Prospects for Multi-Wavelength Polarimetry of Blazars

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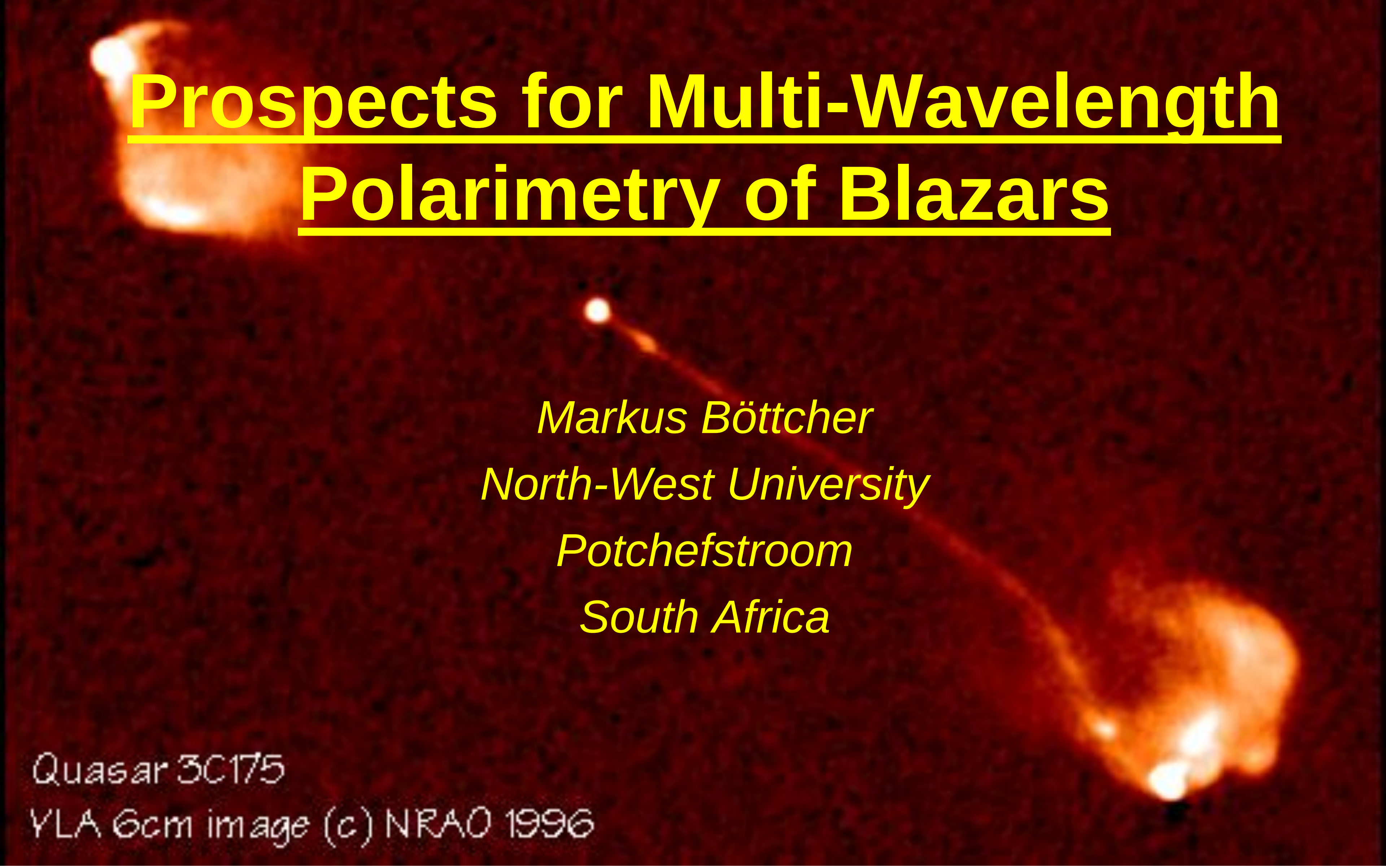
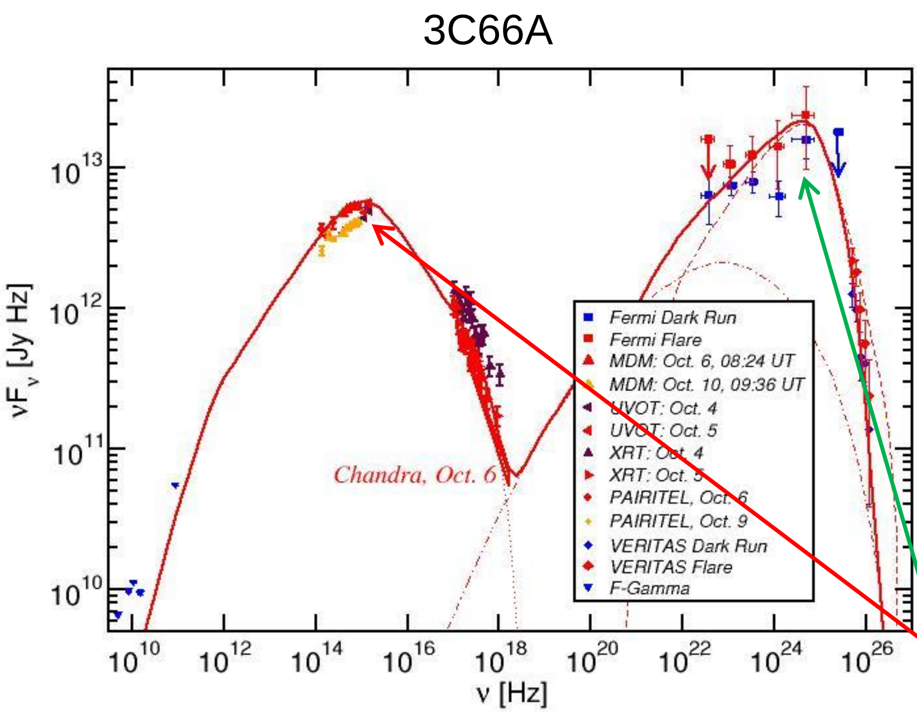


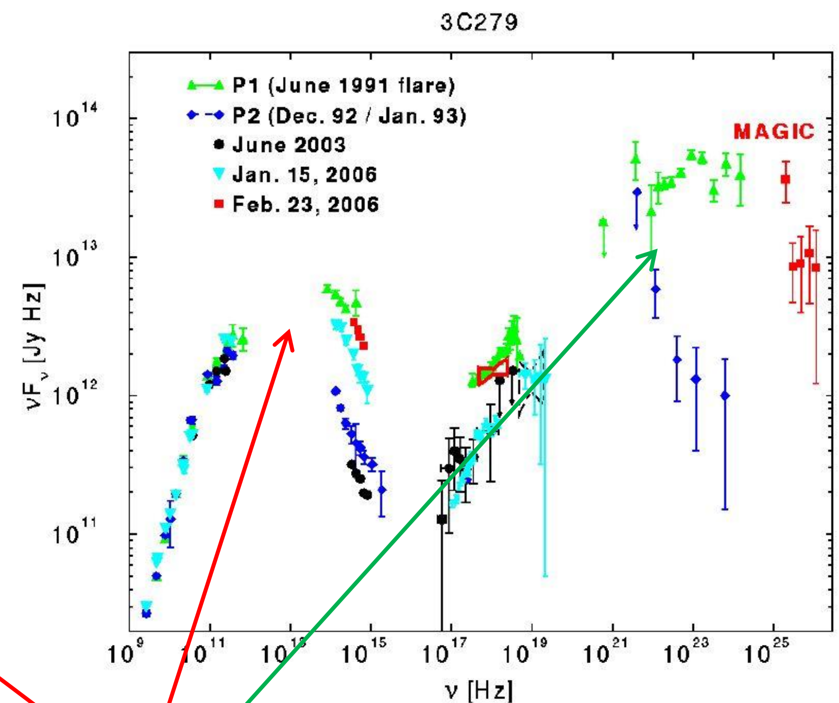
Supported by the South African Research Chairs Initiative (SARChI) of the National Research Foundation of South Africa (grant no. 64789).

Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars with relativistic jets pointing close to our line of sight
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio knots often with superluminal motion
- Radio and optical (and X-ray?) polarization

Blazar Spectral Energy Distributions (SEDs)

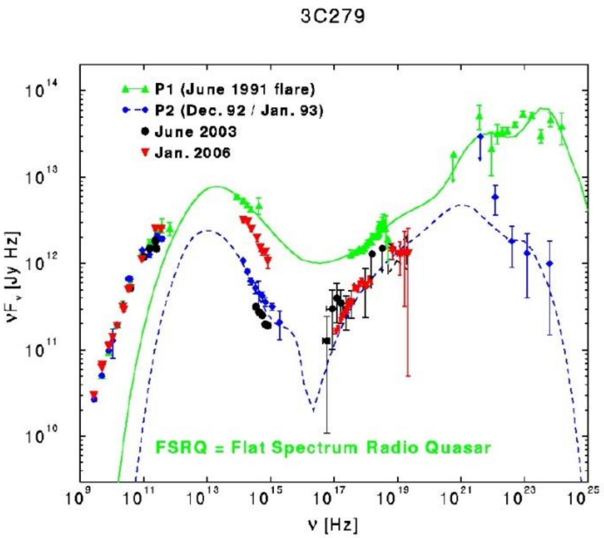




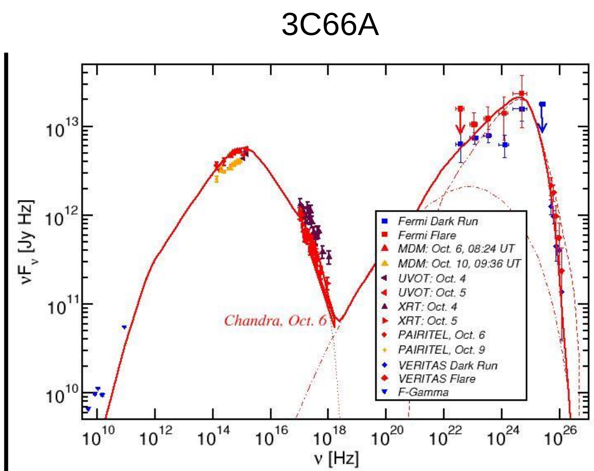
Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

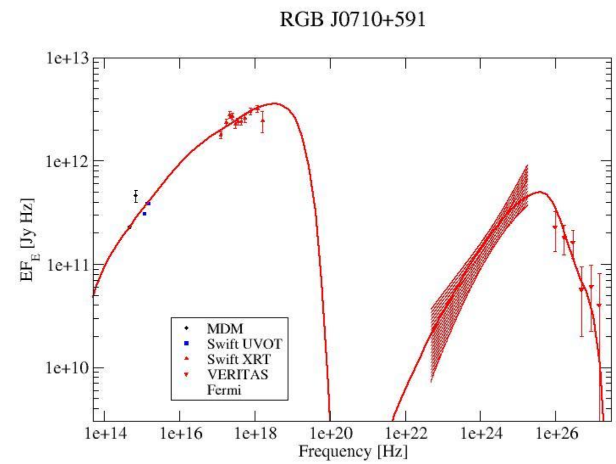
Blazar Classification



(Hartman et al. 2000)



