High Energy Polarization as a Diagnostic of Hadronic Emission Processes in Relativistic Jet Sources

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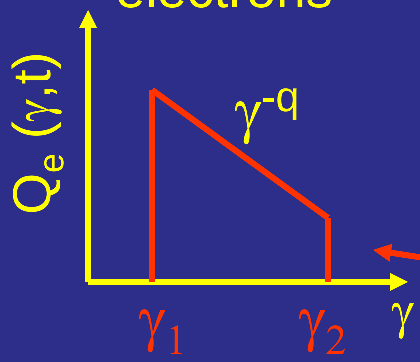
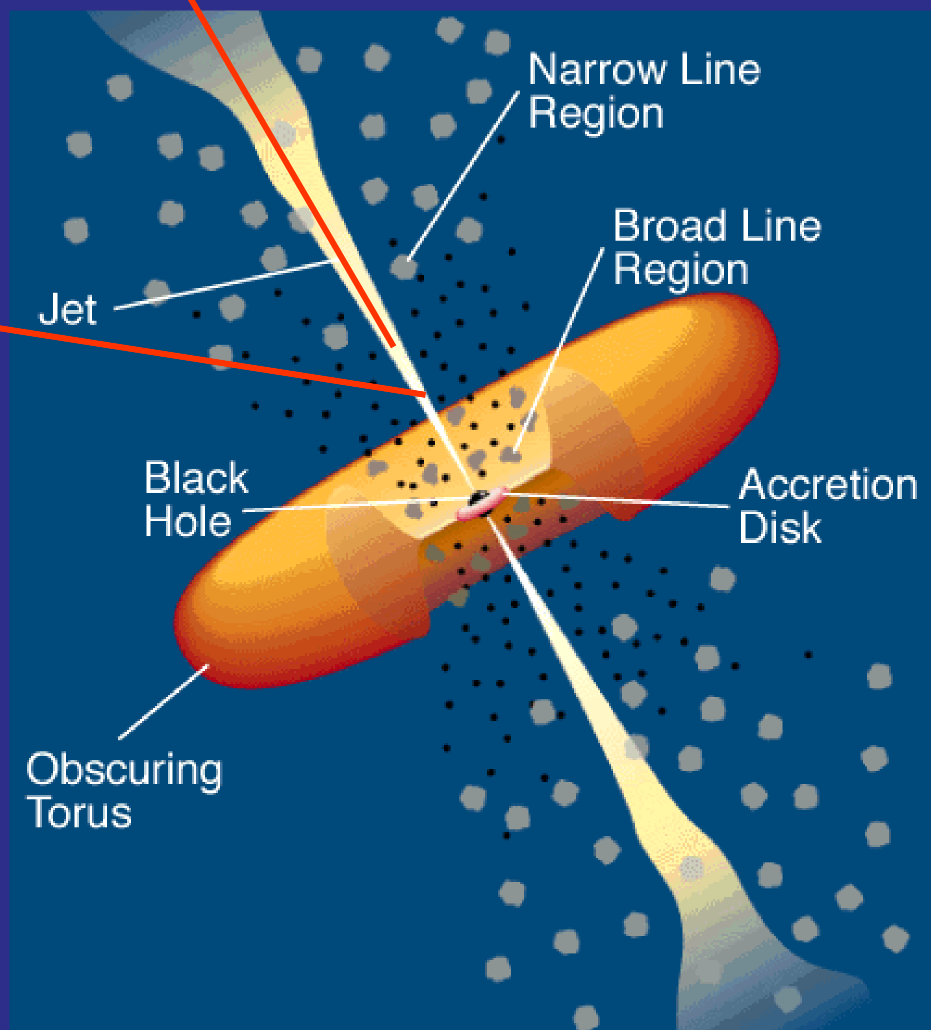
Leptonic Blazar Model

Injection, acceleration of ultrarelativistic electrons

Relativistic jet outflow with $\Gamma \approx 10$





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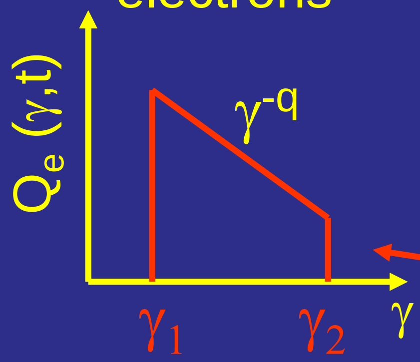

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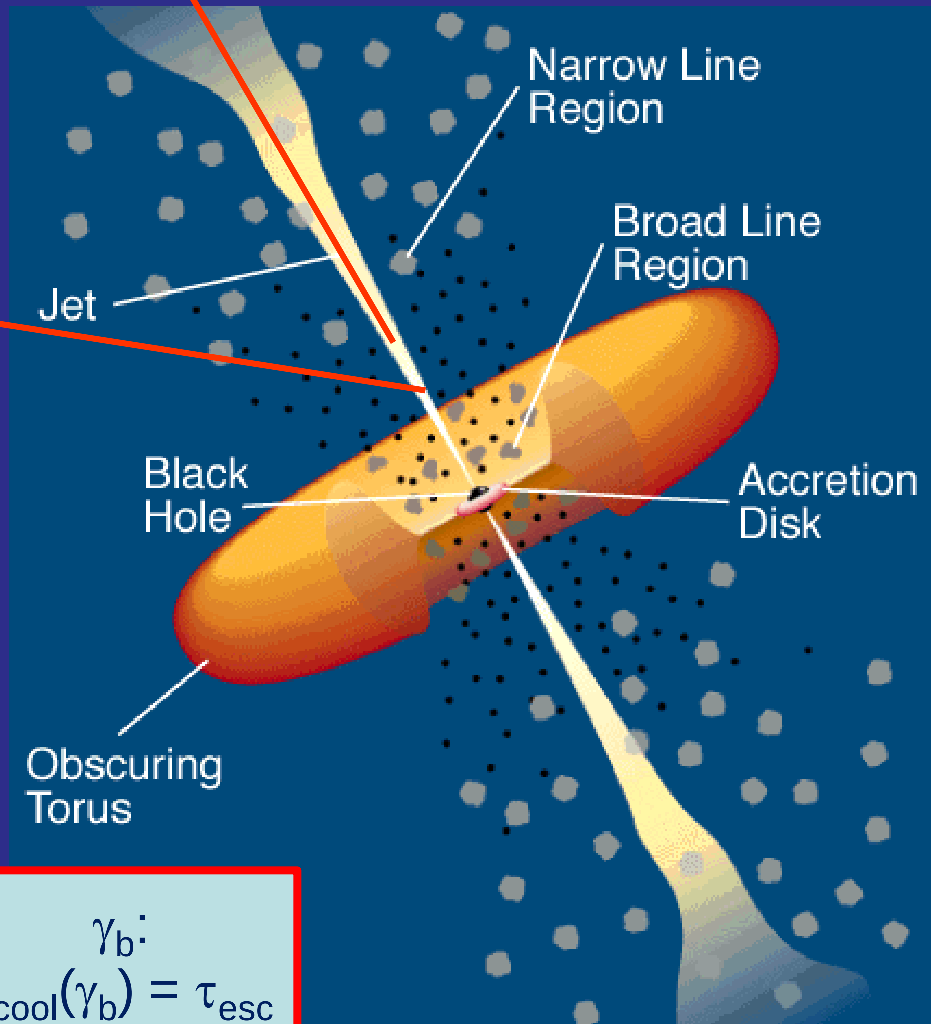
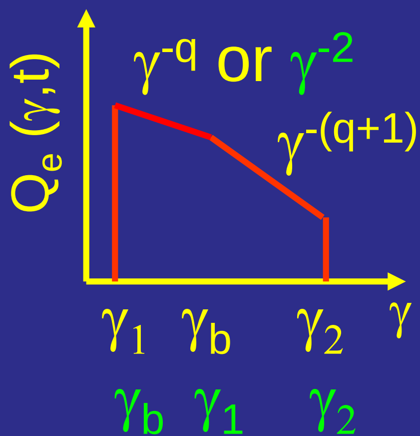


Radiative cooling $\leftrightarrow$ escape =>



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

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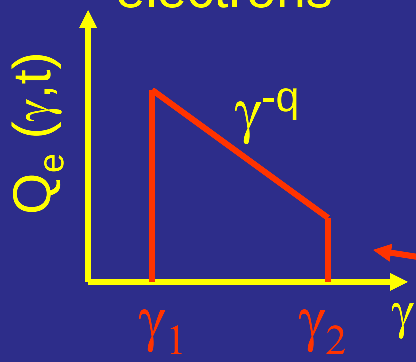

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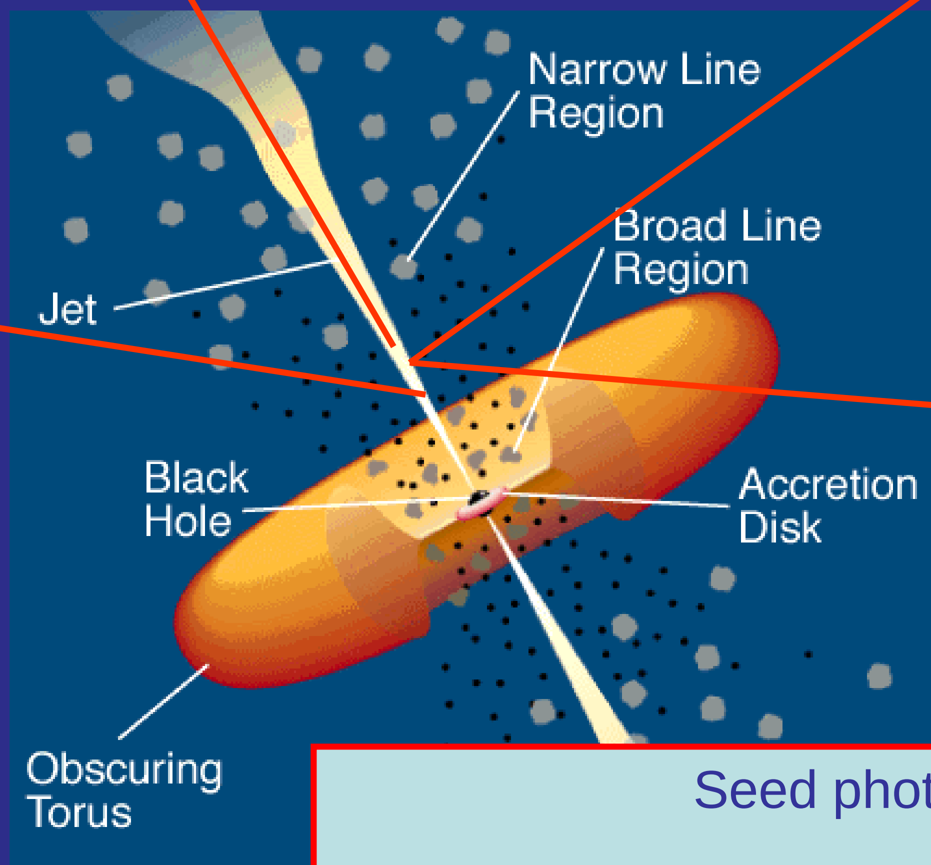
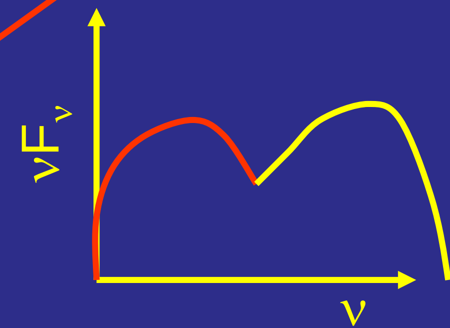
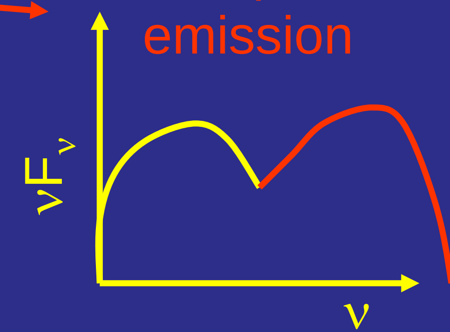


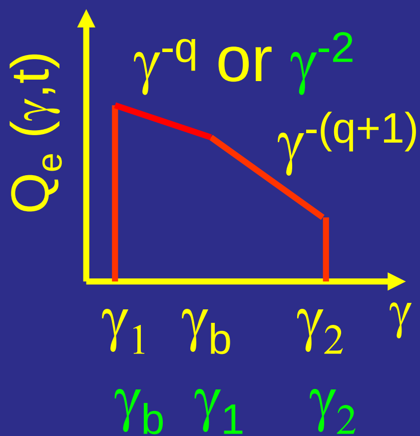
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



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Seed photons:

