# Leptonic and Hadronic Modeling of Gamma-Ray Blazars


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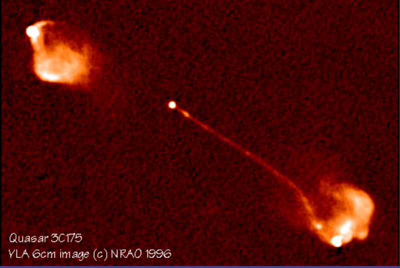
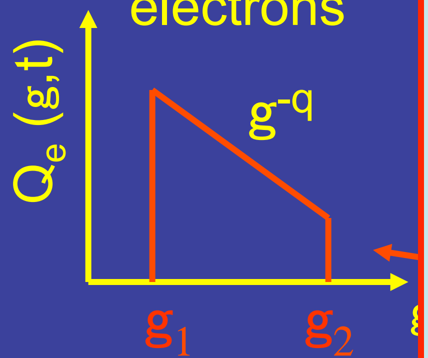
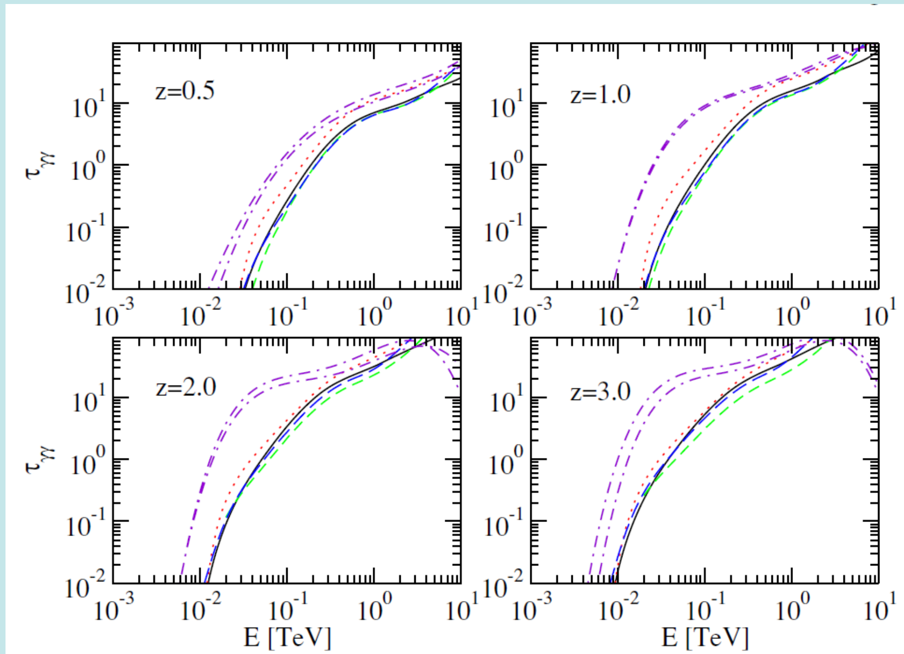
# Leptonic Blazar Model



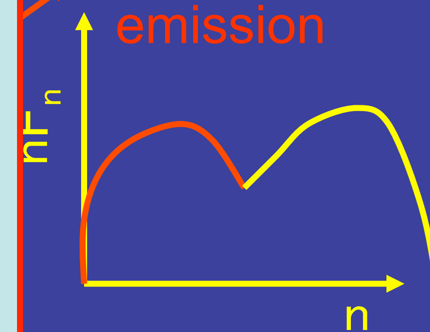

Injection, acceleration of ultrarelativistic electrons



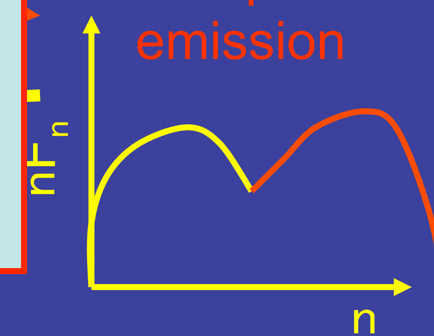




EBL Absorption: Finke et al. (2010)

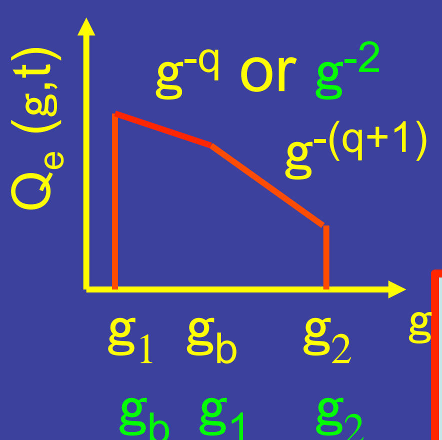
Synchrotron emission




Compton emission




Radiative cooling ↔ escape =>





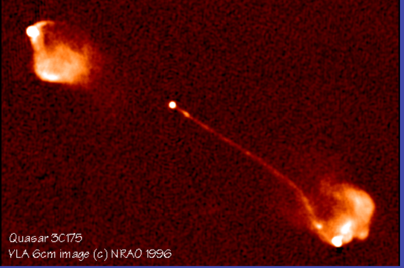
$g_b$:

$t_{cool}(g_b) = t_{esc}$

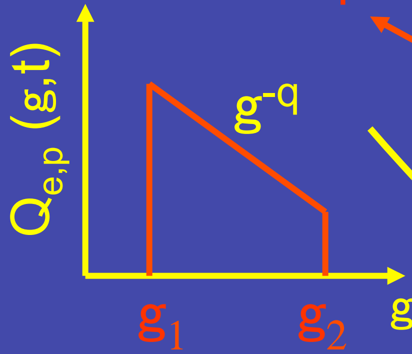
Seed photons:

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

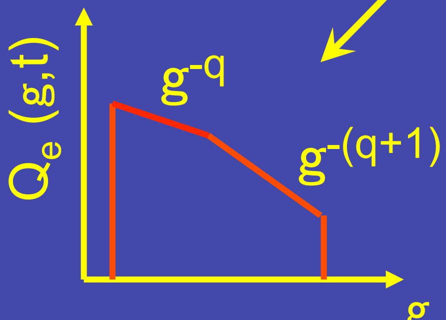
# Hadronic Blazar Model



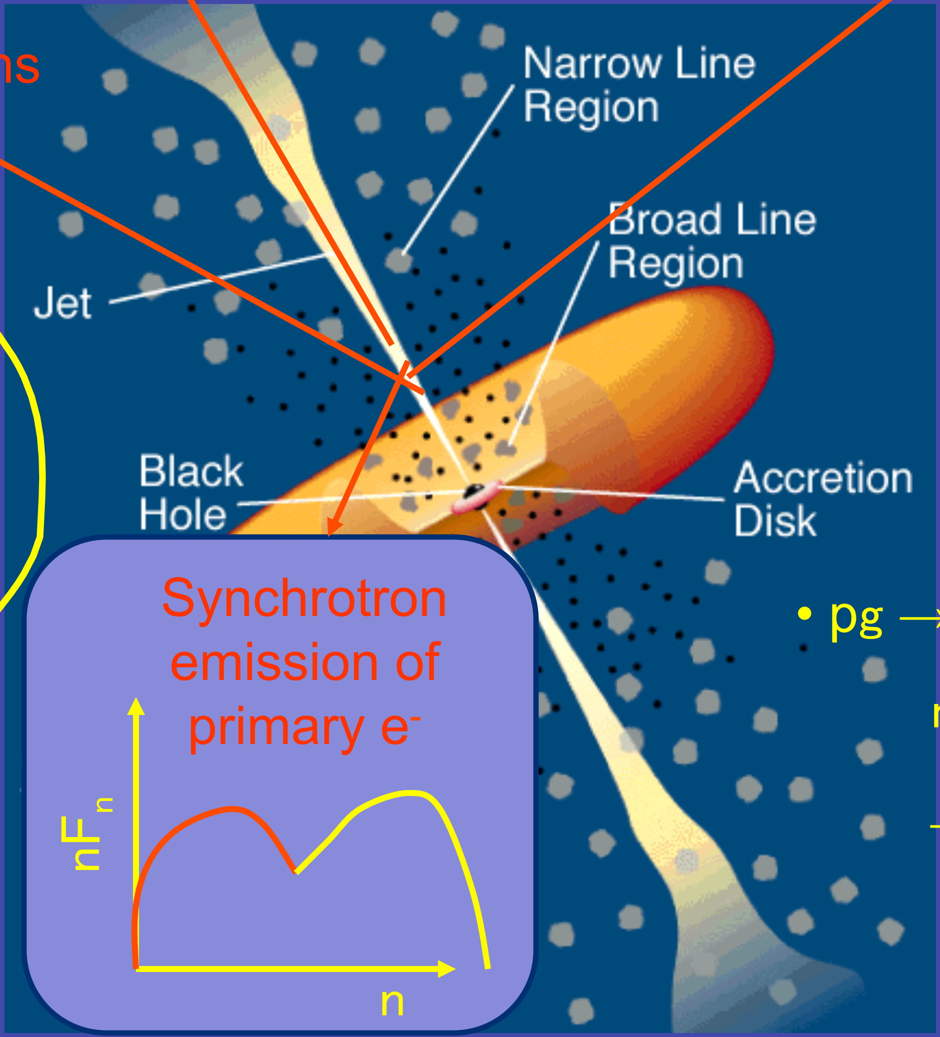

Injection, acceleration of ultrarelativistic electrons and protons



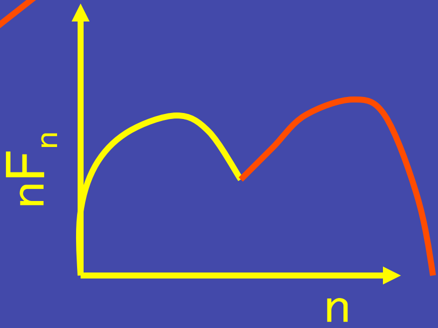

Radiative + adiabatic cooling




Relativistic jet outflow with G ≈ 10




Proton-induced radiation mechanisms:




