Multiwavelength Polarization as a Diagnostic of Jet Physics

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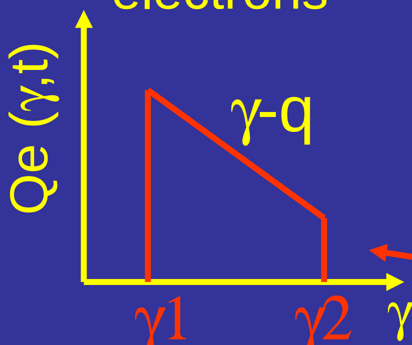
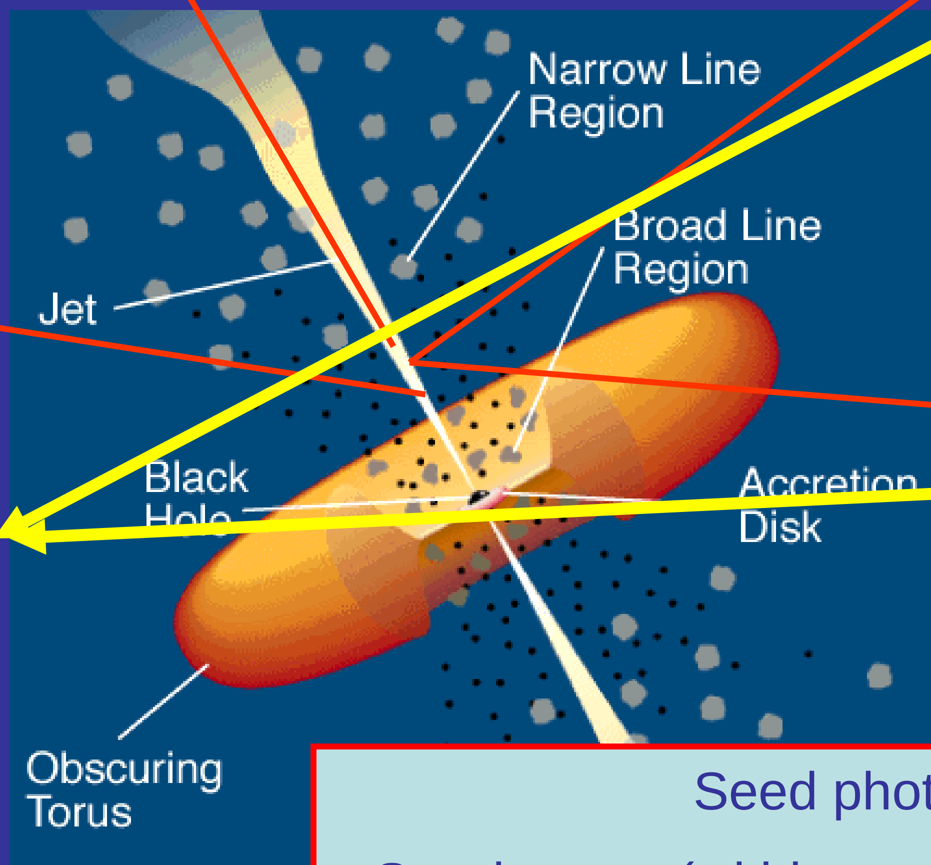
Leptonic Blazar Model

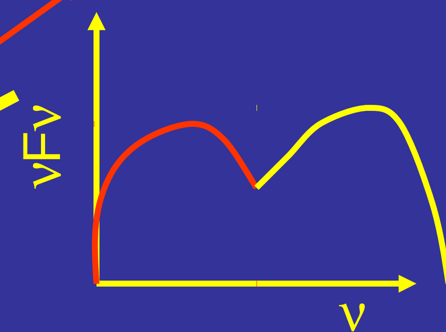
Injection, acceleration of ultrarelativistic electrons



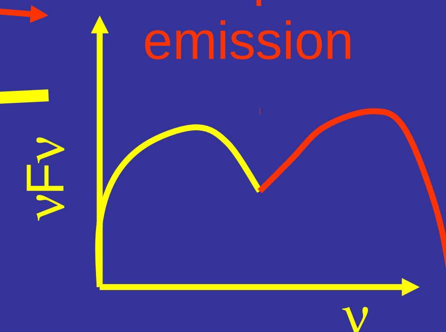
Relativistic jet outflow with $\Gamma \approx 10$



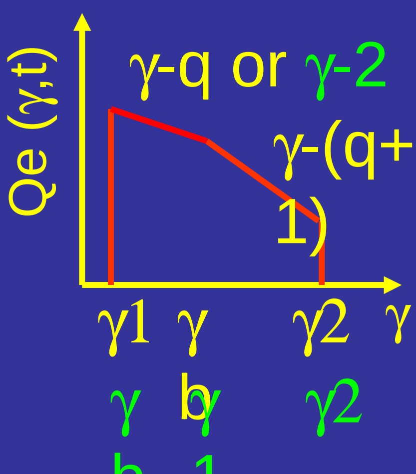
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



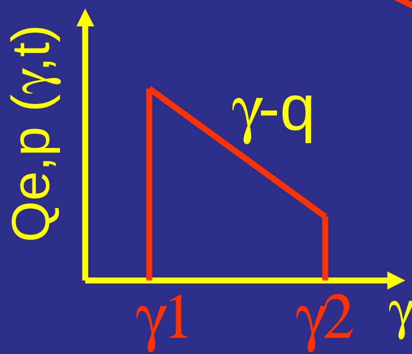
γb: τcool(γb) = τesc

Seed photons:

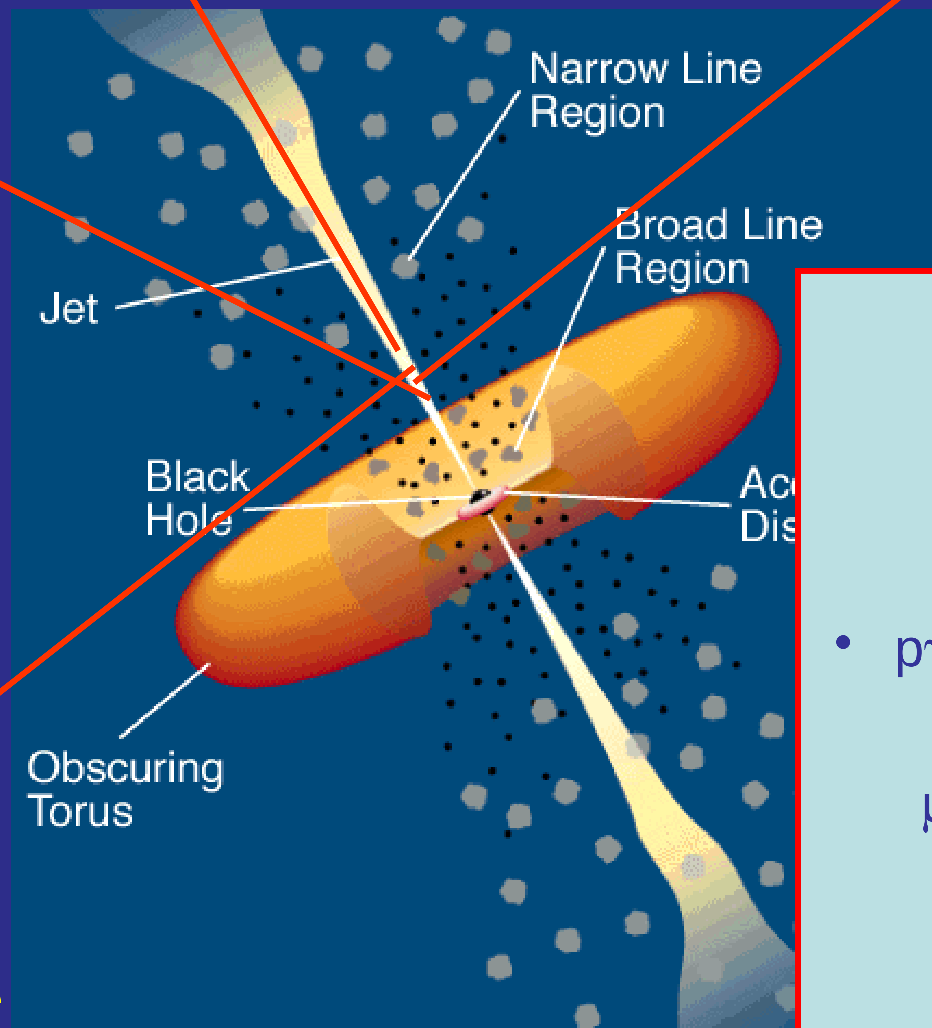
Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

Hadronic Blazar Models

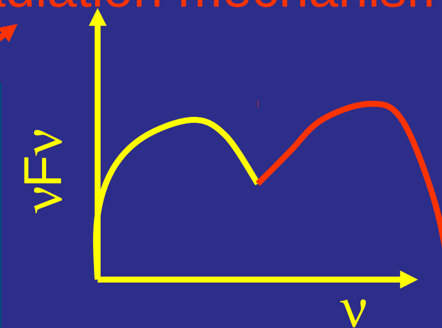
Injection, acceleration of ultrarelativistic electrons and protons



Relativistic jet outflow with $\Gamma \approx 10$

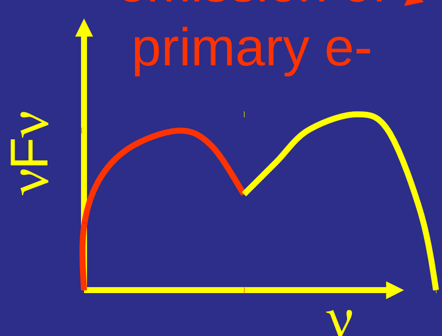


Proton-induced radiation mechanisms



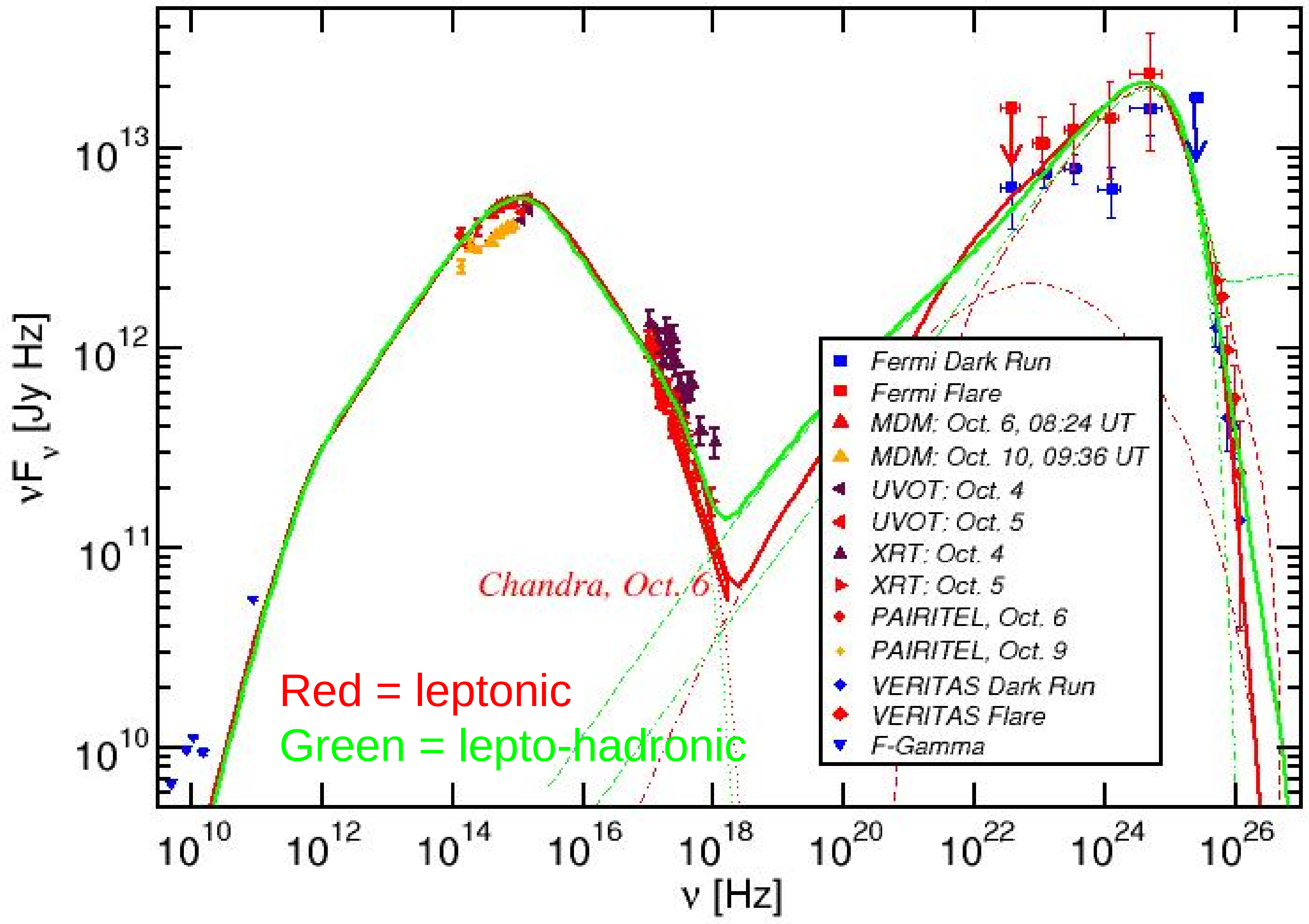
- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$ $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$ — $\mu^+ \rightarrow e^+\nu_e\nu_\mu$ → secondary μ-, e-synchrotron
- Cascades …

