Modeling the Spectral Energy Distributions and Variability of Blazars

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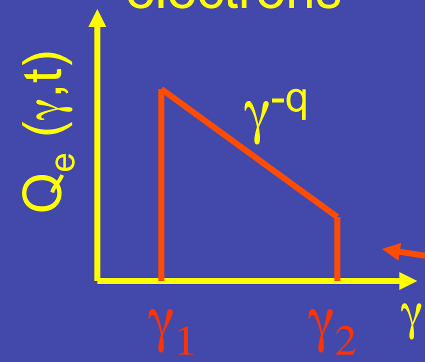
Ohio University, Athens, OH, USA

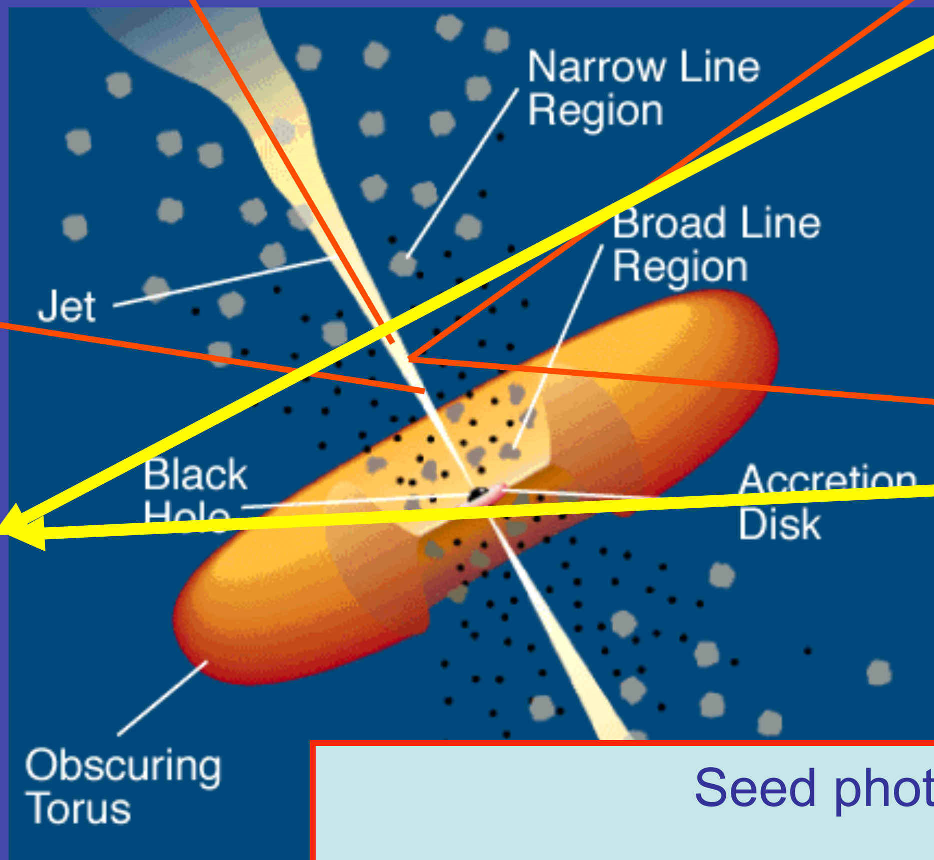
Fermi and Jansky
St. Michael's, MD, November 10, 2011

Leptonic Blazar Model

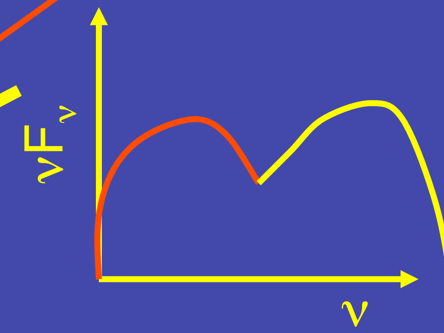
Injection, acceleration of ultrarelativistic electrons



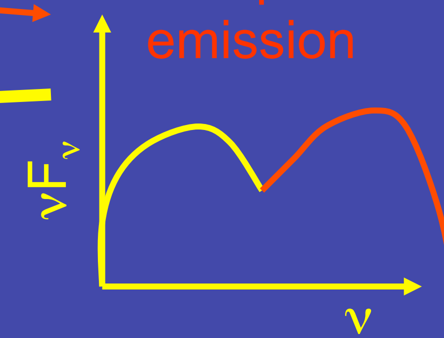
Relativistic jet outflow with $\Gamma \approx 10$



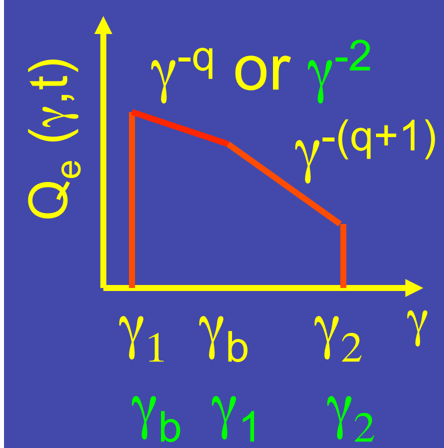
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



γ_b:
$\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

Sources of External Photons

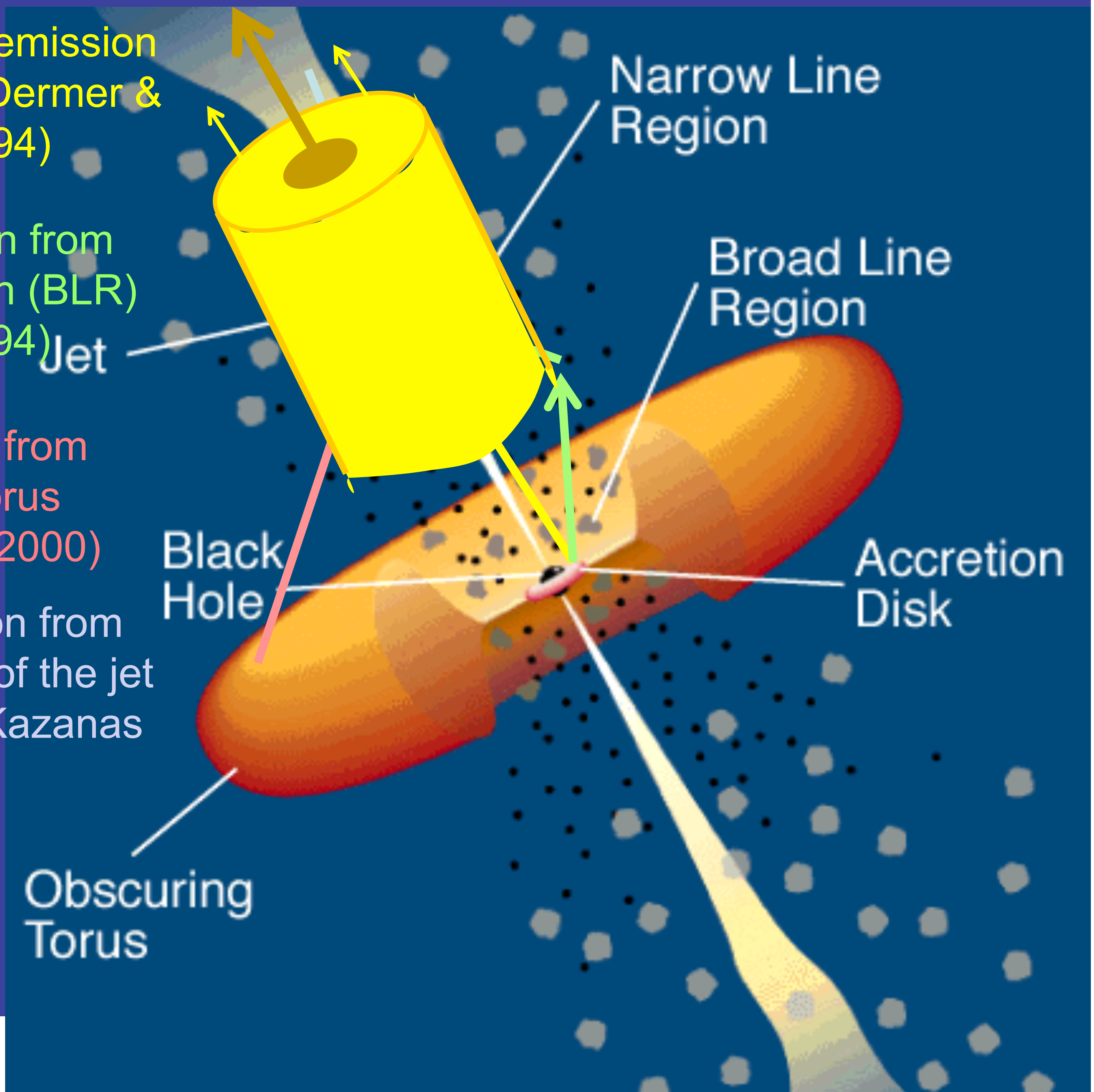
Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)

Optical-UV Emission from the Broad-line Region (BLR) (Sikora et al. 1994)

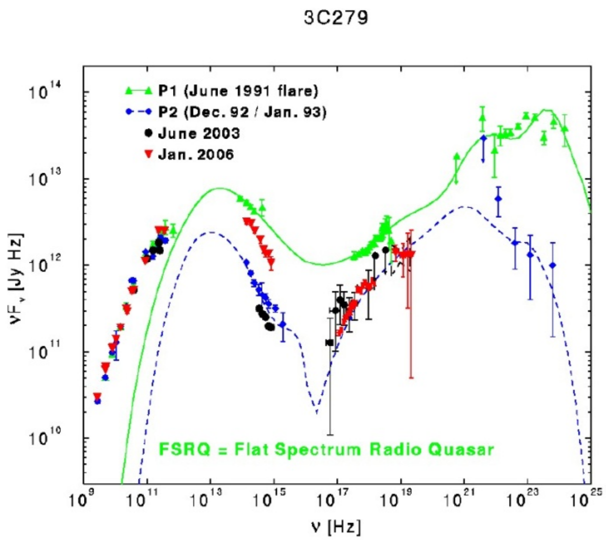
Infrared Radiation from the Obscuring Torus (Blazejowski et al. 2000)

Synchrotron emission from slower/faster regions of the jet (Georganopoulos & Kazanas 2003)

Spine – Sheath Interaction (Ghisellini & Tavecchio 2008)



Blazar Classification



(Hartman et al. 2000)

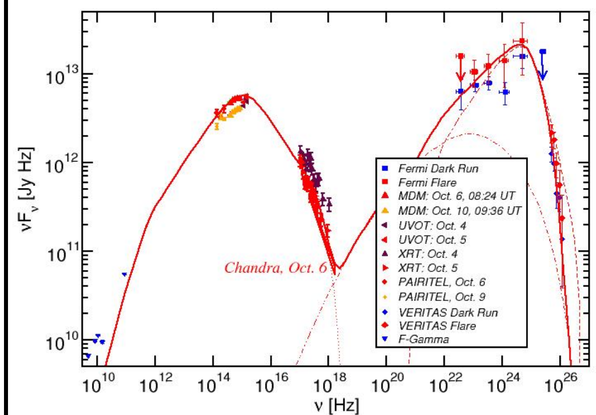
Quasars:

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power

3C66 A



(Abdo et al. 2011)

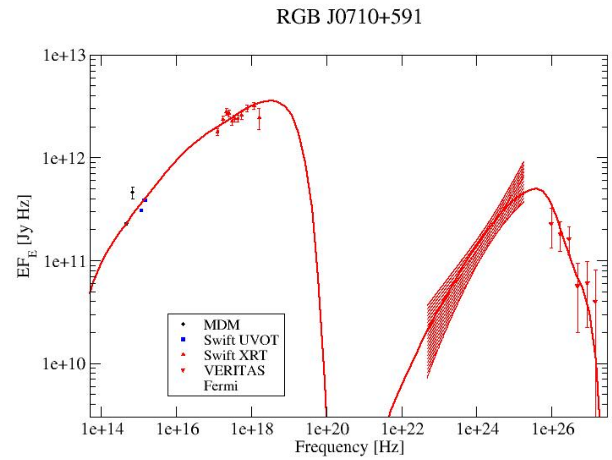
Low-frequency peaked / Intermediate BL Lacs (LBLs/ IBLs):

Peak frequencies at IR/ Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated



(Acciari et al. 2009)

High-frequency peaked BL Lacs (HBLs):

