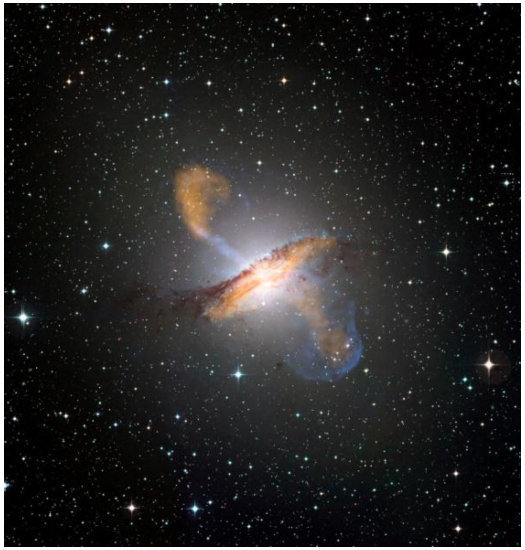
Modeling and Theory of Gamma-Ray Emitting Blazars



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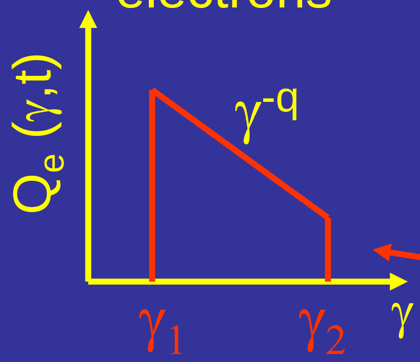
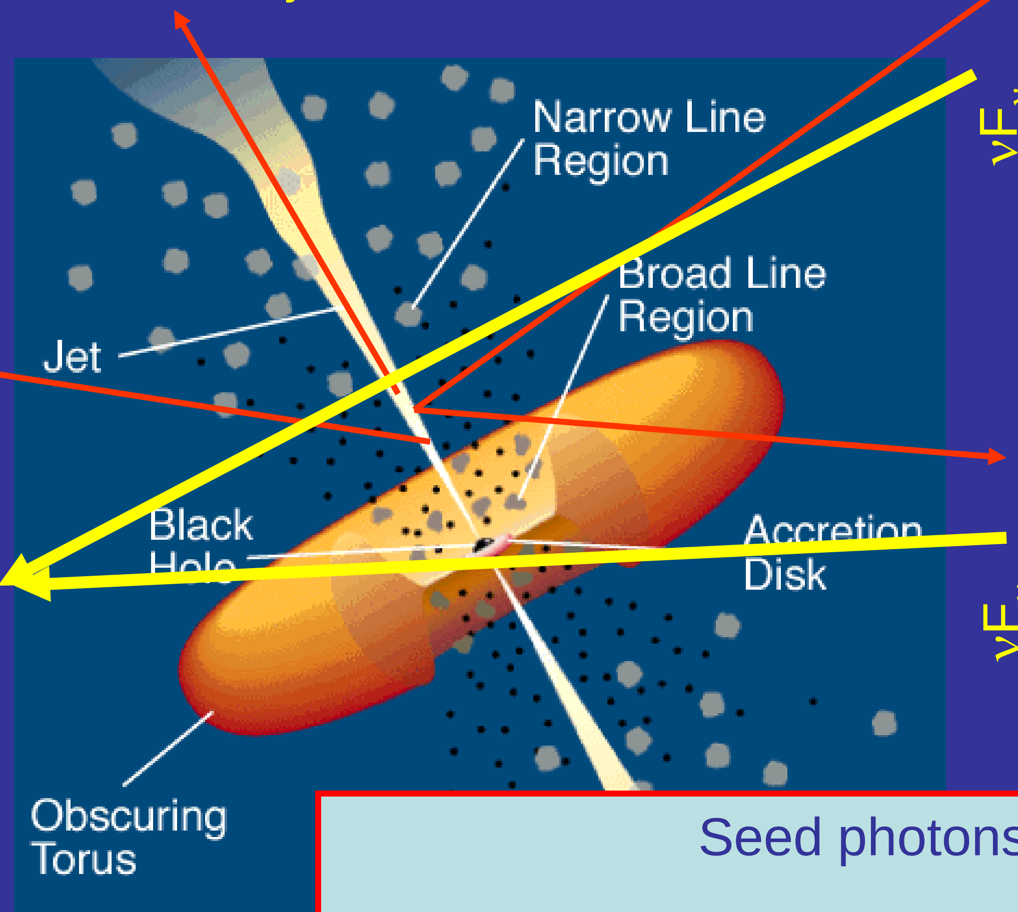
Leptonic Blazar Model

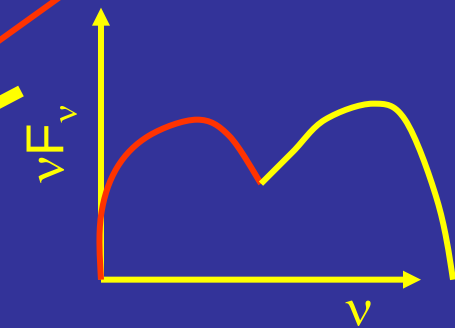
Injection, acceleration of ultrarelativistic electrons



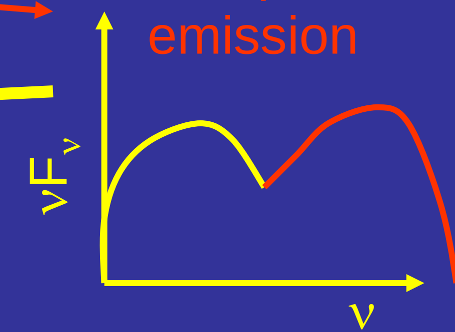
Relativistic jet outflow with $\Gamma \approx 10$



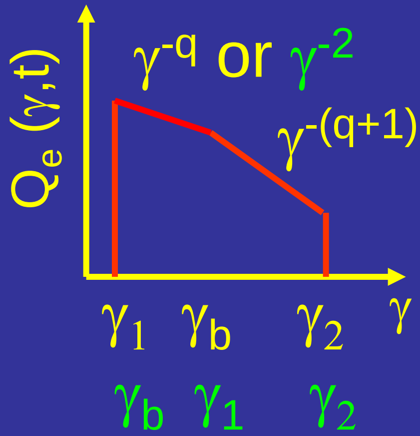
Synchrotron emission



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 (↔ Location of the Blazar Zone)

Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)
→ $d <$ few 100 – 1000 R_s

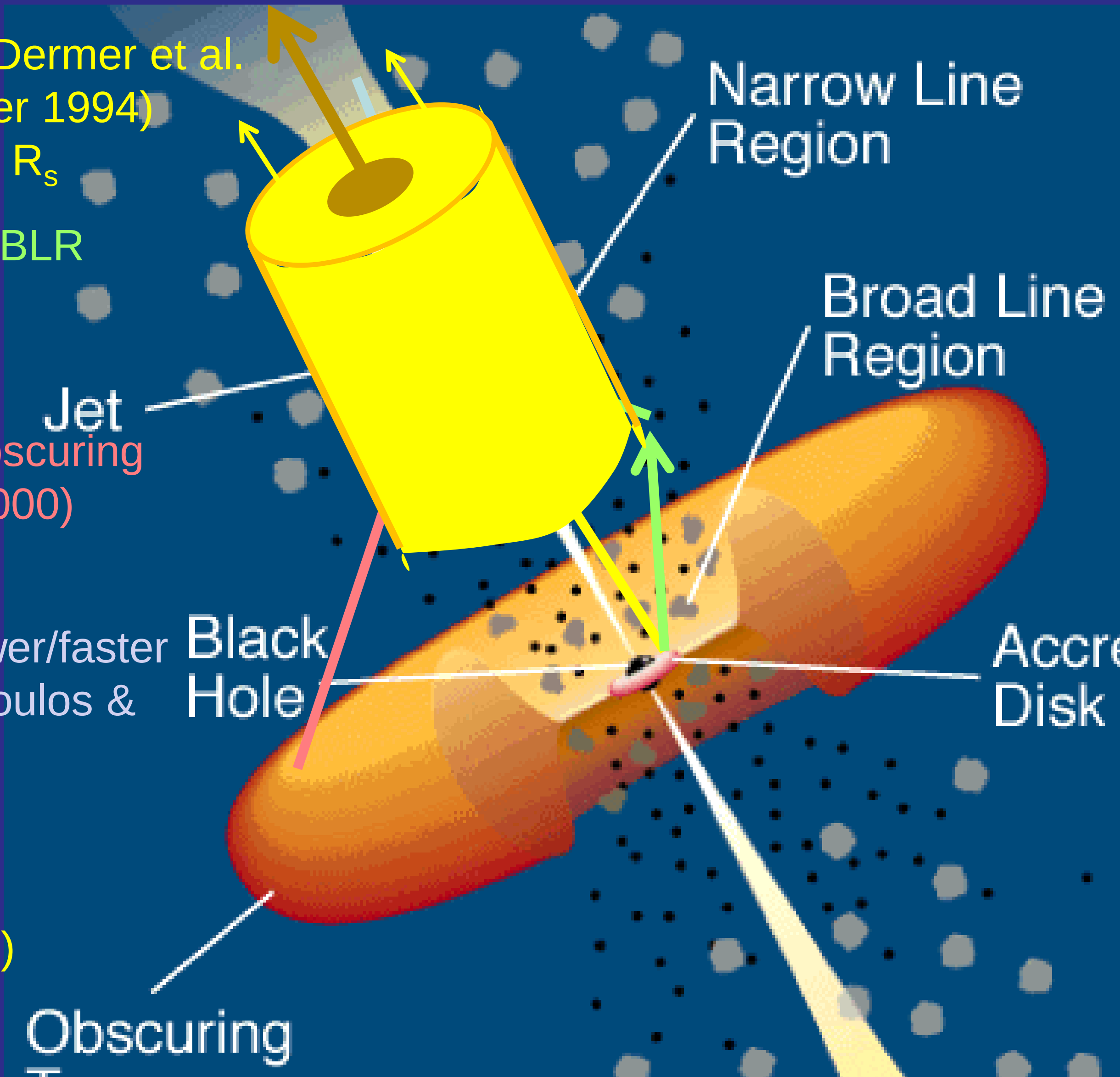
Optical-UV Emission from the BLR (Sikora et al. 1994)
→ $d < \sim$ pc

Infrared Radiation from the Obscuring Torus (Blazejowski et al. 2000)
→ $d \sim$ 1 – 10s of pc

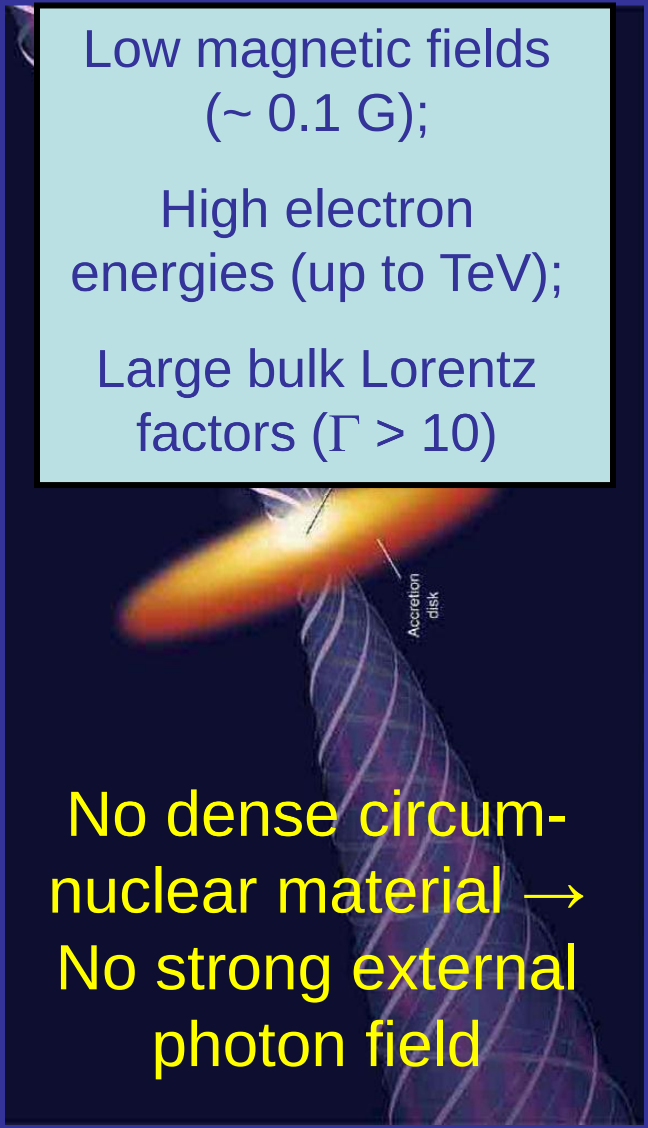
Synchrotron emission from slower/faster regions of the jet (Georganopoulos & Kazanas 2003)
→ $d \sim$ pc - kpc

