Blazars in Context in the Fermi Era

Justin Finke

US Naval Research Laboratory

31 October 2012

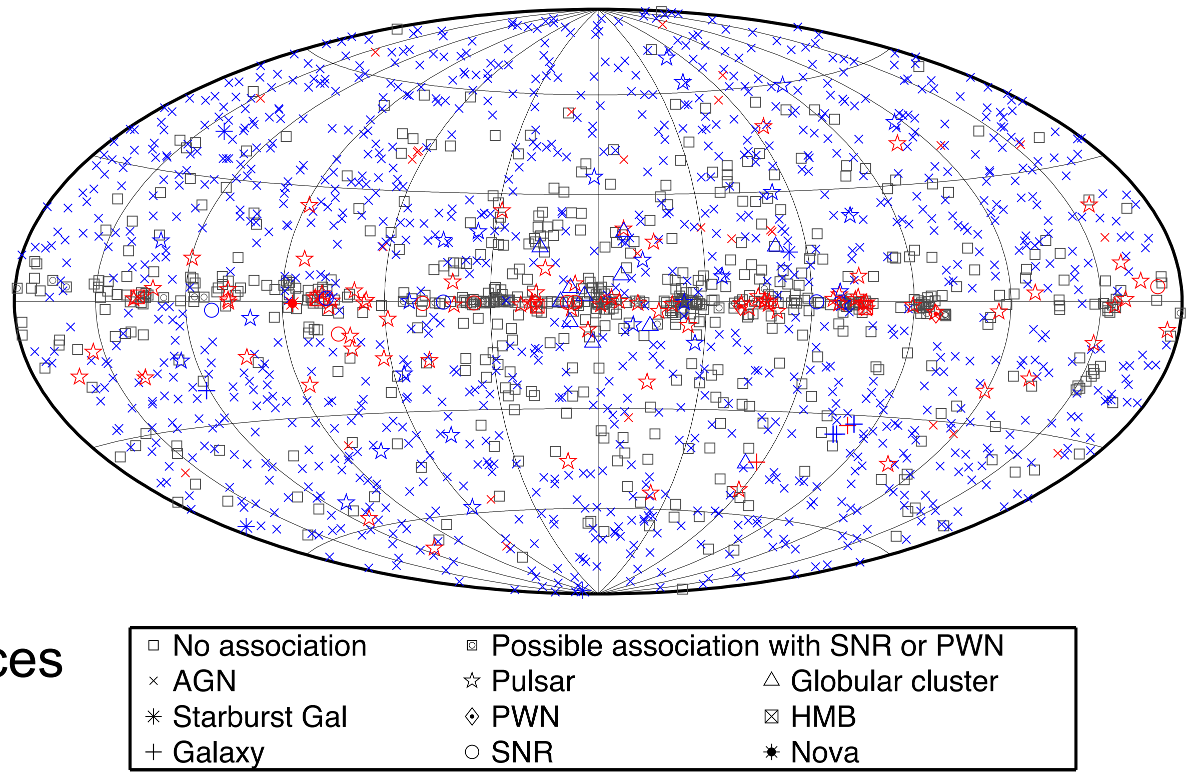
Overview

- Outline
  - Introduction to blazars
  - Blazar sequence
  - Origin of γ-ray spectral break
  - Location of γ-ray emitting region
  - The end of the one-zone leptonic model, and what is next

- This I won't talk about:
  - Radio Galaxies (Jun Kataoka and Paola Grandi later today in "AGN II")
  - Narrow Line Seyfert I galaxies (Filippo D'Ammando later today in "AGN II")
  - Starburst galaxies (Keith Bechtol tomorrow)
  - Using blazar γ-ray emission to probe the EBL and IGMF (Marco Ajello, Alberto Dominguez, and Ievgen Vovk tomorrow, my poster today and tomorrow)

Blazars dominate the γ-ray sky

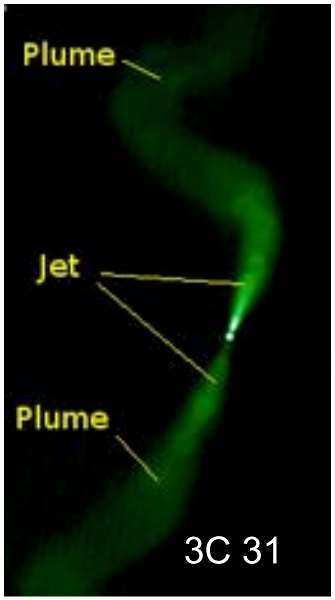
- The Second *Fermi* LAT Catalog:
- 1,298 identified or associated sources
- 84% of these are AGN, mostly blazars
- 575 unassociated sources
- Of the unassociated sources, so far 27% have since been identified as blazars (Massaro et al. 2012, ApJ, 752, 61; talk in "AGN I")



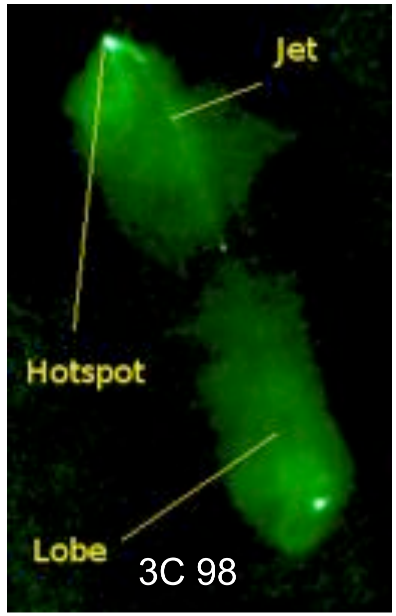
Nolan et al. (2012), ApJ, 199, 31

Fermi is a blazar telescope!

Radio Loud AGN



Fanaroff-Riley I



Fanaroff-Riley II

Radio galaxies seem to be unified with blazars.

Evidence:

- Diffuse radio lobes in BL Lacs
- Statistics of blazars
- Apparent Superluminal motion

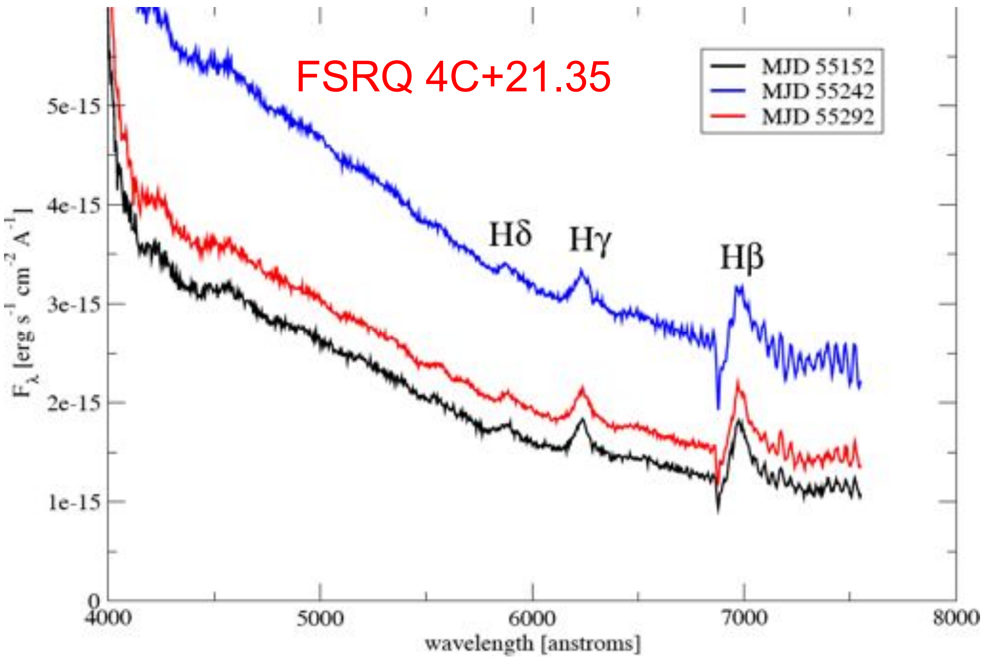
	Low power (L_r<~10^{41} erg s^{-1}), wide opening angle	High power (L_{rr}>~10^{41} erg s^{-1}), narrow opening angle
Jet pointed away from us	FR I	FR II
Jet pointed towards us	BL Lac	FSRQ

Urry & Padovani (1995)

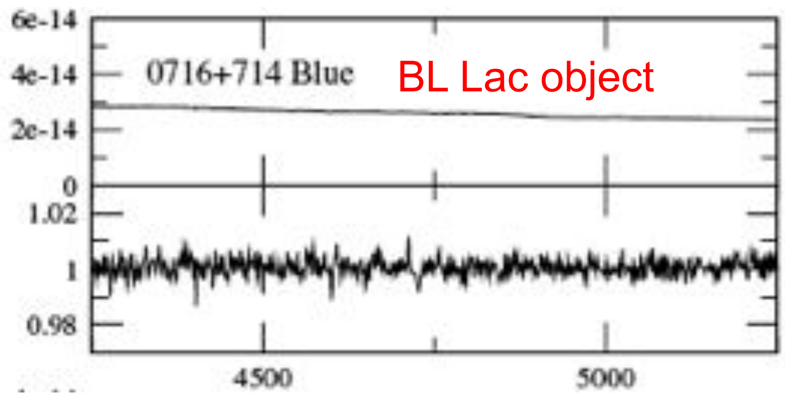
See Jun Kataoka's talk a bit later!

Blazar optical spectra and redshifts

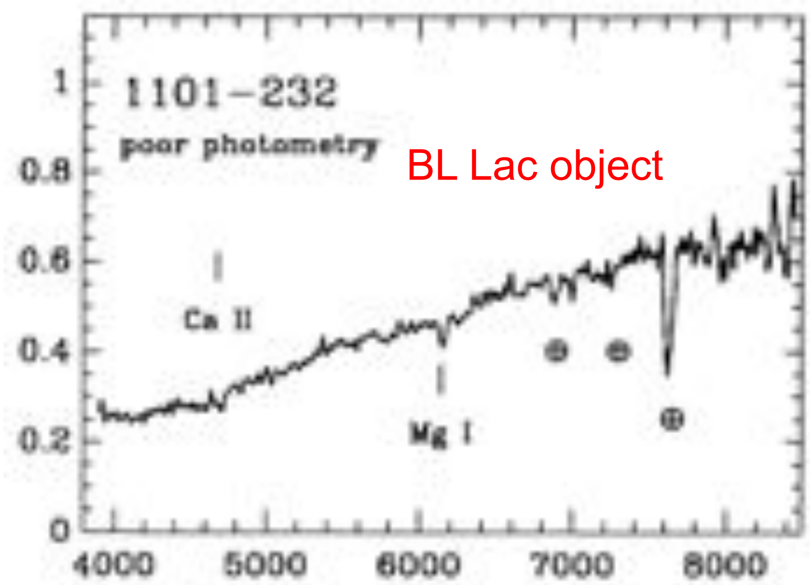
FSRQs: strong broad emission lines
BL Lacs: weak or no broad emission lines



Kuipper telescope (1.5 m; black) and Bok telescope (2.3 m; red, blue). source: http://james.as.arizona.edu/~psmith/Fermi/



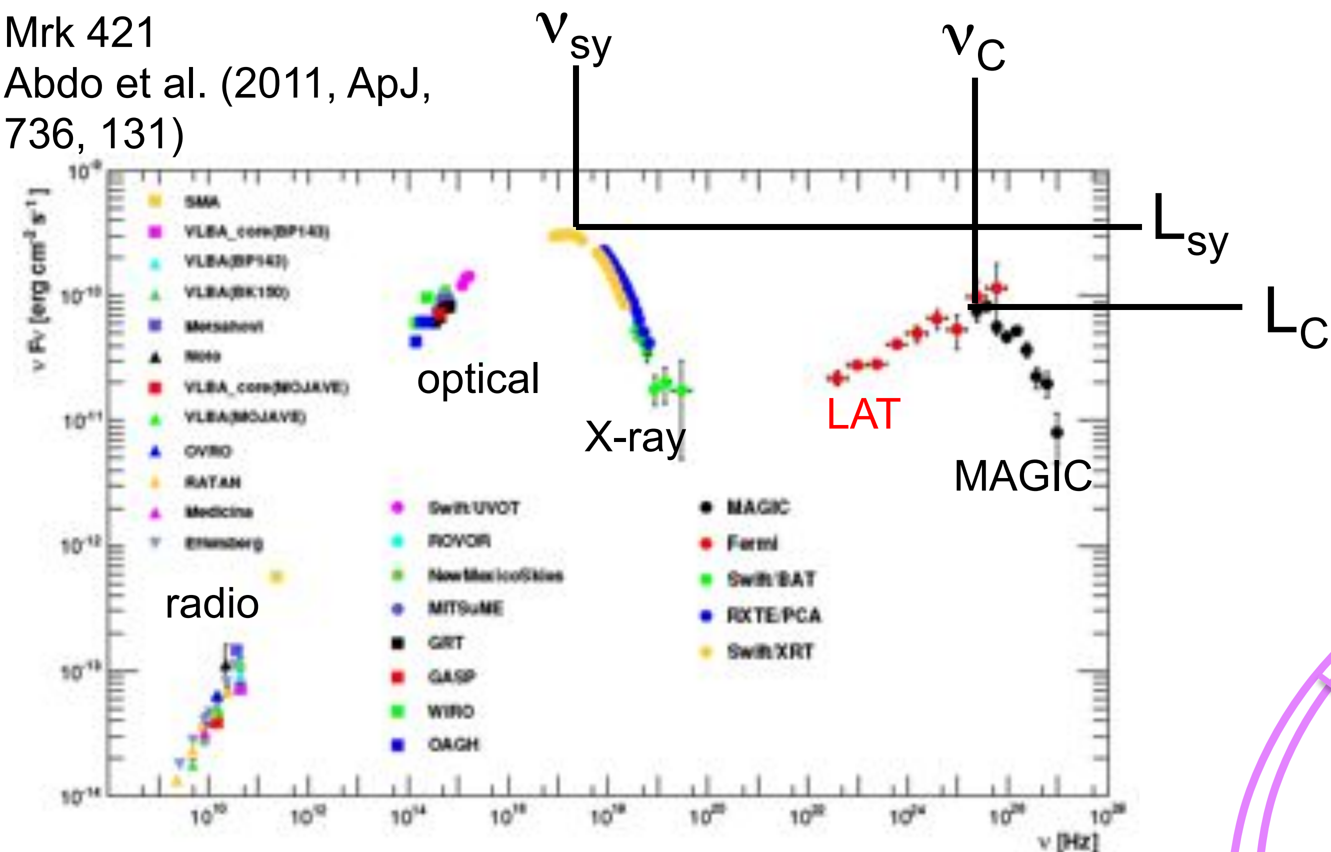
2.4 m Hiltner telescope. JF et al. (2008)

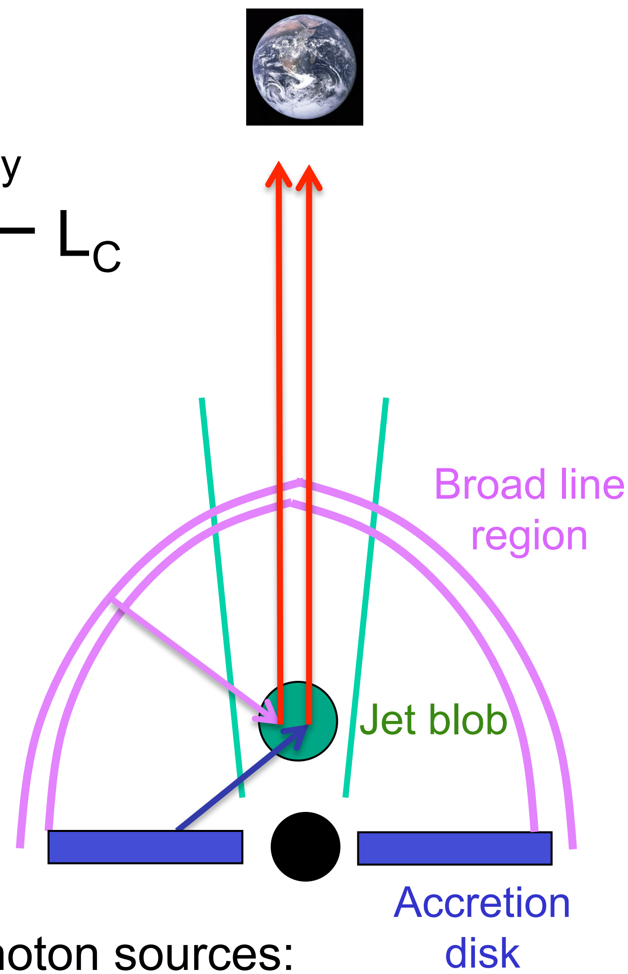


3.9 m Anglo-Australian telescope.
Source: Falomo et al. (1994)