Synchrotron emission of primary e-



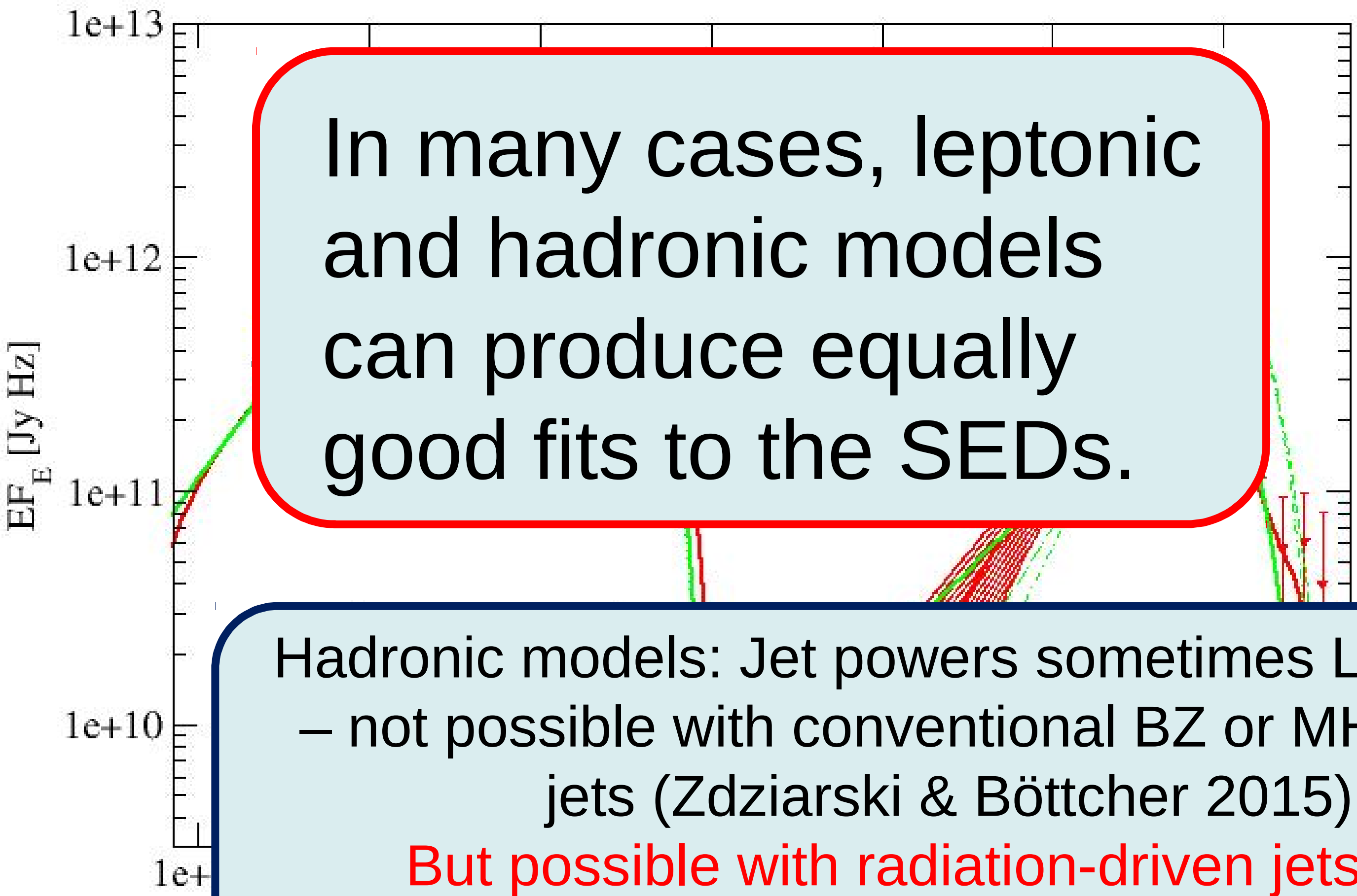
Leptonic and Hadronic Model Fits to Blazar SEDs

3C66A (IBL)



Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)



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

Possible Diagnostics to distinguish:

- Neutrinos *(→ Kadler)*
- Variability
- Polarization

Hadronic models: Jet powers sometimes Ljet > LEdd – not possible with conventional BZ or MHD-driven jets (Zdziarski & Böttcher 2015)

But possible with radiation-driven jets from super-Eddington accretion flows (e.g., Sadowski, Narayan)

Possible Distinguishing Diagnostic: Polarization

- Synchrotron Polarization

For synchrotron radiation from a power-law distribution of electrons with ne (γ) ~ γ-p → Fν ~ ν–α with α = (p–1)/2

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

p = 2 → Π = 69 %

p = 3 → Π = 75 %

Compton Polarization

Compton cross section is polarization-dependent:

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

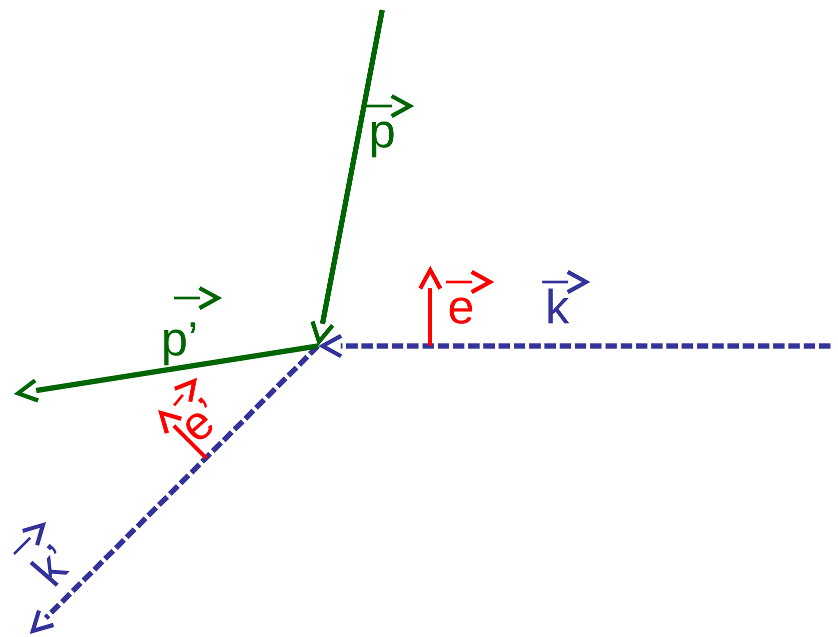
ε = hν/(mec2):

Thomson regime: ε ≈ ε'

⇒dσ/dΩ = 0 if $\vec{e}\cdot\vec{e}'$ = 0

⇒ 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

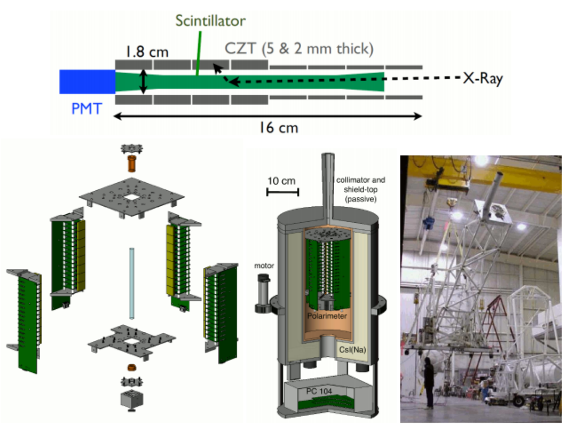
  - External-Compton emission: Unpolarized.

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

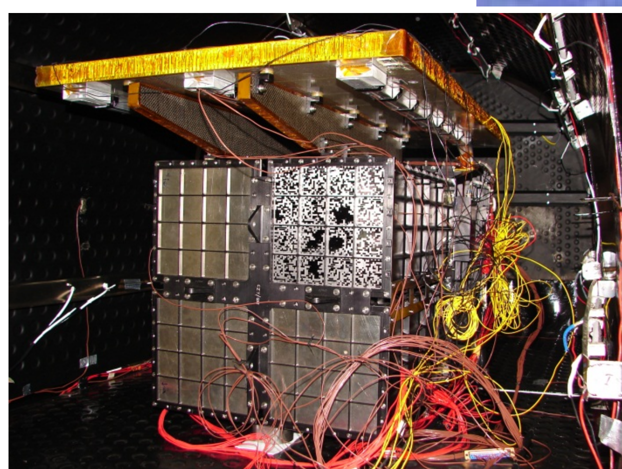
X-ray Polarimeters

INTEGRAL

Astro-H
(→ Y. Tanaka)

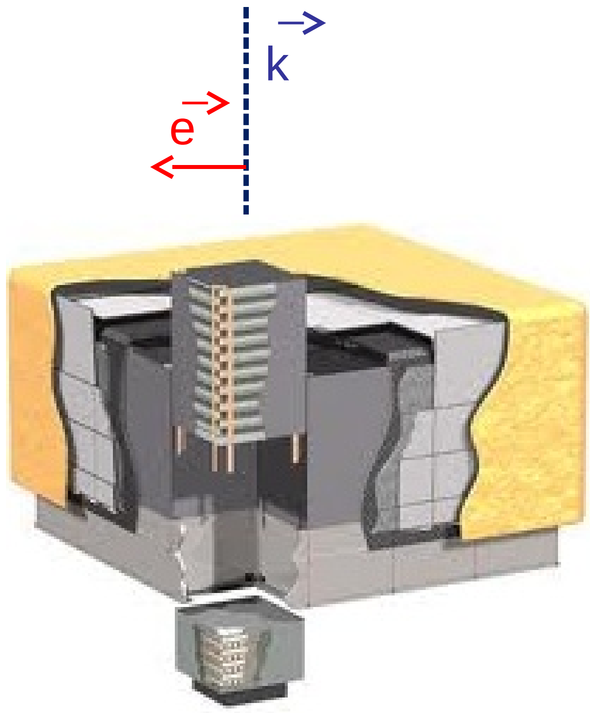


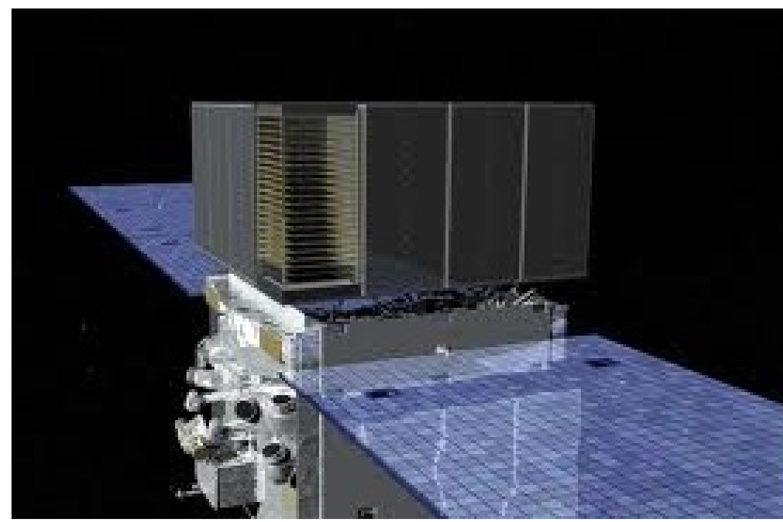
X-Calibur
→ PolSTAR (A. Zajczyk)