Spine – Sheath Interaction (Ghisellini & Tavecchio 2008)

→ $d \sim$ pc - kpc



Spectral modeling results along the Blazar Sequence: Leptonic Models



Low magnetic fields (~ 0.1 G);

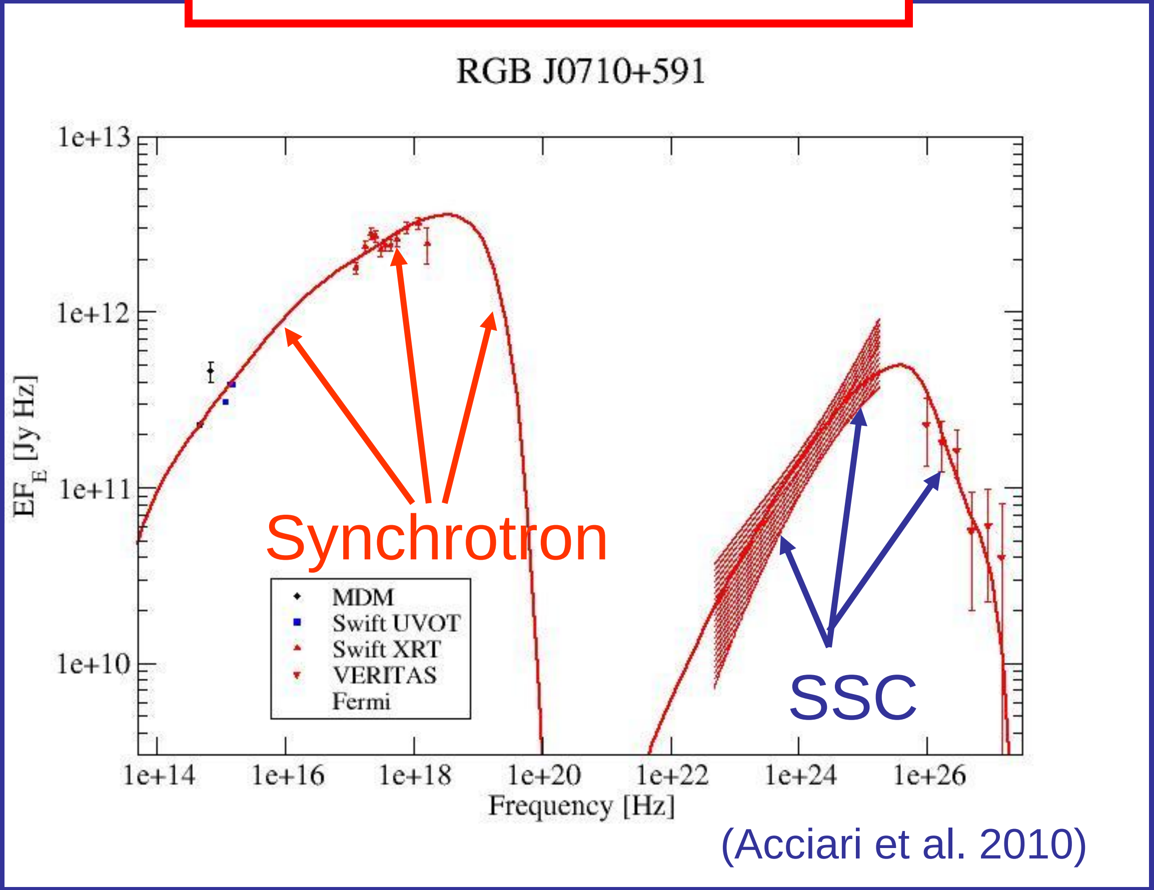
High electron energies (up to TeV);

Large bulk Lorentz factors (Γ > 10)

No dense circum-nuclear material → No strong external photon field

High-frequency peaked BL Lac (HBL):

The "classical" picture



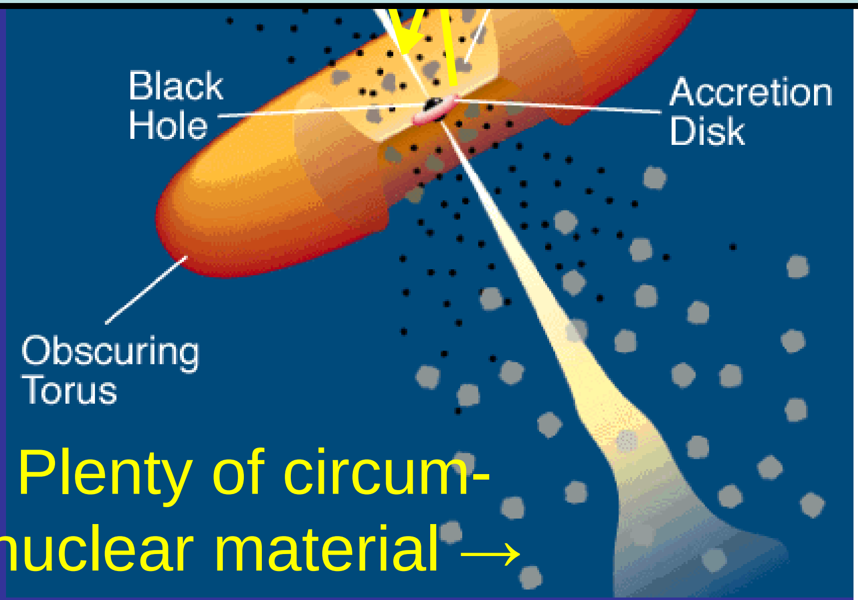
(Acciari et al. 2010)

Spectral modeling results along the Blazar Sequence: Leptonic Models

High magnetic fields (~ a few G);

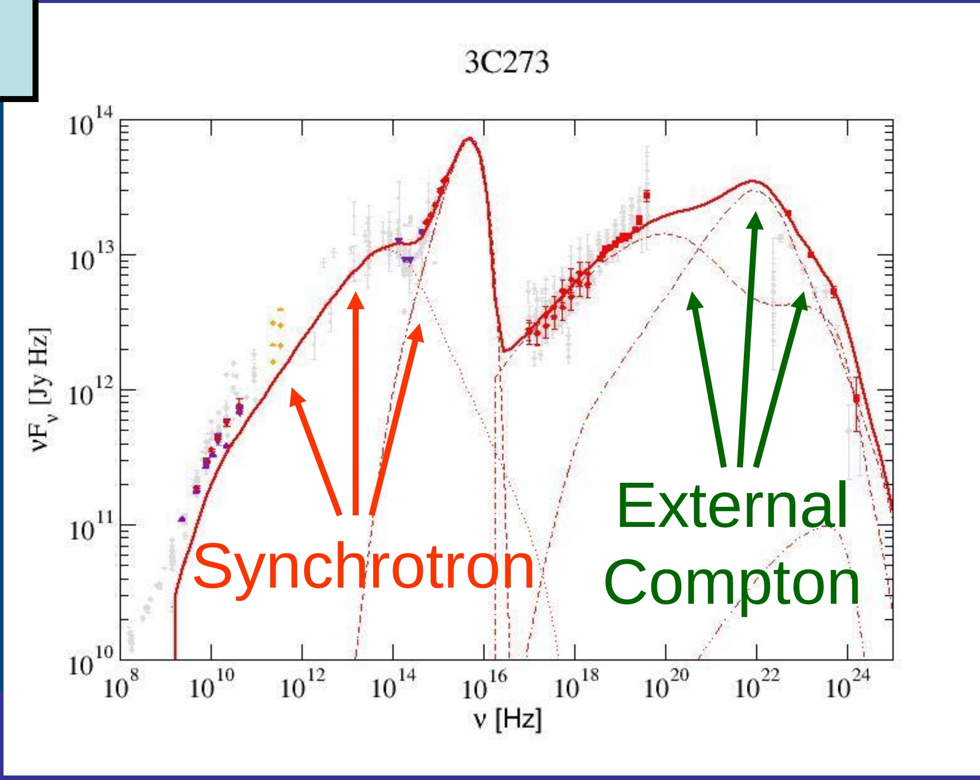
Lower electron energies (up to GeV);

Lower bulk Lorentz factors (Γ ~ 10)

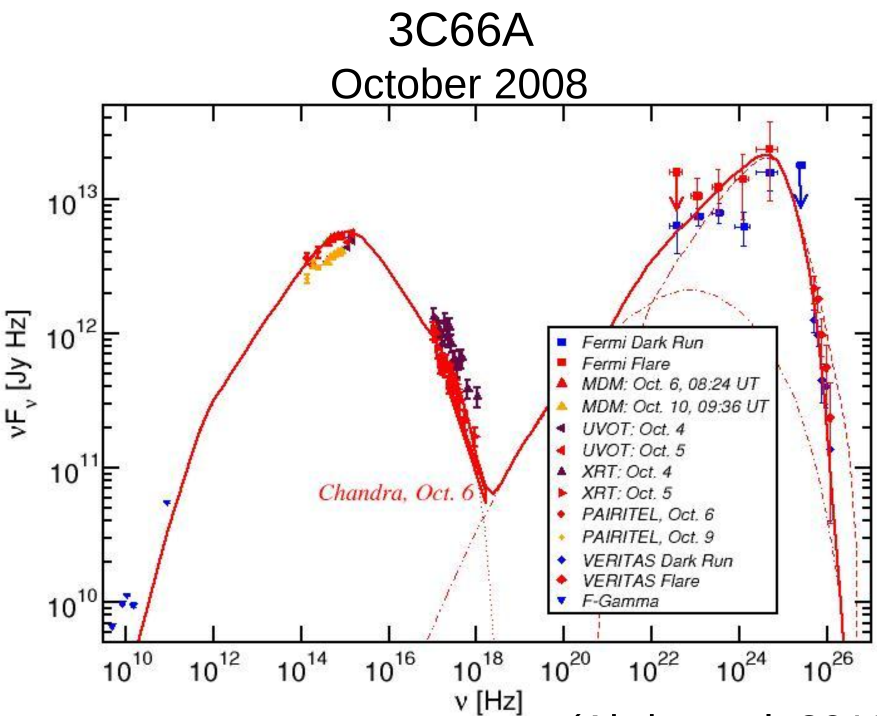


Plenty of circum-nuclear material → Strong external photon field

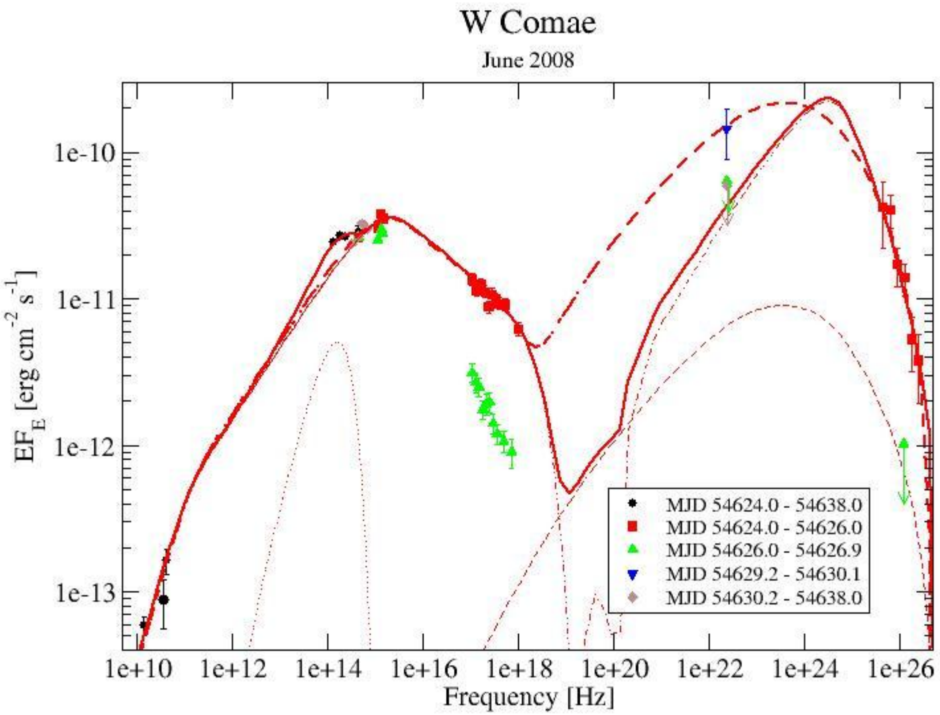
FSRQ



Intermediate BL Lac Objects



(Abdo et al. 2011)



(Acciari et al. 2009)