Nonthermal Blazar Emission

Mrk 421
Abdo et al. (2011, ApJ, 736, 131)





Blazar SEDs dominated by two "bumps":

- Synchrotron bump: peaking at <~ 10^{17} Hz
- Compton bump: peaking at γ-ray energies. Seed photon sources:
  - Synchrotron photons (synchrotron self-Compton or SSC)
  - Broad line region (BLR), accretion disk, or dust torus photons

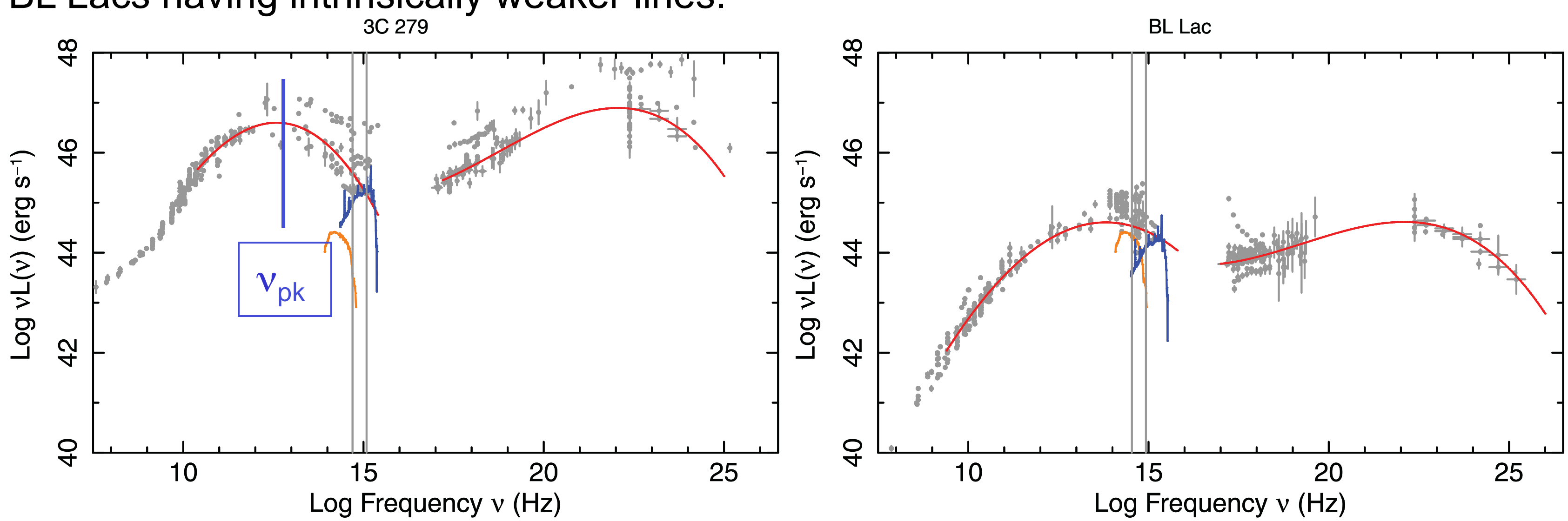
Blazar SEDs

Blazars also classified based on the position of their synchrotron peak (Second LAT AGN Catalog; Ackermann et al. 2011, ApJ, 743, 171).

- 10^{15} Hz < ν_{pk}: *high synchrotron peaked (HSP)*
- 10^{14} Hz < ν_{pk} < 10^{15} Hz: *intermediate synchrotron peaked (ISP)*
- ν_{pk} < 10^{14} Hz : *low synchrotron peaked (LSP)*

Almost all FSRQs are LSPs.

About half of BL Lacs in 2LAC do not have a measured redshift (but see talk by Michael Shaw Thurs.). Could be due to nonthermal continuum overwhelming line emission, or BL Lacs having intrinsically weaker lines.



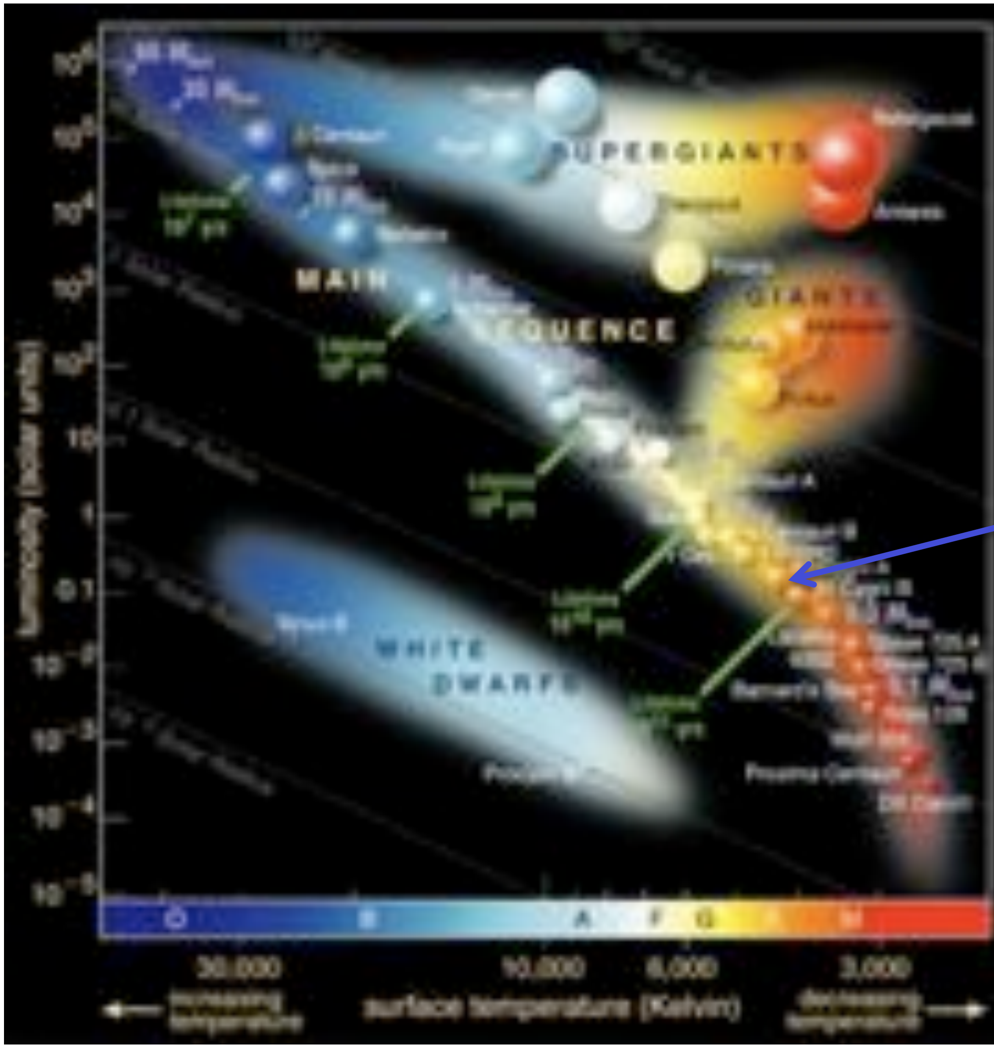
Giommi et al. (2012), MNRAS, 420, 2899

Why do we understand stars so well but not blazars?

Stars	Blazars
Isotropic emitters	Anisotropic emitters
Mostly constant on human type scales	Highly variable on human type scales (as short as hours or minutes)
Energy generation mechanism well understood	Energy generation mechanism (involving black hole) not well understood
Globular clusters allow study of stars of the same approximate age	No way to know if different AGN are the same age
Composition determined from optical spectroscopy	Fully ionized non-thermal plasma, composition can't be determined from optical spectroscopy

Hertzsprung-Russell diagram

Luminosity



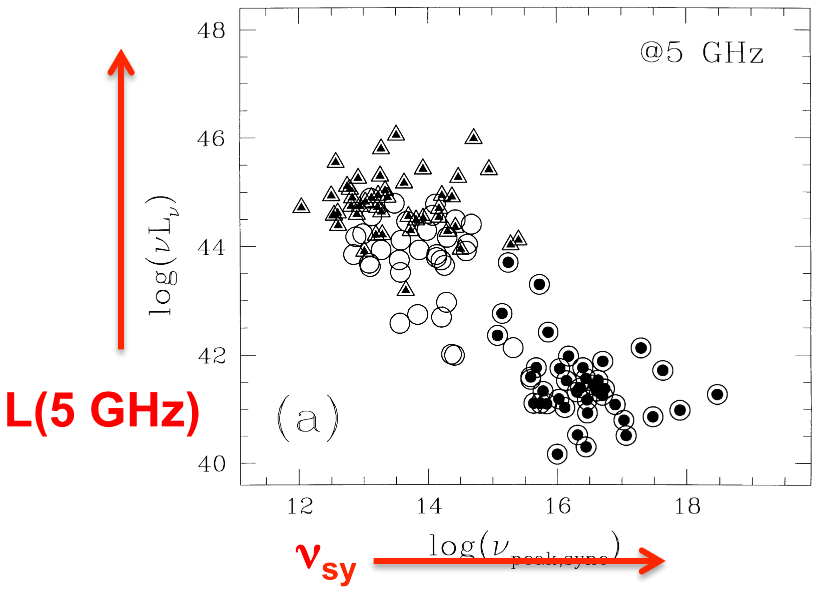
Temperature

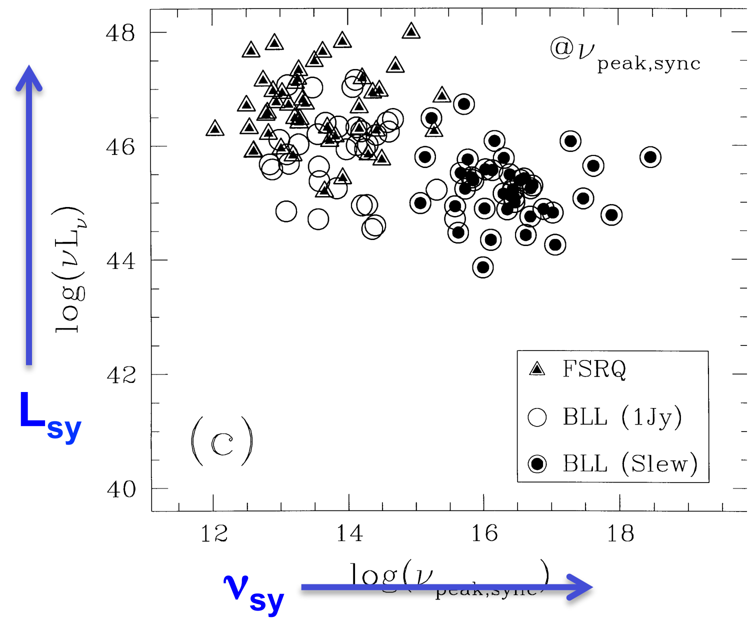
The H-R diagram is a useful tool in our understanding of stellar emission and evolution.

Stars spend most of their lives on the main sequence.

Is there a similar "main sequence" for blazars?

Blazar Sequence





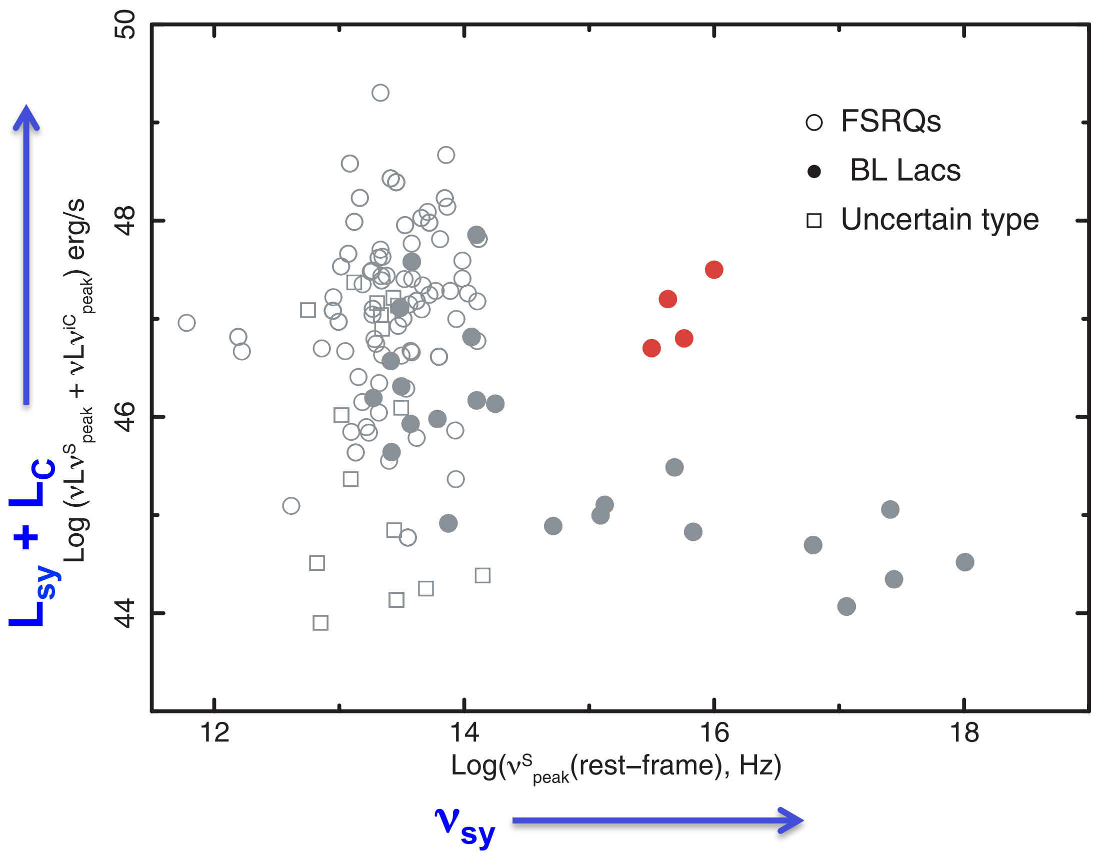
There seems to be a correlation between:

- The radio luminosity and peak frequency of the synchrotron component (left).
- The peak luminosity and peak frequency of the synchrotron component (right).

Explanation? Is it an intrinsic physical effect? Or do bright, high peaked objects have their emission lines swamped by synchrotron emission and their redshifts can't be measured?

Fossati et al. (1998), MNRAS, 299, 433

High-z high-peaked blazars?



Padovani et al. (2012), MNRAS, 422, L48

Rau et al. (2012), A&A, 538, A26 have constrained the redshifts of high-z sources from optical/UV photometry, identifying the Lyman break.

Four high-z sources indeed seem to have high synchrotron peak frequencies and luminosities.

