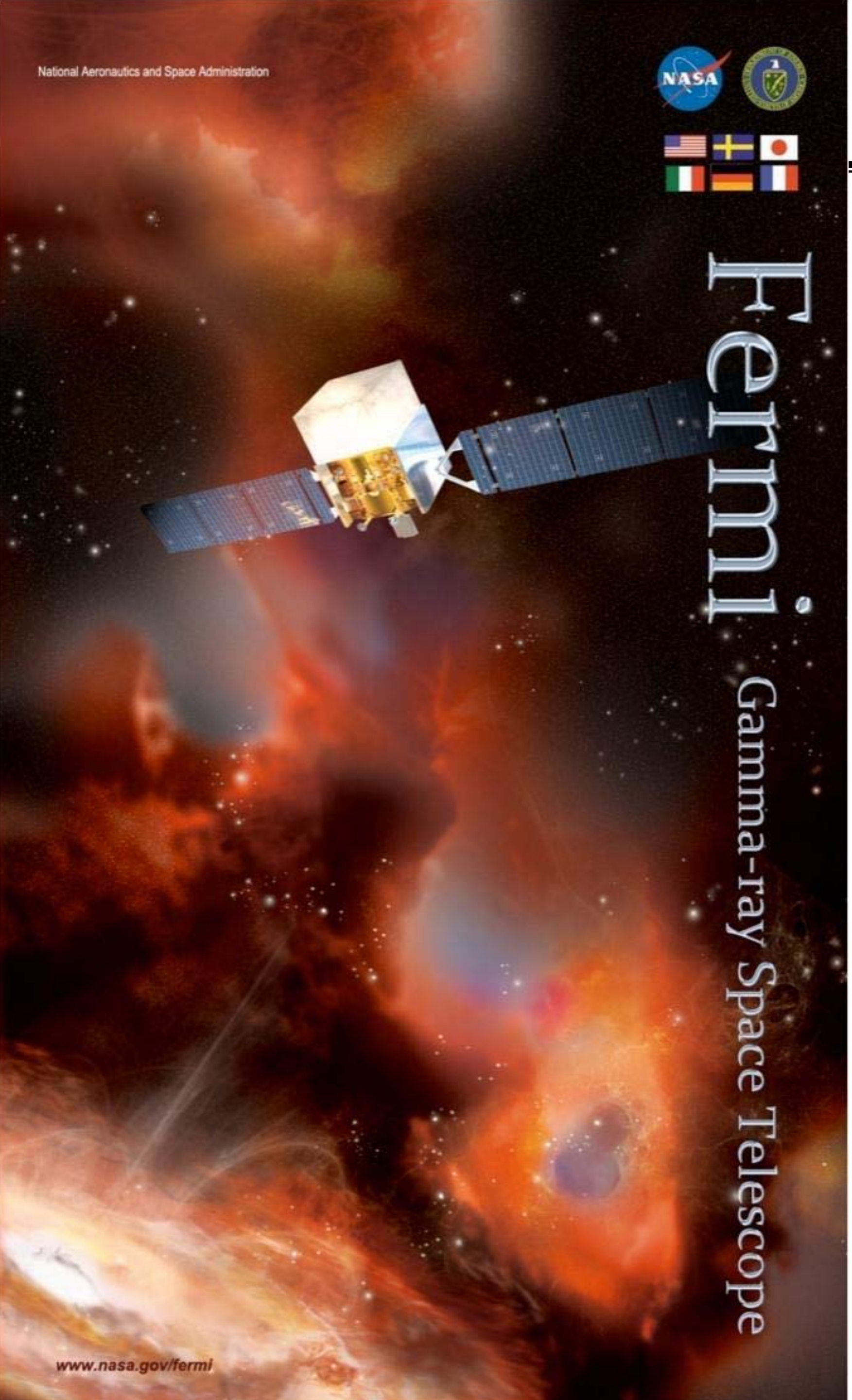


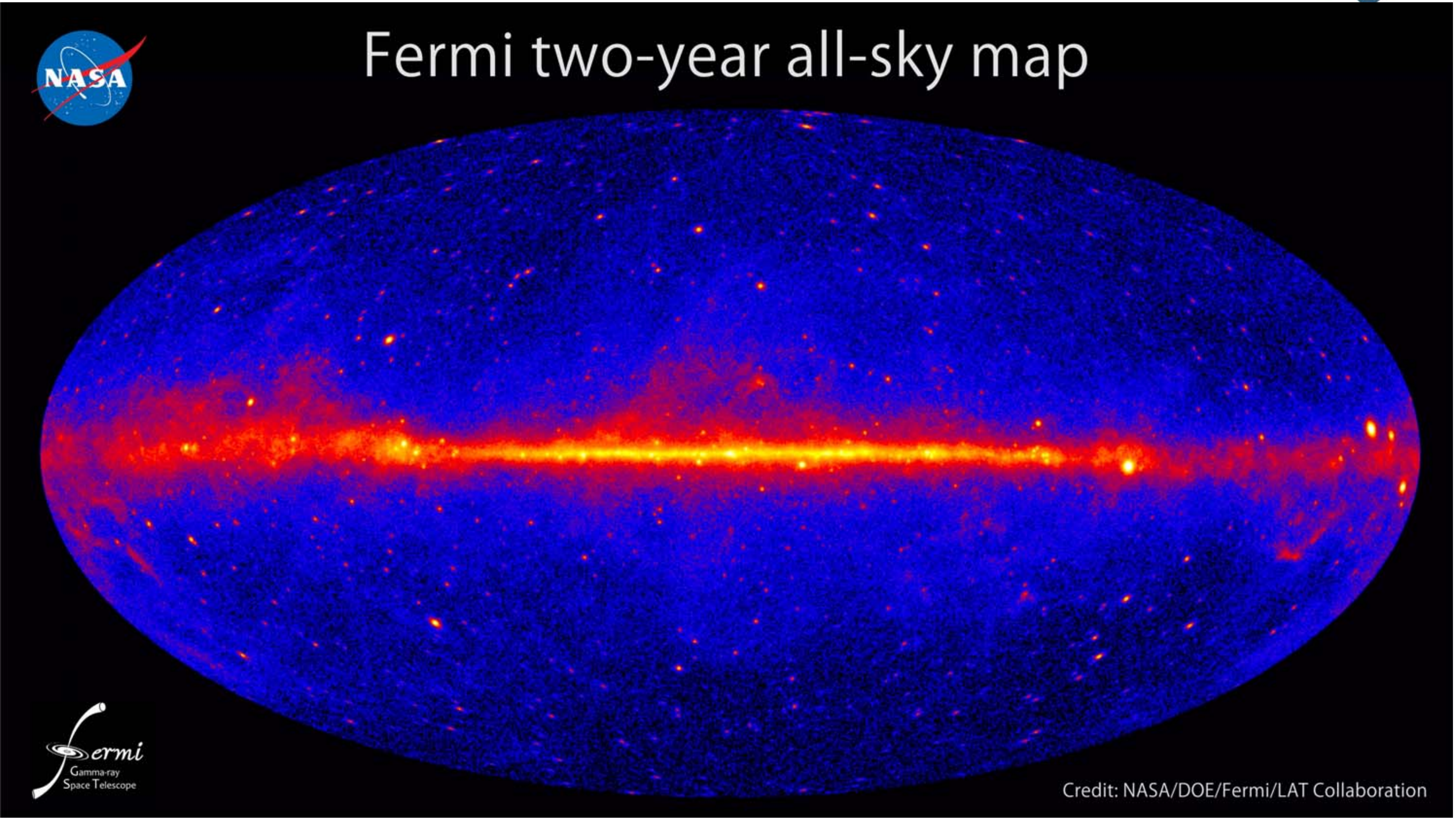
Recent observations of extragalactic jets: a summary

Greg Madejski
SLAC and KIPAC, Stanford University

with many collaborators: Benoit Lott, Lise Escande, Stefan Larsson, Masaaki Hayashida, Yasushi Fukazawa, Krzysztof Nalewajko,

And – of course - Marek Sikora!

Fermi is doing very well



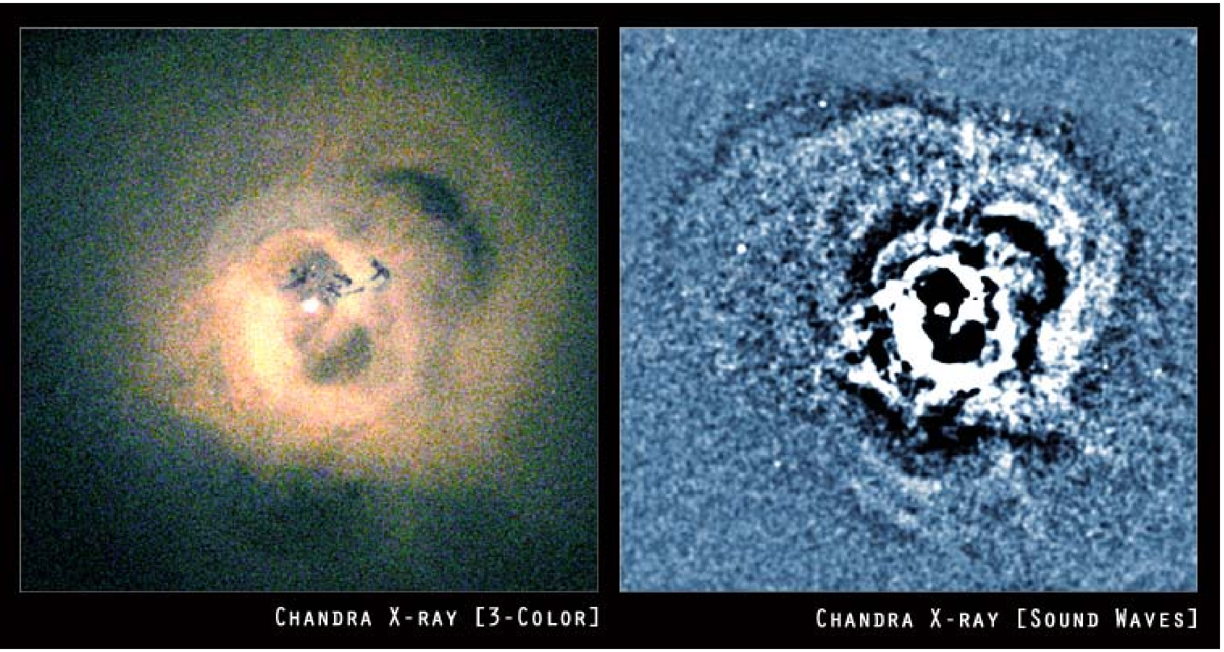
1-year tally: nearly 1500 sources; 2-year catalog in preparation

