Locating the gamma-ray emission in Flat Spectrum Radio Quasars

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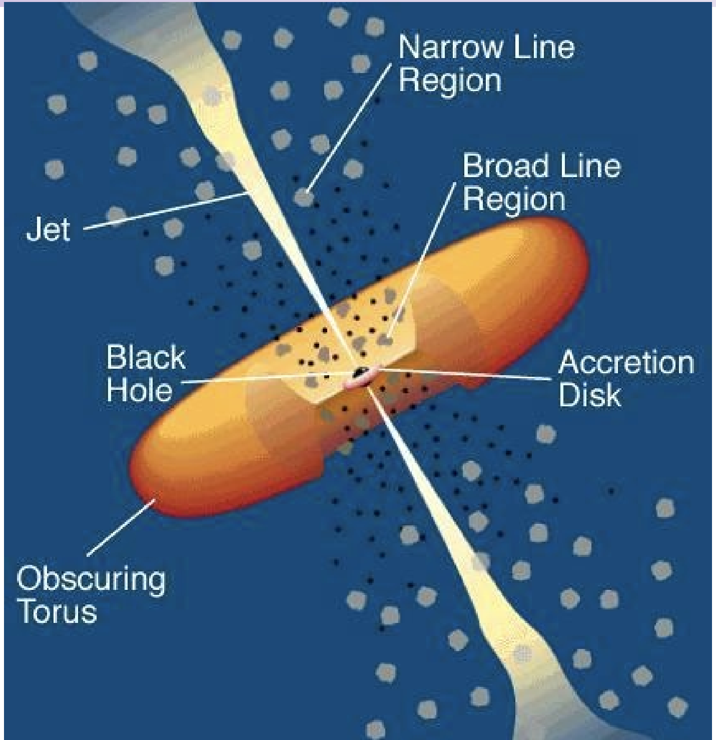
Image credit: M. Kornmesser, ESO

Synopsis

- Background
- The sample
- Constraining size and location of emission region from:
    - Variability timescales
    - Presence of spectral cut-off
    - Energy dependence in cooling timescales
    - VHE photon emission
- Overview

Background

- Flat Spectrum Radio Quasars (FSRQs) are a subclass of blazars characterized by strong broad emission lines
- The close orientation of the jet to the line-of-sight renders the resolution of structures within the jet difficult
- Uncovering the location and origin of the emission is an indirect process
- Two main theories: Broad line region (BLR) and Molecular Torus (MT)