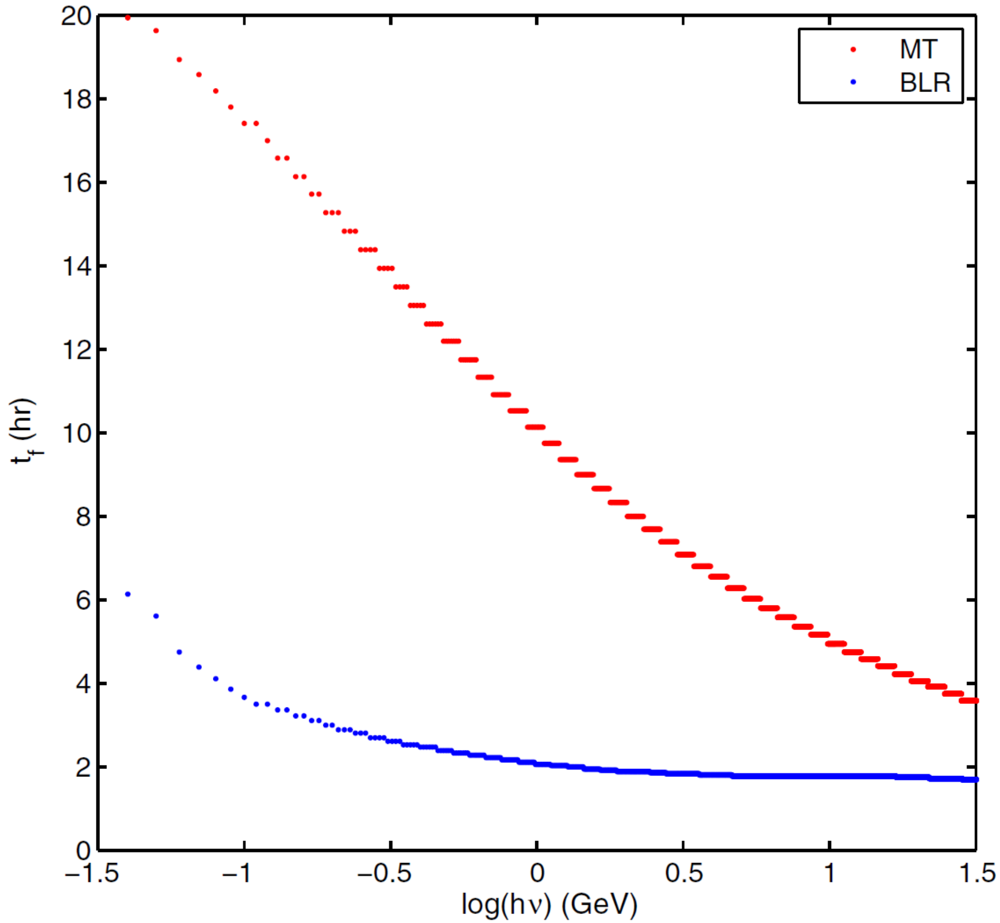
Spectral modeling with pure SSC would require extreme parameters (far sub-equipartition B-field)

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

→ γ-ray production on > pc scales?

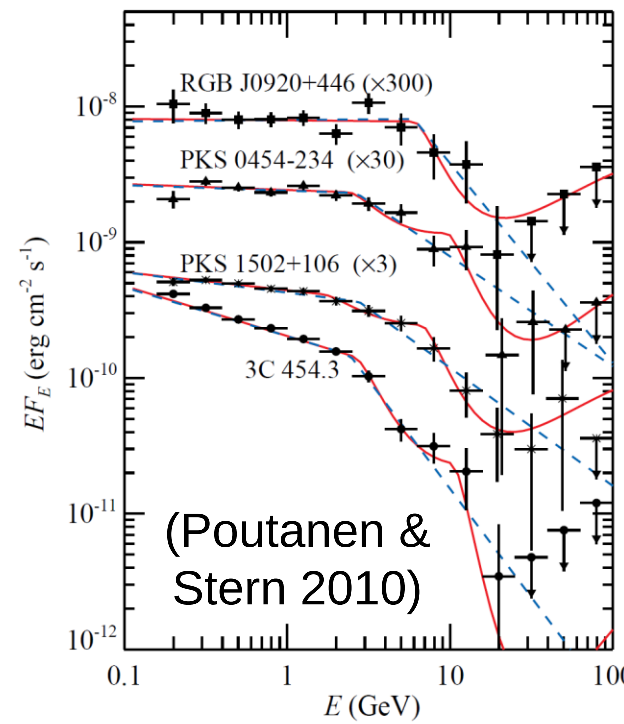
Diagnosing the Location of the Blazar Zone

Energy dependence of cooling times: Distinguish between EC on IR (torus → Thomson) and optical/UV lines (BLR → Klein-Nishina)



(Dotson et al. 2012)

If EC(BLR) dominates: Blazar zone should be inside BLR → γγ absorption on BLR photons → GeV spectral breaks

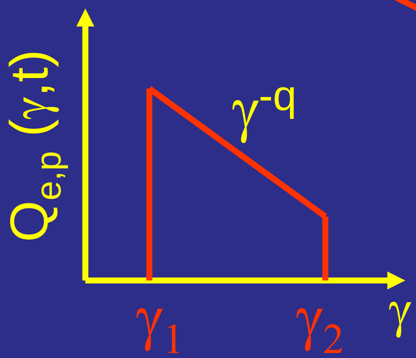


(Poutanen & Stern 2010)

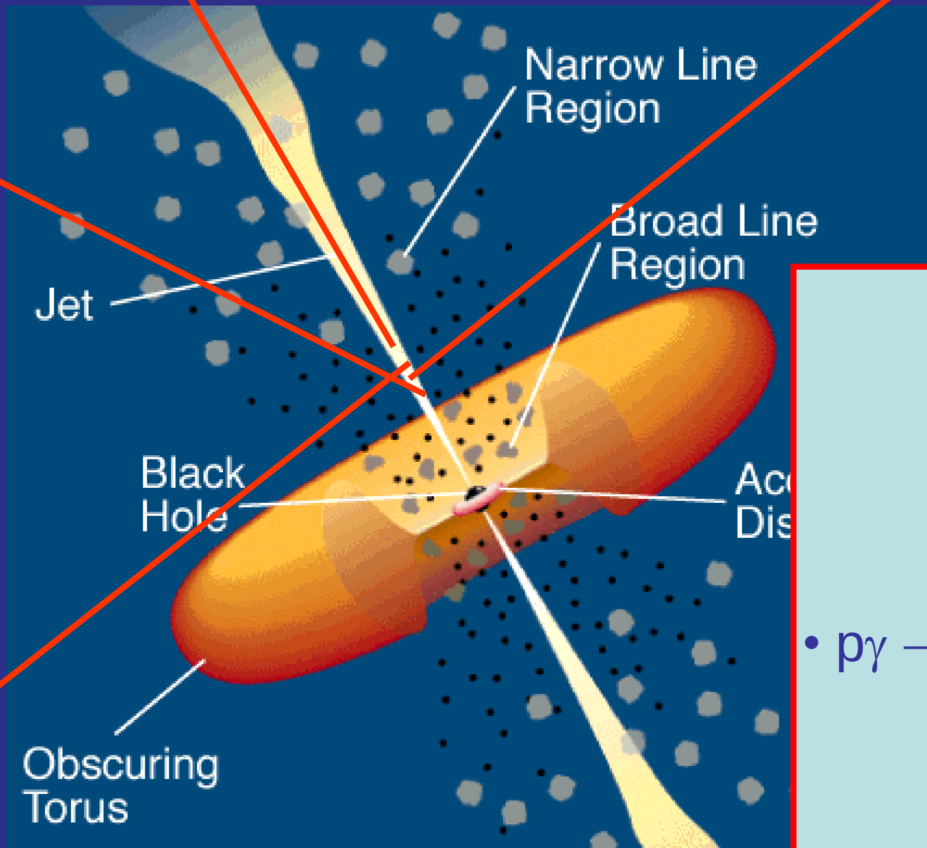
→ No VHE γ-rays expected!
→VHE γ-rays from FSRQs must be from outside the BLR
(e.g., Barnacka et al. 2013)

Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

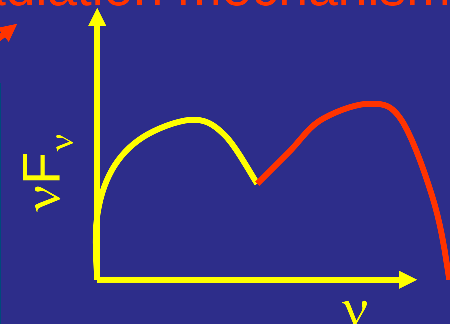


Relativistic jet outflow with $\Gamma \approx 10$



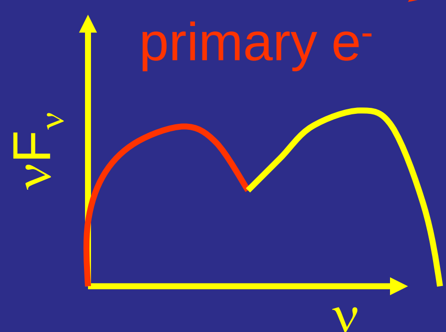
(Mannheim & Biermann 1992; Aharonian 2000; Mücke et al. 2000; Mücke et al. 2003)

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 …

Synchrotron emission of primary e^-



Requirements for lepto-hadronic models

- To exceed p-γ pion production threshold on interactions with synchrotron (optical) photons: $E_p > 7x10^{16} E^{-1}_{ph,eV}$ eV
- For proton synchrotron emission at multi-GeV energies: E_p up to ~ 10^{19} eV (=> UHECR)
- Require Larmor radius

  $r_L \sim 3x10^{16} E_{19}/B_G$ cm ≤ a few x 10^{15} cm => $B \geq 10$ G

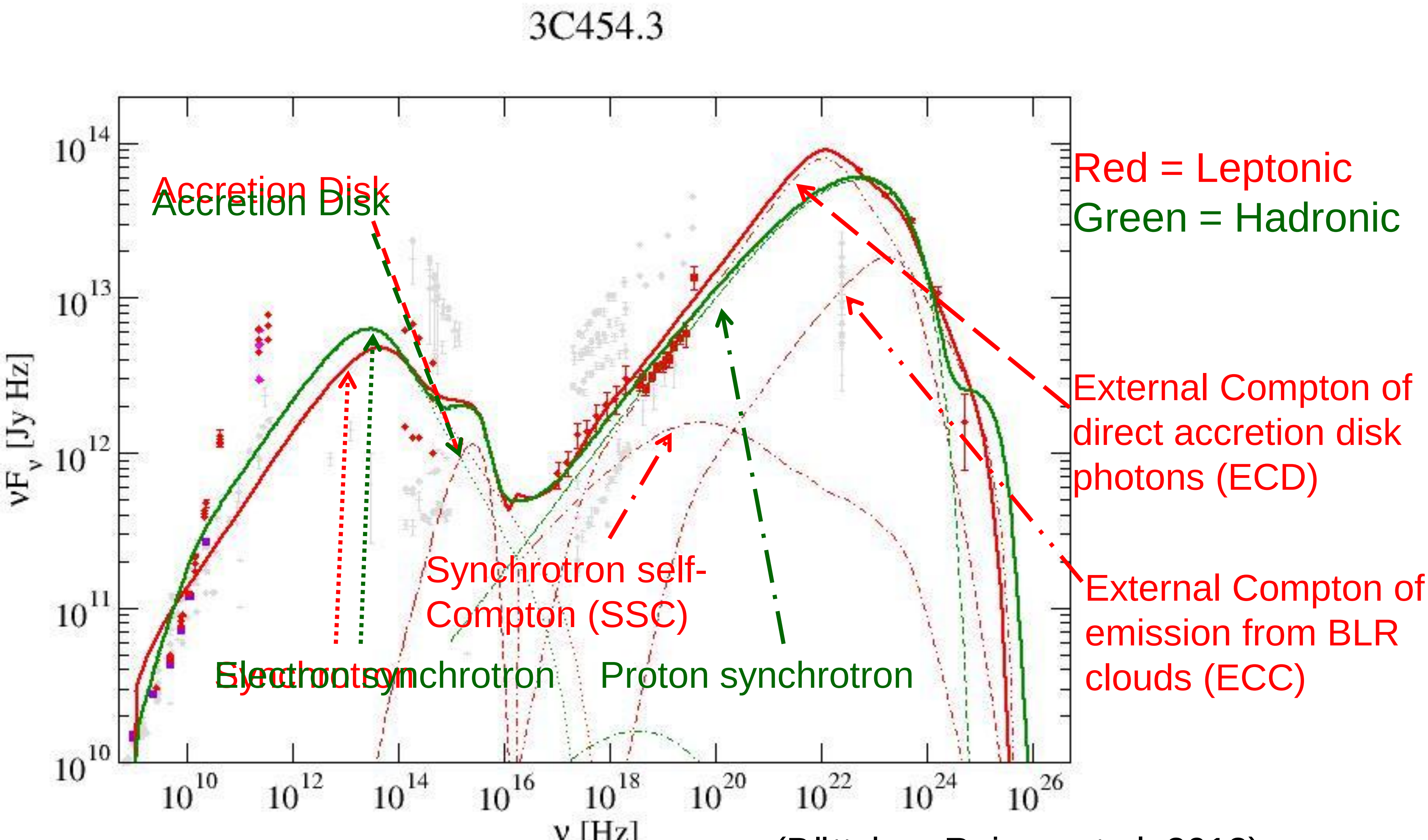
  (Also: to suppress leptonic SSC component below synchrotron)

