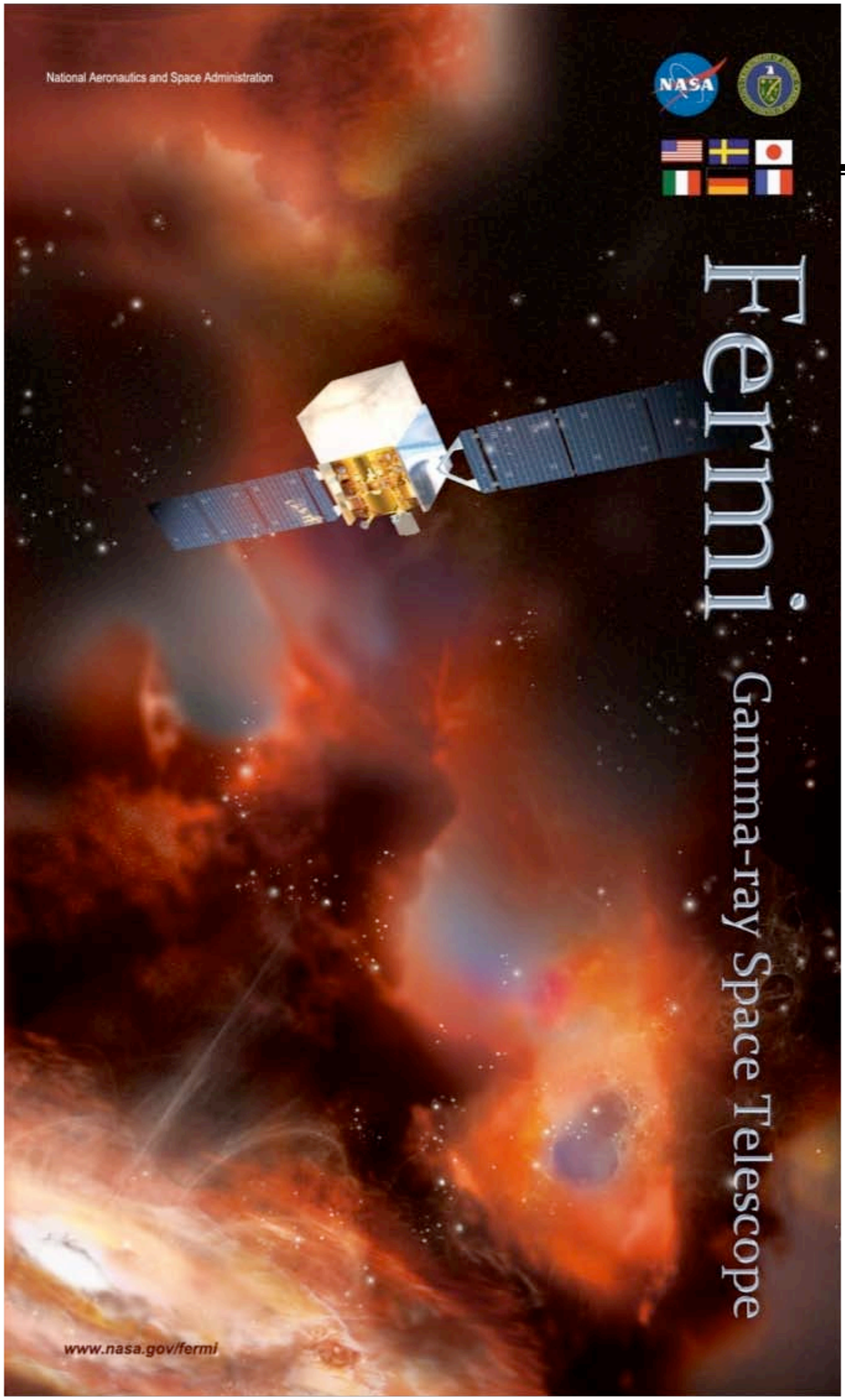
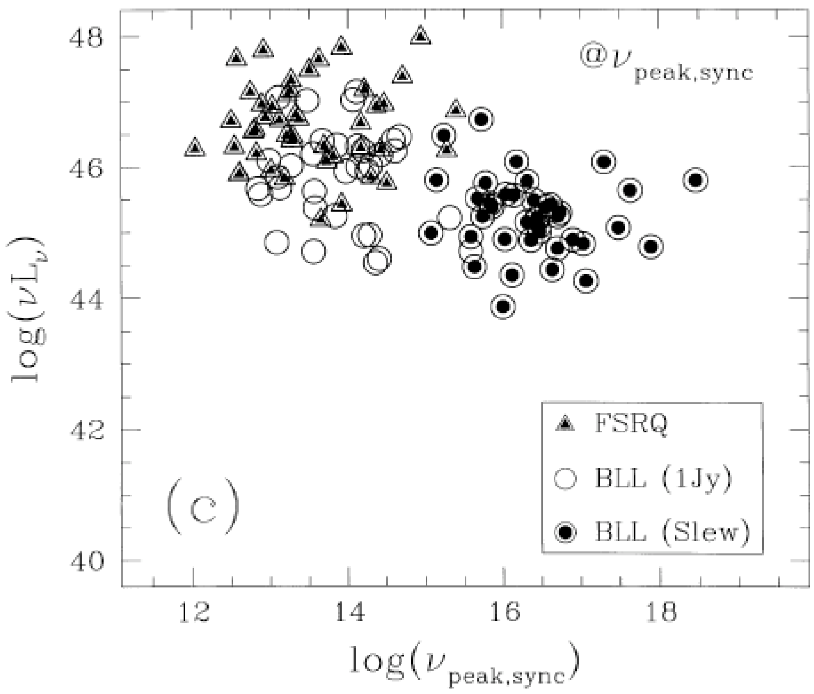


A Physical Model for the Revised Blazar Sequence

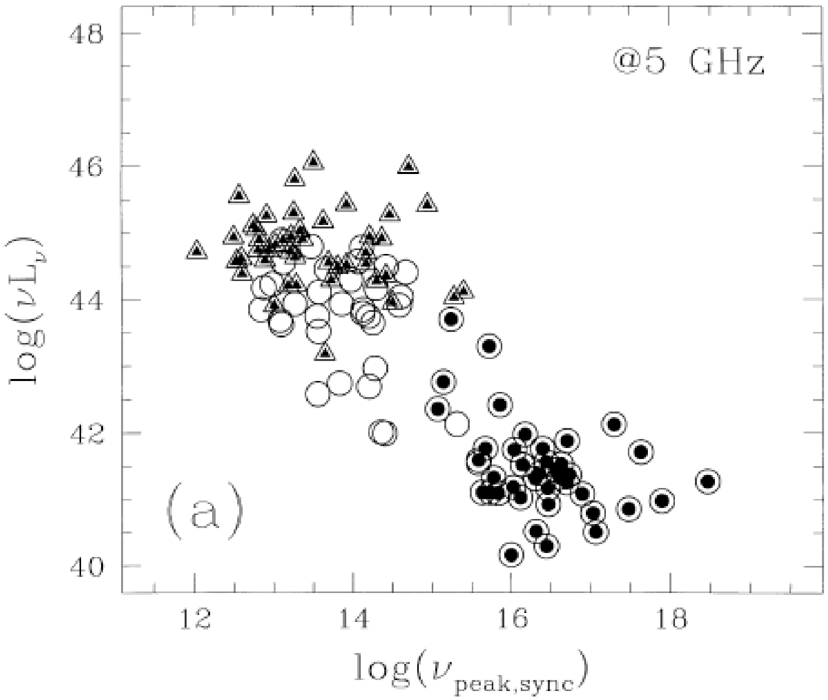
Justin Finke and Charles Dermer

US Naval Research Laboratory

Blazar Sequence - synchrotron component



Synchrotron peak luminosity vs synchrotron peak frequency



5 GHz luminosity vs synchrotron peak frequency

Fossati et al. (1998)

Previous work

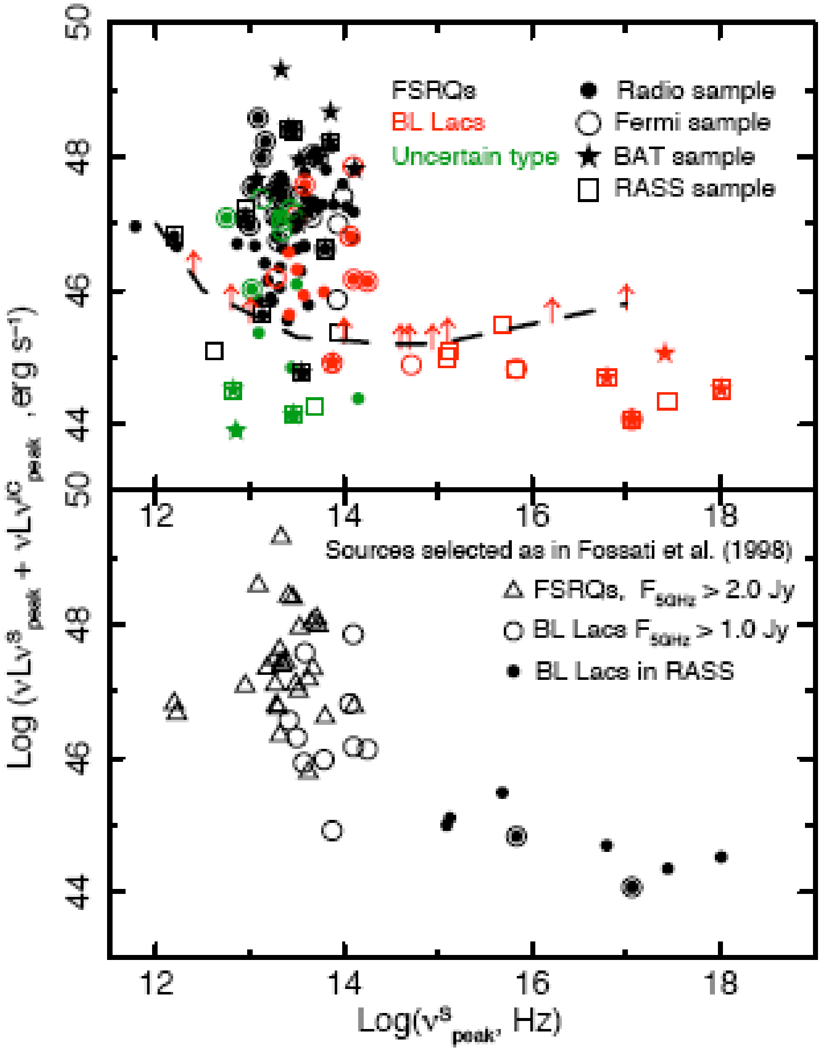
Peaks from fit to Swift / Planck data by Giommi et al. (2011).

“L” shape seen.

Note: y-axis is synchrotron peak + Compton peak.