ASTROSAT
→ Poster by T. Chattopadhyay

Gamma-Ray Polarimetry with Fermi-LAT



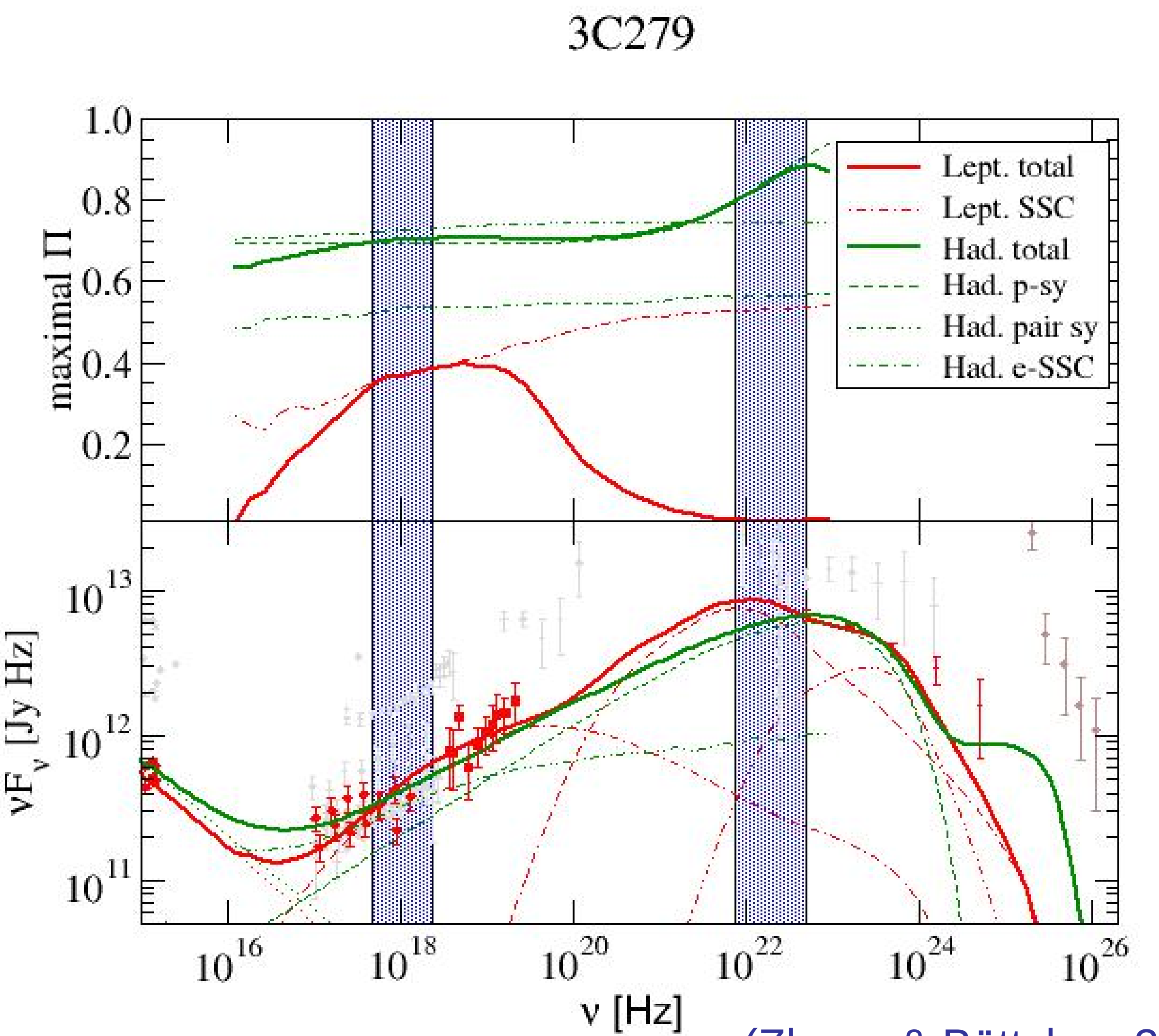


e+e- pair is preferentially produced in the plane of $(\vec{k}, \vec{e})$ of the γ-ray.

Potentially detectable at E < 200 MeV

→ PANGU

X-Ray and Gamma-Ray Polarization: FSRQs

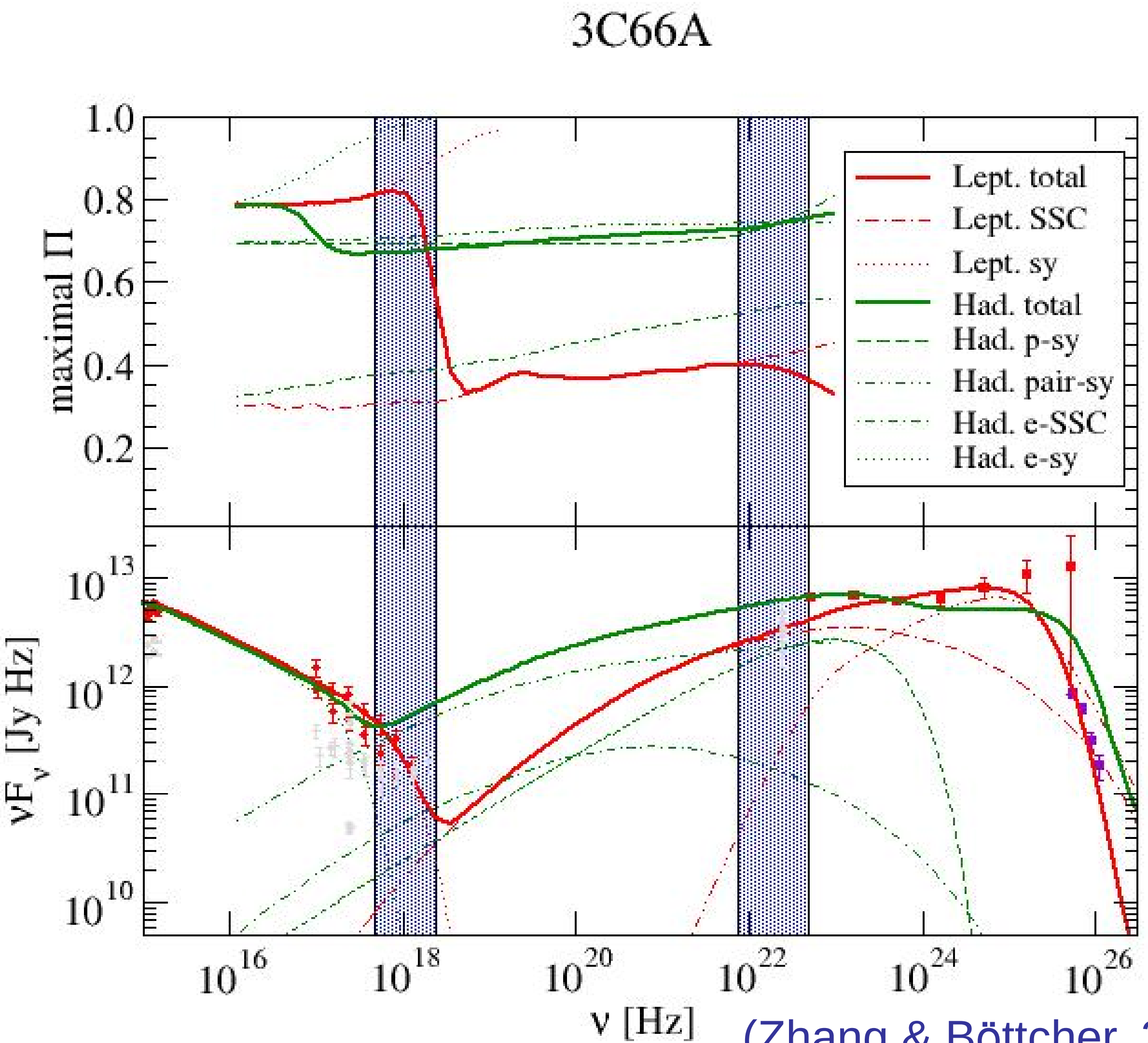


Hadronic model: Synchrotron dominated => High Π, generally increasing with energy (SSC contrib. in X-rays).

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.

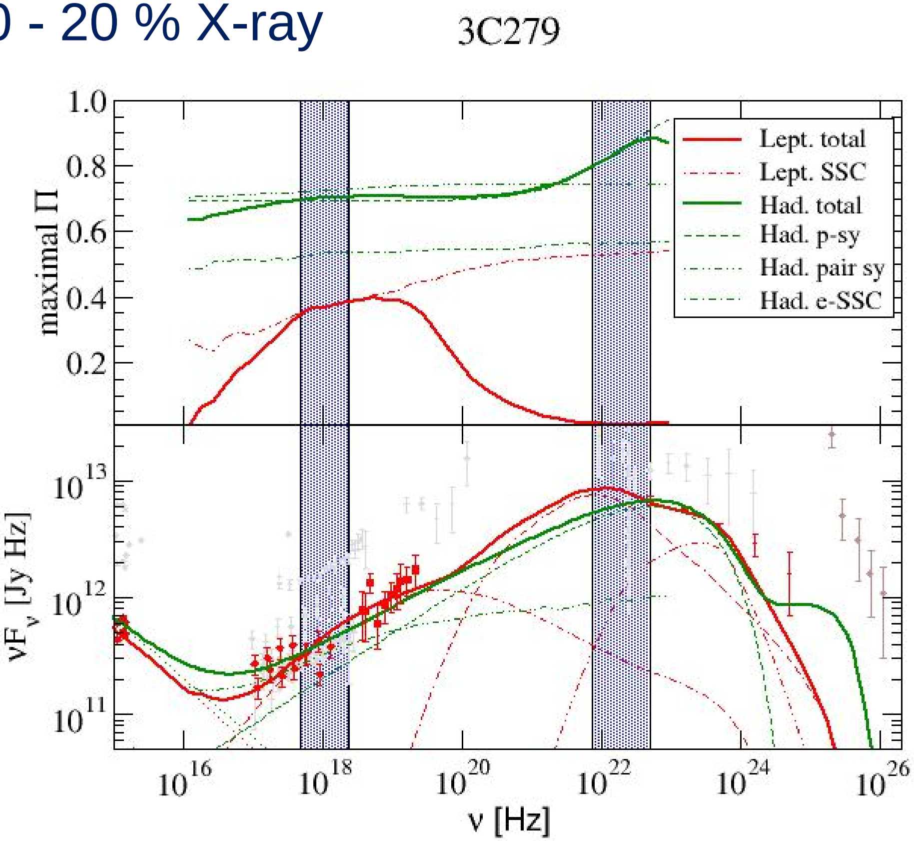
(Zhang & Böttcher, 2013)

Observational Strategy

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

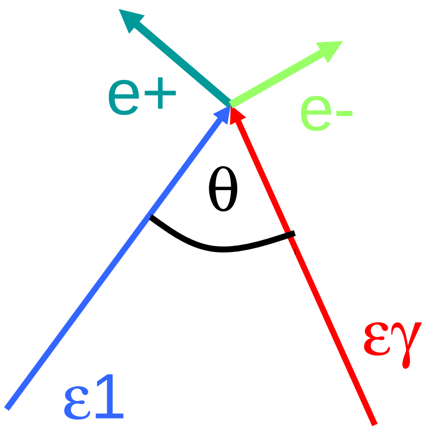
  - Scale results to actual B-field configuration from known synchrotron polarization (e.g., optical for FSRQs/LBLs) => Expect 10 - 20 % X-ray and γ-ray polarization in hadronic models!

