DEPARTMENT OF Physics & Astronomy @OHIO UNIVERSITY

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An Internal Shock Model for the Variability of Blazar Emission

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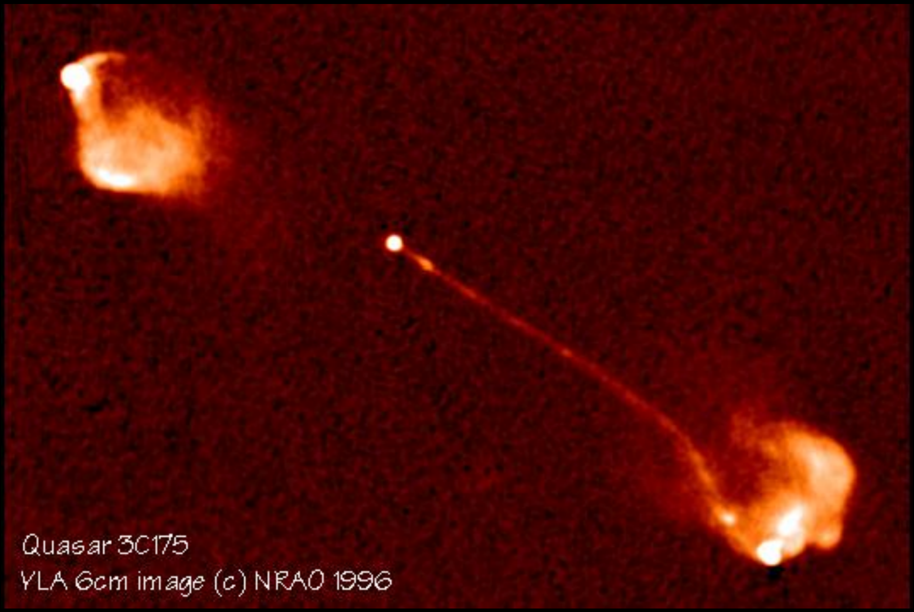
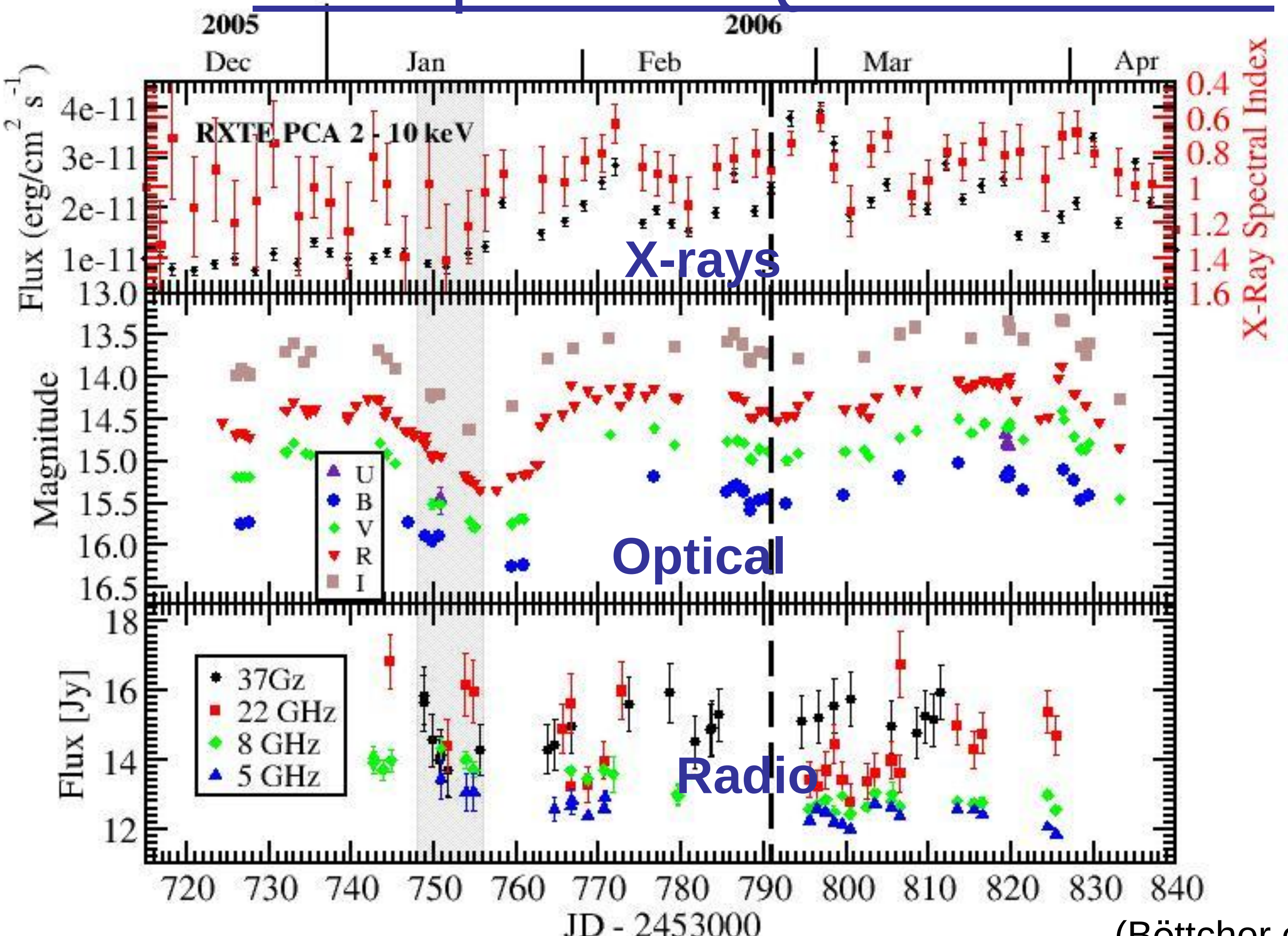
Blazars



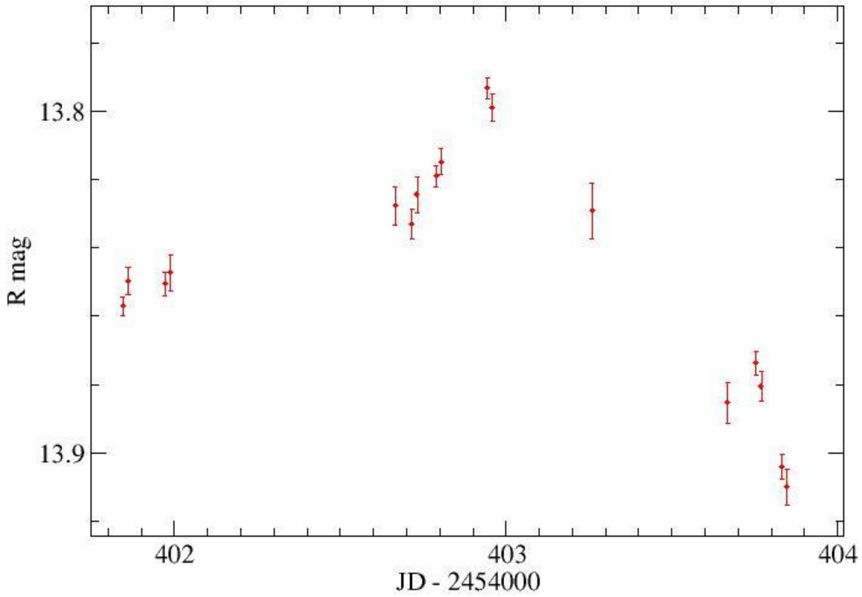
- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

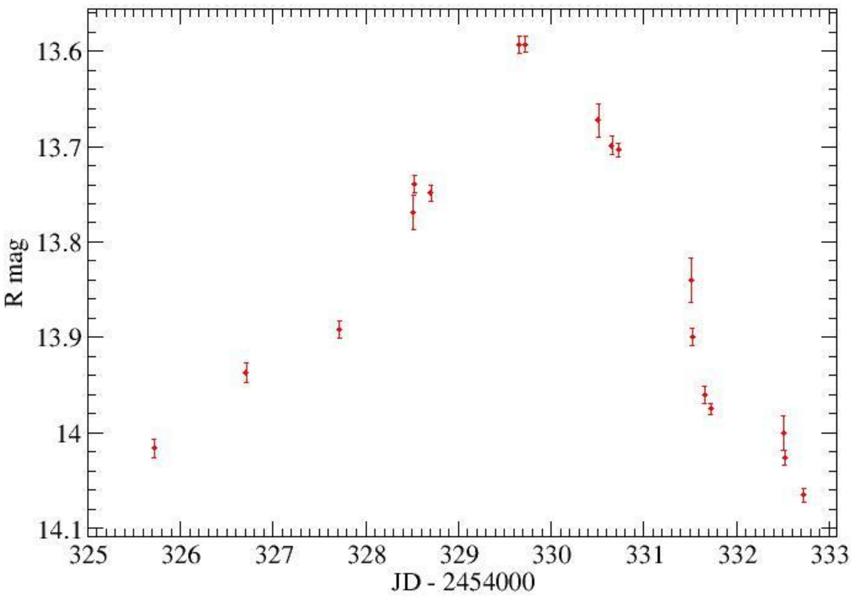
Blazar Variability:
Example: The Quasar 3C279



(Böttcher et al. 2007)

Blazar Variability:
Example: The BL Lac Object 3C66A

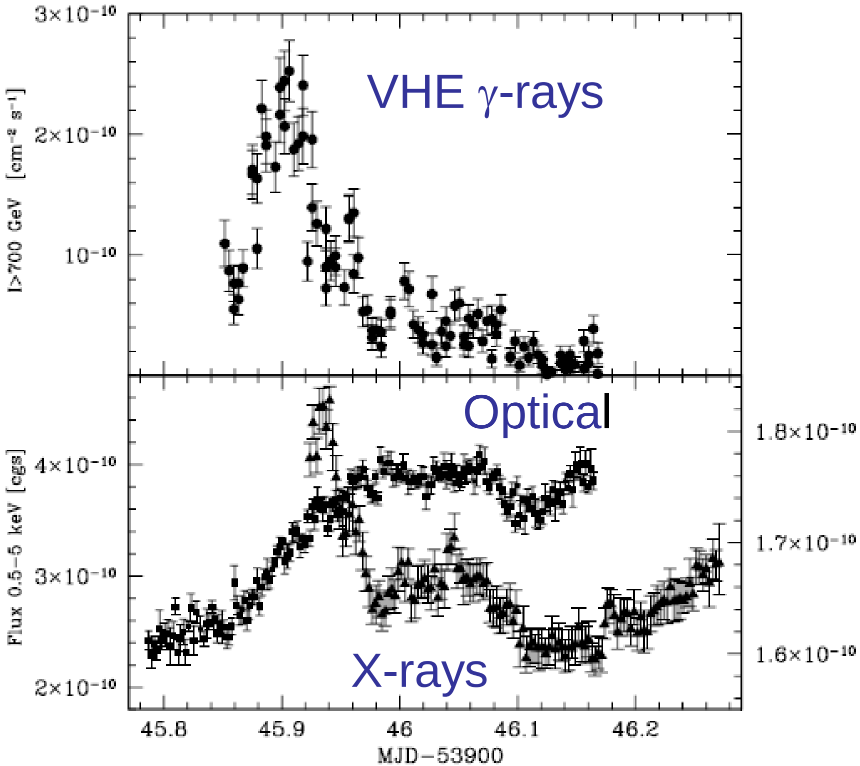




(Böttcher et al. 2009)

