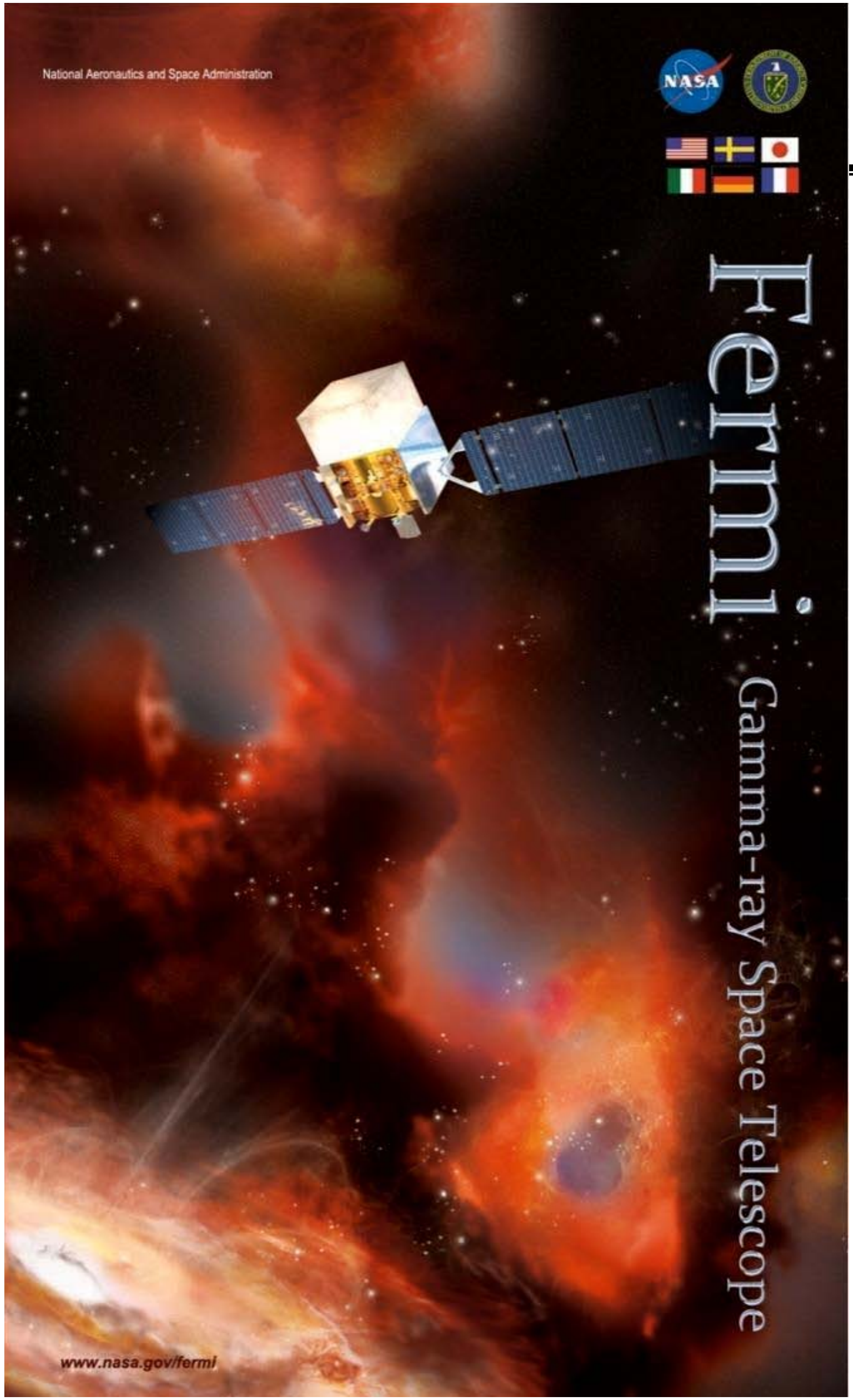


Multi-band observations of 3C454.3 during the γ-ray outburst in November 2010

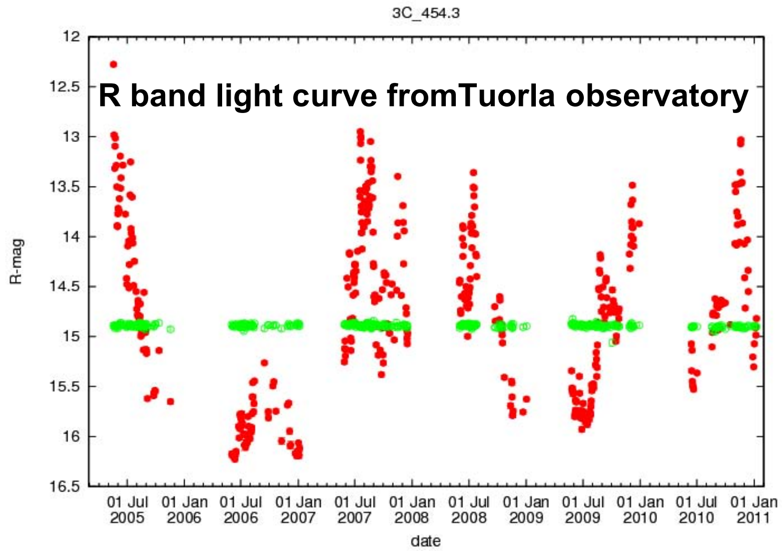
Greg Madejski
SLAC and KIPAC, Stanford University

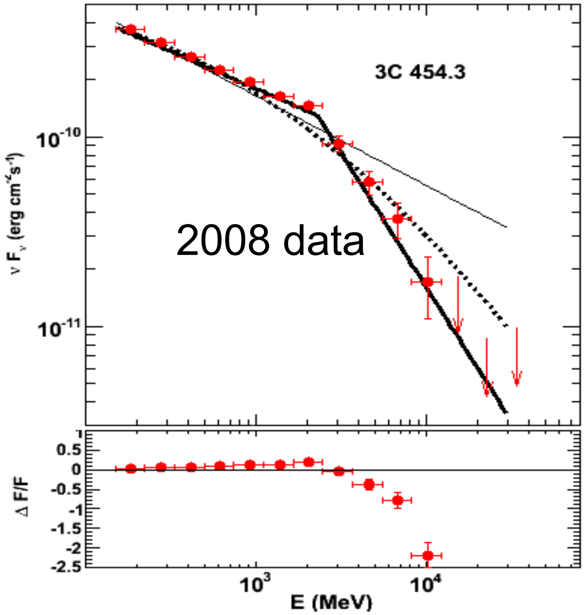
with Benoit Lott, Lise Escande, Stefan Larsson, Masaaki Hayashida, Yasushi Fukazawa, Marek Sikora on behalf of the Fermi-LAT collaboration

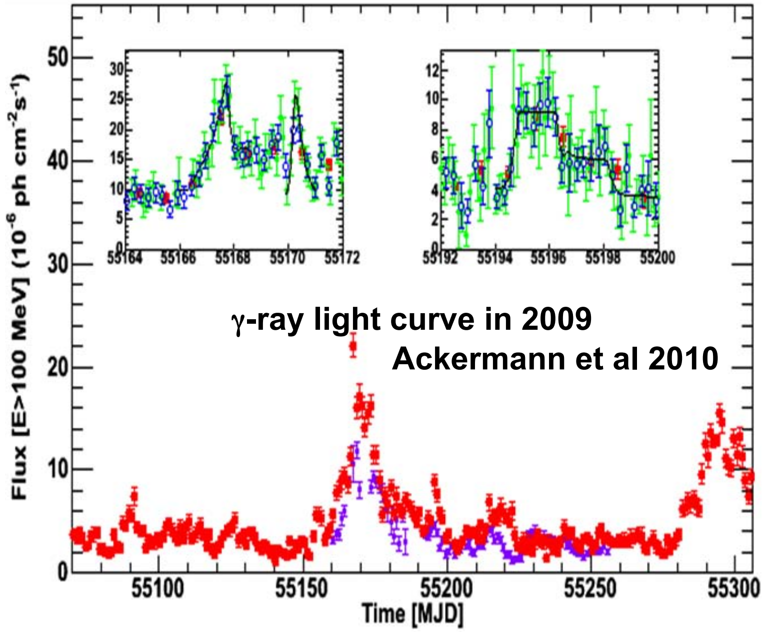
Much of this work is in Abdo et al. 2011, arXiv:1102.0277

Vitals of 3C 454.3

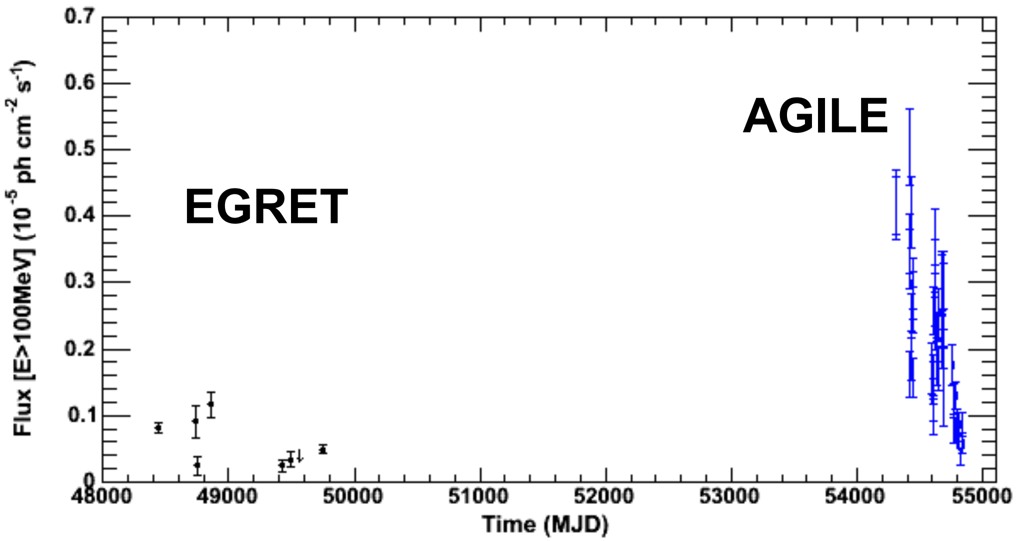
- Well-known quasar at z=0.859
- Bright, variable radio source with superluminal expansion, Γ_{jet} ~ 15
- At times the brightest extragalactic γ-ray source, τ_{var} (x2) ~ 3 hr in 2009
- First blazar w/detected γ-ray spectral break @ 2 GeV– break in the particle spectrum? γ–γ absorption via He II ?







γ-ray light curve of the FSRQ 3C 454.3



General features of the γ-ray time series

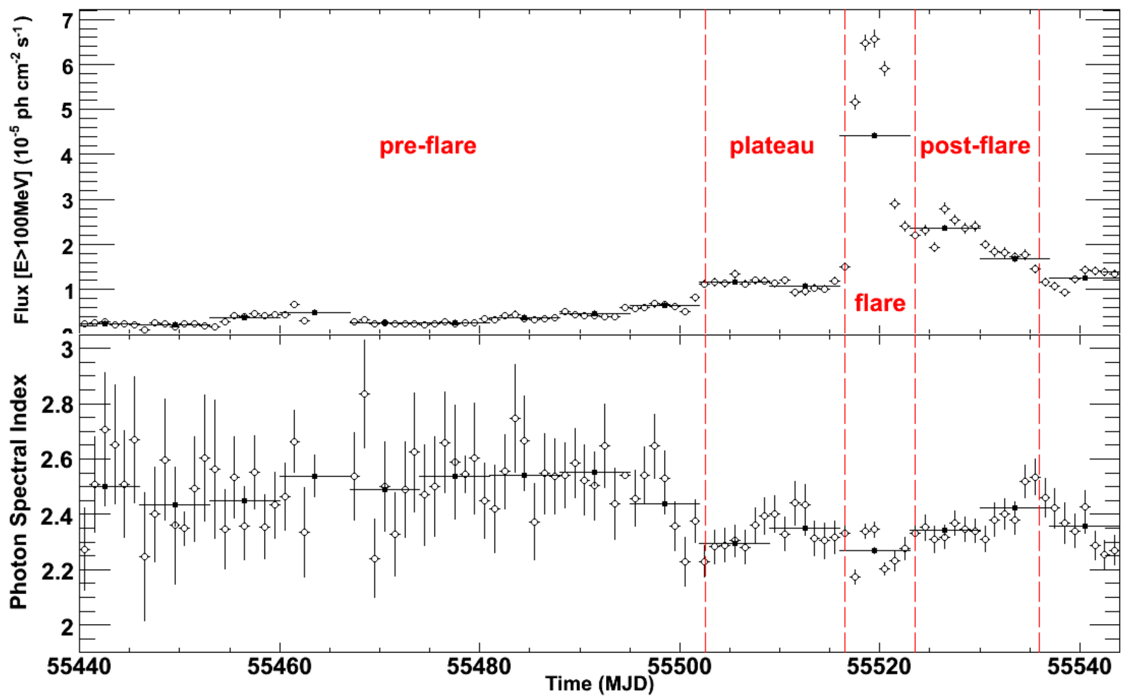
Nov. 2010 flare

- 5-day long outburst with peak daily flux [E>100 MeV] of (66± 2) x 10^{-6} ph cm^{-2} s^{-1} preceeded by a 13-day long plateau

