A Diagnostic Test for Determining the Location of the GeV Emission in Powerful Blazars

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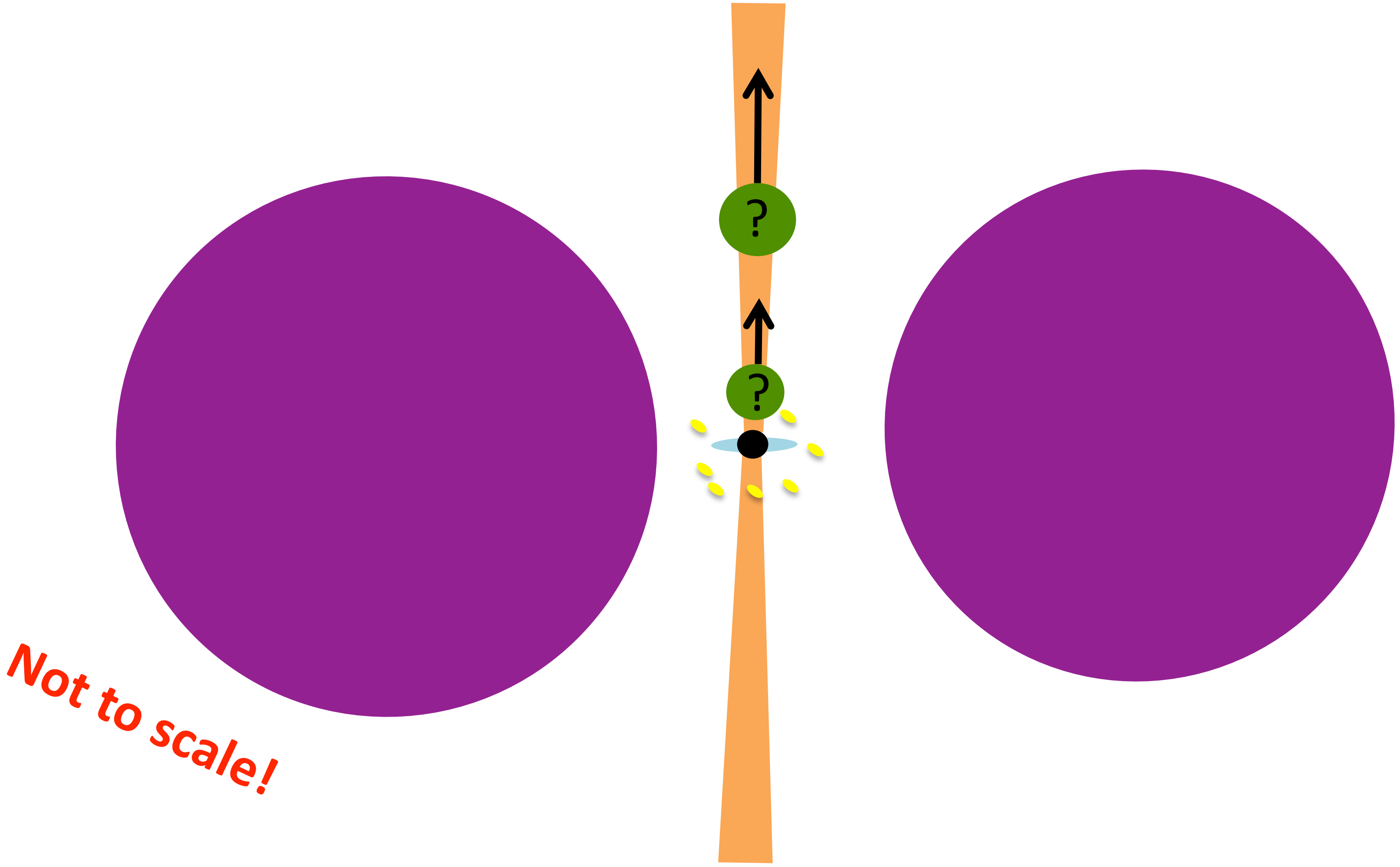
The Issue at Hand