(Abdo et al. 2011)



(Acciari et al. 2009)

Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/ Low-frequency peaked BL Lac Objects (LBLs)

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power

Intermediate-Synchrotron Peaked (ISP): Intermediate BL Lacs (IBLs):

Peak frequencies at IR/Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated

High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):

Low-frequency component from radio to UV/X-rays,

$\nu_{sy} > 10^{15}$ Hz

often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

Flux and Polarization Variability

Multi-wavelength variability on various time scales (months – minutes)

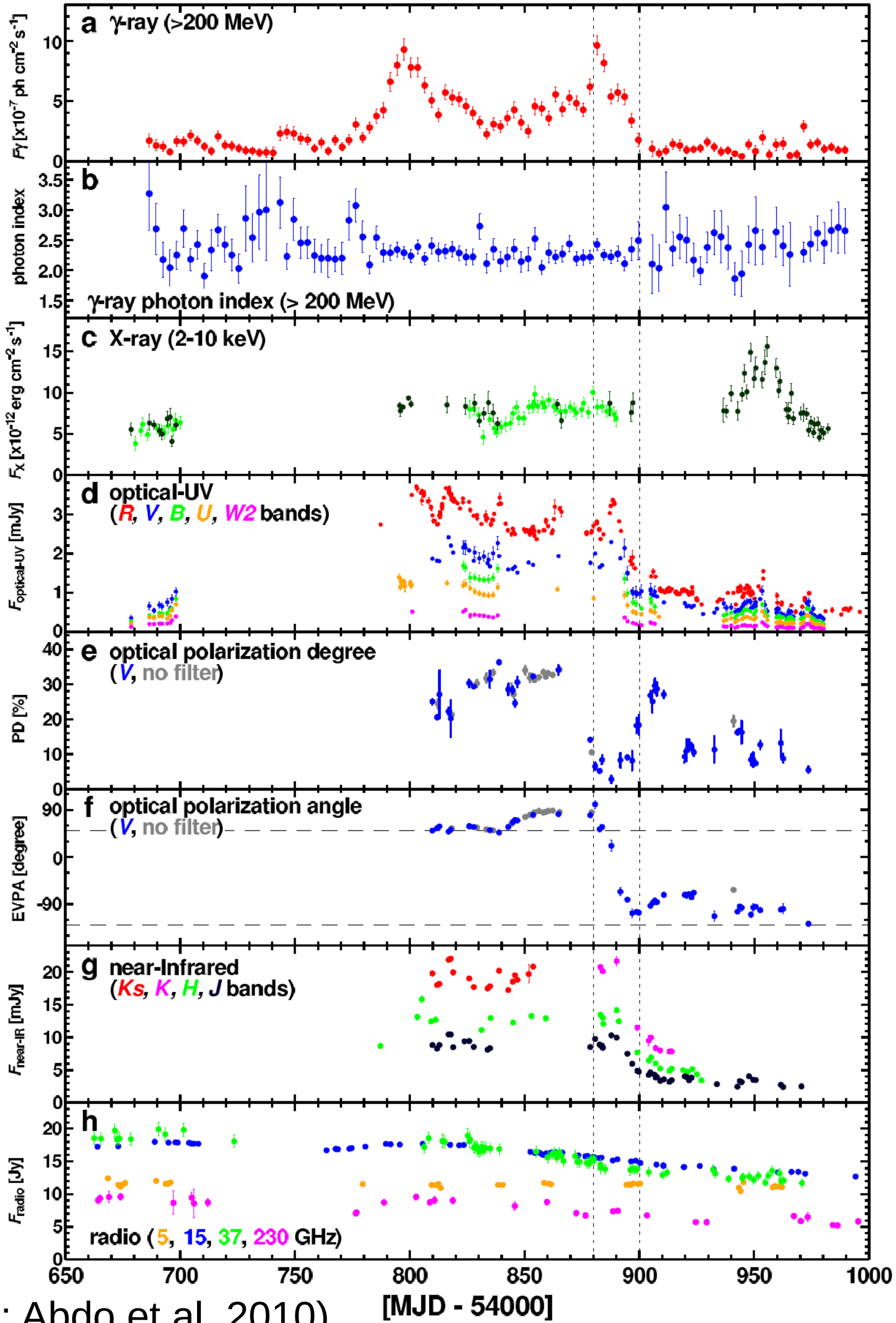
Sometimes correlated, sometimes not

Observed optical polarization degrees

Π_{opt} <~ 30 %

Both degree of polarization and polarization angles vary.

Swings in polarization angle sometimes associated with high-energy flares!



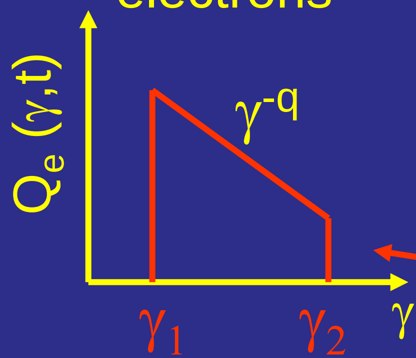
(3C279: Abdo et al. 2010)

Open Physics Questions

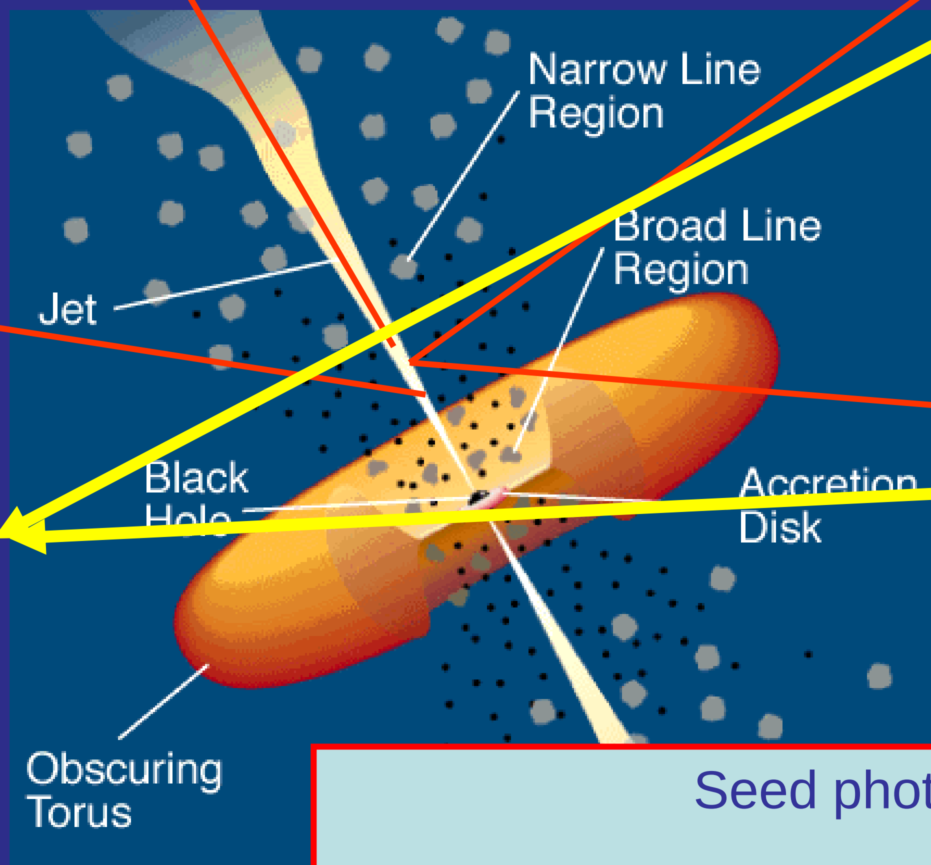
- Source of Jet Power (Blandford-Znajek / Blandford-Payne?)
- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields
- Composition of jets (e^--p or e^+-e^- plasma?) – leptonic or hadronic high-energy emission?
- Mode of particle acceleration (shocks / shear layers / magnetic reconnection?) - role of magnetic fields
- Location of the energy dissipation / gamma-ray emission region

Leptonic Blazar Model

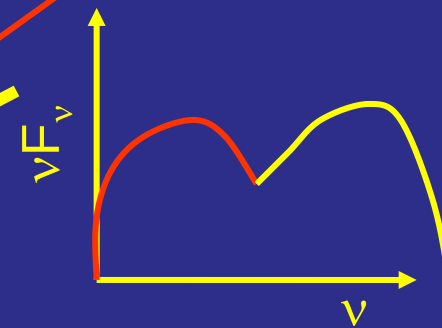
Injection, acceleration of ultrarelativistic electrons



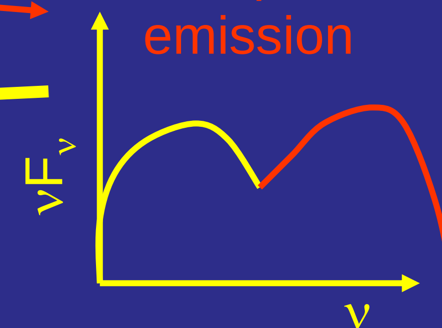
Relativistic jet outflow with $\Gamma \approx 10$



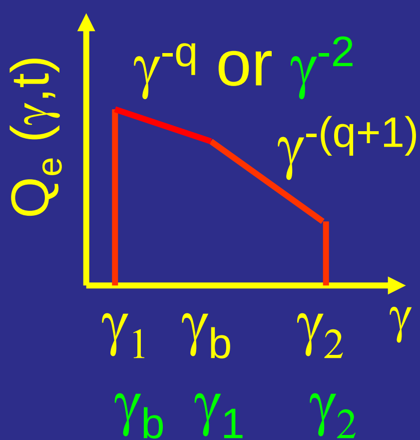
Synchrotron emission



Compton emission



Radiative cooling $\leftrightarrow$ escape =>



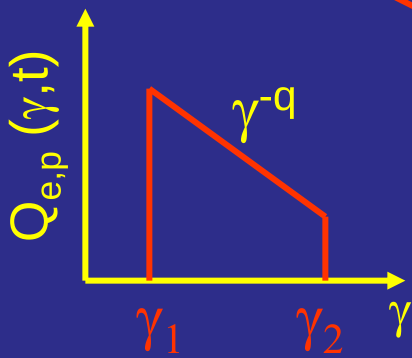
γ_b:
$\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

