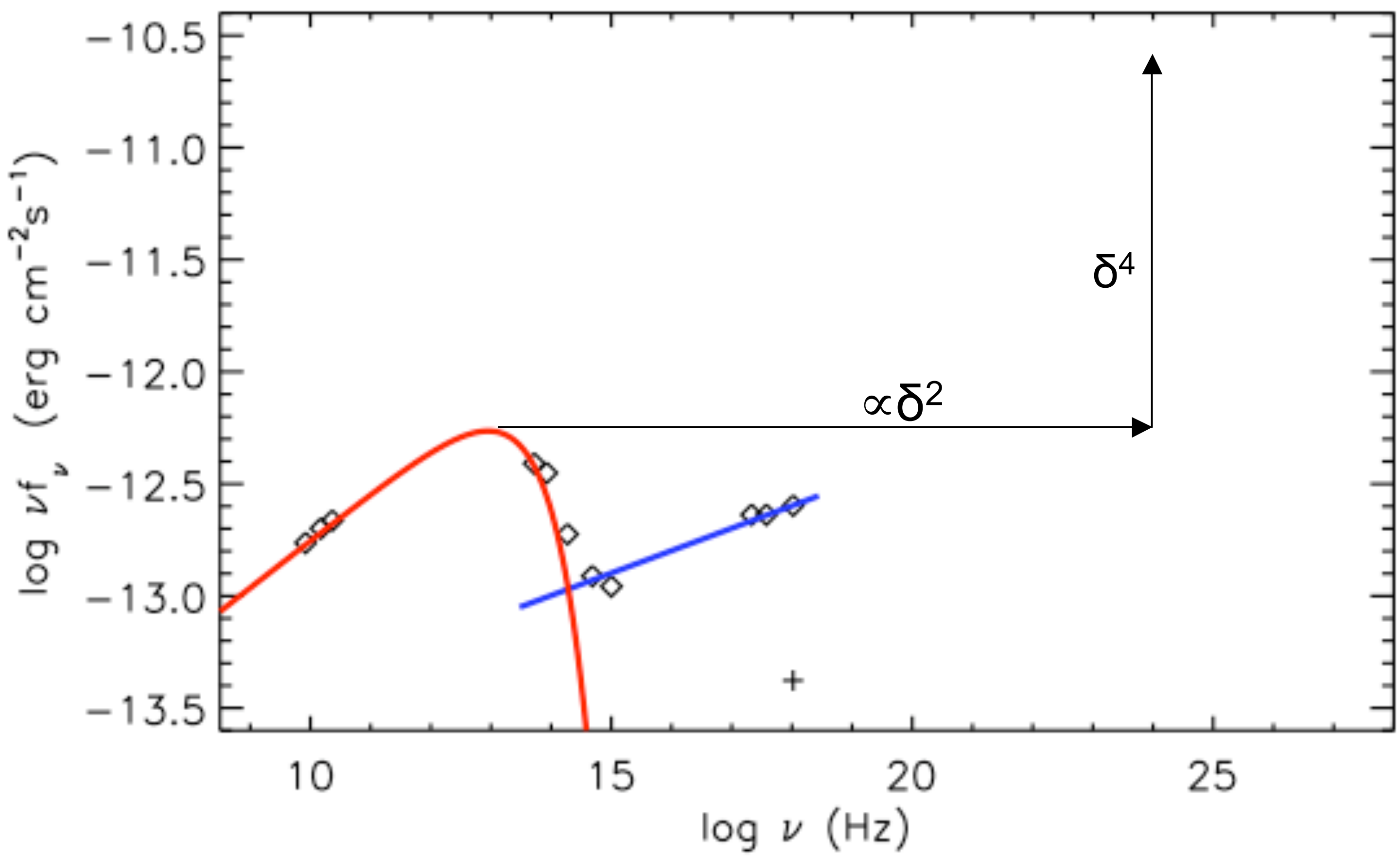


Uchiyama et al. 2006



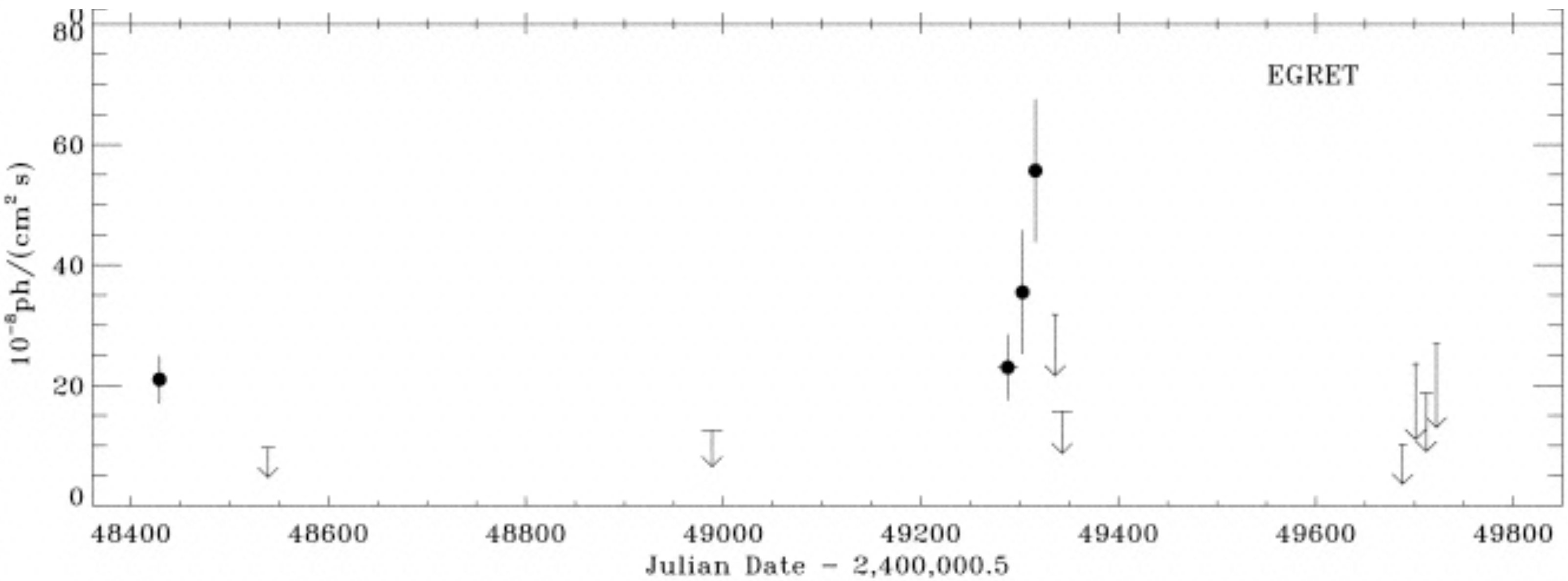


−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
−13.5
log νf_ν (erg cm⁻²s⁻¹)
10
15
20
25
log ν (Hz)