Radio galaxies also are γ-ray emitters

Example: NGC 1275 a.k.a. Per A a.k.a. 3C84

- NGC 1275, a.k.a. 3C84 or Perseus A, is a nearby radio galaxy containing a flat-spectrum, compact (VLBI-scale) variable radio source in the Perseus Cluster
- Detected in the Fermi LAT data, at a much higher level than the upper limit from EGRET ->

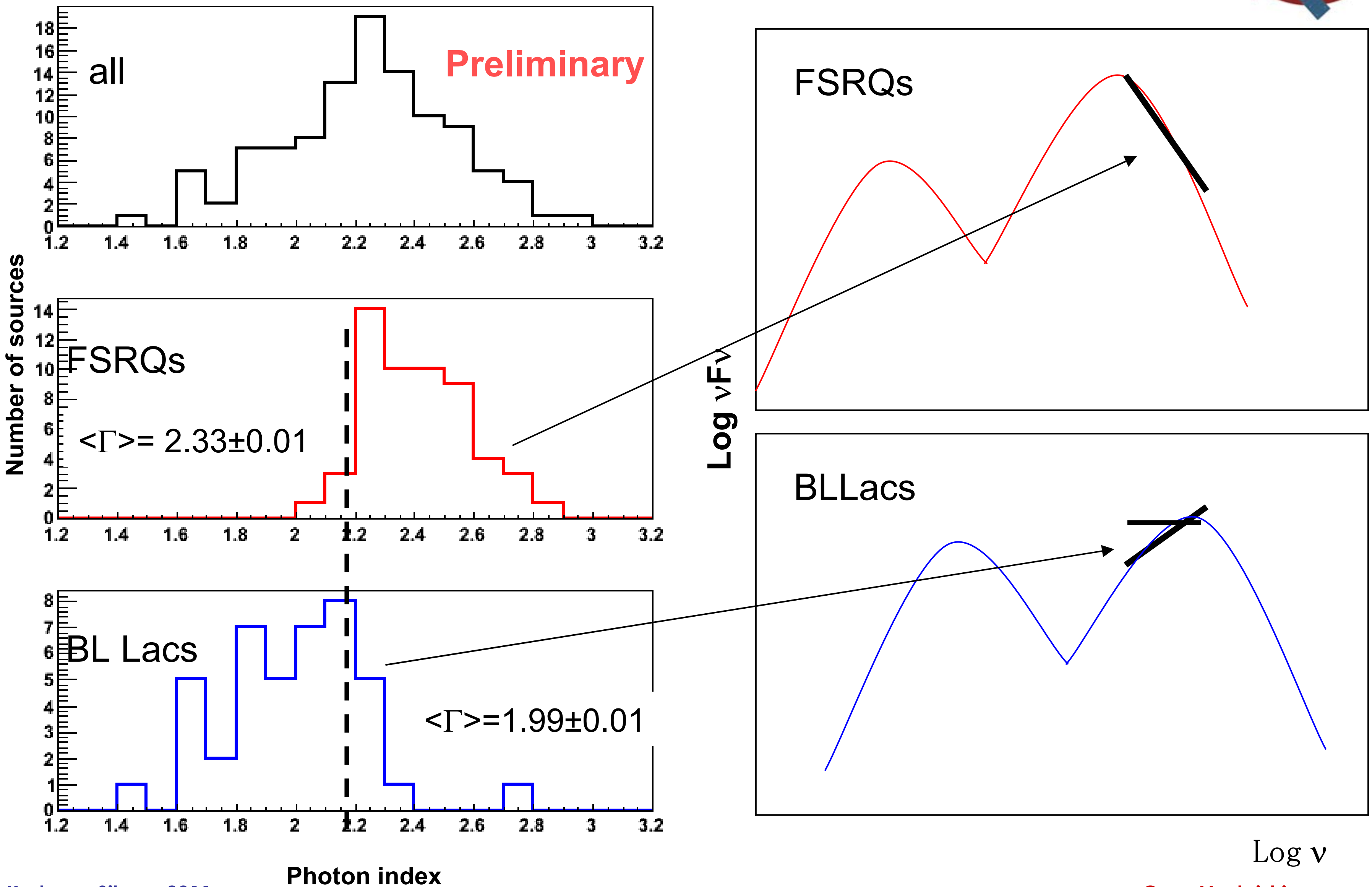
  variable -> *not* the Perseus cluster



* Radio jet is known to be sub-relativistic: hint for spine-sheath jet structure?

The jet is most likely responsible for inflating the ``cavities'' seen in the Chandra images of the Perseus cluster

Fermi LAT spectra of blazars in the context of broad-band spectra: Clear spectral diversity!



Blazars: spectral diversity in γ-rays

Gamma-ray spectra are quite diverse
(early inferences shown here confirmed in 2-yr data)

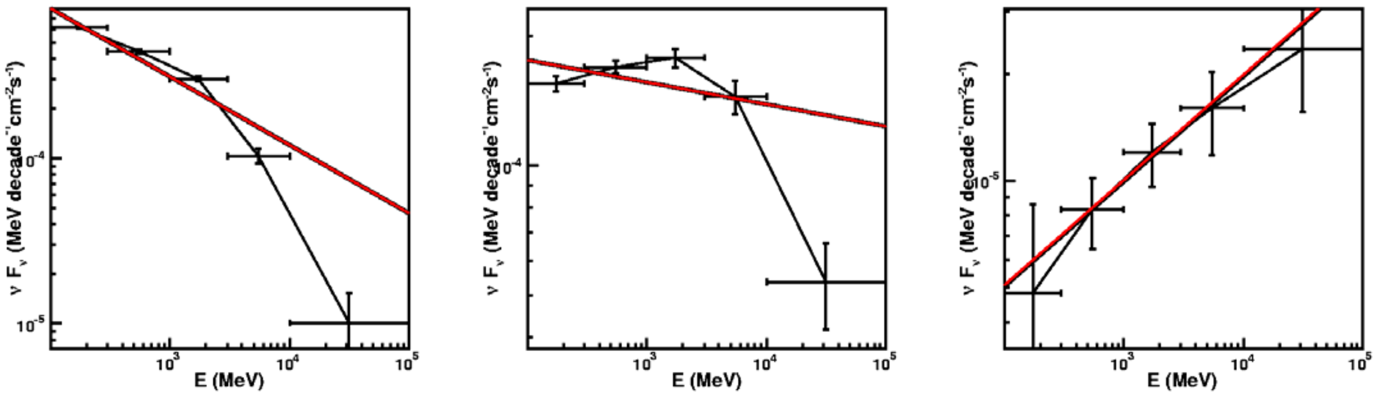
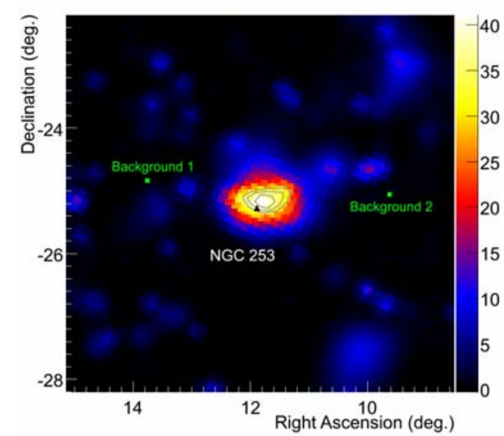


Fig. 10.— Gamma-ray SED of 3 bright blazars calculated in five energy bands, compared with the power law fitted over the whole energy range. Left: 3C454.3 (FSRQ), middle: AO 0235+164 (IBL), right: Mkn 501 (HBL)