- Proton synchrotron
- pg → pp$^0$
  p$^0$ → 2g
- pg → np$^+$ ; p$^+$ → m$^+$n$_m$
  m$^+$ → e$^+$n$_e$$\overline{\text{n}}_m$
  → secondary m-, e-synchrotron
- Cascades …

# Requirements for hadronic models

- To exceed p-g 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 ≤ a few x $10^{15}$ cm => $B \geq 10$ G
  (Also: to suppress leptonic SSC component below synchrotron)

# Semi-analytical hadronic model

- Primary $e^-$ synchrotron + SSC as for leptonic model
- Power-law injection spectrum of ultrarelativistic protons
- Proton spectrum: Quasi-equilibrium - injection; sy., pg, adiabatic cooling;
- Pro … trinos,

  $p^0$-c
- Ser

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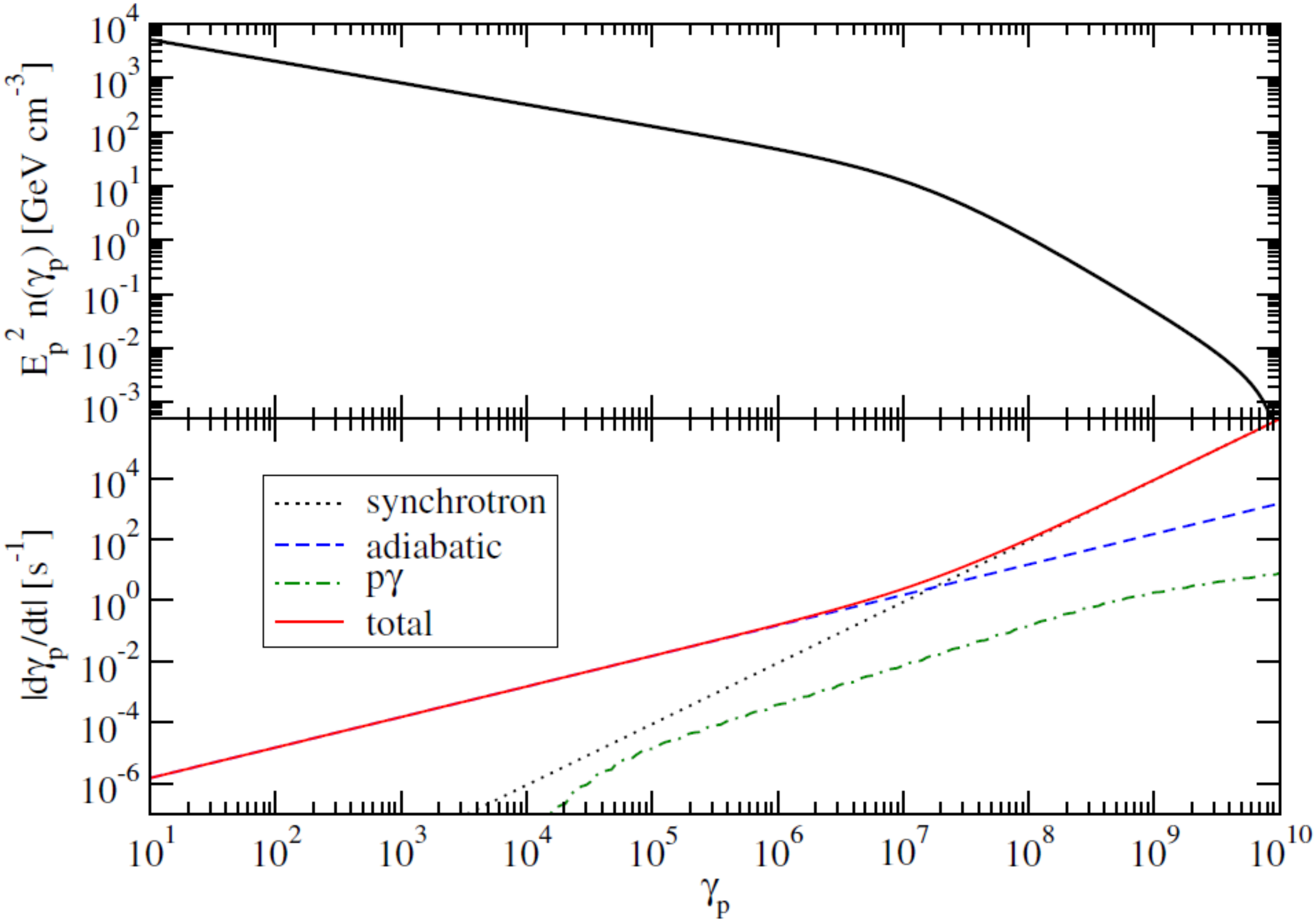
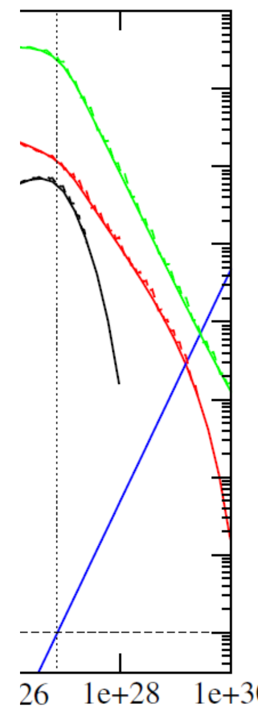
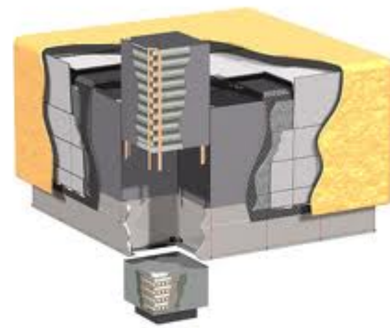
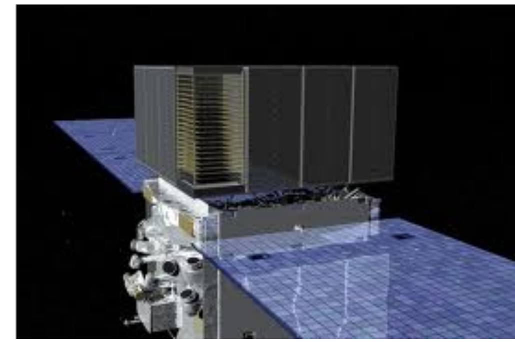


# X-Ray and Gamma-Ray Polarization

## For both leptonic and hadronic models:

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

- Synchrotron polarization:

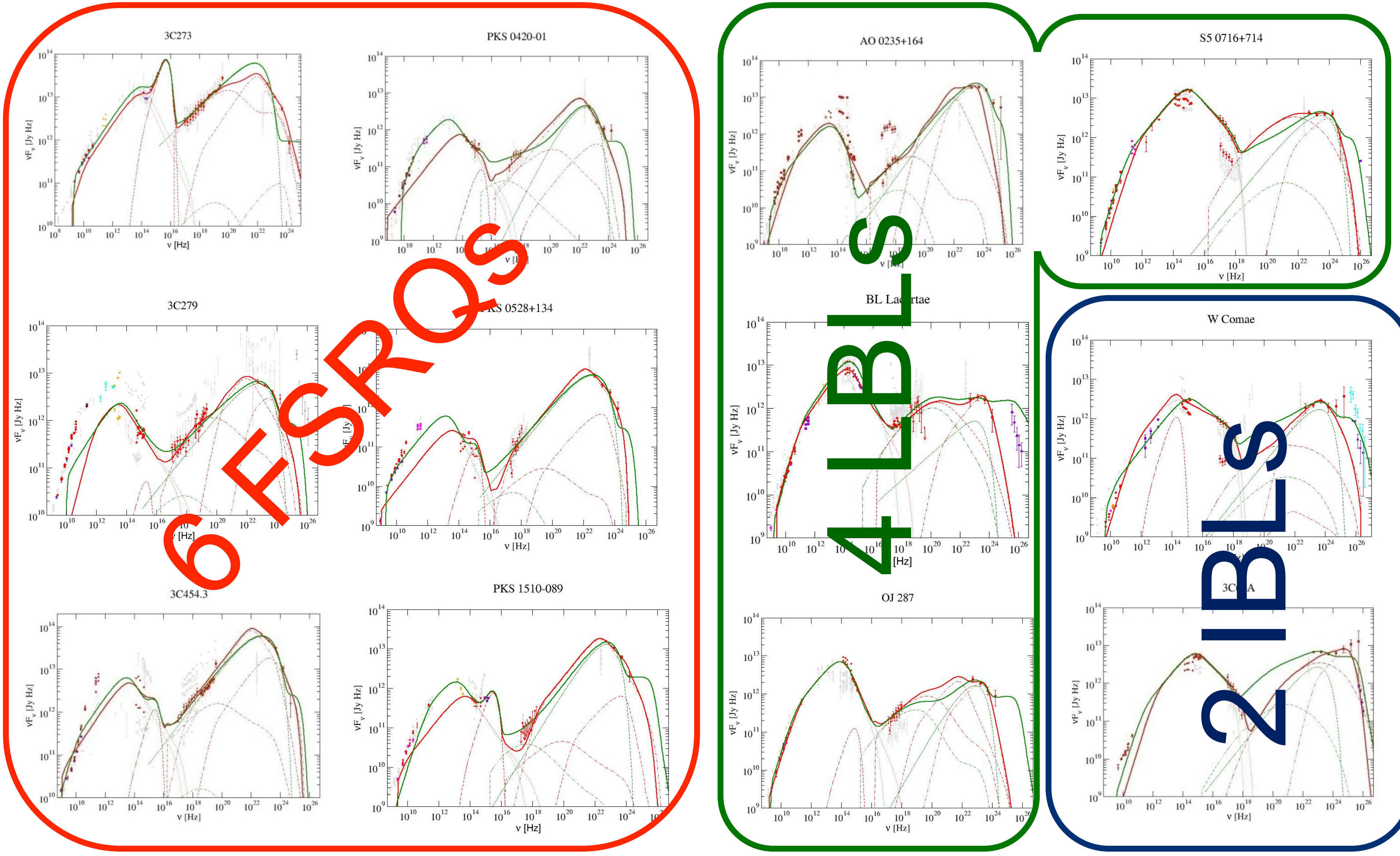
  Standard Rybicki & Lightman description