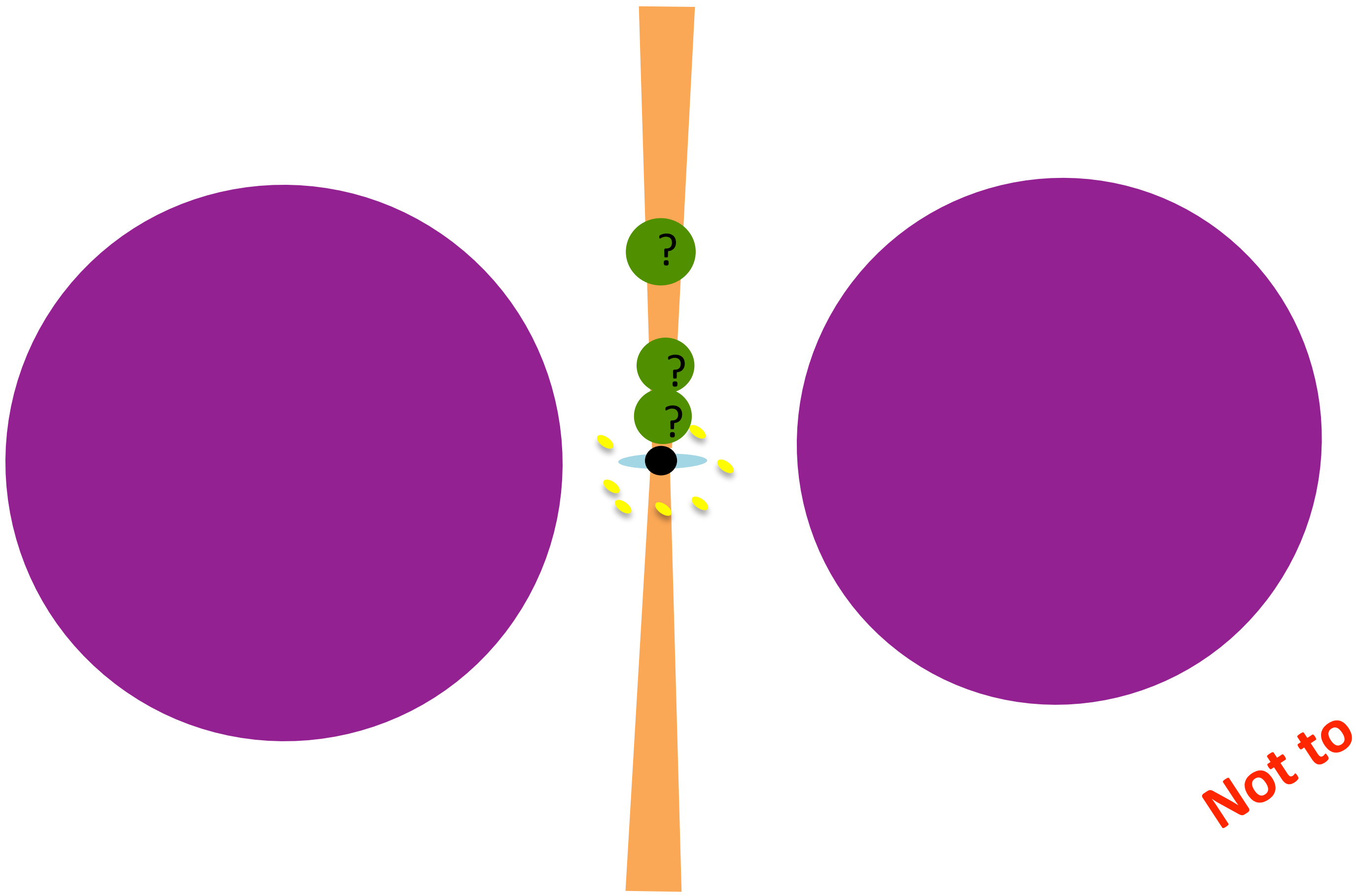
Simply stated: Where is the site of the GeV emission in blazars?

1) Closer to the SMBH (i.e. within the BLR) $R_{BLR} \sim 10^{17}$ cm (~0.1 ly)

2) Farther from the SMBH (i.e. outside the BLR) $R_{MT} \sim 10^{18}$ cm (~1 ly)



Possible Sources of Seed Photons



Not to scale!

Synchrotron Photons?
Accretion Disk Photons?
BLR Photons?
Molecular Torus Photons?

Relativistic Effects

Depending on the direction the photons enter the jet,
U’ (co-moving energy density) scales as different factors of Γ
(Dermer 1994)

For isotropic photon field:

$$U' \approx \frac{\Gamma^2 L}{4\pi c R^2}$$

For photons entering from behind:

$$U' \approx \frac{L}{4\pi c R^2 \Gamma^2}$$

This determines which photon field is prevalent at different distances from the BH.

Which seed photons dominate where?

Assumptions:

$L_{disk} = 10^{45}$ ergs s^{-1} , $L_{ext}=0.1L_{disk}$,$L_{synch}=10^{46}$ ergs s^{-1}

$R_{BLR} = 10^{17}$ cm, $R_{MT} = 10^{18}$ cm, $R_{blob}=10^{16}$ cm $\Gamma_{bulk}=10$

	Inside BLR	Outside BLR
SSC Photons		
Accretion Disk Photons		
BLR Photons		
MT Photons		

Cooling in the BLR vs the MT

BLR

- R = 10^{17} cm
- U'=2.6 ergs cm^{-3}
- Dominated by emission lines (Lyα)
- $\varepsilon_0 = 10^{-5}$ (~10 eV)

MT

- R = 10^{18-19} cm
- U'=2.6 ×10^{-2} ergs cm^{-3}
- BB emission, peaking at T~1000 K (Malmrose 2011)
- $\varepsilon_0 = 10^{-7}$ (~.1 eV)

The critical difference between the BLR and the MT is the energy of the seed photons.
This difference in ε_0 affects the energy regime in which electron cooling takes place, and thus the energy dependence of the cooling time.

A Simple Diagnostic

We propose a model-independent diagnostic that utilizes the energy dependence of electron cooling timescales to determine whether the GeV emission originates from inside or outside the BLR.

