High Energy Flares of FSRQs: The connection of flaring states with the accretion disk luminosity

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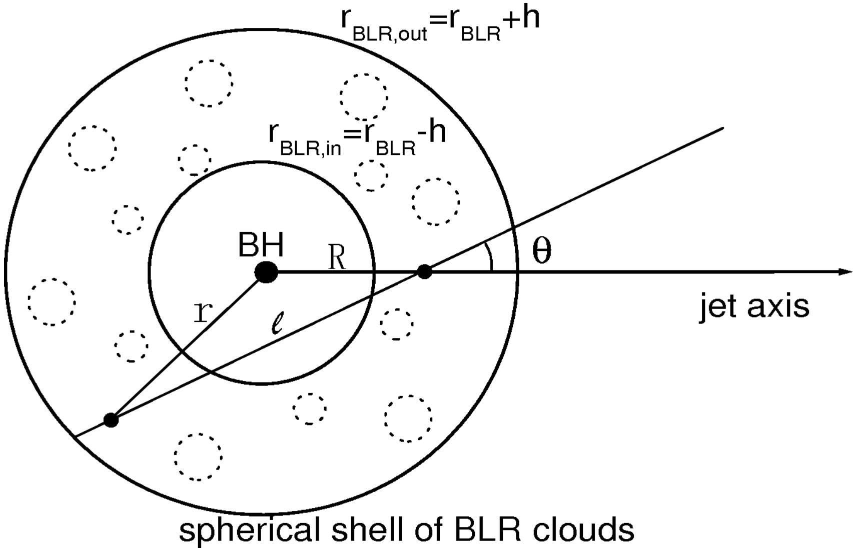
Financial contribution from

PRIN-INAF 2014

$\gamma\gamma$ absorption from BLR

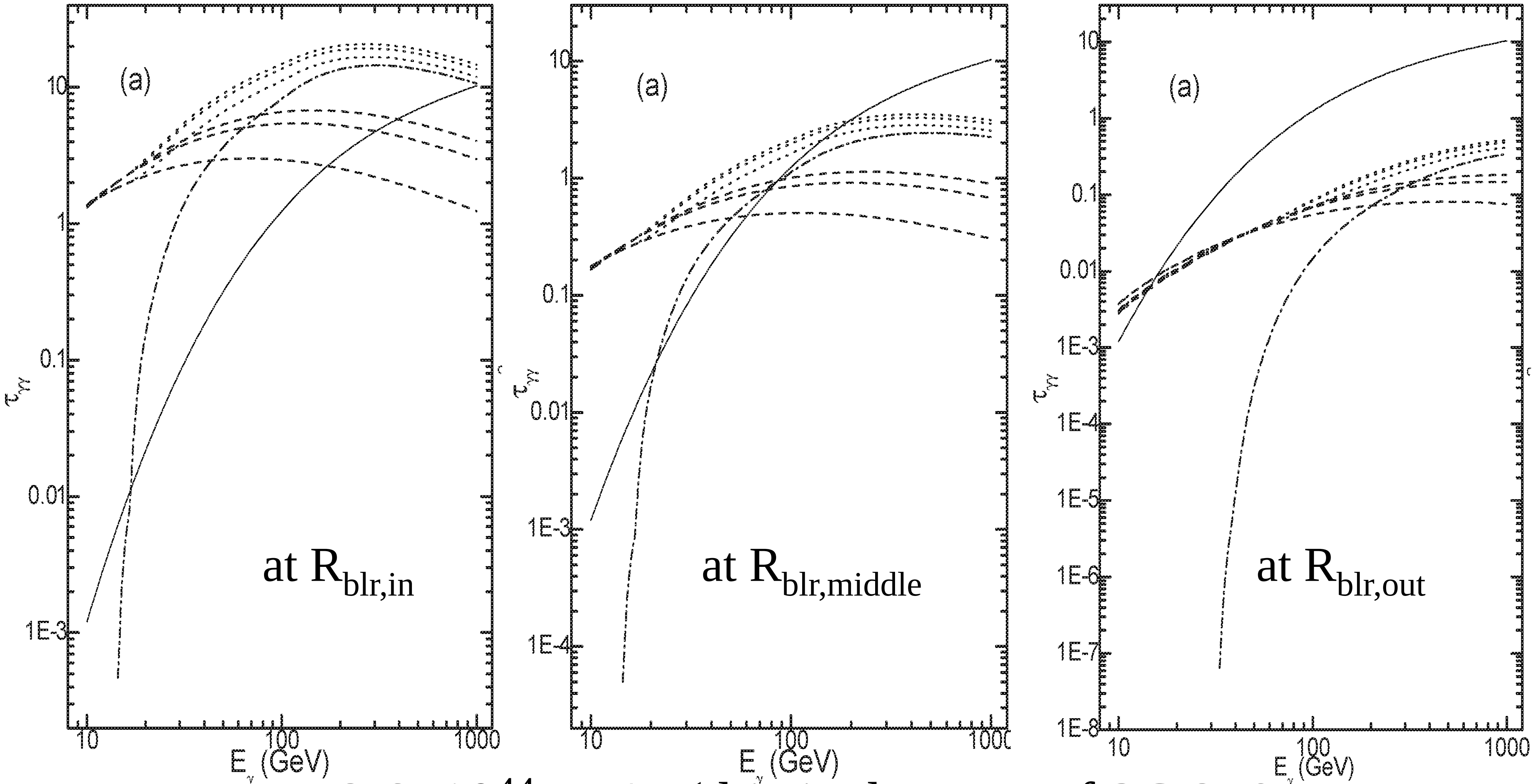
via $\gamma\gamma \rightarrow e^+e^-$ interaction

Liu & Bai 2006
Liu, Bai, Ma 2008



γγ absorption from BLR

Liu & Bai 2006; Liu, Bai, Ma 2008



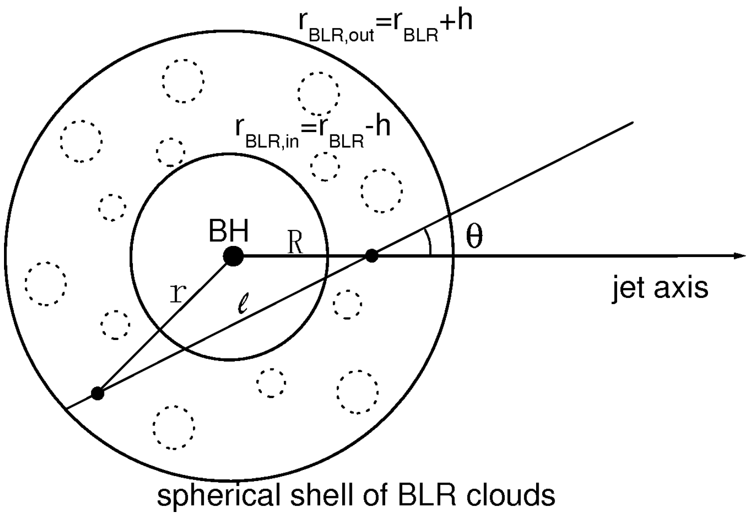
L_{BLR}=2.6x10^{44} erg/s (this is the case of 3C 279,

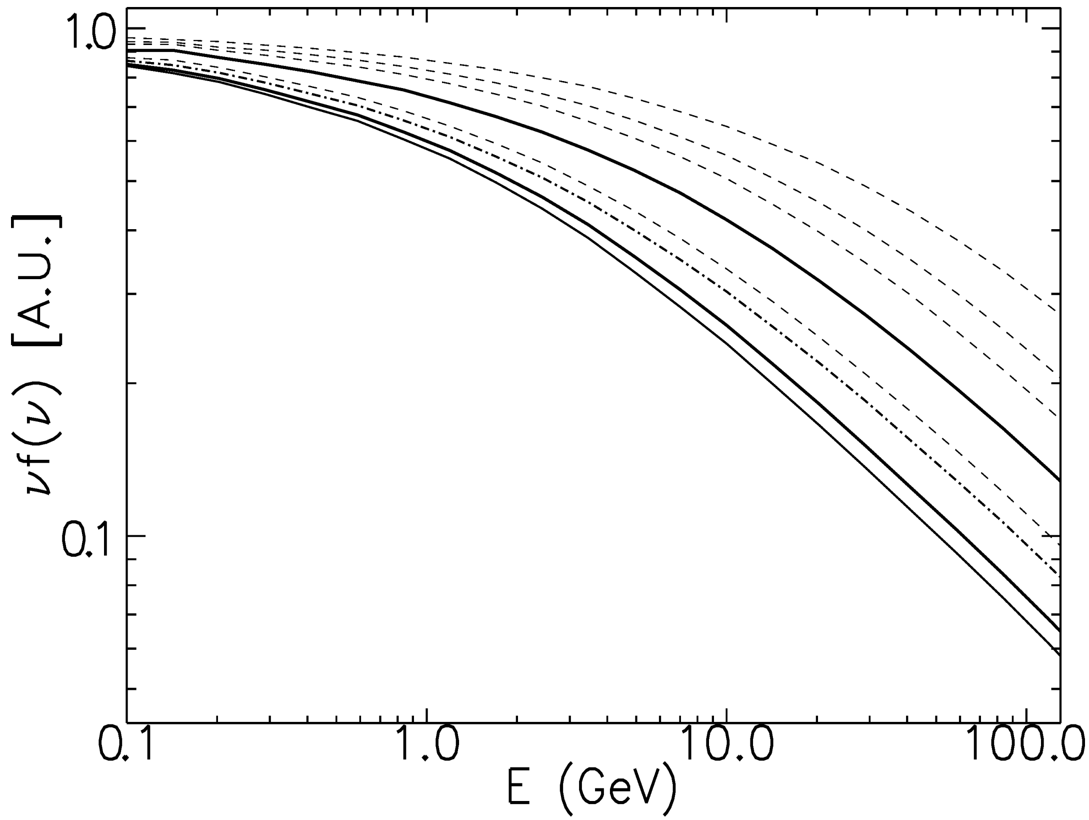
but for 3C 454.3 the BLR is >10 times more luminous)

$\tau_{\gamma\gamma}$ scales as $L_{BLR}^{1/2}$

KN suppression
(External Compton on BLR photons)

Pacciani, Tavecchio et al, 2014, ApJ 790, 45





Klein-Nishina suppretion for a dissipation region at:
solid curves: 0, R_{in}, R_{out} (from Bottom Up)
solid dashed curve: at the center of the shell
dashed curves: 0.95 R_{out}, 1.25 R_{out}, 1.5 R_{out}, 2 R_{out}

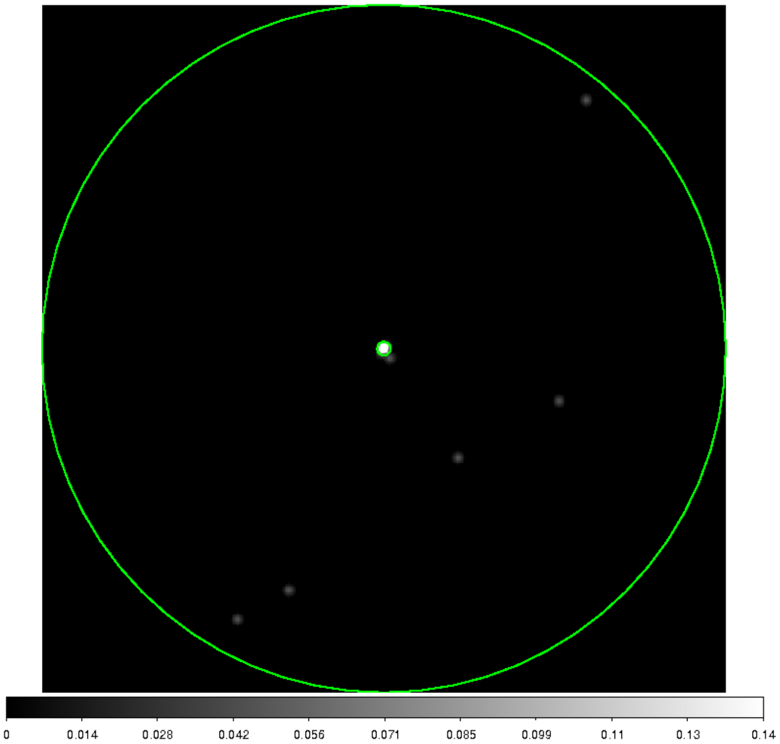
SEARCH within the FERMI-LAT FSRQs sample

SEARCH within the FERMI-LAT FSRQs sample

We started to search for relevant signal at E > 10 GeV in the FERMI-LAT archive from FSRQs and on incoming gamma-ray data (and triggering ToO observations to Swift).

High energy (HE) activity period is defined as the period of time in which the HE photon rate is > 3 x mean HE rate

3C 454.3
Sept. 2013 HE flare



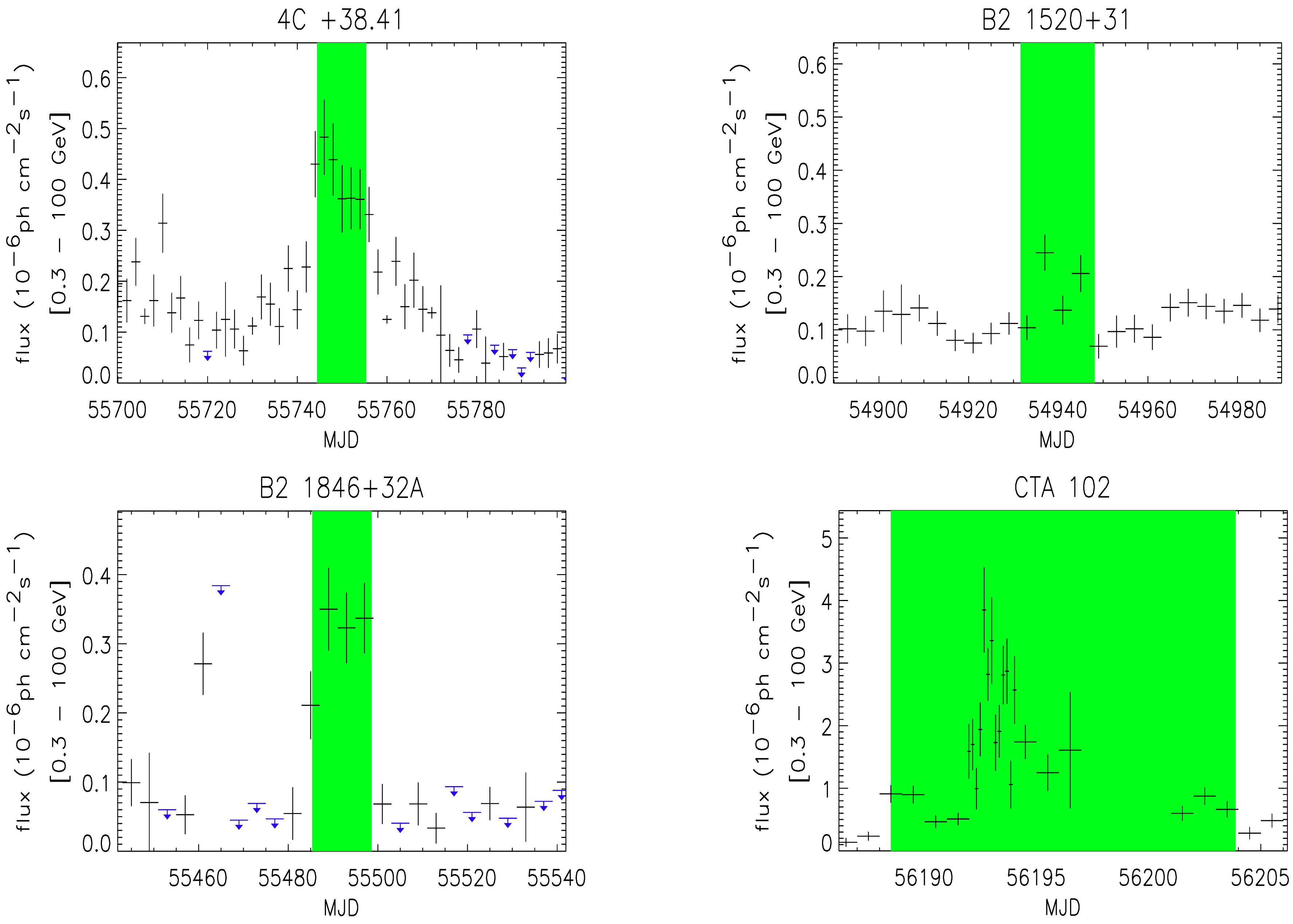
Search within the FERMI-LAT FSRQs sample

We obtained ~40 flares candidates with detections with TS significance
$26 < TS < 136$ ($E_{THR} > 10$ GeV,
but now we have changed the E_{THR} definition)
and
High Energy activity periods
lasting from 1 to 12 days in the host galaxy frame

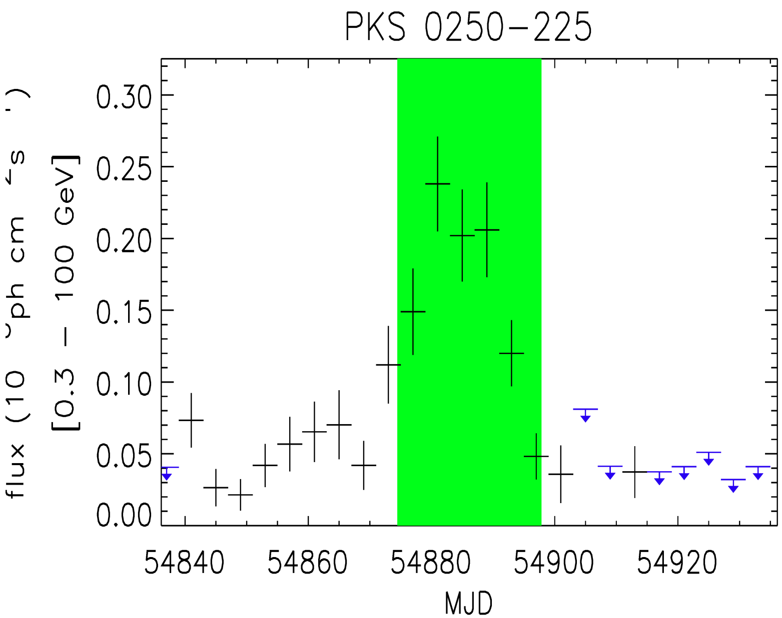
We selected for flares with MWL coverage, for sources with available Broad lines luminosities (to infer the disk luminosity using the mean ratios of Broad Lines luminosities in **Francis 1991** and in Celotti 1997, and assuming $\mathbf{L_{disk}=1/10\ L_{BLR}}$).