- SSC Polarization:

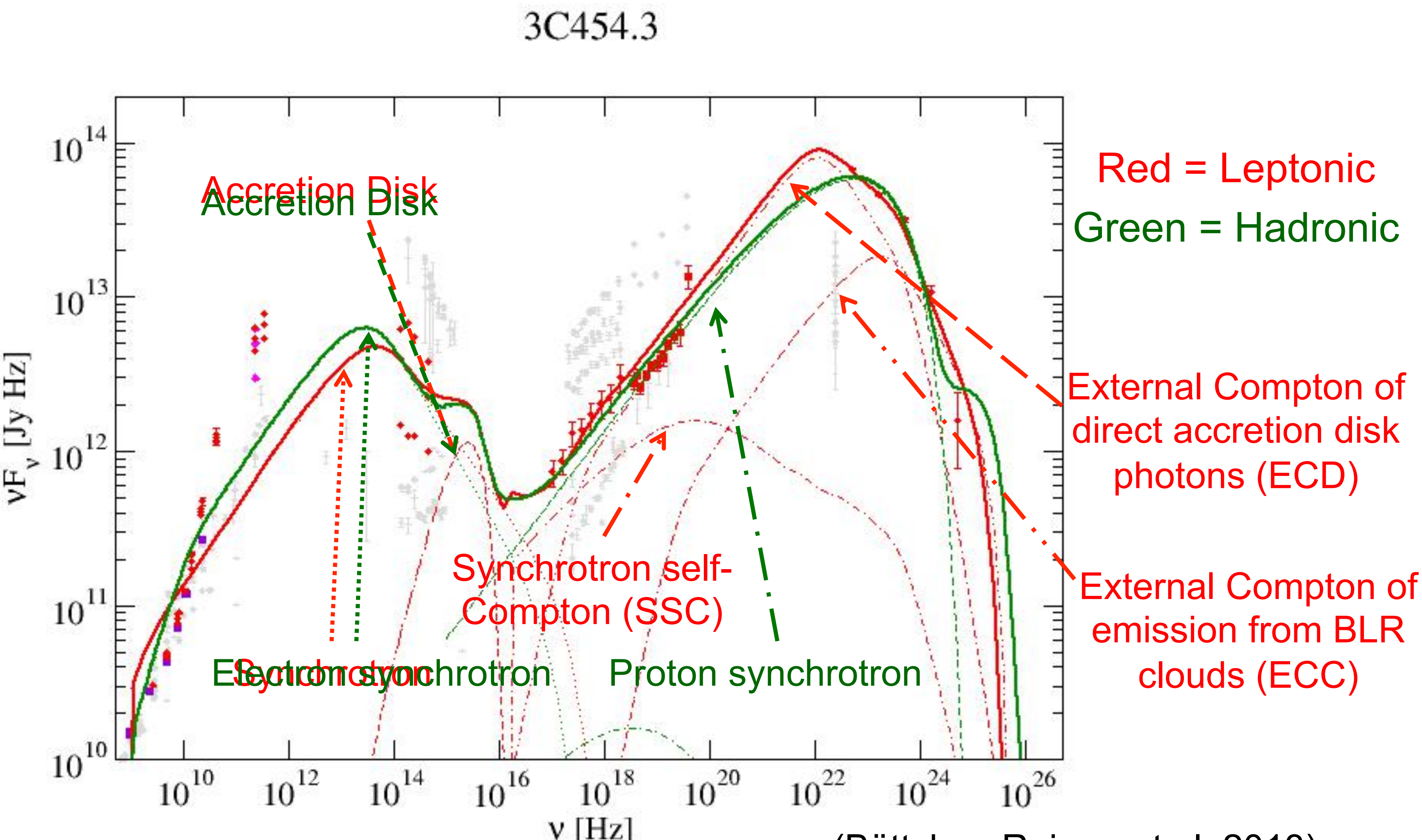
  Bonometto & Saggion (1974) for Compton scattering in Thomson regime

(Zhang & Böttcher, 2013, ApJ, submitted)

# Comparative Modeling of Gamma-Ray Blazars with Leptonic and Hadronic Models

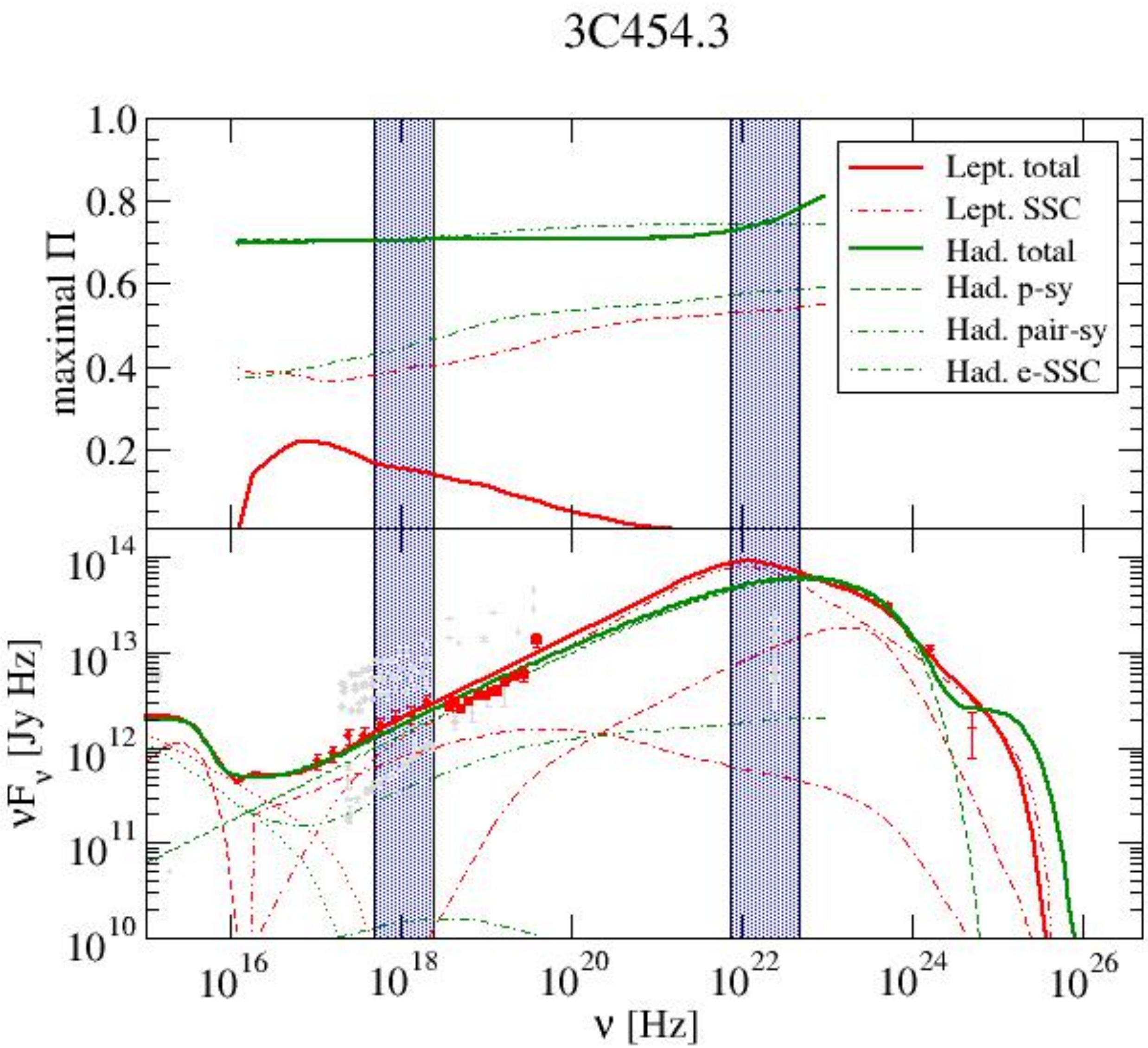


# Leptonic and Hadronic Model Fits to FSRQs




(Böttcher, Reimer et al. 2013)