<- High luminosity sources **low luminosity sources ->**

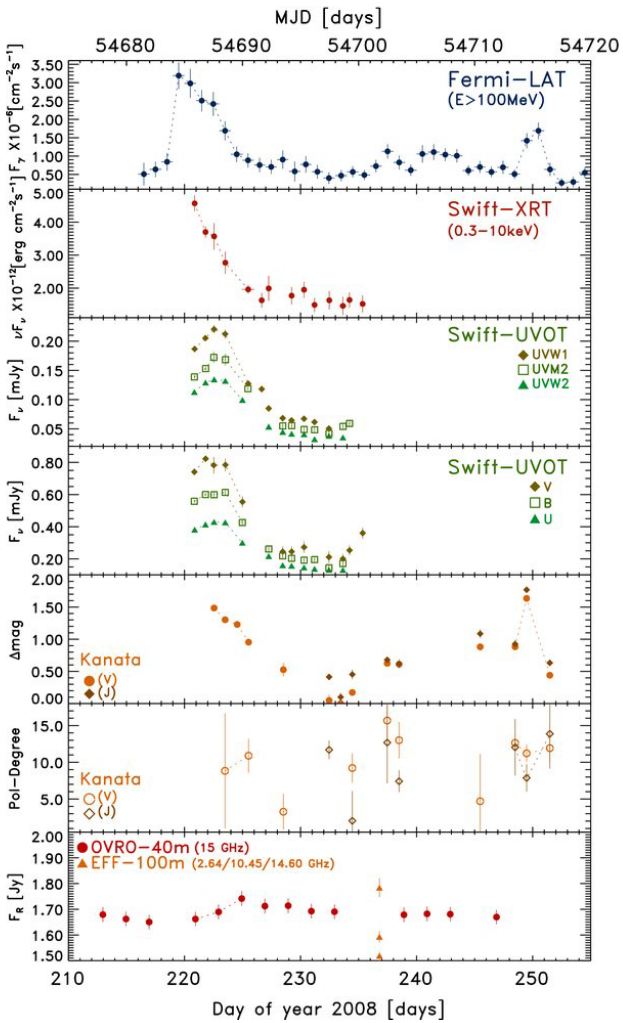
- The spectra diverse – clear association with blazar sub-class
- This has strong implications on contribution of blazars to the diffuse extragalactic gamma-ray background
- We expect both types would contribute at some level;

BUT: starbursts important! ->



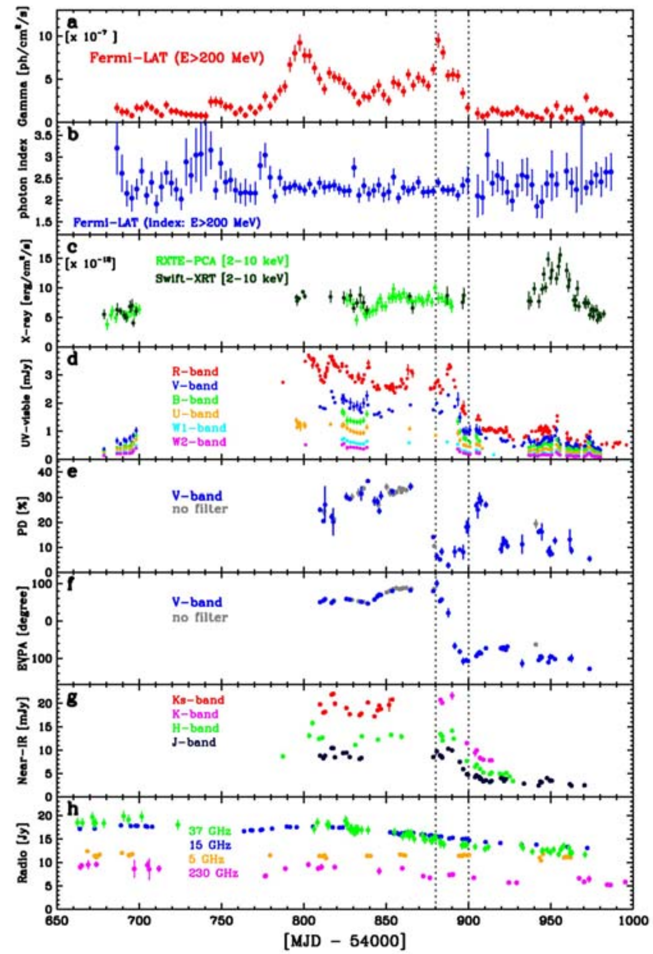
Krakow: Sikora-2011

Deployment of Fermi motivates multi-band observations of blazars



← γ-rays →

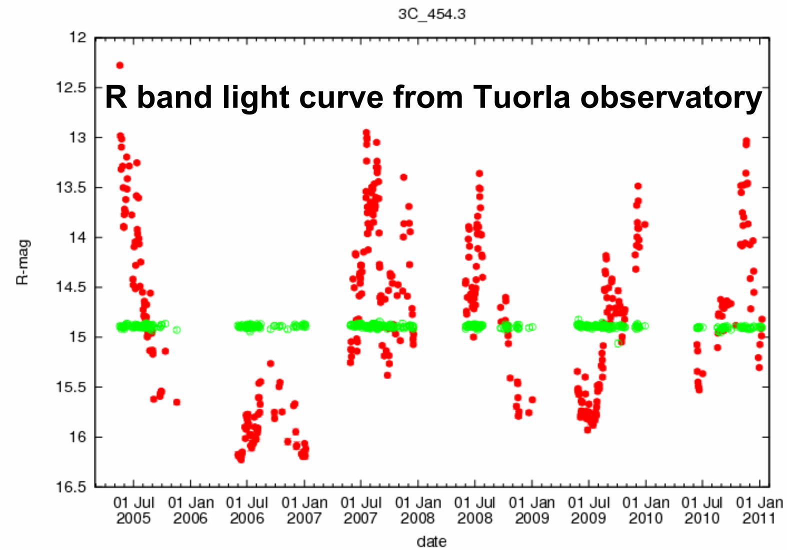
← optical →

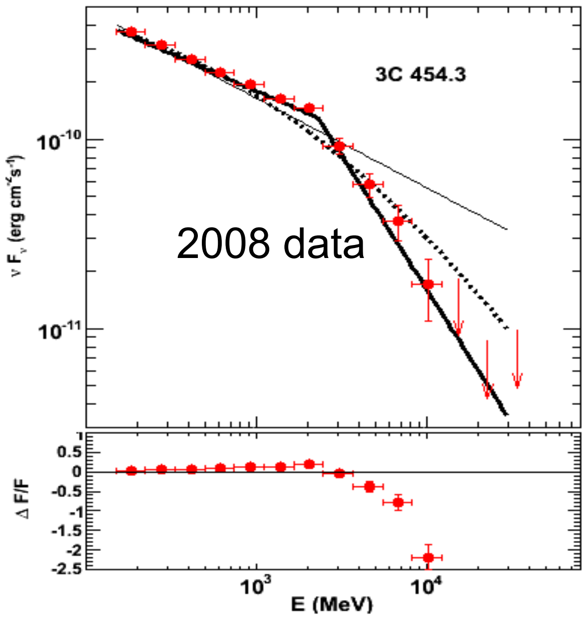


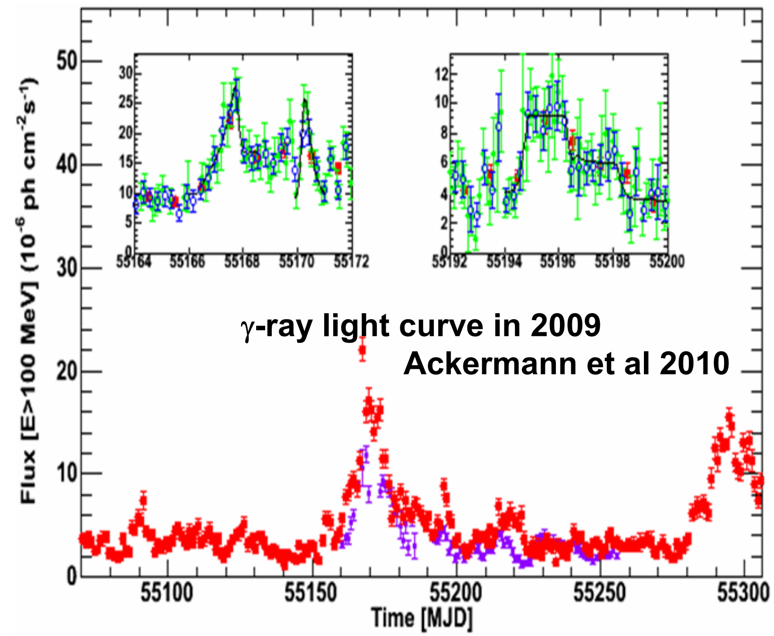
Multi-band time series for PKS 1502+106 (Abdo et al. 2009), 3C279 (Abdo et al. 2010; a detailed MW paper being prepared by Hayashida et al.)

Vitals of 3C 454.3

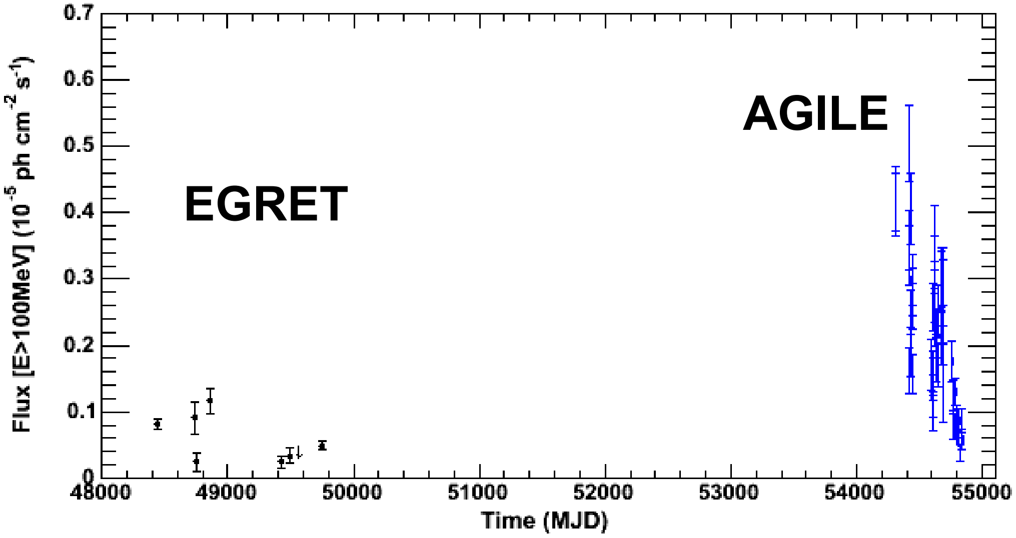
- Well-known quasar at z=0.859
- Bright, variable radio source with superluminal expansion, Γ_{jet} ~ 15
- At times the brightest extragalactic γ-ray source, τ_{var} (x2) ~ 3 hr in 2009
- First blazar w/detected γ-ray spectral break @ 2 GeV– break in the particle spectrum? γ–γ absorption via He II ?