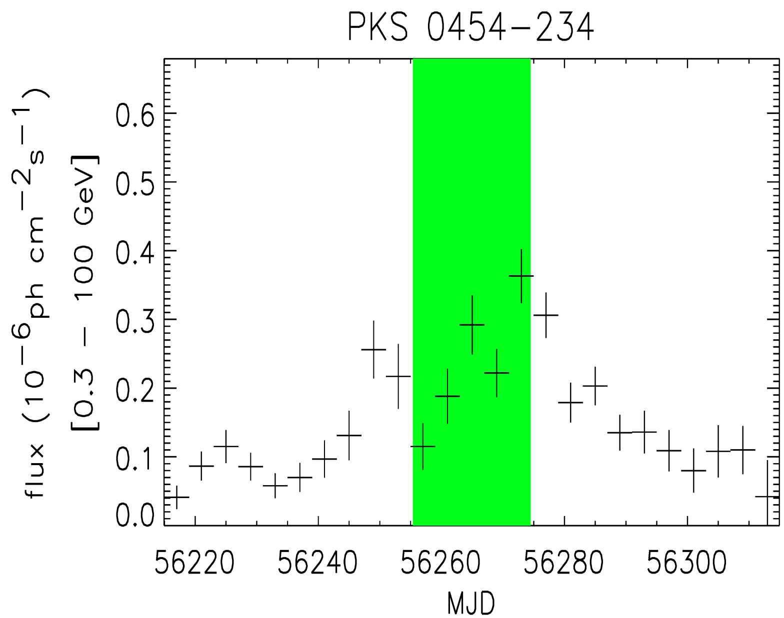
We obtained 10 sources up to Sept. 2013
(3 ToO from HE flares triggered by our program:
PKS 0454-234, PMN J2345-1555, 3C 454.3)
apart GB6 J1239+0443 (Pacciani et al., 2012),
PKS B1424-418 (Tavecchio, Pacciani et al., 2013, **ToO triggered by us**),
3C 279, 4C +21.35, PKS 1510-08
(but we collected other HE flares within the last year)

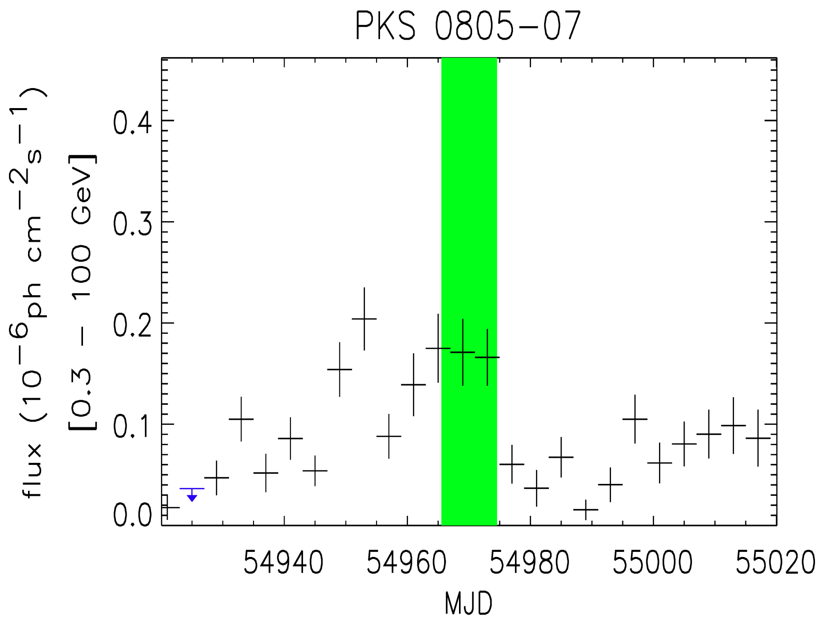
Search within the FERMI-LAT FSRQs sample (I)

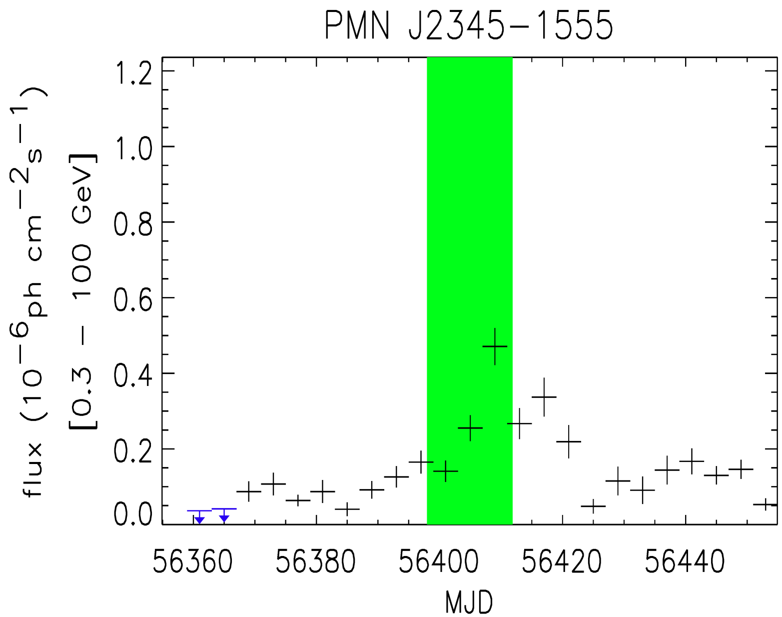


Search within the FERMI-LAT FSRQs sample (II)

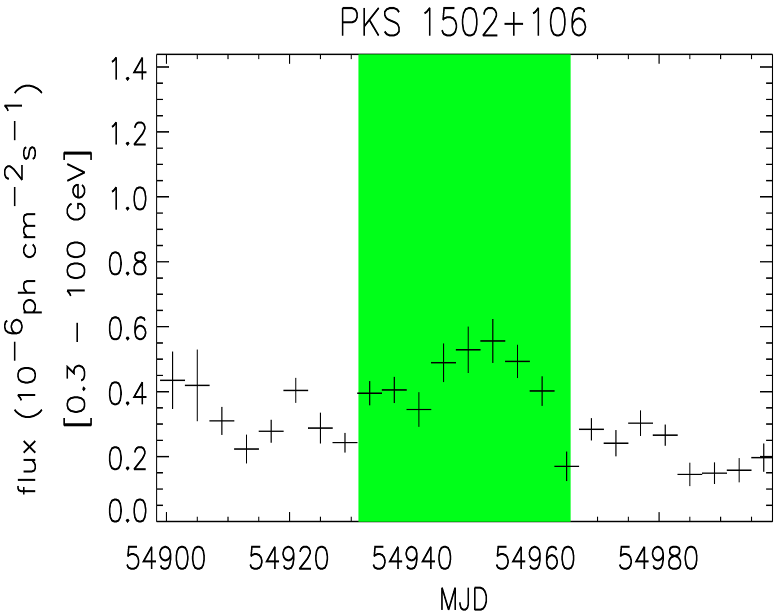




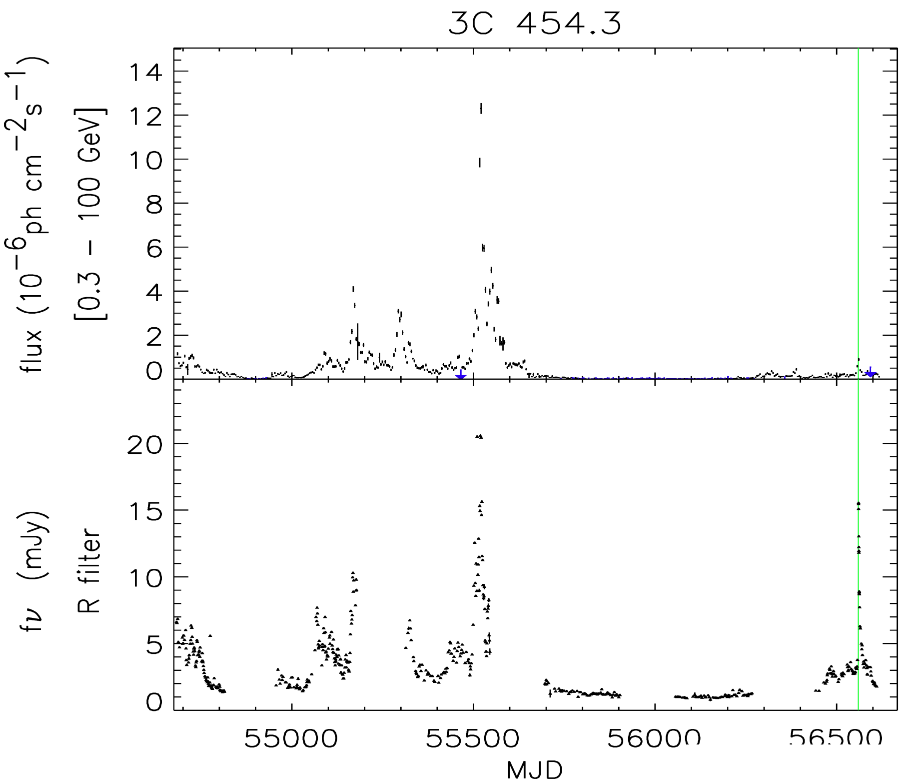


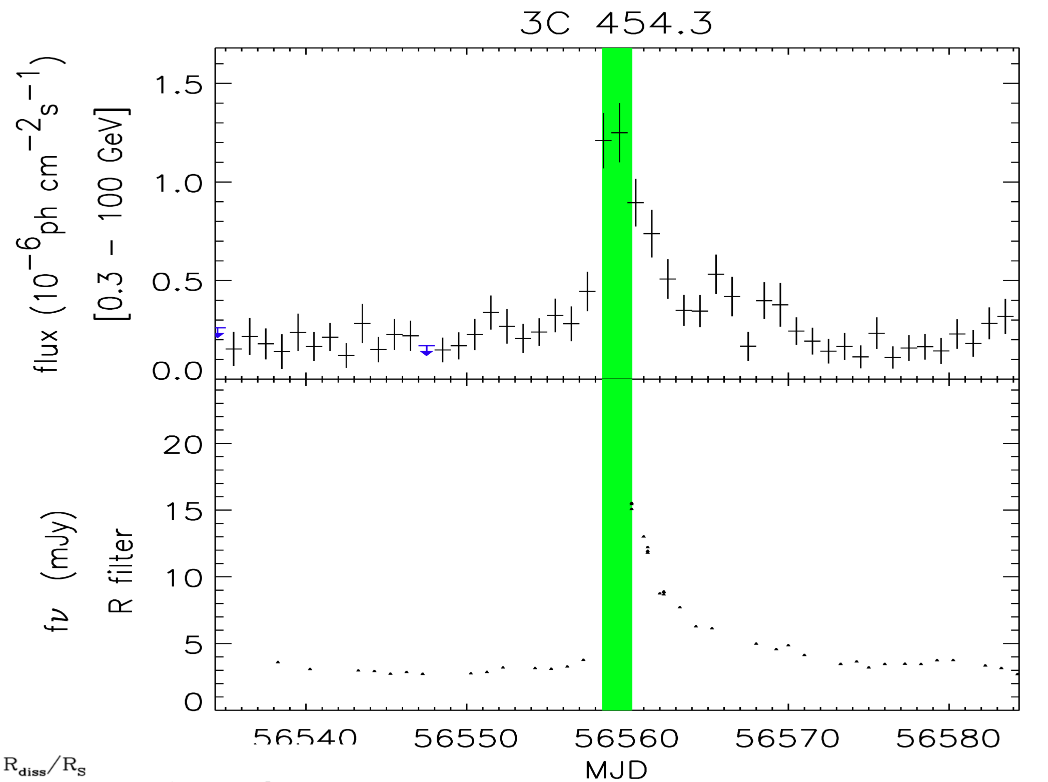


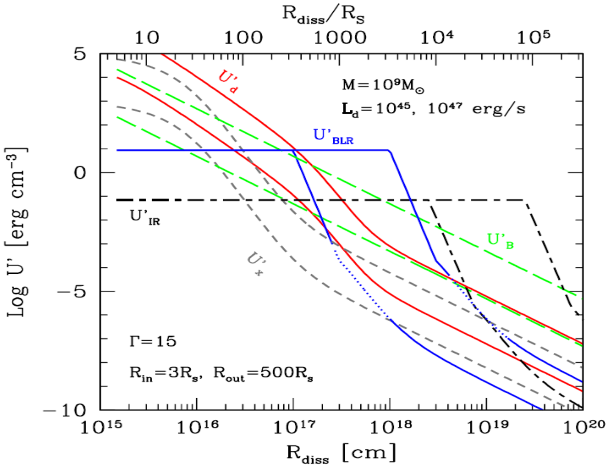
Search within the FERMI-LAT FSRQs sample (III)



Search within the FERMI-LAT FSRQs sample (IV)

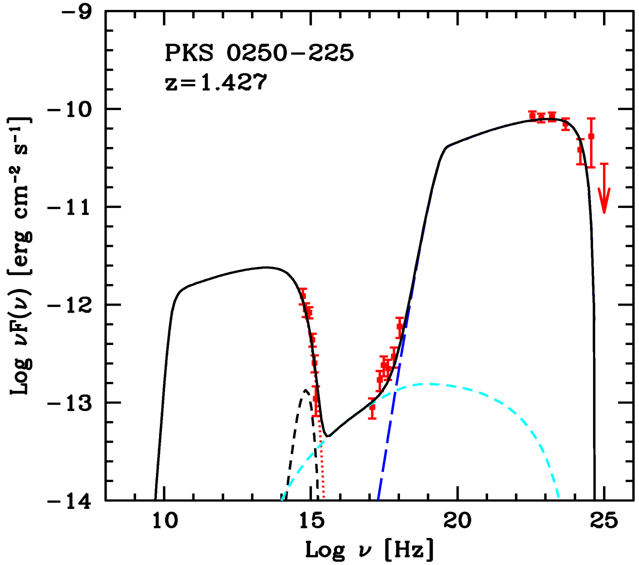




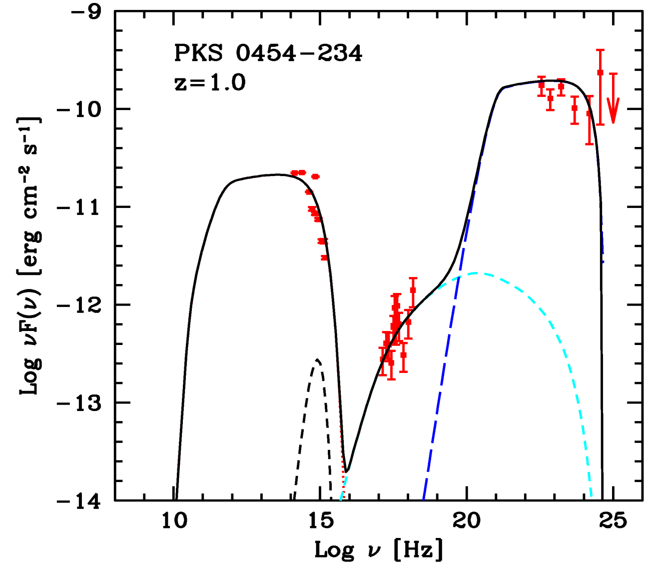


Ghisellini & Tavecchio 2009

SEDs and modeling (i)

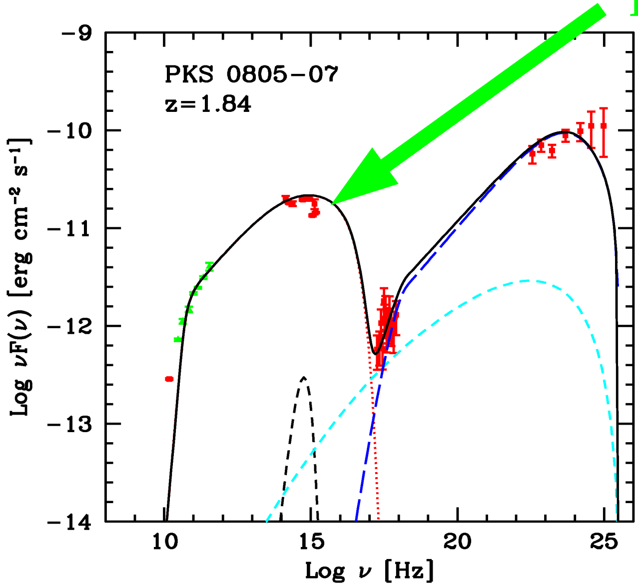


dist=3 pc
B=25 mG
L_{disk}=5.3x10^{45} erg/s

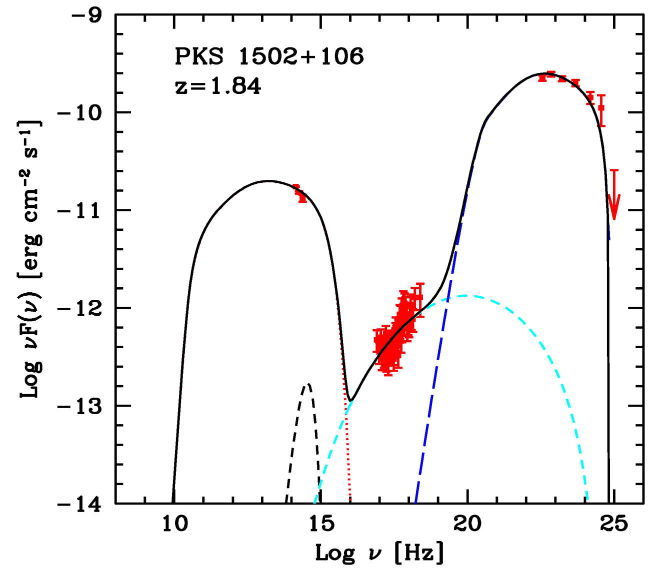


dist=2.5 pc
B=35 mG
L_{disk}=3.7x10^{45} erg/s

IGM absorption in UV

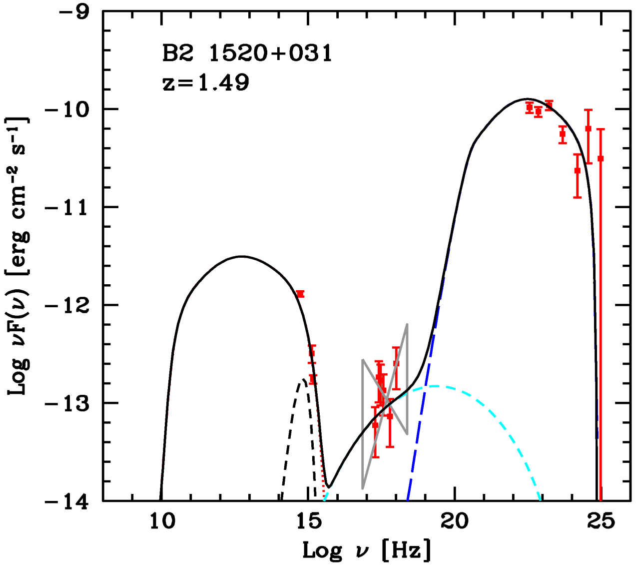


dist=0.8 pc
B=315 mG
L_{disk}=24x10^{45} erg/s

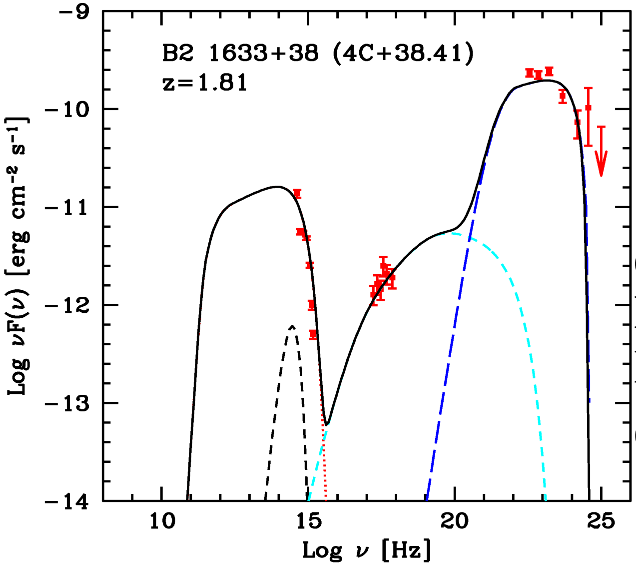


dist=2 pc
B=110 mG
L_{disk}=15x10^{45} erg/s

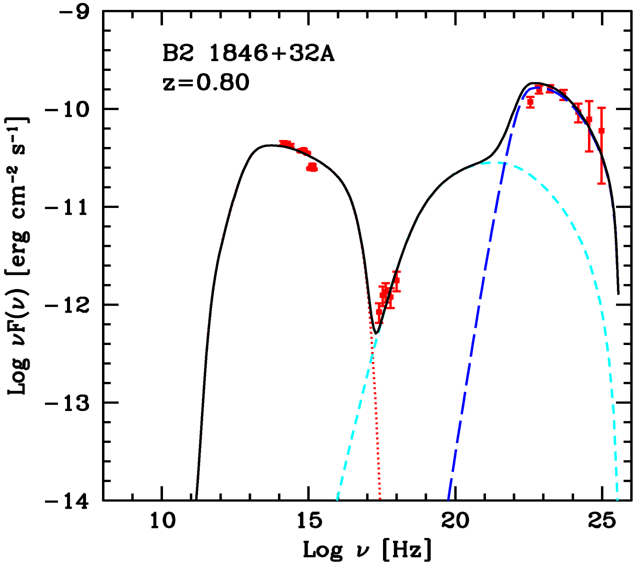
SEDs and modeling (ii)



