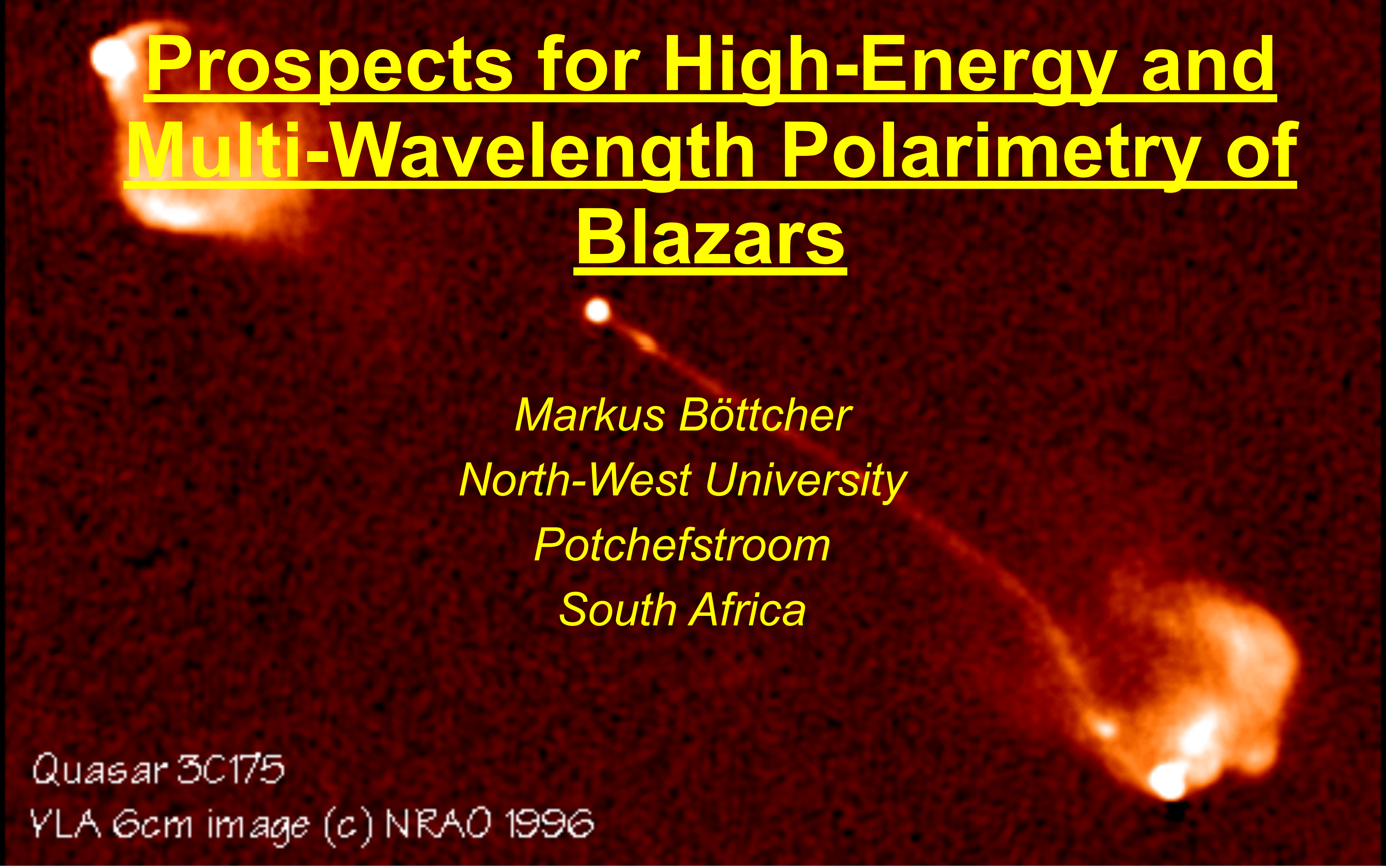
Prospects for High-Energy and Multi-Wavelength Polarimetry of Blazars

Markus Böttcher
North-West University
Potchefstroom
South Africa



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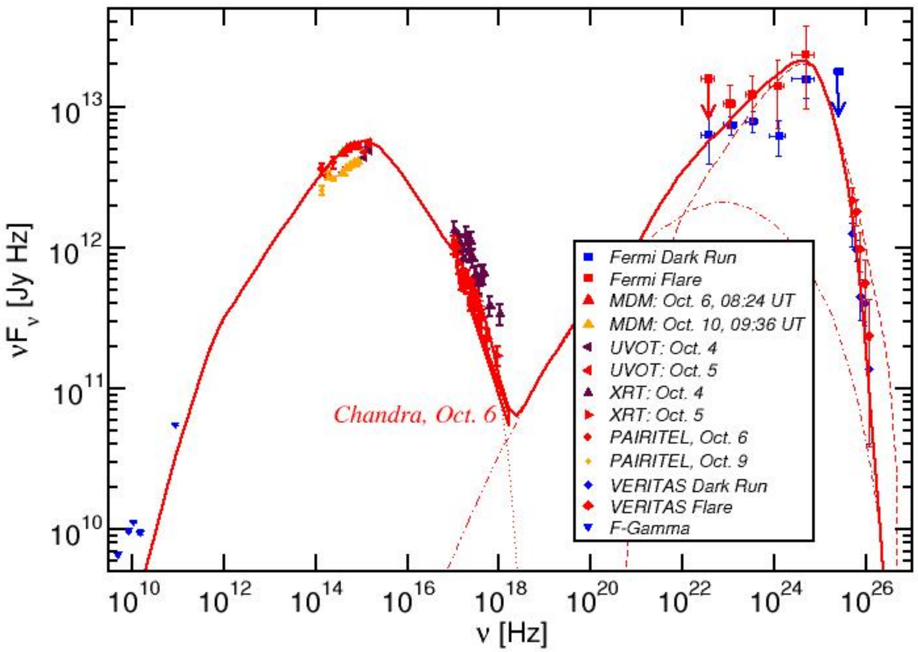
UNIBESITI YA BOKONE-BOPHIRIMA

Blazars

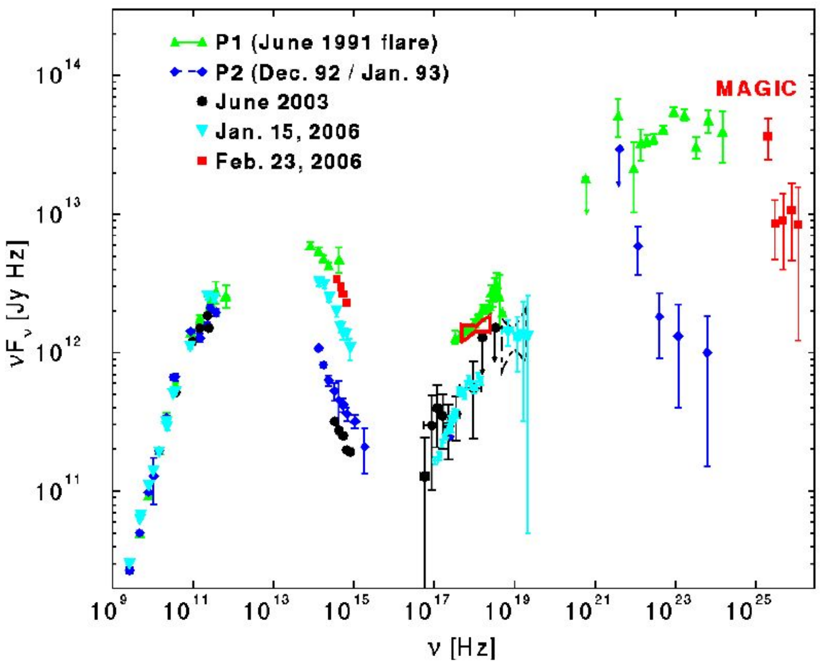
- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars with relativistic jets pointing close to our line of sight
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio knots often with superluminal motion
- Radio and optical polarization

Blazar Spectral Energy Distributions (SEDs)

3C66A

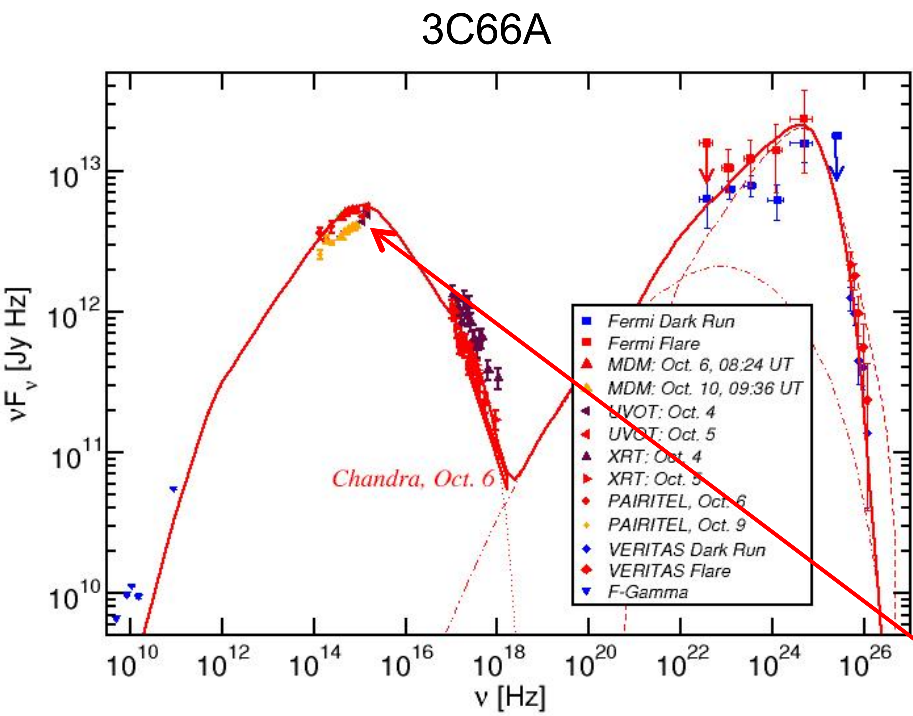


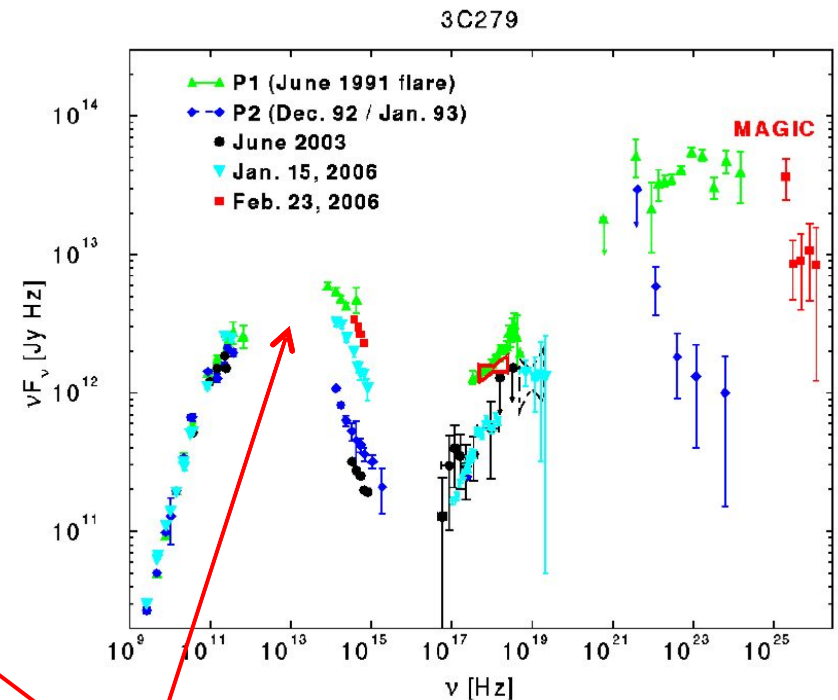
3C279



Non-thermal spectra with two broad bumps:

Blazar Spectral Energy Distributions (SEDs)

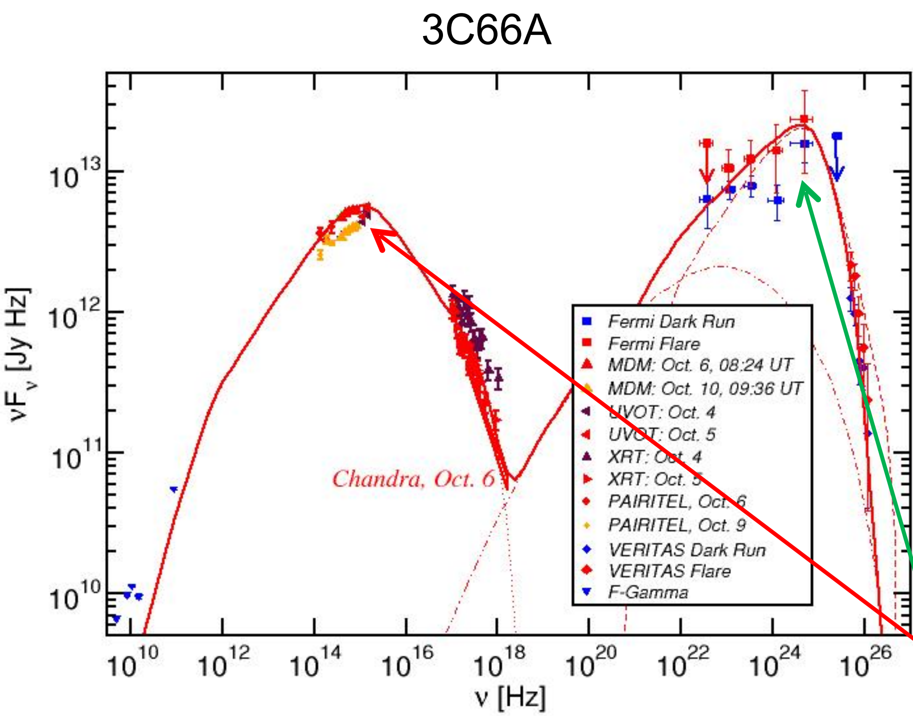


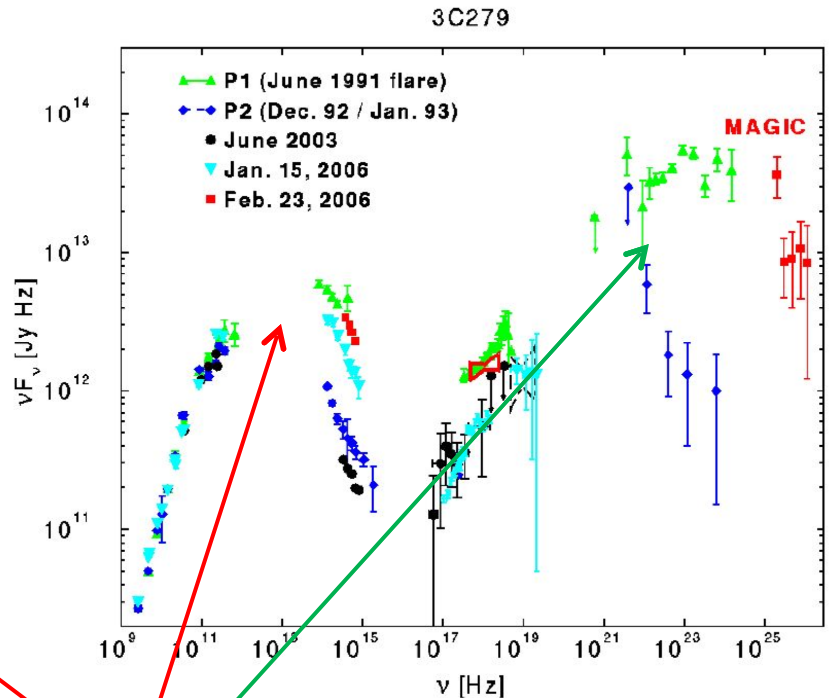


Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)

Blazar Spectral Energy Distributions (SEDs)

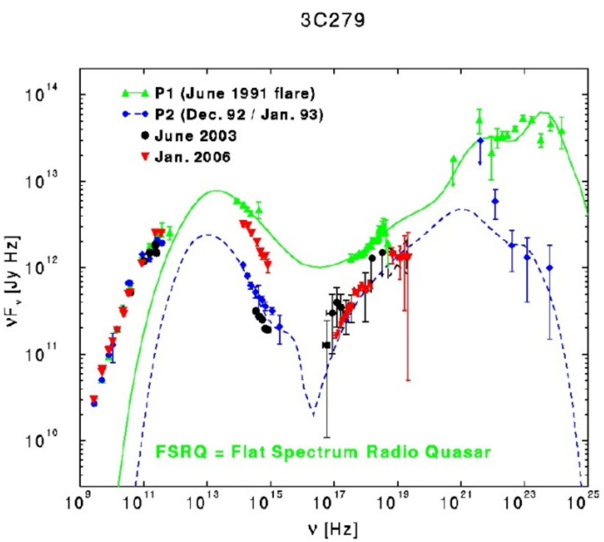




Non-thermal spectra with two broad bumps:

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

Blazar Classification



(Hartman et al. 2000)

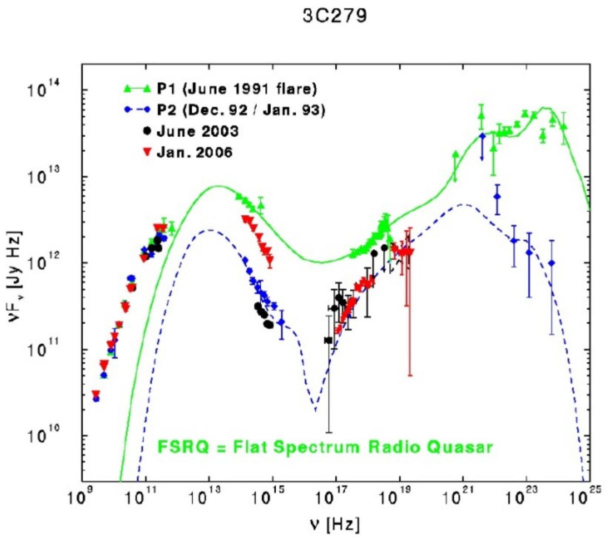
Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/ Low-frequency peaked BL Lac Objects (LBLs)

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

Blazar Classification



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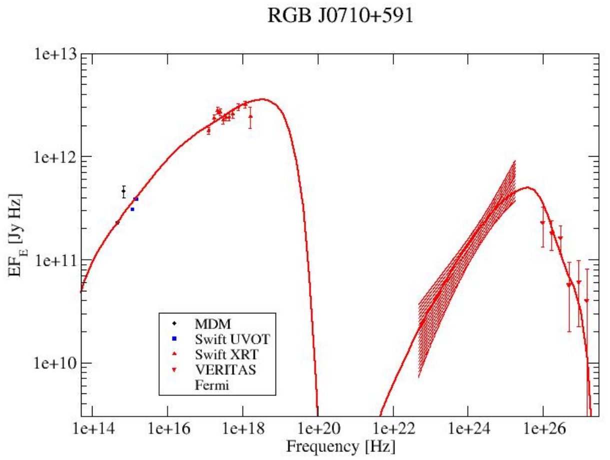

(Acciari et al. 2009)

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<u>High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):</u>

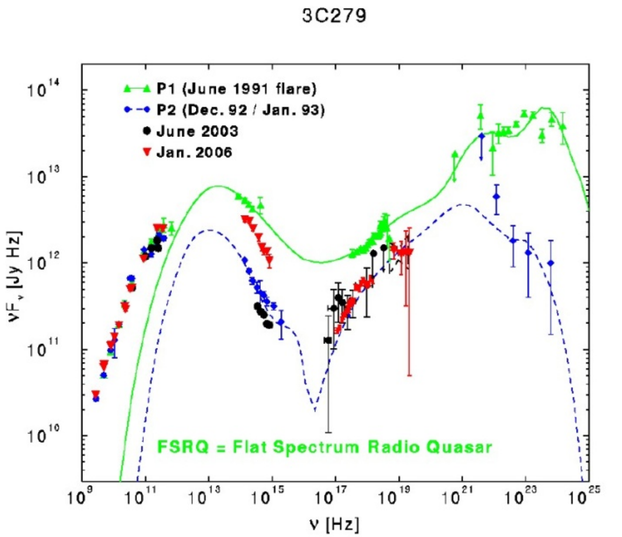
Low-frequency component from radio to UV/X-rays,

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

often dominating the total power

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

Blazar Classification



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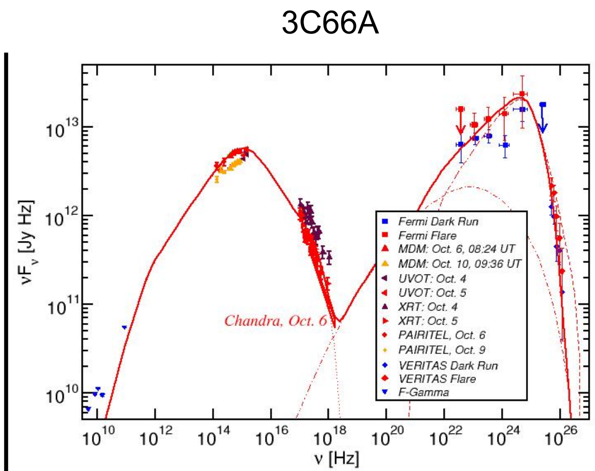

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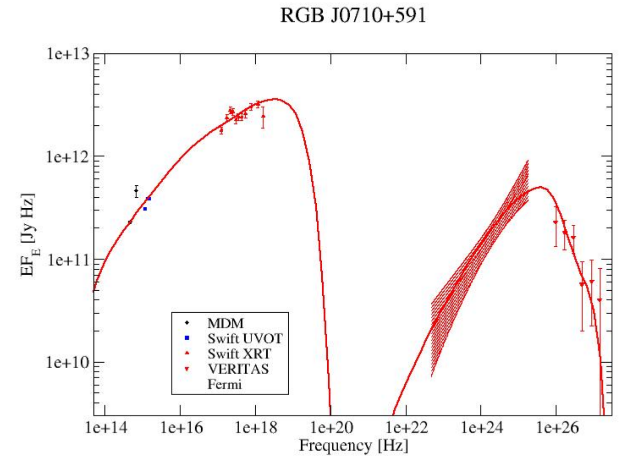

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$\nu_{sy} \leq 10^{14}$ Hz

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

<u>Intermediate-Synchrotron Peaked (ISP): Intermediate BL Lacs (IBLs):</u>

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

<u>High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):</u>

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

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

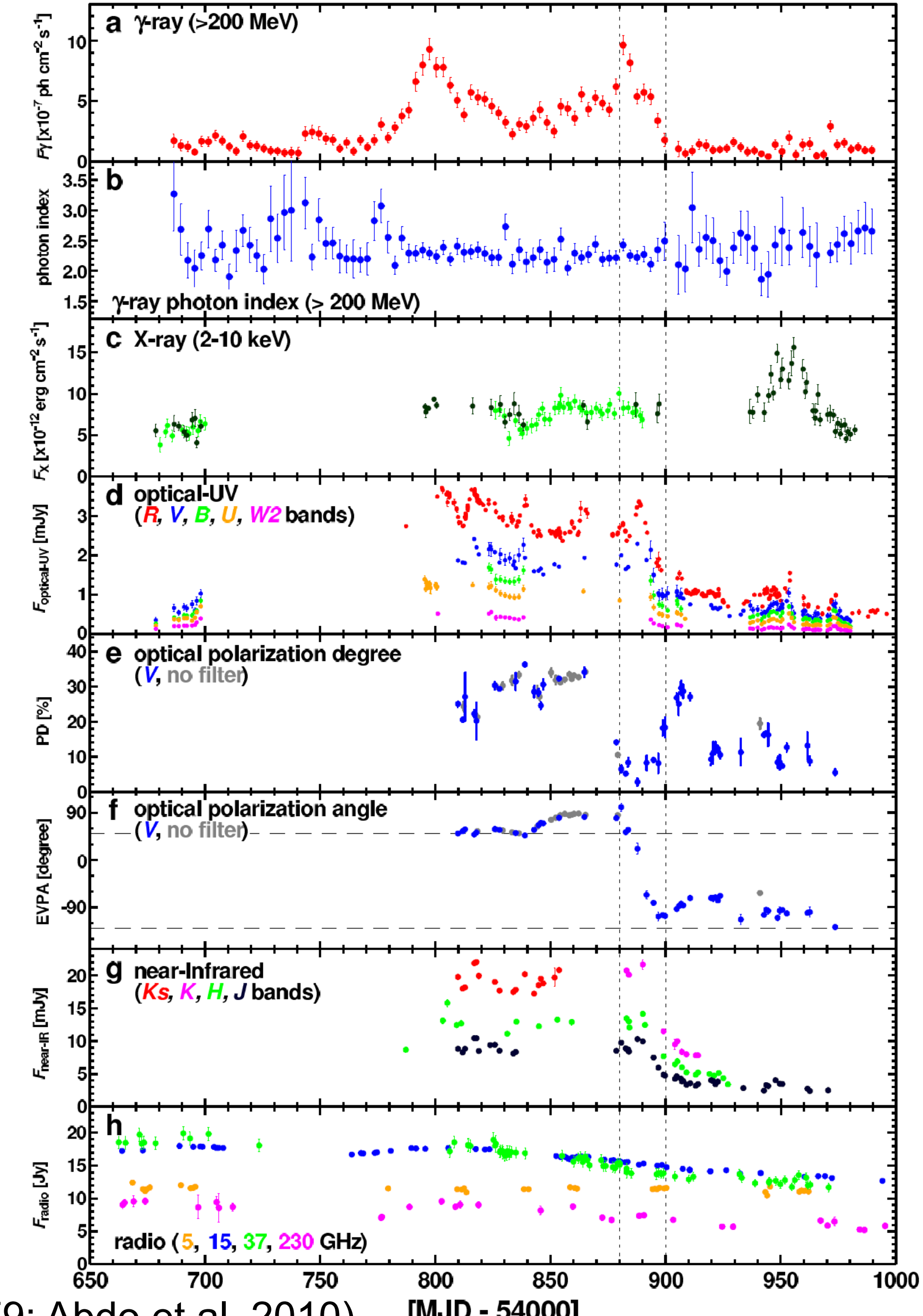
often dominating the total power

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



(3C279: Abdo et al. 2010)