# Polarization: 3C454.3

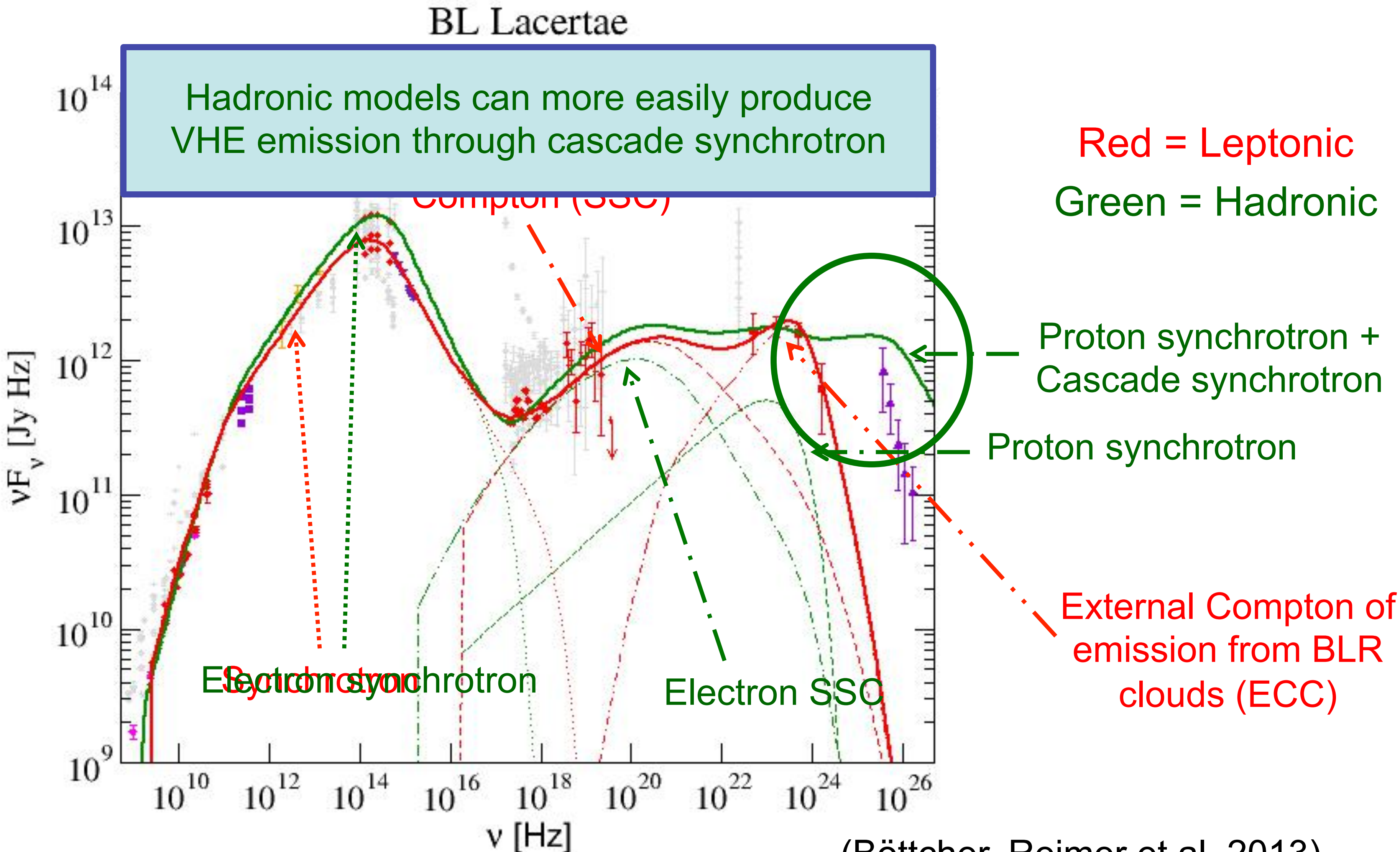



**Hadronic model:**
**Synchrotron dominated**
**=> High P**

**Leptonic model:**
**X-rays SSC dominated:**
**P ~ 20 %;**
**g-rays EC dominated**
**=> Negligible P.**

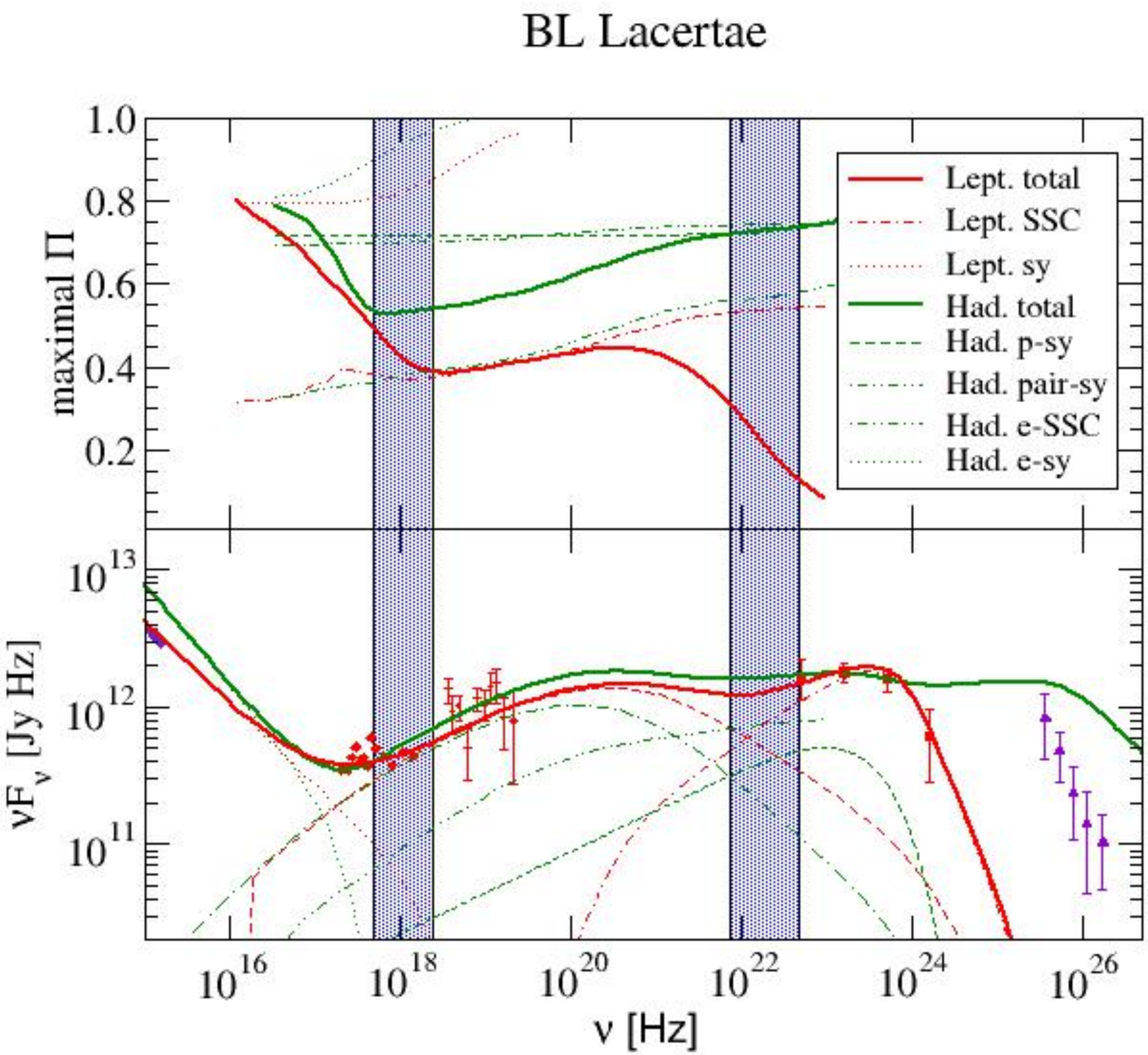
(Zhang & Böttcher 2013)

# Leptonic and Hadronic Model Fits to LBLs




(Böttcher, Reimer et al. 2013)

# Polarization: BL Lacertae




**Hadronic model:**

**Mostly synchrotron dominated => High P, except for X-rays, where SSC may dominate.**

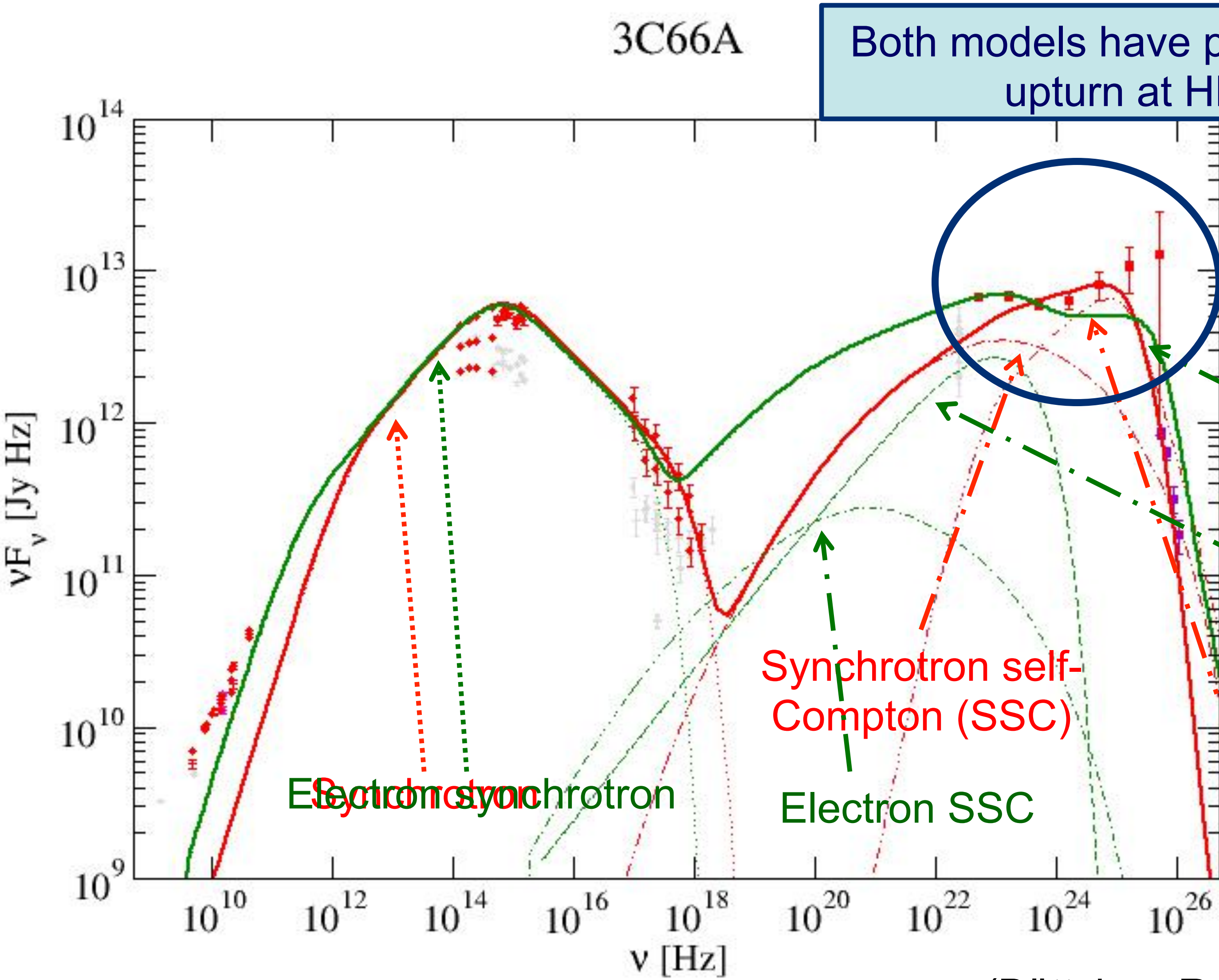
**Leptonic model:**

**X-rays = transition from sy. to SSC: P rapidly decreasing with energy; g-rays EC dominated => Negligible P.**

(Zhang & Böttcher 2013)