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

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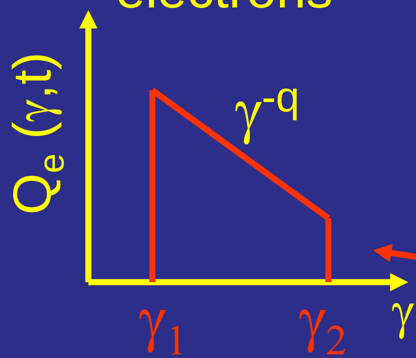
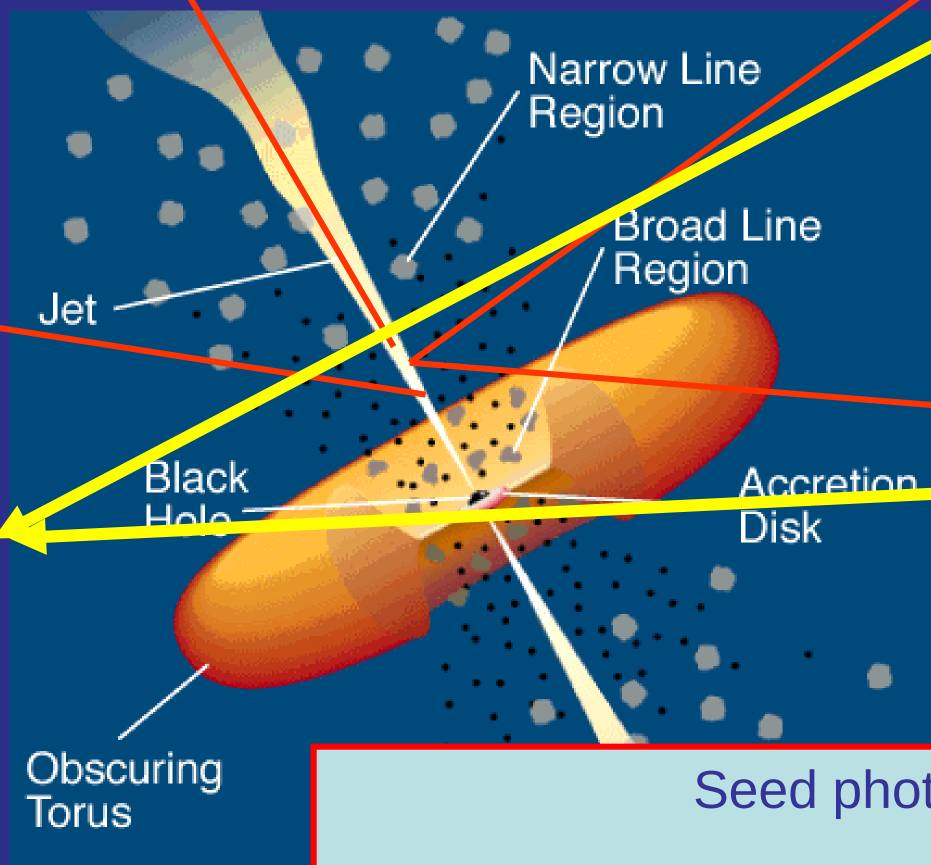
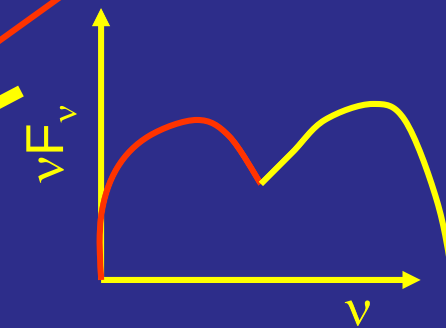


Relativistic jet outflow with $\Gamma \approx 10$



Synchrotron emission



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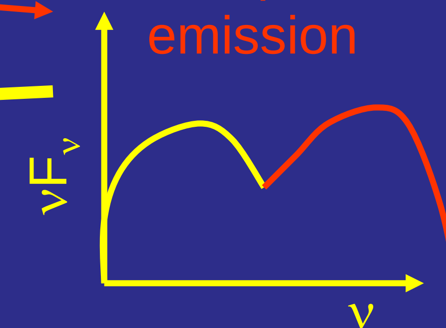

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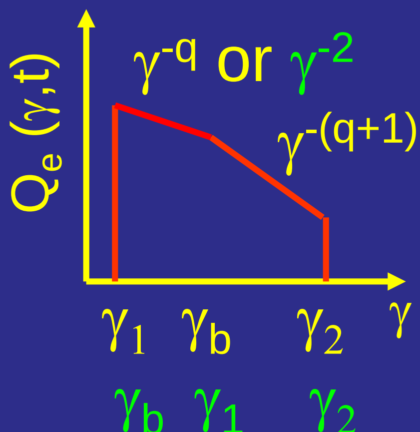

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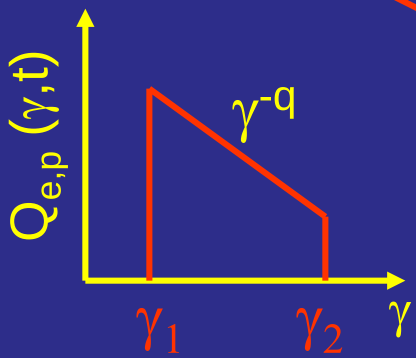
Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons



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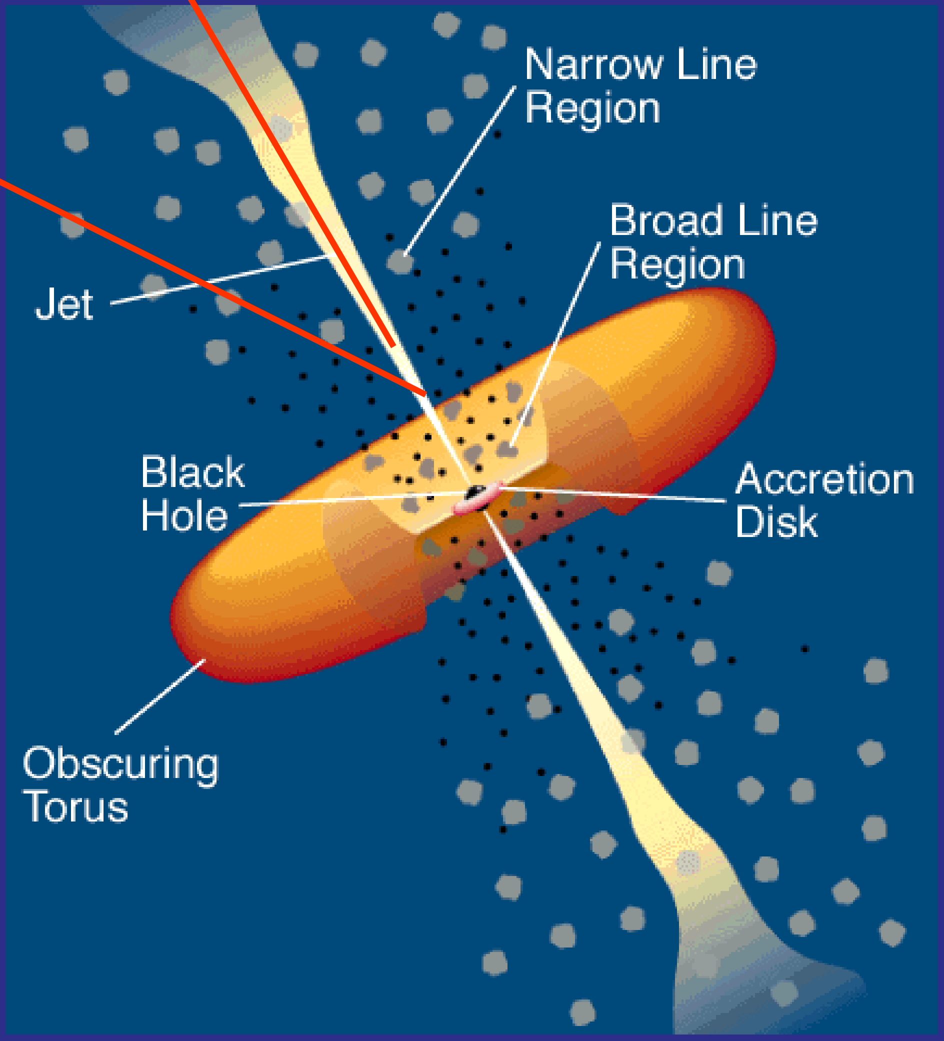

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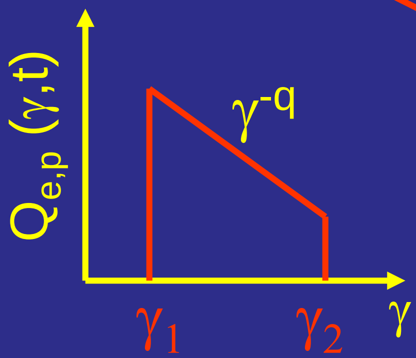

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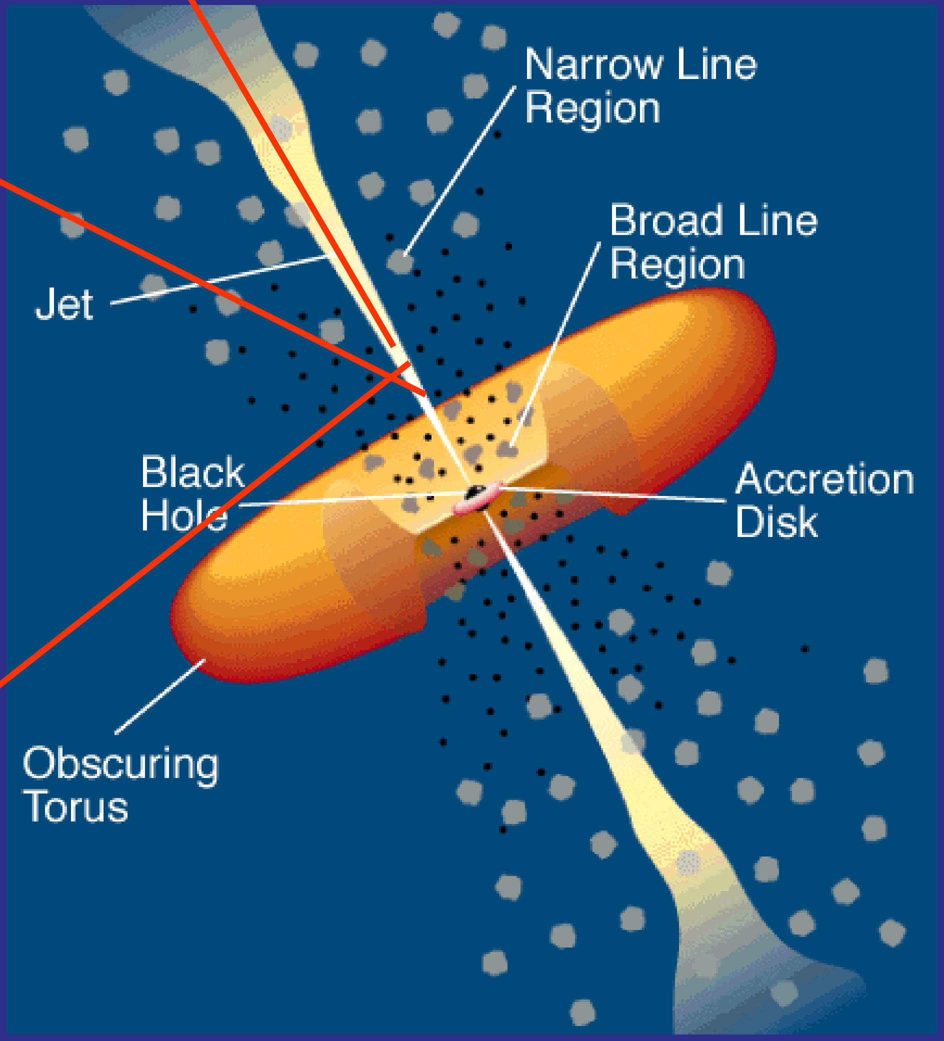
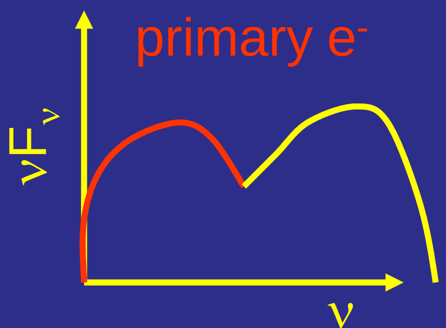


Synchrotron emission of primary e^-



Hadronic Blazar Models

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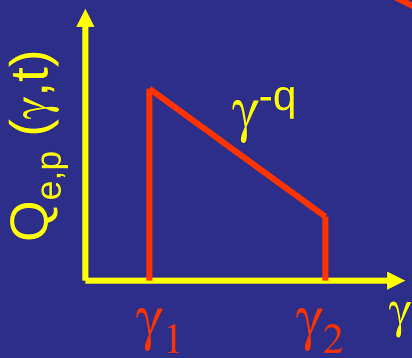

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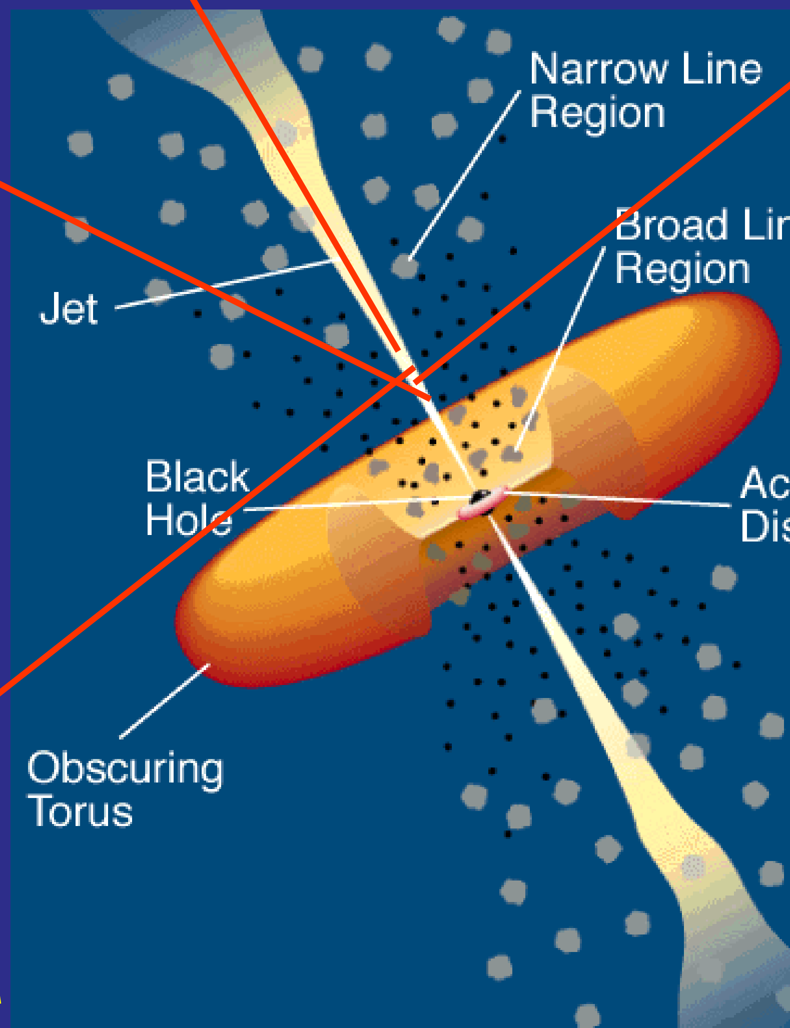