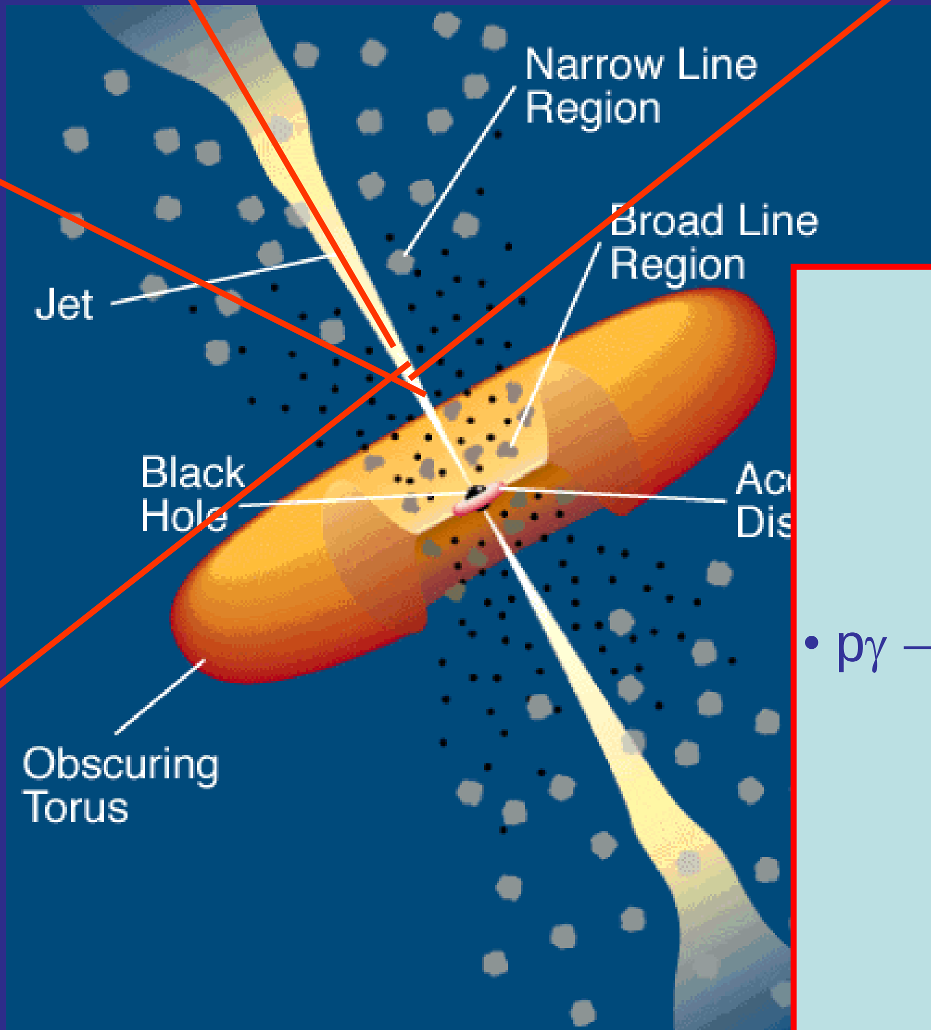
Synchrotron (within same region [SSC] or external sources, e.g., accretion disk, BLR, dust torus (EC = External Compton)

Hadronic Blazar Models

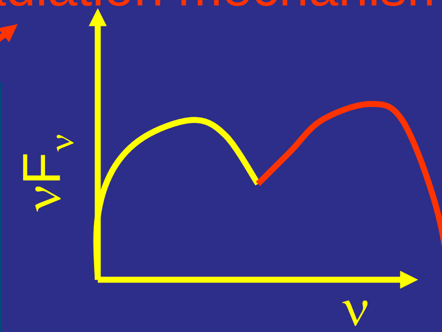
Injection, acceleration of ultrarelativistic electrons and protons



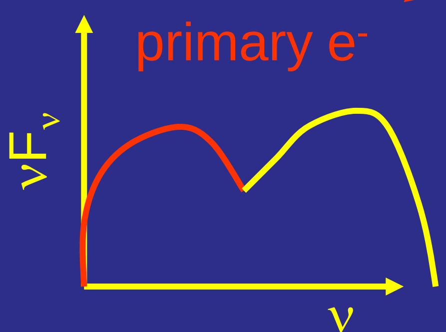
Relativistic jet outflow with $\Gamma \approx 10$



Proton-induced radiation mechanisms



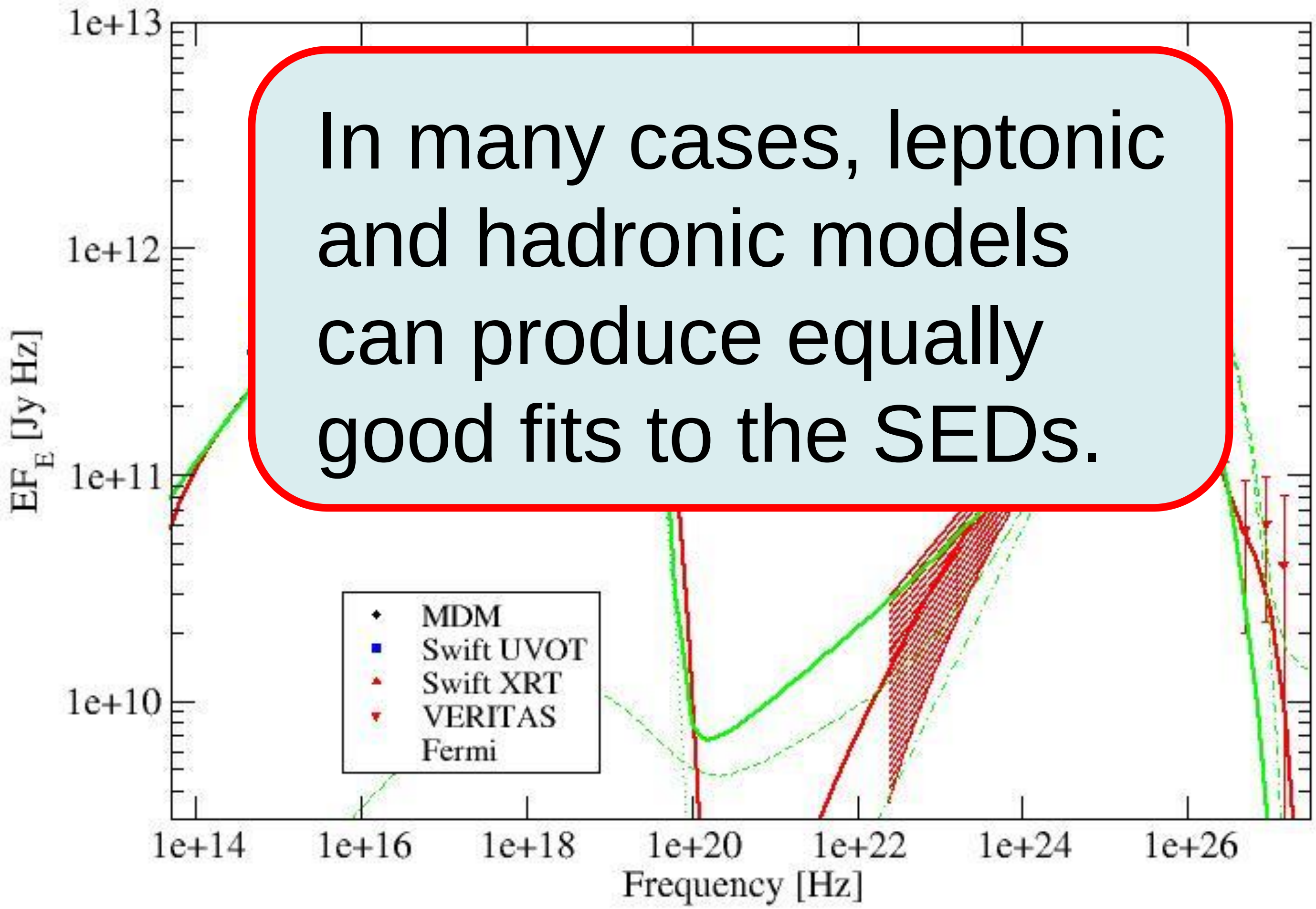
Synchrotron emission of primary e^-



- 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 …

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
- Variability
- Polarization

Possible Distinguishing Diagnostic: Polarization

- Synchrotron Polarization

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

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

$p = 2 \rightarrow \Pi = 69\ \%$

$p = 3 \rightarrow \Pi = 75\ \%$

Compton Polarization

Compton cross section is polarization-dependent:

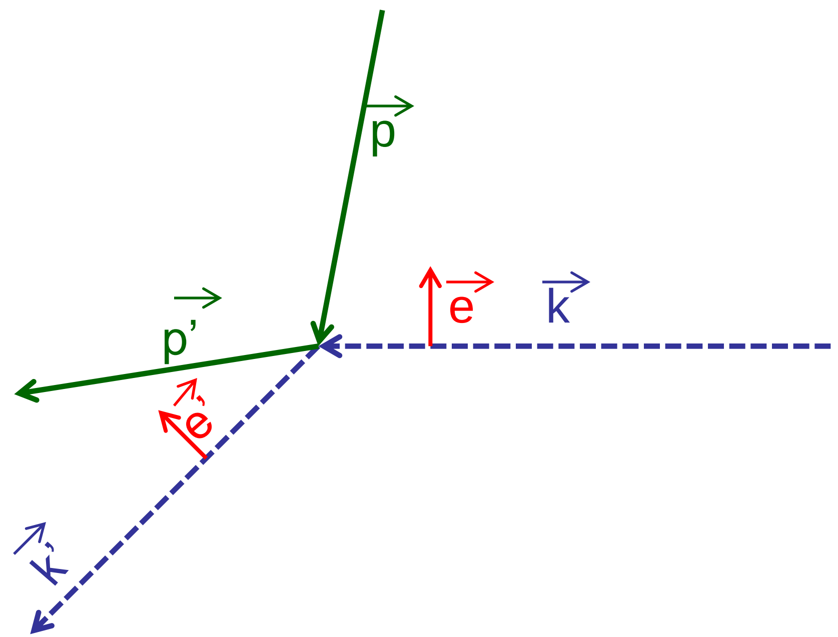
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4} \left(\frac{\epsilon'}{\epsilon}\right)^2 \left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$$

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

Thomson regime: $\varepsilon \approx \varepsilon'$
$\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e}\cdot\vec{e}' = 0$

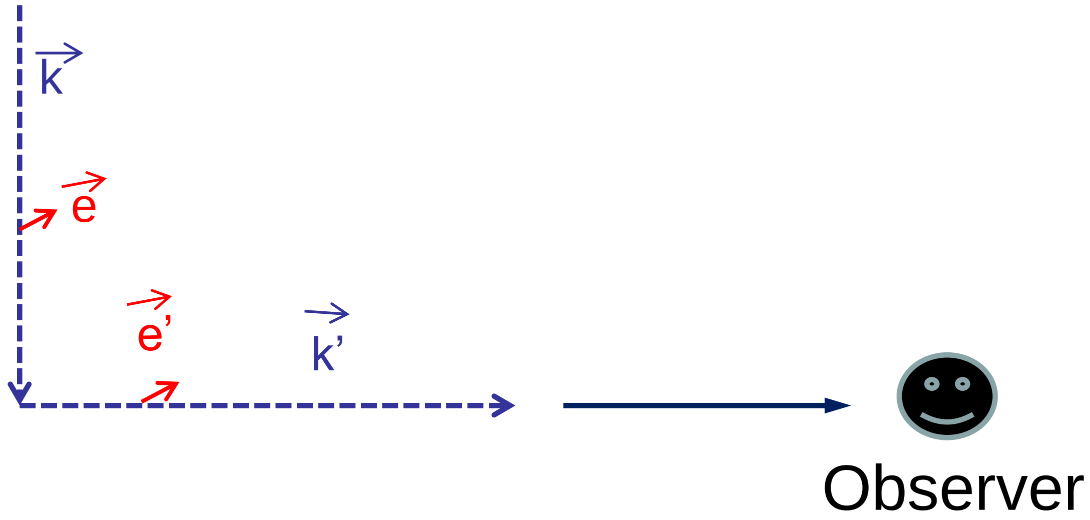
$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

Preferred polarization direction is preserved.