* onset of plateau marked by weak but significant spectral hardening: Γ=2.50 ±0.02 to 2.32 ±0.03

- decrease in flux by ~ x3 in 4 days

- But at a high resolution…



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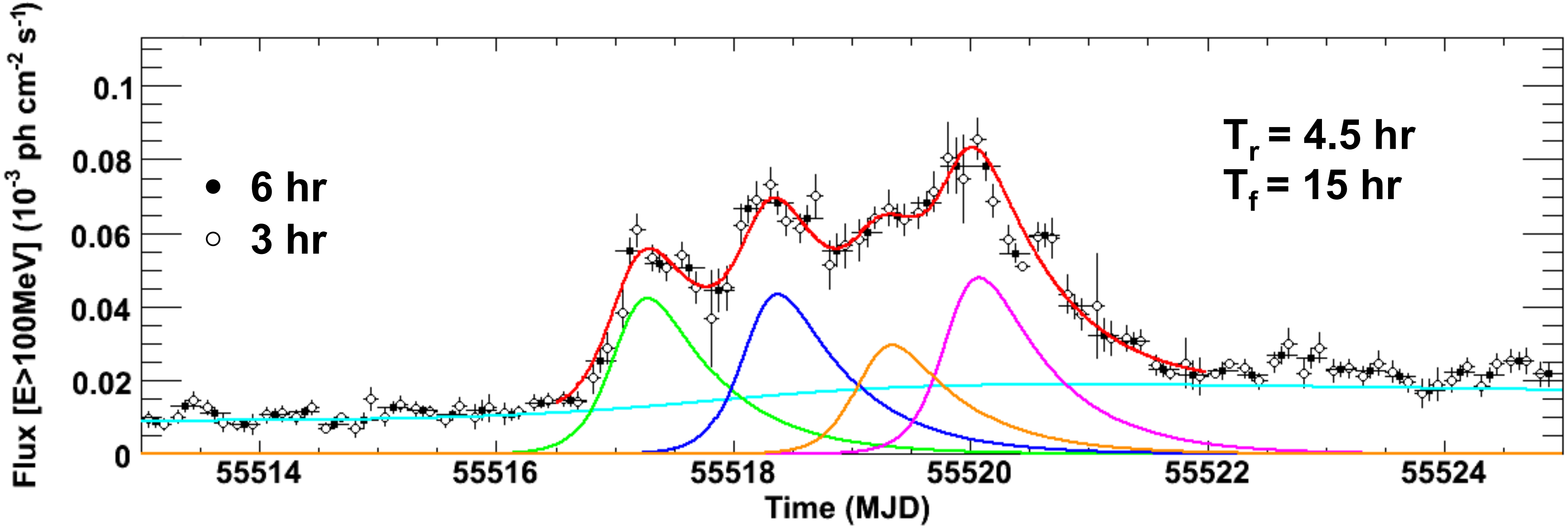
High-resolution light curve

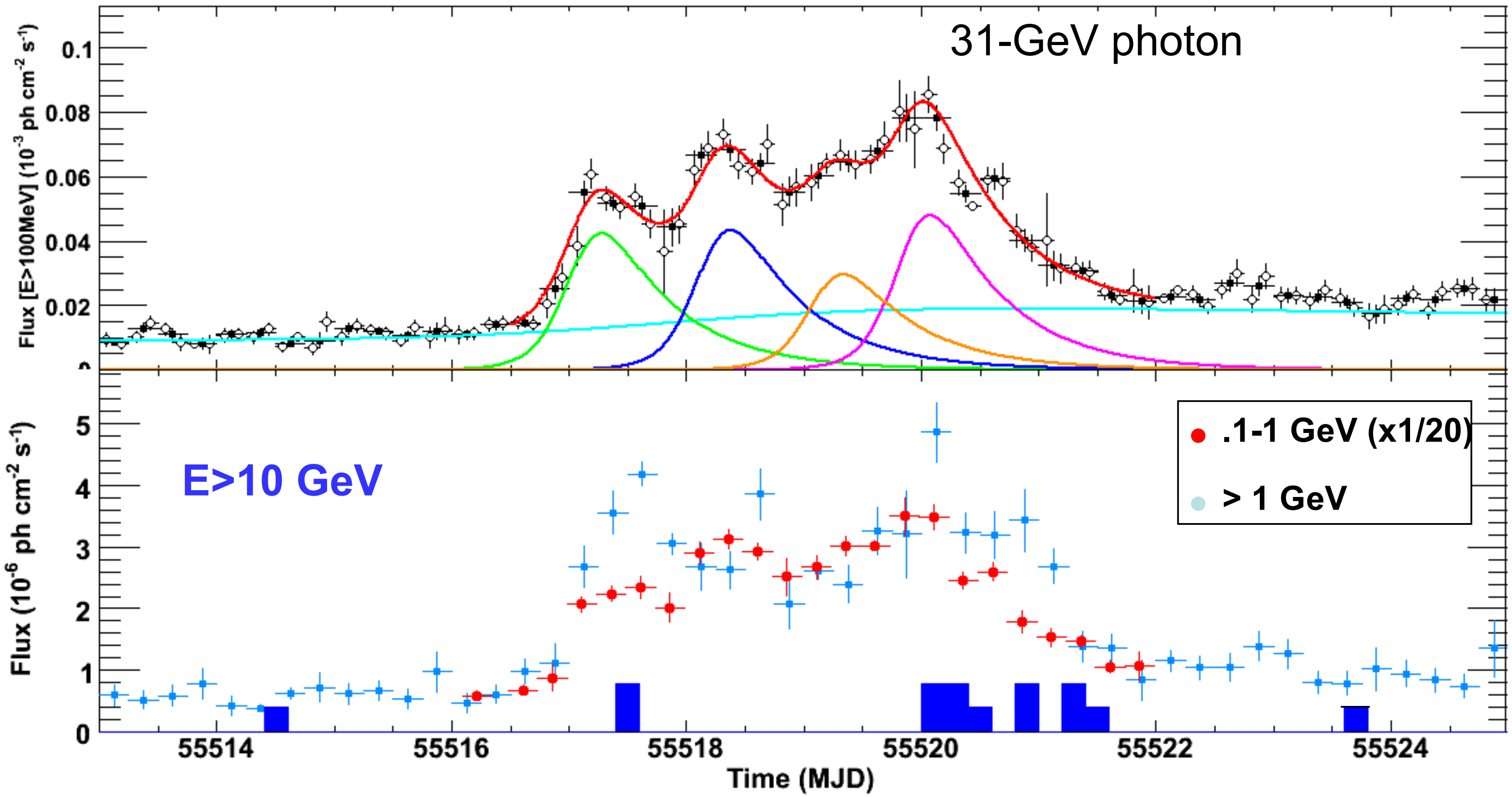


- 3-hr peak: F_{100}= (85 ± 5) x 10^{-6} ph cm^{-2} s^{-1}
- most luminous AGN yet observed: isotropic L_γ = (2.1 ± 0.2) x10^{50} erg s^{-1}
- 4x flux increase in ~12 hr: ~ 6 hr doubling time
- 4 subflares fitted with same T_r (4.5 hr) and same T_f (15 hr)

$$F = 2F_0(e^{(t_0-t)/T_r} + e^{(t-t_0)/T_f})^{-1}$$

- dL/dt ~ 10^{46} erg s^{-2} largest ever measured for a blazar (dwarfs PKS2155-304, Mrk 501…)

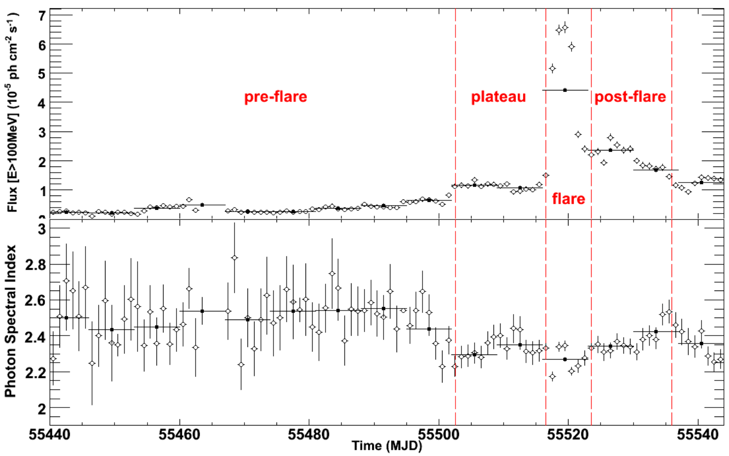
Highest-energy photons and $\tau_{\gamma\gamma}$

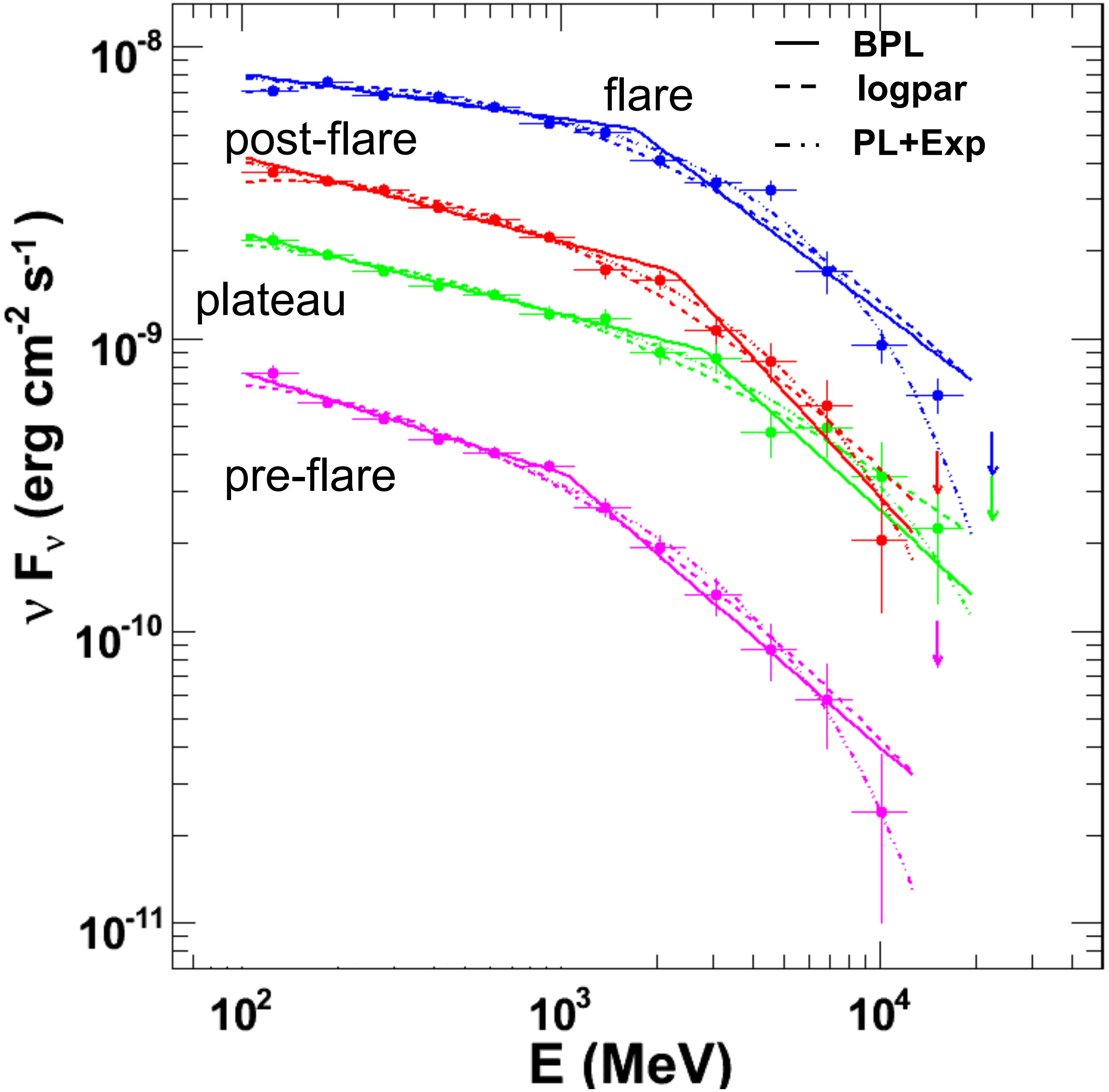


* $\gamma\gamma$ -opacity constraints for E_{max}= 31 GeV:
* With L_{BLR}=3x10^{45} erg s^{-1} (Pian et al 05), R_{em} = 0.14 pc (cf. Reimer 07)
* Since R_{BLR} ~ 0.2 pc (Kaspi et al 07, the emission is close to or beyond the broad-line region