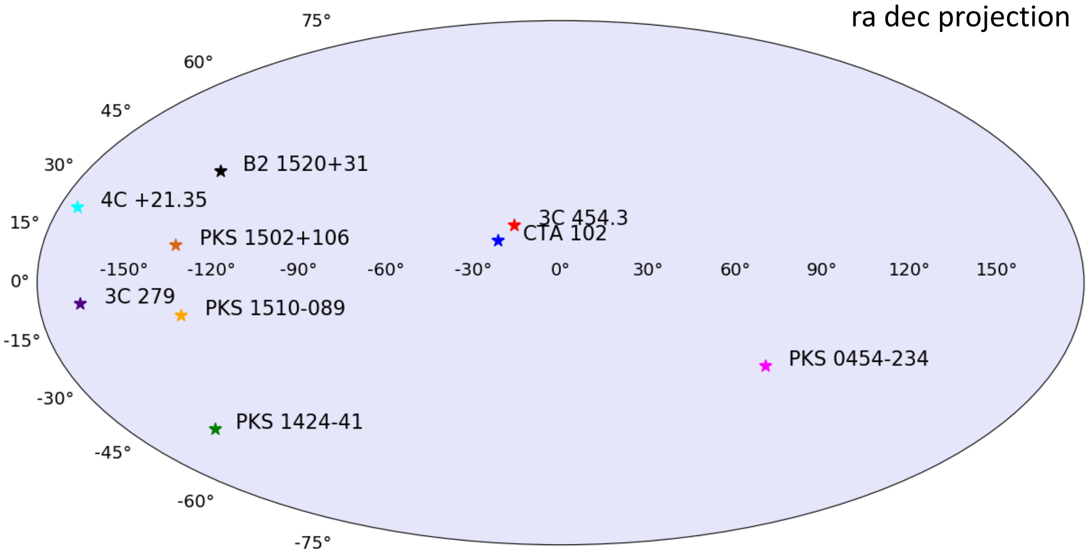


Urry and Padovani 1995*

*https://ui.adsabs.harvard.edu/abs/1995PASP..107..803U/abstract

The sample

- Sample of the nine of the brightest FSRQs reported in the 4FGL catalog
- Each source is also required to have had two flaring episodes with averaged daily flux > 10^{-6} ph cm^{-2} s^{-1} within 1σ uncertainty* and a known redshift measurement
- The energy range considered is 100 MeV-300 GeV and time interval investigated is 4th August 2008 to 4th August 2016
- From the eight year lightcurve identify periods of high activity in order to maximise photon statistics



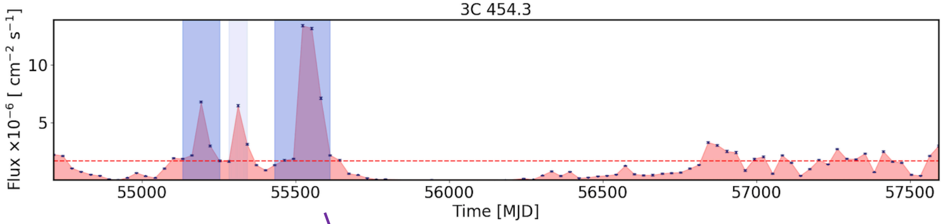
*See list of monitored sources https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

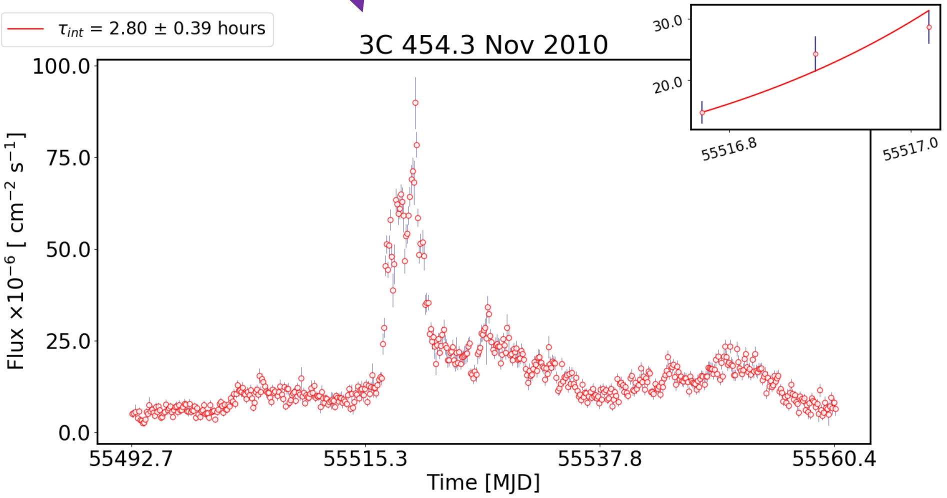
Variability timescales

- Two brightest identified flare periods re-analysed with 3 hour binning
- Can relate the intrinsic variability timescales to the size of the emission region r:

$$r \leqslant c\delta\tau_{int}$$

- Here δ is the Doppler factor of the jet as measured from radio observations (Jorstad et al. 2017)*
- Short variability timescales, typically of the order of a few hours and indicates compact emission regions of size ~ 10^{13} m





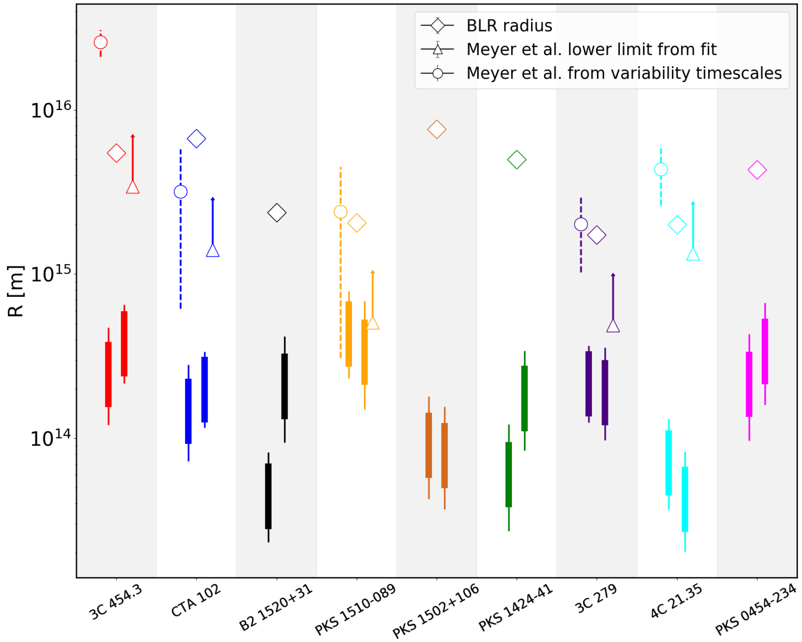
*https://ui.adsabs.harvard.edu/abs/2017ApJ...846...98J/abstract