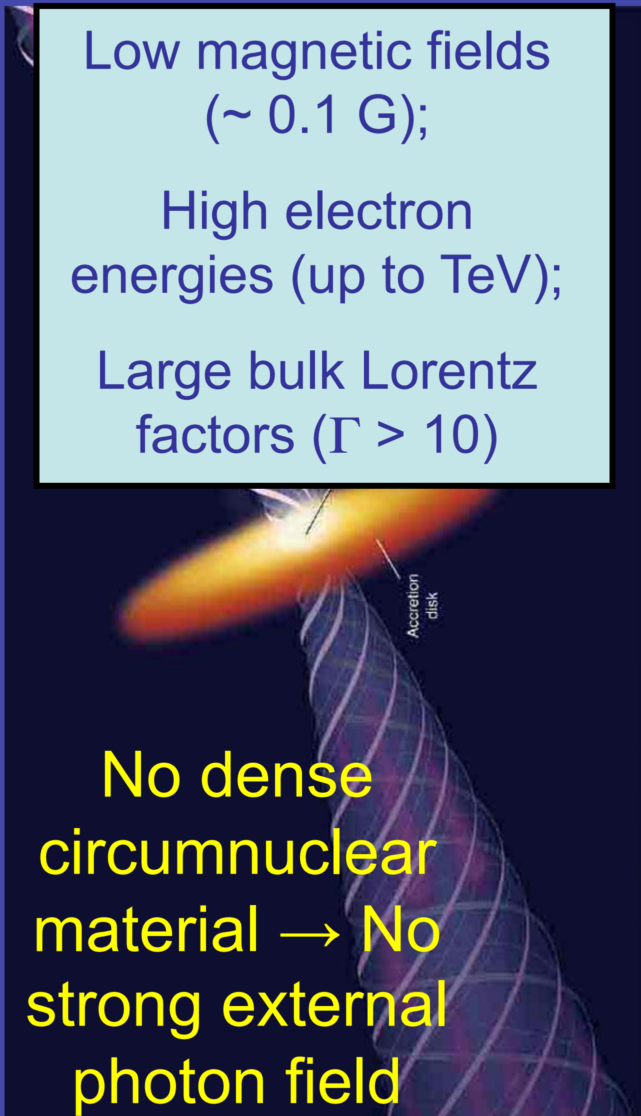
Low-frequency component from radio to UV/X-rays,

$\nu_{sy} > 10^{15}$ Hz

often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

Spectral modeling results along the Blazar Sequence: Leptonic Models



Low magnetic fields (~ 0.1 G);

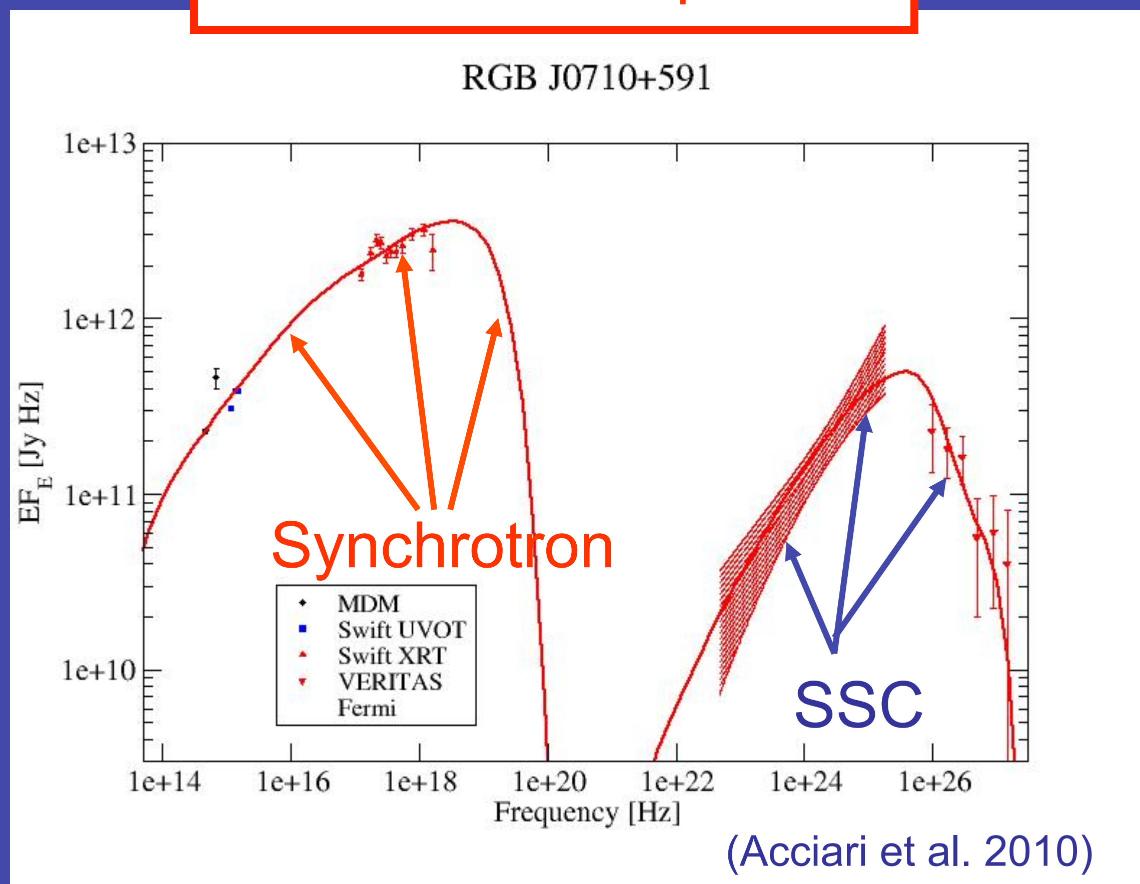
High electron energies (up to TeV);

Large bulk Lorentz factors (Γ > 10)

No dense circumnuclear material → No strong external photon field

High-frequency peaked BL Lac (HBL):

The "classical" picture



(Acciari et al. 2010)

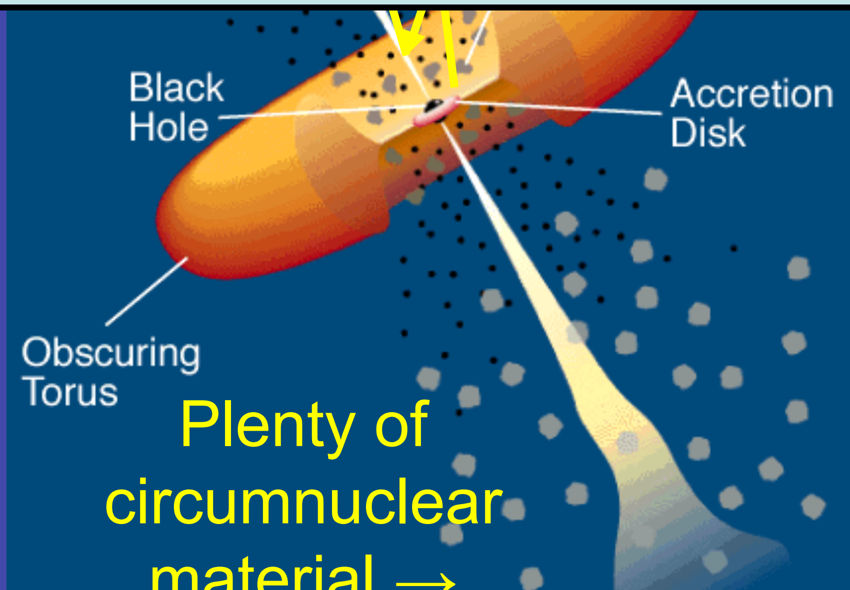
Spectral modeling results along the Blazar Sequence: Leptonic Models

High magnetic fields (~ a few G);

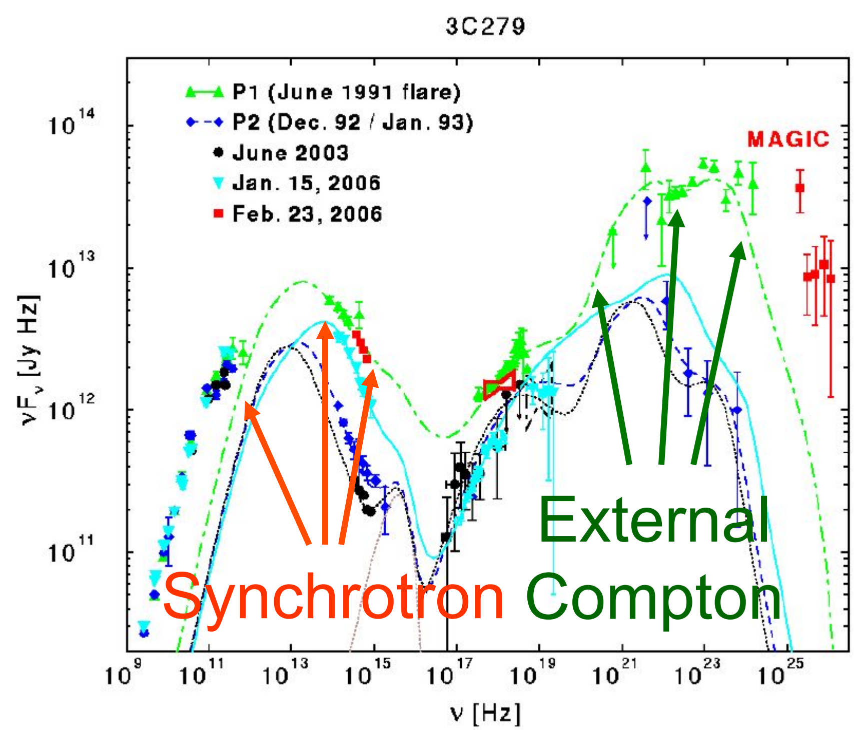
Lower electron energies (up to GeV);

Lower bulk Lorentz factors (Γ ~ 10)

Radio Quasar (FSRQ)

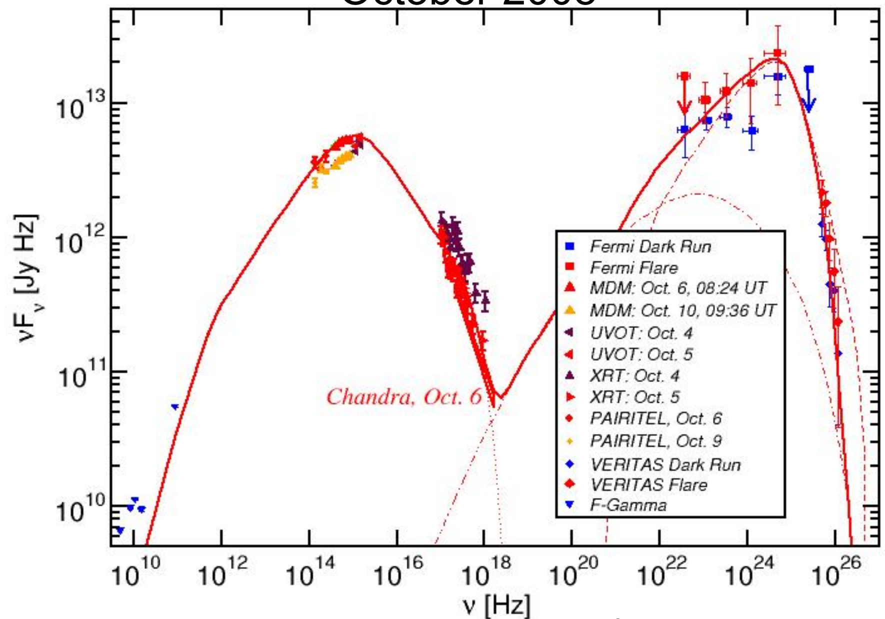


Plenty of circumnuclear material → Strong external photon field

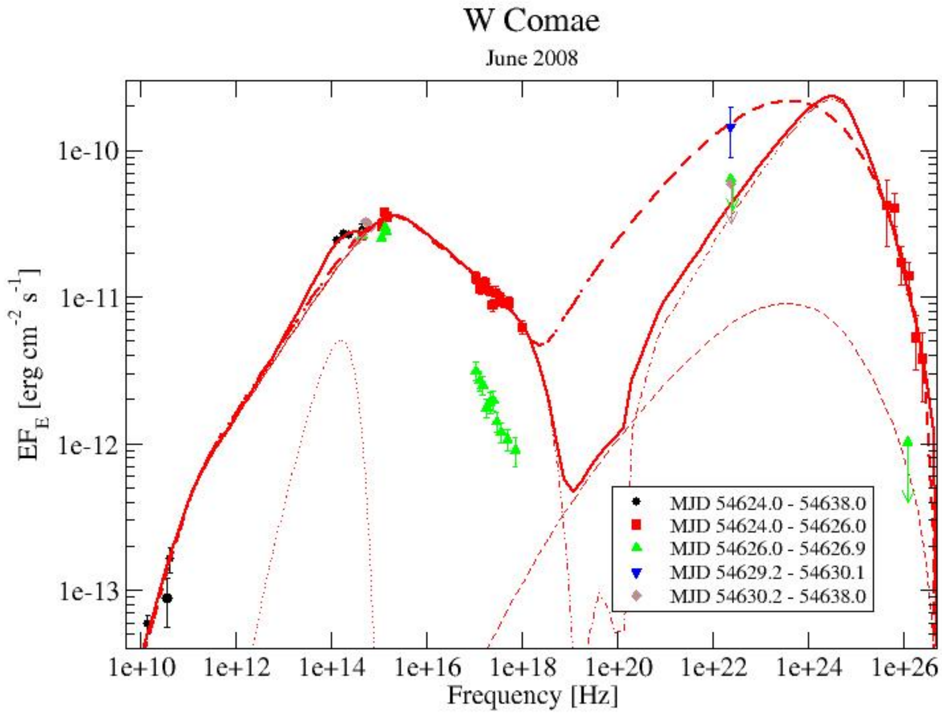


Intermediate BL Lac Objects

3C66A
October 2008



(Abdo et al. 2011)



(Acciari et al. 2009)

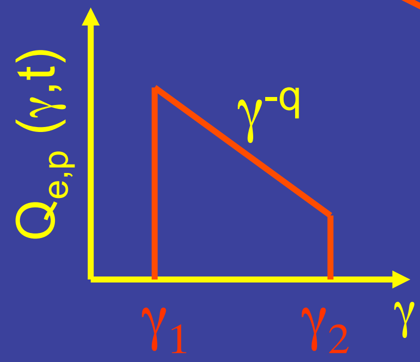
Spectral modeling with pure SSC would require extreme parameters (far sub-equipartition B-field)

Including External-Compton on an IR radiation field allows for more natural parameters and near-equipartition B-fields

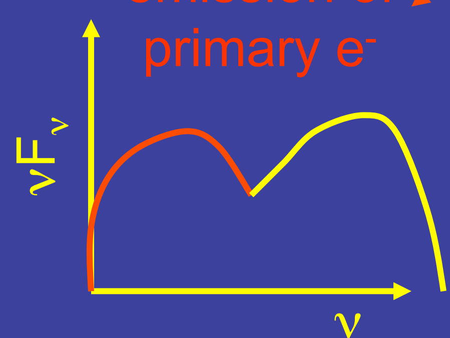
→ γ-ray production on > pc scales?