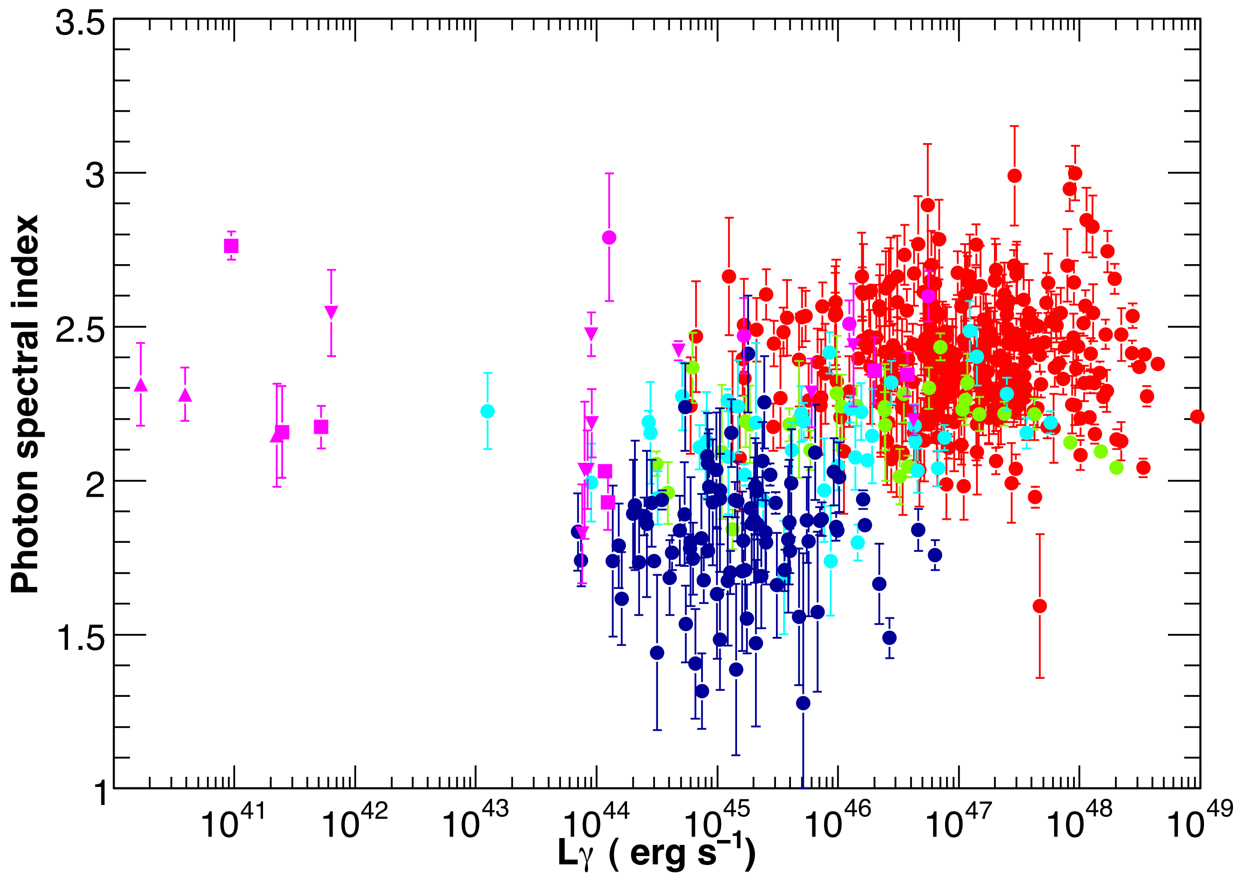
What about the gamma rays?

Correlation found between LAT spectral index and LAT γ-ray luminosity.

LAT spectral index is a proxy for γ-ray peak frequency (or energy), so this is a similar plot for γ-rays.

A correlation is evident.

Where are the four new sources on this plot?



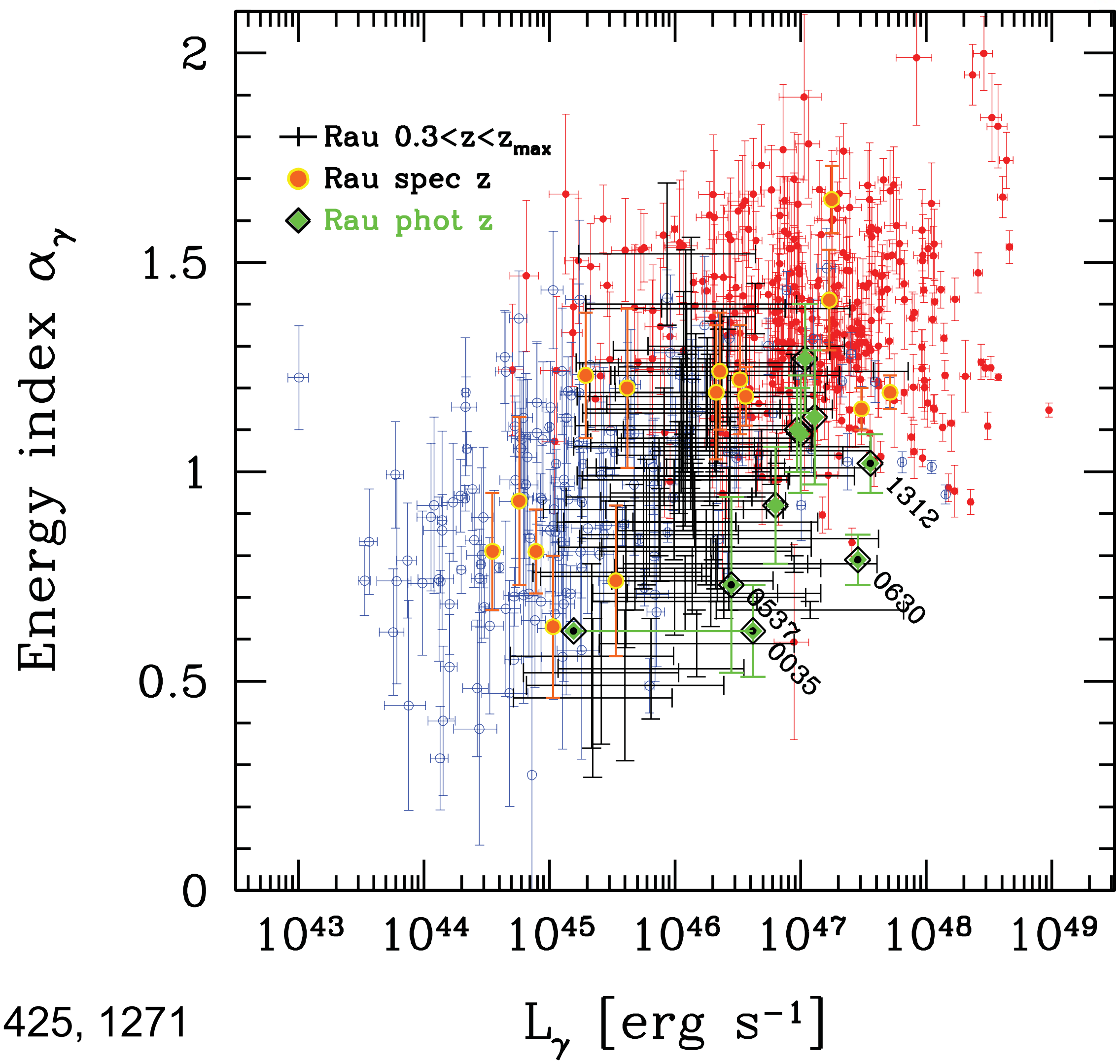
Ackermann et al. (2012), ApJ, 743, 141

What about the gamma rays?

LAT spectral index is a proxy for γ-ray peak frequency (or energy)

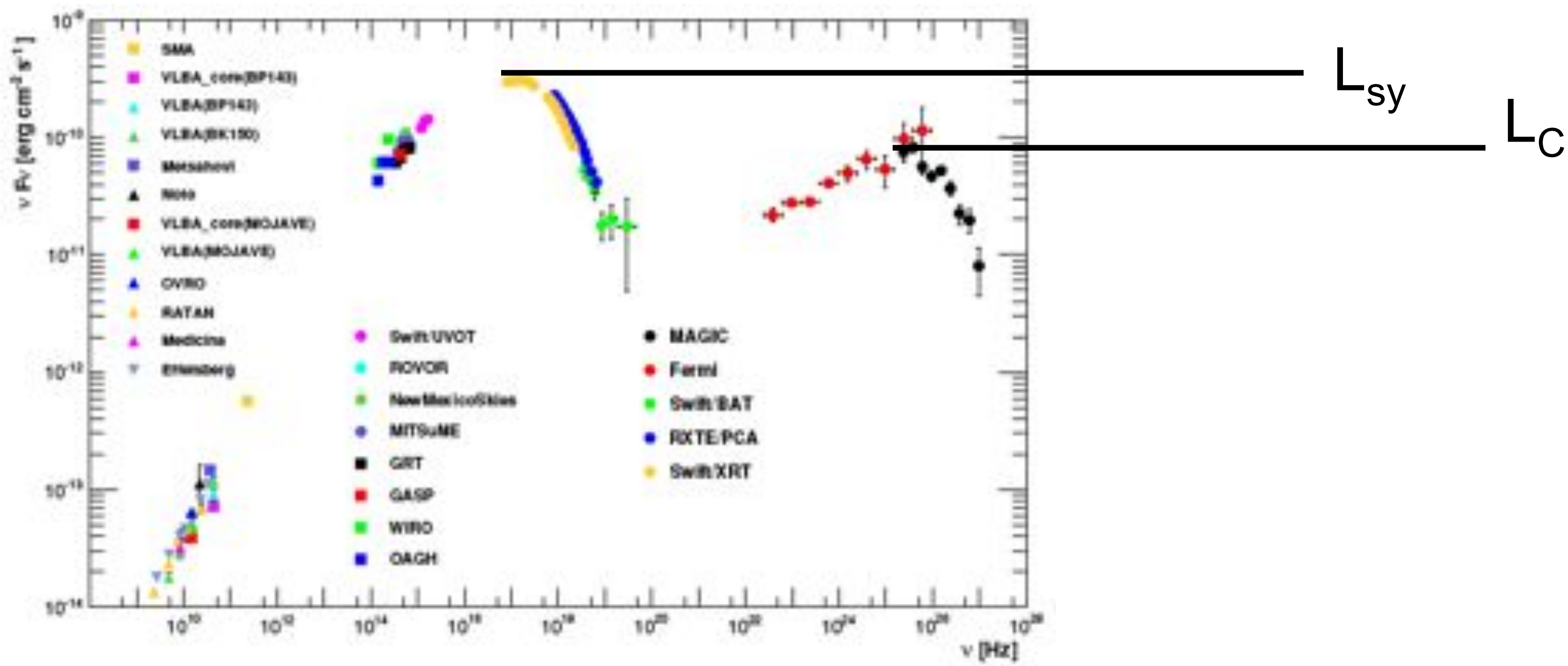
These new objects seem to be consistent with previously known sources and correlation.

But it certainly is possible in the future that high L_γ low α_γ sources will be found as more redshifts are found.



Ghisellini et al. (2012), MNRAS, 425, 1271
See also:
Meyer et al. (2012), ApJ, 752, L4

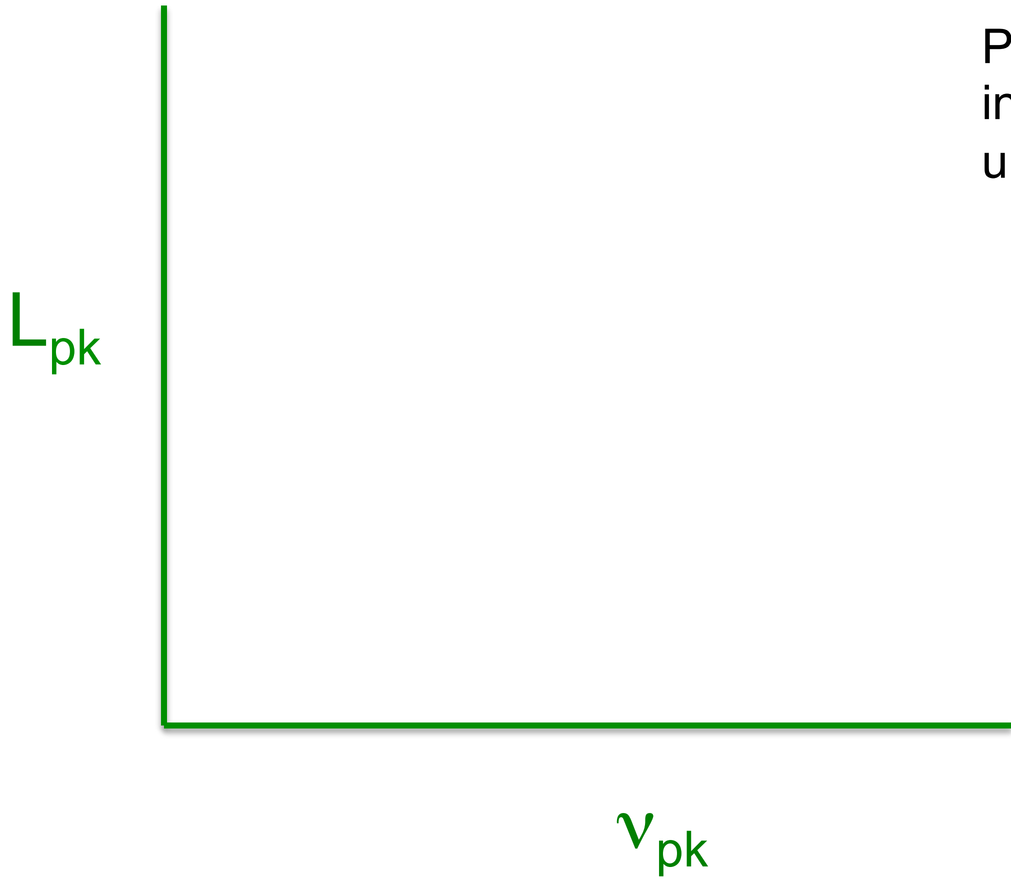
Compton Dominance



Compton dominance: $A_C = L_C/L_{sy} = F_C/F_{sy}$

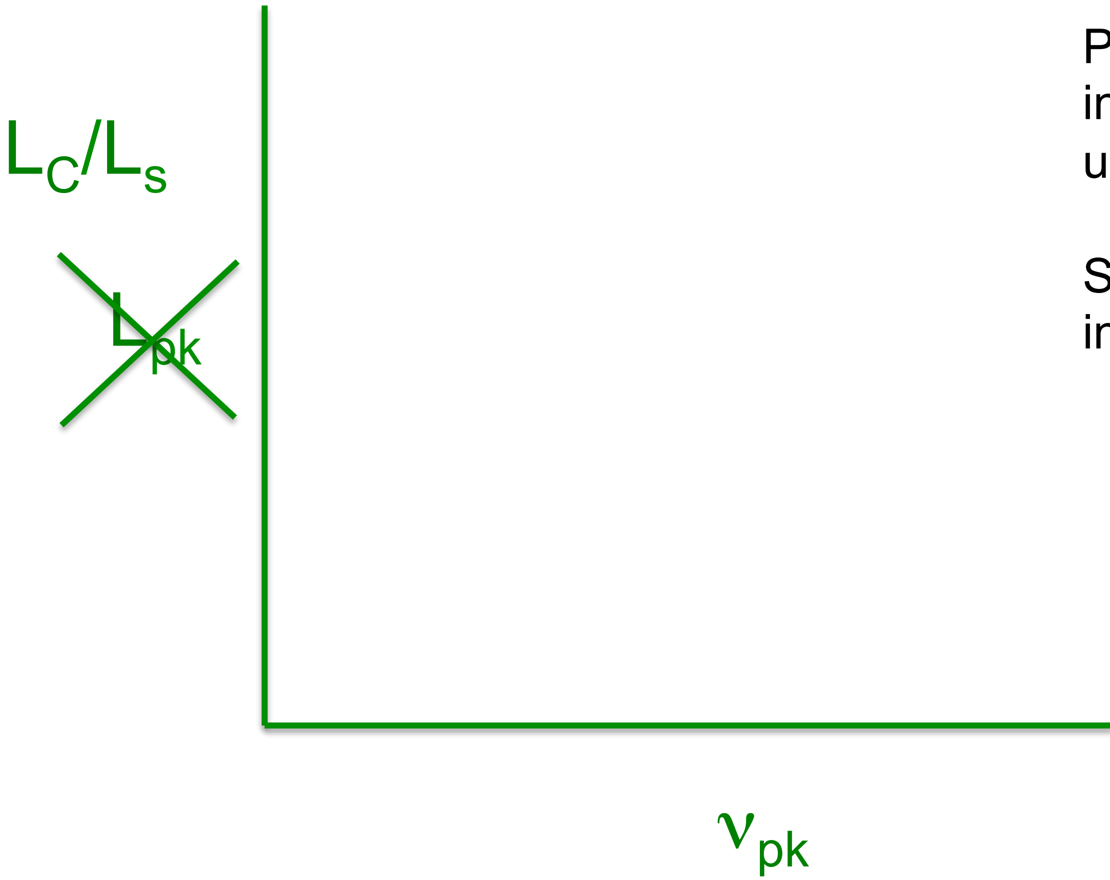
This quantity is redshift-independent

What about the gamma rays?



