# Relativistic Jets from Active Galactic Nuclei

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# The AGN Zoo

Spirals

Seyferts

Emission lines

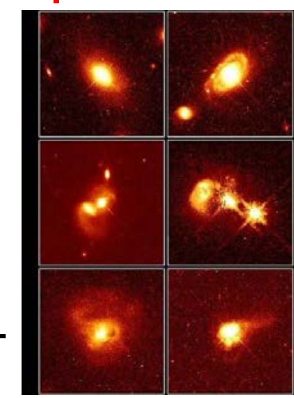
| Broad and narrow | Narrow |
|---|---|
| Seyfert 1 | Seyfert 2 |

Ellipticals

Radio loud

Radio quiet

Radio quiet quasars



Radio spectrum

Flat

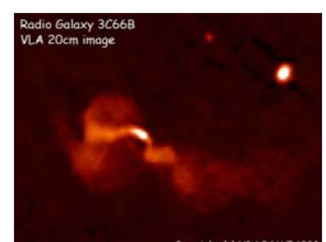
Steep

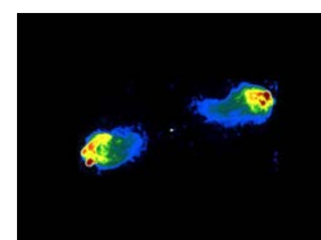
Steep Spectrum Radio Quasars

Radio galaxies

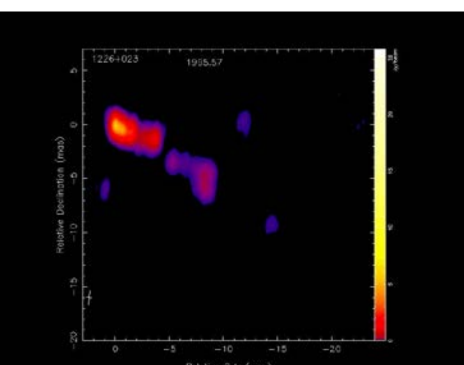
FR I

FR II



Blazars

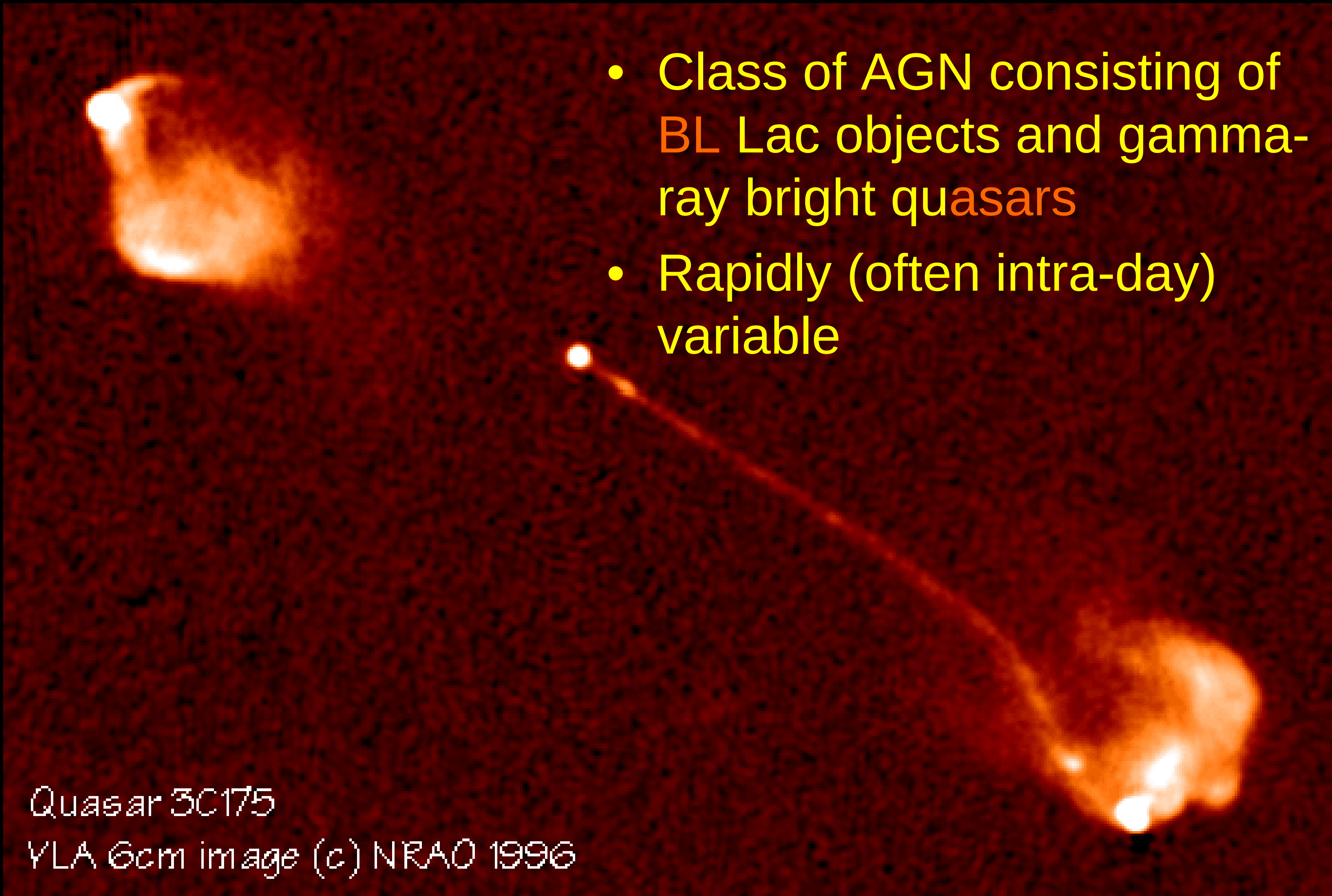


Emission lines

| Weak/absent | Strong |
|---|---|
| BL Lac Objects | Flat Spectrum Radio Quasars |

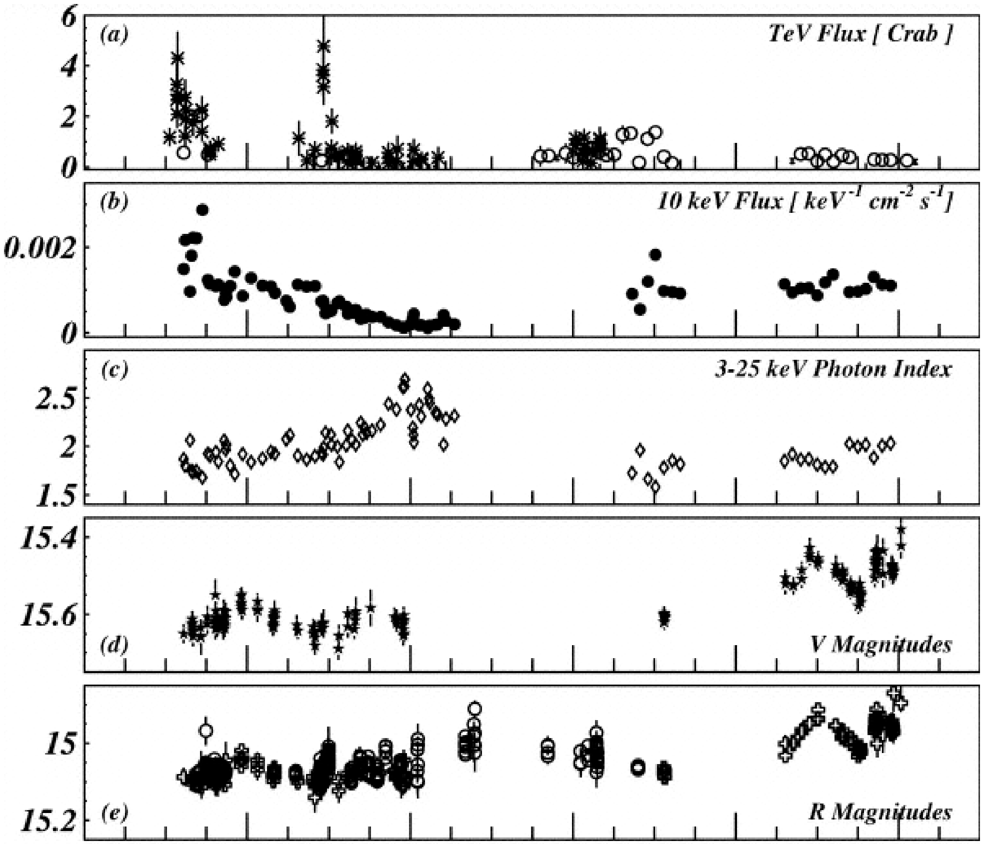
# Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable



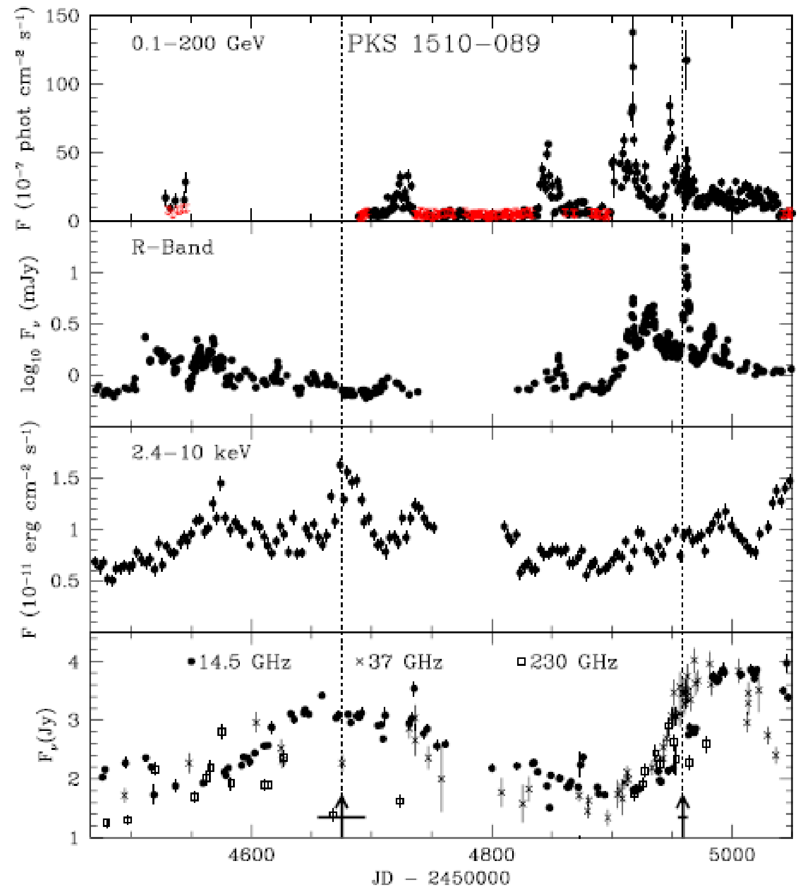
# Multiwavelength Variability

1ES 1959+650 (2002)



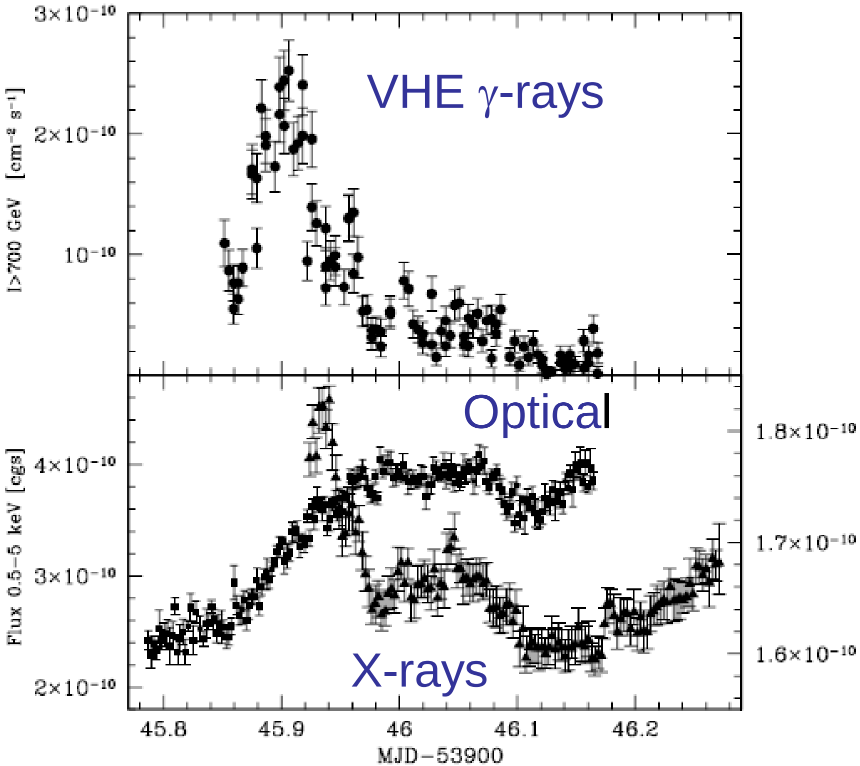

(Krawczynski et al. 2004)

PKS 1510-089 (2008 - 2009)



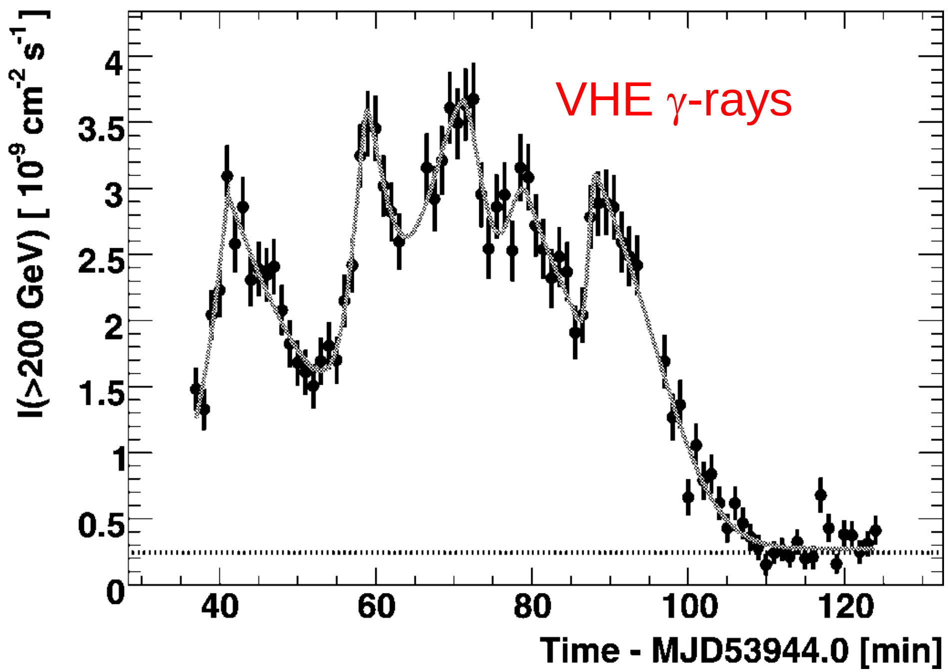

(Marscher al. 2010)