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

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

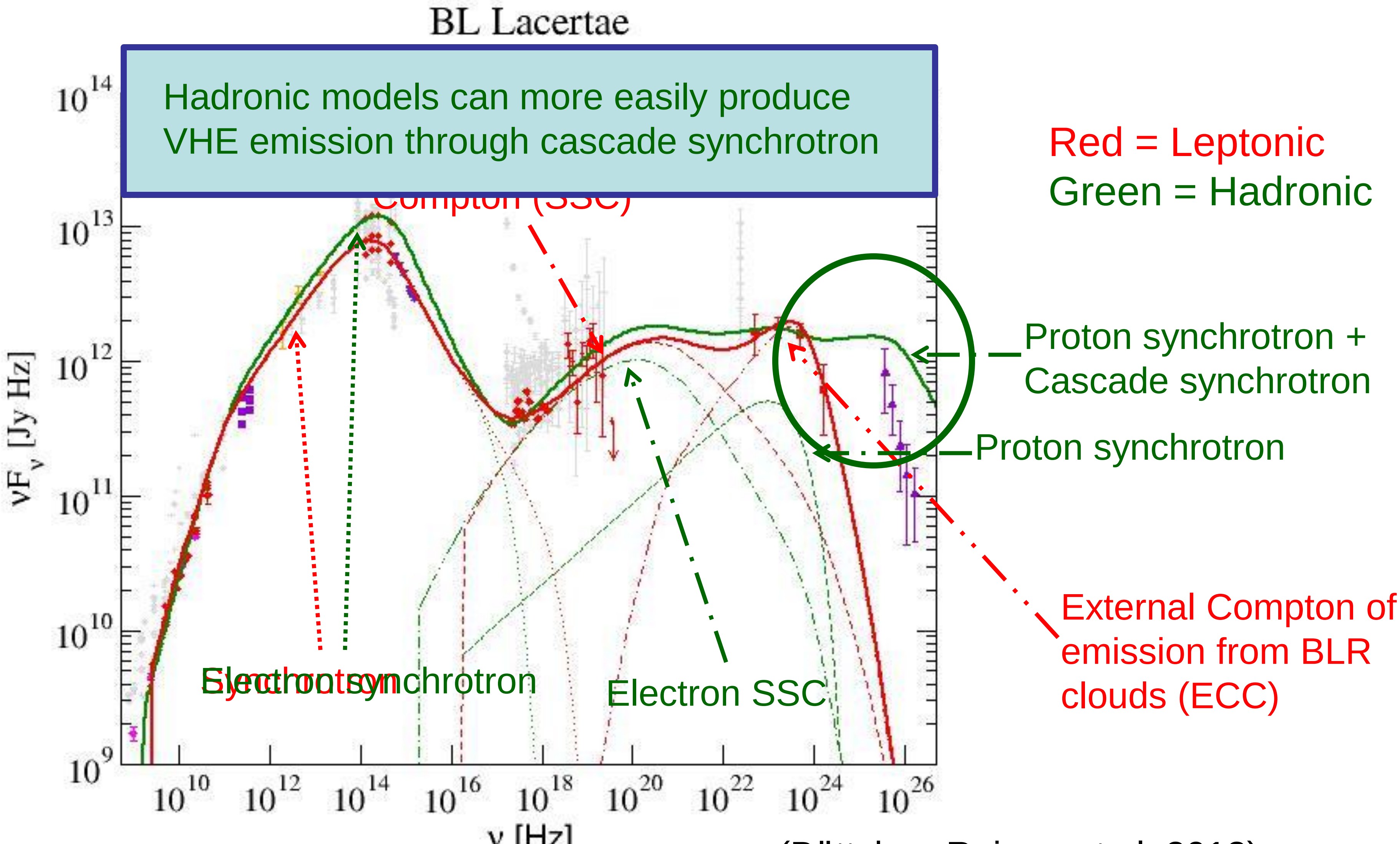
  → Geometrical effects?

Leptonic and Hadronic Model Fits along the Blazar Sequence



(Böttcher, Reimer et al. 2013)

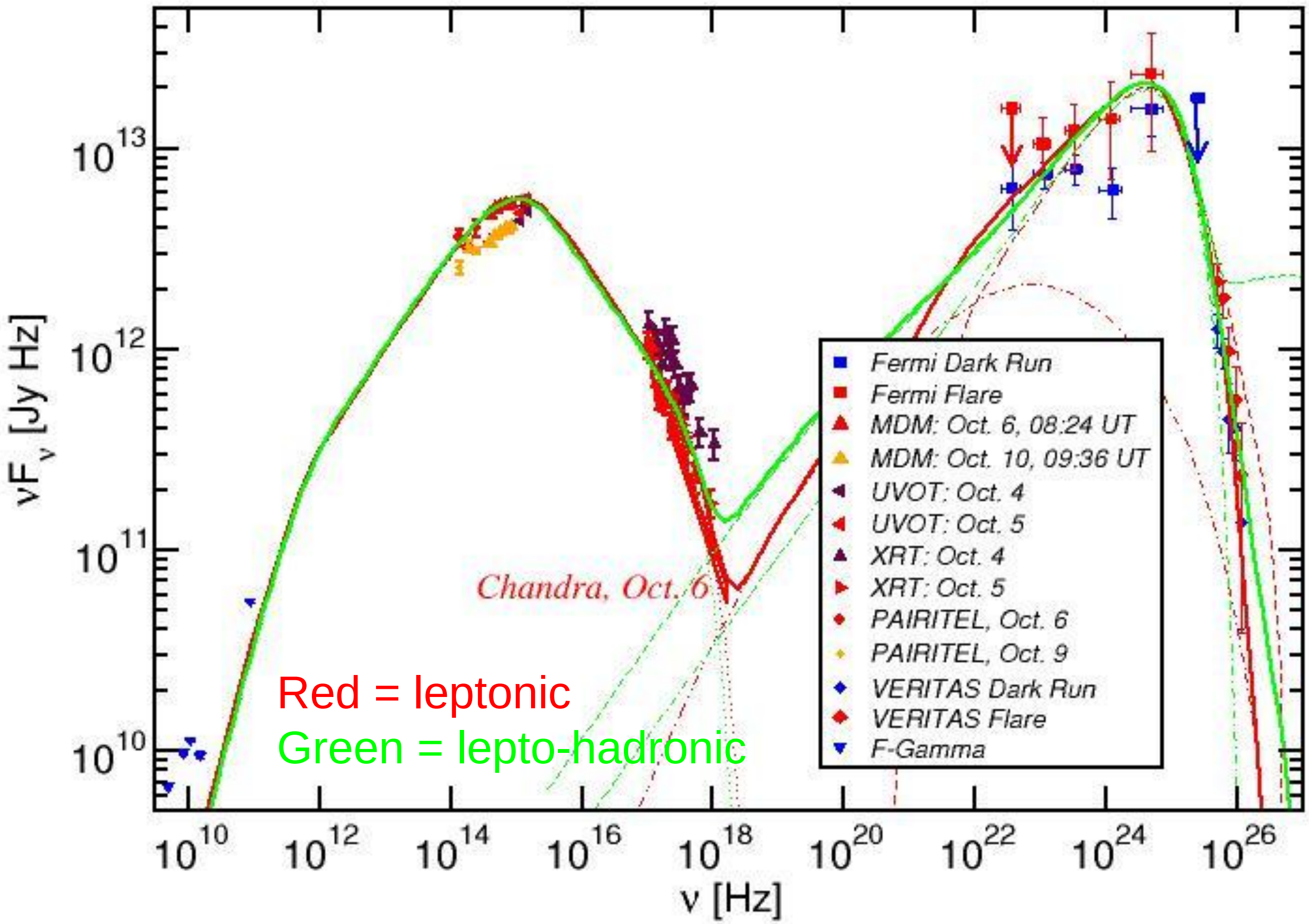
Leptonic and Hadronic Model Fits along the Blazar Sequence



(Böttcher, Reimer et al. 2013)

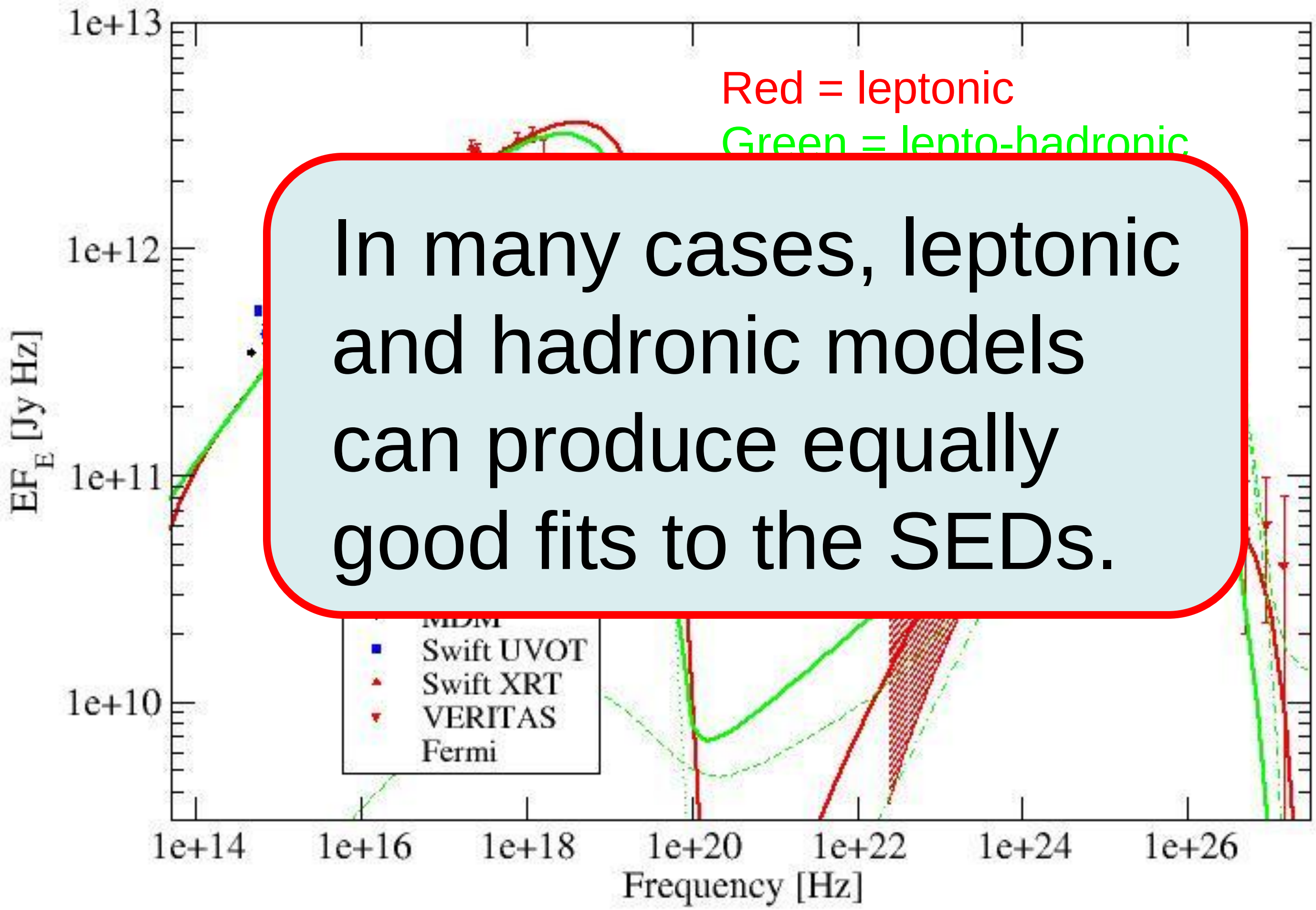
Leptonic and Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)



Lepto-Hadronic Model Fits Along the Blazar Sequence

RGB J0710+591 (HBL)