Hadronic Blazar Models

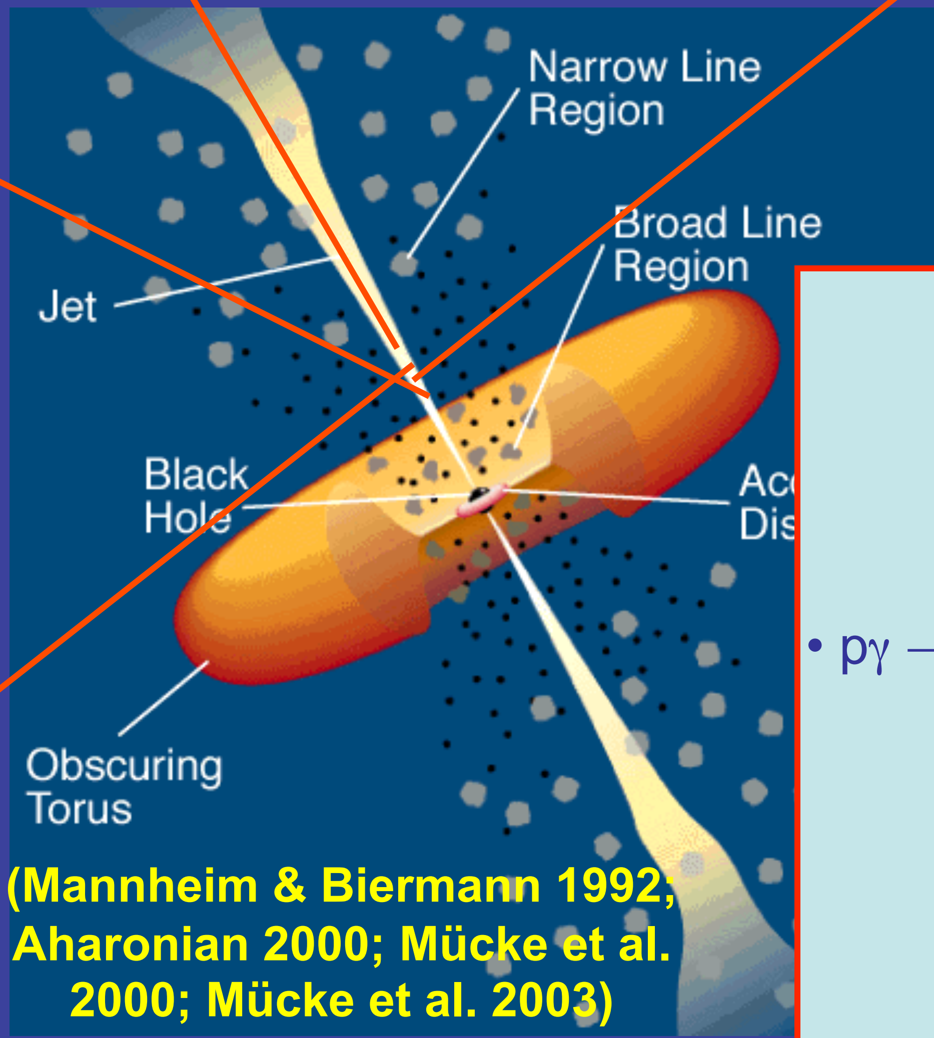
Injection, acceleration of ultrarelativistic electrons and protons



Synchrotron emission of primary e^-

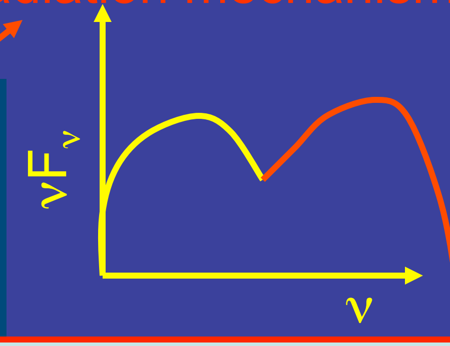


Relativistic jet outflow with $\Gamma \approx 10$



(Mannheim & Biermann 1992; Aharonian 2000; Mücke et al. 2000; Mücke et al. 2003)

Proton-induced radiation mechanisms:



- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Requirements for lepto-hadronic models

- To exceed p-γ pion production threshold on interactions with synchrotron (optical) photons: $E_p > 7 \times 10^{16} E^{-1}_{ph,eV}$ eV
- For proton synchrotron emission at multi-GeV energies: E_p up to ~ 10^{19} eV (=> UHECR)
- Require Larmor radius

  $r_L \sim 3 \times 10^{16} E_{19}/B_G$ cm $\leq$ a few x 10^{15} cm => $B \geq 10$ G

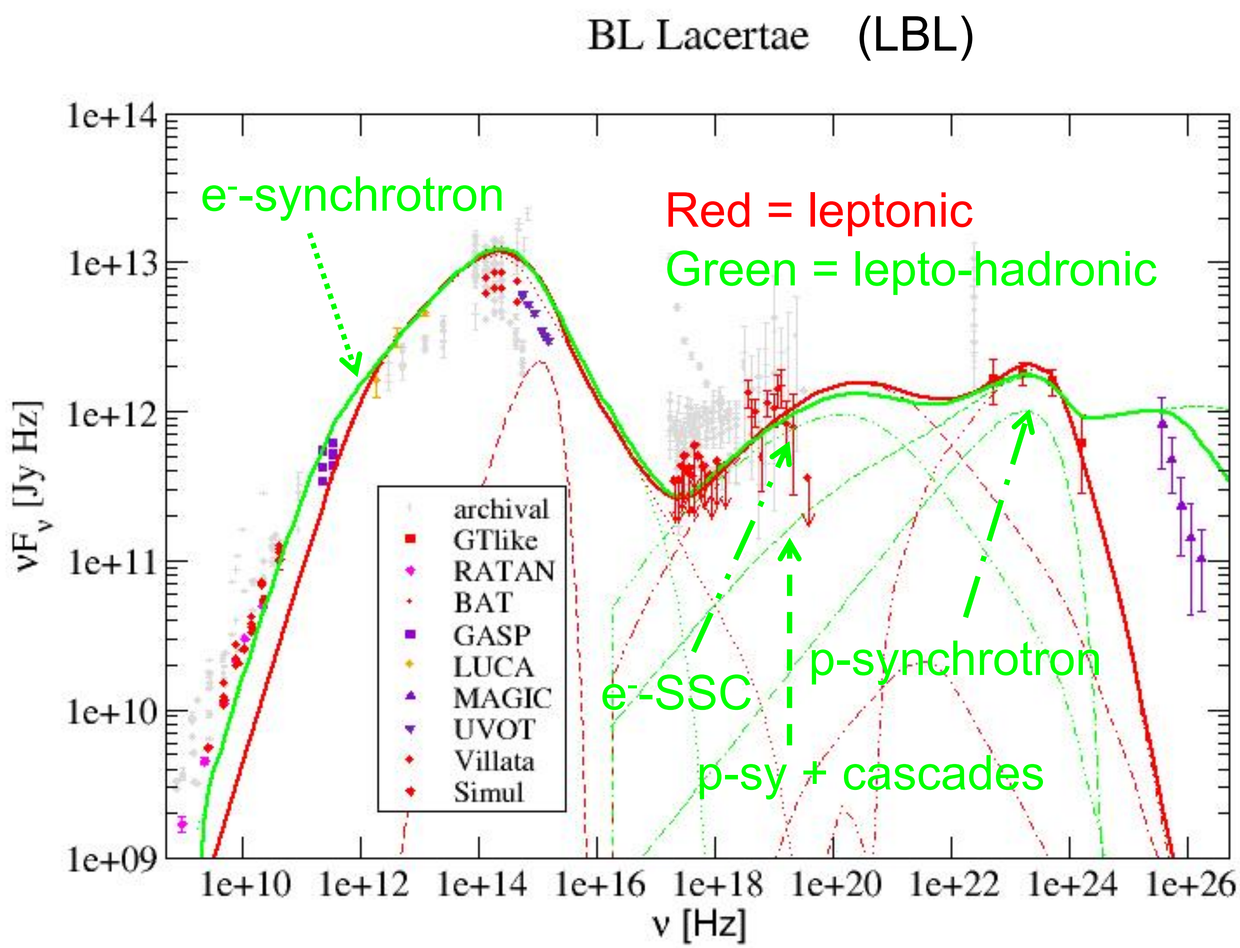
  (Also: to suppress leptonic SSC component below synchrotron)

=> Synchrotron cooling time: t_{sy} (p) ~ several days

=> Difficult to explain intra-day (sub-hour) variability!

→ Geometrical effects?

Lepto-Hadronic Model Fits Along the Blazar Sequence

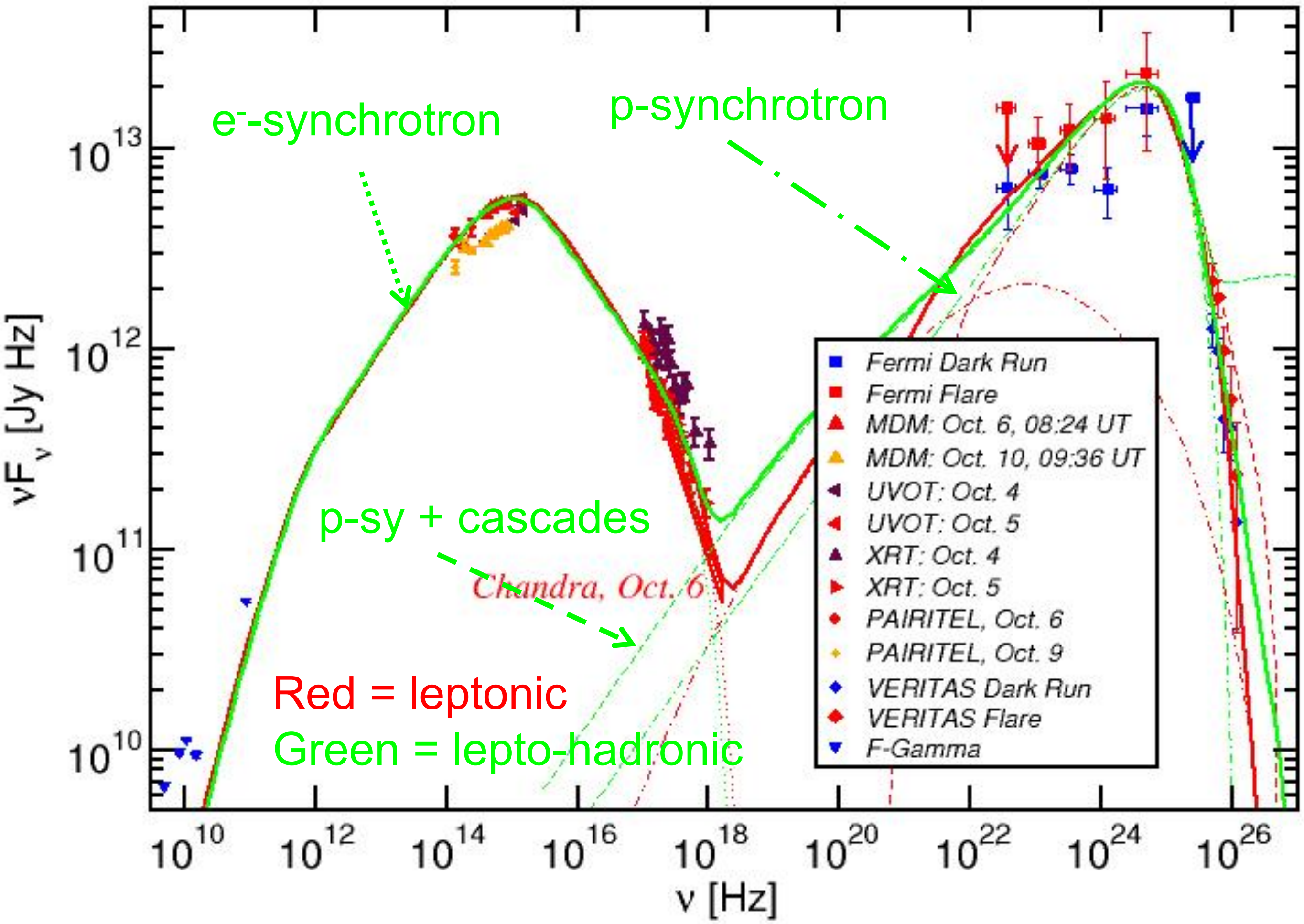


Strongly peaked γ-ray spectra achievable by p-synchrotron.