But upper right may be filled in with BL Lacs with unknown redshift.

“L” (or “V”) shape also seen by Nieppola et al. (2006), Meyer et al. (2011)



Giommi et al. (2011) arXiv:1108.1114

Explanation

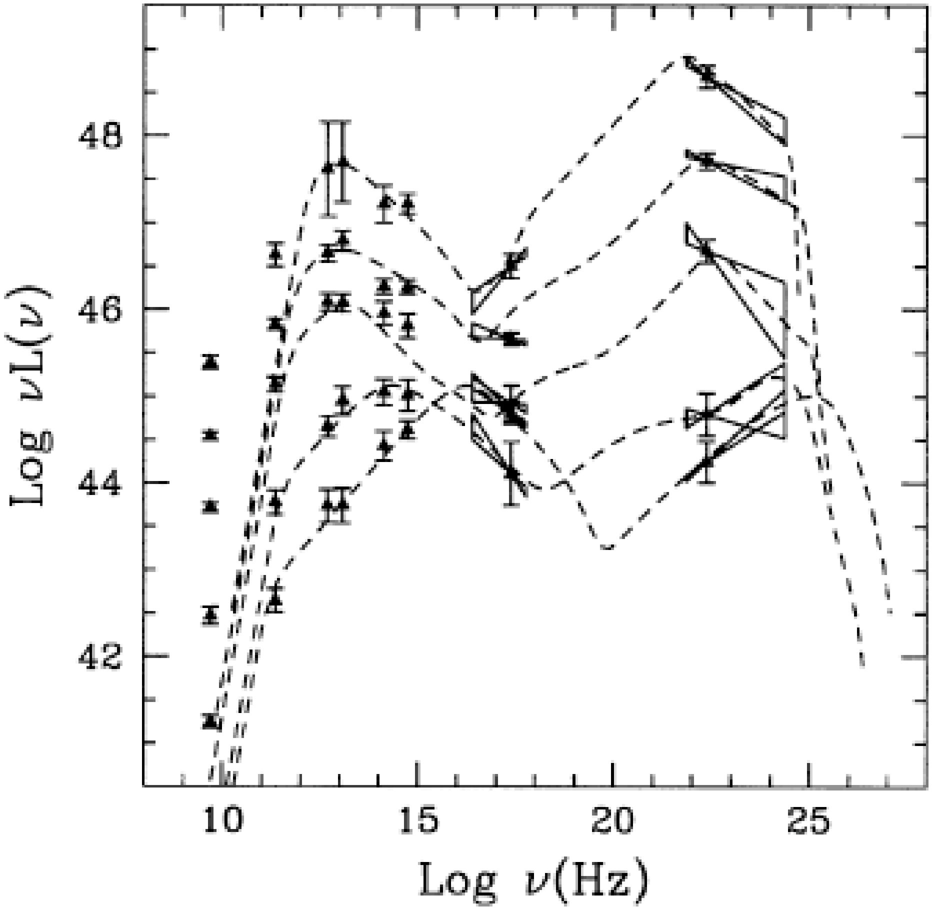
External radiation field for Compton scattering correlates with power injected into electrons.

As power increases, greater external radiation field leads to greater Compton scattering, and hence more Compton dominance.

At the same time, the greater scattering cools the electrons more, leading to a lower cooling break energy.

$$\gamma_c = \frac{3m_e c^2}{4c\sigma_{\rm T}(u'_B + u'_{sy} + u'_{ext})t_{esc}}$$

The peak frequency is directly related to this cooling break energy.



Ghisellini et al. (1998)

Calculating the synchrotron peak

Abdo et al. (2010; CA: P. Giommi; M. Mazziotta; A. Tramacere) fit LBAS blazars to determine peak frequencies and luminosities:

$$\nu F_{\nu} = a \cdot \nu^{3} + b \cdot \nu^{2} + c \cdot \nu + d.$$

They provided empirical formulae for finding the peak frequency based on optical, radio, and X-ray data (α_{ro}, α_{ox}).

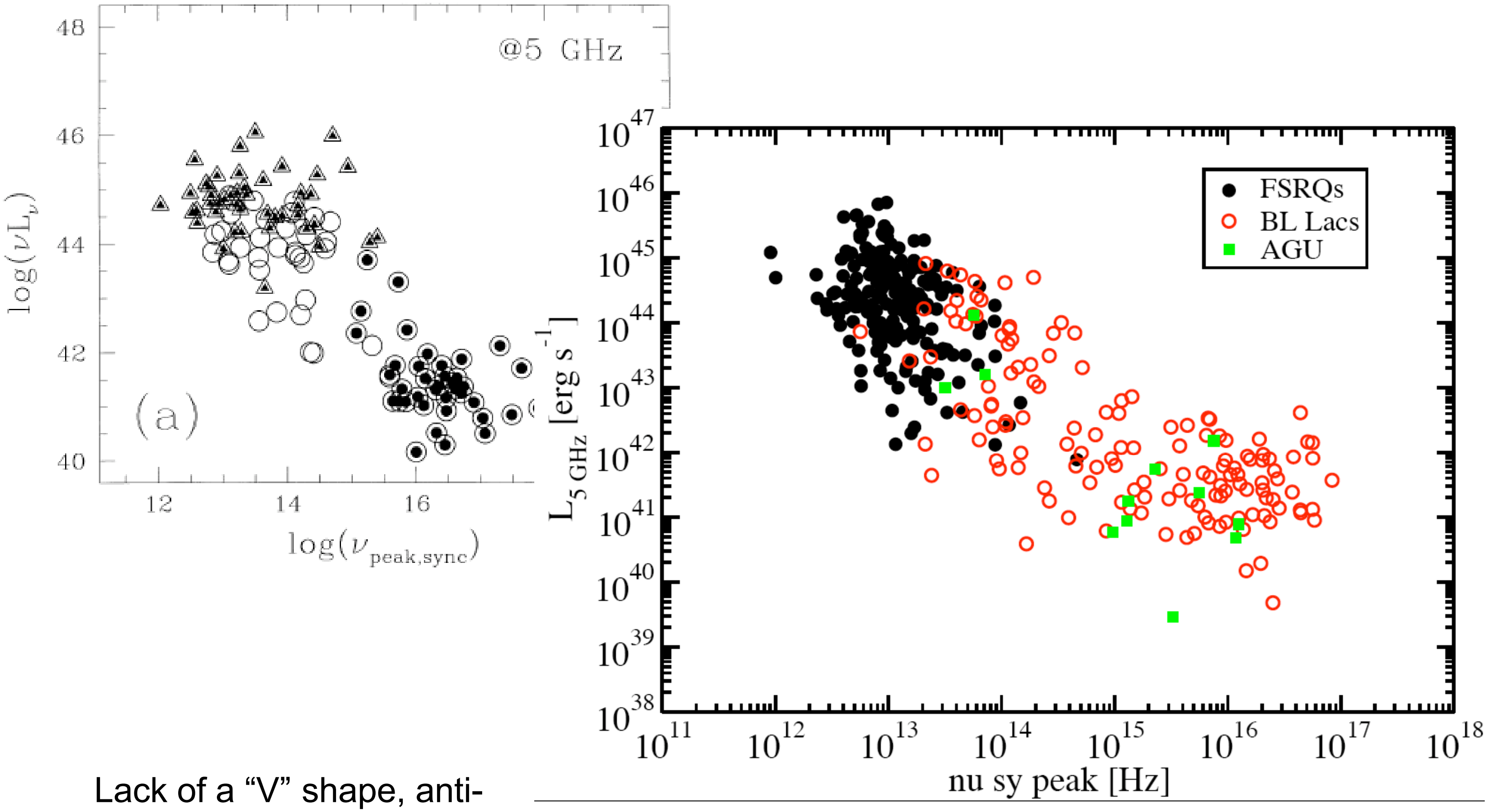
The 2LAC provides peak synchrotron frequency for sources with enough data using these formulae.

Can also use Abdo et al. (2010) empirical formula to calculate peak flux (normalized to 5 GHz flux density):

$$\mathrm{Log}(\nu_{peak_S} F(\nu_{peak_S})) = 0.5 \cdot \mathrm{Log}(\nu_{peak S}) - 20.4 + 0.9 \cdot \mathrm{Log}(\mathrm{R}_{5\mathrm{GHz}}),$$

Can use this to create the blazar sequence from the 2LAC.

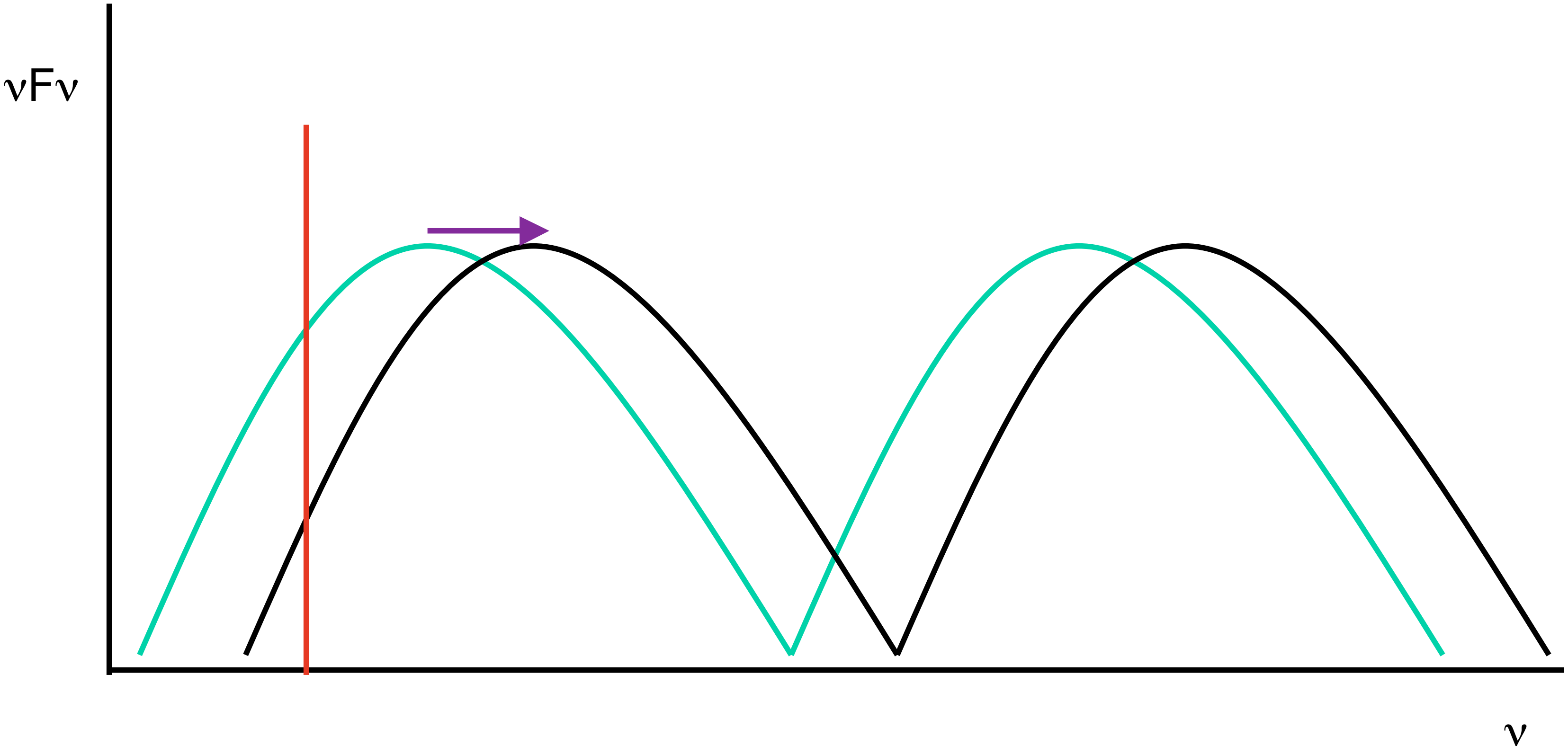
5 GHz diagram



Lack of a “V” shape, anti-correlation is more clear. Explanation?