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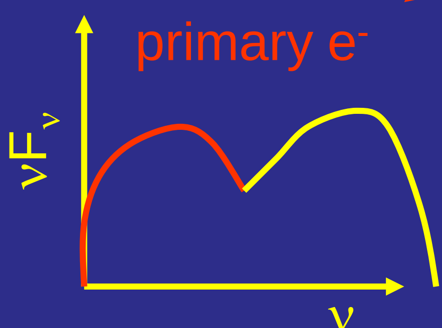
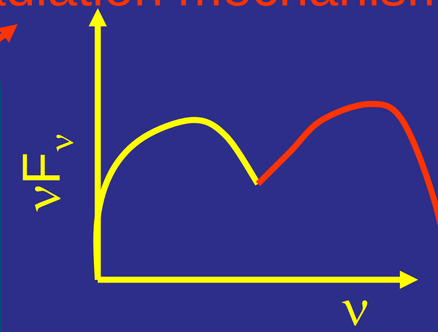
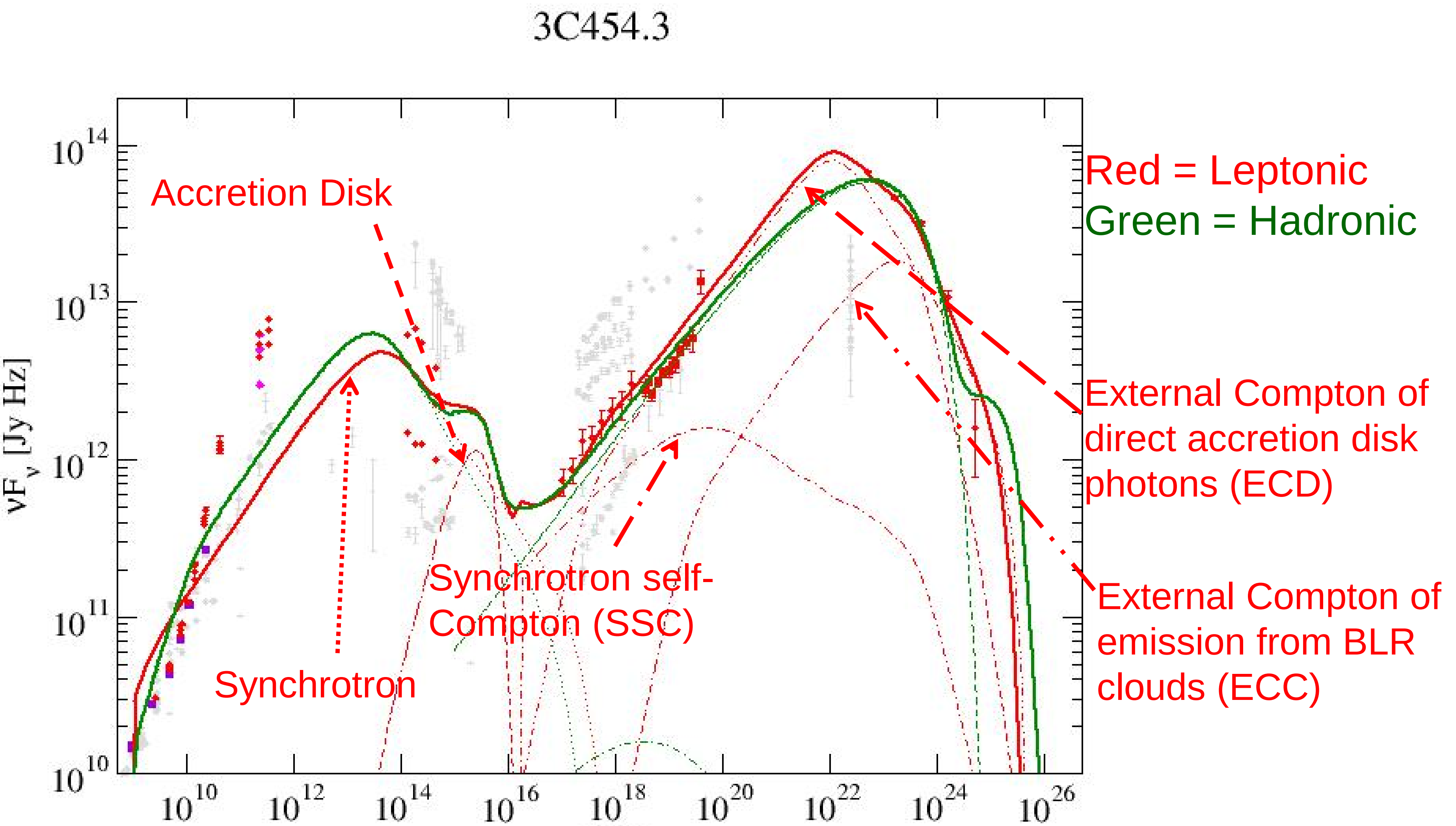


Proton-induced radiation mechanisms



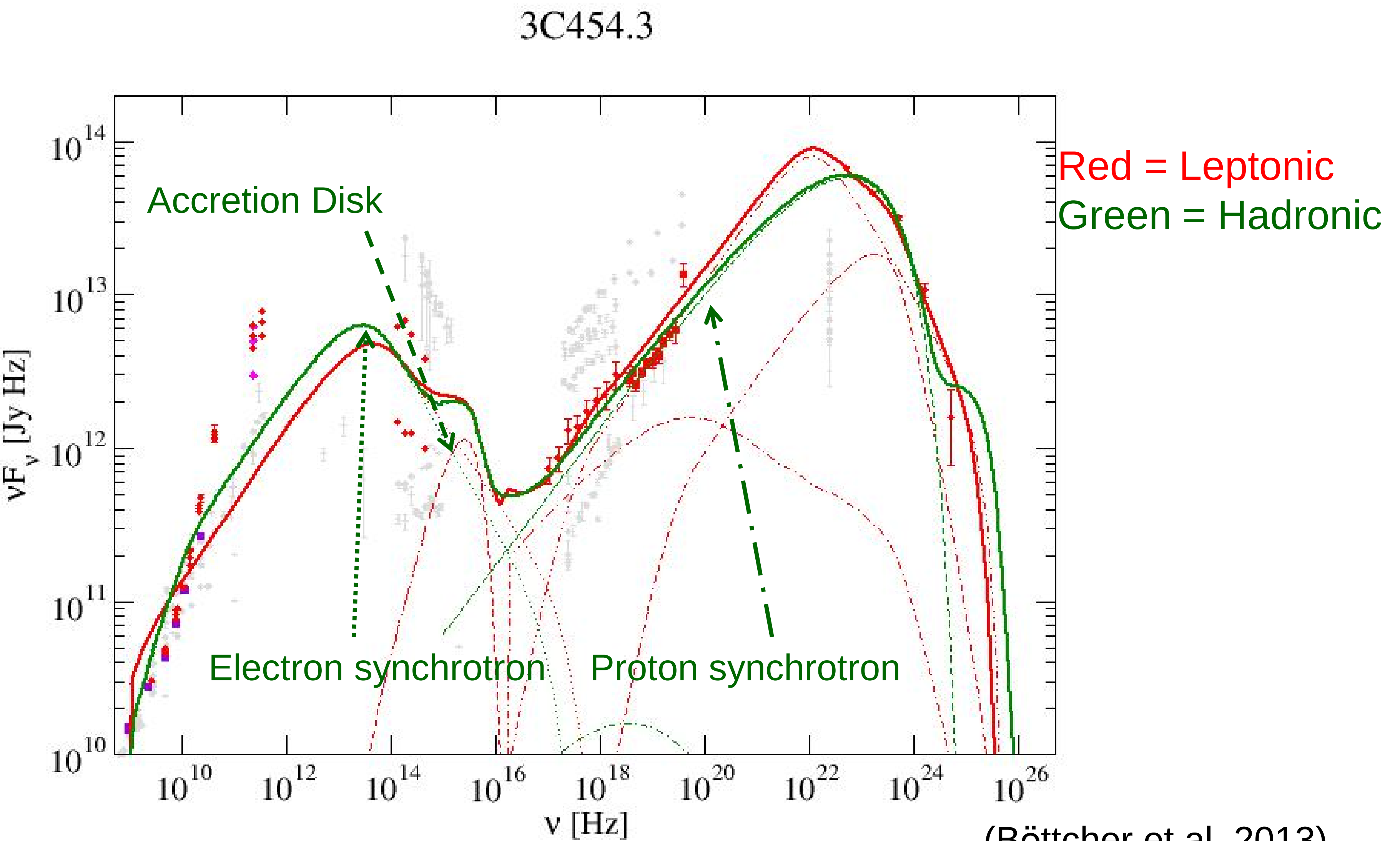
- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu_\mu}$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Leptonic and Hadronic Model Fits to Blazar SEDs



(Böttcher et al. 2013)

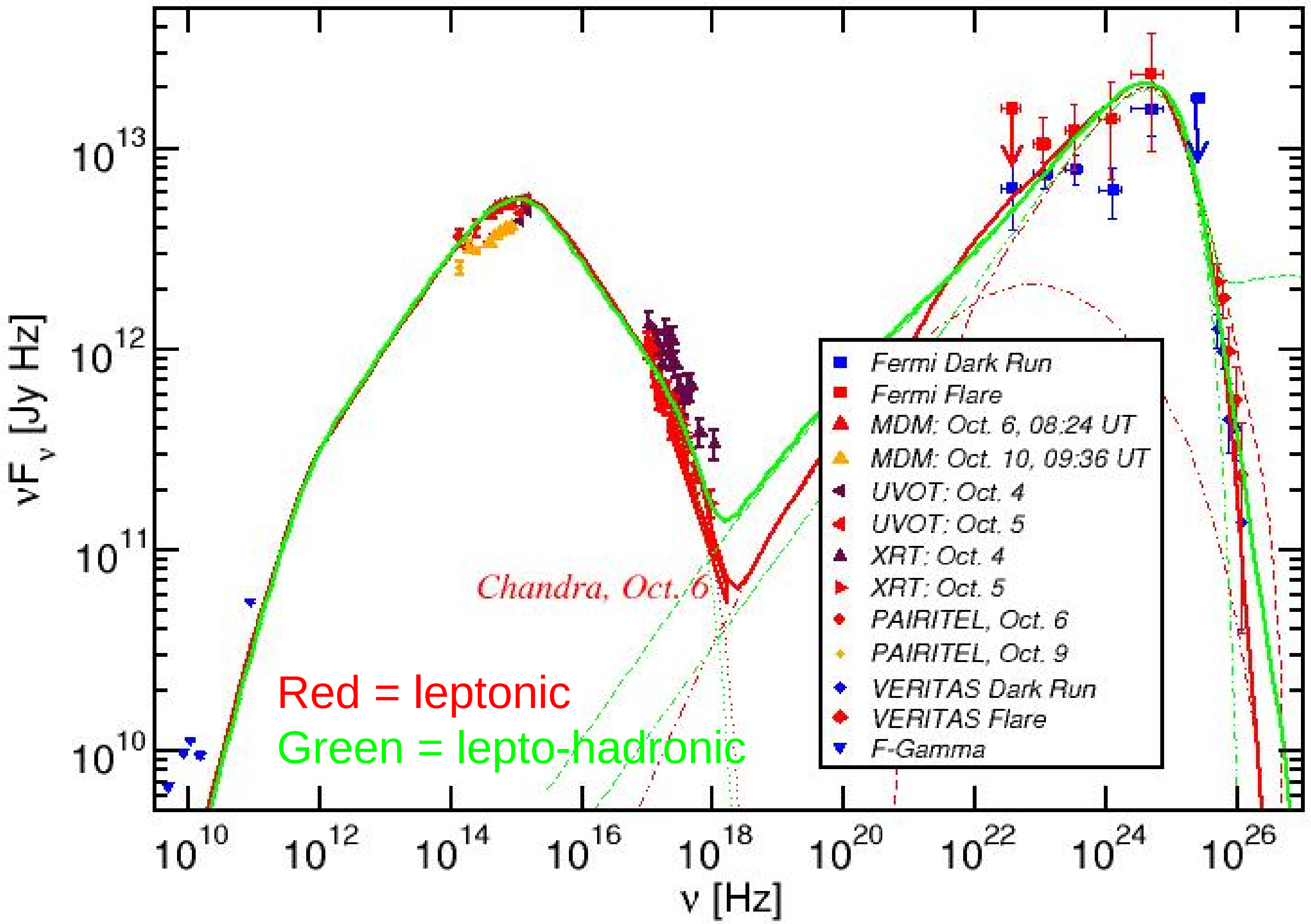
Leptonic and Hadronic Model Fits to Blazar SEDs



(Böttcher et al. 2013)