Cooling Times

The cooling time of electrons depends on energy loss rate from synchrotron and Compton processes

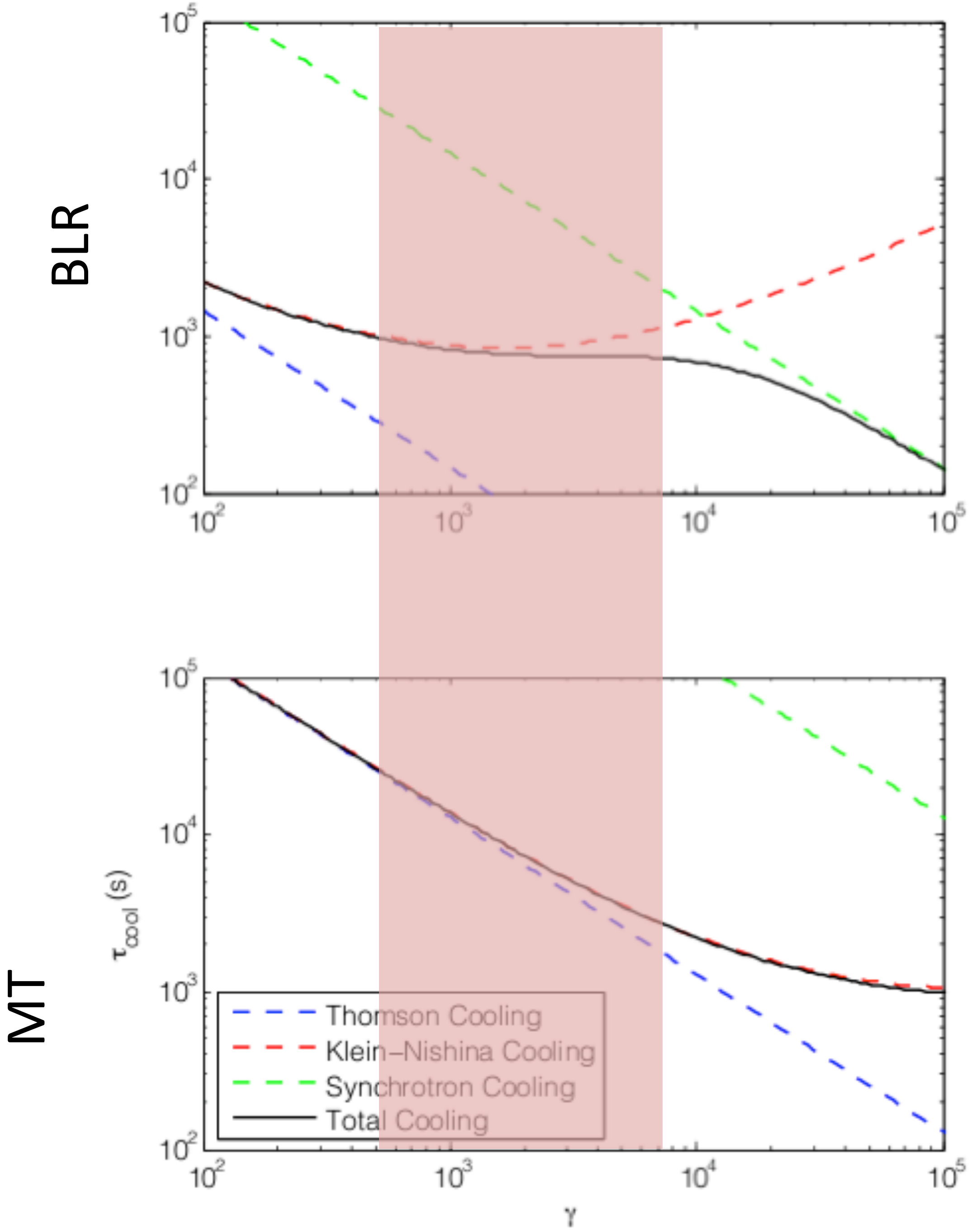
$$\tau_{cool} = \gamma / \dot{\gamma}_{total}$$

