OHIO UNIVERSITY

DEPARTMENT OF Physics & Astronomy @OHIO UNIVERSITY

Models for the Spectral Energy Distributions and Variability of Blazars

Markus Böttcher

Ohio University, Athens, OH, USA

ASTROPHYSICAL INSTITUTE

OHIO UNIVERSITY

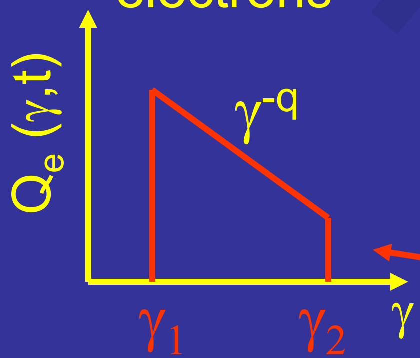
Fermi Meets Jansky
Bonn, Germany, June 21, 2010

Outline:

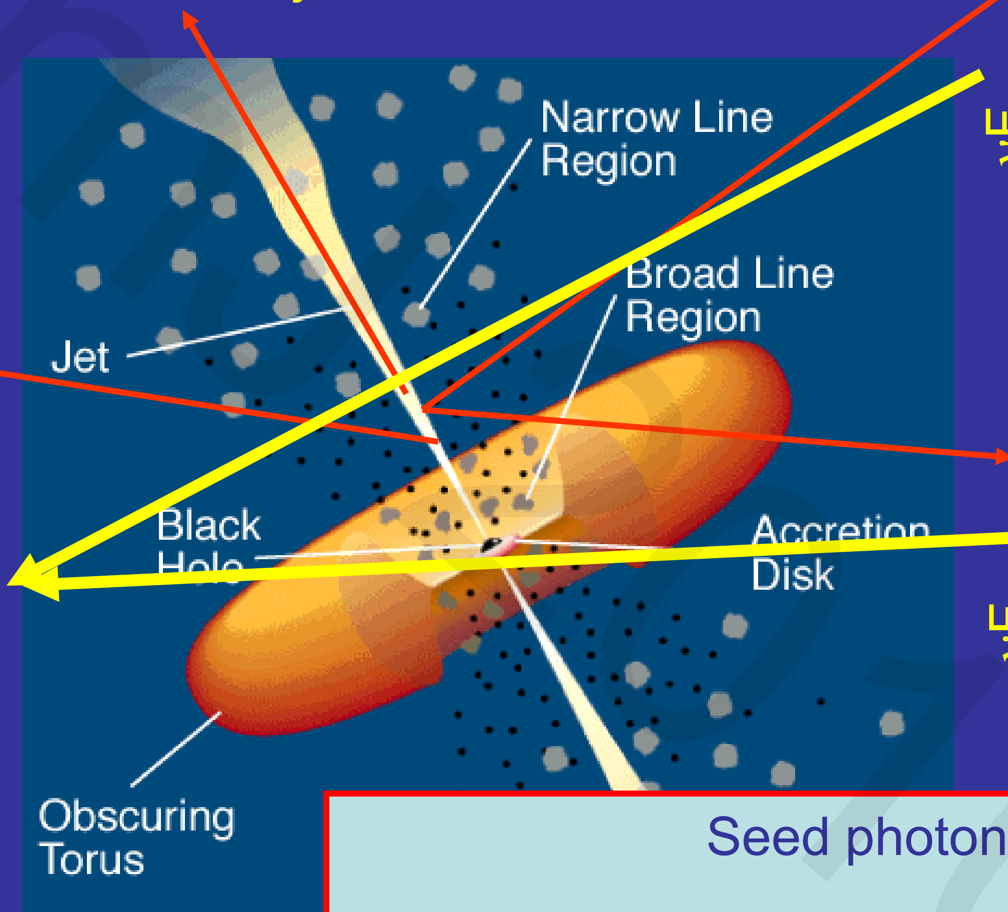
1) Introduction to leptonic and lepto-hadronic blazar models
2) Modeling results along the blazar sequence
3) Redshift constraints from blazar SED modeling
4) Inhomogeneous, time-dependent blazar models

Leptonic Blazar Model

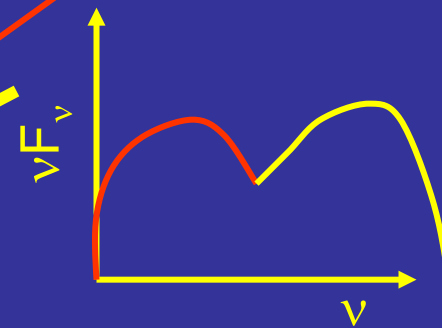
Injection, acceleration of ultrarelativistic electrons



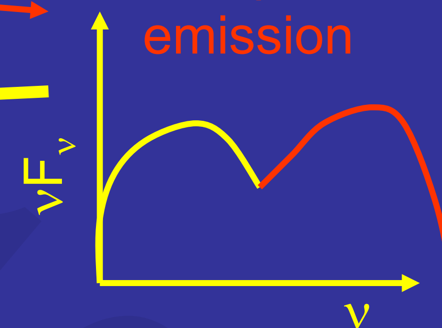
Relativistic jet outflow with $\Gamma \approx 10$



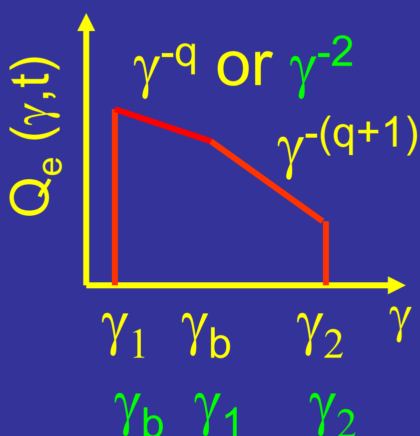
Synchrotron emission



Compton emission



Radiative cooling $\leftrightarrow$ 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

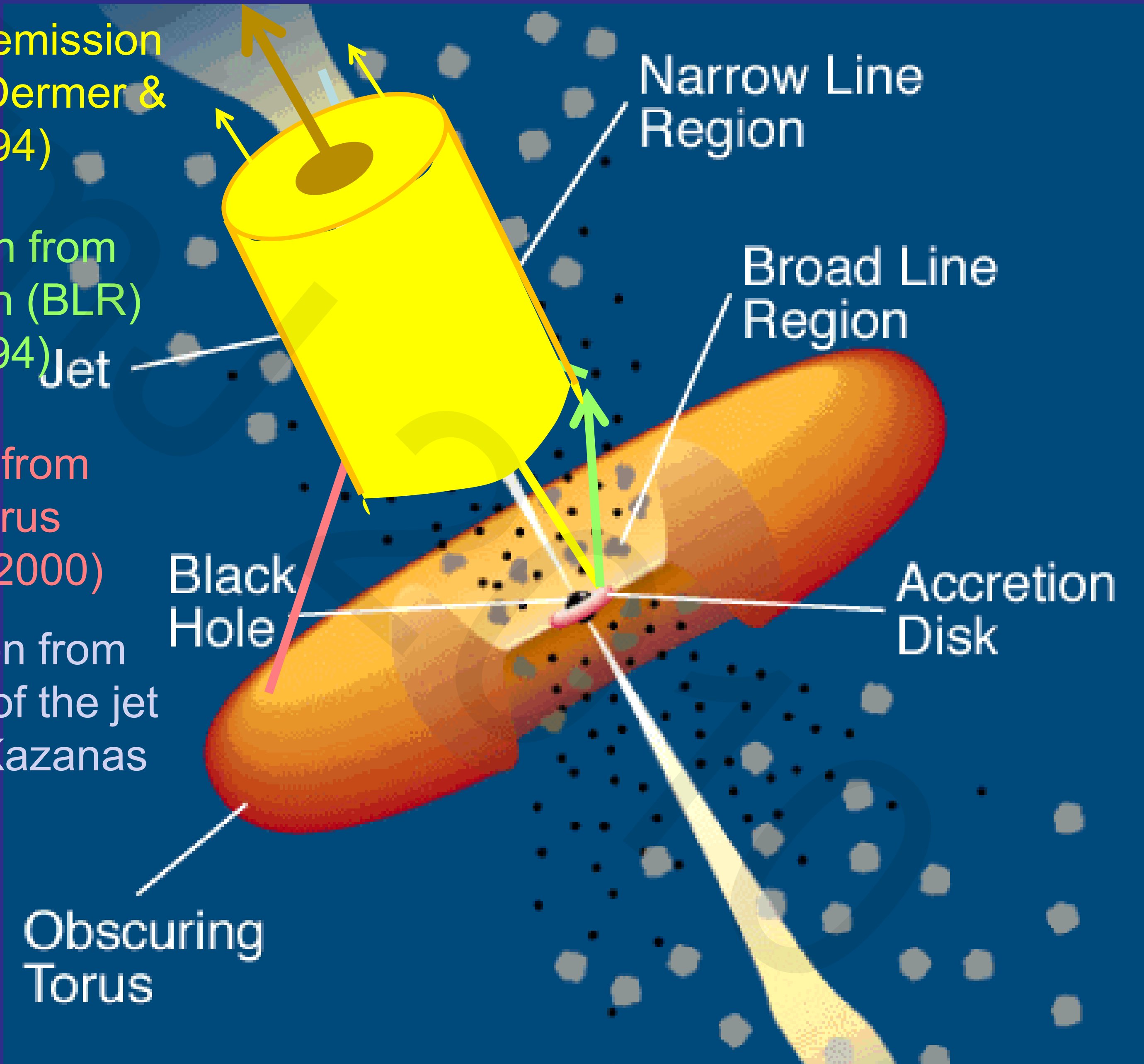
Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)

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

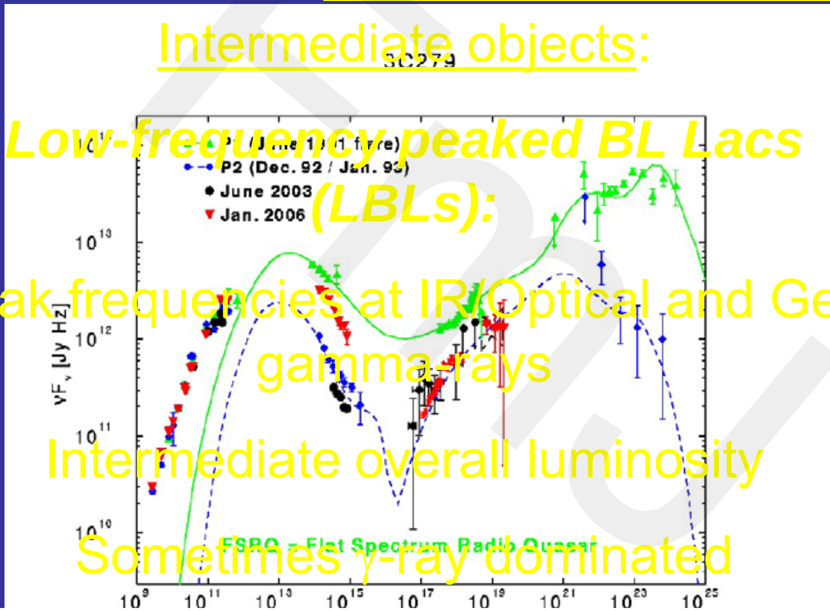
Intermediate objects:

Low-frequency peaked BL Lacs (LBLs):

Peak frequencies at IR/Optical and GeV gamma-rays

Intermediate overall luminosity

Sometimes γ-ray dominated

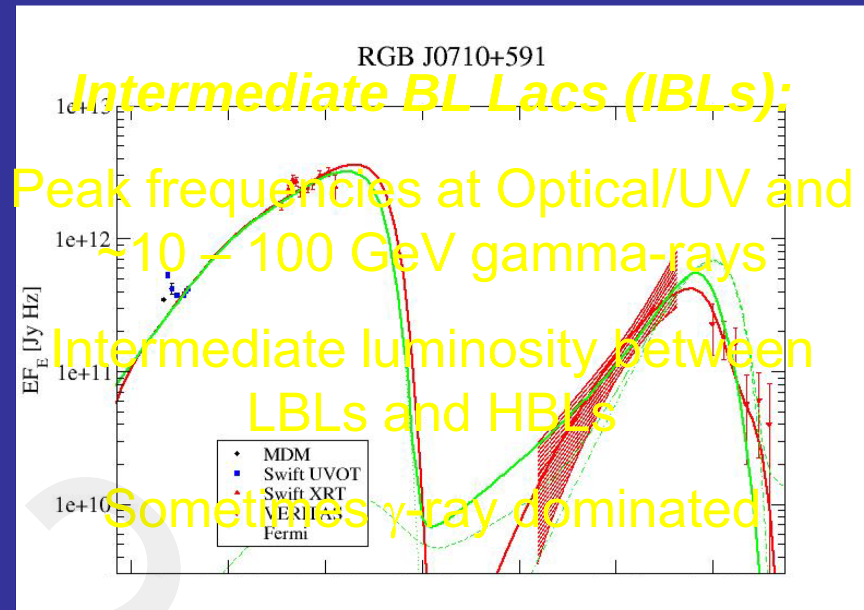


Intermediate BL Lacs (IBLs):

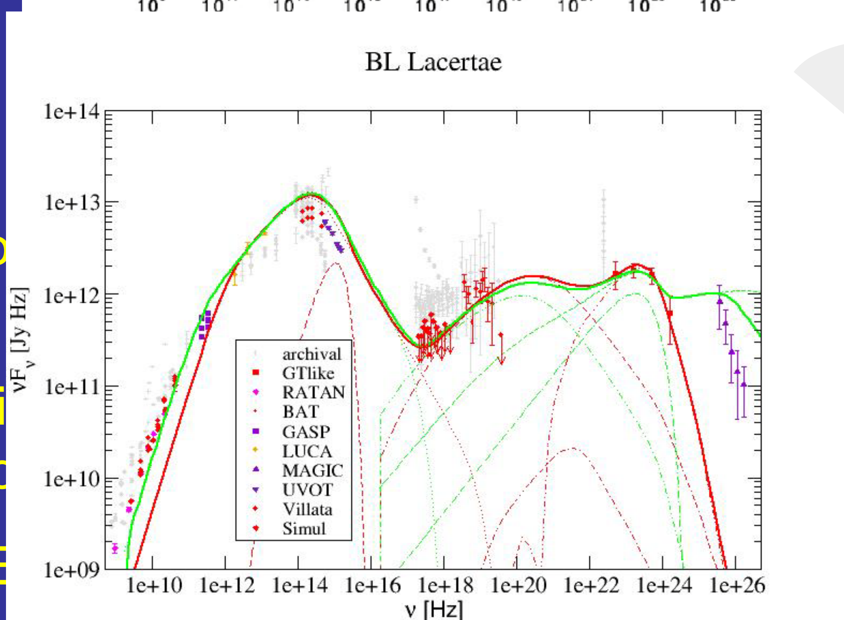
Peak frequencies at Optical/UV and ~10 – 100 GeV gamma-rays

Intermediate luminosity between LBLs and HBLs

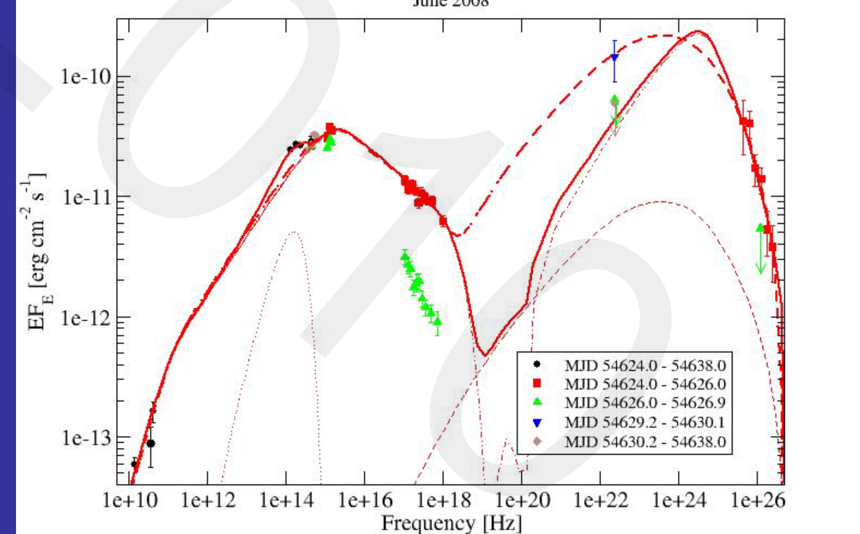
Sometimes γ-ray dominated



(Acciari et al. 2010)