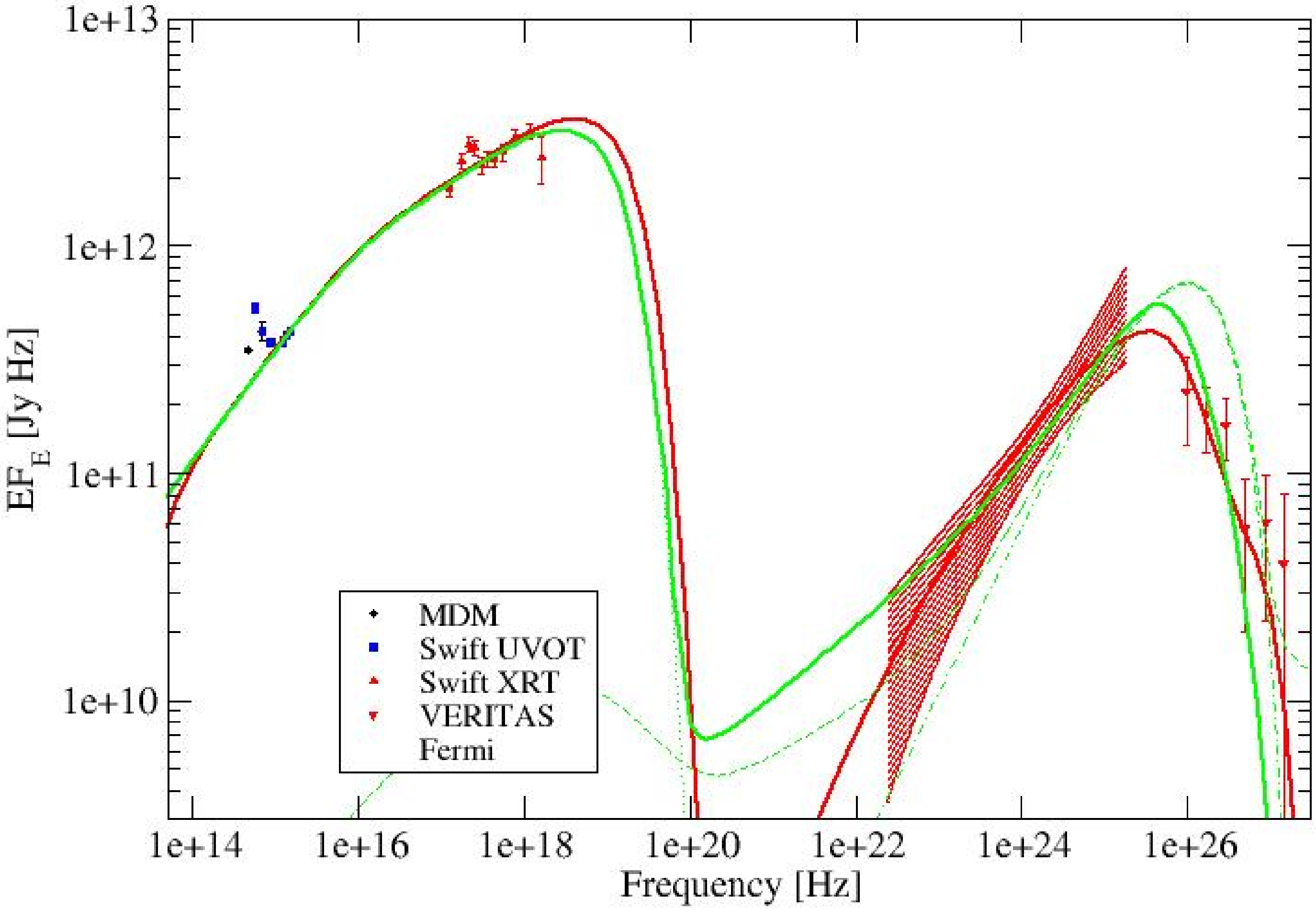
Leptonic and Hadronic Model Fits to Blazar SEDs

3C66A (IBL)



Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)



Lepto-Hadronic Model Fits to Blazar SEDs

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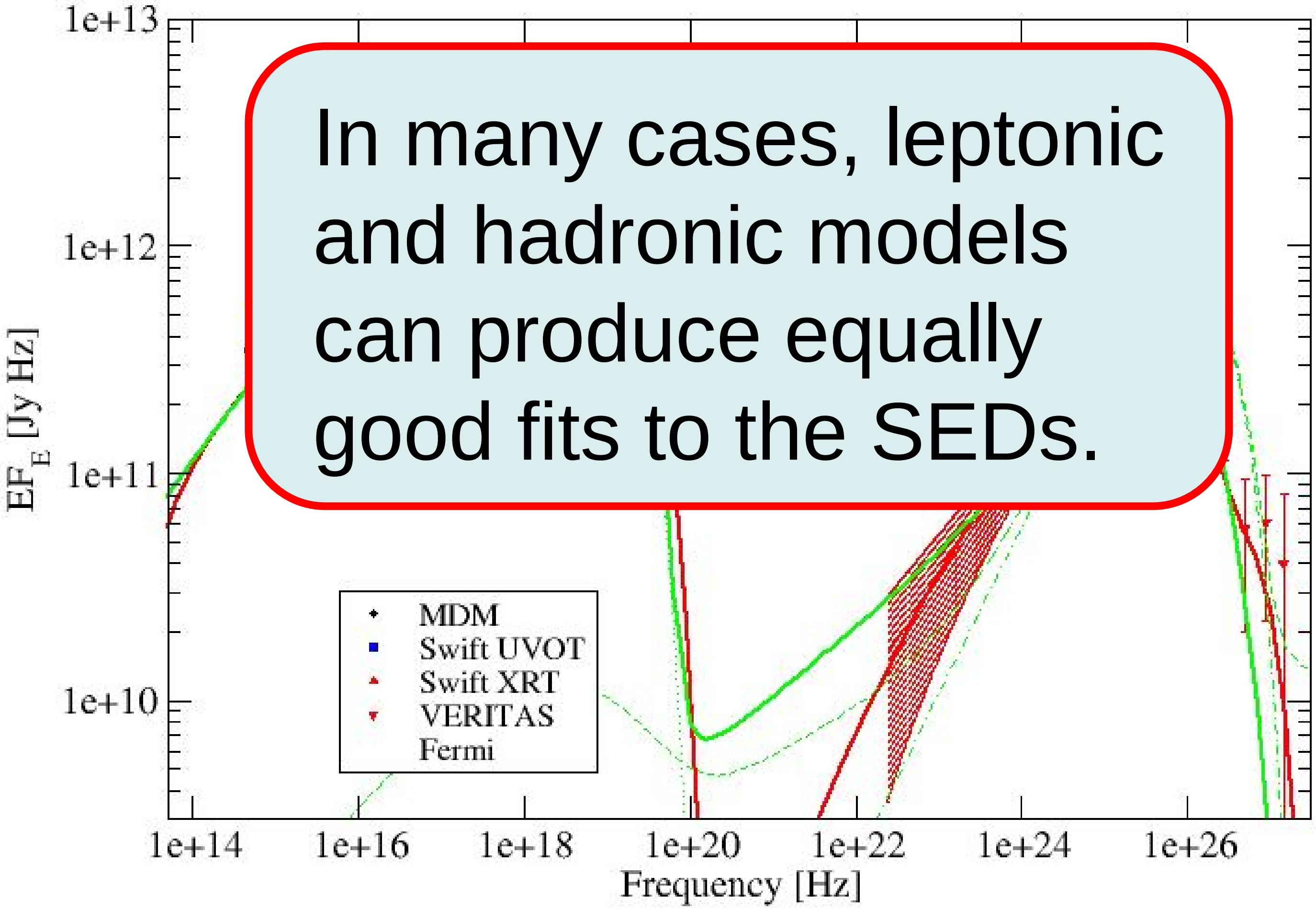


In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Possible Diagnostics to distinguish:

- Neutrinos
- Variability
- Polarization

Possible Distinguishing Diagnostic: Polarization

- Synchrotron Polarization

For synchrotron radiation from a power-law distribution of electrons with ne (γ) ~ γ^{-p} $\rightarrow$ $F_\nu \sim \nu^{-\alpha}$ with $\alpha = (p-1)/2$

$$\Pi_{PL}^{sy} = \frac{p+1}{p+7/3} = \frac{\alpha+1}{\alpha+5/3}$$

p = 2 $\rightarrow$ Π = 69 %

p = 3 $\rightarrow$ Π = 75 %

Compton Polarization

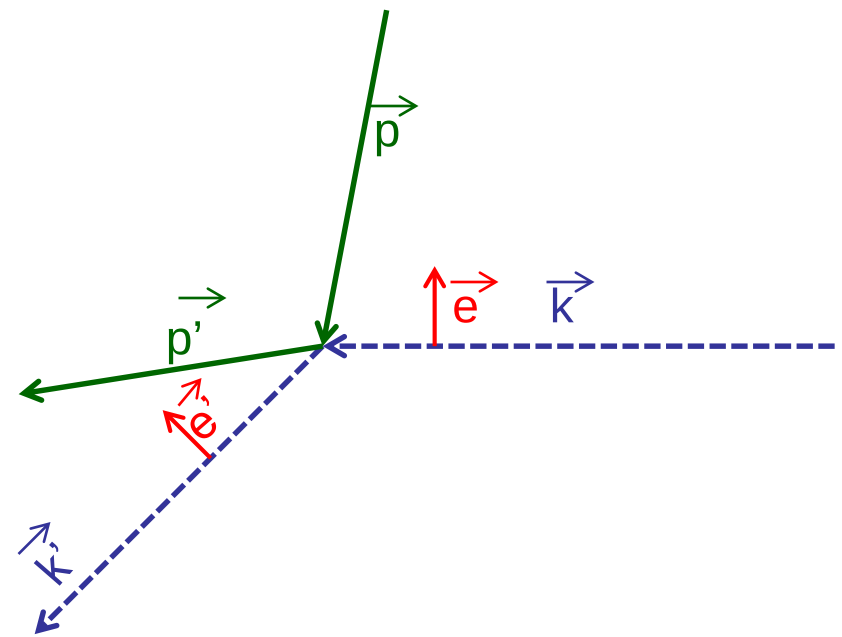
Compton cross section is polarization-dependent:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{\epsilon'}{\epsilon}\right)^2\left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$$

$\varepsilon = h\nu/(m_e c^2)$:

Thomson regime: $\varepsilon \approx \varepsilon'$

$\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e}\cdot\vec{e}' = 0$



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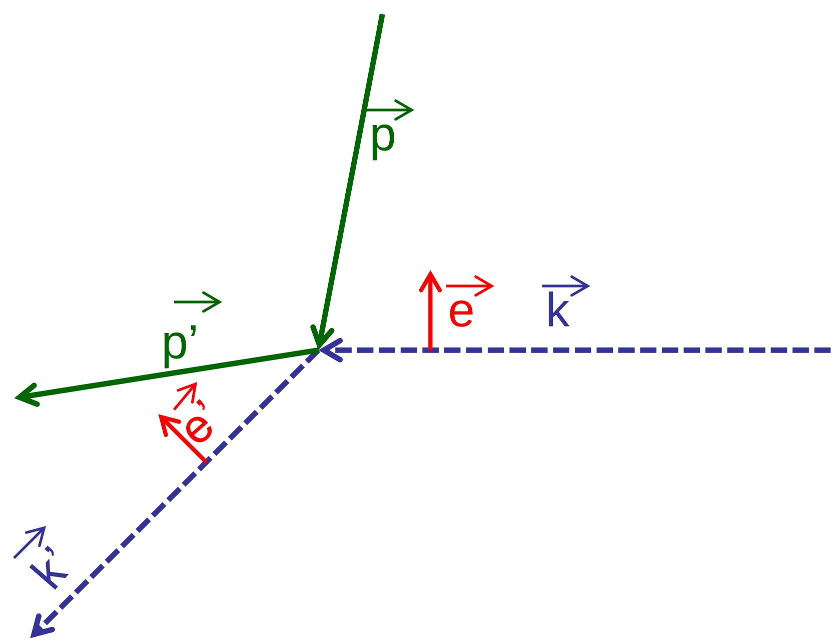
$\varepsilon = h\nu/(m_e c^2)$:

Thomson regime: $\varepsilon \approx \varepsilon'$

$\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e}\cdot\vec{e}' = 0$

$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

Preferred polarization direction is preserved; polarization degree reduced to ~ ½ of target-photon polarization .