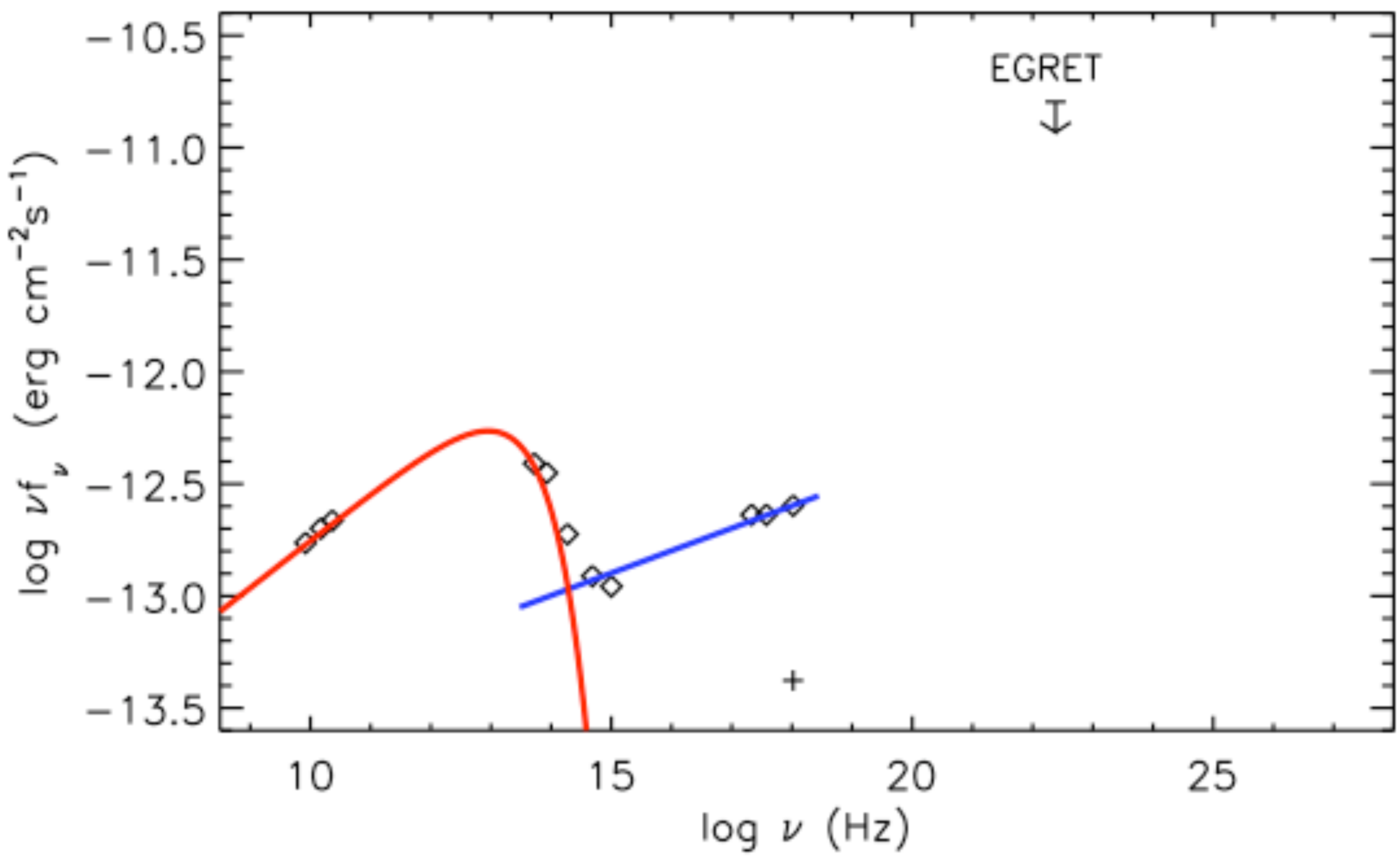


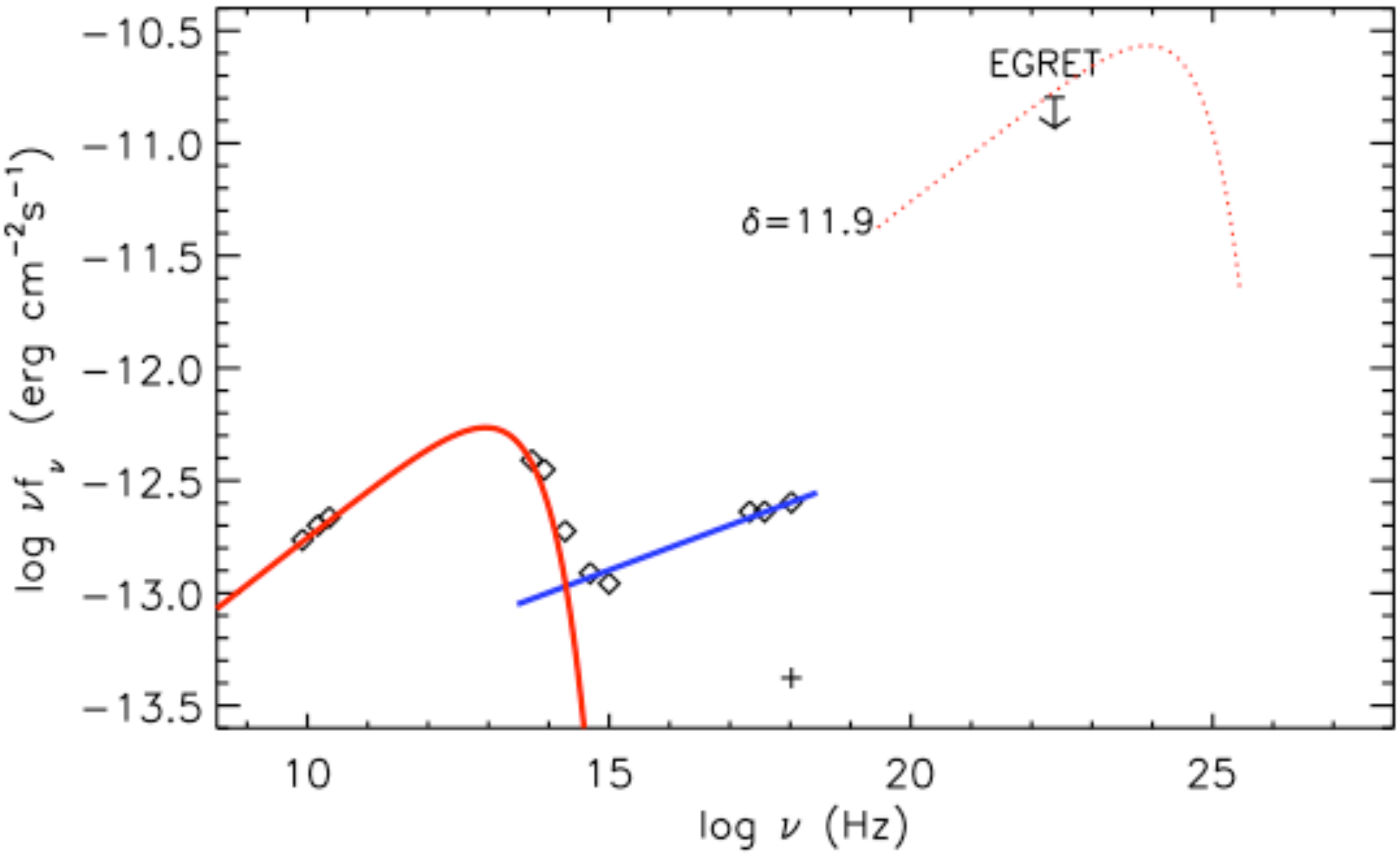
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
−13.5
log νf_ν (erg cm⁻²s⁻¹)
10
15
20
25
log ν (Hz)
δ⁴
∝δ²

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

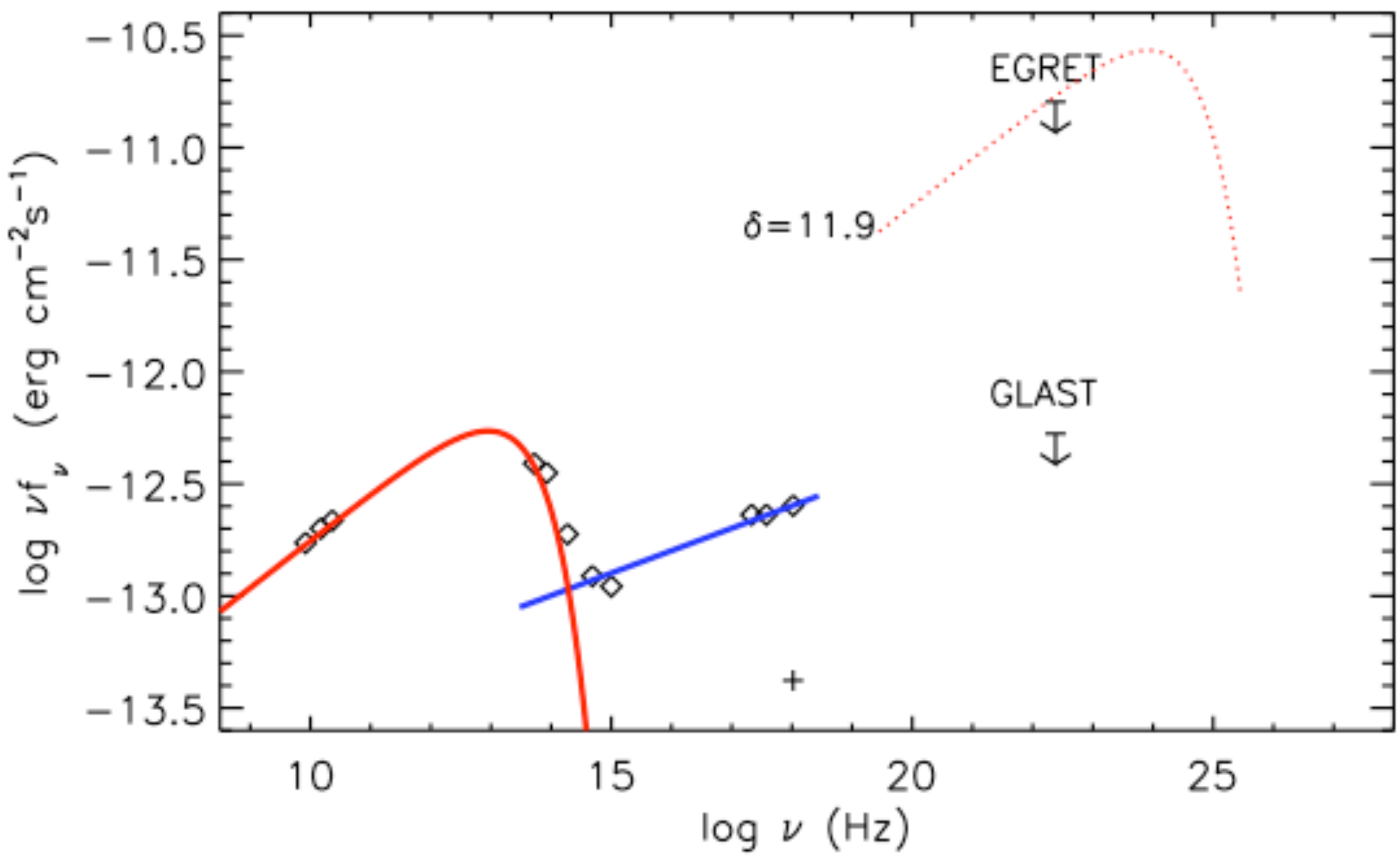


Von Montigny et al 1997

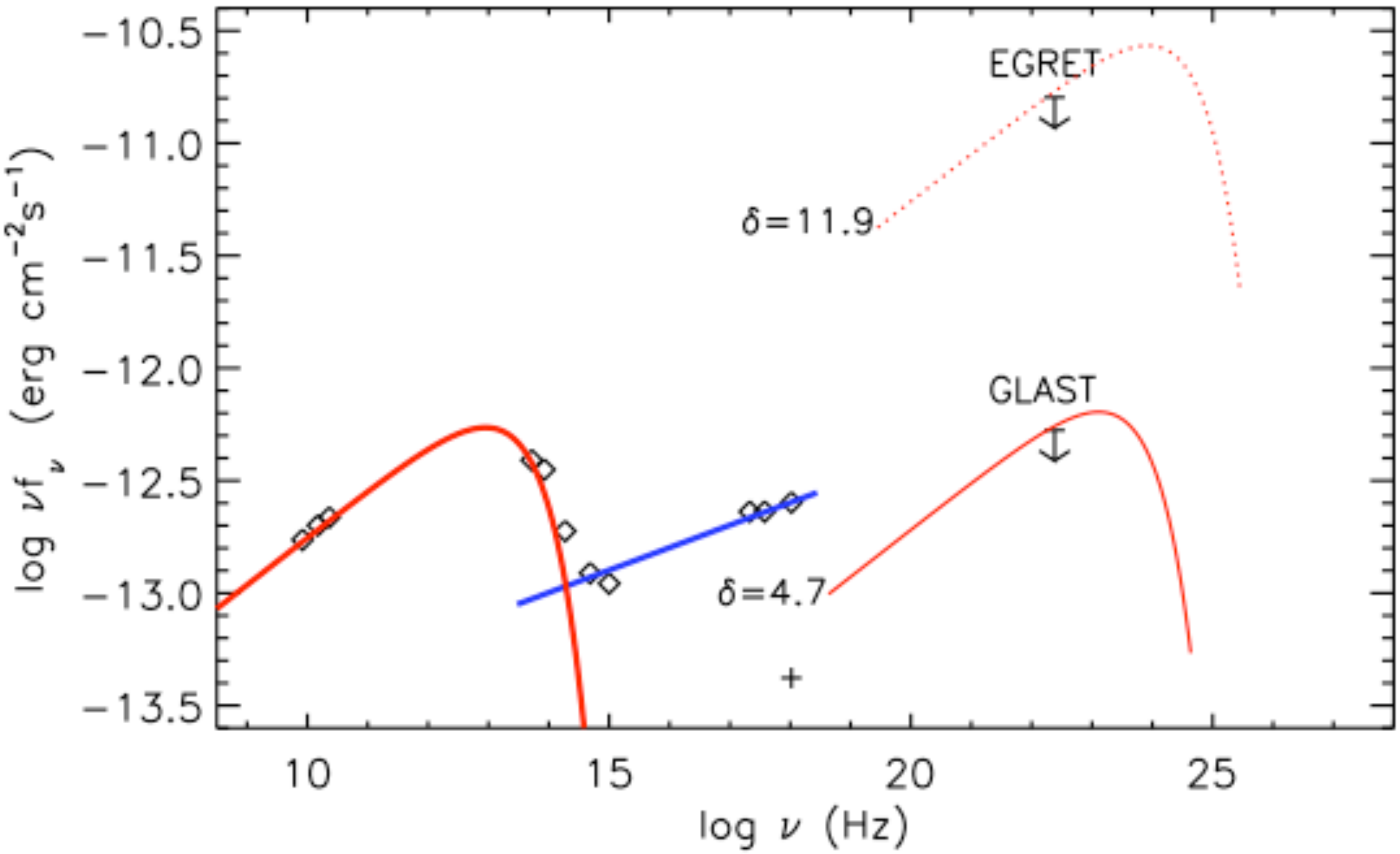

EGRET
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
−13.5
log νf_ν (erg cm^{-2}s^{-1})
10
15
20
25
log ν (Hz)