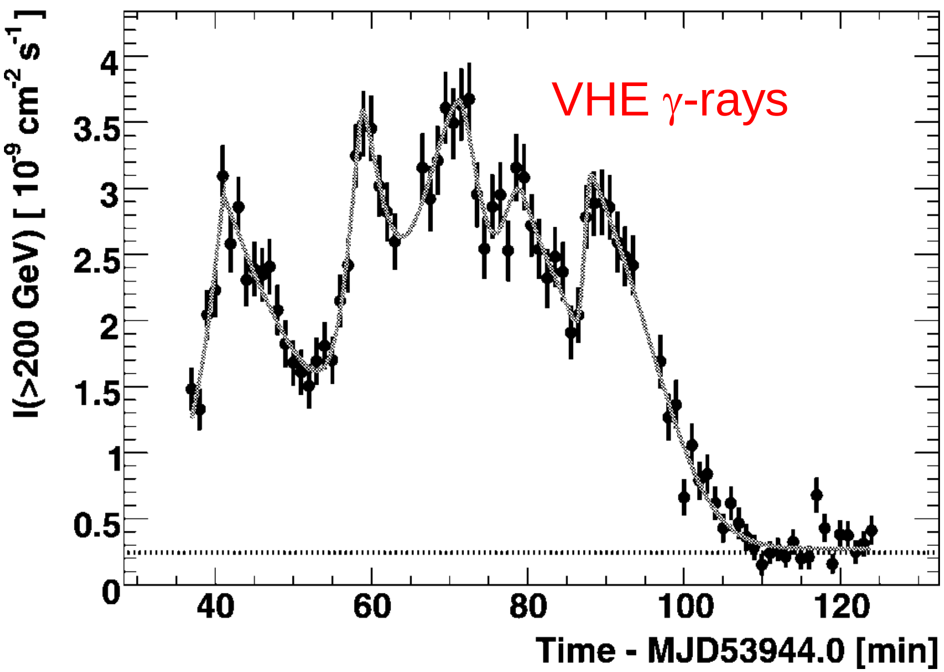
Optical Variability on timescales
of a few hours.

Blazar Variability: Variability of PKS 2155-304



(Costamante et al. 2008)

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



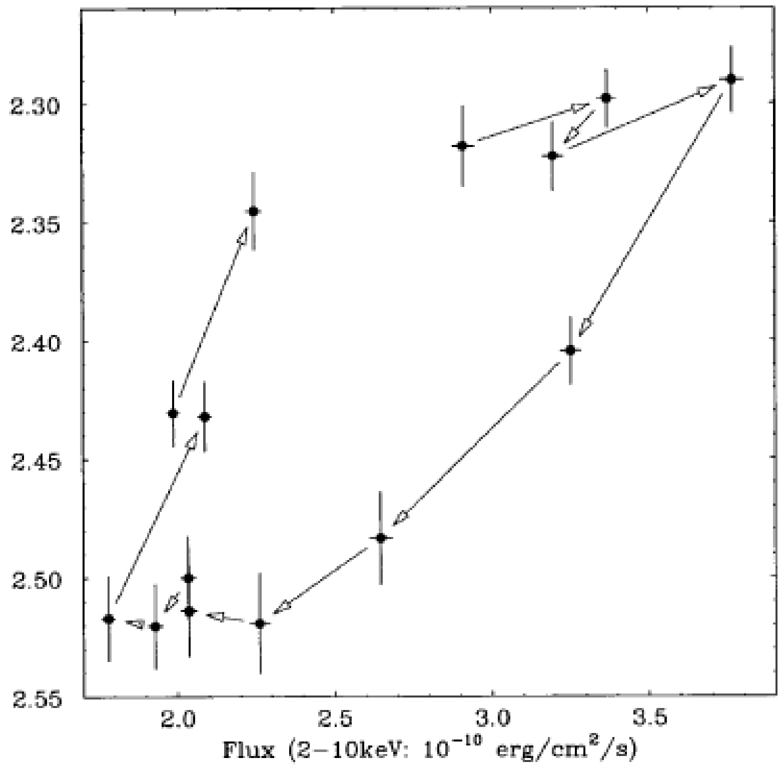
(Aharonian et al. 2007)

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

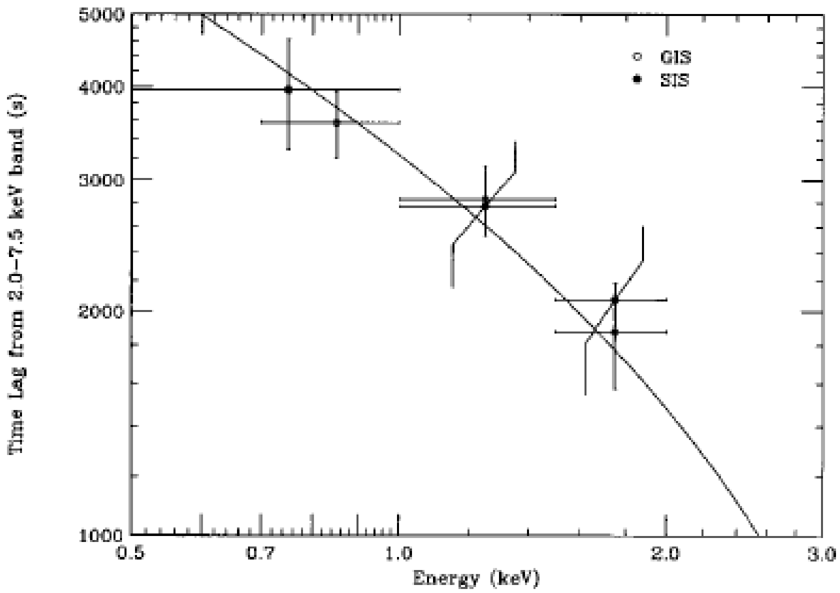
Spectral Variability

Hardness-Intensity Diagrams

Spectral Hardness

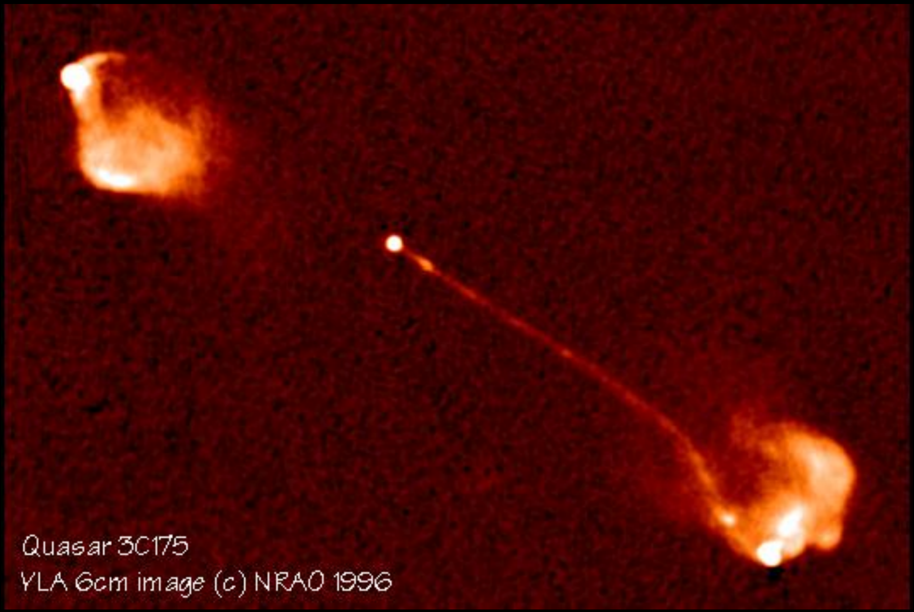


Spectral Time Lags



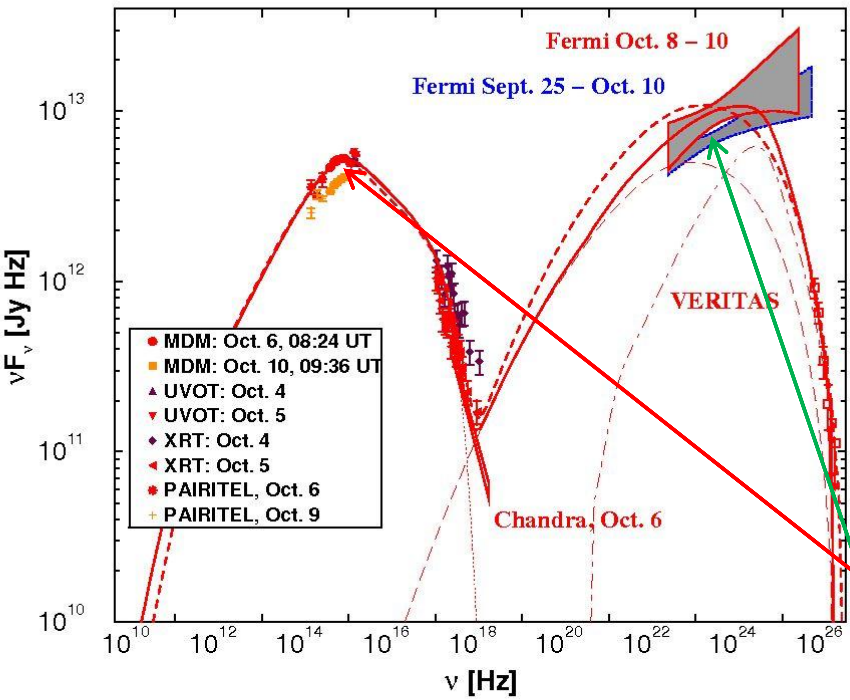
(Mrk 421; Takahashi et al. 1996)

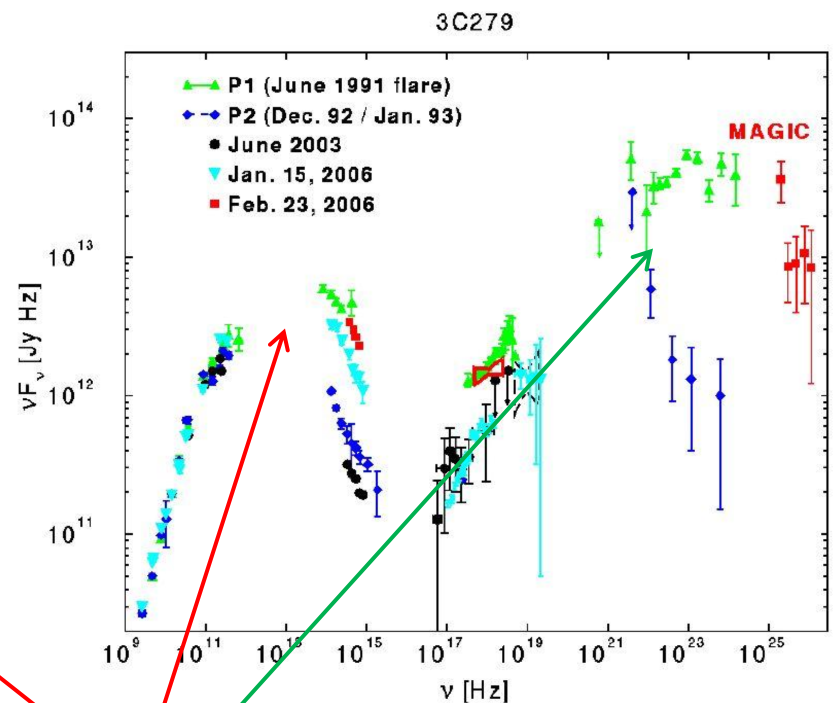
Blazars



- 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)