# Blazar Variability: Variability of PKS 2155-304




(Costamante et al. 2008)

VHE γ-ray and X-ray variability often closely correlated

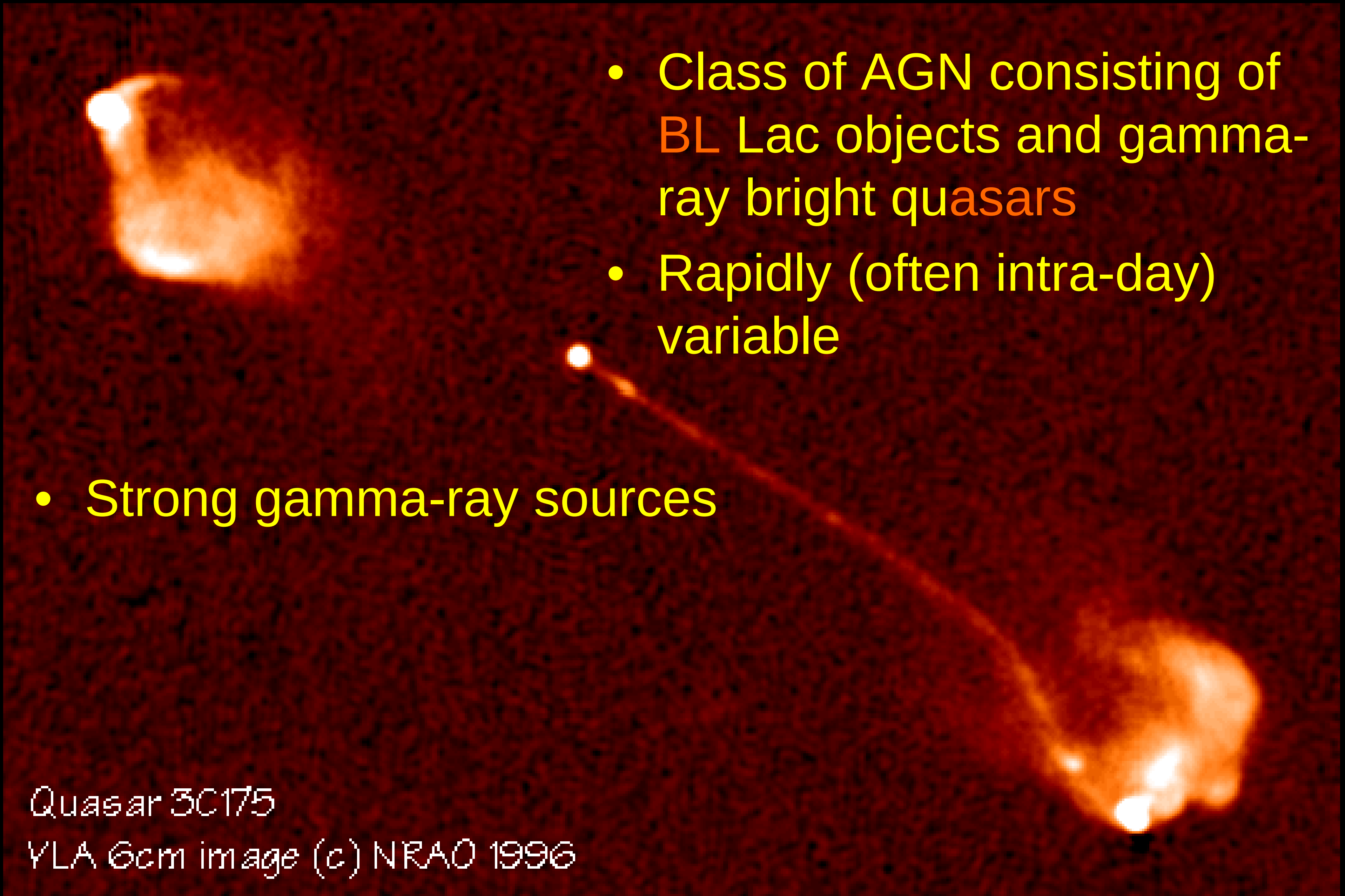



(Aharonian et al. 2007)

VHE γ-ray variability on time scales as short as a few minutes!

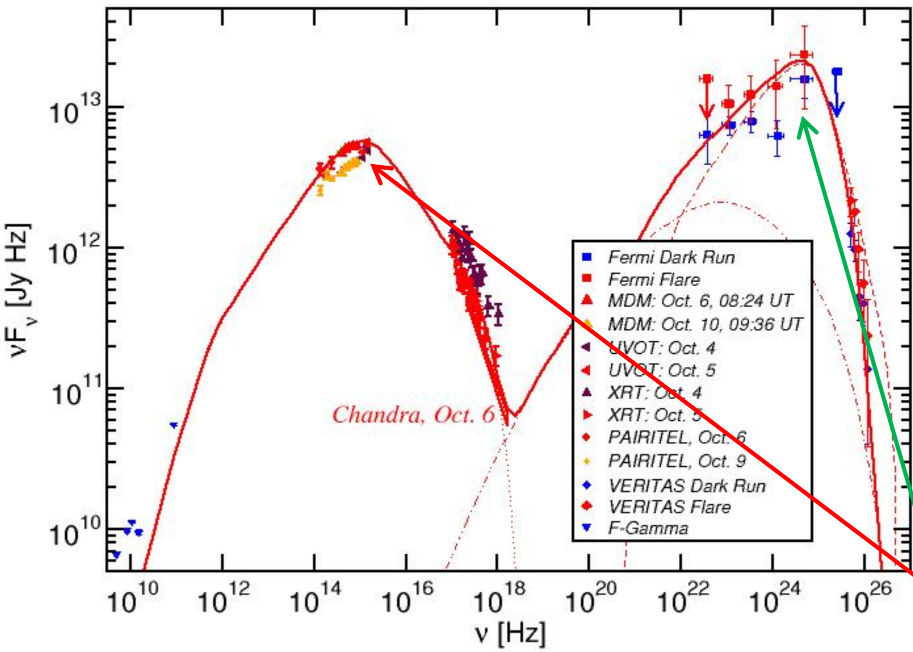
# Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources

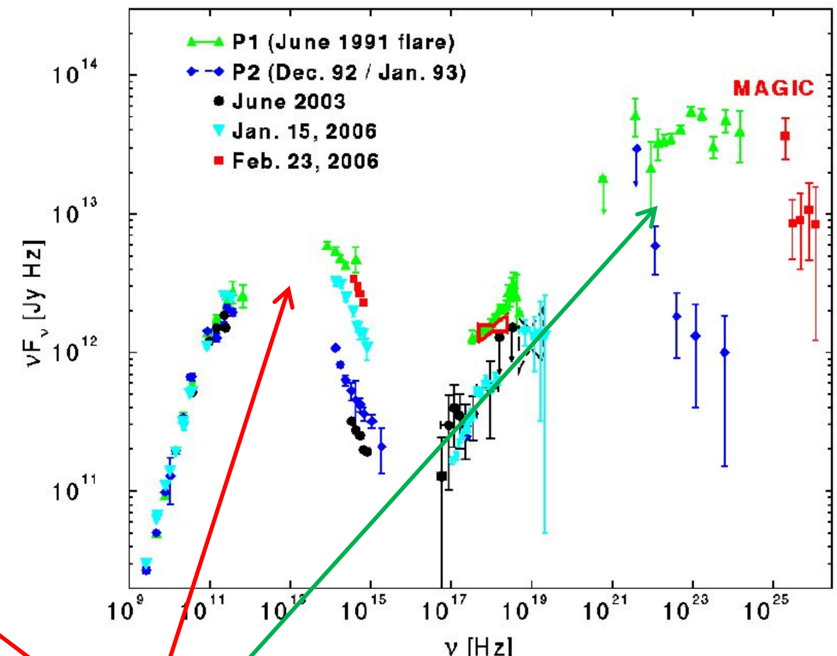


# Blazar Spectral Energy Distributions (SEDs)

3C66A




3C279

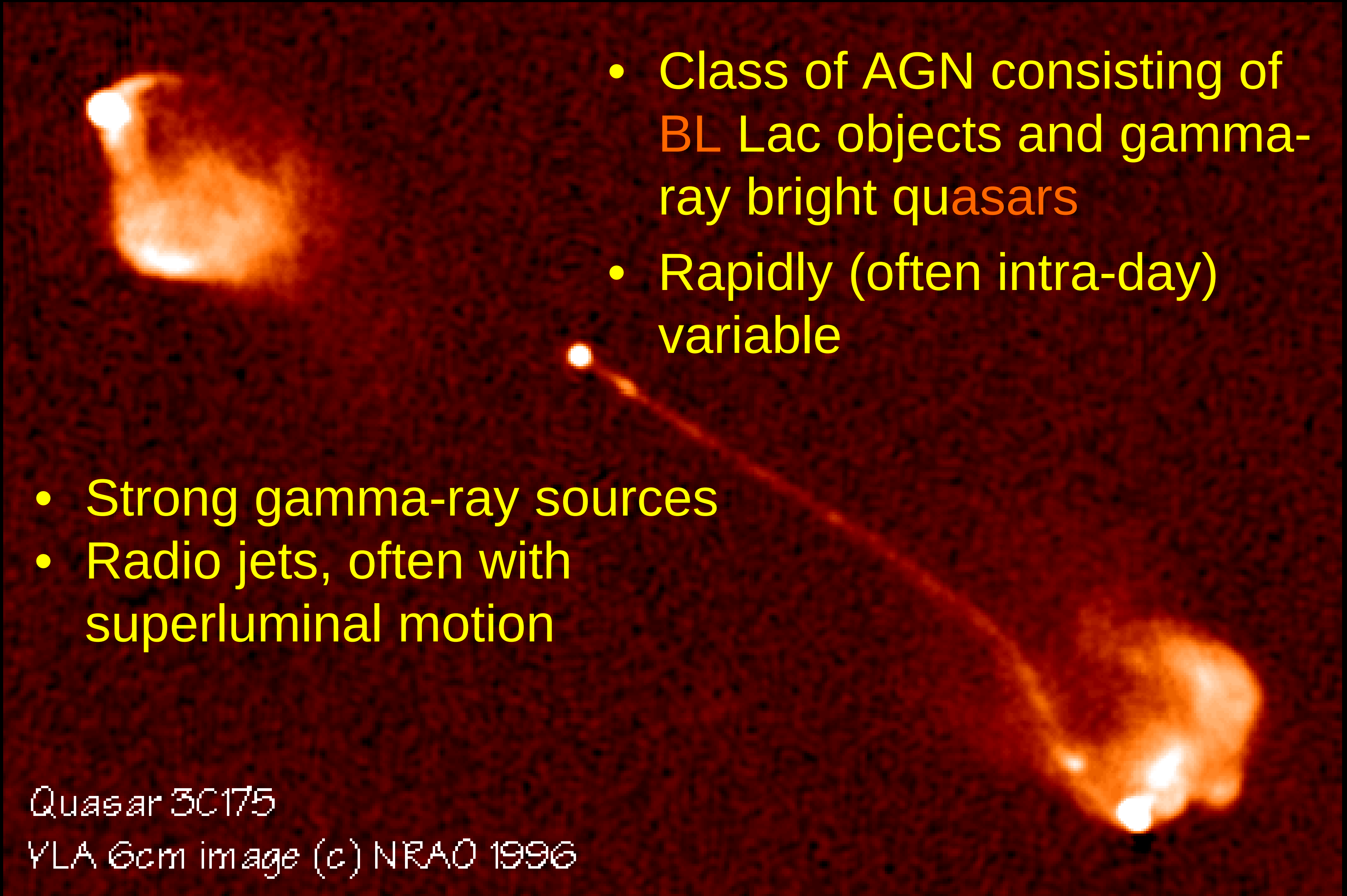



Non-thermal spectra with two broad bumps:

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

# Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio jets, often with superluminal motion