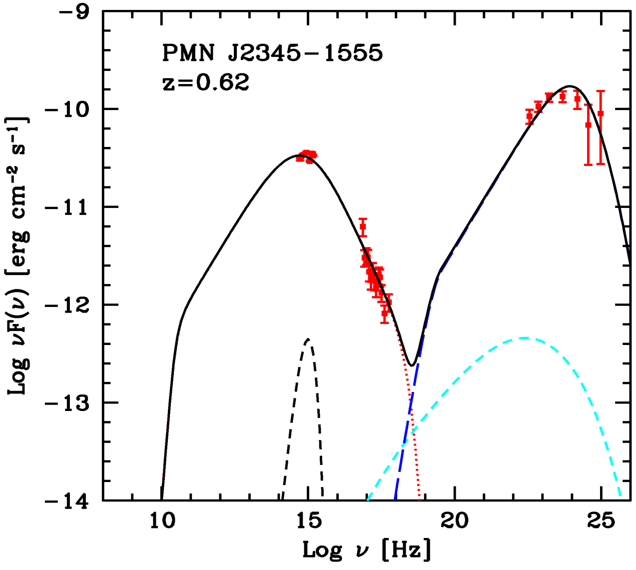
dist=1.3 pc
B=63 mG
L_{disk}=8x10^{45} erg/s



dist=0.5 pc
B=250 mG
L_{disk}=50x10^{45} erg/s

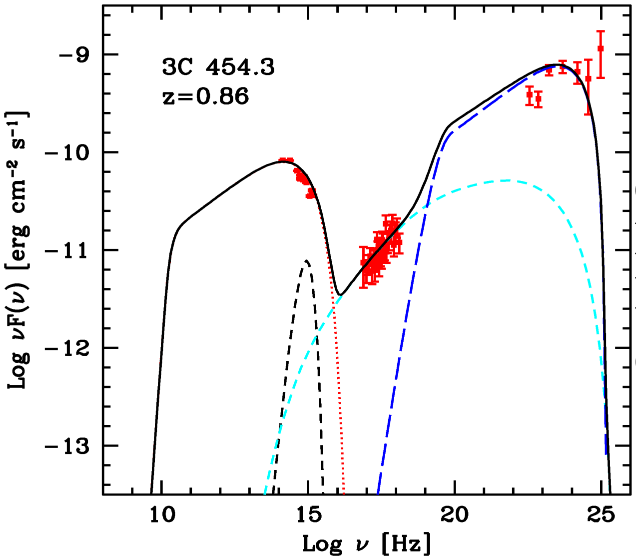


dist=0.2 pc
B=620 mG
L_{disk}=3.4x10^{45} erg/s

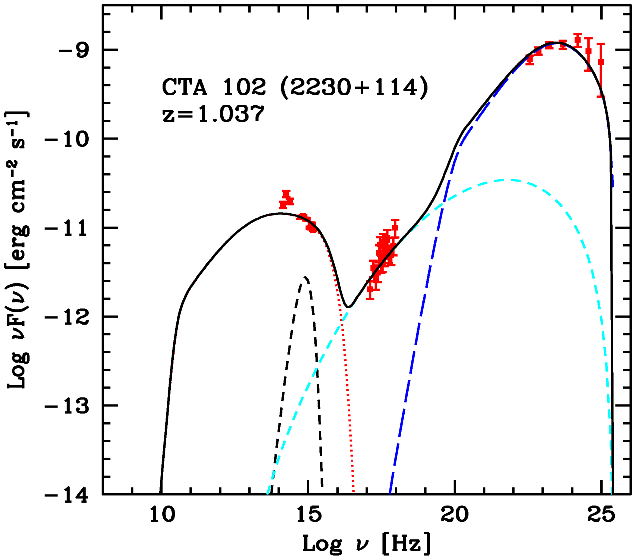


dist=0.7 pc
B=210 mG
L_{disk}=1.5x10^{45} erg/s

SEDs
and modeling (iii)



dist=0.5 pc
B=230 mG
L_{disk}=33x10^{45} erg/s

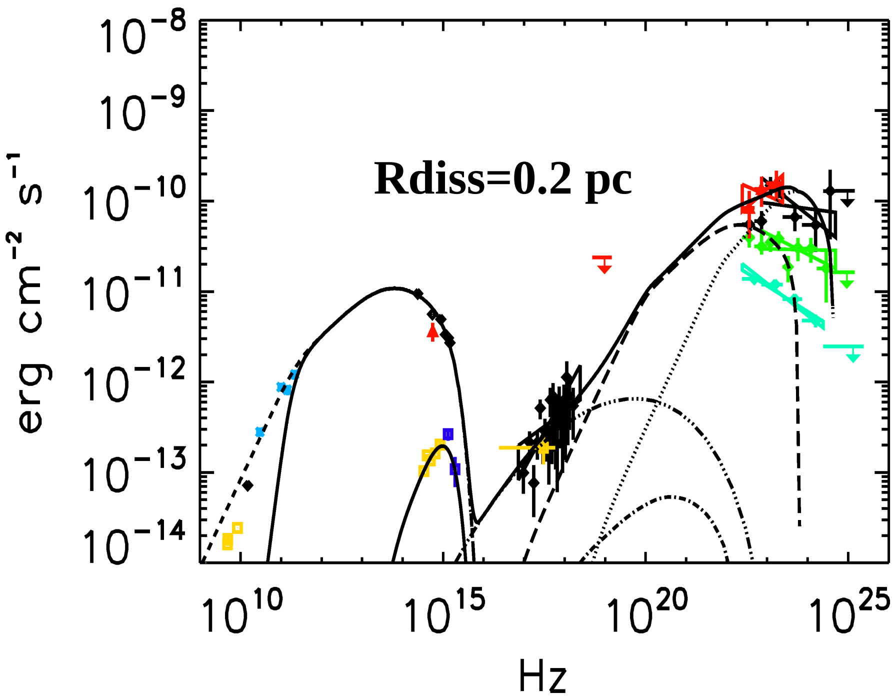


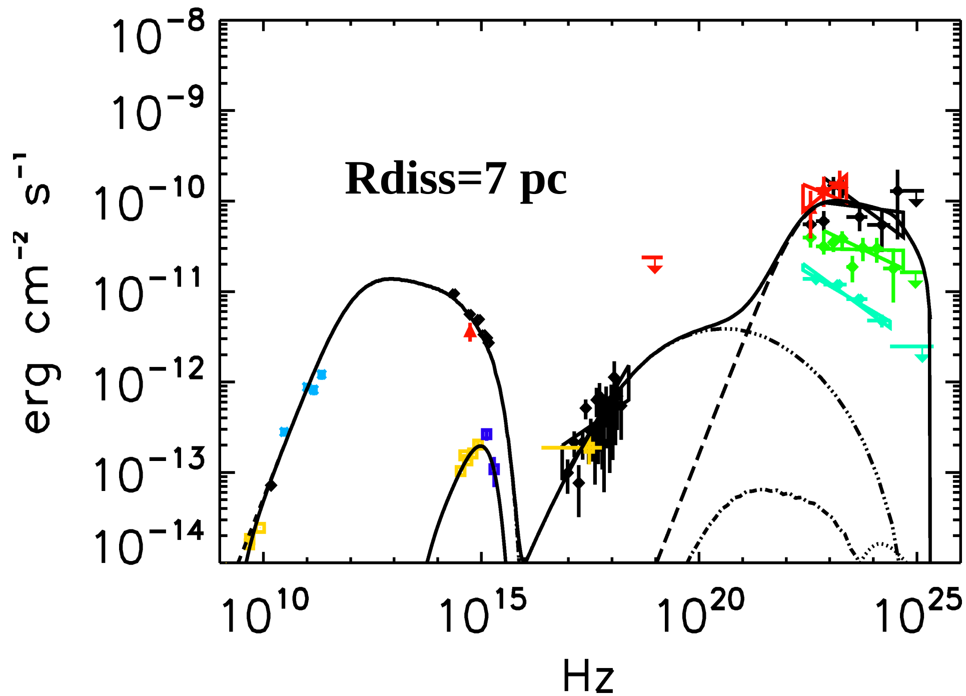
dist=0.3 pc
B=140 mG
L_{disk}=41x10^{45} erg/s

GB6 J1239+0443 (z=1.76) Multiepoch SED (I)

AGILE/GRID and simultaneous data in red

FERMI-LAT data (4-day integration around the flare)
and simultanous data in black
Fermi-LAT data in green (30-day integration around the flare)
Fermi-LAT data in cyan (2FGL catalog)



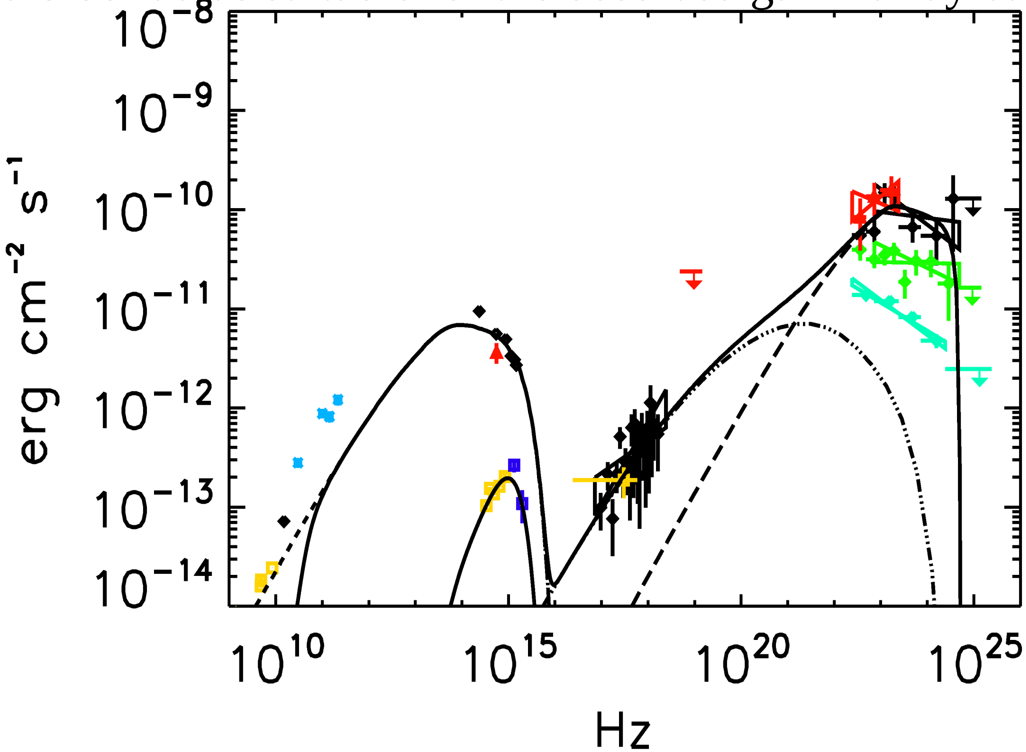


Dissipation region at 0.2 pc from the SMBH
(Just outside the BLR)
Rblob=6.7*10^{16}cm
B=0.6 Gauss

Dissipation region at 7 pc from the SMBH
Rblob=2*10^{18}cm
B=1*10^{-2} Gauss
This model gives a satisfactory gamma-ray spectral shape, but the expected variability is ~10^{2} days

GB6 J1239+0443 (z=1.76) Multiepoch SED (II)

Relaxing the relation between blob radius and dissipation region (as in Tavecchio 2011), and using a blob radius suitable for the observed gamma-ray variability



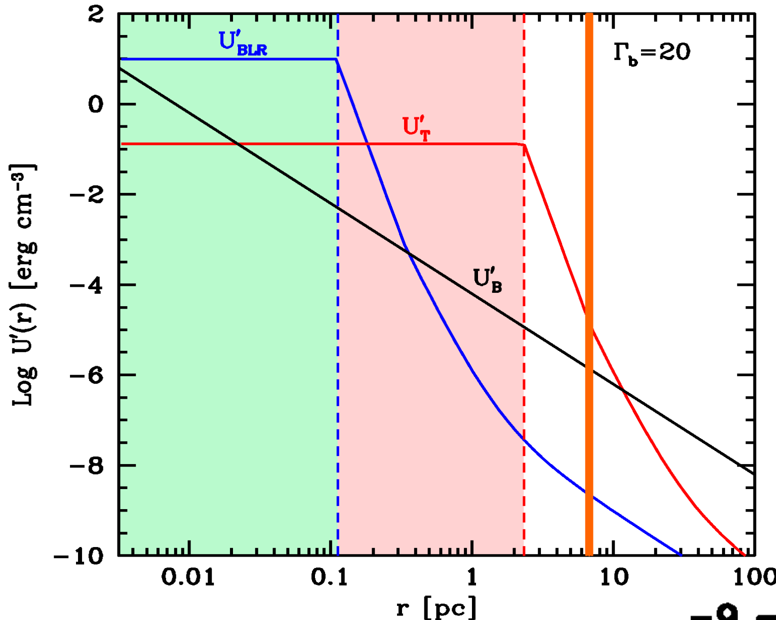
Model is for a dissipation region at 5 pc from the central BH, a blob radius of $1*10^{17}$ cm, B=$7*10^{-2}$ Gauss

R_{blob}=0.0067*R_{diss} in agreement within a factor 2 with Bromberg and Levinson 2009 (R_{blob}=$10^{-2.5}$ R_{diss}) inverting R_{diss}=2.5*$L_{jet,46}$(R_{BLR}/0.1 pc)$^{-1}$ and using R_{diss} =5 pc, we obtain L_{jet}=3.5*10^{46} erg/s.

We need to assume that the p/e number ratio is ~0.1 to accomplish such a luminosity.