$$\dot{\gamma}_{total} = \dot{\gamma}_{synch} + \dot{\gamma}_{IC}$$

$$\dot{\gamma}_{IC,T} \propto \gamma^2$$

$$\dot{\gamma}_{IC,KN} \propto \log(\gamma)$$

$$\dot{\gamma}_{synch} \propto \gamma^2$$

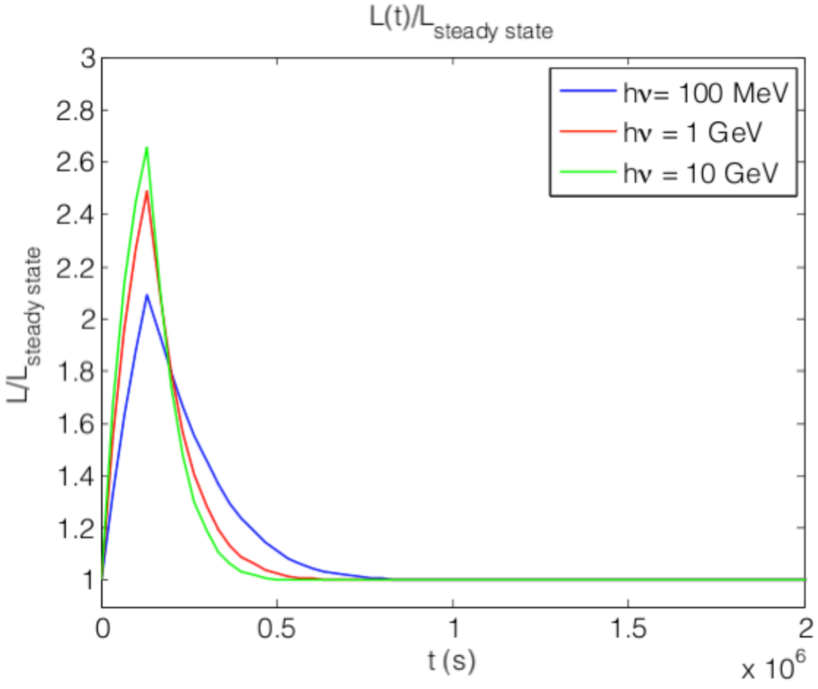


Because the emission is dependent on the electron distribution, this energy-independence of the electron cooling time in the BLR should be manifested in a flare at these energies also being energy independent.

Simulation Results

Emission Site Inside the BLR

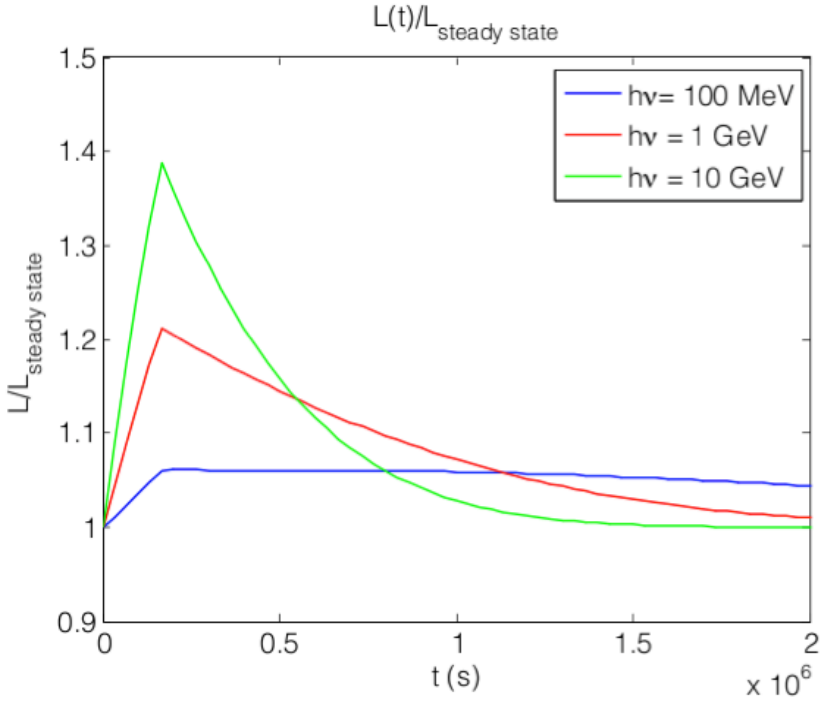
$U_{BLR} = 2.6 \times 10^{-2}$ ergs cm^{-3},$\varepsilon_0=3\times10^{-5}$



- Variations should be achromatic
- Comparable decay timescales at different energy bands

Emission Site Outside the BLR

$U_{MT} = 2.6 \times 10^{-4}$ ergs cm^{-3},$\varepsilon_0=1.6\times10^{-7}$



- Variations are energy dependent
- Decay timescale depends heavily on energy

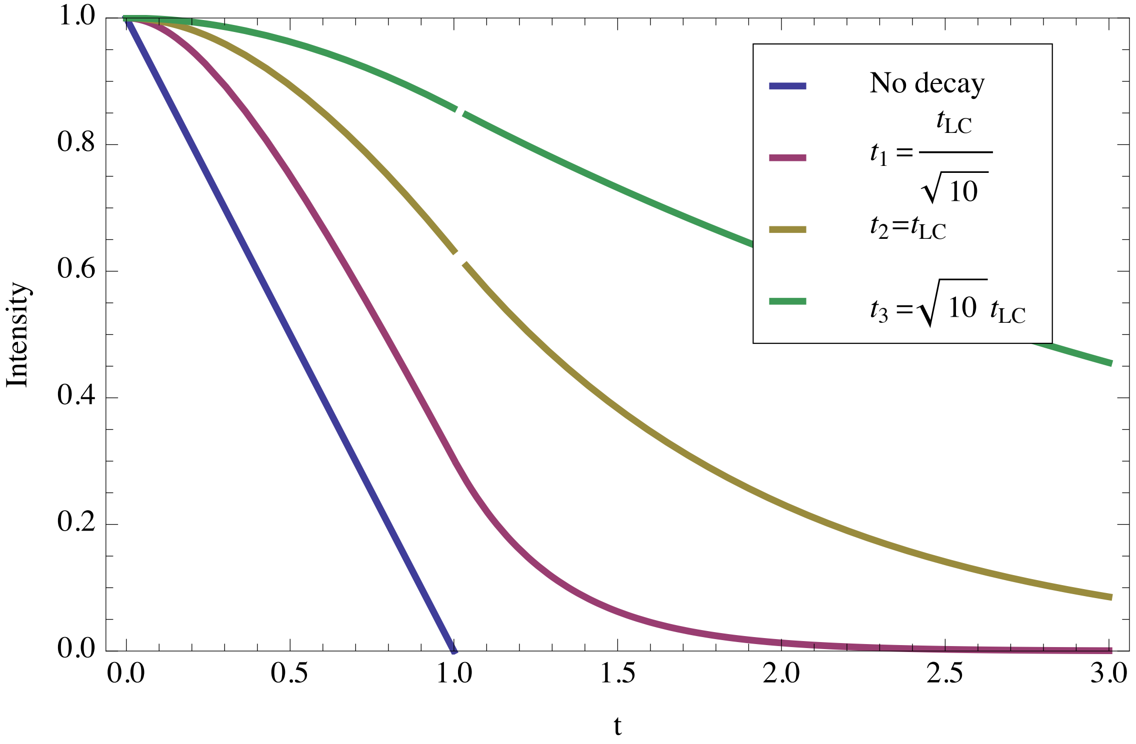
Assumptions: $L_{ext}=10^{44}$ ergs s^{-1} $U_{EC}/U_B \sim 100$, $\Gamma=10$