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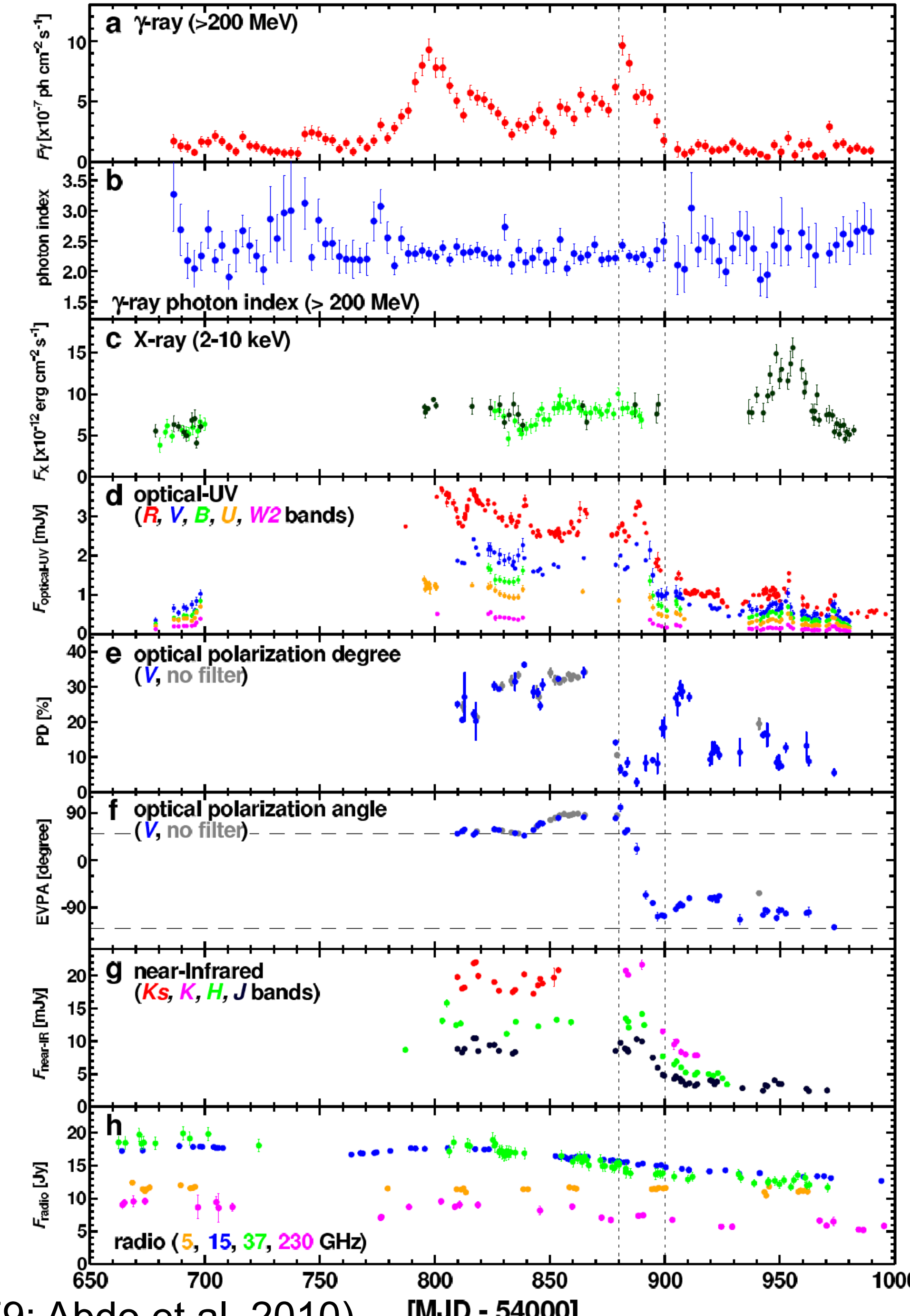
Observed optical polarization degrees

Π_{opt} <~ 30 %



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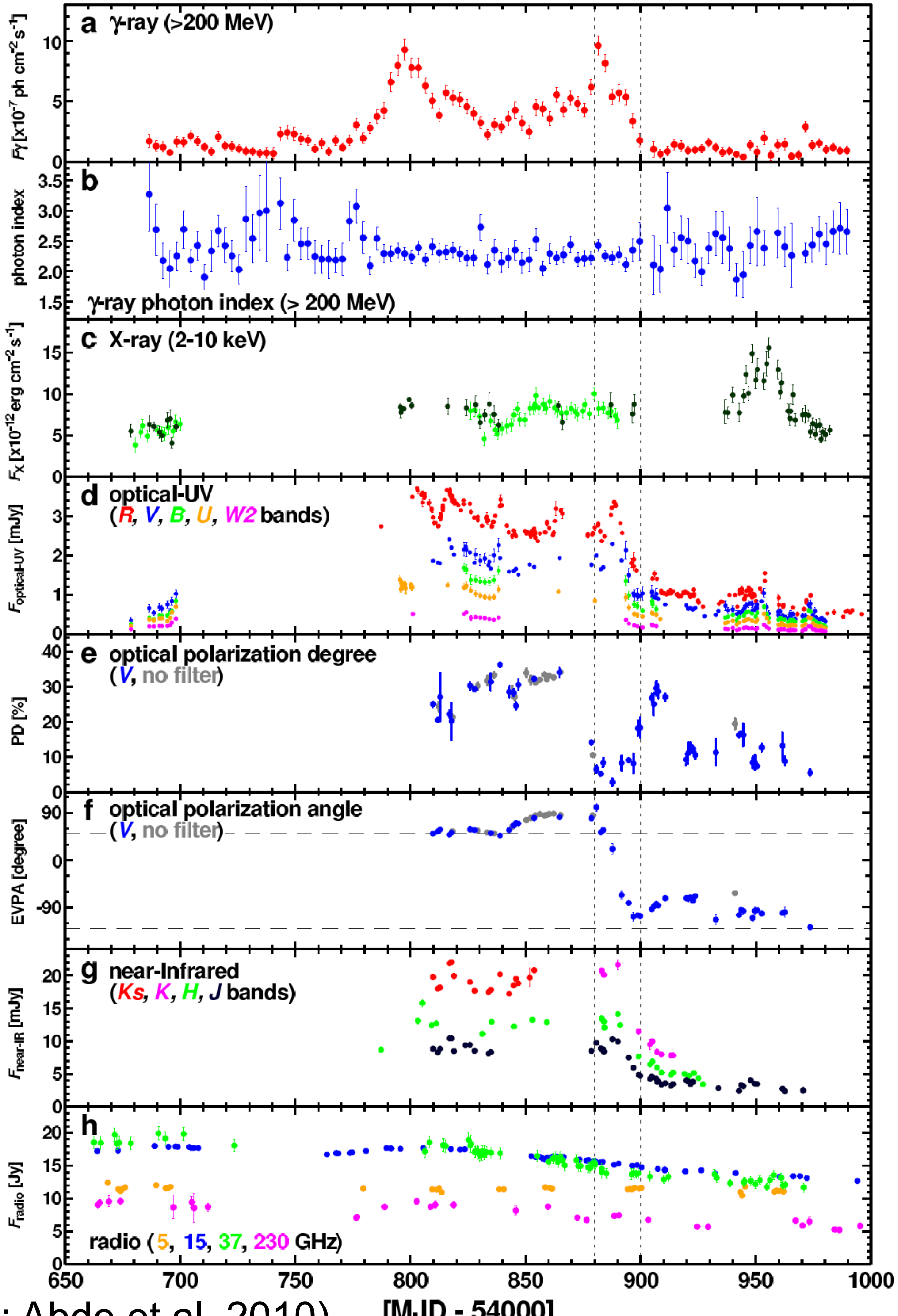
Flux and Polarization Variability

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!



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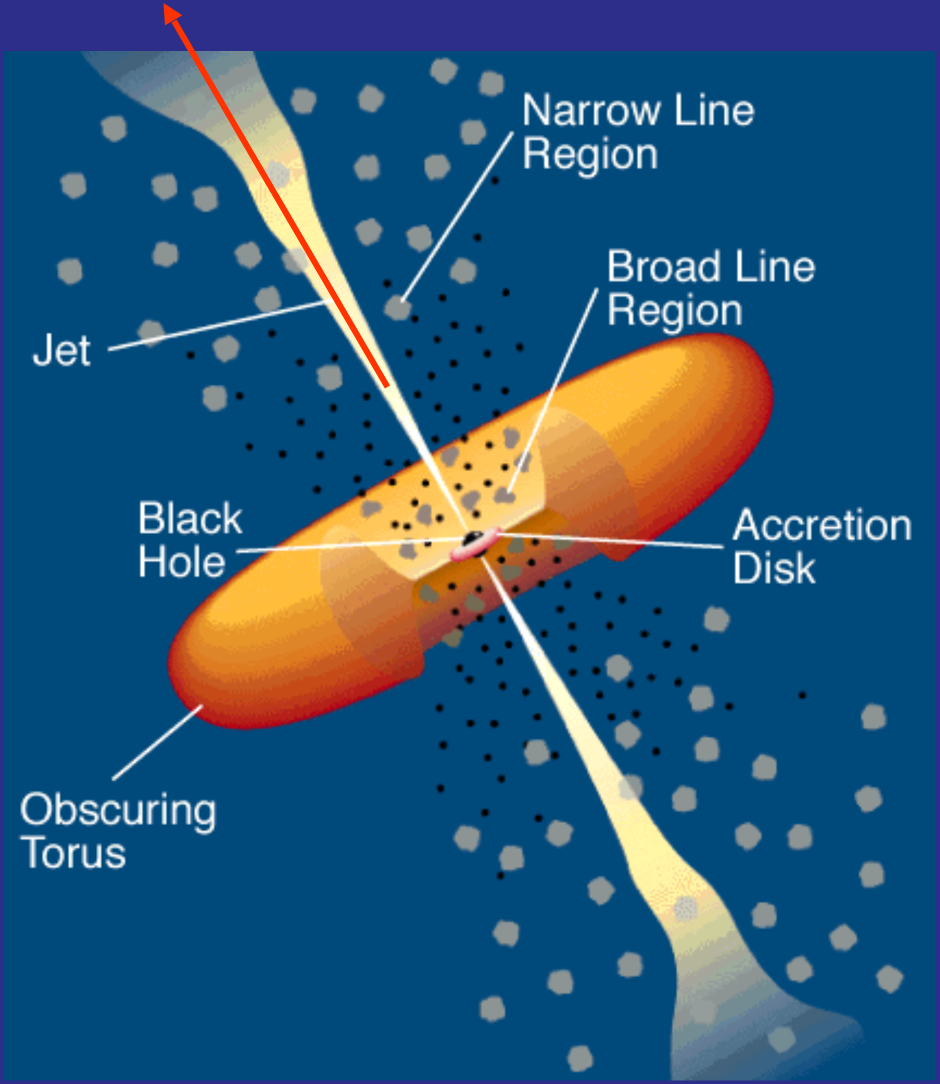
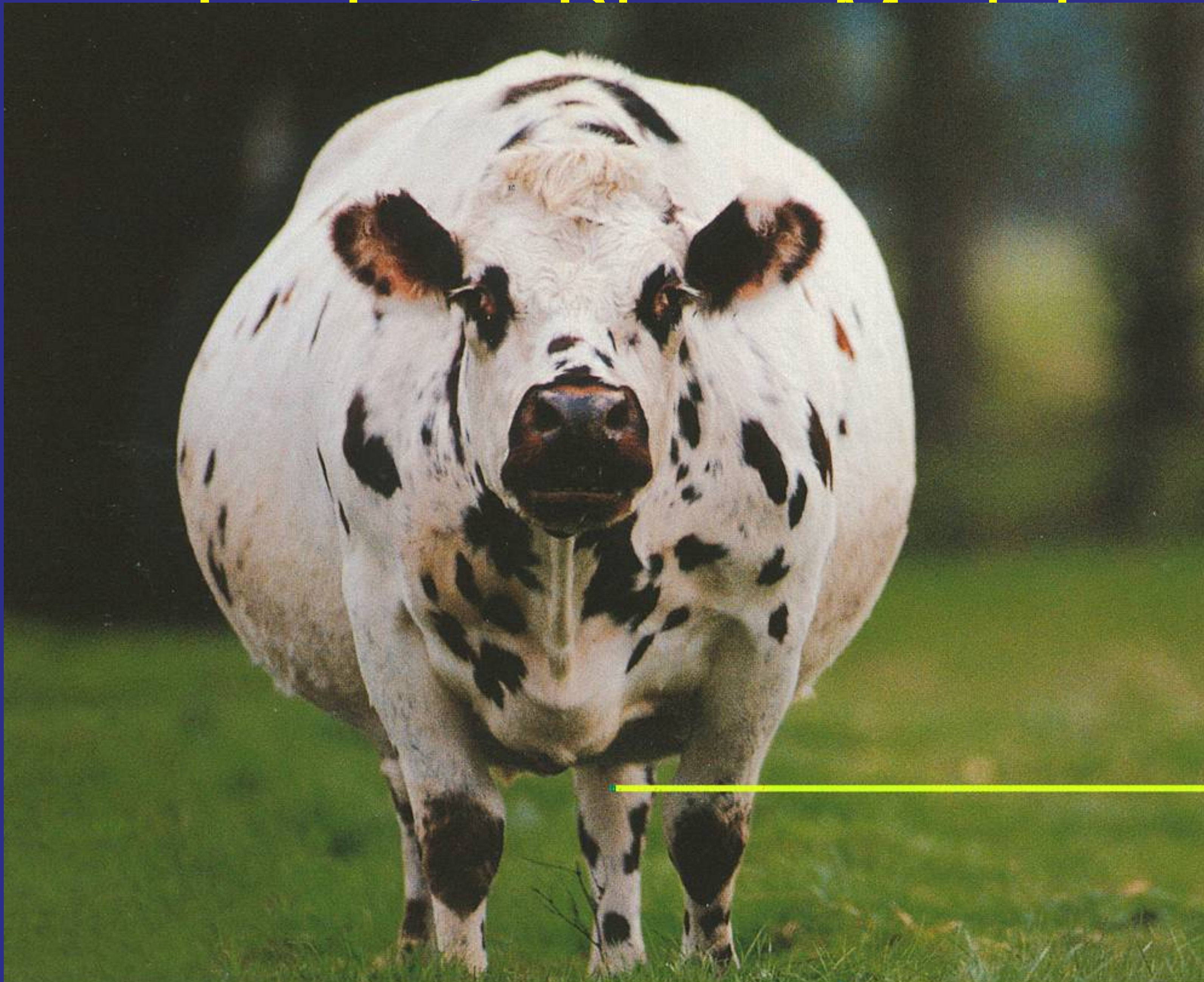
Open Physics Questions

- 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

Relativistic jet outflow with $\Gamma \approx 10$





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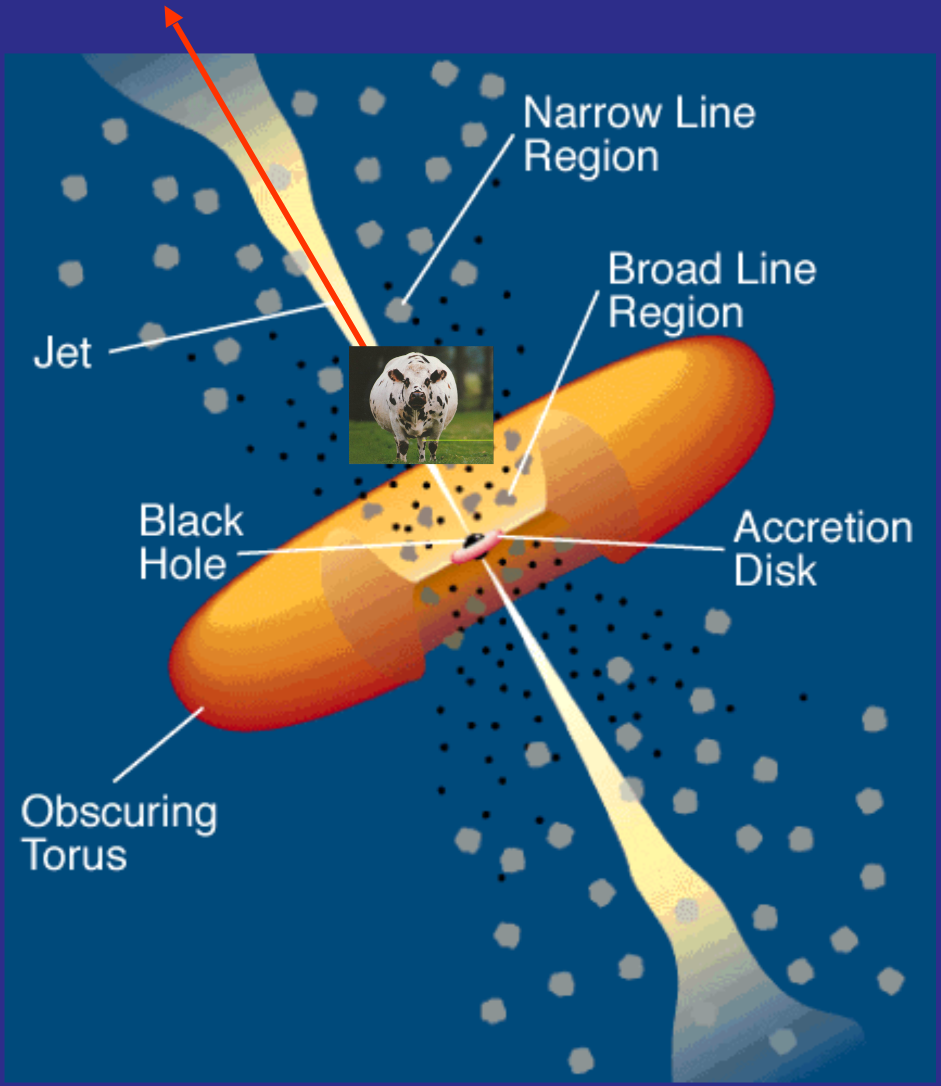
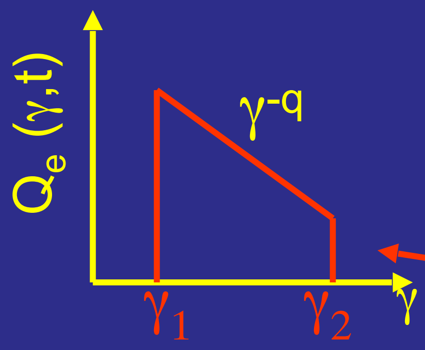


Leptonic Blazar Model

Injection, acceleration of ultrarelativistic electrons



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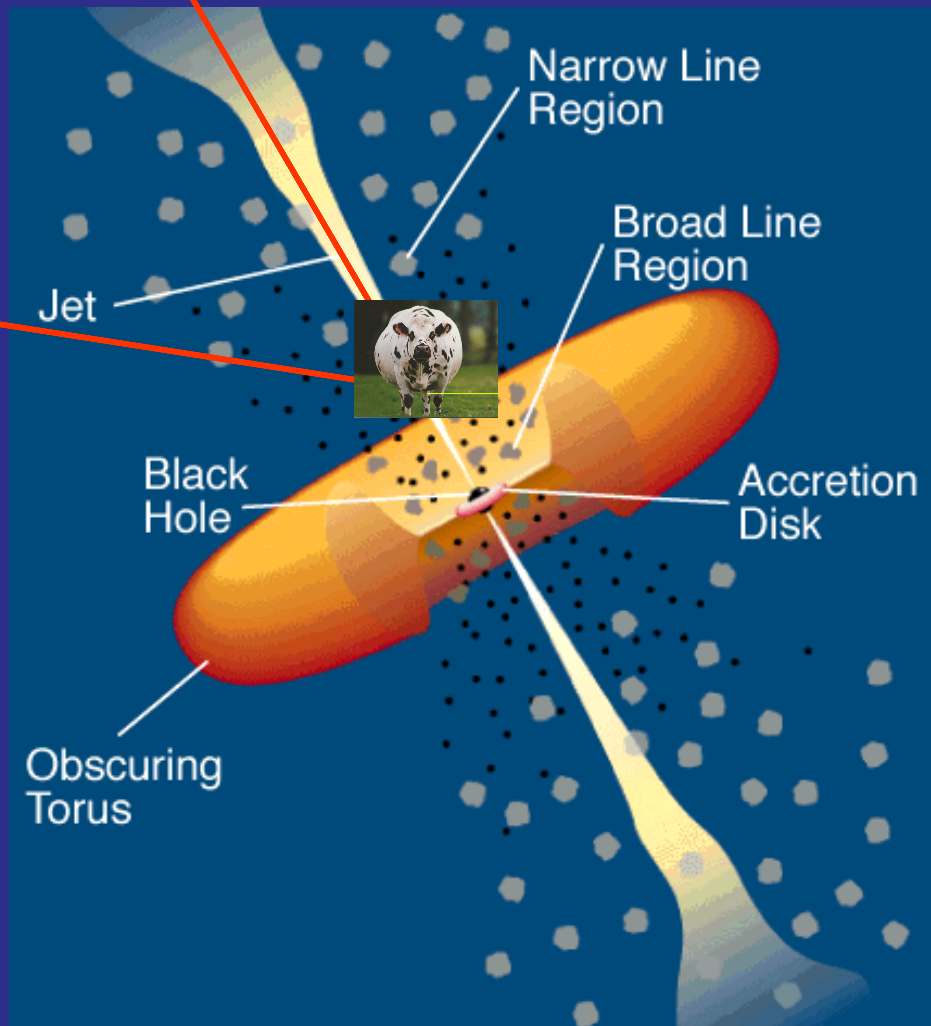

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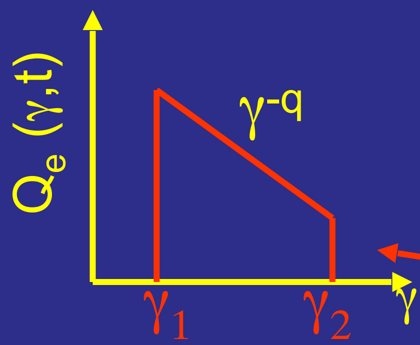

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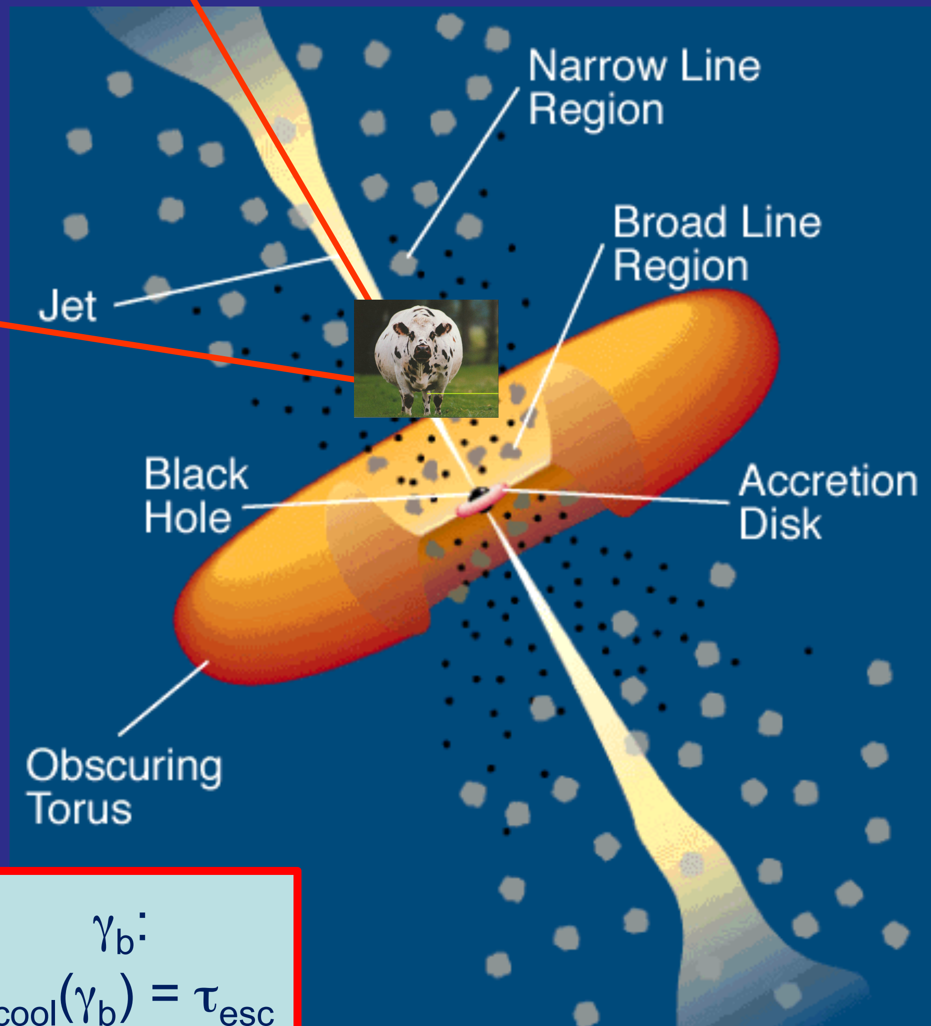
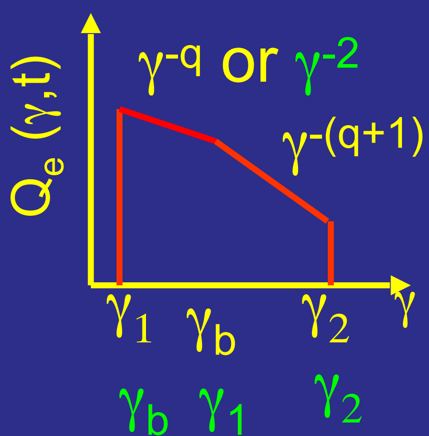


Radiative cooling $\leftrightarrow$ escape =>



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

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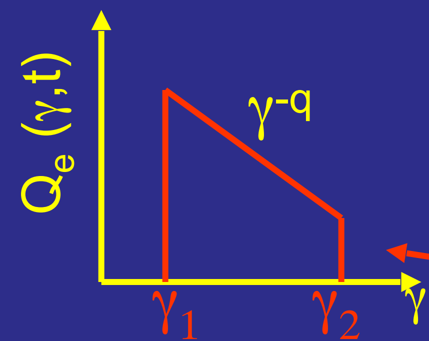

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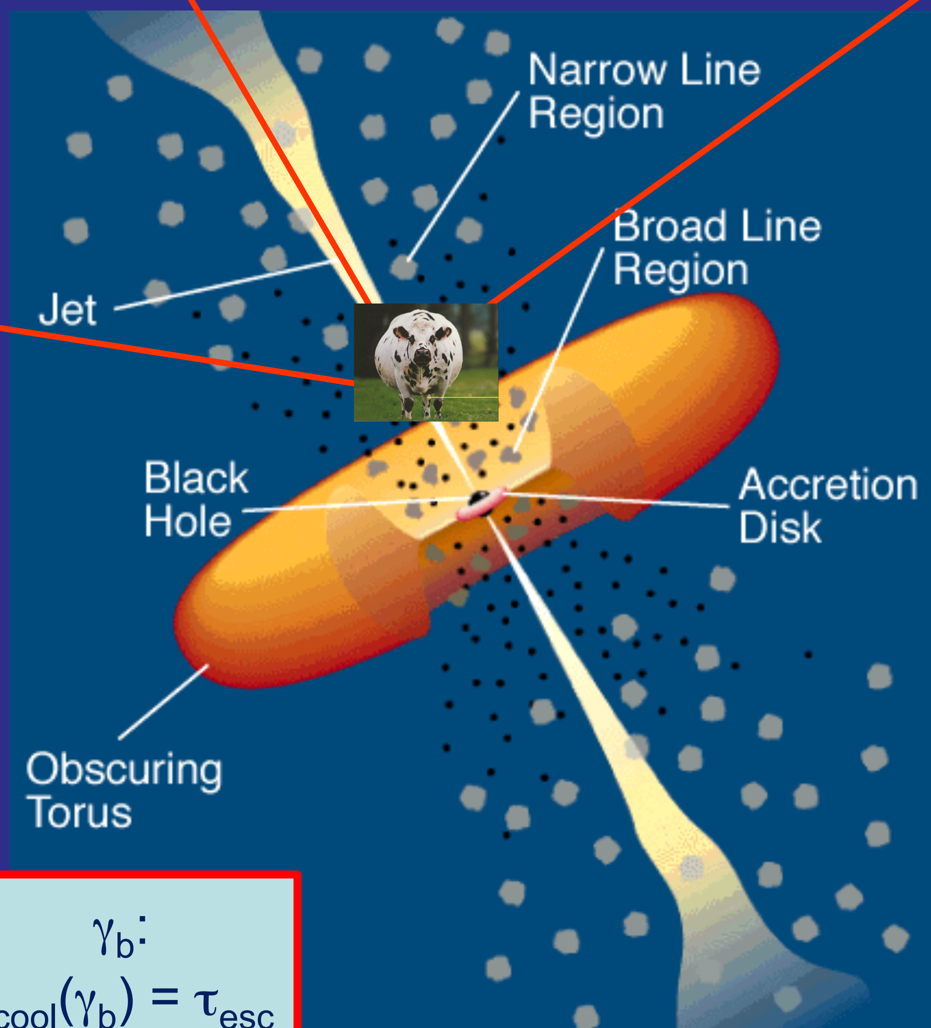
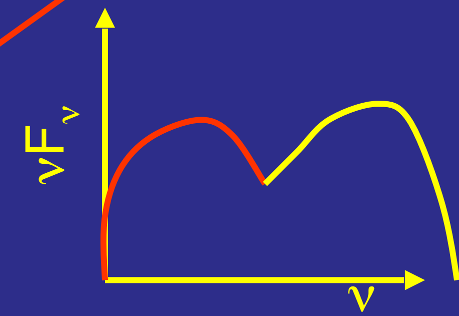