Calculation of X-Ray and Gamma-Ray Polarization in Leptonic and Hadronic Blazar Models

- Synchrotron polarization:

  Standard Rybicki & Lightman description

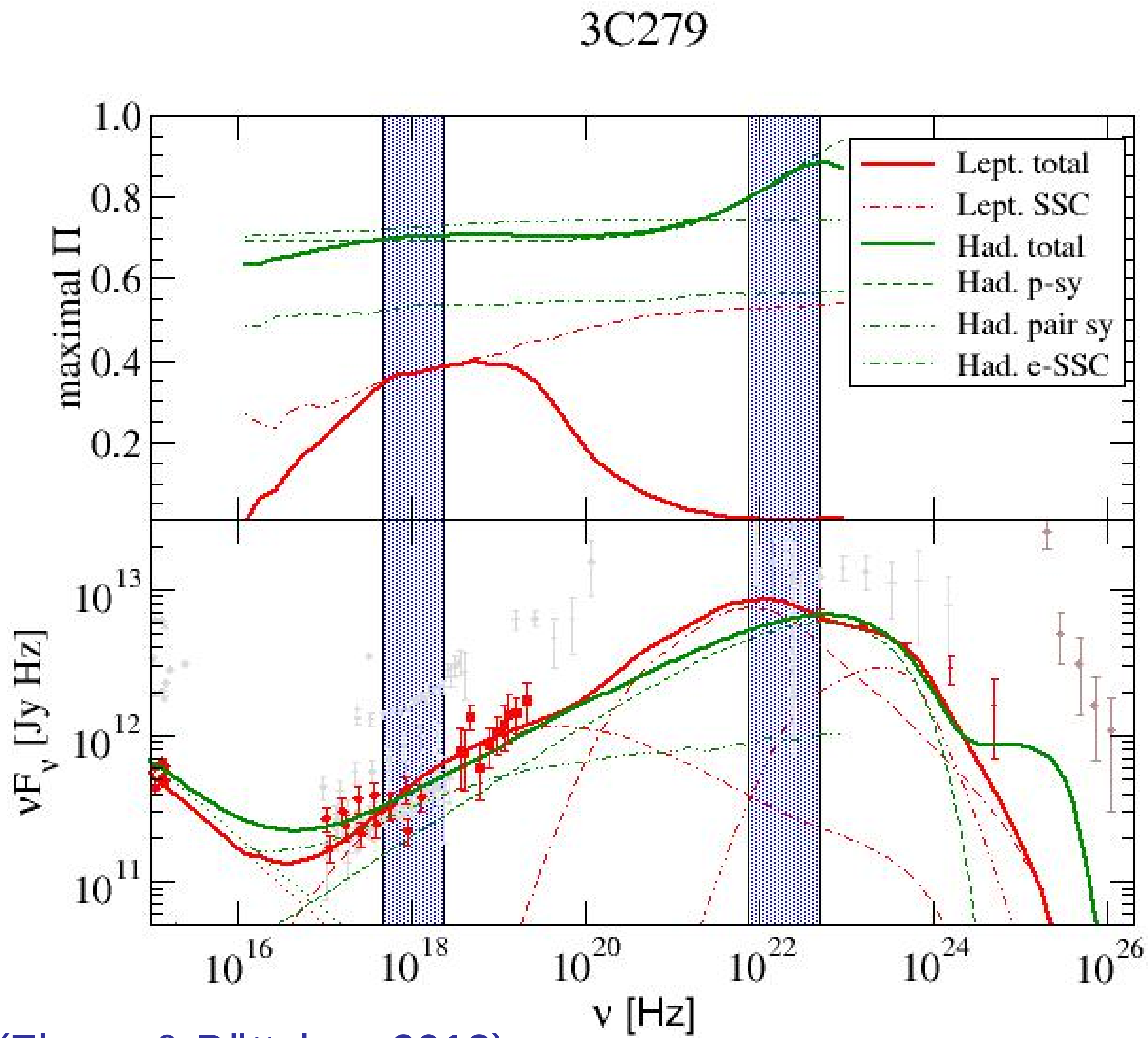
- SSC Polarization:

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

- External-Compton emission: Unpolarized.

Upper limits on high-energy polarization, assuming perfectly ordered magnetic field perpendicular to the line of sight (Zhang & Böttcher 2013)

X-Ray and Gamma-Ray Polarization: FSRQs

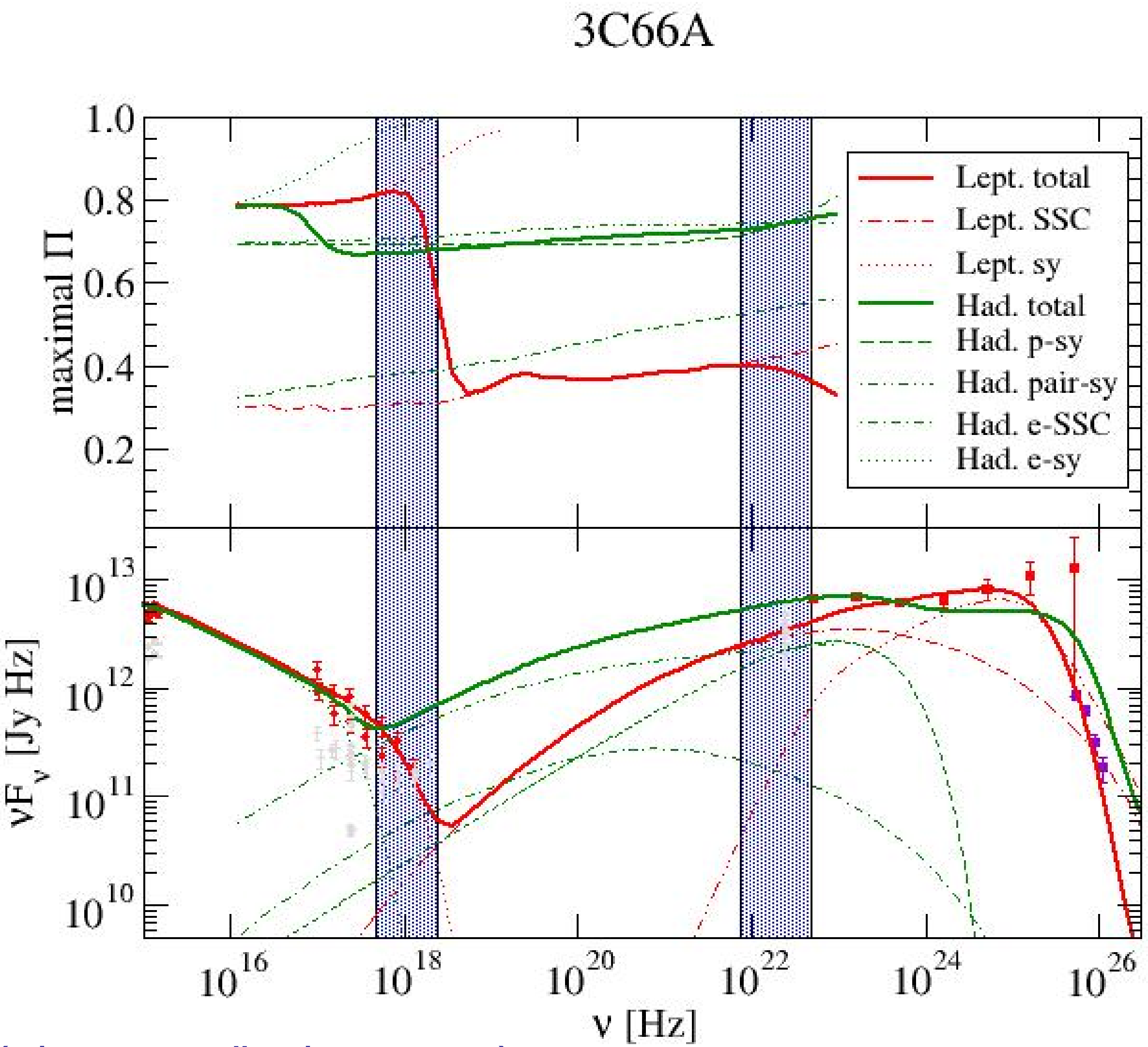


Hadronic model:
Synchrotron dominated
=> High Π, generally increasing with energy (SSC contrib. in X-rays).

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

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: 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.

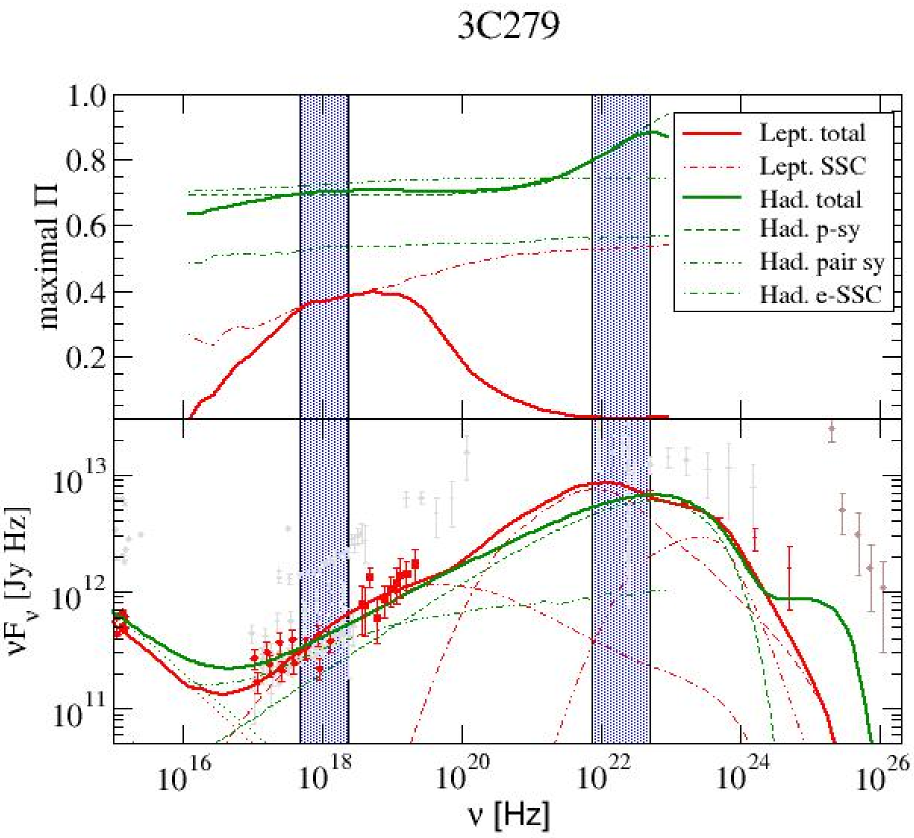
(Zhang & Böttcher, 2013)

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!

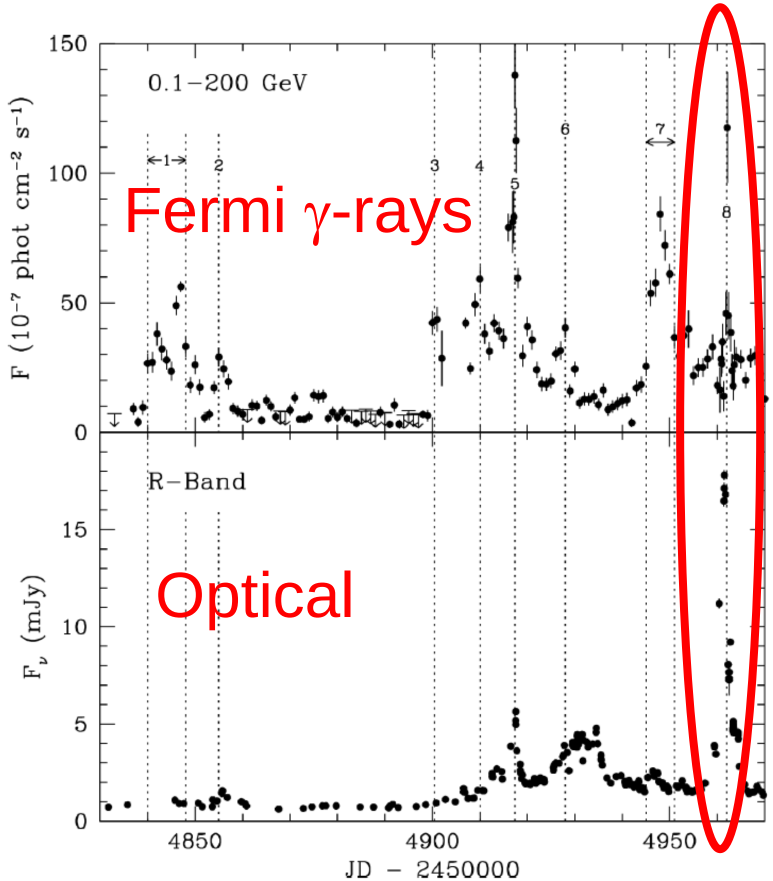
- X-ray and γ-ray polarization values substantially below synchrotron polarization will favor leptonic models, measurable γ-ray polarization clearly favors hadronic models!

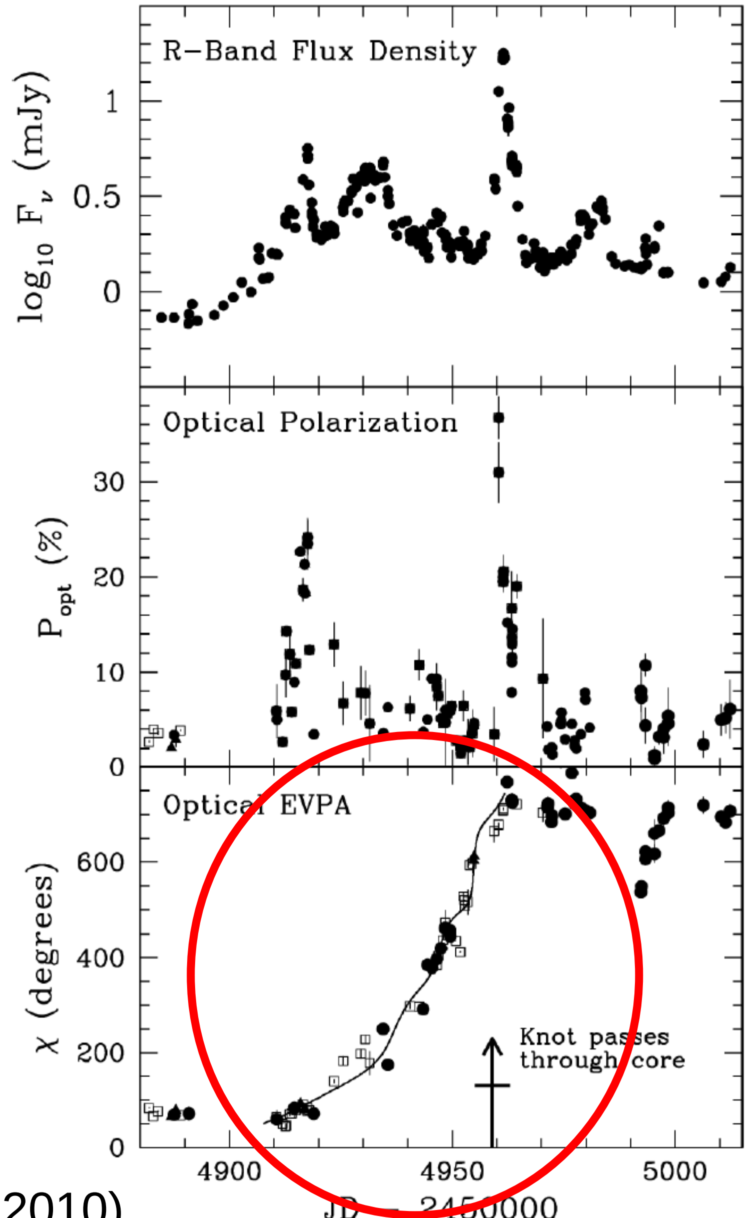


(Zhang & Böttcher, 2013)