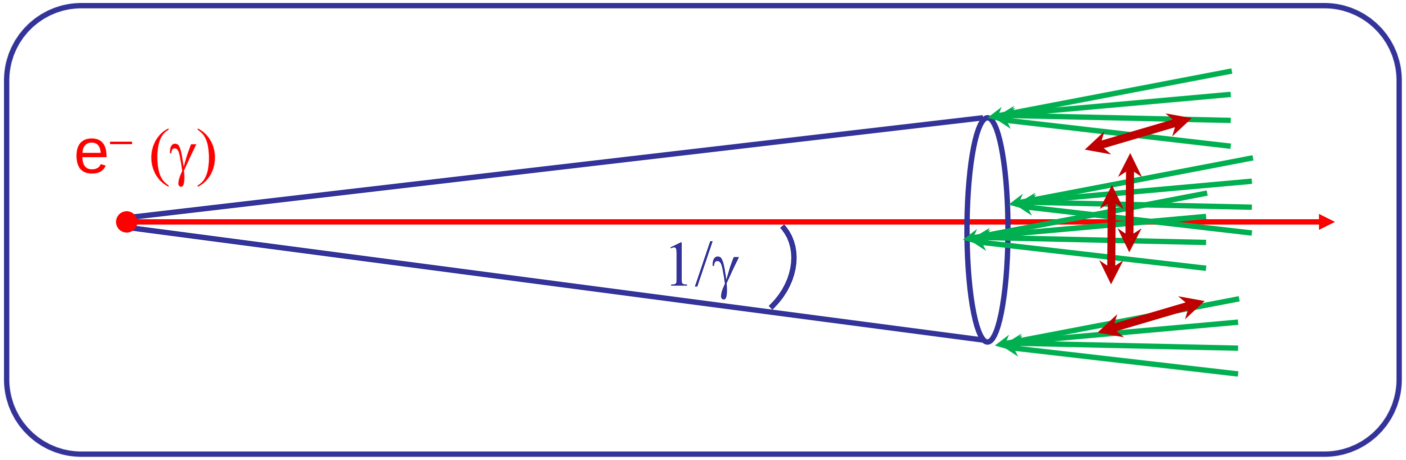
Compton Polarization

Compton scattering of an anisotropic radiation field by **non-relativistic** electrons induces polarization perpendicular to the plane of scattering.



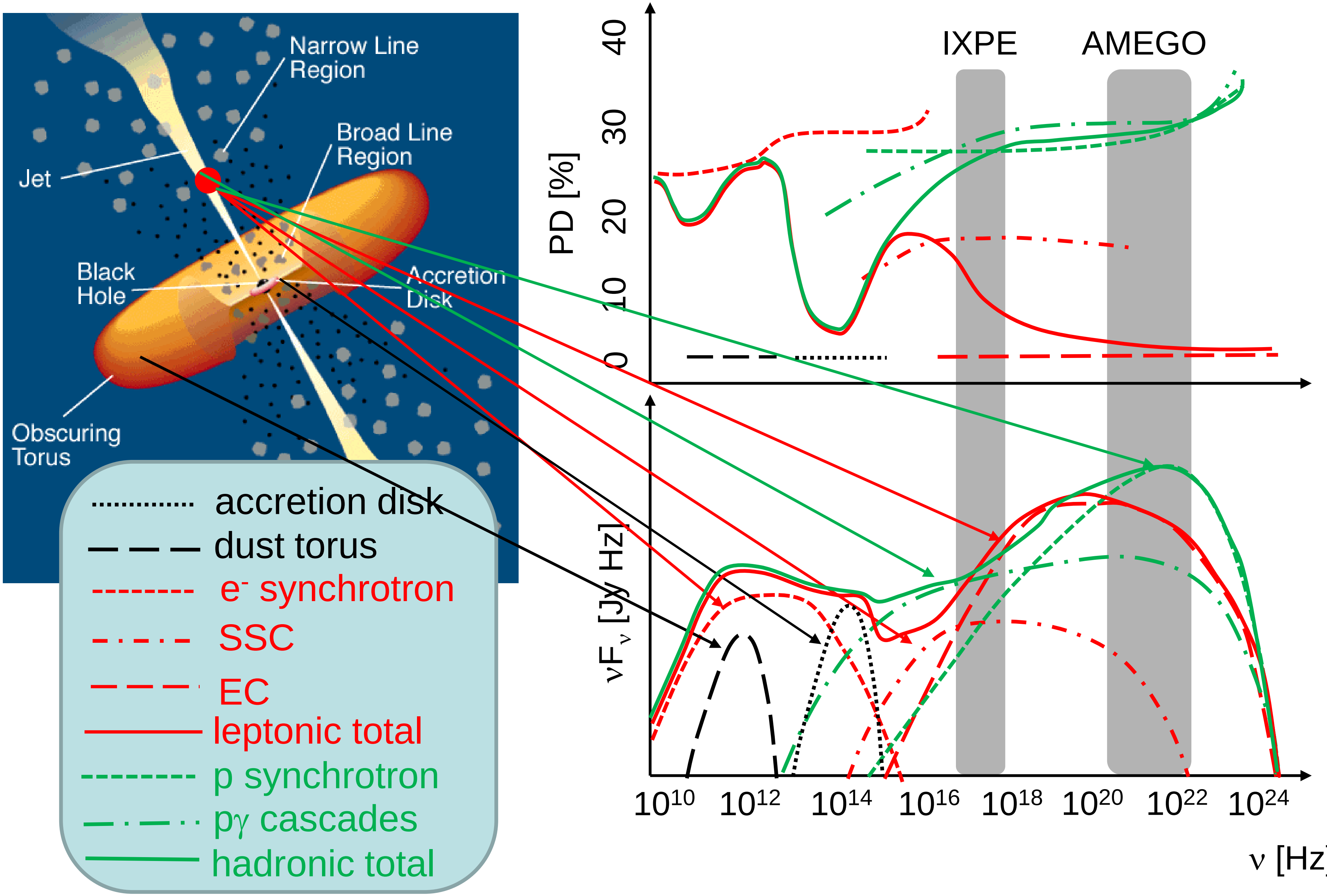
Compton Scattering by Relativistic Electrons

- Relativistic aberration => approx. axisymmetric radiation field in co-moving frame of e^-

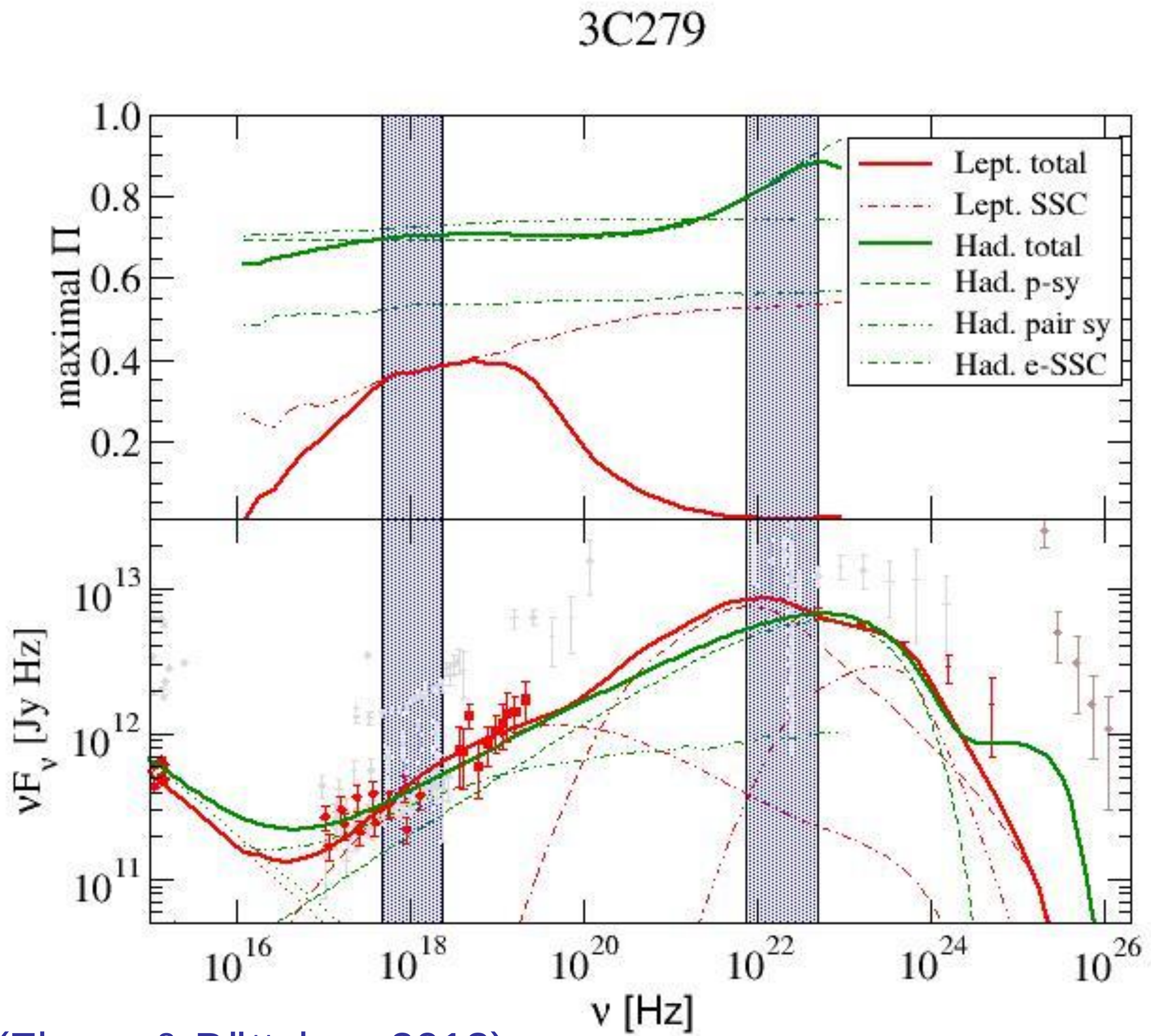


- Unpolarized target photons (EC emission) → **Unpolarized**
- Polarized target photons (SSC) → **SSC polarization ~ ½ of target (synchrotron) photon polarization**