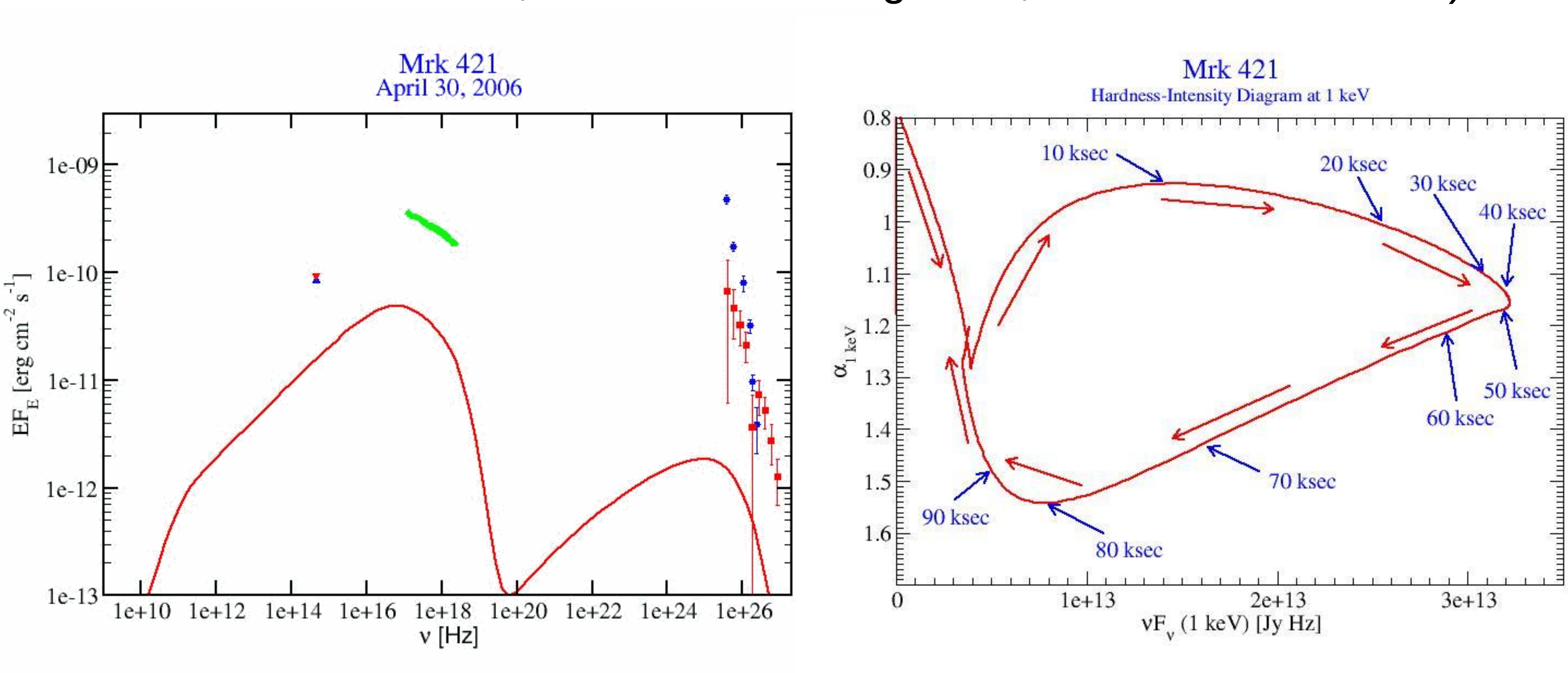
In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Possible Diagnostics to distinguish:

- Neutrinos
- Variability
- Polarization(?)

Distinguishing Diagnostic: Variability

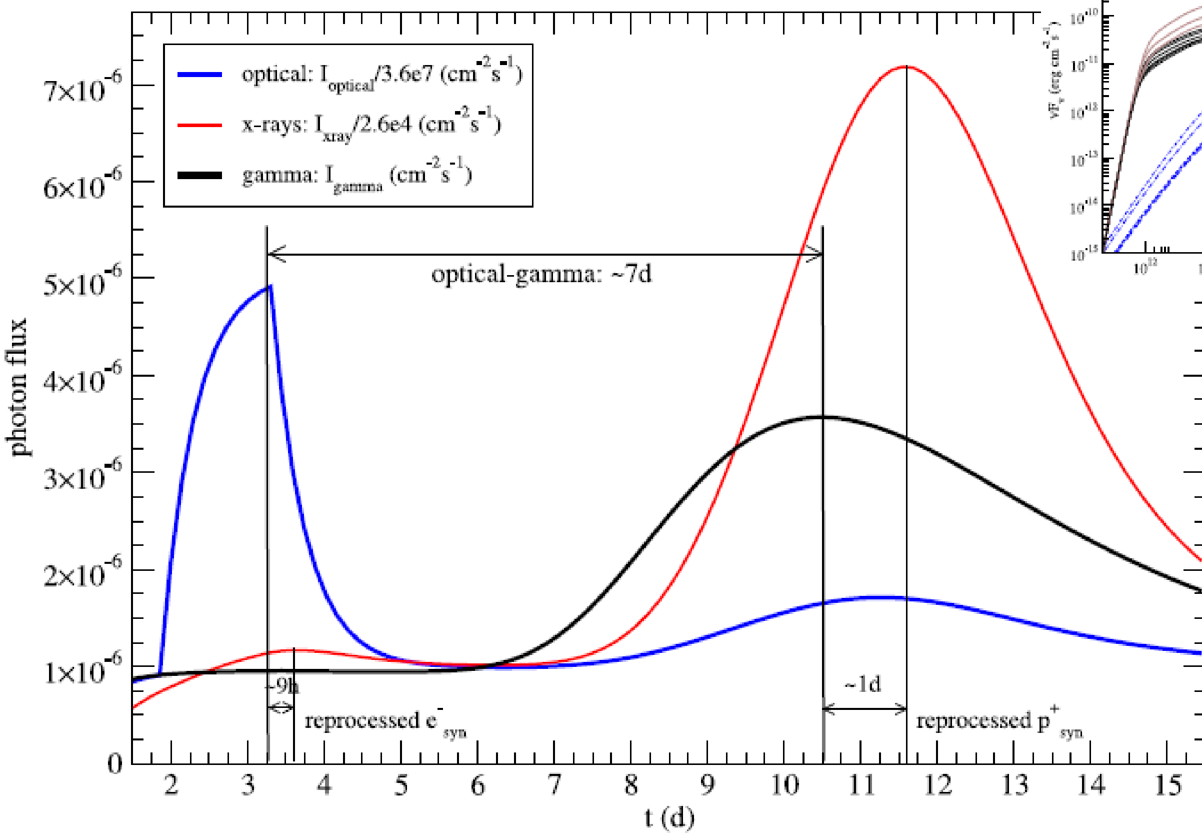
- Time-dependent leptonic one-zone models produce correlated synchrotron + gamma-ray variability (Mastichiadis & Kirk 1997, Li & Kusunose 2000, Böttcher & Chiang 2002, Moderski et al. 2003)

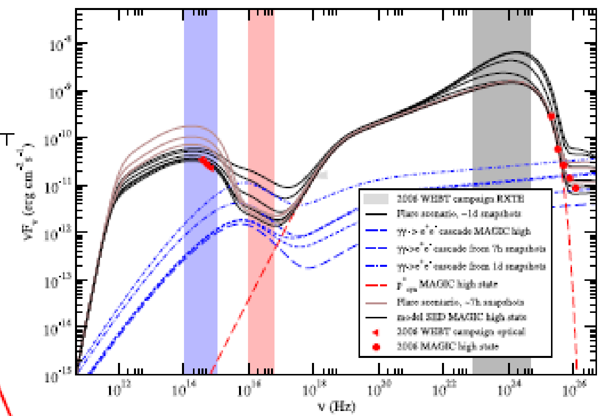


Time-dependent leptonic one-zone model for Mrk 421

Distinguishing Diagnostic: Variability

- Time-dependent hadronic models can produce uncorrelated variability / orphan flares (Dimitrakoudis et al. 2012, Mastichiadis et al. 2013, Weidinger & Spanier 2013)

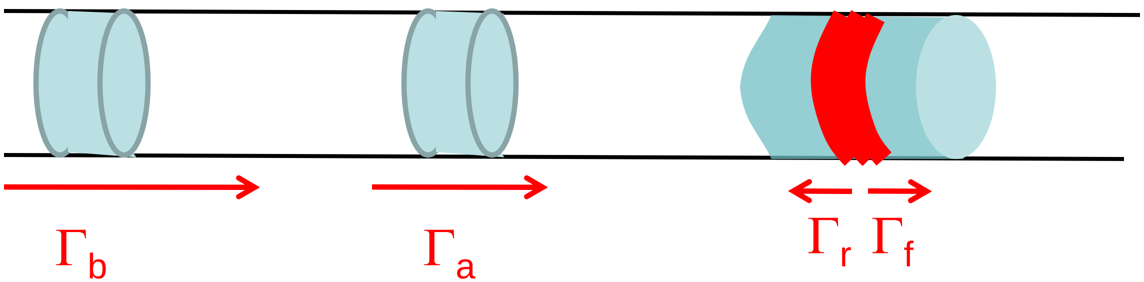




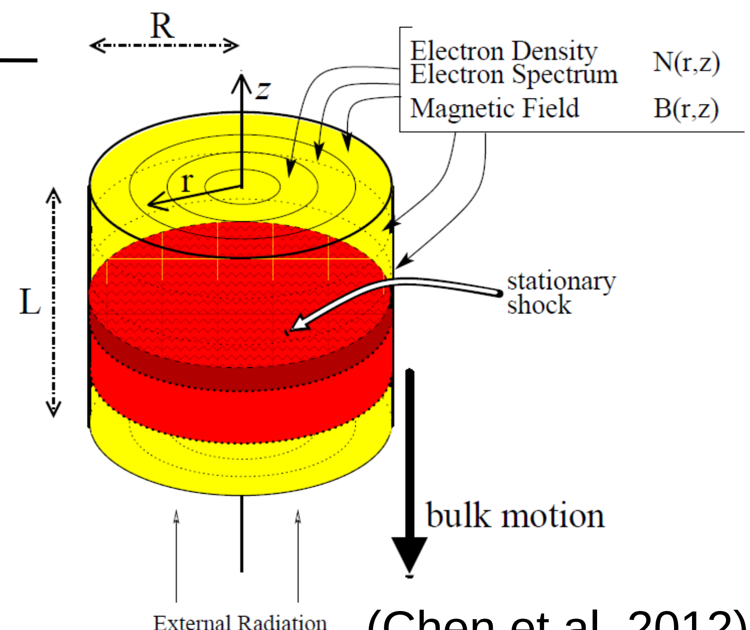
(M. Weidinger)

The Internal Shock Model

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 $\gamma_1 < \gamma < \gamma_2$



(Chen et al. 2012)

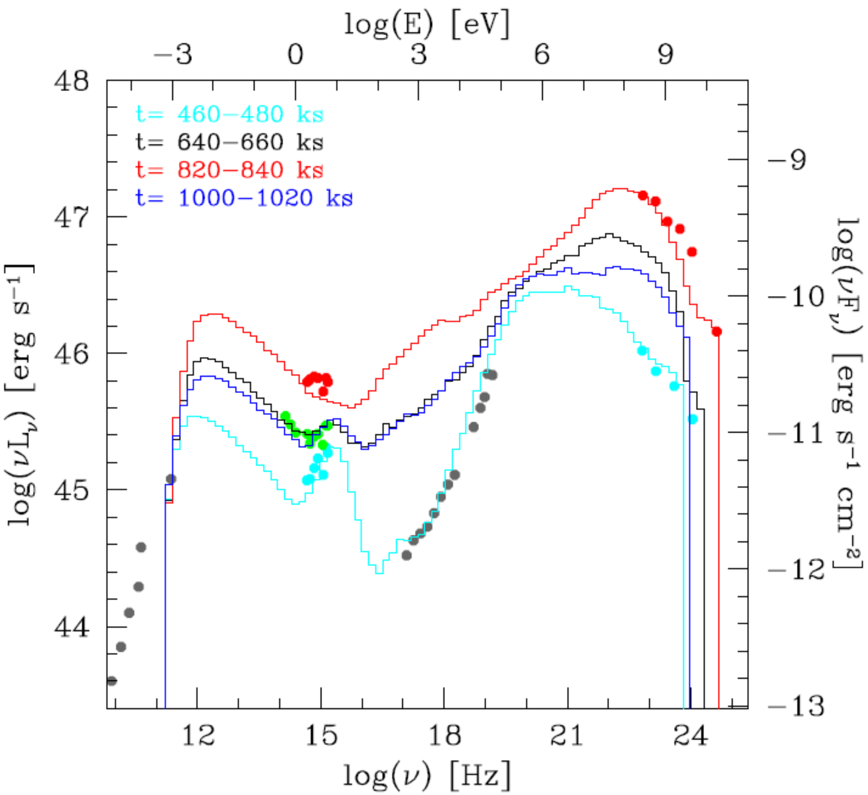
Time-dependent, inhomogeneous radiation transfer