Synchrotron emission



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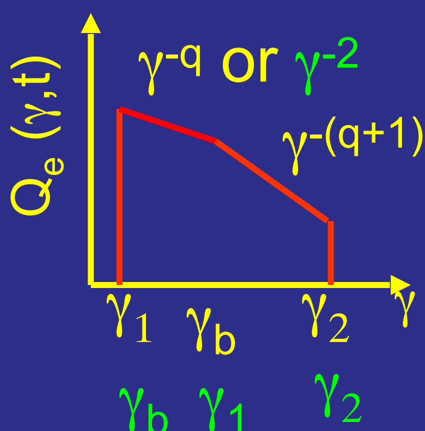

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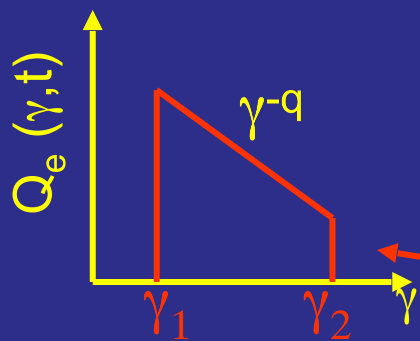

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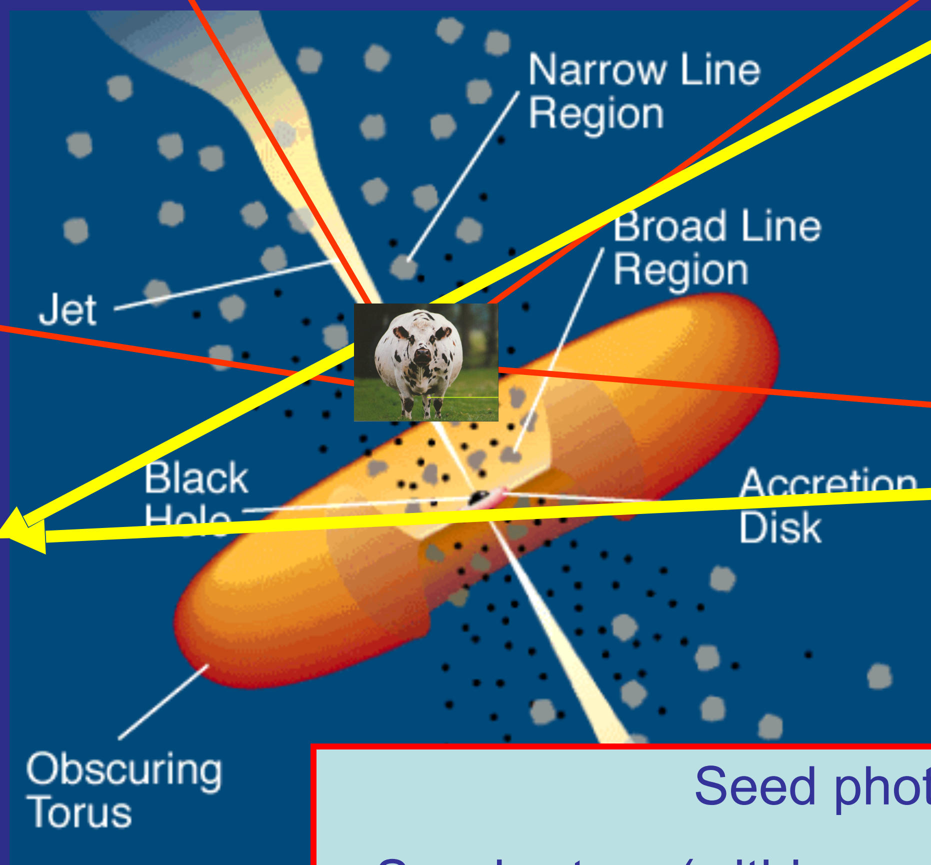

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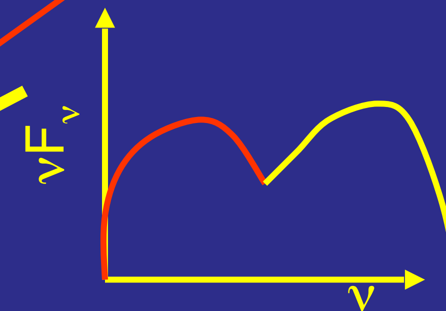
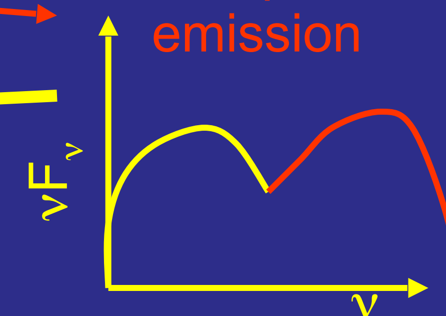


Compton emission



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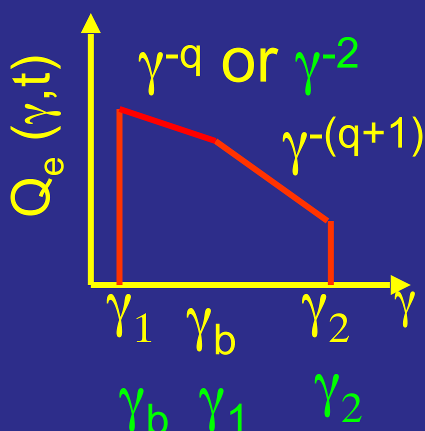

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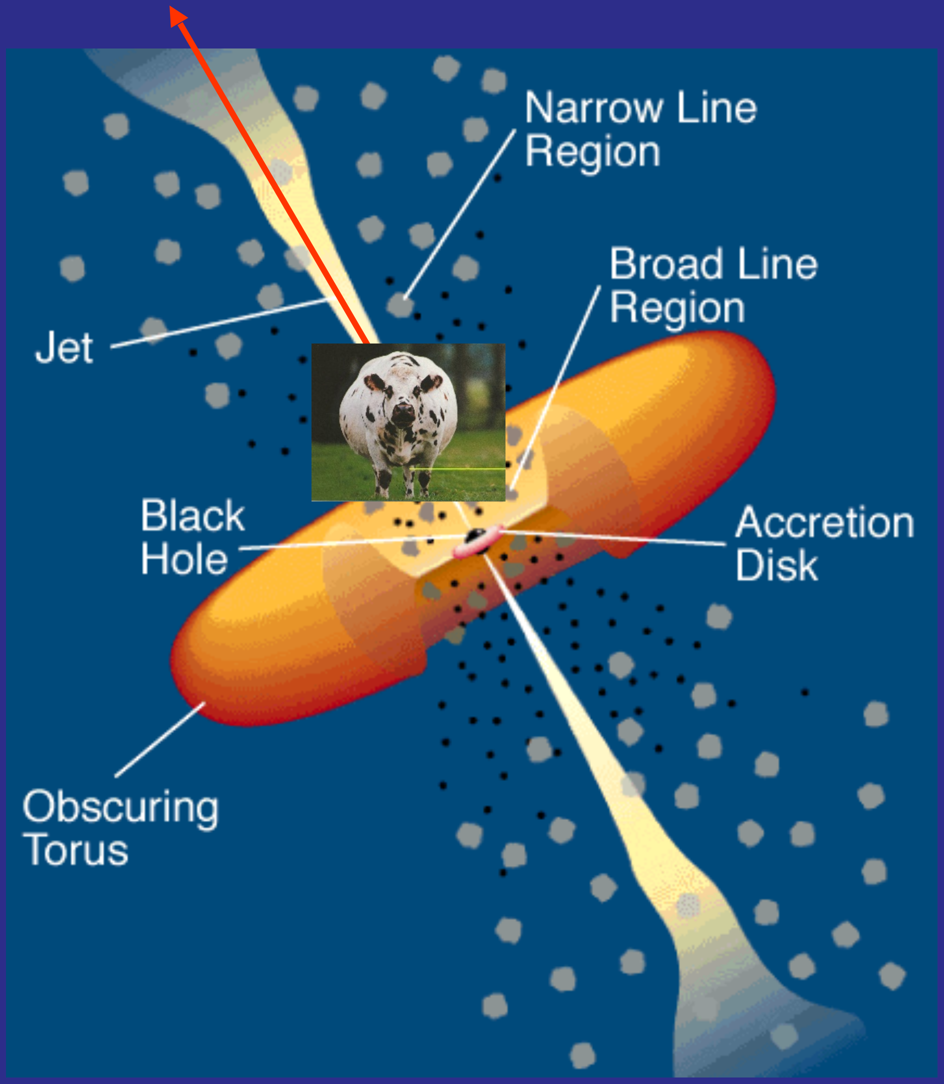
$\tau_{cool}(\gamma_b) = \tau_{esc}$

Seed photons:

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

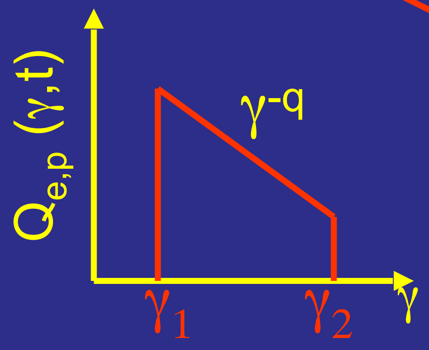
Hadronic Blazar Models

Relativistic jet outflow
with $\Gamma \approx 10$



Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons



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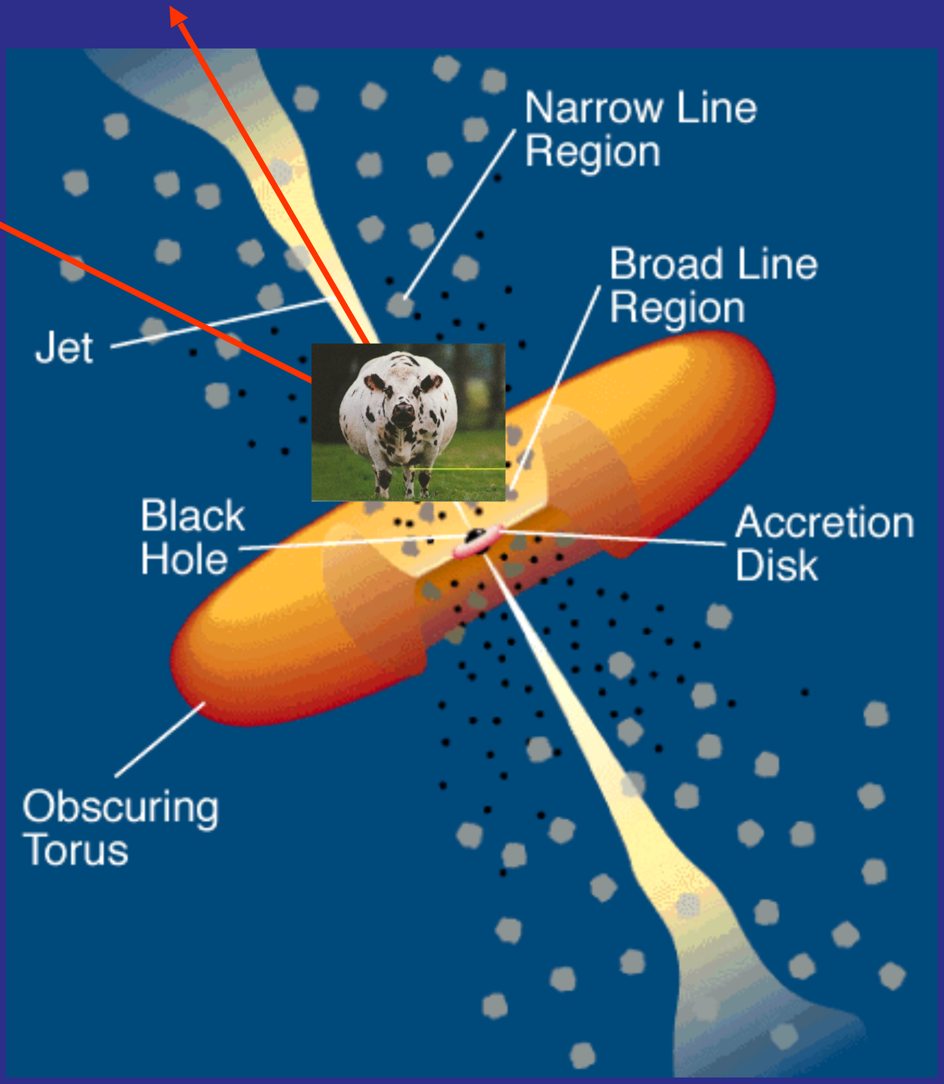

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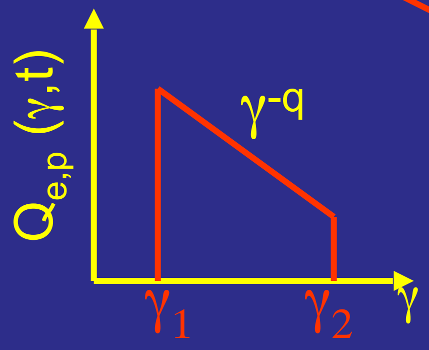
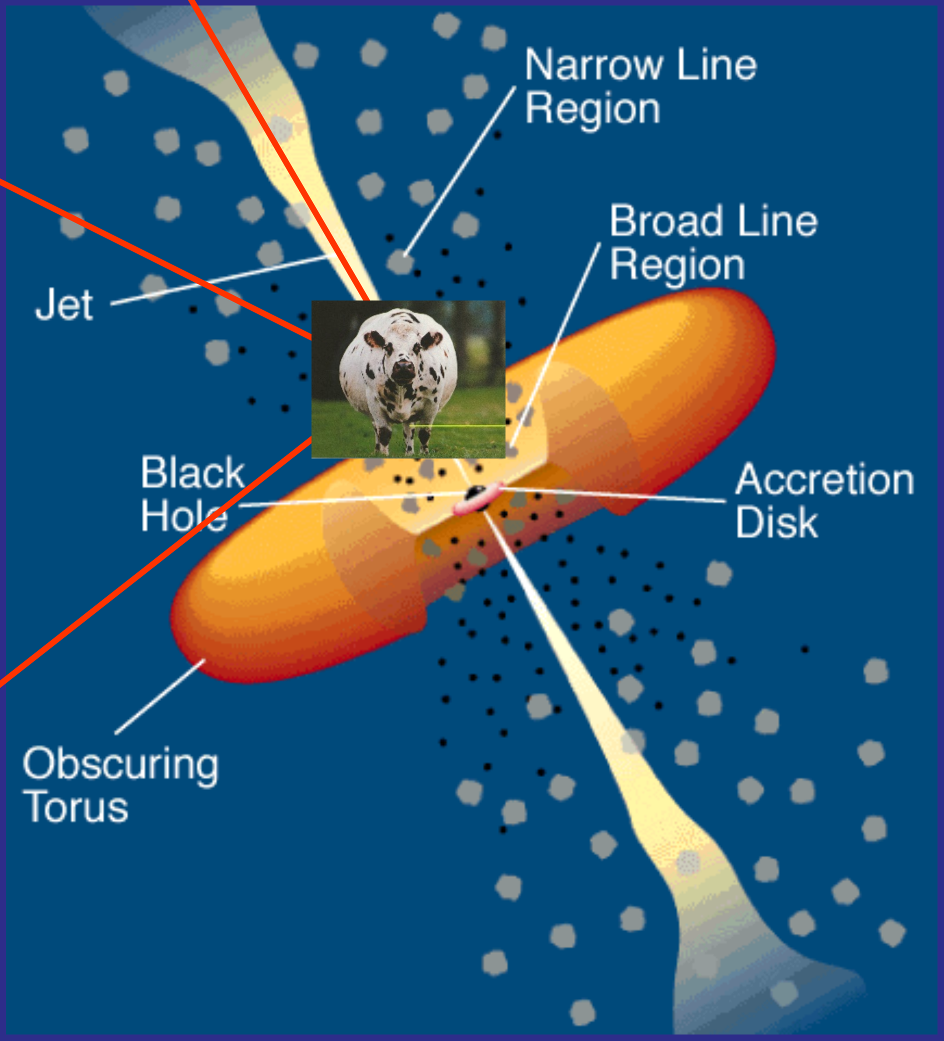
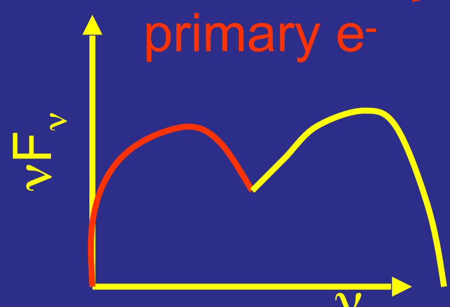




Synchrotron emission of primary e^-



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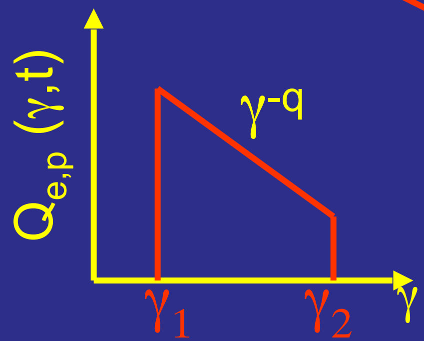
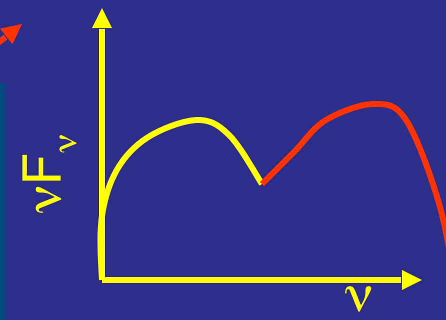
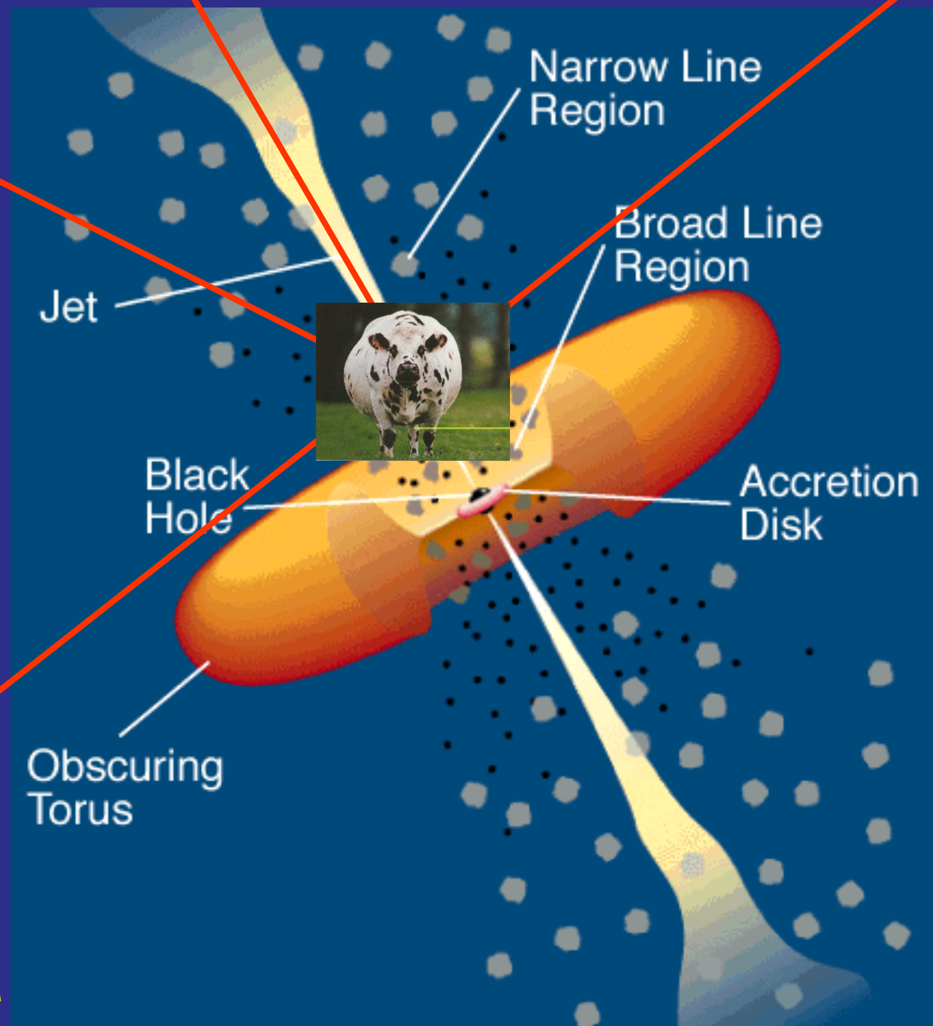


Relativistic jet outflow with $\Gamma \approx 10$

Proton-induced radiation mechanisms:





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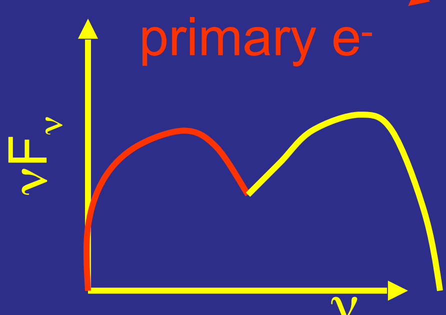

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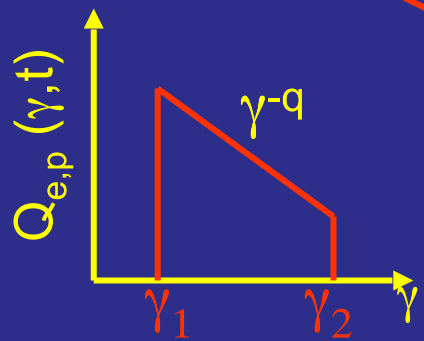

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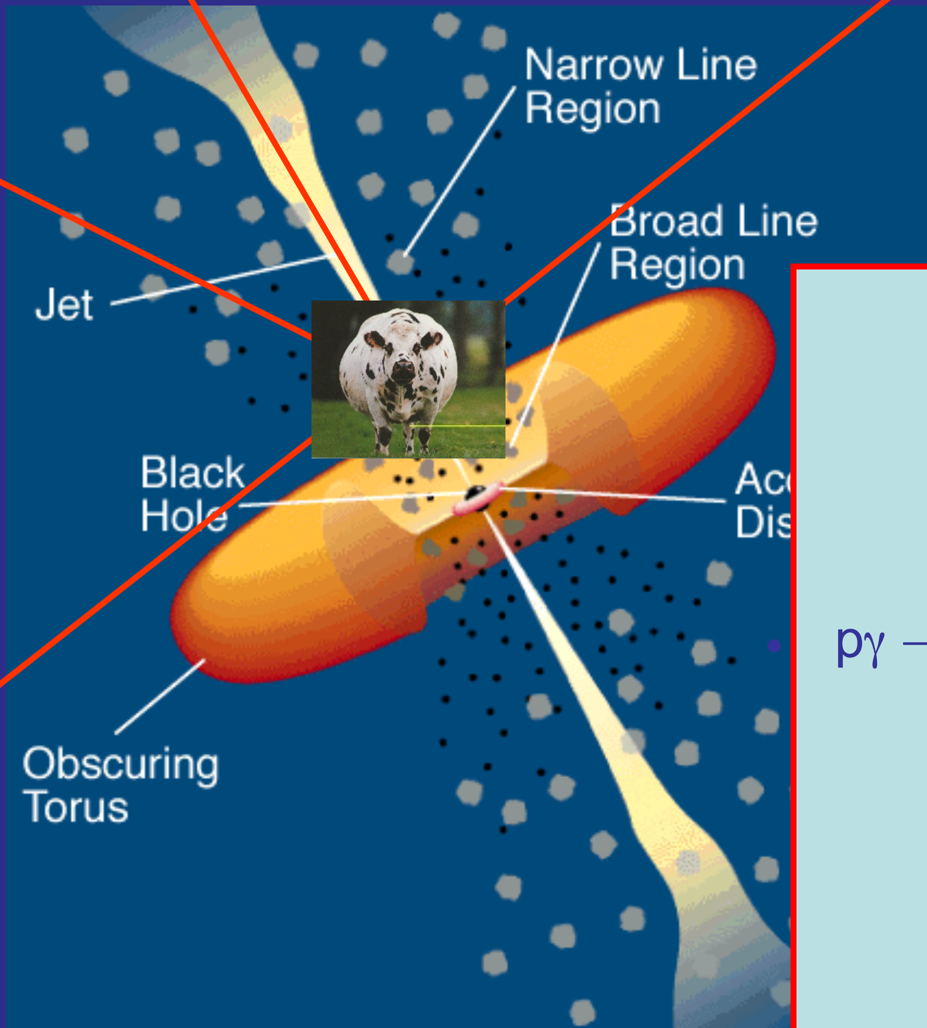

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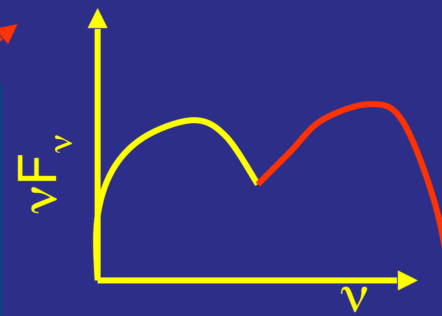

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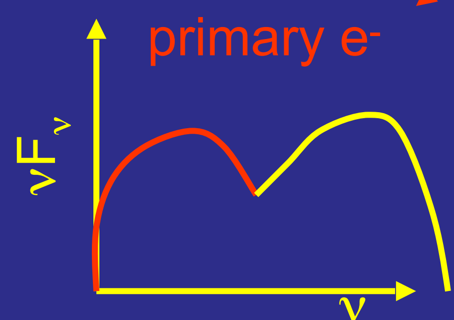


- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$

$p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$

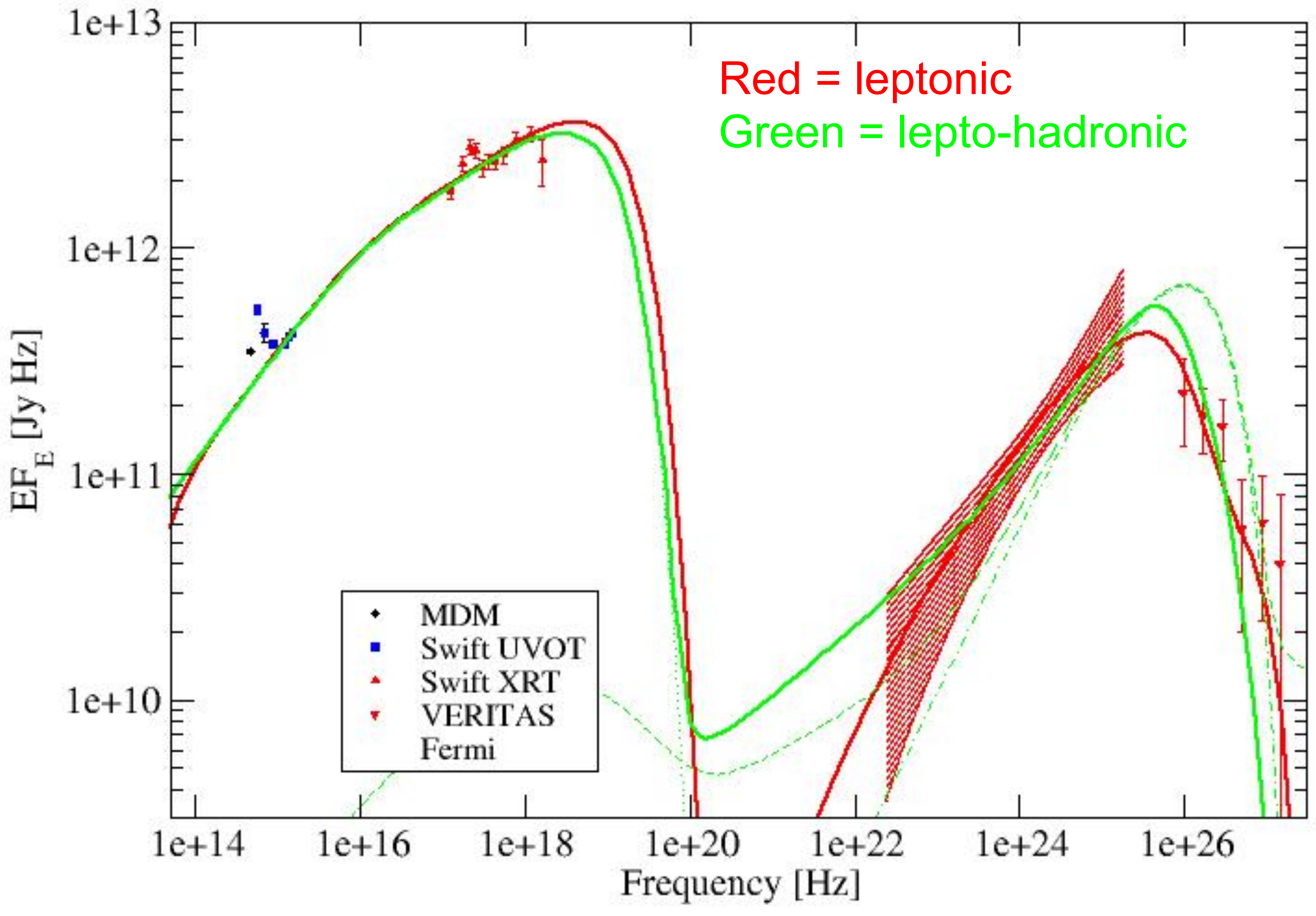
$\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$

$\rightarrow$ secondary μ-, e-synchrotron

- Cascades …

Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)



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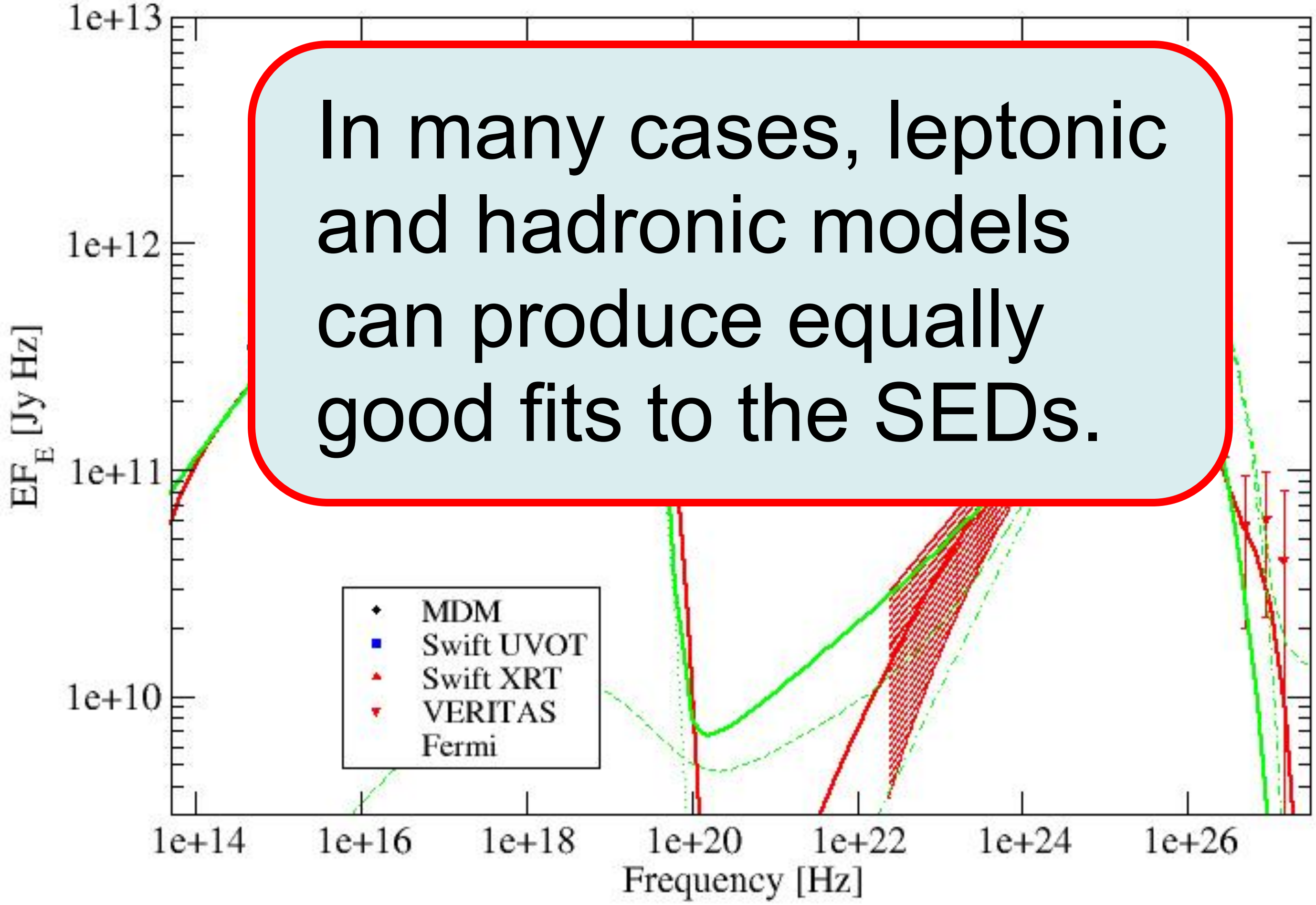

In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Lepto-Hadronic Model Fits to Blazar SEDs

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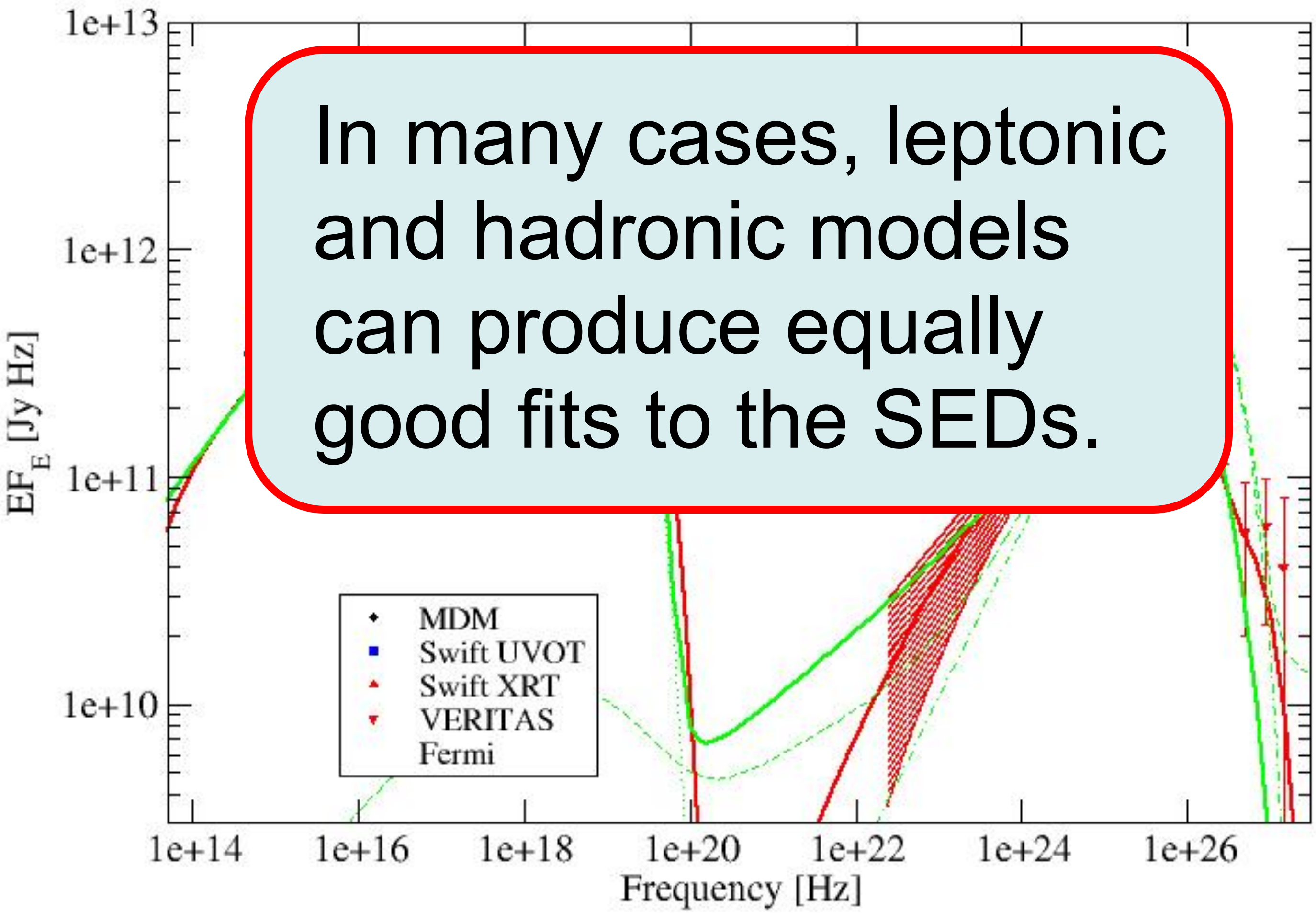

Possible Diagnostics to distinguish:

- 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 $\alpha = (p-1)/2$

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

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

p = 2 → Π = 69 %

p = 3 → Π = 75 %

Compton Polarization

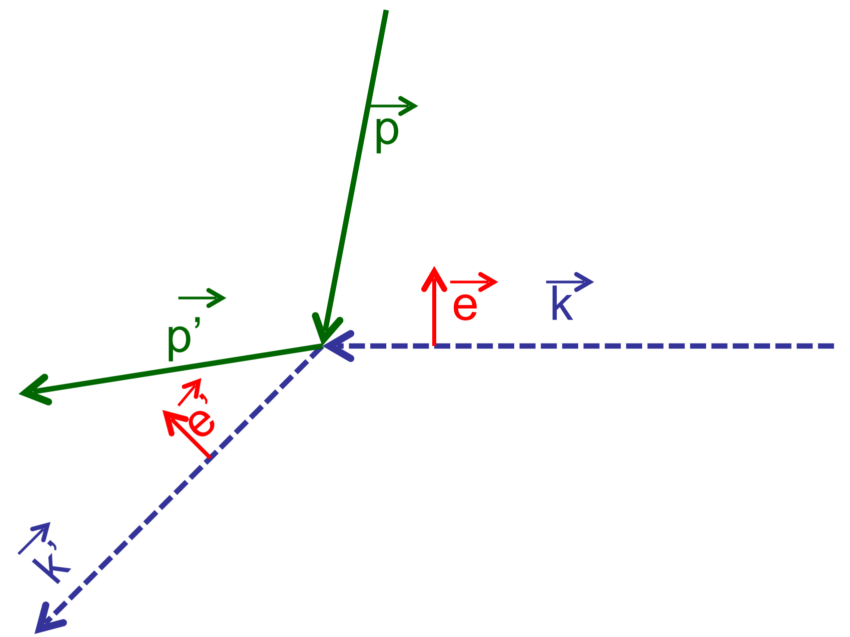
Compton cross section is polarization-dependent:

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

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

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

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



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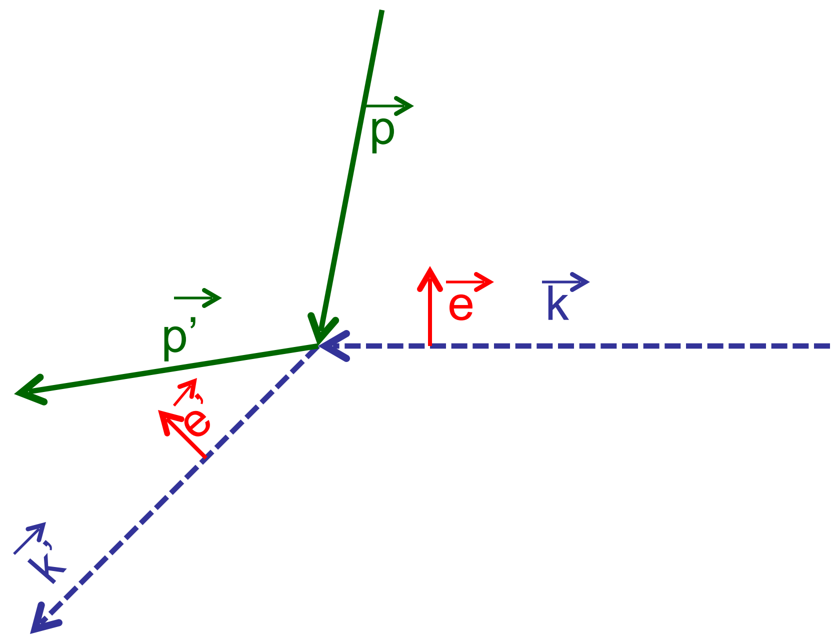
$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

Preferred polarization direction is preserved.



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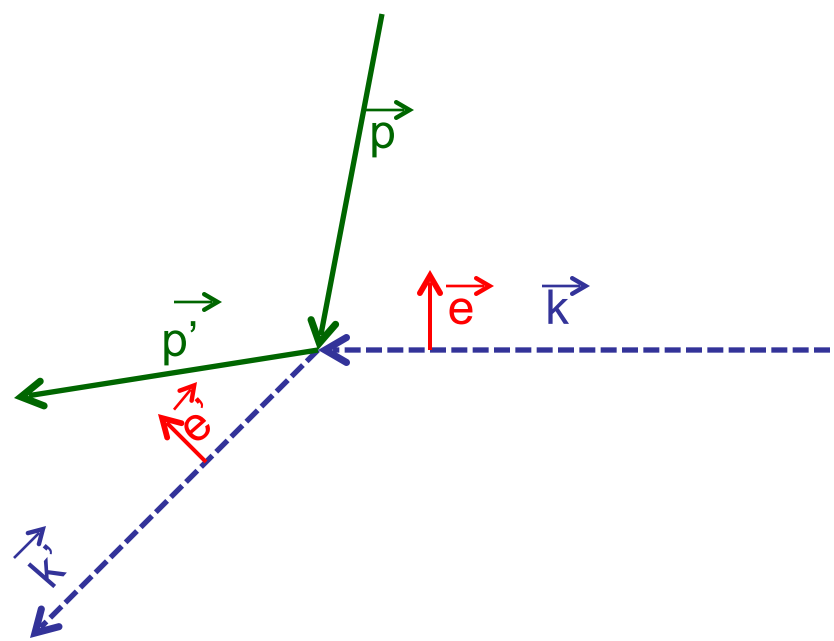
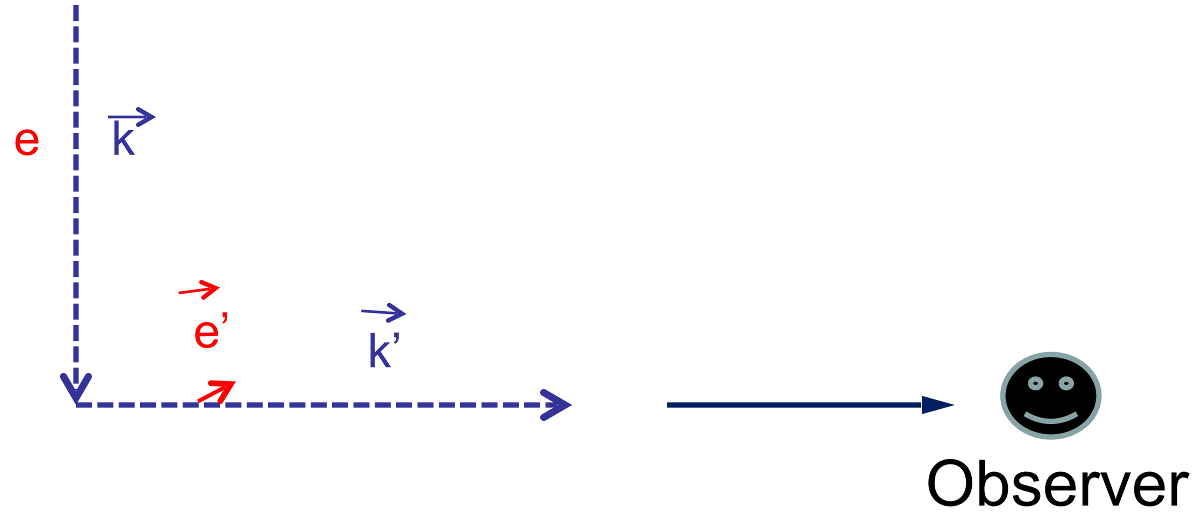
$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

Preferred polarization direction is preserved.



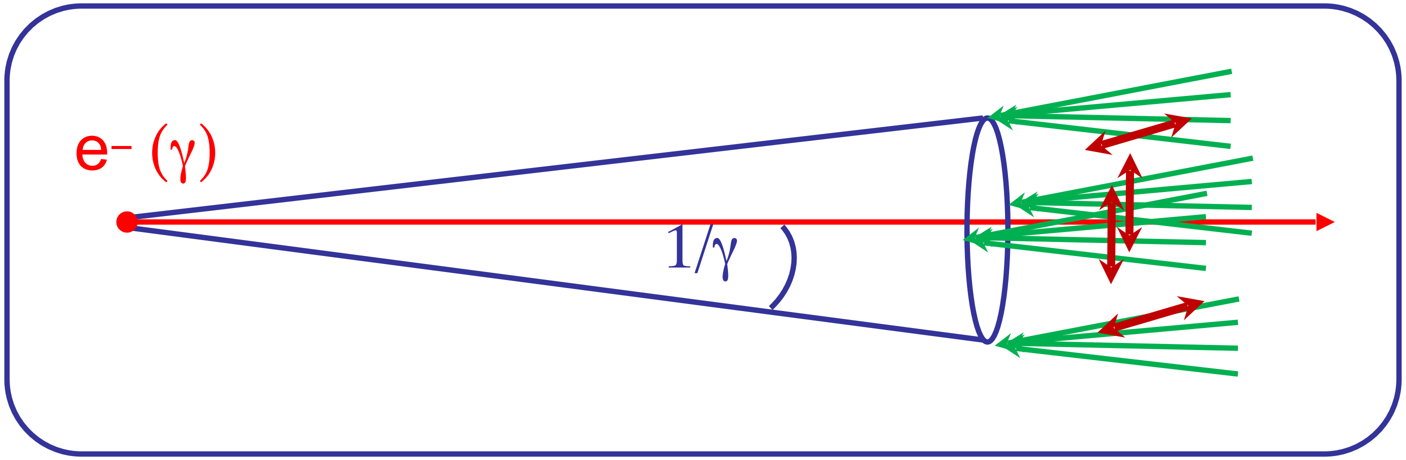
Compton Polarization

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



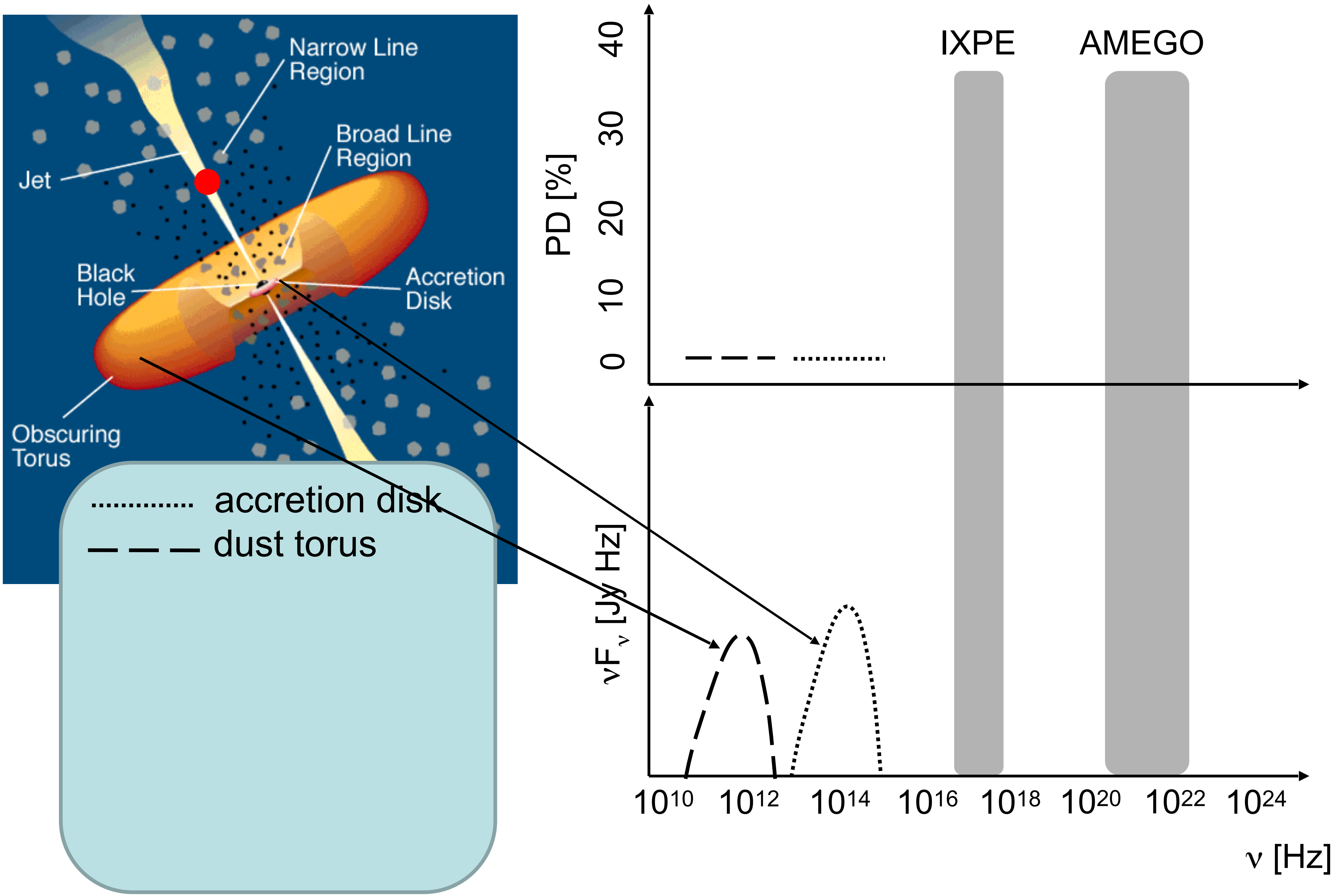
Compton Scattering by Relativistic Electrons

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

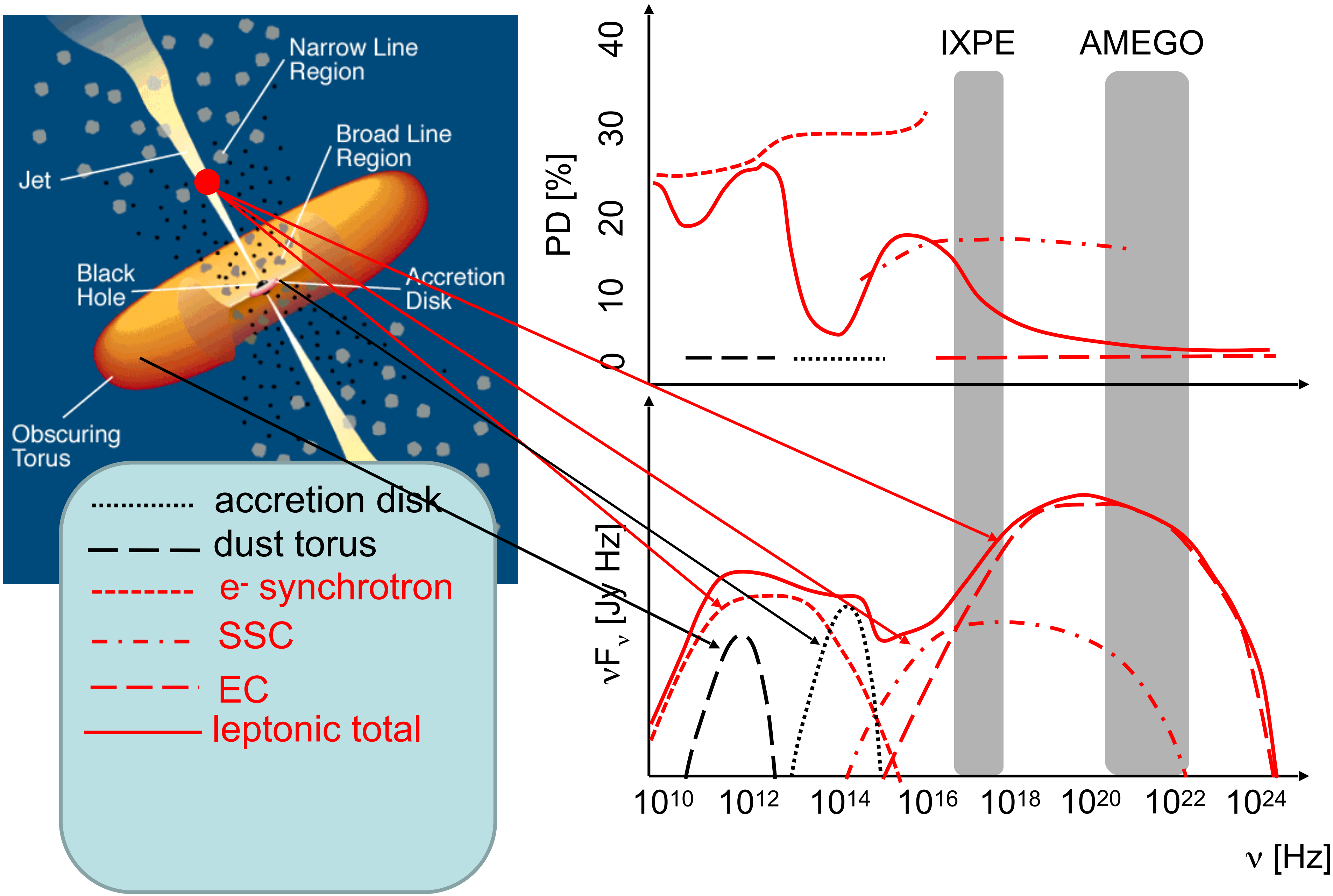


- Unpolarized target photons (EC emission) $\rightarrow$ **Unpolarized**
- Polarized target photons (SSC) $\rightarrow$ **SSC polarization ~ ½ of target (synchrotron) photon polarization**