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



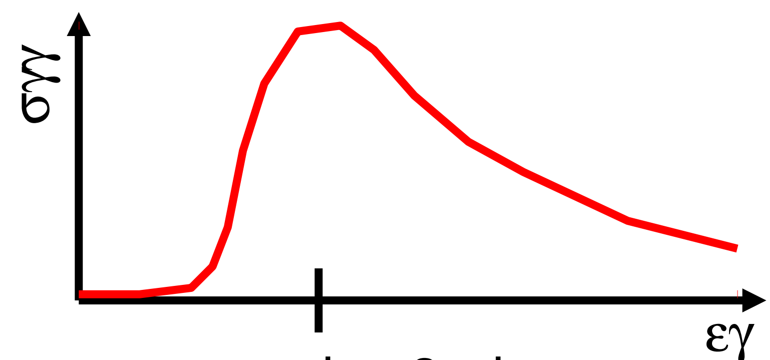
Gamma-Gamma Absorpton / Pair production

Threshold energy Ethr for a γ-ray interacting with a background photon field of photons with characteristic photon energy E1:



$\varepsilon_{thr} \sim 1/\varepsilon_1$

$\varepsilon = E_{ph}/(m_e c^2)$



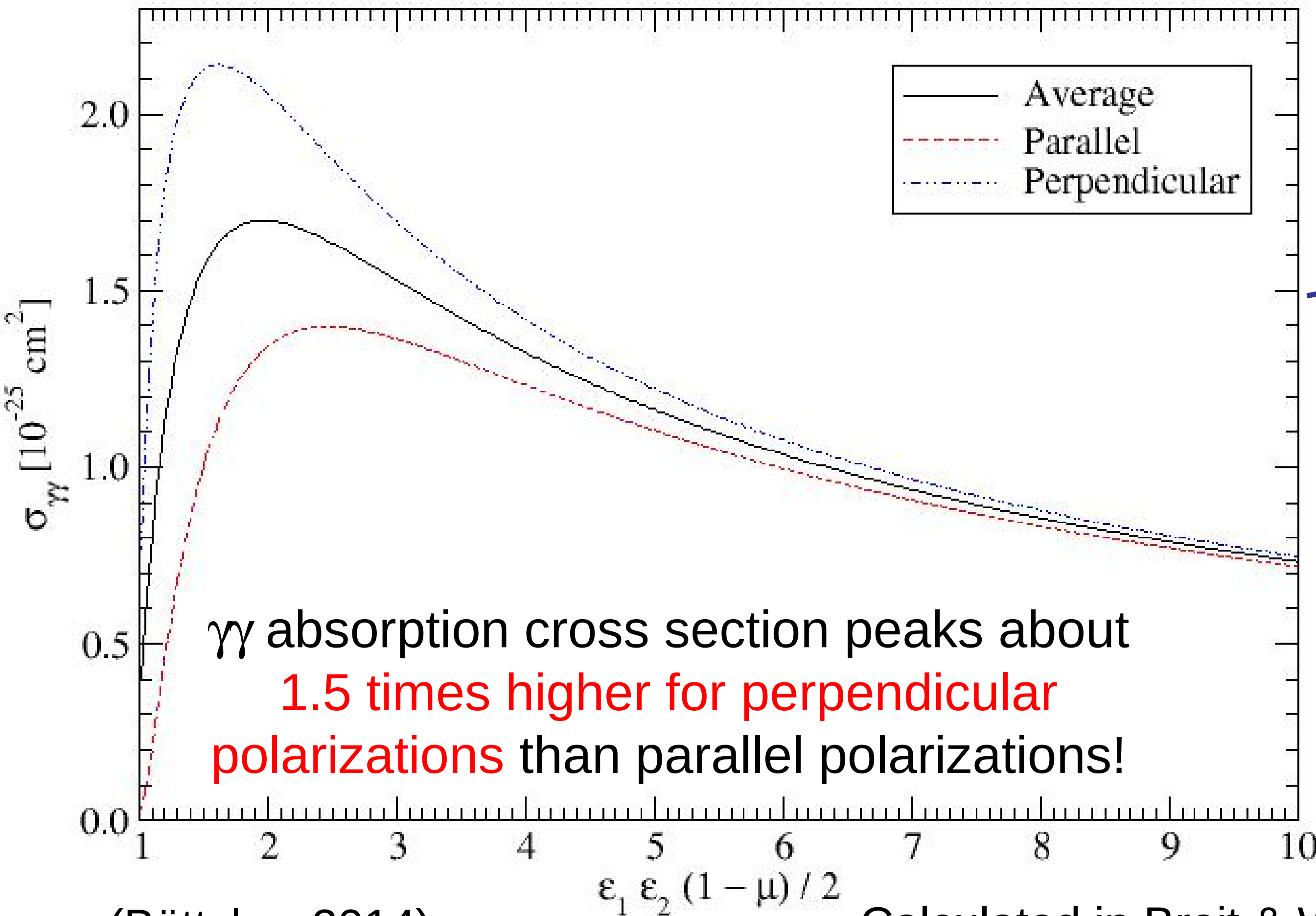
$\varepsilon_{peak} = 2\ \varepsilon_{thr} \sim 2/\varepsilon_1$

Lack of γγ absorption signatures in blazars and GRBs used for lower limits on Doppler factors

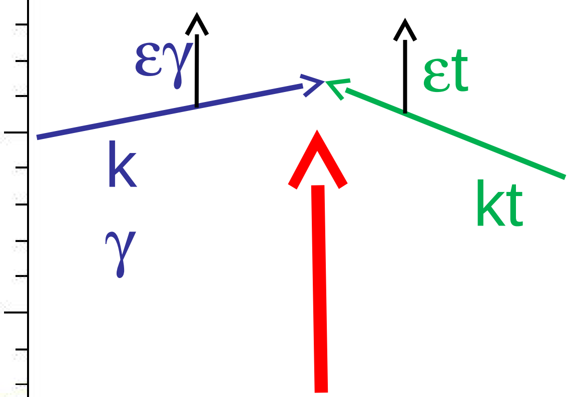
(Baring 1993; Dondi & Ghisellini 1995)

Polarization-Dependence of Gamma-Gamma Absorption

For polarized γ-rays and target photons:



γγ absorption cross section peaks about 1.5 times higher for perpendicular polarizations than parallel polarizations!



γγ absorption suppressed!

(Böttcher 2014)

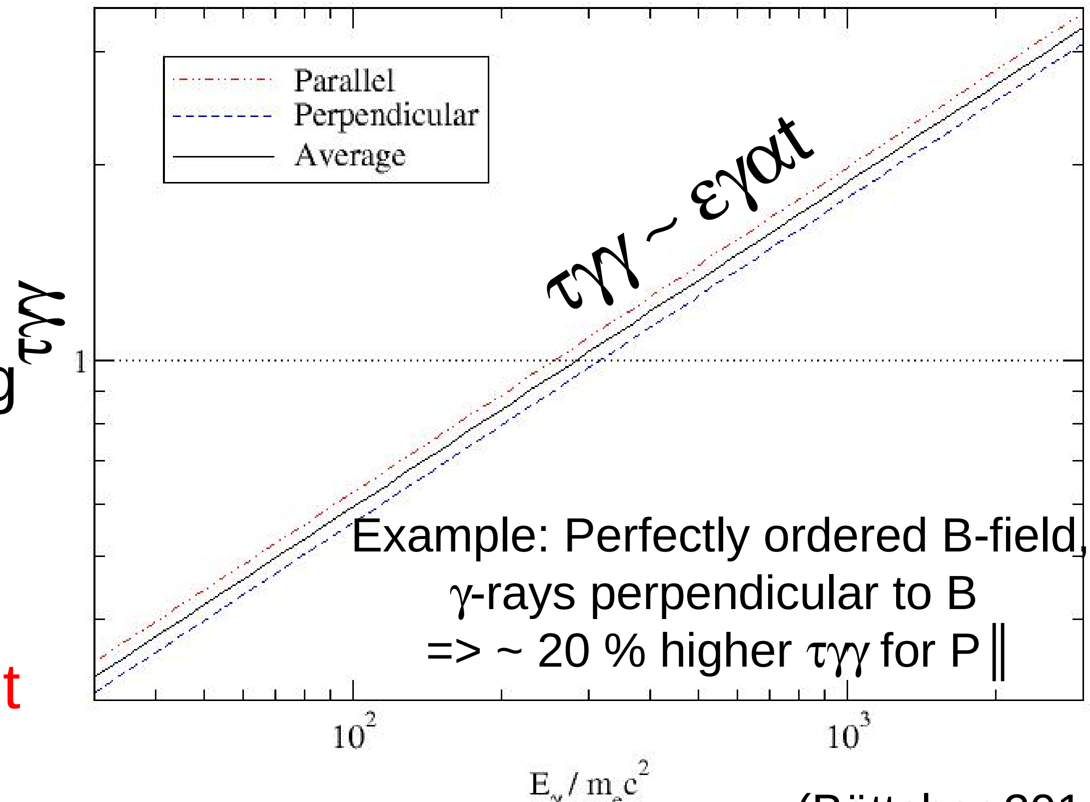
Calculated in Breit & Wheeler (1934)

$\gamma\gamma$ absorption in a high-energy synchrotron source (GRB)

γ-ray and target photons have the same orientation of polarization (perpendicular to B-field: $P_\perp > P_\parallel$) =>

- $\gamma\gamma$ absorption is suppressed

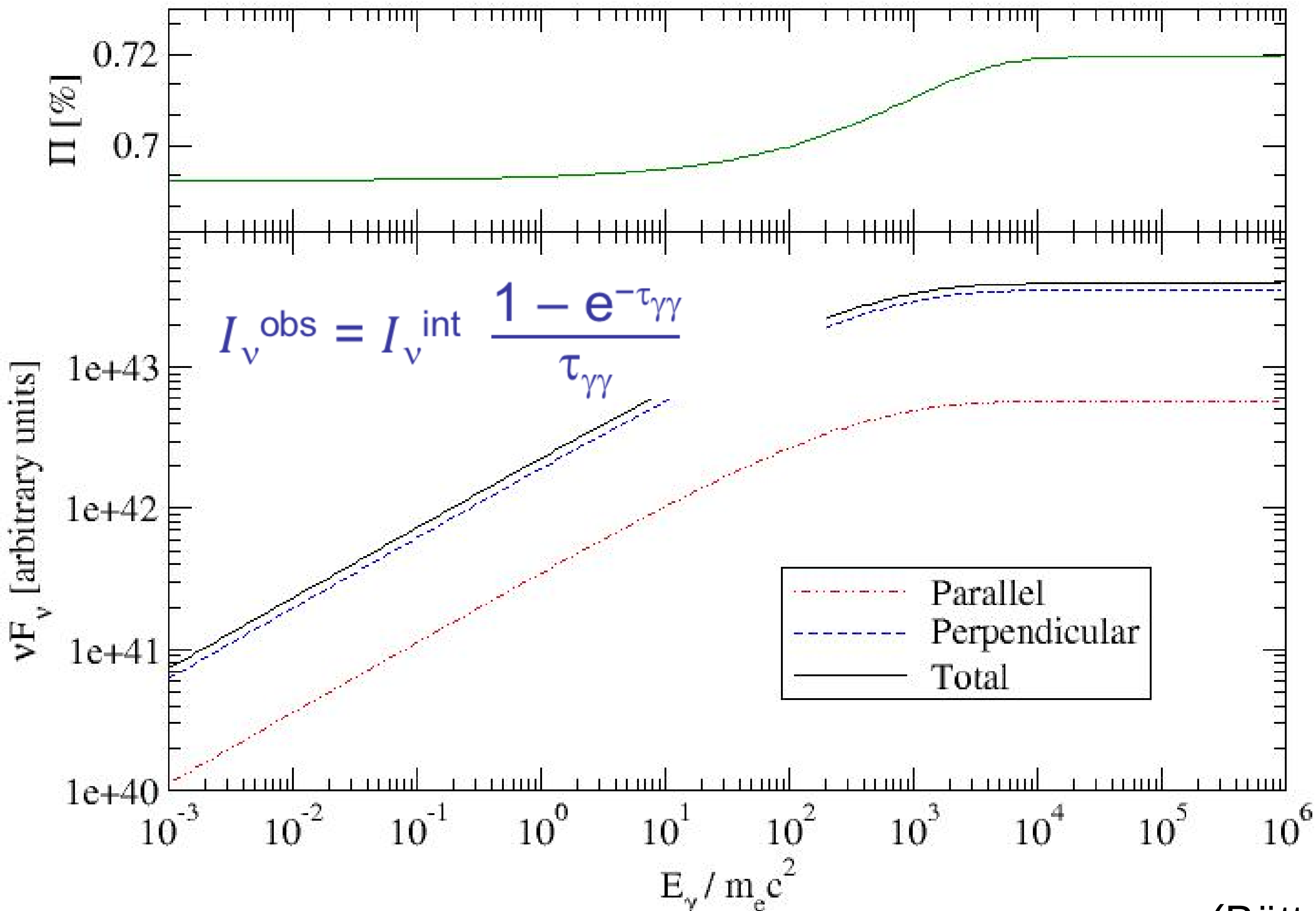
- $\gamma\gamma$ absorption is more pronounced for $P_\parallel$ (absorbed more strong by $P_\perp$) => Degree of Polarization (Π) increases due to polarization-dependent $\gamma\gamma$ absorption!