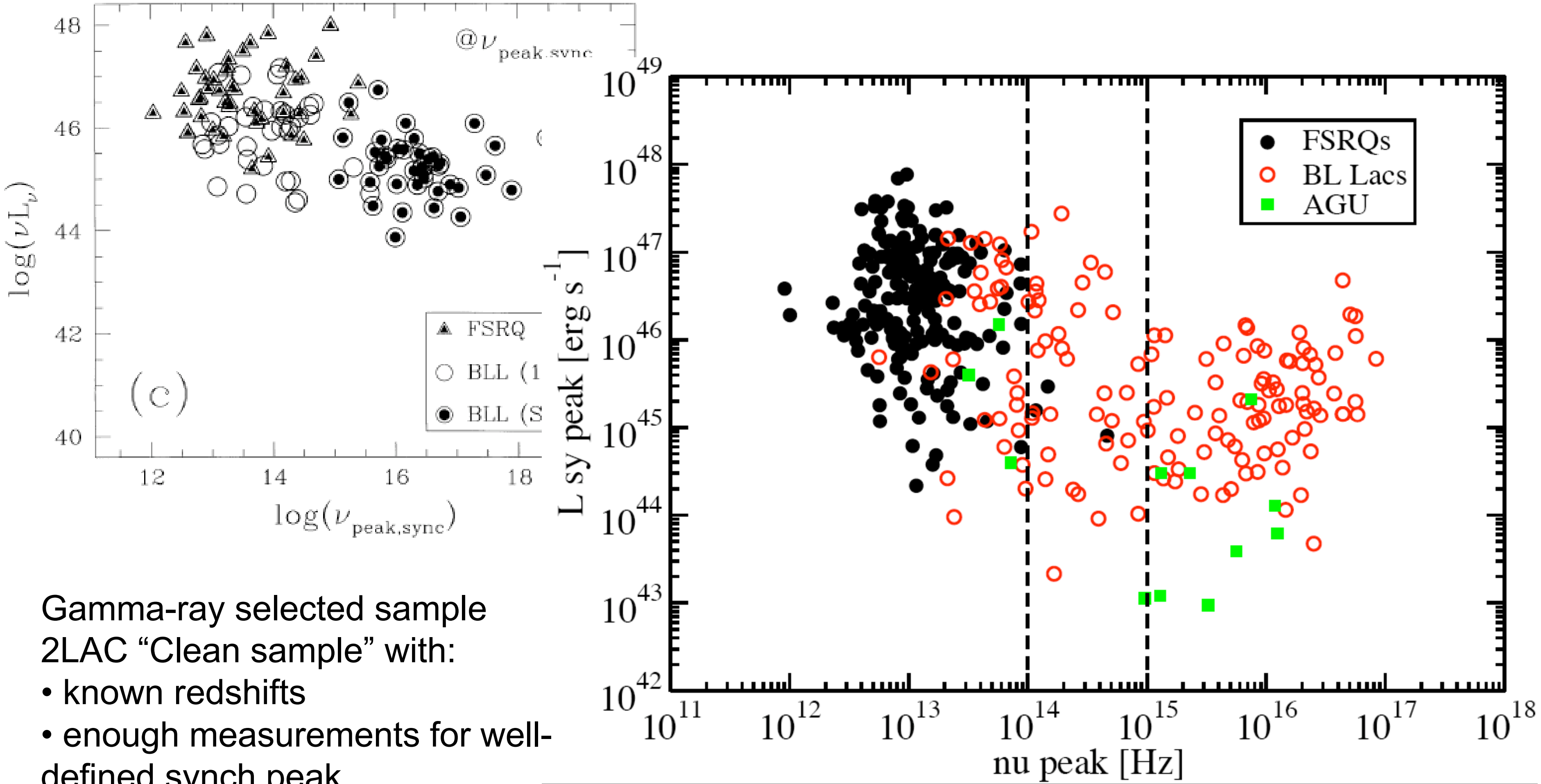
5 GHz diagram

Simple explanation: as synchrotron bump moves to higher frequencies, radio flux will decrease (e.g., Lister et al. 2011).



A physical effect, or a result of the way the peak frequency is calculated?

2LAC blazar sequence



Gamma-ray selected sample

2LAC “Clean sample” with:

- known redshifts
- enough measurements for well-defined synch peak.
- ~ 350 sources
- “V” shape seen

Correlations

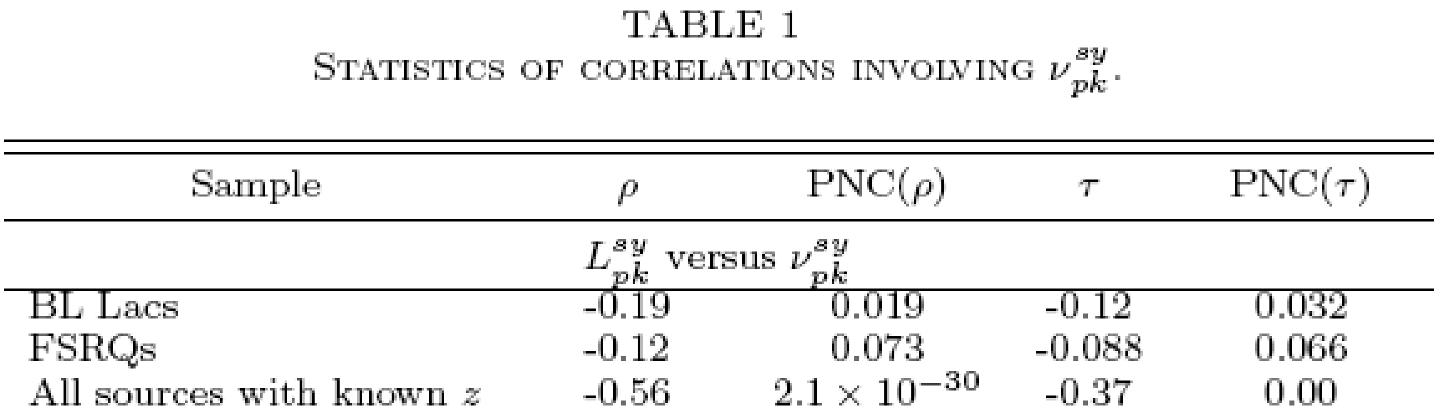


TABLE 1

STATISTICS OF CORRELATIONS INVOLVING ν_{pk}^{sy}.

Sample	ρ	PNC(ρ)	τ	PNC(τ)
	L_{pk}^{sy} versus ν_{pk}^{sy}			
BL Lacs	-0.19	0.019	-0.12	0.032
FSRQs	-0.12	0.073	-0.088	0.066
All sources with known z	-0.56	2.1×10^{-30}	-0.37	0.00

[redacted]

Spearman and Kendall Rank Coefficients

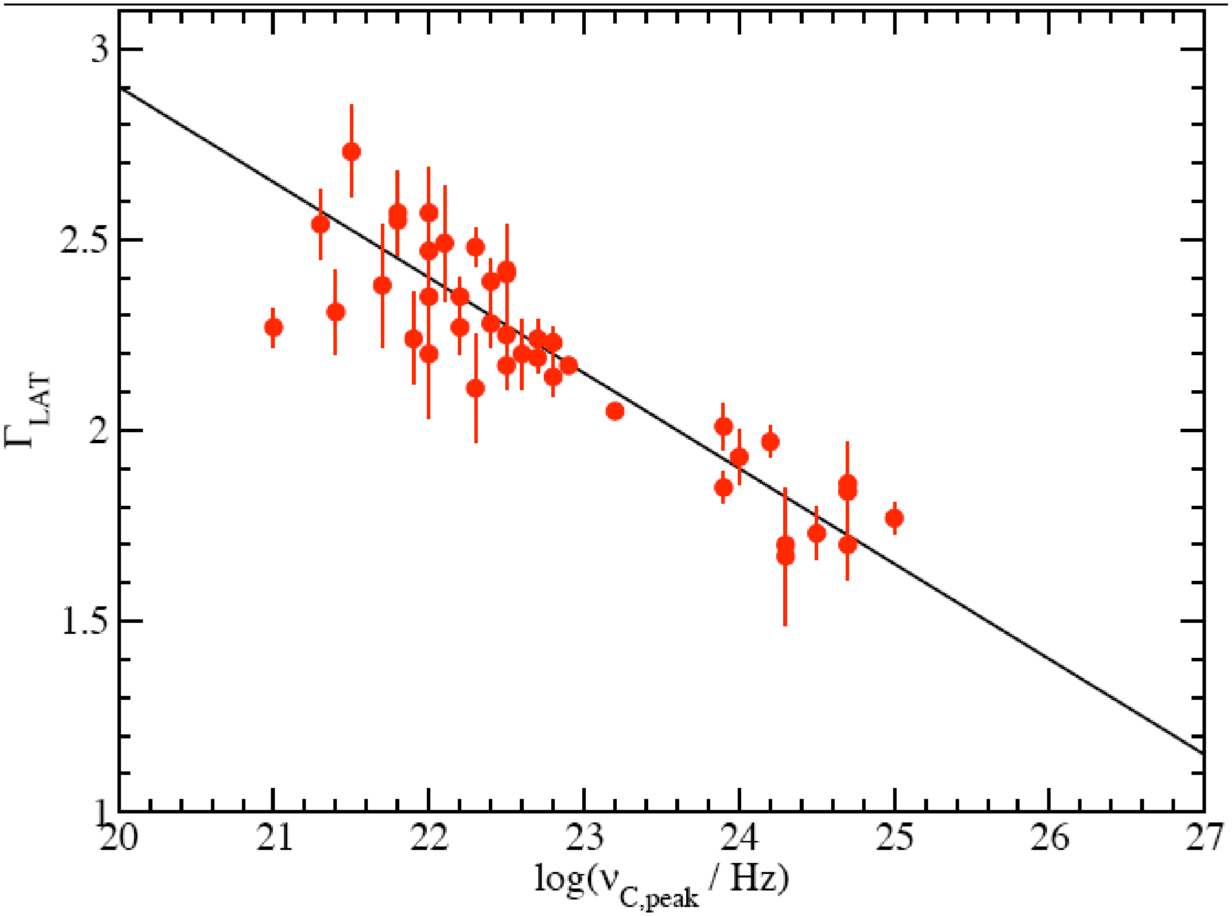
Can objects with unknown z ruin this anti-correlation?