PKS 1424-41

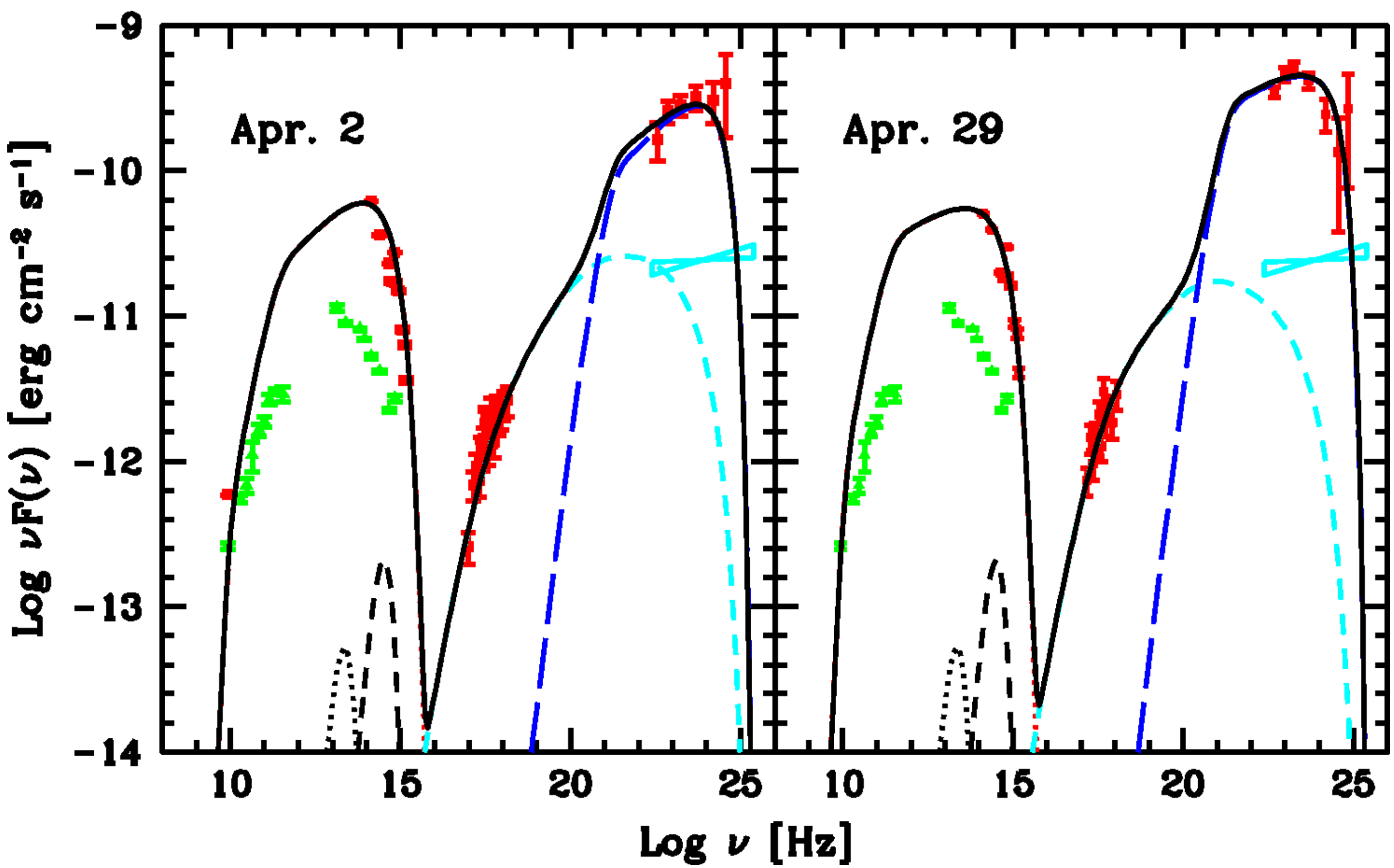
z=1.52

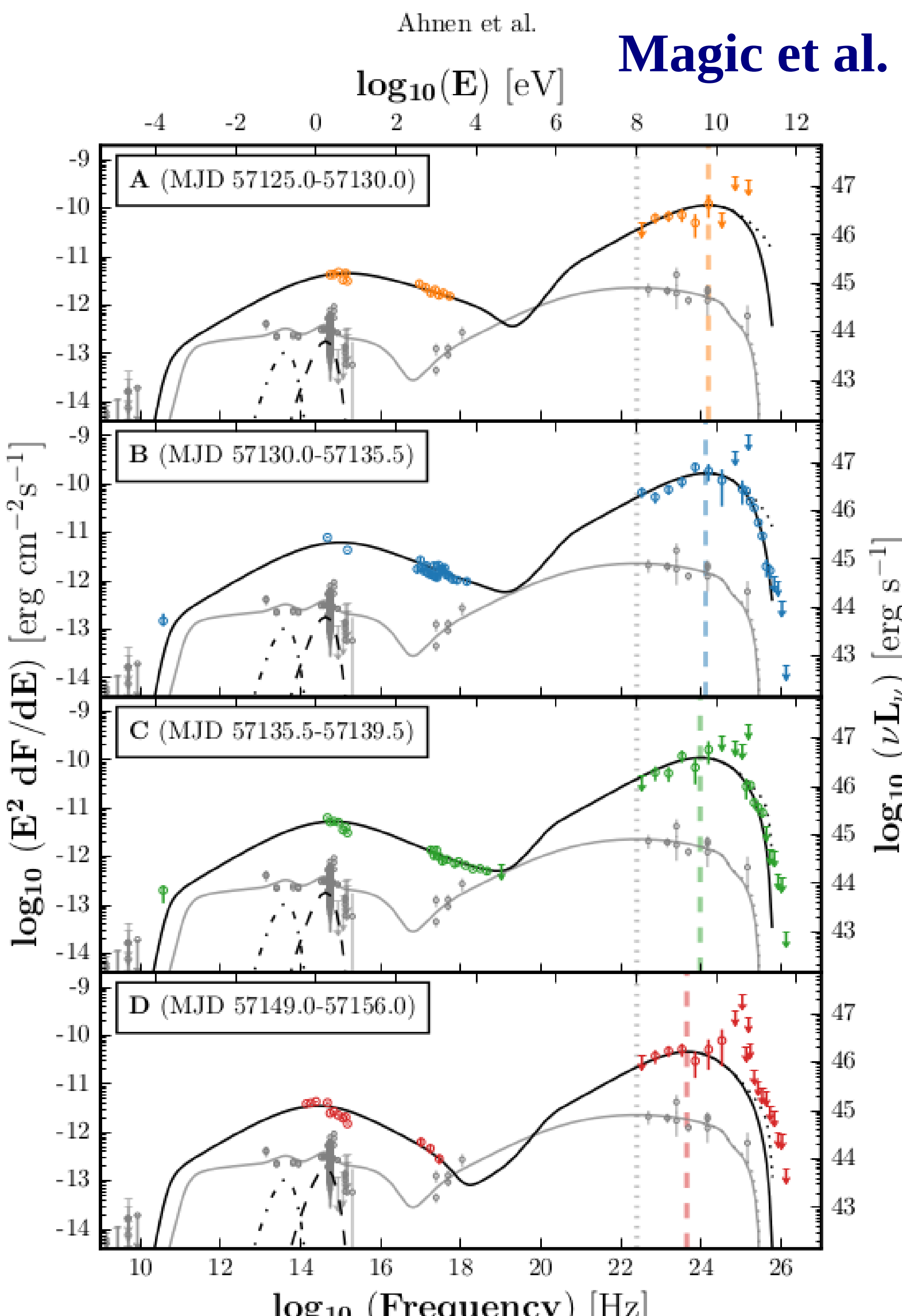


From the broad Mg II line:
$L_{Mg\ II}$=5.4*10^{43} erg/s (Stickel 89)
we derived the BLR luminosity (Celotti 1997)
and in turn the disk luminosity
(we assumed a BLR/disk luminosity ratio 0.1)

L_{disk}=1*10^{46} erg/s

B =6*10^{-3} G
Γ=20
Dist = 7 pc
R=1-1.2 pc
Variability time Scale 30 d, comparable with long term modulation of the light curve, but not with the daily variability.





PKS 1441+25

$z=0.94$

L_{disk}~$2*10^{45}$ erg/s

R_{in}^{BLR}~0.05 pc

dist~0.1 pc

A pessimistic evaluation of attenuation (γγ abs + KN) at 50 GeV (sat frame) is < 3

So the emission region must be at the edge or outside the BLR.

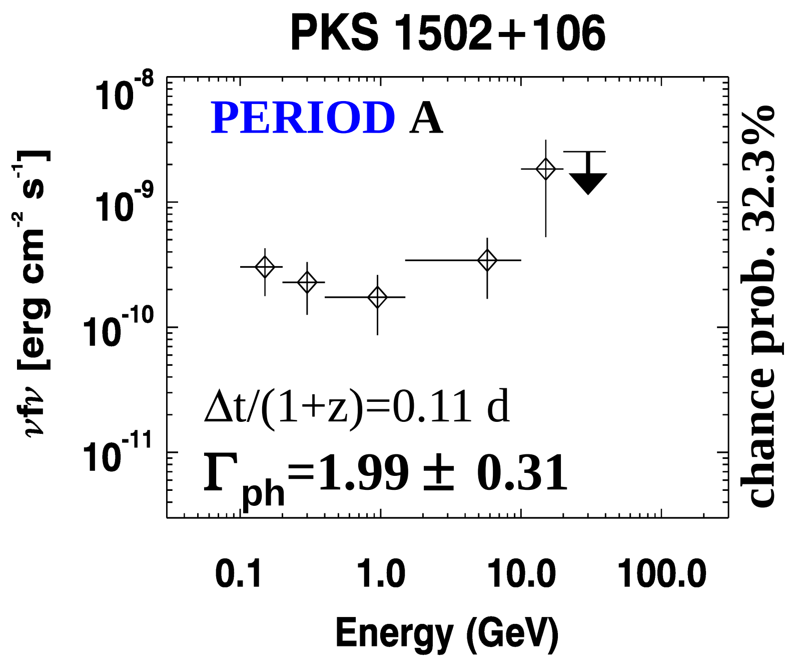
Fast HE flares

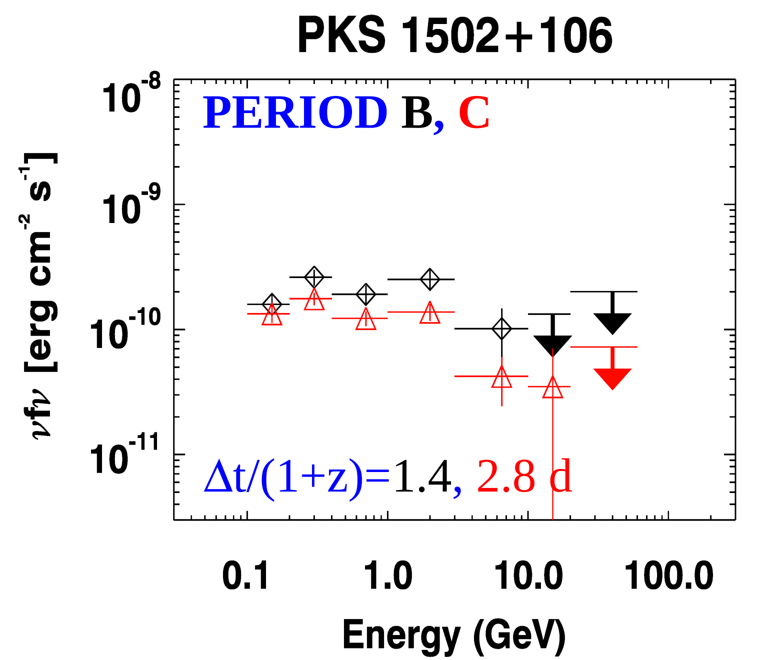
From the 4 brightest HE flares we searched for fast variability at HE (E> 10 GeV).

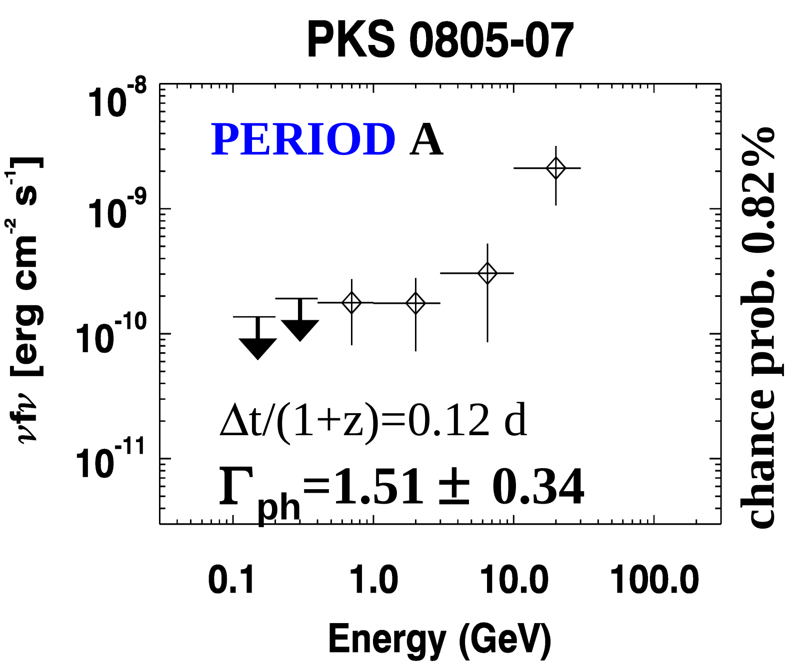
For all these 4 sources we found **short periods (period A)** lasting from **1.5 hours** to less than **6 hours of very bright HE emission and hard spectra.**

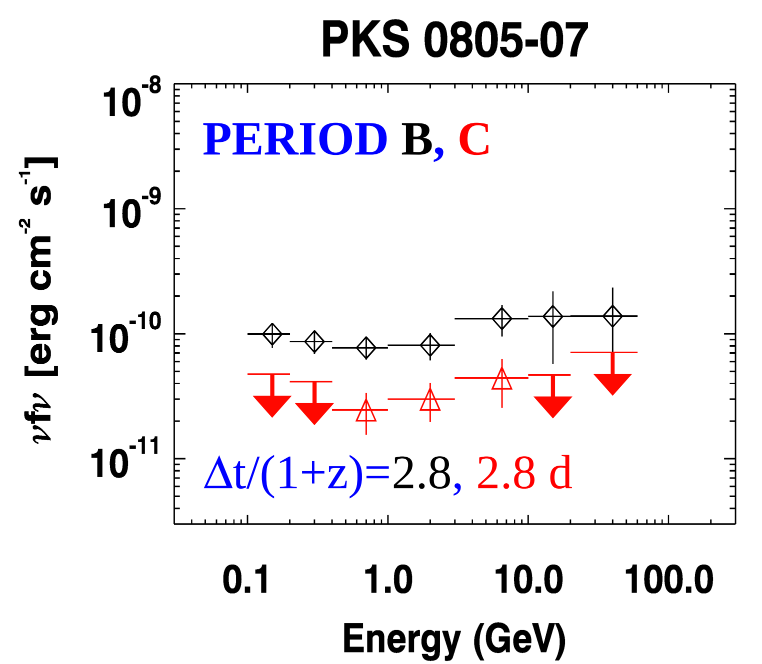
NB: in the following, the gamma-ray photon index of periods A (**Γ_{ph}**) are **evaluated in** the energy range **0.2-10 GeV** (they are **not biased by the selection criteria**, i.e. the search for bright emission at HE, E>10 GeV)

Fast HE flares and spectral evolution (i)

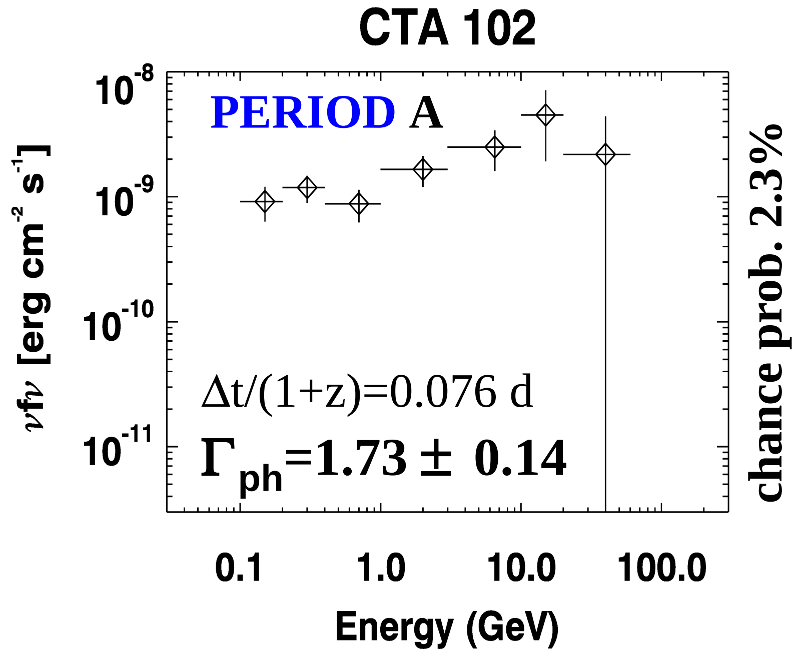


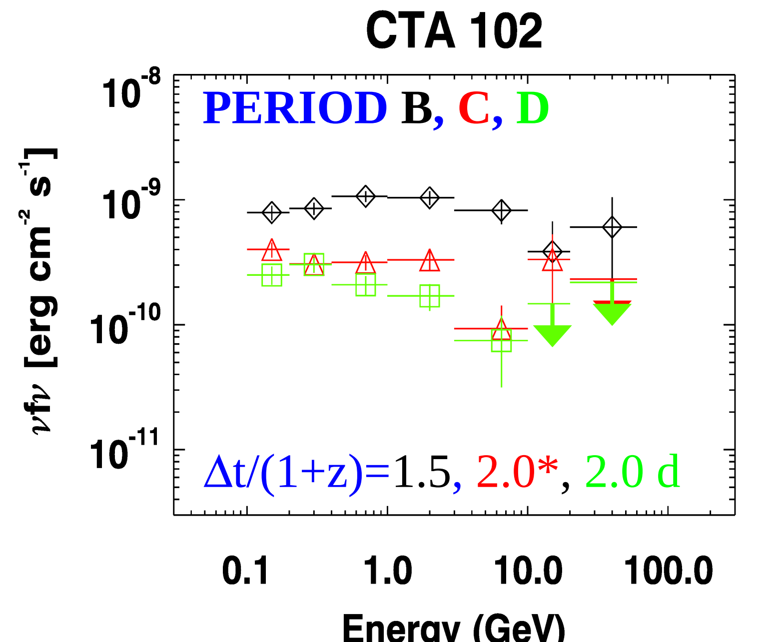




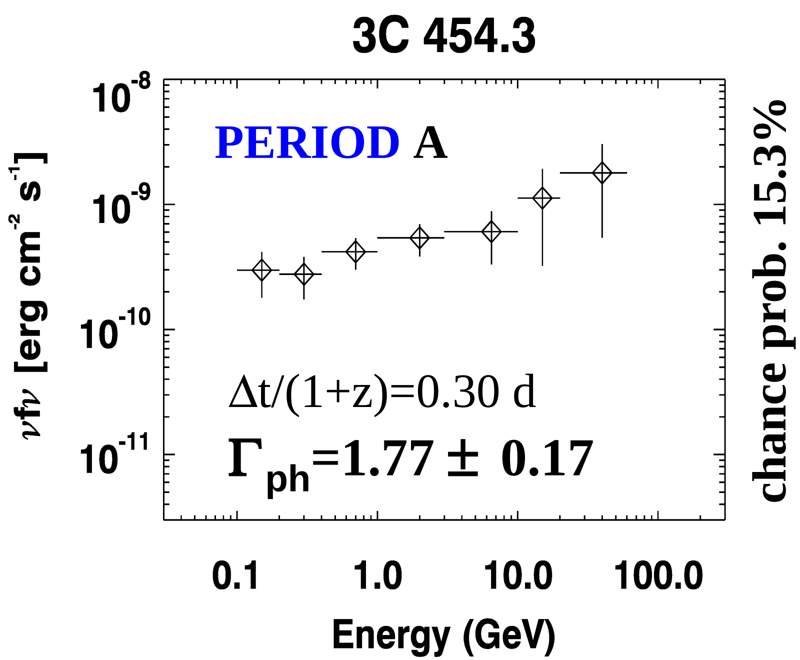


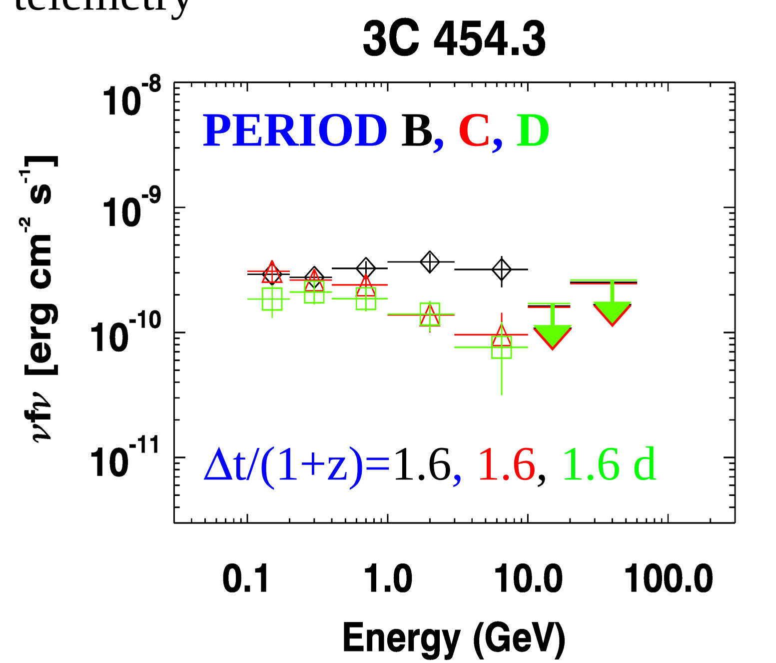
Fast HE flares and spectral evolution (ii)





*period C starts 5 d after period B due to a gap in the telemetry





Fast HE flares and spectral evolution (ii.j)

CTA 102 and 3C 454.3 gamma-ray spectra of period B are consistent with the slow cooling scenario, with:

low energy Γ_{ph} consistent with Γ_{ph} of period A,

and

$\Delta\Gamma_{ph}=0.75 \pm 0.32$ (3C 454.3)

$\Delta\Gamma_{ph}=0.72 \pm 0.35$ (CTA 102)

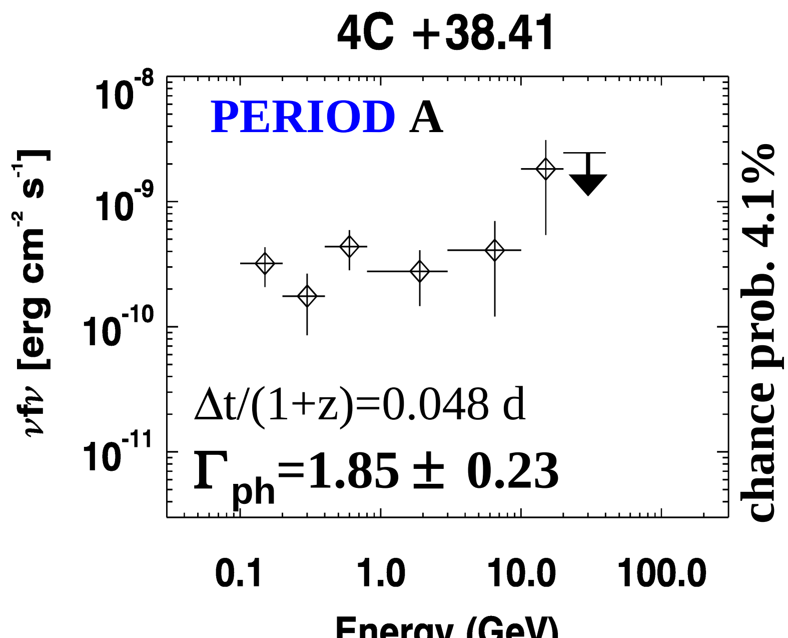
In the dusty torus photon field, the expected cooling time is ~ 1 hour for electrons with γ=30000 (~ 30 GeV EC photons)

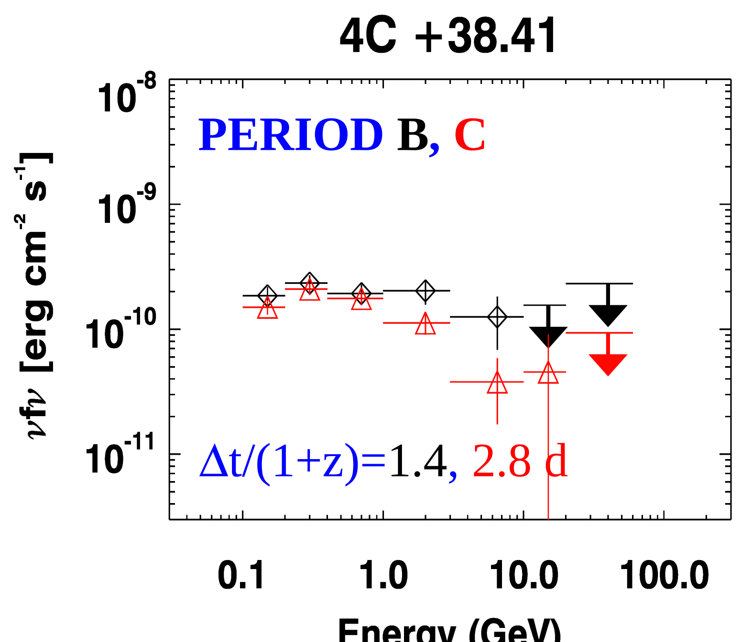
Fast HE flares and spectral evolution (iii)

We have **some** source (B2 1520+031, 4C 38.41, PKS 0250-225) with a **gamma-ray spectrum that mimics the BLR absorption features** proposed in Poutanen & Stern 2010.