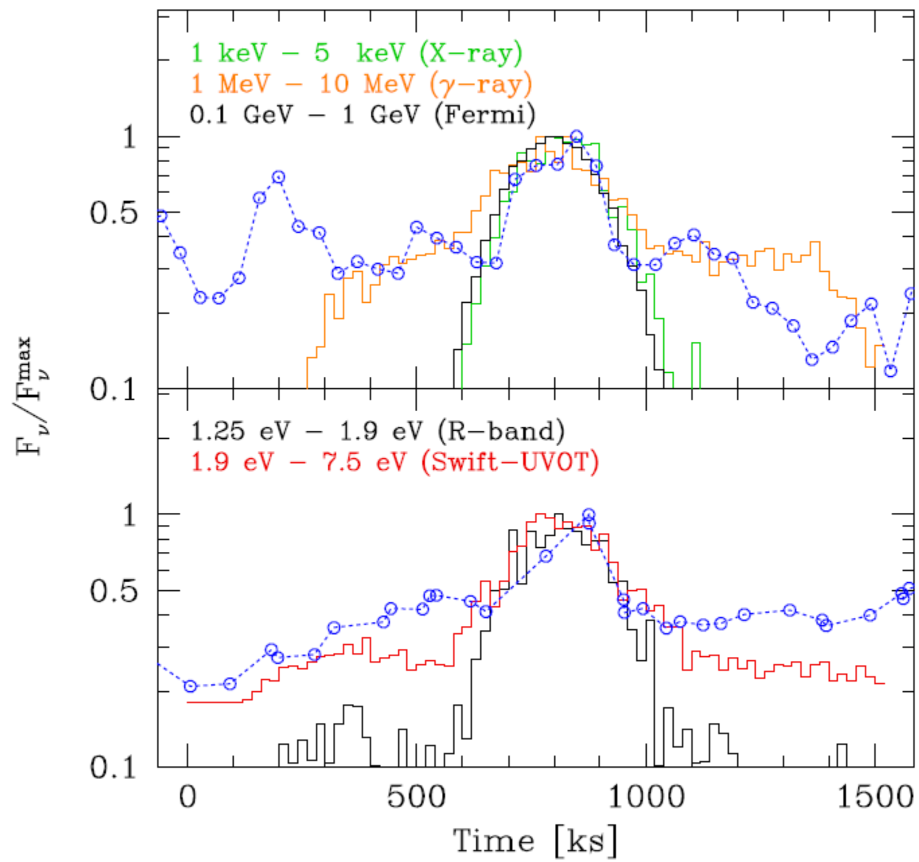
- Synchrotron
- SSC (→ Light travel time effects!)
- External Compton

Sokolov et al. (2004), Mimica et al. (2004), Sokolov & Marscher (2005), Graff et al. (2008), Böttcher & Dermer (2010), Joshi & Böttcher (2011), Chen et al. (2011, 2012)

Internal Shock Model

Time-dependent SED and light curve fits to PKS 1510-089
(SSC + EC[BLR])





(Chen et al. 2012)

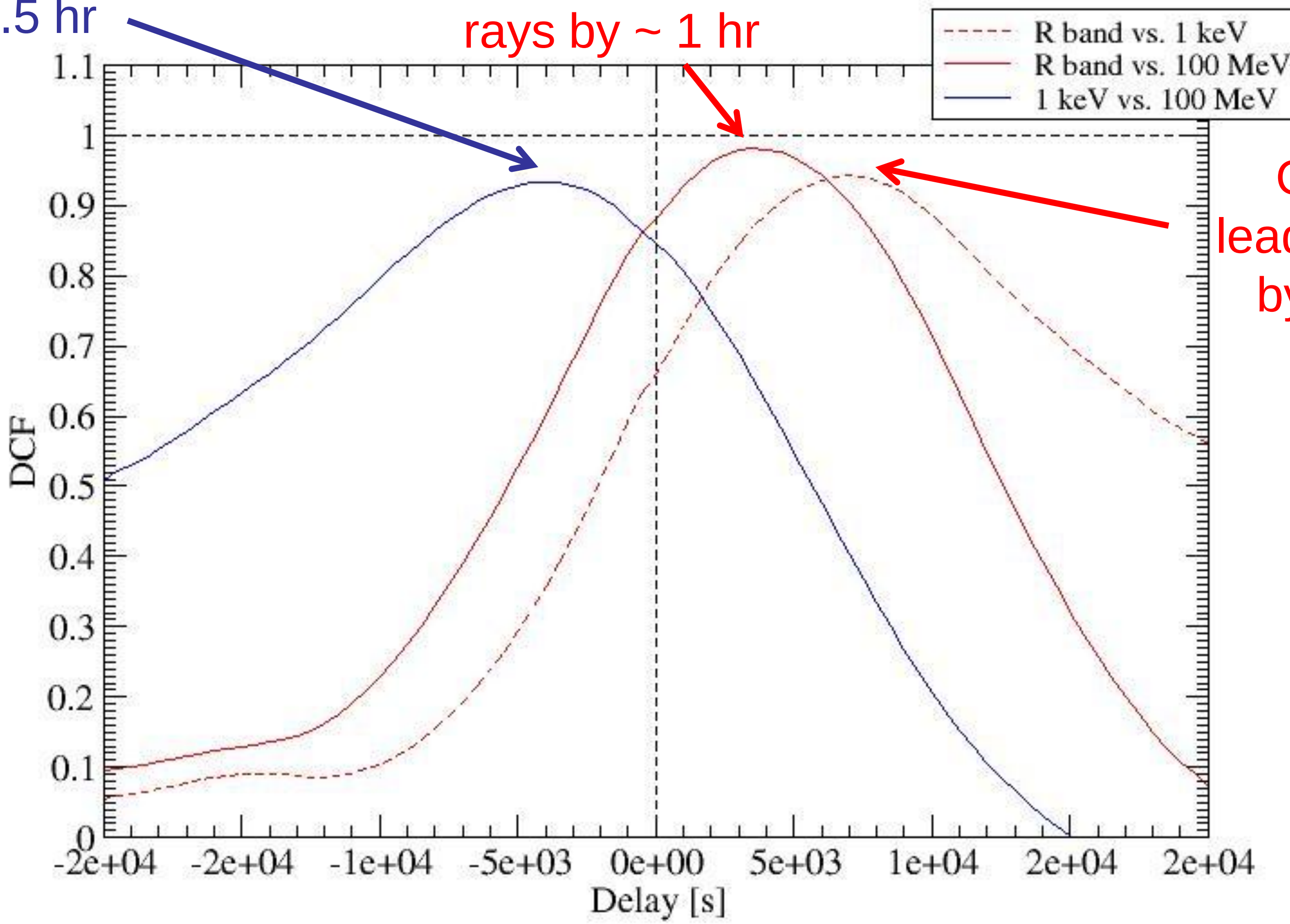
Internal Shock Model

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

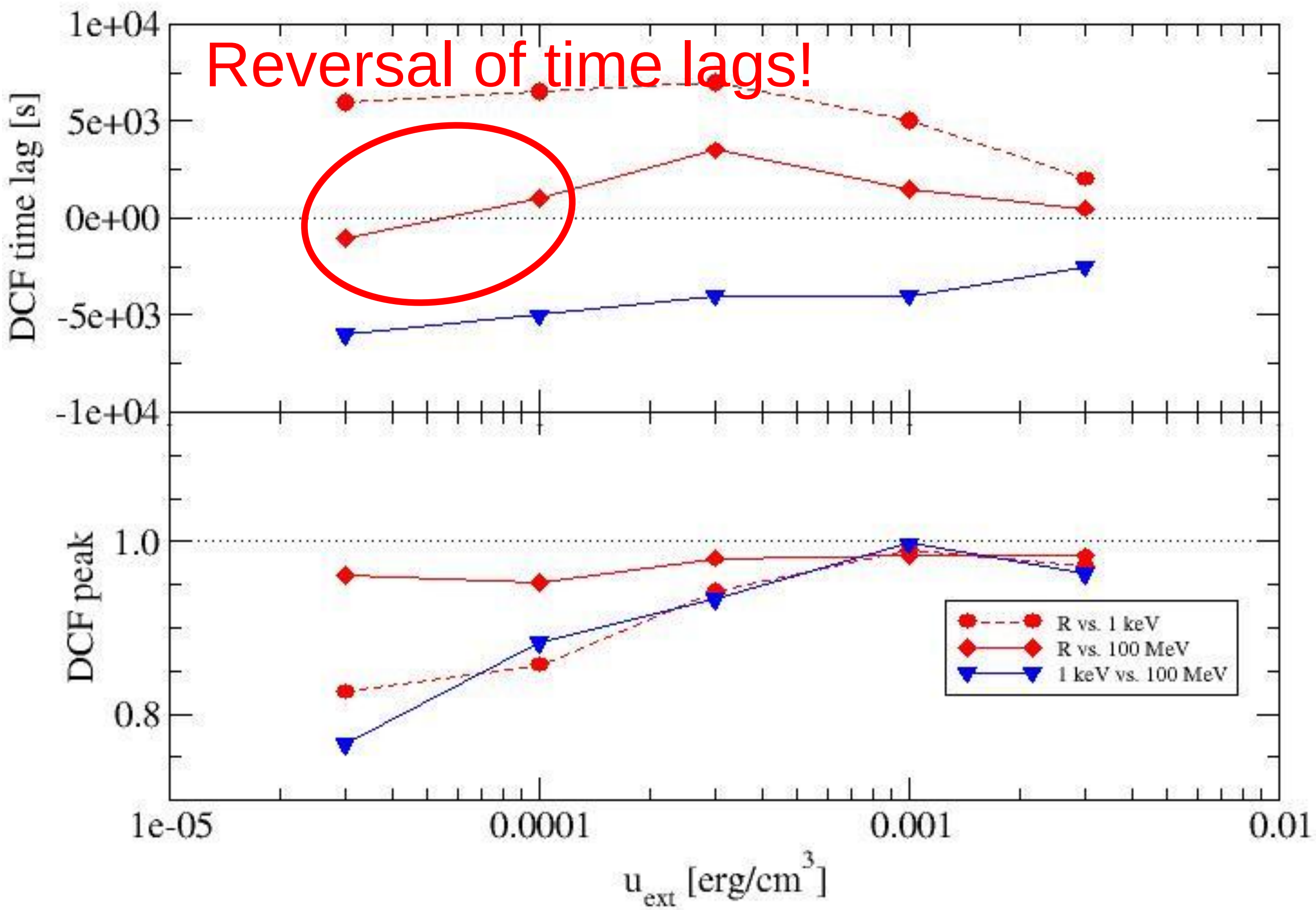


(Böttcher & Dermer 2010)

Parameter Study

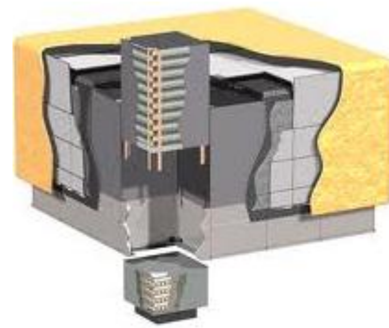
Varying the External Radiation Energy Density

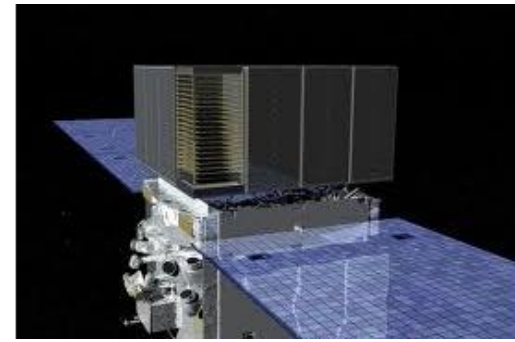
DCFs / Time Lags



(Böttcher & Dermer 2010)

Possible Distinguishing Diagnostic: X-Ray and Gamma-Ray Polarization





Upper limits on high-energy polarization, assuming perfectly ordered magnetic field perpendicular to the line of sight

- Synchrotron polarization:

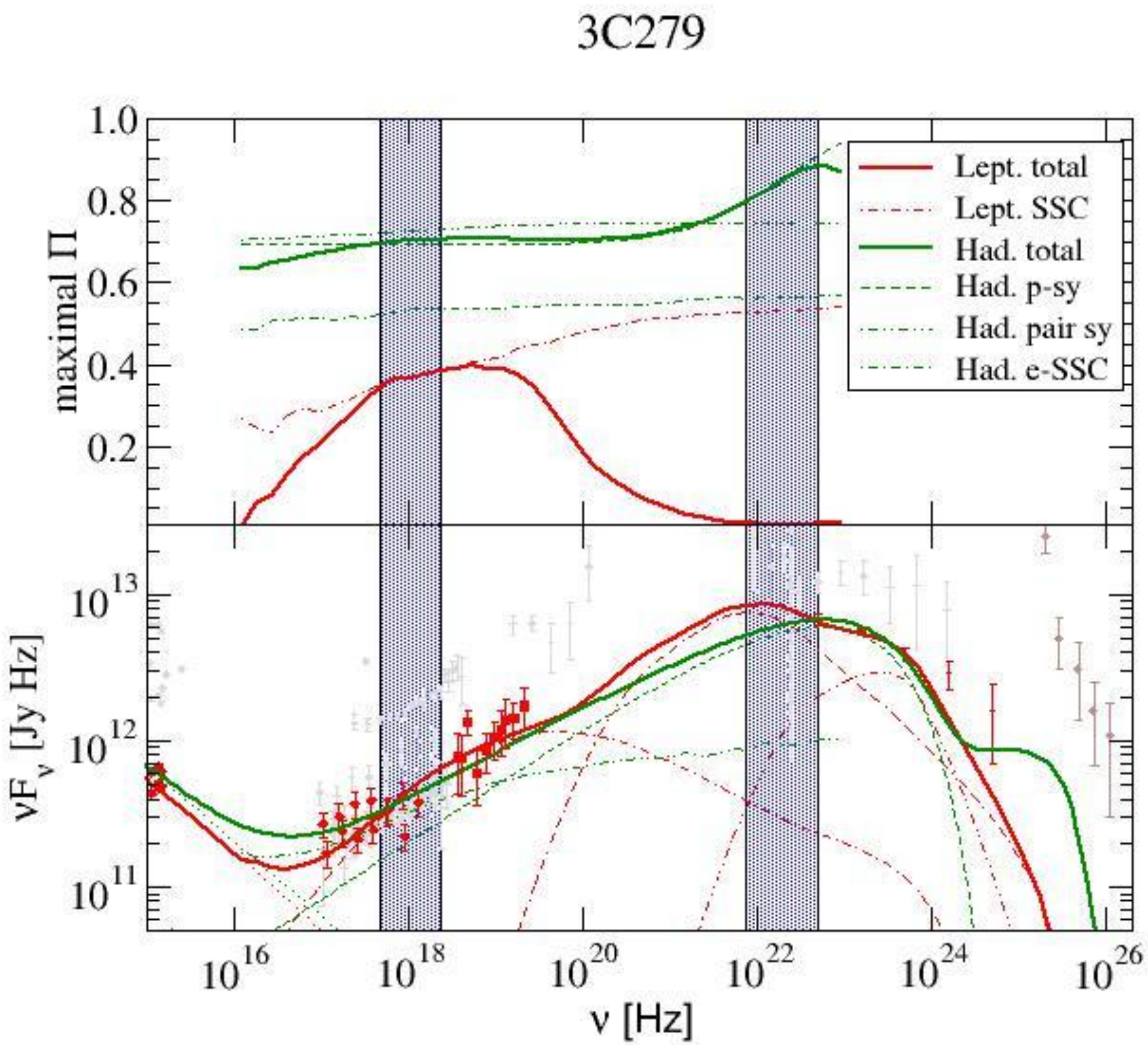
  Standard Rybicki & Lightman description

- SSC Polarization:

  Bonometto & Saggion (1974) for Compton scattering in Thomson regime

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: FSRQs

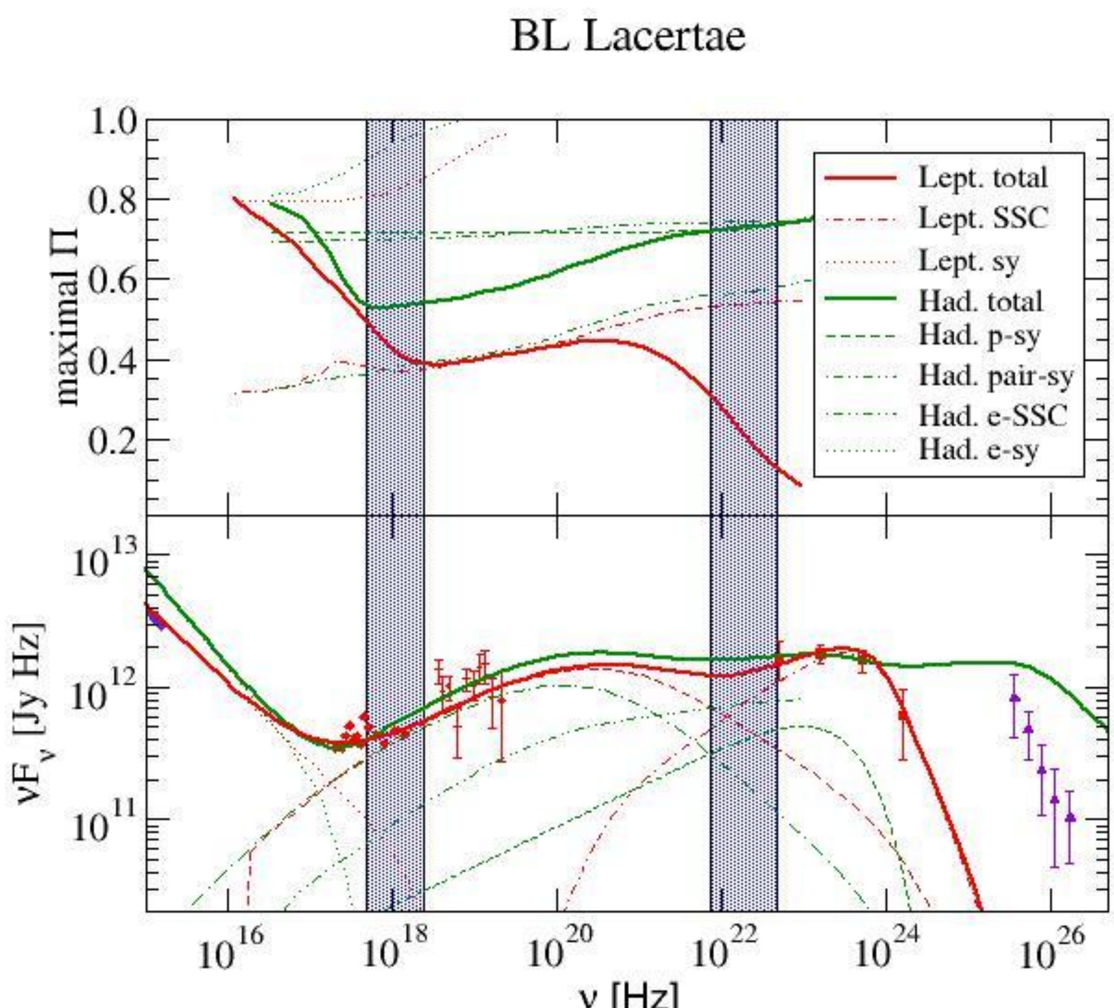


Hadronic model: Synchrotron dominated => High Π, generally increasing with energy (SSC contrib. in X-rays).

Leptonic model: X-rays SSC dominated: Π ~ 20 – 40 %; γ-rays EC dominated => Negligible Π.

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: LBLs

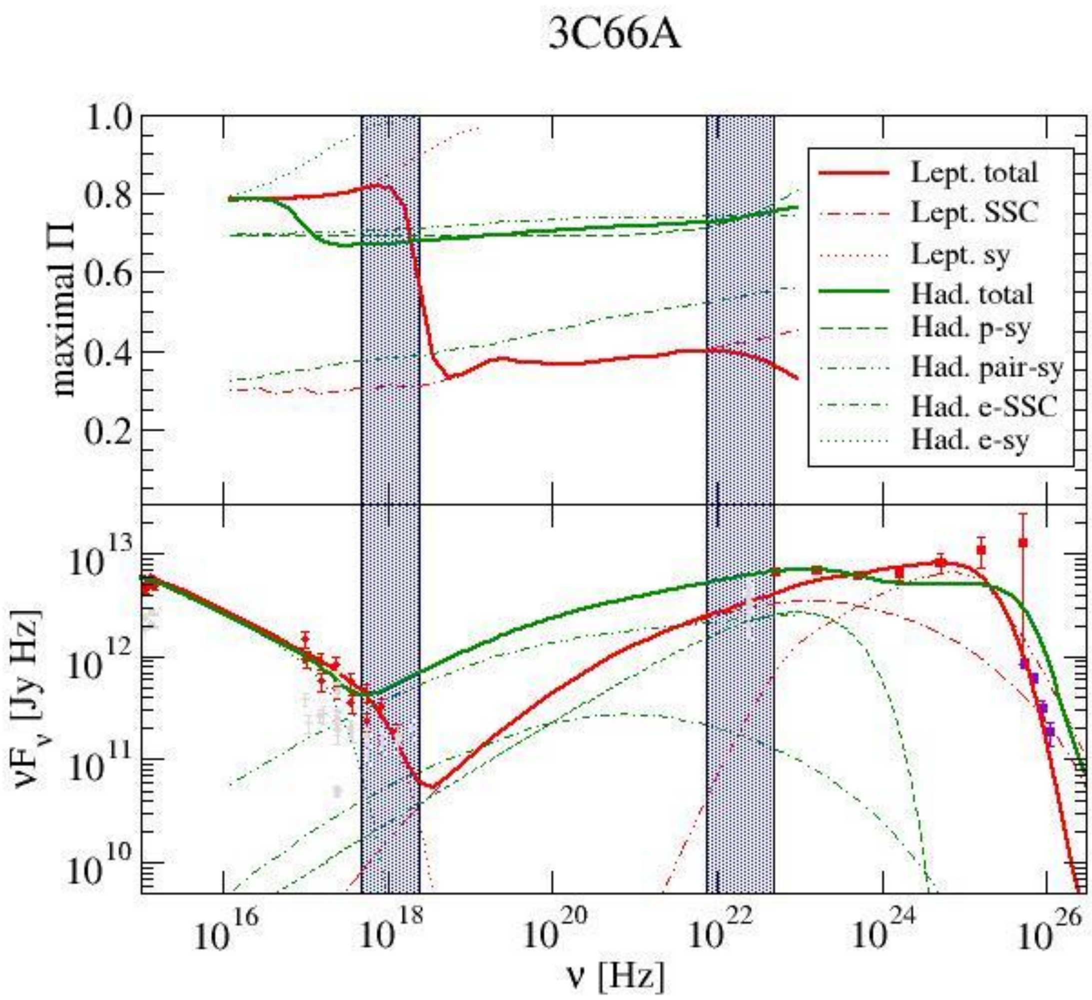


Hadronic model:
Mostly synchrotron dominated => High Π, except for X-rays, where SSC may dominate.

Leptonic model:
X-rays = transition from sy. to SSC:
Π rapidly decreasing with energy;
γ-rays EC dominated
=> Negligible Π.

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: IBLs

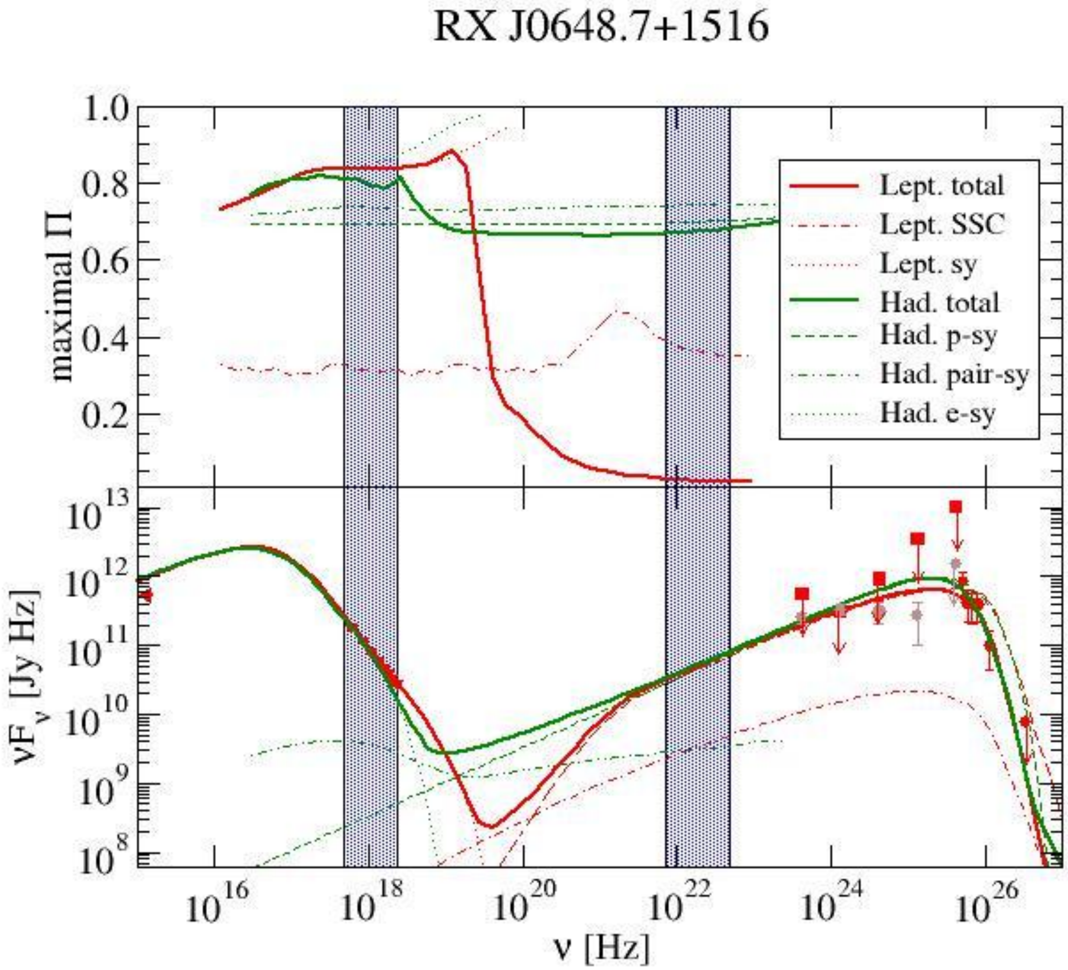


Hadronic model: Synchrotron dominated => High Π, throughout X-rays and γ-rays

Leptonic model: X-rays sy. Dominated => High Π, rapidly decreasing with energy; γ-rays SSC/EC dominated => Small Π.