Polarization Angle Swings

- Optical + γ-ray variability of LSP blazars often correlated
- Sometimes O/γ flares correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)





PKS 1510-089 (Marscher et al. 2010)

Polarization Angle Swings

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- Someti…
  inc…
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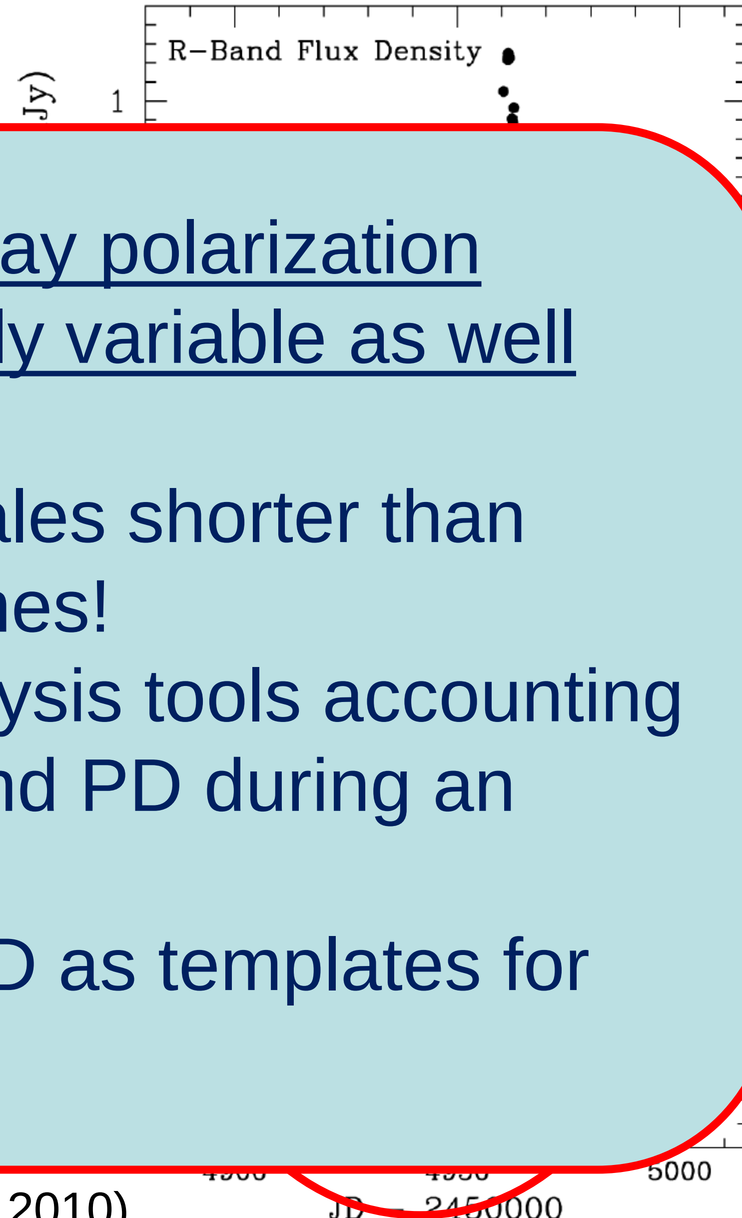
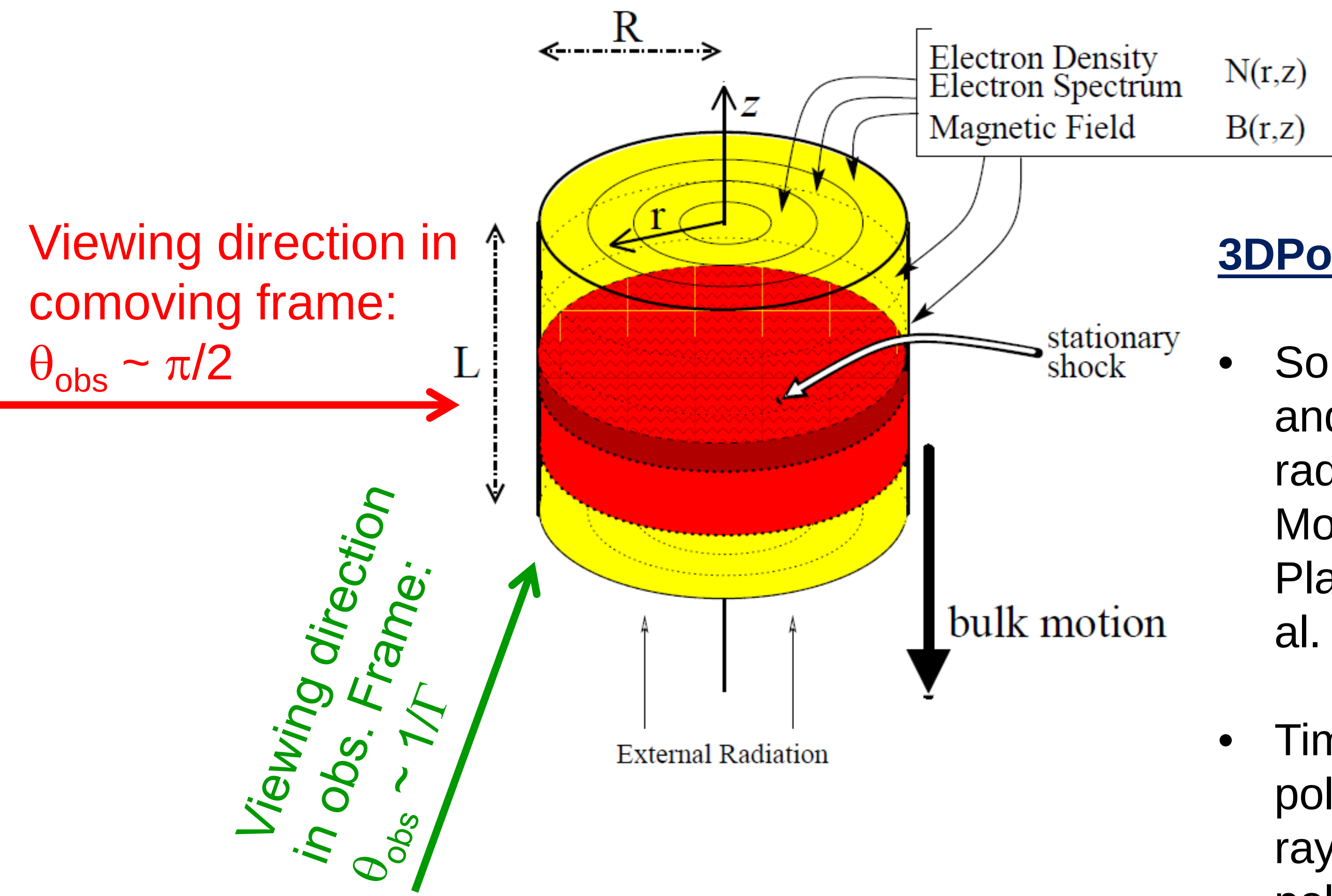


X-ray / Gamma-Ray polarization (PA and PD) are likely variable as well

- Changing on time scales shorter than required exposure times!
- Need to develop analysis tools accounting for time-varying PA and PD during an individual exposure!
- Use optical PA and PD as templates for analysis?

PKS 1510-089 (Marscher et al. 2010)

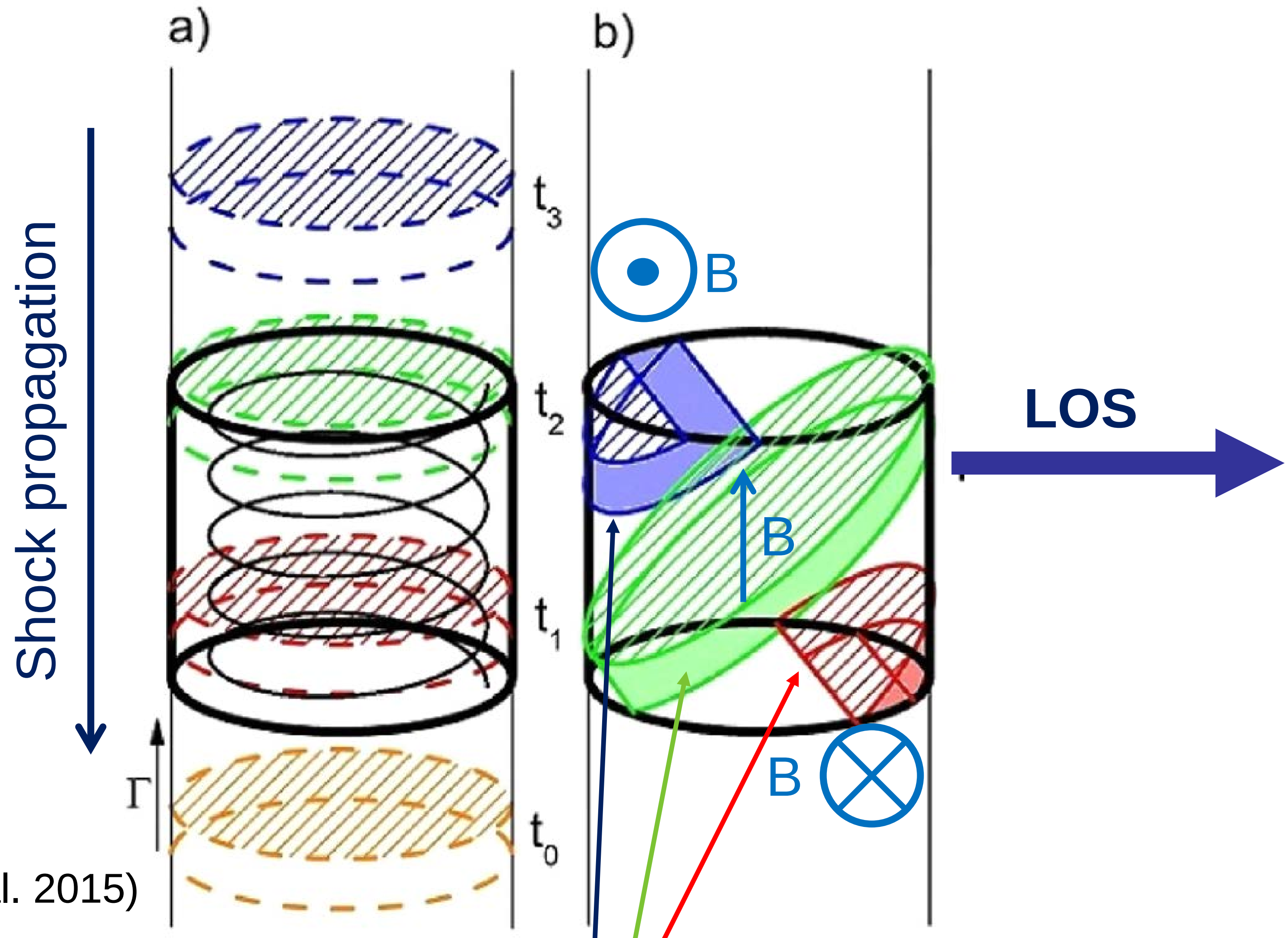
Tracing Synchrotron Polarization in the Internal Shock Model



3DPol (Zhang et al. 2014)

- Solve electron dynamics and (unpolarized) radiation transfer with Monte-Carlo / Fokker-Planck scheme (Chen et al. 2011, 2012)
- Time-dependent, polarization-dependent ray tracing for polarization signatures

Light Travel Time Effects



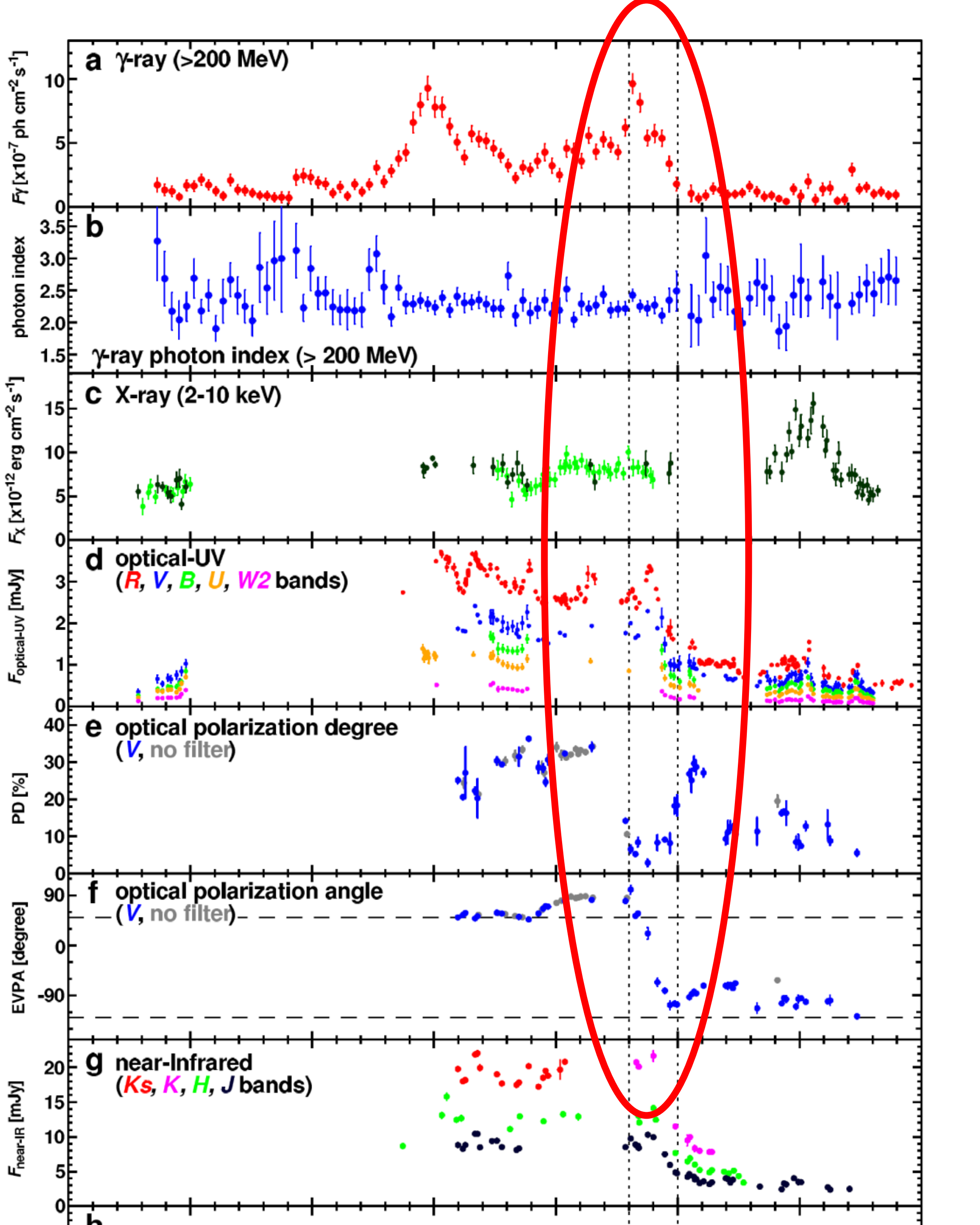
(Zhang et al. 2015)