High-Energy Component

Fitting the high-energy comonents of blazars in the LBAS sample, Abdo et al. (2010) found a relationship between the LAT spectral index and peak frequency of the Compton component:

$$Log(\nu^{IC}_{\text{peak}}) = -4.0 \cdot \Gamma + 31.6$$

This can be used to calculate the peak Compton frequency for the 2LAC sample.

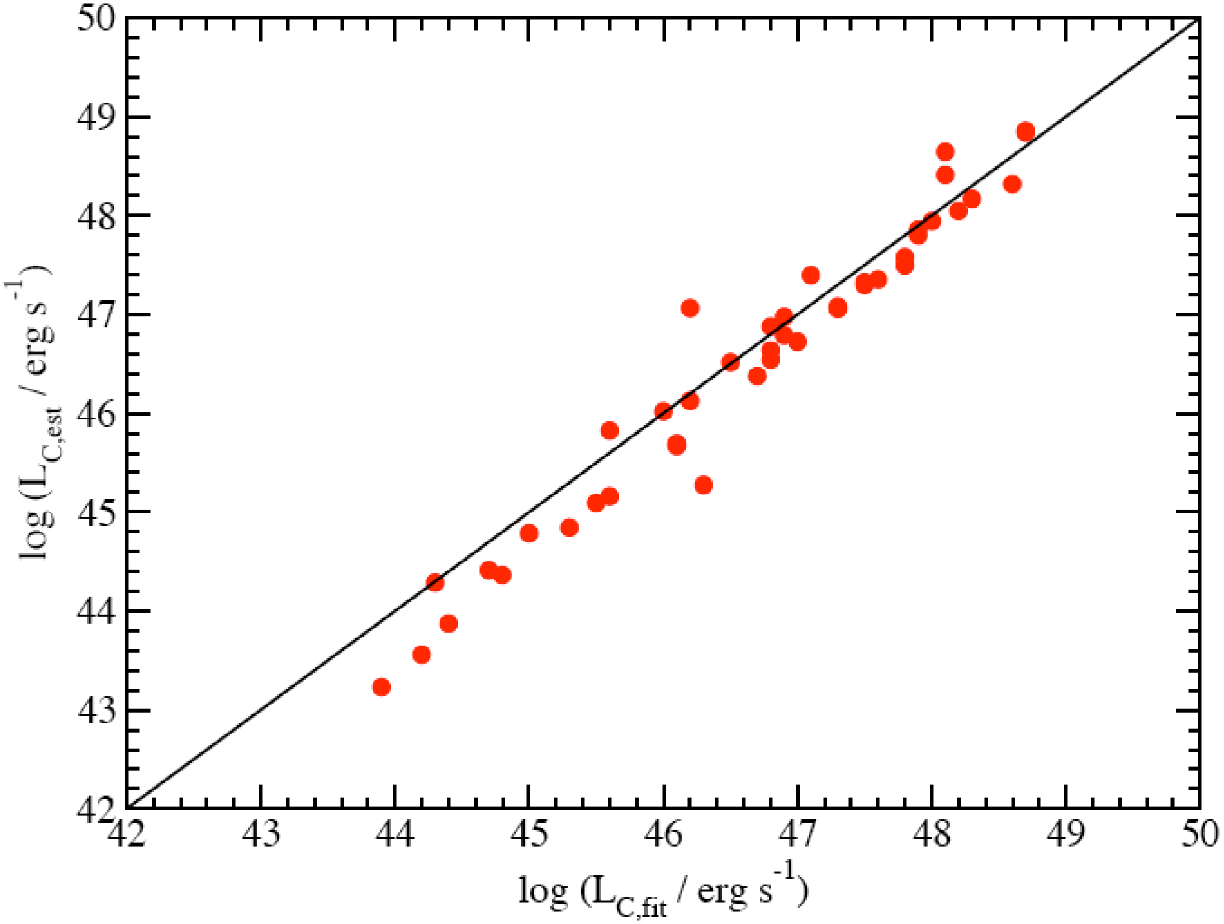


High-Energy Component

Once the peak frequency is known, the power law can be extrapolated to find the peak Compton luminosity.

~10% of the 350 sources in our sample are also in the 58 month *Swift*-BAT catalog. For these objects their BAT spectra were also used to constrain the Compton peak.

For the LBAS, L_{pk}^{C} from the fit (Abdo et al. 2010) and from the extrapolation:

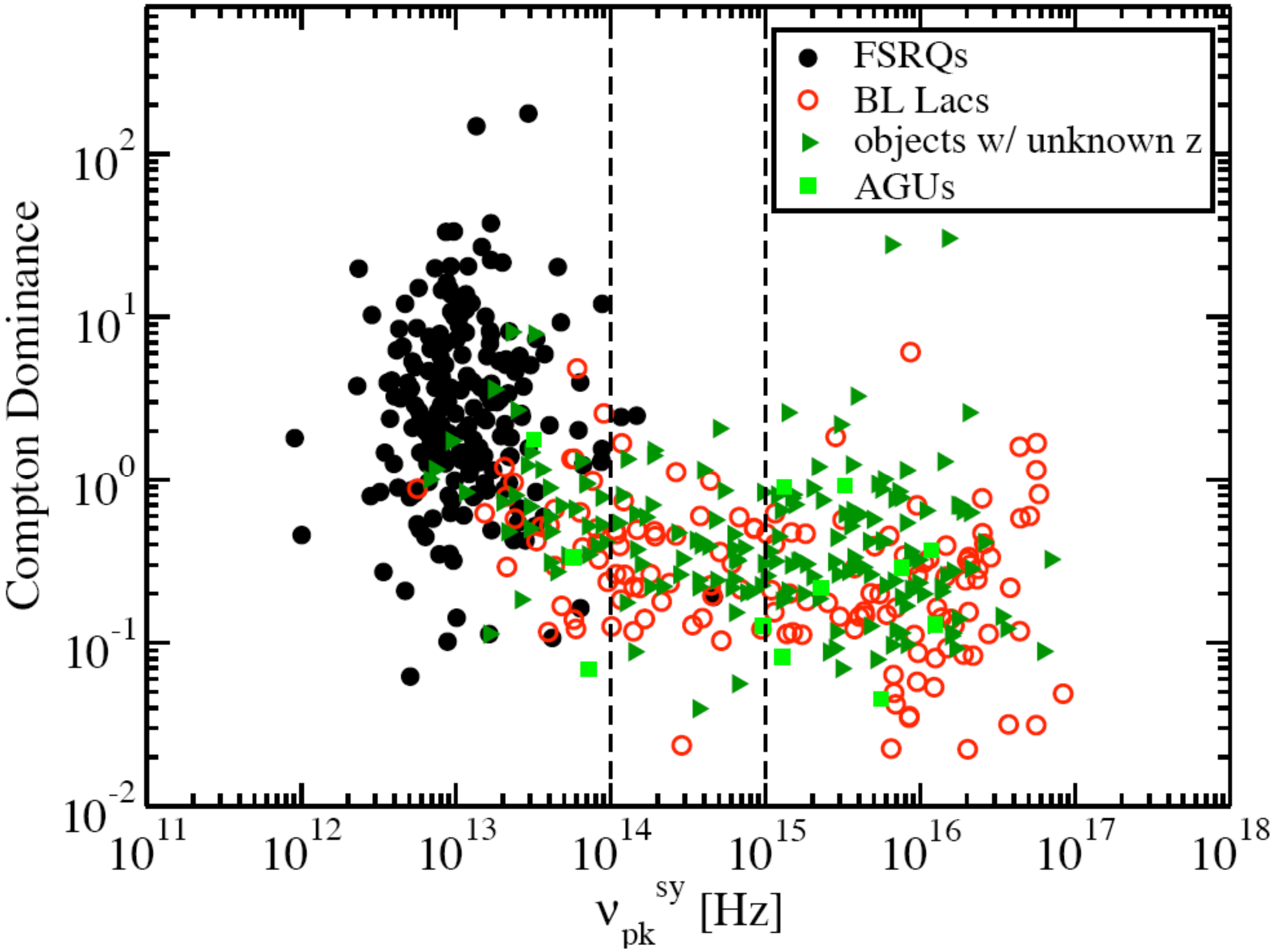


Compton Dominance

Compton dominance: definitely an anti-correlation, and an "L" shape.

Compton dominance does not depend on redshift.

Sources with unknown redshifts are also plotted.



Correlations

Sample	ρ	PNC(ρ)	τ	PNC(τ)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
A_C versus ν_{pk}^{sy}				
BL Lacs	-0.30	2.3×10^{-4}	-0.22	1.2×10^{-4}
FSRQs	8.9×10^{-3}	0.90	6.3×10^{-3}	0.89
All sources with known z	-0.63	4.2×10^{-40}	-0.43	0.00
All sources 1	-0.63	0.00	-0.44	0.00
All sources 2	-0.62	0.00	-0.43	0.00
All sources 3	-0.60	0.00	-0.42	0.00

Unknown z -> z=0

Unknown z -> z=0.35

Unknown z -> z=4.0

Spearman and Kendall Rank Coefficients

Objects with unknown redshift do not destroy the correlation!