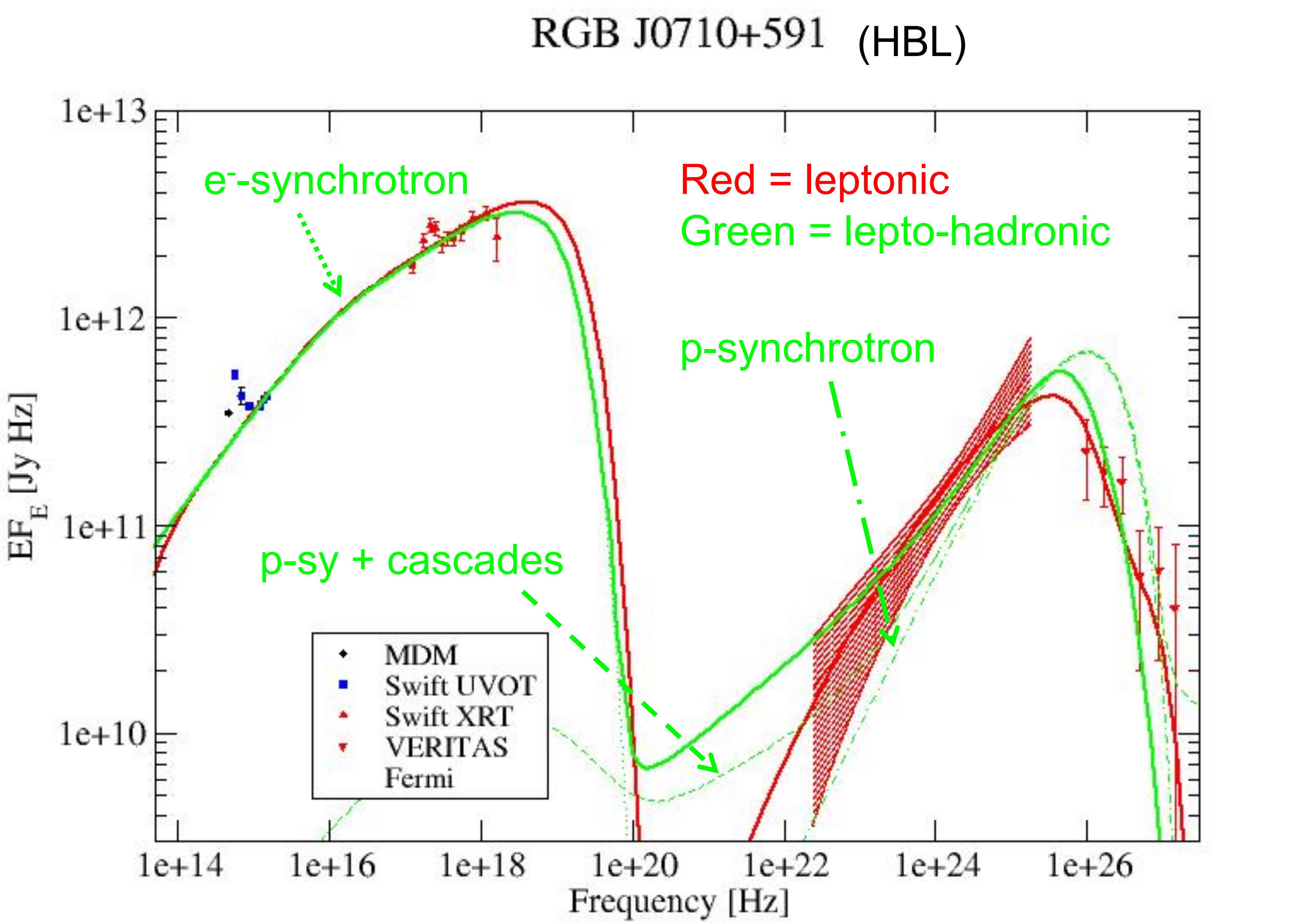
Cascades allow extension to VHE γ-rays, but produce flat extension towards X-rays

Lepto-Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)

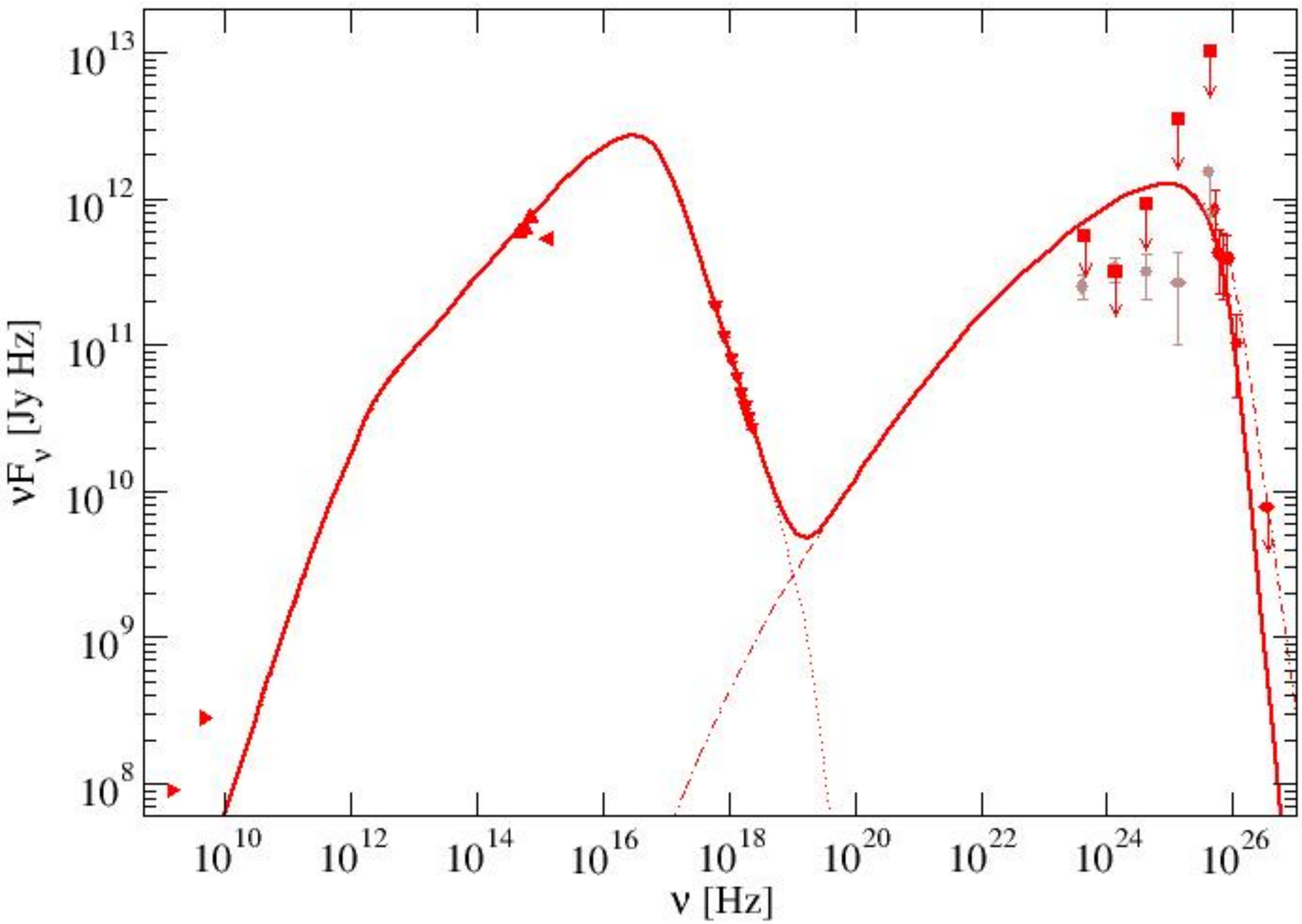


Lepto-Hadronic Model Fits Along the Blazar Sequence



HBLs Disfavouring SSC

RX J0648+152



Aliu et al. (2011): in press

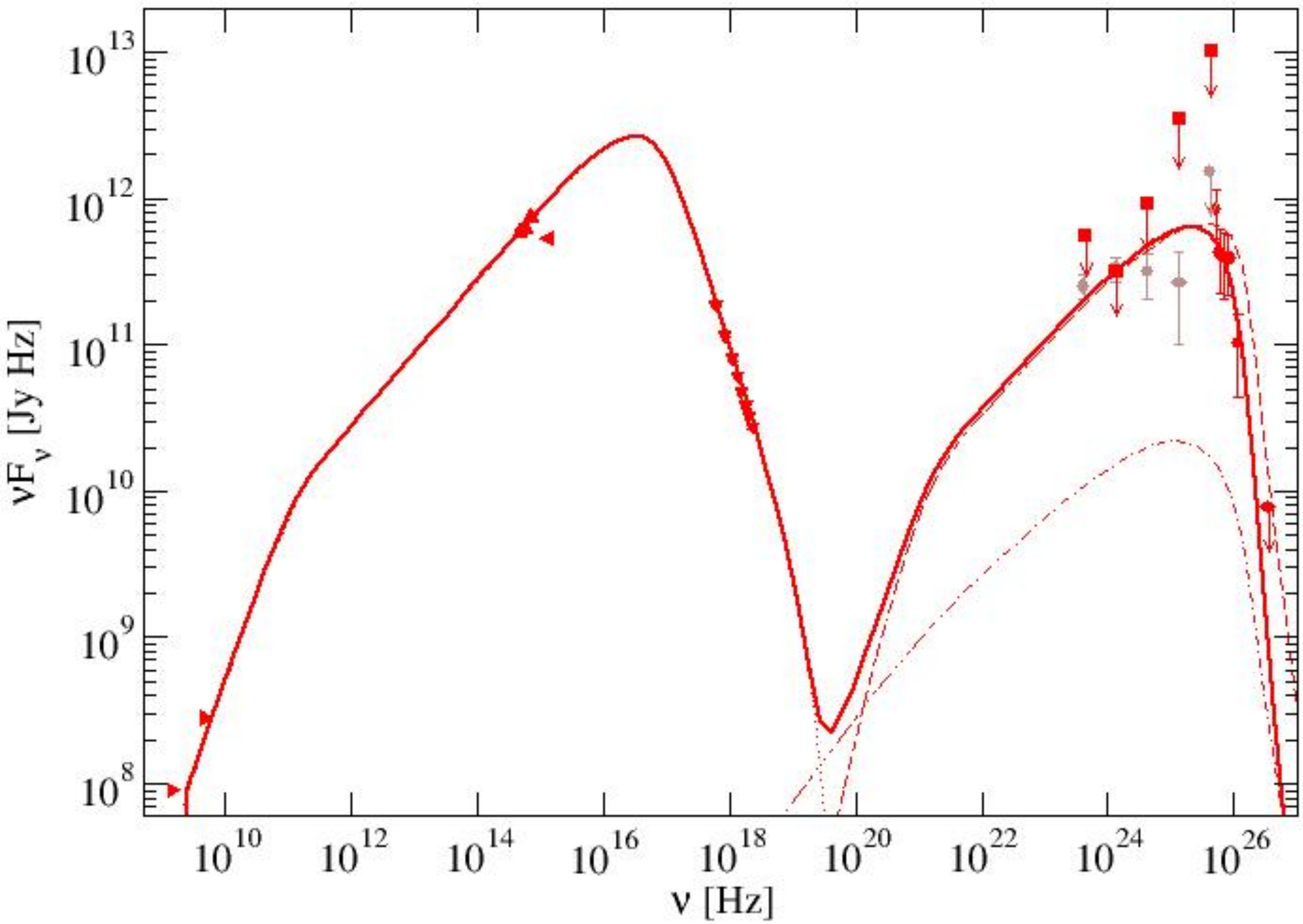
Pure Leptonic SSC:

Overpredicting Fermi flux;

$L_B/L_e = 0.16$

HBLs Disfavouring SSC

RX J0648+152



Aliu et al. (2011): in press

Leptonic SSC + EC:

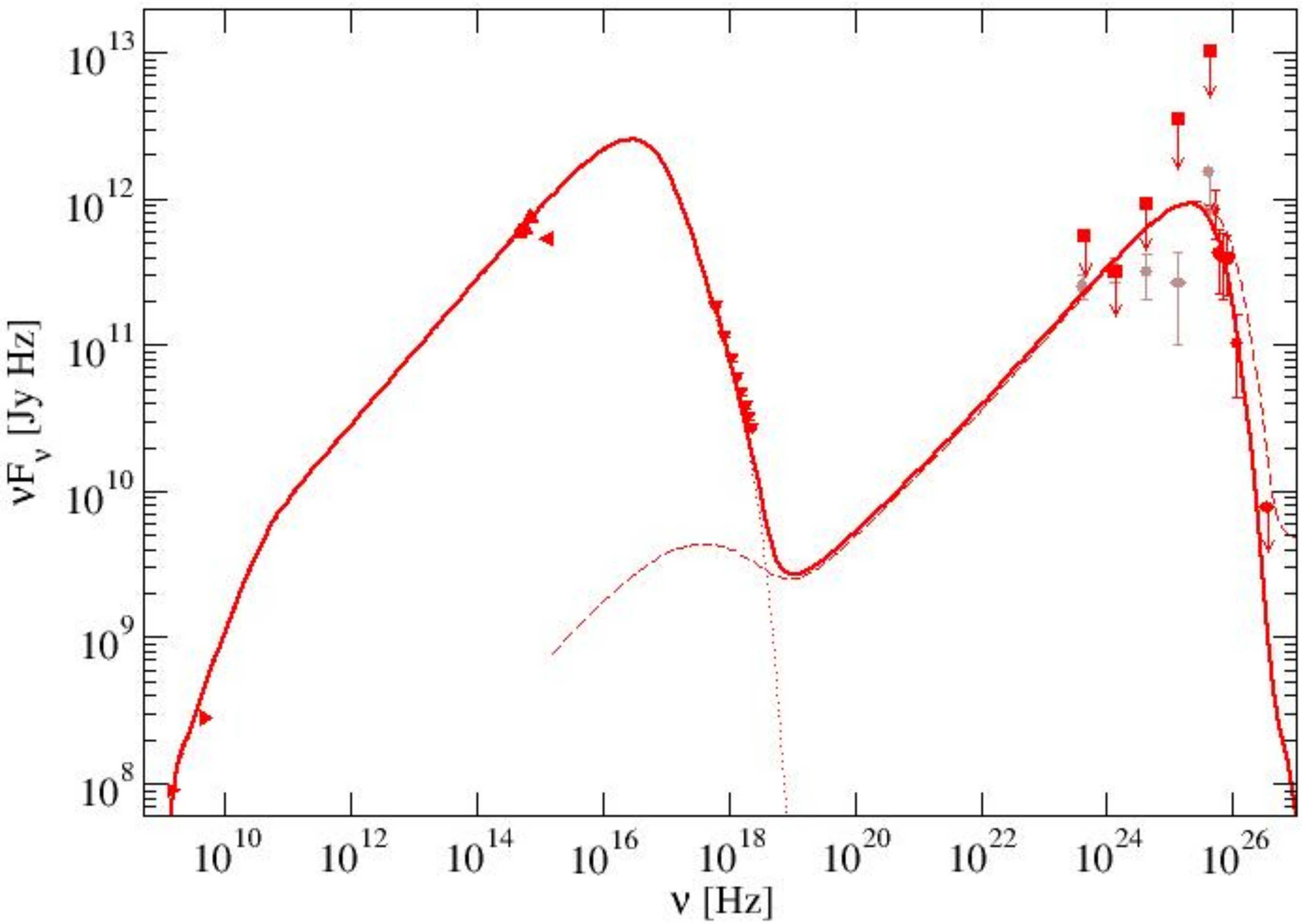
$T_{ext} = 10^3$ K

Good description of entire SED

$L_B/L_e = 41$

HBLs Disfavouring SSC

RX J0648+152



Aliu et al. (2011): in press

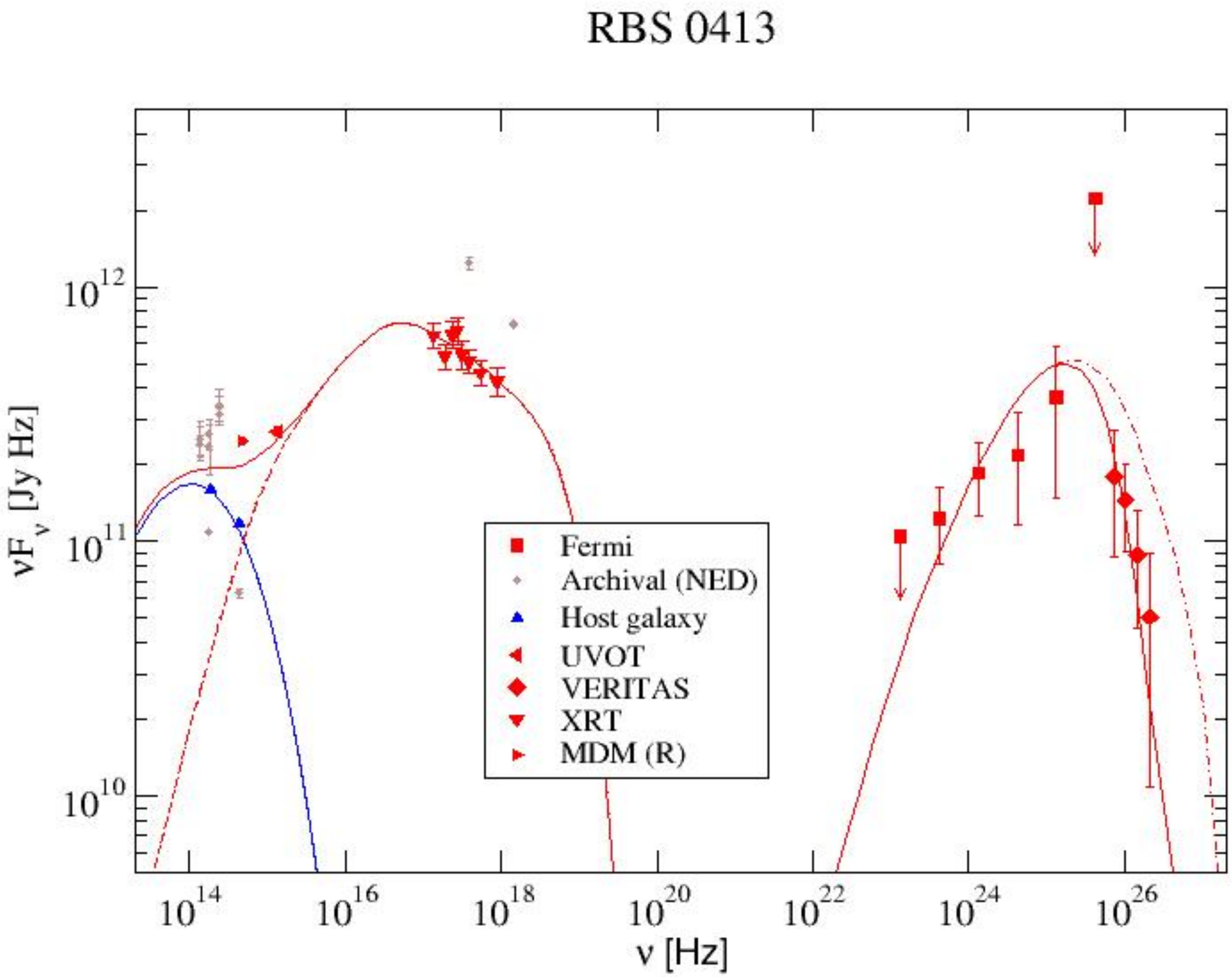
Hadronic:

$L_p = 2*10^{45}$ erg/s
$E_{p,max} = 1.5*10^{19}$ eV

Good description of entire SED

$L_B/L_p = 4.2$

HBLs Disfavouring SSC



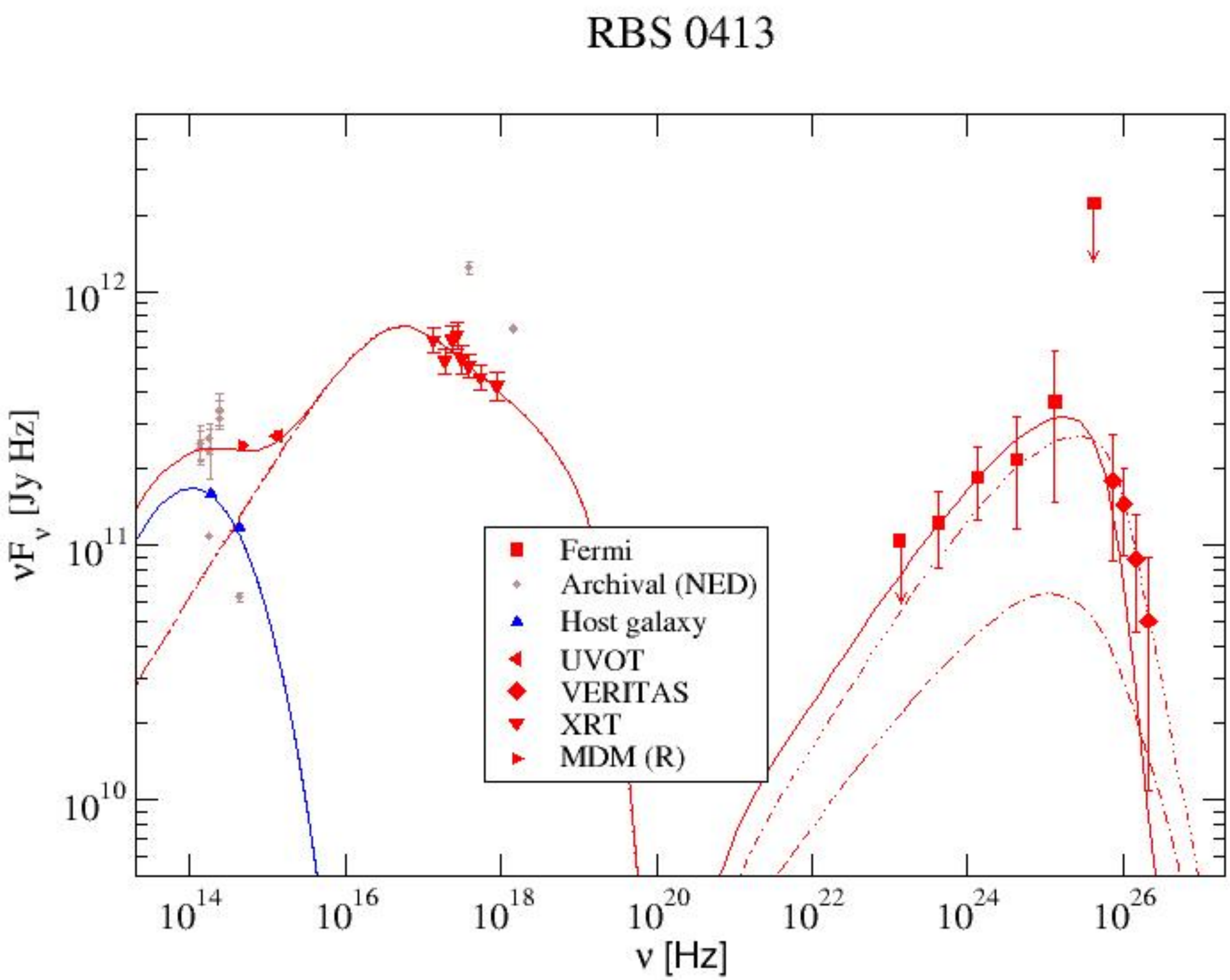
Aliu et al. (2012): in prep.

Pure Leptonic SSC:

Mismatch in Fermi spectral index;

$L_B/L_e = 0.06$

HBLs Disfavouring SSC



Aliu et al. (2012): in prep.

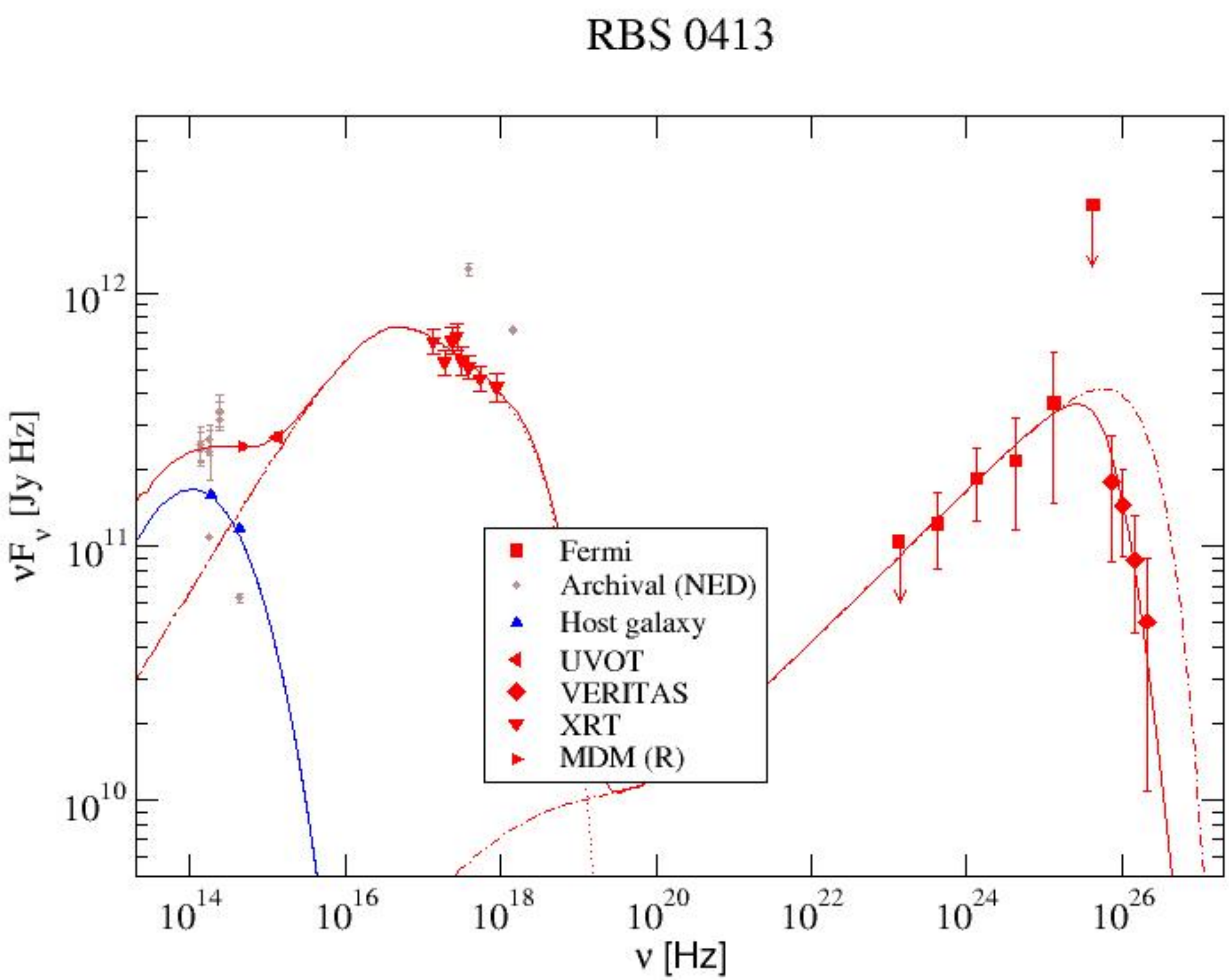
Leptonic SSC + EC:

$T_{ext} = 1.5*10^3$ K

Good description of entire SED

$L_B/L_e = 1.2$

HBLs Disfavouring SSC



Hadronic:

$L_p = 2*10^{46}$ erg/s
$E_{p,max} = 1.6*10^{19}$ eV

Good description of entire SED

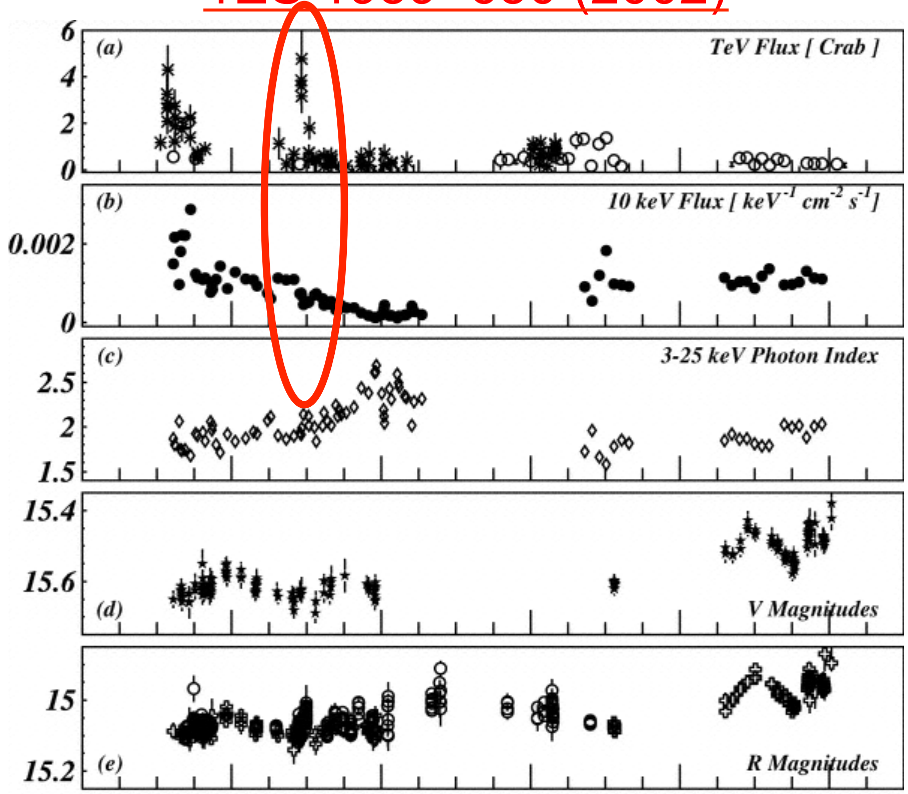
$L_B/L_p = 0.95$

Aliu et al. (2012): in prep.

Problems of spherical, homogeneous models

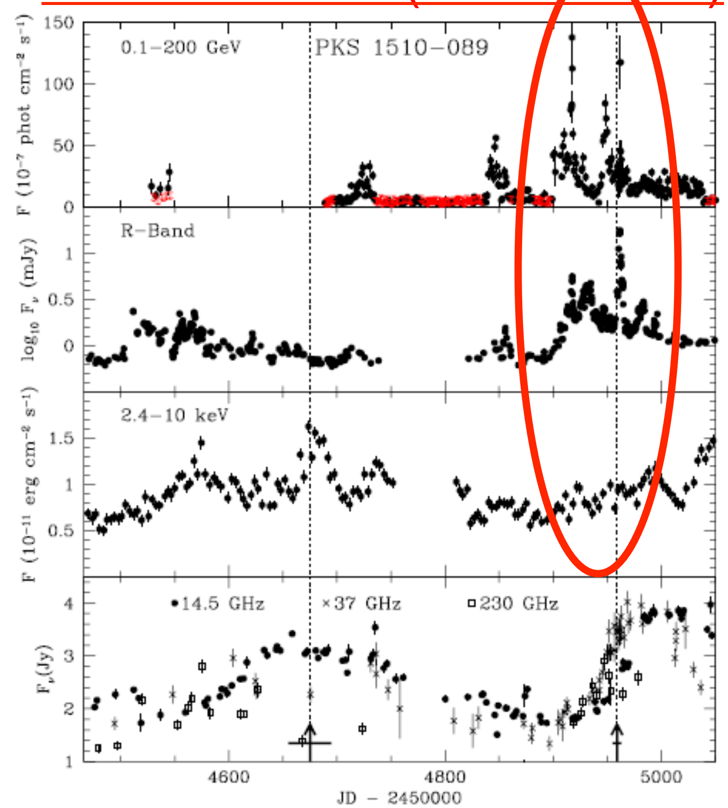
If the entire SED is produced by the same electron population, variability at all frequencies should be well correlated – but …

1ES 1959+650 (2002)



(Krawczynski et al. 2004)

PKS 1510-089 (2008 - 2009)



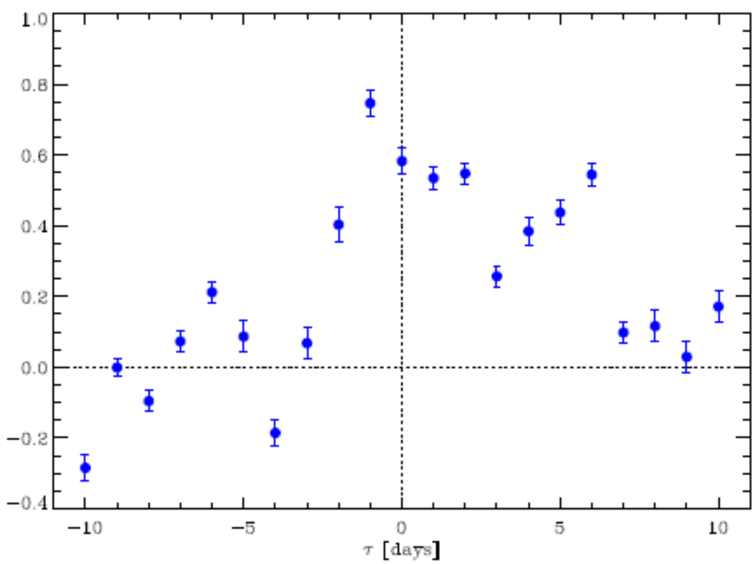
(Marscher al. 2010)

Problems of spherical, homogeneous models

Cross-correlations between frequency bands and time lags do not show a consistent picture

3C454.3 (2007):
AGIIE γ-rays vs. R-band

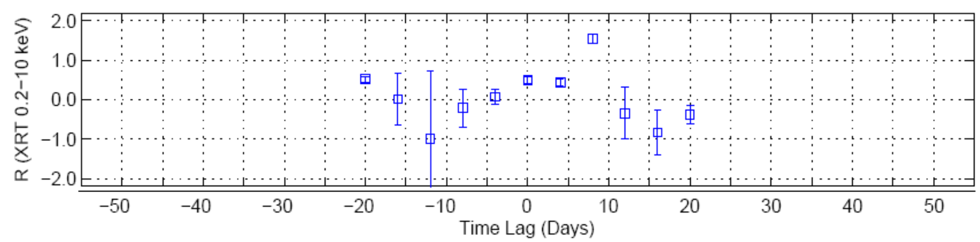
Discrete Correlation Function (DCF)



(Donnarumma et al. 2007)

=> Possible < 1 day delay (hard lag) of γ-rays behind R-band (?)

Markarian 421 (2005 - 2006):
X-rays vs. TeV γ-rays



(Horan et al. 2008)

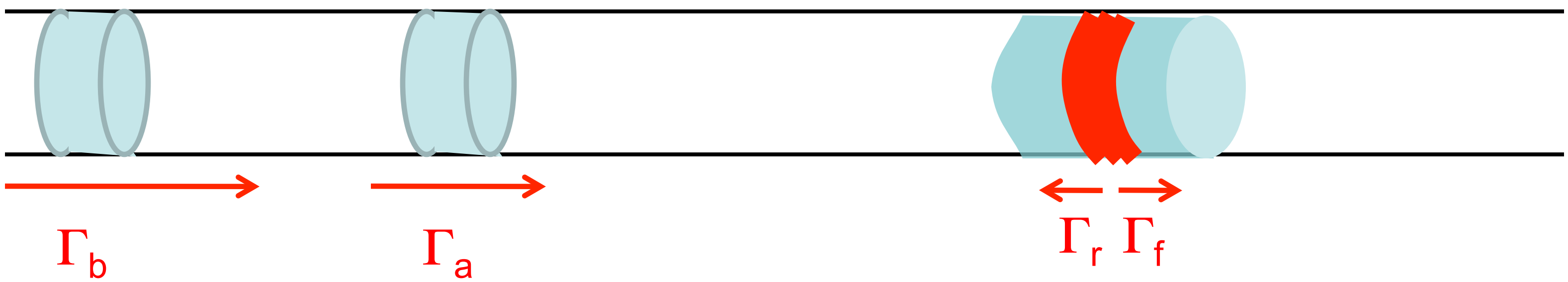
=> (0.2 – 10 keV) X-rays leading the VHE γ-rays by ~ 1 week?

Time lags and spectral hysteresis between different X-ray energies seen with changing sign /direction!

The Internal Shock Model for Blazars

(Böttcher & Dermer 2010)

The central engine ejects two plasmoids (*a,b*) into the jet with different, relativistic speeds (Lorentz factors $\Gamma_b >> \Gamma_a$)



Shock acceleration → Injection of particles with
$Q(\gamma) = Q_0\, \gamma^{-q}$ for $\gamma_1 < \gamma < \gamma_2$

γ_2 from balance of acceleration and radiative cooling rate
γ_1 from normalization to overall energetics

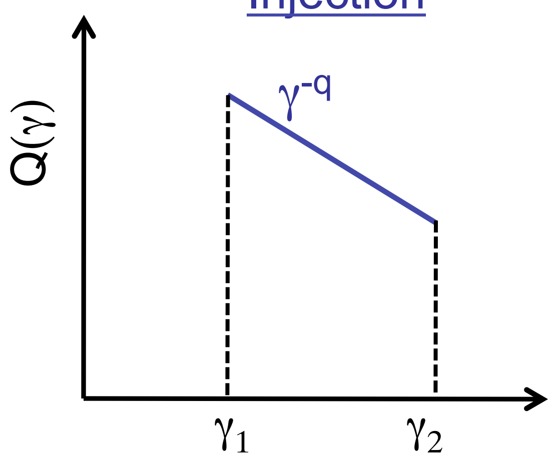
Detailed numerical simulations:
Sokolov et al. (2004), Mimica et al. (2004), Sokolov & Marscher (2005), Graff et al. (2008), Joshi & Böttcher (2011)

Time-Dependent Electron Distributions

Competition of injection of a power-law distribution of relativistic electrons with radiative cooling

At any given time $t_{em}(x)$ = time elapsed since the shock has crossed a given point x

Injection

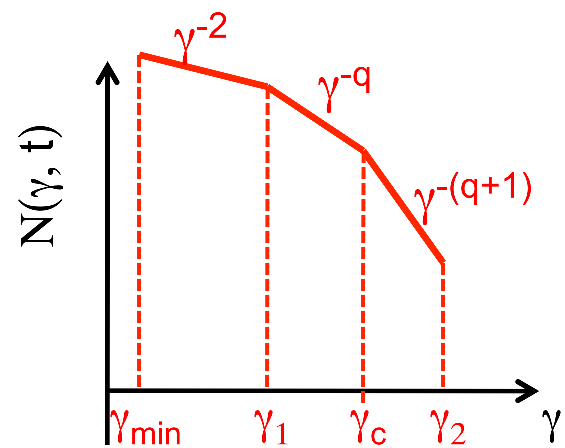


$$d\gamma/dt = -\nu_0 \gamma^2$$

$$\rightarrow \quad t_{cool} = \gamma/|d\gamma/dt| = 1/(\nu_0 \gamma)$$

→ Spectral break at γ_c, where $t_{em}(x) = t_{cool}$

Time-dependent electron distribution:



$$\gamma_{min} = (\gamma_1^{-1} + \nu_0 t)^{-1}$$

Radiation Mechanisms

1) Synchrotron: Delta-Function Approximation

=> $\nu F_\nu^{sy} (t_{obs})$
can be calculated fully analytically!