Variability timescales

- Assuming a simple one-zone emission model in which the entire width of the jet is responsible for the emission
- Can relate size of the emission region, r, to its distance from the central engine, R, using:

$$r = \psi R,$$

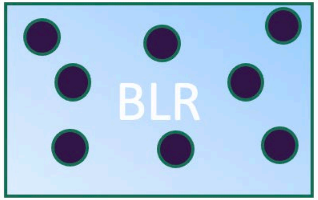
- Here ψ is the semi-aperture opening angle of the jet and has typical values between 0.1 - 0.25
- Emission is predicted to be coming from within the BLR for all sources

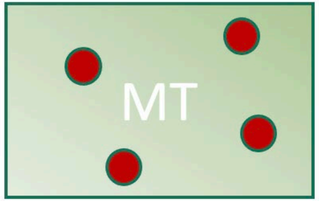


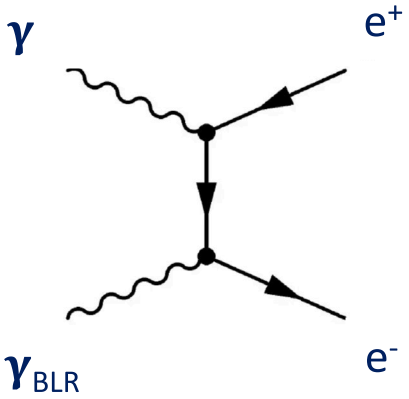
Presence of spectral cut-off

- The BLR is a photon-rich environment and the interaction between these photons and gamma-ray photons can lead to photon-photon pair production
- The MT has a much lower photon density than the BLR, meaning there is less likelihood of pair production
- Emission originating from the BLR would therefore be expected, in general, to be better described by a model with a cut-off (such as a log parabola)
- Re-analyse in daily bins and compared the fits using an Akaike Information Criterion (AIC) test
- The AIC of a model s is given by:

$$\mathrm{AIC}_s = -2\ln \mathrm{L}_s + 2\mathrm{k}_{f_s}$$

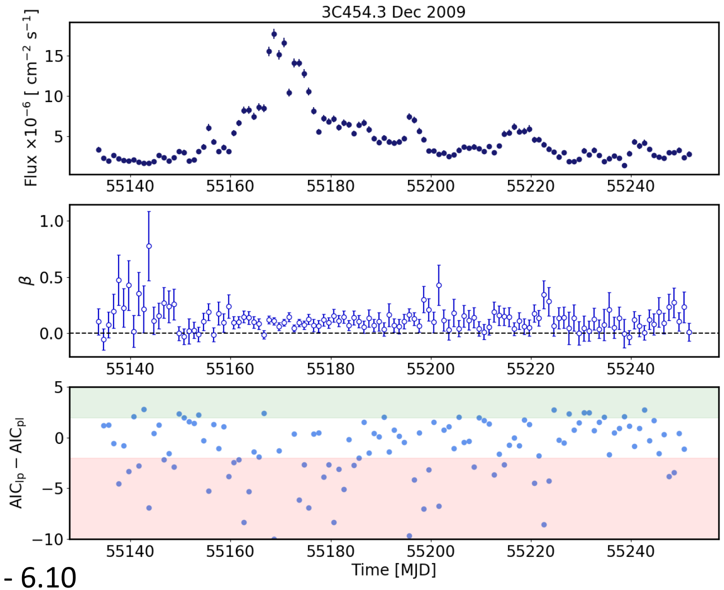






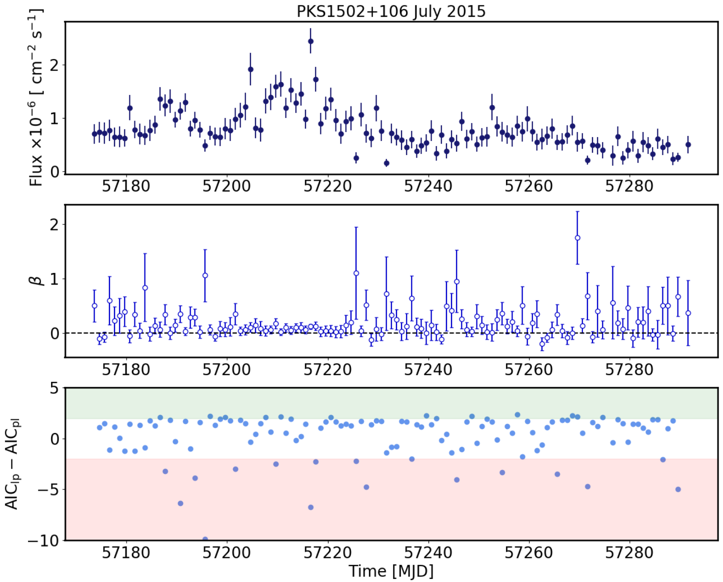
Presence of spectral cut-off

- To compare two models, we look at the difference in AIC values. An AIC difference of >2 generally means that the model with the higher AIC is significantly worse



Δ_{AIC} = - 6.10

Find evidence of cut-off in 7 of the 18 flares



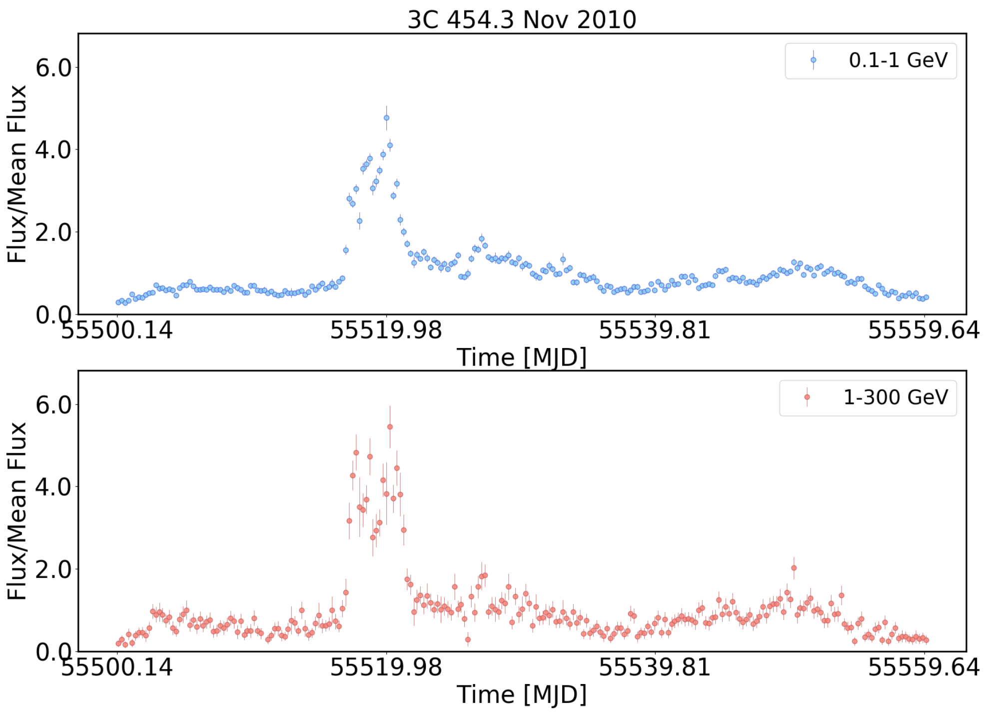
Δ_{AIC} = - 0.40

The remaining 11 flares were found to favour neither model over the other and broadly agrees with Costamante et al. 2018*