A Little Theory

Inject electrons as power law between two electron energies:

$$Q_e(\gamma) = Q_0 \gamma^{-q} \; H(\gamma; \gamma_1, \gamma_2) \; .$$

Equilibrium solution, injection balanced with escape and injection

slow cooling solution, $\gamma_1 < \gamma_c$:

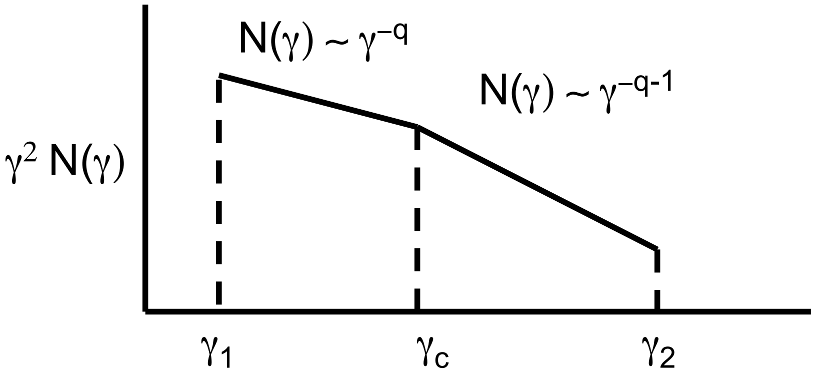
$$N_e(\gamma) \approx Q_0 t_{esc} \begin{cases} (\gamma/\gamma_c)^{-q} & \gamma_1 < \gamma < \gamma_c \\ (\gamma/\gamma_c)^{-q-1} & \gamma_c < \gamma < \gamma_2 \end{cases}$$

$$\gamma_c = \frac{3 m_e c^2}{4 c \sigma_{\rm T} (u'_B + u'_{sy} + u'_{ext}) t_{esc}}$$

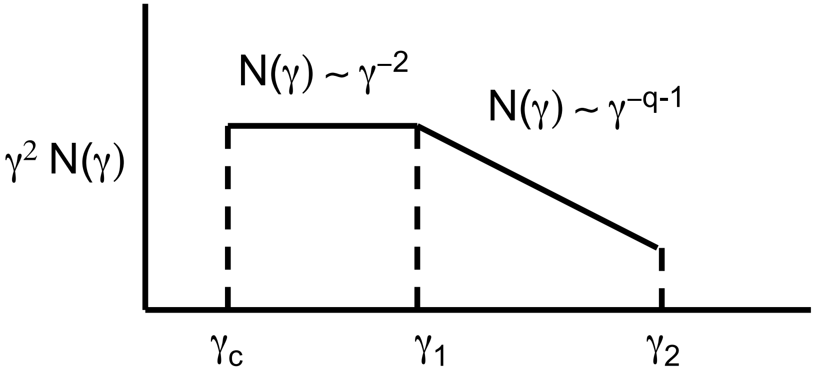
fast cooling solution, $\gamma_c < \gamma_1$:

$$N_e(\gamma) \approx Q_0 t_{esc} \begin{cases} (\gamma/\gamma_1)^{-2} & \gamma_c < \gamma < \gamma_1 \\ (\gamma/\gamma_1)^{-q-1} & \gamma_1 < \gamma < \gamma_2 \end{cases}$$

Slow cooling, peak associated with cooling break



Fast cooling, peak associated with minimum injection break



See, e.g., Boettcher & Dermer (2002)

A Little Theory

Peak frequency is associated with max(γ_c, γ_1).

γ_c depends on power, but γ_1 does not, presumably.

Once γ_c is less than γ_1 , synchrotron peak luminosity will be roughly independent of peak frequency.

$$\epsilon_{pk} = \frac{h\nu_{pk}}{m_e c^2} = \delta_{\mathrm{D}} \epsilon_B \begin{cases} \gamma_c^2 & \gamma_1 < \gamma_c \\ \gamma_1^2 & \gamma_c < \gamma_1 \end{cases}$$

$$L^{sy}_{pk} = L^{sy}_{\epsilon_{pk}} = \frac{2\delta_{\mathrm{D}}^4}{3} c\sigma_{\mathrm{T}} u'_B Q_0 t_{esc} \begin{cases} \gamma_c^3 & \gamma_1 < \gamma_c \\ \gamma_1^3 & \gamma_c < \gamma_1 \end{cases}$$

Scale injected electrons:

$$Q_0 = Q_{00}\ell$$

Scale injected Lorentz factor with power:

$$\Gamma = \Gamma_0 \ell^g$$

Scale injected magnetic field with power:

$$B = B_0 \ell^b$$

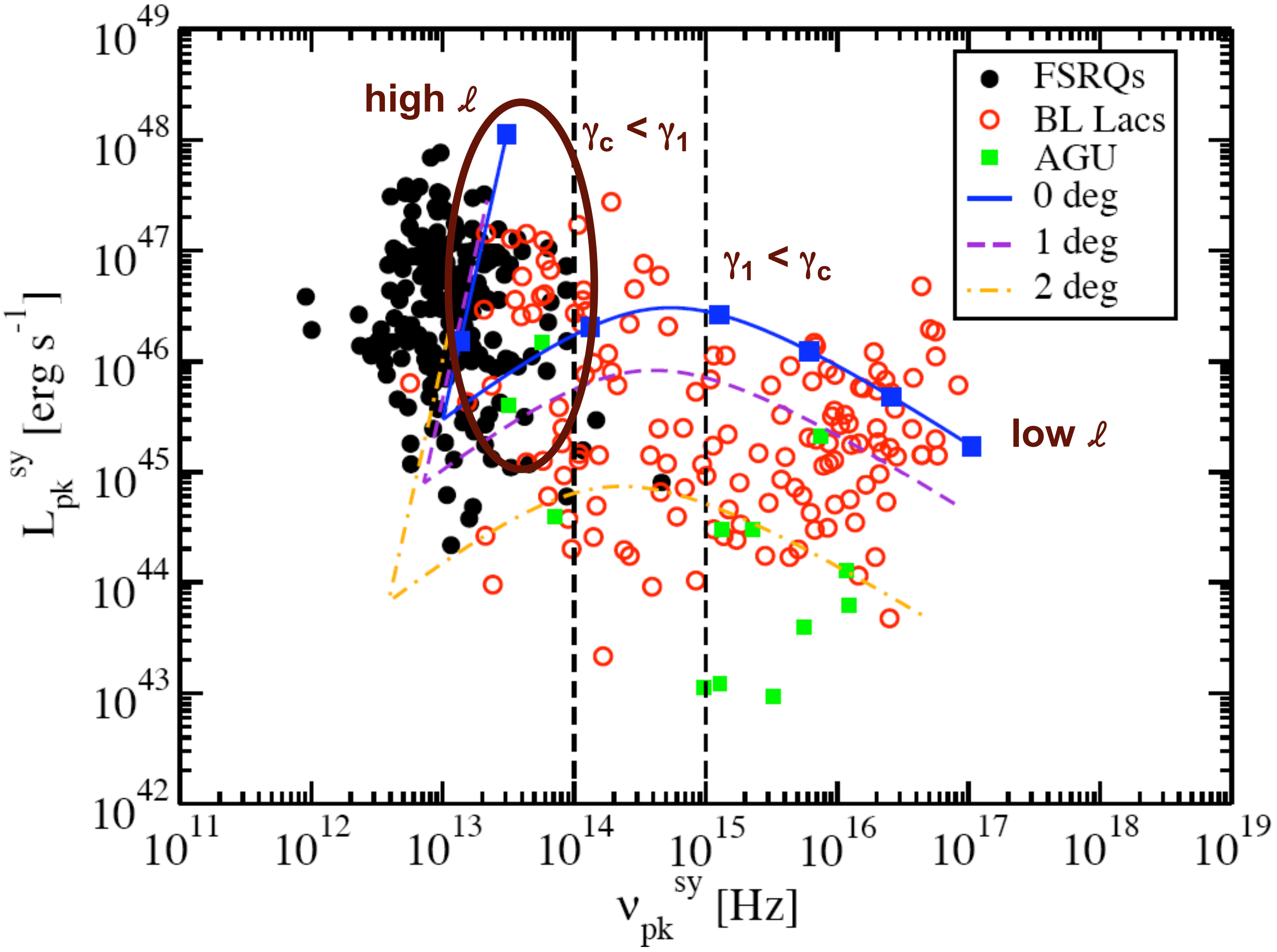
Scale external radiation field with power:

$$u_{ext} = u_0 \ell^a$$

So we assume blazars are two parameter engines: θ, ℓ

Reproducing Blazar Sequence

A clever choice of parameters can reproduce the “V” shape in the L_{pk}-ν_{pk} diagram



Reproducing Blazar Sequence

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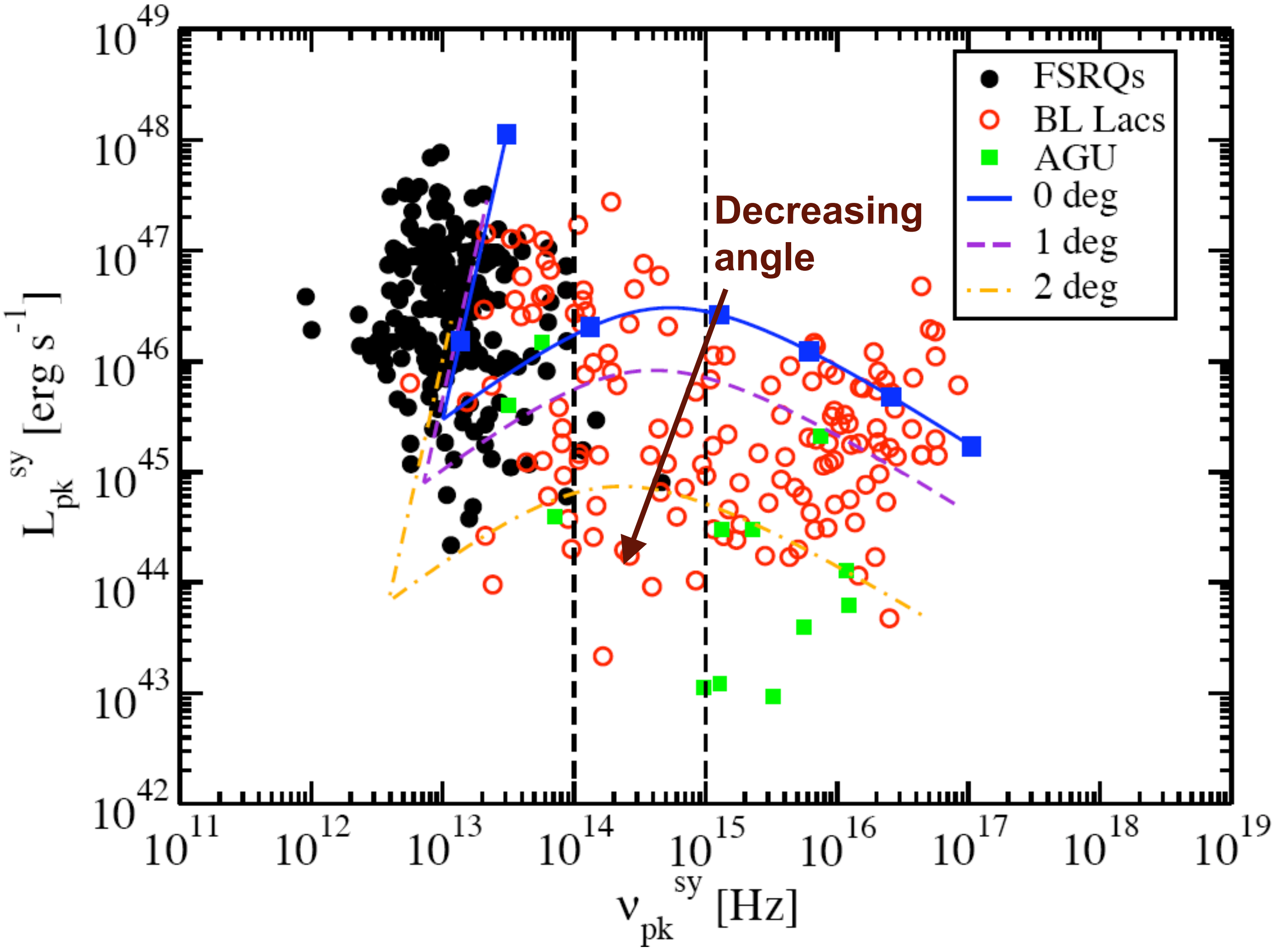