γ-ray νFν spectrum

- preflare and plateau: BPL and PL+expcutoff give similar quality fits, significantly better than Log-parabola
- none of tested functions gives a good fit for the flare period





γ-ray results of the giant Nov 2010 flare

* Flare average $F_{E>100}$= 43 x 10^{-6} ph cm^{-2} s^{-1}, L_γ ~ 10^{50} erg s^{-1}
  L_{Edd}~ (0.6-5)x10^{47} erg s^{-1} ; L_{disk}~ 7x10^{46} erg s^{-1} (Bonnoli et al. 10)
  with δ_{min} from VLBI or $\gamma\gamma$ -opacity constraints (~ 20), L_γ ~ L_{disk}

- Spectrum consistent with broken power law, modest spectral variability with flux

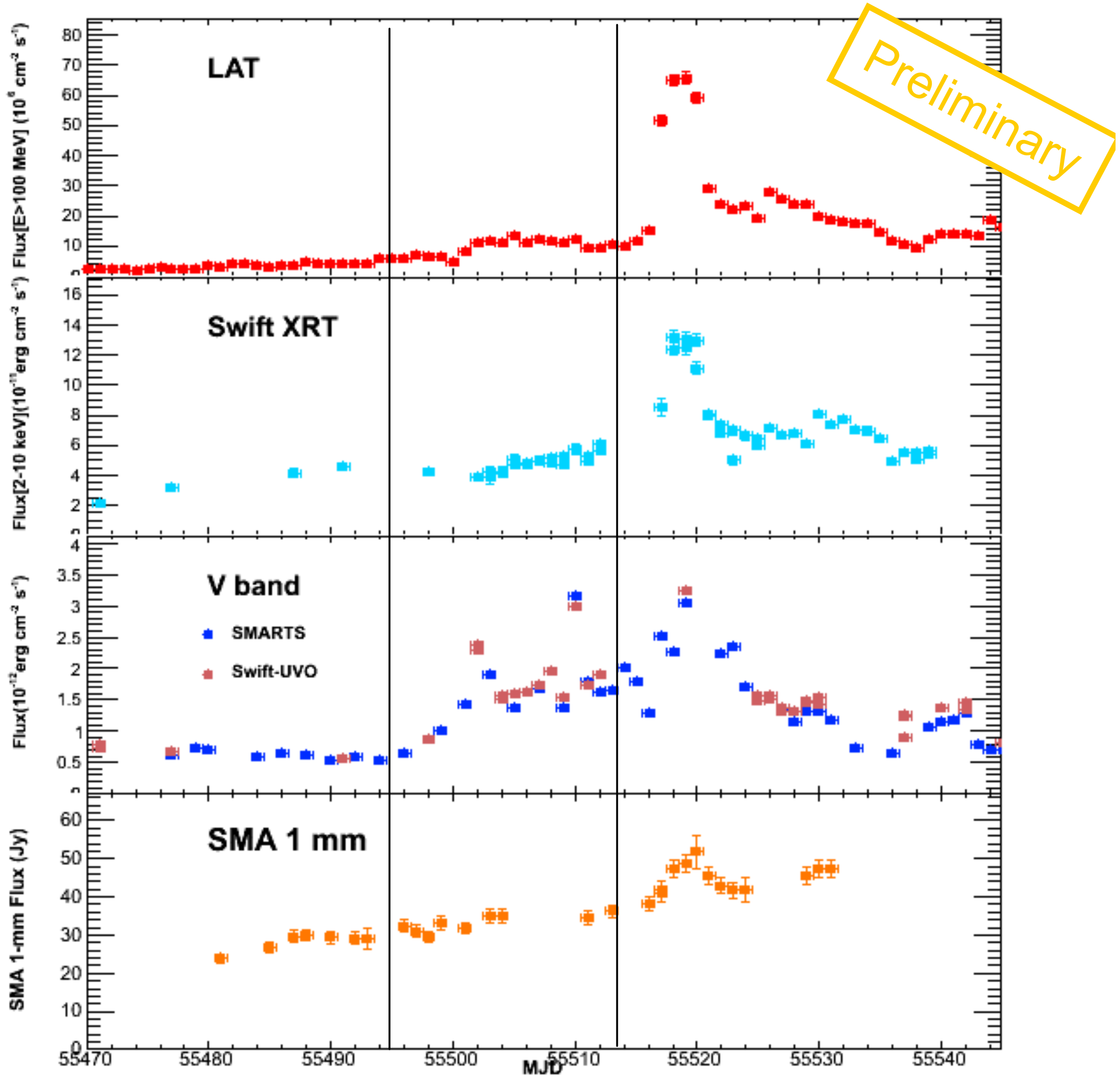
- Comoving size of the emission region: R' = c t_{var} δ_{min}/(1+z) ~ 3 x 10^{15} cm = 0.001 pc

- $\gamma\gamma$ -opacity constraints for E_{max}=31 GeV -> with L_{BLR}=3x10^{45} erg s^{-1} (Pian et al. 05)
  r_{em}=0.14 pc, (Reimer et al. 2007 formalism)
  compares to r_{BLR}=0.2 pc (Kaspi et al. 2007)

- Likely scenario: compact source at a considerable distance from the BH
  Do we see a pattern here? 3C279, 4C21.35, ...?

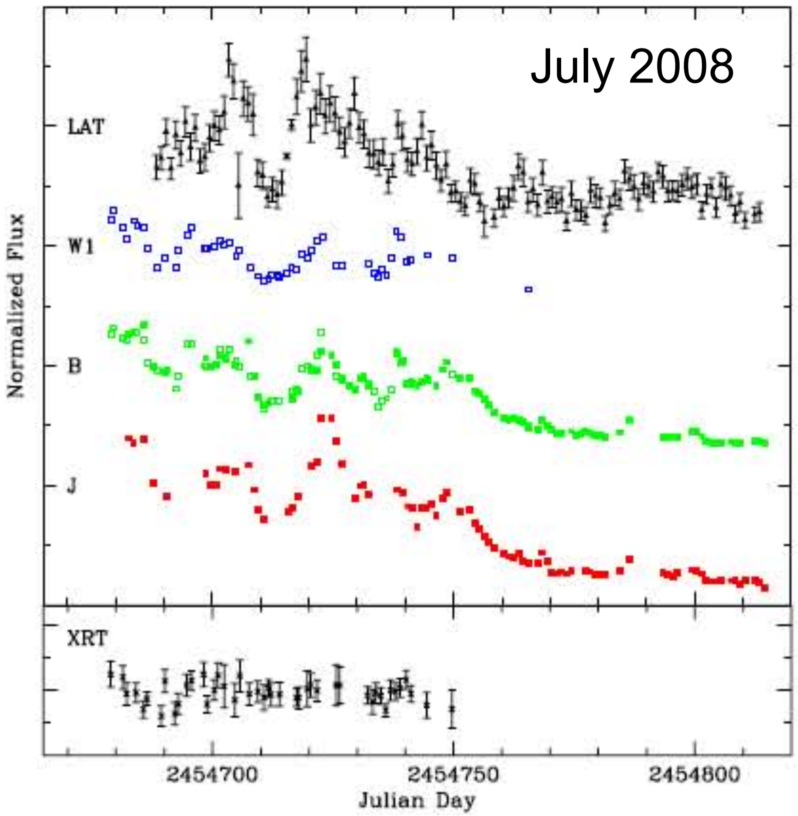
Not just γ-rays!

- The giant flare seen in all bands
- Generally fractional variability increases with energy
- Onset of the ``plateau'' correlated with fast rise in the optical band
- Several isolated optical flares?