Multiwavelength Polarization of Blazars



X-Ray and Gamma-Ray Polarization in FSRQs

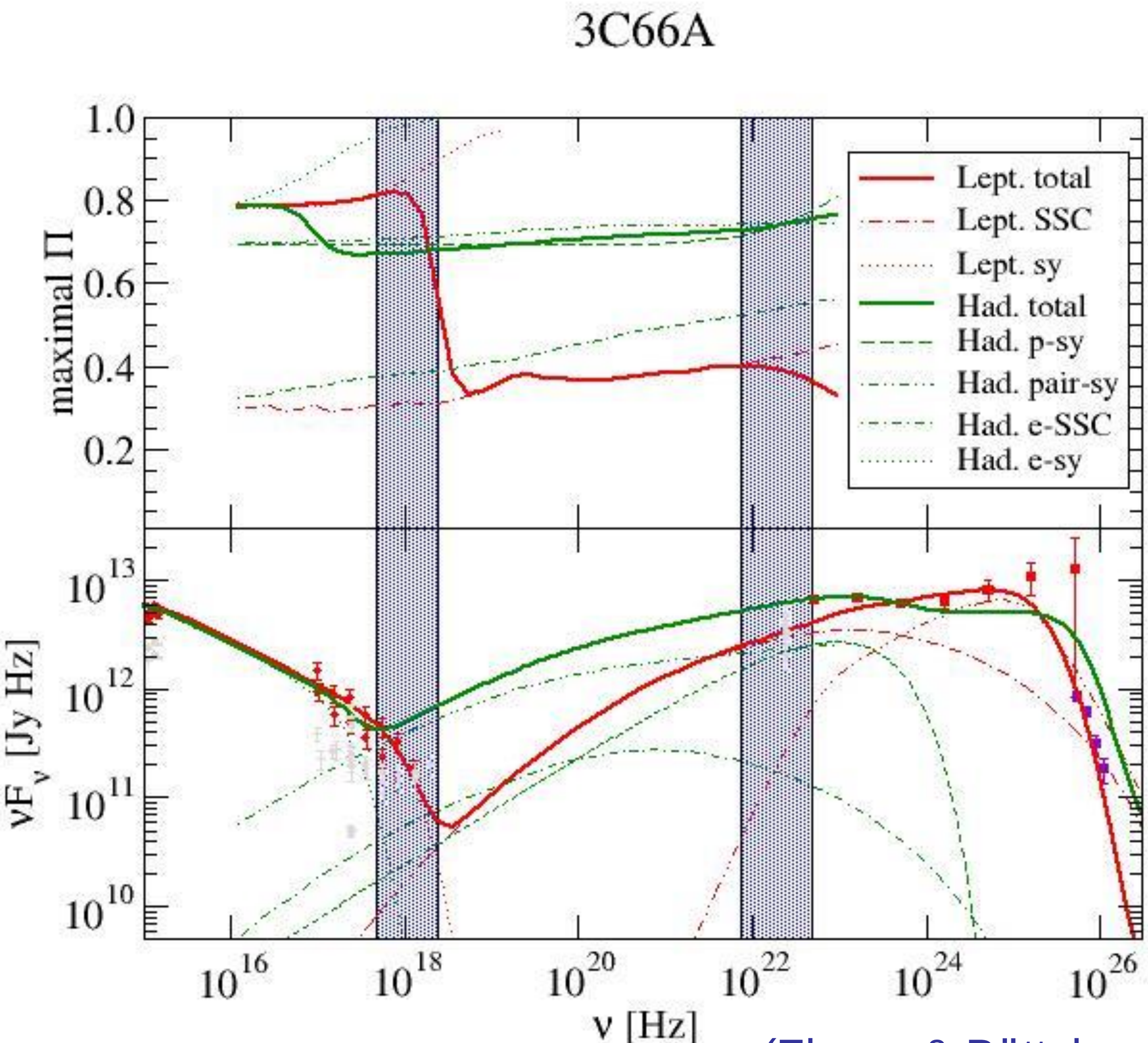


Hadronic model:
Synchrotron dominated
=> High Π, generally increasing with energy (SSC contrib. in X-rays).

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

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization in ISP blazars



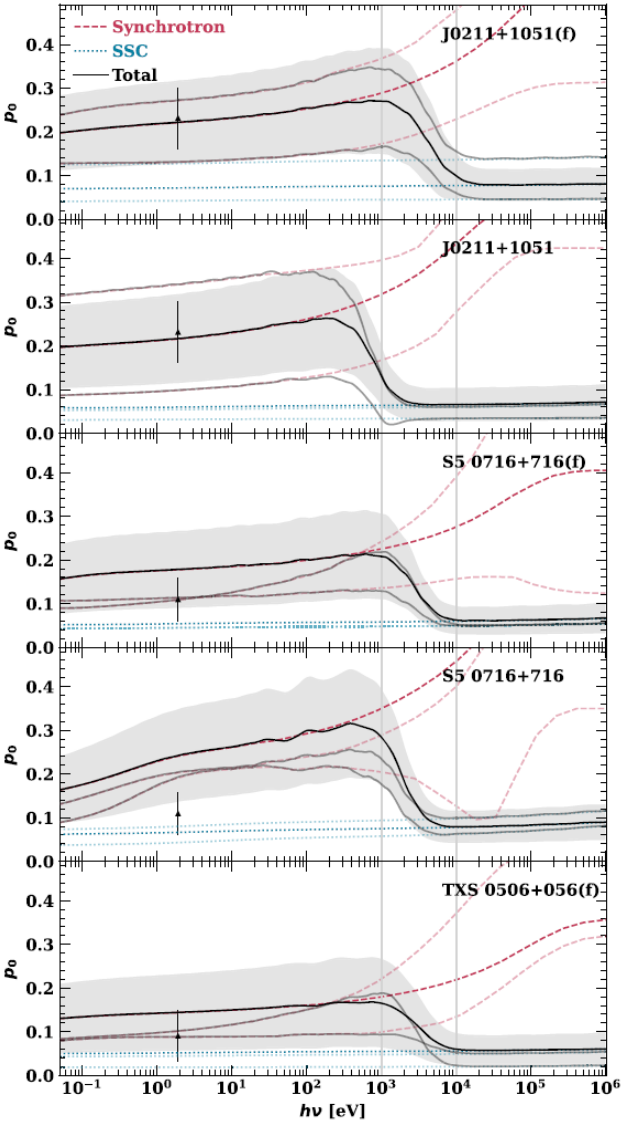
Hadronic model: Synchrotron dominated => High Π, throughout X-rays and γ-rays

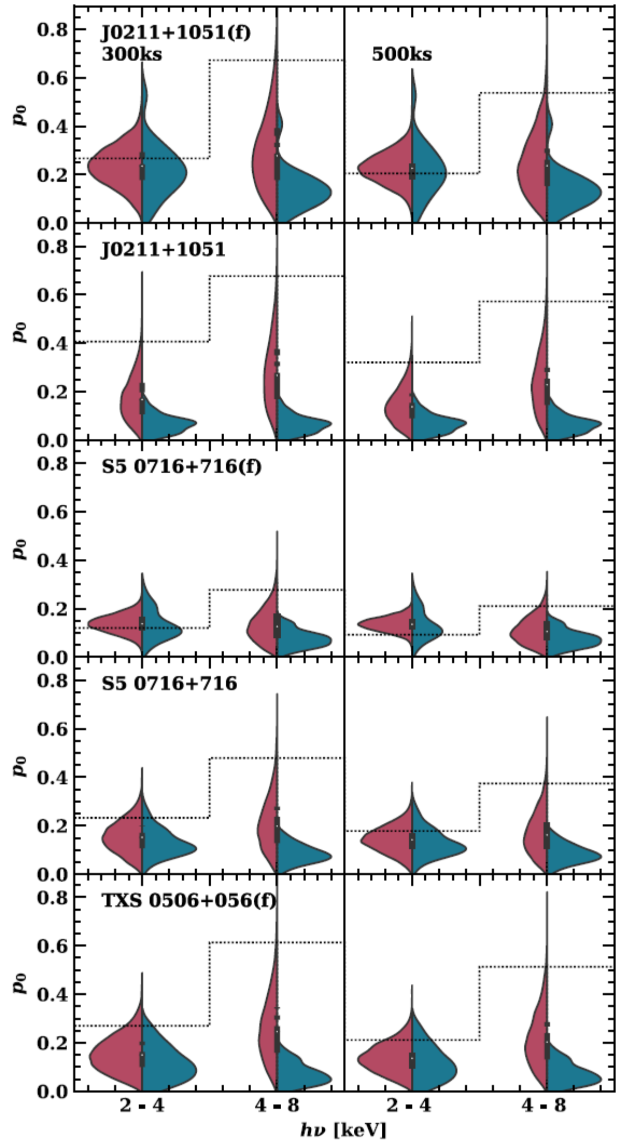
Leptonic model: X-rays sy. Dominated => High Π, rapidly decreasing with energy; γ-rays SSC/EC dominated => Small Π.

(Zhang & Böttcher, 2013)

Simulated MWL polarization in ISP blazars – IXPE predictions

Synchrotron (low-energy) X-ray polarization possibly detectable within 300 – 500 ksec, but not SSC polarization.