Reproducing Blazar Sequence

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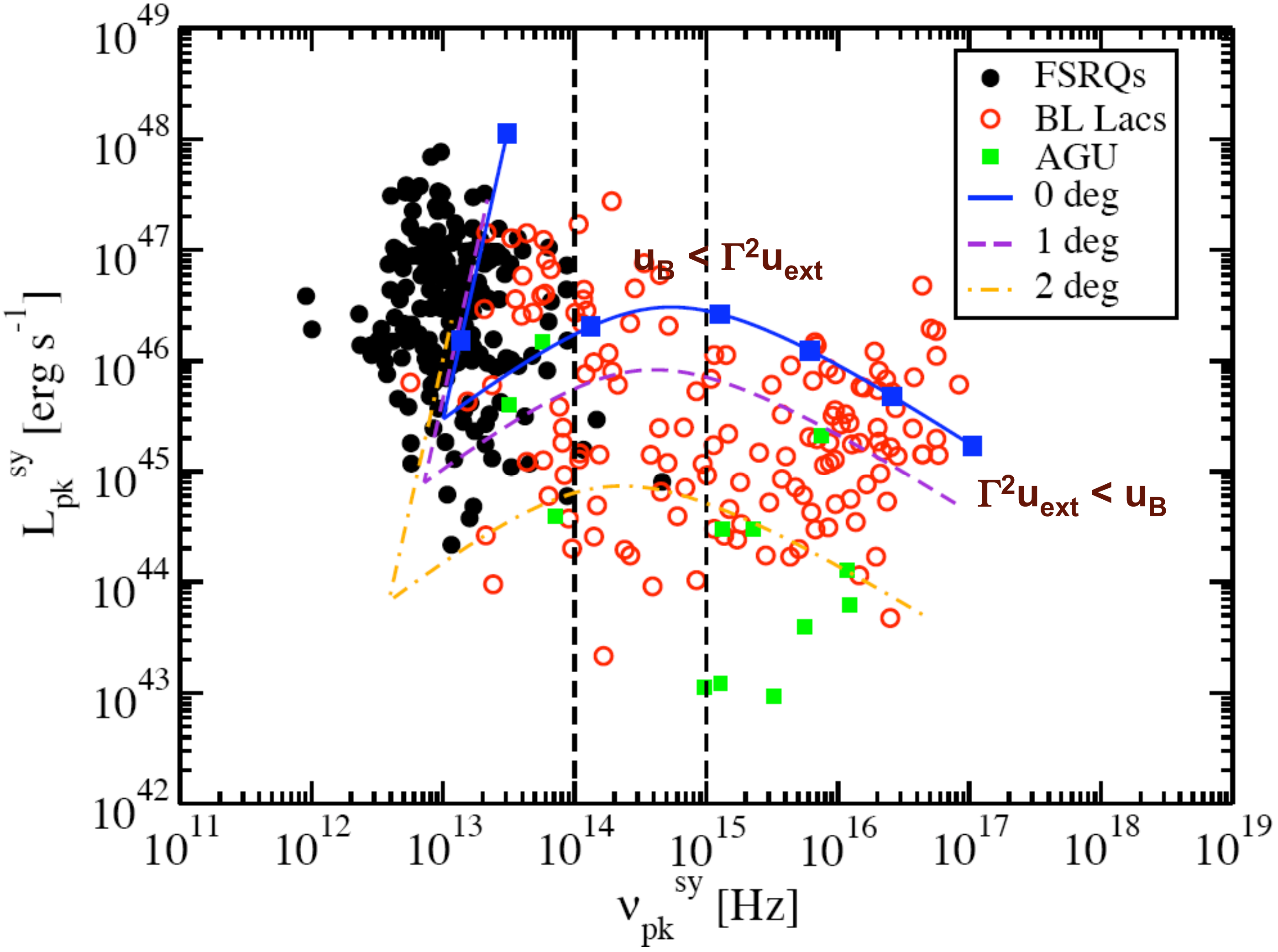
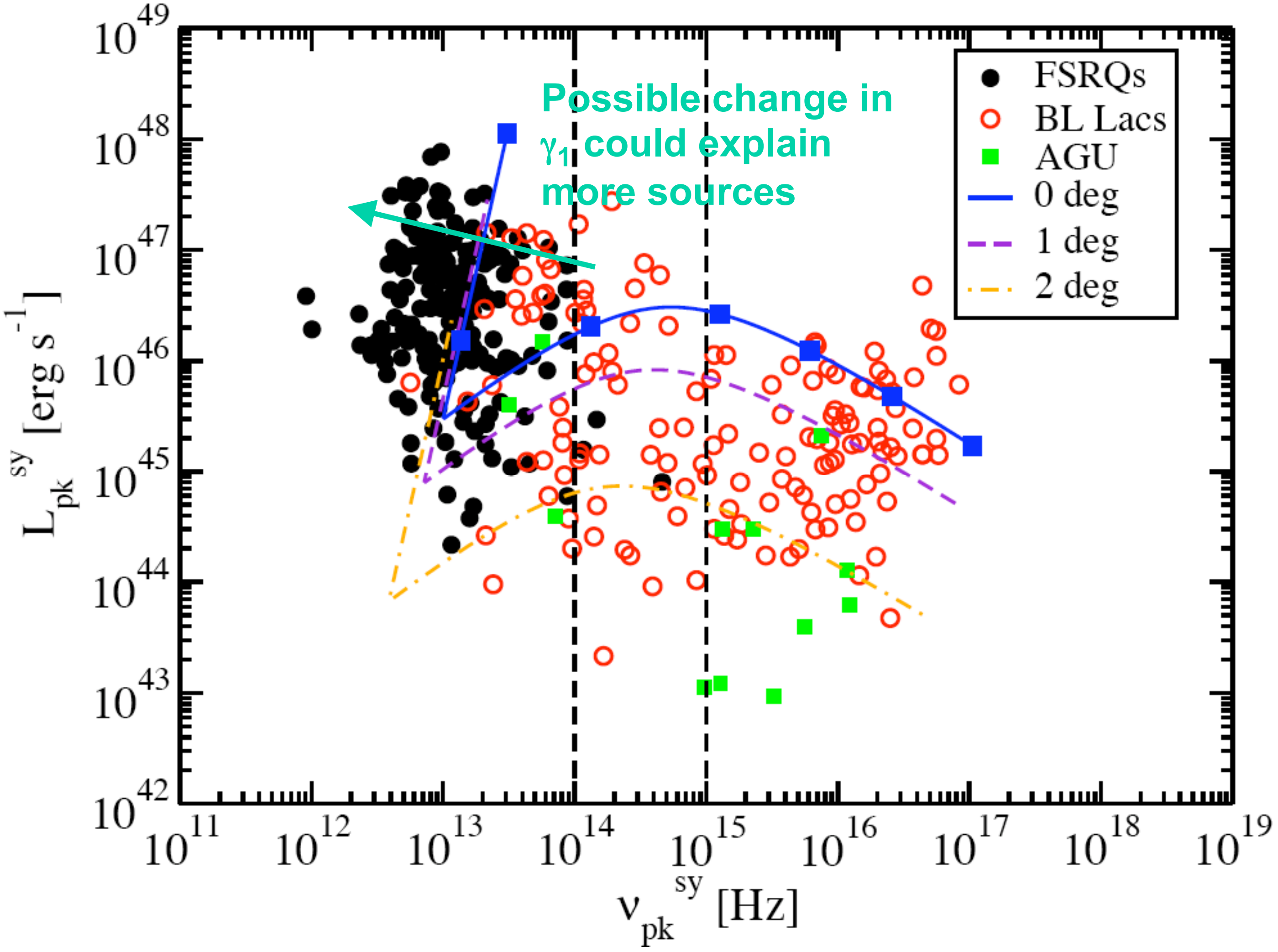