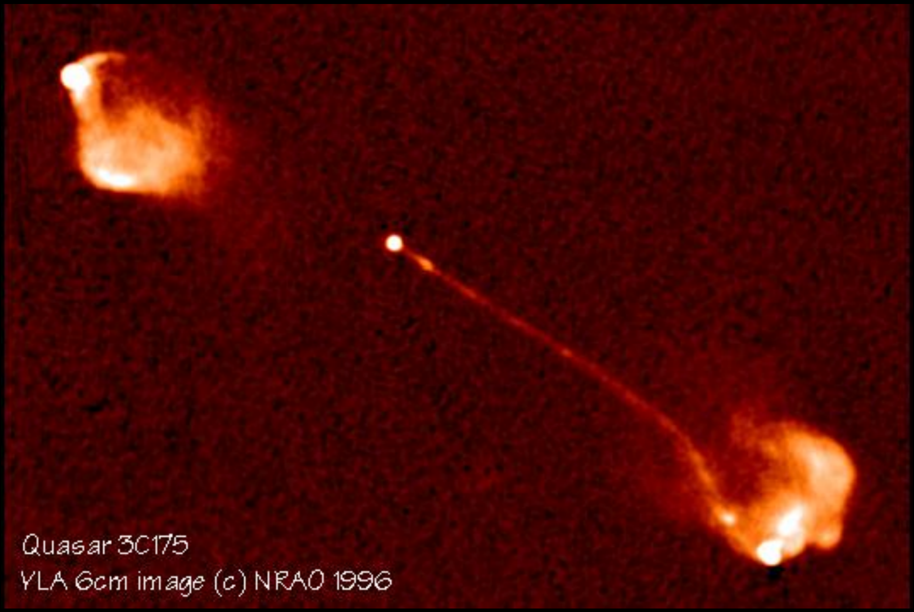




Non-thermal spectra with two broad bumps:

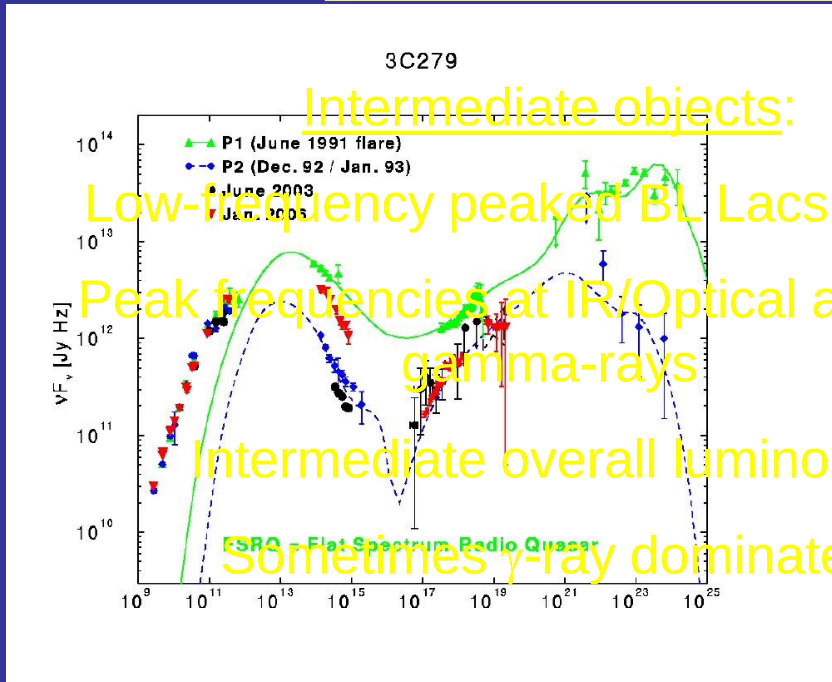
- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

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
- Radio and optical polarization

Blazar Classification



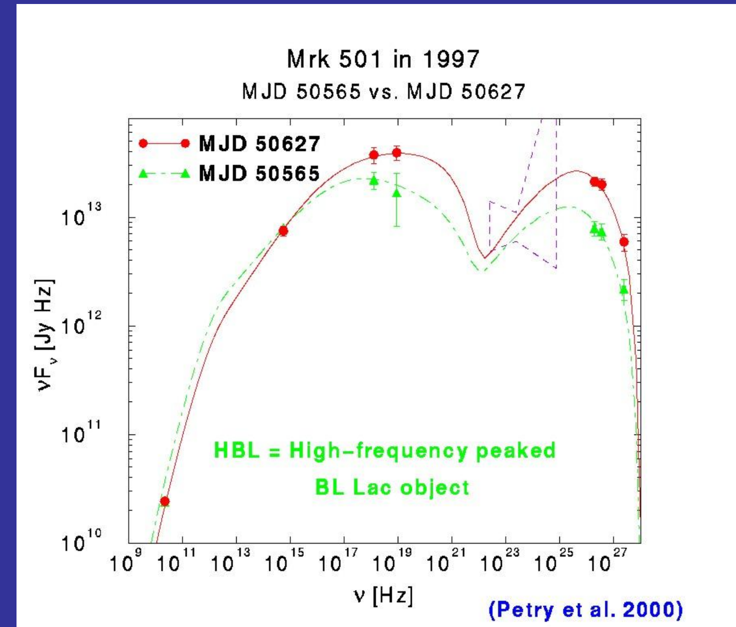
Intermediate objects:

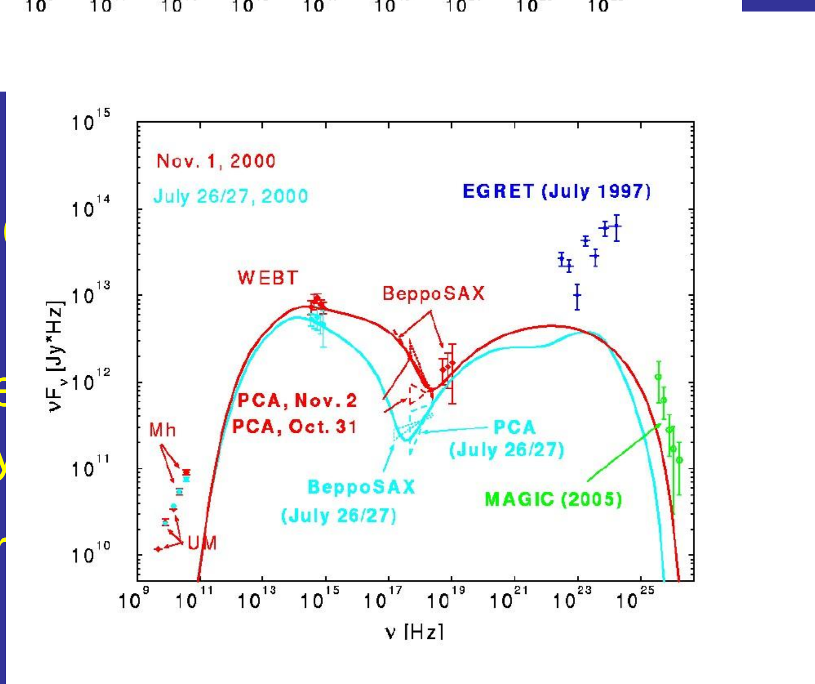
Low-frequency peaked BL Lacs (LBLs):

Peak frequencies at IR/Optical and GeV gamma-rays

Intermediate overall luminosity

Sometimes γ-ray dominated





Low-fre…

High-fre…
to γ-ray…

Peak fr…

High-frequency peaked BL Lacs (HBLs):

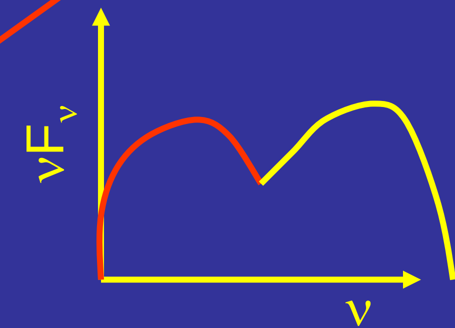
Low-frequency component from radio to UV/X-rays, often dominating the total power

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

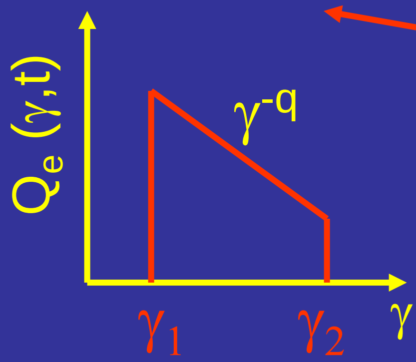
Leptonic Blazar Models

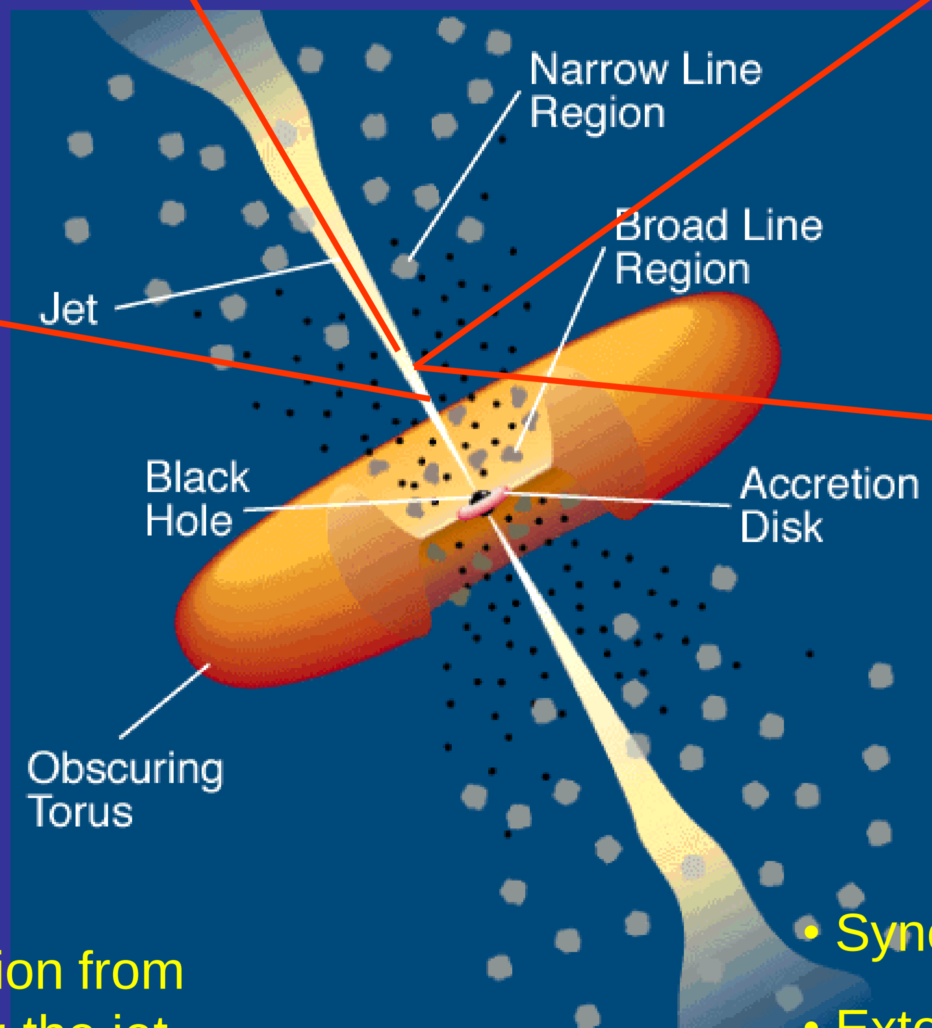
Relativistic jet outflow with $\Gamma \approx 10$

Synchrotron emission

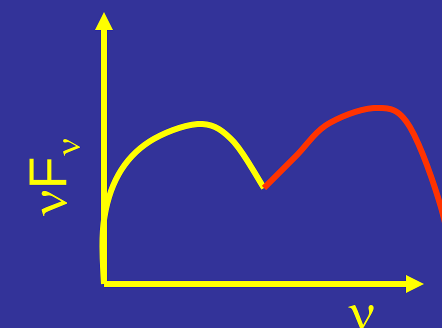


Injection, acceleration of ultrarelativistic electrons





Compton emission



Injection over finite length near the base of the jet.