Potential selection effect involving sources with unknown redshifts

What about the gamma rays?



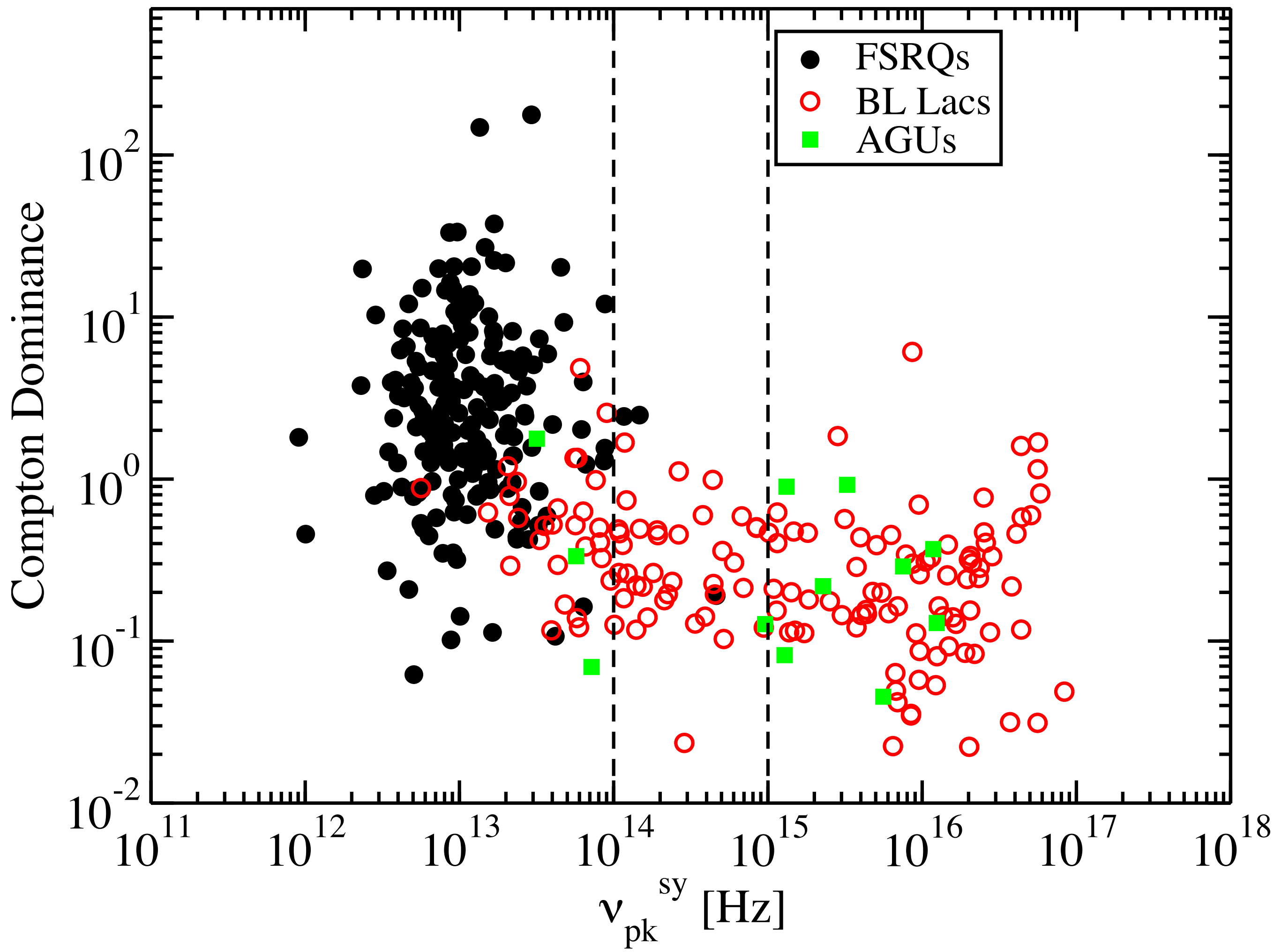
Potential selection effect involving sources with unknown redshifts

Solution: Plot redshift independent quantities

Compton dominance and the sequence

An anti-correlation clearly exists

What about sources without known redshifts?



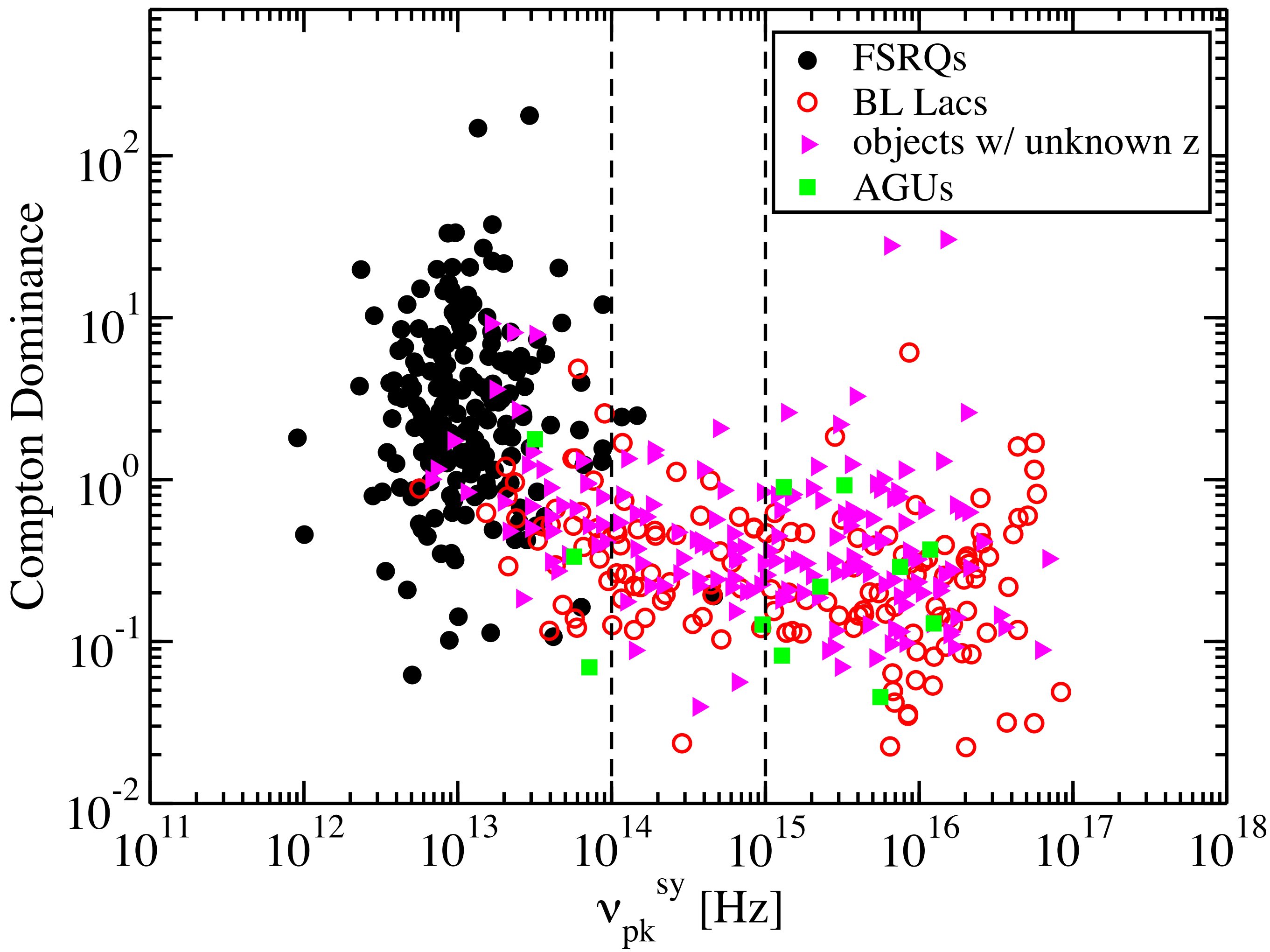
JF (2012), ApJ, submitted

Compton dominance and the sequence

ν_{pk} is in the rest frame of the source, it is a lower limit for objects with unknown z

An anti-correlation clearly exists, even with objects with unknown z plotted

Thus, at least this part of the "blazar sequence" seems to be physical and not the result of a selection effect.

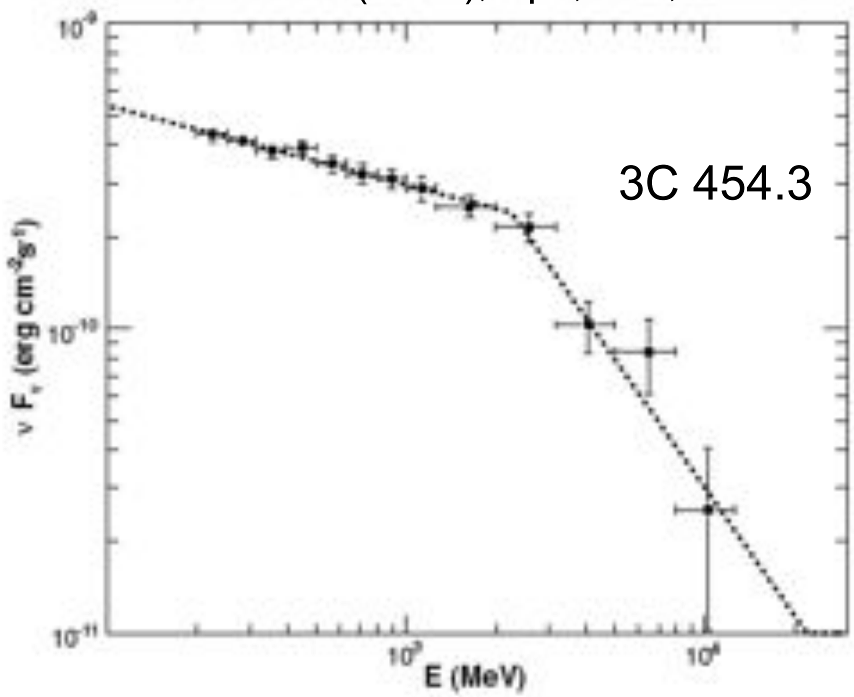


JF (2012), ApJ, submitted

Gamma ray spectral breaks

Gamma-ray spectral break

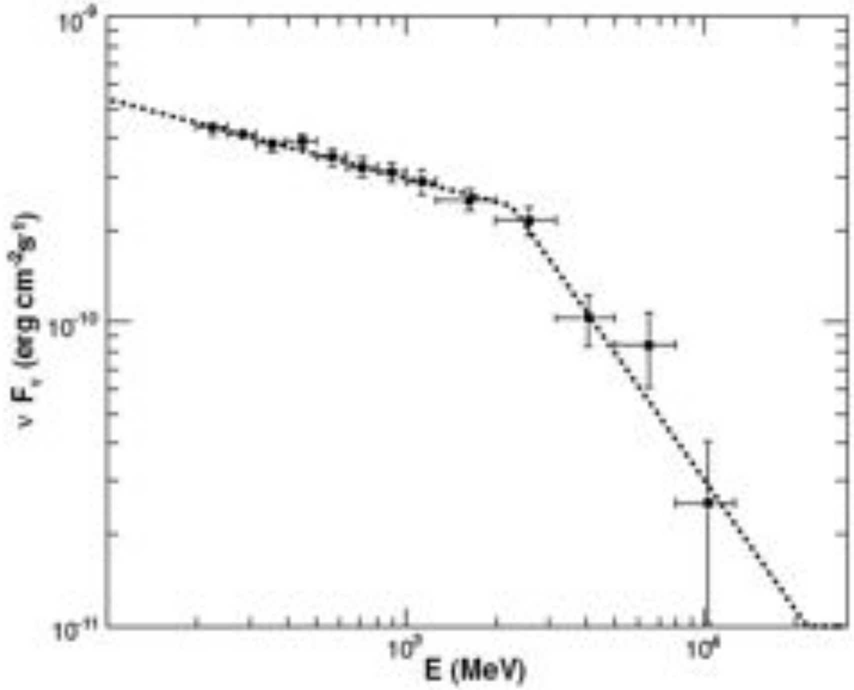
Abdo et al. (2009), ApJ, 699, 817



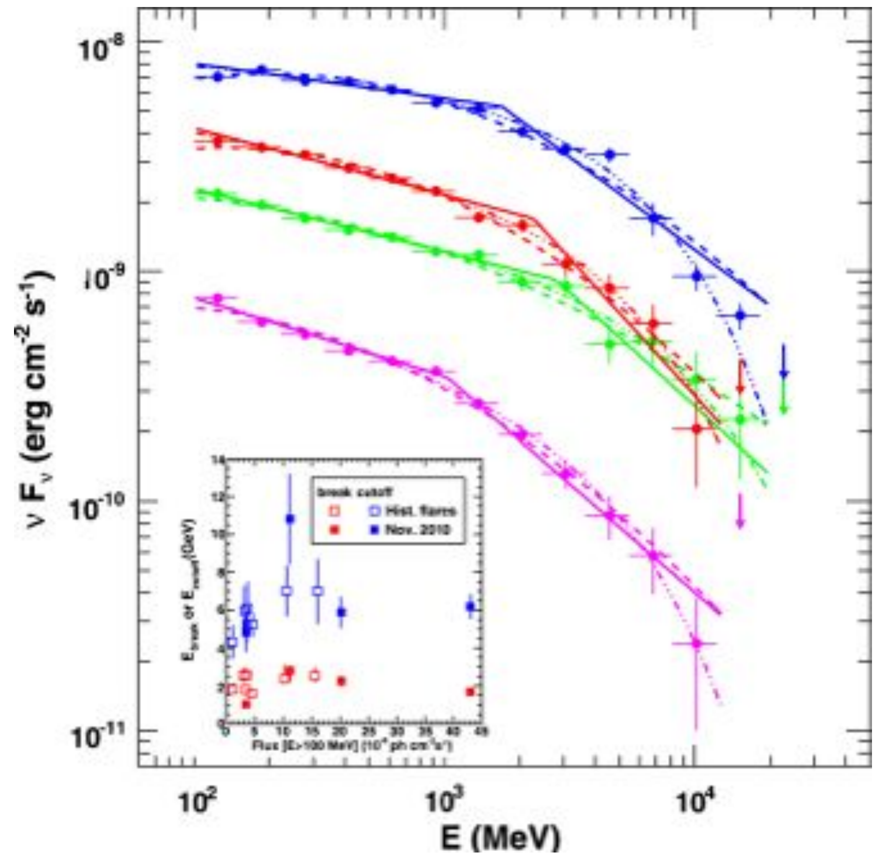
Spectral breaks at ~ a few GeV have been found in the γ-ray spectra of many LSP FSRQs and BL Lacs, most prominently in the extremely bright 3C454.3.