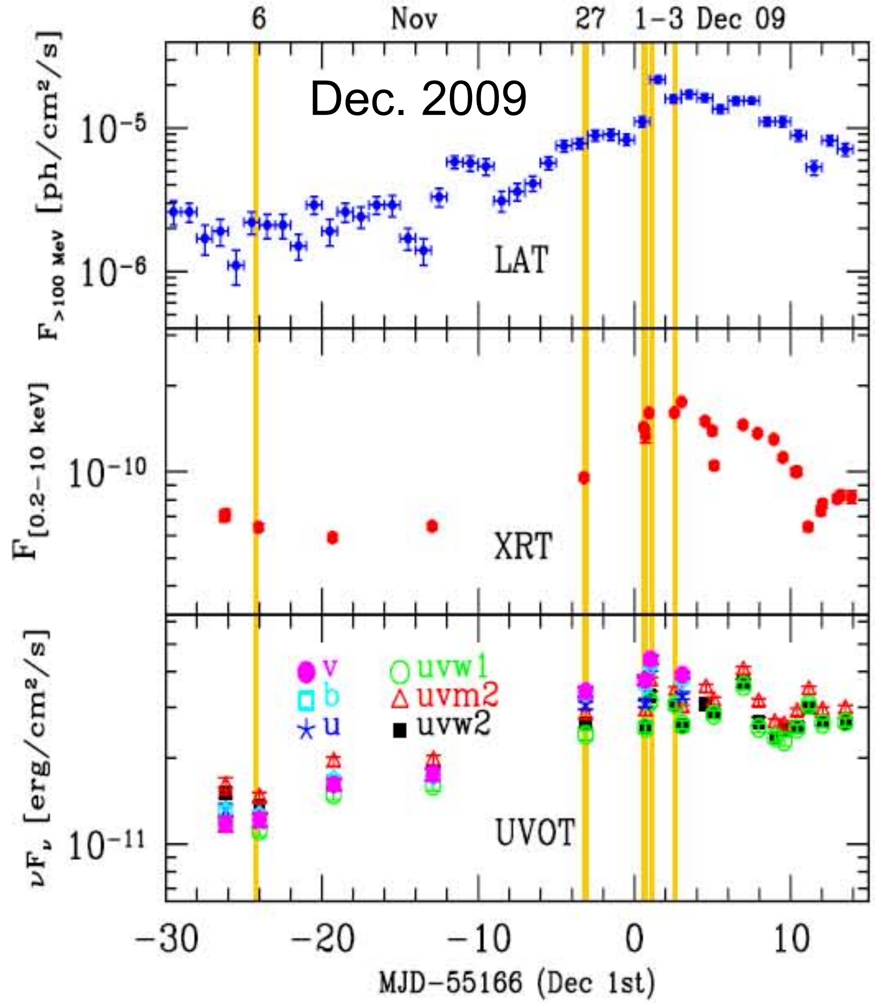


Correlated variability in previous flares

Bonning et al. 09



Bonnoli et al. 10

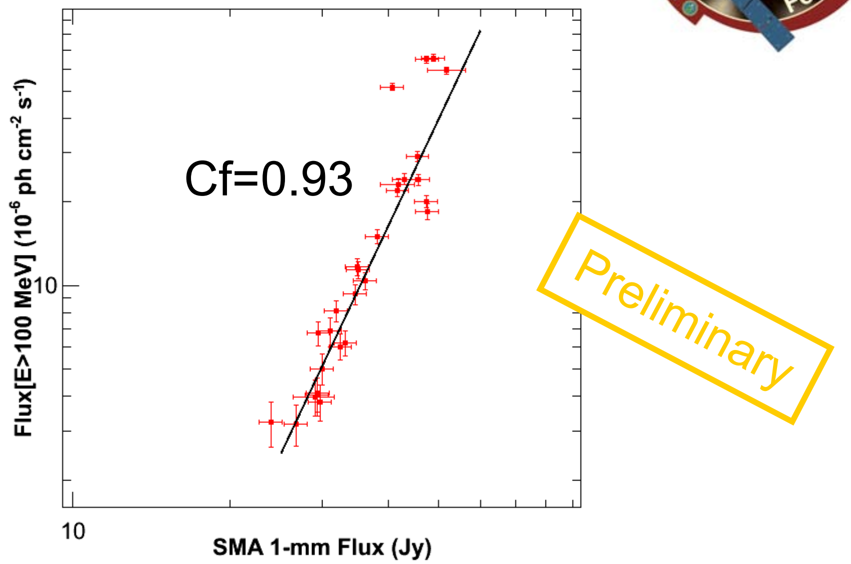


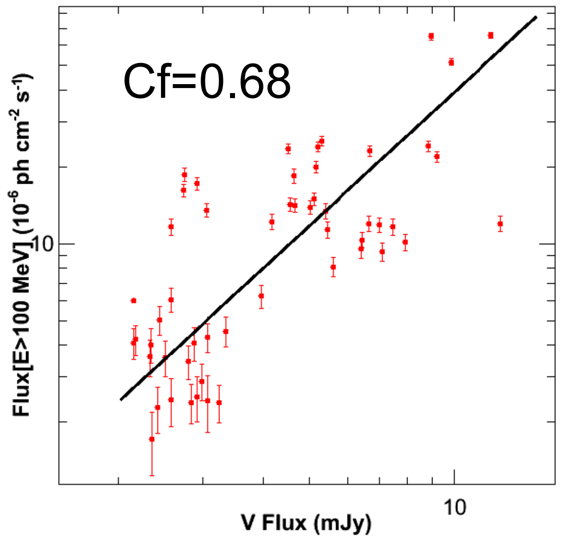
Short lag (<1 day) between optical and γ-rays (Vercellone et al. 09; 10; Donnarumma et al. 09, Bonning et al. 09, Pacciani et al. 10…)

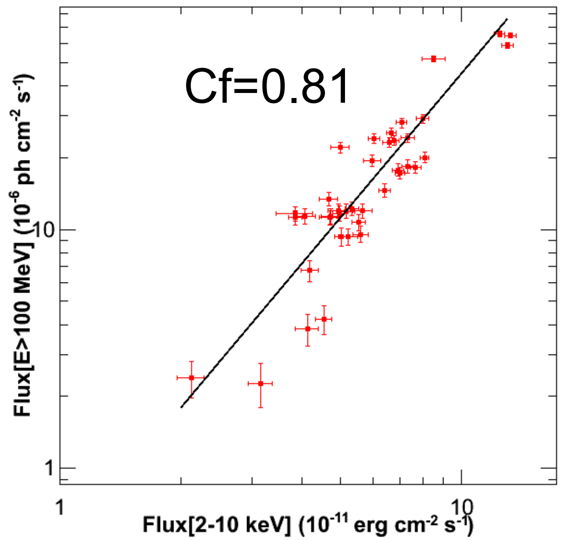
Correlation of mm, optical, X-ray fluxes vs γ-ray flux

Correlations between γ-rays and other bands (2010 data)

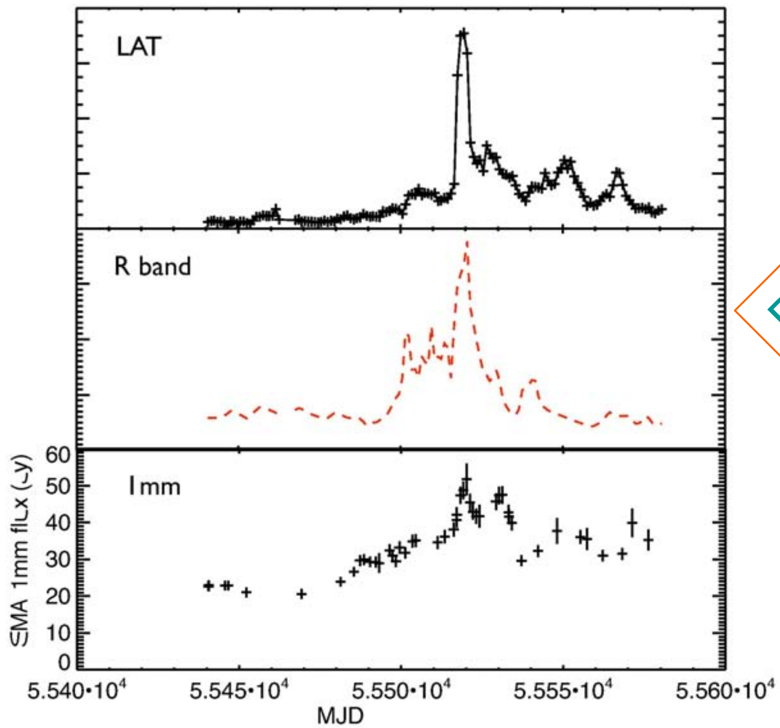
- $F_\gamma \propto F_{mm}^4$
- $F_\gamma \propto F_{opt}^4$
- $F_\gamma \propto F_X^2$



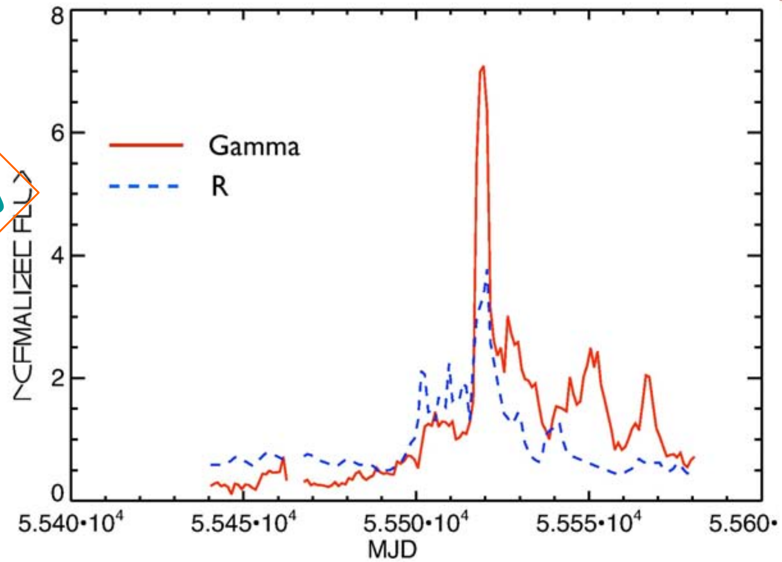


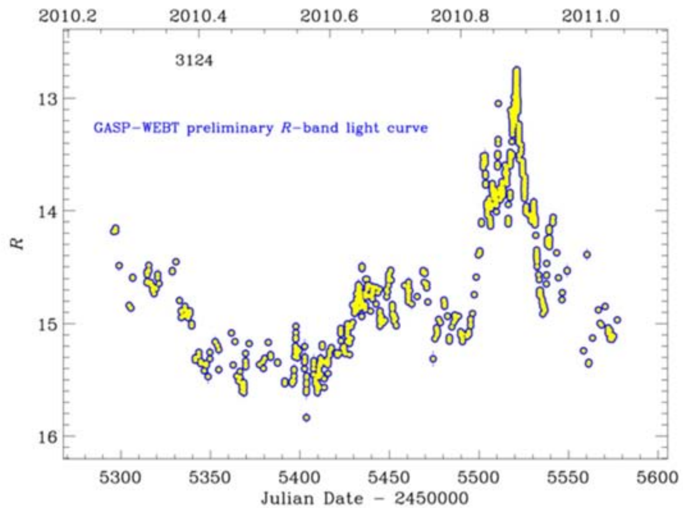


3C454.3 Multi-band observations: lags/leads



Preliminary

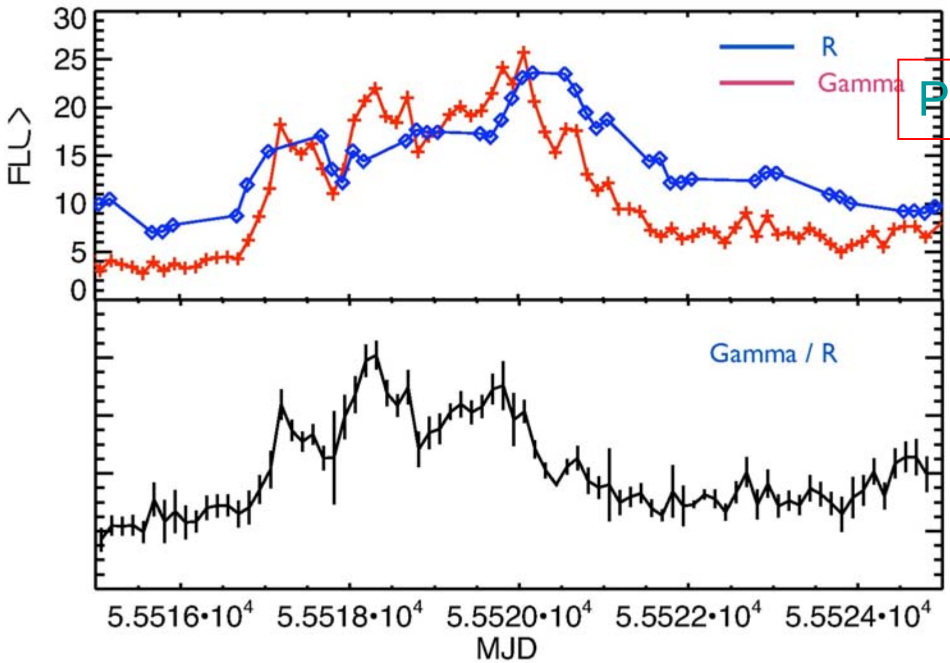


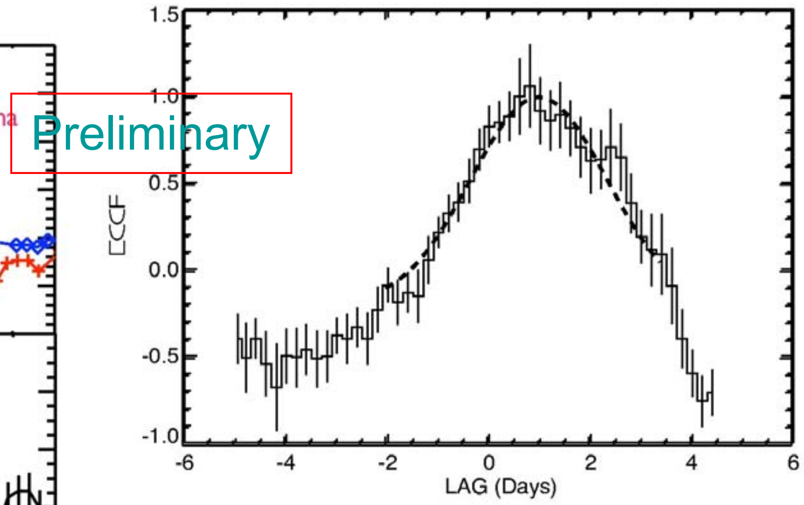


- Optical flux during the brightest, sharpest outbursts seems to lag γ-rays

* millimeter flux lags even more…

Optical / γ-ray lag

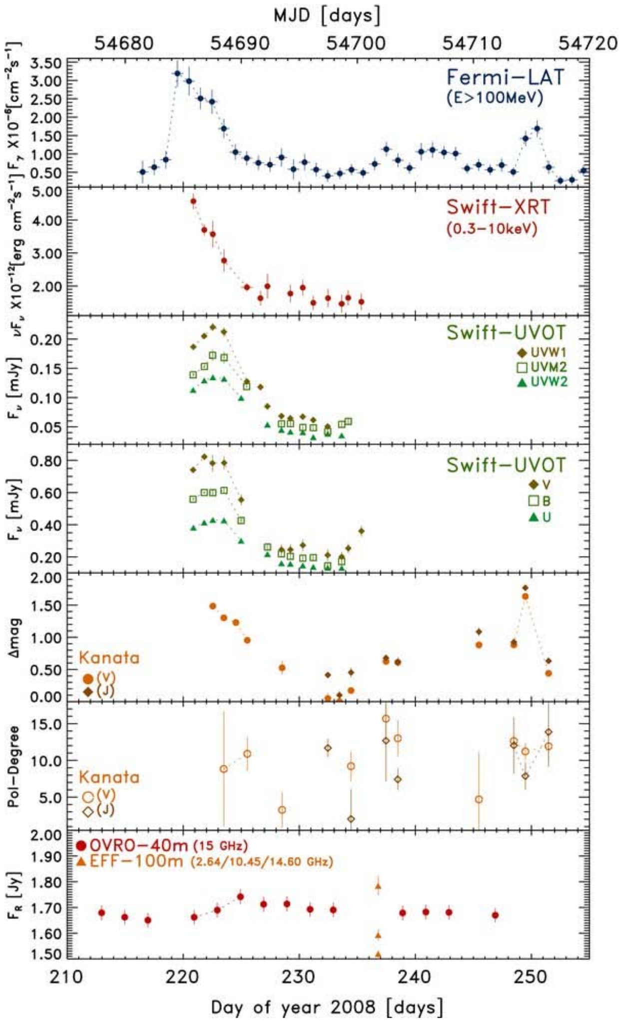




LAG = 1.0 +/-0.2 (Plotted gaussian fit)
0.8 +/-0.3 (Narrow peak fit)