Additional contribution from $\gamma\gamma$ absorption along the jet

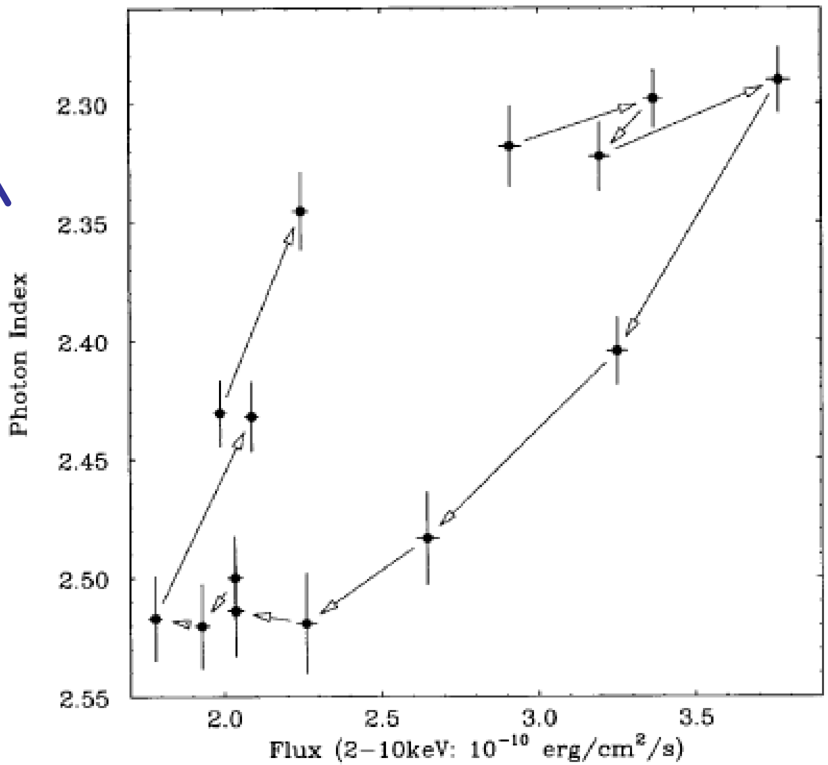
Seed photons:

- Synchrotron (SSC)
- External Sources (EC)

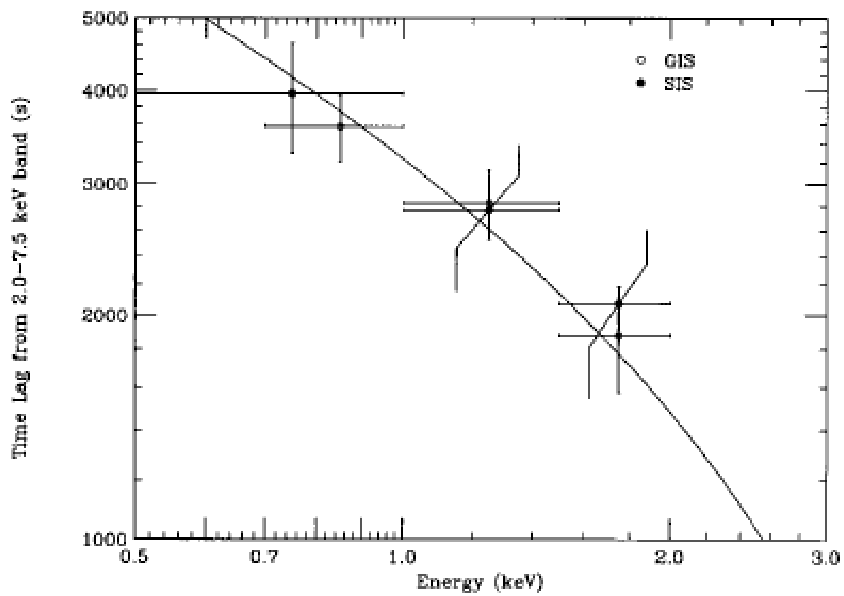
Spectral Variability

Hardness-Intensity Diagrams

Spectral Hardness



Spectral Time Lags



(Takahashi et al. 1996)

Interpretation of Spectral Variability in Blazars

If energy-dependent (spectral) time lags are related to energy-dependent synchrotron cooling time scale:

$d\gamma/dt = -\nu_0\gamma^2$ with $\nu_0 = (4/3)\, c\, \sigma_T\, u'_B$

$t_{cool} = \gamma/|d\gamma/dt| = 1/(\nu_0\gamma)$

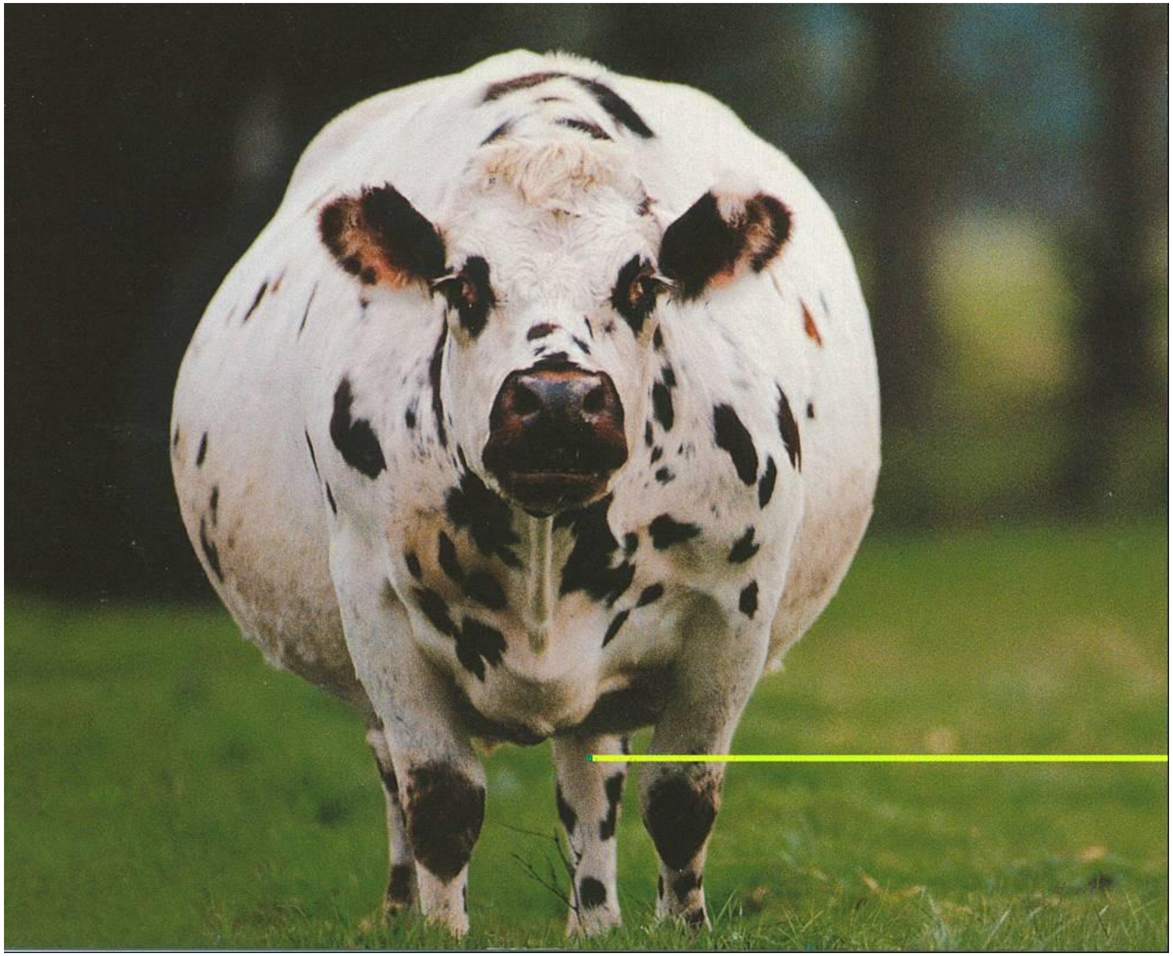
and

$\nu_{sy} = 3.4*10^6\, (B/G)\, (D/(1+z))\, \gamma^2$ Hz

$\Rightarrow\ \Delta t_{cool} \sim B^{-3/2}\, (D/(1+z))^{1/2}\, (\nu_1^{-1/2} - \nu_2^{-1/2})$

=> Measure time lags between frequencies ν_1, ν_2
→ estimate Magnetic field (modulo D/[1+z])!