2) External-Compton: Delta-Function Approximation (Thomson)

+ mono-energetic, isotropic external radiation field

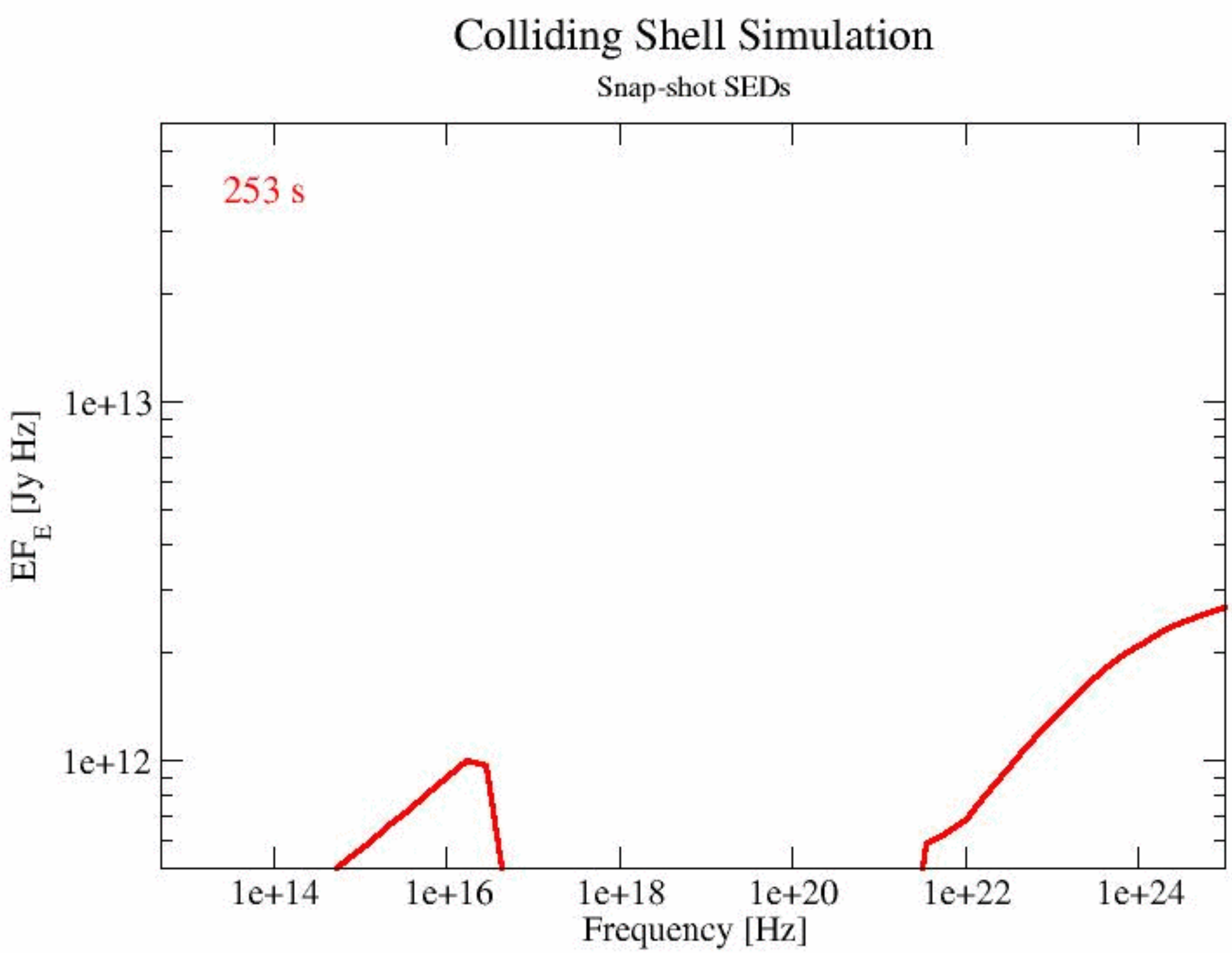
=> $\nu F_\nu^{EC} (t_{obs})$
can be calculated fully analytically!

3) Synchrotron-Self Compton: Delta-Function Approximation (Thomson)

=> Two integrations to be done numerically.