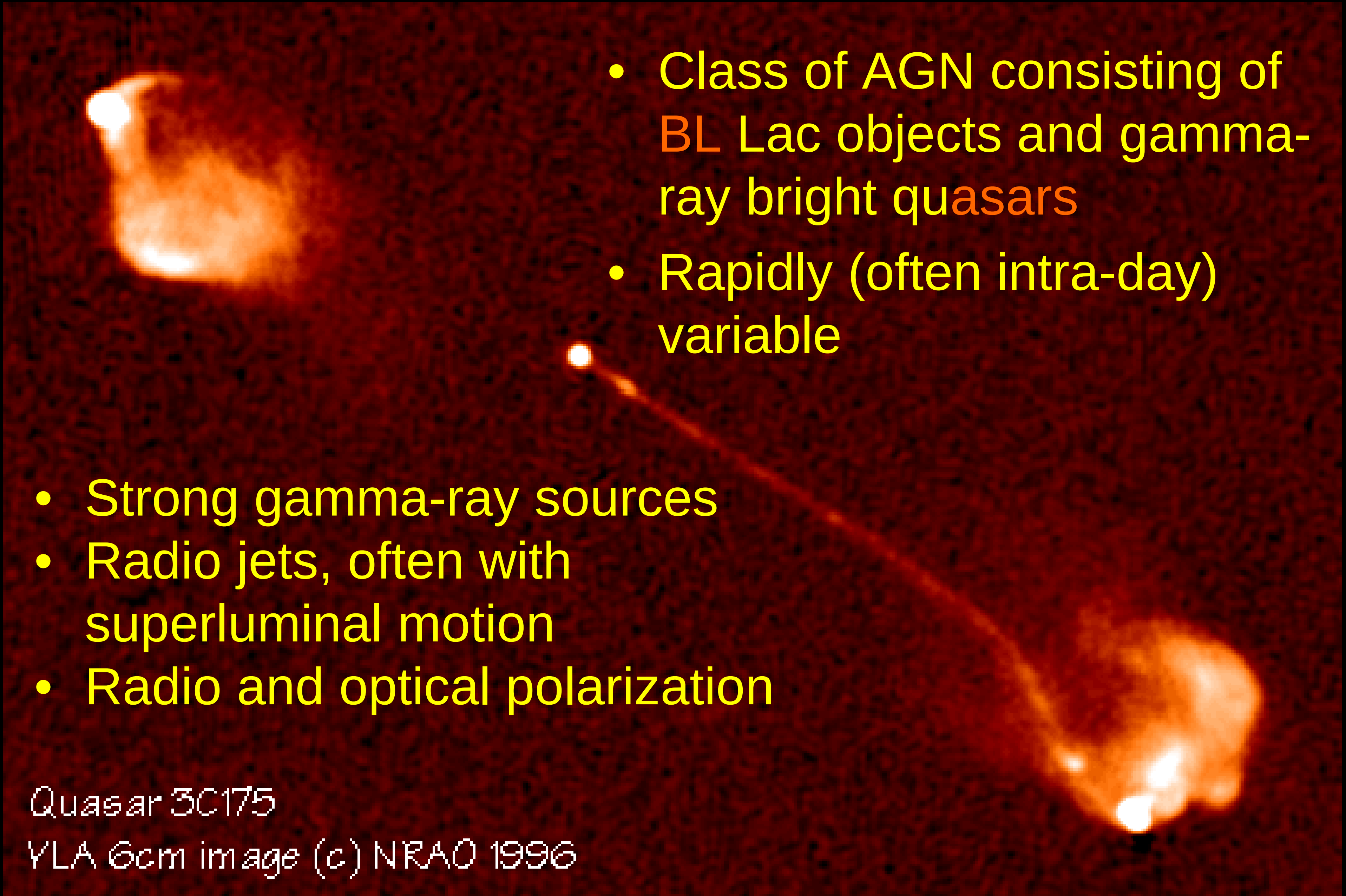
# Superluminal Motion

The MOJAVE Project (Lister et al.)

# Blazars

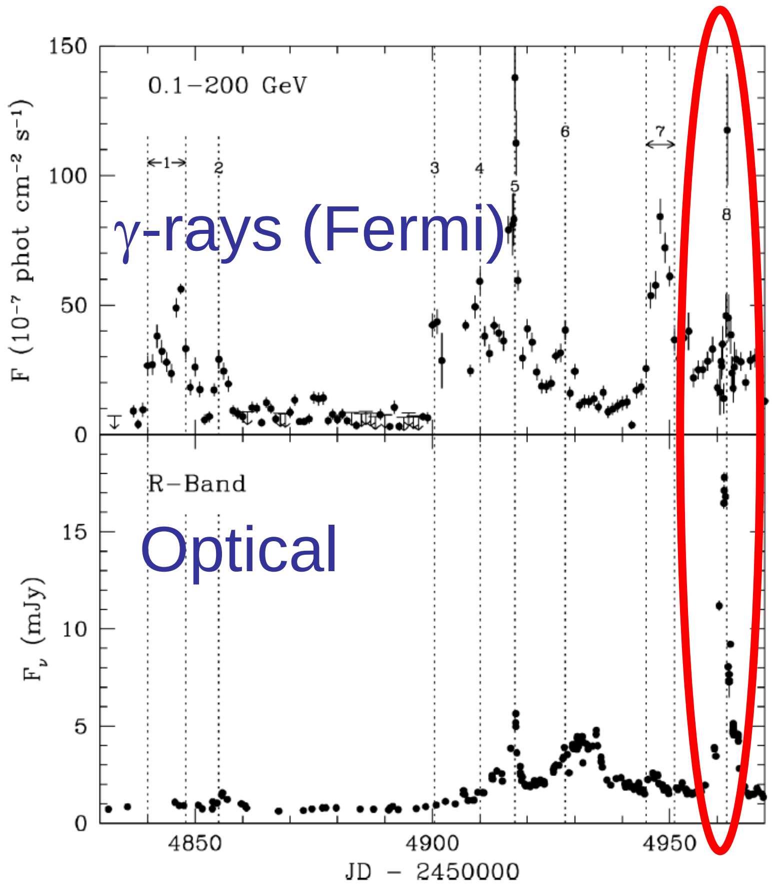
- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

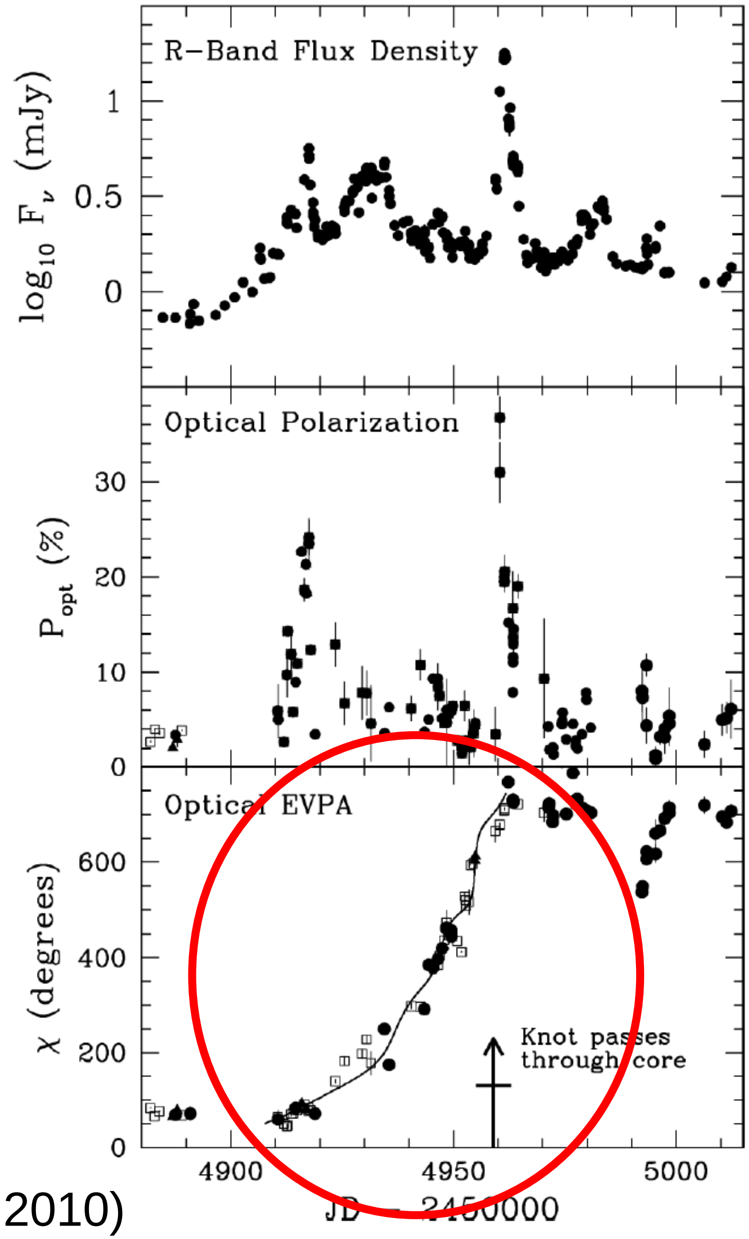
- Strong gamma-ray sources
- Radio jets, often with superluminal motion
- Radio and optical polarization



# 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)



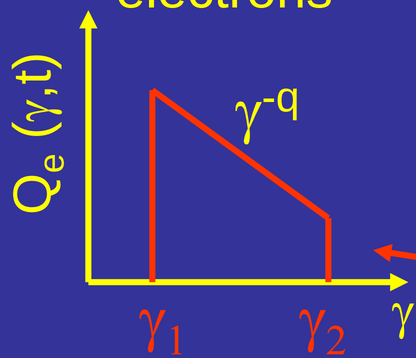

PKS 1510-089 (Marscher et al. 2010)

# Open Physics Questions

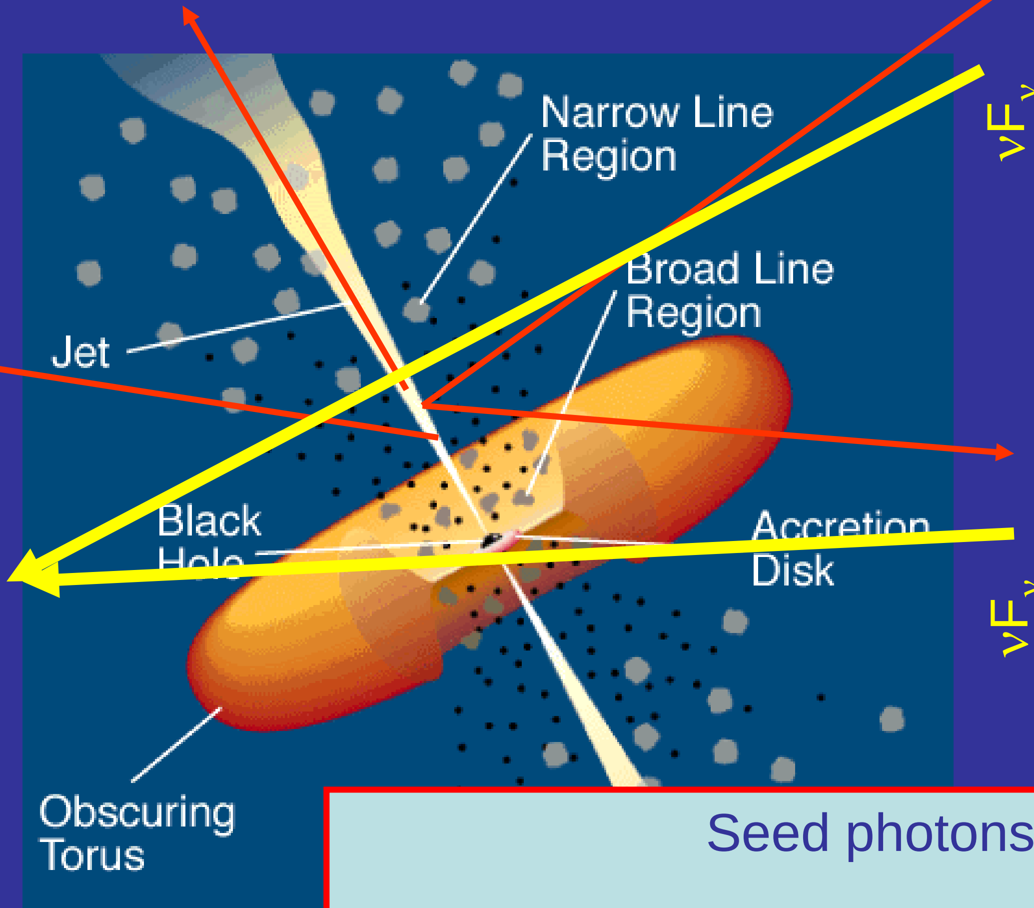
- Source of Jet Power (Blandford-Znajek / Blandford/Payne?)
- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields
- Composition of jets ($e^-$-p or $e^+$-$e^-$ plasma?) – leptonic or hadronic high-energy emission?
- Mode of particle acceleration (shocks / shear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

# Leptonic Blazar Model

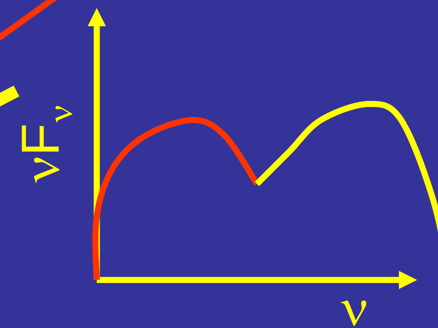
Injection, acceleration of ultrarelativistic electrons



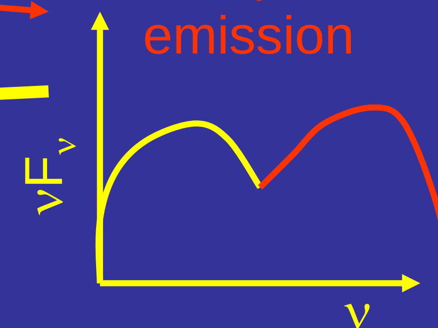

Relativistic jet outflow with $\Gamma \approx 10$



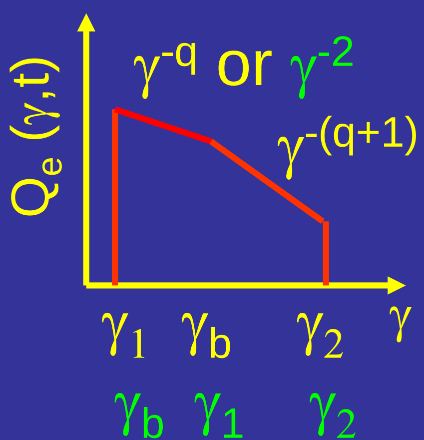

Synchrotron emission




Compton emission




Radiative cooling $\leftrightarrow$ escape =>




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

Seed photons:

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

# Sources of External Photons (↔ Location of the Blazar Zone)

Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)
→ d < few 100 – 1000 $R_s$