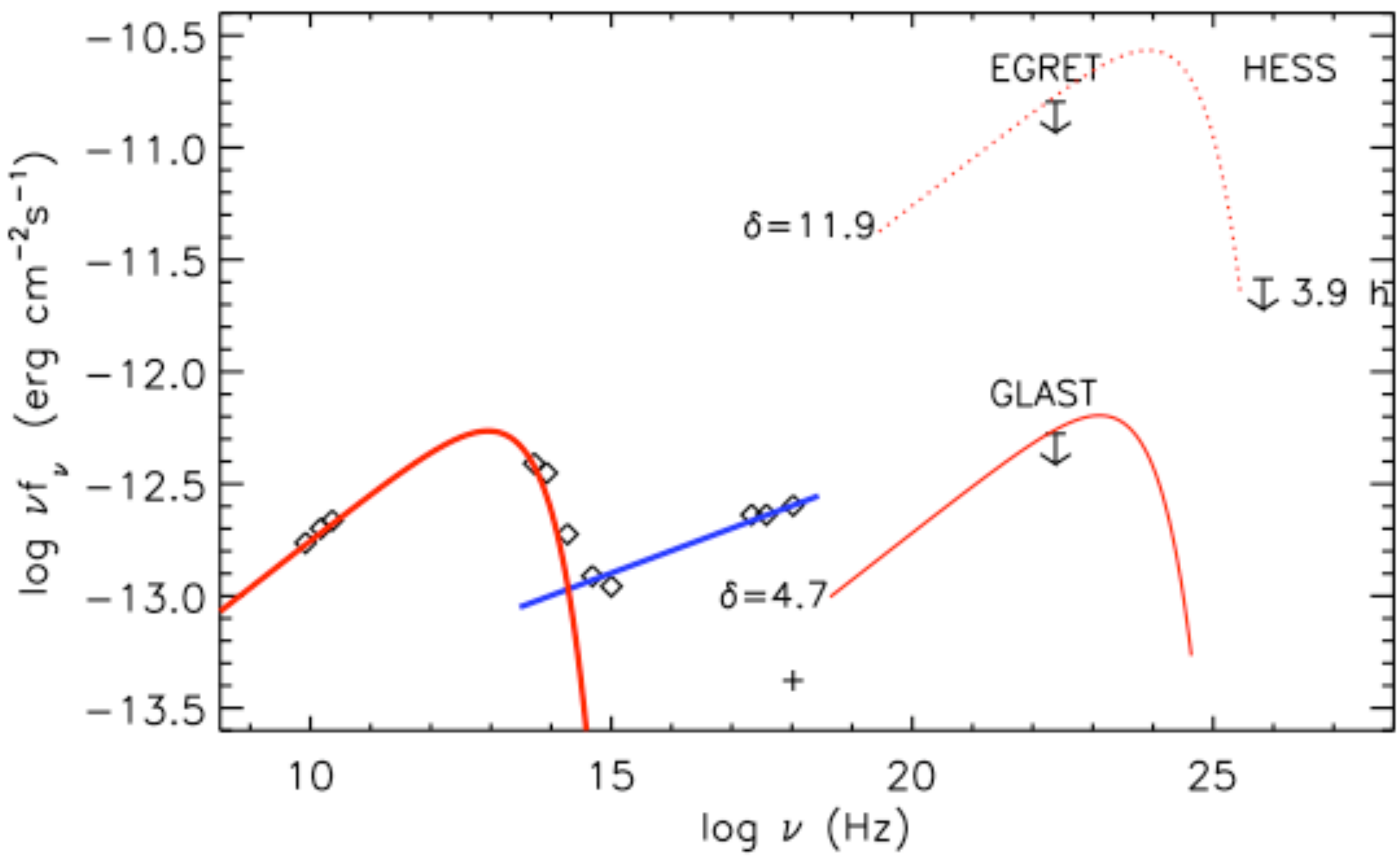
<u>Cool:</u> Existing good old EGRET limits require δ<11.9



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

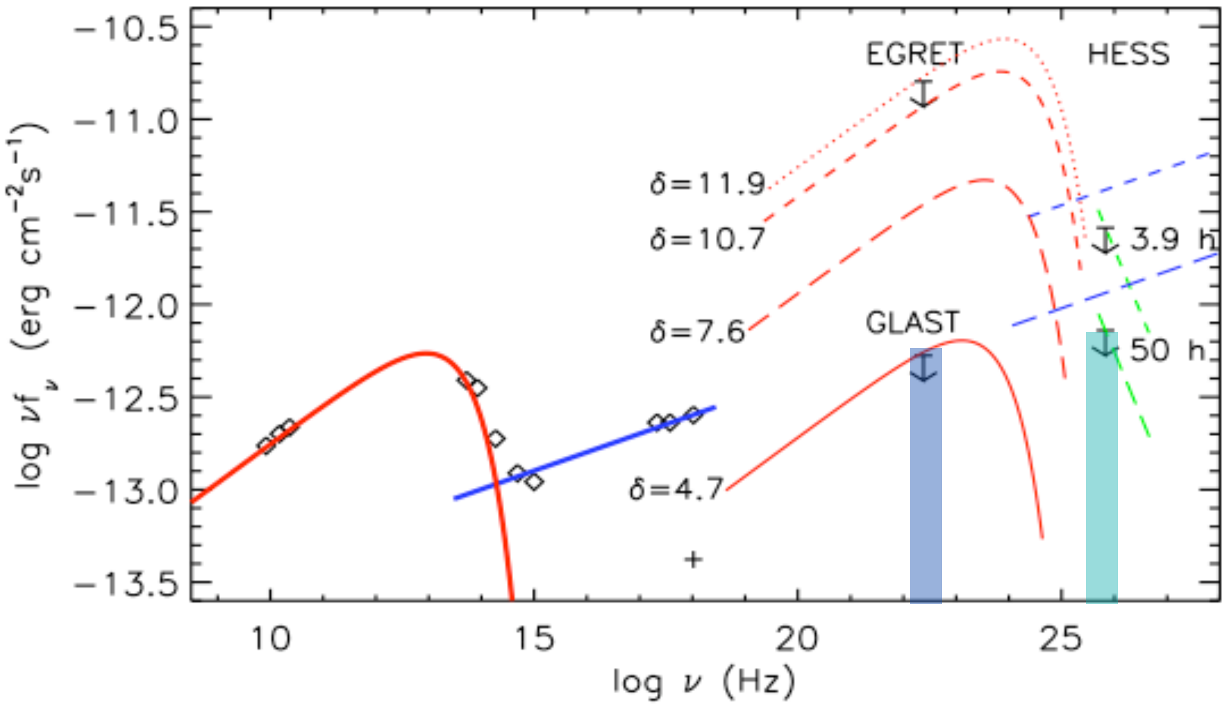


In the EC/CMB hypothesis, values of $\delta<\sim 10$ require extremely high jet power ($L_{jet}>\sim 10^{47-49}$ erg/s, Dermer & Atoyan 04, Uchiyama et al. 2006). This is not easy.



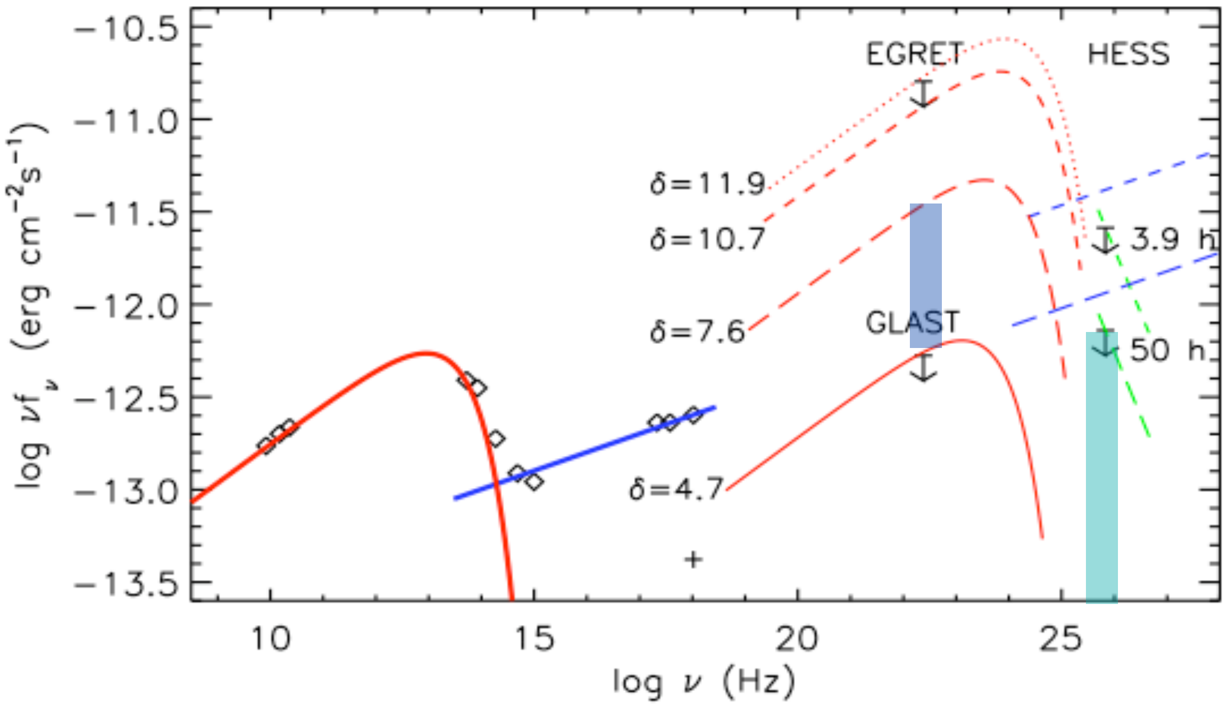
EGRET
HESS
δ=11.9
3.9 h
GLAST
δ=4.7
log νf_ν (erg cm^-2 s^-1)
log ν (Hz)
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
−13.5
10
15
20
25

Putting the constraints together.