Gamma-ray spectral break

Abdo et al. (2009), ApJ, 699, 817



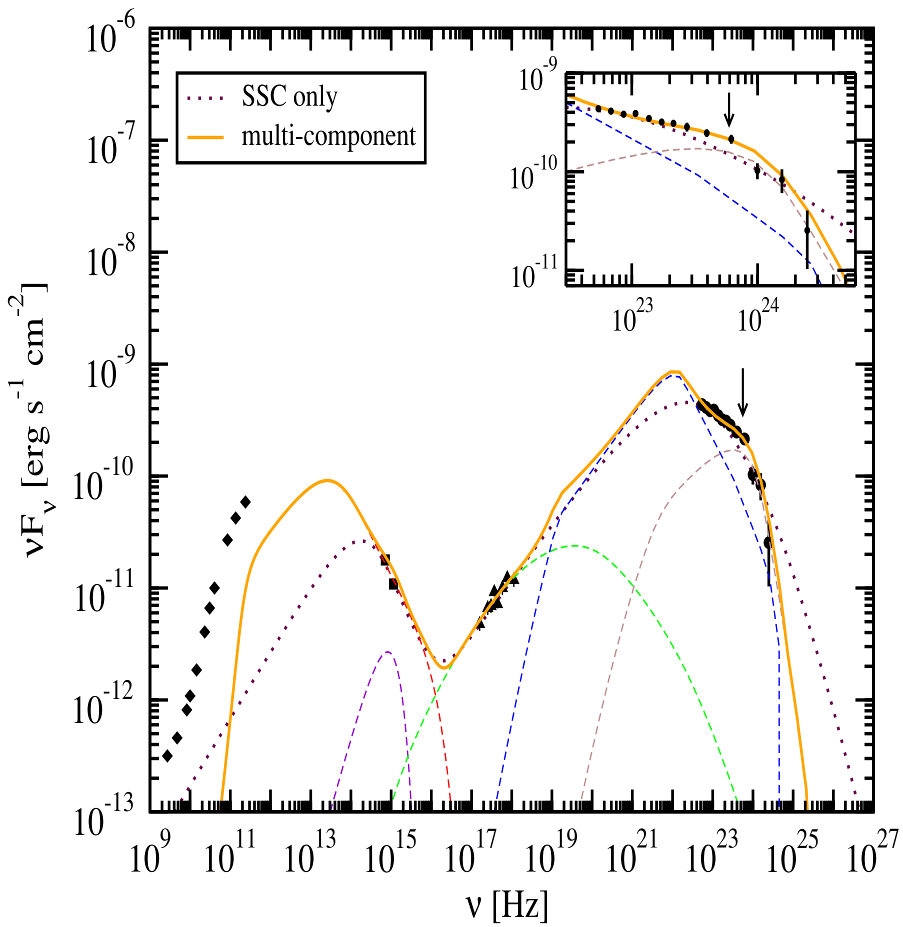
Abdo et al. (2011), ApJ, 733, L26

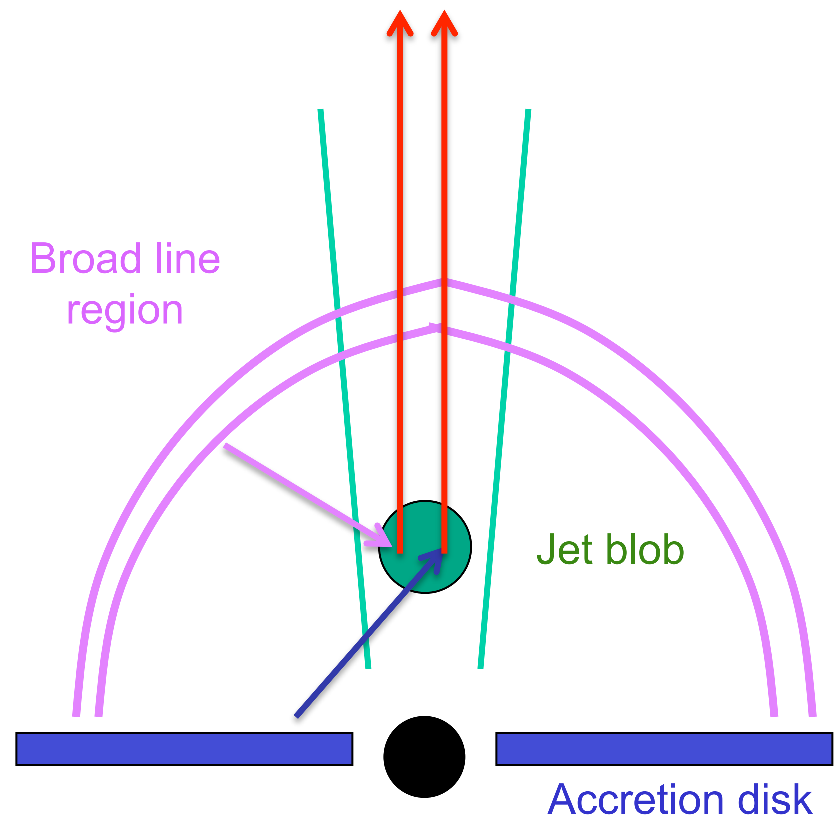


What are some possible causes of this spectral break?

Combination of scattering components

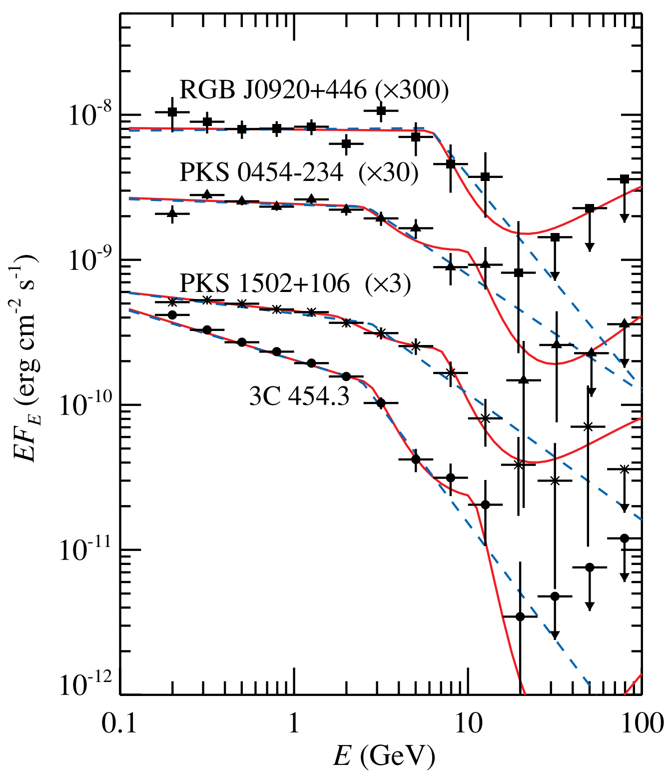
A combination of disk and broad line scattering components with KN cutoff can reproduce the γ-ray spectrum





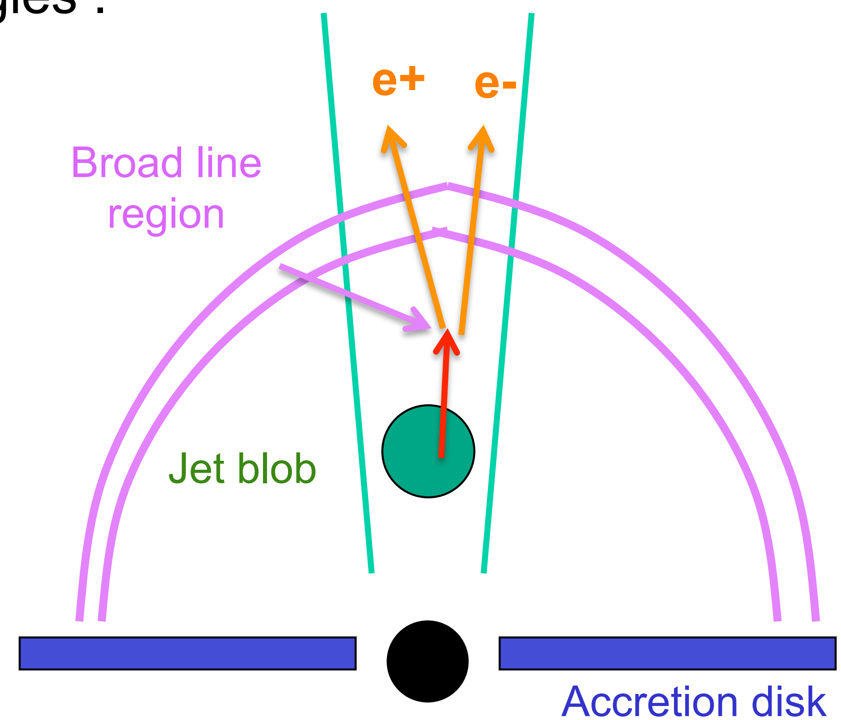
JF & Dermer (2010)

Photoabsorption with BL He II Lyα photons

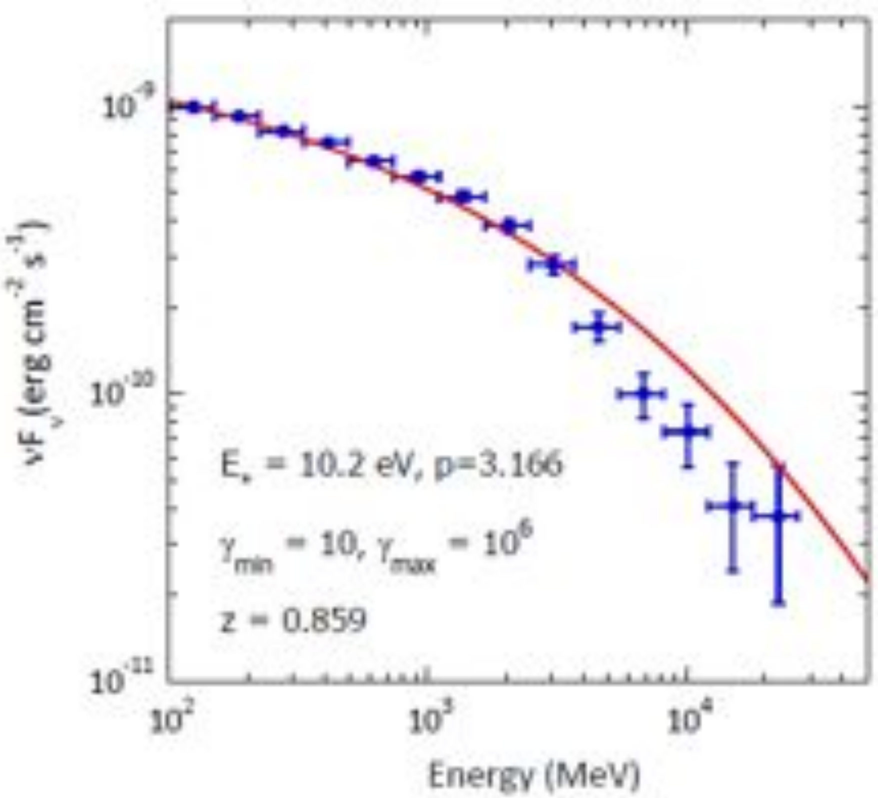


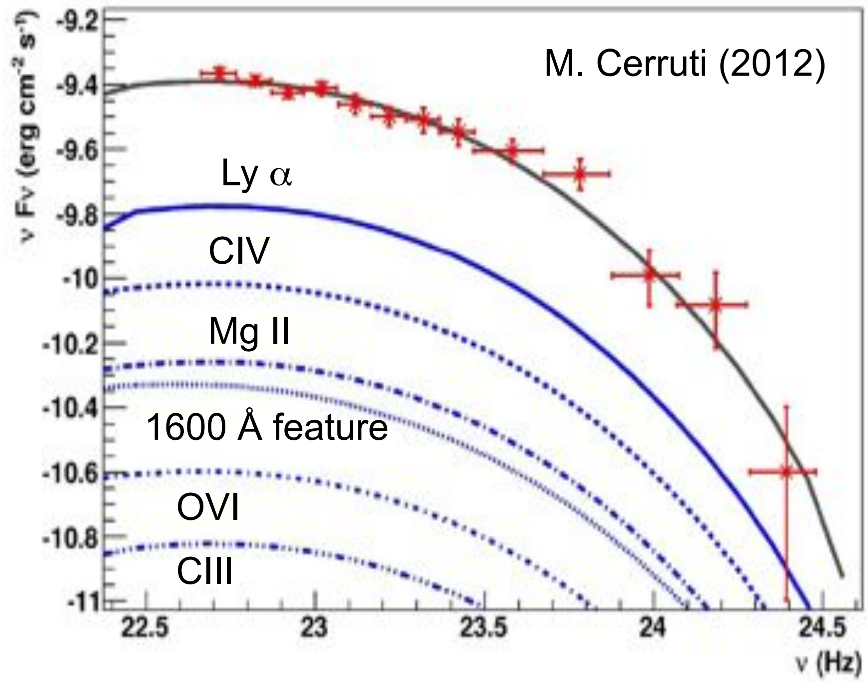
Poutanen & Stern (2010)
See also poster 8.4

Gamma rays photoabsorbed by He II recombination (54.4 eV) and Lyα (40.8 eV) photons from the BLR would create a break at ~ 5GeV in the rest frame of the object, around the observed break energies .



Compton-scattering BL H Lyα photons





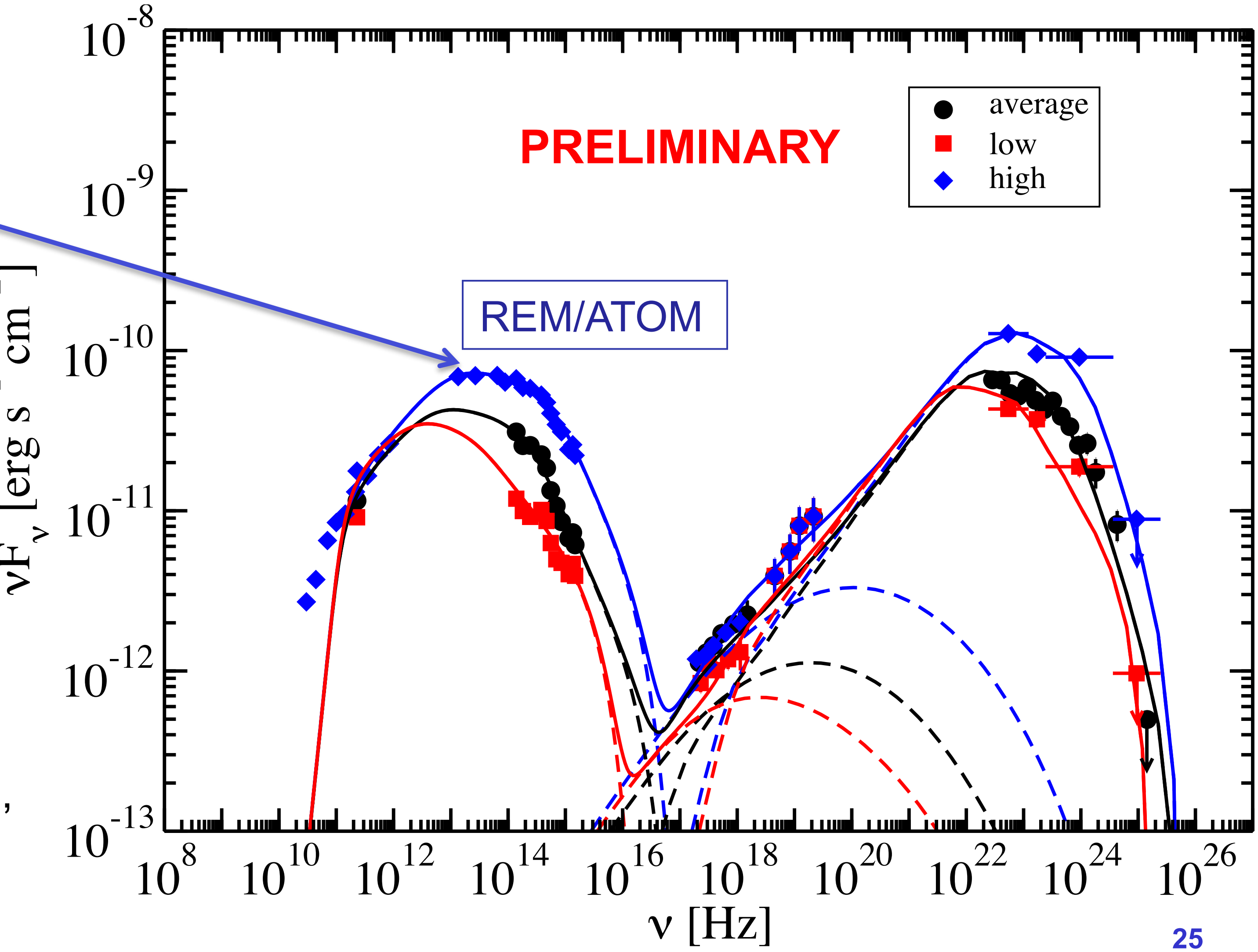
Model with power law electron distribution ***does not*** provide good fit

Model with log-parabola electron distribution ***does*** provide good fit

Curvature in electron spectrum?