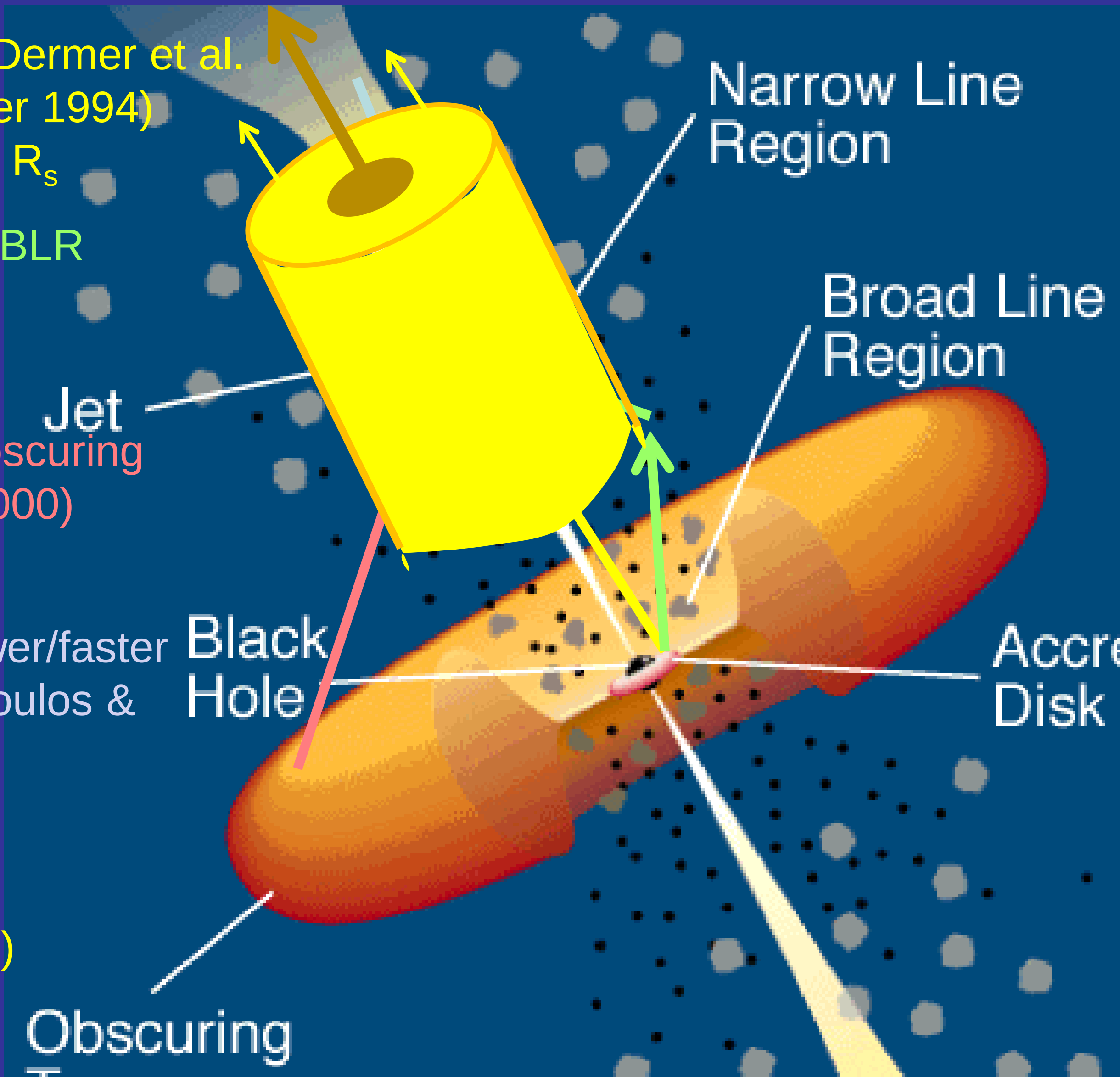
Optical-UV Emission from the BLR (Sikora et al. 1994)
→ d < ~ pc

Infrared Radiation from the Obscuring Torus (Blazejowski et al. 2000)
→ d ~ 1 – 10s of pc

Synchrotron emission from slower/faster regions of the jet (Georganopoulos & Kazanas 2003)
→ d ~ pc - kpc

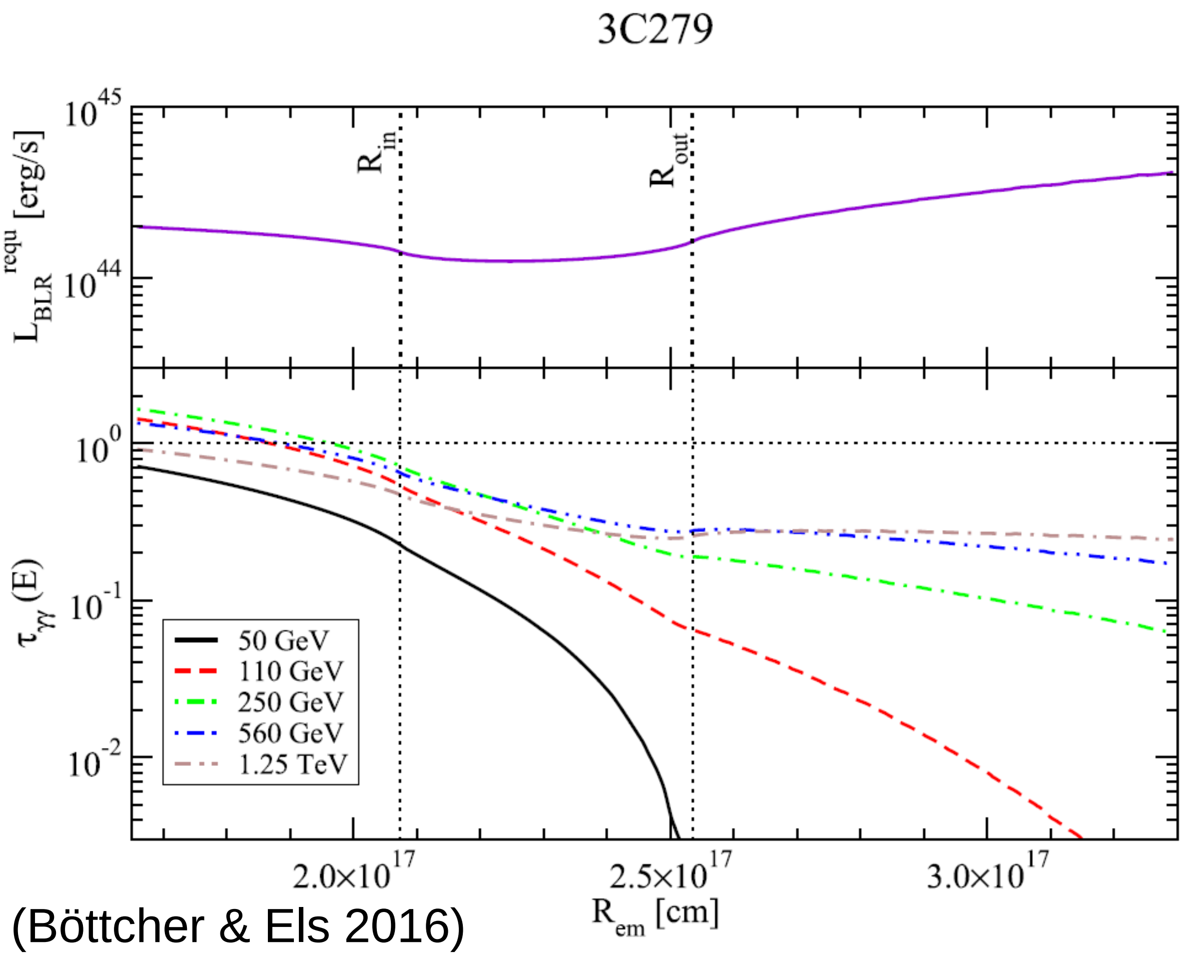
Spine – Sheath Interaction (Ghisellini & Tavecchio 2008)

→ d ~ pc - kpc



# Gamma-Gamma Absorption

- External: EBL
- Internal: BLR Radiation field



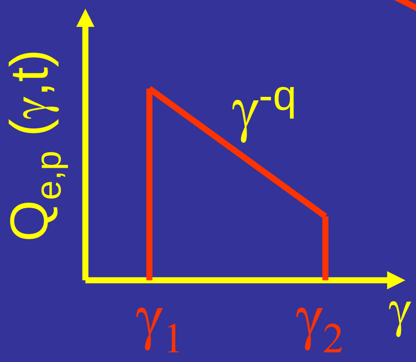

(Böttcher & Els 2016)

$R_{em} \geq R_{BLR}$

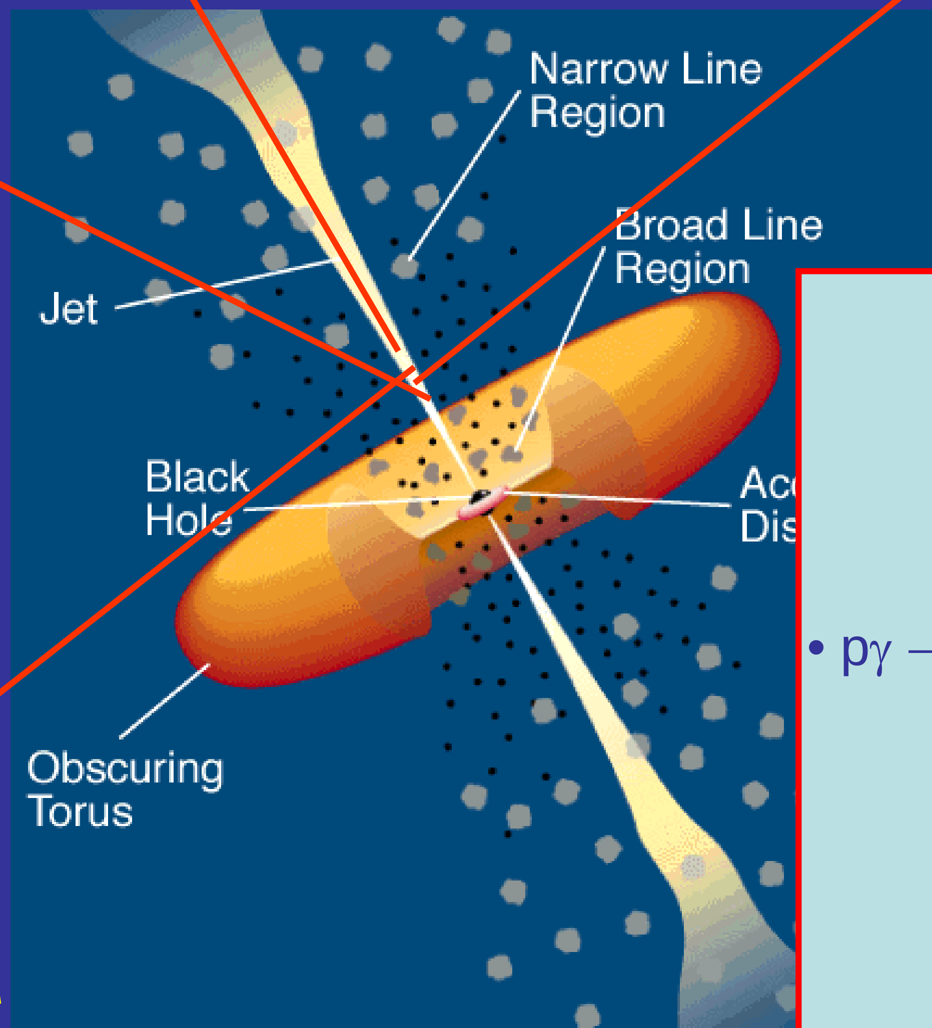
Constraint particularly important for VHE-detected FSRQs (3C279, PKS 1510-089, …)

# Hadronic Blazar Models

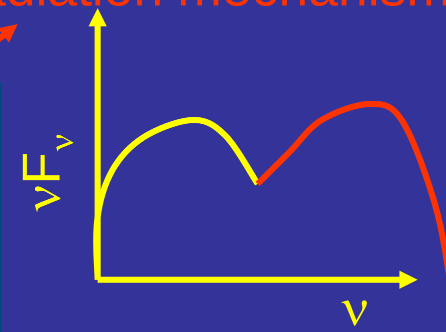
Injection, acceleration of ultrarelativistic electrons and protons



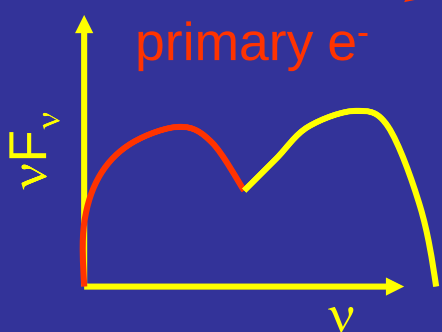

Relativistic jet outflow with $\Gamma \approx 10$




Proton-induced radiation mechanisms




Synchrotron emission of primary $e^-$

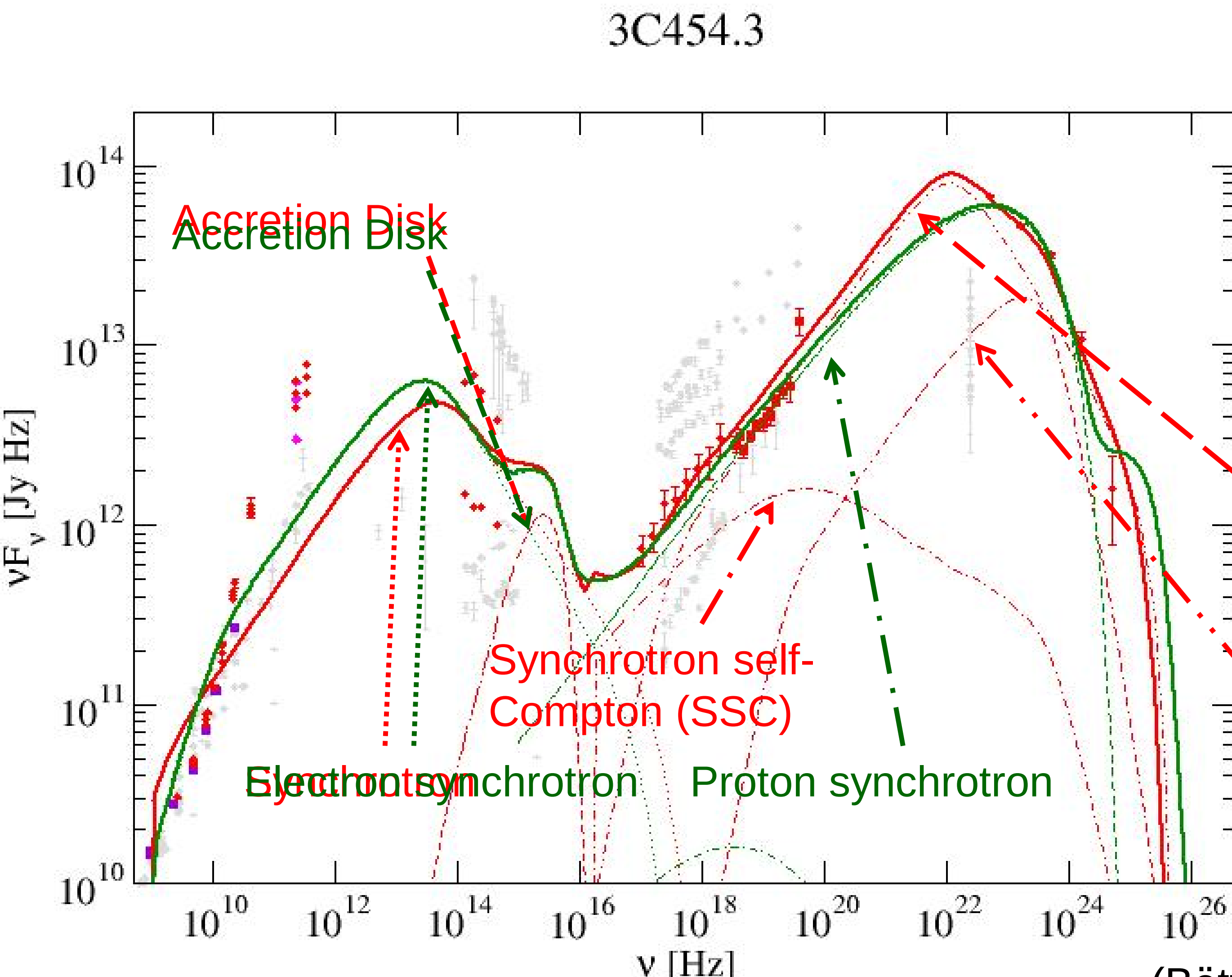



- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$ ; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu_\mu}$
  $\rightarrow$ secondary $\mu$-, e-synchrotron
- Cascades …