We performed the time-resolved spectral analysis for the brightest of these sources: **4C 38.41, revealing a pattern similar to the 4 sources above.**

The absorption like feature of the gamma-ray spectrum integrated on long periods is produced by integrating together the two periods: the hard flare (period A) and its spectral evolution(period B).





The distant scenario

- The bright HE emission witnesses against BLR absorption and Klein-Nishina suppression (for EC on BLR photons)
- The leptonic SED modeling is only consistent with a dissipation region at parsec scale
- The spectral evolution from an hard spectrum is consistent with the slow cooling scenario (chromatic cooling) on Torus seed photons (while the cooling on BLR photons is in Klein-Nishina regime and it is expected to be achromatic).
- **But the CTA 102 light curve** shows a variability pattern which is **inconsistent with slow cooling** (what is the lower activity period in between two higher activity periods, with a duration of 0.5 days?).

what is the engine?

Reasonable engines acting at large distance from the SMBH are:

- Magnetic reconnection (Giannios 2013)
- Turbulence in the jet (Narayan & Piran 2012, Marscher 2014)

Magnetic reconnection scenario

at ~1 TeV:

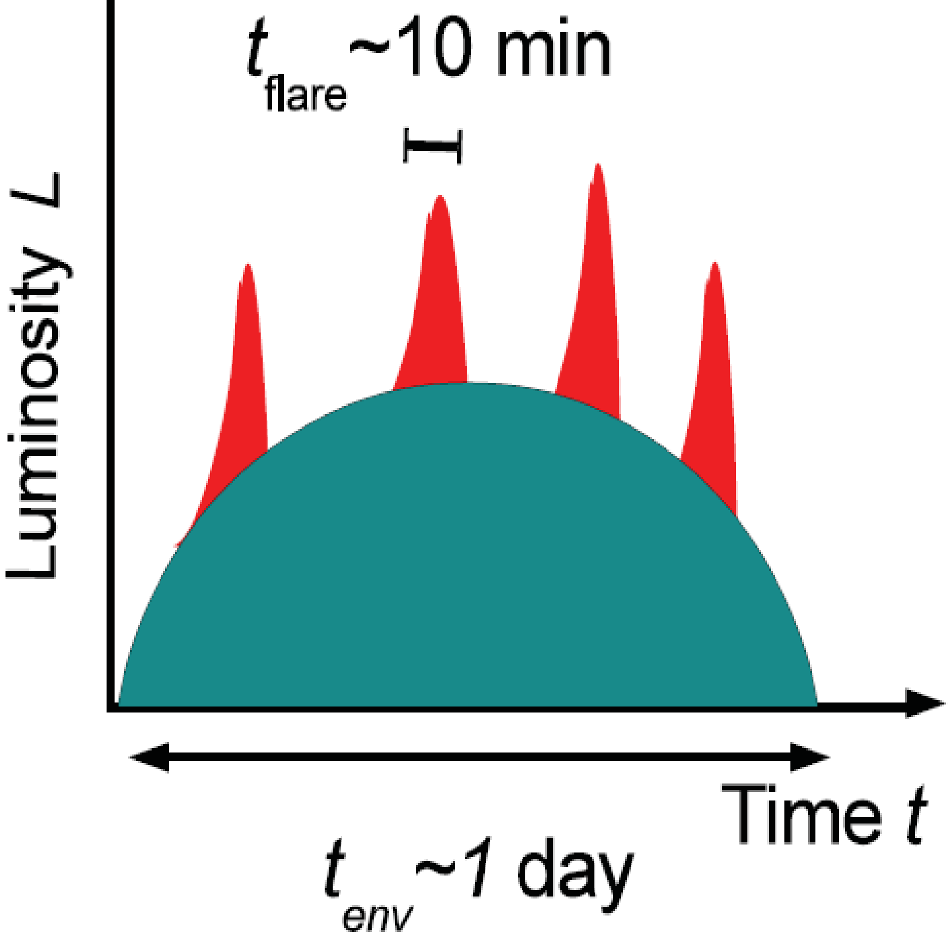


Figure 2. A sketch of the envelope-flare structure of the emission from a reconnection layer. The envelope duration corresponds to that of the reconnection event: $t_{\rm env} = l'/\Gamma_{\rm j}\epsilon c$. Monster plasmoids power fast flares which show exponential rise and last for $t_{\rm flare} = 0.1l'/\delta_{\rm p}c$. For an envelope of $\sim$1 d blazar flaring, the model predicts that monster plasmoids result in $\sim$10-min flares.

Giannios 2013

Variability time scale from the SED modeling is ~30 d, comparable with long term modulation of the light curve, but we observe also sub-daily variability.

Recent scenario for magnetic reconnections proposed for strongly magnetized jets (Giannios 2013) includes an envelope emission (lasting ~1 day) powered by plasmoids, together with fast flares (lasting ~10 min) generated by grown "monster plasmoids".

In low magnetized plasma (such as at several parsec), reconnection time scales are longer and longer flares (days to weeks) could arise (Giannios 2013).

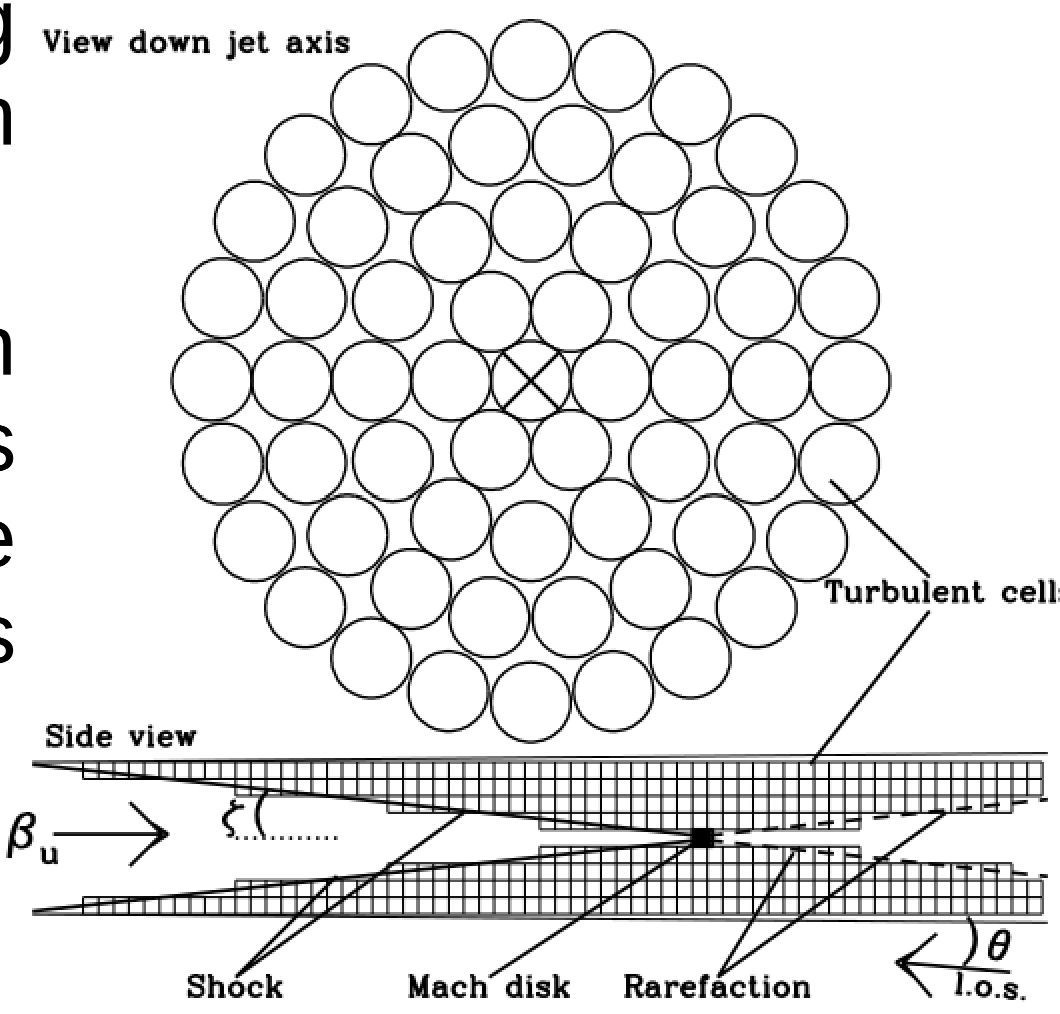
"Monster plasmoids" contain energetic particles freshly injected by the reconnection event (Uzdensky et al. 2010)

Turbulence in the jet

electron acceleration is caused by standing conical recollimation shocks.

Flux and polarization variability originates from turbulence in the flow, approximated as cilindrical cells

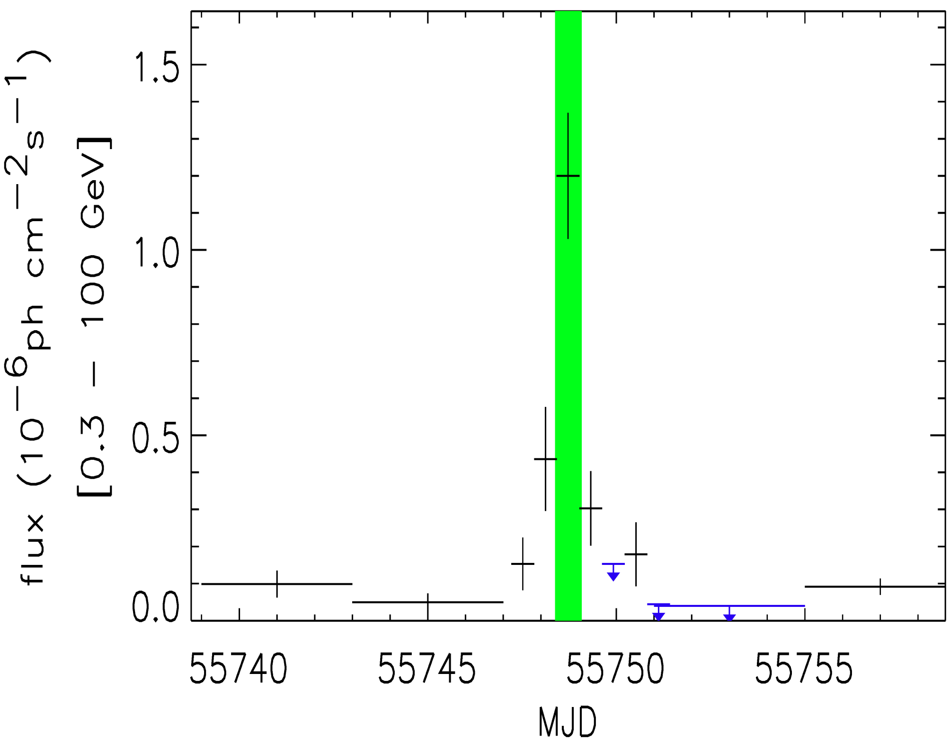
(Marscher 2014)

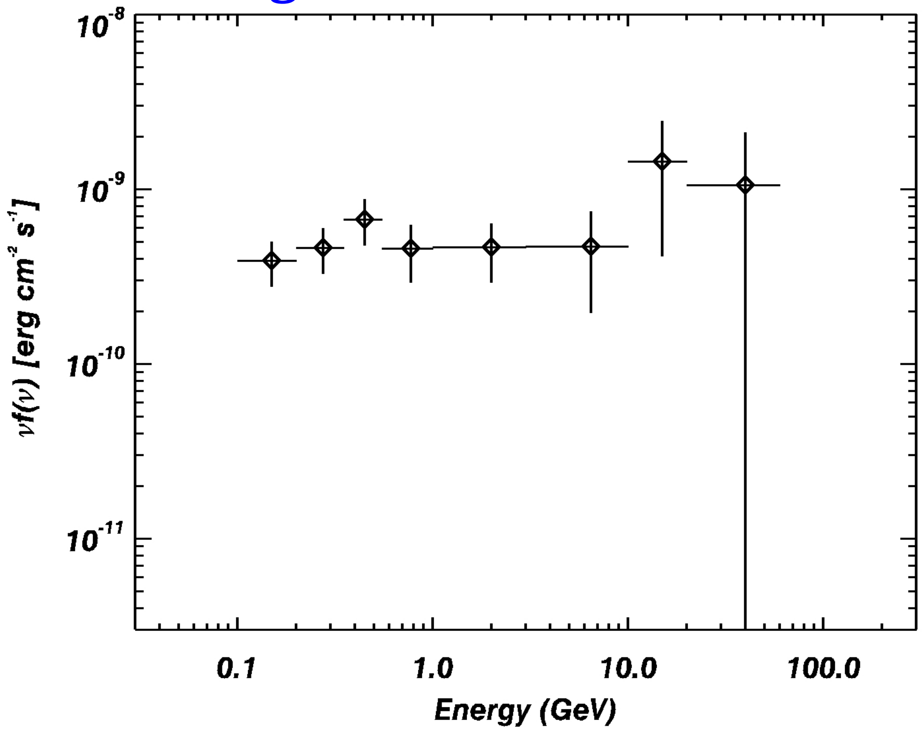


But there are also short HE flares for which the slow-cooling scenario does not work

(we did not had it in the 13 source sample because of the request of simultaneous Swift data)

Z=0.7 , L_{disk}~1.5×10^{45} erg/s





But see also Britto 2015 (3C 454.3 may-July 2015 flares), Coogan 2016 Hayashida 2015 (3C 279, December 2013 – April 2014).

HOW MANY SOURCES?
HOW MANY FLARES?

Work in progress

HOW MANY SOURCES? HOW MANY FLARES?

Work in progress

- We slightly changed the search criteria, we scan the FERMI-LAT data sample searching for HE emission from FSRQs (with almost the same method shown before:
  - We defined HE gamma-ray with a threshold **E_{THR} > min (10 GeV, 20 GeV /(1+z))**
  - Selecting periods with HE gamma-ray **counting rate grater than 3 times the average** counting rate
  - **at least 3 HE gamma-rays** (E> E_{THR}) within the period
  - TS > 25 (S/NR > 5) for E > E_{THR}

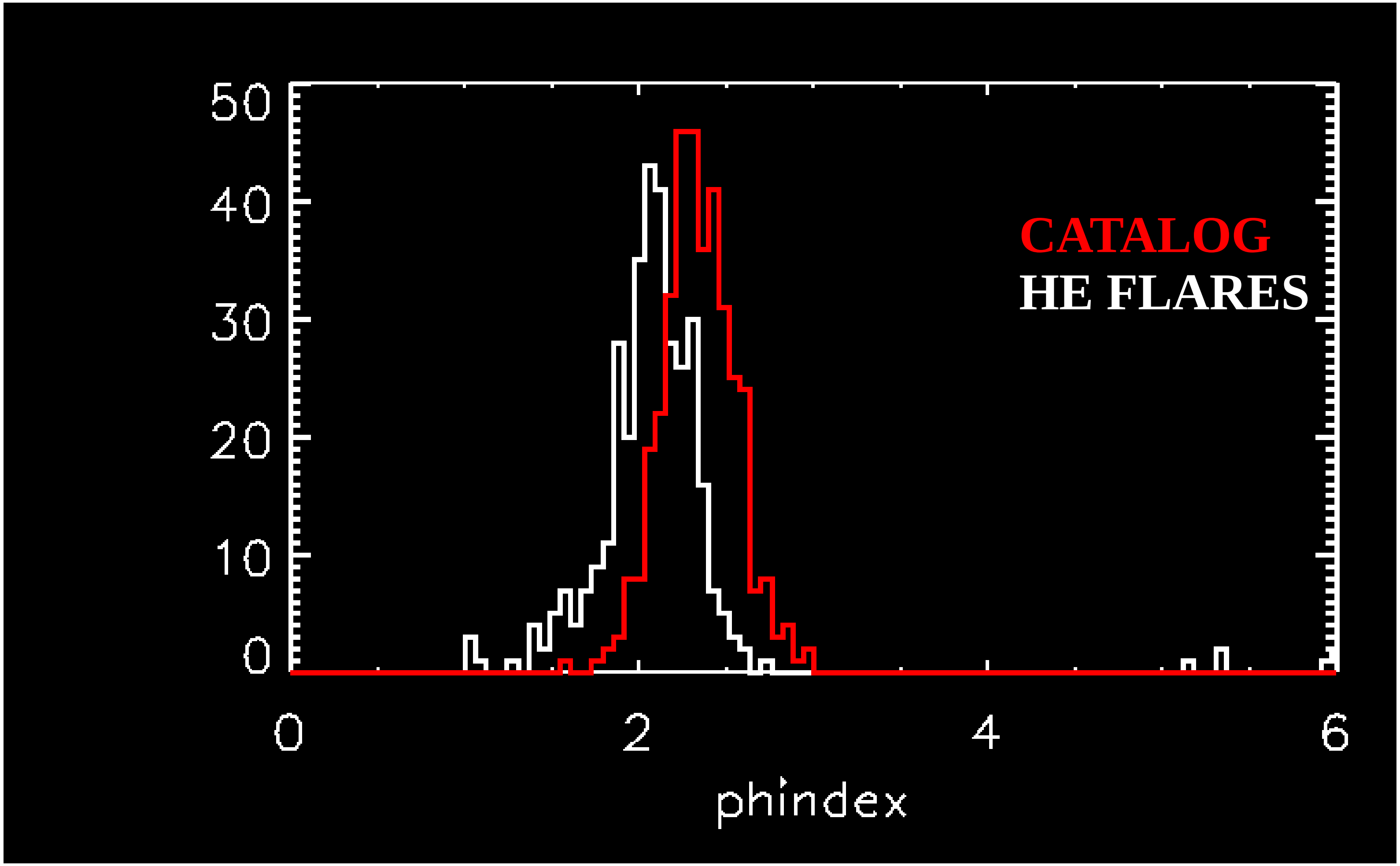
HOW many sources?
HOW many FLARES?