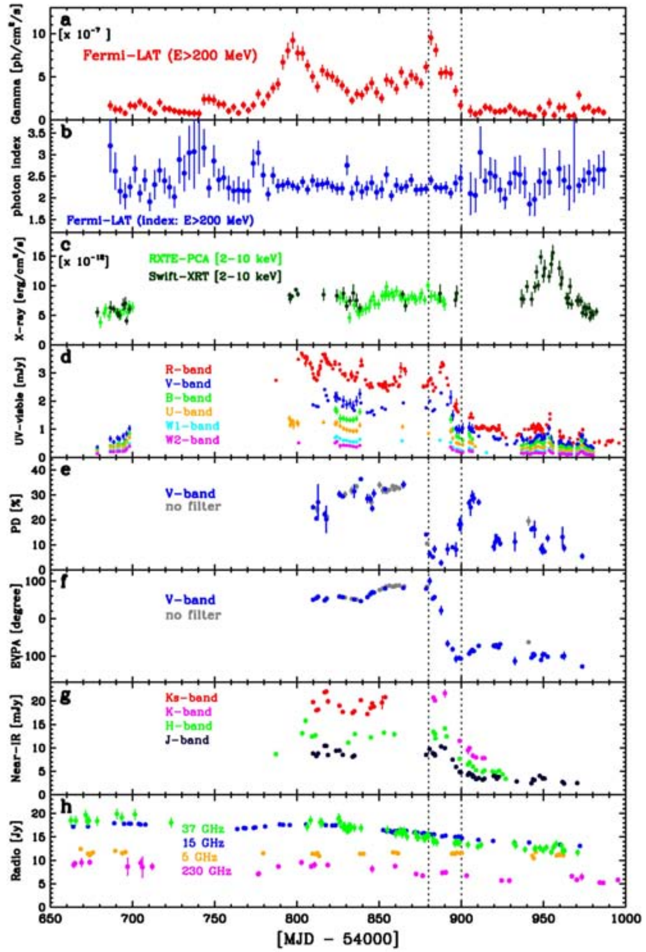
- Simple DCF: the optical lags γ-rays by ~ 1 day
- It is universal, or one-off?
- What does it mean?

Optical – γ-ray lags might be common



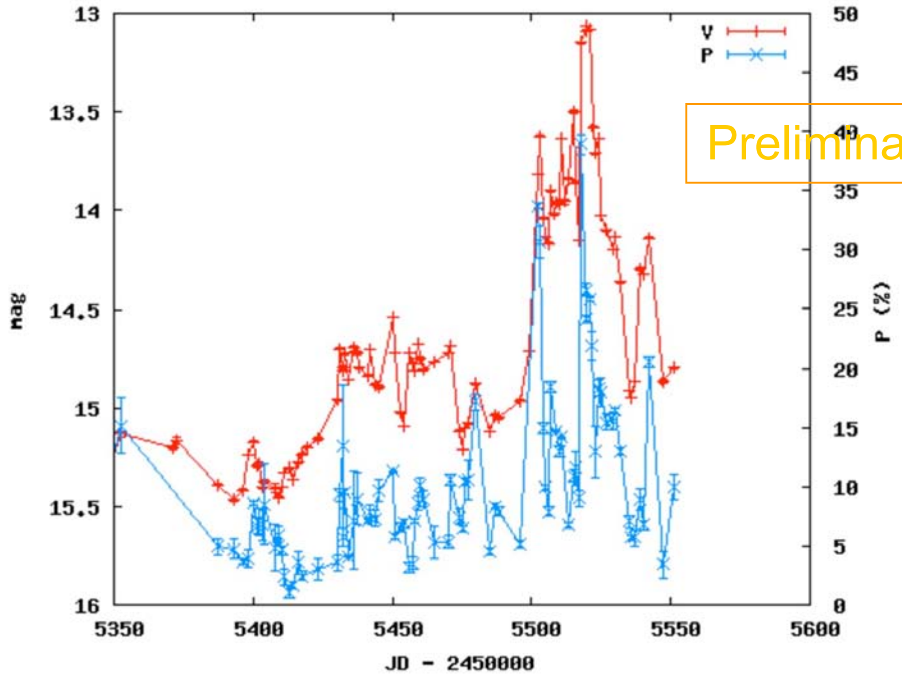
← γ-rays →

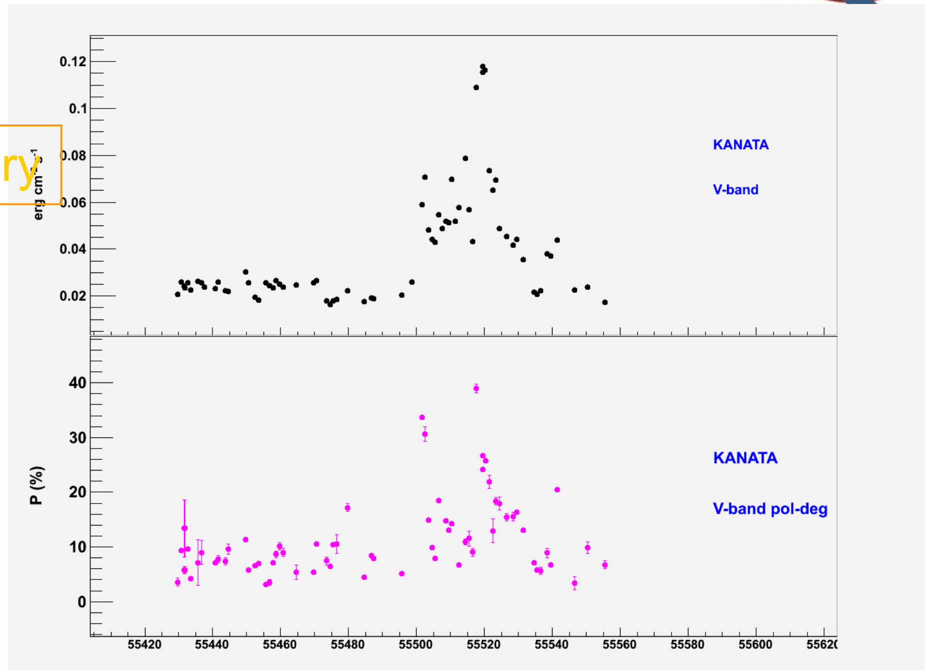
← optical →



Multi-band time series for PKS 1502+106 (Abdo et al. 2009), 3C279 (Abdo et al. 2010; details in the poster by Hayashida et al.)

Optical polarization data





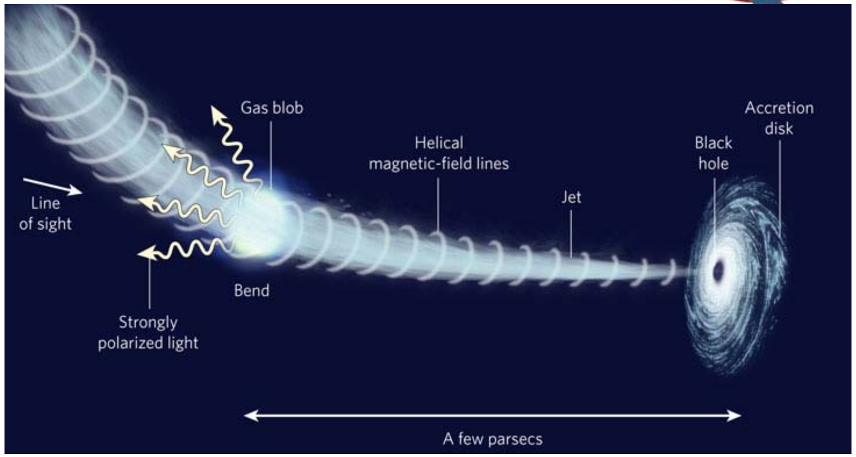
Optical polarization data for 3C454.3 from the KANATA telescope

Time series of optical polarization might provide the missing piece of the puzzle

Degree of polarization reasonably well correlated w/opt. flux
-> seems to slightly lag the γ-ray flux

Degree of polarization is an excellent proxy for the strength of the ordered *B* field!

Possible interpretation of the optical-γ-ray lags



What does it mean?

• Accepted scenario: both γ-rays and optical photons from the same electrons

•Lags must be then a competition of magnetic vs. photon energy densities
U_B (magnetic, generated by the jet)
vs. U_{ph} (steady, external to the jet)

* No "obvious scenario" but *one workable picture*:
- relatively steady flow, until…
- some external or internal agent (MHD instability? oblique shock? curvature of the jet?) alters the local structure of the flow
- this accelerates particles & causes gradual compression (growth) of the ordered component of magnetic field
- accelerated particles immediately Compton-scatter external radiation
- as the *B* field grows, the particles also radiate synchrotron radiation –
  - B field grows gradually -> synchrotron emission (=optical) lags γ-rays

• *Alternatively*: Lag is caused by a different dependence of U_B vs. U_{ph} as a function of distance along the jet: U_{ph} drops faster than U_B

Conclusions: 3C454.3 the champion

* Remarkable object, remarkable Nov. 2010 flare seen in all bands

• γ-ray flux (L_{app} ~ 10^{50} erg s^{-1}) might set a record for the LAT lifetime…

• Rich features in the γ-ray band (Abdo et al. 2011)

rapid variability, yet 30 GeV flux not γ–γ absorbed by disk photons

-> compact source at a considerable distance from the BH?

• MW correlations essential! In summary:

* Radio flux relatively steady –

- source becomes fully optically thin only in the sub-mm / IR band

* Optical lagging γ-rays by ~ a day – competition between U_{ph} & U_B

- Optical (synchrotron) emission delayed due to gradual increase of B field associated with the same event (shock?) that accelerates particles
- Gamma-rays (inverse Compton) are more prompt, since U_{ph}(ext) is relatively steady

Possible interpretation of the optical-γ-ray lags

What does it mean?