# Requirements for lepto-hadronic models

- To exceed p-$\gamma$ pion production threshold on interactions with synchrotron (optical) photons: $E_p > 7\text{x}10^{16}\ E^{-1}_{ph,eV}$ eV
- For proton synchrotron emission at multi-GeV energies: $E_p$ up to ~ $10^{19}$ eV (=> UHECR)
- Require Larmor radius
  $r_L \sim 3\text{x}10^{16}\ E_{19}/B_G$ cm ≤ a few x $10^{15}$ cm => $B \geq 10$ G
  (Also: to suppress leptonic SSC component below synchrotron) – inconsistent with radio-core-shift measurements if emission region is located at ~ pc scales (e.g., Zdziarski & Böttcher 2015).
- Low radiative efficiency: Requiring jet powers $L_{jet} \sim L_{Edd}$

# Leptonic and Hadronic Model Fits along the Blazar Sequence




Red = Leptonic
Green = Hadronic

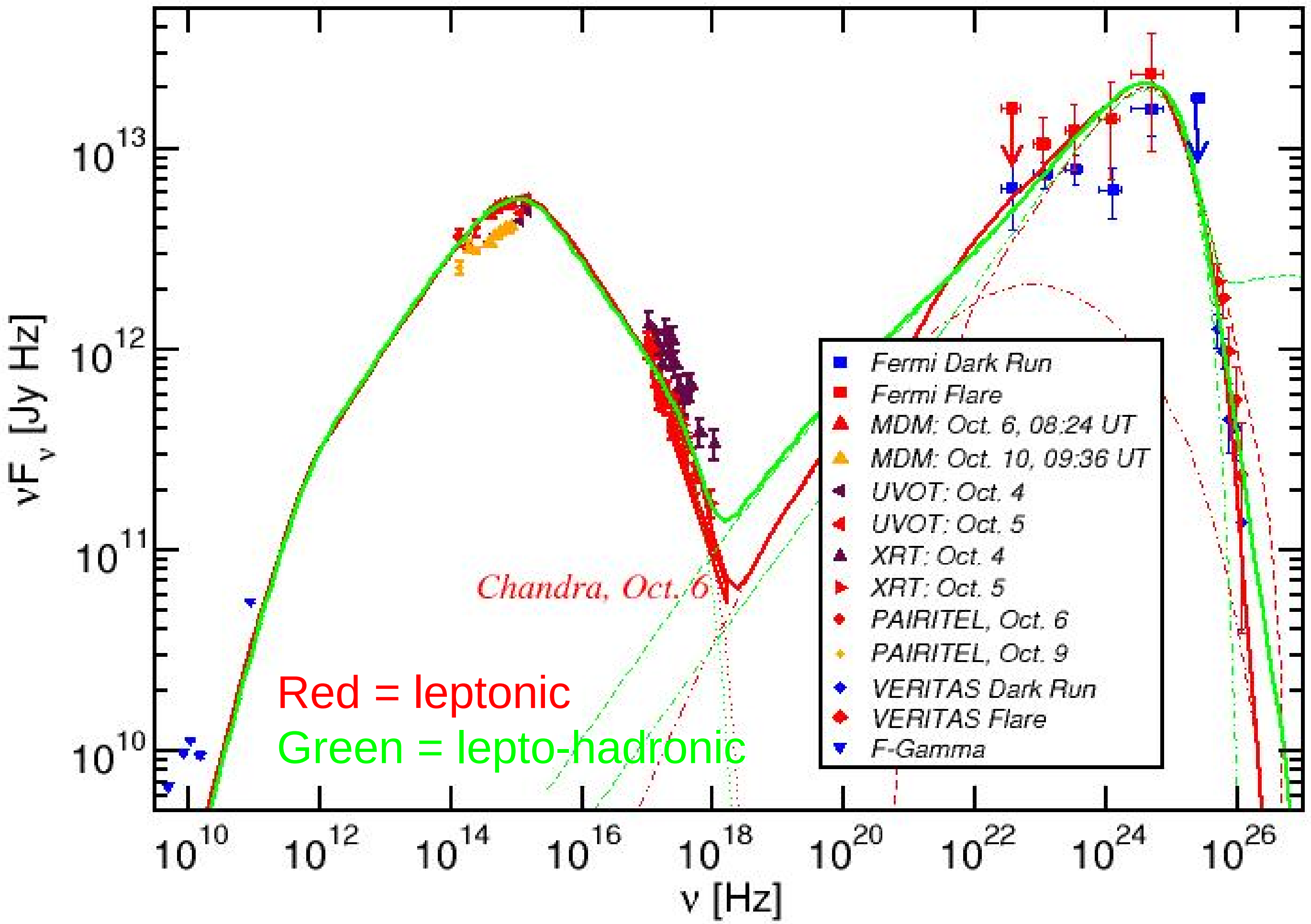
External Compton of direct accretion disk photons (ECD)

External Compton of emission from BLR clouds (ECC)

(Böttcher et al. 2013)

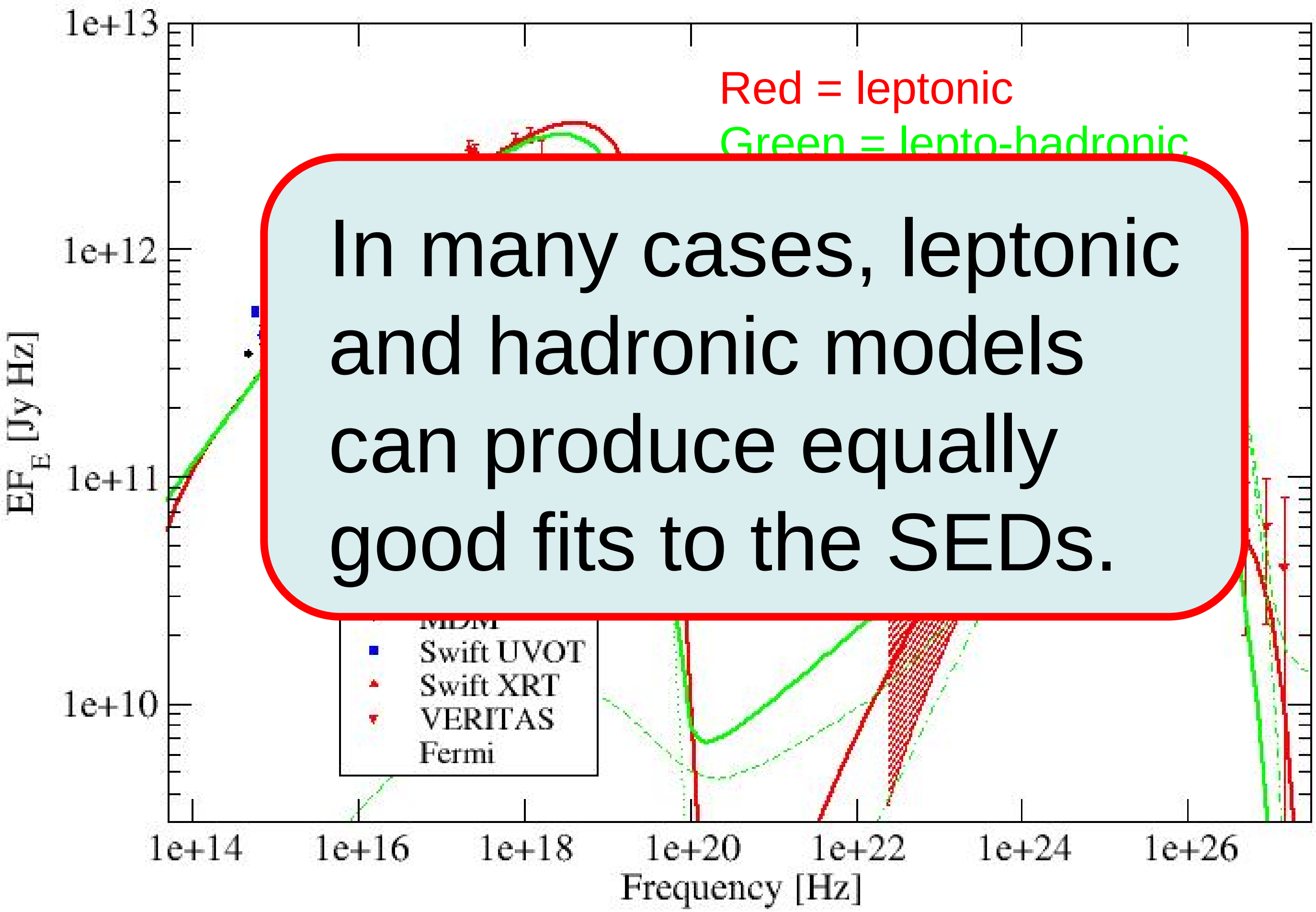
# Leptonic and Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)



# Lepto-Hadronic Model Fits Along the Blazar Sequence

RGB J0710+591 (HBL)




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

<u>Possible Diagnostics to distinguish:</u>

- Variability
- Neutrinos
- Polarization

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

For perfectly ordered, homogeneous B-field:

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

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

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

# Compton Polarization

Compton cross section is polarization-dependent:

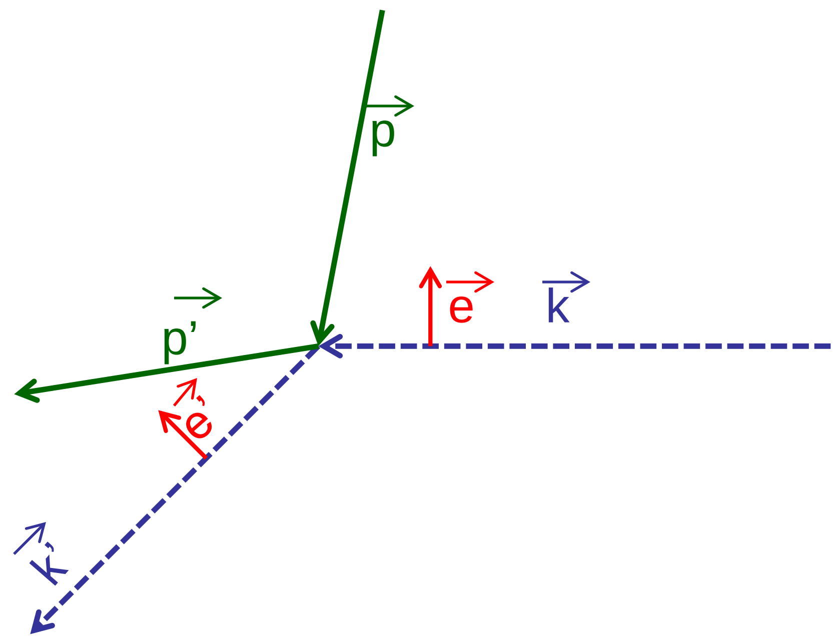
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{\epsilon'}{\epsilon}\right)^2\left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$$

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

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

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

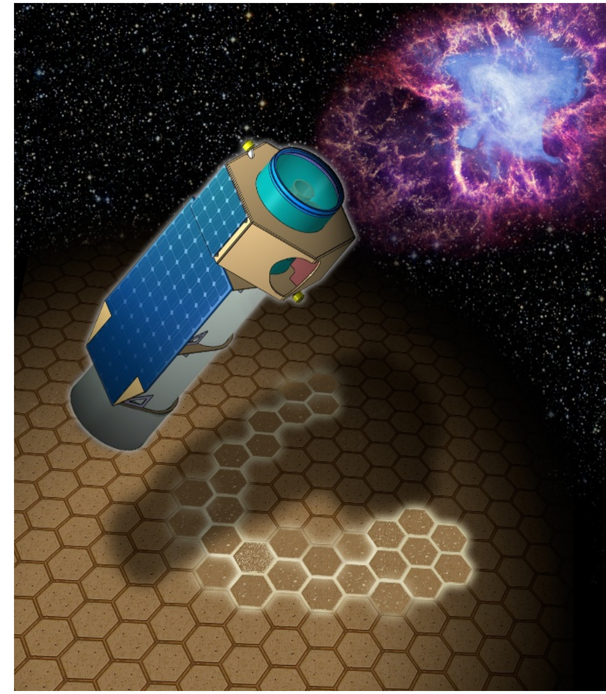
$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!