(Abdo et al. 2010)



(Acciari et al. 2009)

Lo ... to

Hi ... ys

to ... r

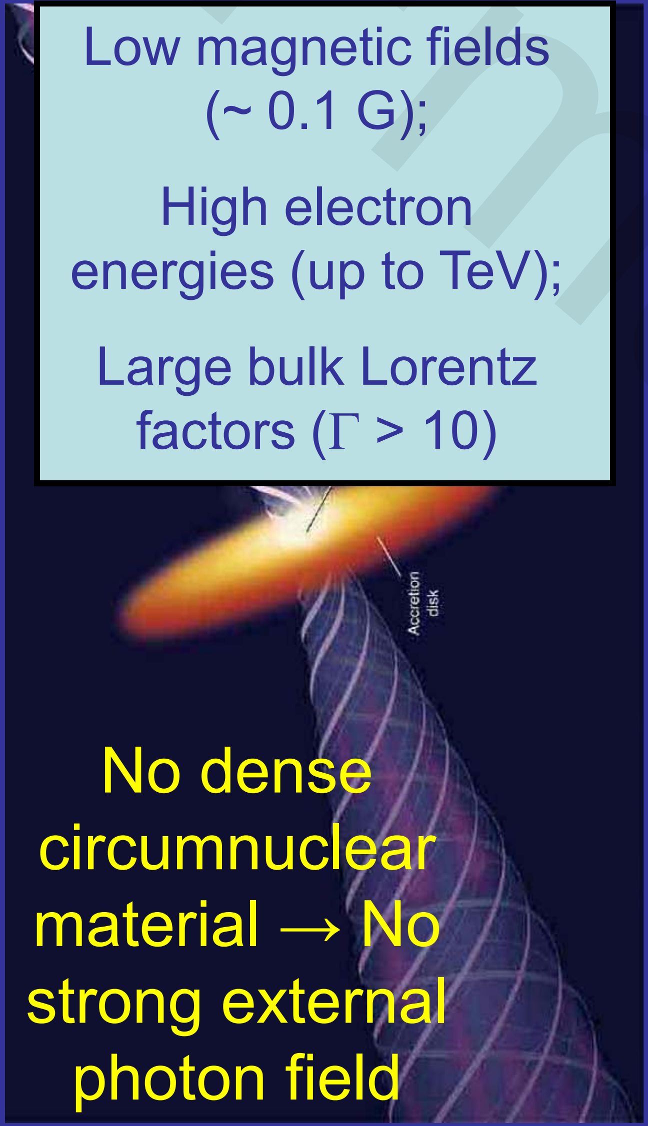
SE ... ys

Spectral modeling results along the Blazar Sequence: Leptonic Models

Low magnetic fields (~ 0.1 G);

High electron energies (up to TeV);

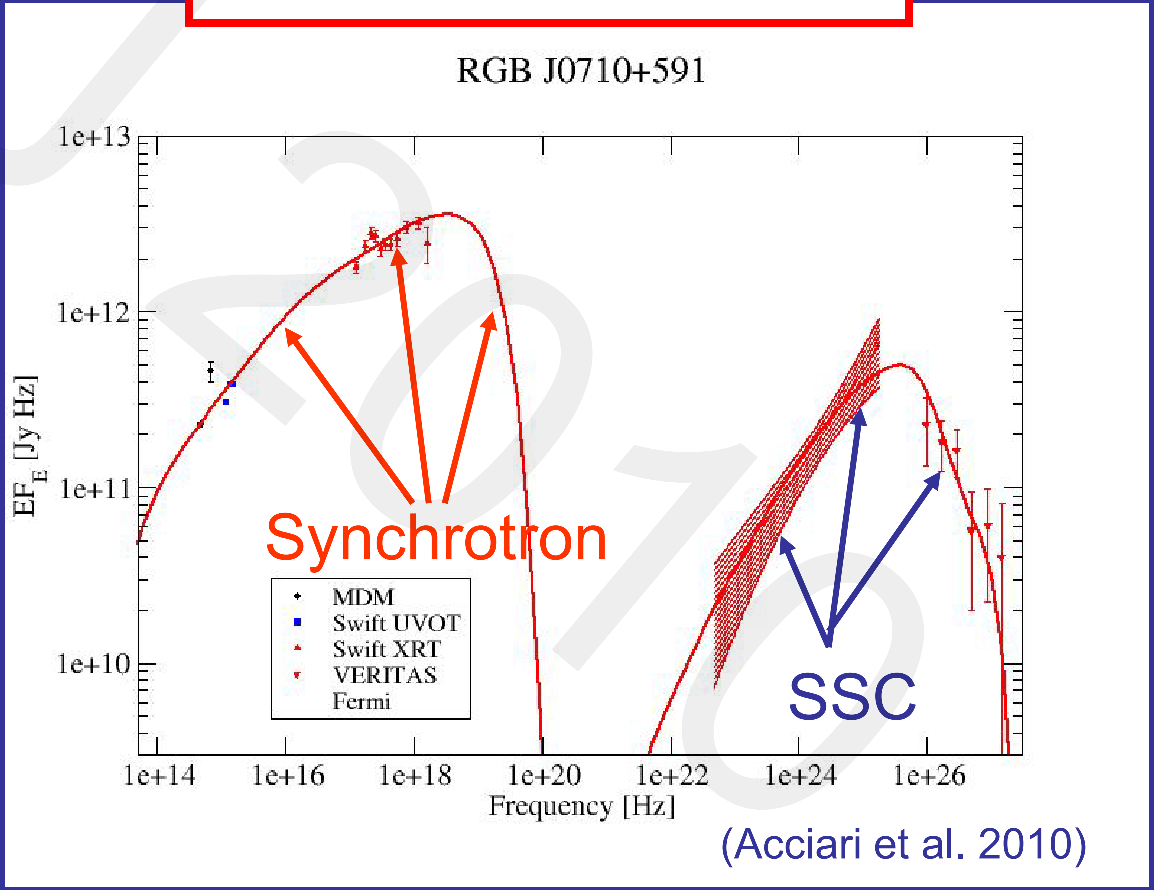
Large bulk Lorentz factors (Γ > 10)



No dense circumnuclear material → No strong external photon field

High-frequency peaked BL Lac (HBL):

The "classical" picture



(Acciari et al. 2010)

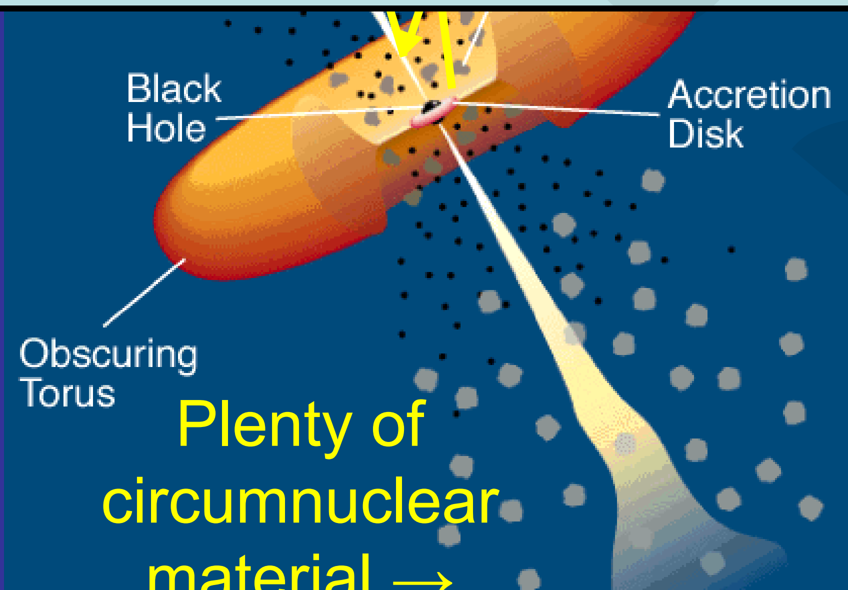
Spectral modeling results along the Blazar Sequence: Leptonic Models

High magnetic fields (~ a few G);

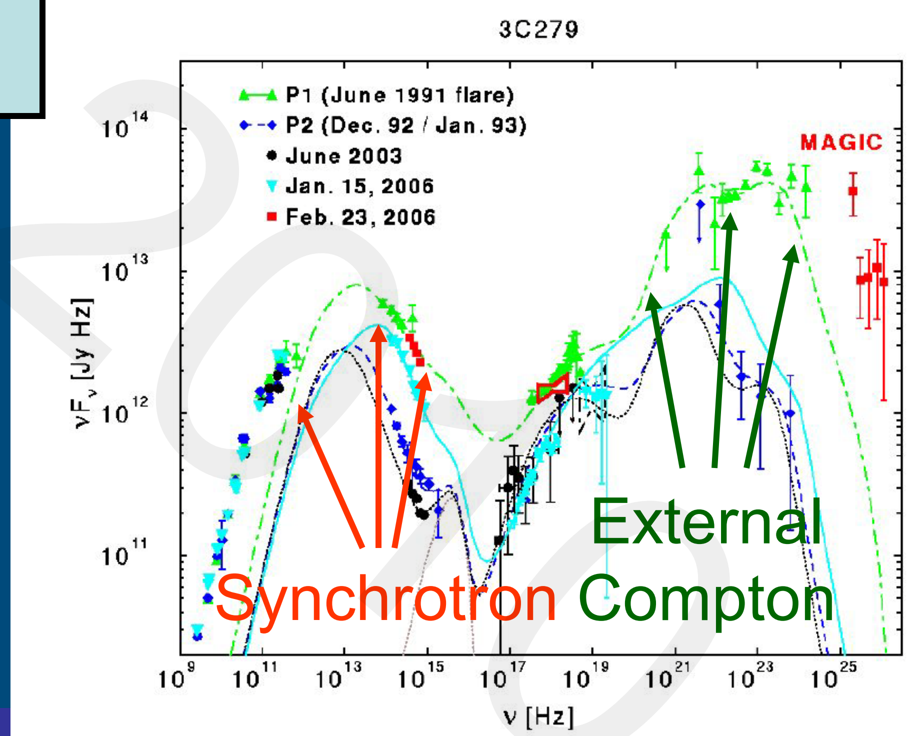
Lower electron energies (up to GeV);

Lower bulk Lorentz factors ($\Gamma \sim 10$)

Radio Quasar (FSRQ)



Plenty of circumnuclear material → Strong external photon field



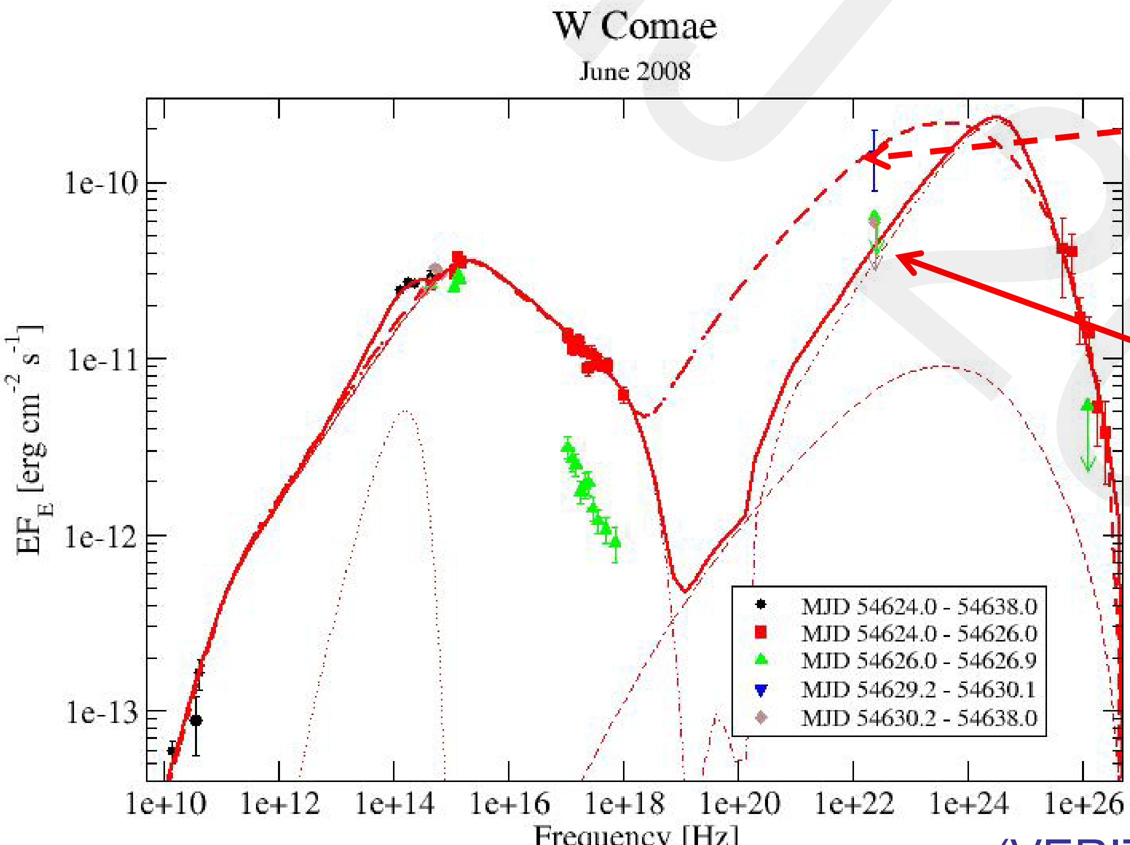
Intermediate BL Lacs: W Comae

Major VHE γ-ray flare detected by VERITAS in June 2008.

Pure SSC requies far sub-equipartition B-field.

Fit with EC from IR radiation field yields more plausible parameters.