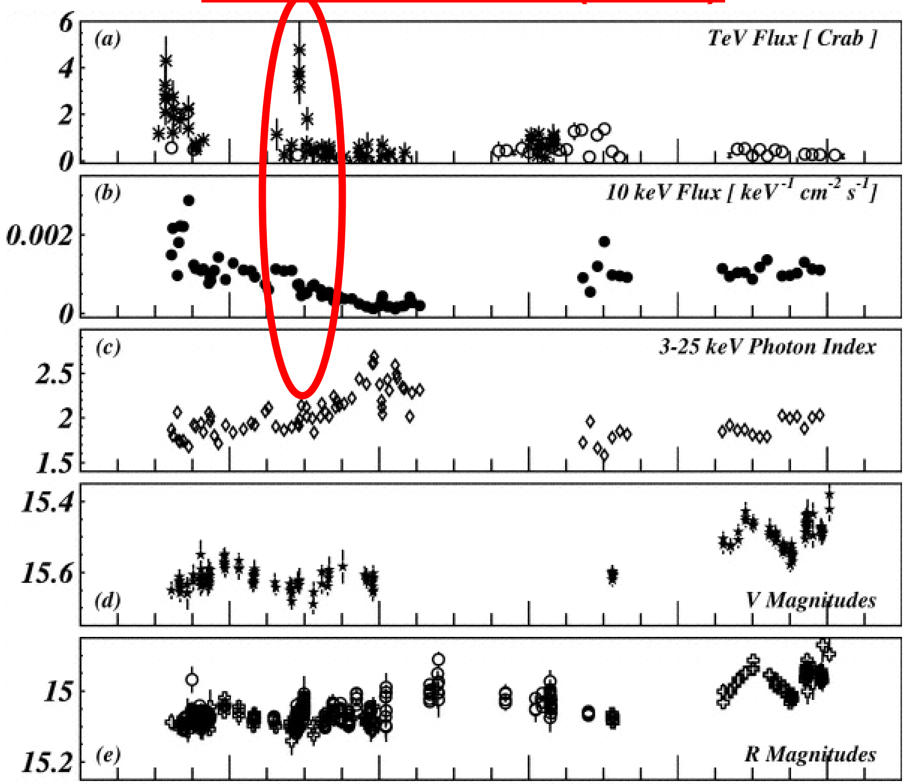
The simplest version assumes that the emission region is spherical …



Problems of spherical, homogeneous models

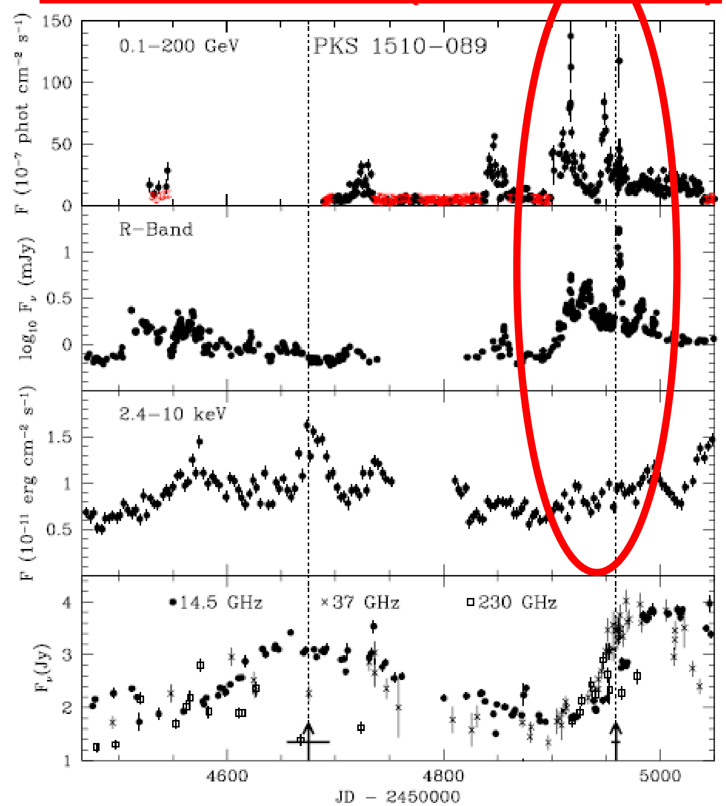
If the entire SED is produced by the same electron population, variability at all frequencies should be well correlated – but …

1ES 1959+650 (2002)



(Krawczynski et al. 2004)

PKS 1510-089 (2008 – 2009)



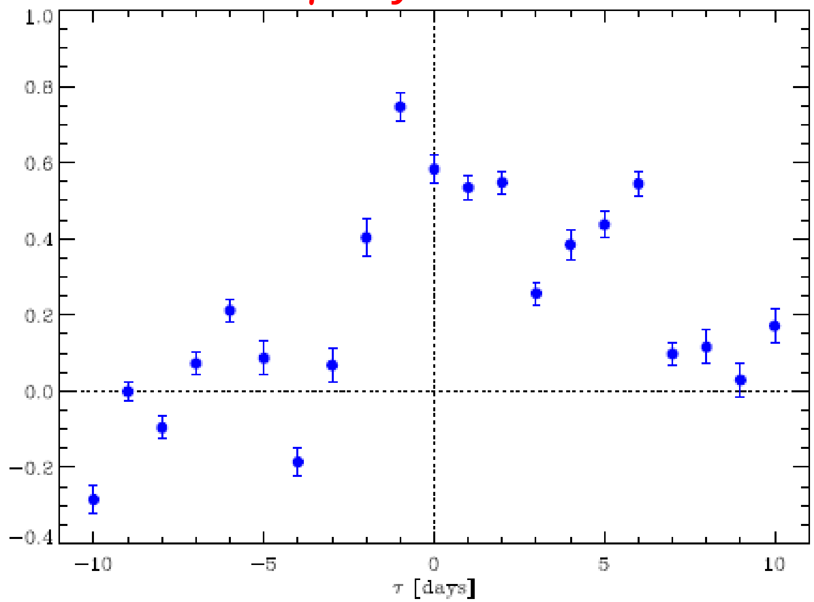
(Marscher al. 2010)

Problems of spherical, homogeneous models

Cross-correlations between frequency bands and time lags do not show a consistent picture

3C454.3 (2007):
AGIlE γ-rays vs. R-band

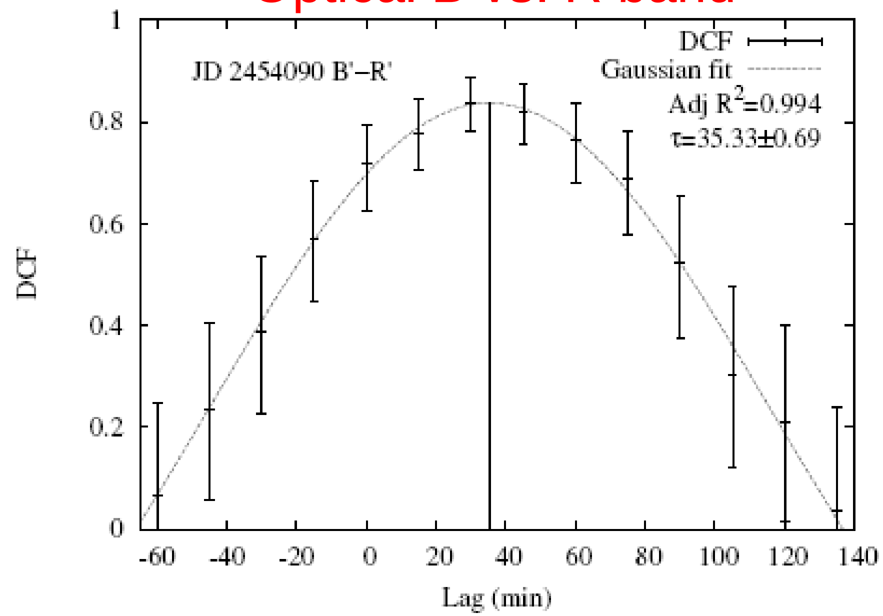
Discrete Correlation Function (DCF)



(Donnarumma et al. 2007)

=> Possible < 1 day delay (hard lag) of γ-rays behind R-band (?)

S5 0716+714 (2006):
Optical B vs. R band



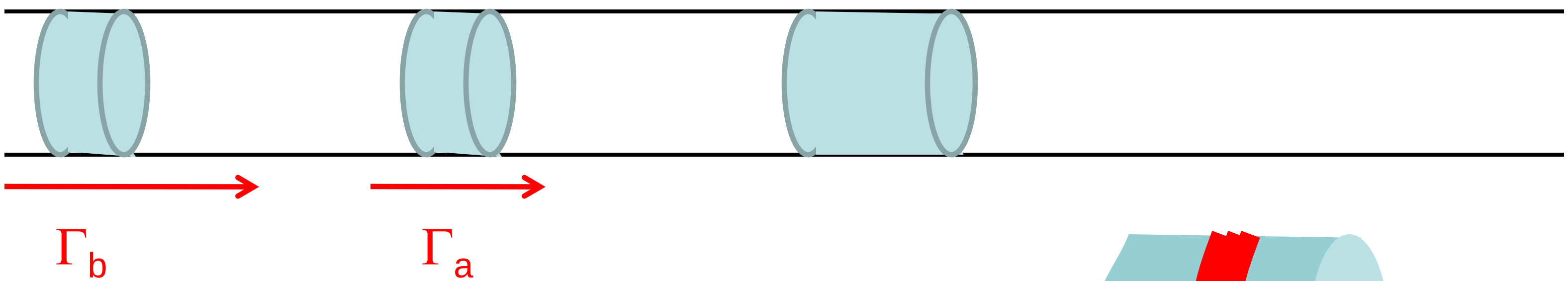
(Wu et al. 2010)

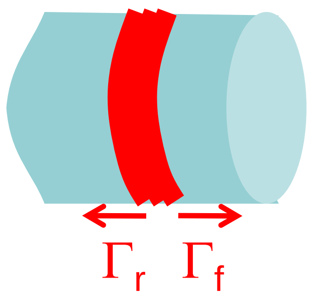
=> ~35 minute delay (soft lag) of R vs. B band

The Internal Shock Model for Blazars

(Böttcher & Dermer 2010)

The central engine ejects two plasmoids (*a,b*) into the jet with different, relativistic speeds (Lorentz factors $\Gamma_b >> \Gamma_a$)





Shock acceleration

→ Injection of particles with

$Q(\gamma) = Q_0\, \gamma^{-q}$ for $\gamma_1 < \gamma < \gamma_2$

γ_2 from balance of acceleration and synchr. Cooling rate

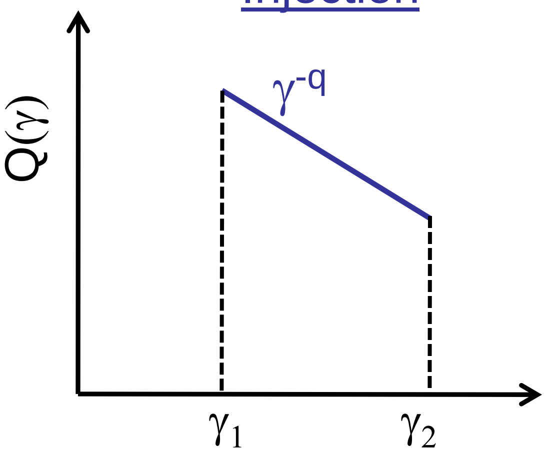
γ_1 from normalization to overall energetics

Time-Dependent Electron Distributions

Competition of injection of a power-law distribution of relativistic electrons with radiative cooling

At any given time $t_{em}(x)$ = time elapsed since the shock has crossed a given point x

Injection

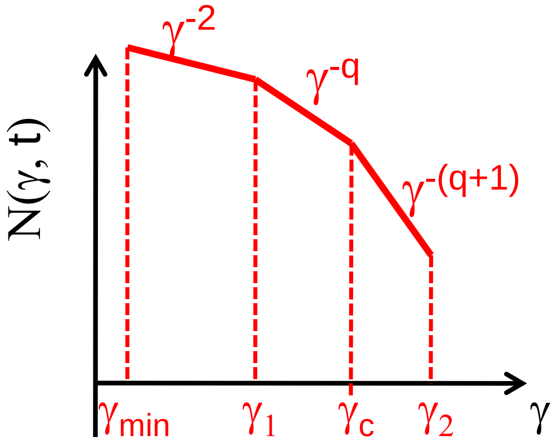


$d\gamma/dt = -\nu_0\gamma^2$

$\rightarrow$ $t_{cool} = \gamma/|d\gamma/dt| = 1/(\nu_0\gamma)$

$\rightarrow$ Spectral break at γ_c, where $t_{em}(x) = t_{cool}$

Time-dependent electron distribution:



$\gamma_{min} = (\gamma_1^{-1} + \nu_0 t)^{-1}$

Radiation Mechanisms

$$\nu F_\nu(\epsilon, t_{\rm obs}) = \frac{D^4\, \pi R^2}{d_L^2} \int\limits_{\overline{x}_{\rm min}}^{\overline{x}_{\rm max}} \overline{\epsilon}\, j_{\overline{\epsilon}}(\overline{x}, \overline{t}_{\rm x,em})\, d\overline{x}$$

1) Synchrotron

$$B_{f,r} = \sqrt{8\pi r\, \epsilon_B \left(\overline{\Gamma}_{f,r}^2 - \overline{\Gamma}_{f,r}\right) n'_{a,b}\, m_p c^2}$$

Delta-function approximation for synchrotron emissivity:

$$j_{\overline{\epsilon},\rm sy} = \frac{c\, \sigma_T\, B^2\, \overline{\epsilon}}{48\pi^2\, b^2\, \gamma_{\rm sy}}\, n_e(\gamma_{\rm sy})$$

=> $\nu F_\nu^{sy}\ (t_{obs})$
can be calculated fully analytically!