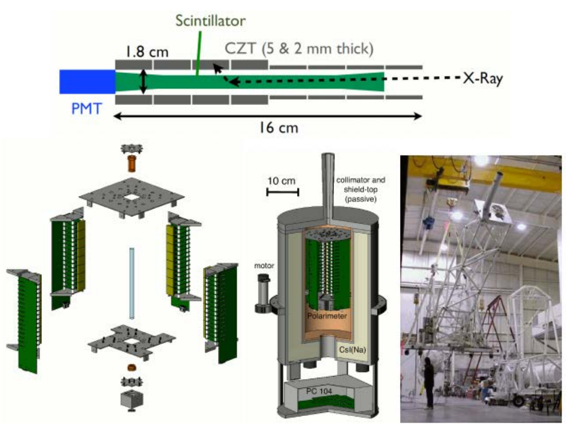

Preferred polarization direction is preserved; polarization degree reduced to ~ ½ of target-photon polarization .

# X-ray Polarimeters

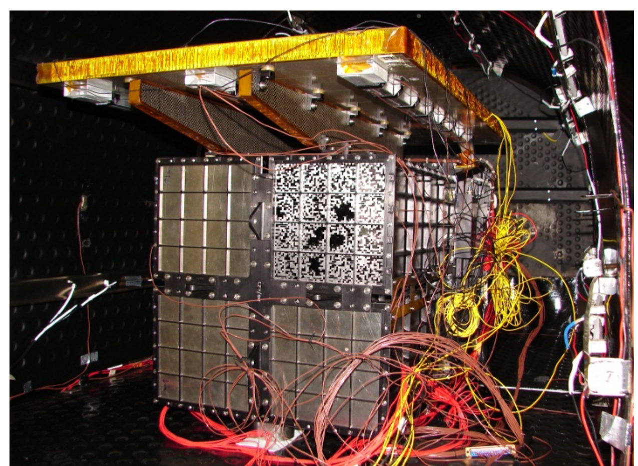
INTEGRAL

XIPE

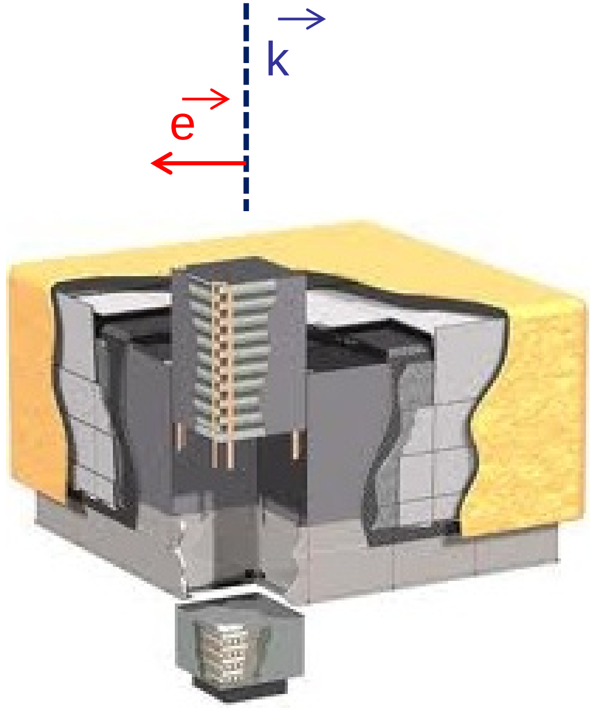


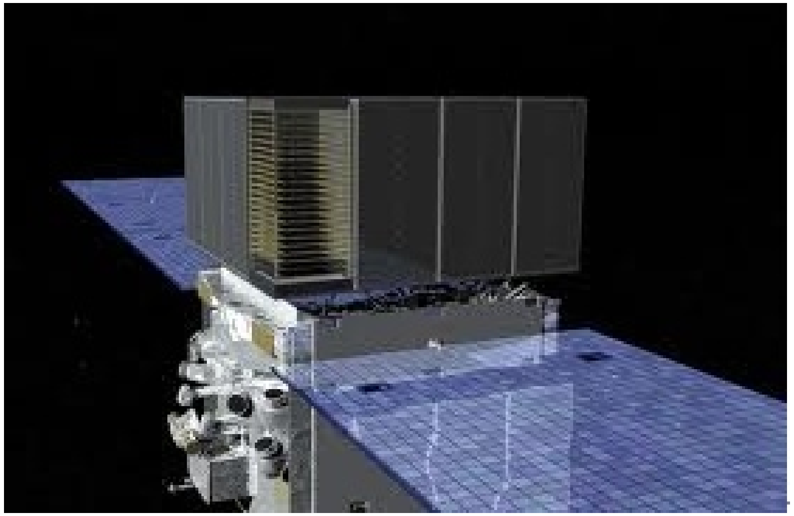

X-Calibur
→ PolSTAR



ASTROSAT

# Gamma-Ray Polarimetry with Fermi-LAT



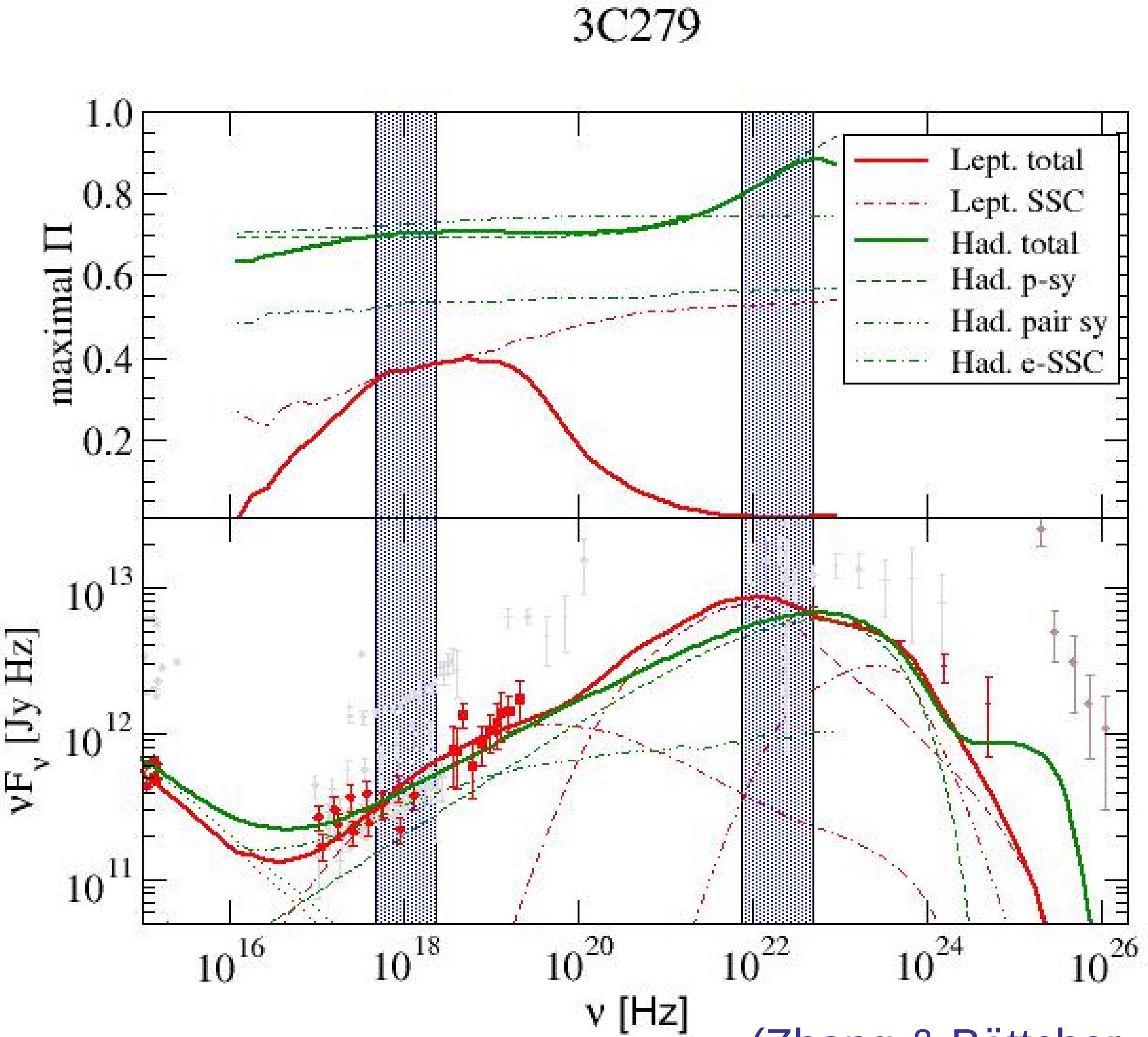



$e^+e^-$ pair is preferentially produced in the plane of $(\vec{k}, \vec{e})$ of the $\gamma$-ray.

Potentially detectable at E < 200 MeV

→ PANGU / eASTROGAM

# X-Ray and Gamma-Ray Polarization: FSRQs

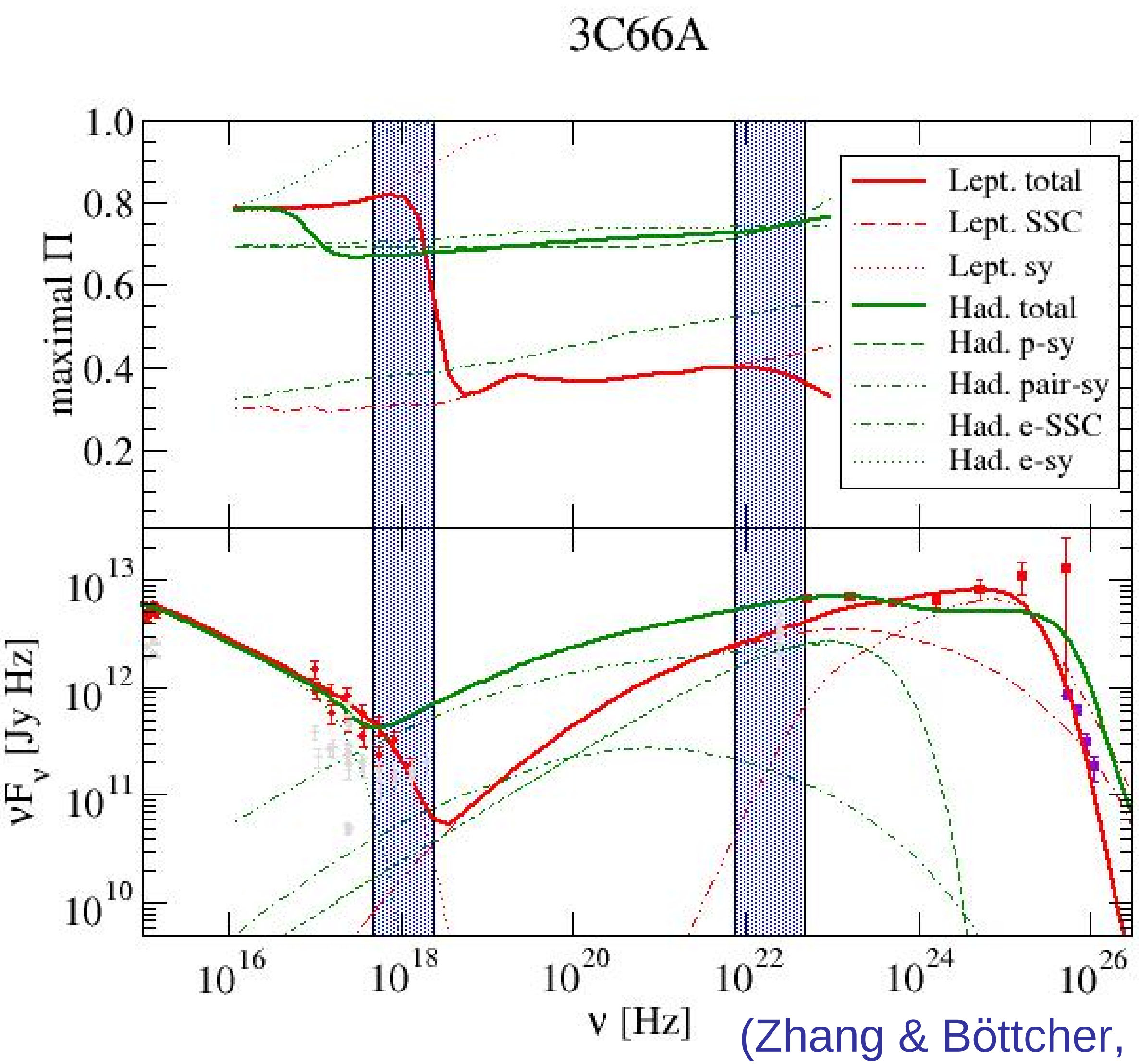



**Hadronic model: Synchrotron dominated => High Π, generally increasing with energy (SSC contrib. in X-rays).**

**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.**

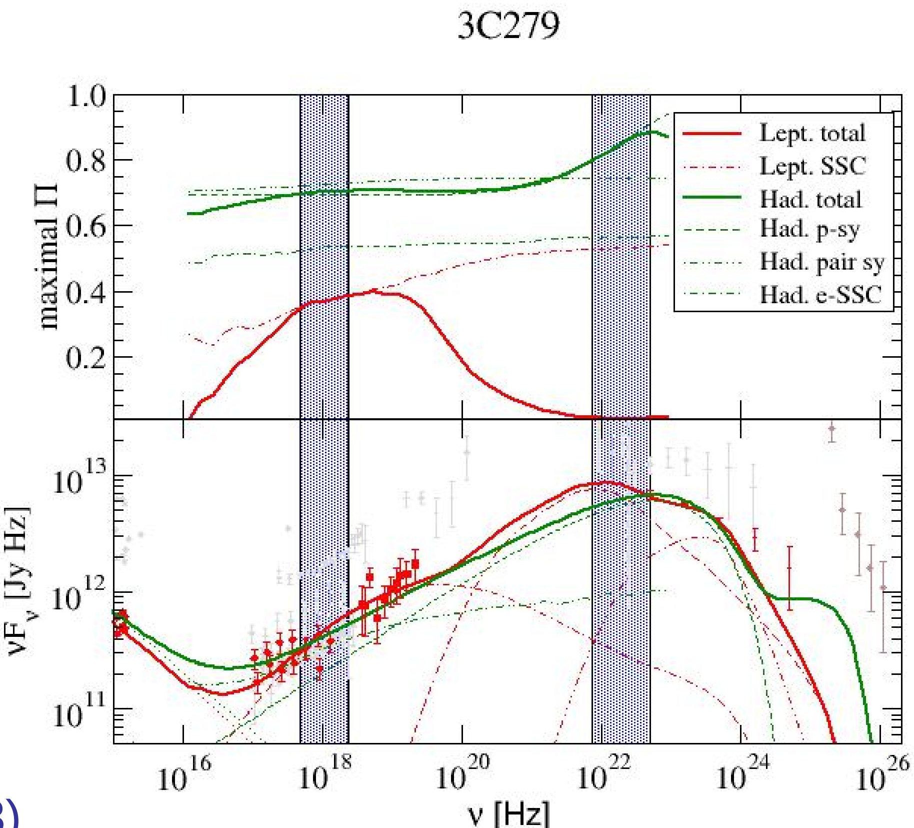
(Zhang & Böttcher, 2013)