High flux state on MJD 54624



SSC fit:

B = 0.24 G

$L_B/L_e = 2.3 \cdot 10^{-3}$

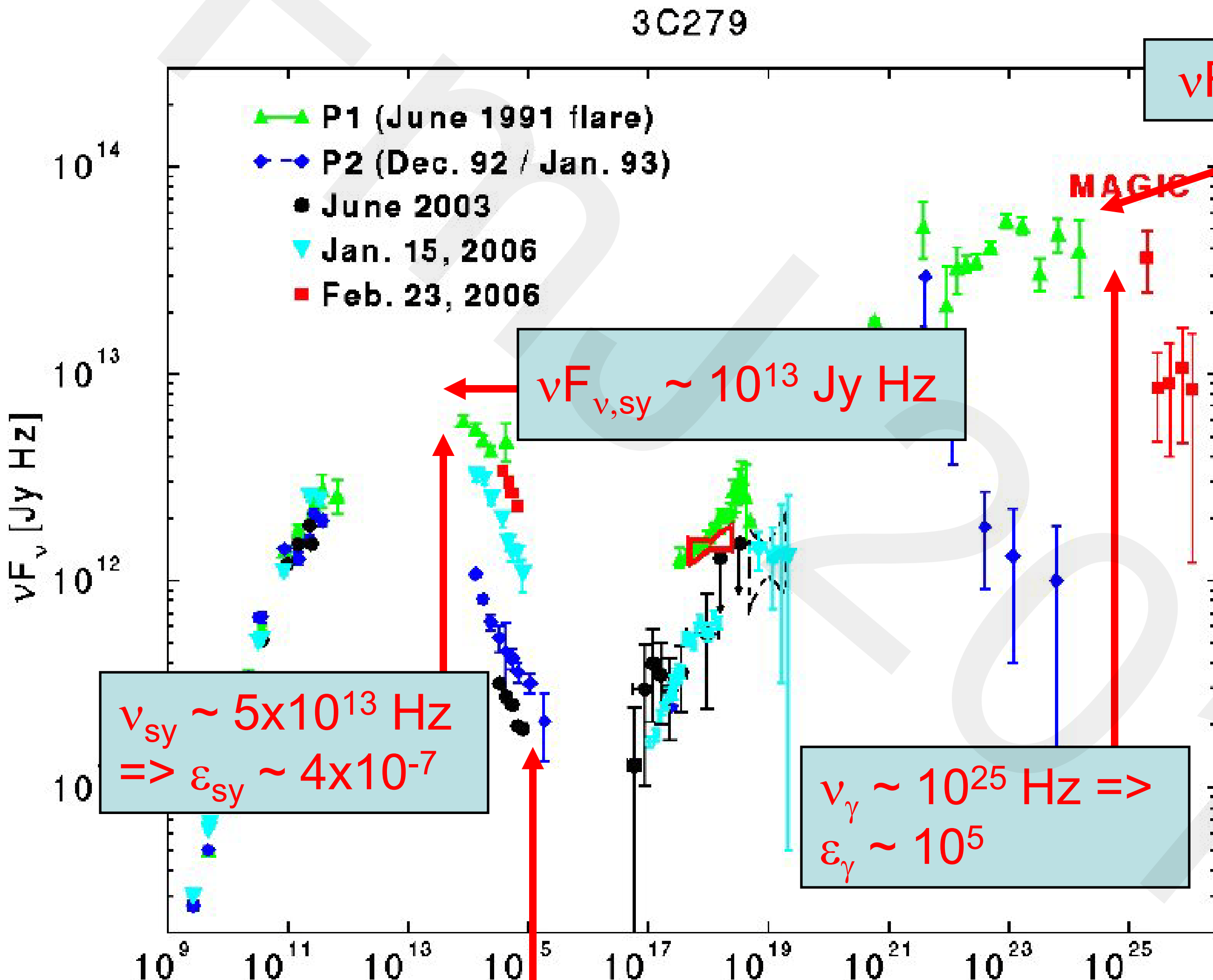
EC fit:

B = 0.35 G

$L_B/L_e = 0.32$

(VERITAS: Acciari et al. 2009)

The Quasar 3C279 on Feb. 23, 2006



$\nu F_{\nu,\gamma} \sim 5\times10^{13}$ Jy Hz

$\nu F_{\nu,sy} \sim 10^{13}$ Jy Hz

$\nu_{sy} \sim 5\times10^{13}$ Hz => $\varepsilon_{sy} \sim 4\times10^{-7}$

$\nu_\gamma \sim 10^{25}$ Hz => $\varepsilon_\gamma \sim 10^5$

Accretion disk: $L_D \sim 2\times10^{45}$ erg/s; $\varepsilon_D \sim 10^{-5}$

Feb. 23:

- High optical flux
- Steep optical spectrum (α = 1.7 -> p = 4.4)
- High X-ray flux
- Soft X-ray spectrum

Parameter Estimates: SSC

- Optical index α = 1.7 => p = 4.4 => cooling break (3.4 -> 4.4) would not produce a νF_ν peak => peak must be related to low-energy cutoff, $\gamma_p = \gamma_1$

- Separation of synchrotron and gamma-ray peak

  => $\gamma_p = (\varepsilon_\gamma/\varepsilon_{sy})^{1/2} \sim 1.6 \times 10^5$

- $\nu_{sy} = 4.2 \times 10^6 \, \gamma_p^2 \, B_G \, D/(1+z)$ Hz

  => $\mathbf{B_G \, D_1 \sim 7 \times 10^{-5}}$

Parameter Estimates: External Compton

- External photons of $\epsilon_s \sim 10^{-5}$ can be Thomson scattered up to $\epsilon_\gamma \sim 10^5$ => Accretion disk photons can be source photon field.
- Location of gamma-ray peak

  => $\gamma_p = (\epsilon_\gamma/[\Gamma^2 \epsilon_s])^{1/2} \sim 10^4\ \Gamma_1^{-1}$
- $\nu_{sy} = 4.2\text{x}10^6\ \gamma_p^{\ 2}\ B_G\ D/(1+z)$ Hz

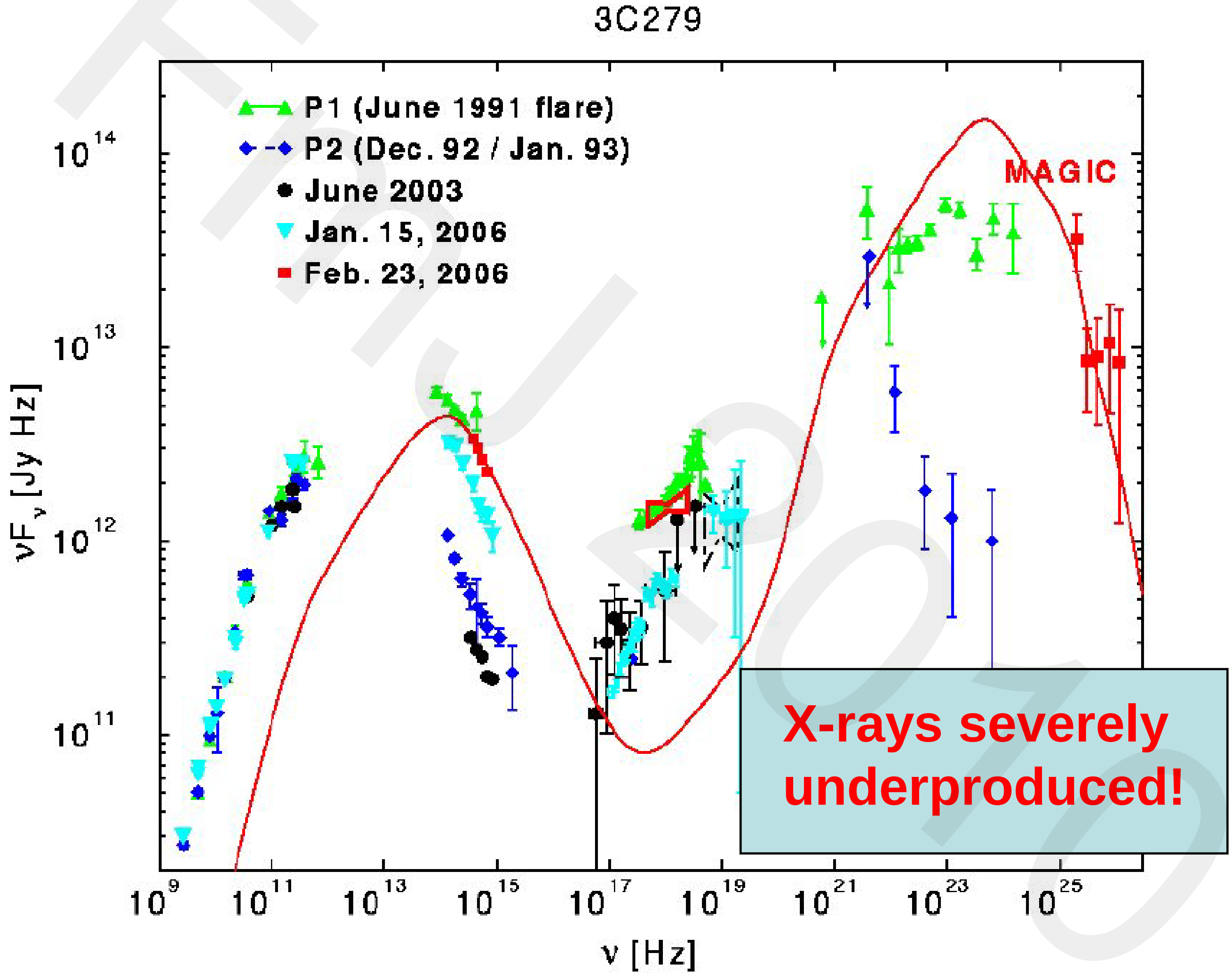
  => $B_G \sim 1.8\text{x}10^{-2}\ \Gamma_1^{\ 2}\ D_1^{\ -1}$
- Relate synchrotron flux level to electron energy density, $e_B = u'_B/u'_e$

  => $e_B \sim 10^{-8}\ \Gamma_1^{\ 7}\ R_{16}^{\ \ 3}$

a) $\Gamma \sim 15$, B ~ 0.03 G, $e_B \sim 10^{-7}$

b) $e_B \sim 1$, B ~ 0.25 G, $\Gamma \sim 140\ R_{16}^{\ -3/7}$

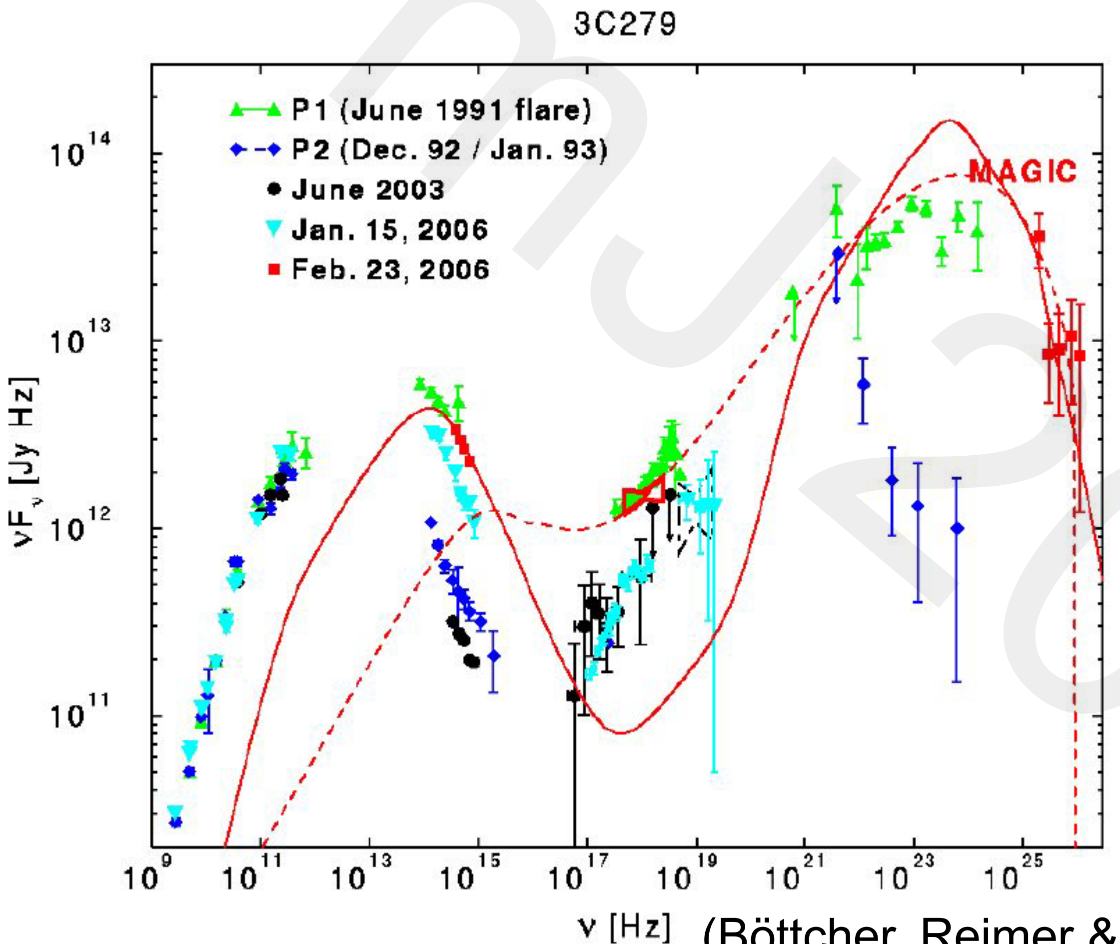
Attempted leptonic one-zone model fit, EC dominated



(Böttcher, Reimer & Marscher 2009)

Alternative: Multi-zone leptonic model

X-ray through gamma-ray spectrum reproduced by SSC; optical spectrum has to be produced in a different part of the jet.



(Böttcher, Reimer & Marscher 2009)

$L_{inj} = 2.3*10^{49}$ erg/s

$\gamma_{min} = 10^4$

$\gamma_{max} = 10^6$

$q = 2.3$

$B = 0.2$ G

$\Gamma = D = 20$

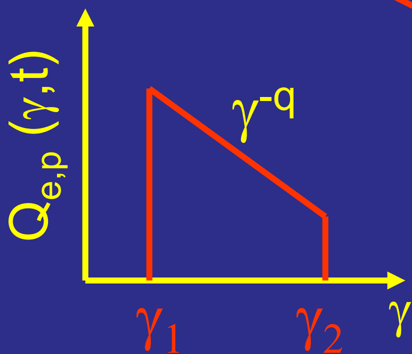
$R_B = 6*10^{15}$ cm

$u'_B/u'_e = 2.5*10^{-4}$

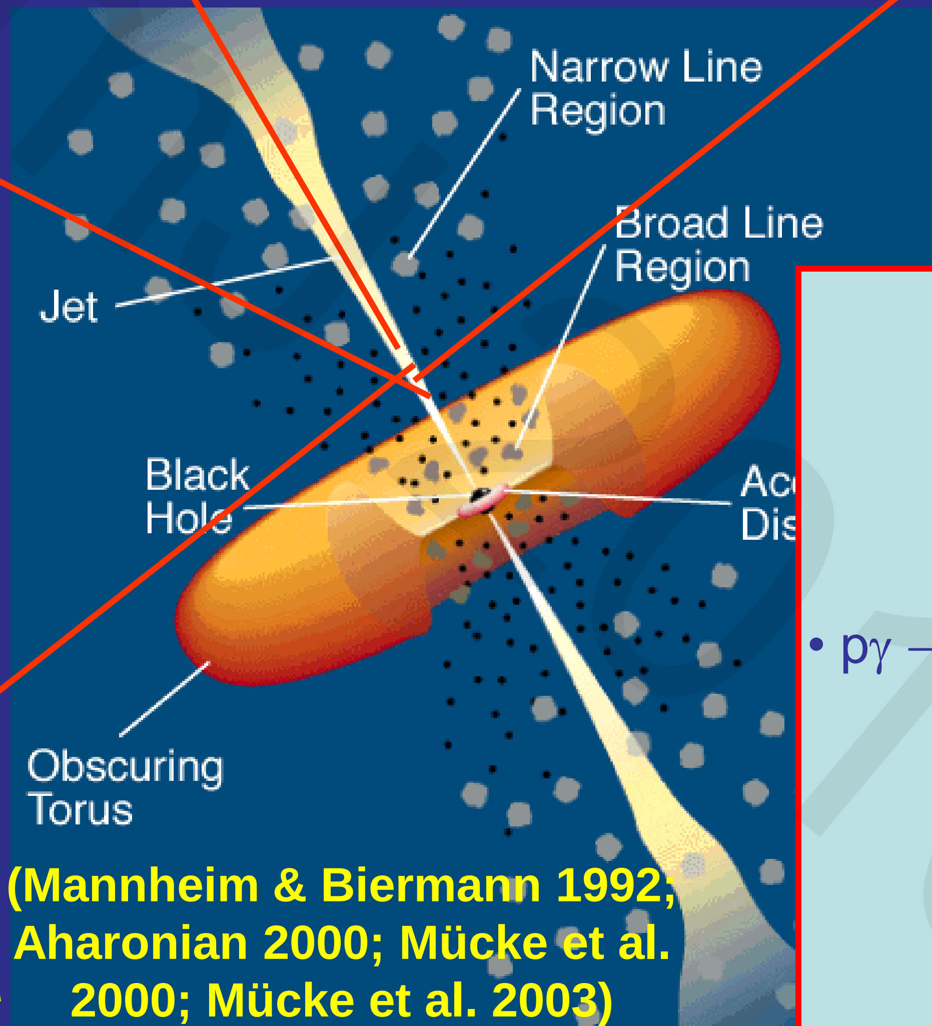
Requires far sub-equipartition magnetic fields!