Shock positions at equal photon-arrival times at the observer

Application to the FSRQ 3C279

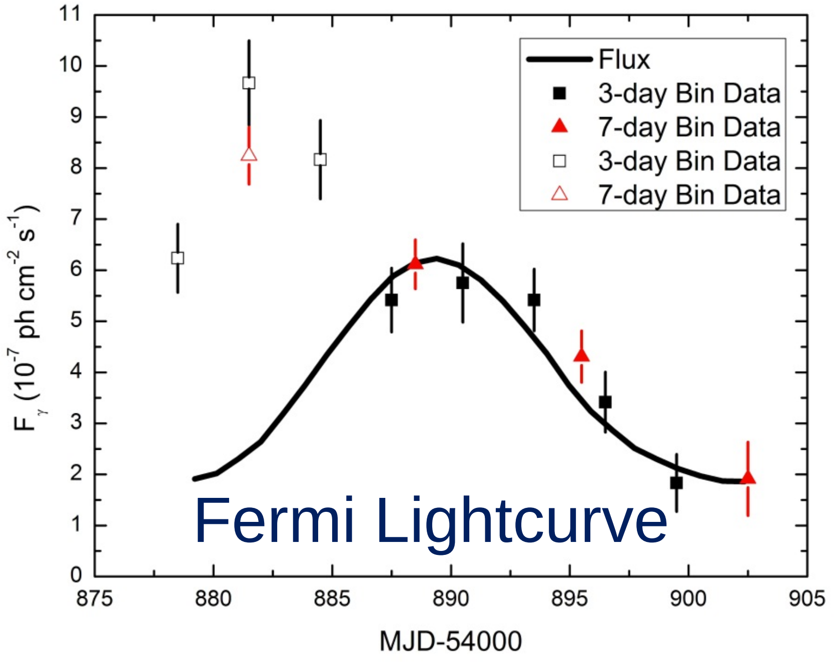
Simultaneous optical + γ-ray flare, correlated with a 180º polarization-angle rotation .

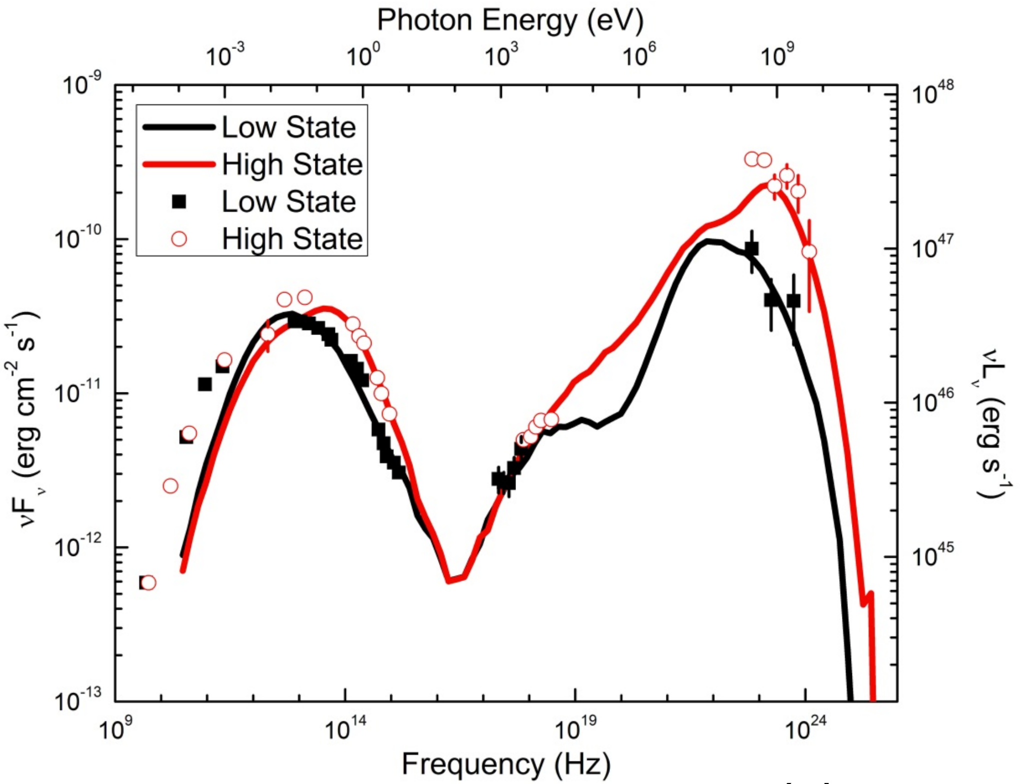
(Abdo et al. 2010)

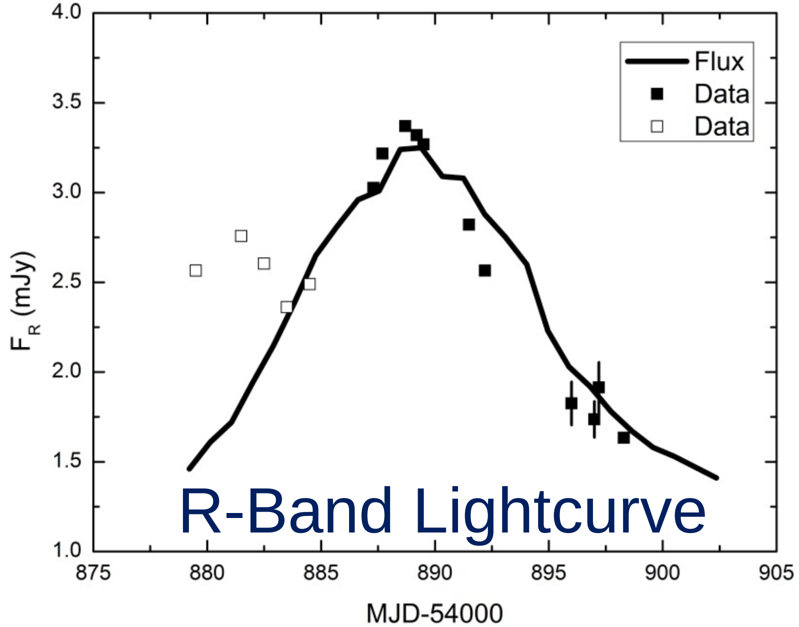


Application to 3C279

Simultaneous fit to SEDs, light curves, polarization-degree and polarization-angle swing



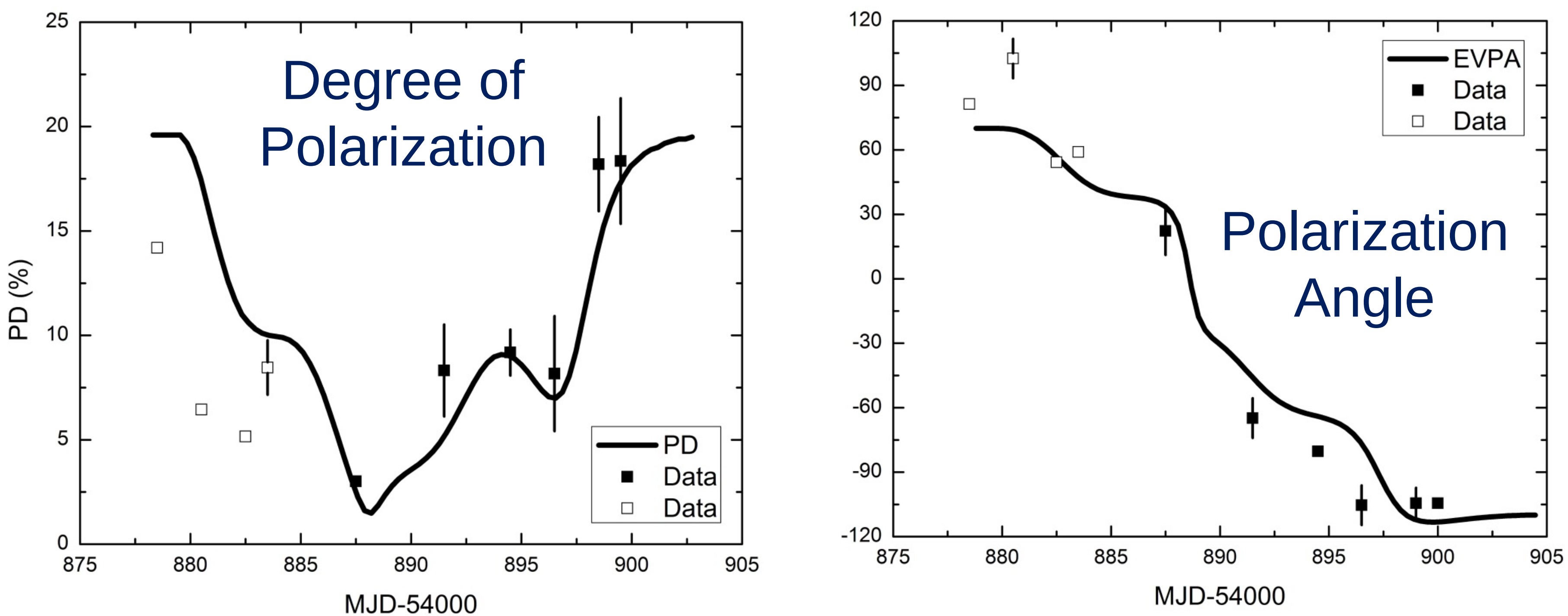




(Zhang et al. 2015)

Application to 3C279

Requires particle acceleration
and reduction of magnetic field,
as expected in magnetic reconnection!



(Zhang et al. 2015)

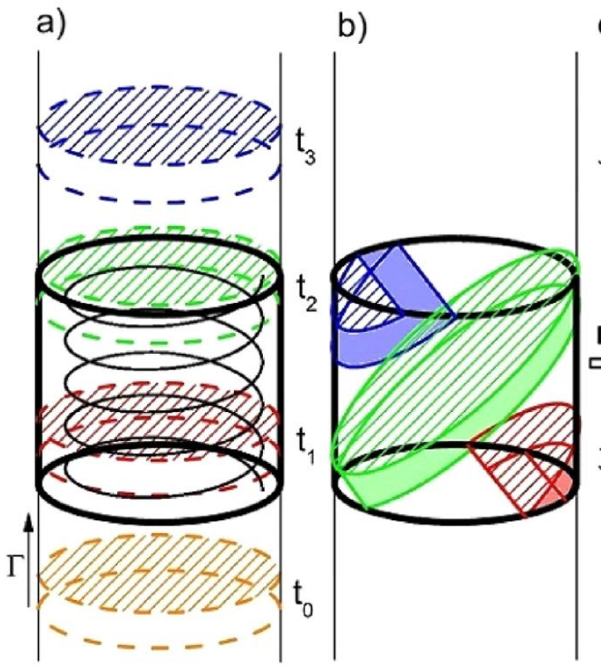
The Lepto-Hadronic Version

- Lepto-hadronic (p-synchrotron dominated) 3D time- and polarization-dependent internal shock model (Zhang, Diltz & Böttcher 2016)

- Model setup as for leptonic (3DPol) model, but include injection of ultrarelativistic protons

- Electron + proton evolution with locally isotropic Fokker-Planck equation

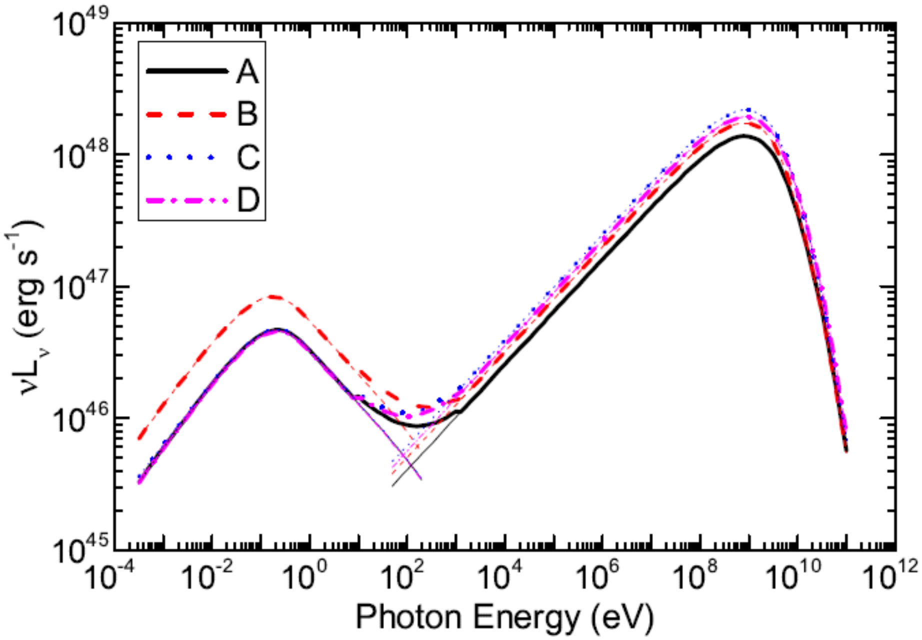
- Fully time- and polarization-dependent ray tracing