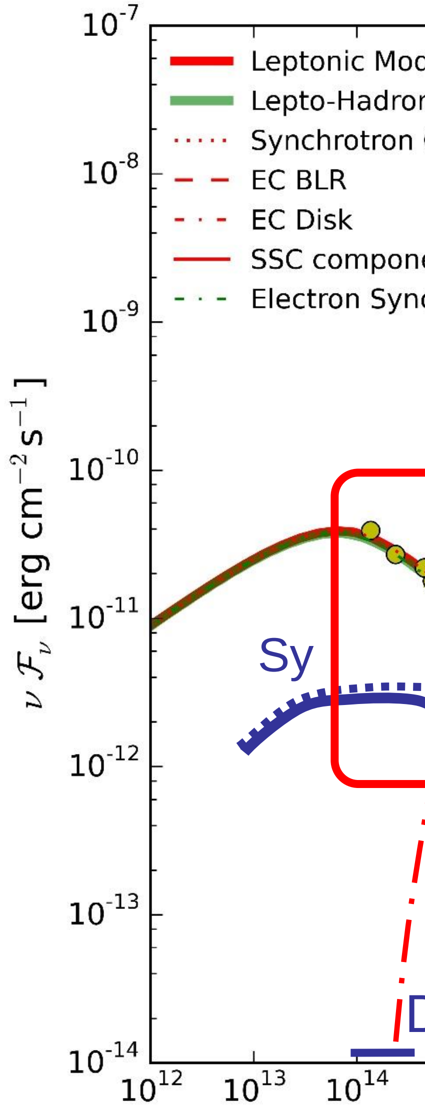


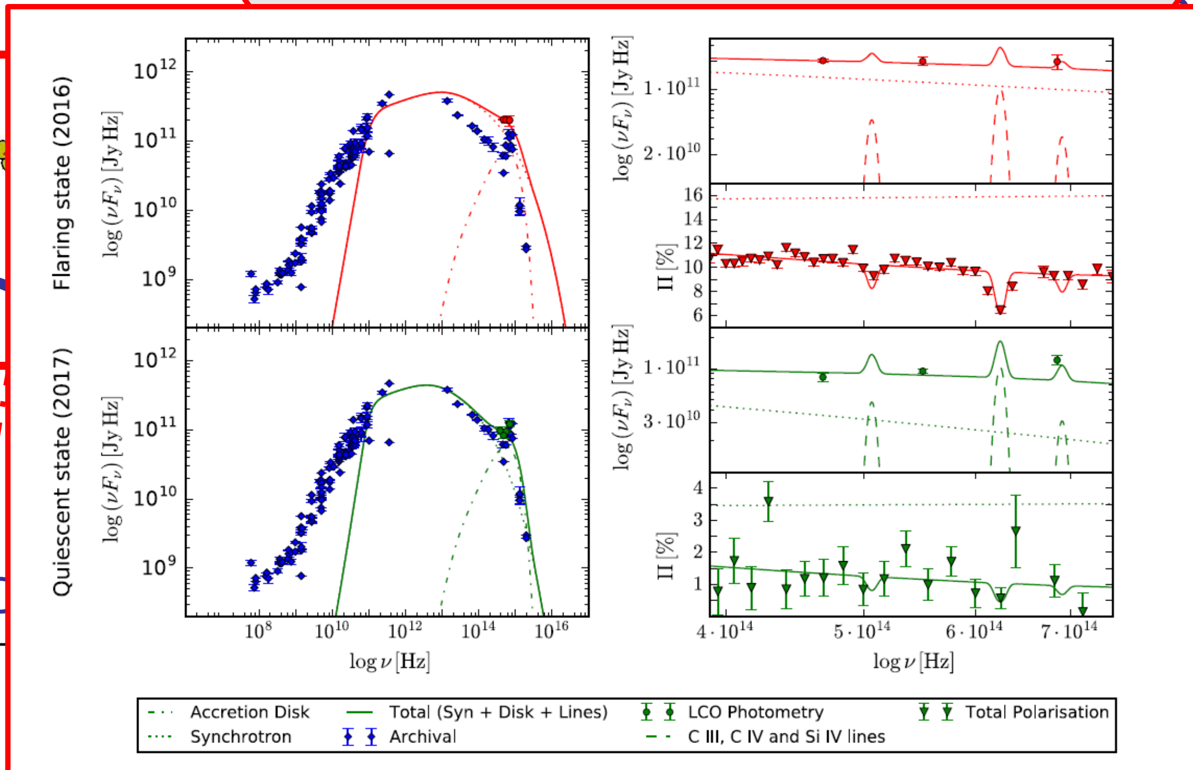


(Peirson et al. 2022)

Spectropolarimetry of FSRQ-type blazars

Optical Spectropolarimetry separates jet synchrotron from accretion-disk emission
→ Constrain Black Hole mass
(Schutte et al. 2022)

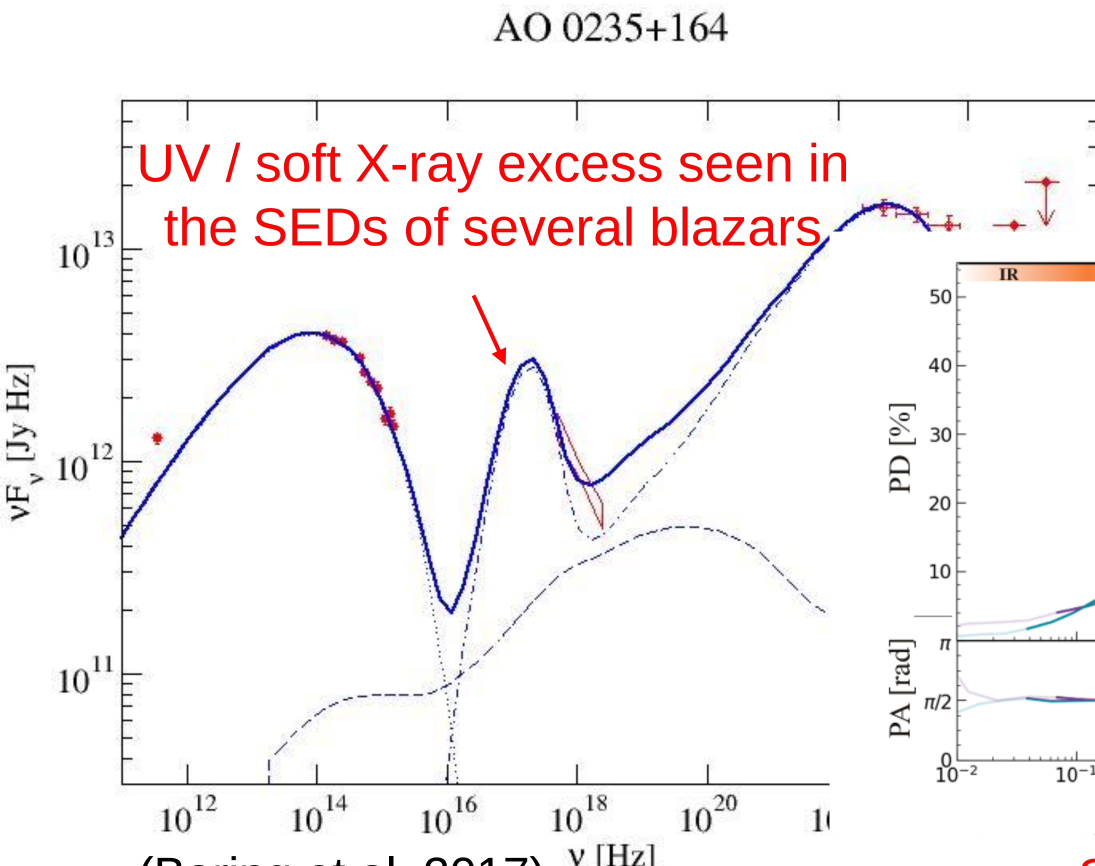




2016)

The "Big Blue Bump"

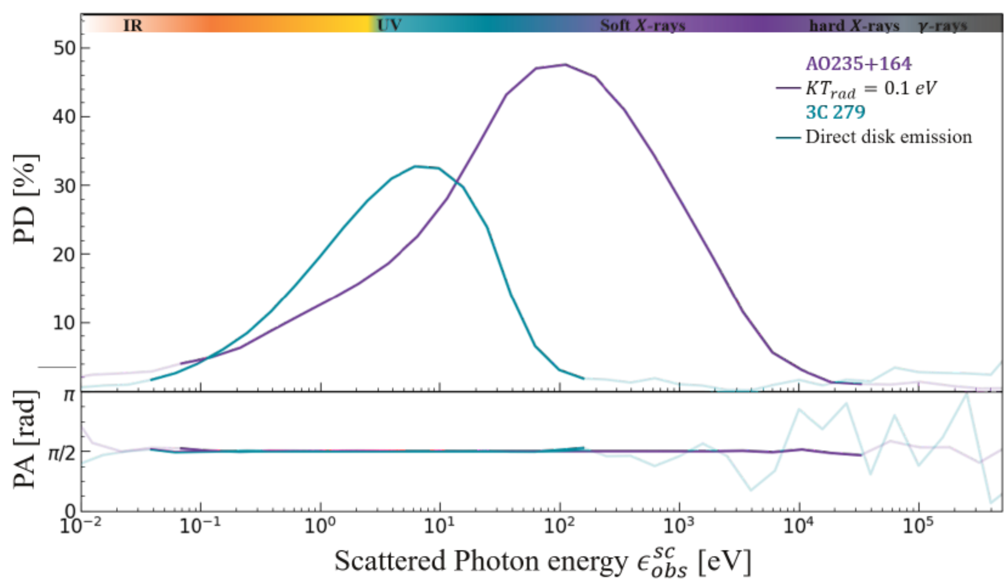
- Accretion disk + Corona? → **Unpolarized**
- Additional synchrotron component? → **Moderately polarized**
- Bulk Compton scattering of external radiation field by thermal electrons → **Potentially highly polarized**



UV / soft X-ray excess seen in the SEDs of several blazars

(Baring et al. 2017)

(Dreyer & Böttcher 2021)



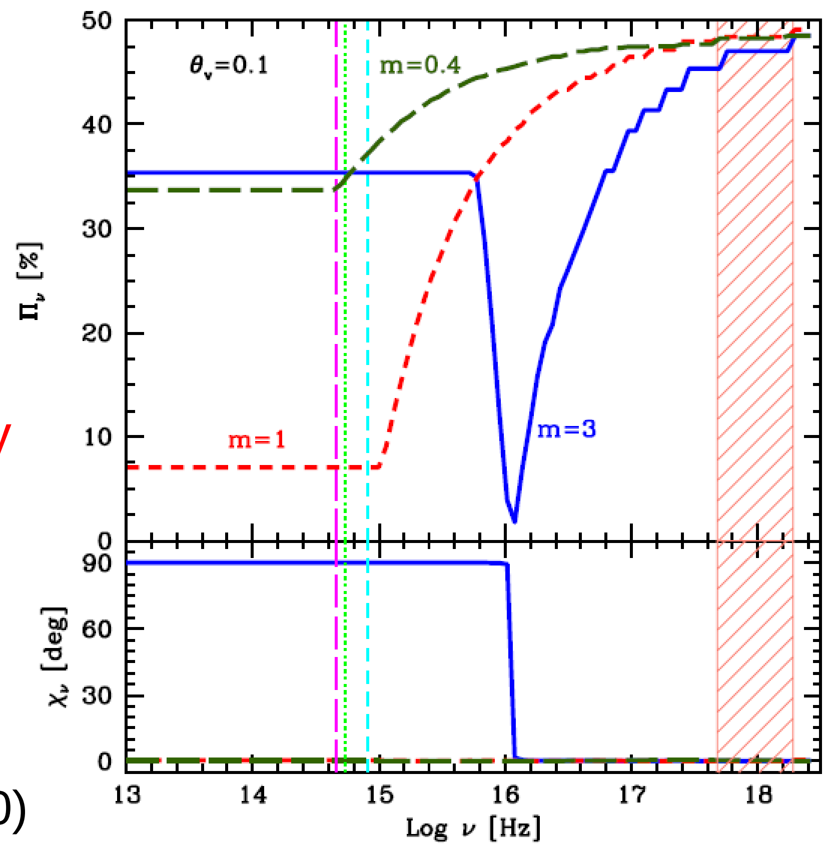
→ See poster by Lenté Dreyer

X-Ray Polarization in HBLs: Diagnosing particle acceleration

Optical and X-ray emission dominated by electron synchrotron.