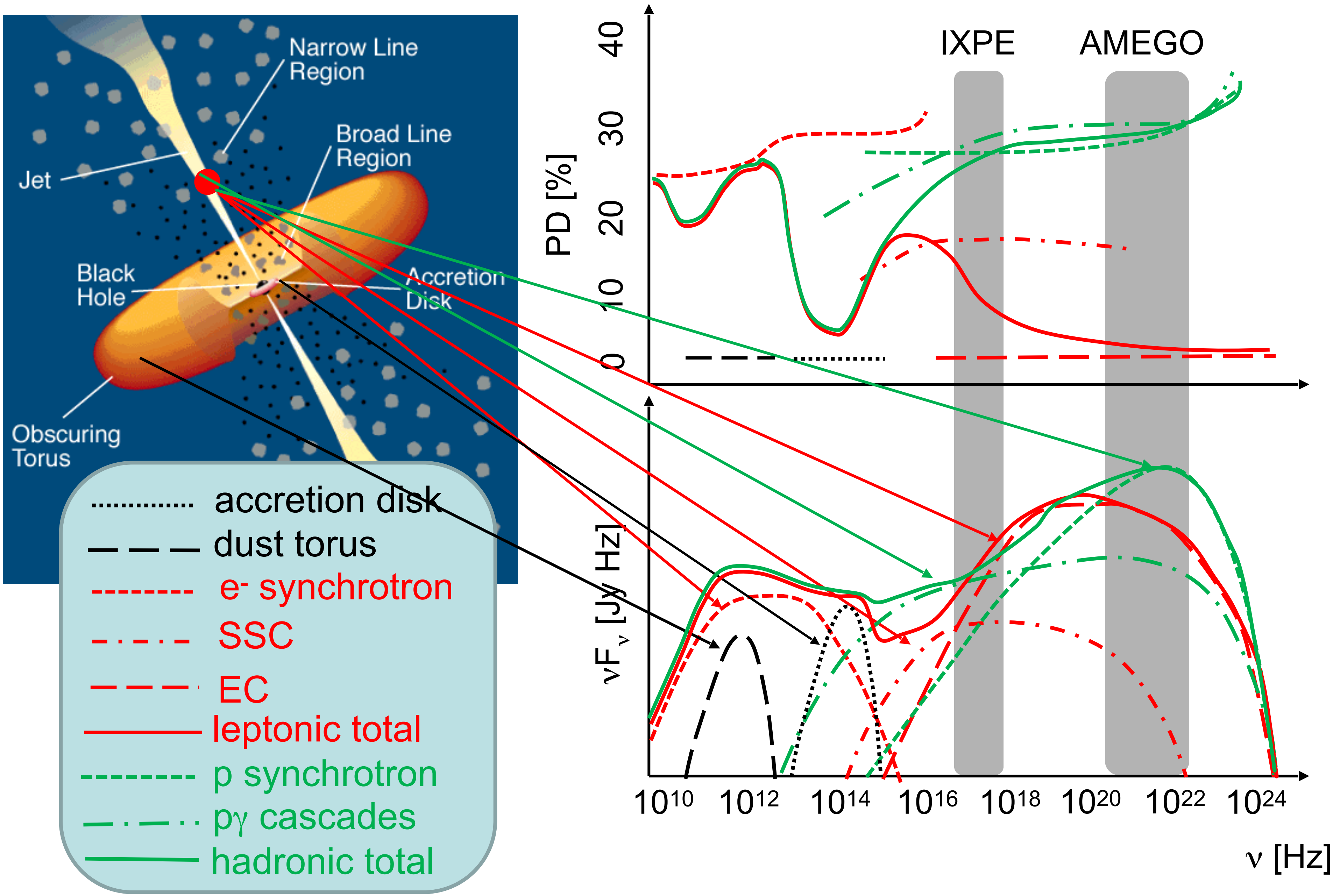
Multiwavelength Polarization of Blazars



Multiwavelength Polarization of Blazars

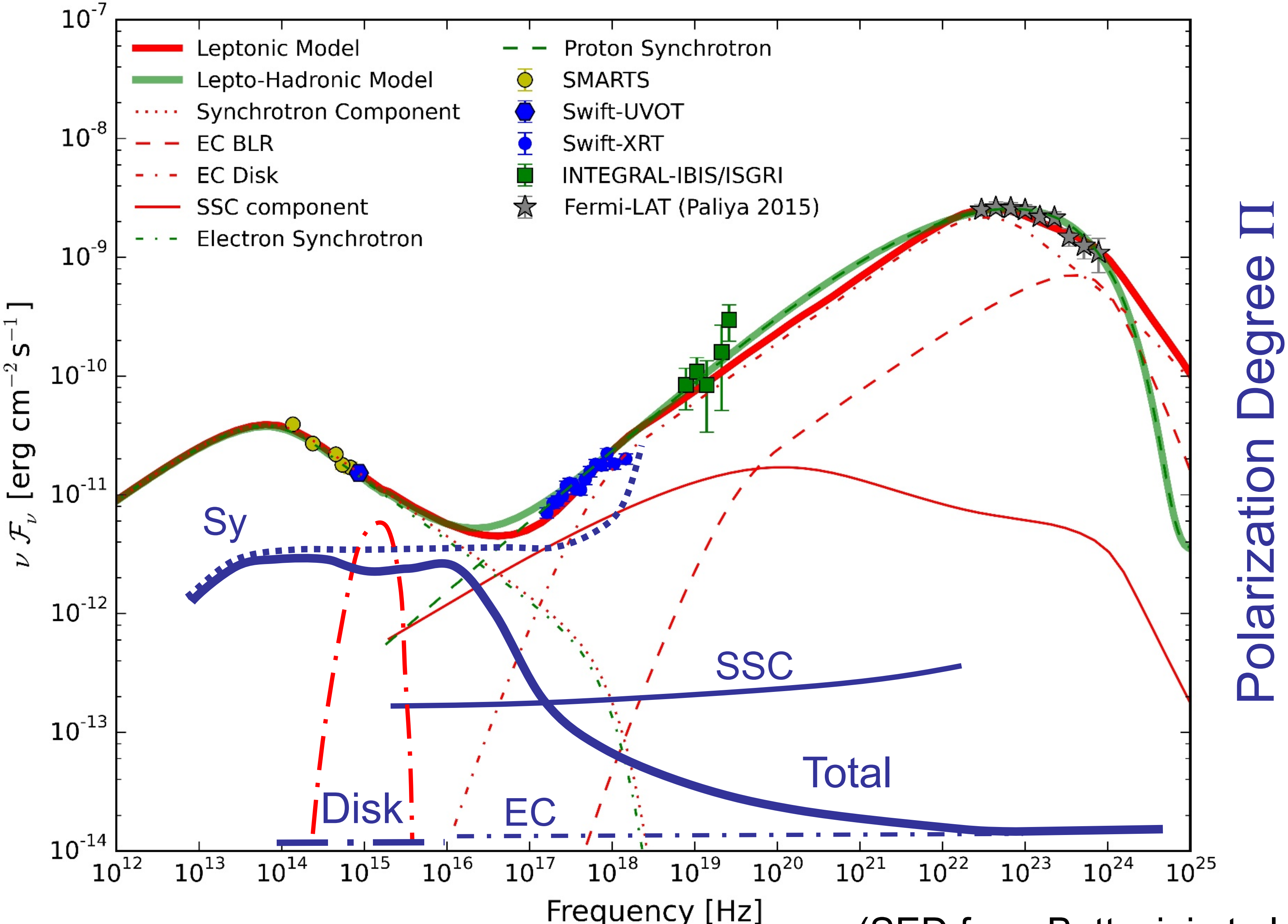


Multiwavelength Polarization of Blazars



MWL Polarization of LSP blazars

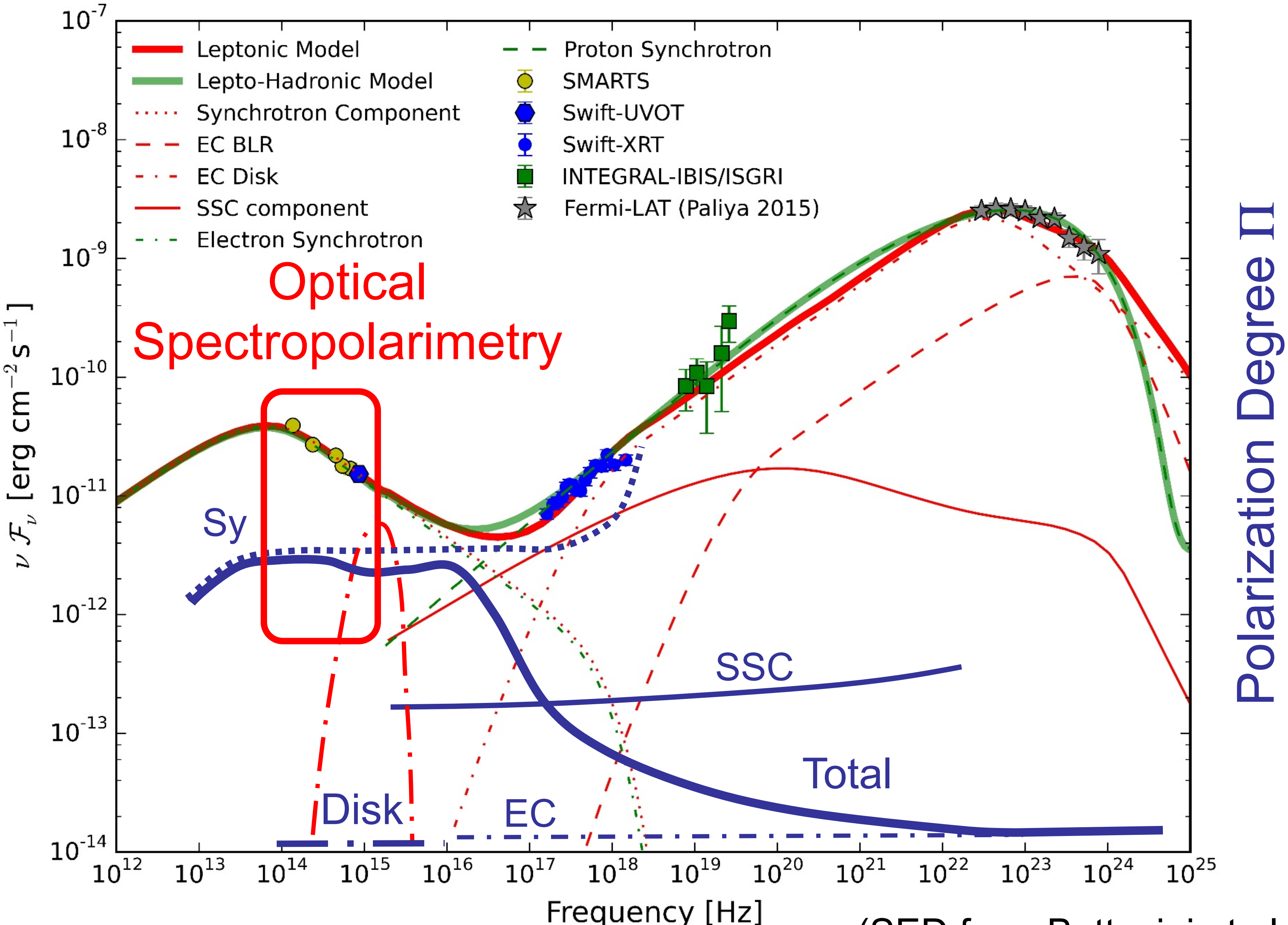
3C279



(SED from Bottacini et al. 2016)

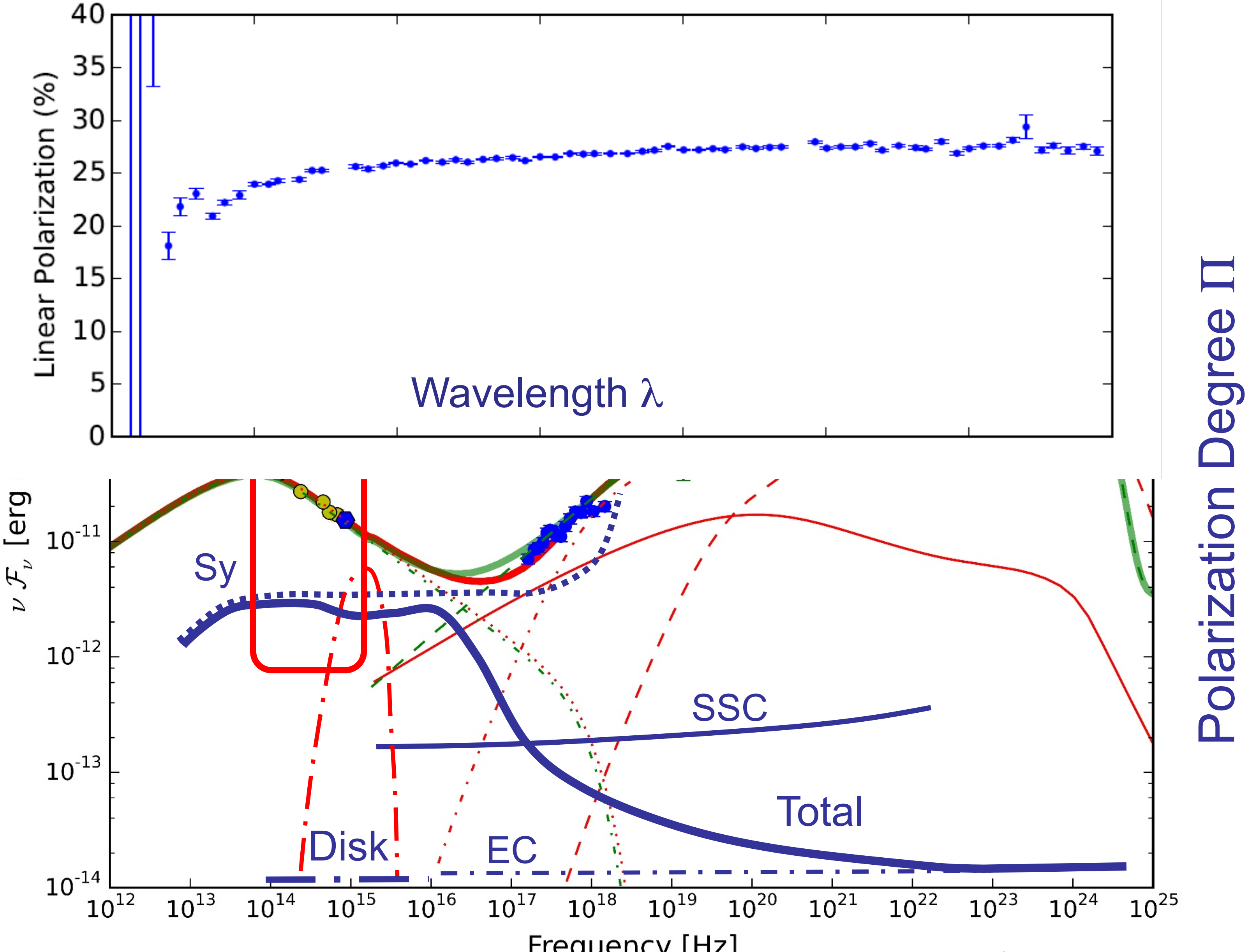
MWL Polarization of LSP blazars

3C279



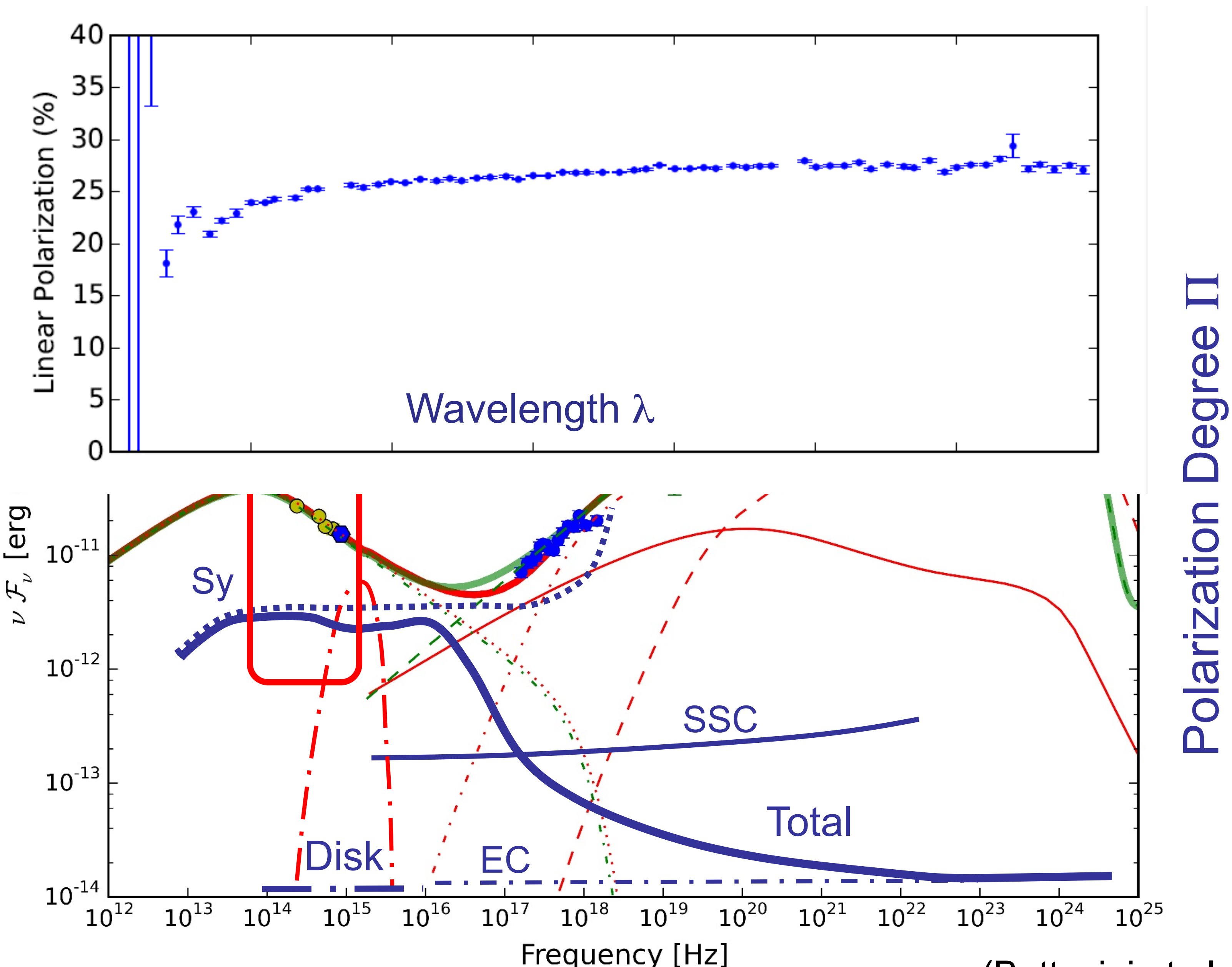
(SED from Bottacini et al. 2016)

Multiwavelength Polarization



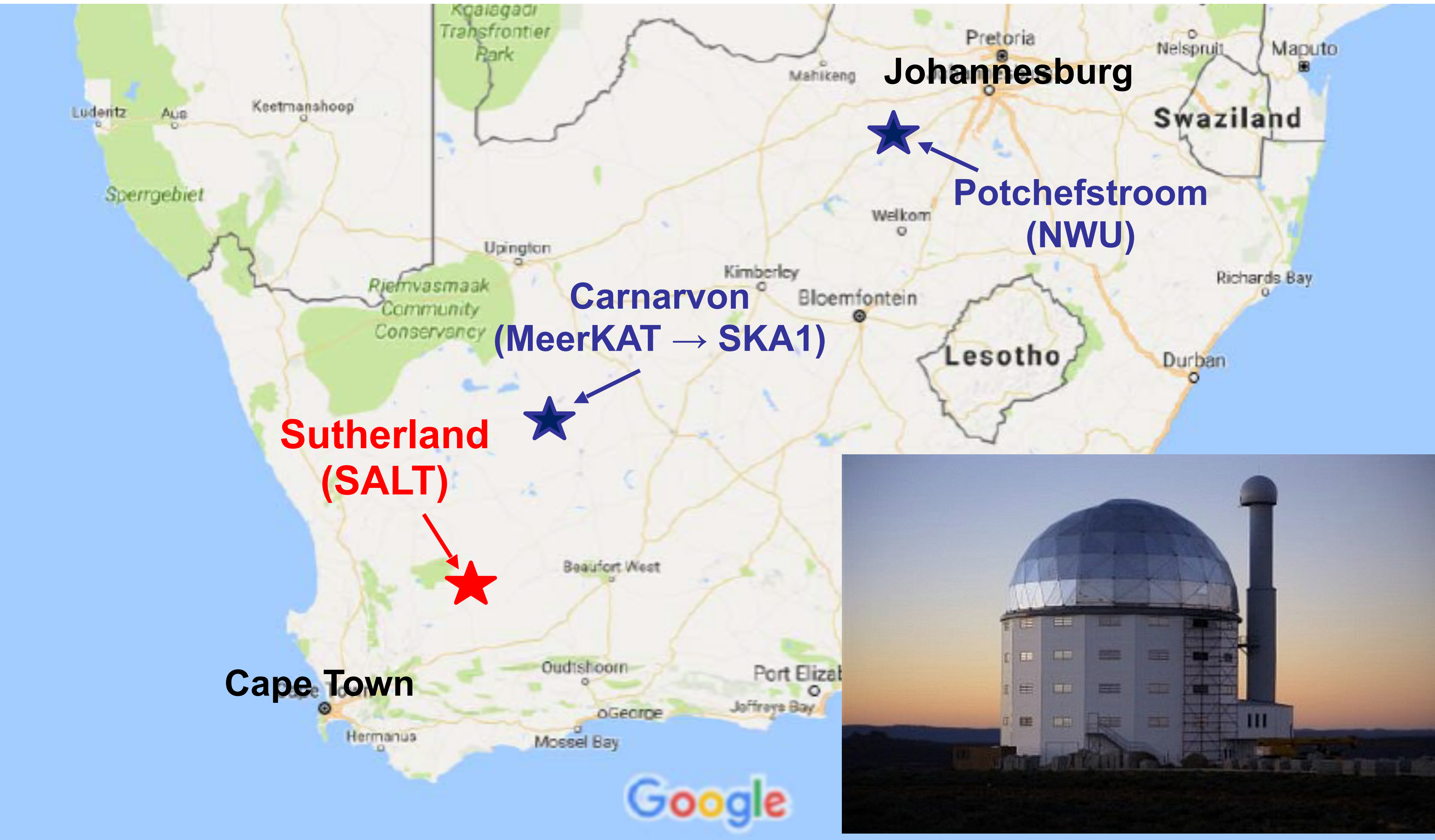
(Bottacini et al. 2016)

Multiwavelength Polarization

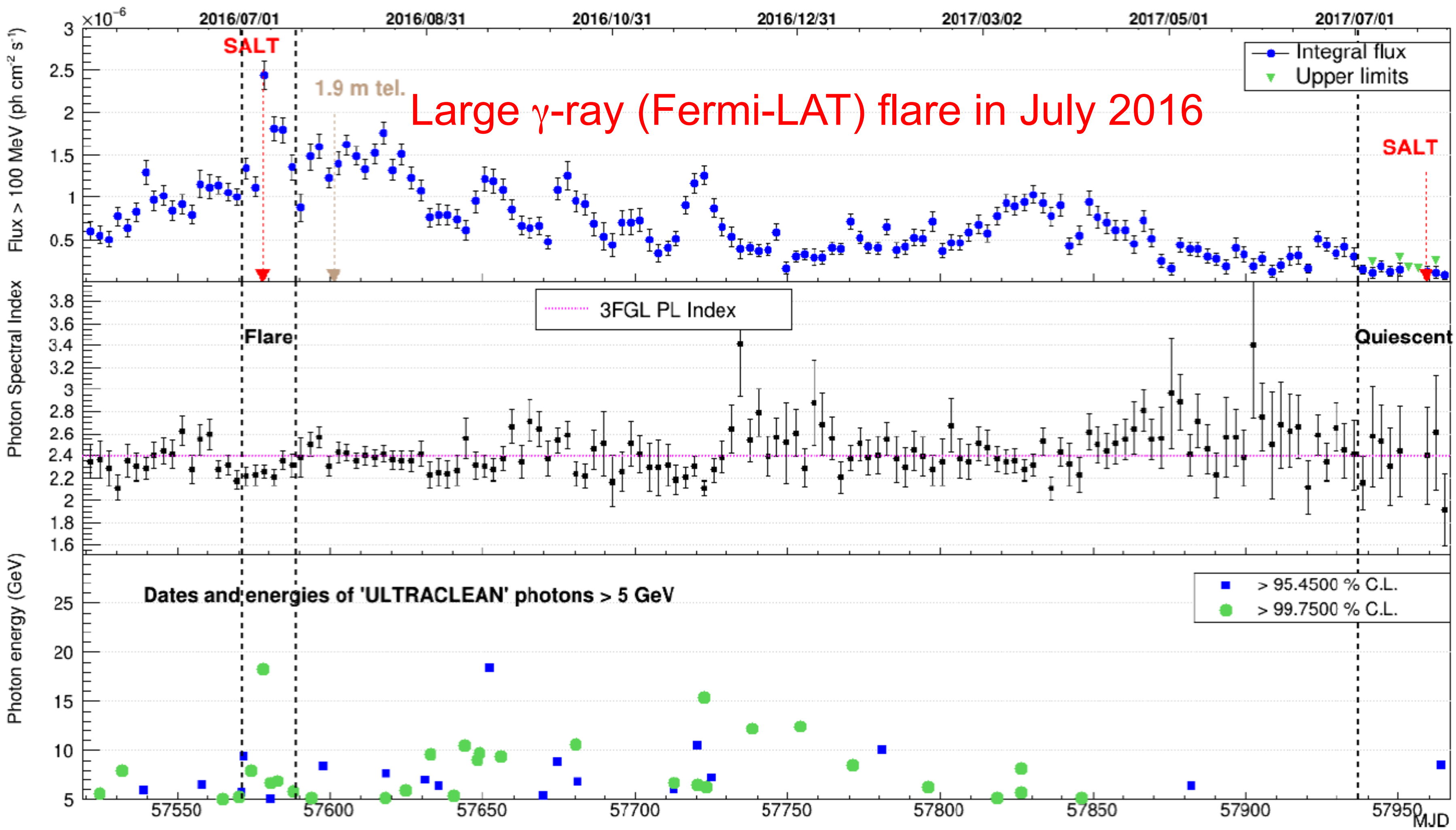


(Bottacini et al. 2016)

The Southern African Large Telescope (SALT)



Example: 4C +01.02 (FSRQ at z = 2.1)

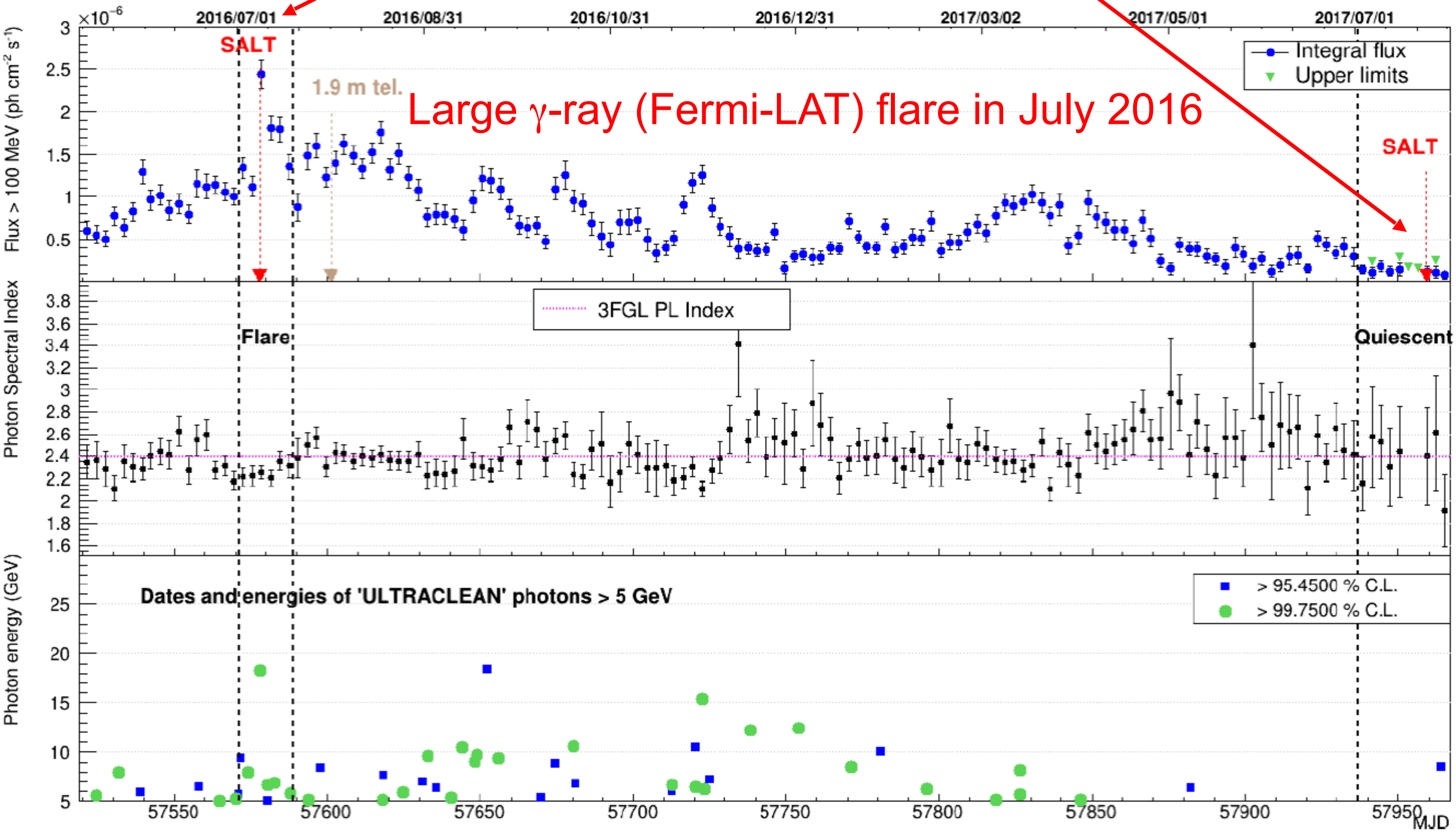


(Schutte et al., in prep.)