γ-ray light curve of the FSRQ 3C 454.3



General features of the γ-ray time series

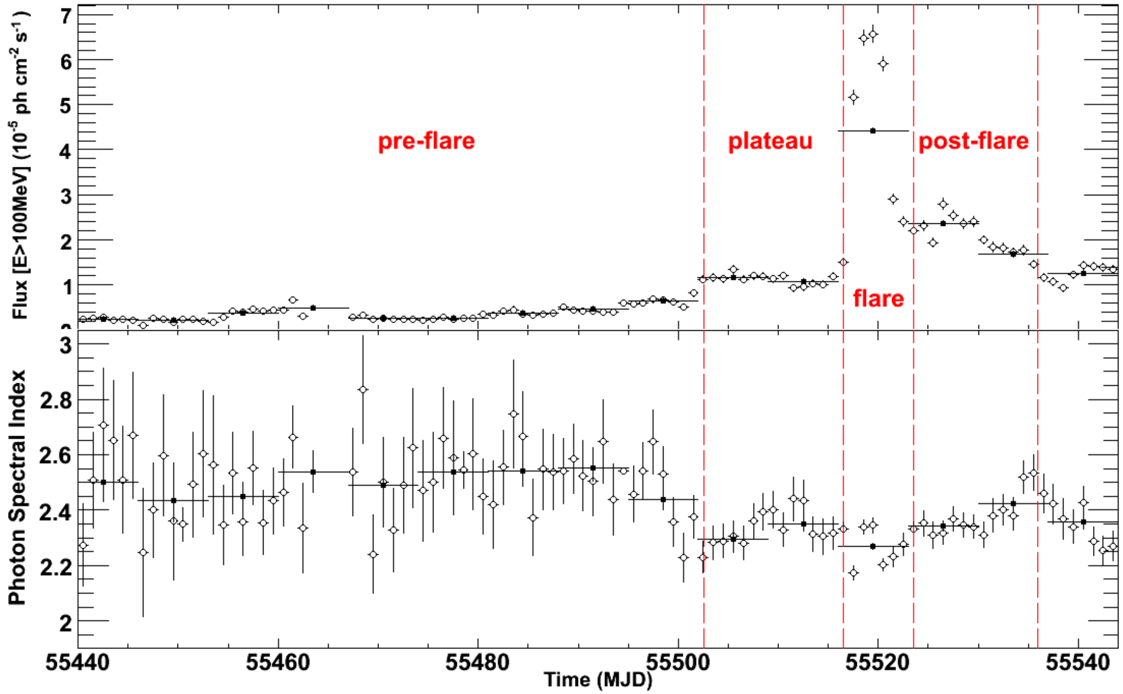
Nov. 2010 flare

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

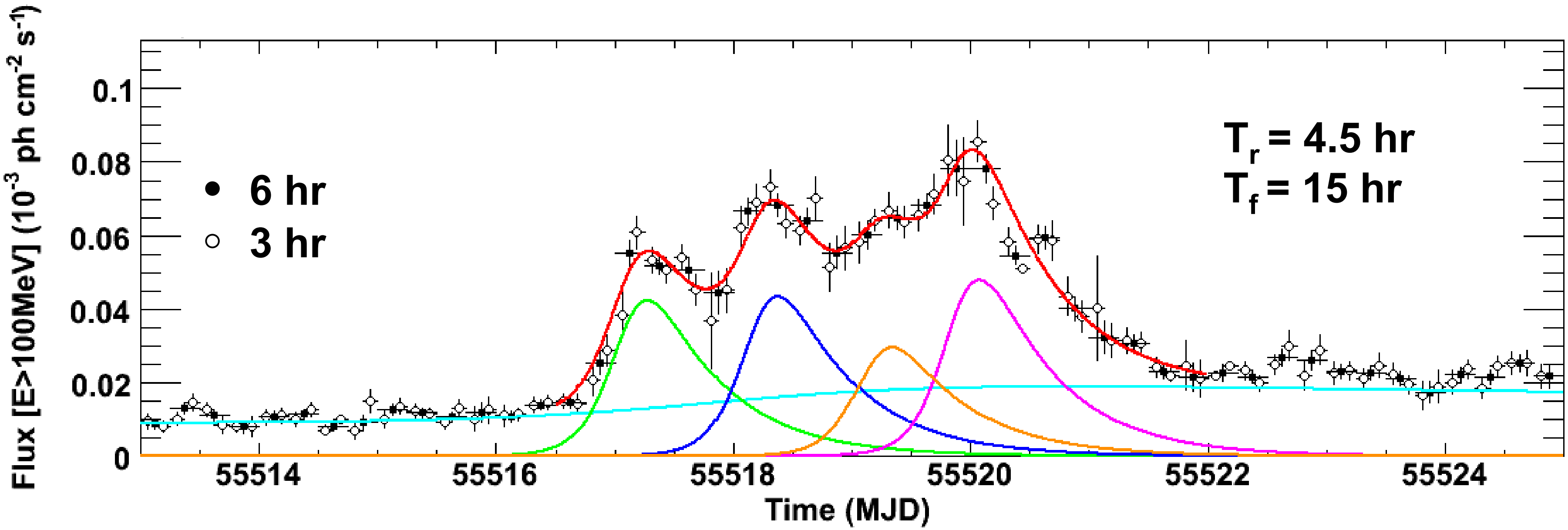
* onset of plateau marked by weak but significant spectral hardening: $\Gamma = 2.50 \pm 0.02$ to 2.32 ± 0.03

- decrease in flux by ~ x3 in 4 days

- But at a high resolution…



High-resolution light curve

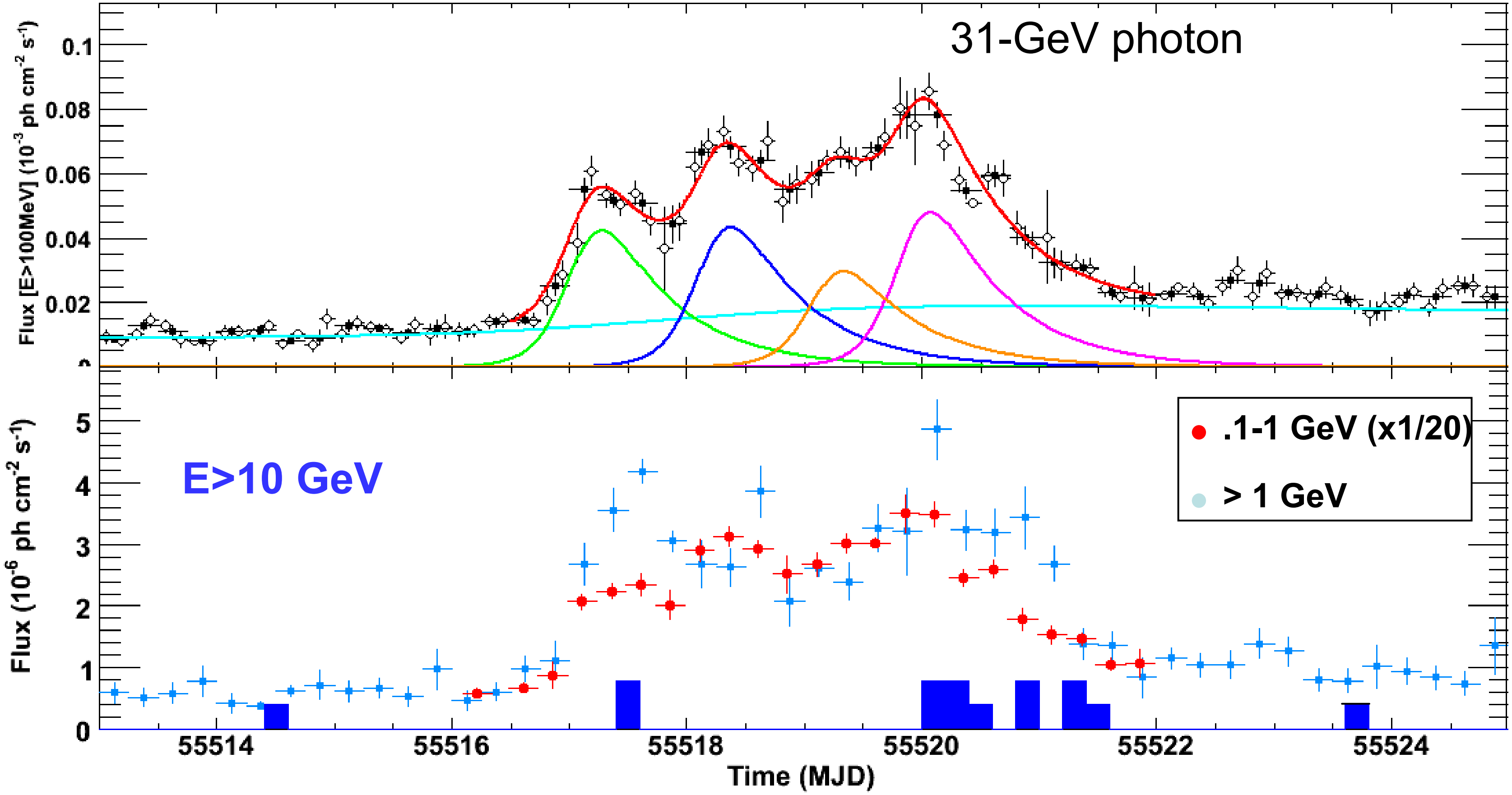


- 3-hr peak: F_{100}= (85 ± 5) x 10^{-6} ph cm^{-2} s^{-1}
- most luminous AGN yet observed: isotropic L_γ = (2.1 ± 0.2) x10^{50} erg s^{-1}
- 4x flux increase in ~12 hr: ~ 6 hr doubling time
- 4 subflares fitted with same T_r (4.5 hr) and same T_f (15 hr)