*https://ui.adsabs.harvard.edu/abs/arXiv:1804.02408

Energy dependence in cooling timescales

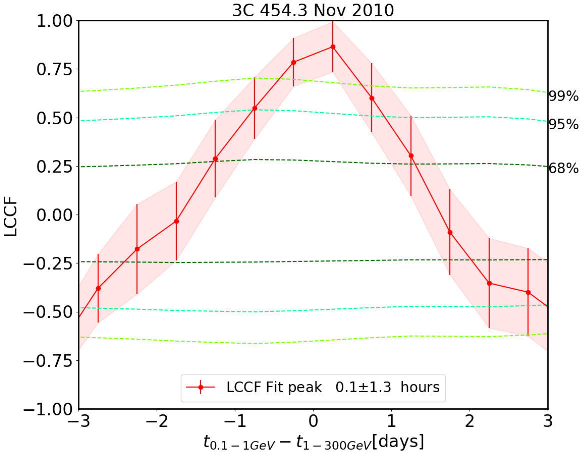
- Another key difference is IC scattering takes place in the Klein-Nishina regime when the emission region is located inside the BLR, and in the Thomson regime for emission from within the MT
- This results in energy-independent electron cooling times for emission from the BLR and energy-dependent cooling timescales for regions within the MT (for example see Dotson et al. (2012)*)
- To investigate this, I re-analysed the flare periods in two distinct energy ranges: 0.1 - 1 GeV (low energy) and 1 - 300 GeV (high energy), binned in six hourly intervals



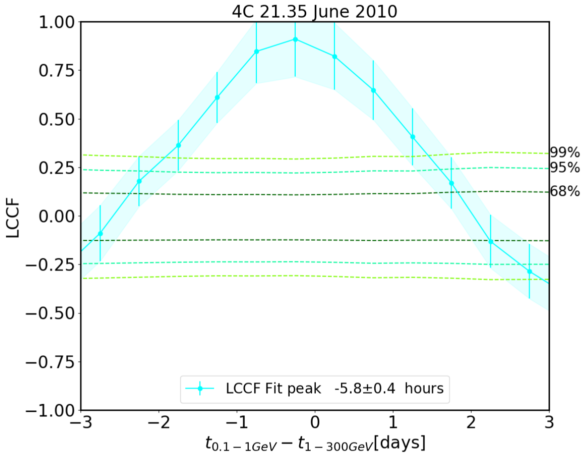
*https://ui.adsabs.harvard.edu/abs/2012ApJ...758L..15D/abstract

Energy dependence in cooling timescales

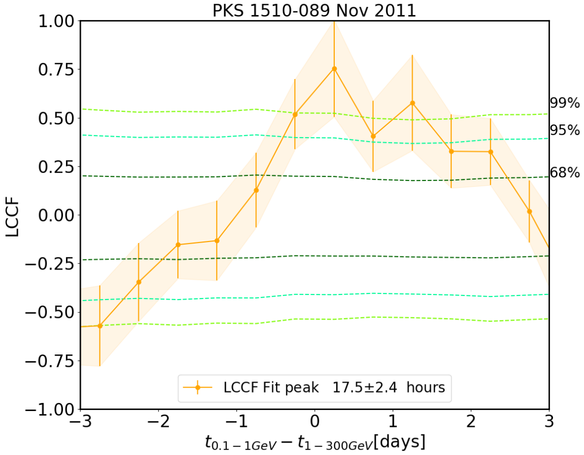
- LCCF applied to high and low-energy lightcurves to search for correlations in the data and fitted with Gaussian to find peak
- Significance of the observed peaks obtained from Monte Carlo simulations of 1000 artificial lightcurves



A peak at 0 indicates absence of time-lag implying BLR origin. Found in 4 flares



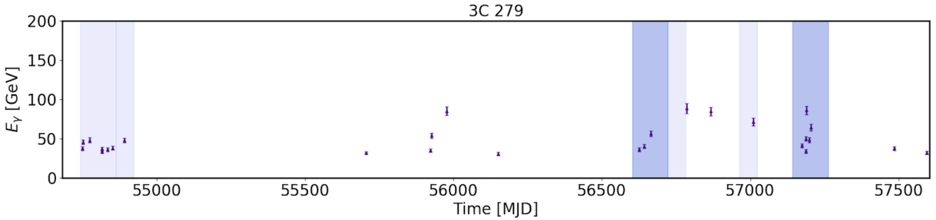
Two flares show a negative temporal lag. Does not constrain the location of the emission to either the BLR or MT but can be interpreted as evidence that the MeV and GeV components of the flare have different origin