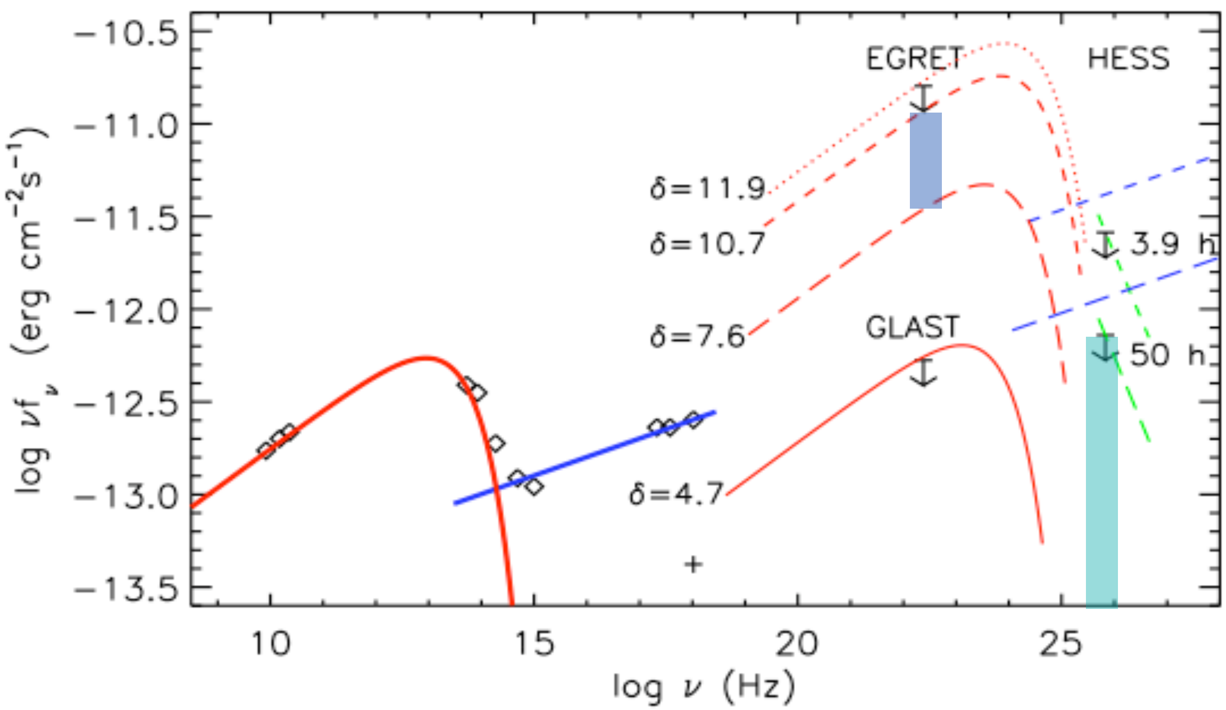
Neither GeV nor TeV emission is detected: δ<4.7
No constraints on the synchrotron model.
EC/CMB requires too much power. Strongly disfavored.

Putting the constraints together.



GeV emission is detected at a low level: 4.7<δ<7.6
TeV emission still is too weak to be detected
No constraints on the synchrotron model.
EC/CMB requires a lot of power. Disfavored.

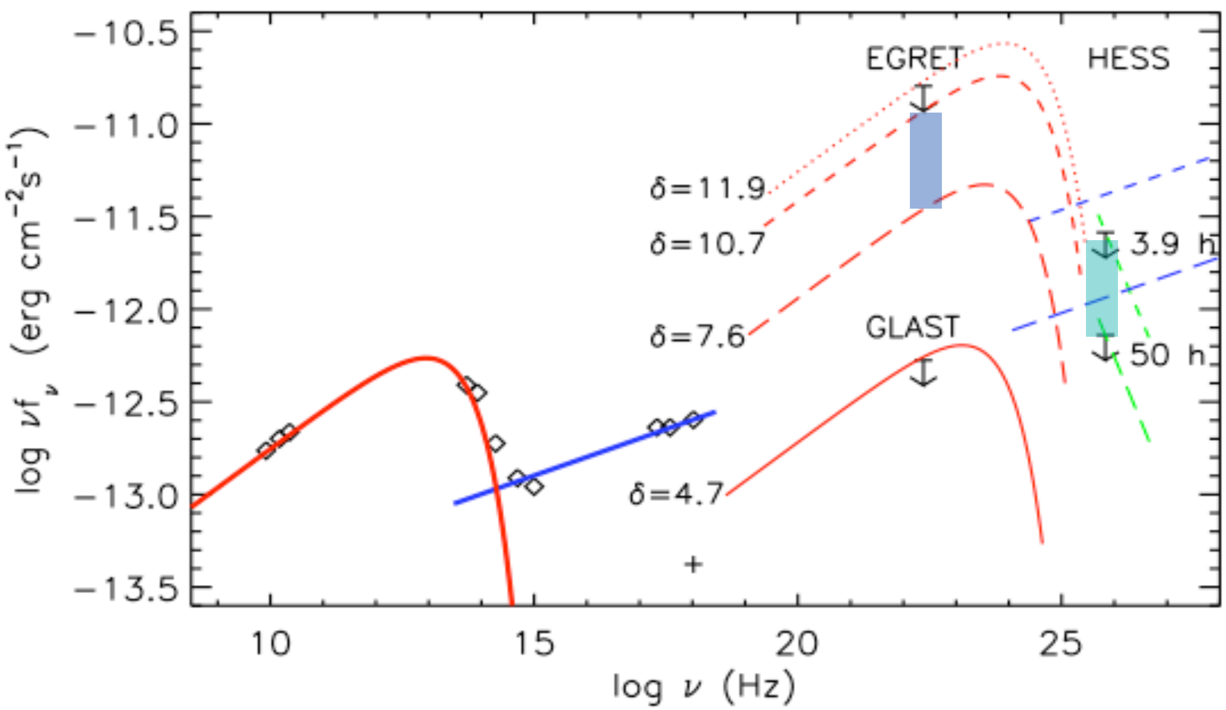
Putting the constraints together.



Jet* GeV emission is detected at a high level: 7.6<δ<11.9
If we do not detect the corresponding TeV emission
at a level between the 3.9 and 50 hour limits,
the synchrotron model is OUT.

*hard, steady

Putting the constraints together.



Jet GeV emission is detected at a high level: 7.6<δ<11.9
If we do detect the corresponding TeV emission
at a level between the 3.9 and 50 hour limits,
the synchrotron model is IN.

2. The extended radio lobes of two FR I radio galaxies

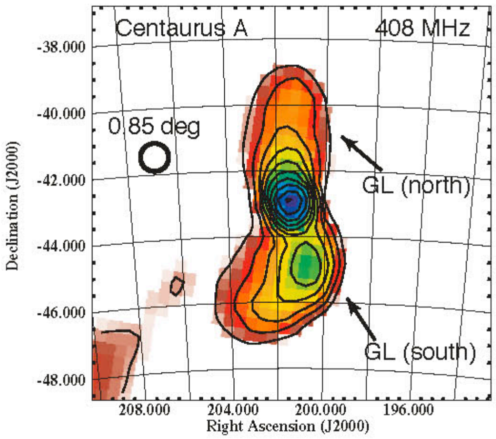
For starters, we need:

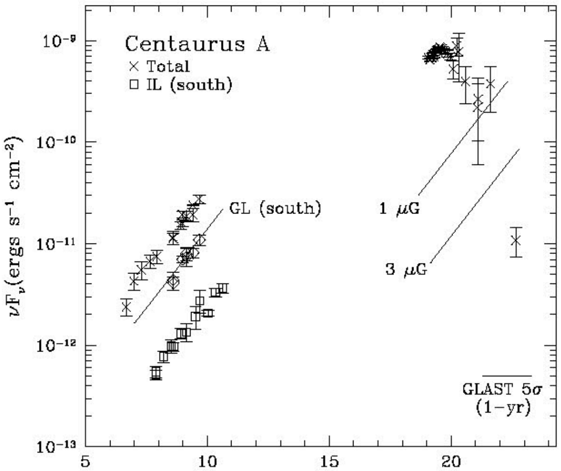
High galactic latitude to avoid contamination from unresolved sources.

Large angular size (>30’) to be resolved by LAT.

Weak core to avoid contamination of the lobe GeV flux.

Cen A, an 8 degree wide, nearby source (Cheung 2007)