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

- 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:

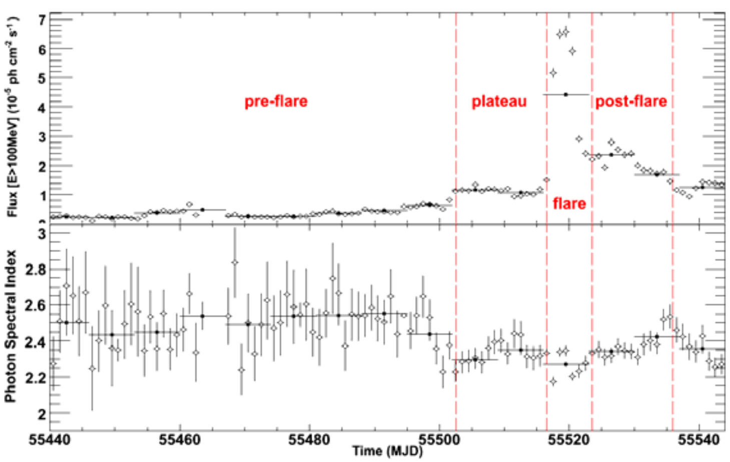
* With L_{BLR}=3x10^{45} erg s^{-1} (Pian et al 05), R_{em} = 0.14 pc (cf. Reimer 07)

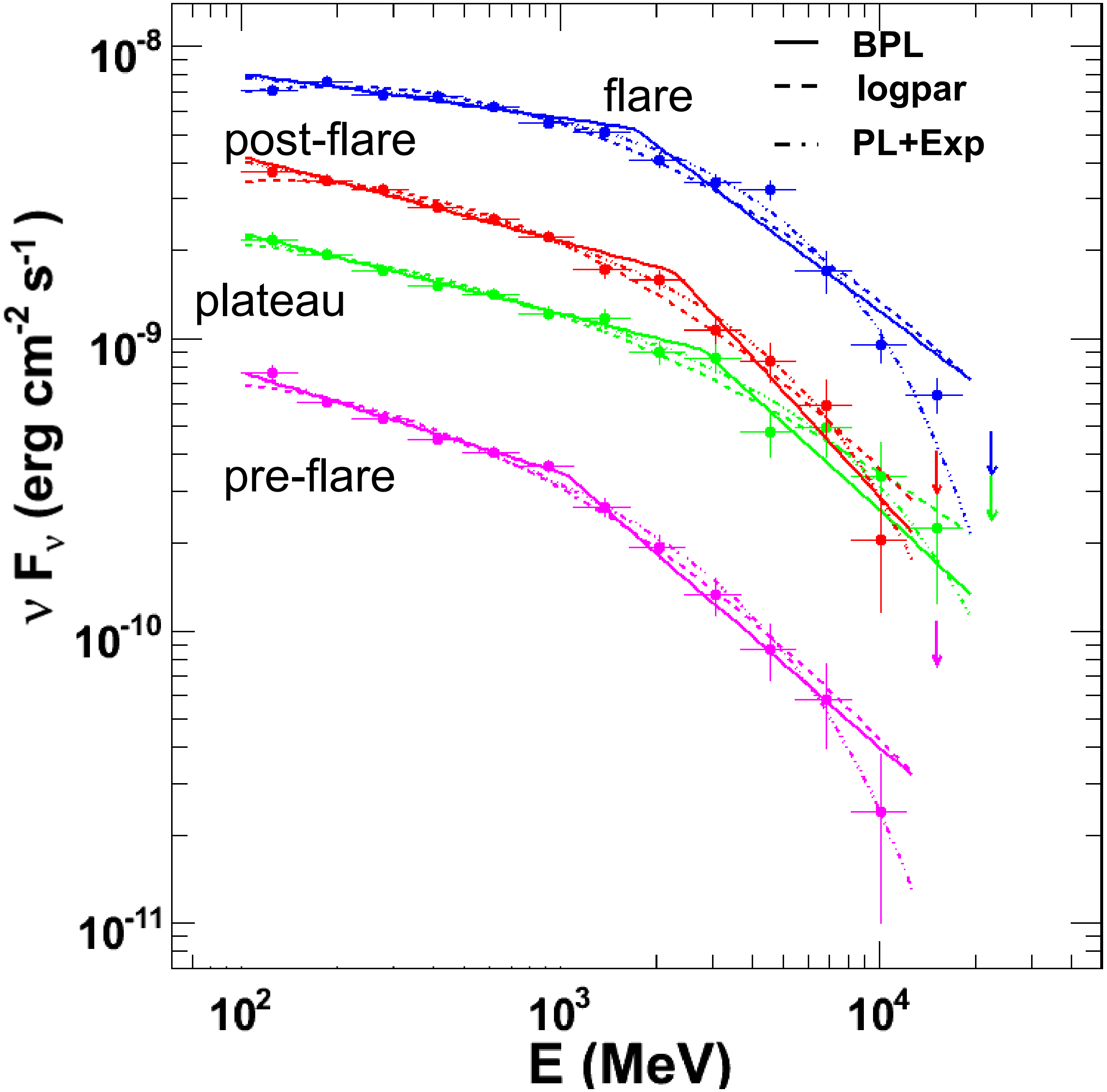
* Since R_{BLR} ~ 0.2 pc (Kaspi et al 07, the emission is close to or beyond the broad-line region

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**





Greg Madejski

γ-ray results of the giant Nov 2010 flare

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

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

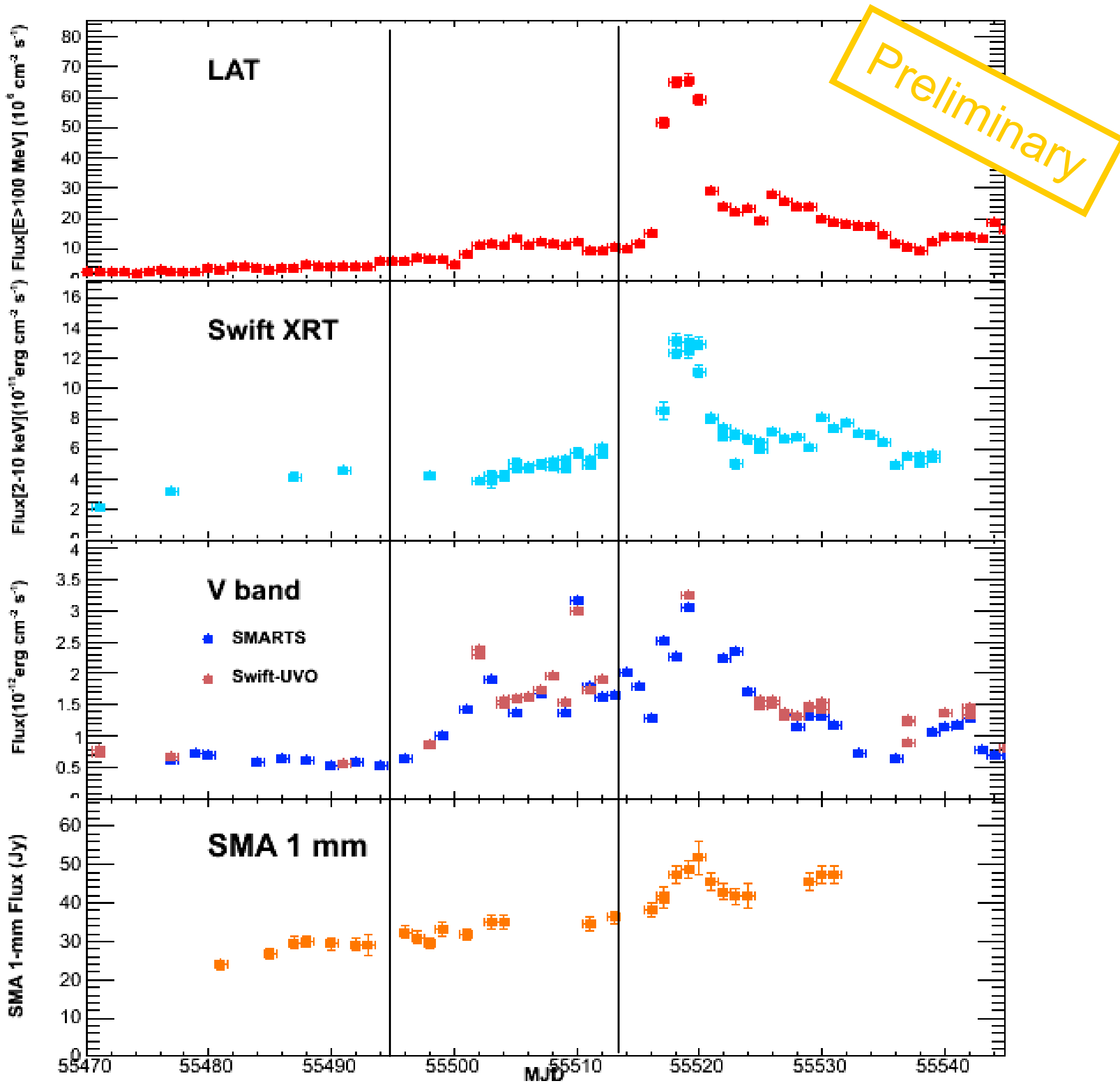
- Comoving size of the emission region: $R' = c\, t_{var}\, \delta_{min}/(1+z) \sim 3 \times 10^{15}$ cm = 0.001 pc