# Observational Strategy

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

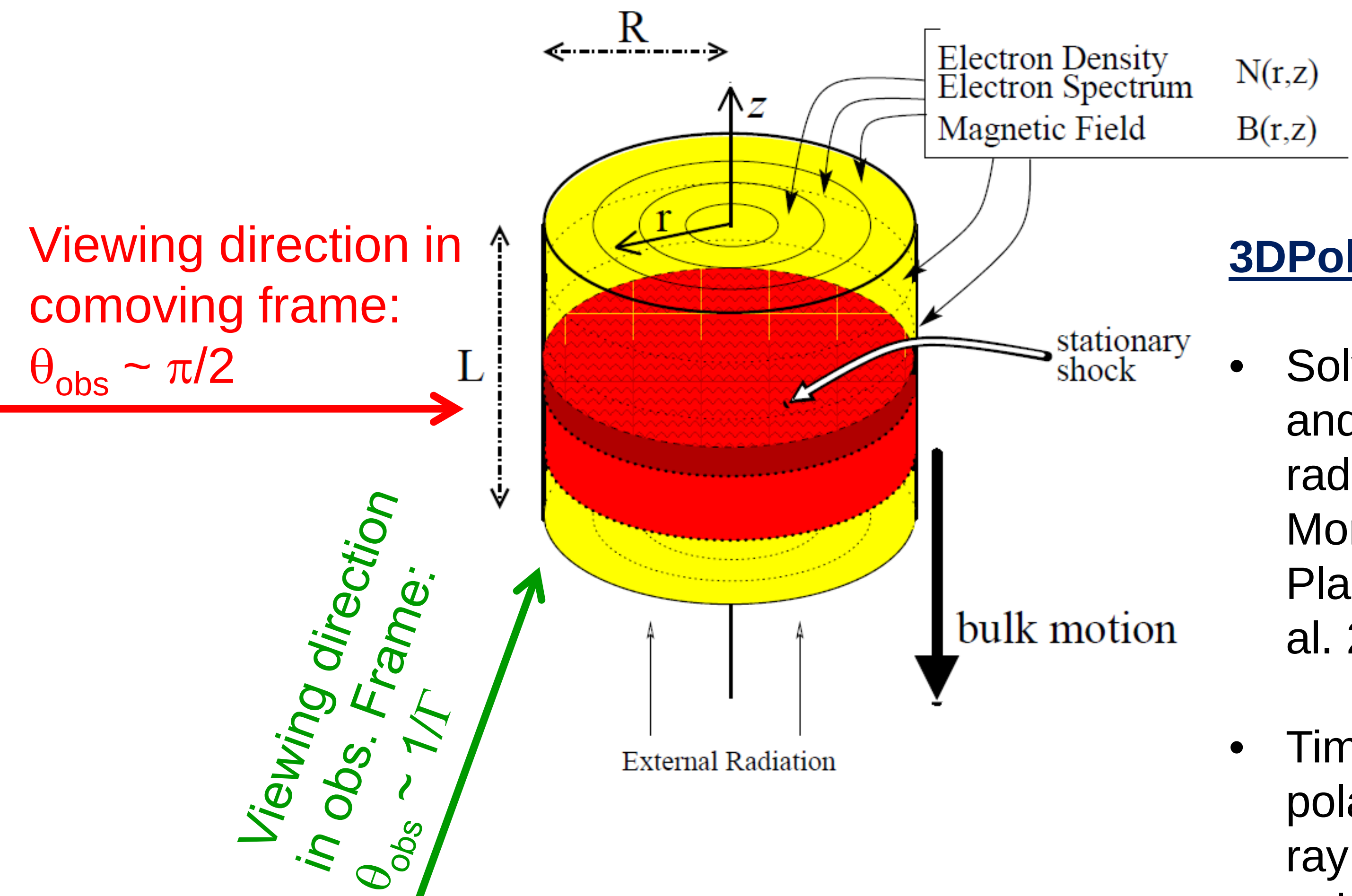
- Scale results to actual B-field configuration from known synchrotron polarization (e.g., optical for FSRQs/LBLs)
  => Expect 10 - 20 % X-ray and $\gamma$-ray polarization in hadronic models!

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




(Zhang & Böttcher 2013)

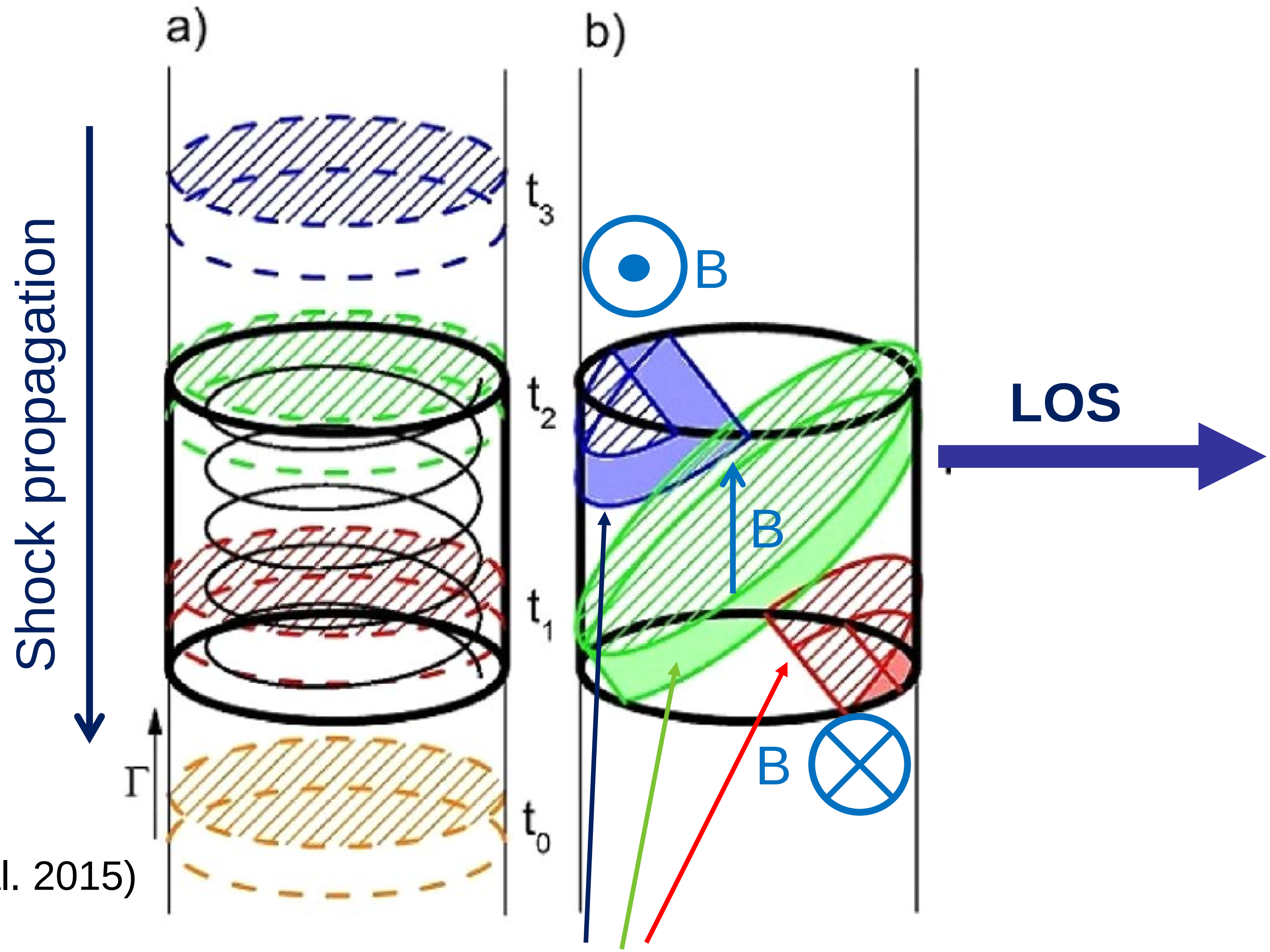
# Tracing Synchrotron Polarization in the Internal Shock Model




**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

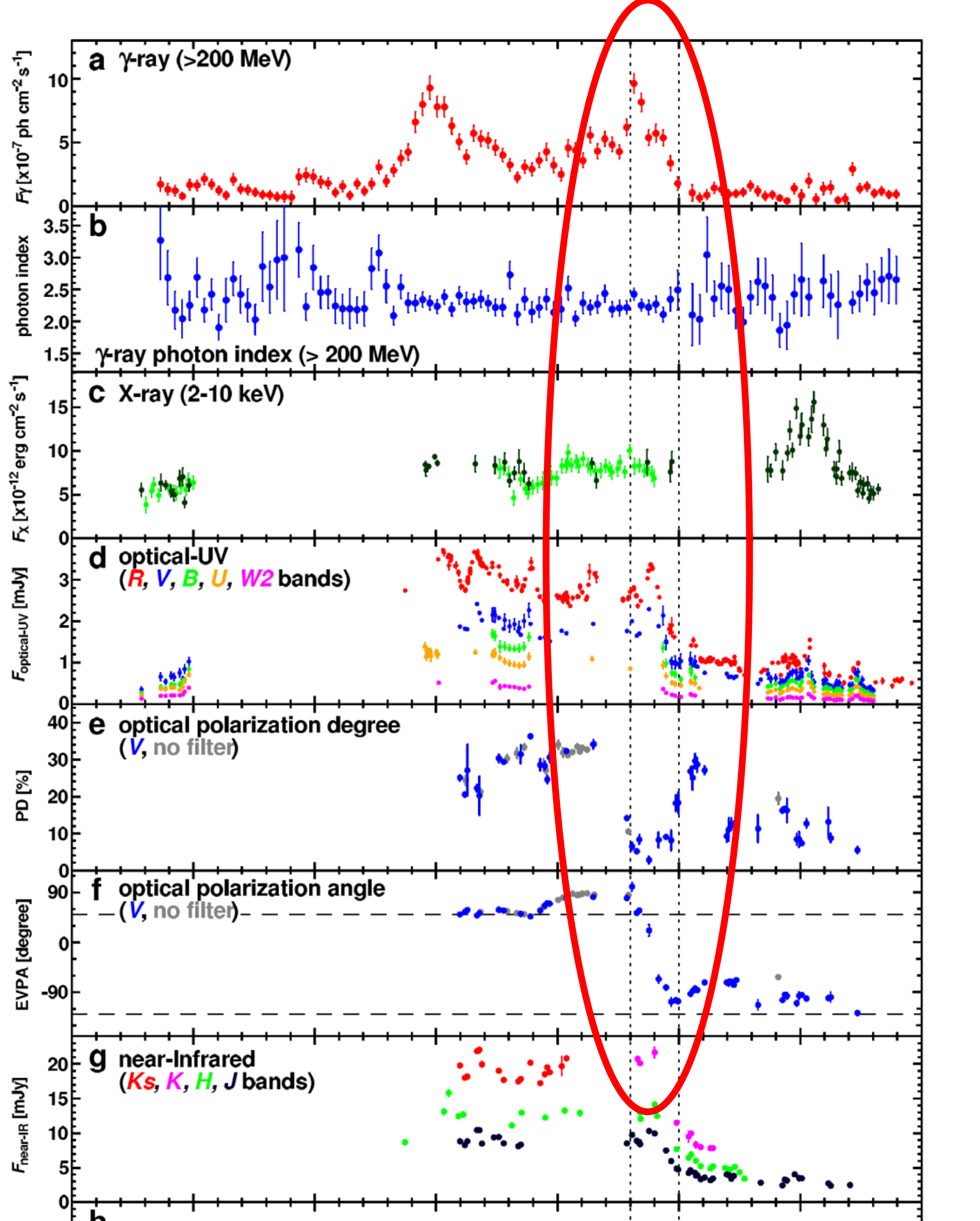



(Zhang et al. 2015)

Shock positions at equal photon-arrival times at the observer

# Application to the FSRQ 3C279

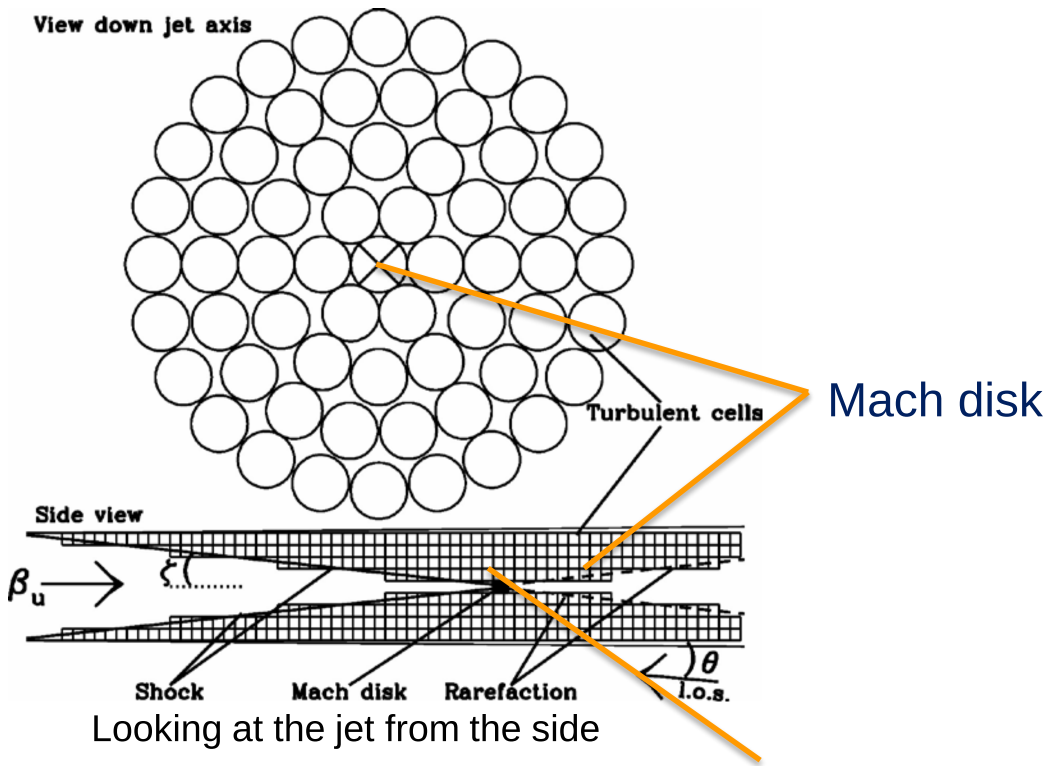
Simultaneous optical + $\gamma$-ray flare, correlated with a 180° polarization-angle rotation .