From the first 6 years of FERMI-LAT data:

- With this trigger metho, we found **85 sources:**
  - **40 FSRQs with PowerLaw spectrum** from the 2nd FERMI-LAT CATALOG
  - **45 FSRQs with LogParabolic spectrum** from the 2nd FERMI-LAT CATALOG
- for a **total of 275 flares**
- **50 mwl campaigns.**

PowerLaw photon-index distribution for HE flares (I)

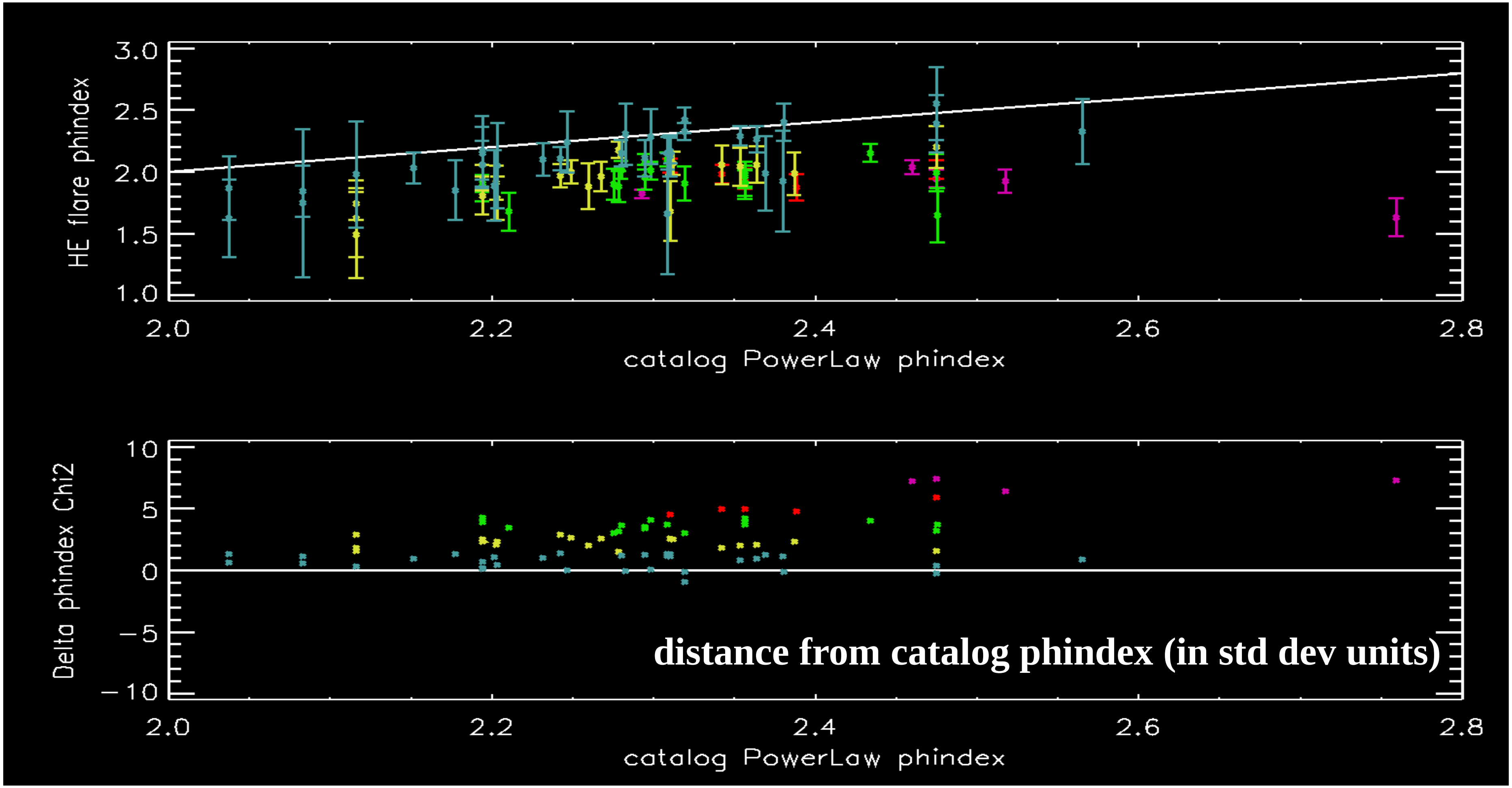
(fitting below E_{THR}: **200 MeV - E_{THR}**)



PowerLaw photon-index distribution for HE flares (II)

(fitting below E_{THR}: **200 MeV – E_{THR}**)

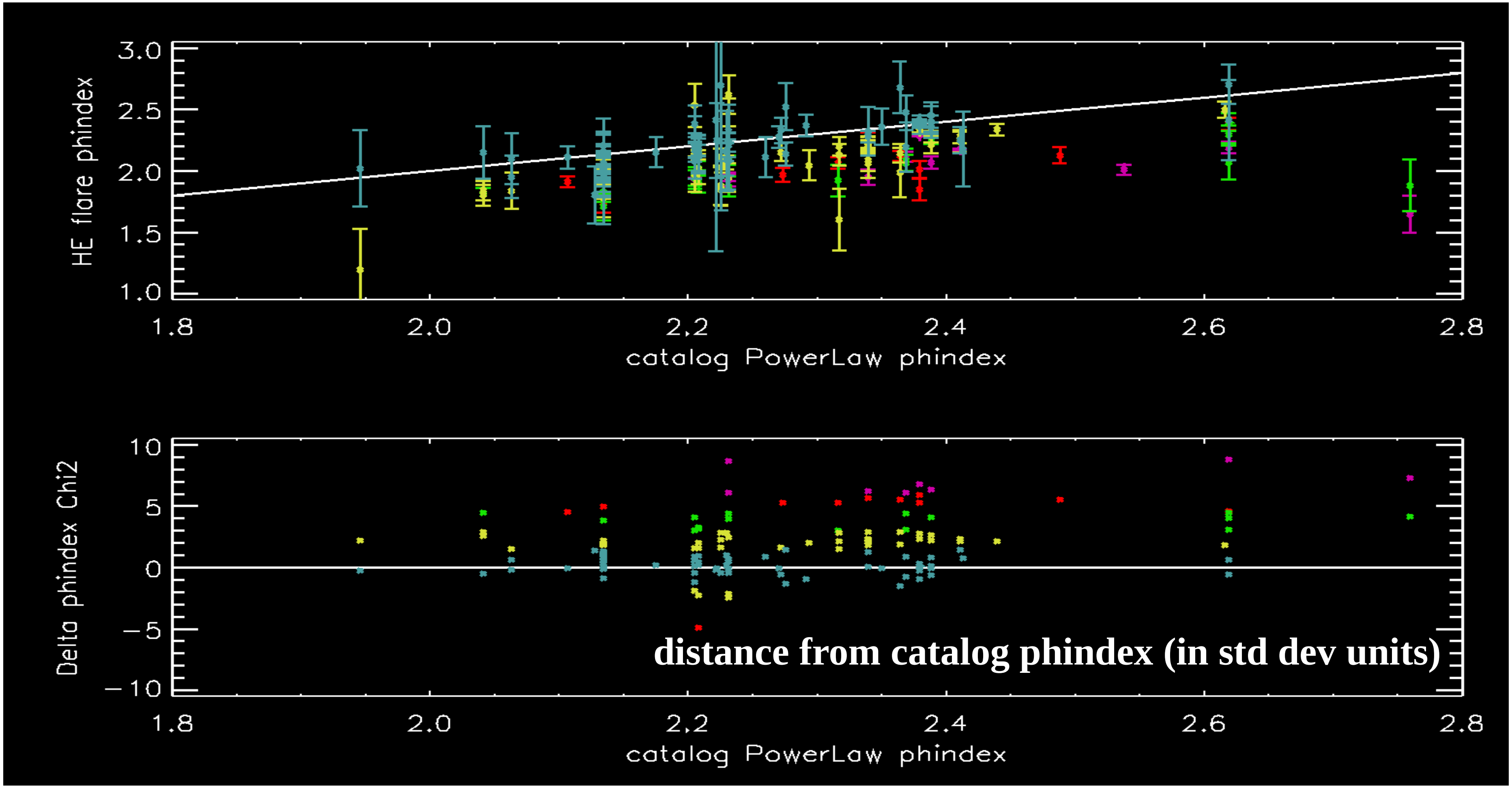
sources with PowerLaw spectrum in the 2nd FERMI-LAT catalog:



PowerLaw photon-index distribution for HE flares (III)

(fitting below E_{THR}: **200 MeV – E_{THR}**)

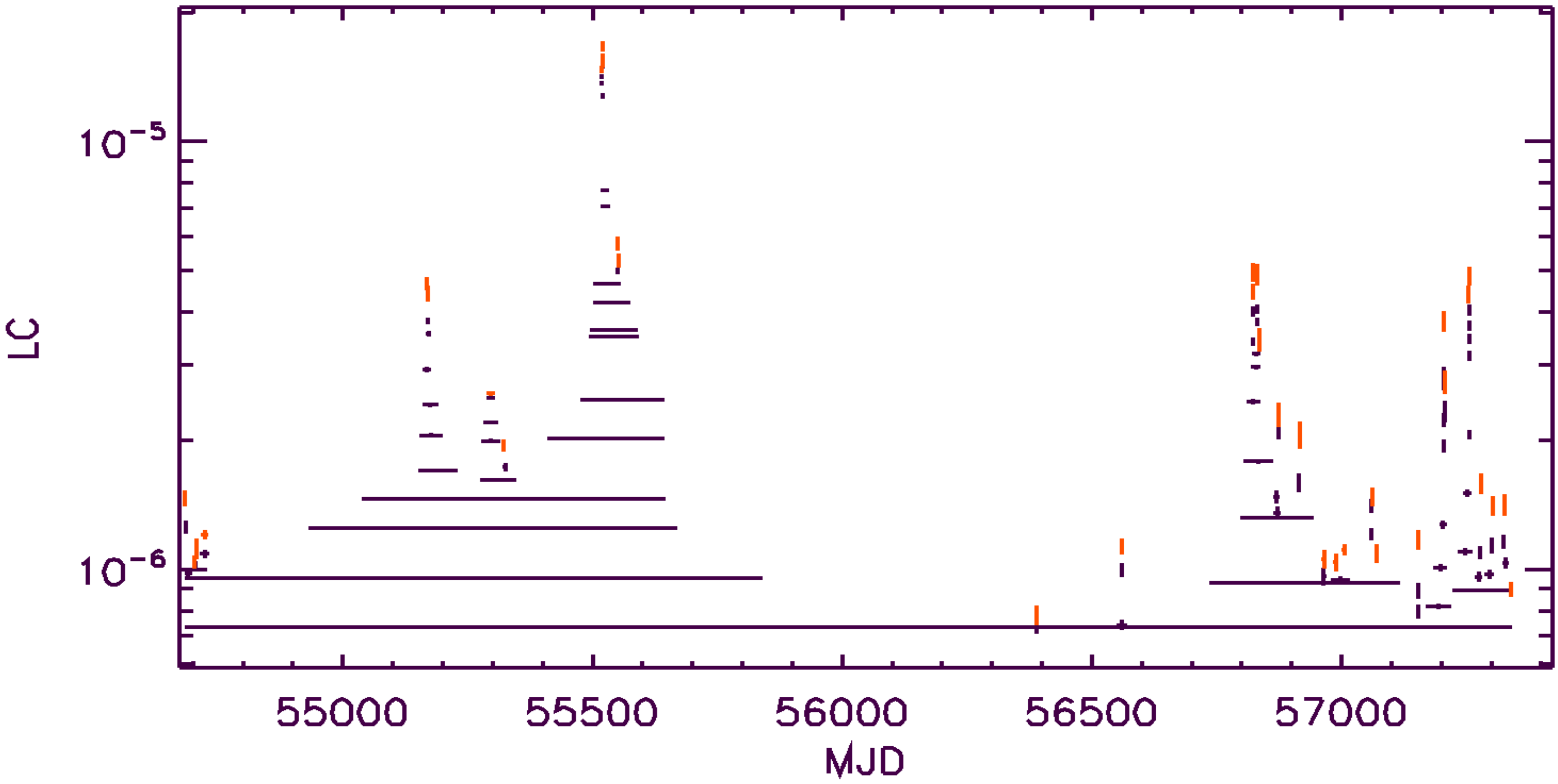
sources with LogParabolic spectrum in the 2nd FERMI-LAT catalog:



How many flares? The comparison with the full sample of gamma-ray flares of FSRQs

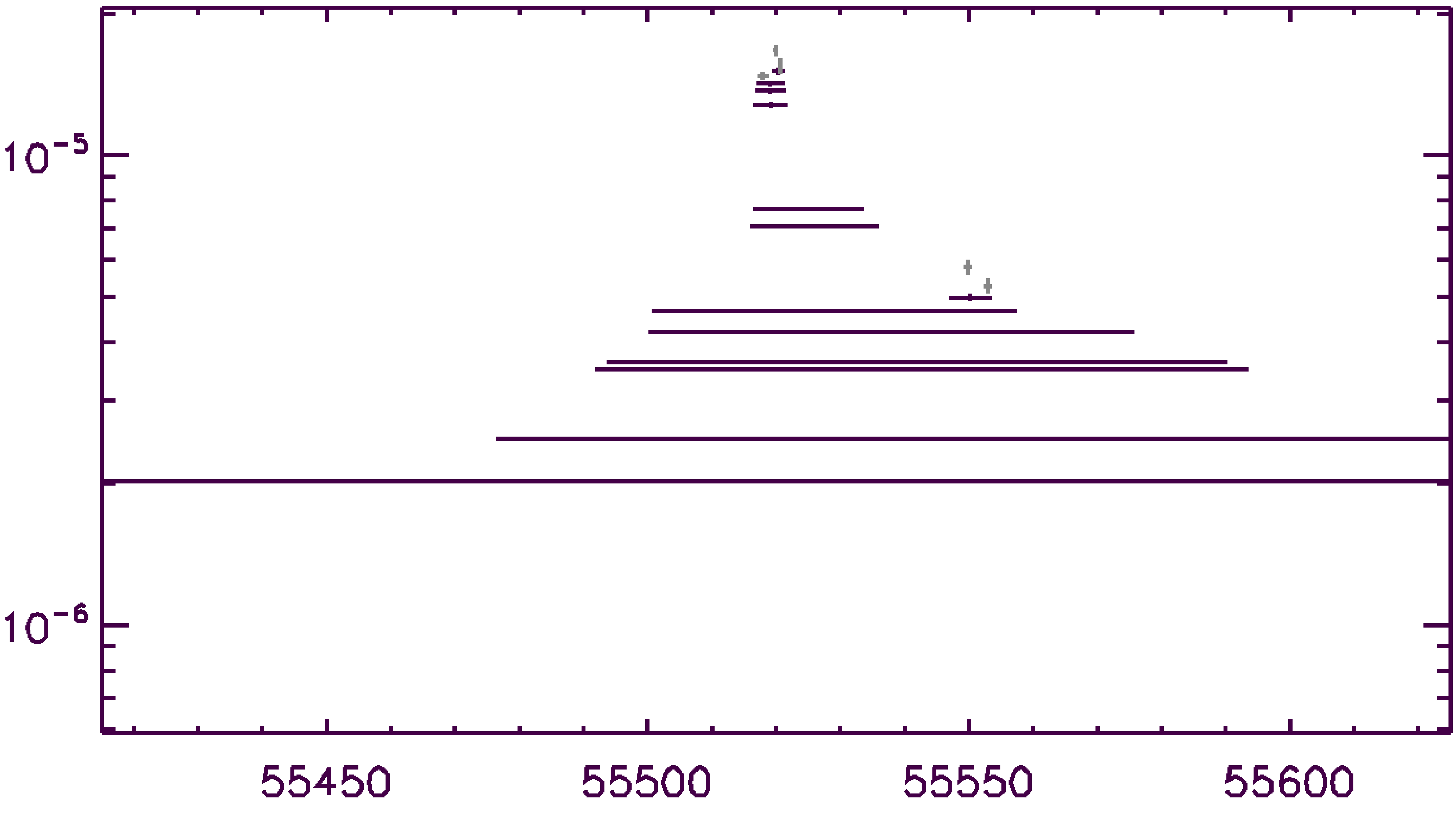
- With a similar clustering method used for the search for HE flares, we searched for gamma-ray flares of FSRQs in the energy range **0.3-300 GeV**.
- We took into account exposure, and chance coincidence **(rejected with a Prob ~$3*10^{-7}$ including repetitions)**.
- Solar flares are rejected, Asking the source to be at >15 deg from the sun during flare.
- Flares from closeby sources are rejected studying the angular distribution of events during flare.
- Peak fluxes evaluated with **photometry** are **compared with the full likelihood** analysis, and eventually the flare is validated.