Radiation Mechanisms (contd.)

2) External-Compton

Delta-function approximation for Compton cross section:

$$\frac{d\sigma}{d\epsilon_c\, d\Omega_c} \approx \sigma_T\, \delta(\epsilon_c - \gamma^2[1 - \beta\overline{\mu}_c]\epsilon_s)\, \delta(\Omega_c - \Omega_e)\ H(1 - \gamma\epsilon_s[1 - \beta\overline{\mu}_c]).$$

Assume mono-energetic, isotropic external radiation field

=> νF_ν^{EC} (t_{obs})
can be calculated fully analytically!

Radiation Mechanisms (contd.)

3) Synchrotron-Self Compton

Emissivity with delta-function approximation
for the Compton cross section:

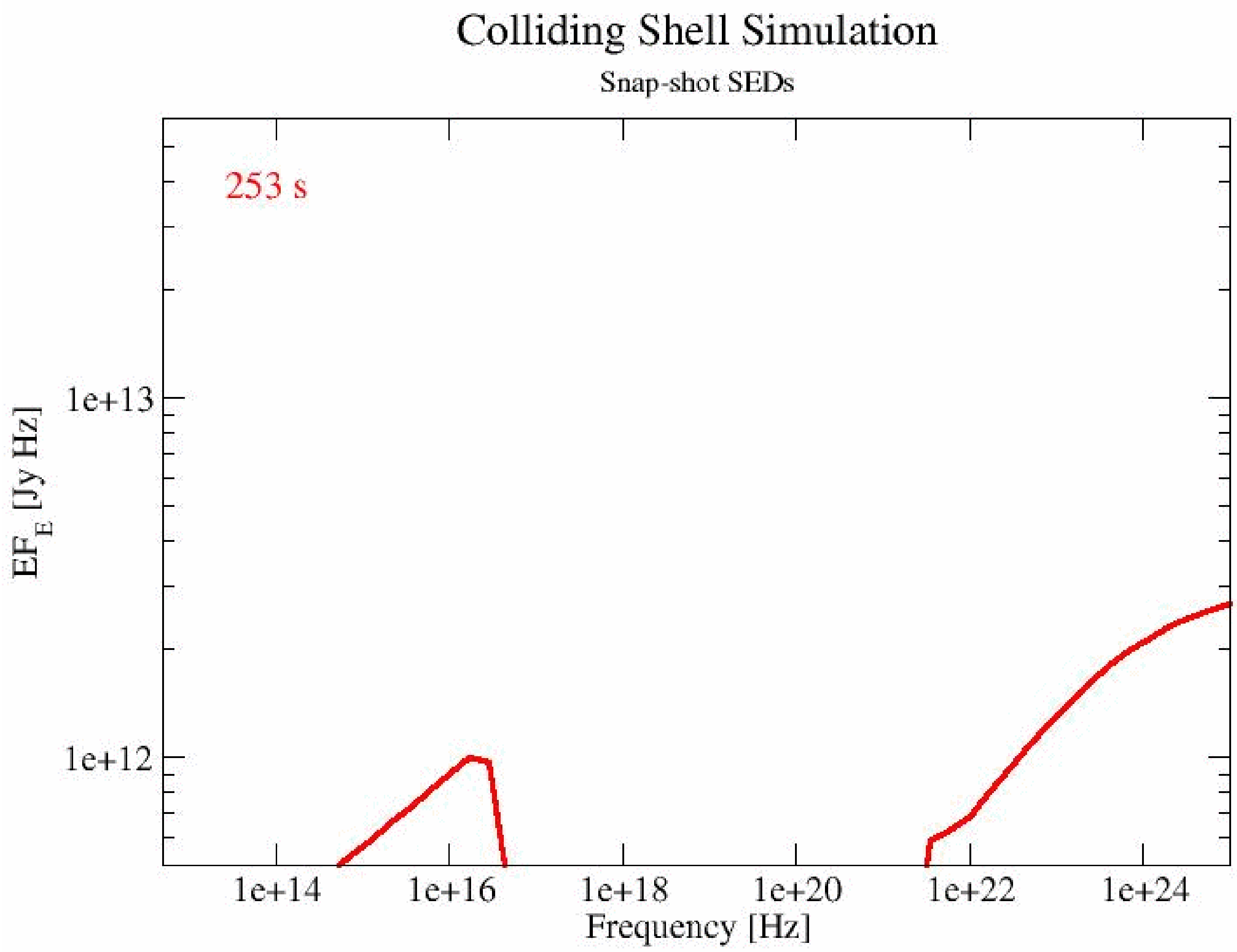
$$j_{\overline{\epsilon},\mathrm{SSC}}(\overline{x},\overline{t}_{\mathrm{x,em}}) \approx \frac{c\,\sigma_T\,m_e c^2}{8\pi}\overline{\epsilon}^{1/2}\int\limits_{4\pi} d\overline{\Omega}_s \int\limits_0^{1/(\overline{\epsilon}[1-\overline{\mu}_c])} d\overline{\epsilon}_s\,\sqrt{1-\overline{\mu}_c}\,\frac{\overline{n}_{\mathrm{ph}}(\overline{\epsilon}_s,\overline{\Omega}_s,\overline{x},\overline{t}_{\mathrm{x,em}})}{\overline{\epsilon}_s^{1/2}}\,n_e(\gamma_c,\overline{x},\overline{t}_{x,em})$$

=> $n_{ph}^{sy}(\varepsilon_s, x, t)$ =
Integral over the retarded synchrotron photon distributions
from all shocked regions of the jet!

$n_{ph}^{sy}(\varepsilon_s, x, t)$
can be calculated fully analytically
=> Two integrations to be done numerically.