# Leptonic and Hadronic Model Fits to IBLs

Both models have problems with apparent upturn at HE gamma-rays




Red = Leptonic

Green = Hadronic

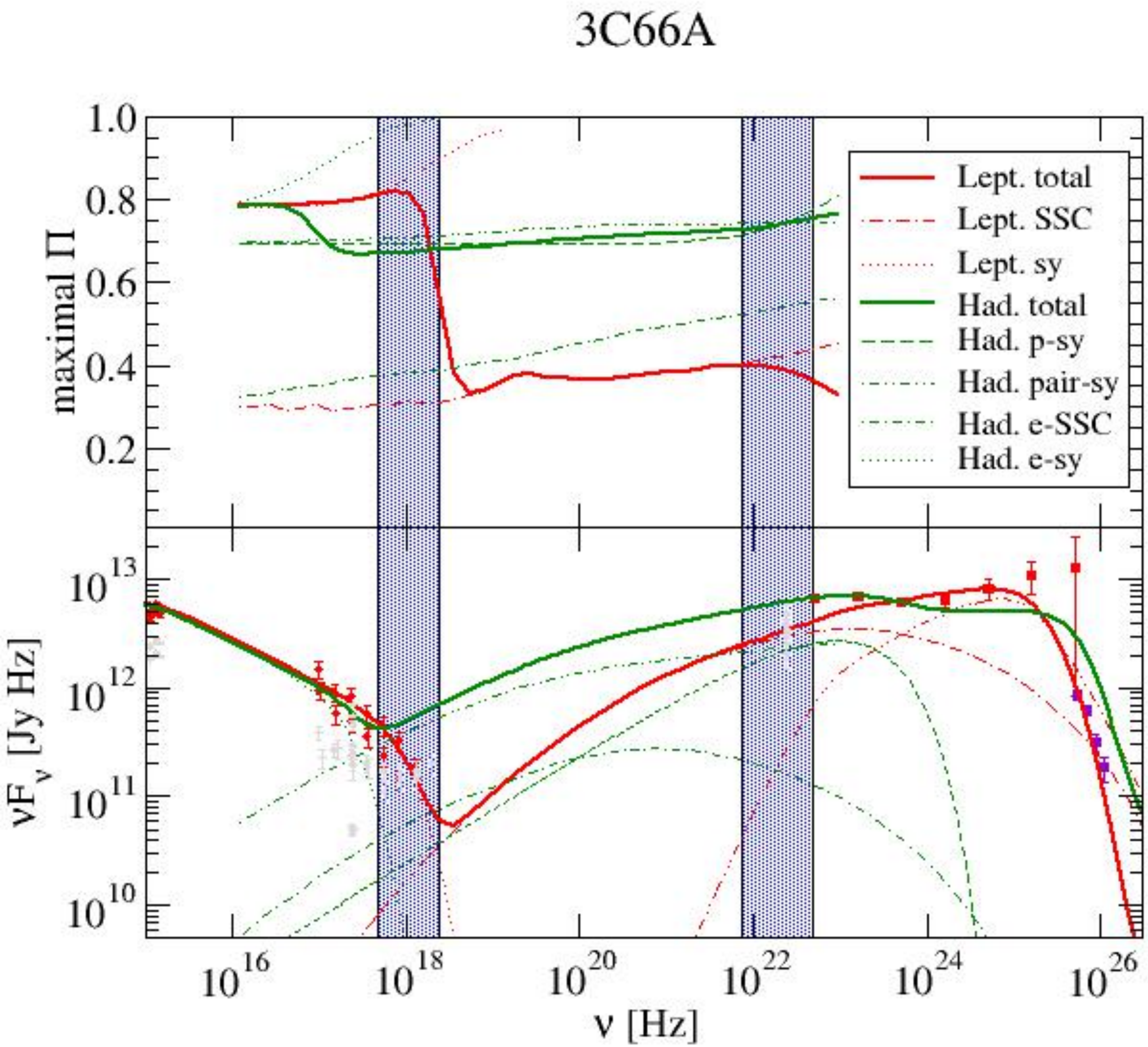
Proton synchrotron + Cascade synchrotron

Proton synchrotron

External Compton of emission from warm dust (ECIR)

(Böttcher, Reimer et al. 2013)

# Polarization: 3C66A




**Hadronic model:**

**Synchrotron dominated => High P, throughout X-rays and g-rays**

**Leptonic model:**

**X-rays sy. Dominated => High P, rapidly decreasing with energy;**

**g-rays SSC/EC dominated => Small P.**

(Zhang & Böttcher 2013)

# Characteristic Model Parameters

## Flat Spectrum Radio Quasars (FSRQs)

| Parameter | Leptonic model | Hadronic model |
|---|---|---|
| Kinetic jet power in electrons $L_e$ [erg/s] | $(5 – 10) \times 10^{44}$ | $(1 – 10) \times 10^{43}$ |
| Kinetic jet power in protons $L_p$ [erg/s] ($n_p = n_e$) | $(5 – 90) \times 10^{45}$ | $(3 – 40) \times 10^{48}$ |
| Magnetic field [G] | 1 – 4 | 10 – 20 |
| Doppler factor D | 15 – 25 | 15 – 25 |
| Electron injection $g_{min}$ | $\sim 10^3$ | 200 – 900 |
| Electron injection $g_{max}$ | $\sim 5 \times 10^4$ | $(1 – 4) \times 10^4$ |
| Electron injection index $q_e$ | 3.2 – 3.8 | 2.9 – 4.1 |
| Proton injection $E_{max}$ [eV] | | $(1 - 4) \times 10^{18}$ |
| Proton injection index $q_p$ | | 1.6 – 2.4 |

Proton dominated (if $n_e \sim n_p$), approx. e-B equipartition

Strongly proton dominated

# Characteristic Model Parameters

## Low-Frequency-Peaked BL Lacs (LBLs)

| **Parameter** | **Leptonic model** | **Hadronic model** |
|---|---|---|
| Kinetic jet power in electrons $L_e$ [erg/s] | $(1 – 10) \times 10^{44}$ | $(9 - 150) \times 10^{42}$ |
| Kinetic jet power in protons $L_p$ [erg/s] ($n_p = n_e$) | $(5 – 90) \times 10^{44}$ | $\sim 10^{49}$ |
| Magnetic field [G] | 1 – 3 | 10 – 100 |
| Doppler factor D | 10 – 20 | 10 – 20 |
| Electron injection $g_{min}$ | $\sim 10^3$ | 100 – 300 |
| Electron injection $g_{max}$ | $\sim 10^5$ | $\sim 10^4$ |
| Electron injection index $q_e$ | 3.0 – 3.5 | 3.0 – 3.5 |
| Proton injection $E_{max}$ [eV] | | $(5 – 50) \times 10^{17}$ |
| Proton injection index $q_p$ | | 1.3 – 2.4 |

Proton dominated (if $n_e \sim n_p$), approx. e-B equipartition

Strongly proton dominated

# Characteristic Model Parameters

## Intermediate BL Lacs (IBLs)

| Parameter | Leptonic model | Hadronic model |
|---|---|---|
| Kinetic jet power in electrons $L_e$ [erg/s] | $(1 – 10) \times 10^{44}$ | $(1 - 30) \times 10^{42}$ |
| Kinetic jet power in protons $L_p$ [erg/s] ($n_p = n_e$) | $(1 – 10) \times 10^{44}$ | $\sim(2 – 100) \times 10^{46}$ |
| Magnetic field [G] | 0.1 – 1 | 10 – 30 |
| Doppler factor D | 30 - 40 | 15 – 30 |
| Electron injection $g_{min}$ | $\sim (1 – 9) \times 10^{3}$ | ~ 800 |
| Electron injection $g_{max}$ | $\sim 10^{5}$ | $\sim (1 – 2) \times 10^{4}$ |
| Electron injection index $q_e$ | 2.4 – 2.8 | 2.6 – 2.8 |
| Proton injection $E_{max}$ [eV] | | $\sim 1.5 \times 10^{18}$ |
| Proton injection index $q_p$ | | 2.0 |

Approx. Equipartition between all constituents

Strongly proton dominated

# Summary

- Both leptonic and hadronic origin of high-energy emission from AGN jets are viable.

- Leptonic models often possible near ($e^-$ - B) equipartition (but proton dominated if $n_p = n_e$); hadronic models always proton dominated.

- Hadronic models consistent with AGN jets as sources of UHECRs; require large jet powers ($10^{47}$ – $10^{49}$ erg/s).