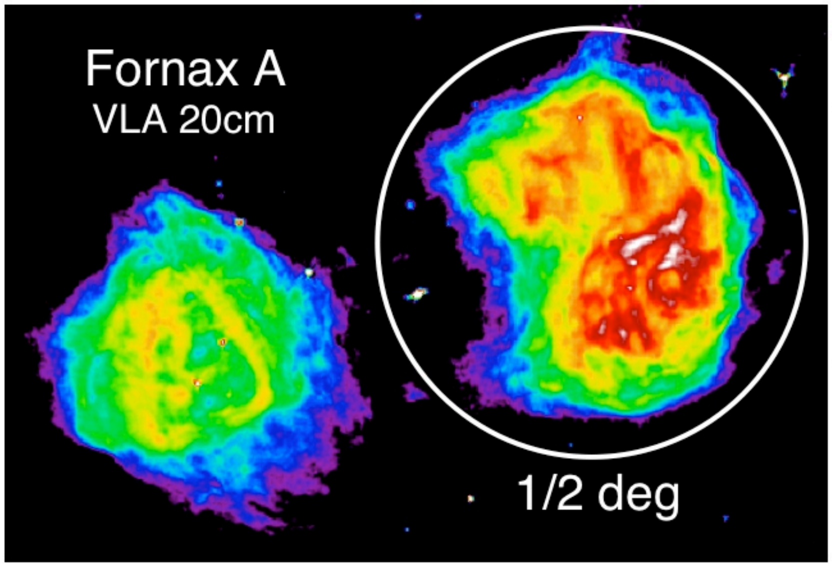


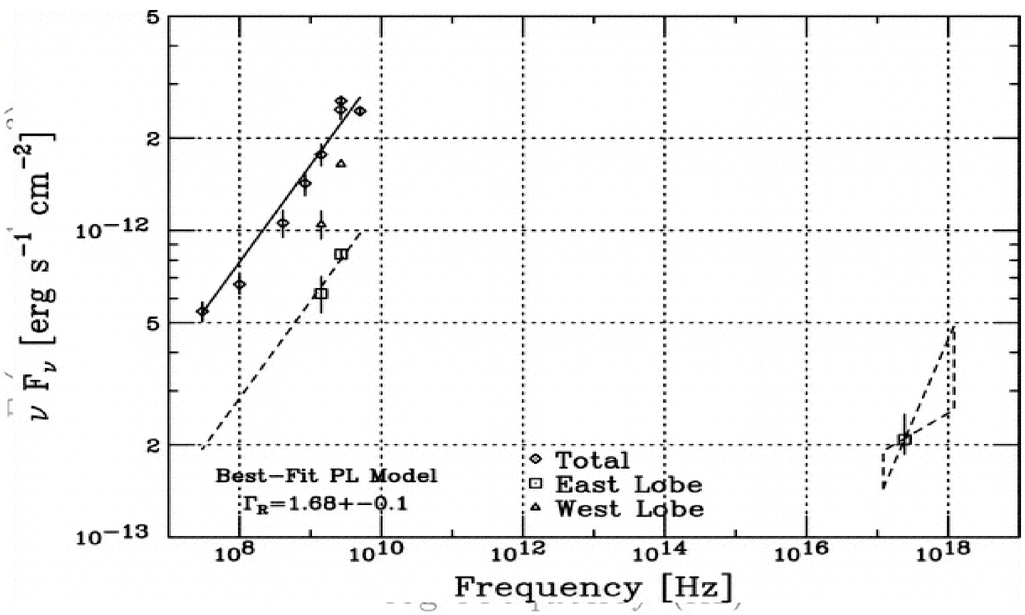
Good: radio SED of the giant radio lobes continues unbroken up to at least 43 GHz, so the EC/CMB SED definitively extends up to 100 GeV into the LAT regime.

Problem: to estimate the level of the GLAST Emission, one needs a value for the magnetic field. If the magnetic field is high (>~20 μG), then we won't see anything.

What we need: an X-ray detection of the EC/CMB from the giant lobes To obtain the magnetic field, not available for Cen A.

Fornax A, big enough for GLAST (Isobe et al. 06, Cheung 07, Sambruna et al 07





The good news: We have X-ray XMM lobe detection,

we know the magnetic field, B=1.25 μG

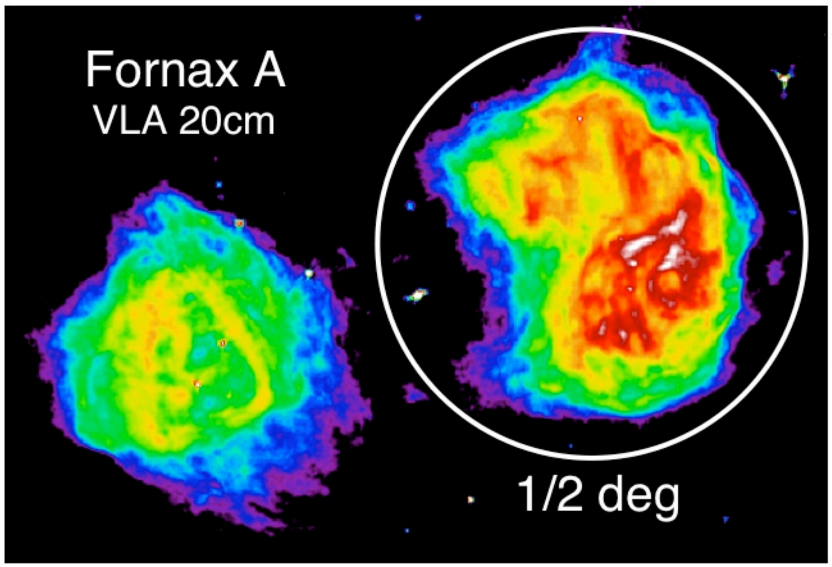
We only know the synchrotron SED up to 5 GHz.

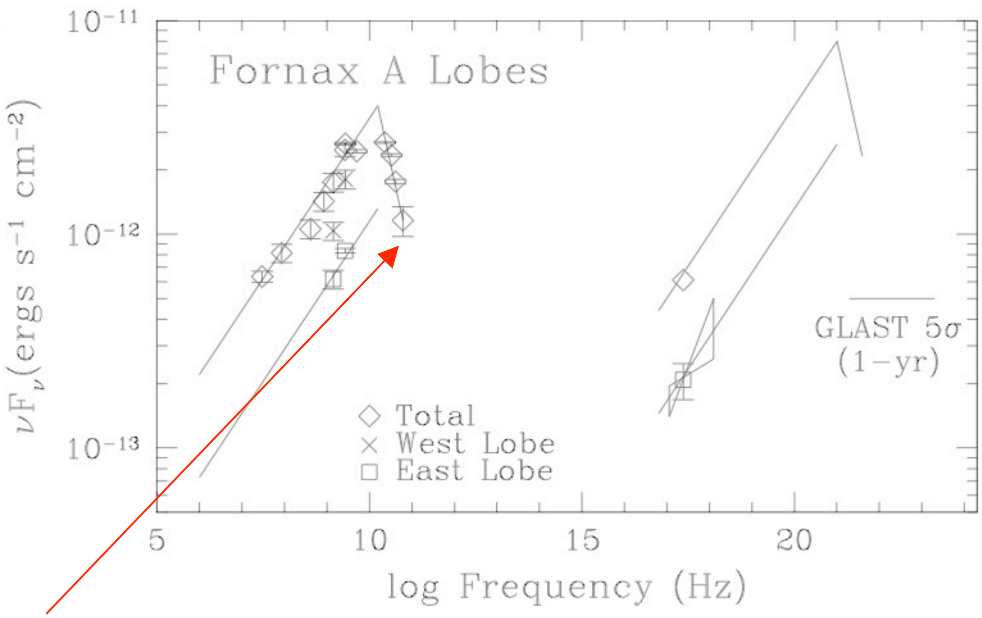
Isn't it very tempting to assume the radio continues straight up at higher frequencies??? This would give us a great GeV flux!

Άλλαι μεν βουλαί ανθρώπων, άλλα δε θεός κελεύει.

Άλλαι μεν βουλαί ανθρώπων, άλλα δε θεός κελεύει.
Men wish one thing, God orders another.*

Άλλαι μεν βουλαί ανθρώπων, άλλα δε θεός κελεύει.
Men wish one thing, God orders another*





*As revealed by WMAP measurements

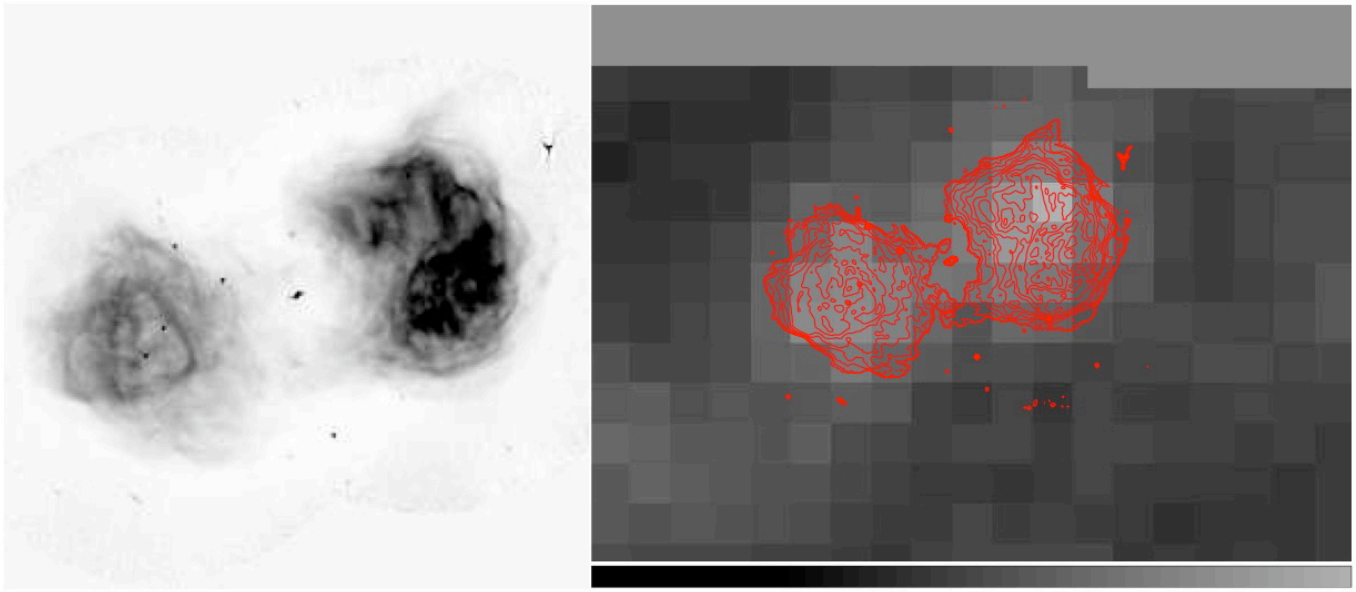


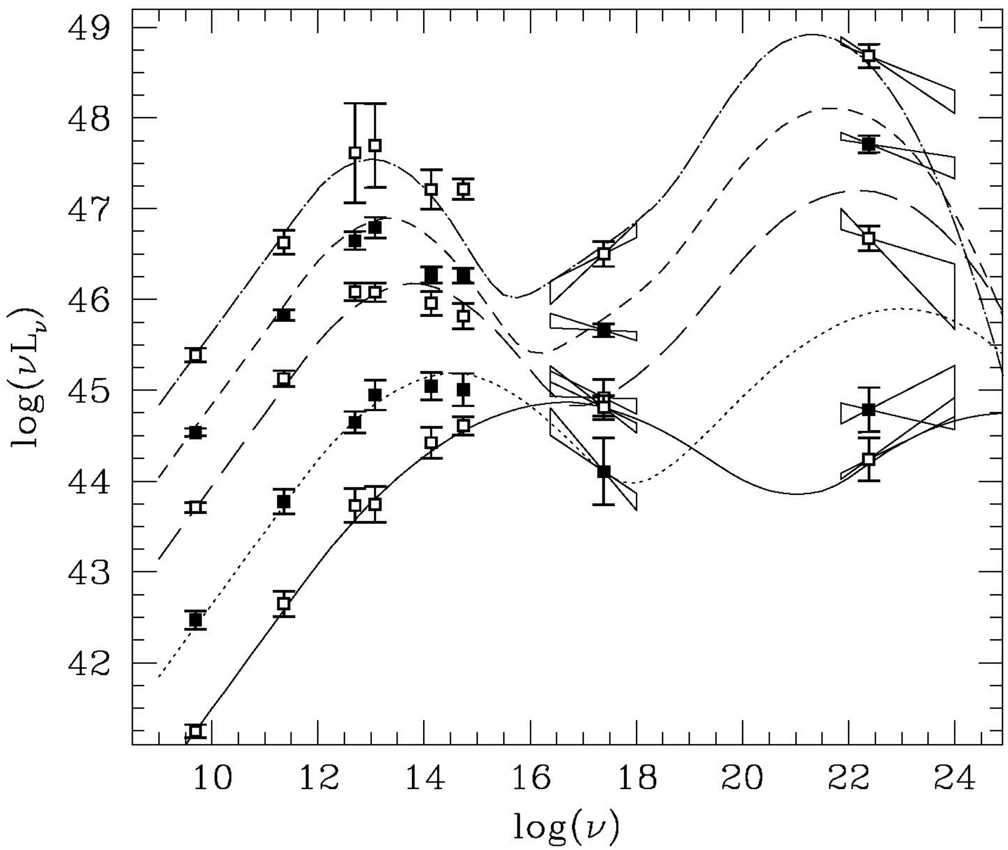
FIGURE 1. *(a, Left):* The *VLA* 5 GHz image of Fornax A [4], showing the bright E and W lobes and a weak core. *(b, Right):* Simulation of the LAT image of Fornax A during the first year of the survey (see text). North is up and East to the right.