- $\gamma\gamma$ -opacity constraints for E_{max}=31 GeV -> with $L_{BLR}=3\times 10^{45}$ 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, ...?
  Ugly picture: that's <u>not</u> where the gravitational energy is released... (Roger B.'s talk)

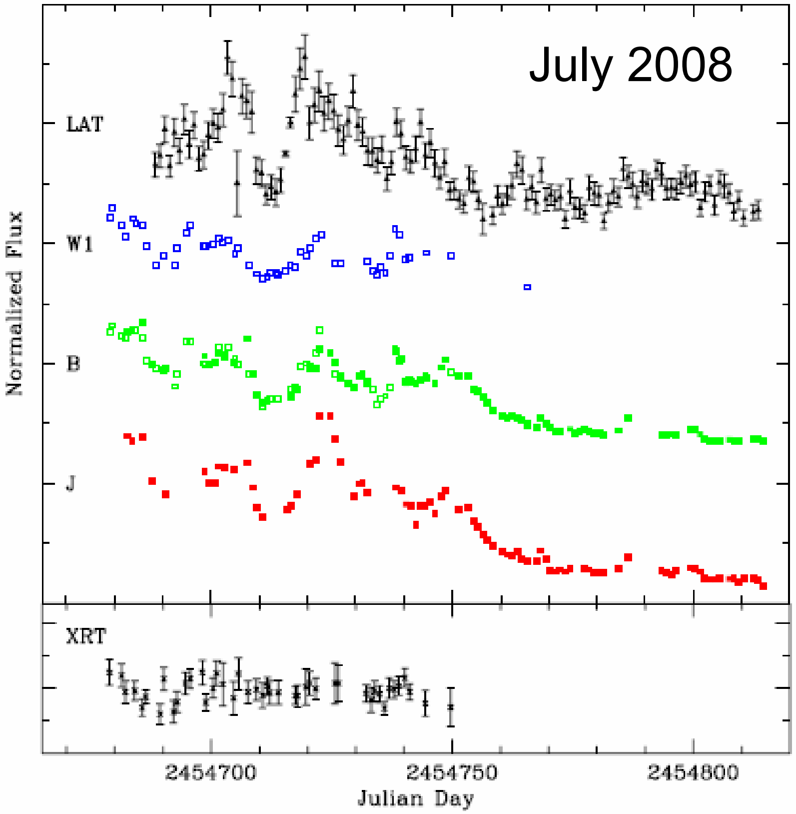
Not just γ-rays!

- 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?

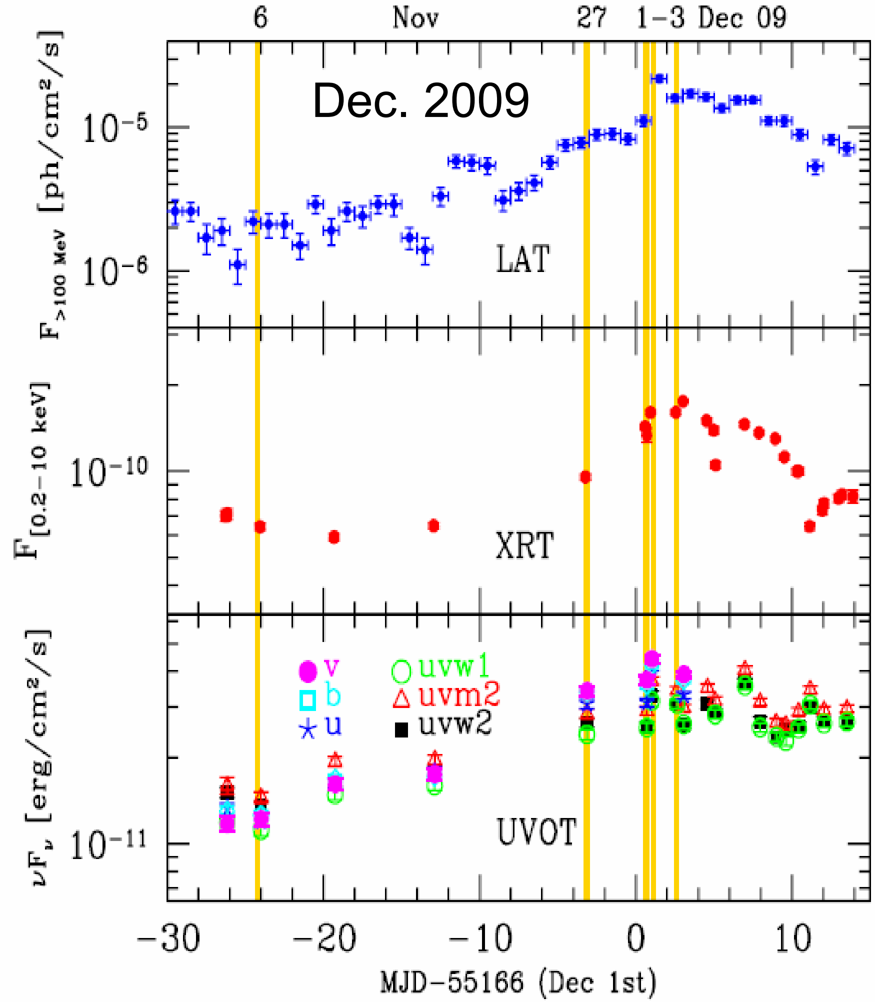


Correlated variability in previous flares

Bonning et al. 09



Bonnoli et al. 10

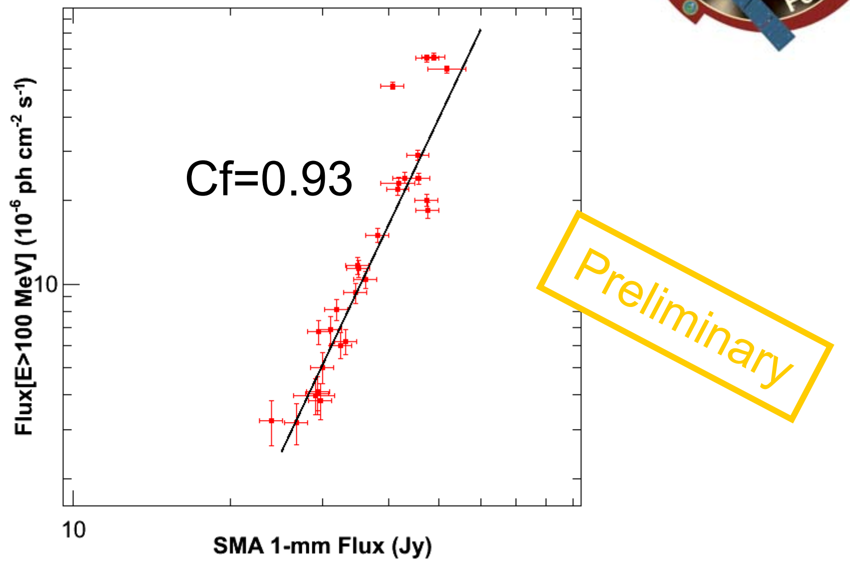


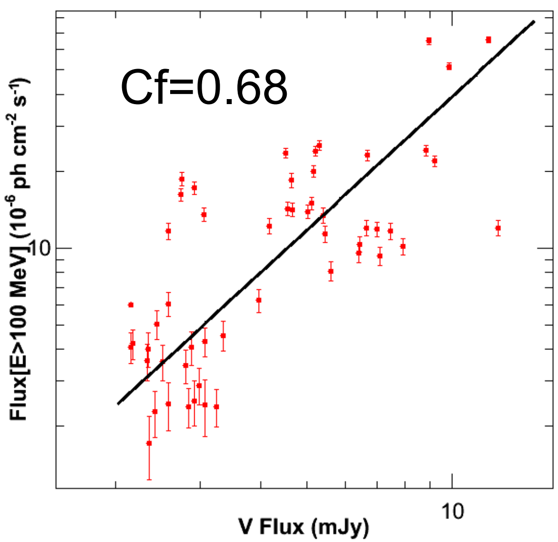
Short lag (<1 day) between optical and γ-rays (Vercellone et al. 09; 10; Donnarumma et al. 09, Bonning et al. 09, Pacciani et al. 10…)