Lepto-Hadronic Blazar Models

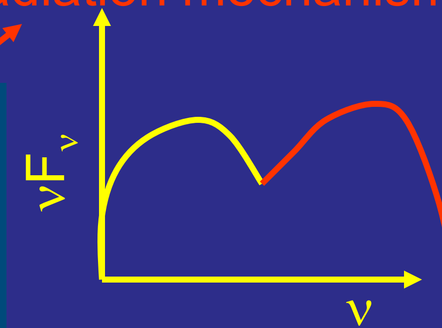
Injection, acceleration of ultrarelativistic electrons and protons



Relativistic jet outflow with $\Gamma \approx 10$

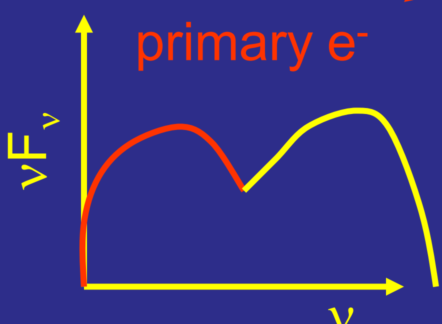


Proton-induced radiation mechanisms



- 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 …

Synchrotron emission of primary e^-



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

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!

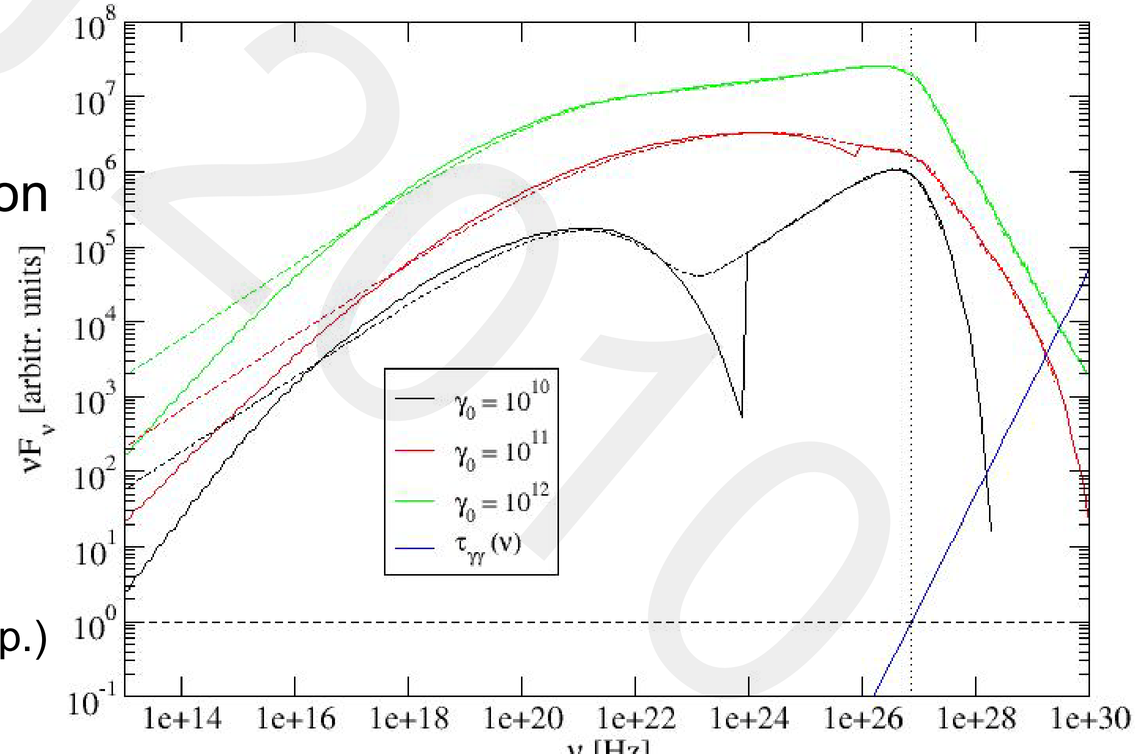
→ Geometrical effects?

Semi-analytical lepto-hadronic model

- Synchrotron + SSC as for leptonic model
- Power-law distribution of ultrarelativistic protons
- Production rates of final decay products (electrons, positrons, neutrinos, π^0-decay photons) from Kelner & Aharonian (2008) templates
- Semi-analytical representation of cascades:

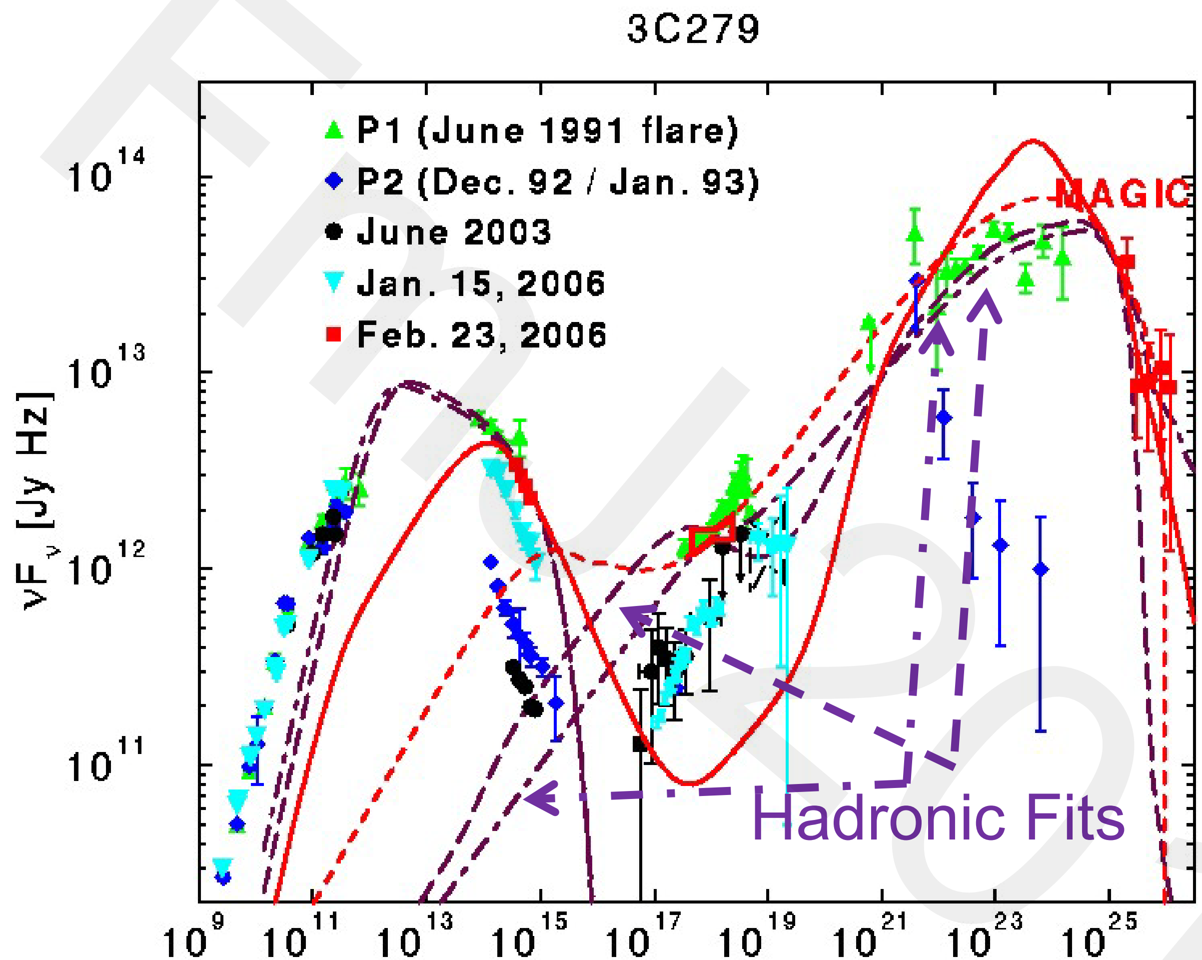
  - $\gamma\gamma$ pair production through delta-function approximation

  - synchrotron emissivity from single electron through $j_\nu(\gamma) \sim \nu^{1/3} e^{-\nu/\nu_0(\gamma)}$



(Böttcher & Reimer 2010, in prep.)

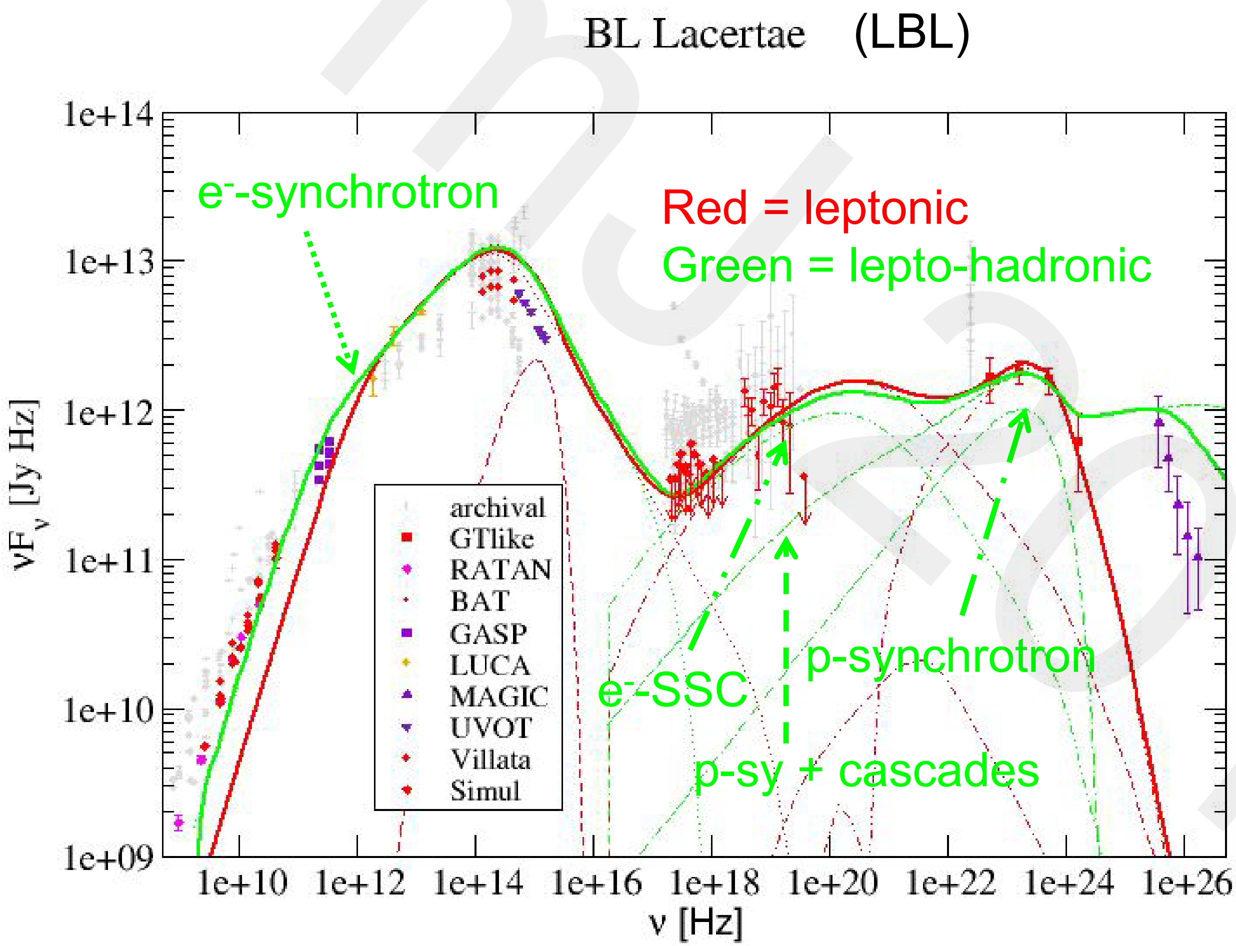
Hadronic Model Fits



(Böttcher, Reimer & Marscher 2009)

- **Optical and γ-ray spectral index can be decoupled**
- **X-rays filled in by electromagnetic cascades**
- **However: Requires very large jet luminosities, $L_j \sim 10^{49}$ erg/s**

Lepto-Hadronic Model Fits Along the Blazar Sequence



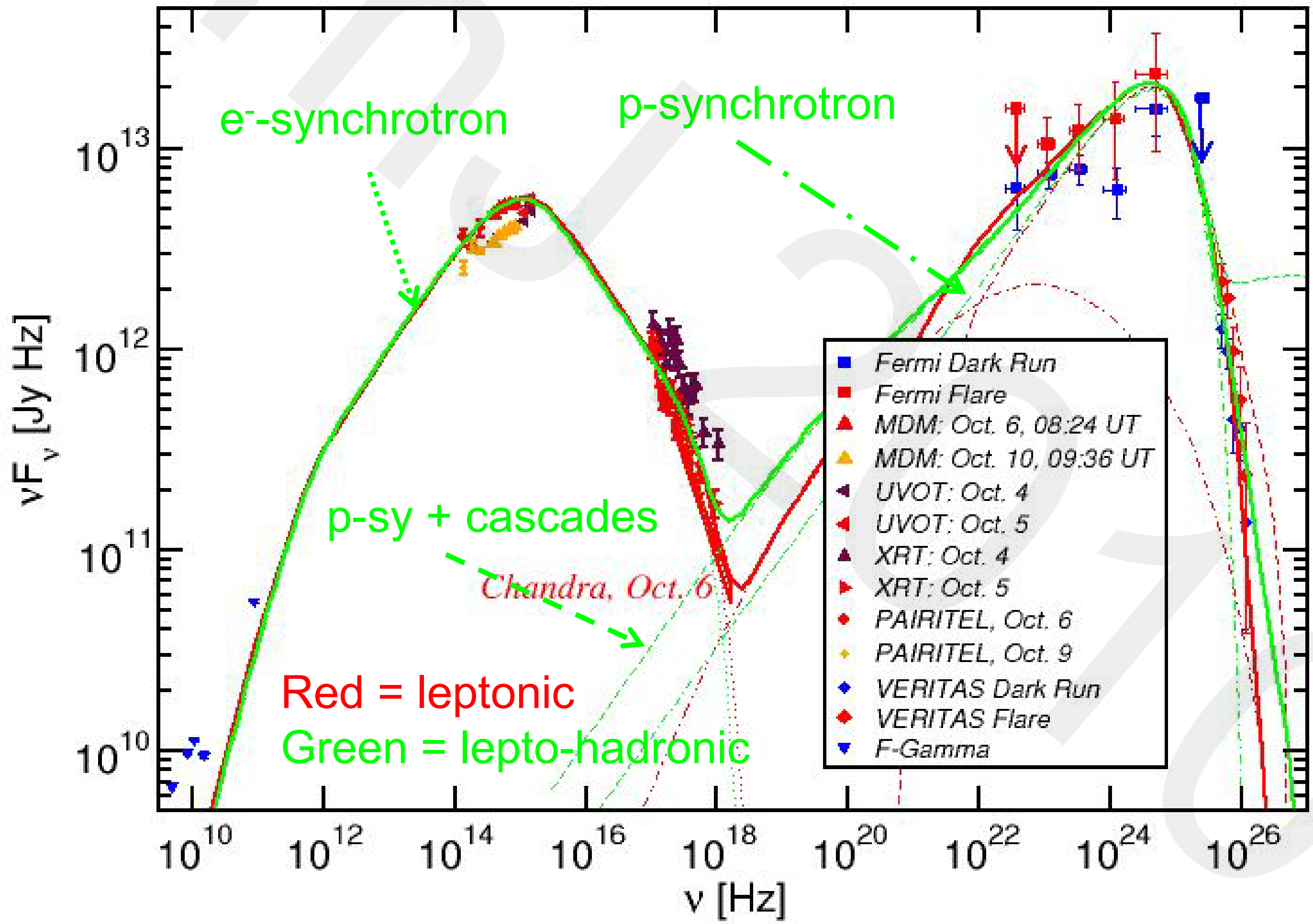
Strongly peaked γ-ray spectra achievable by p-synchrotron.