Example: 4C +01.02 (FSRQ at z = 2.1)

SALT spectropolarimetry observations in July 2016 (flare) and July 2017 (quiescent)

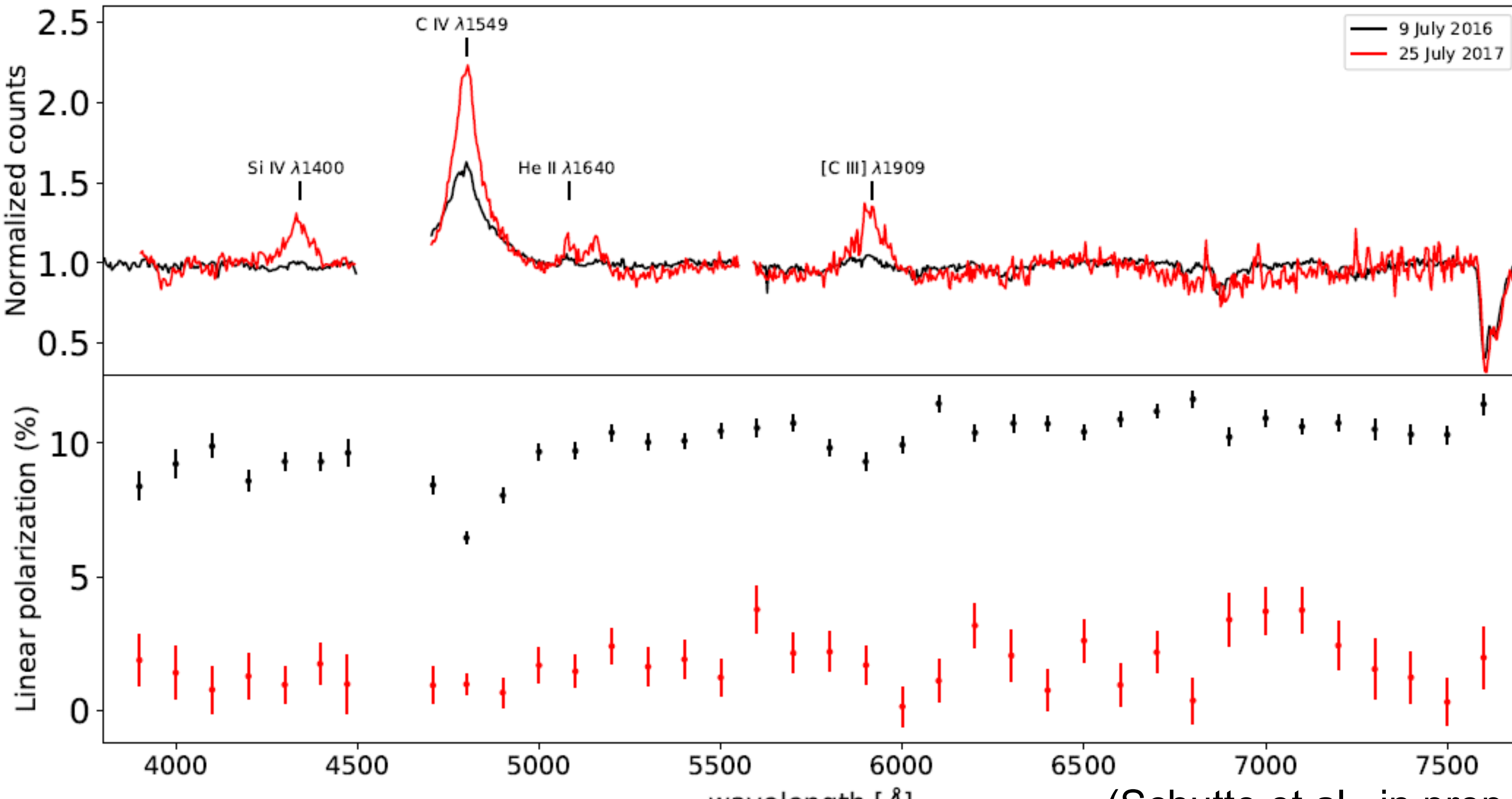
Large γ-ray (Fermi-LAT) flare in July 2016



(Schutte et al., in prep.)

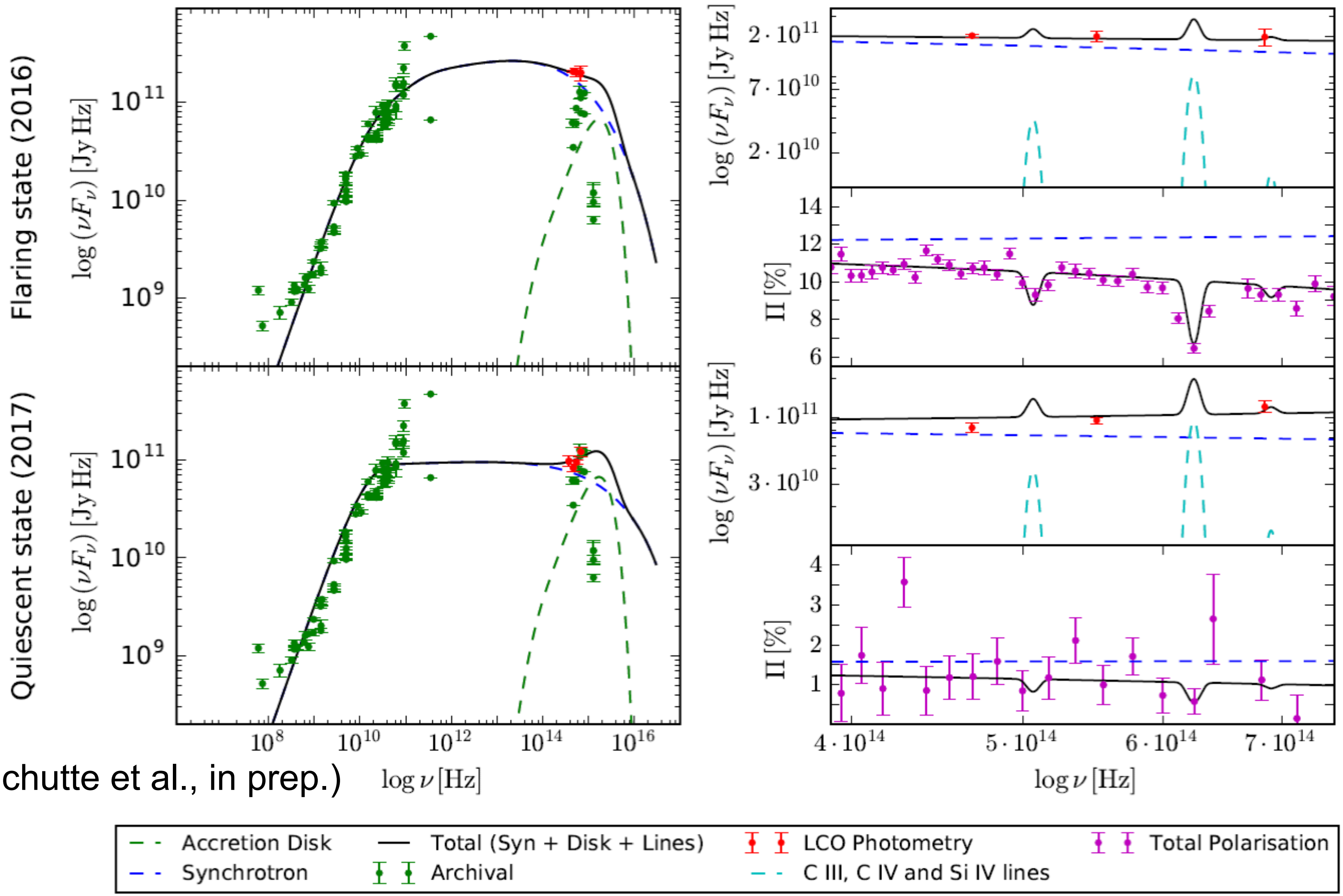
4C +01.02 (PKS B0106+013)

Significant (and time-variable) optical polarization, decreasing towards shorter wavelength => Addition of unpolarized component (accretion disk).



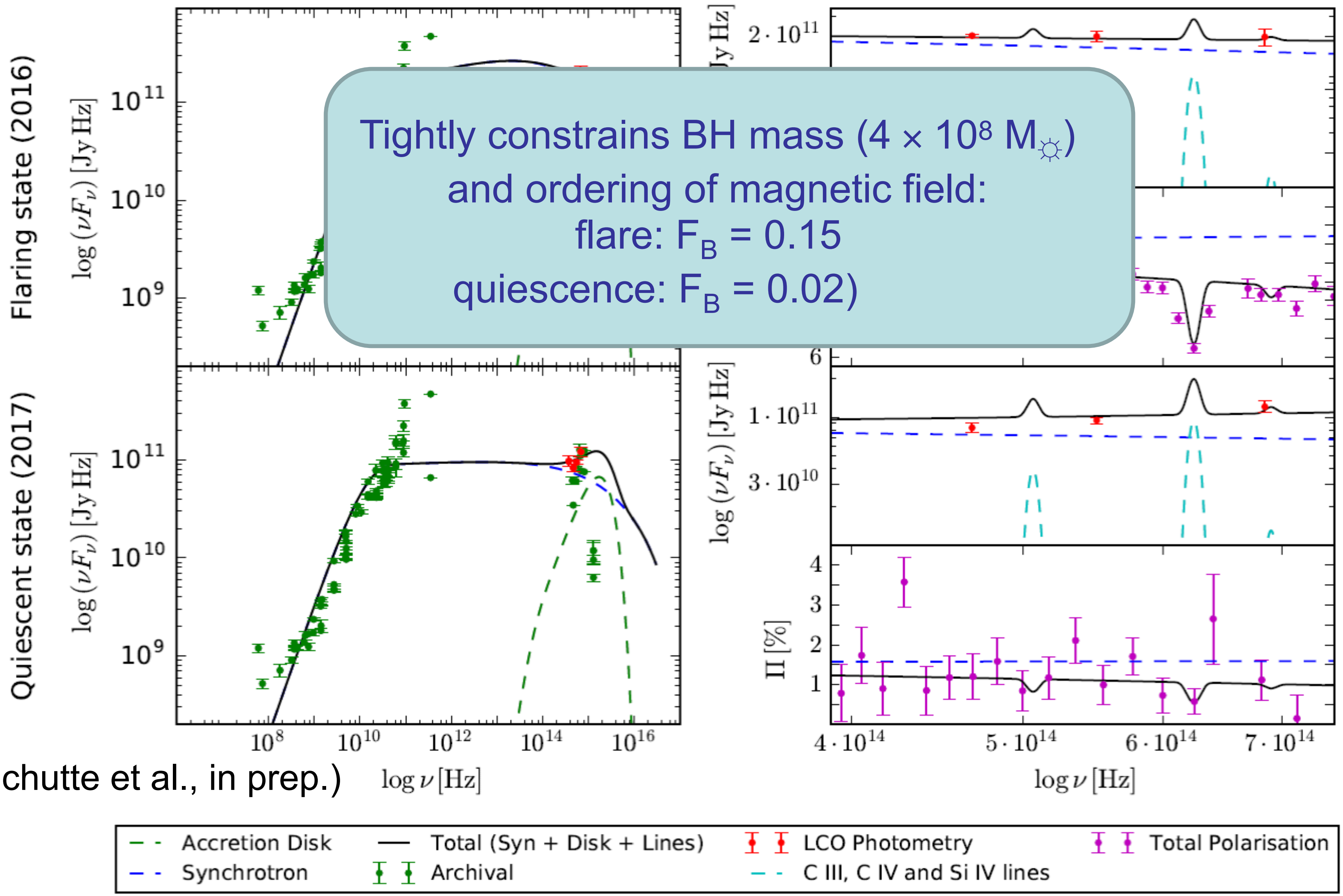
(Schutte et al., in prep.)

4C +01.02: Combined SED + spectropolarimetry modeling



(Schutte et al., in prep.)

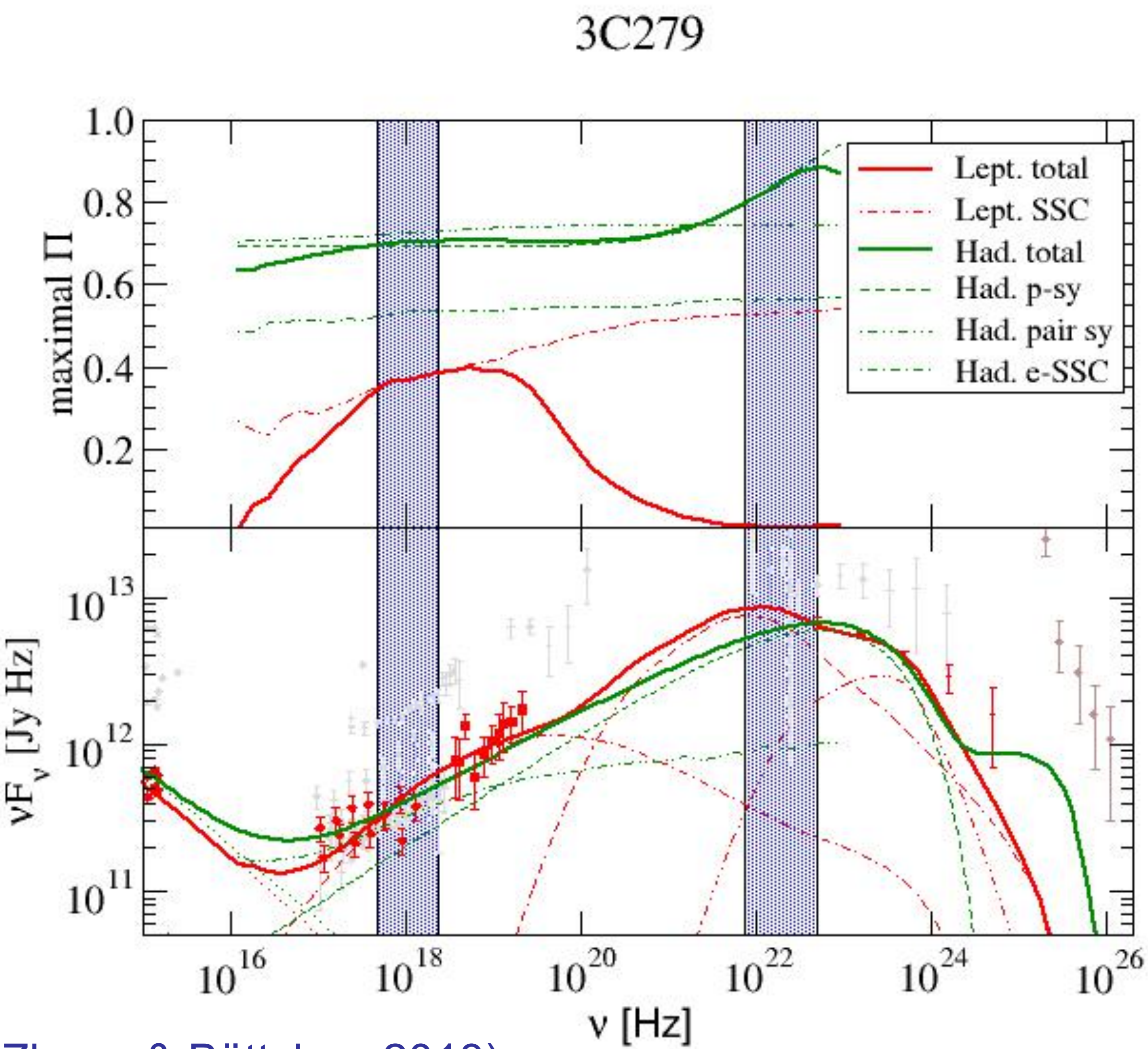
4C +01.02: Combined SED + spectropolarimetry modeling



Tightly constrains BH mass (4×10^8 $M_\odot$)
and ordering of magnetic field:
flare: $F_B = 0.15$
quiescence: $F_B = 0.02$)

(Schutte et al., in prep.)

X-Ray and Gamma-Ray Polarization: LSP Blazars

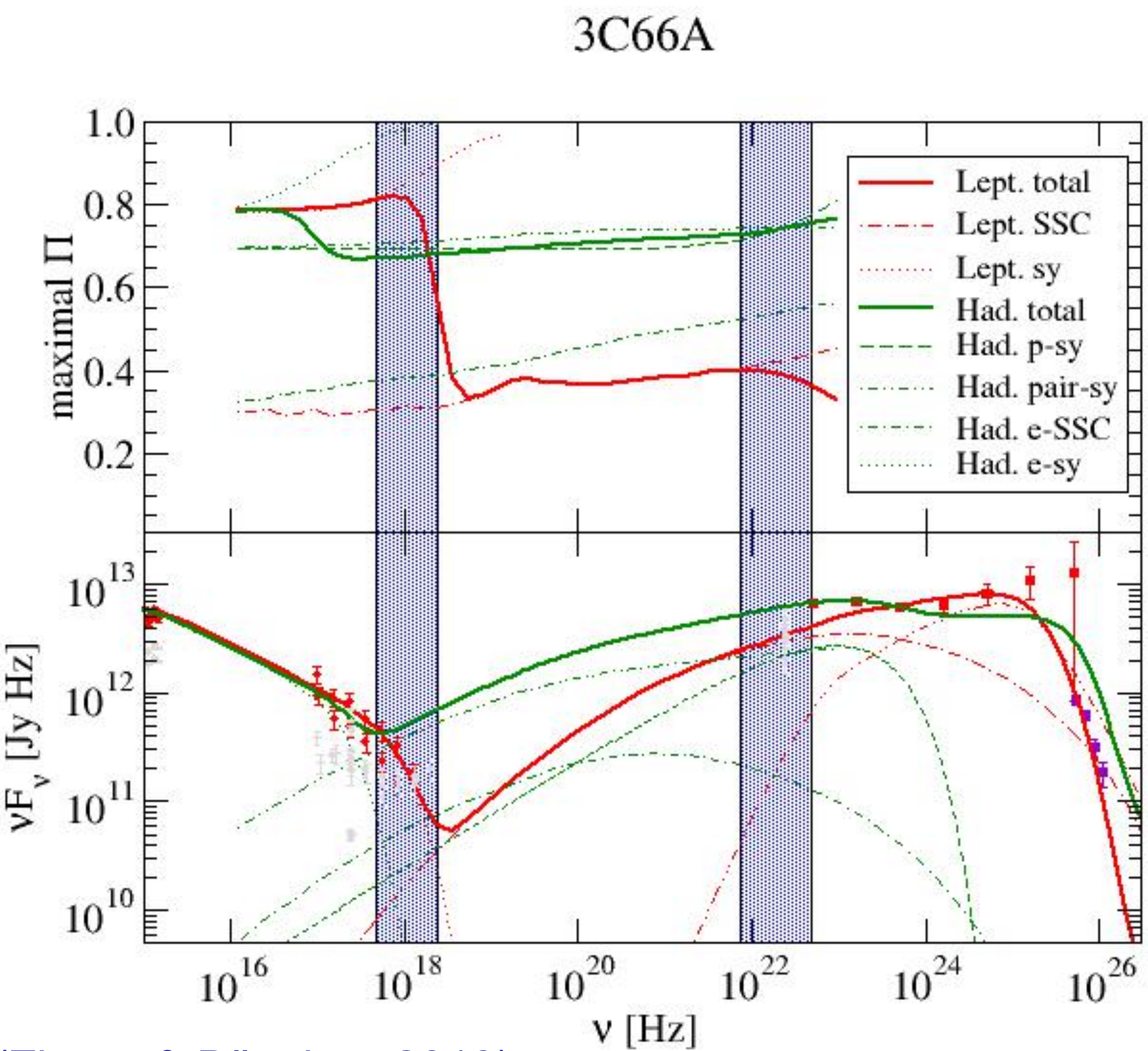


Hadronic model:
Synchrotron dominated
=> High Π, generally increasing with energy (SSC contrib. in X-rays).

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

(Zhang & Böttcher, 2013)

X-Ray and Gamma-Ray Polarization: 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.

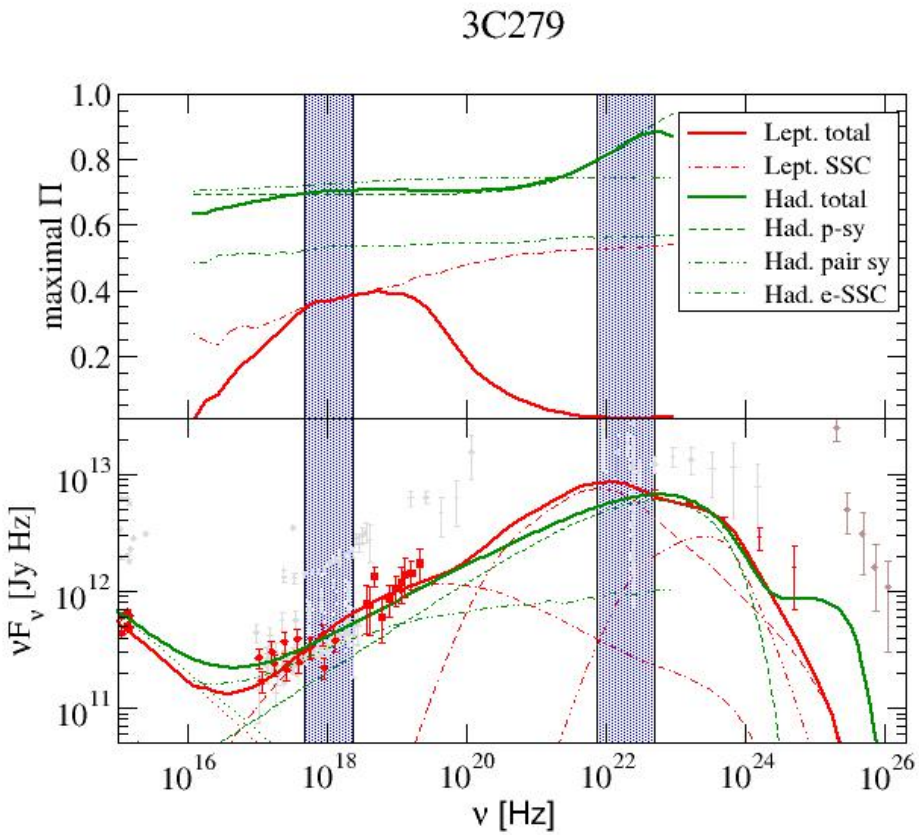
(Zhang & Böttcher, 2013)

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!

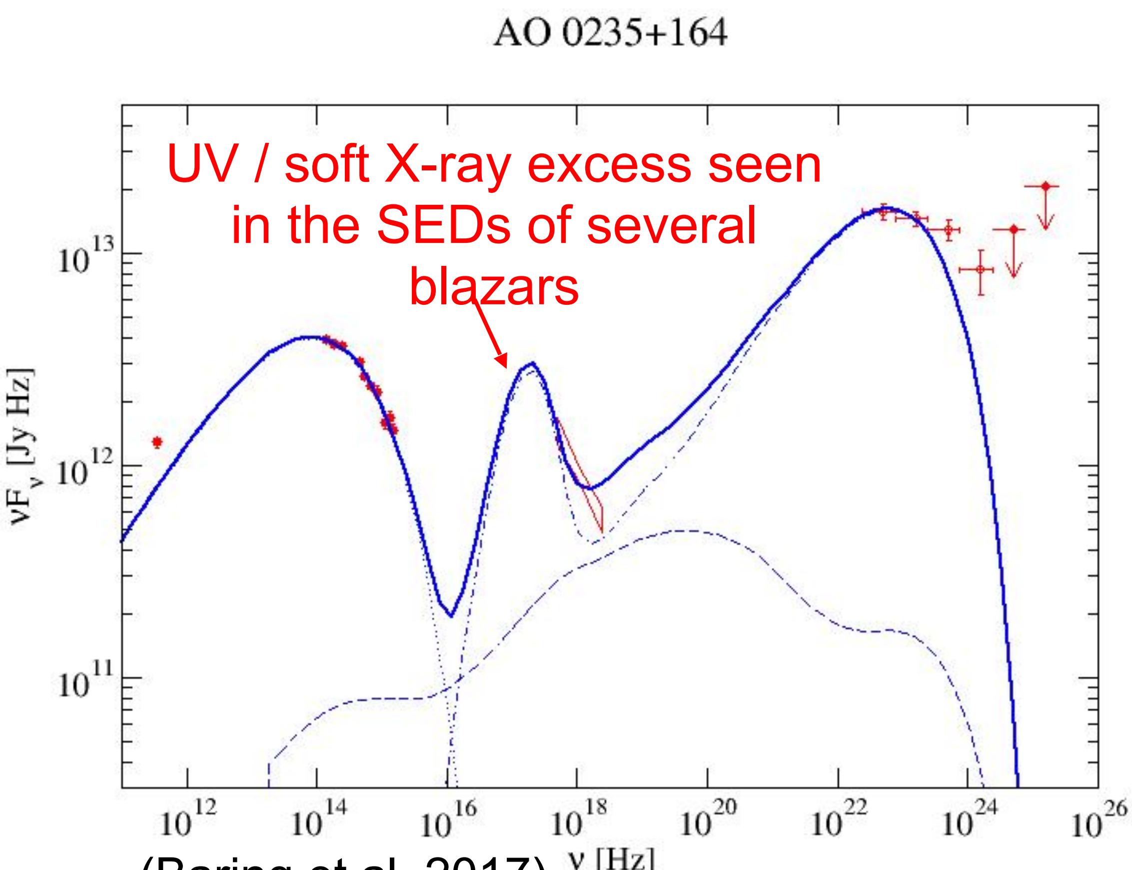
- X-ray and γ-ray polarization values substantially below synchrotron polarization will favor leptonic models, measurable γ-ray polarization clearly favors hadronic models!