Still, with a good instrument like LAT, we will still see and resolve the two radio lobes.

This will be the first radio galaxy, for which we will have a complete description of the EED and B field In the lobes.

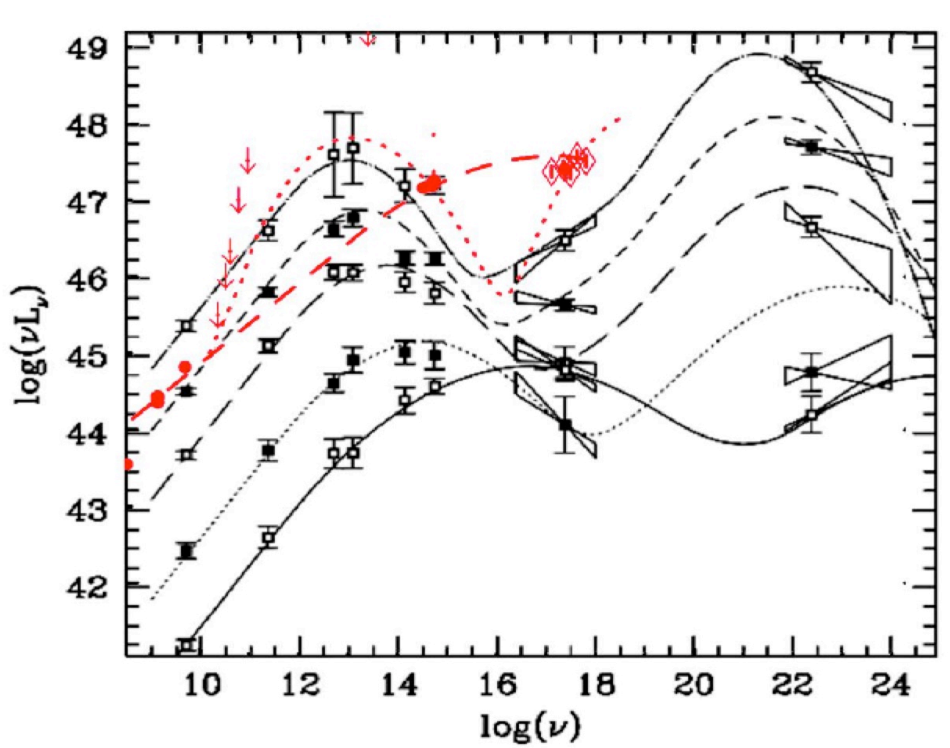
3. A Seyfert Galaxy

The blazar sequence



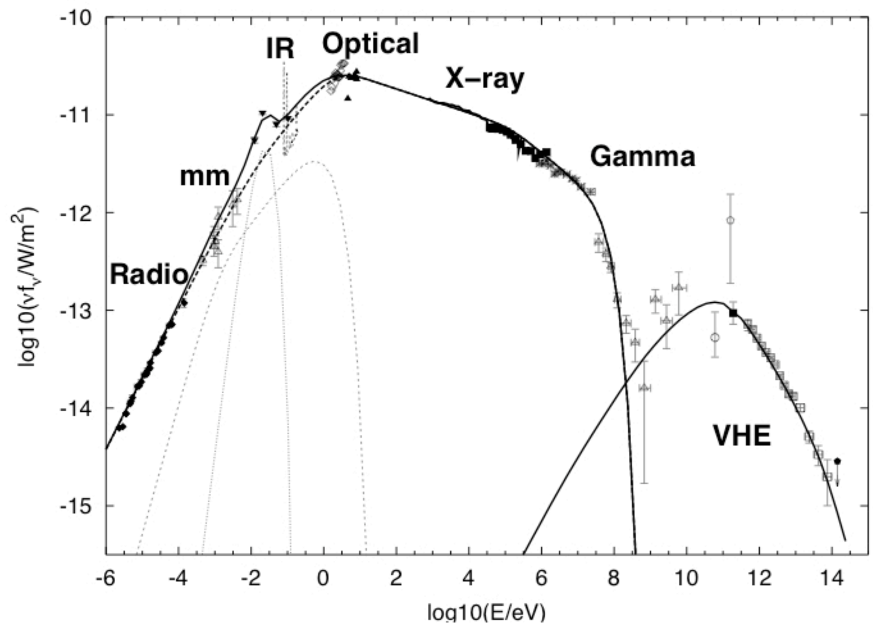
Fossati et al. 98

The blazar sequence has issues…
Expect modifications with GLAST.



Perlman et al. 98, Padovani et al. 03, Giommi et al. 2007

Extreme accelerators?



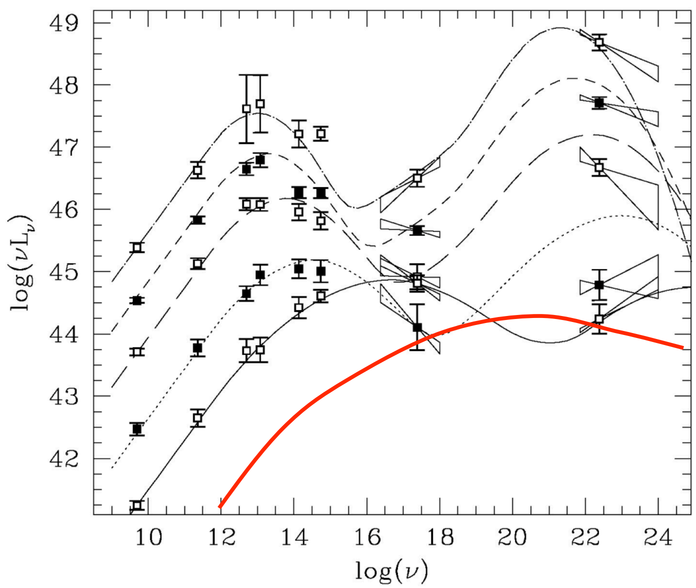
Horns & Aharonian 04

The maximum synchrotron frequency by shock acceleration is ~ 150 MeV (modulo beaming), independent of the magnetic field: acceleration time equals the light crossing time of a region the size of the Larmor radius (e.g. Drury 83).

No extragalactic extreme accelerator has been observed so far, although synchrotron emission up to ~10 MeV is observed from the Crab nebula (e.g. de Jager 96).

Costamante: Streching the blazar sequence, with extreme extragalactic accelerators

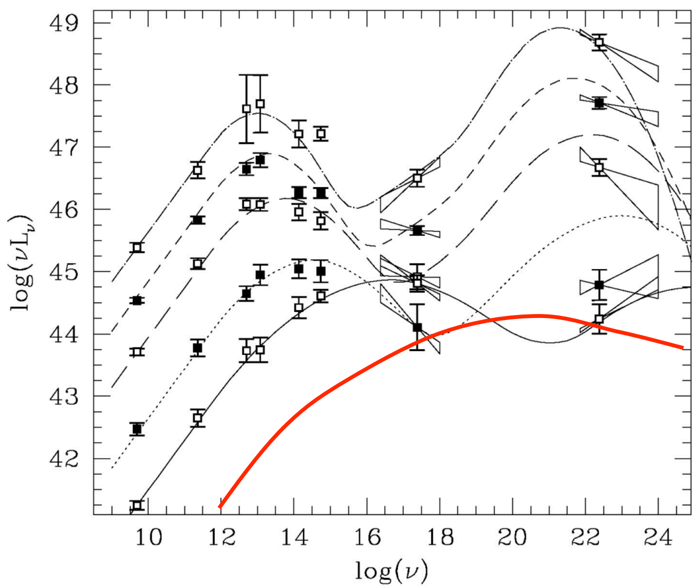
Visualize this:



Sources of much lower radio power than the current lowest power members of the blazar sequence, and with a synchrotron peak frequency at ~100 MeV energies.

Do such extreme extragalactic accelerators exist?