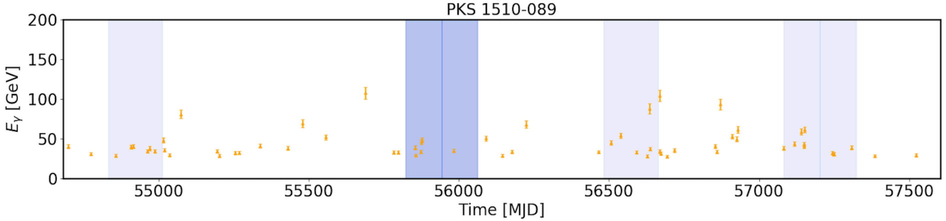


A positive time-lag indicates MT origin. Found in 4 flares

VHE photon emission

- The observation of VHE photons (E > 20 GeV) is generally difficult to explain if one assumes emission coming from the inner regions of the BLR as photon-photon pair production would make the escape of the high energy photons less probable
- To quantify this, I investigate VHE photons emitted by the sample over the entire eight year observation period
- Find some instances of VHE photon emission outside the flare period indicating GeV flares are not necessarily a predictor of VHE emission
- This reinforces the requirement for comprehensive sky surveys in the VHE regime (for example with CTA* and SWGO**)

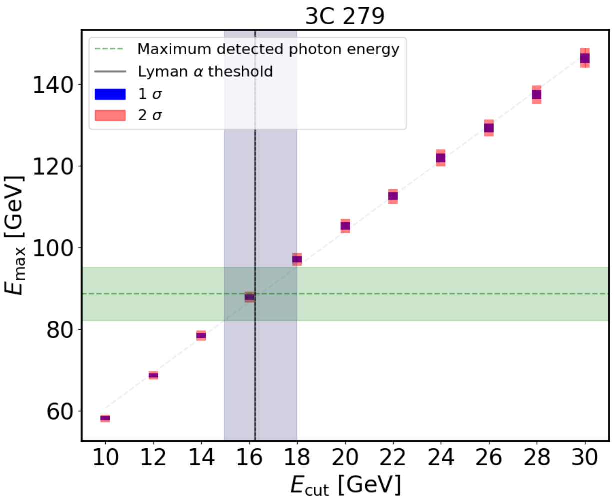


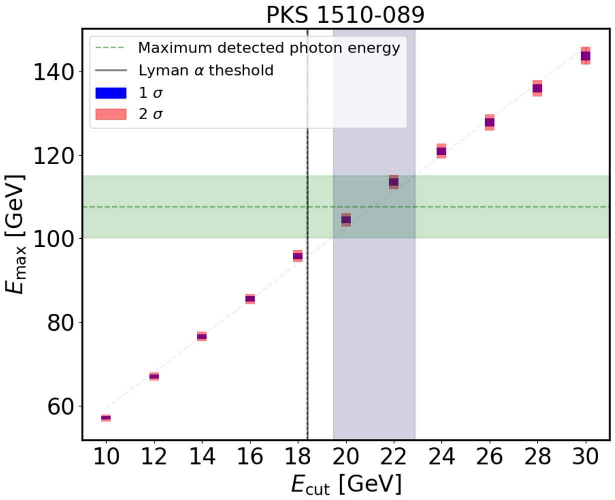


* Science with the Cherenkov Telescope Array: https://ui.adsabs.harvard.edu/abs/2019scta.book.....C/abstract
**SWGO Astro2020 APC White Paper: https://ui.adsabs.harvard.edu/abs/2019BAAS...51g.109H/abstract

VHE photon emission

- Compare the energy of the most energetic photon observed with the *Fermi*-LAT for each source to the expected photon energy distribution assuming BLR origin of emission
- Simulate 1000 observations for all sources assuming a range of intrinsic cut-off energies
- Test if predicted cut-off is compatible with expected onset of the intrinsic cut-off due to interaction with Lyman alpha photons in the BLR. This is the case for only three sources: 3C 454.3, 3C 279 and 4C 21.35





Overview

- The mixed results of the different investigations indicate that a more complex emission model than a simple one-zone leptonic model is required
- There is evidence to suggest the presence of multiple simultaneously active emission regions both within the BLR and the MT, in most individual sources even during the same flaring episode
- For more details on how I define flares, overall results for each specific source and a comparison to other studies, see our recently published paper https://ui.adsabs.harvard.edu/abs/2021MNRAS.500.5297A/abstract