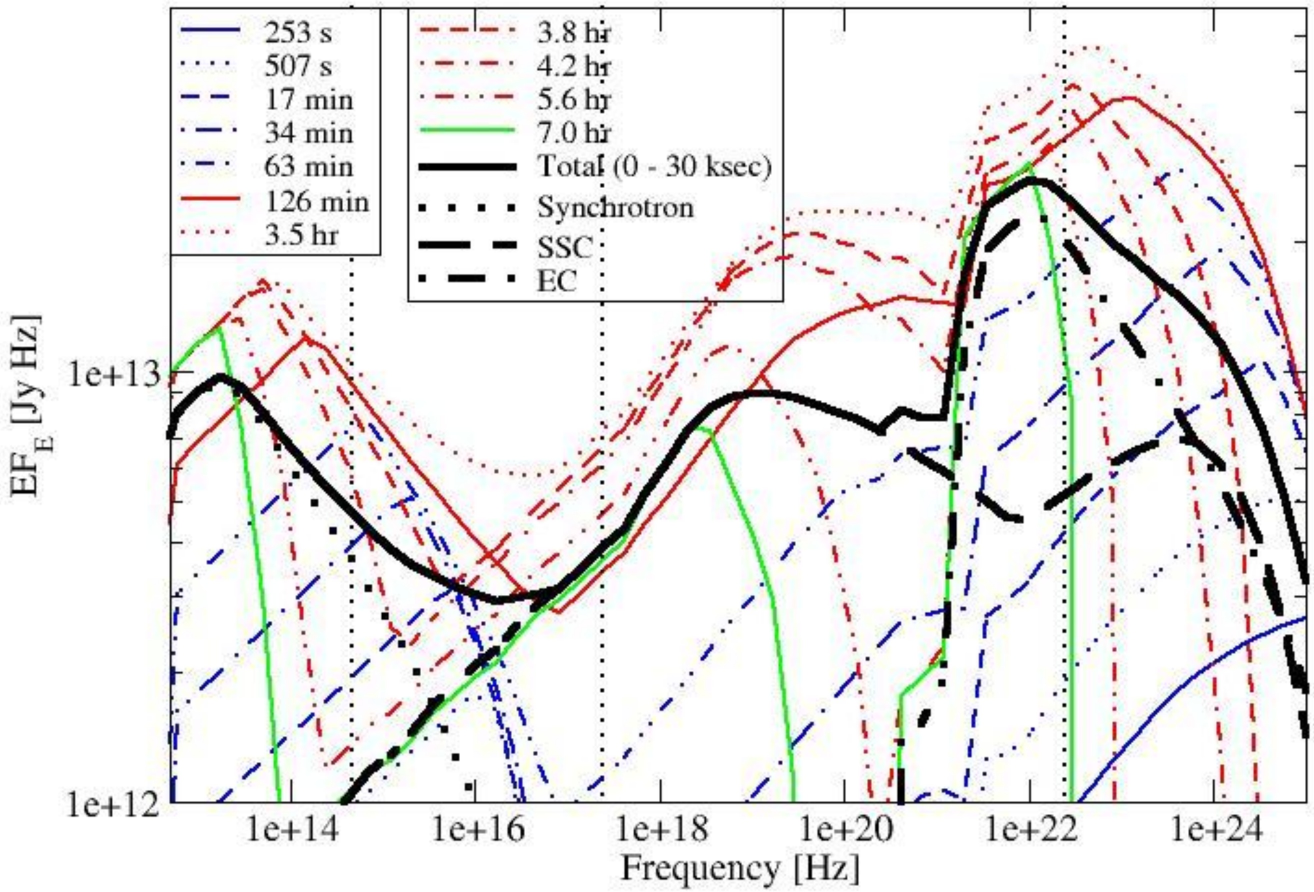
Baseline Model

Parameters / SED characteristics typical of FSRQs or LBLs



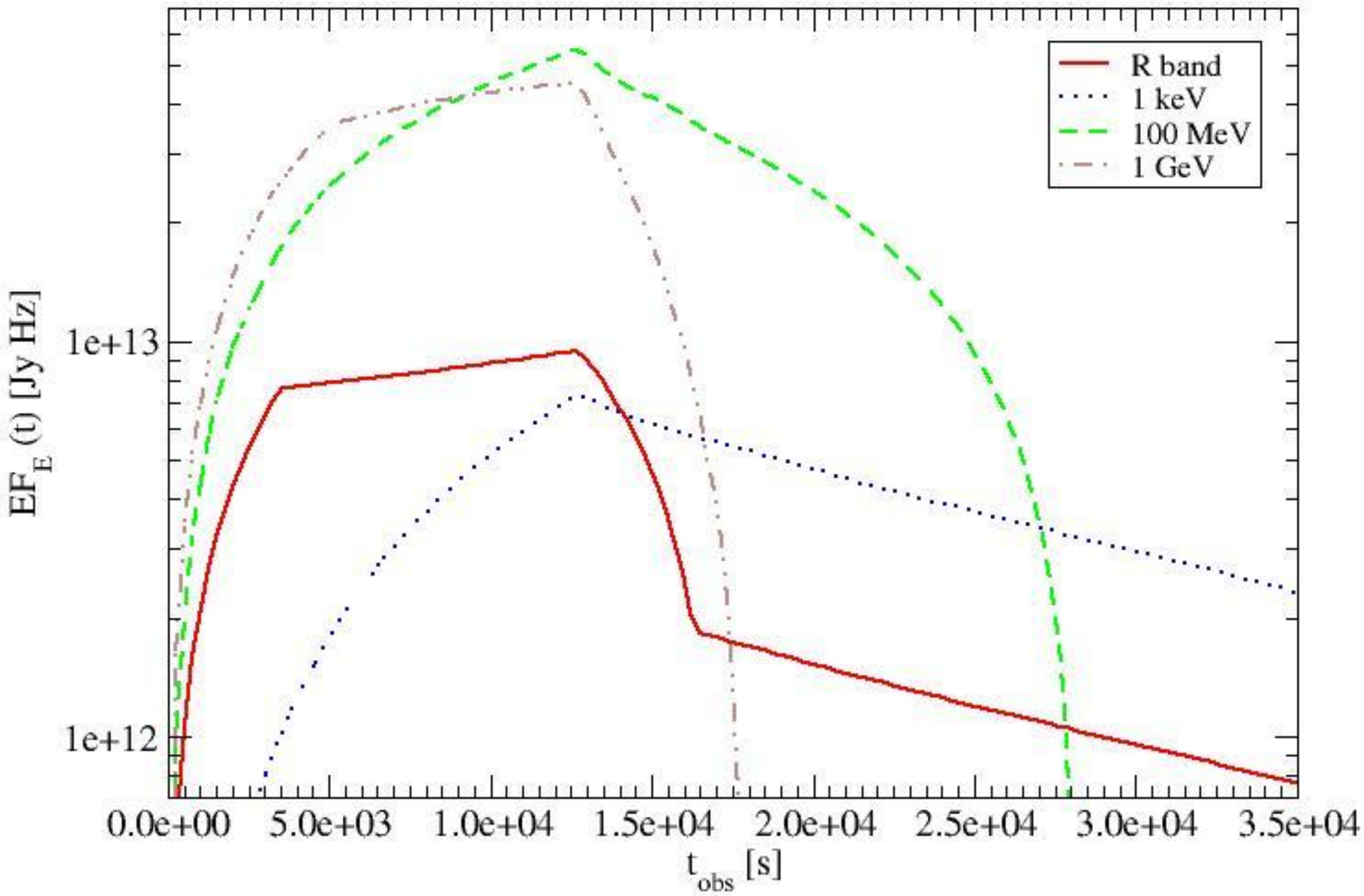
Baseline Model

Snap-shot SEDs and time-averaged SED over 30 ksec



Baseline Model

Light Curves

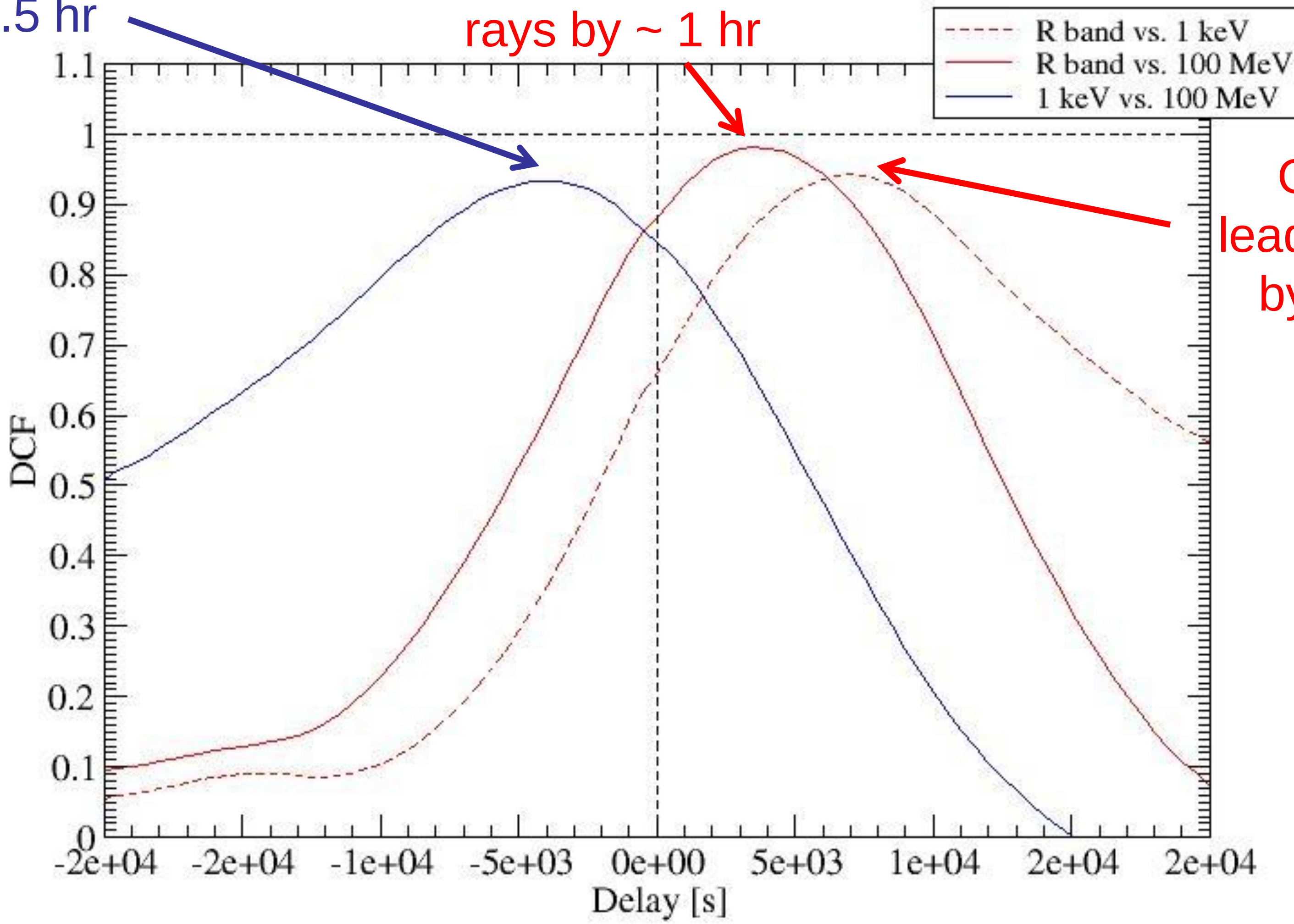


Baseline Model

Discrete Correlation Functions

X-rays lag behind HE γ-rays by ~ 1.5 hr

Optical leads HE γ-rays by ~ 1 hr

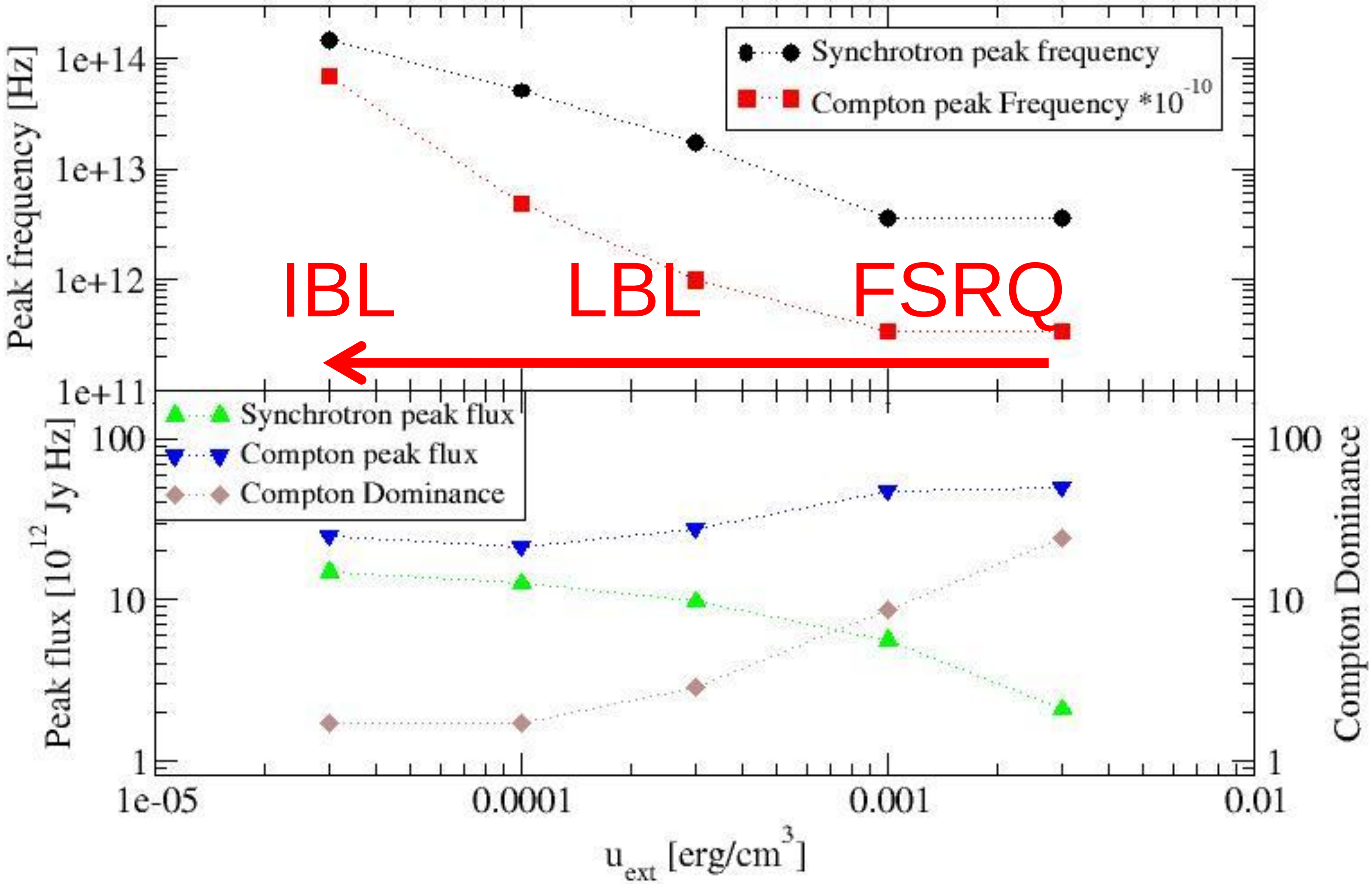


Optical leads X-rays by ~ 2 hr

Parameter Study

Varying the External Radiation Energy Density

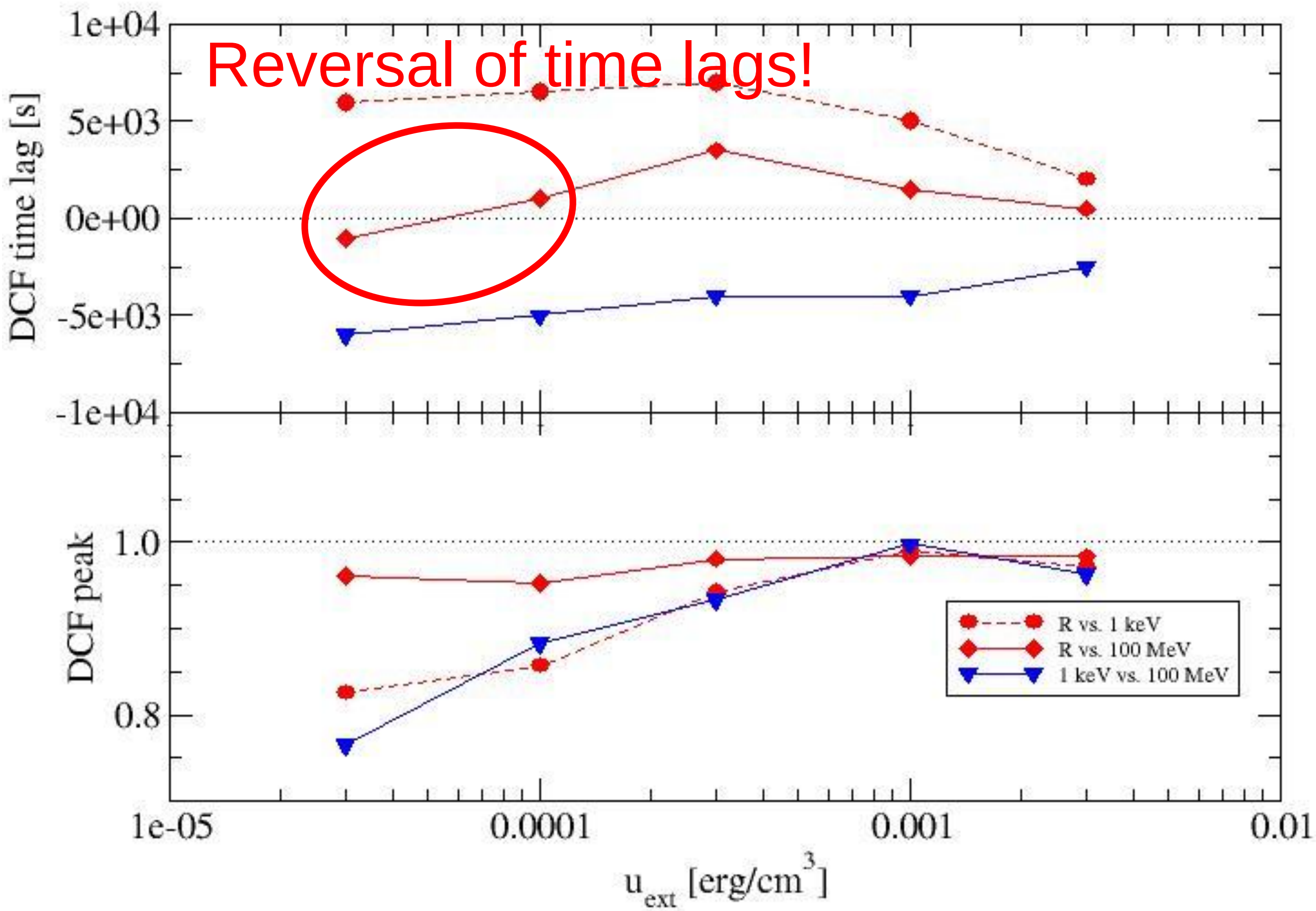
SED Characteristics



Parameter Study