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

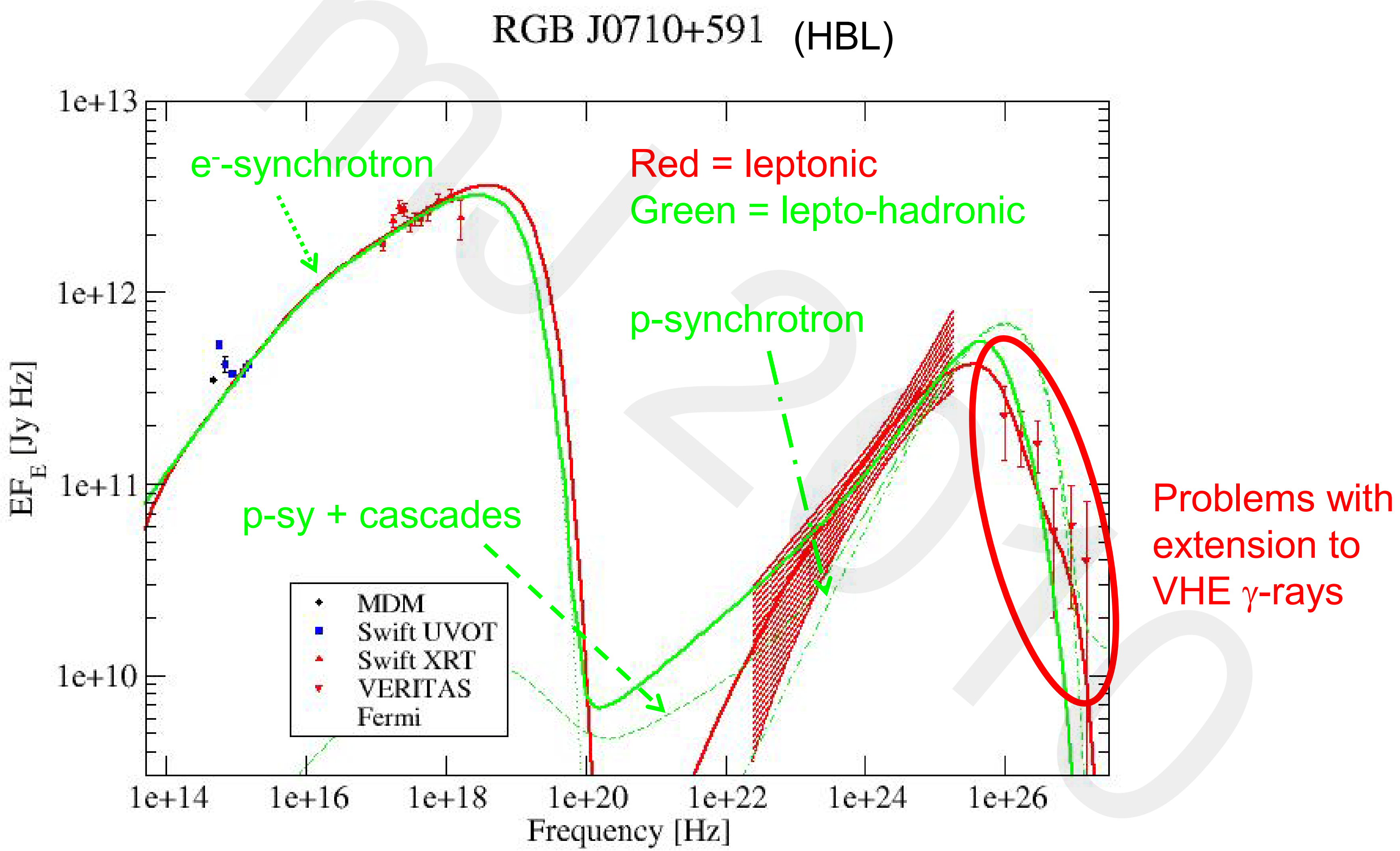
-> Problems with hard Fermi Sources …

Lepto-Hadronic Model Fits Along the Blazar Sequence

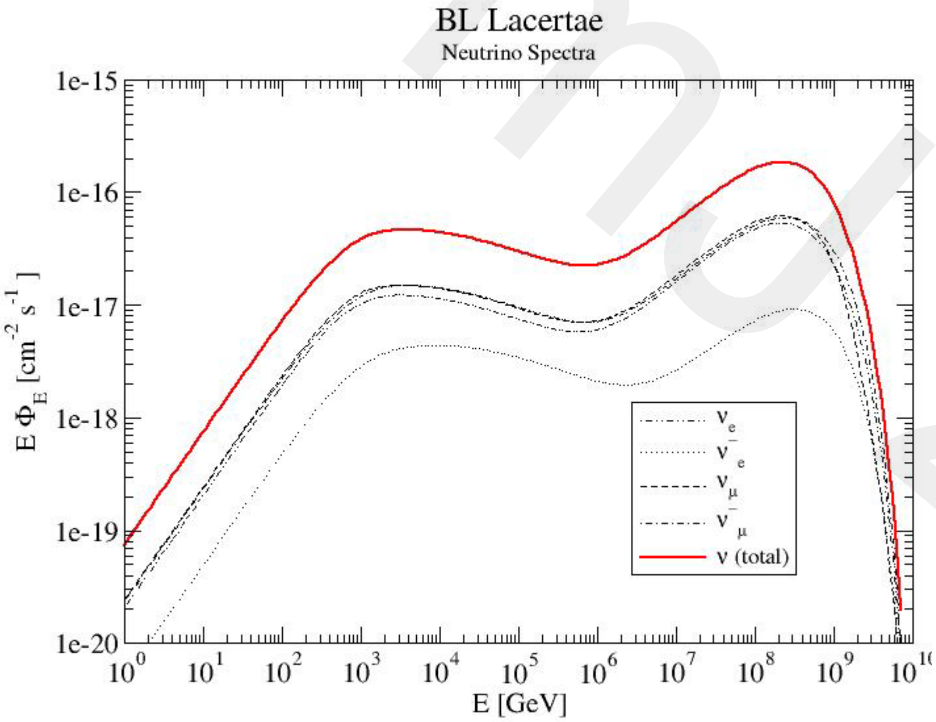
3C66A (IBL)

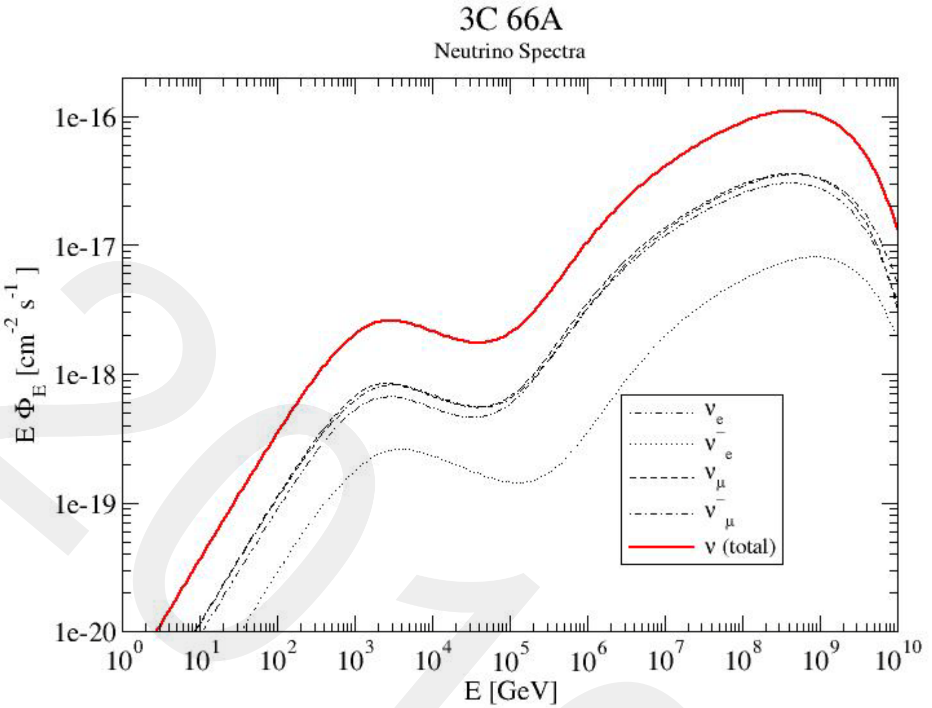


Lepto-Hadronic Model Fits Along the Blazar Sequence



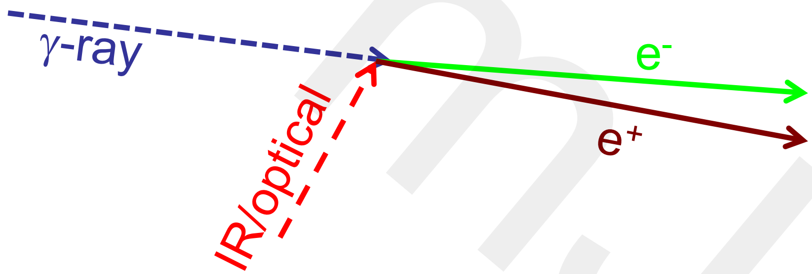
Lepto-Hadronic Model Fits: Neutrino Spectra



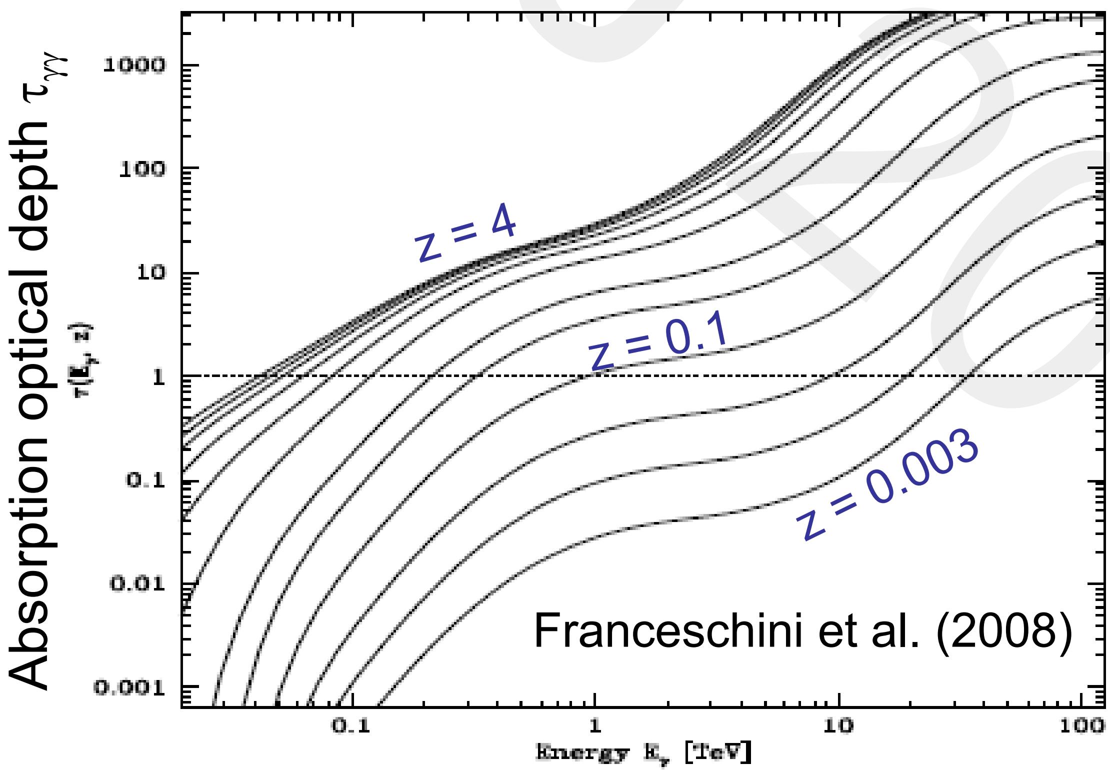


Substantial neutrino flux at TeV energies, but dominant fraction at PeV – EeV.

γ–γ Absorption in the Extragalactic Background Light



High-Energy γ-rays are absorbed in intergalactic space by γ–γ pair production



$$F_\gamma^{obs} = F_\gamma^{em} \, e^{-\tau_{\gamma\gamma}}$$

(Stecker et al. 2006; Gilmore et al. 2009; Finke et al. 2010)

Redshift Estimates from SED Modeling:

Often adopted approach:

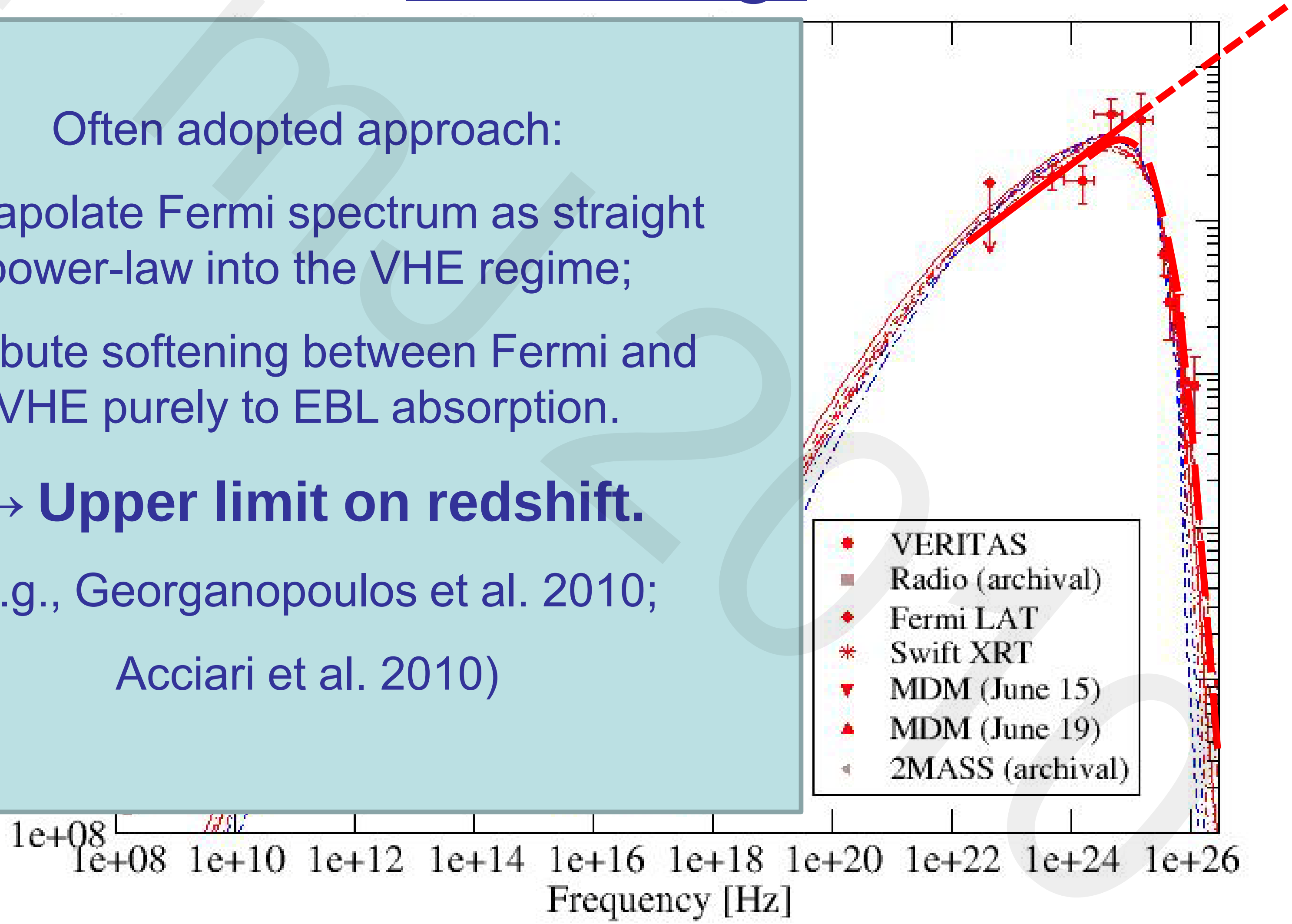
Extrapolate Fermi spectrum as straight power-law into the VHE regime;

Attribute softening between Fermi and VHE purely to EBL absorption.