(Böttcher 2014)

γγ absorption in a high-energy synchrotron source (GRB)

=> Expect increasing polarization at break due to γγ-absorption



(Böttcher 2014)

Dependence on Spectral Index

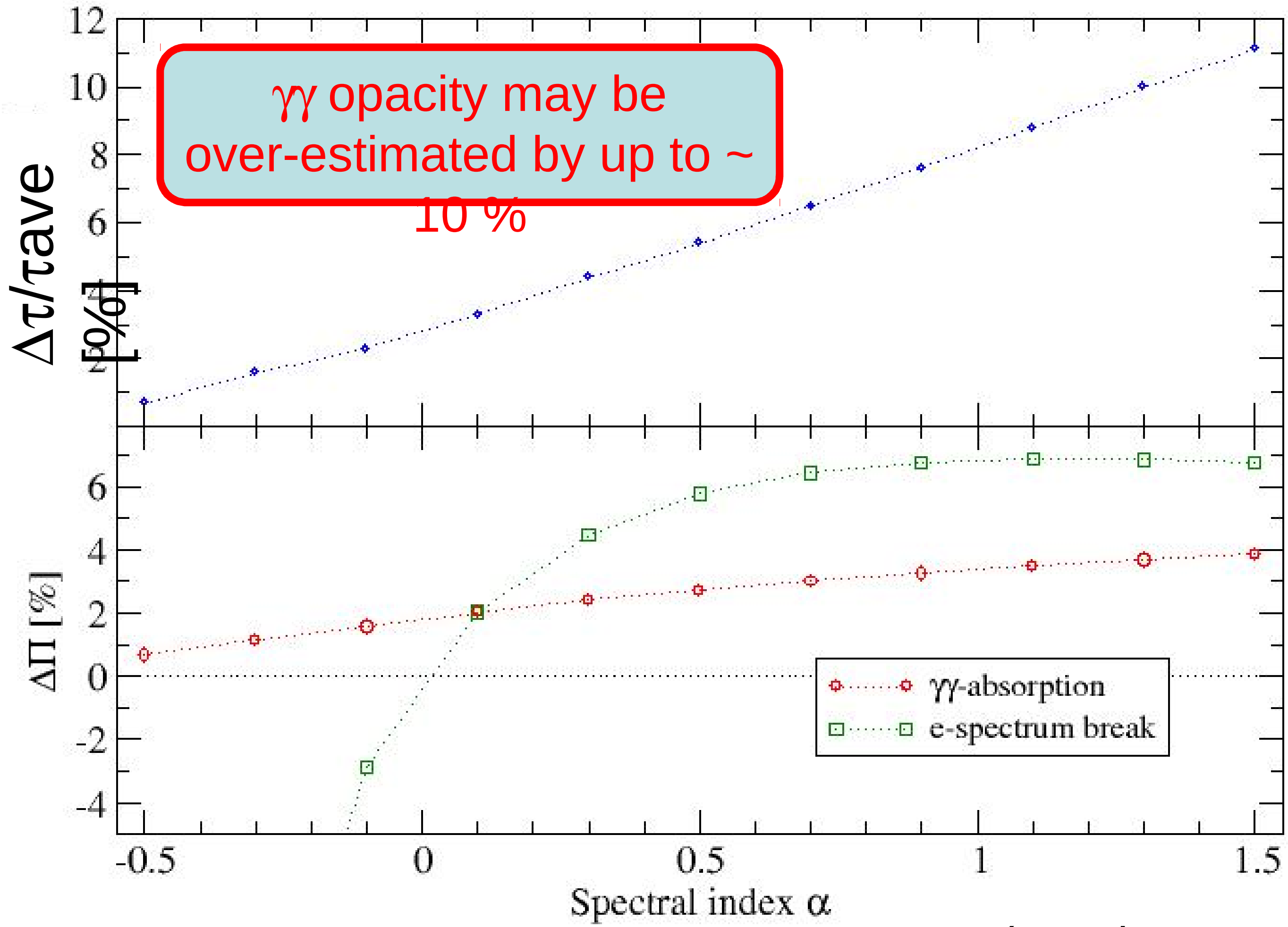
$$I_\nu^{obs} = I_\nu^{int} \frac{1 - e^{-\tau_{\gamma\gamma}}}{\tau_{\gamma\gamma}}$$

$\tau\gamma\gamma \sim \varepsilon\gamma\alpha t$

=> Spectral break by $\Delta\alpha\gamma = \alpha t$

Compare $\Delta\Pi$ from polarization-dependent $\gamma\gamma$-absorption with $\Delta\Pi$ from change in underlying electron spectrum.

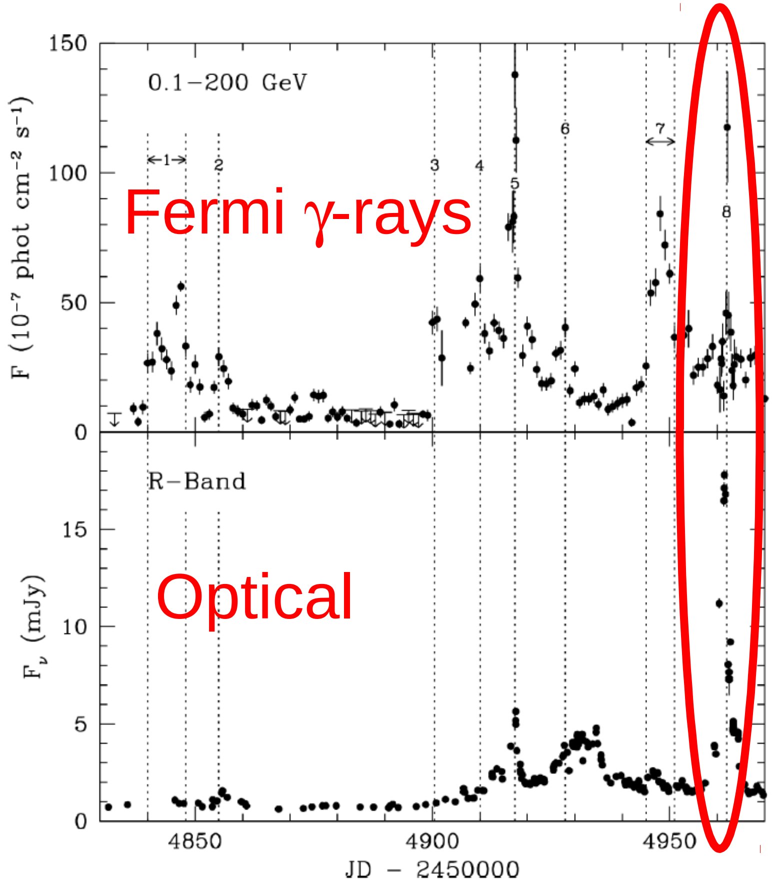
$$\Pi = \frac{\alpha+1}{\alpha+5/3}$$

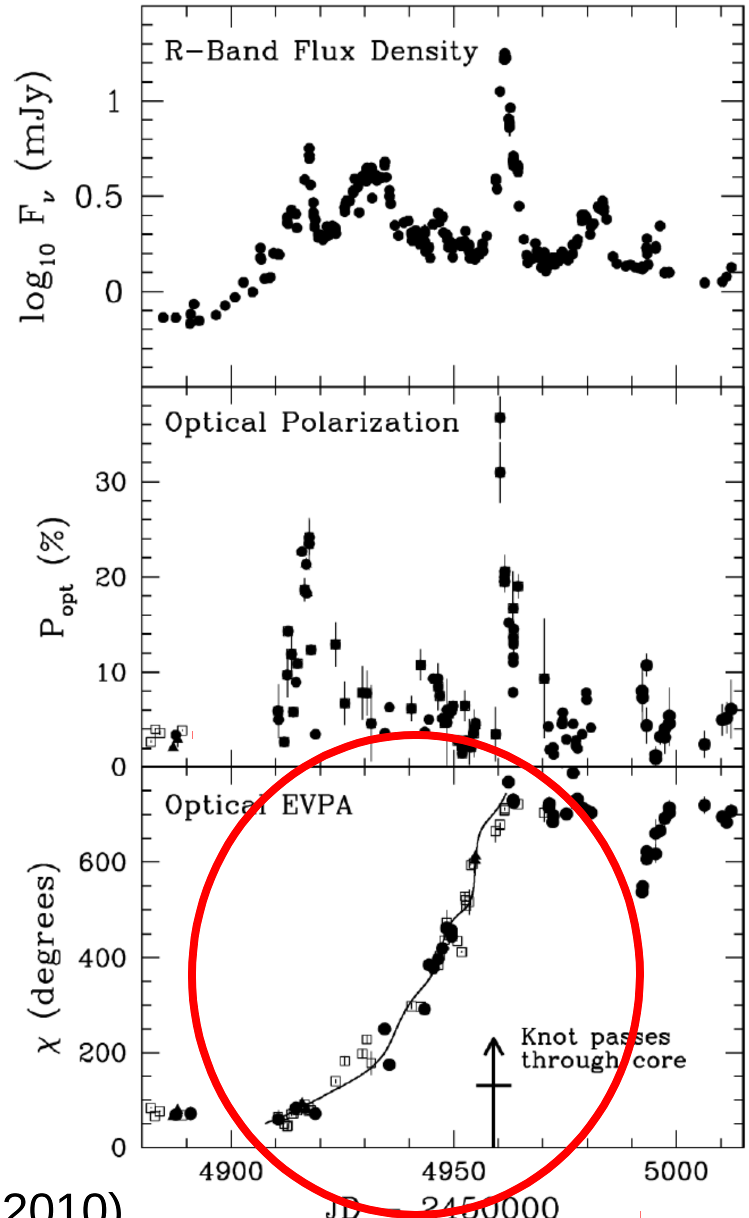


(Böttcher 2014)