Varying the External Radiation Energy Density

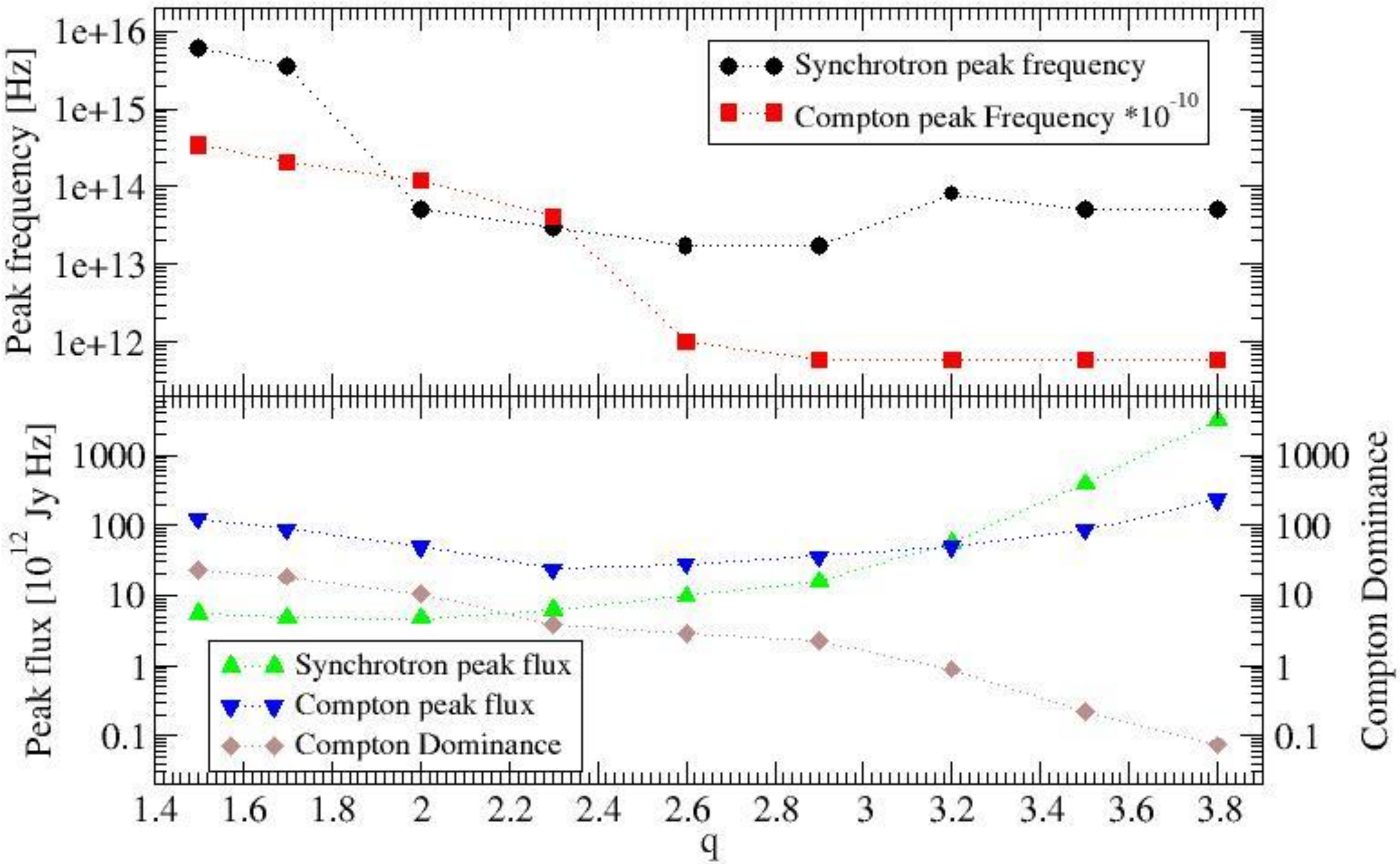
DCFs / Time Lags



Parameter Study

Varying the External Radiation Energy Density

SED Characteristics

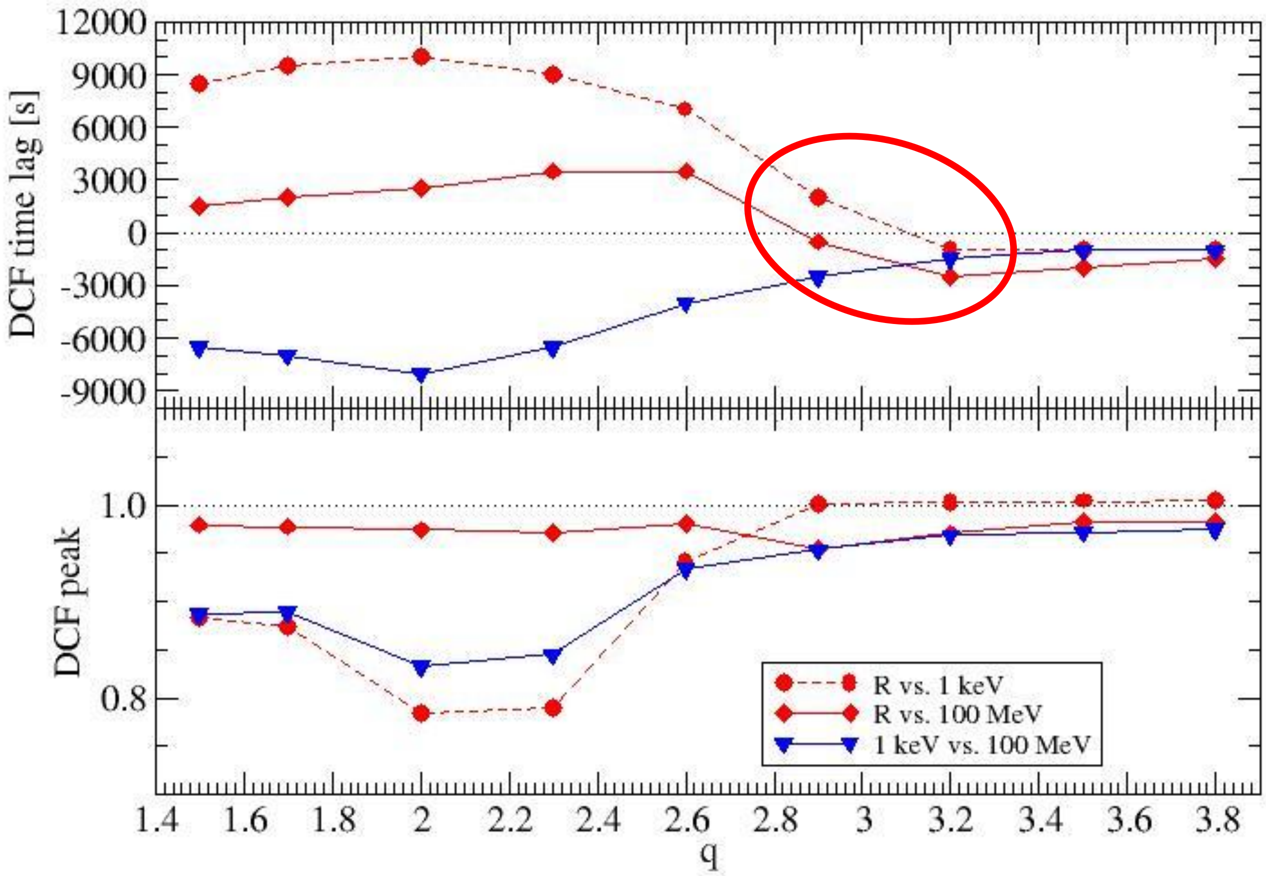


Parameter Study

Varying the External Radiation Energy Density

DCFs / Time Lags

Reversal of time lags!



Summary

- *We developed a semi-analytical internal shock model for blazars: Synchrotron + EC analytical; SSC: 2 numerical integrations.*
- *Appropriate to reproduce SEDs of FSRQs and LBLs*
- *Predicts optical lead before higher-energy emission by 1 – 2 hours*
- *Magnitude and sign of time lags sensitive to various poorly constrained parameters.*