- Possible distinguishing diagnostics:
  (1) Rapid, (un)-correlated variability
  (2) X-ray (gamma-ray?) polarization

Based on:


Böttcher, M., Reimer, A., Sweeney K., & Prakash, A., 2013, ApJ, **768**, 54

Zhang, H. & Böttcher, M., 2013, ApJ, submitted

# A Word from the Shameless-Commerce Department

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.

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- 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
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- 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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Boettcher · Harris
Krawczynski (Eds.)

Relativistic Jets
from Active Galactic Nuclei

WILEY-VCH

Edited by M. Boettcher, D. E. Harris, and H. Krawczynski

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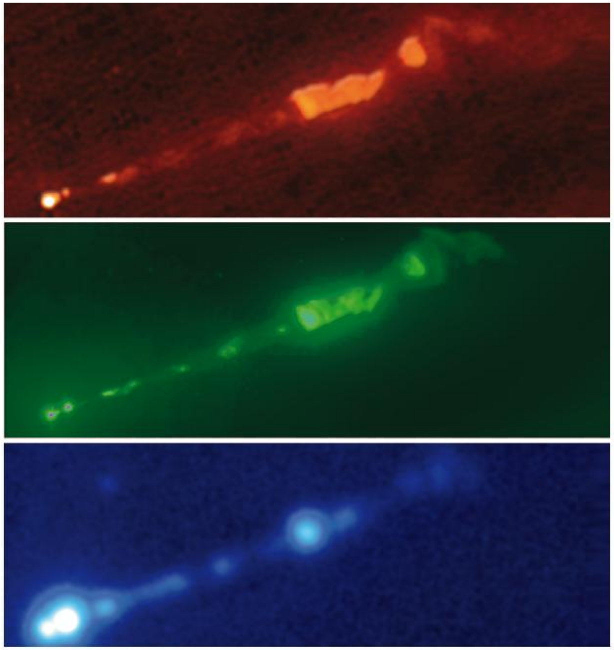
## Relativistic Jets from Active Galactic Nuclei

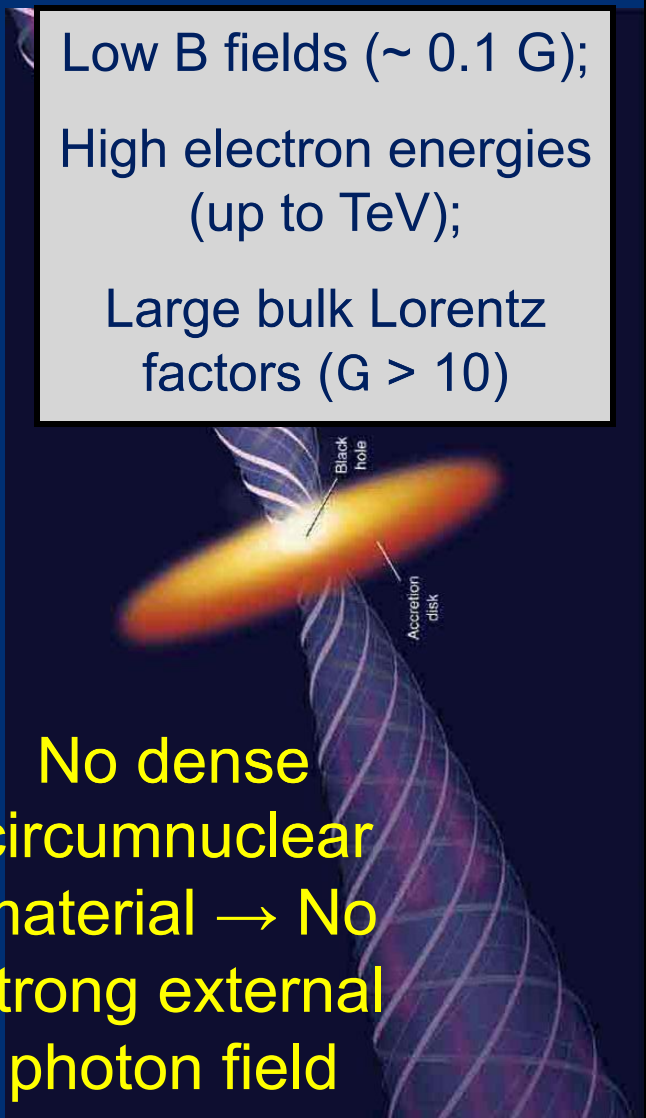


# Spectral modeling results along the Blazar Sequence: Leptonic Models

Low B fields (~ 0.1 G);

High electron energies (up to TeV);

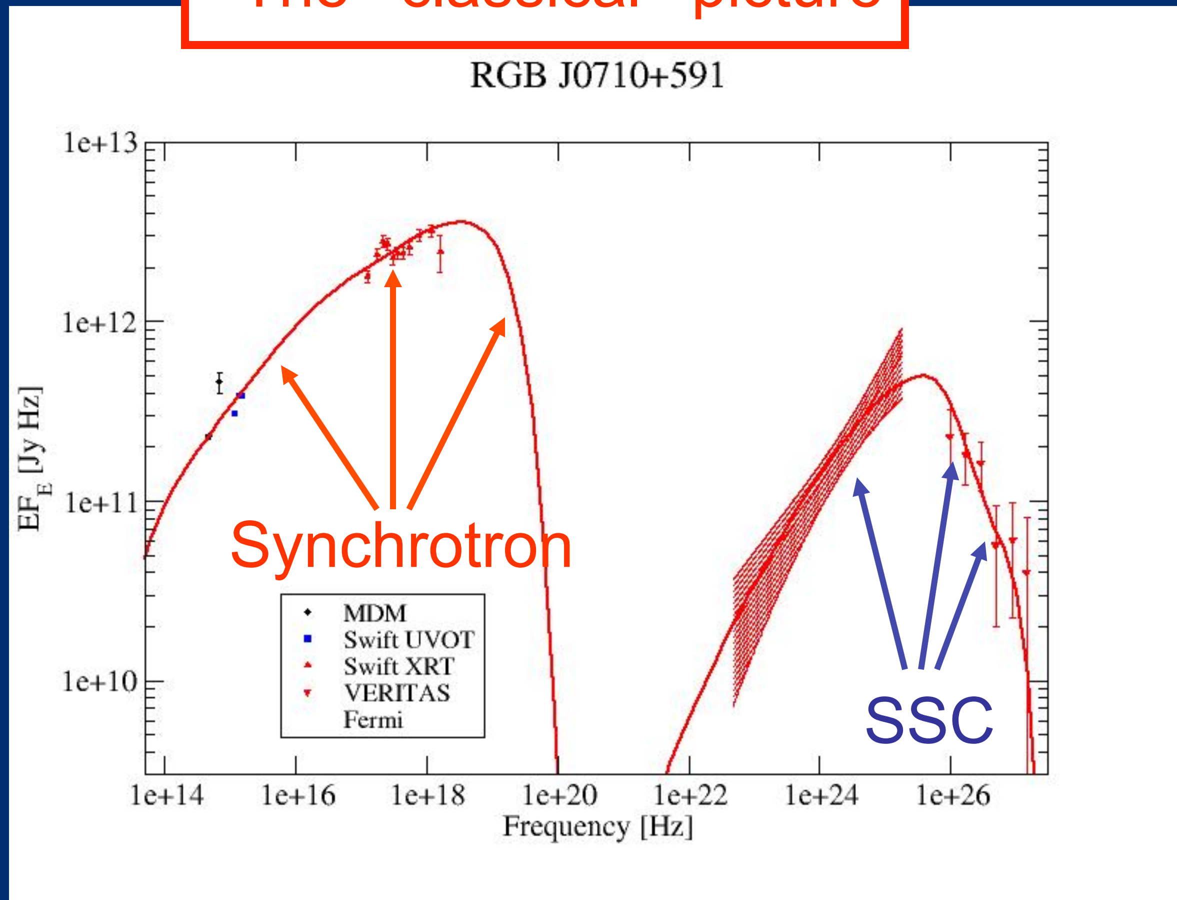
Large bulk Lorentz factors (G > 10)




No dense circumnuclear material → No strong external photon field

High-frequency peaked BL Lac (HBL):

The “classical” picture



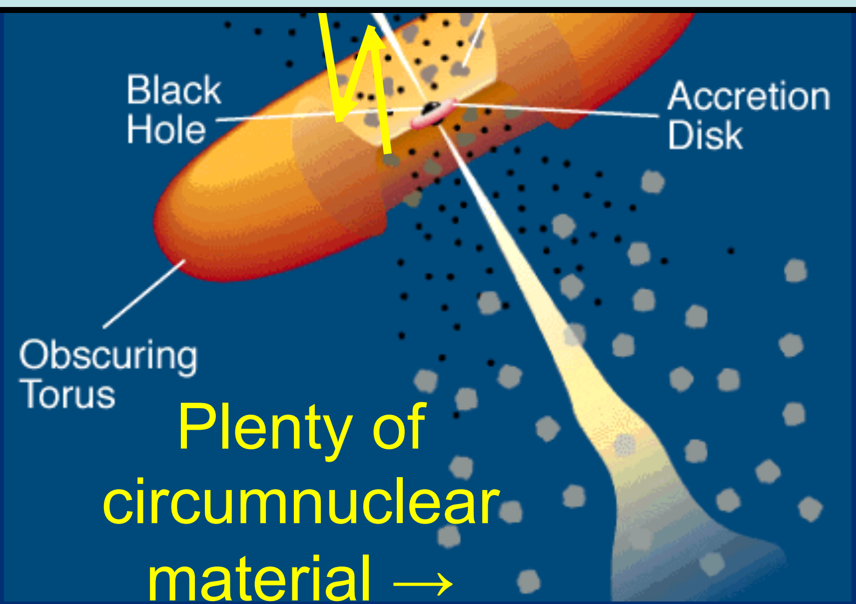
# Spectral modeling results along the Blazar Sequence: Leptonic Models

High magnetic fields (~ a few G);