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Locating the gamma-ray emission region in the brightest *Fermi*-LAT flat-spectrum radio quasars

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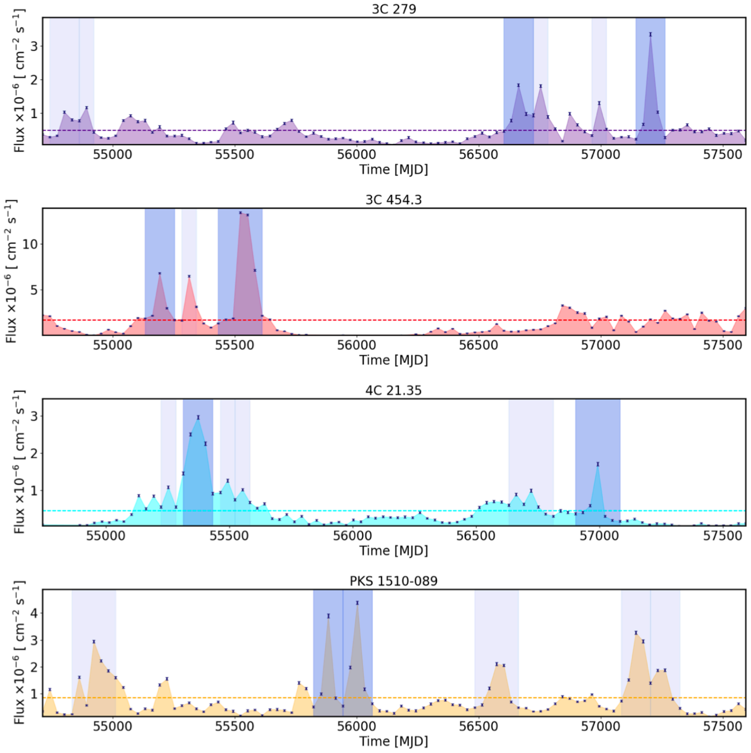
Thank you !

Back-up slides

Defining flare periods

- Look for local peaks in 8 year lightcurve binned in monthly intervals
- Proceed in both directions as long as the corresponding bins are successively lower in flux
- Impose the following conditions
    - The peak of the flare must have a flux greater than twice the average flux during the entire observation period
    - Each bin in the flare must also have a flux greater than the average flux during the observation period
- For this study I focus on the two brightest flares from each source



Summary of results

Source	Sizes of emission region from variability time-scales (10^{13} m)[a] Flare 1, Flare 2	Spectral cut-off Flare 1, Flare 2	Energy-dependent cooling Flare 1, Flare 2	VHE photons from BLR
3C 454.3	3.87 ± 0.84, 7.38 ± 1.03	BLR, BLR	MT, BLR	Compatible
CTA 102	4.78 ± 0.86, 3.59 ± 0.59	BLR, BLR	Multizone, BLR	Incompatible
B2 1520+31	0.70 ± 0.12, 3.27 ± 0.91	Inconclusive, Inconclusive	Inconclusive, Inconclusive	Incompatible
PKS 1510−089	6.82 ± 1.03, 5.30 ± 1.56	Inconclusive, BLR	MT, MT	Incompatible
PKS 1502+106	0.93 ± 0.18, 1.33 ± 0.09	Inconclusive, Inconclusive	MT, BLR	Incompatible
PKS 1424−41	0.77 ± 0.24, 2.76 ± 0.66	Inconclusive, Inconclusive	Inconclusive, Inconclusive	Incompatible
3C 279	4.11 ± 0.34, 4.23 ± 1.28	Inconclusive, BLR	Inconclusive, BLR	Compatible
4C 21.35	2.05 ± 0.66, 1.67 ± 0.12	BLR, Inconclusive	Multizone, Inconclusive	Compatible
PKS 0454−234	4.55 ± 0.79, 3.91 ± 0.67	Inconclusive, Inconclusive	Inconclusive, Inconclusive	Incompatible

Note. [a]The variability time-scales imply extremely compact emission regions. Assuming the entire width of the jet to be responsible for the emission, all time-scales are compatible with BLR origin of emission.