(Zhang & Böttcher, 2013)

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**



(Baring et al. 2017)

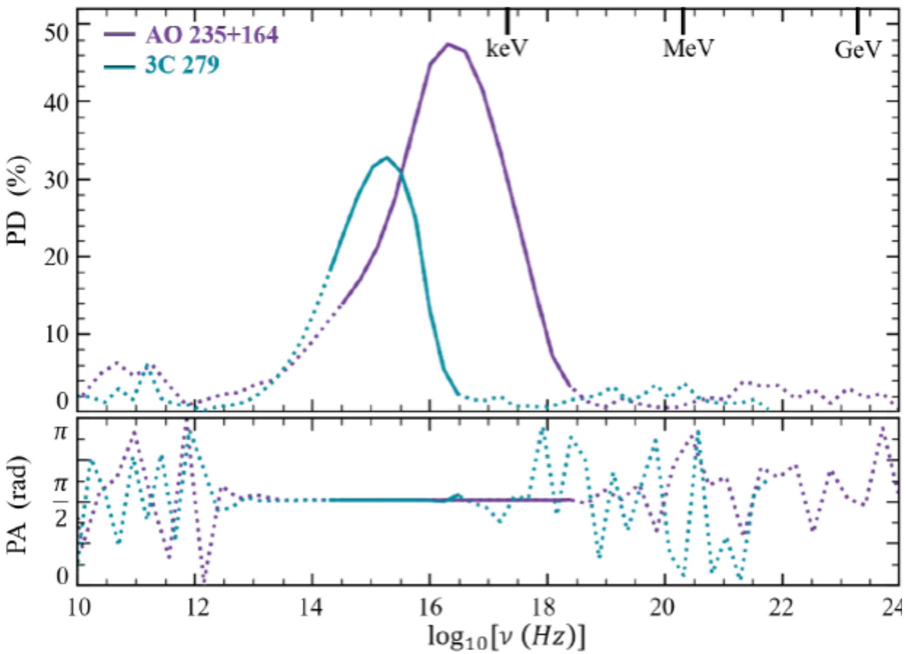
Baring et al. (2017): Monte-Carlo simulations of Diffusive Shock Acceleration

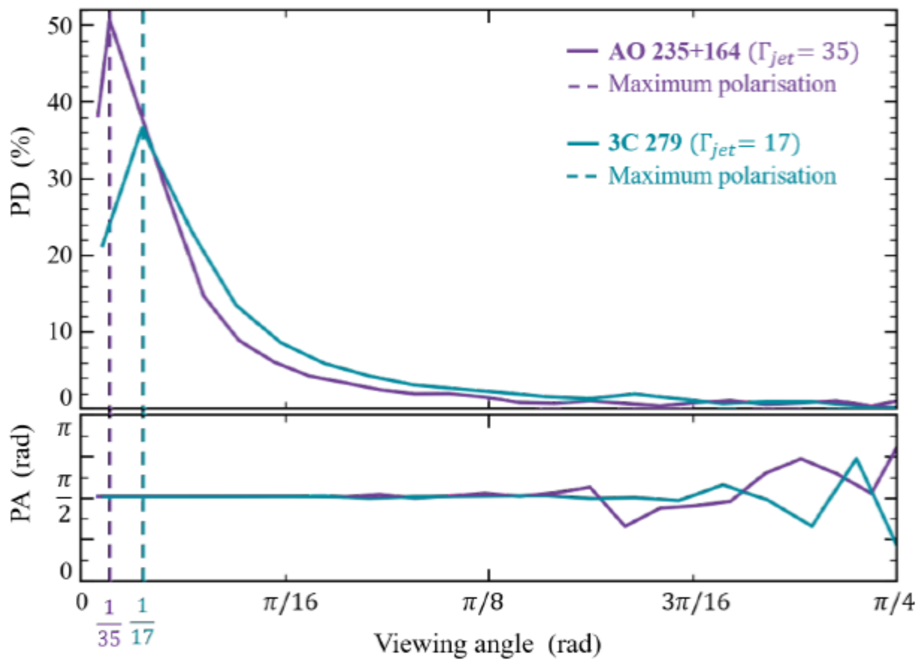
→ Modeling of the soft X-ray excess as bulk Comptonization of IR radiation from dusty torus by shock-heated, thermal electrons tightly constrains thermal vs. non-thermal particle populations

→ Tight constraints on pitch-angle diffusion and plasma parameters

Simulating Polarization of the Bulk Compton Feature

- Using a newly developed polarization-dependent Compton scattering Monte-Carlo code (MAPPIES – Dreyer & Böttcher 2020a, ApJ, in press)
- If due to bulk Compton, the soft X-ray excess in AO 0235+164 could be polarized up to ~ 50 % in soft X-rays (if viewing angle ~ 1/Γ).





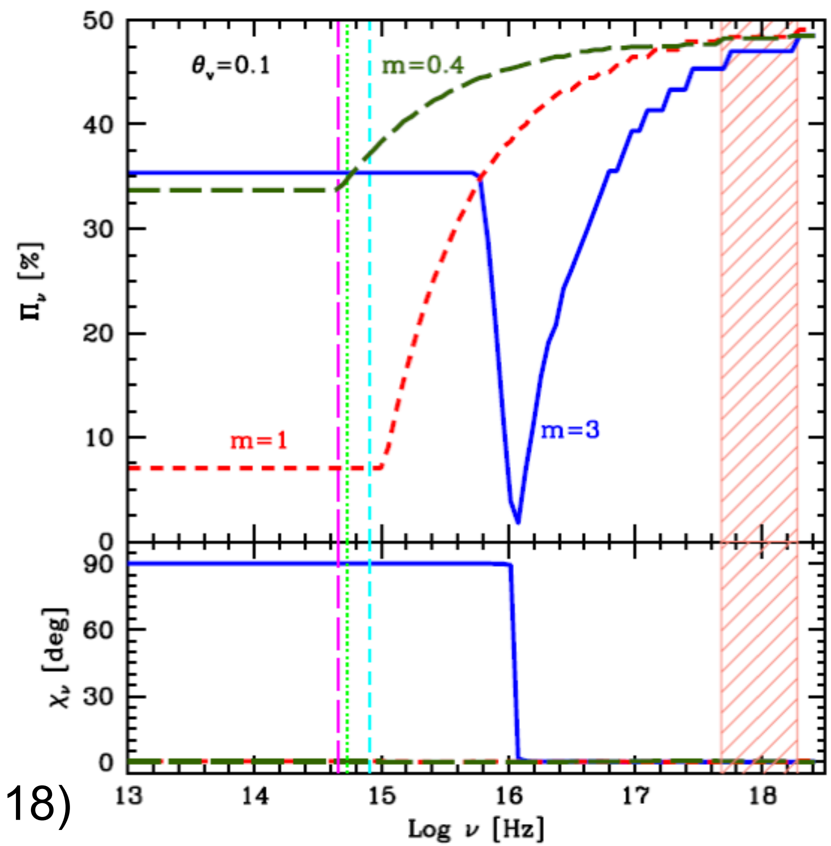
Dreyer & Böttcher 2020b, ApJ, submitted

X-Ray and Gamma-Ray Polarization: HBLs

In both leptonic and hadronic models, optical and X-ray emission are dominated by jet synchrotron.

X-ray polarimetry may reveal mode of particle acceleration:

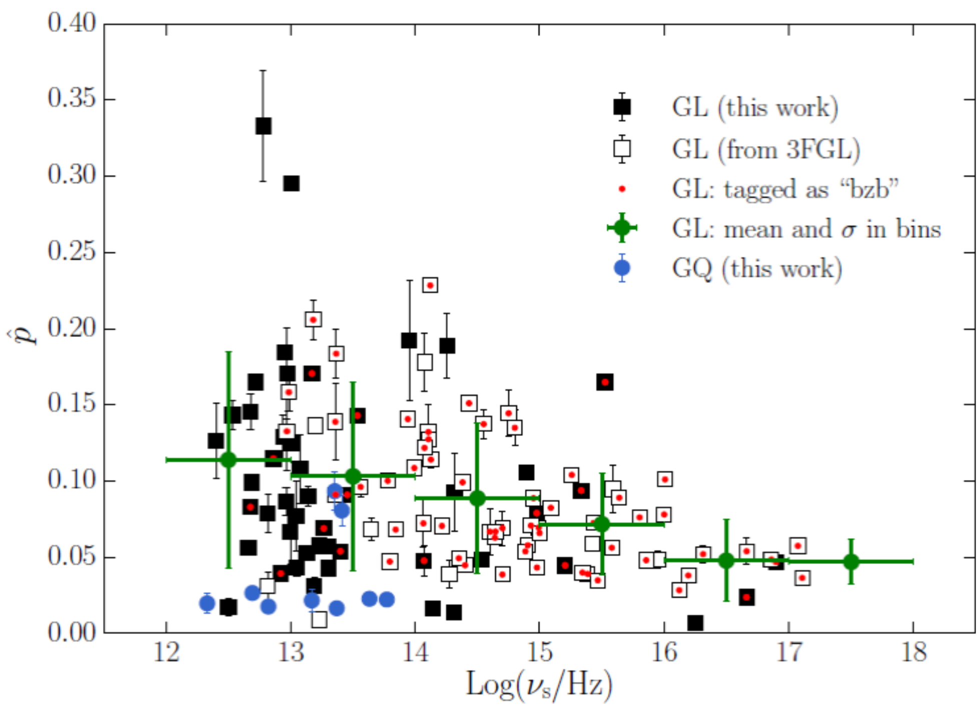
- Magnetic reconnection: Acceleration in turbulent regions → Low PD
- Shocks: Significant (up to 50 %) X-ray polarization; likely higher PD in X-rays than in the optical (smaller emission region?)



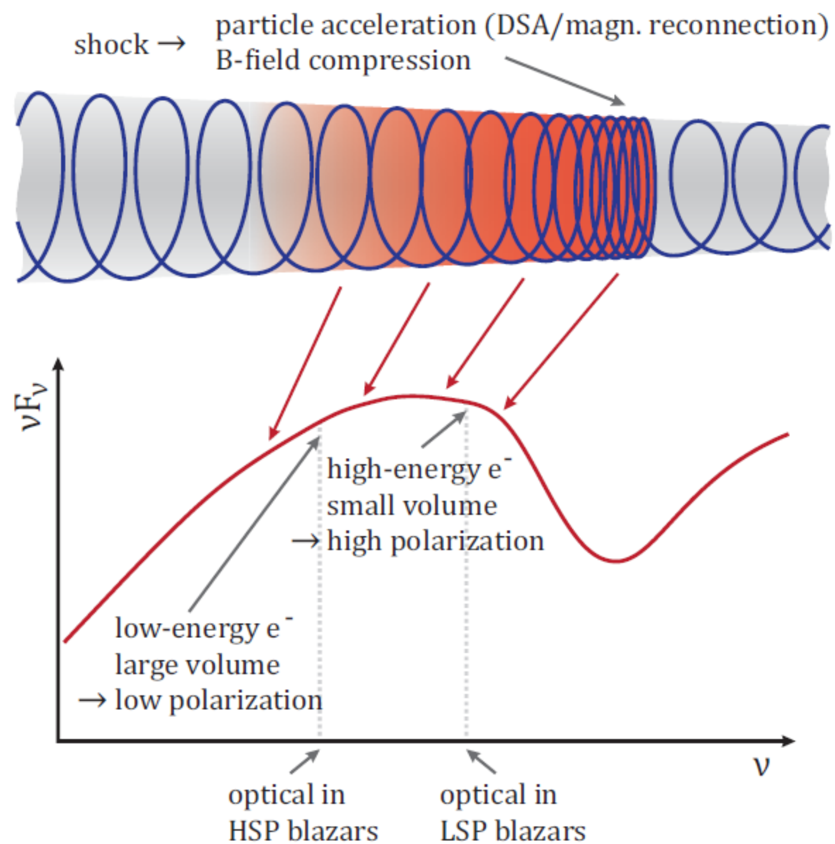
(Tavecchio et al. 2018)

X-Ray and Gamma-Ray Polarization: HBLs

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



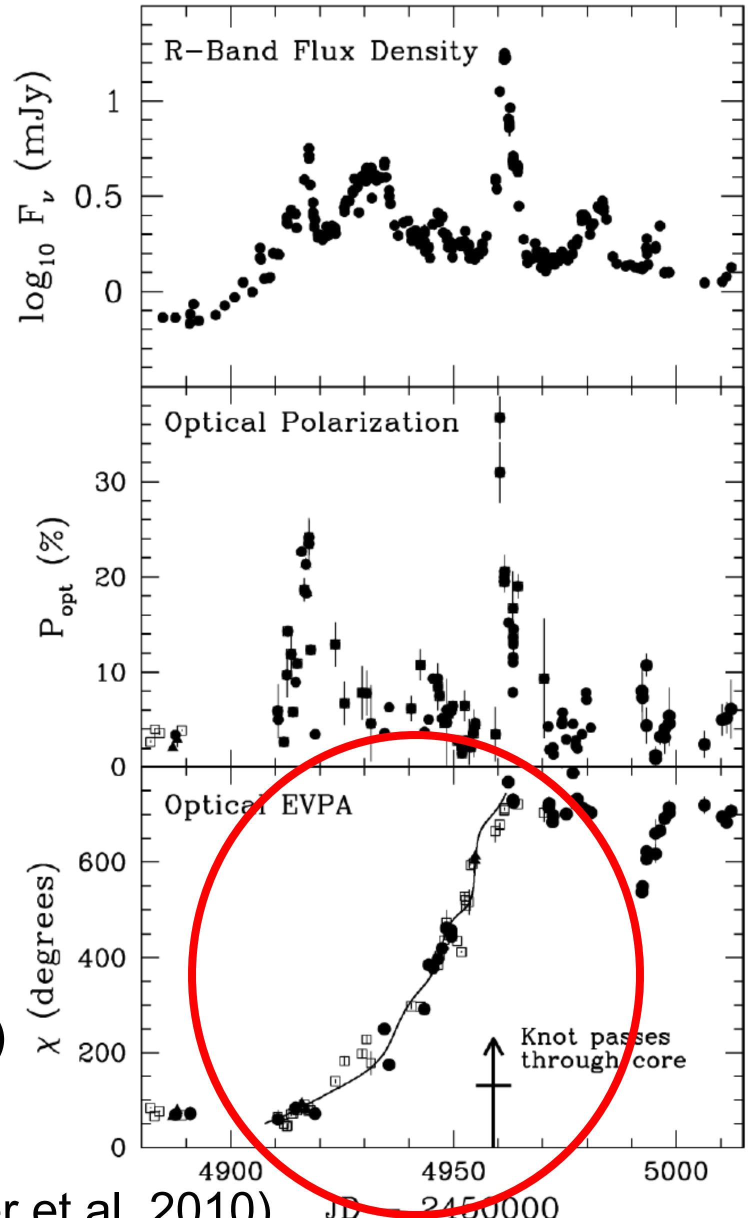
(Angelakis et al. 2016 – ROBOPOL)



Caution: PA Swings

- Sometimes Optical / γ–ray flares are correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)
- Duration typically several days
- X-ray polarimetry observations of faint sources may require day-long observations → Polarization measurement smeared out / destroyed!
- Models proposed for PA swings:
  - Helical jet/pattern motion
  - Turbulent cells → Stochastic PA variations (TEMZ)
  - Kink instabilities
  - Helical B-fields in internal shocks

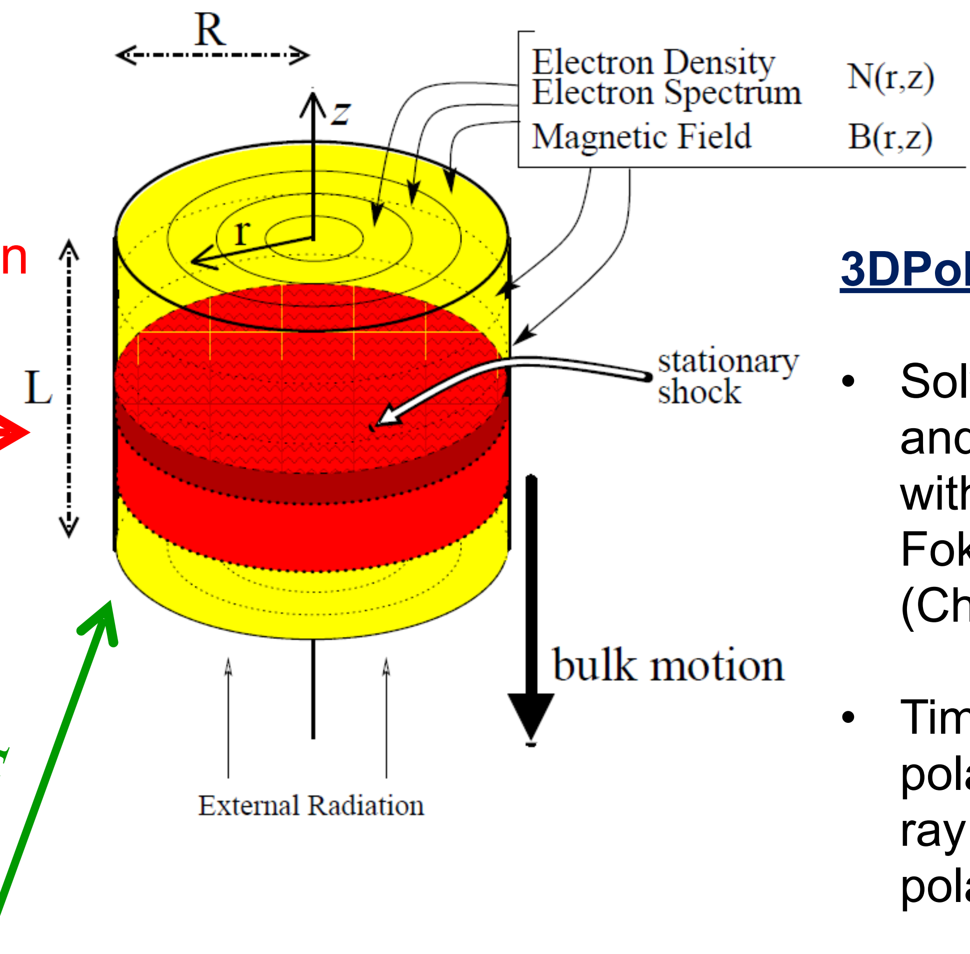
(see Böttcher 2019 for a review and refs.)



PKS 1510-089 (Marscher et al. 2010)

Tracing Synchrotron Polarization in the Internal Shock Model

Viewing direction in comoving frame: $\theta_{obs} \sim \pi/2$

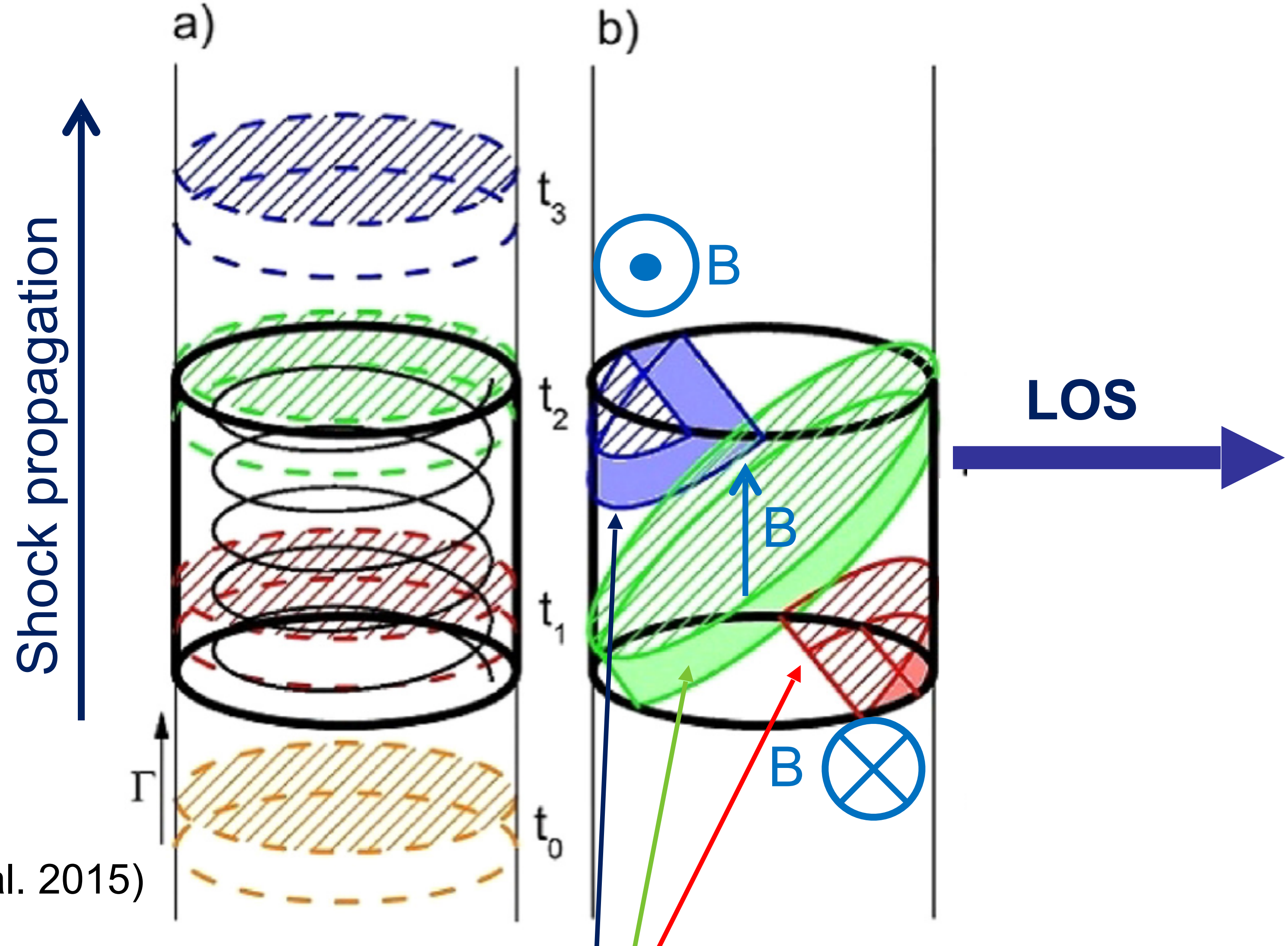


Viewing direction in obs. Frame: $\theta_{obs} \sim 1/\Gamma$

3DPol (Zhang et al. 2014)

- Solve electron dynamics and 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



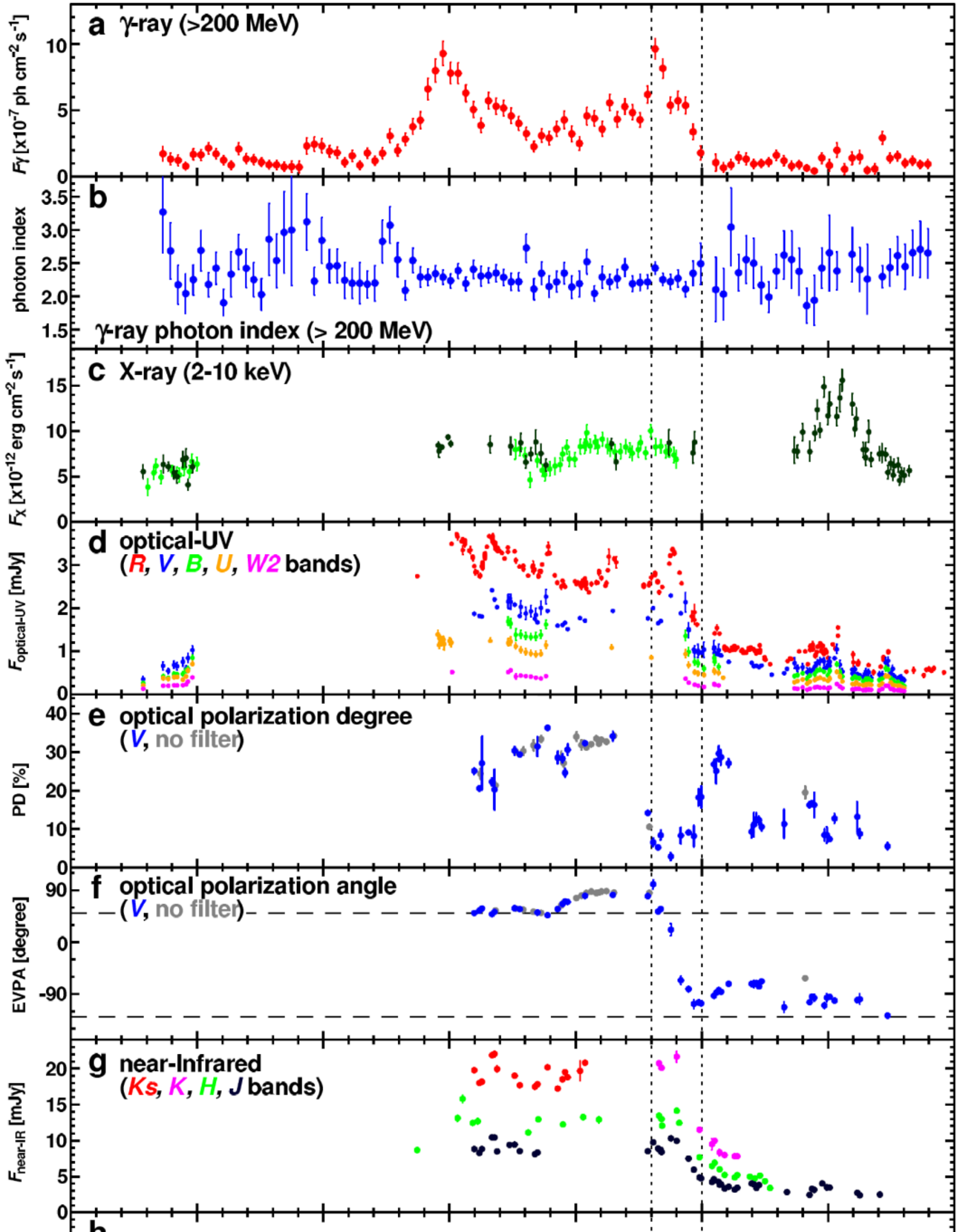
(Zhang et al. 2015)

Shock positions at equal photon-arrival times at the observer

Application to the FSRQ 3C279

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

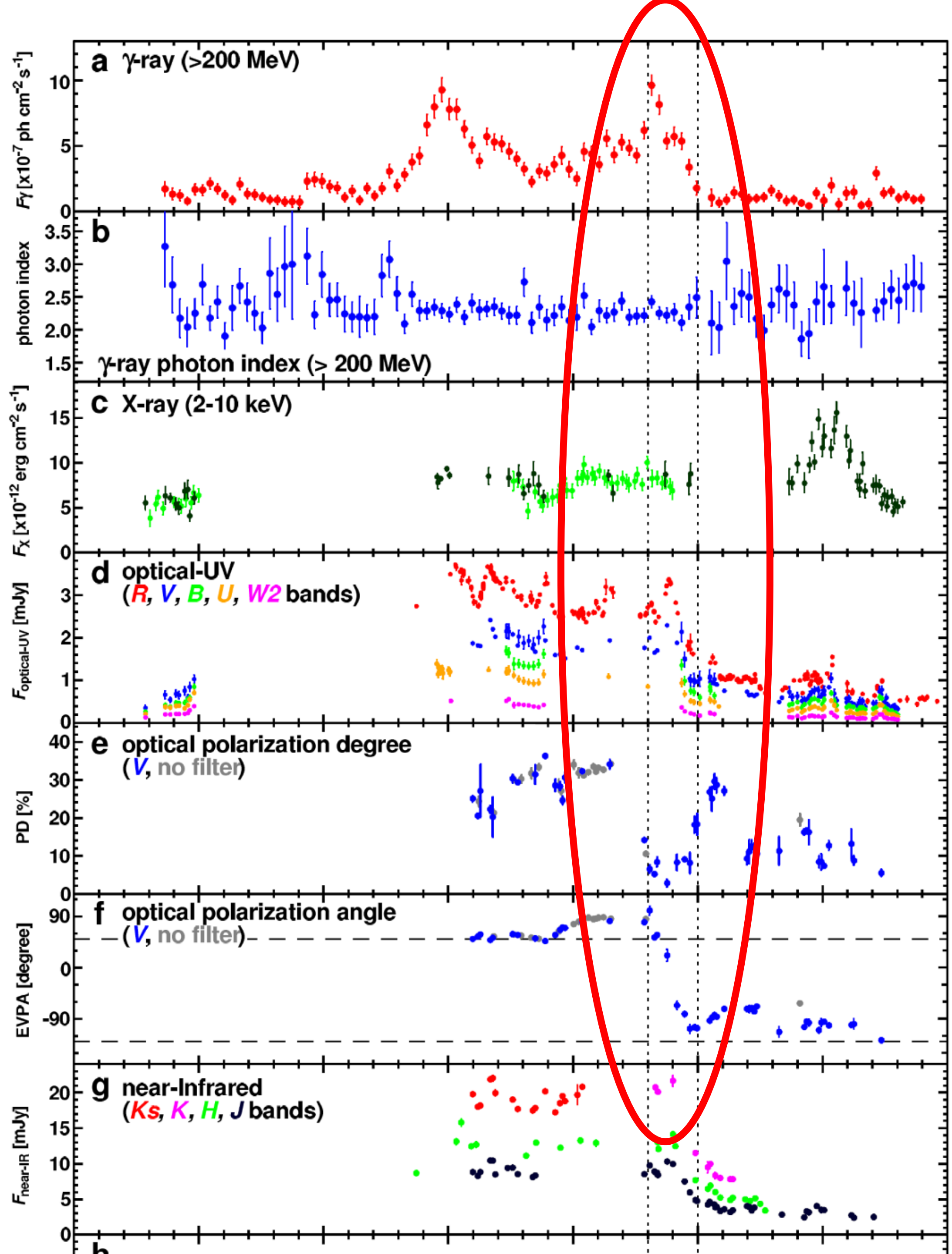
(Abdo et al. 2010)



Application to the FSRQ 3C279

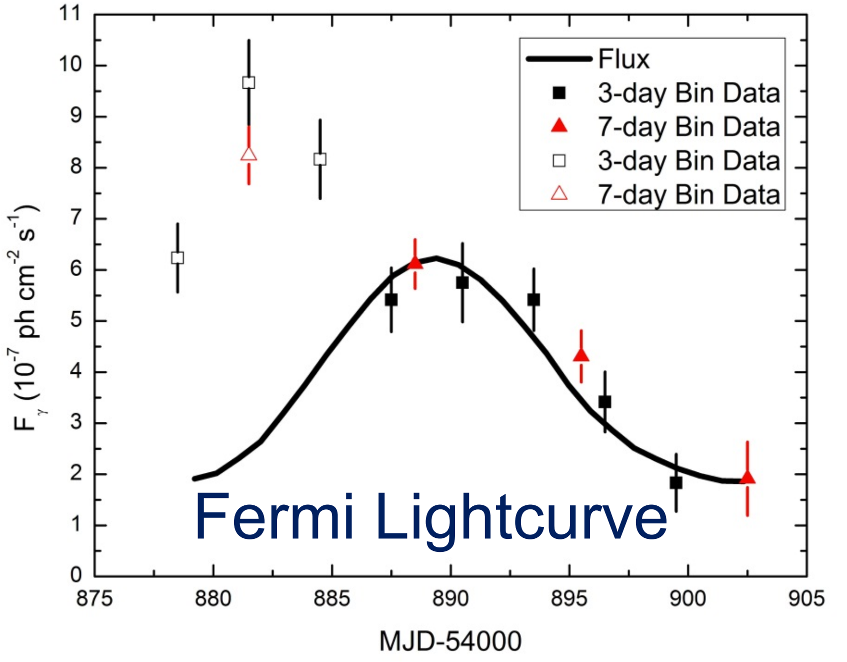
Simultaneous optical + γ-ray flare, correlated with a 180° polarization-angle rotation .