Polarization Angle Swings

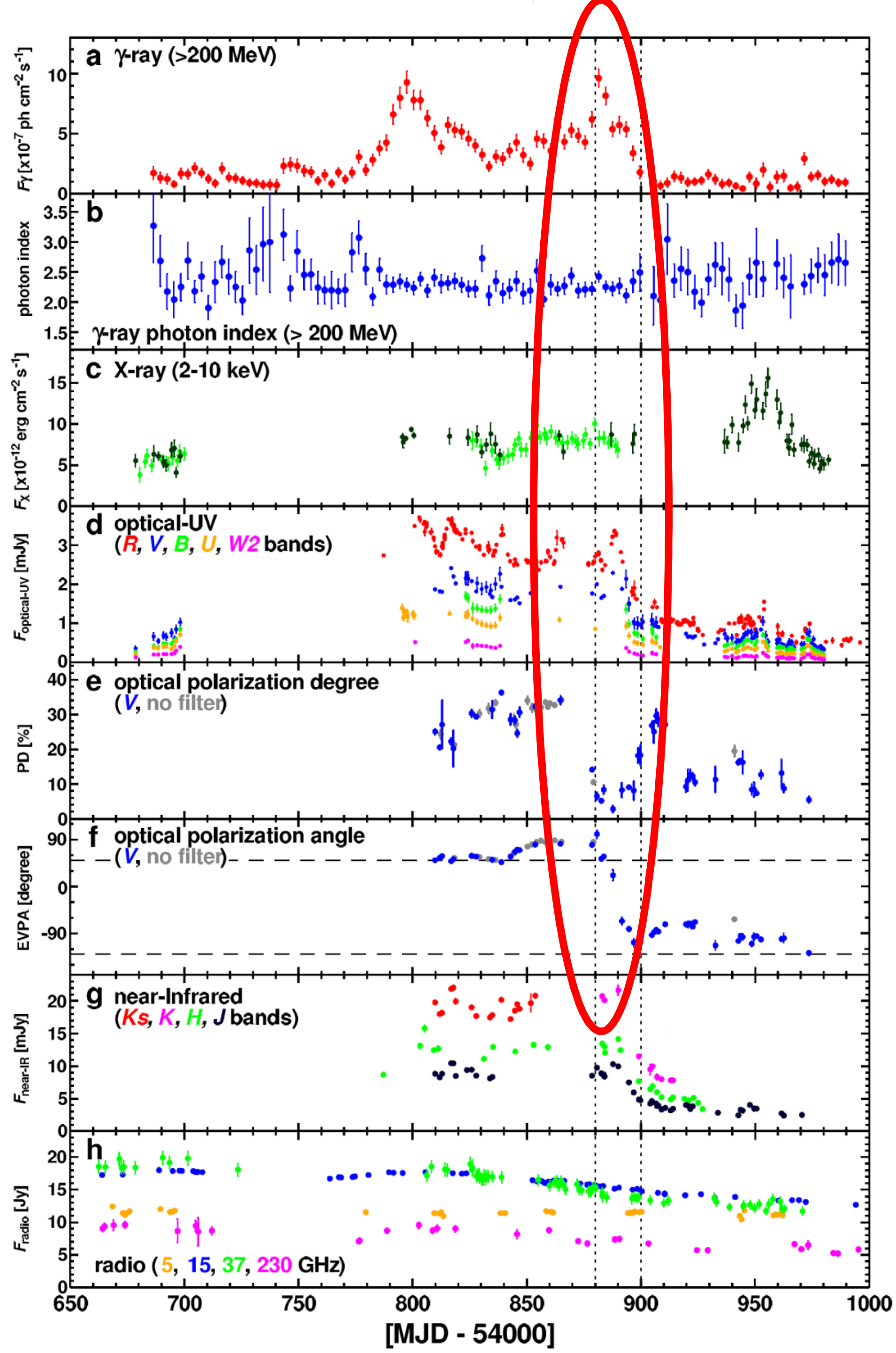
- Optical + γ-ray variability of LSP blazars often correlated
- Sometimes O/γ flares correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)





PKS 1510-089 (Marscher et al. 2010)

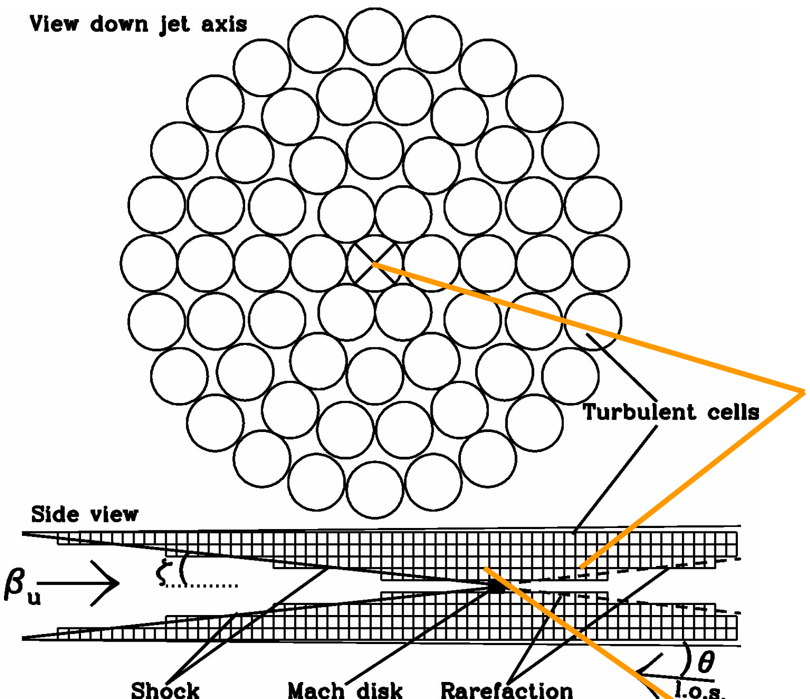
Polarization Swings



3C279 (Abdo et al. 2009)

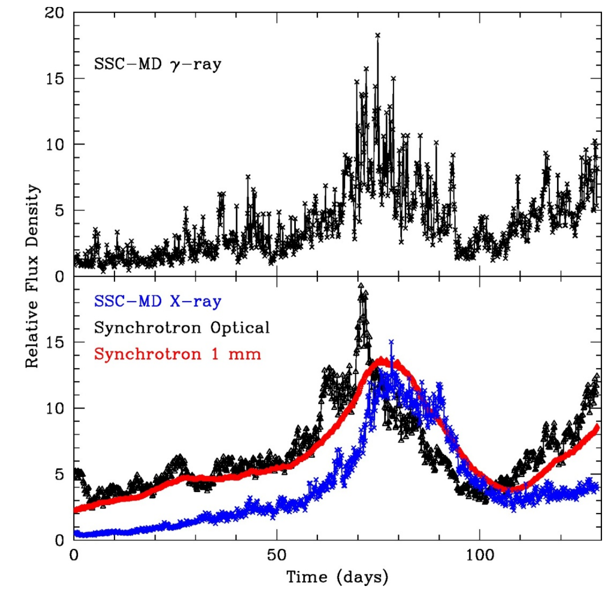
Previously Proposed Interpretations:

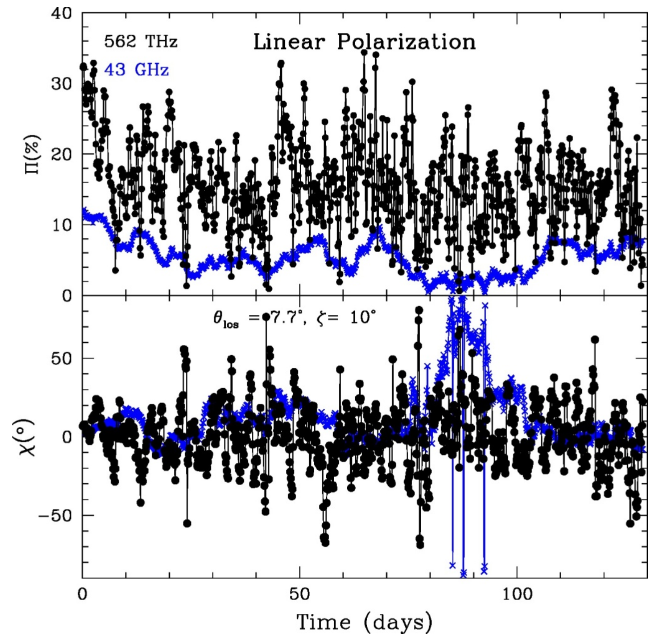
- Helical magnetic fields in a bent jet
- Helical streamlines, guided by a helical magnetic field
- Turbulent Extreme Multi-Zone Model (Marscher 2014)