PKS 0537-441

Curvature in IR/optical spectrum: implies curvature is in electron distribution?



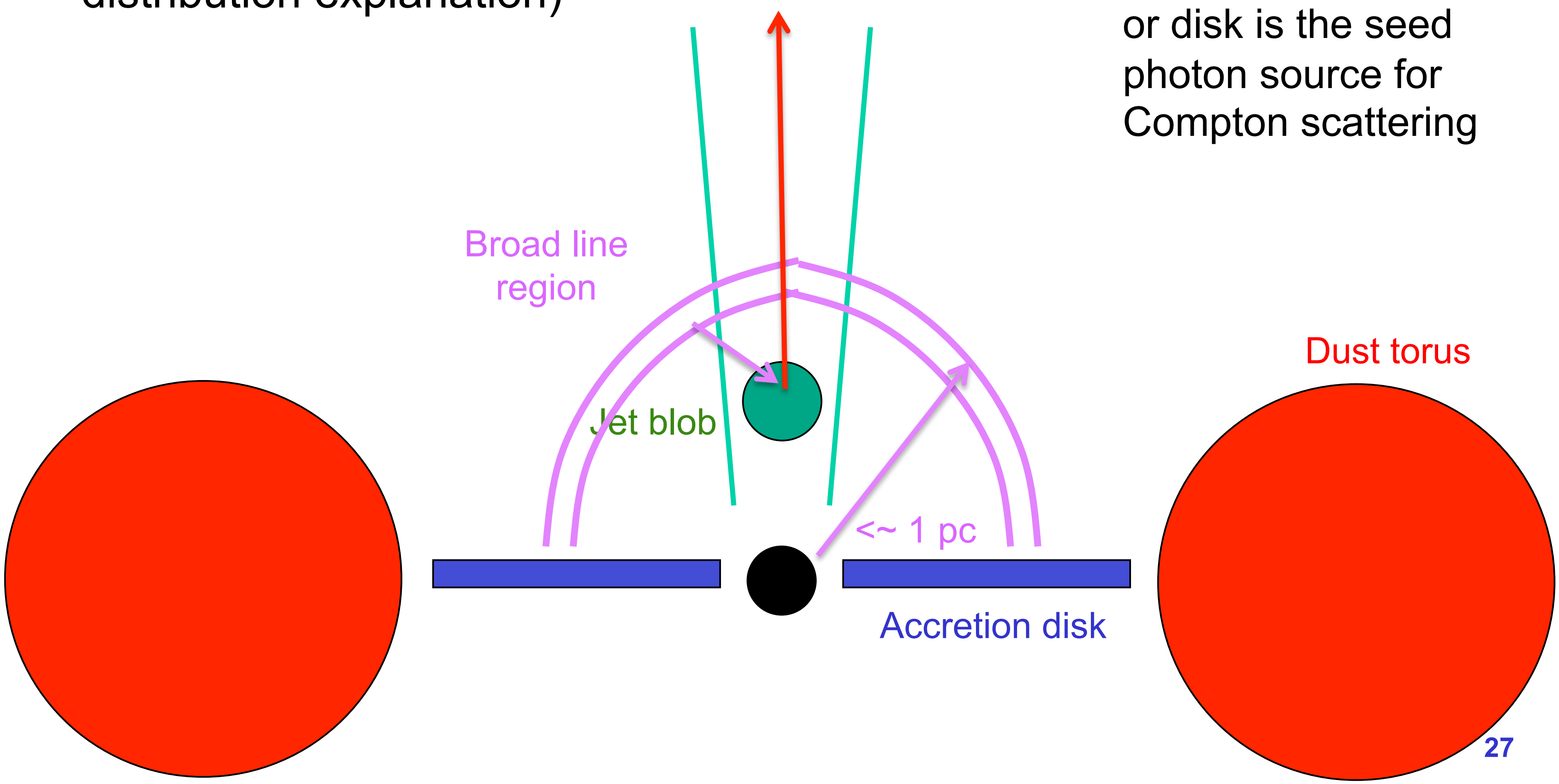
D'Ammando et al., in preparation

Location of the γ-ray emitting region

Location of γ-ray emitting region

Most of these methods assume the γ-ray emitting region is within the Broad line region (except the intrinsic to the electron distribution explanation)

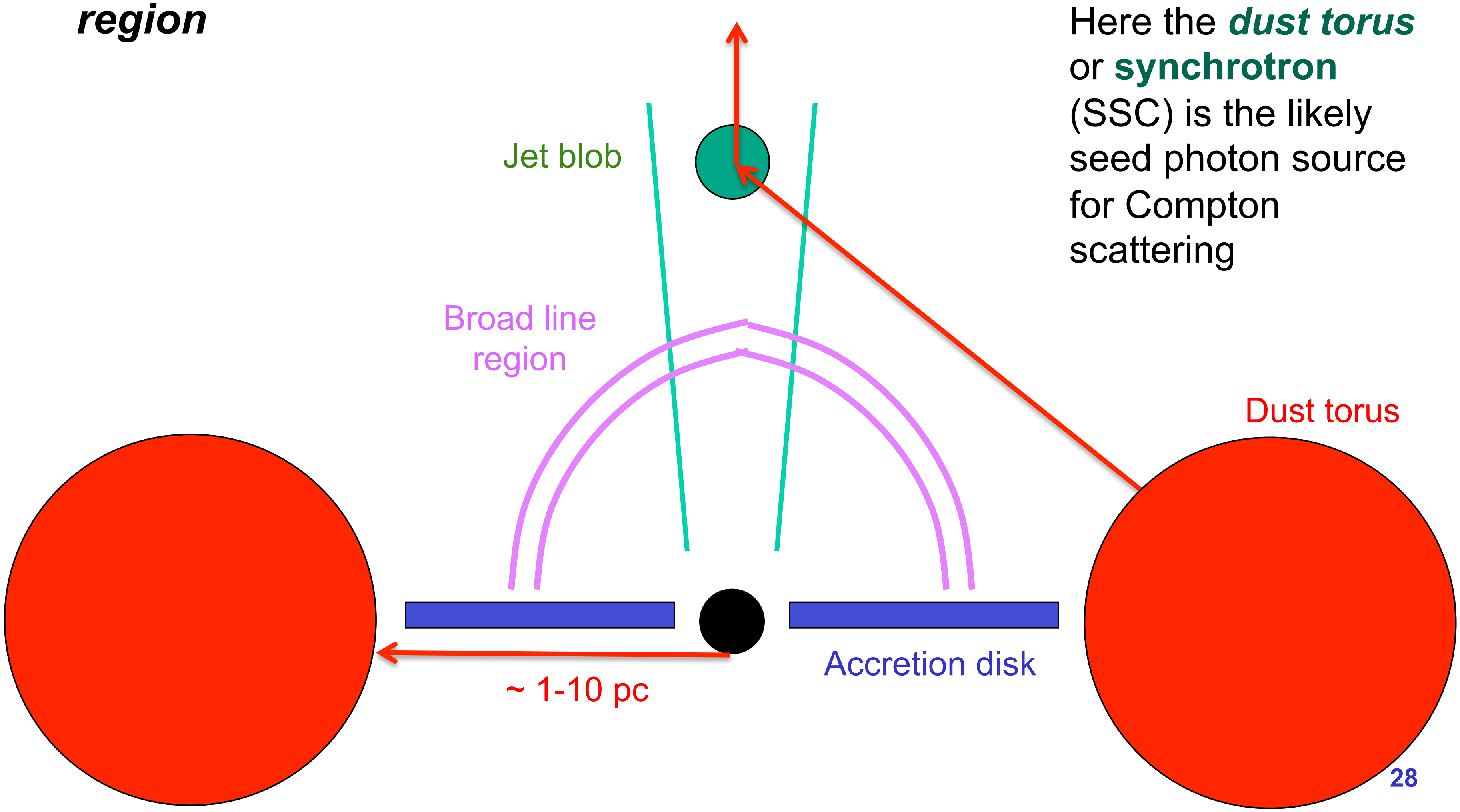
Here the broad line or disk is the seed photon source for Compton scattering



Location of γ-ray emitting region

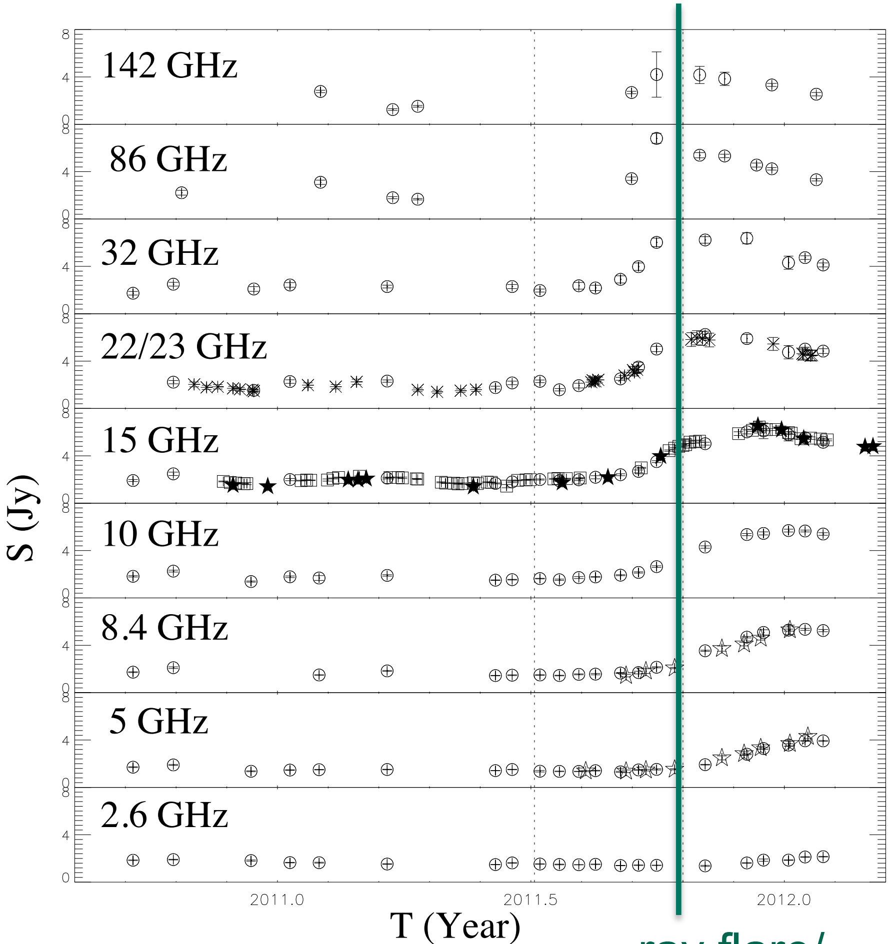
But there is some evidence that the emitting region is outside the broad line region

Here the ***dust torus*** or **synchrotron** (SSC) is the likely seed photon source for Compton scattering



Evidence for large distances from BH

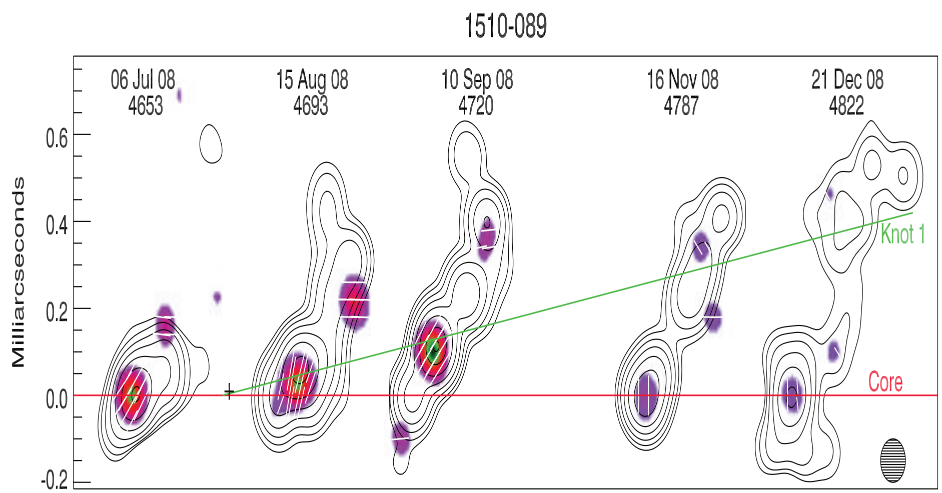
PKS 1510-089



γ-ray flare/ knot ejection

~40 day increase in radio flux associated with γ-ray flare

One can determine the speed of the blob by following its motion after it is ejected during the γ-ray flare

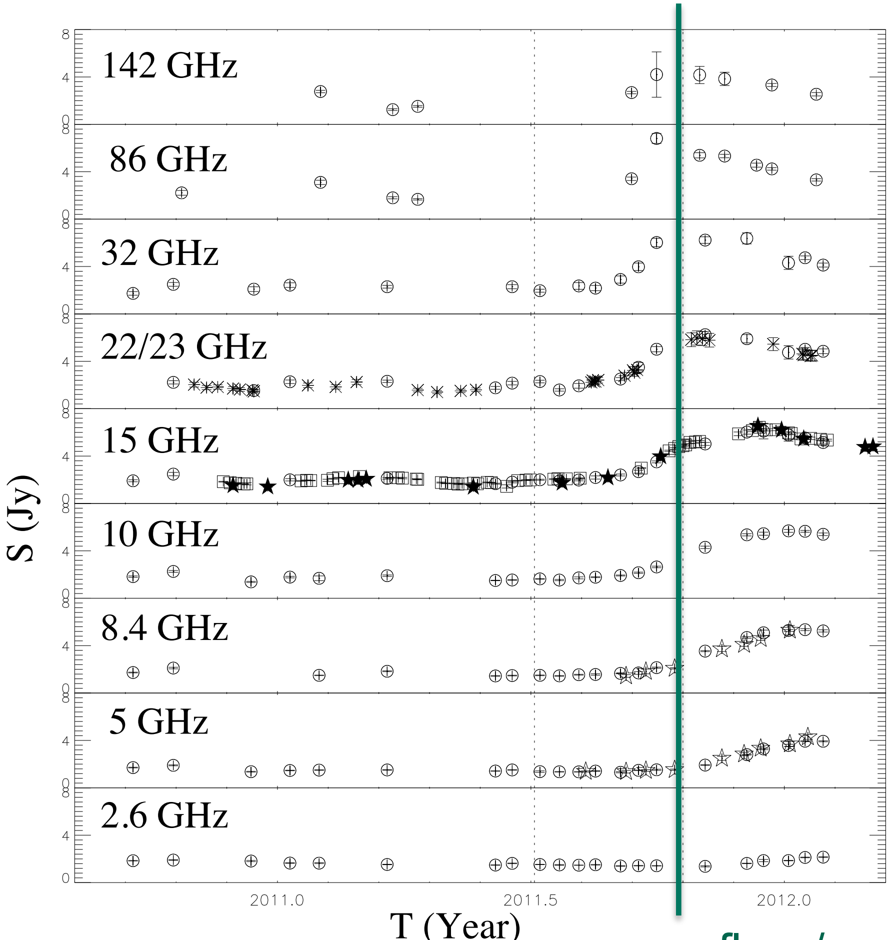


Orienti et al. (2012) arXiv:1210.4319; also see her poster

Marscher et al. (2010), ApJ, 710, L126

Evidence for large distances from BH

PKS 1510-089



γ-ray flare/ knot ejection

Orienti et al. (2012) arXiv:1210.4319; also see poster 4.4

~40 day increase in radio flux associated with γ-ray flare

Assuming γ-ray flare is associated with same region as slower radio flare, one can determine the projected distance:

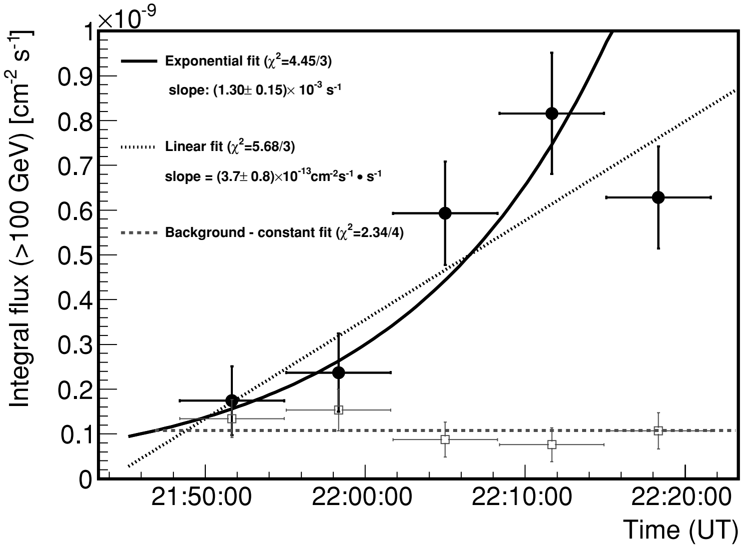
$D_{proj} = v*t/(1+z) = (25c)*(40 \text{ days})/(1.36) = 0.6$ pc

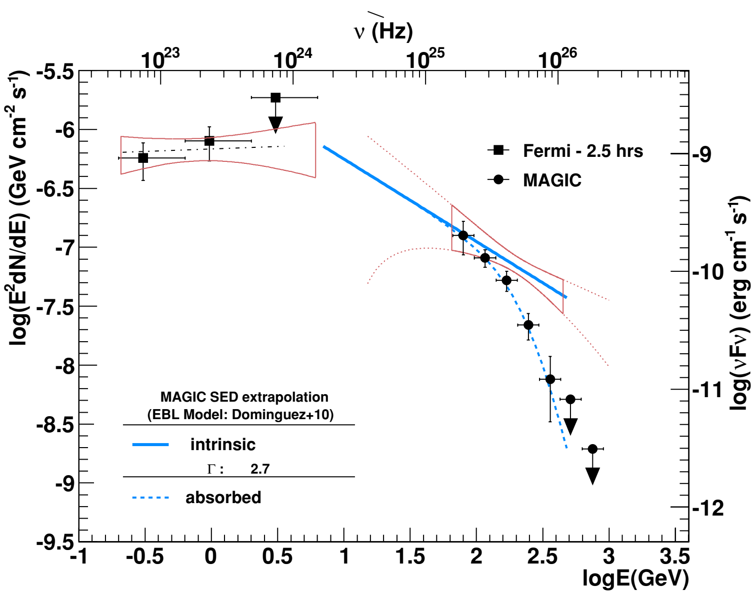
Assuming angle to line of sight:

$\theta = 2$ deg; D = 17 pc
$\theta = 5$ deg; D = 6.9 pc

Emission seems to be outside BLR (<~ 1 pc)

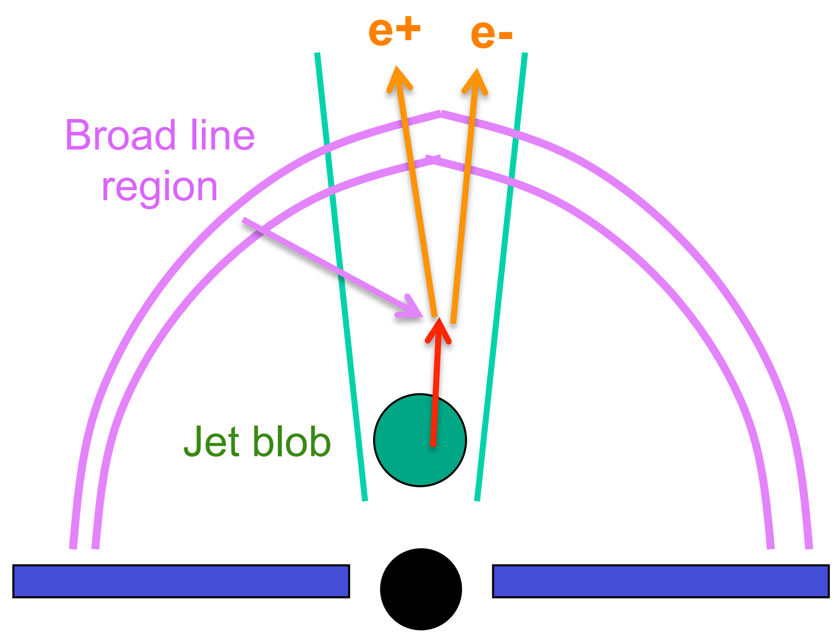
Evidence for large distances from BH





Rapid emission (~10 minute timescale) from 4C+21.35 out to 400 GeV discovered with MAGIC (Aleksic et al. 2011).

If the γ-ray emitting region was within the BLR, these photons would not be able to escape.



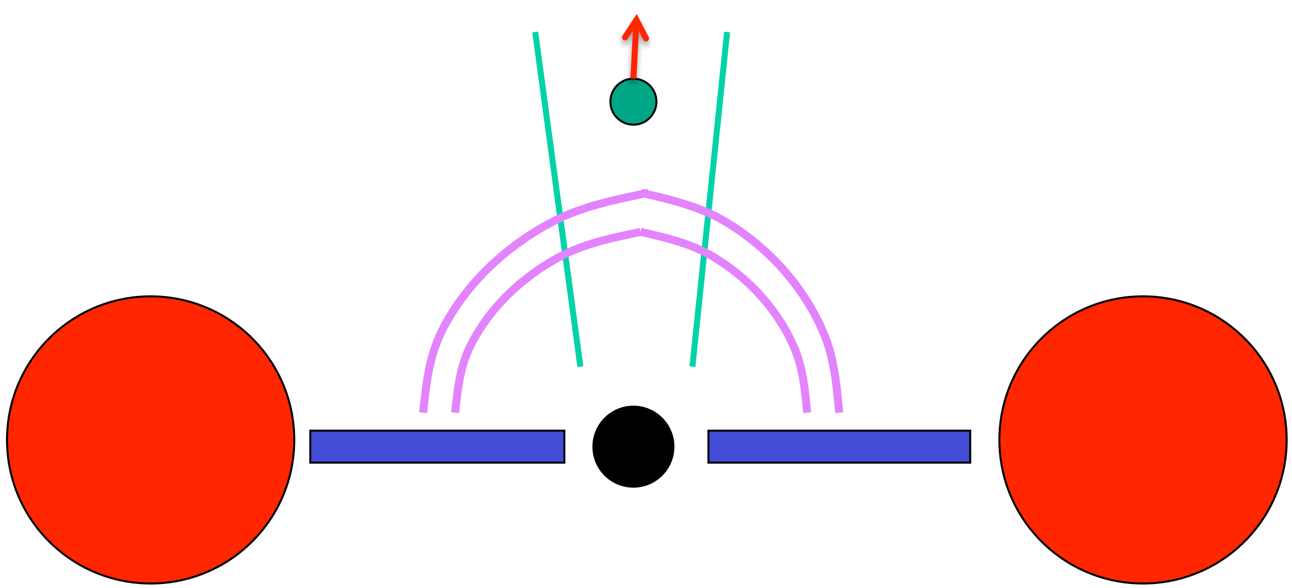
Rapid variability far from the black hole?

From light travel time arguments, the variability timescale limits the size of the emitting region to:

$$R'_b \lesssim c\delta_{\rm D} t_v / (1+z)$$

If the jet opening angle takes up the entire cross section of a conical jet, it must be very close to the black hole (r <~ 0.01 pc) to be consistent with typical jet opening angles (1.0°) and Doppler factor ($\delta_D \sim 30$).

How can so much power be transported and released so far from the black hole in such a small region?



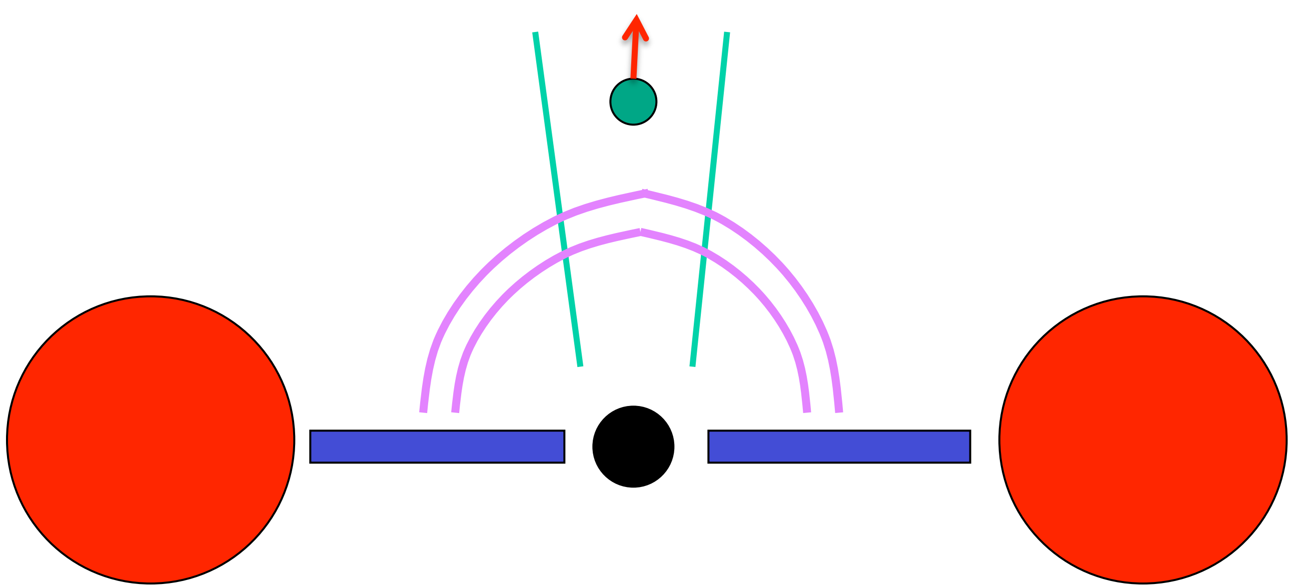
Rapid variability far from the black hole?

Jet reconfinement shock (e.g., Aleksic et al. 2011, Tavecchio et al. 2011)

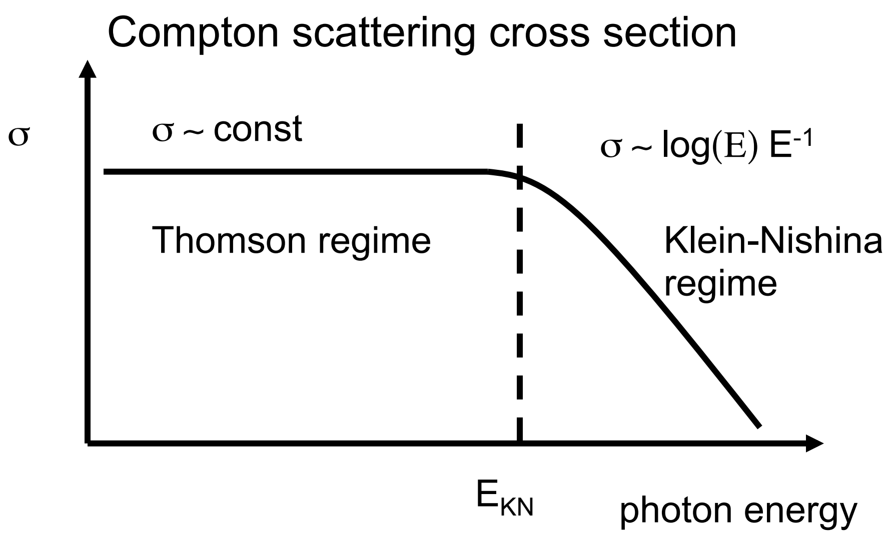
Turbulent cell model (Marscher & Jorstad 2010; poster 1.6)

Magnetic field reconnection leading to anisotropic electron distributions (Cerutti et al. 2012, Nalewajko et al. 2012)

Energy transport from inner to outer jet regions by neutrons (Dermer, Murase, & Takami 2012)



Finding the location of the emitting region



$E_{KN} \sim (E_{seed})^{-1}$

Dust torus: 10^3 K black body, $E_{seed} \sim 0.3$ eV

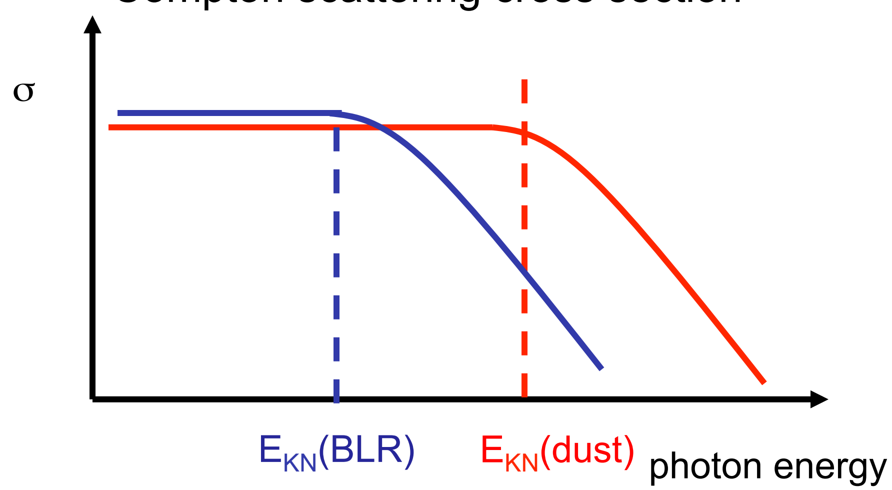
Lyα broad line: $E_{seed} \sim 10$ eV

So if you can determine E_{KN}, one can determine E_{seed}. But how can you find E_{KN}?

Variability!

Dotson et al. (2012), ApJ, 758, L15

Finding the location of the emitting region



$E_{KN} \sim (E_{seed})^{-1}$

Dust torus: 10^3 K black body, $E_{seed} \sim 0.3$ eV

Lyα broad line: $E_{seed} \sim 10$ eV

So if you can determine E_{KN}, one can determine E_{seed}. But how can you find E_{KN}?

Variability!

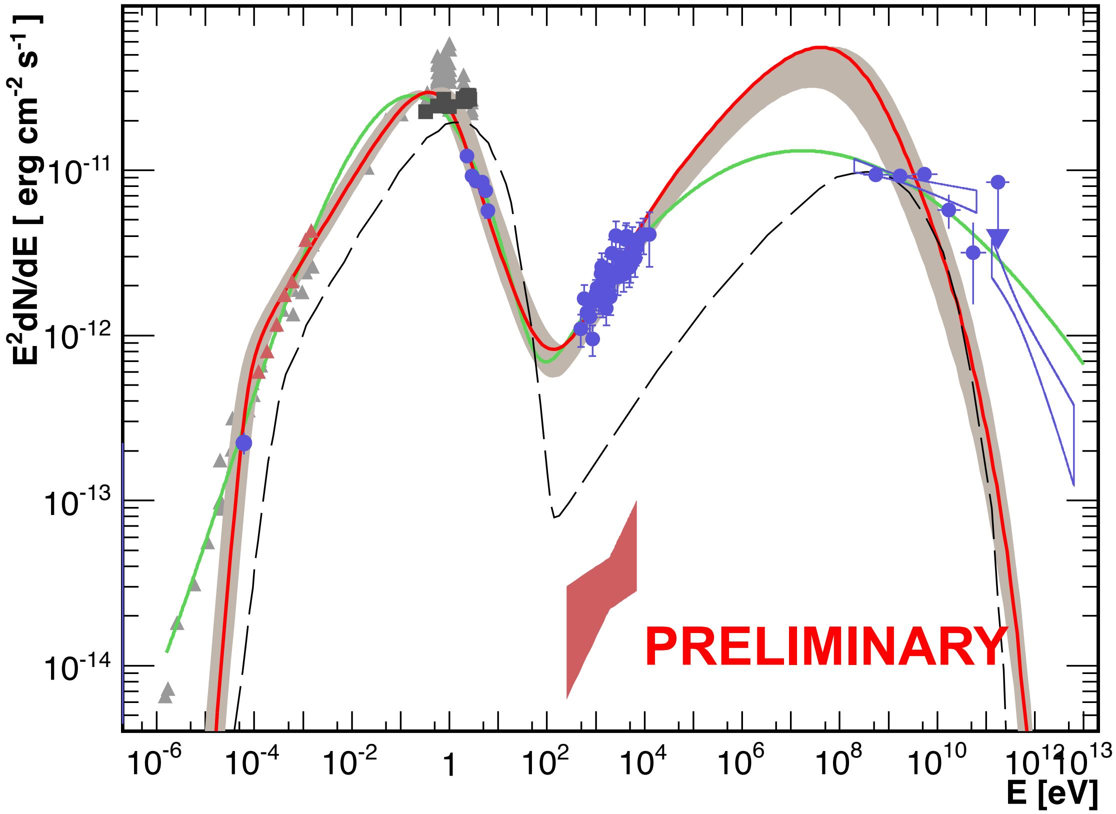
Scattering dust photons will be more efficient at higher energies, leading to greater cooling and different variability than scattering Lyα photons.