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: HBLs



Hadronic model:
Synchrotron dominated
=> High Π

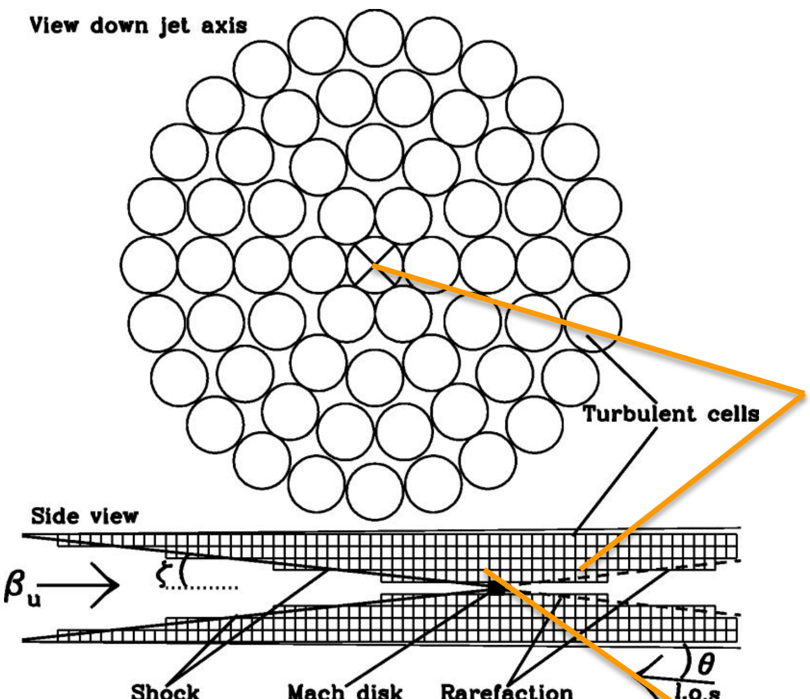
Leptonic model:
X-rays sy. Dominated =>
High Π, rapidly
decreasing with energy;
γ-rays SSC/EC dominated
=> Small Π.

(Zhang & Böttcher, 2013)

Partially Dis-ordered Magnetic Fields

→ Turbulent Extreme Multi-zone (TEMZ) Model (Marscher 2012)

- Many turbulent cells across jet cross-section;
- Each cell has random B direction;
- Explain rapid variability on > pc scales by only a small fraction of cells being active

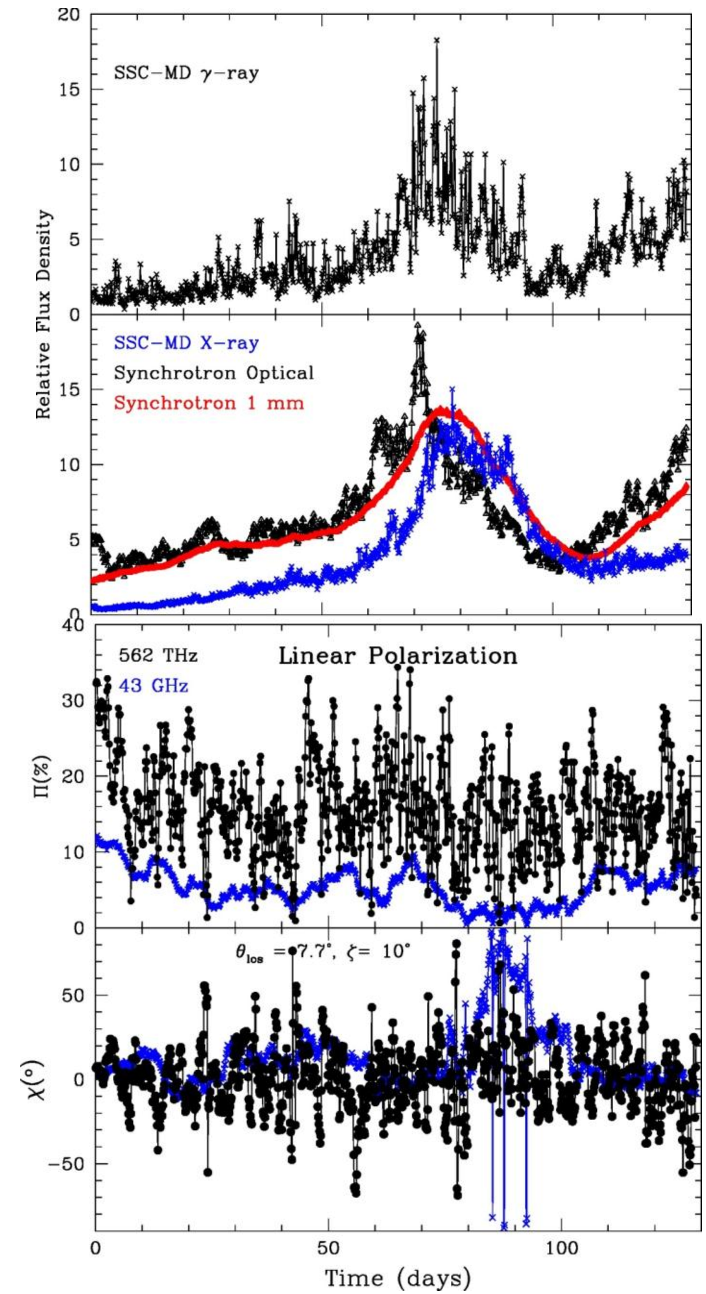


Mach disk

Looking at the jet from the side

Conical standing shock

(A. Marscher)

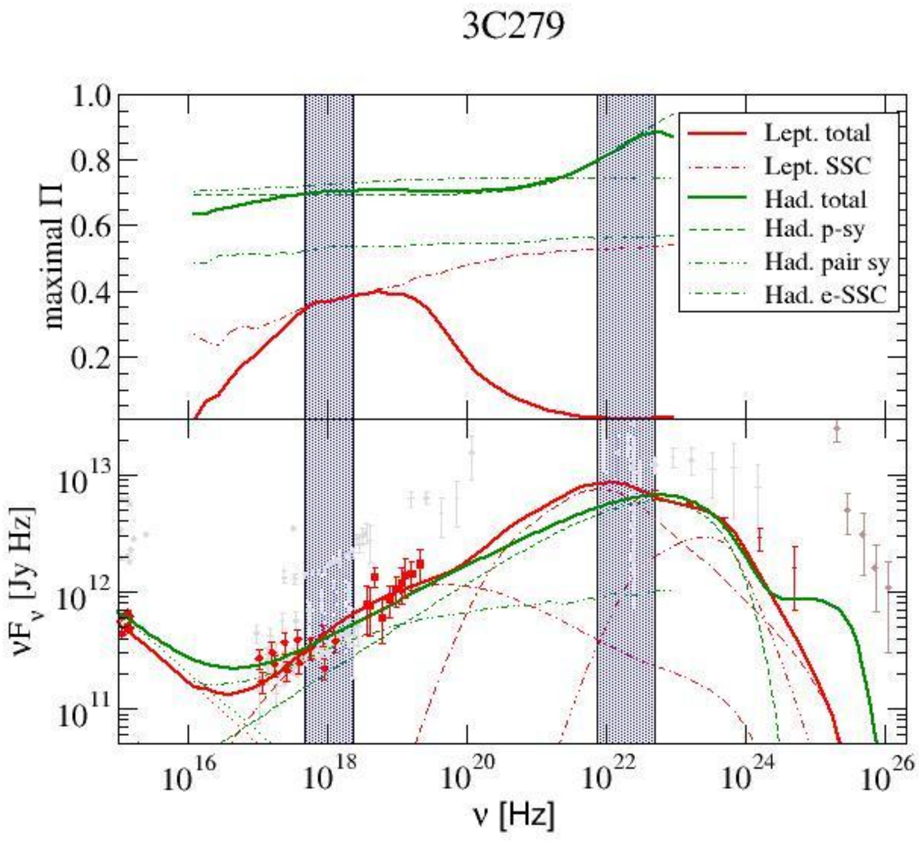


Observational Strategy

- Results shown here are **upper limits** (perfectly ordered magnetic field perpendicular to line of sight)

- Scale results to actual B-field configuration from known synchrotron polarization (e.g., optical for FSRQs/LBLs) => Expect 10 - 20 % X-ray and γ-ray polarization in hadronic models!

- X-ray and γ-ray polarization values substantially below synchrotron polarization will favor leptonic models, measurable γ-ray polarization clearly favors hadronic models!



Summary

1. Both leptonic and hadronic models can generally fit blazar SEDs well.

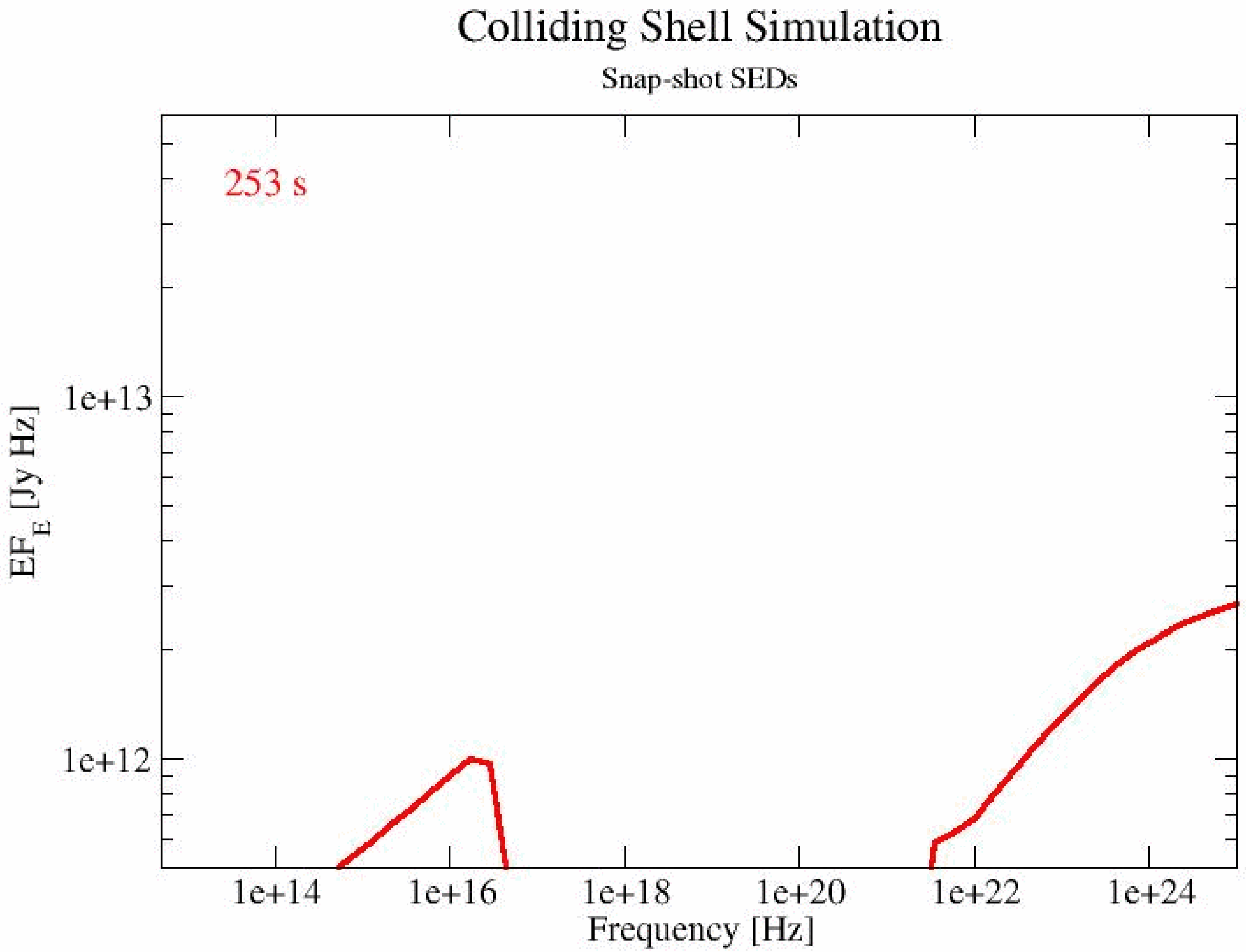
2. Distinguishing diagnostics: Variability, Polarization, Neutrinos?

3. Time-dependent hadronic models are able to predict uncorrelated synchrotron vs. gamma-ray variability

4. X-Ray / Gamma-Ray polarimetry as potential diagnostic? Hadronic Models predict high degree of X/gamma polarization

Internal Shock Model

Parameters / SED characteristics typical of FSRQs or LBLs



(Böttcher & Dermer 2010)