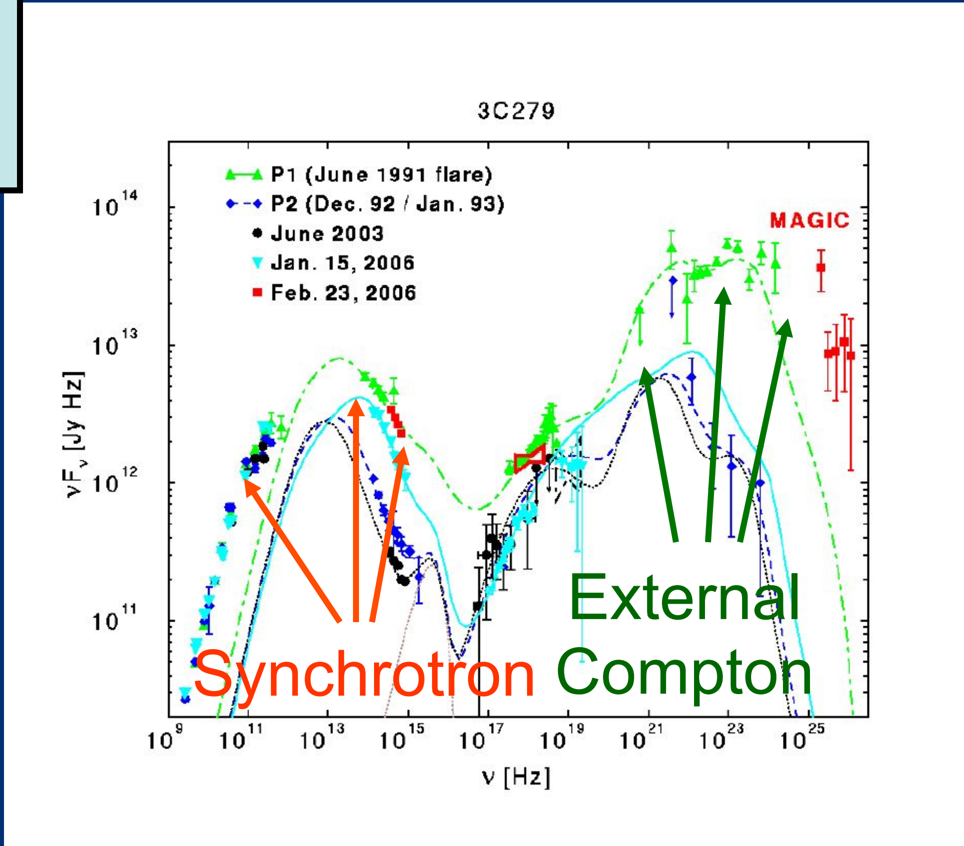
Lower electron energies (up to GeV);

Lower bulk Lorentz factors (G ~ 10)

Radio Quasar (FSRQ)



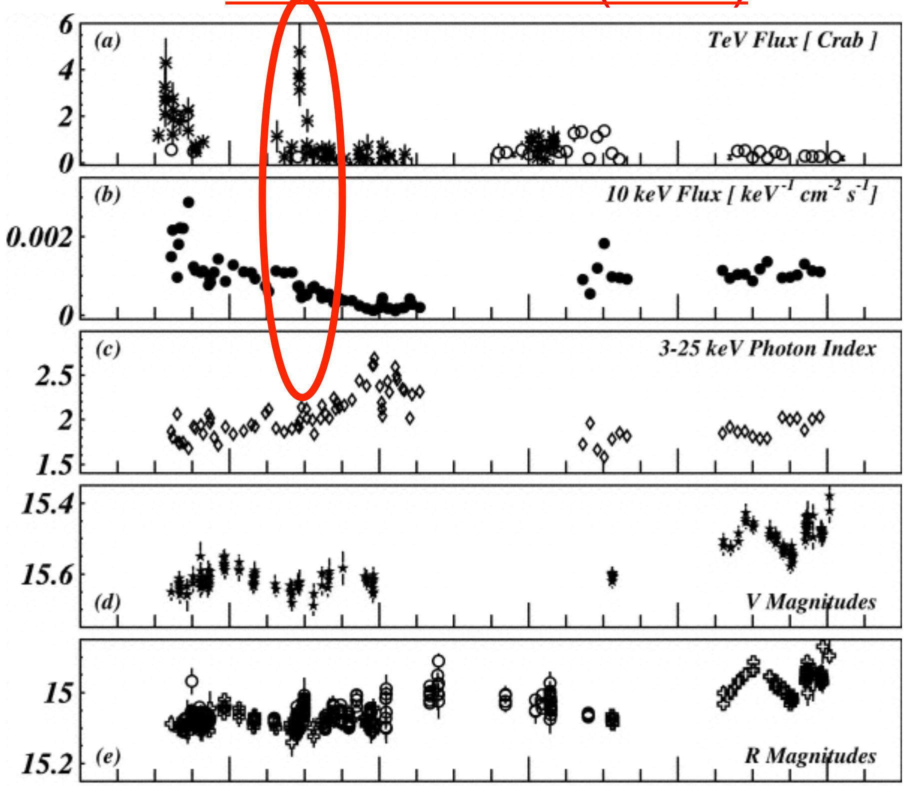

Plenty of circumnuclear material → Strong external photon field



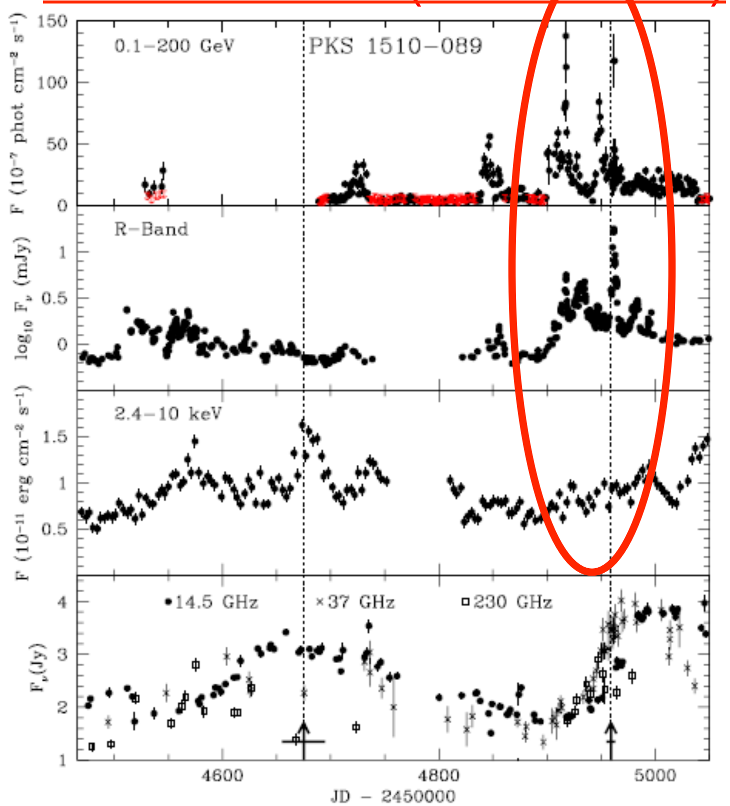
# Problems of spherical, homogeneous, leptonic models

Apparently uncorrelated variability among optical / X-rays / g-rays

1ES 1959+650 (2002)



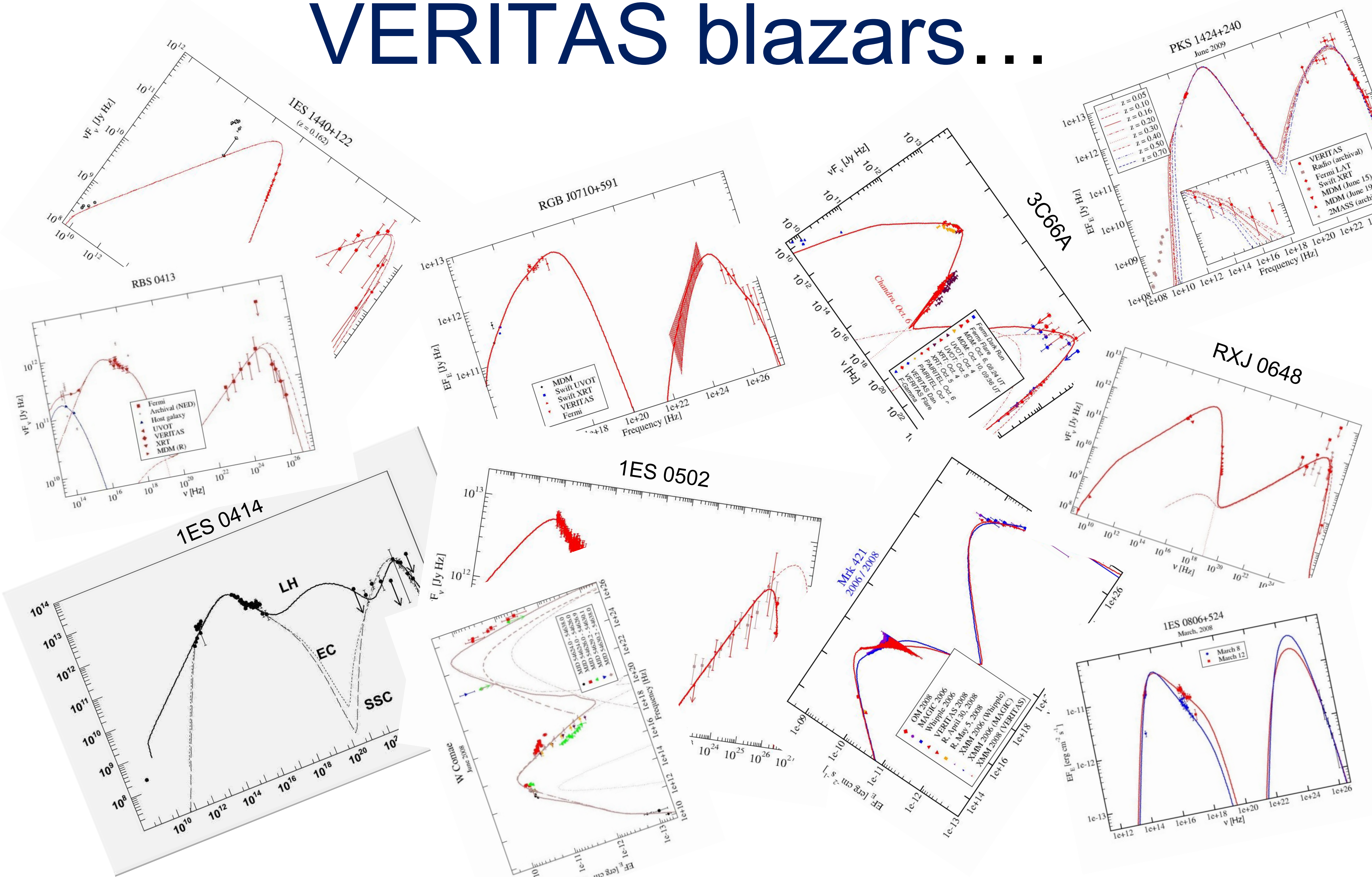

PKS 1510-089 (2008 - 2009)