•Accepted scenario: both γ-rays and optical photons from the same electrons

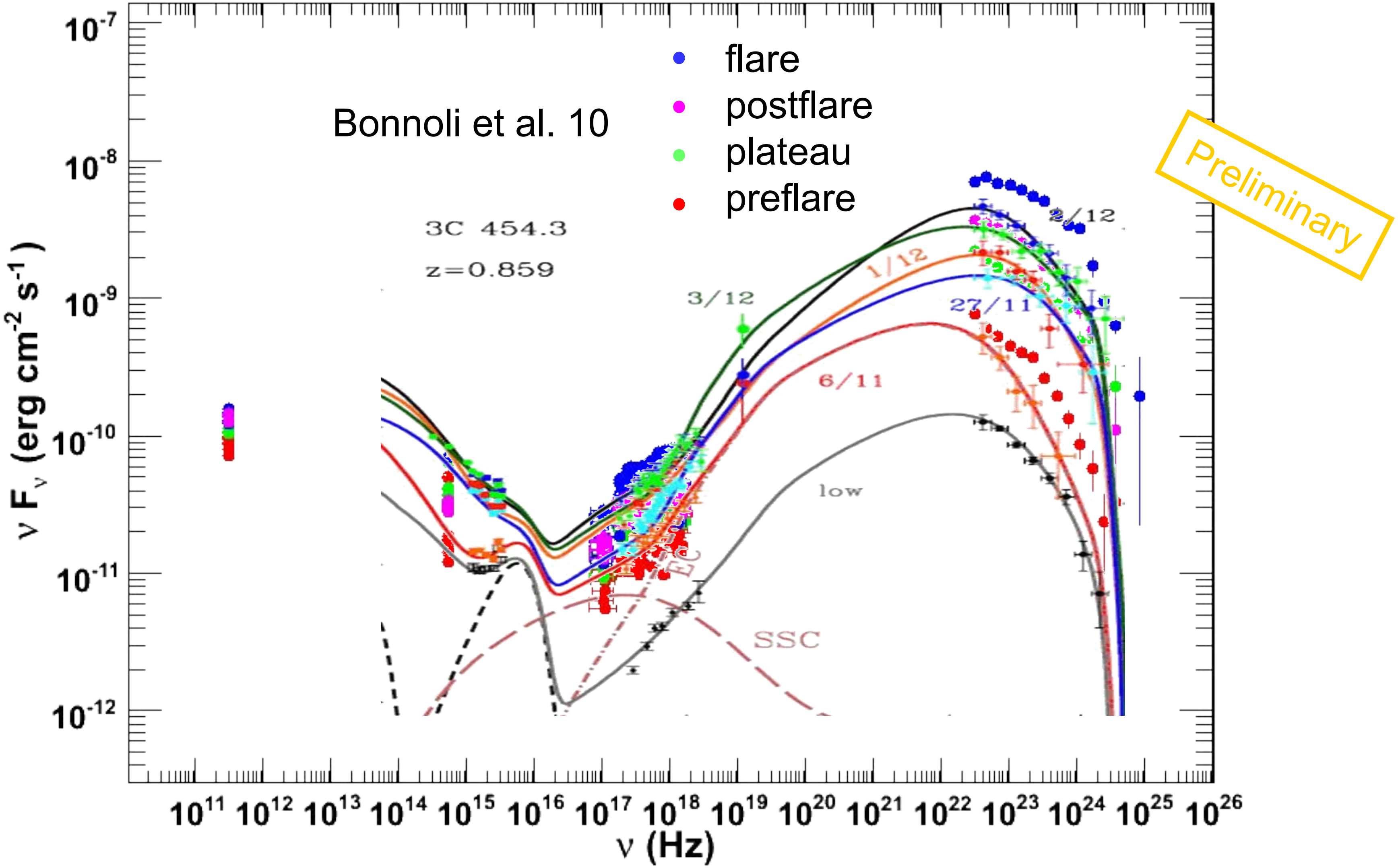
* Lags must be then a competition of U_B vs. U_{ph}

* No "obvious scenario" but the good workable picture is:
  - relatively steady flow, until…
  - some external or internal agent (MHD instability? oblique shock? curvature of the jet?) changes of the local structure of the flow
  - this accelerates particles & causes gradual compression (growth) of magnetic field
  - accelerated particles immediately Compton-scatter external radiation
  - As the *B* field grows, the particles also radiate synchrotron radiation –
    - B field grows gradually -> synchrotron emission (=optical) lags γ-rays

Alternatively: Lag is caused by a different dependence of

Such a lag can be produced in the EC model in the region where energy density
of external radiation, as measured in the source co-moving frame, drops faster
with a distance than the energy density of the magnetic field within a jet.
Under such conditions, the convolution of the particle injection
rate with the radiation efficiencies of the EC and synchrotron emission will first
generate the γ-ray peak and then the optical peak.
If confirmed, the ~ 10-day lag may imply the location of
the activity (blazar) zone at distances corresponding with those postulated
to explain, the 2009 optical polarization-swing-event in terms of the scenario
of a source propagating along the curved trajectory (Abdo et al. 2010).

Broad-band SED



Correlated variability in previous flares (2)

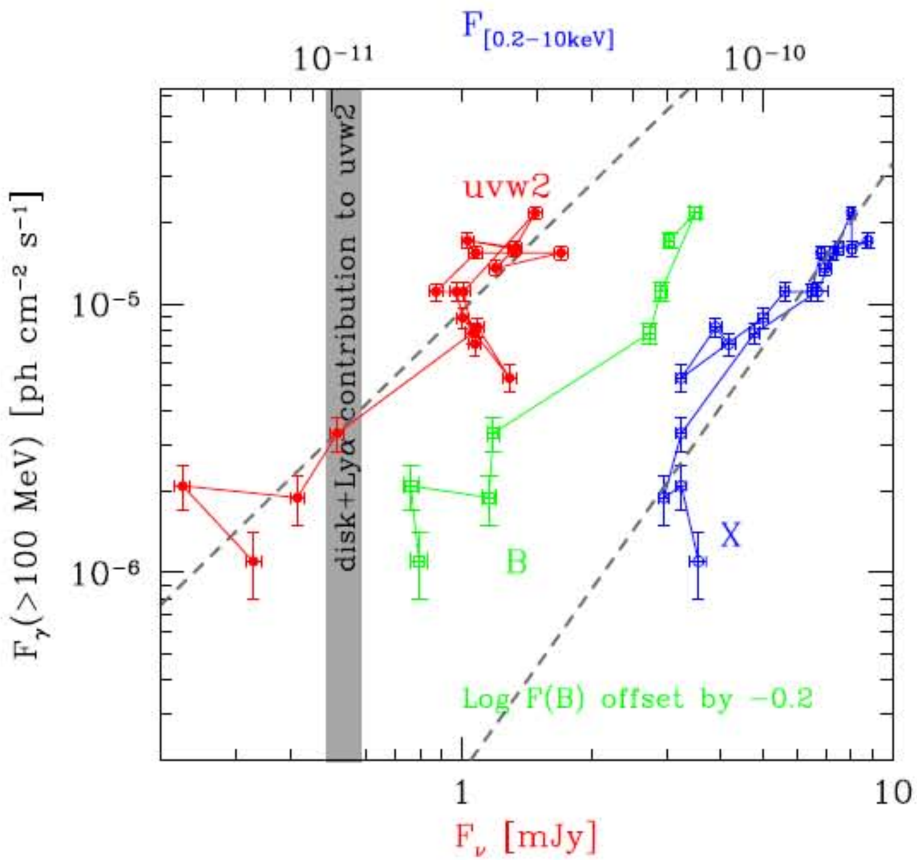
- correlated variability between
  - γ-rays and optical
  - γ-rays and X-rays

- ~ quadratic dependence of γ-rays wrt optical, X-rays

- SSC in X-rays / EC in γ-rays $\rightarrow F_x \alpha F_\gamma^2$ opposite to observed trend

- inverse correlation between B and dissipated power invoked

Bonnoli et al. 10



December 09 flare

ATels on November 2010 Giant Flare

Radio: 3036 (Gurwell & Wehrle)

NIR: 2988 (Carrasco et al.), 3042 (Carrasco et al.)

Optical: 3003 (Larionov et al), 3005 (Semkov et al.), 3022 (Bonning et al.), 3047 (Krajci et al.)

INTEGRAL: 3055 (Pian et al.)

AGILE: 2995 (Vercellone et al.), 3034 (Striani et al.), 3043 (Striani et al.), 3049 (Striani et al.)

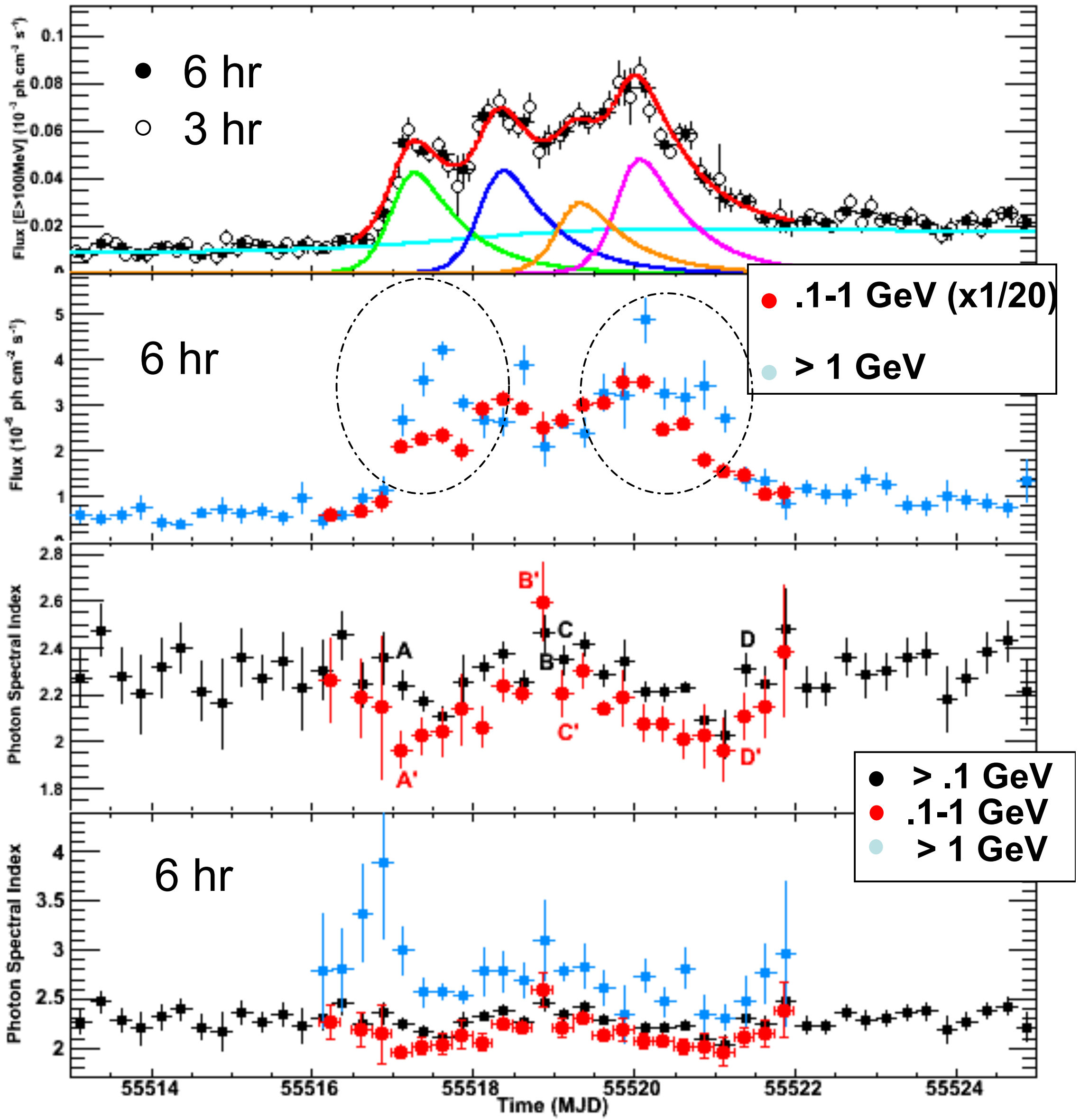
Fermi-LAT: 3041 (Sanchez & Escande)

Flux/index light curves

- F[E>1 GeV] light curve has sharper structures than F[E>100 MeV] light curve

- Significant differences during rise (~ 15 hr lag) and fall of the main flare

- Confirmed by trend of spectral index obtained over different energy ranges



Flux[E>E_0] vs photon index

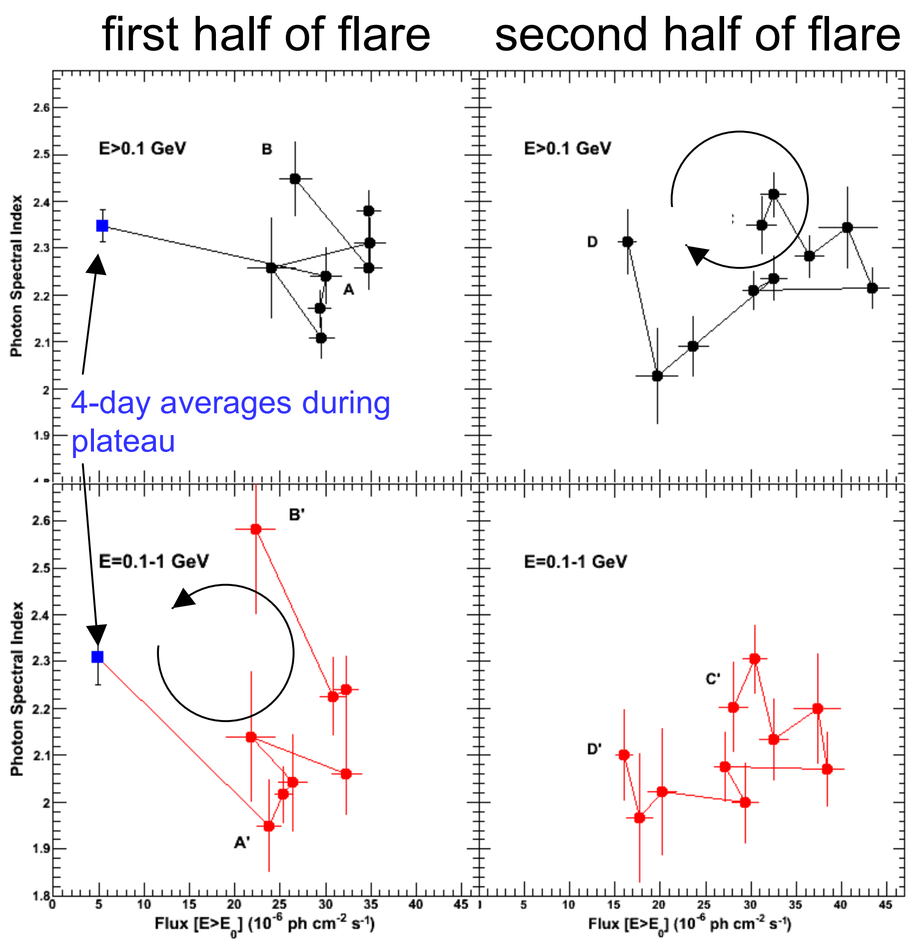
E_0 decorrelation energy (=163 MeV)