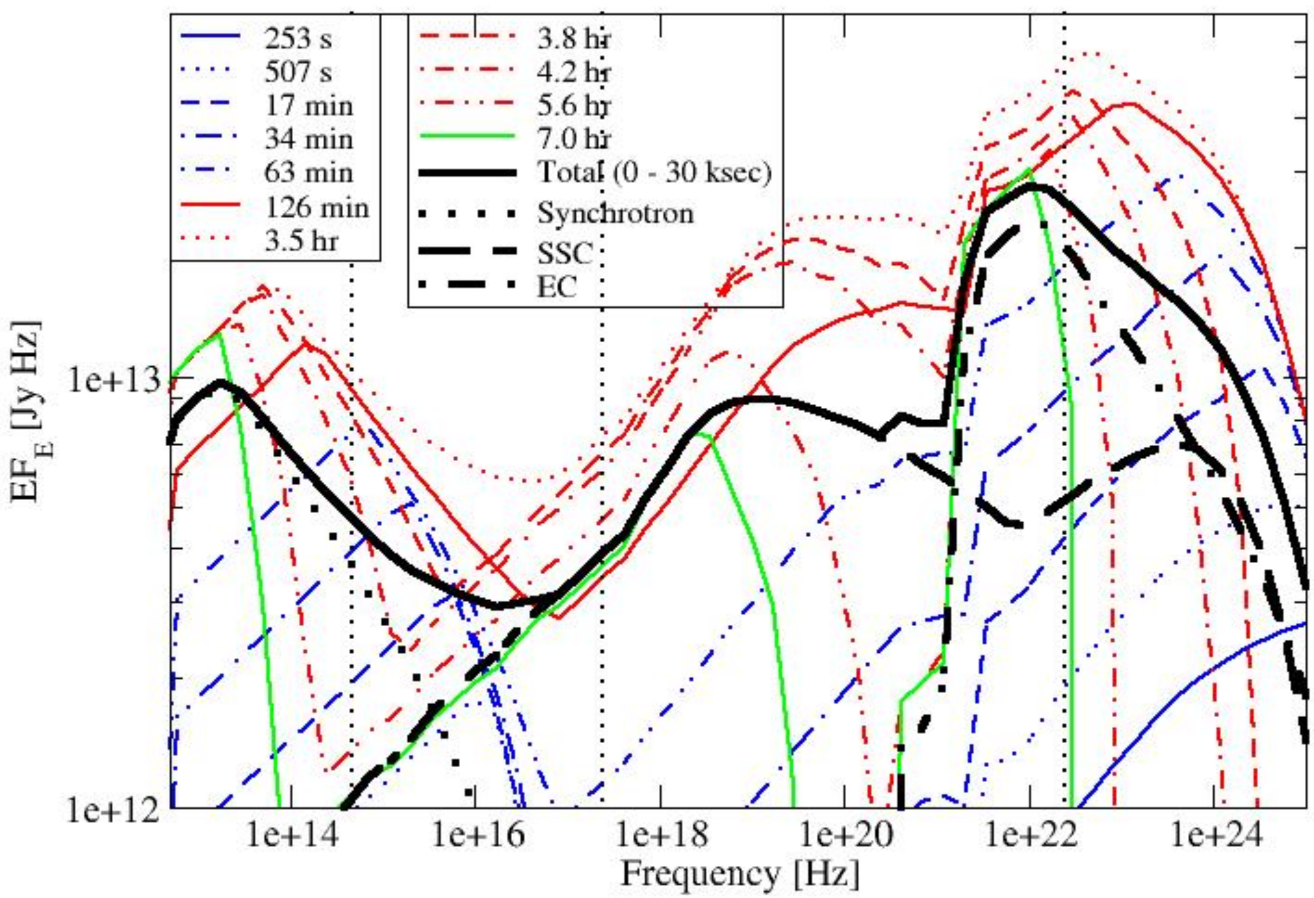
Baseline Model

Parameters / SED characteristics typical of FSRQs or LBLs



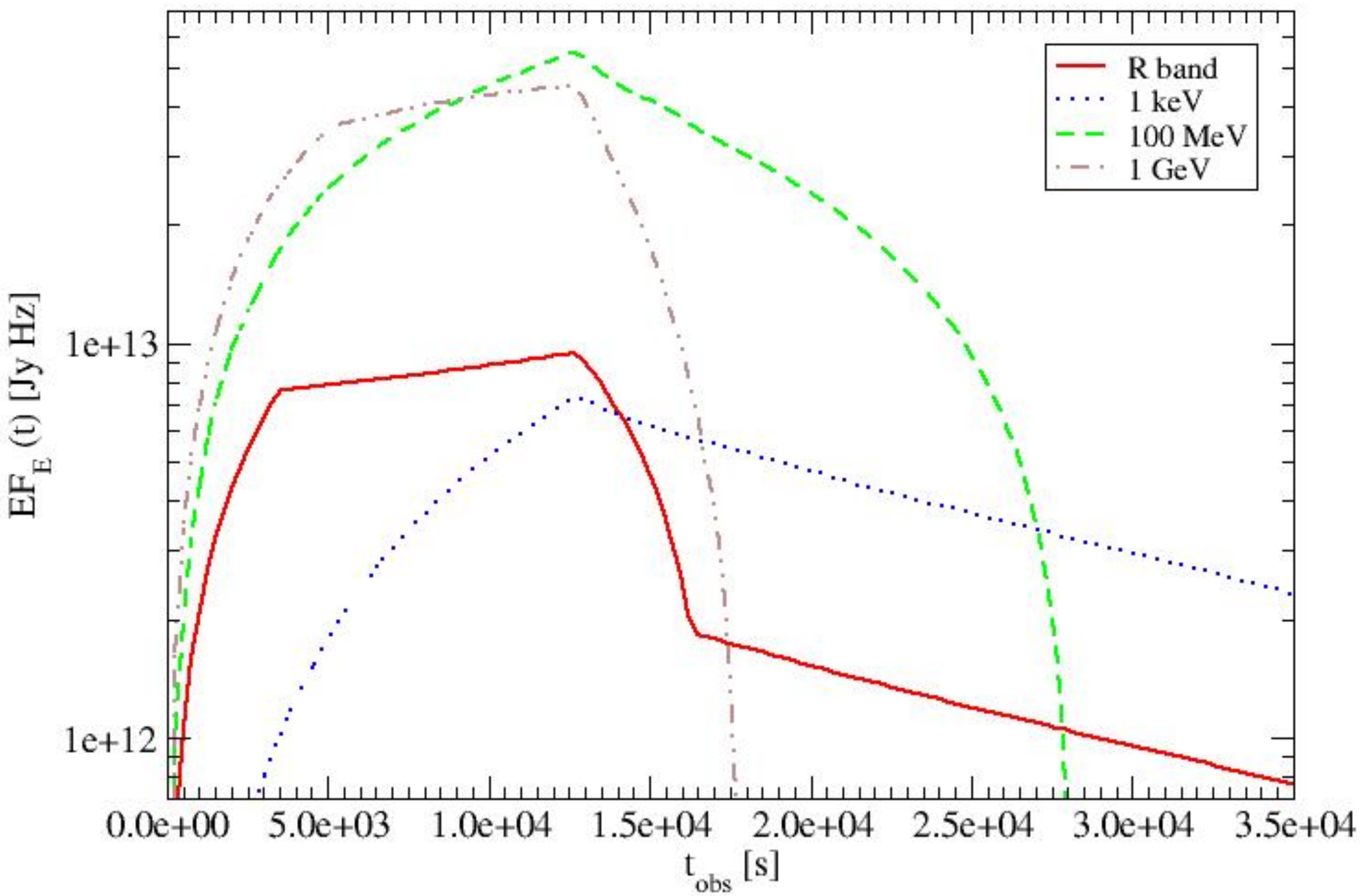
Baseline Model

Snap-shot SEDs and time-averaged SED over 30 ksec



Baseline Model

Light Curves

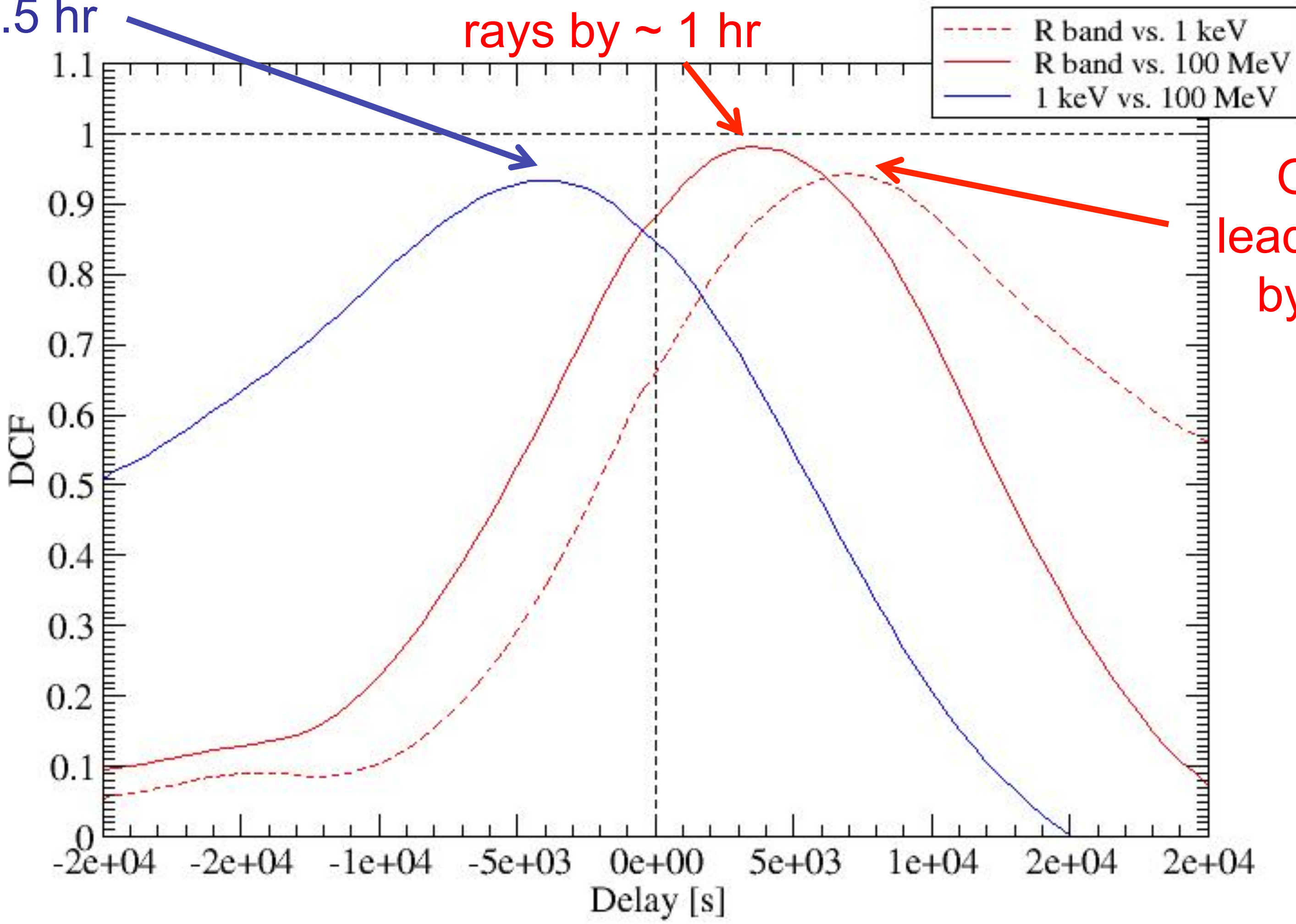


Baseline Model

Discrete Correlation Functions

X-rays lag behind HE γ-rays by ~ 1.5 hr

Optical leads HE γ-rays by ~ 1 hr

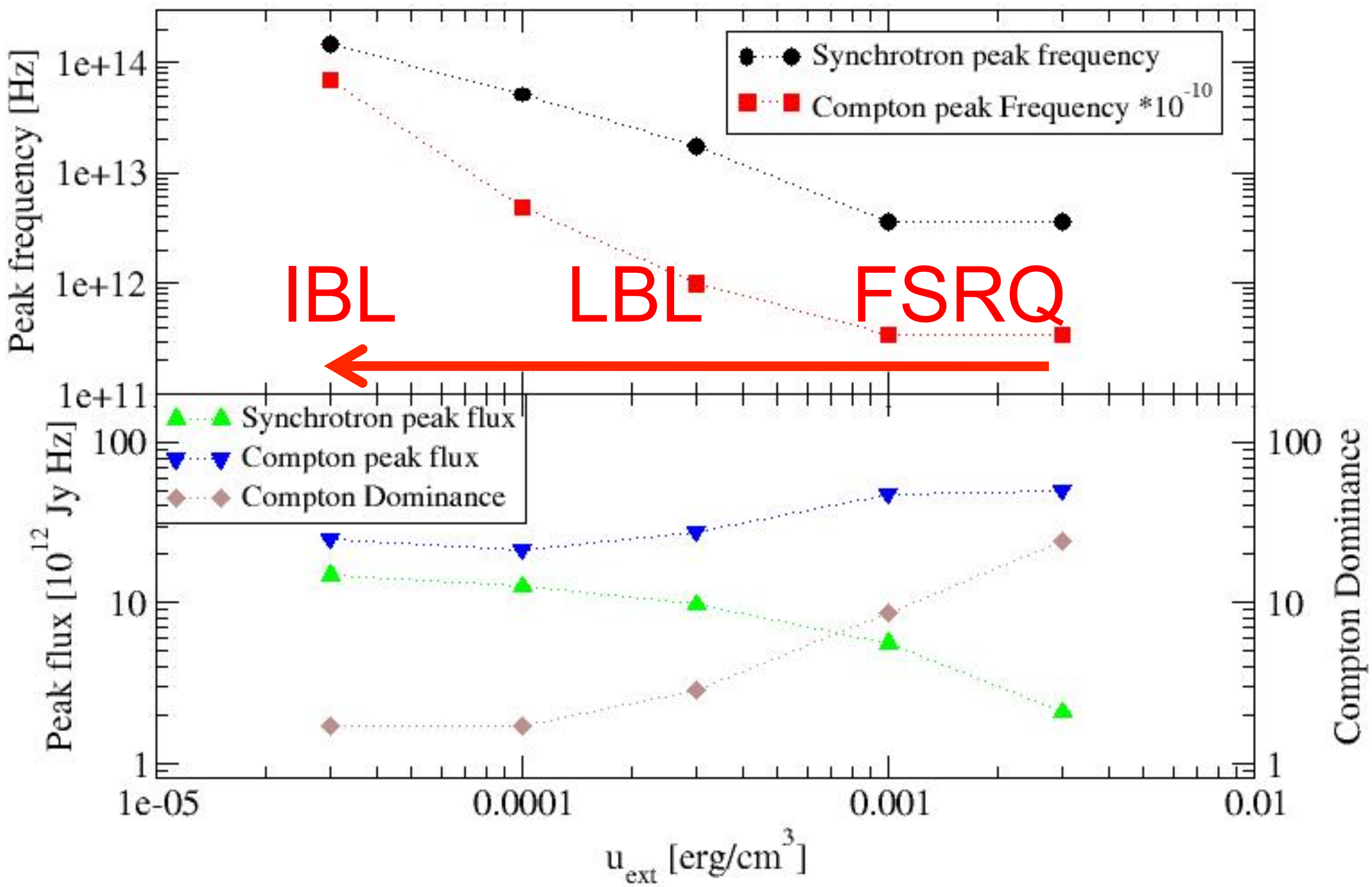


Optical leads X-rays by ~ 2 hr

Parameter Study

Varying the External Radiation Energy Density

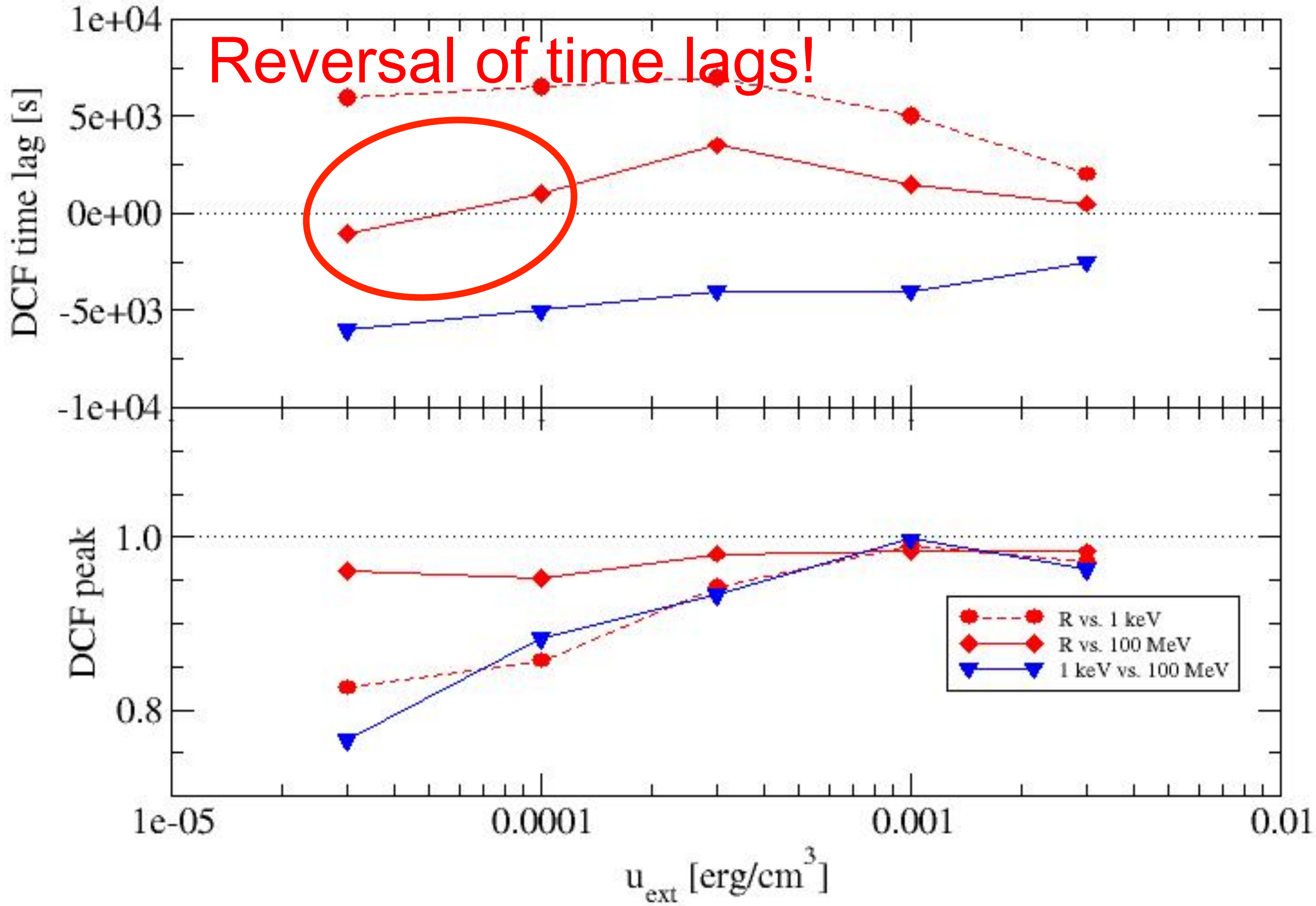
SED Characteristics



Parameter Study

Varying the External Radiation Energy Density

DCFs / Time Lags



Summary

1. Leptonic models generally allow for successful models for all classes of blazars, with increasing external-Compton dominance along the sequence from HBL → IBL → LBL → FSRQ.

2. Even IBLs seem to require external (IR) radiation fields → γ-ray emission at > pc scales?

3. Some VHE HBLs disfavour pure SSC.

4. Lepto-hadronic models provide successful SED fits to many VHE blazars, but rapid variability is hard to explain.

5. Semi-analytical internal-shock model can be used to predict inter-band time lags: Slight parameter variations can lead to reversal of time lags.

Written by a carefully selected consortium of researchers working in the field, this book provides an up-to-date summary of the current observational and theoretical understanding of relativistic jets, focusing on jets from active galactic nuclei. As such, this monograph includes a history and theory refresher, an overview of observational results from all wavelengths, from radio to gamma-rays, analytical and numerical theoretical results, and a description of current research topics.

From the contents:

- Introduction and Historical Perspective
- Special Relativity of Jets
- Radiation Processes
- Central Engines, Acceleration, Collimation and Confinement of Jets
- Observational Details: Radio
- Optical, Infrared and UV Observations
- Observational Details: X-rays
- Unresolved Emission from the Core: Observations and Models
- Particle Acceleration in Turbulent Magnetohydrodynamic Shocks
- Simulations of Jets from Active Galactic Nuclei and Gamma-ray bursts
- Jet Structure, Collimation and Stability – Recent Results from Analytical Methods and Simulations
- Jets and AGN Feedback

Markus Boettcher obtained his PhD at the University of Bonn and the Max Planck Institute for Radio Astronomy in Bonn, Germany. Postdoctoral positions included stays at Rice University, Houston, TX, and with the U.S. Naval Research Lab. in Washington, DC. Since 2002 he is holding a professorship at Ohio University. His Research interests are active galactic nuclei, galactic black-hole candidates and gamma-ray bursts.

D. E. Harris received his PhD from the California Institute of Technology in 1961. For the following twenty years he held research positions at a number of radio observatories in Europe, Canada, Puerto Rico, and South America. Since 1980 he has been with the High Energy Division of the Center for Astrophysics, Cambridge, Massachusetts. His field of investigation is non-thermal processes in extragalactic sources, involving radio and X-ray analyses of galaxies and quasars.

Henric Krawczynski is a Physics professor at Washington University in St. Louis. He obtained his PhD at the University of Hamburg, Germany, and worked at the Max-Planck-Institute for Nuclear Physics and at Yale University as post-doctoral researcher before joining Washington University in 2002. His research includes the development of X-ray and γ-ray telescopes and the analysis and interpretation of X-ray and γ-ray observations of galactic and extragalactic black holes, galaxies and galaxy clusters.

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Relativistic Jets from Active Galactic Nuclei