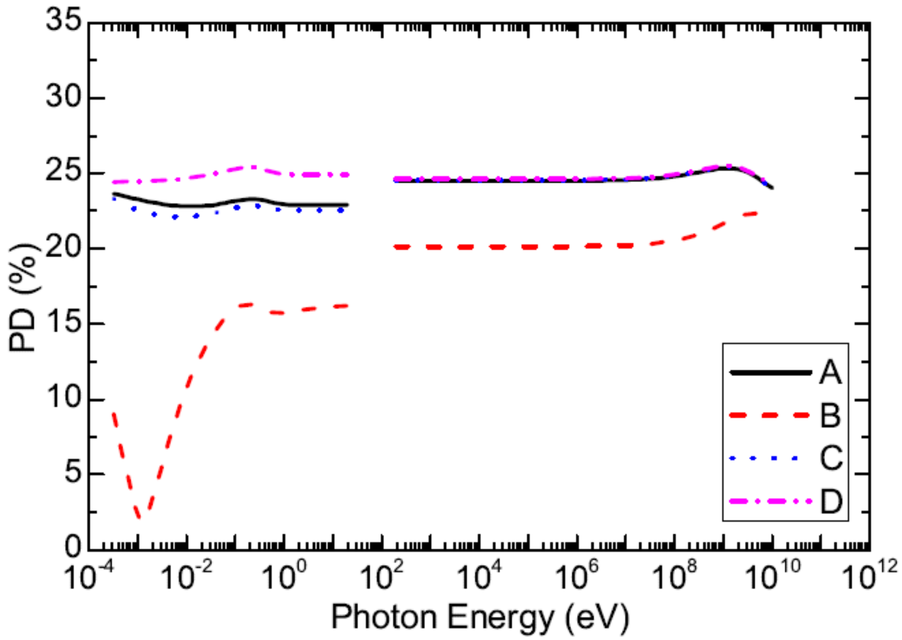
3D Lepto-Hadronic Internal Shock model

Example case: Magnetic energy dissipation (reducing B-field, additional e and p injection)

(Zhang et al. 2016)

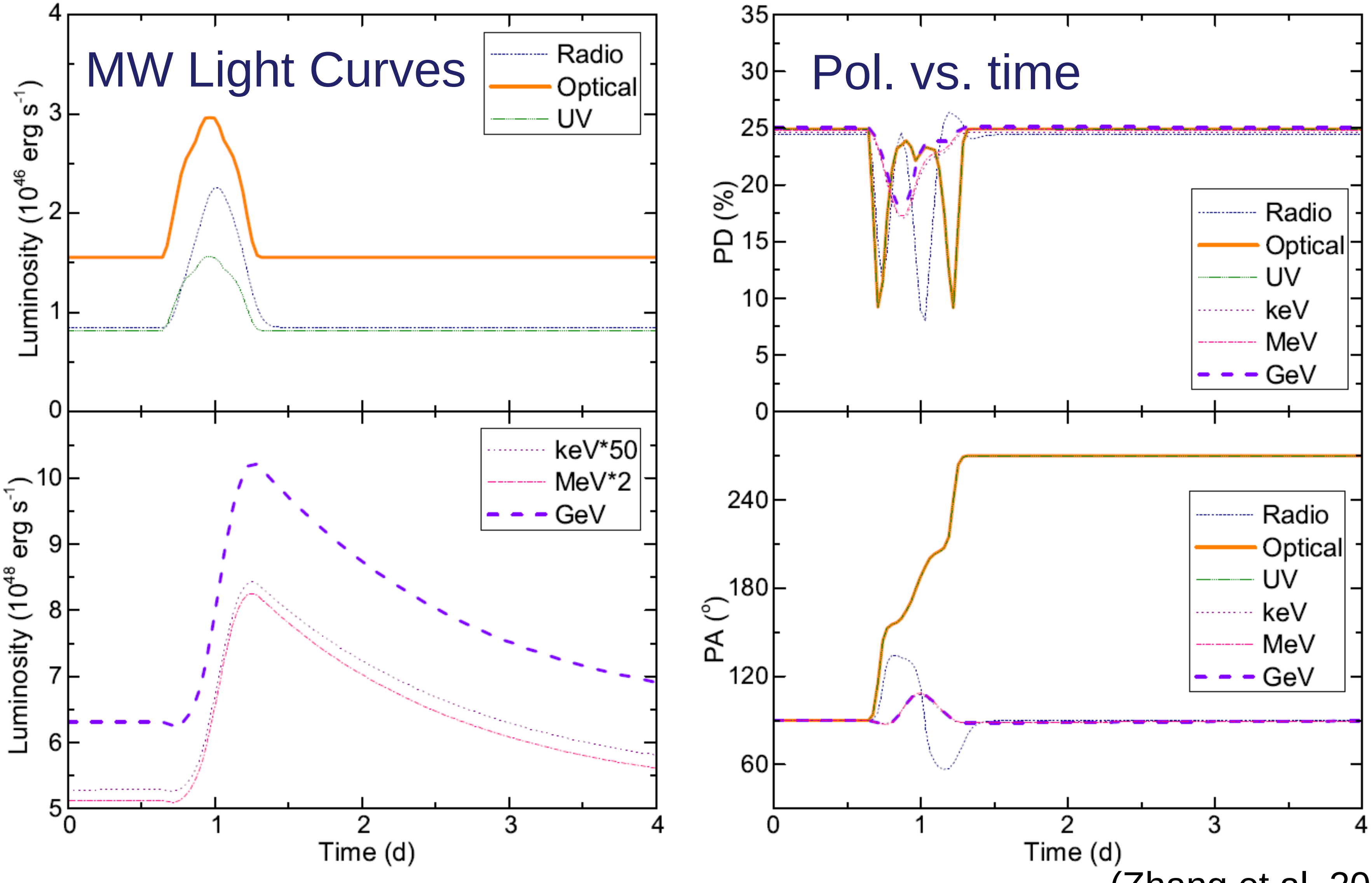


Snap-Shot SEDs



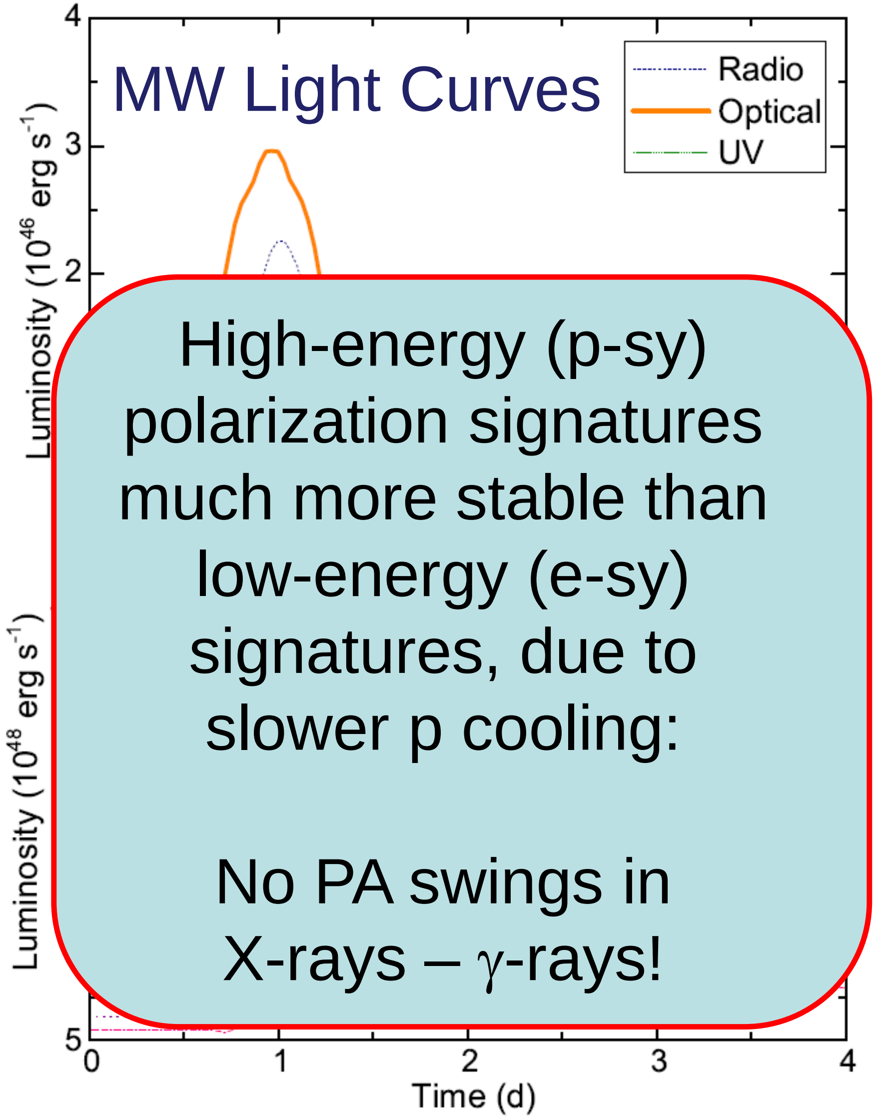
Pol. Deg. vs. Photon Energy

3D Lepto-Hadronic Internal Shock model



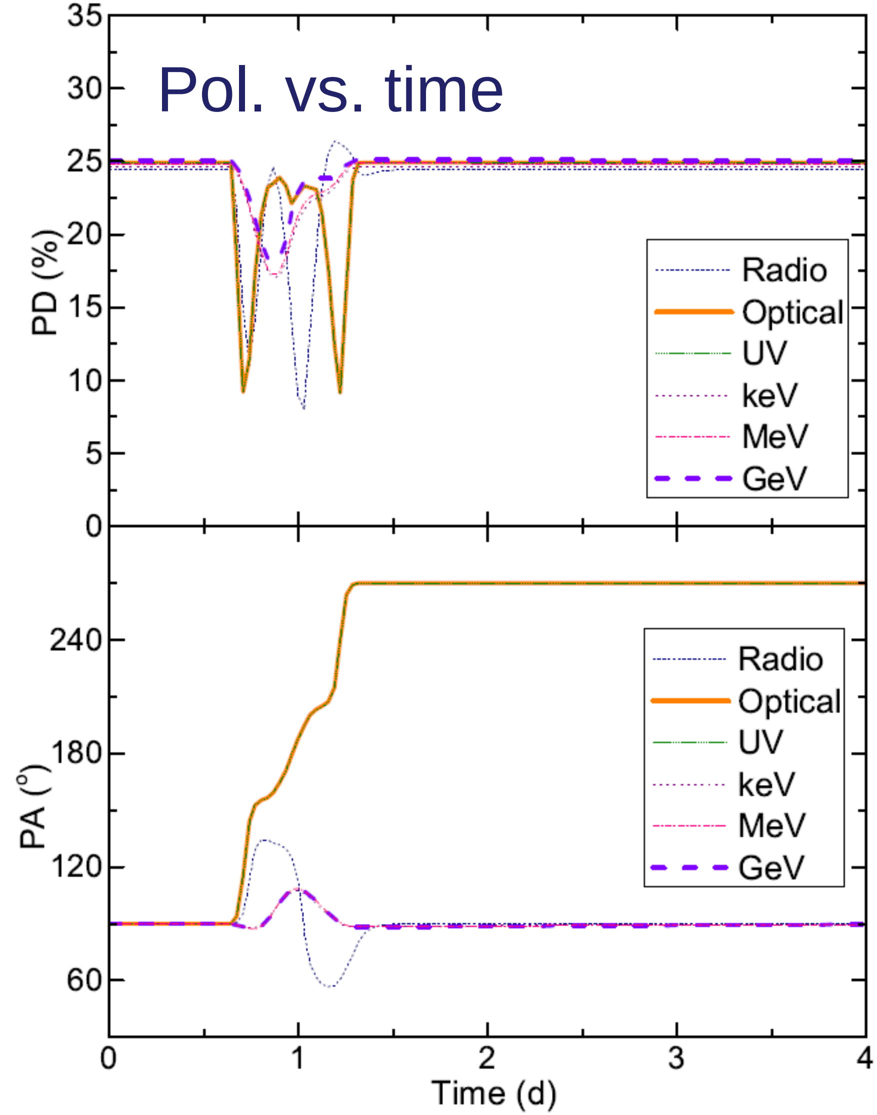
(Zhang et al. 2016)

3D Lepto-Hadronic Internal Shock model



High-energy (p-sy) polarization signatures much more stable than low-energy (e-sy) signatures, due to slower p cooling:

No PA swings in X-rays – γ-rays!



(Zhang et al. 2016)

Summary

1. Significant X-ray and γ-ray polarization in blazars would strongly favour hadronic models

2. Polarization-angle swings correlated with MW flares are possible with a straight jet, pervaded by a helical B field. Fit to 3C279 event suggests magnetic energy dissipation as driver of flaring activity.

3. 3D time- and polarization-dependent radiation transfer simulations for a proton-synchrotron dominated lepto-hadronic model: High-energy (X-ray/gamma-ray) polarization signatures are expected to be less variable than low-energy (e-synchrotron) ones. PA swings in X-rays / γ-rays are unlikely if high-energy emission has hadronic origin.

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