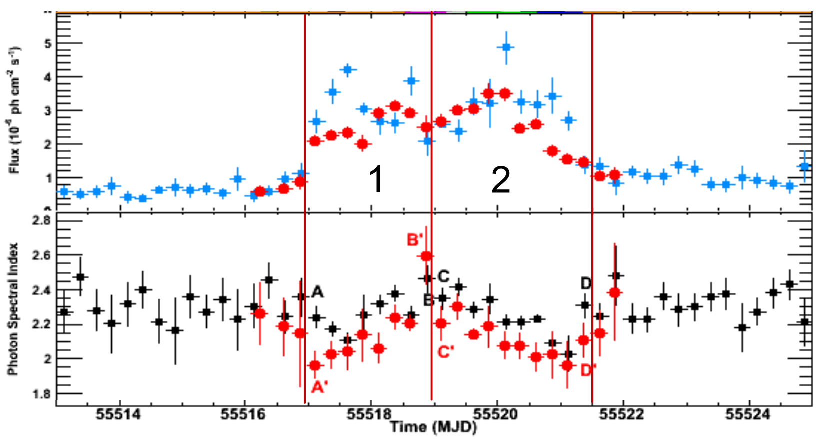
Initial significant hardening in 0.1-1 GeV range

When $F_{0.1\text{-}1\ GeV}$ levels off, the photon index in this range remains constant while $F_{>1\ GeV}$ keeps rising

Clockwise pattern in second part of the flare (hard lag effect)

Alternative dominance of acceleration and cooling?





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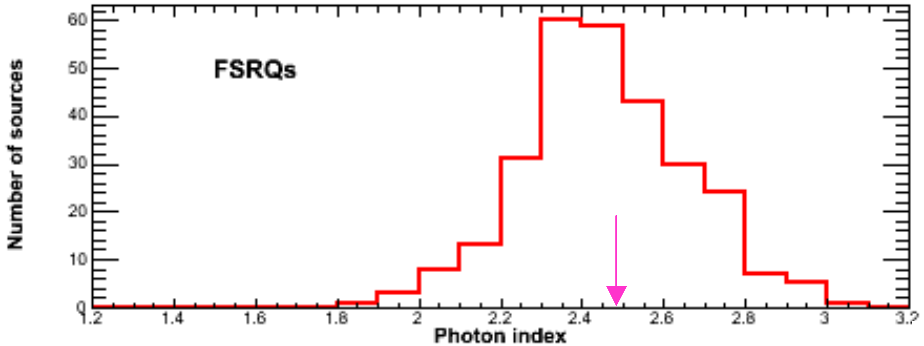
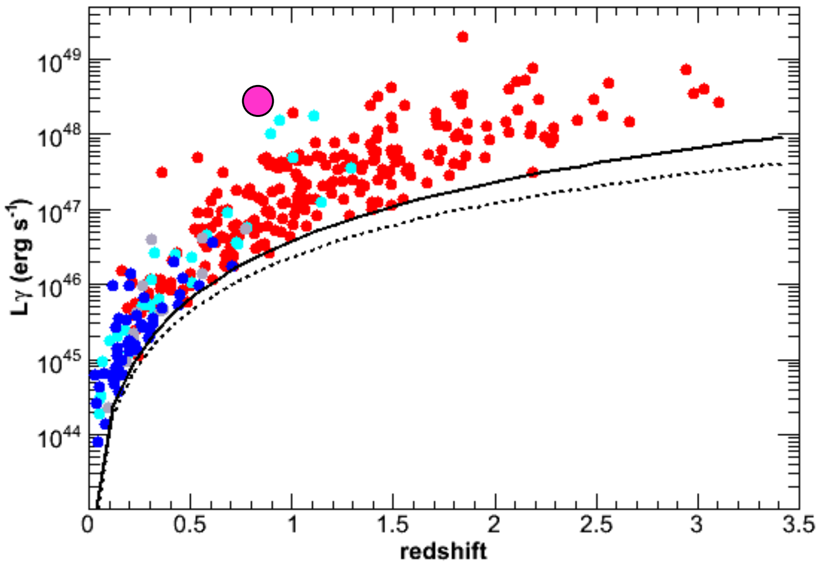
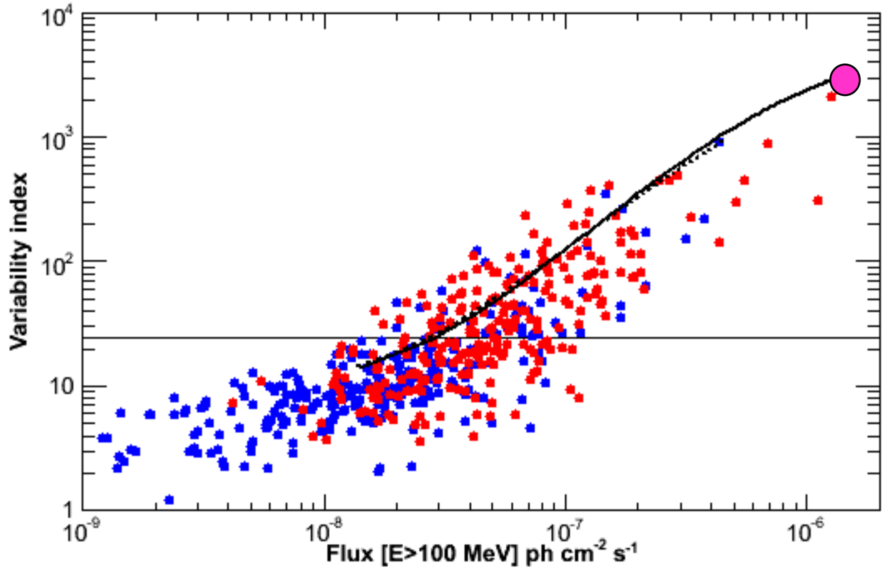
Is 3C 454.3 special? 1LAC properties

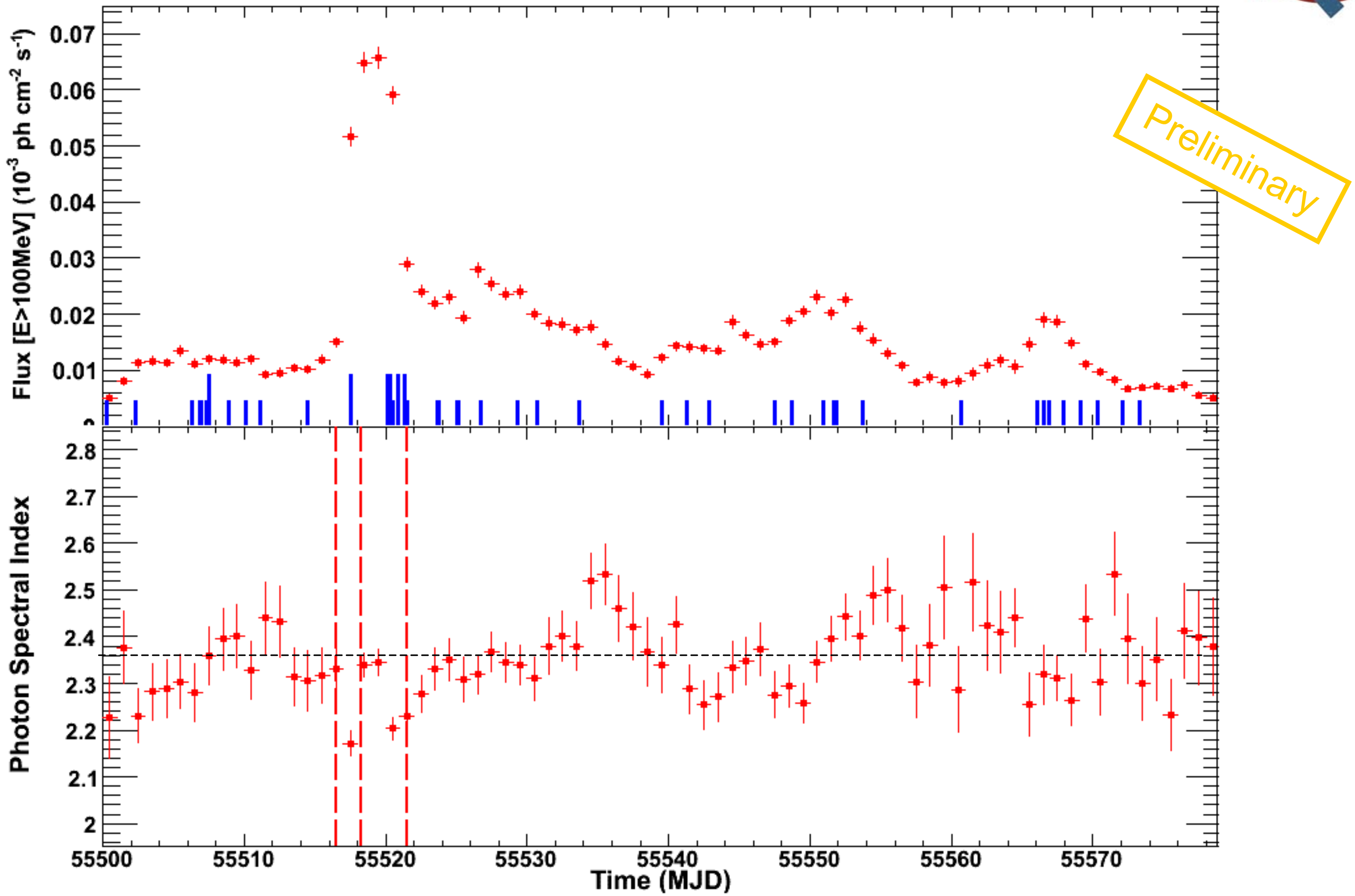


$$V = \sum_i \frac{(F_{\rm i} - F_{\rm av})^2}{\sigma_{\rm i}^2 + (f_{rel} F_{\rm av})^2}$$