Light-Crossing Effects

- We assume cooling in the Thomson regime (i.e. flare located in the MT)

- Flare decay time includes time delays associated with light-crossing times

- Will the application of our diagnostic be affected by light-travel times?



There is a noticeable difference in the cooling time at different energies, even when light-travel time delays are included.

Feasibility Study

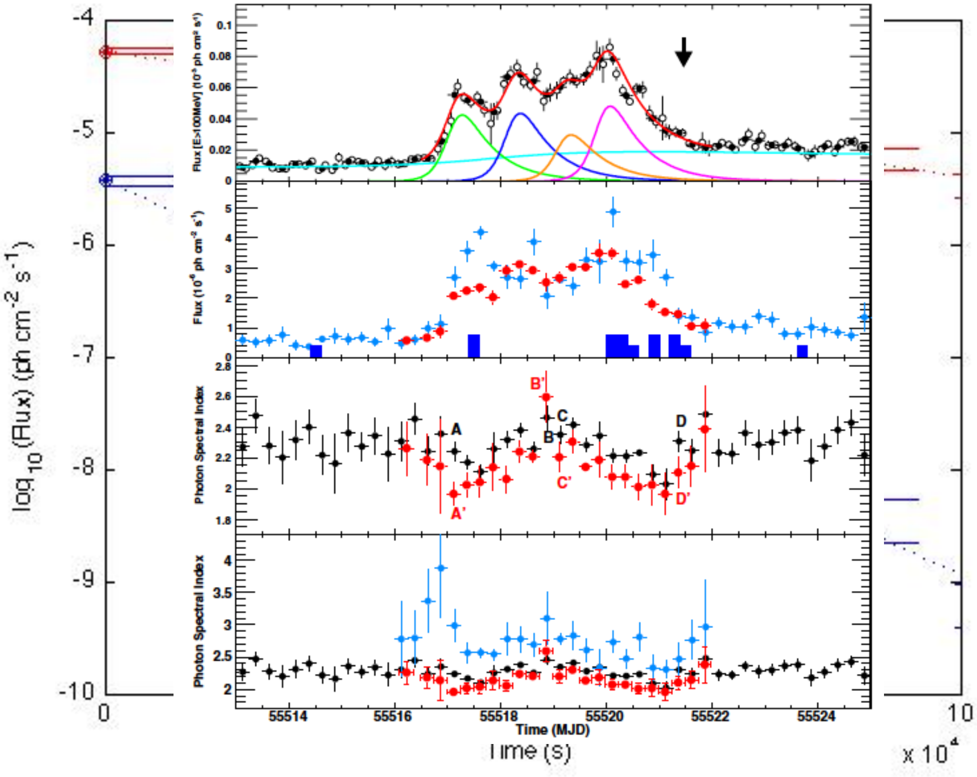
Will observational error prevent us from applying our diagnostic?

The test:
Using maximum fluxes at 100 MeV and 1 GeV from flare of 3C 454.3, we assumed an exponential decay ($F=F_0\ e^{-t/tc}$) and applied the <u>maximum error</u> to data points.

After performing a linear fit on those lines:

$t_1 = 12{,}378 \pm\ 8914$ s

$t_{0.1} = 39{,}142 \pm\ 9778$ s



$\sigma_1 = 5.0 \times 10^{-7}$ ergs s^{-1} cm^{-2}

$\sigma_{.1} = 5.0 \times 10^{-6}$ ergs s^{-1} cm^{-2}

Application to 3C 454.3

- $t_{\text{rising}} = 4.5 \pm 1$ hrs
- $t_{\text{falling}} = 15 \pm 2$ hrs

- Decay time is noticeably longer than light-crossing time → we must be seeing radiative cooling
- According to our diagnostic, $t_{100\text{ MeV}}/t_{1\text{ Gev}} = 3.16$
- By visual inspection, the difference in cooling times at 100 MeV and 1 GeV is not different by a factor of 3.16.

- Further analysis is needed!