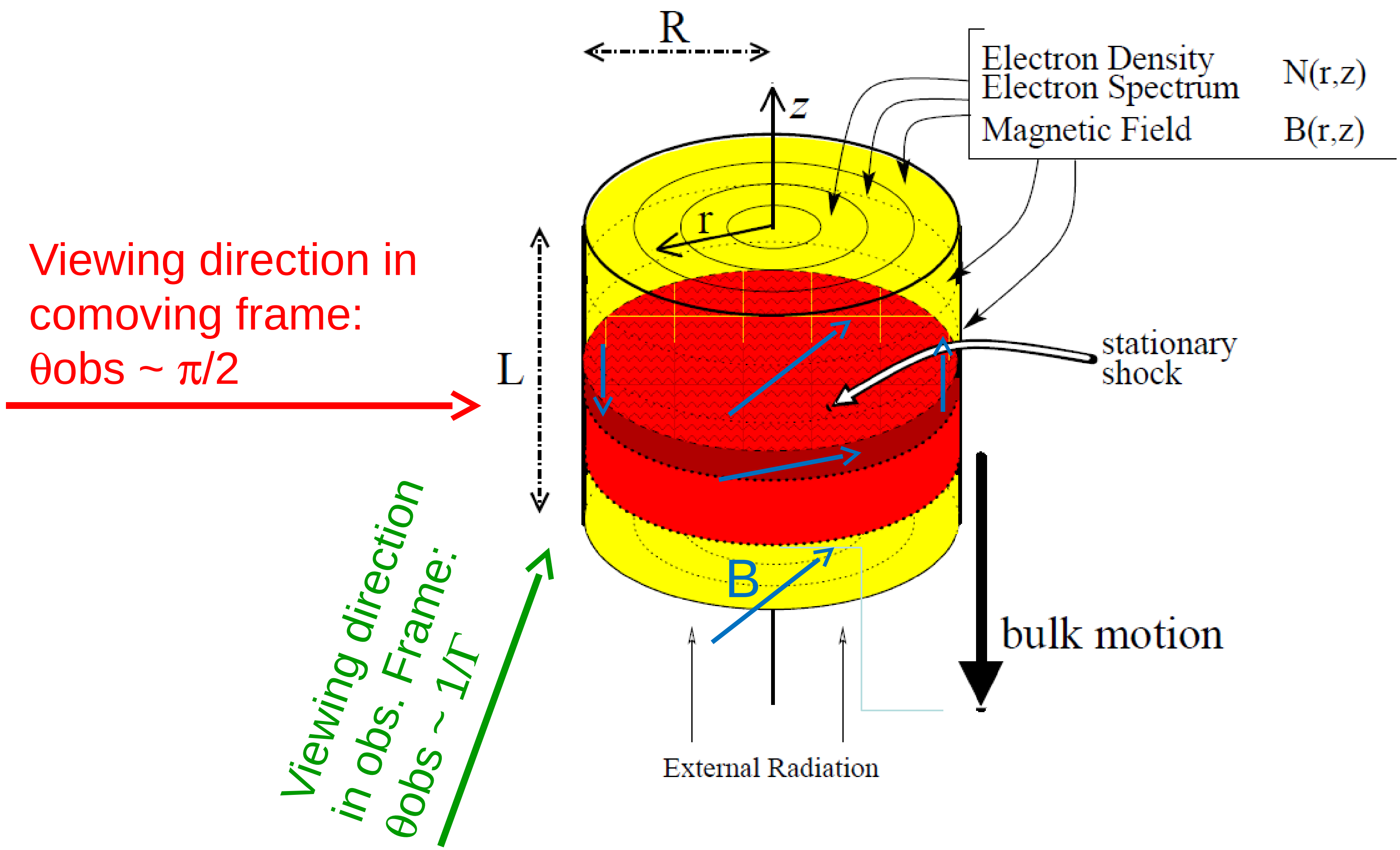
Mach disk

Looking at the jet from the side

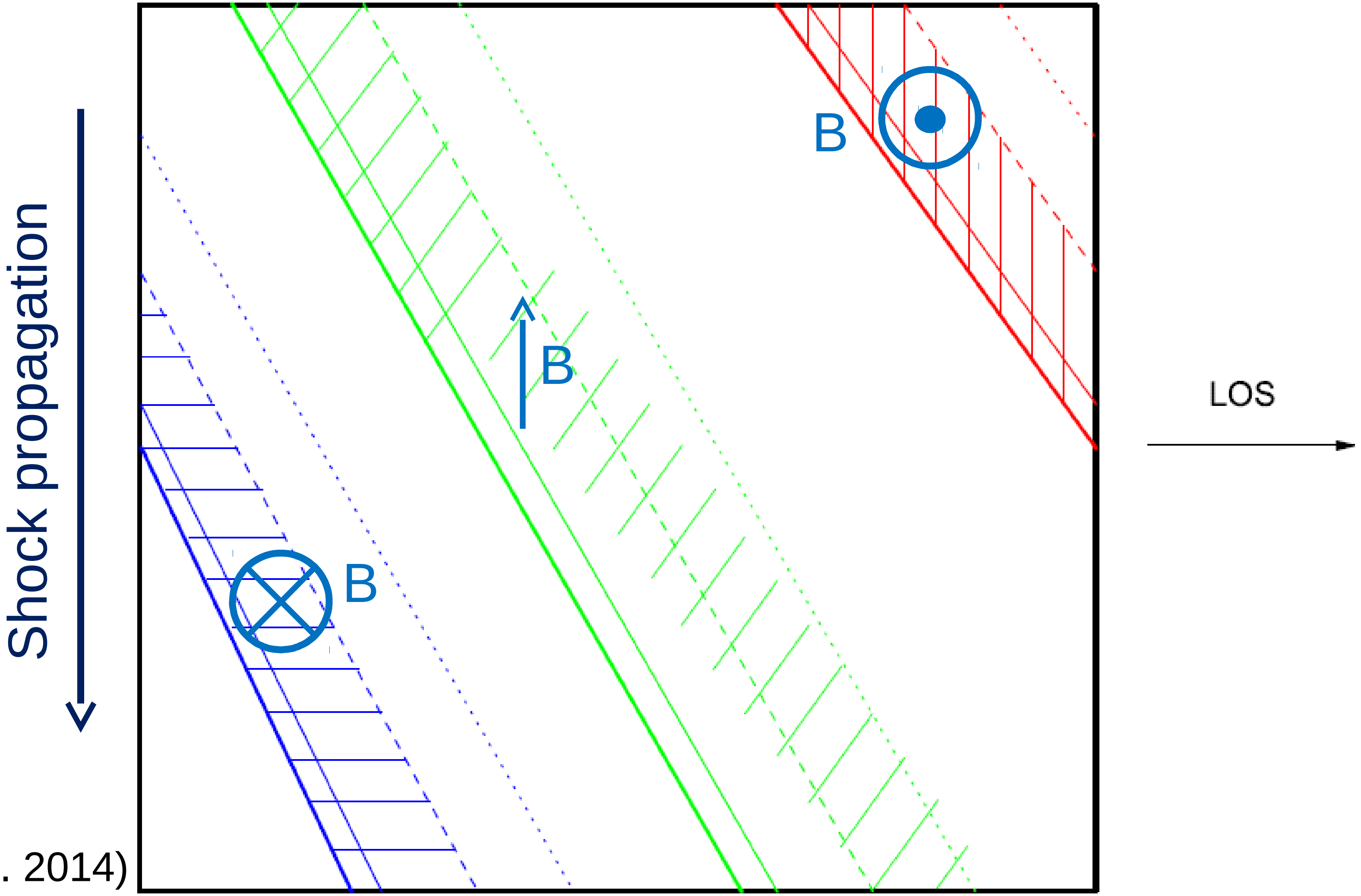




Tracing Synchrotron Polarization in the Internal Shock Model



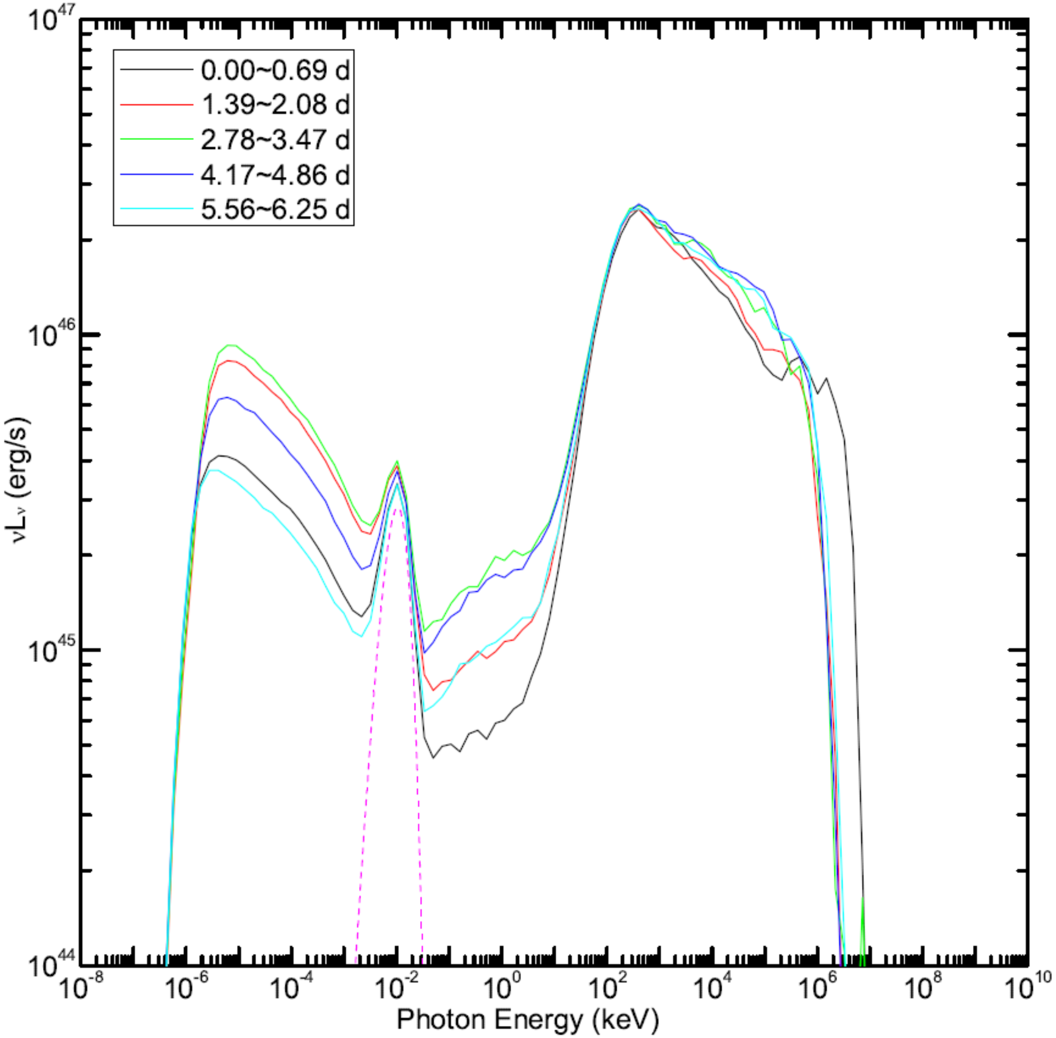
Light Travel Time Effects



(Zhang et al. 2014)

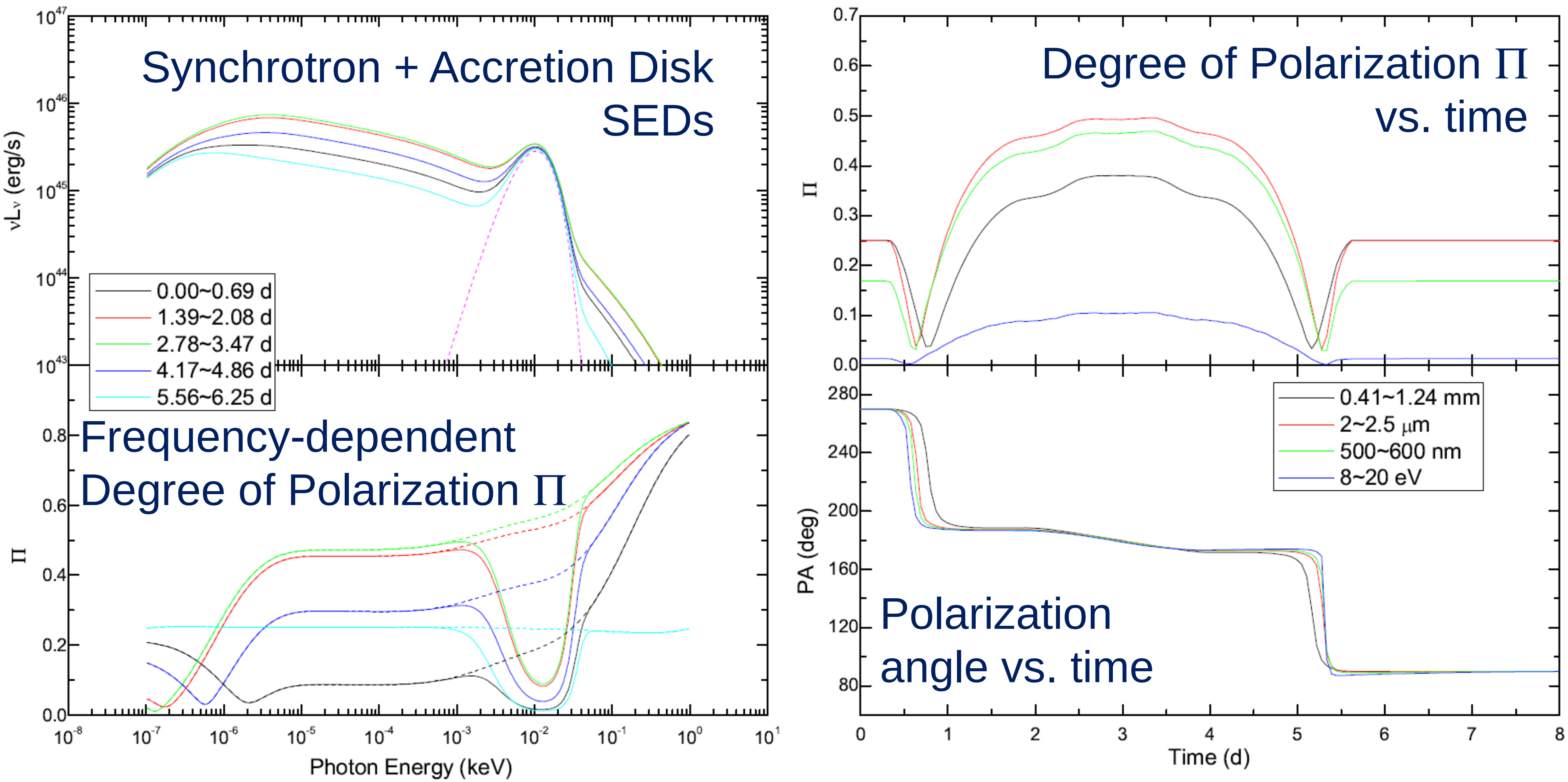
Shock positions at equal photon-arrival times at the observer

Flaring Scenario: Magnetic-Field Compression perpendicular to shock normal



Baseline parameters based on SED and light curve fit to PKS 1510-089 (Chen et al. 2012)

Flaring Scenario: Magnetic-Field Compression perpendicular to shock normal



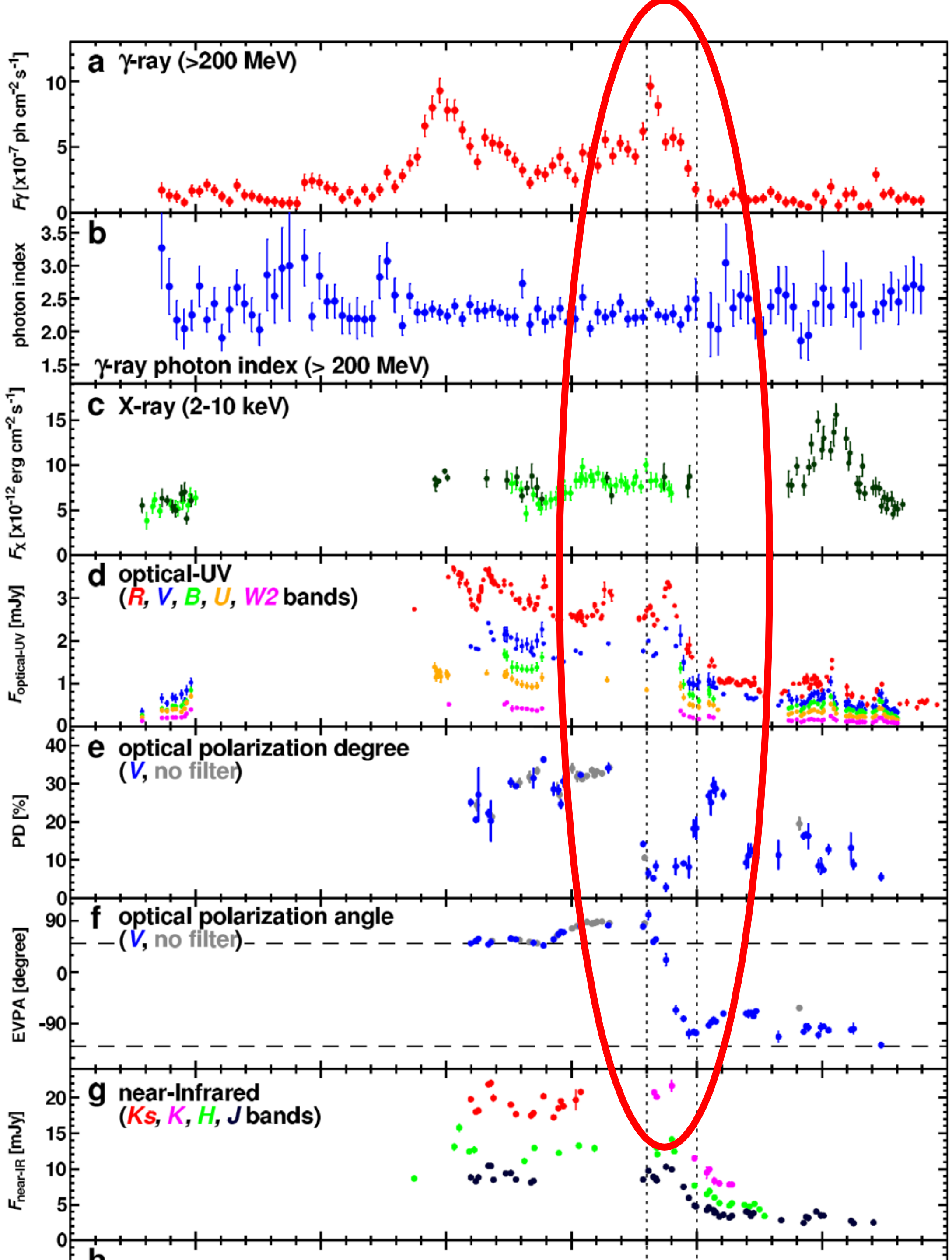
PKS 1510-089

(Zhang et al. 2014)