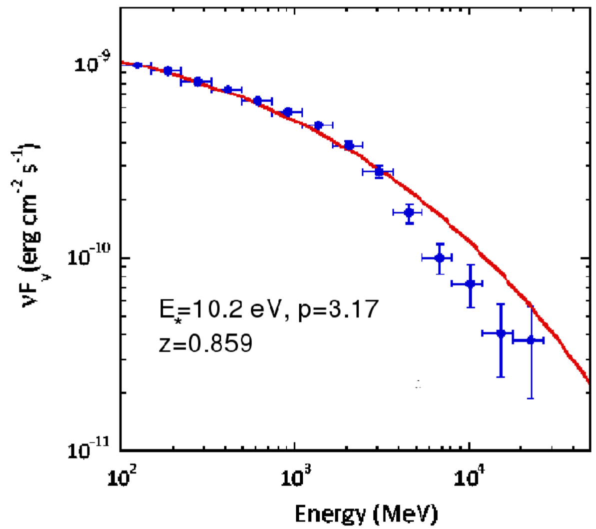


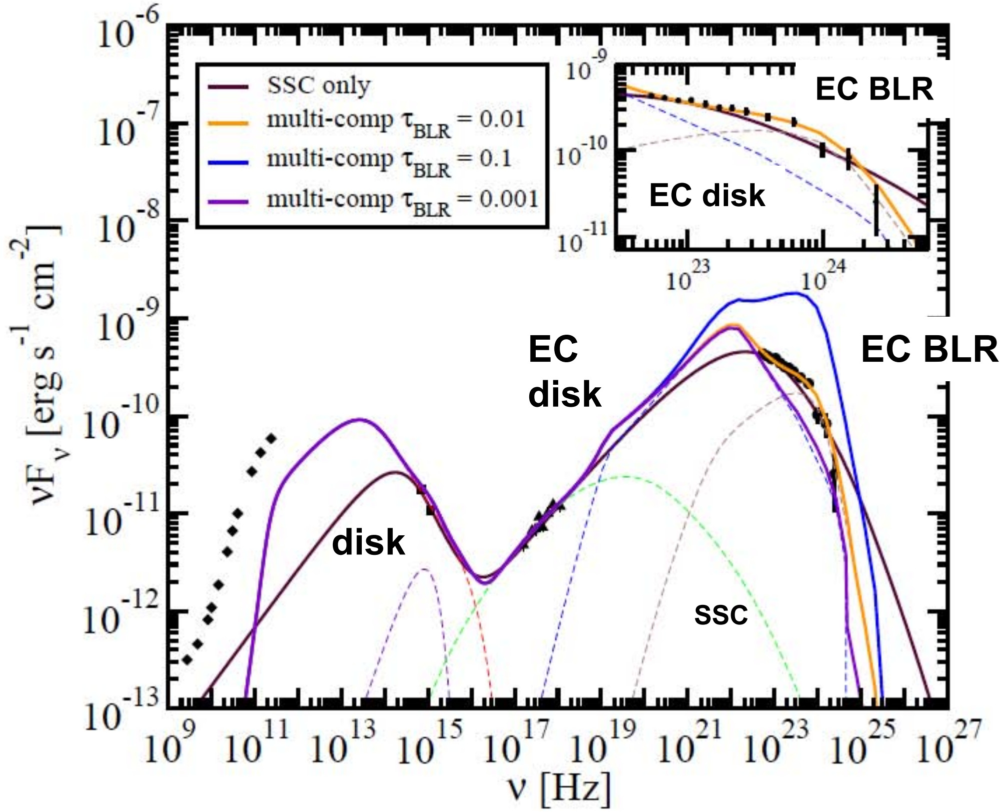
Continuous spectral evolution

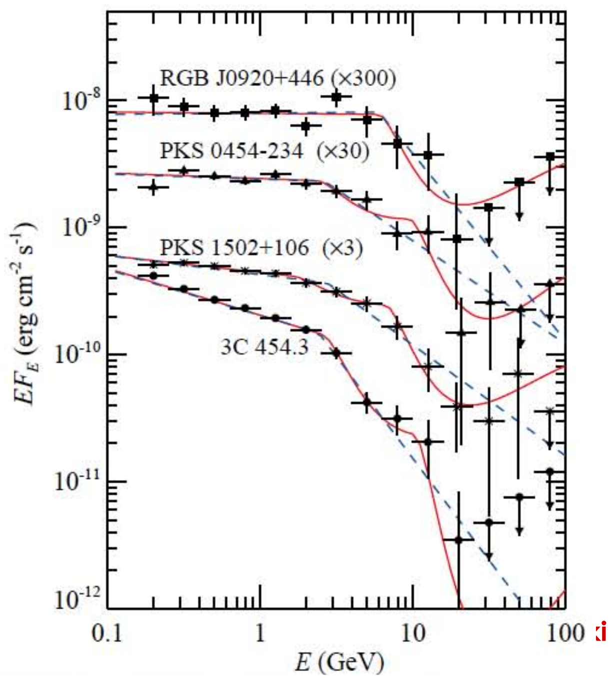


Constant break-energy issue

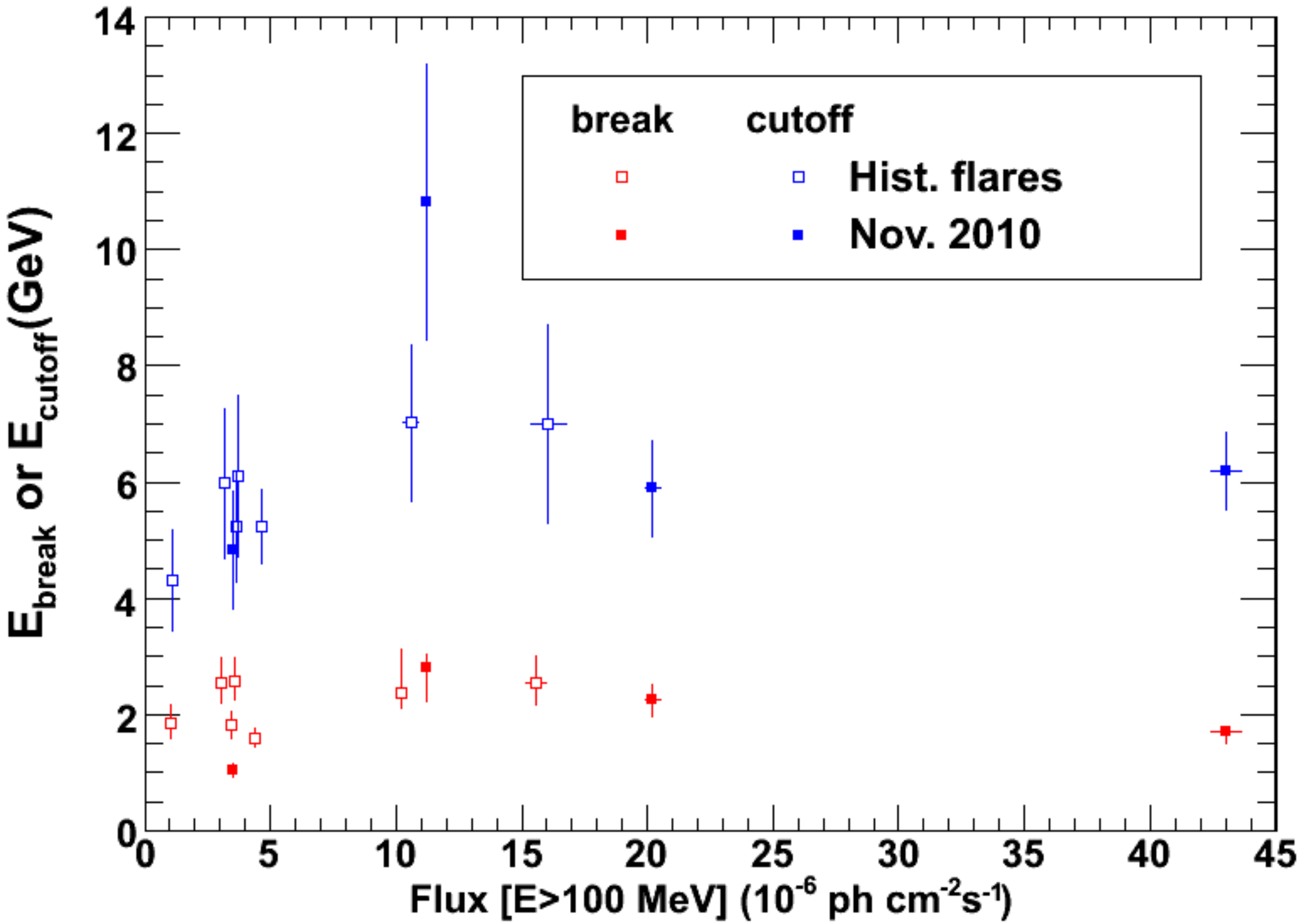
- $\gamma\gamma$ attenuation from He II recombination line photons (Poutanen & Stern 2010)
- intrinsic electron spectral breaks (Abdo et al. 2009)
- Ly α scattering (Abdo et al. 2010)
- hybrid scattering (Finke & Dermer) scenarios
  Break results from sum of two different EC components: disk (low-energy γ,high-energy e) BLR (high-energy γ,lower-energy e)
  →hard lag !



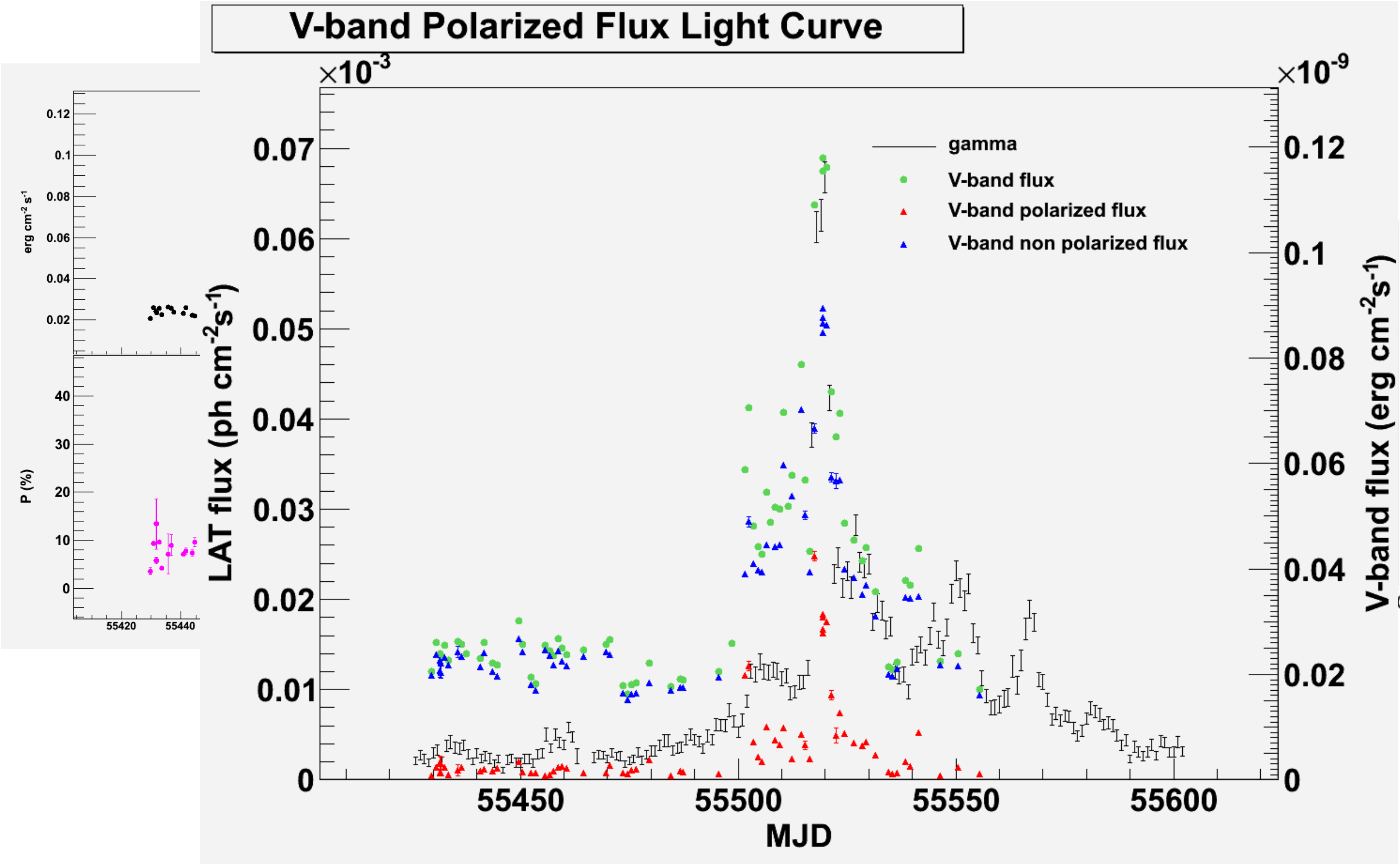




Evolution of energy break with flux



No strong evolution of break (or cutoff) energy is found while the flux varies by a factor ~ 40


V-band Polarized Flux Light Curve
×10^-3
×10^-9
gamma
V-band flux
V-band polarized flux
V-band non polarized flux
LAT flux (ph cm^-2 s^-1)
V-band flux (erg cm^-2 s^-1)
MJD
55450
55500
55550
55600
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.12
0.1
0.08
0.06
0.04
0.02
0
erg cm^-2 s^-1
P (%)
55420
55440

Conclusion

• a truly amazing event

• record flux might not be exceeded during entire LAT livetime…

• rich spectral features in the gamma-rays
  significant hardening during flare
  hard lag, delayed arrival of high-energy photons
  approximate constancy of break energy

• MW correlations should provide a wealth of important information