3C 454.3 photometric LC (0.3-300 GeV)

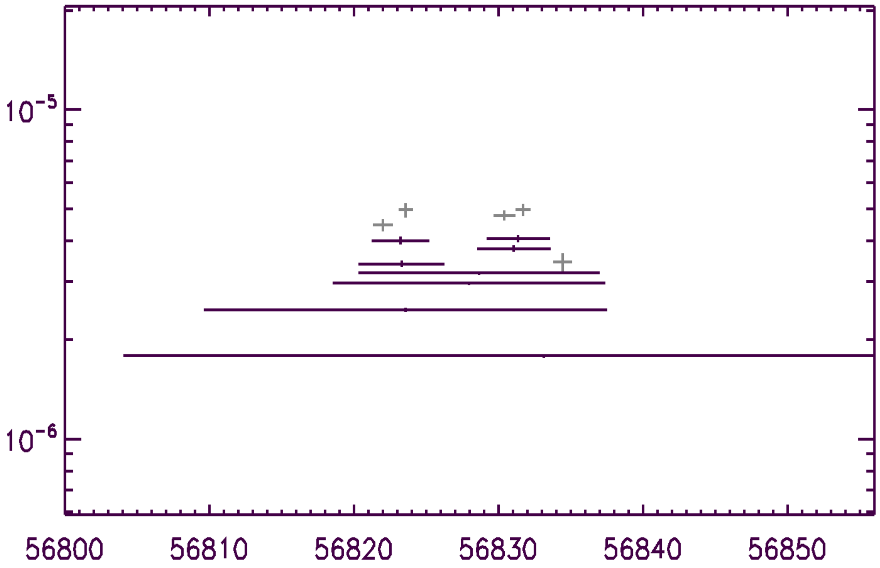


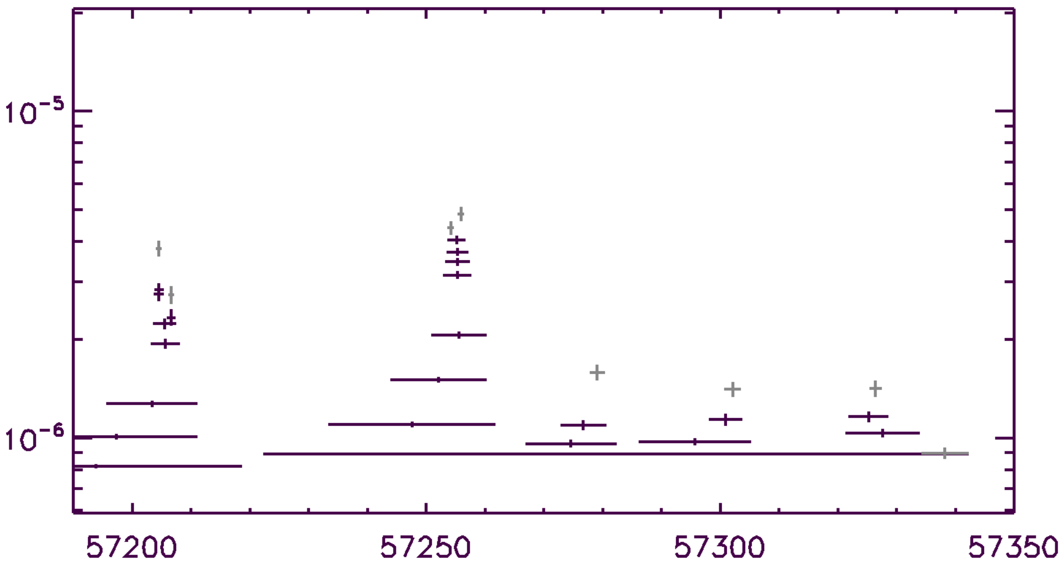
For each segment the Flux level is the mean Flux within the segment
Each level has a chance prob. with respect to the parent one of < 3.+10-7 including repetitions
Peak fluxes are shown in red
Contrary to usual LC, No typical timescales (time binning) spoil the peak flux estimation

3C 454.3 photometric LC (the brightest flare)

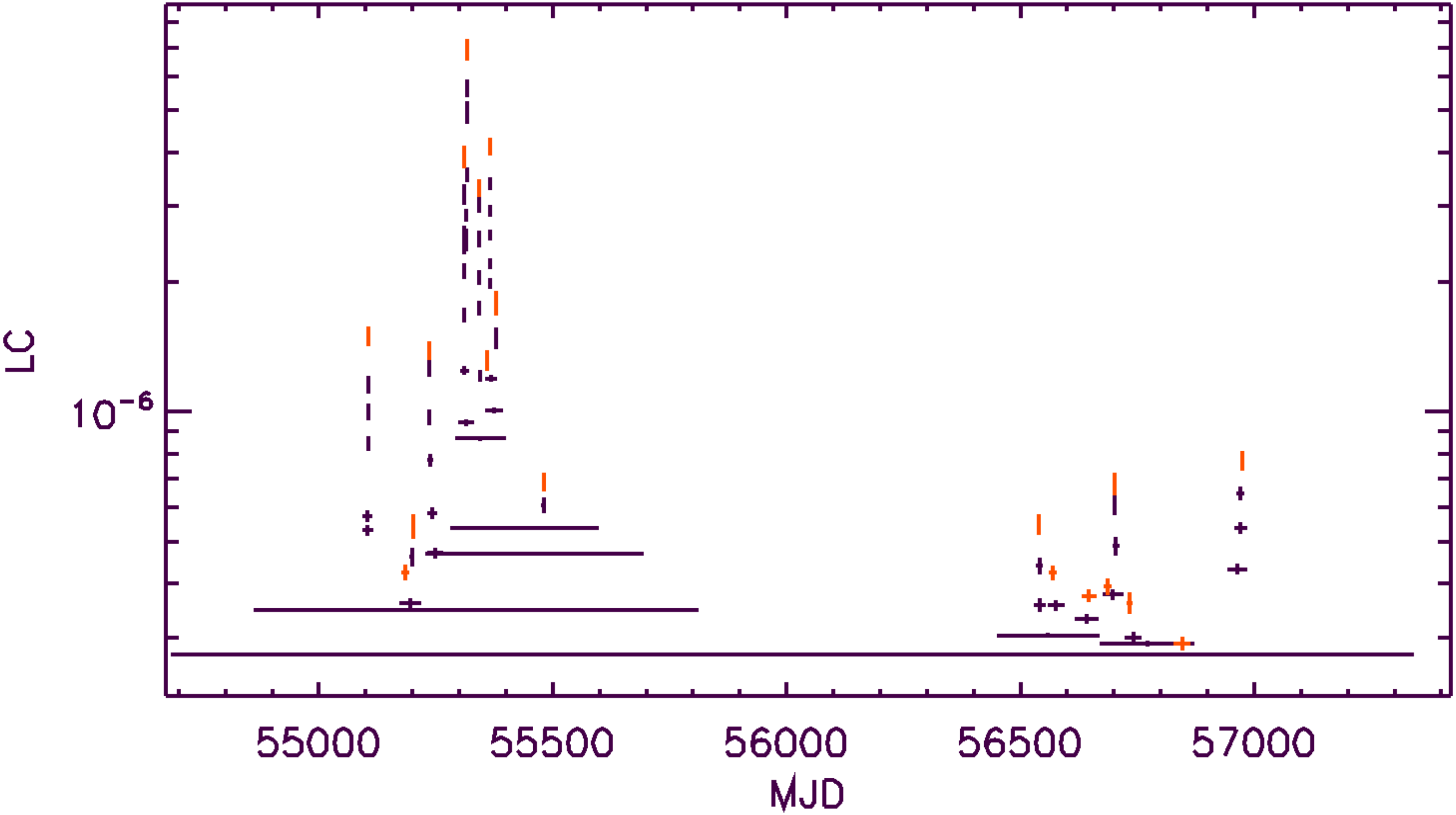


3C 454.3 photometric LC (other flares)

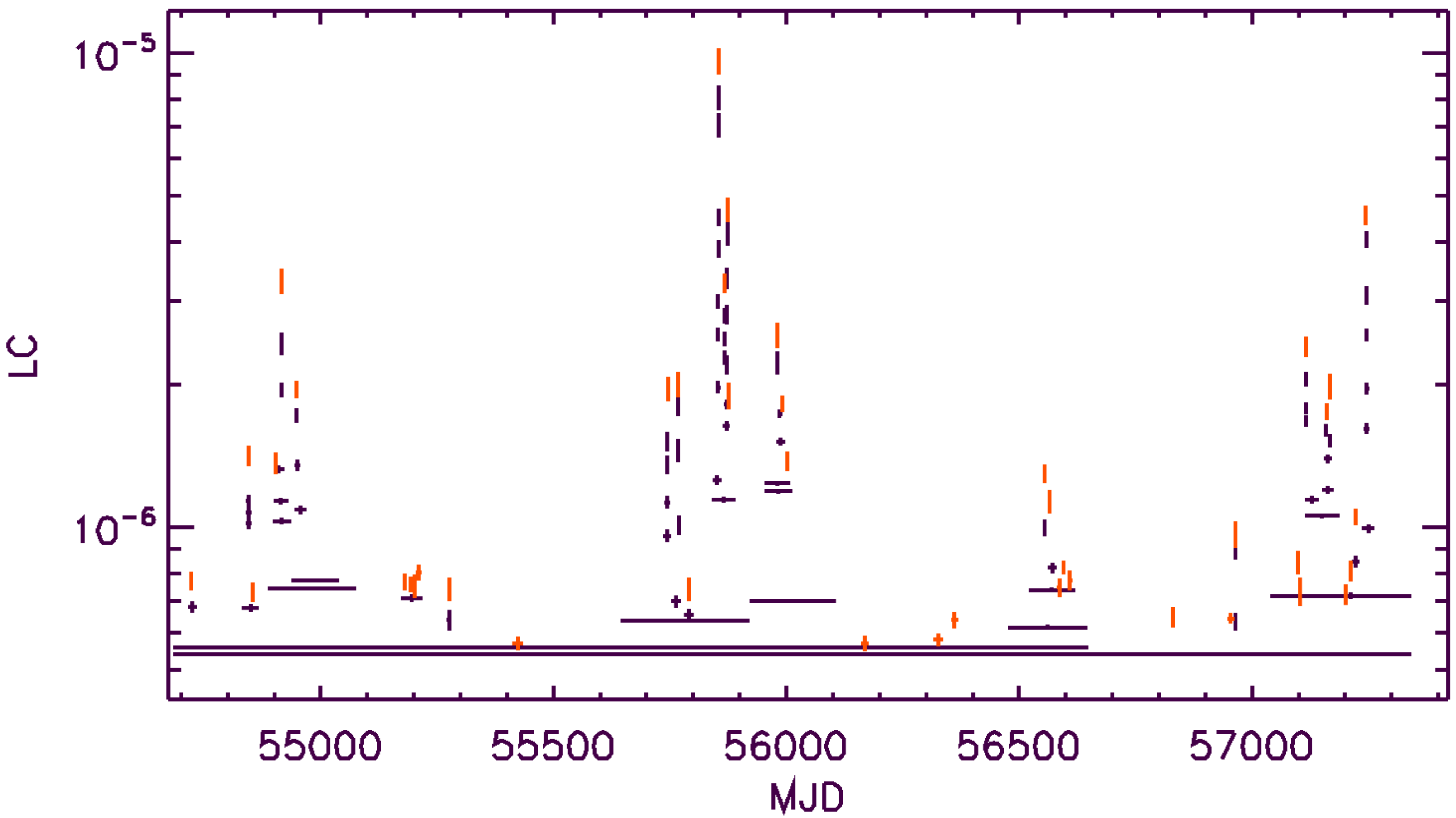




PKS 1222-216 phot. LC (0.3-300 GeV)

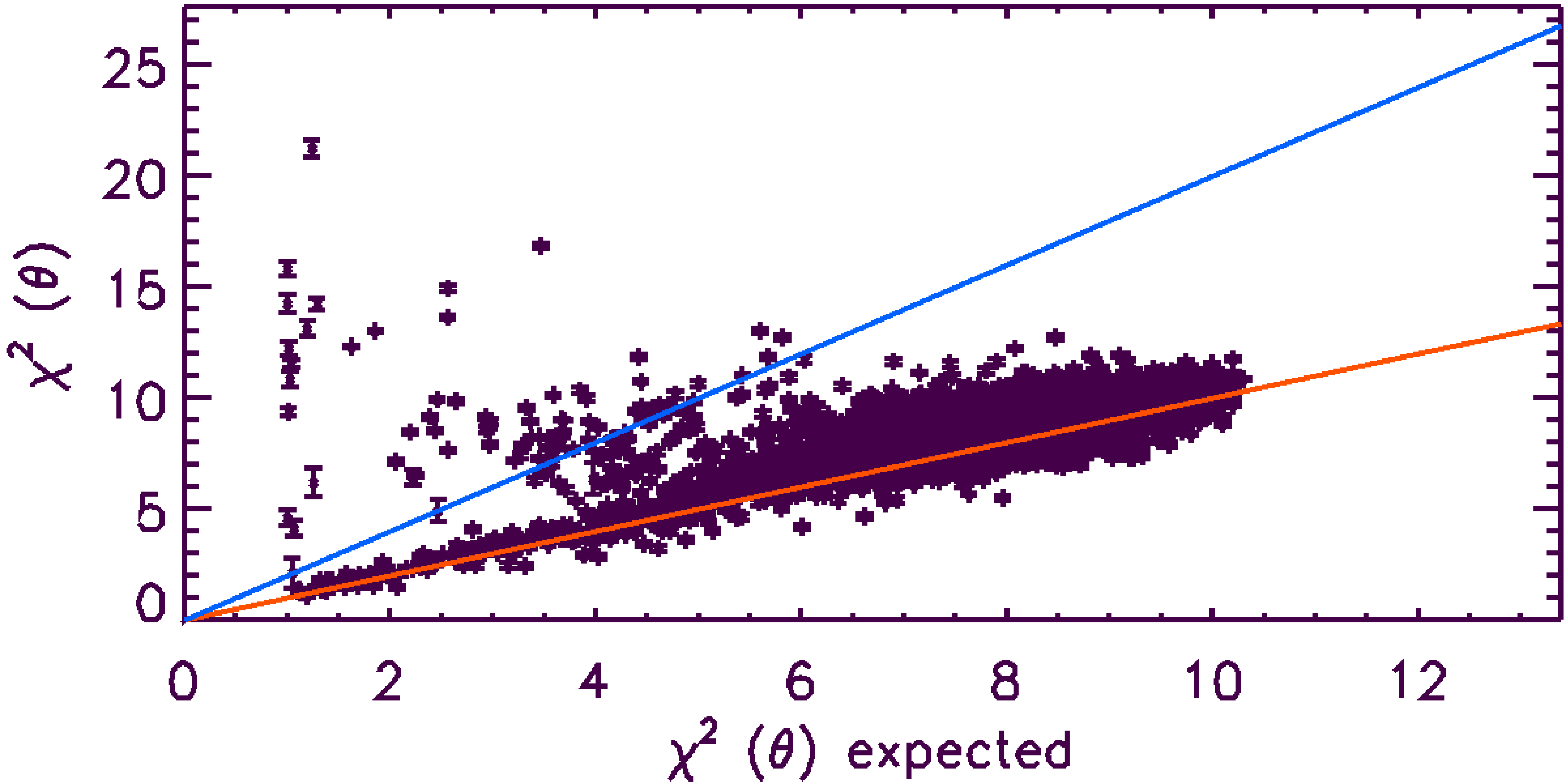


PKS 1510-08 phot. LC (0.3-300 GeV)



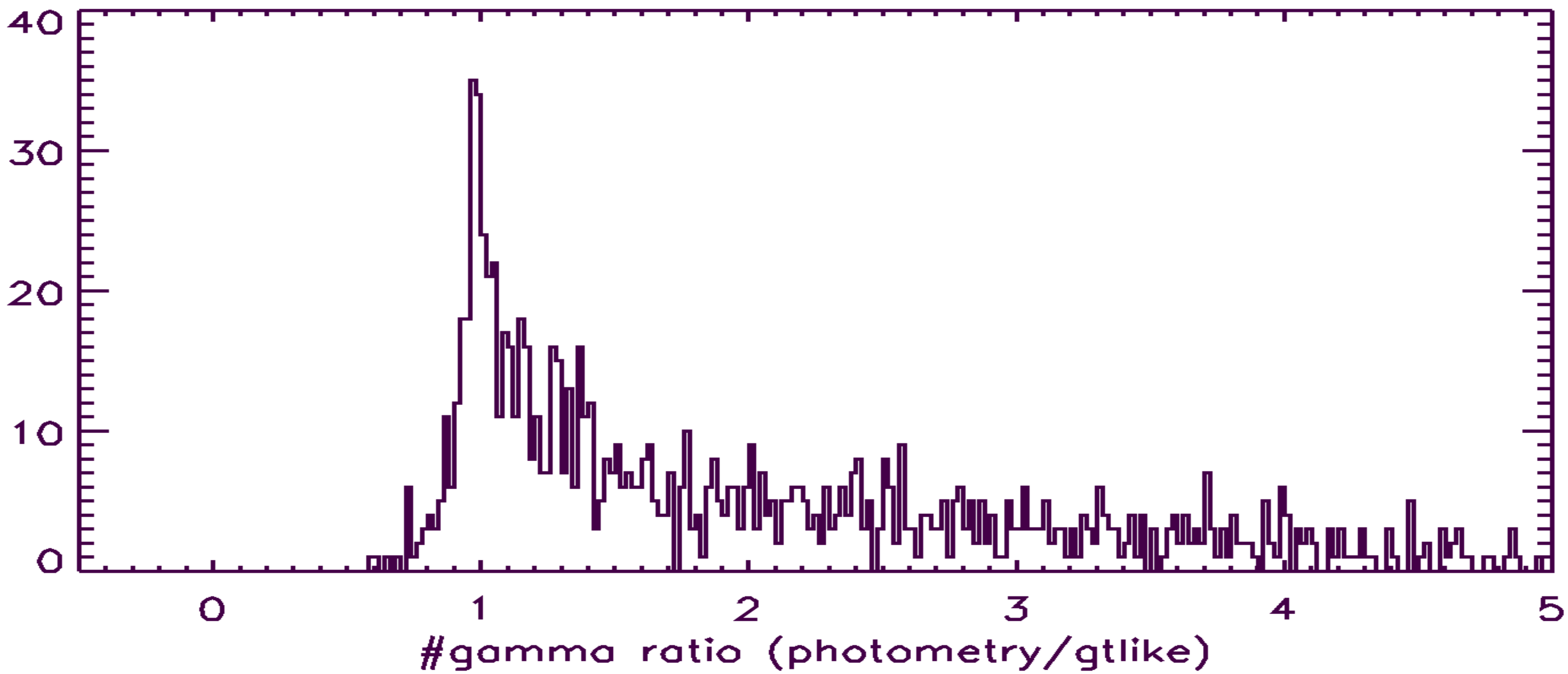
How many flares?
The comparison with the full sample of gamma-ray flares of FSRQs

angular distribution of events during flare

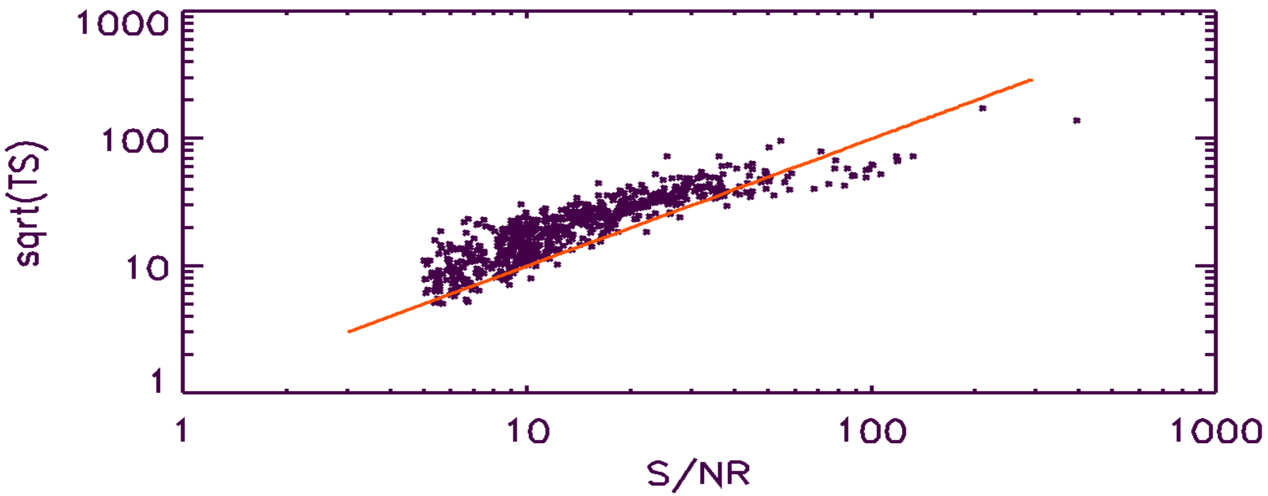


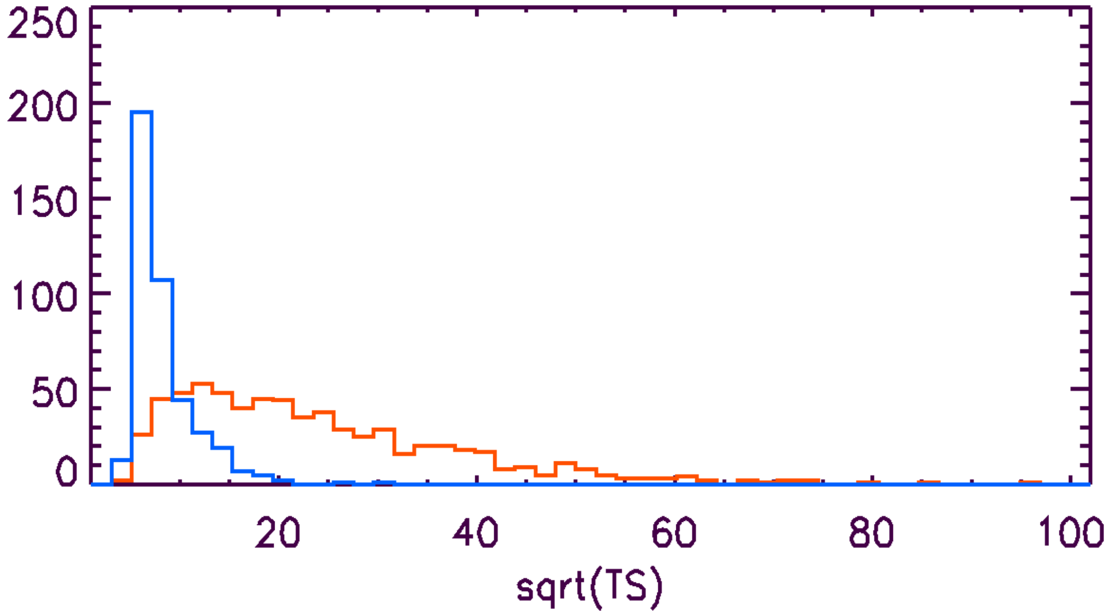
How many flares?
Photometry-likelihood comparison