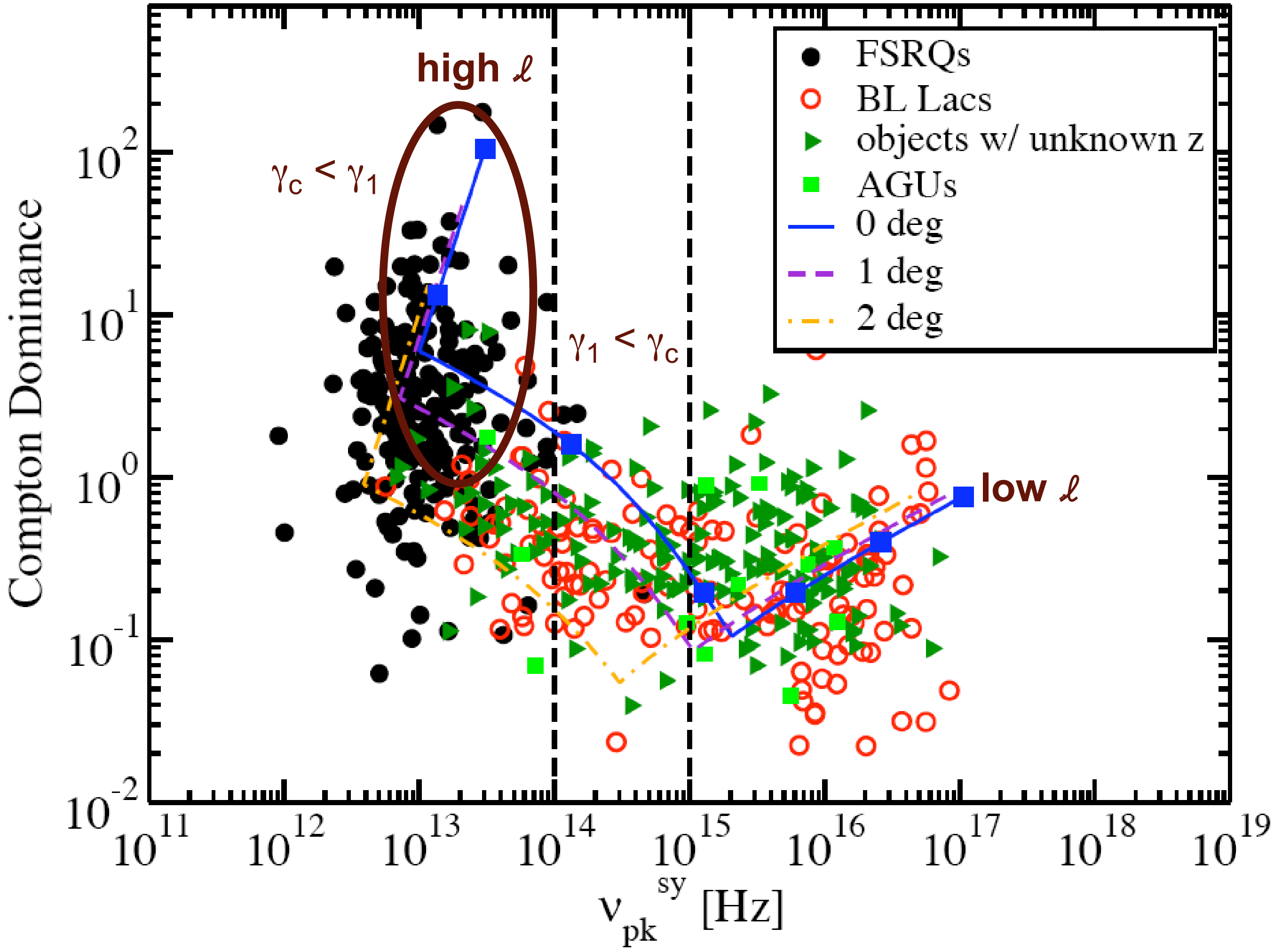
Reproducing Blazar Sequence

A clever choice of parameters can reproduce the “V” shape in the L_{pk}-ν_{pk} diagram



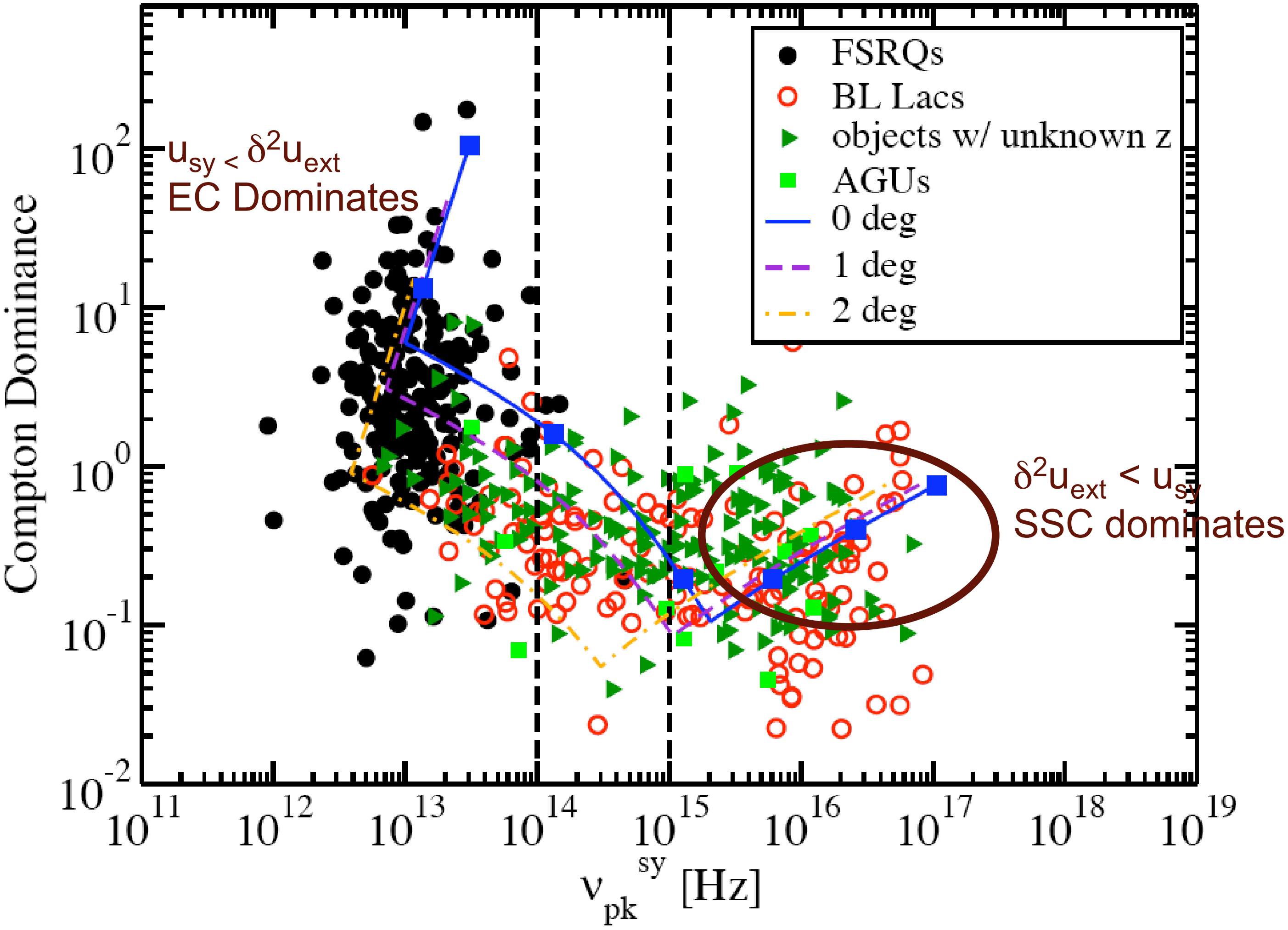
Reproducing Blazar Sequence

It can also reproduce the "L" shape on the A_C-ν_{pk} diagram



Reproducing Blazar Sequence

It can also reproduce the “L” shape on the A_C-ν_{pk} diagram



$u_{sy} < \delta^2 u_{ext}$
EC Dominates

$\delta^2 u_{ext} < u_{sy}$
SSC dominates

Summary

- Blazar sequence generated from the 2LAC (L_{pk}-ν_{pk} and A_C-ν_{pk}).

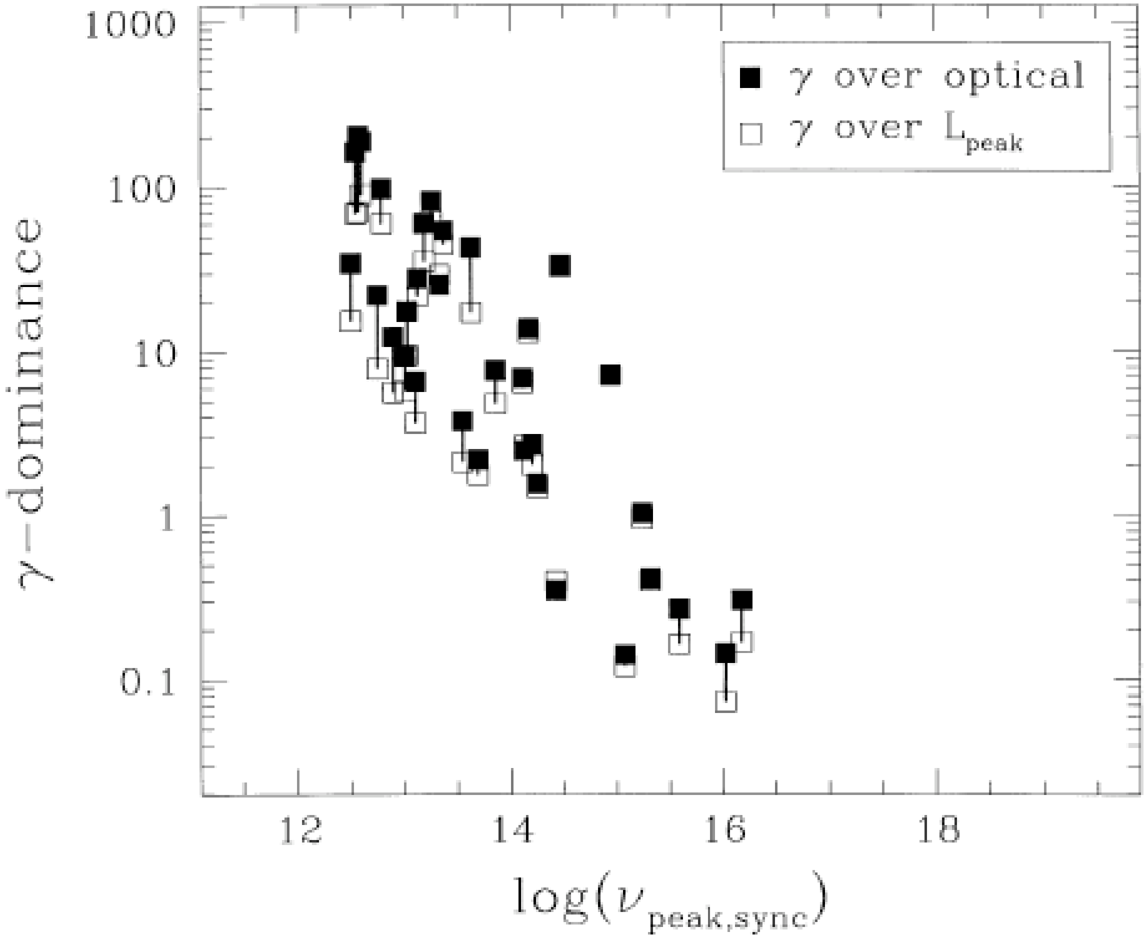
- Largest sample yet for Compton Dominance plot.

- Blazars with unknown z could ruin L_{pk}-ν_{pk} anti-correlation, but not A_C-ν_{pk} anti-correlation.

- Standard cooling scenario seems to explain “V” and “L” shapes on L_{pk} -ν_{pk} and A_C-ν_{pk} diagrams if ν_{pk} is associated with the maximum of γ_c and γ_1.