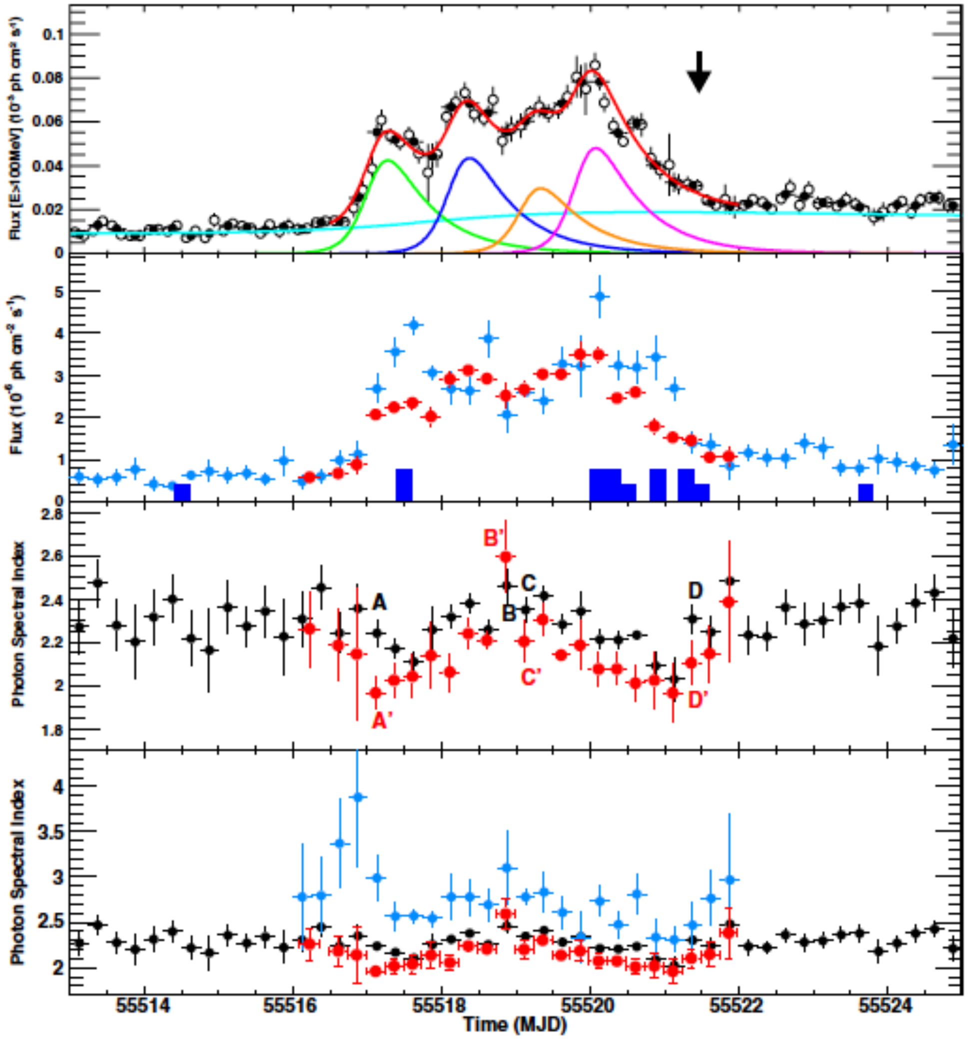


Image: Abdo et al 2011

Conclusions

- We have a model-independent diagnostic that depends on the difference in photon energy between BLR and MT photons

- The difference in photon energy causes cooling to occur in different energy regimes, and therefore an energy dependence (or independence) of the light-curves