Dotson et al. (2012), ApJ, 758, L15

The end of the one zone leptonic model?

The end of the one zone leptonic model?

AP Librae – HESS & LAT detected ISP BL Lac



Extremely narrow synchrotron component, very broad (X-ray to TeV γ-ray) Compton component

Cannot be fit with a one-zone synchrotron/Compton model

Green curve: not a radiative model fit, an empirical fit with two 3rd degree polynomials

Abramowski et al. (in preparation)

Other sources where one-zone leptonic models have problems

PKS 2155-304 – Aharonian et al. (2007), Finke et al. (2008), Begelman et al. (2008) – rapid variability, requires extreme parameters (δ_D, B)

3C 279 – Böttcher et al. (2009), ApJ, 703, 1168 – can't reproduce SED, including X-ray spectrum

3C 454.3 – Ogle et al. (2011), ApJS, 195, 19 – unusual and variable IR emission

PKS 2005-489 – Abramowski et al. (2011), A&A, 533, 110 – rapid variability requires extreme parameters (δ_D, B)

AO 0235+164 – Ackermann et al. (2012), ApJ, 751, 159 – unusual X-ray spectrum

1ES 0414+009 – Aliu et al. (2012) ApJ, 755, 118 – poor fit to flat (Γ=2) LAT spectrum

PKS 1510-089 – Nalewajko al. (2012) arXiv:1210.4552 – requires extreme energy density in external radiation field

What comes after the one zone leptonic model?

- ***Multi-zone models***
  - Graff et al. (2008), ApJ, 689, 68
  - Böttcher et al. (2008), ApJ, 679, L9
  - Marscher & Jorstad (2010) arXiv:1005.5551
  - Tavecchio et al. (2011, A&A, 534, 86),
  - Nalewajko et al. (2012 arXiv:1210.4552)

- ***Hadronic models***
  - Mücke et al. (2003), Aph, 18, 593
  - Böttcher (2010) arXiv:1006.5048
  - Dermer et al. (2012), ApJ, 755, 147
  - Cerruti et al. (2012) arXiv:1210.5024

- ***Intergalactic cascade models***
  - Essey et al. (2010, 2011)
  - Tavecchio et al. (2011), MNRAS, 414, 3566

Summary

- *Fermi* has provided evidence, independent of redshift, that there is an anti-correlation between Compton dominance and the peak synchrotron frequency, a key component of the “blazar sequence”.

- The cause of the γ-ray spectral break is still a mystery, although several causes have been proposed.

- The location of the γ-ray emitting region in the jet is still ambiguous, although γ-ray variability may be the key to resolving this issue.

- *Fermi* and multi-wavelength observations are forcing us to look for models beyond the standard one-zone leptonic models

Extra slides

Blazar Sequence

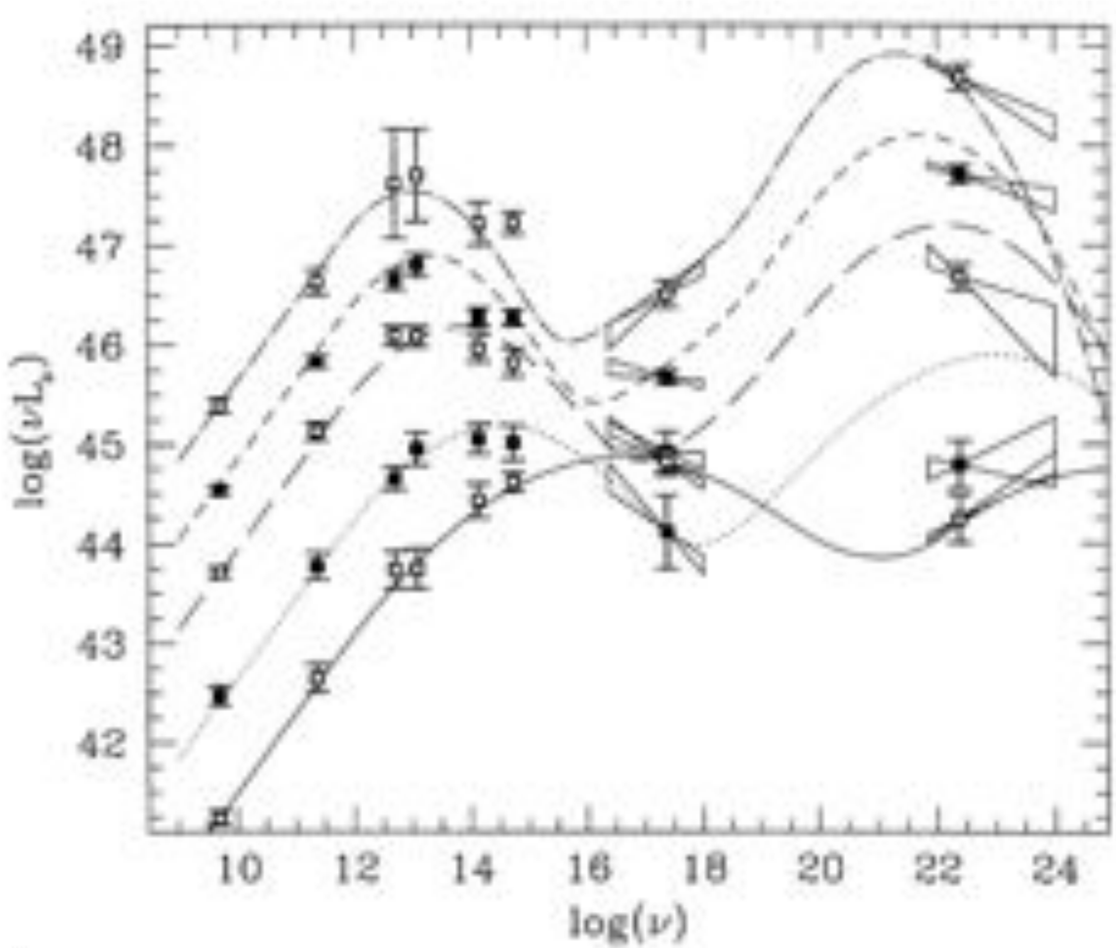
Sequence from low power BL Lacs to high power FSRQs, binned by 5 GHz radio luminosity.

Explanation for sequence: more powerful sources have stronger broad lines.

The BLs provide the external radiation field for Compton scattering, leading to a larger Compton component.

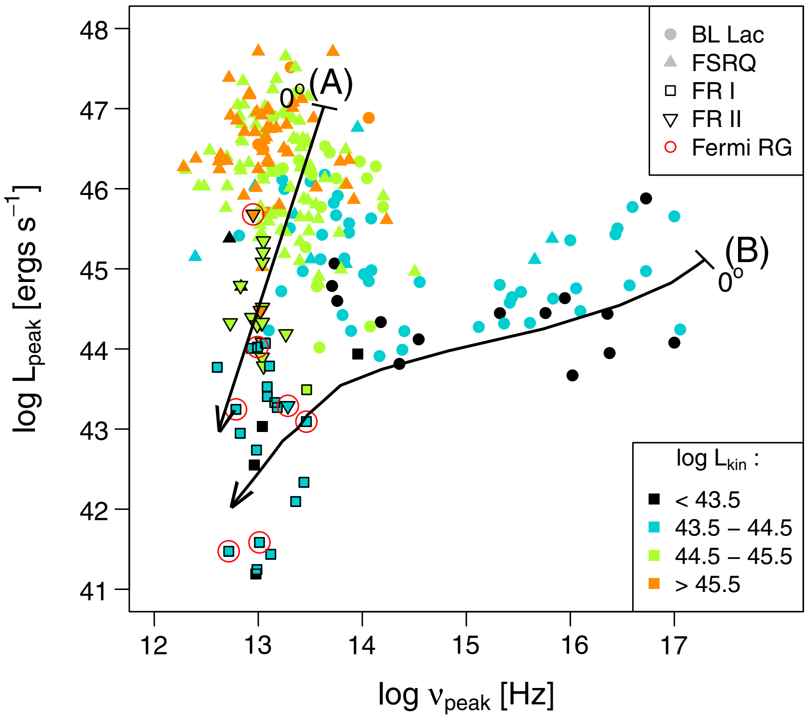
More intense BLs, more cooling, and lower peaks.

$$\gamma_c = \frac{3m_e c^2}{4c\sigma_T(u'_B + u'_{sy} + u'_{ext})t_{esc}}$$



Fossati et al. (1998), MNRAS, 299, 433
Ghisellini et al. (1998), MNRAS, 301, 541

More recent work



As instruments improve, more sources with low peak frequency and low peak luminosity have been found. Also, radio galaxies have been placed on this diagram.

Explanation: dichotomy between decelerating and non-decelerating jets.

See Giovanni Fossati's talk in "AGN II"

Meyer et al. (2011), ApJ, 740, 98

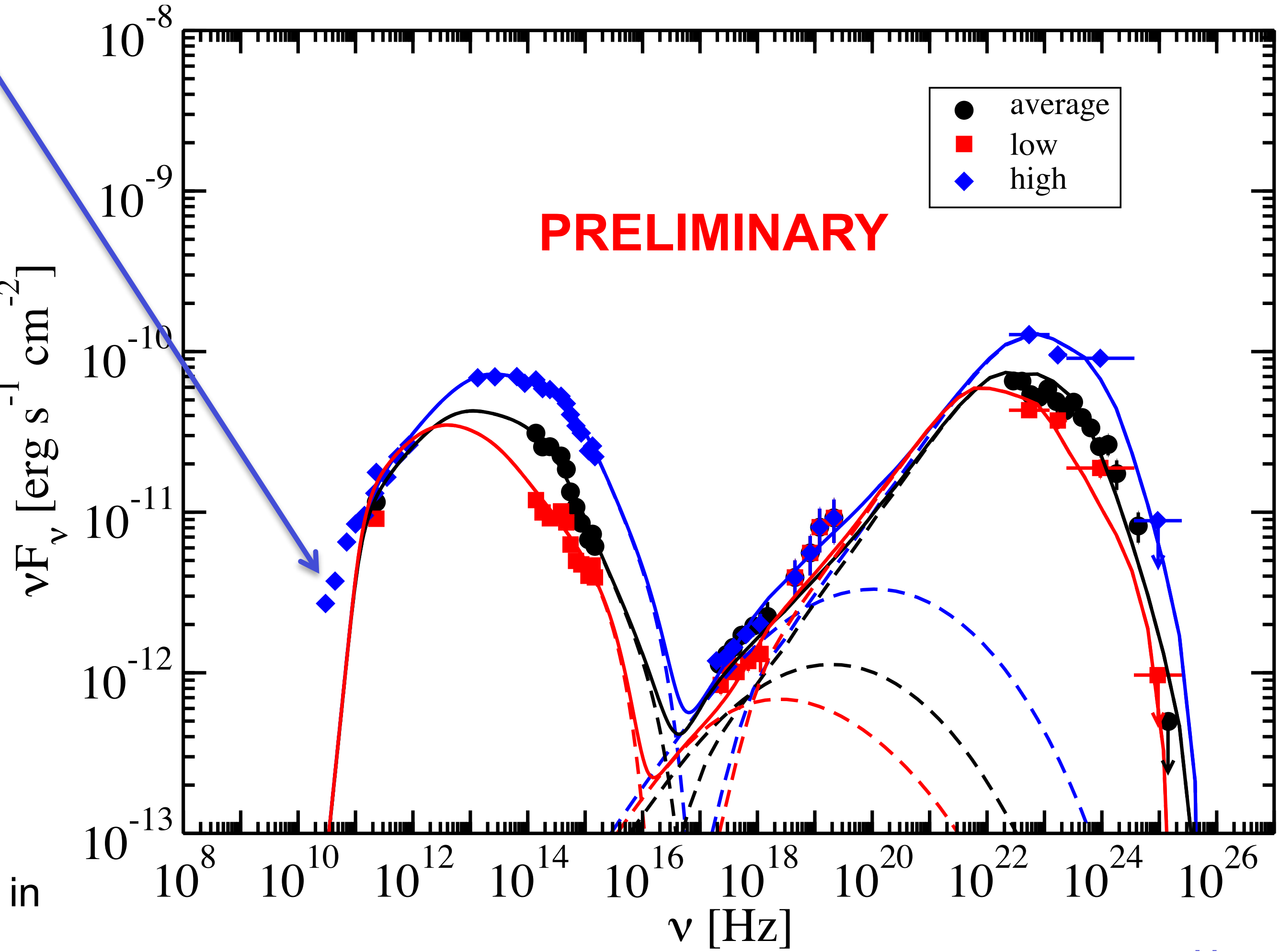
Multi-zone models

PKS 0537-441

Typically it is assumed that radio emission is from larger, extended portion of jet.

For observed optical/ γ-ray variability timescales, jet would be self-absorbed at radio energies.

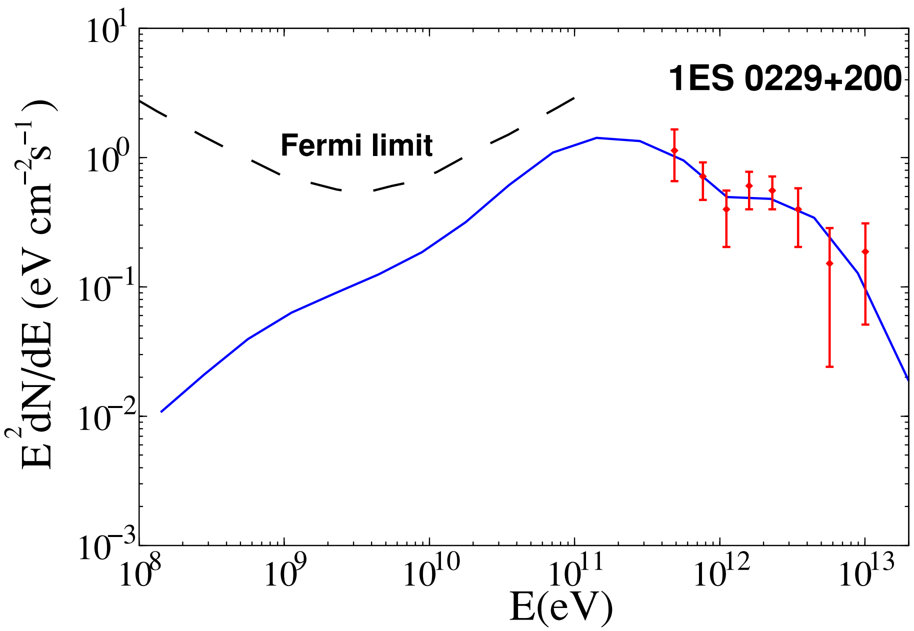
So multi-zone models seem "natural".



D'Ammando et al., in preparation

Cosmic Ray interactions with the CMB and EBL

Blazars are leading candidates for UHECR sources. The cosmic rays could interact with CMB and EBL photons, producing TeV γ rays, nonvariable and mostly independent of the other MWL emission from that source.



Essey et al. (2011)