→ **Upper limit on redshift.**

(e.g., Georganopoulos et al. 2010;

Acciari et al. 2010)



More Realistic Aproach: Constrain SED through lower-frequency (radio – GeV) SED

Example: PKS 1424+240

VERITAS Detection during the period February – June 2009

Motivated by Fermi detection of a hard GeV spectrum

Current "knowledge" of redshift:

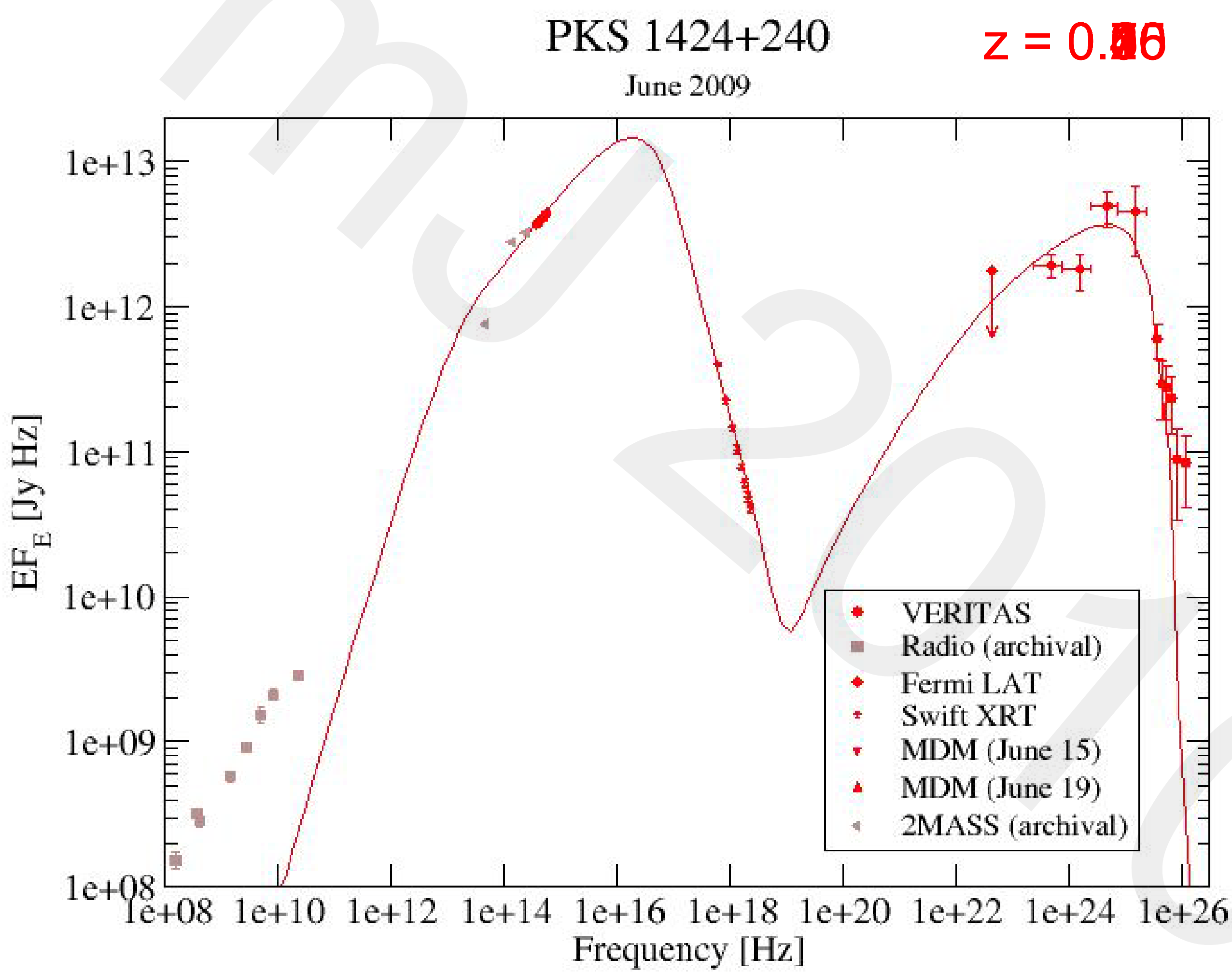
SIMBAD: **z = 0.16** (but no reference)

Sbarufatti et al. (2005): Limit from non-detection of host galaxy: **z > 0.67**

Connecting extrapolated Fermi spectrum with observed VERITAS spectrum through $\gamma\gamma$ absorption in the Extragalactic Background Light: **z < 0.6**

PKS 1424+240

Model fits with pure SSC models for a variety of redshifts



PKS 1424+240

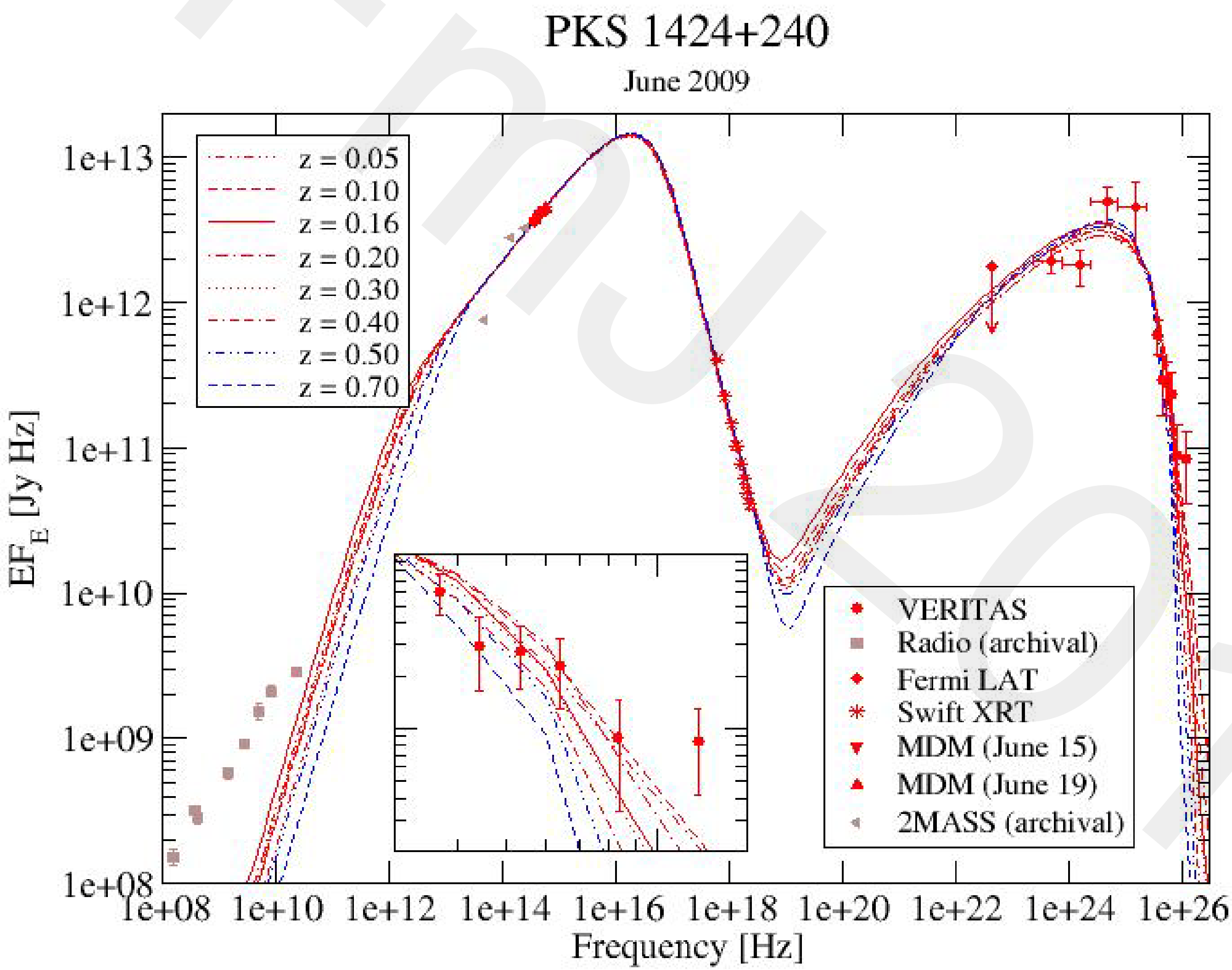
SSC fit parameters for a variety of redshifts

Parameter	z = 0.05	z = 0.10	z = 0.16	z = 0.30	z = 0.40	z = 0.50	z = 0.70
L_e [10^{43} erg/s]	1.60	4.12	8.07	18.9	29.2	47.1	88.8
L_B [10^{43} erg/s]	1.66	5.47	12.2	31.1	45.9	49.8	66.2
ε_B	1.04	1.33	1.50	1.65	1.57	1.06	0.75
B [G]	0.37	0.31	0.30	0.24	0.25	0.18	0.14
D	15	18	20	30	35	45	60

L_e = kinetic power in relativistic electrons
L_B = Poynting flux
$\varepsilon_B = L_B/L_e$ = magnetic-field equipartition fraction
D = Doppler factor

Fits for $z \geq 0.5$ require large Doppler factors

PKS 1424+240



- Pure SSC models provide a reasonable fit; no EC component required.

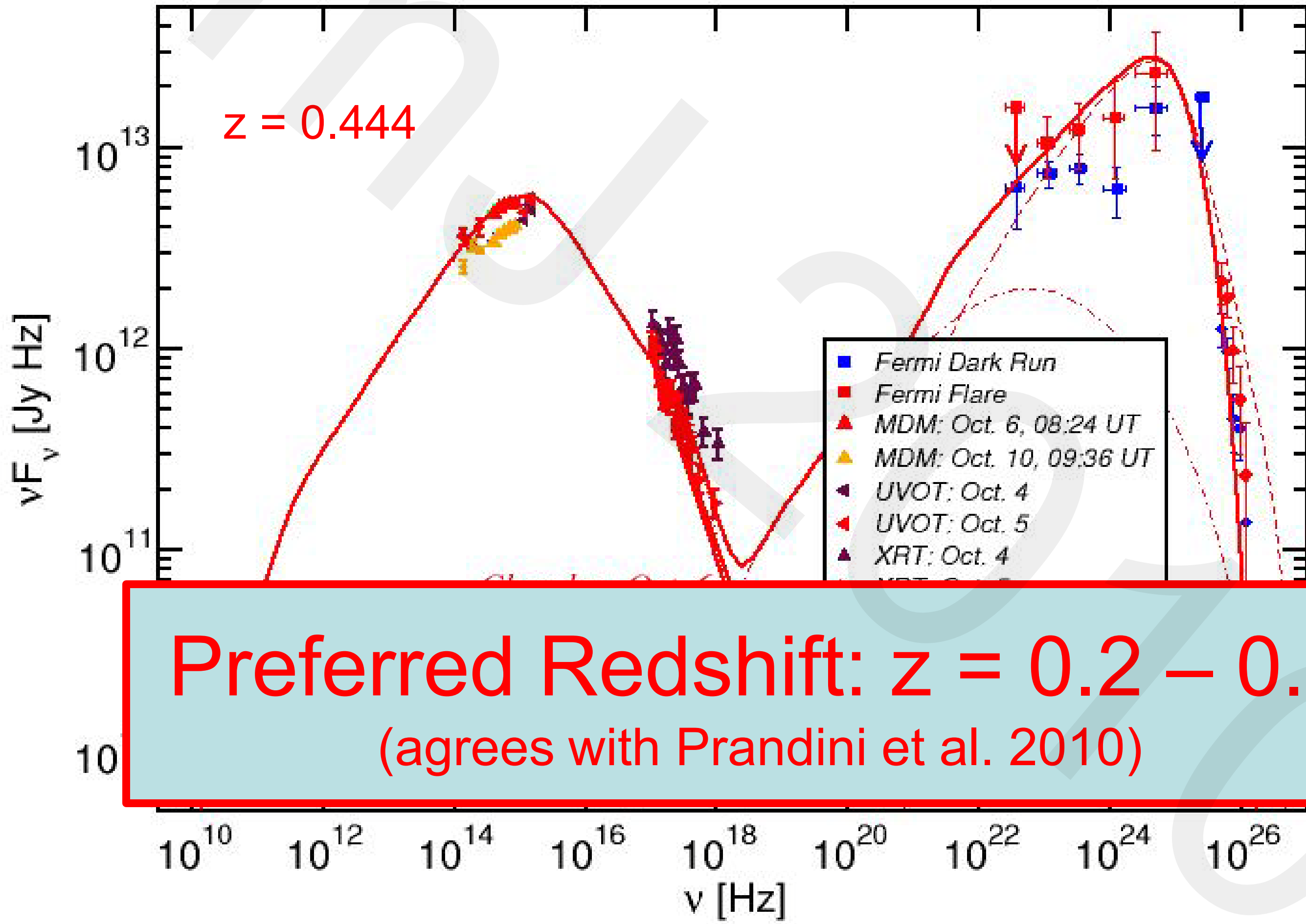
- For larger redshift, increasing discrepancy with VHE γ-ray spectral index

→ z ≤ 0.4

Redshift of 3C66A

Often quoted value of z = 0.444 is highly uncertain (Bramel et al. 2005), based on only one single emission line.

Model fits for different values of z = 0.1 – 0.444:



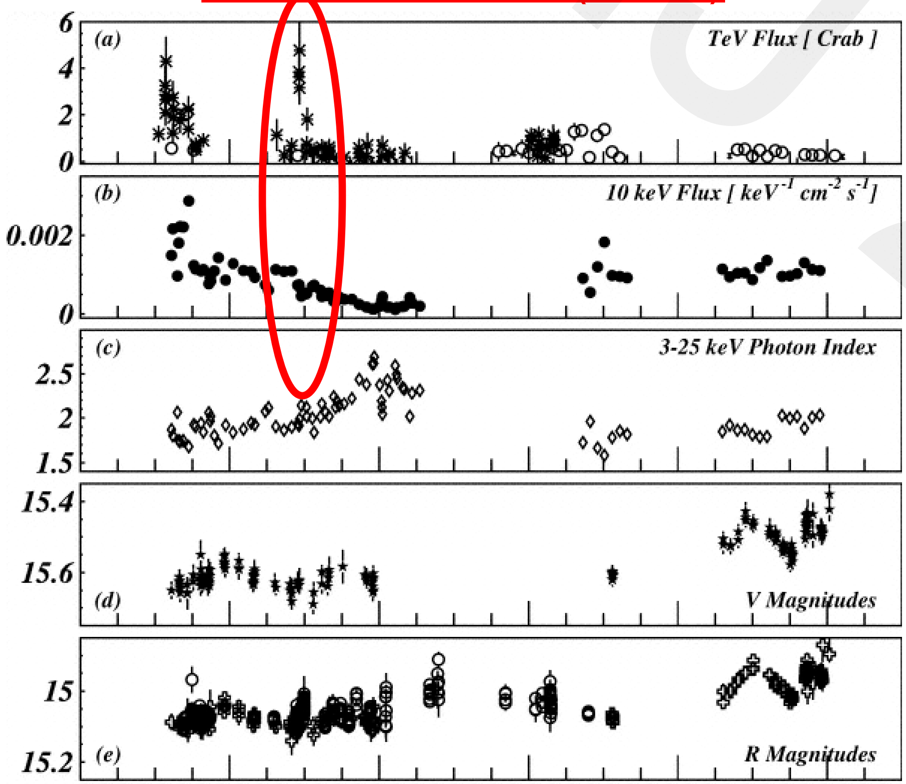
Preferred Redshift: z = 0.2 – 0.3

(agrees with Prandini et al. 2010)

Problems of spherical, homogeneous models

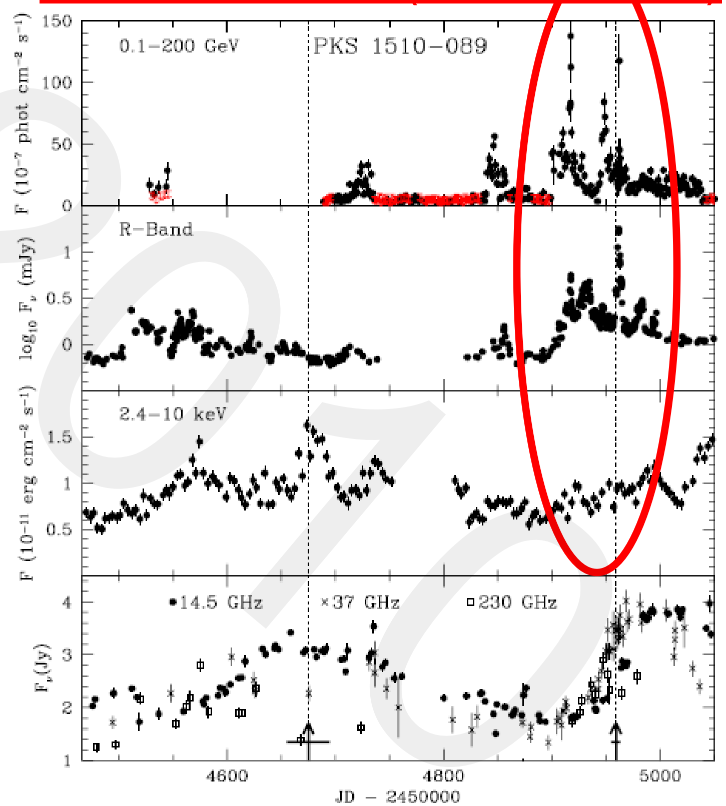
If the entire SED is produced by the same electron population, variability at all frequencies should be well correlated – but …