- LC times effects are quantifiable and do not erase energy dependence of flares

- Method is feasible for brightest flares

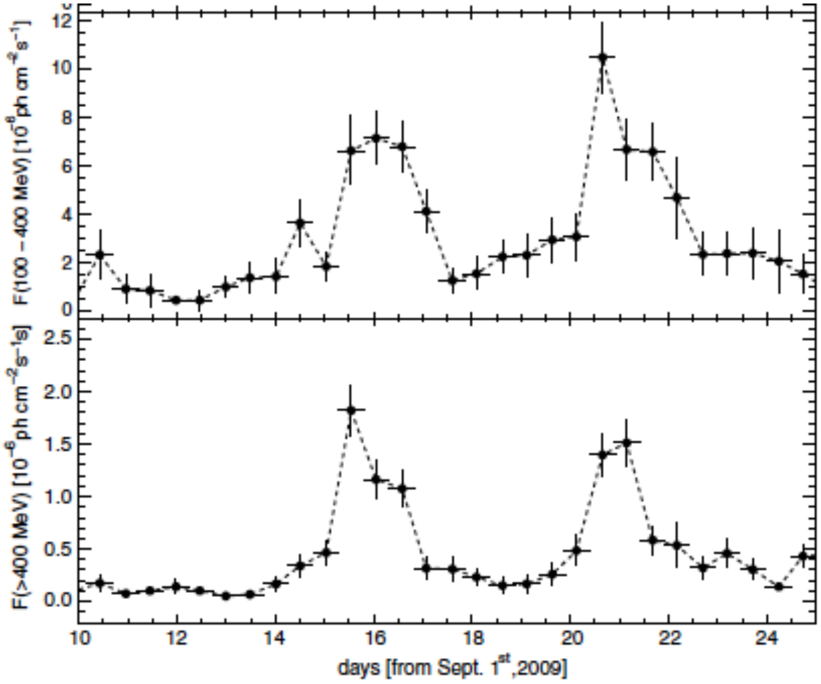
Back up slides

Application to *Fermi* Data

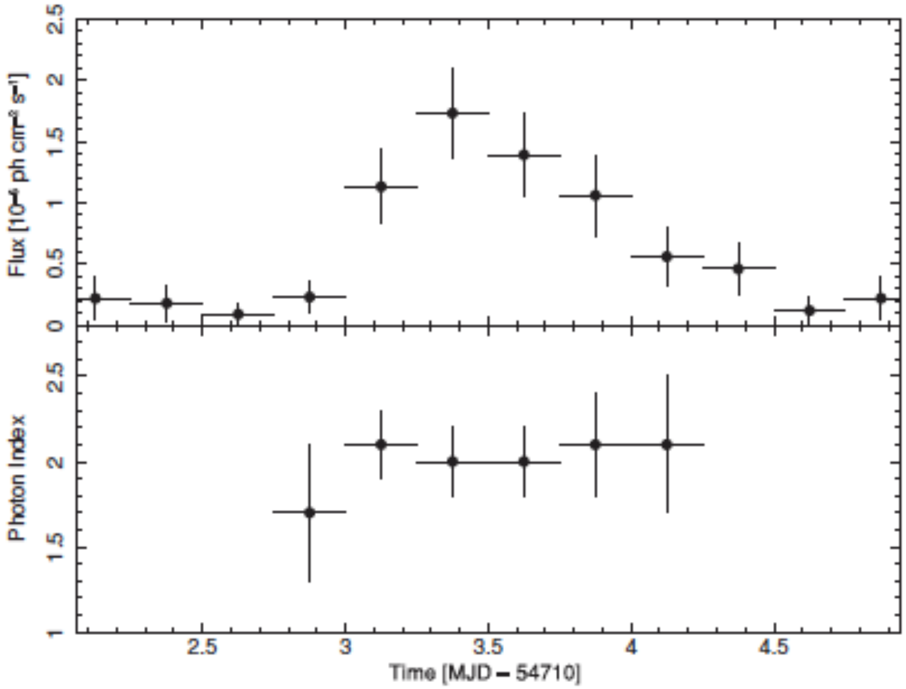
Flare requirements:

- Bright flares → maximize number of photons, reduce erros
- Short flares (a few hours) → ensures that electron cooling time (fastest time scales) is observed

Candidate flares



3C 273 (Abdo et al 2010) 12 hr bins



PKS 1454-354 (Abdo et al 2009) 6 hr bins

Numerical Simulation of the Diagnostic

To simulate a flare I modified a pre-existing code (written by Georganopoulos, Perlman, and Wingert).

The Code

•Spherical emitting region, Magnetic field (B), Electron injection q(γ,t)
•Electrons cool via synchrotron and IC cooling and escape stochastically after $t_{esc} \approx R/c$
•Evolution of electron energy distribution (EED) described by

$$\frac{\partial n(\gamma,t)}{\partial t} + \frac{\partial}{\partial \gamma}[\dot{\gamma} n(\gamma,t)] + \frac{n(\gamma,t)}{t_{esc}} = q(\gamma,t)$$

$$\frac{\partial n(\gamma,t)}{\partial t}+\frac{\partial}{\partial\gamma}[\dot{\gamma}n(\gamma,t)]+\frac{n(\gamma,t)}{t_{esc}}=q(\gamma,t)$$

Discretized (Chang & Cooper 1970):

$$\frac{n_{j,i+1}-n_{j,i}}{\Delta t}=-\frac{\dot{\gamma}_{j+1,i+1}n_{j+1,i+1}-\dot{\gamma}_{j,i+1}n_{j,i+1}}{\Delta\gamma}+q_{j,i+1}-\frac{n_{j,i+1}}{t_{esc}}$$

•Advances in time until a steady state is reached, calculates n(γ,t), for each time-step

•After steady state, ouputs observed synchrotron, SSC, and EC luminosities

•To simulate a flare, the electron injection is increased for a fixed time, and the system returns to a new steady state

Synchrotron Photons?