Streching the blazar sequence, with extreme extragalactic accelerators

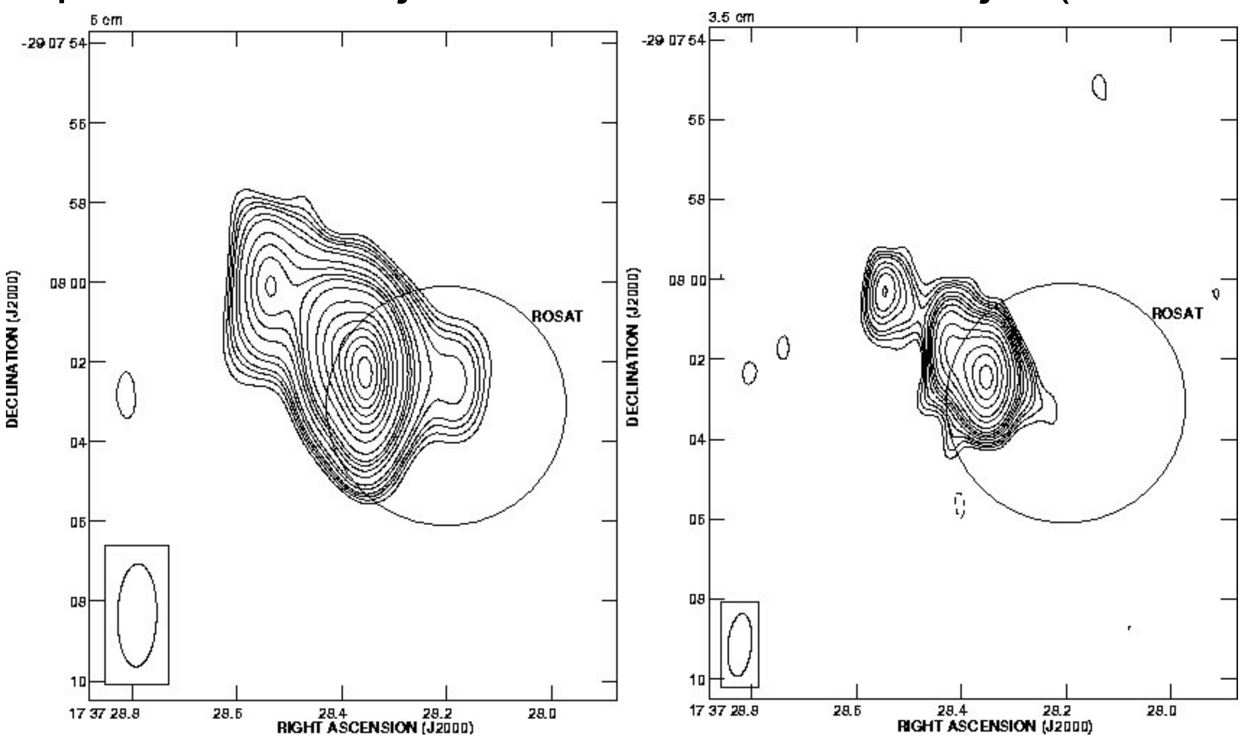


We know that as one moves from powerful to weak sources, the pc scale jets slow down (e.g. Jorstad et al. 05, Piner & Edwards 04, Cohen 07) and the large scale jets shrink and become subrelativistic (FRII to FRI transition)

<u>If we go to even weaker sources, they should have smaller and slower jets (i.e. possibly visible counter-jet).</u>

Seyfert 1 galaxy GRS 1724-292: The first extragalactic extreme particle accelerator?

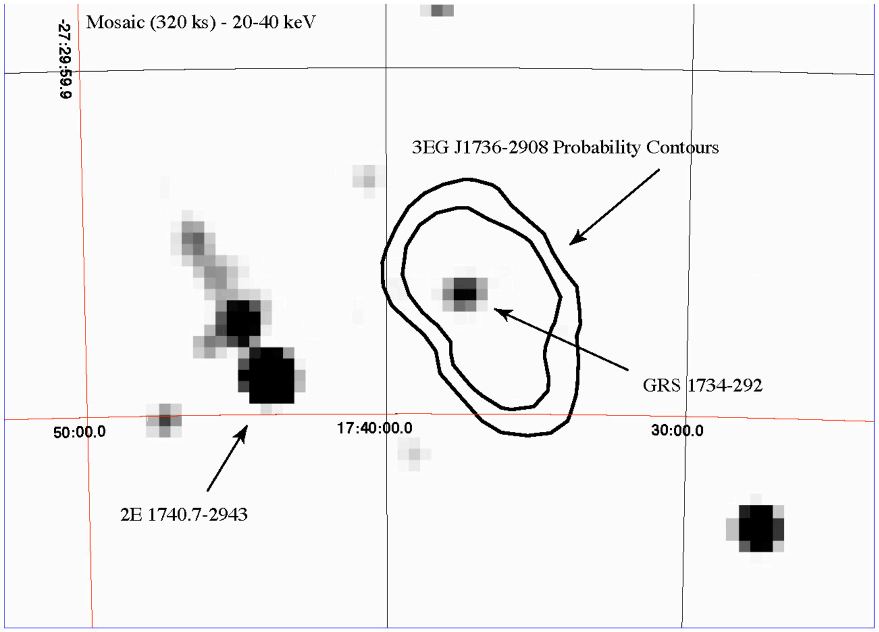
- Nice, ~ 2 Kpc scale radio jet, with a visible counterjet (Marti et al. 1998)



But several Sy 1 have similar radio features, <u>so what's the big deal?</u>

Is GRS 1724-292 the EGRET source 3EG J1736-2908?

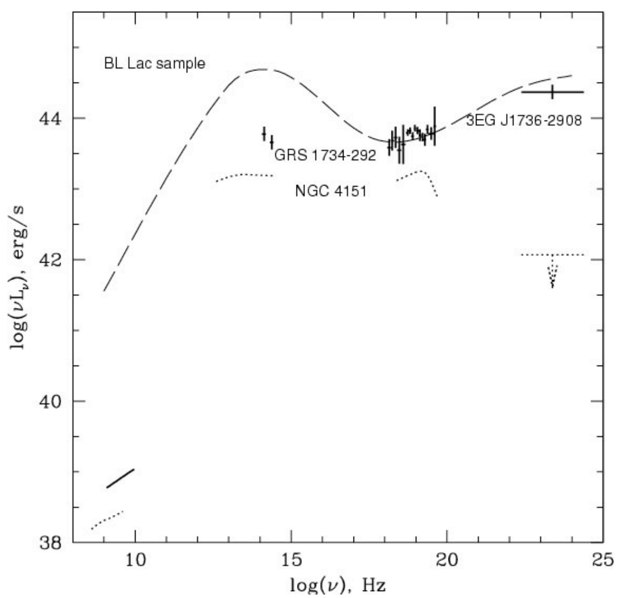
INTEGRAL image by Di Cocco et al. 04

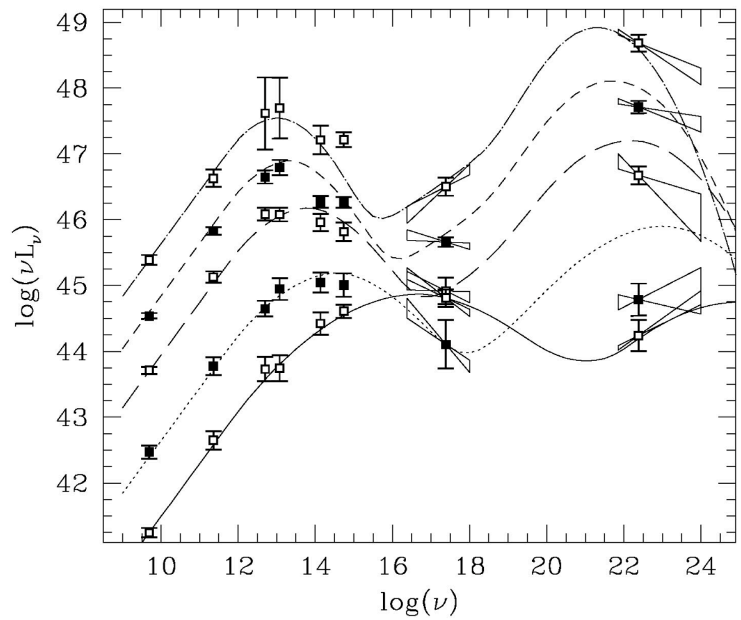


The only radio to hard X-ray source in the error box.

GLAST will confirm or reject this.

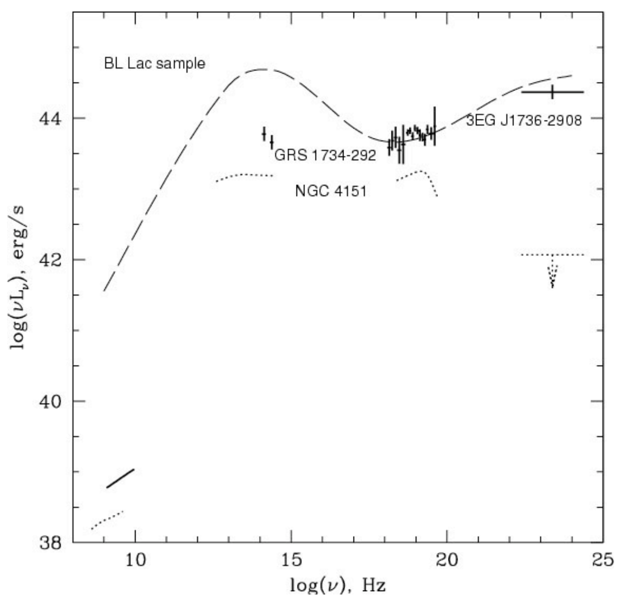
Sazonov et al. 04

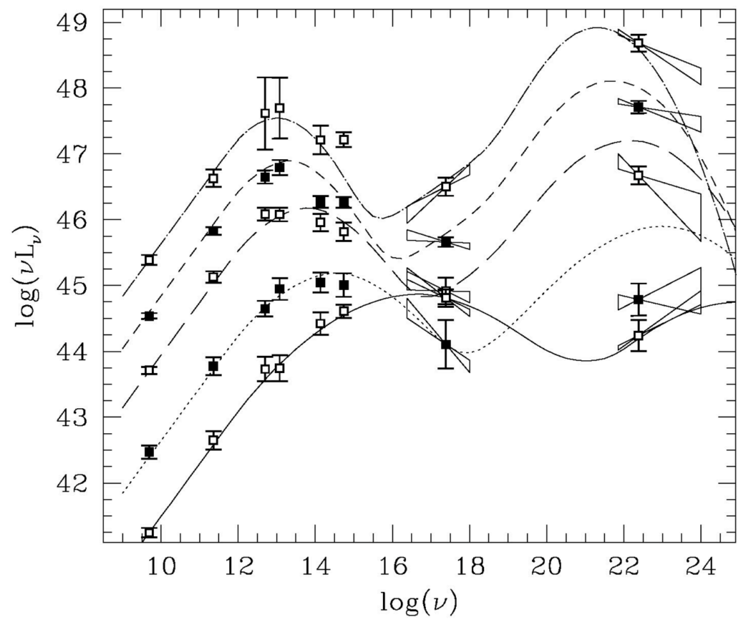




A GLAST confirmation, together with the MeV-GeV SED, will provide with the first extragalactic synchrotron source to go up to γ-ray energies.

Sazonov et al. 04





Extra-
extra
credit:

If the synchrotron SED clearly goes beyond ~150 MeV, then we see a process that IS NOT shock acceleration

4. The sneak preview

High Energy Variability Of Synchrotron-Self Compton Emitting Sources: Why One Zone Models Do Not Work, And How We Can Fix It

Philip Graff[1], M. Georganopoulos[1], E. S. Perlman[1], D. Kazanas[2]

[1]University of Maryland, Baltimore County, [2]NASA, GSFC

With the anticipated launch of GLAST, the existing X-ray telescopes, and the enhanced capabilities of the new generation of TeV telescopes, developing tools for modeling the variability of high energy sources such as blazars and microquasars is becoming a high priority. We point out the serious, innate problems one zone synchrotron-self Compton models have in simulating high energy variability. We then present the first steps toward a multi zone model where non-local, time delayed Synchrotron-self Compton electron energy losses are taken into account. By introducing only one additional parameter, the length of the system, our code will not only simulate variability properly, but it will be able to treat sources at stages of high Compton dominance, a situation typical of flaring systems.