Extra slides

Gamma-ray Component

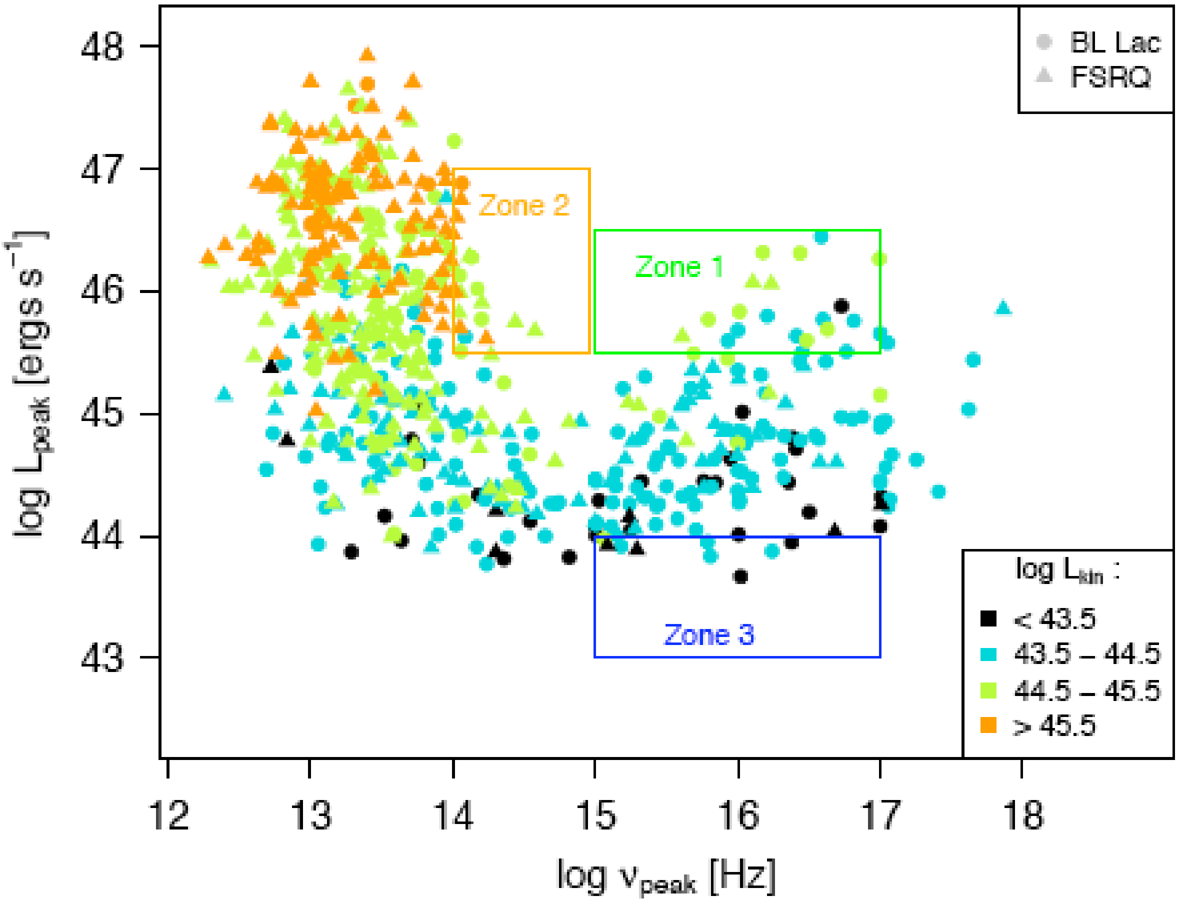


Compton dominance = γ-ray dominance = $L_{pk,C}$ / $L_{pk,sy}$

Compton dominance vs synchrotron peak frequency EGRET era, ~ 30 sources

Fossati et al. (1998)

Other works



Meyer et al. (2011)

Meyer et al. (2011)
“V” shape (or “L” shape)

Intermediate SED shapes don’t appear common.

Meyer et al. explain this as due to viewing angle effects in stratified jets.

Other recent works have similar “V” or “L” shape: e.g., Nieppola et al. (2006), Giommi et al. (2011).

But upper right may be filled in with BL Lacs with unknown redshift (Giommi et al. 2011).

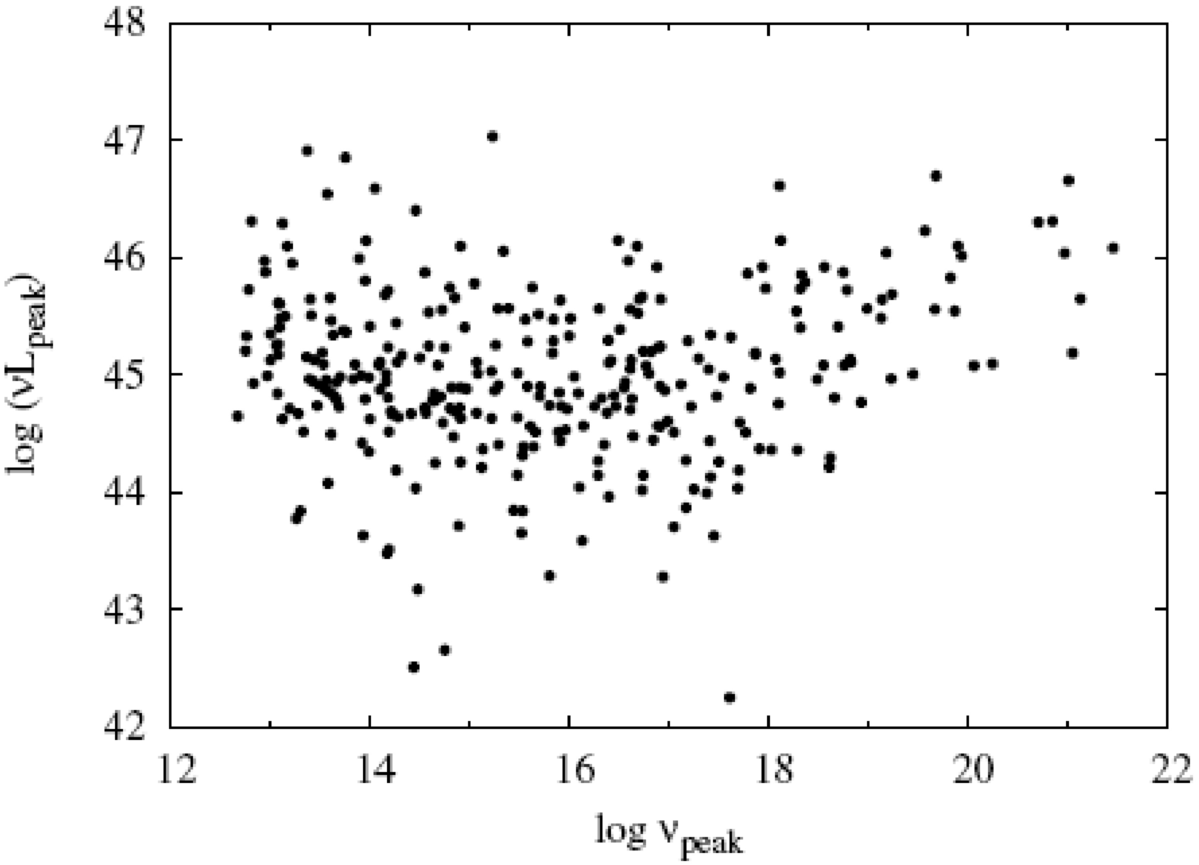
Other works

Nieppola et al. (2006) fit BL Lacs with log-parabola to locate synchrotron peaks

They also found “V” or “L” shape.

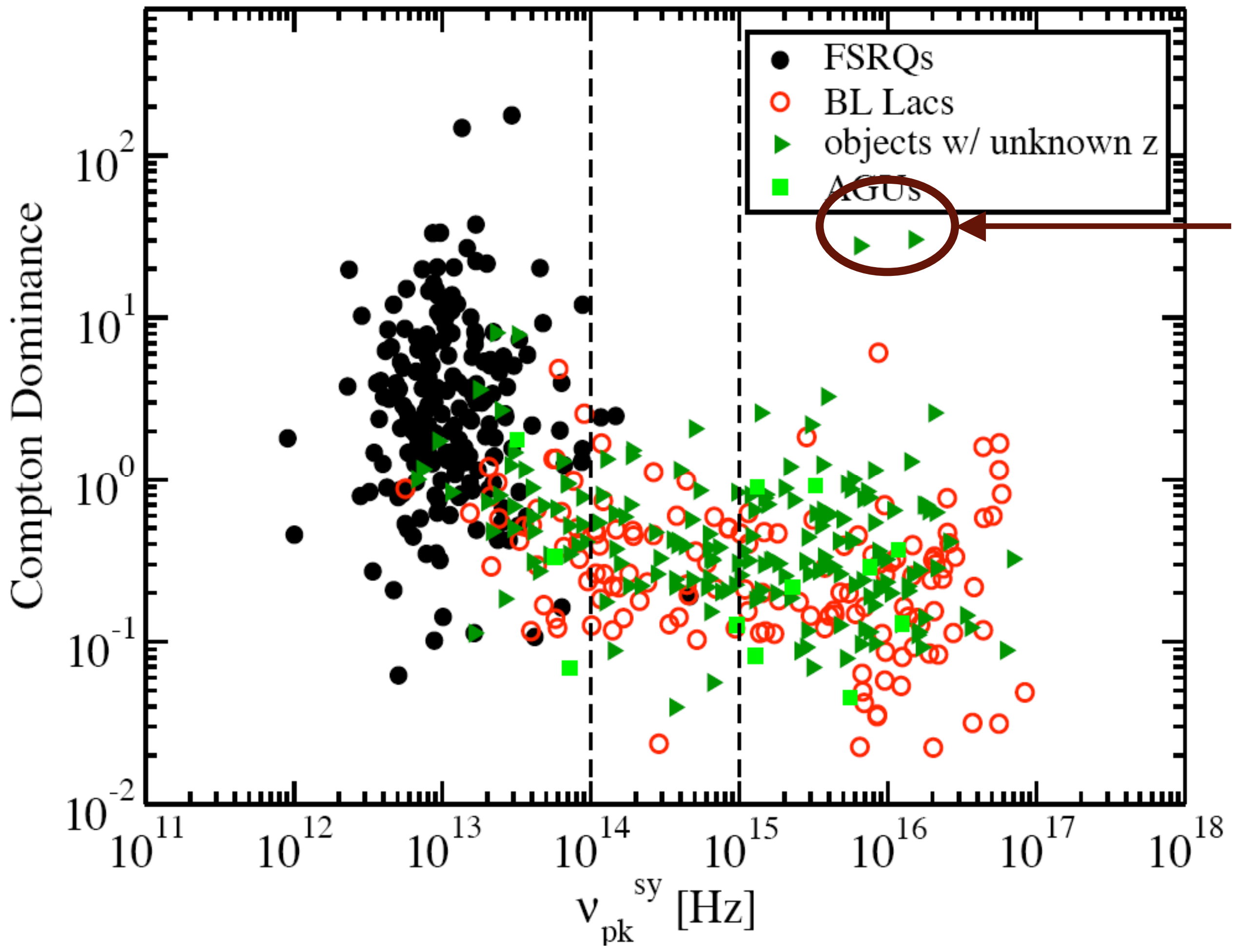
Problems with fitting with log-parabola versus third-order polynomial?

Also, no FSRQs included.



Nieppola et al. (2006)

Outliers



2FGL J0059.2-0151
(1RXS 005916.3-015030)
and
2FGL J0912.5+2758
(1RXS J091211.9+27595)

Hardest sources in 2LAC, also large error bars. When propagating errors in spectral index, A_C is consistent with 1, within error bars.