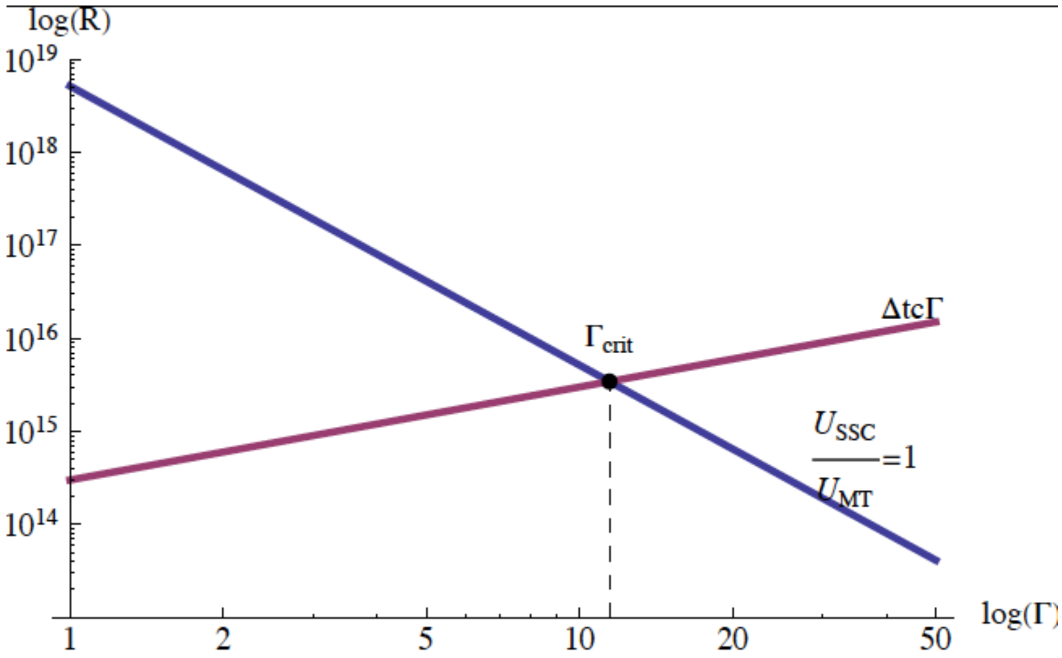
- Fast variability only indicates small size of emission region

$$R = \Delta t c \Gamma$$

  - Most models assume entire cross-section of jet flares, this is not necessarily the case!

$$U_{SSC} = \frac{L_{sync}}{4\pi R^2 c \Gamma^4}$$

$$U_{MT} = U_{ph}\Gamma^2$$



- It is possible that $U_{SSC} > U_{MT}$

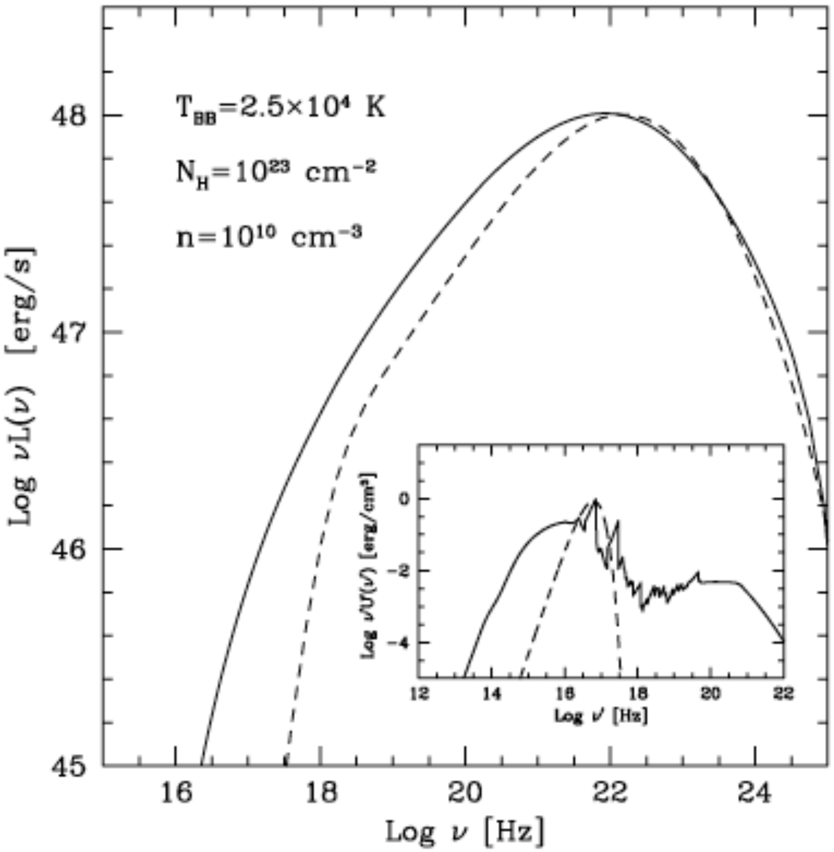
Characterizing the BLR

- BLR measured primarily by reverberation mapping

- Measures time delays between disturbances in continuum emission and broad emission lines
  ➔ Δt ≈ $2R_{BLR}/c$ (Peterson 1993)

- $R_{BLR} \propto L^{1/2}$ (Bentz 2006)

- BLR emission dominated by optical/UV emission from Lyα lines (Tavecchio 2008)



Characterizing the MT

- At large distances, BLR emission decays as r^{-2}
- MT photons dominate farther from the black hole (Arbeiter 2002)
- MT radiates in IR
- Fast variability still OK if only part of jet cross-section is radiating
- Difficult to characterize because of contributions in the IR from synchrotron radiation in the lobes & jet, obscuration by cool dust (Cleary 2007)

Seed Photons: An Overview

Synchrotron Photons

- minimum photon density in the source
- For SSC processes to dominate $U_{synch} > U_{EC}$
- SSC will dominate on if emission site is located far from EC source

Accretion Disk Photons

- Photon energy scales as$R_{AD}^{-3/4}$, so disk is smaller for higher energy photons
- Emission site needs to be close to accretion disk ($R \sim R_{AD}$)

BLR Photons

- Accretion disk photons reprocessed as line emission
- Dominated by UV emission (Lα)

Molecular Torus Photons

- Radiates thermally in the IR
- Can dominate if emission site is beyond BLR