1. The One Zone Model

When modeling blazer radiation, past models have all incorporated some form of a one zone model. However, these models are limited by the following factors:

- •High-energy electrons cool faster than the light crossing time
- •Light crossing effects must be considered

When neither of these are accounted for, this produces variability on scales less than the light crossing time, which is incorrect. One must consider the time that it takes for light to be transmitted from different parts of the zone, and as Chiaberge and Ghisellini (1999) showed in their paper, and as shown below in Figure 1, the shortest observable variability that can be trusted is the light crossing time of the zone.

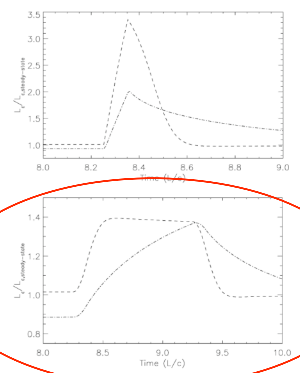


Figure 1. Here the injection is only increased for only one tenth of the light crossing time. The upper graph shows their development over time without delays accounted for. The lower graph accounts for these delays and shows that the

2. The Multi Zone Model

In this model, we couple the equations describing each zone in the following fashion:

Zone 1: $$\frac{\partial n(\gamma,t)}{\partial t}+\frac{\partial}{\partial\gamma}[\dot{\gamma}n(\gamma,t)]+\frac{n(\gamma,t)}{t_{esc}}=q(\gamma,t)$$

Zone 2: $$\frac{\partial n(\gamma,t)}{\partial t}+\frac{\partial}{\partial\gamma}[\dot{\gamma}n(\gamma,t)]+\frac{n(\gamma,t)}{t_{esc}}=q(\gamma,t)$$

Zone 3: $$\frac{\partial n(\gamma,t)}{\partial t}+\frac{\partial}{\partial\gamma}[\dot{\gamma}n(\gamma,t)]+\frac{n(\gamma,t)}{t_{esc}}=q(\gamma,t)$$

⋮ ⋮

By doing so, we are able to examine the same spatial region while decreasing the light crossing time for any single zone. The only new physical parameter introduced is the length of the entire system.

Formulas for the emissions were taken as delta functions as described by Rybicki and Lightman (1979) in order to expedite the simulation.

Time steps in this simulation were used as the escape time of the electrons from one cell to the next. This way, variations in the electron energy distribution would be transmitted at the proper rate and this allows variations to be measured at the smallest interval that can be trusted. Below is a graphical example of the multi zone model, Figure 2.

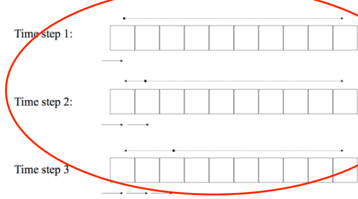


Figure 2. This depicts the energetic electrons (lower arrows) propagating from cell to cell at each time step and the radiated photons (upper dashed arrows) propagating throughout the system at the speed of light.

In the coupling of the equations, the light present in a cell incorporated light from all other cells at proper time delays. This was achieved by using the following formula:

$$U(x,t,\varepsilon)=\int_{l_{min}}^{l_{max}} L\left(l,t=|x-l|/c,\varepsilon\right)/4\pi c(x-l)^2\, dl$$

In this formula, *l* is the distance along the zones. The time calculation used for *L* finds the retarded time for the light travel. The most important implication of this addition is that it enables the model to be able to properly handle and simulate inverse Compton dominated states in blazars.

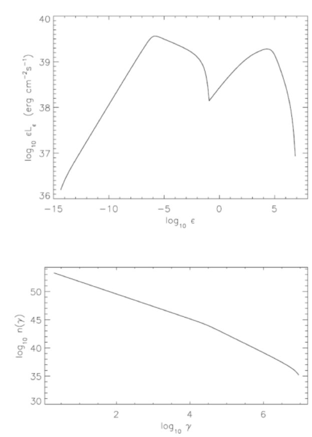


Figure3. The upper graph is the spectral energy distribution from a synchrotron dominated blazar. The injection is a power-law function with an index of 2.2. The first peak is in the X-ray region and is from synchrotron emission. The second peak is just below the TeV region and is from synchrotron-self Compton emission. The lower graph displays the electron energy distribution

4. Orphan Flare Case Studies

Orphan flares have been observed by Krawczynski, et. al. (2004) and Blazejowski, et. al. (2005). They are the appearance of a flare in the gamma ray region of emission without an accompanying flare in the X-ray spectrum. They occur infrequently and we are not sure exactly what causes them. Below are two possible explanations for these flares and simulations in the multi zone model.

EXAMPLE 1: Flare in TeV range with no accompanying X-ray flare.

- •Caused by a production of more low-energy electrons
- •Provides seed photons for current high-energy electrons
- •Dominance or near-dominance of inverse Compton cooling

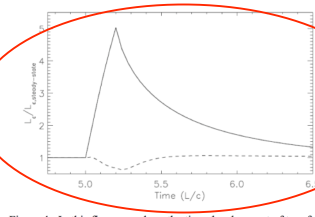


Figure 4. In this figure we show the time development of two frequencies of light. The dashed line is X-ray and the solid line is TeV emission.

EXAMPLE 2: Delayed flare in TeV range following a regular flare

- •Pulse adds more high-energy electrons
- •Not able to be simulated with a one zone model
- •Requires an "echo" effect from light transmission between zones
- •Electrons cool as they travel, and emit radio photons in a later zone
- •Photons travel back to the beginning and are Compton scattered

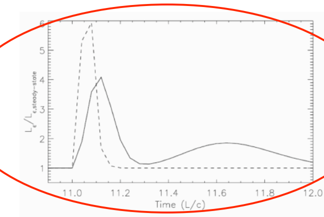


Figure 5. In this figure we show the time development of two frequencies of light. The dashed line is X-ray emission and the solid line is TeV.

5. Citations and Acknowledgements

Blazejowski, et. al. "A Multiwavelength View of the TeV Blazar Markarian 421: Correlated Variability, Flaring, and Spectral Evolution." *The Astrophysical Journal*. 630: 130-141, 2005 September 1.

Chiaberge, Marco and Ghisellini. "Rapid Variability in the Synchrotron Self-Compton Model for Blazars." *Mon. Not. R. Astron. Soc.* 306: 551-560, 1999.

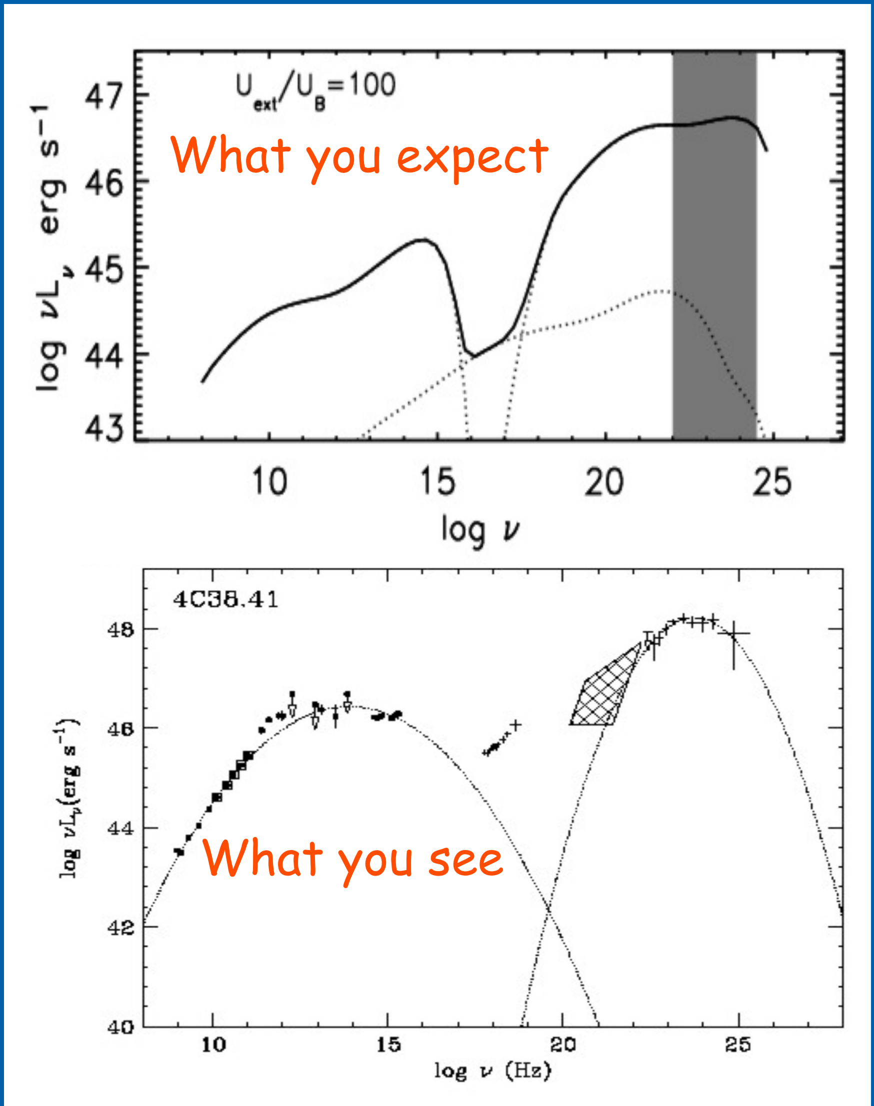
Krawczynski, et. al. "Multiwavelength Observations of Strong Flares from the TeV Blazar 1ES 1959+650." *The Astrophysical Journal*. 601: 151-164, 2004 January 20.

Rybicki, G. and Lightman. *Radiative Processes in Astrophysics*. New York: John Wiley & Sons, 1979.

This project is part of Philip Graff's senior thesis that is in progress. The authors acknowledge support from a Chandra theory grant and a NASA long-term space astrophysics grant.

1. EC off the BLR has problems

- External Compton scattering of BLR photons disagrees with the spectra of high Compton dominance blazars.
- Final confirmation/ rejection of this will have to await for GLAST.



SSC, back to where we started from (almost)

Q: *But can SSC produce superquadratic variations like those seen in 3c 279? (Wehrle et al. '98)*

A: Yes, it does so naturally, when the SSC power is comparable or higher than the synchrotron power.

Even more so when the second order (SSC2) is relevant.