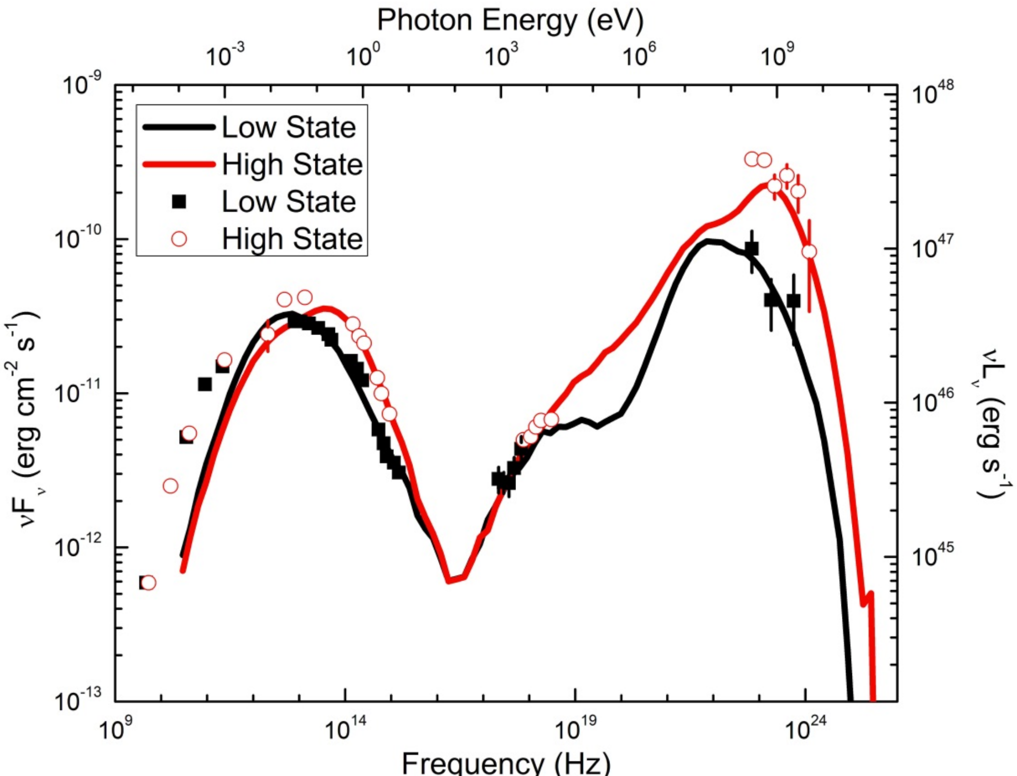
(Abdo et al. 2010)

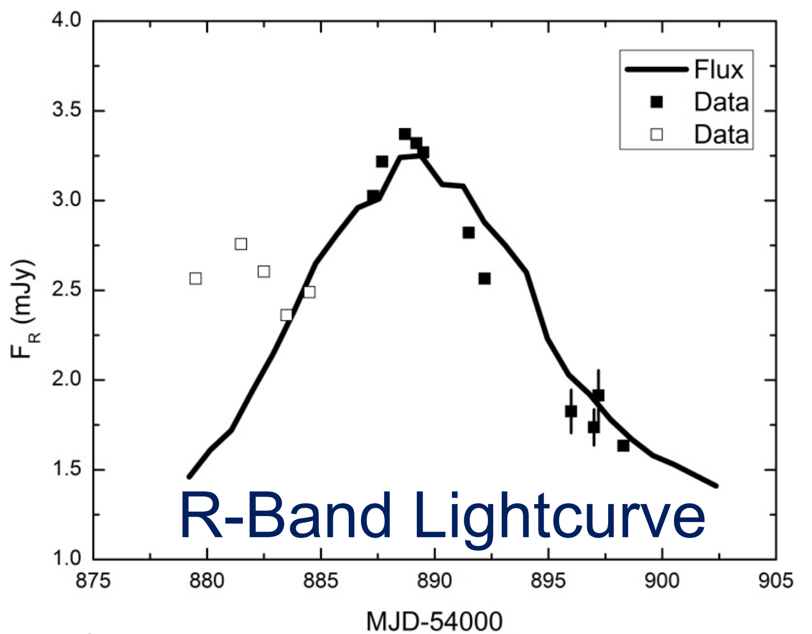


Application to 3C279

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



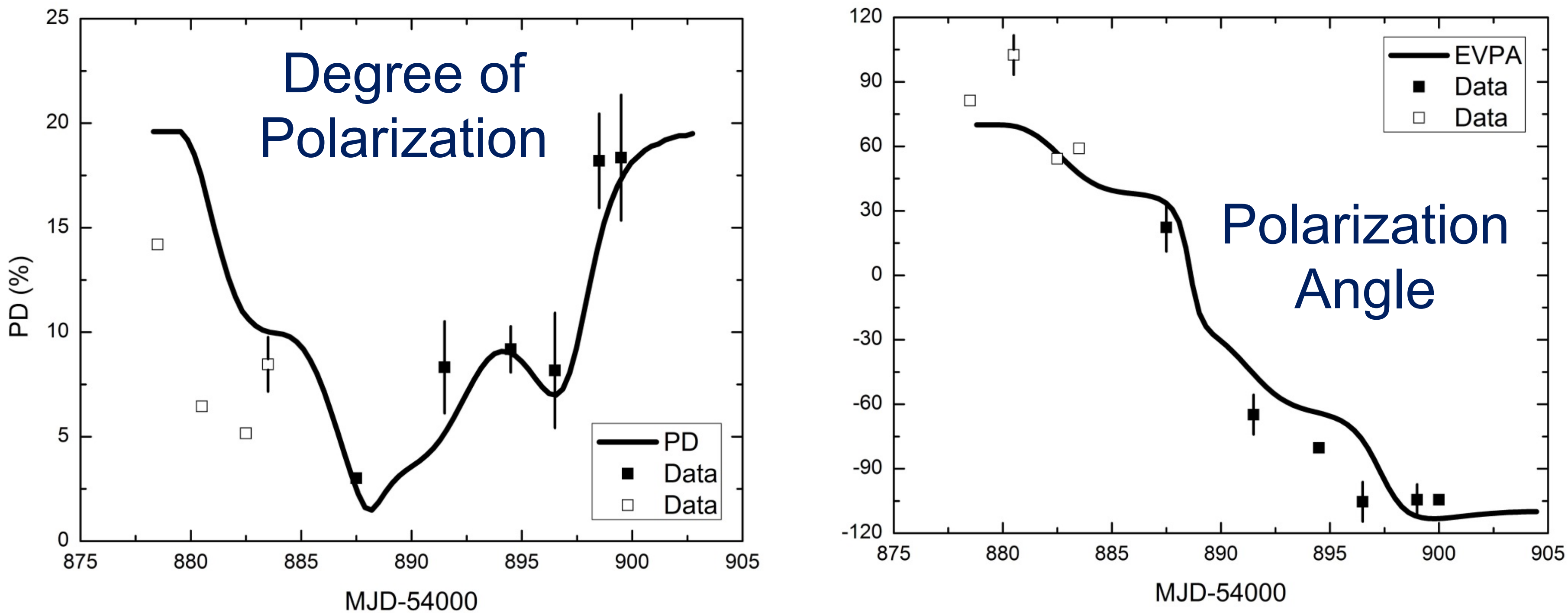




(Zhang et al. 2015)

Application to 3C279

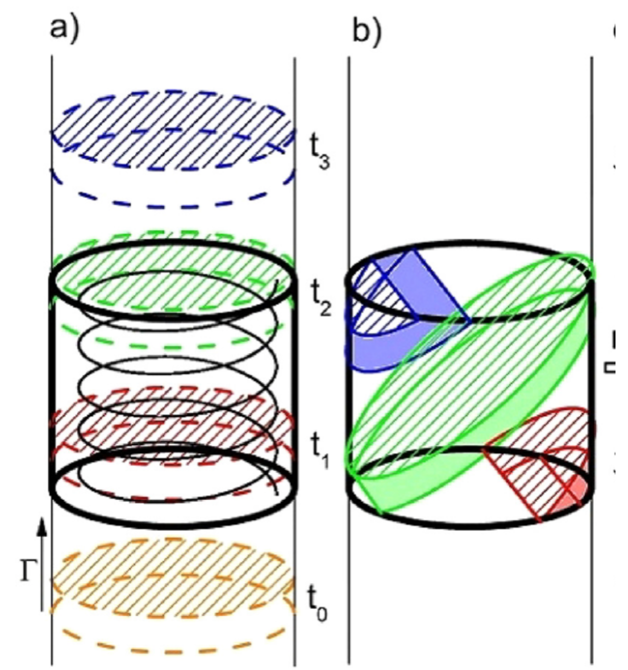
Requires particle acceleration
and reduction of magnetic field,
as expected in magnetic reconnection!



(Zhang et al. 2015)

The Lepto-Hadronic Version

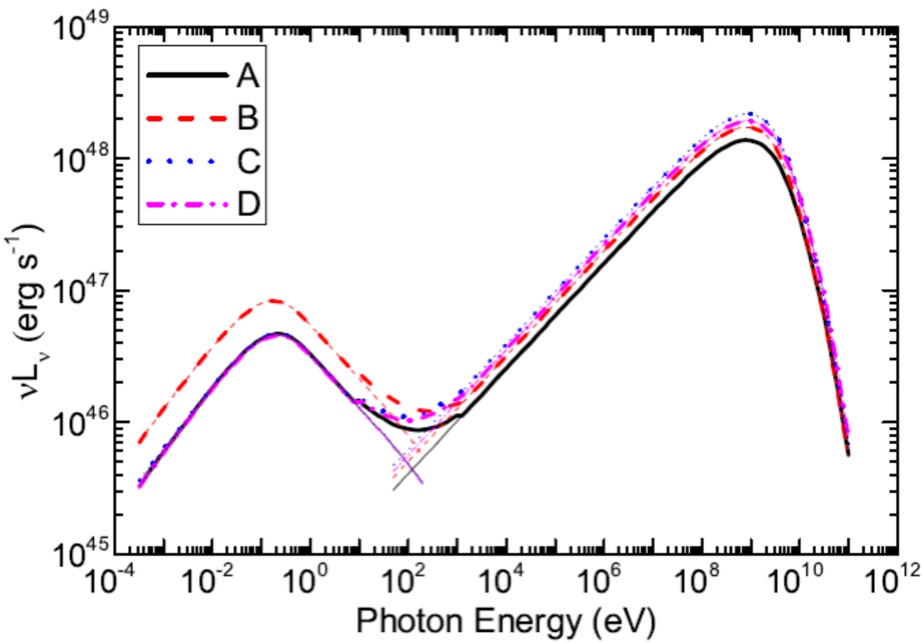
- Lepto-hadronic (p-synchrotron dominated) 3D time- and polarization-dependent internal shock model (Zhang, Diltz & Böttcher 2016)
- Model setup as for leptonic (3DPol) model, but include injection of ultrarelativistic protons
- Electron + proton evolution with locally isotropic Fokker-Planck equation
- Fully time- and polarization-dependent ray tracing

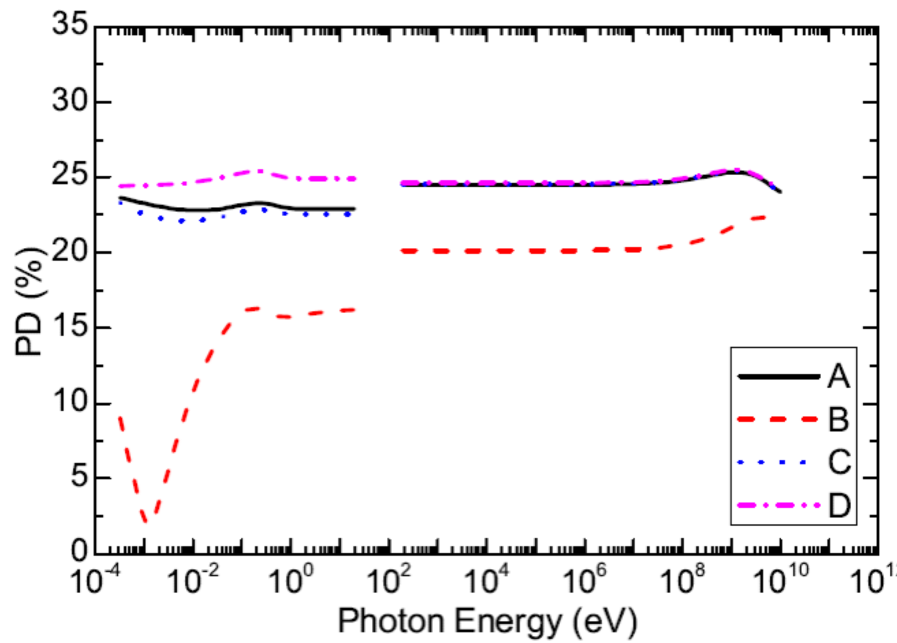


3D Lepto-Hadronic Internal Shock model

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

(Zhang et al. 2016)

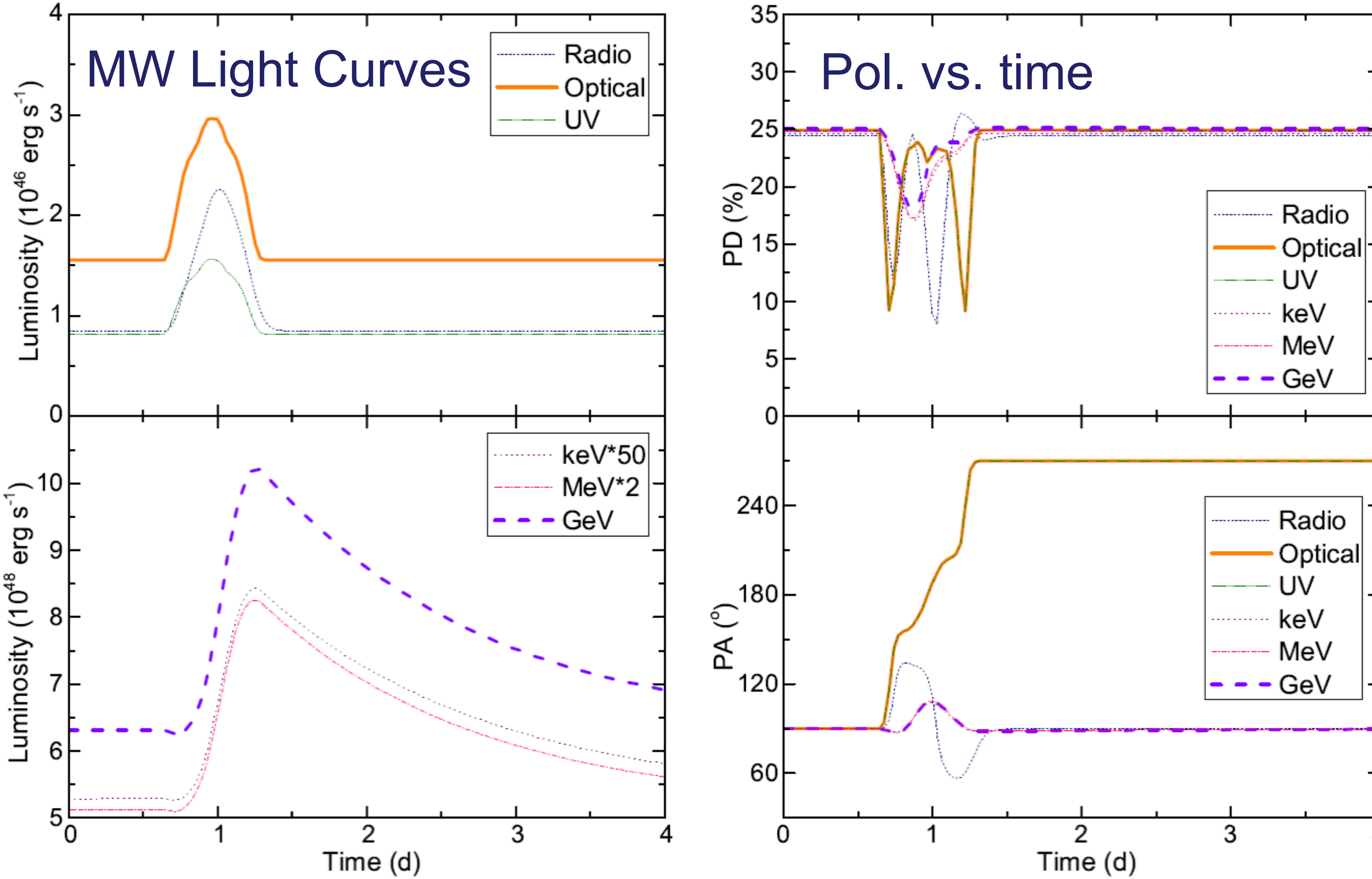




Snap-Shot SEDs

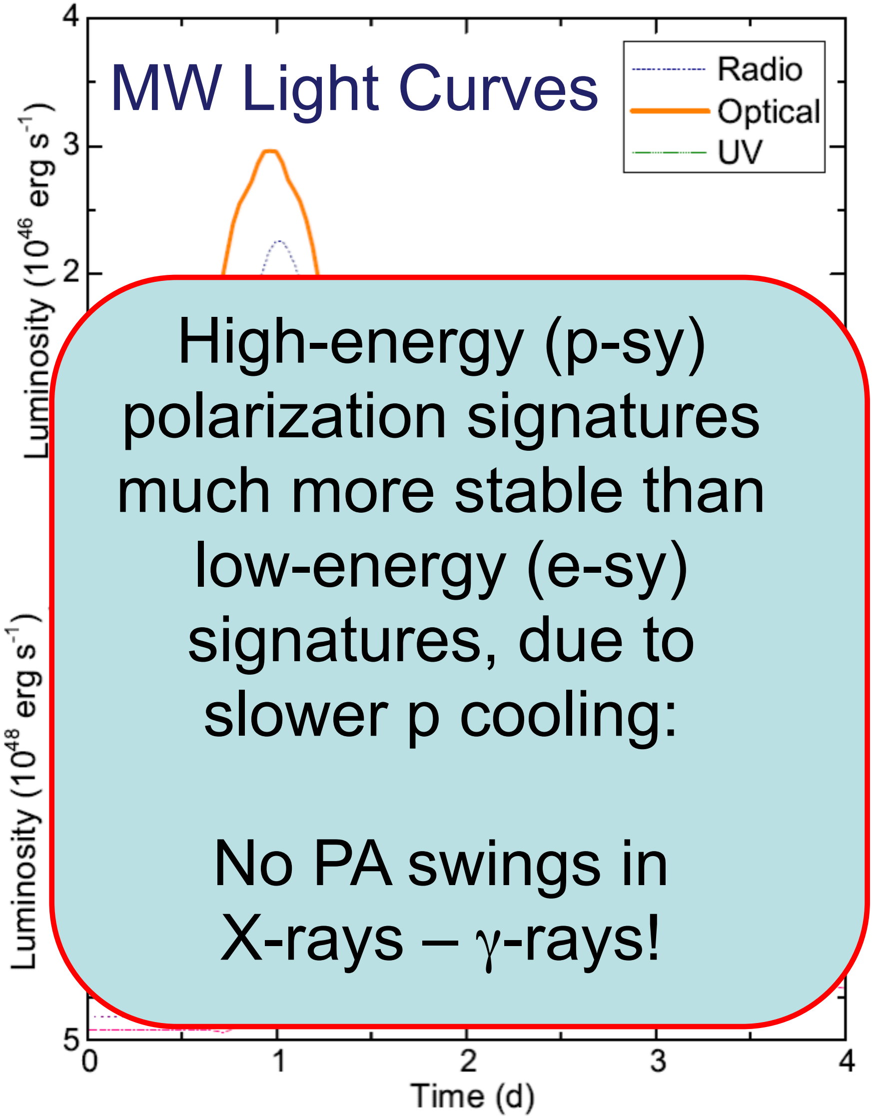
Pol. Deg. vs. Photon Energy

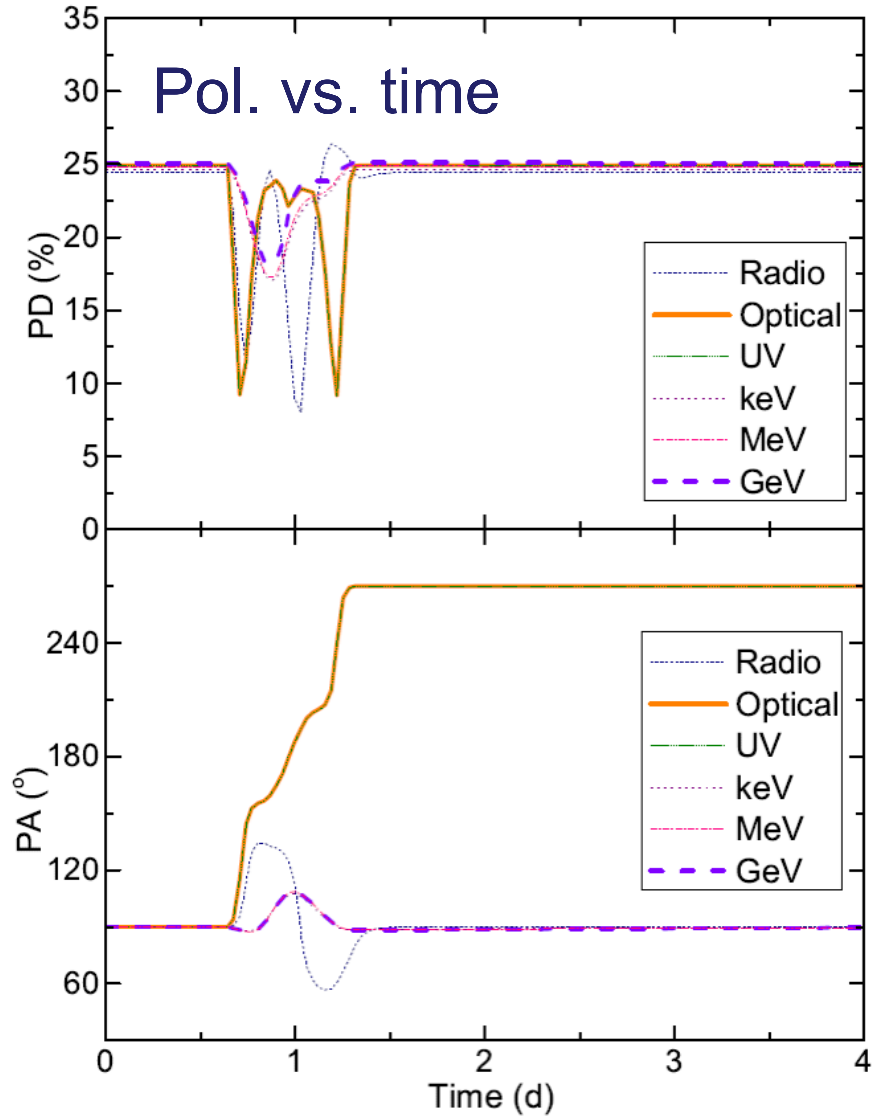
PA swings in hadronic models



(Zhang et al. 2016)

PA swings in hadronic models





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. X-ray / γ-ray polarimetry of blazars may help answer several outstanding questions:

   a) X-ray – optical co-spatiality?
   b) Mode of particle acceleration (shocks vs. magnetic reconnection)
   c) Leptonic vs. hadronic emission
   d) Nature and origin of “big blue bump” / soft X-ray excess

2. Optical spectropolarimetry + SED modeling tightly constrains unpolarized emission components (e.g., accretion disk) → Measure BH mass

3. Optical PA swings may be modeled with straight shock-in-jet model with helical magnetic fields

4. If PA swings are also present in X-rays, potential problem for X-ray polarimetry of blazars

5. In hadronic models, optical PA swings may not be mirrored in high-energy polarization.

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Thank you!

NRF National Research Foundation