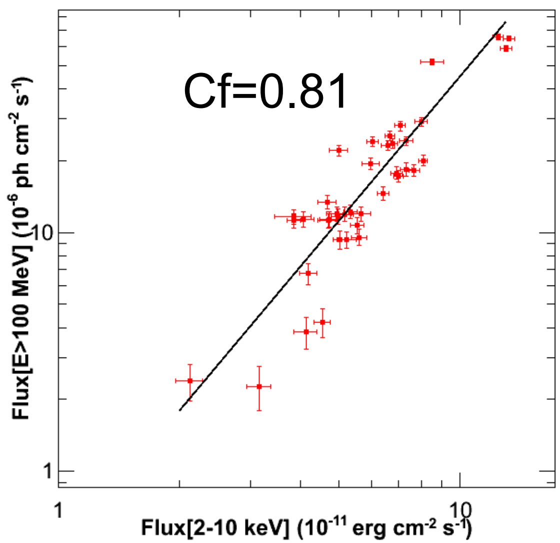
Correlation of mm, optical, X-ray fluxes vs γ-ray flux

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

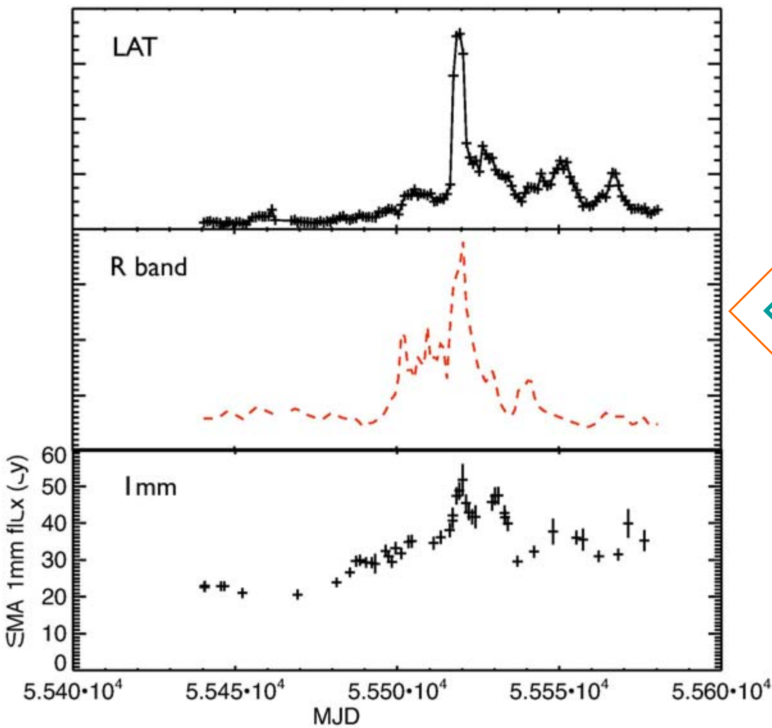
- $F_{\gamma} \alpha F_{mm}^{4}$
- $F_{\gamma} \alpha F_{opt}^{4}$
- $F_{\gamma} \alpha F_{X}^{2}$



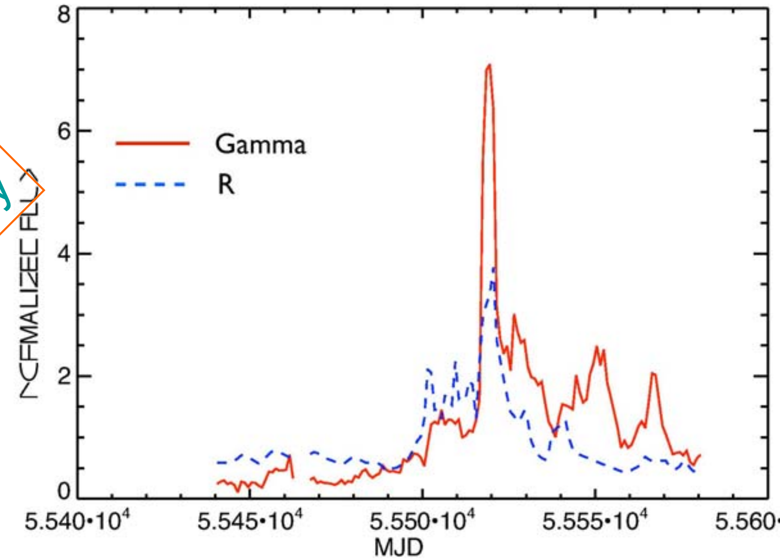


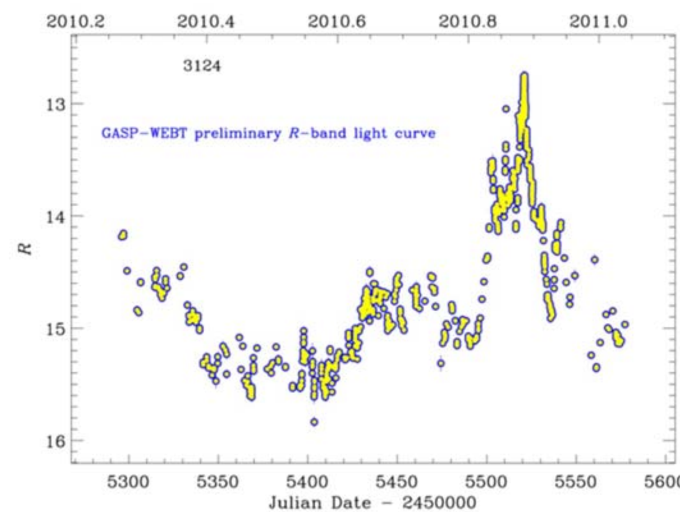


3C454.3 Multi-band observations: lags/leads



Preliminary

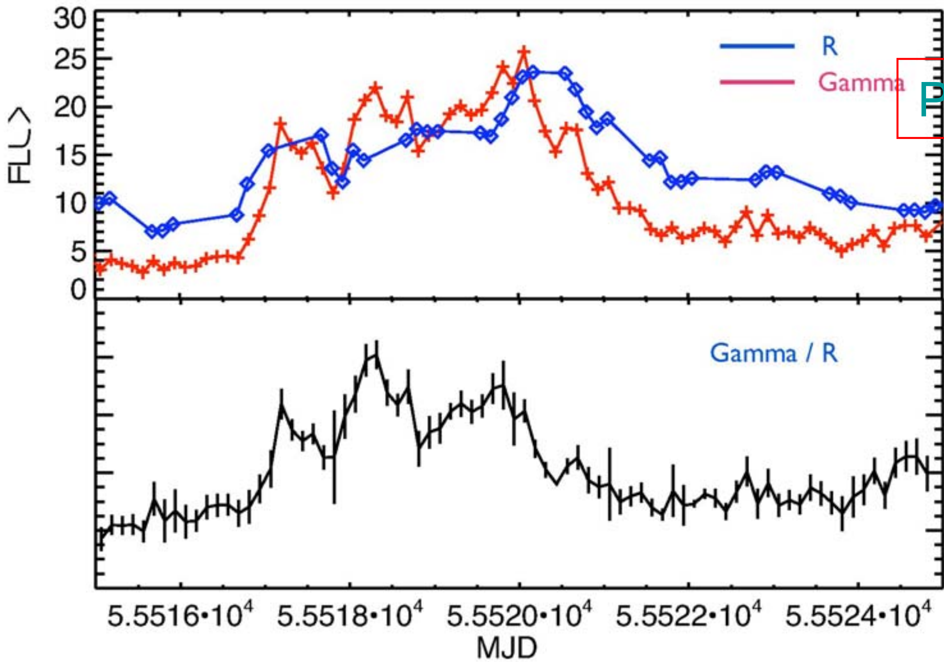


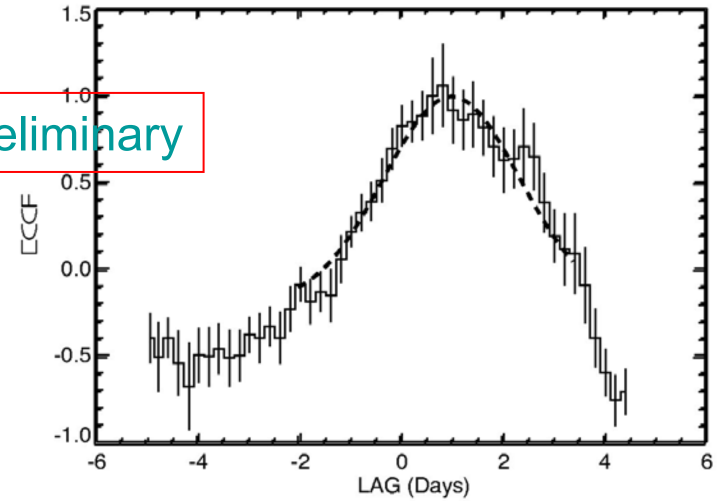


• Optical flux during the brightest, sharpest outbursts seems to lag γ-rays

* millimeter flux lags even more…

Optical / γ-ray lag

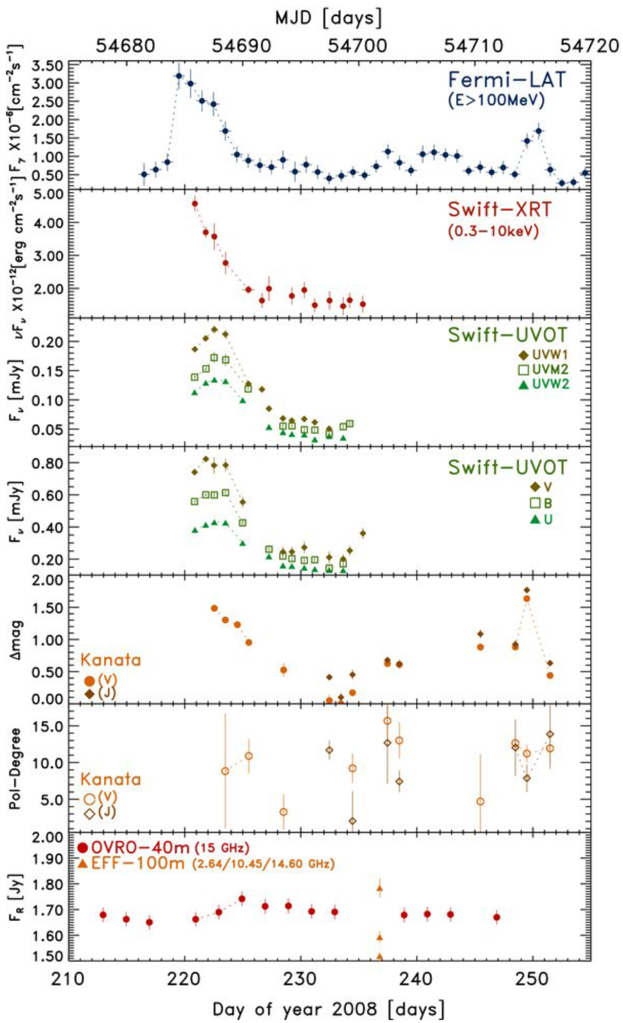




LAG = 1.0 +/-0.2 (Plotted gaussian fit)
0.8 +/-0.3 (Narrow peak fit)