(Krawczynski et al. 2004)

(Marscher al. 2010)

# Models already used for several VERITAS blazars…



# Caveats (Hadronic model)

- Neglecting p, m synchrotron radiation => Need

(a) proton energy losses synchrotron dominated

or (b) $t_{decay,m} << t_{sy,m}$ ⇔ $B << 56 / g_{p,9}$ G

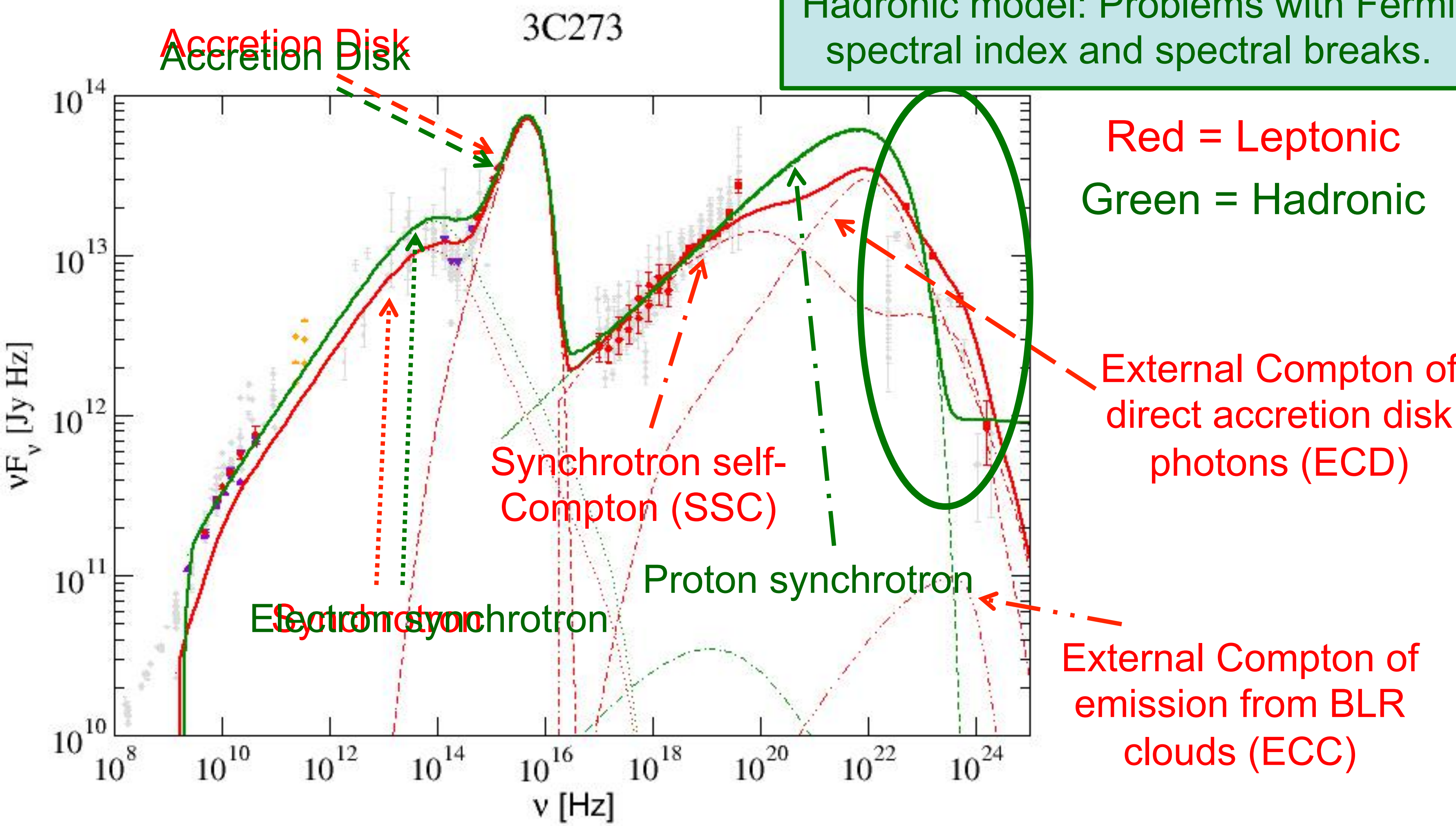
- Neglecting external radiation fields

But may be important in FSRQs

(depending on $R_{BLR}$ and location of emission region)

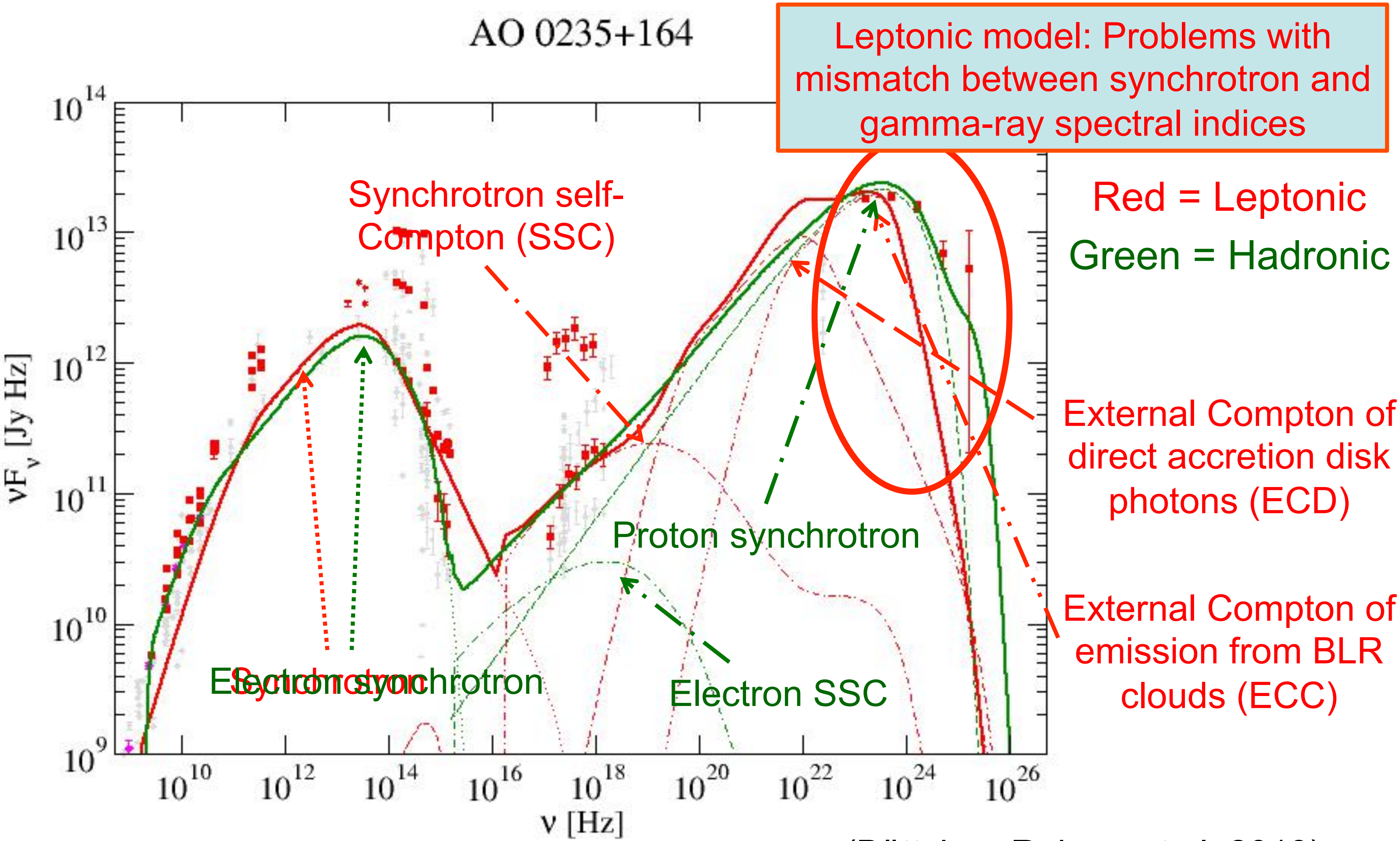
# Leptonic and Hadronic Model Fits to FSRQs

Hadronic model: Problems with Fermi spectral index and spectral breaks.




(Böttcher, Reimer et al. 2013)

# Leptonic and Hadronic Model Fits to LBLs




(Böttcher, Reimer et al. 2013)