1ES 1959+650 (2002)



(Krawczynski et al. 2004)

PKS 1510-089 (2008 - 2009)

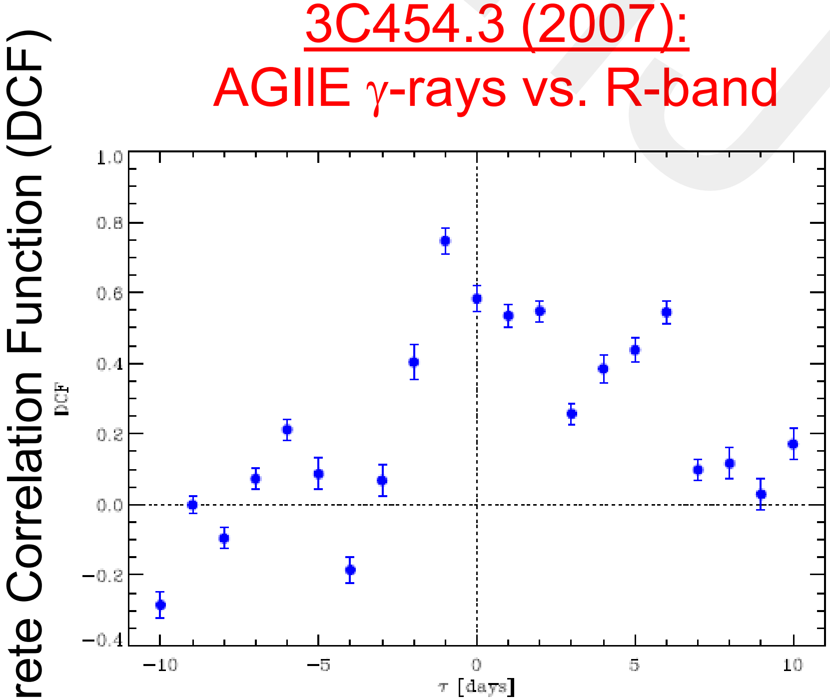


(Marscher al. 2010)

Problems of spherical, homogeneous models

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

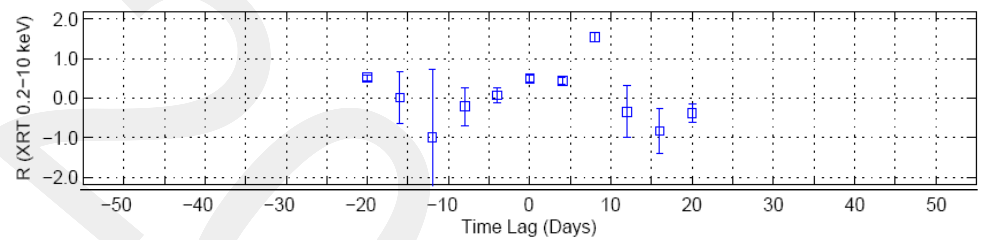
3C454.3 (2007):
AGILE γ-rays vs. R-band



(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)

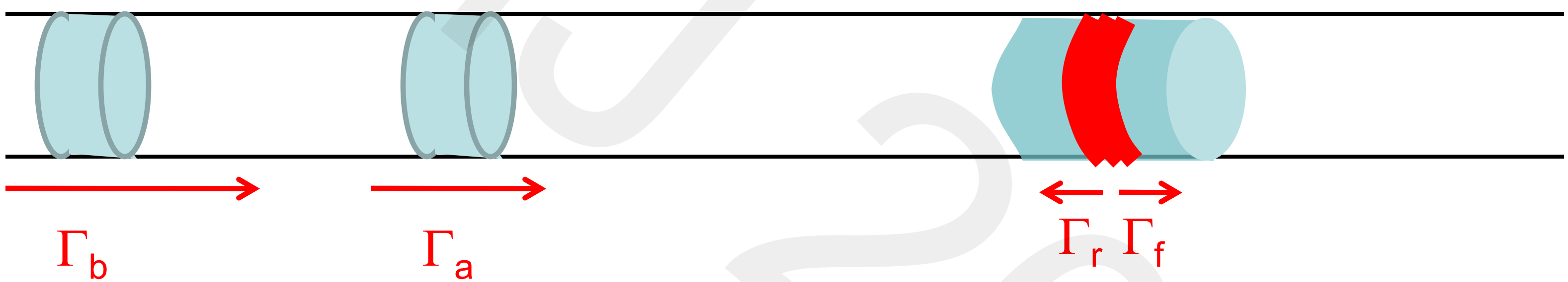
=> (0.2 – 10 keV) X-rays leading the VHE γ-rays by ~ 1 week?

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

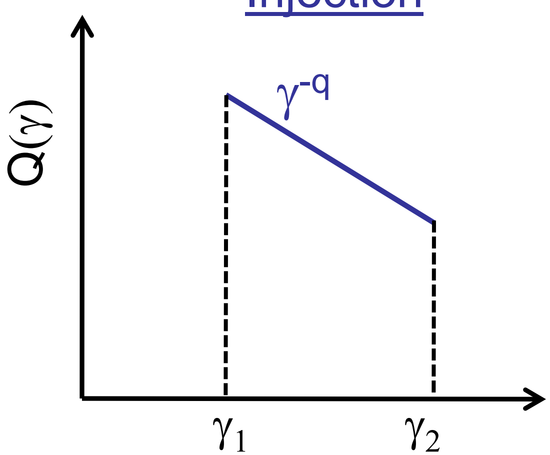
Detailed numerical simulations:
Sokolov et al. (2004), Mimica et al. (2004), Sokolov & Marscher (2005), Graff et al. (2008), Joshi (2009)

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

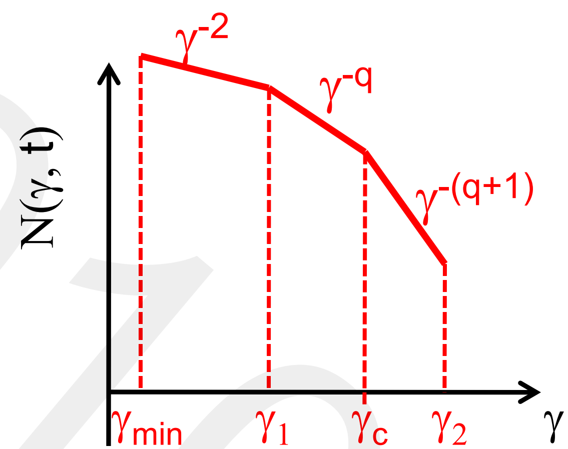


$$d\gamma/dt = -\nu_0\gamma^2$$

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

$\rightarrow$ 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

$$\nu F_\nu(\epsilon, t_{\rm obs}) = \frac{D^4\,\pi R^2}{d_L^2} \int\limits_{\overline{x}_{\rm min}}^{\overline{x}_{\rm max}} \overline{\epsilon}\, j_{\overline{\epsilon}}(\overline{x}, \overline{t}_{\rm x,em})\; d\overline{x}$$

1) Synchrotron

$$B_{f,r} = \sqrt{8\pi r\,\epsilon_B\,\left(\overline{\Gamma}_{f,r}^2 - \overline{\Gamma}_{f,r}\right) n'_{a,b}\, m_p c^2}$$

Delta-function approximation for synchrotron emissivity:

$$j_{\overline{\epsilon},{\rm sy}} = \frac{c\,\sigma_T\,B^2\,\overline{\epsilon}}{48\pi^2\,b^2\,\gamma_{\rm sy}}\, n_e(\gamma_{\rm sy})$$

=> νF_ν^{sy} (t_{obs})
can be calculated fully analytically!

Radiation Mechanisms (contd.)

2) External-Compton

Delta-function approximation for Compton cross section

+ mono-energetic, isotropic external radiation field

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

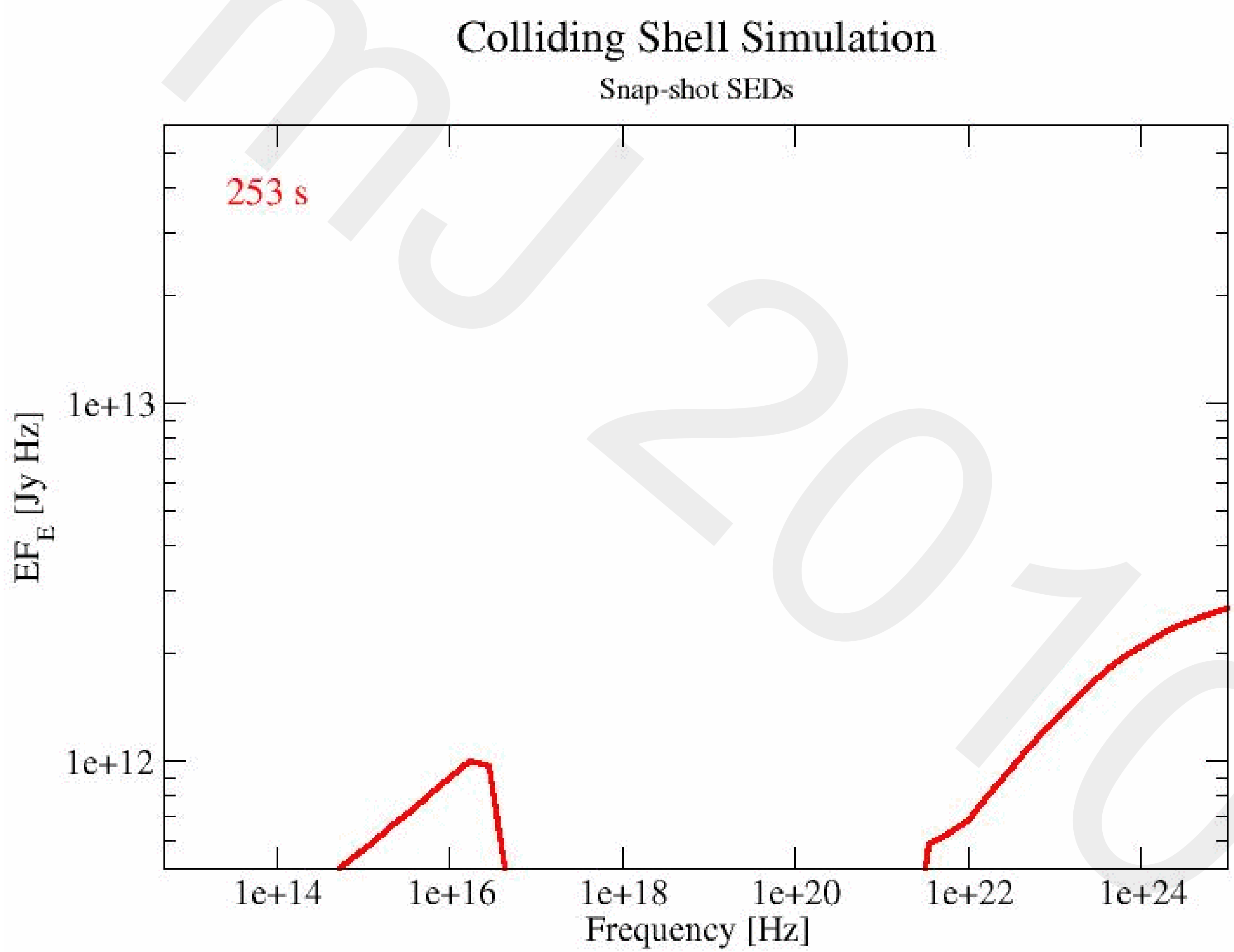
3) Synchrotron-Self Compton

Emissivity with delta-function approximation
for the Compton cross section:

=> Two integrations to be done numerically.