- The likelihood evaluates sources counts, diffuse bkg within the chosen time interval
- The photometry avaluates the investigate source counts+bkg within the extraction region, bkg is estimated from the long integration, bkg source counts are evaluated from the catalog.
- photometric source counts and likelihood source counts could not coincide (especially at low source flux)
- If the likelihood and photometric based flux for the investigated source do not correspond, the photometric peak flux could be ascribed to a bkg source, and the peak must be rejected.

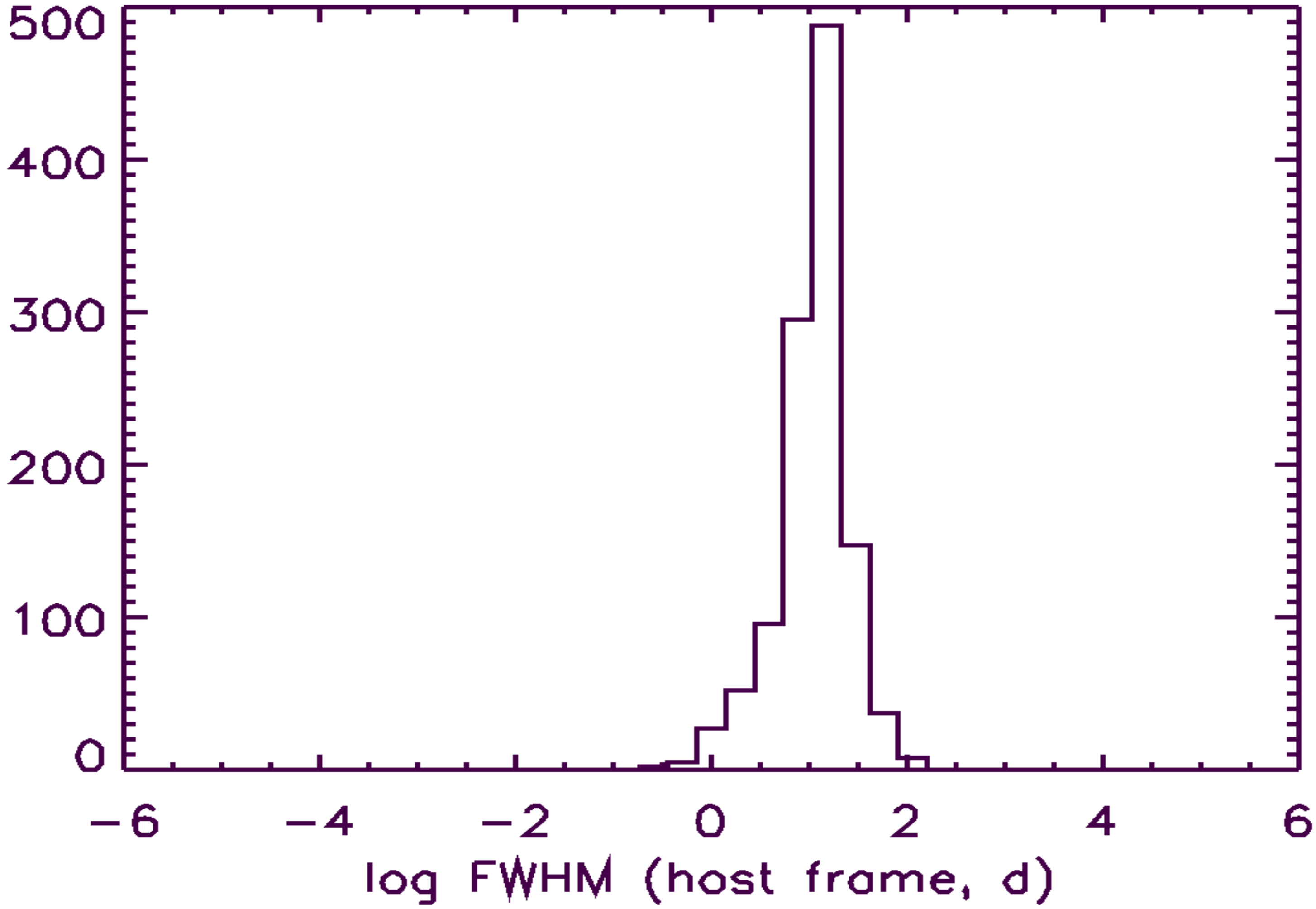


Sample significance





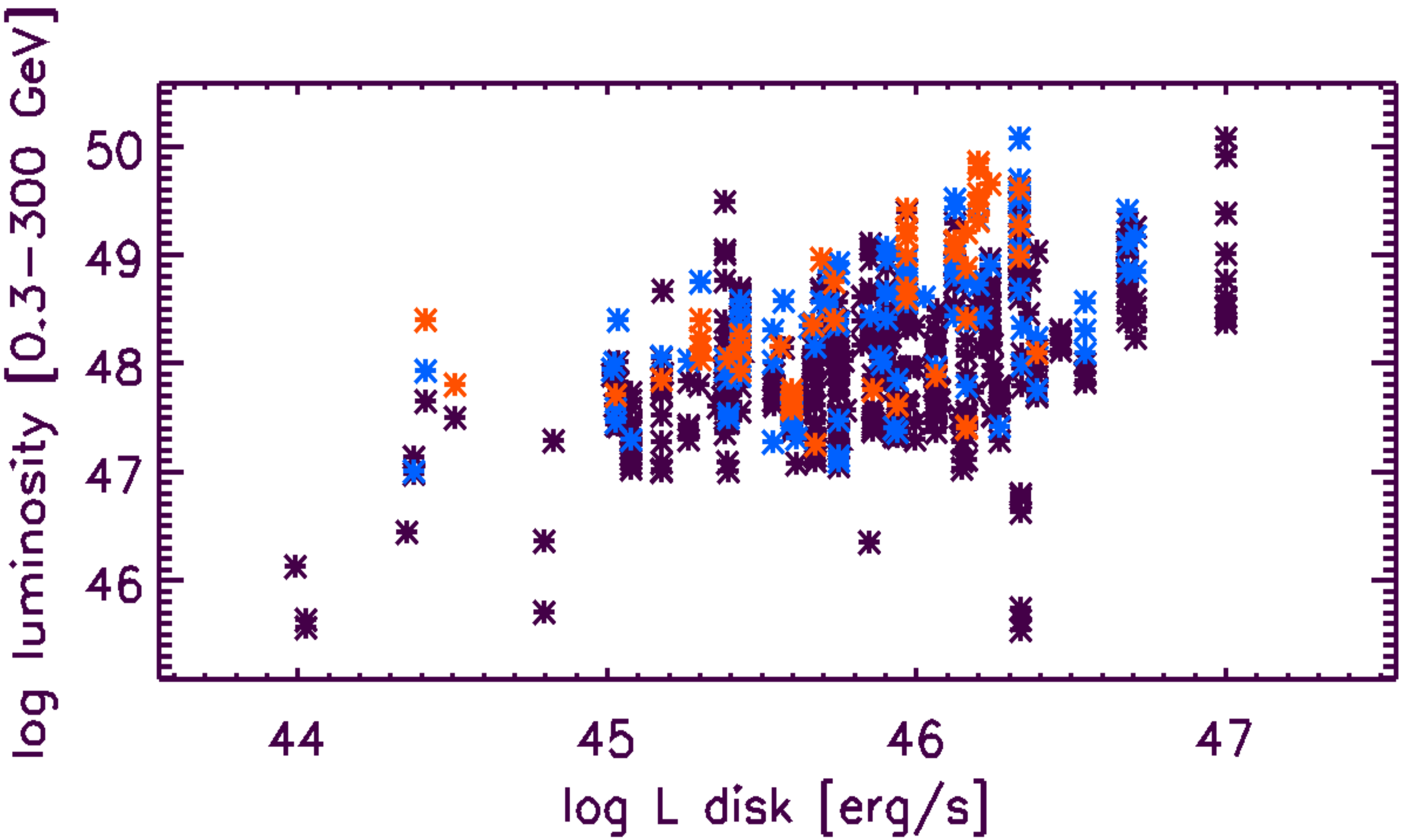
FWHM distribution of flares



Within this study, the typical dyinamic timescale is < 20 days

The jet to disk correlation during flares
(dynamic time scales < 20 days)

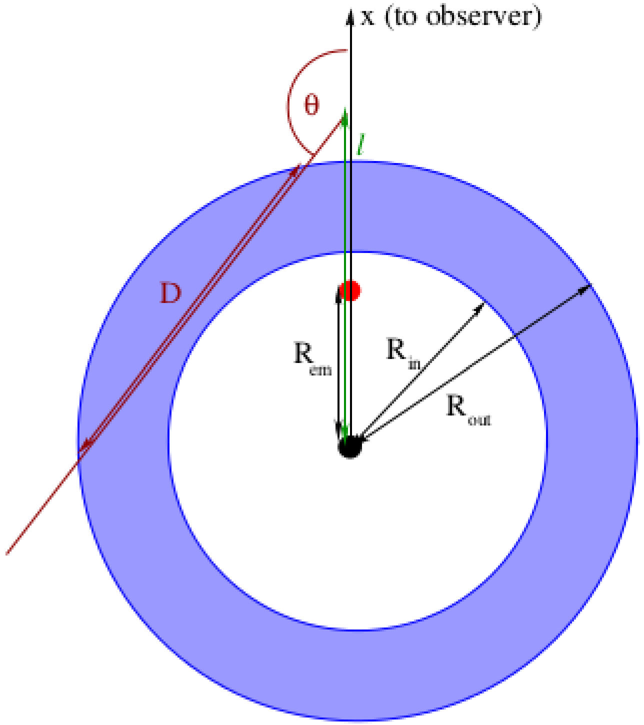
- red: flares with significant emission above 35/(1+z) GeV (TS>25)
- blue: flares with some emission above 35/(1+z) GeV (TS > 9)



Opacity computations at $R_{diss} = R_{BLR}/2$

- The opacity becomes low as the dissipation region approaches the internal radius of the BLR. Moreover, the opacity computed value strongly depends on the BLR model.
- At distances of the order of $R_{BLR}/2$, the opacity is high and the computation do not strongly depends on the details of the modeling.

  - We use the **Boettcher 2016** model, normalized to the observed Broad Line luminosities



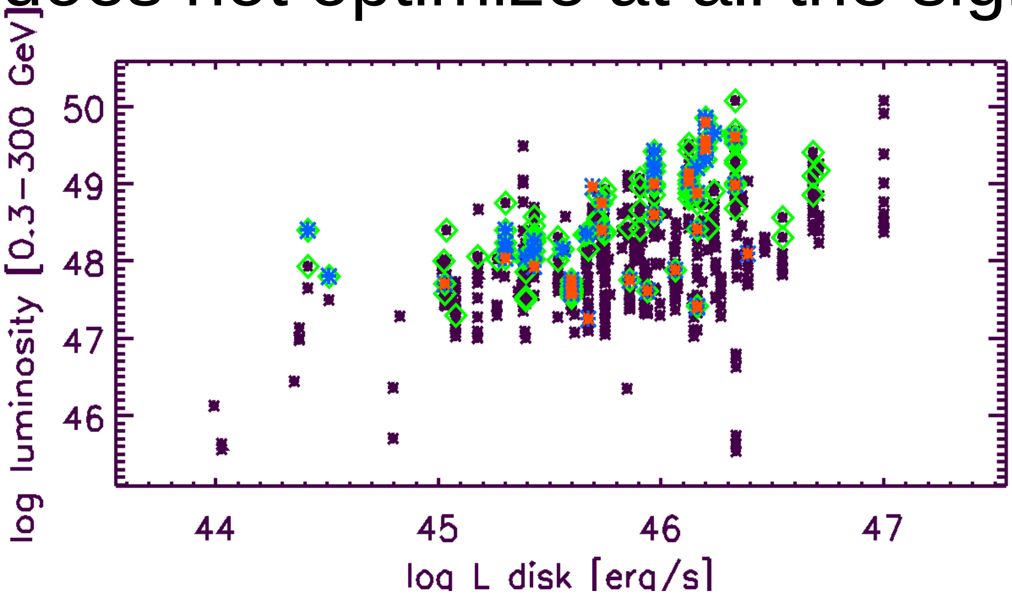
Opacity computations at $R_{diss} = R_{BLR}/2$

- Using the **Boettcher 2016** model, normalized to the observed Broad Line luminosities, the opacity **at $R_{diss} = R_{BLR}/2$** is estimated :
- $\tau_{\gamma\gamma} \sim 4.5*(Ldisk/1.*10^{46})^{0.5}$ assuming $R_{BLR} = 10^{17}*(Ldisk/1.*10^{45})^{0.5}$ cm (Ghisellini 2009)
- $\tau_{\gamma\gamma} \sim 1.9 * 2^{\log10(Ldisk/1.*10^{\wedge}46)}$ assuming $R_{BLR} = 7.7*10^{17}(L_{disk}/10^{46})^{0.684}$ cm (Wu 2004)

With a gamma-ray only sample, the opacity argument can be used to discriminate flares at $R_{diss} > R_{BLR}/2$

The HE flares ratio

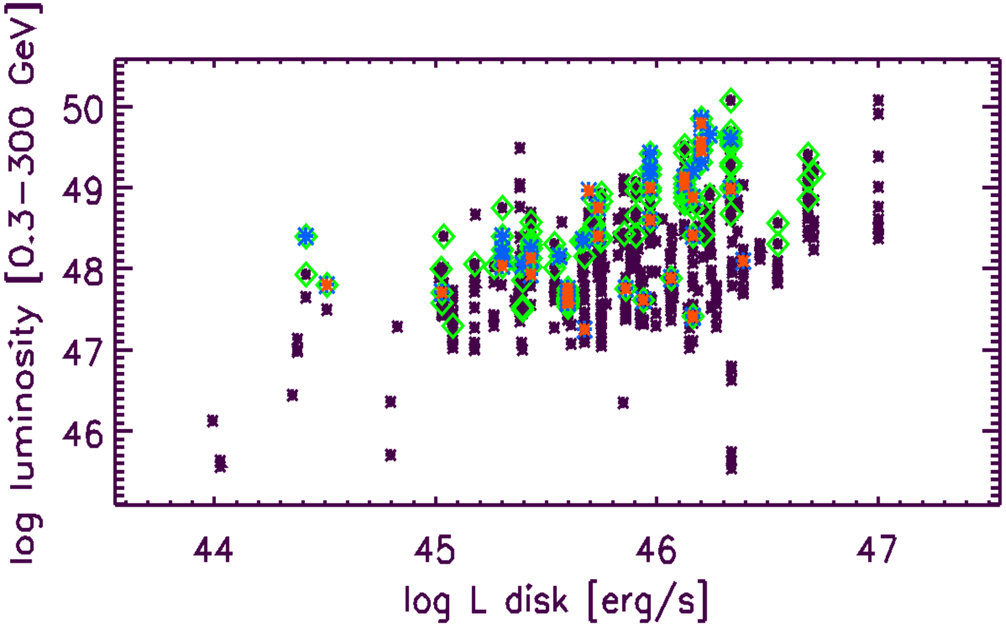
(it is a lower limit only, due to the procedure: the peak search does not optimize at all the significance of the HE component)



Green squares:
detecatble signal above 35/(1+z) GeV

Assuming a R_{BLR} scaling as in Ghisellini 2009:
$R_{BLR} = 10^{17} * (Ldisk/1.*10^{45})^{0.5}$ cm

we have **(red stars)**
26% (+10-5)% sist. ±3% stat
of detectables HE flares
with **opacity $\tau_{\gamma\gamma} < 1*(Ldisk/1.*10^{46})^{0.5}$**



Assuming a R_{BLR} scaling as in Wu 2004:
$R_{BLR} = 7.7*10^{17}(L_{disk}/10^{46})^{0.684}$ cm

We have **(red stars)** a similar number of flares with
opacity $\tau_{\gamma\gamma} < 1*2^{log10(Ldisk/1.*10^{\wedge}46)}$

we observe 48% of the expected HE flares

Conclusions

From Broad band MWL campaigns on 13 flares, and the relevant HE gamma-ray emission in HE flares, the gamma-ray dissipating region is placed toward the edges, or outside the Broad Line Region to avoid gamma-gamma absorption (mainly for bright disks ~10^{46} erg/s and KN suppression)

From the whole gamma-ray flaring sample, at least ~26% of gamma-ray flares comes from $R_{diss} > R_{BLR}/2$

HE flares are harder than the mean source gamma-ray spectra

The flaring luminosity (with time scales of < 20 days) correlates with disk emission. This requires that the bulk of the HE flares sample is powered or "catalysed" by accretion (by B?)
(Narayan 2003, Tcheckhovskoy 2011, Sbarrato 2014, Ghisellini 2014)

Does this fact rules out reconnection and turbulences?

Resonably, Zamaninasab 2014, showed that for a sample of 76 Radio Loud AGN the B^2 field at 10^4 r_s correlates with L_{disk}.