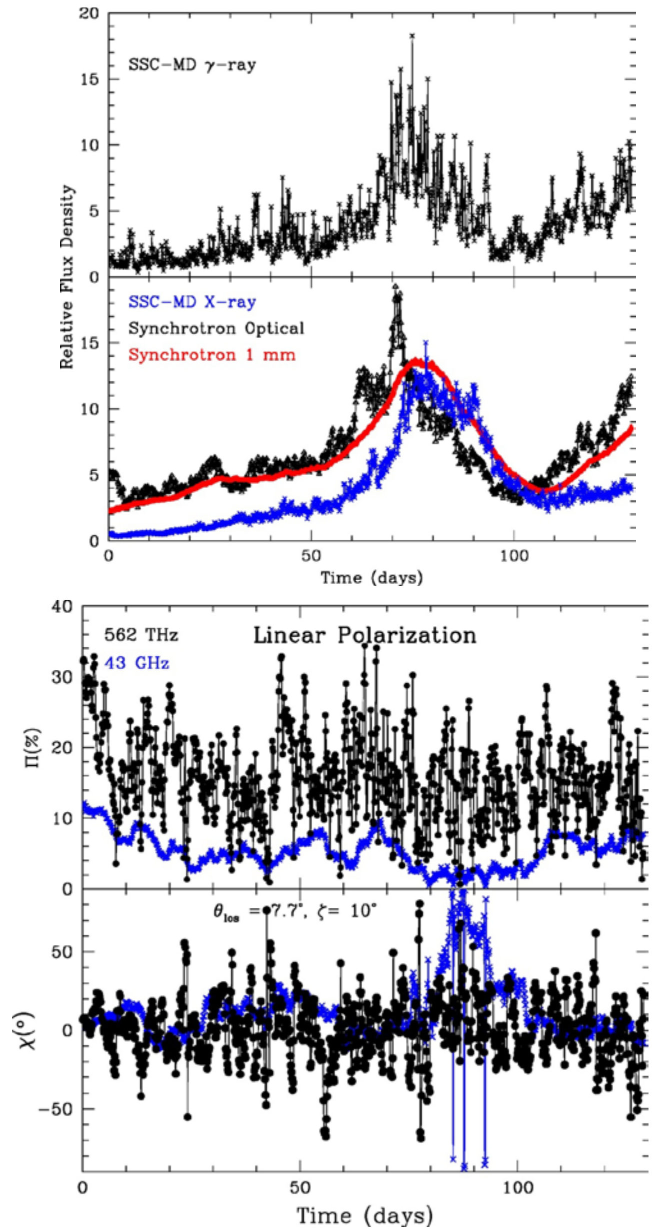

(Abdo et al. 2009)

# Proposed Alternatives

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

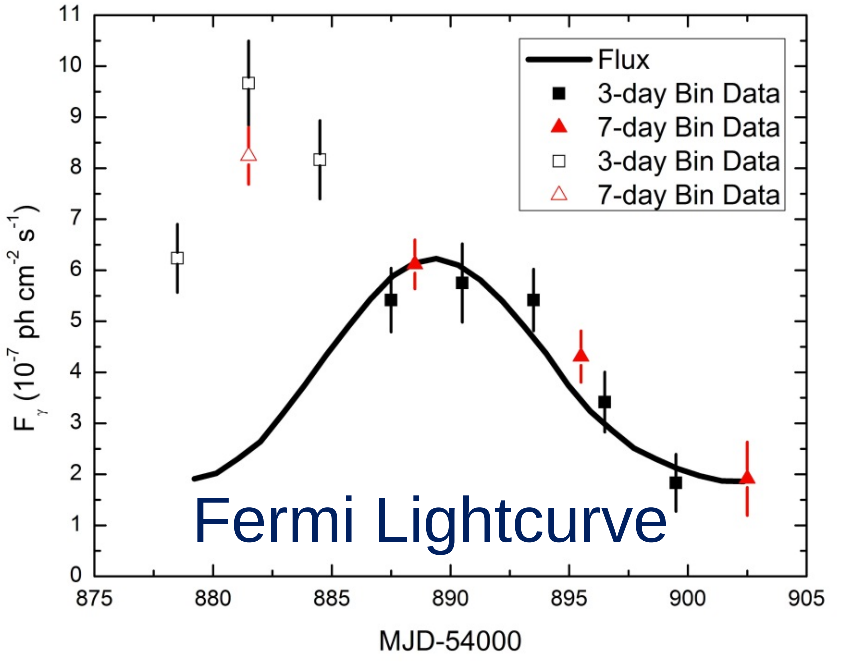


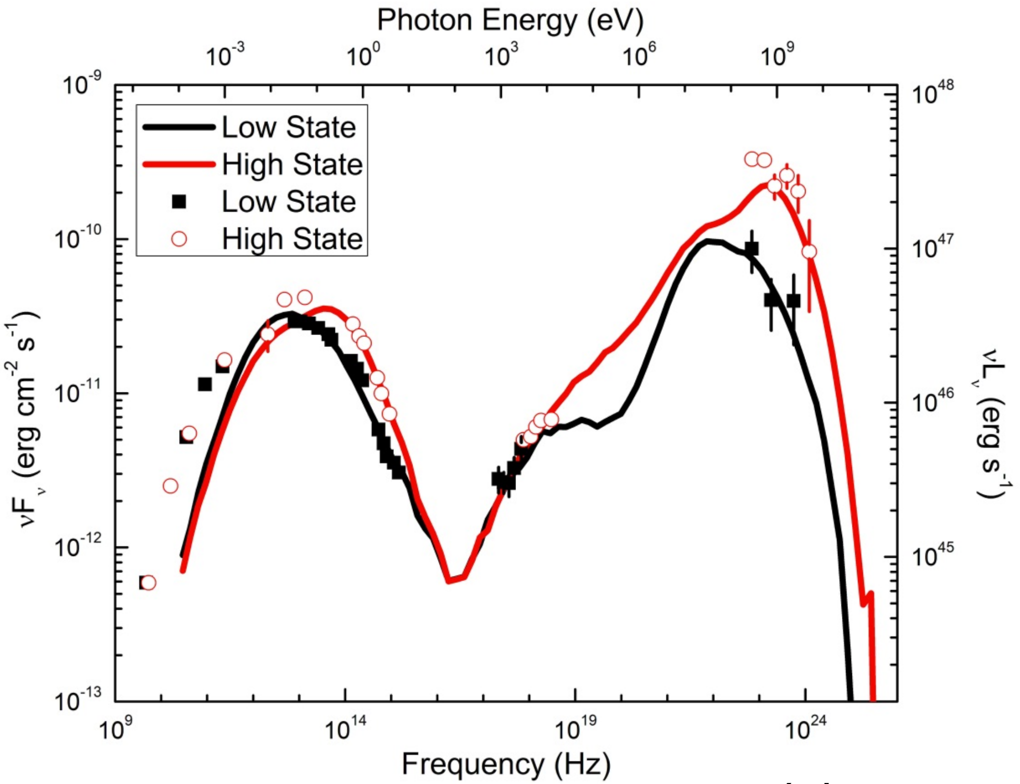

Looking at the jet from the side

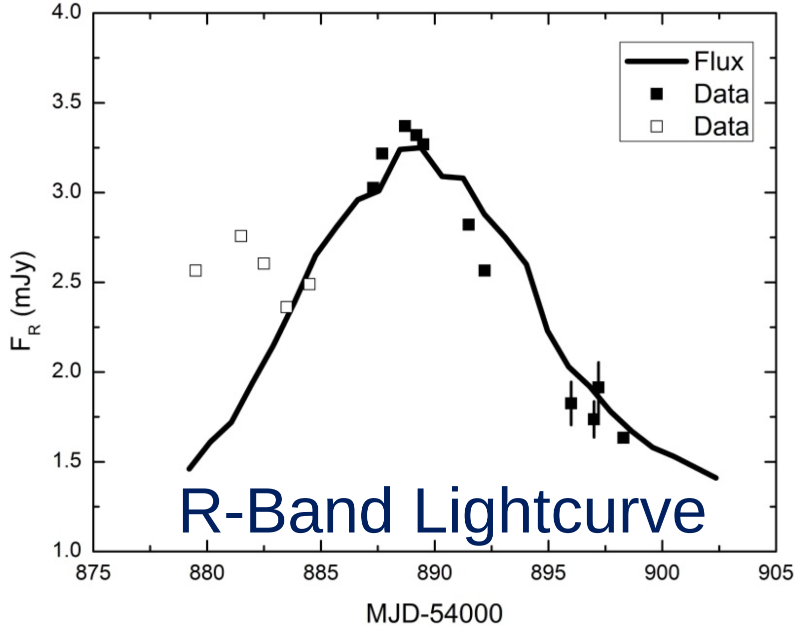


# Application to 3C279

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



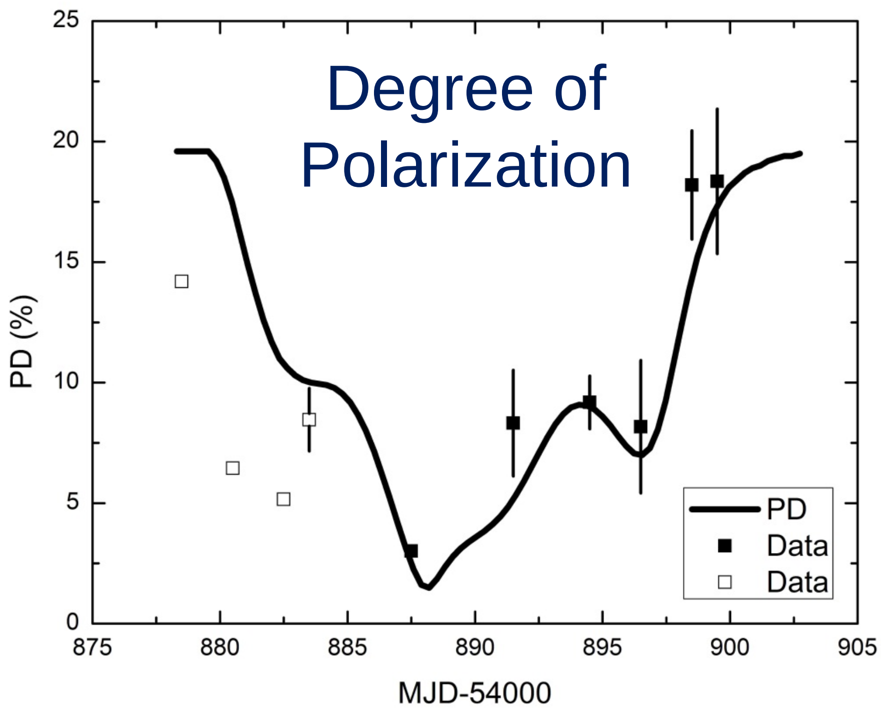



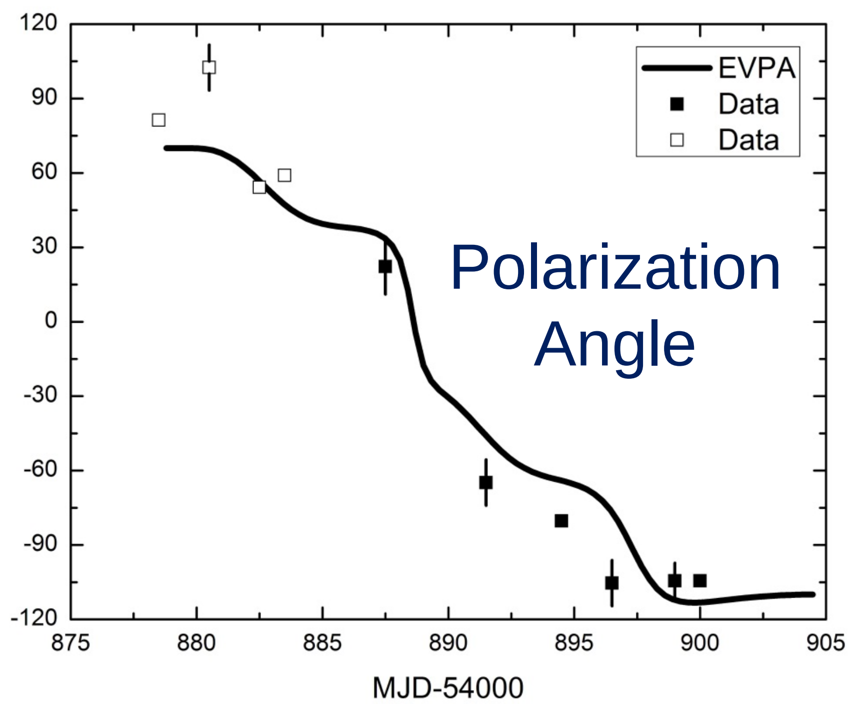




(Zhang et al. 2015)

# Application to 3C279

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




(Zhang et al. 2015)

# Summary

1. Lepontic and hadronic models generally provide equally good SED fits. Possible diagnostics: Neutrinos, Variability, Polarization
2. High-Energy Polarization as Diagnostic: X-rays and $\gamma$-rays are expected to be more highly polarized in hadronic models than leptonic ones.
3. Polarization-angle swings correlated with MW flares do not require non-symmetric jet features and can simply be explained through light-travel-time effects in a straight jet with a helical magnetic field.
4. For 3C279, this model implies a mechanism of magnetic energy dissipation driving the mutli-wavelength flaring activity.