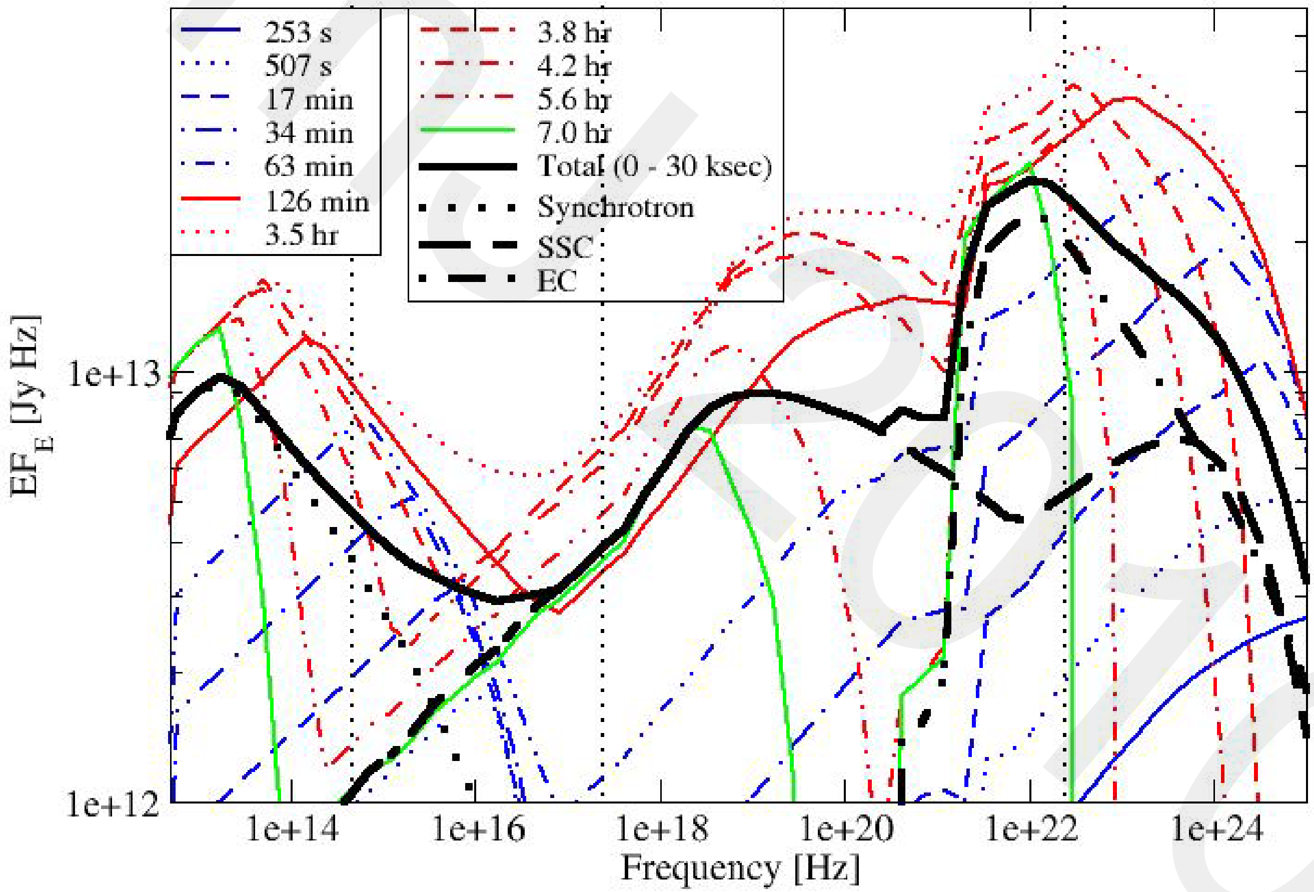
Baseline Model

Parameters / SED characteristics typical of FSRQs or LBLs



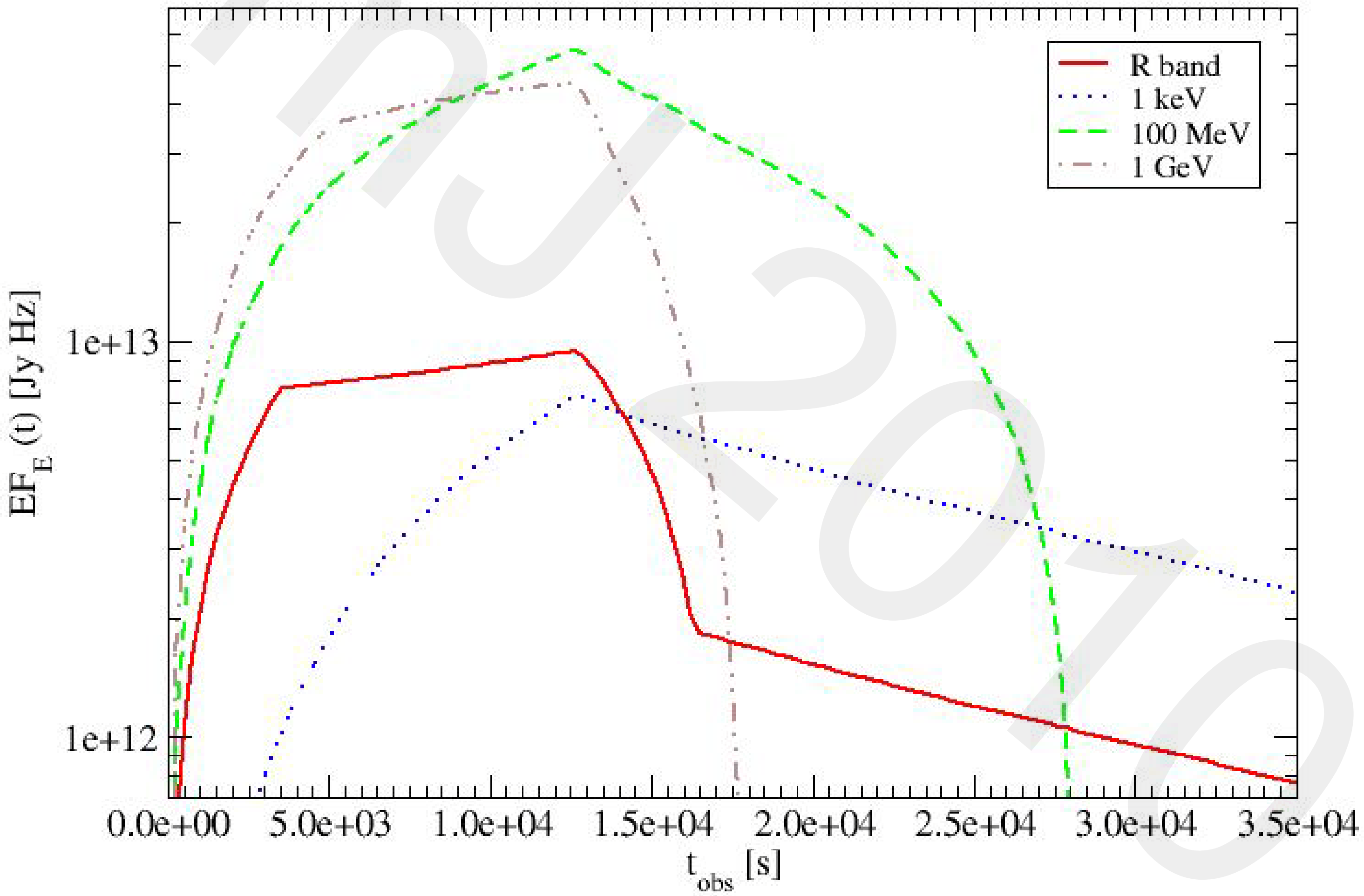
Baseline Model

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



Baseline Model

Light Curves



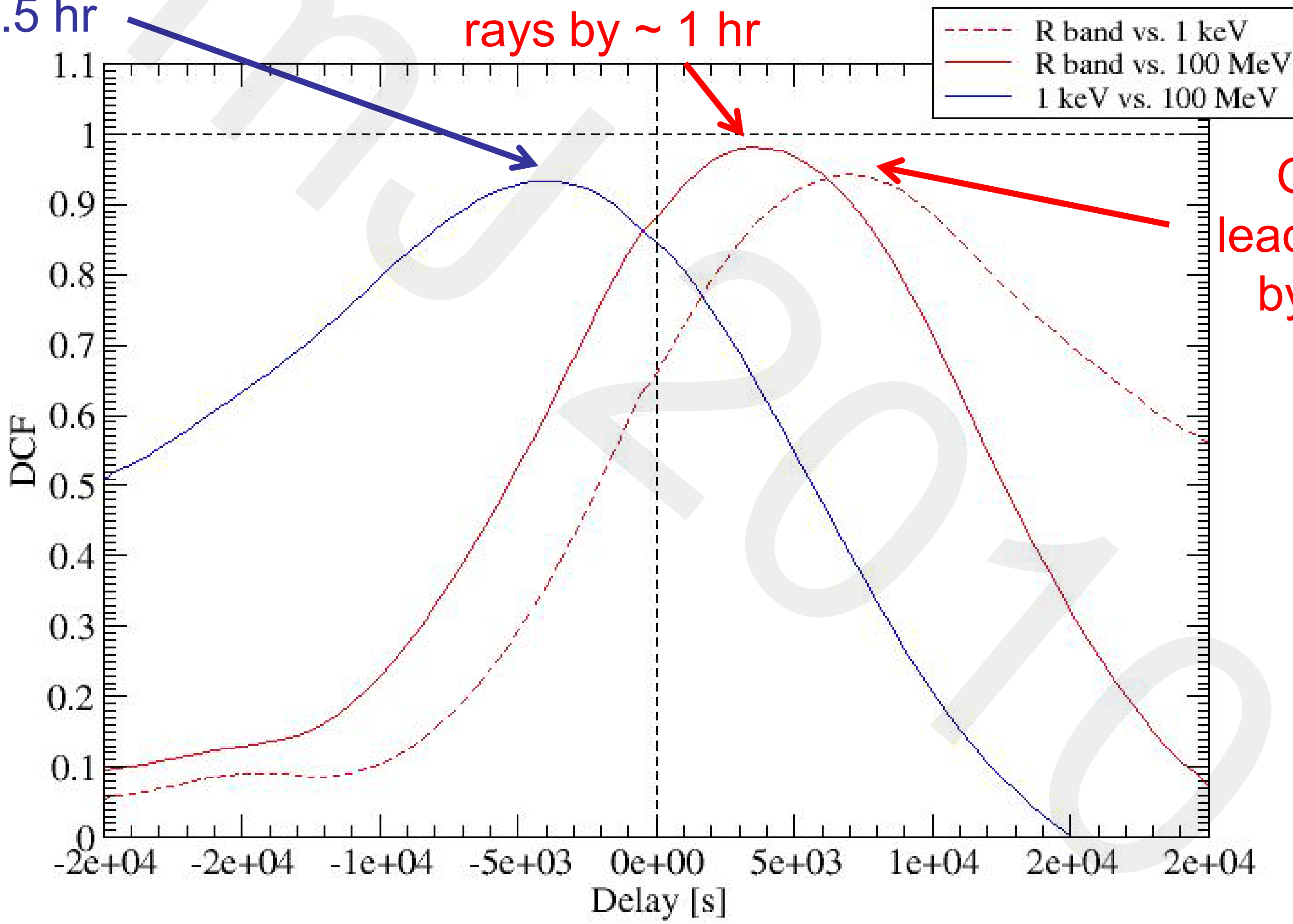
Baseline Model

Discrete Correlation Functions

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

Optical leads HE γ-rays by ~ 1 hr

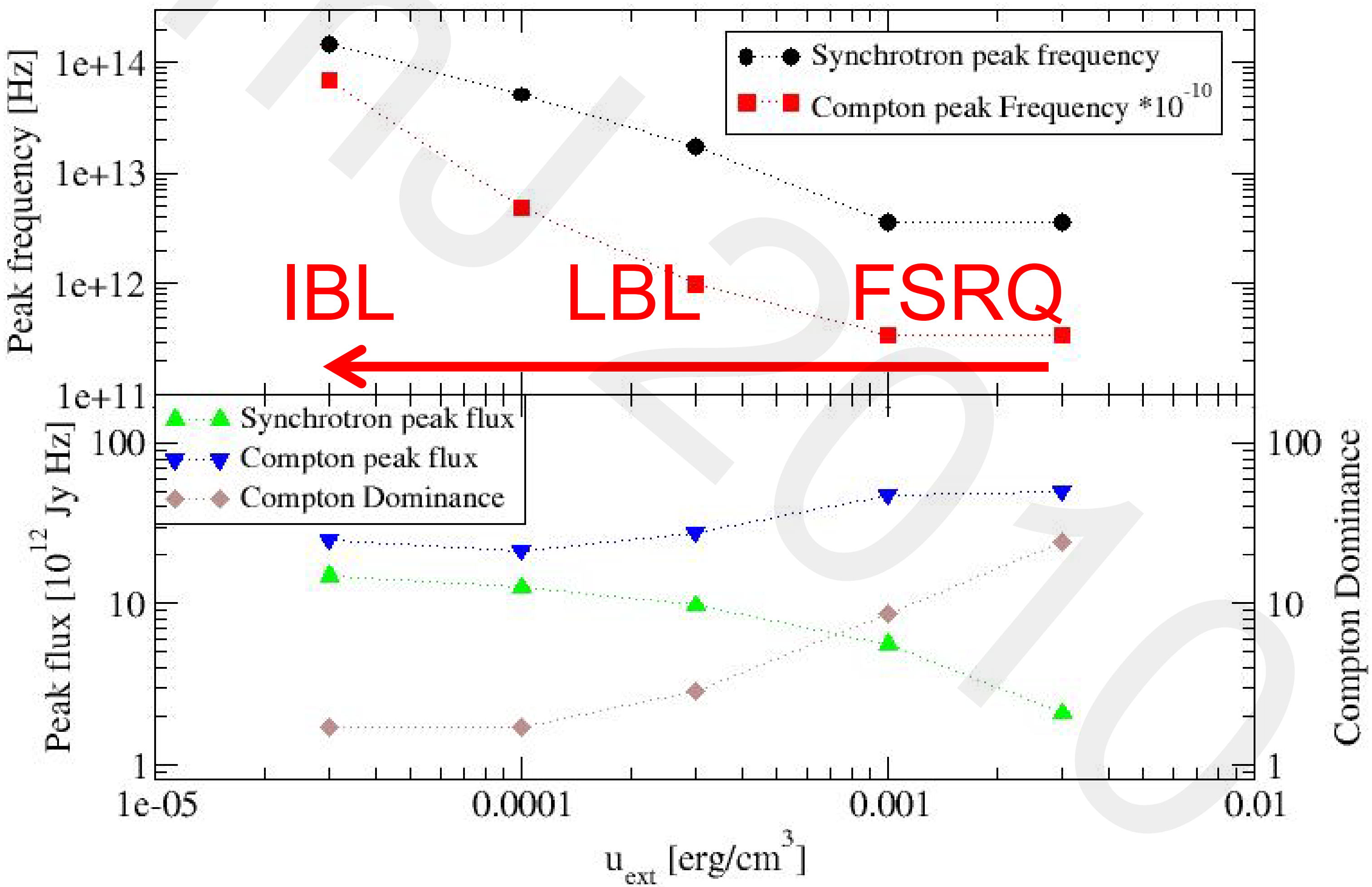
Optical leads X-rays by ~ 2 hr



Parameter Study

Varying the External Radiation Energy Density

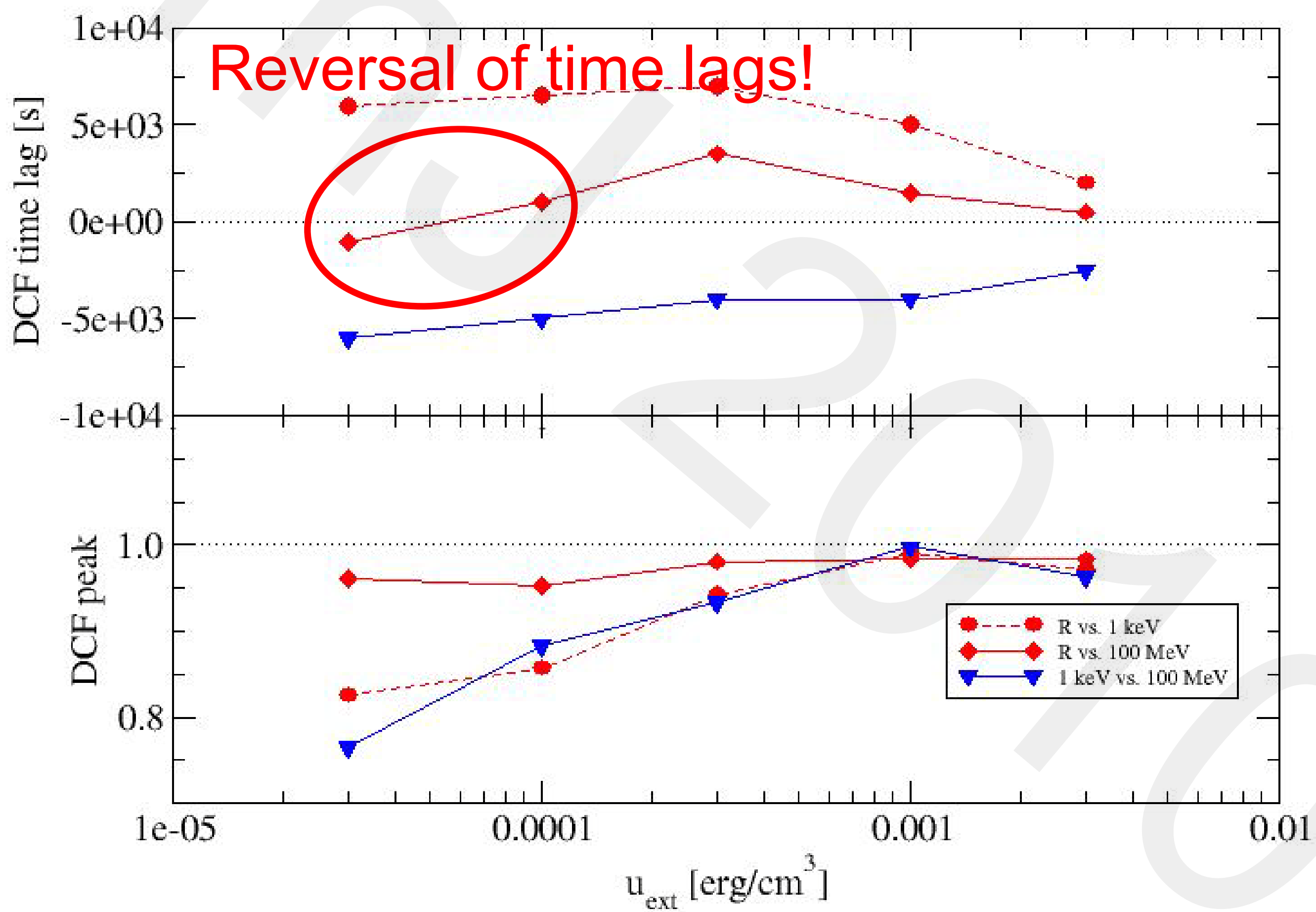
SED Characteristics



Parameter Study

Varying the External Radiation Energy Density

DCFs / Time Lags



OHIO UNIVERSITY

ASTROPHYSICAL INSTITUTE
OHIO UNIVERSITY

Summary

1. Leptonic models generally allow successful models for all classes of blazars, with increasing external-Compton dominance along the sequence from HBL → IBL → LBL → FSRQ, but problems with the VHE emission of FSRQ 3C279.
2. Lepto-hadronic models provide successful SED fits to many blazars, in particular, 3C279, including VHE emission, but rapid variability is hard to explain.
3. SED modeling can be used to constrain redshifts of BL Lac objects: PKS 1424+240 → $z < 0.4$; 3C66A → $z = 0.2 – 0.3$.
4. Much progress in time-dependent, inhomogeneous models, in particular shock-in-jet models.
5. Semi-analytical internal-shock model can be used to predict inter-band time lags: Slight paramter variations can lead to reversal of time lags.