X-ray polarimetry may reveal mode of particle acceleration:

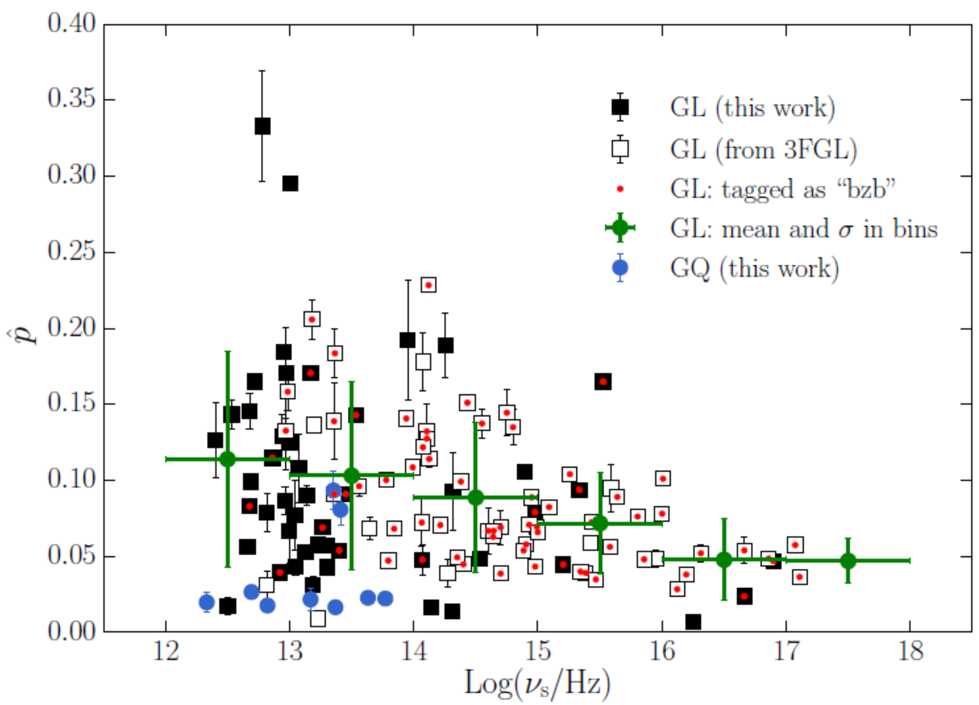
- Magnetic reconnection: Acceleration in turbulent regions → Low PD ($\lesssim$ 20 %)
- Shocks: Significant (up to ~ 50 %) X-ray polarization; likely higher PD in X-rays than in the optical (smaller emission region?)



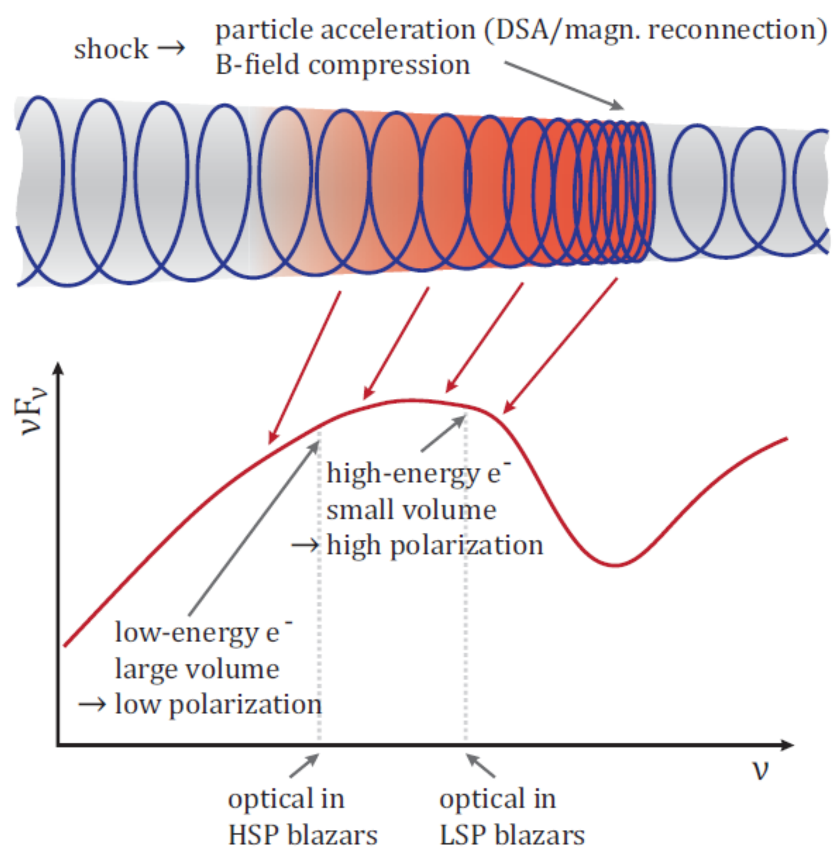
(Tavecchio et al. 2018, 2020)

X-Ray Polarization in HBLs

Evidence for particle acceleration + B-field compression at shocks across blazar classes

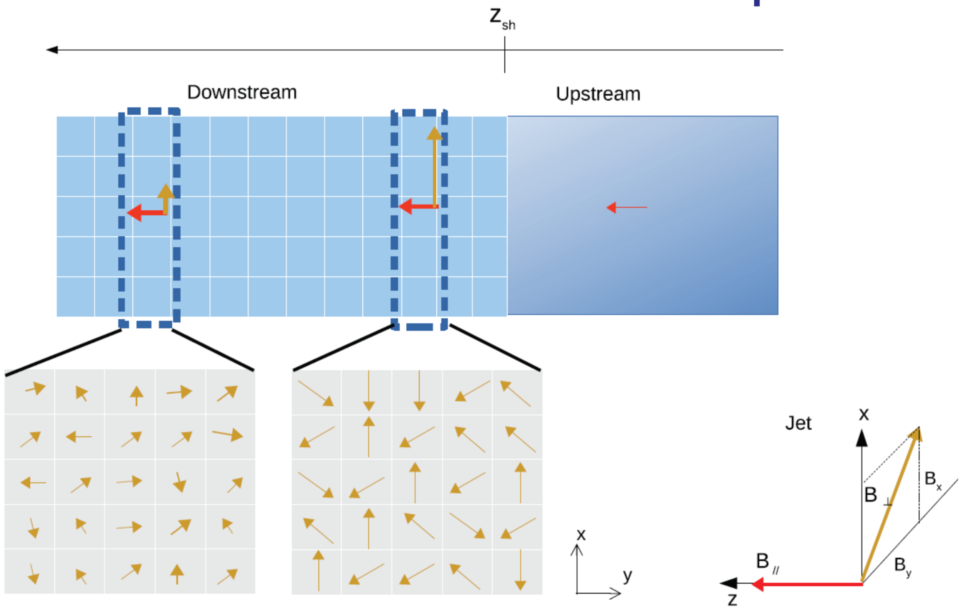


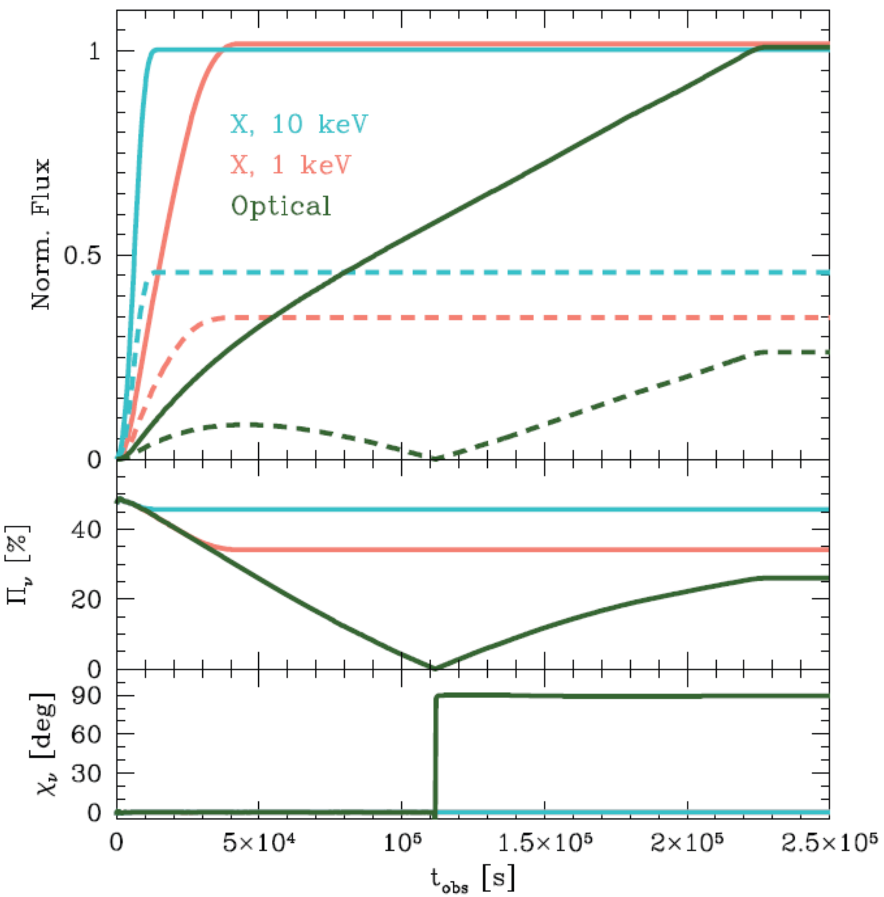
(Angelakis et al. 2016 – ROBOPOL)



X-Ray Polarization in HBLs: Shocks

Time dependent simulation:





- Almost constant X-ray PD, up to ~ 40 %
- More complex behaviour in the optical

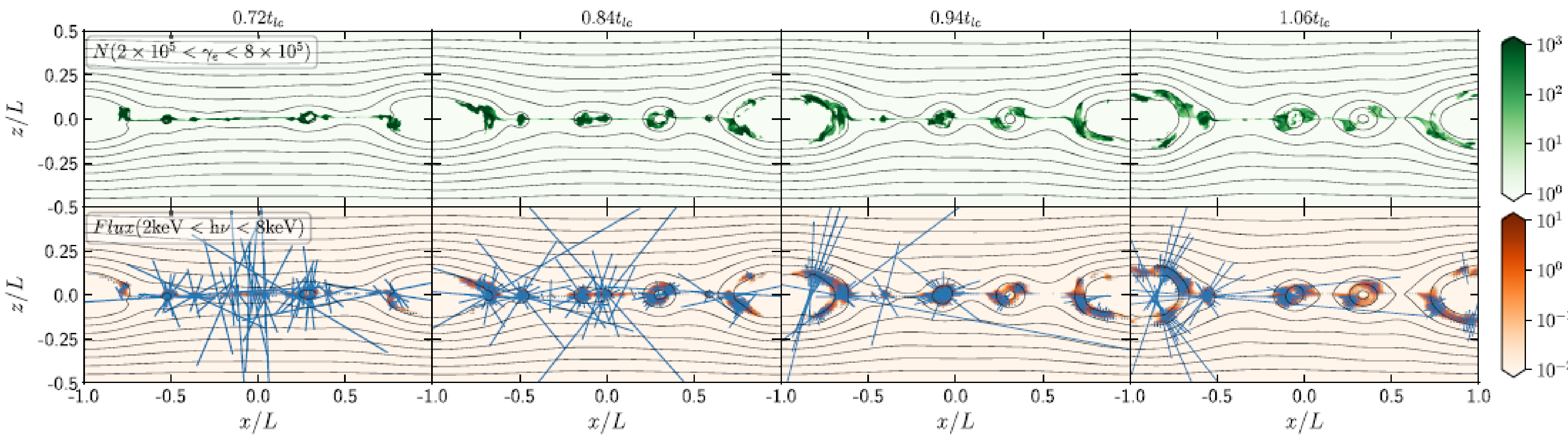
(Tavecchio et al. 2020)

X-Ray Polarization in HBLs: Magnetic Reconnection

Likely triggered by kink instability (Bodo et al. 2020; Zhang et al. 2021, 2022)

Coupled PIC + polarized radiation transfer simulations:

X-ray emitting plasma



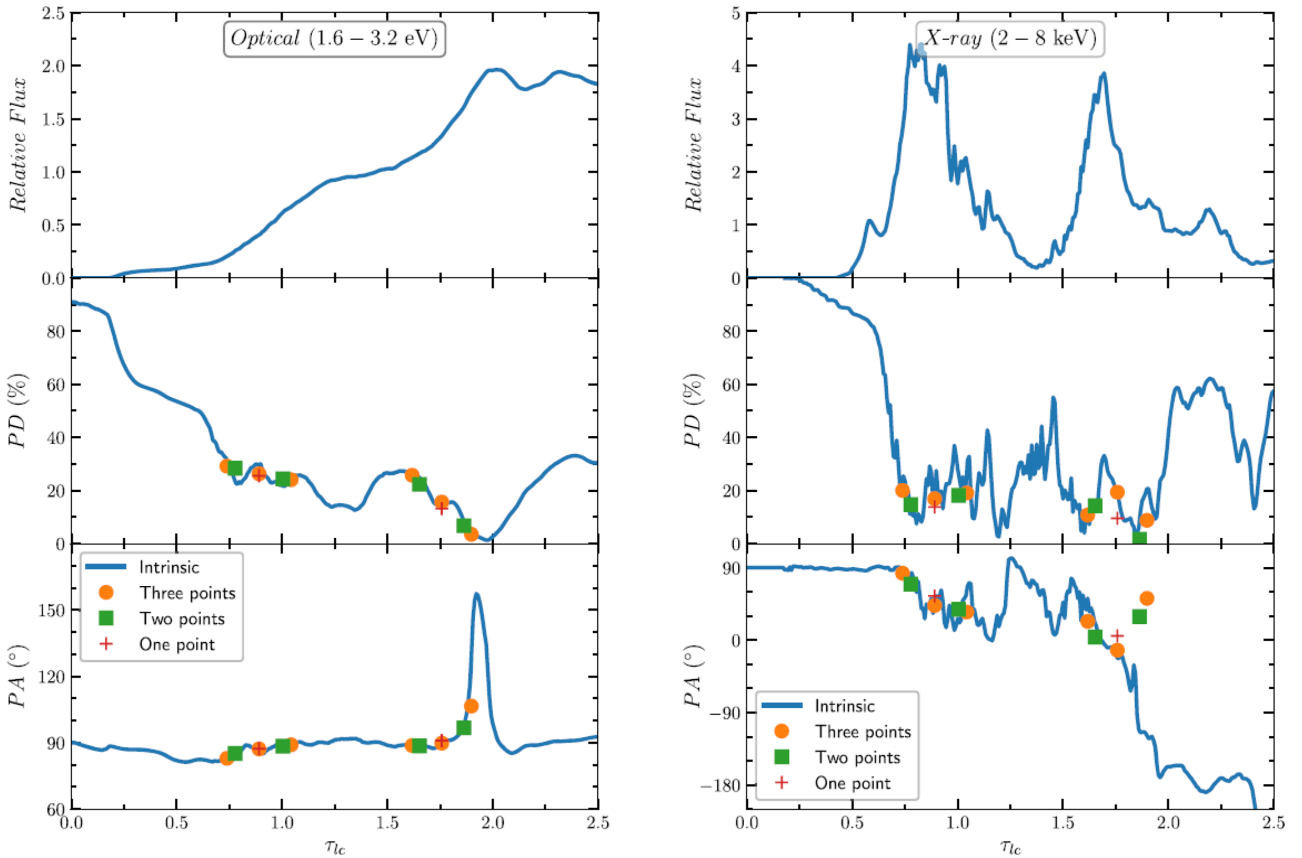
Polarized X-ray emission

(Zhang et al. 2021)

X-Ray Polarization in HBLs: Magnetic Reconnection

Coupled PIC + polarized radiation transfer simulations:

- Erratic X-ray PD variations, up to ~ 20 %
- Intrinsic PD of optical and X-ray similar, but temporal depolarization might lower measured X-ray PD.



(Zhang et al. 2021)

X-Ray Polarization in HBLs: Diagnosing particle acceleration

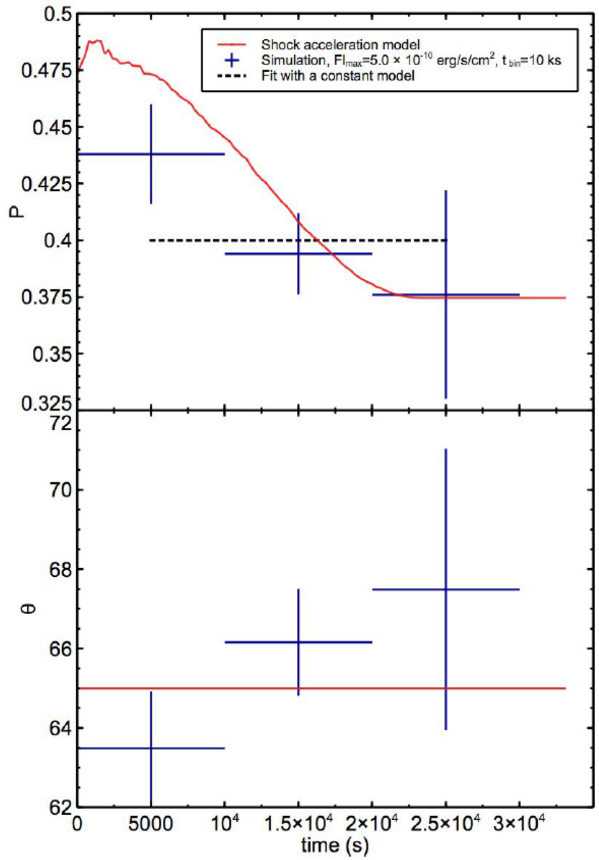
Simulations of 3 different acceleration scenarios:

- Diffusive shock acceleration (DSA)
- Magnetic reconnection (kink instability)
- Turbulence (TEMZ)

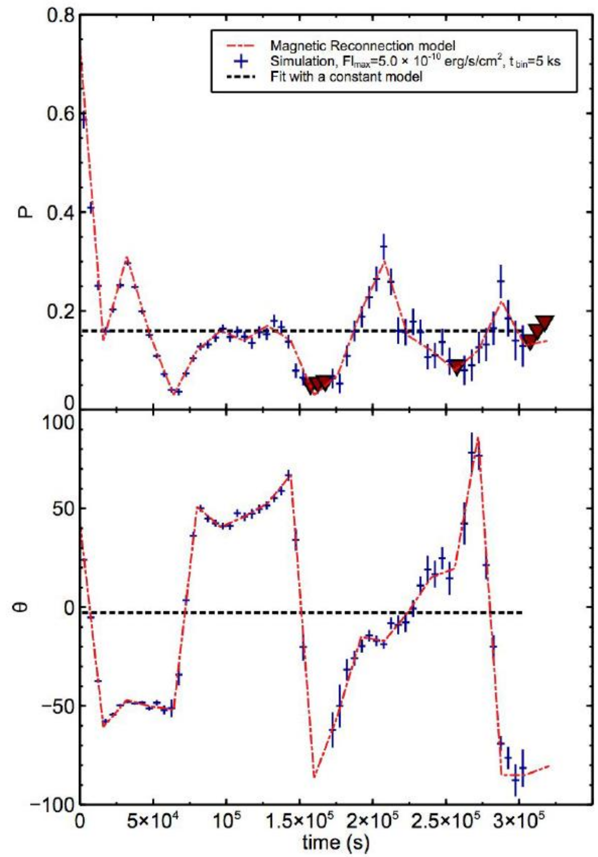
IXPE can distinguish DSA and magnetic reconnection if sources are bright enough for polarization detection in 5 – 10 ks time slices.

(Di Gesu et al. 2022)

Shock (based on Tavecchio et al. 2020)



Magnetic Reconn. (based on Bodo et al. 2020)



Summary

1. X-ray polarimetry of blazars promises insights into several aspects / questions:

   a) Leptonic vs. hadronic emission
   b) Disentangling thermal vs. non-thermal emission components
   c) Nature and origin of "big blue bump"
   d) Mode of particle acceleration (shocks vs. magnetic reconnection)
   e) Structure of shock-compressed / turblent magnetic field

2. Polarization-angle variability might dilute measured polarization degree in long observations.

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