Application to the FSRQ 3C279

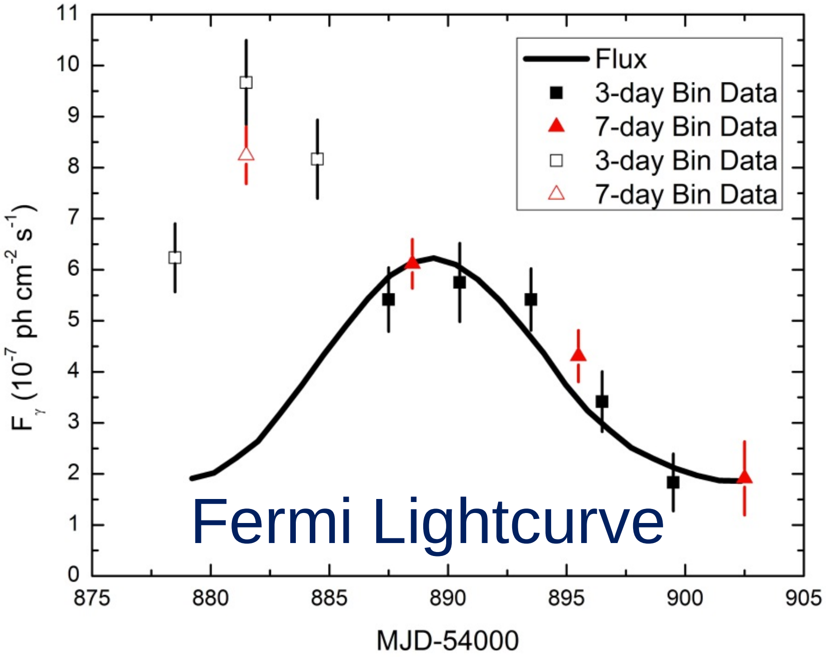
Simultaneous optical + γ-ray flare, correlated with a 180o polarization-angle rotation .

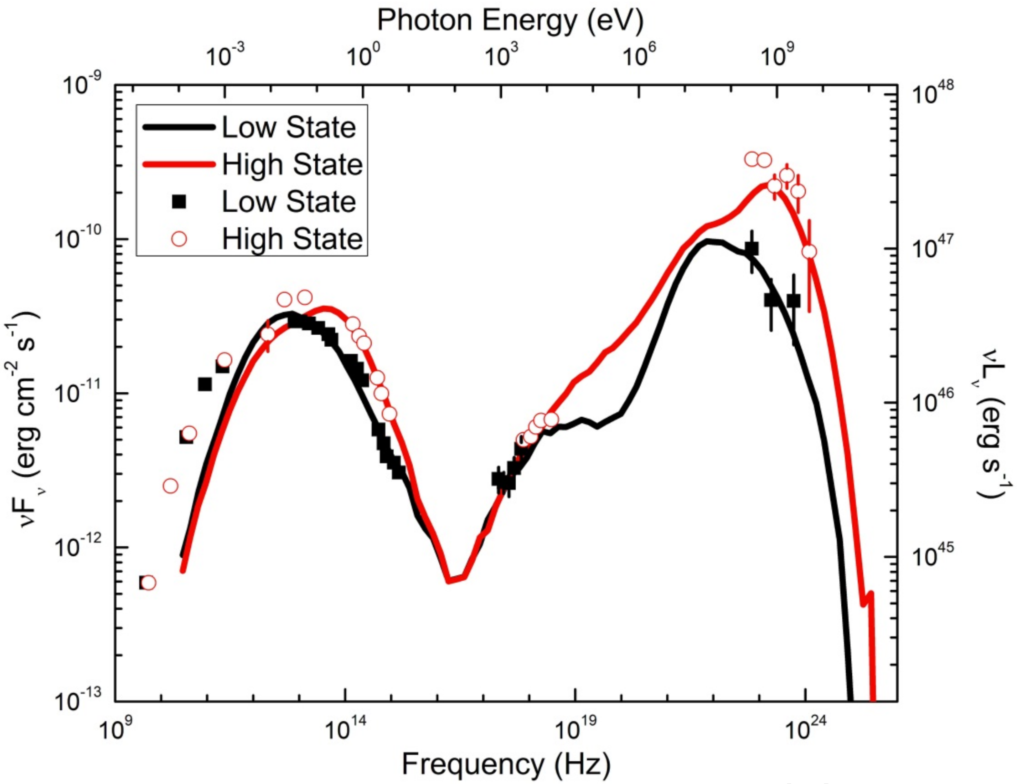
(Abdo et al. 2009)

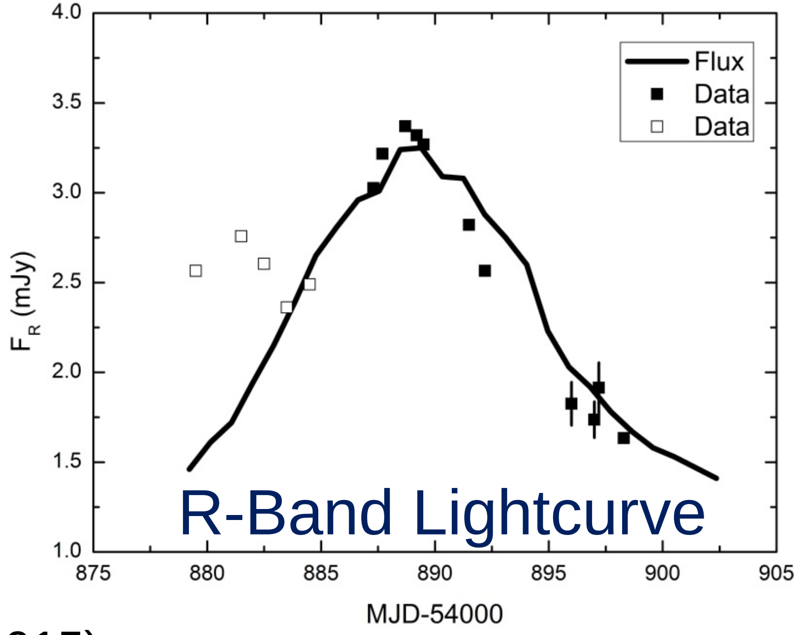


Application to 3C279

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



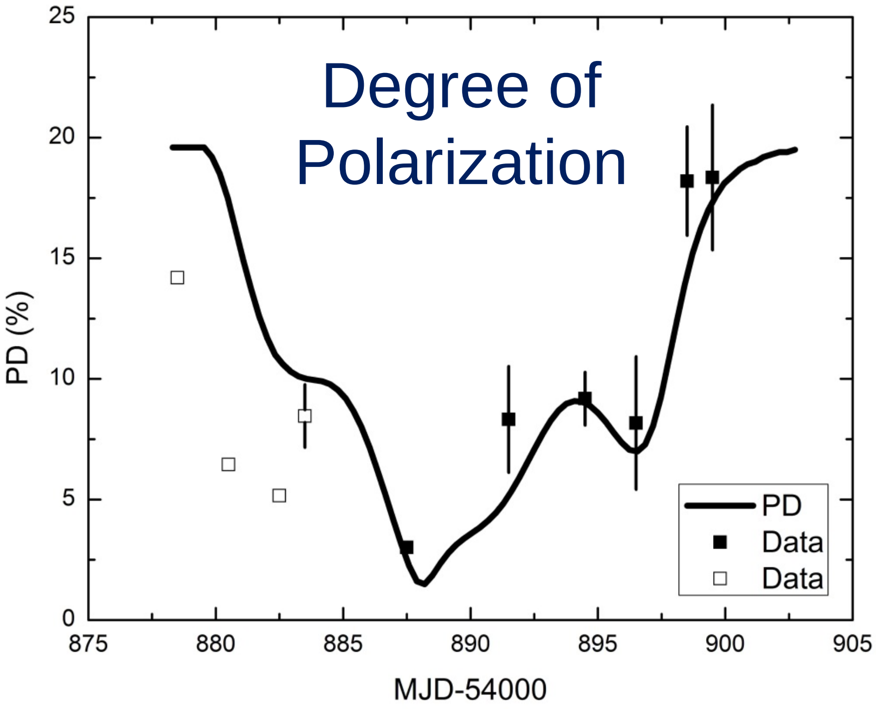


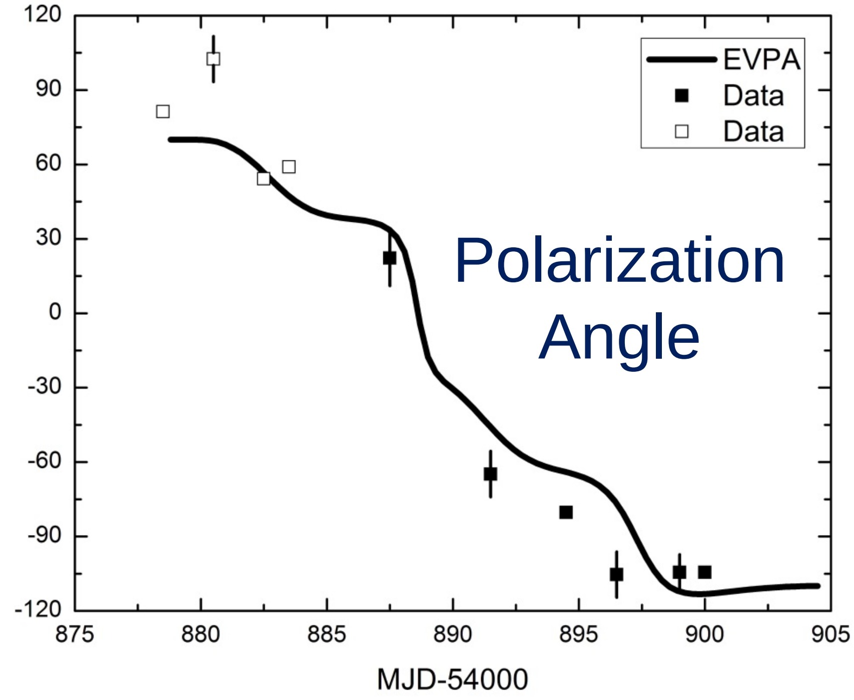


(Zhang et al. 2015)

Application to 3C279

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





(Zhang et al. 2015)

Summary

1. Both leptonic and hadronic models can fit blazar SEDs well. Possible distinguishing diagnostic: Hadronic models predict large hard X-ray / γ-ray polarization.

2. Intrinsic $\gamma\gamma$-absorption of polarized γ-rays in polarized target photon fields is suppressed compared to unpolarized emission; degree of polarization is expected to increase due to polarized $\gamma\gamma$-absorption.

3. Synchrotron polarization swings (correlated with γ-ray flares) do **not** require non-axisymmetric jet features!

7. Simultaneous fit to SEDs, lightcurves, polarization degree and polarization-angle swing of 3C279 requires magnetic energy dissipation.

Haocheng Zhang: Still looking for a postdoc position!

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