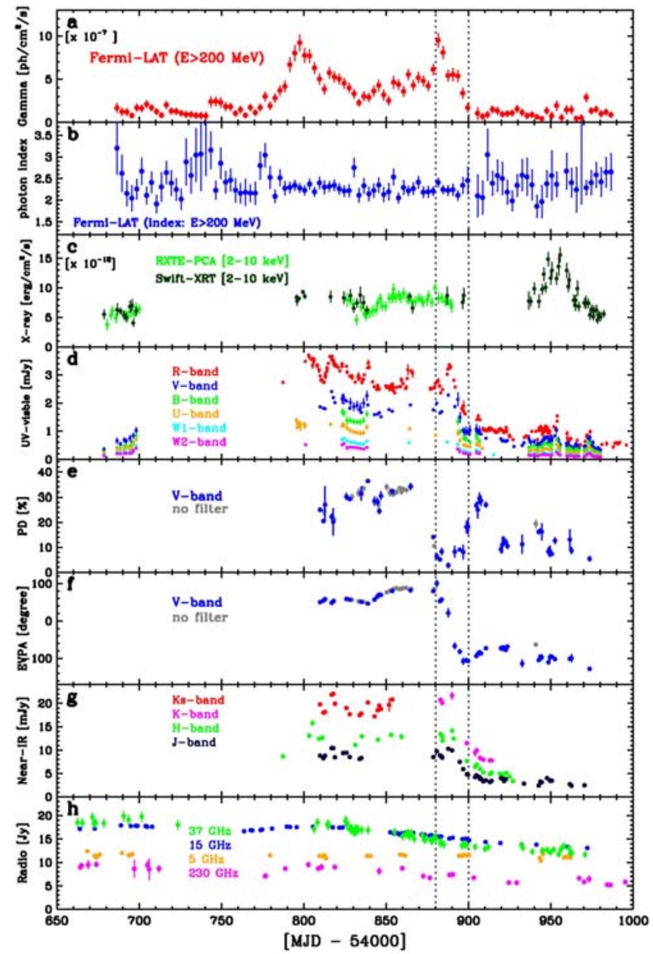
- Simple DCF: the optical lags γ-rays by ~ 1 day
- It is universal, or one-off?
- What does it mean?

Optical – γ-ray lags might be common



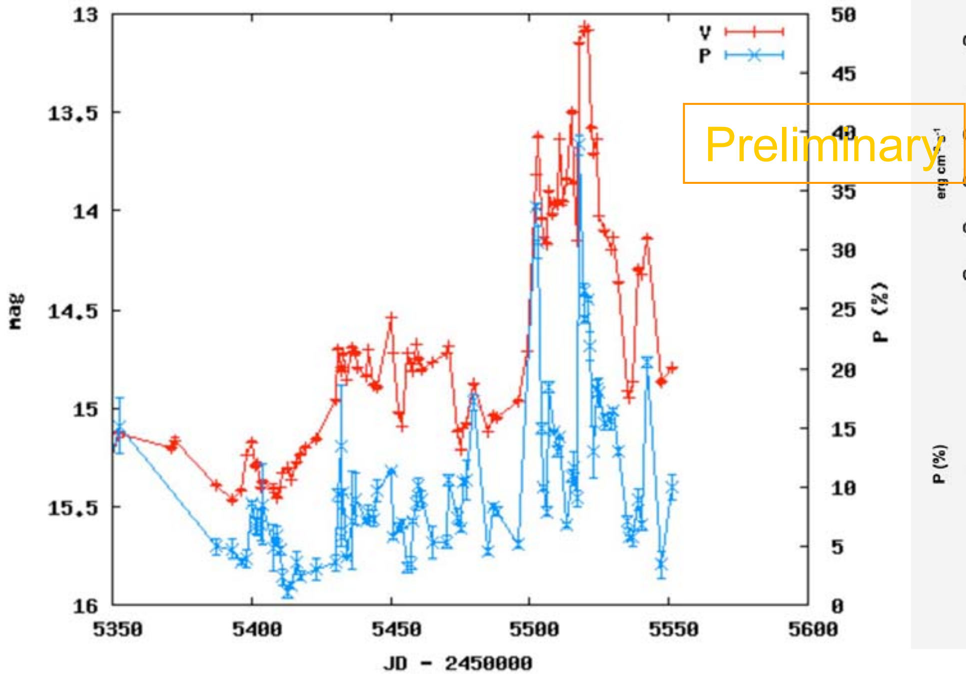
← γ-rays →

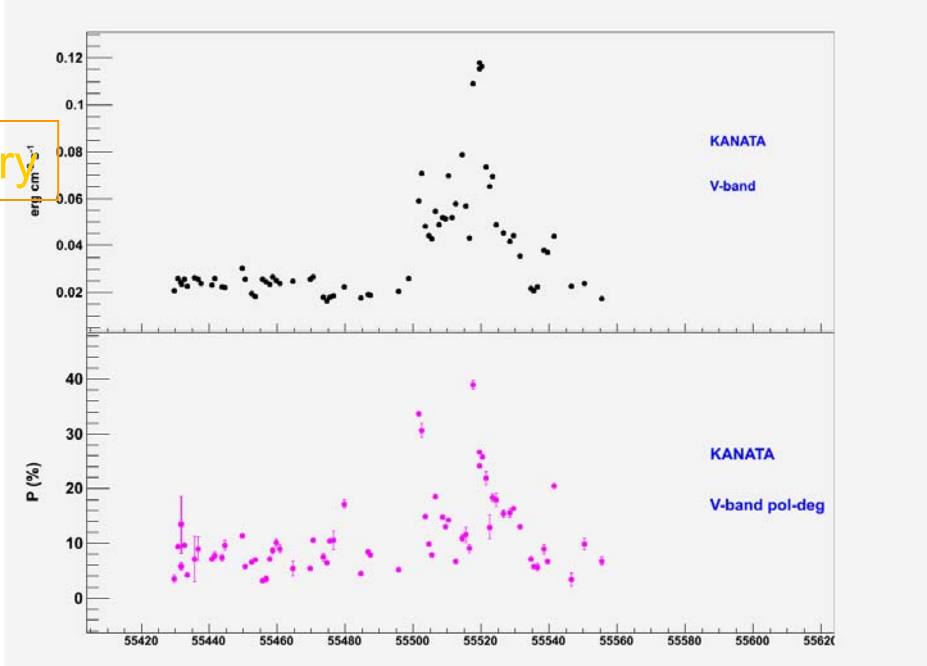
← optical →



Multi-band time series for PKS 1502+106 (Abdo et al. 2009), 3C279 (Abdo et al. 2010; Hayashida et al. 2011)

Magnetic personalities of blazars: Optical polarization data





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

Time series of <u>optical polarization</u> might provide the missing piece of the puzzle

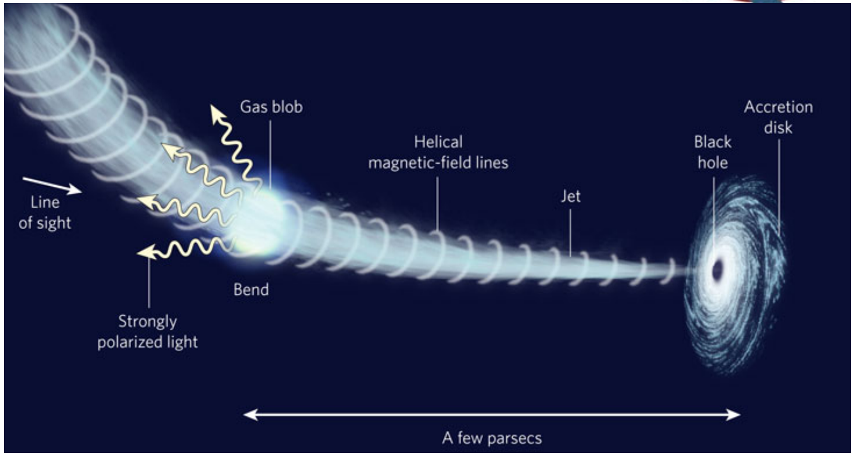
Degree of polarization reasonably well correlated w/opt. flux
-> seems to slightly lag the γ-ray flux

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 ($L_{app} \sim 10^{50}$ 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 $\gamma-\gamma$ absorbed by disk photons

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

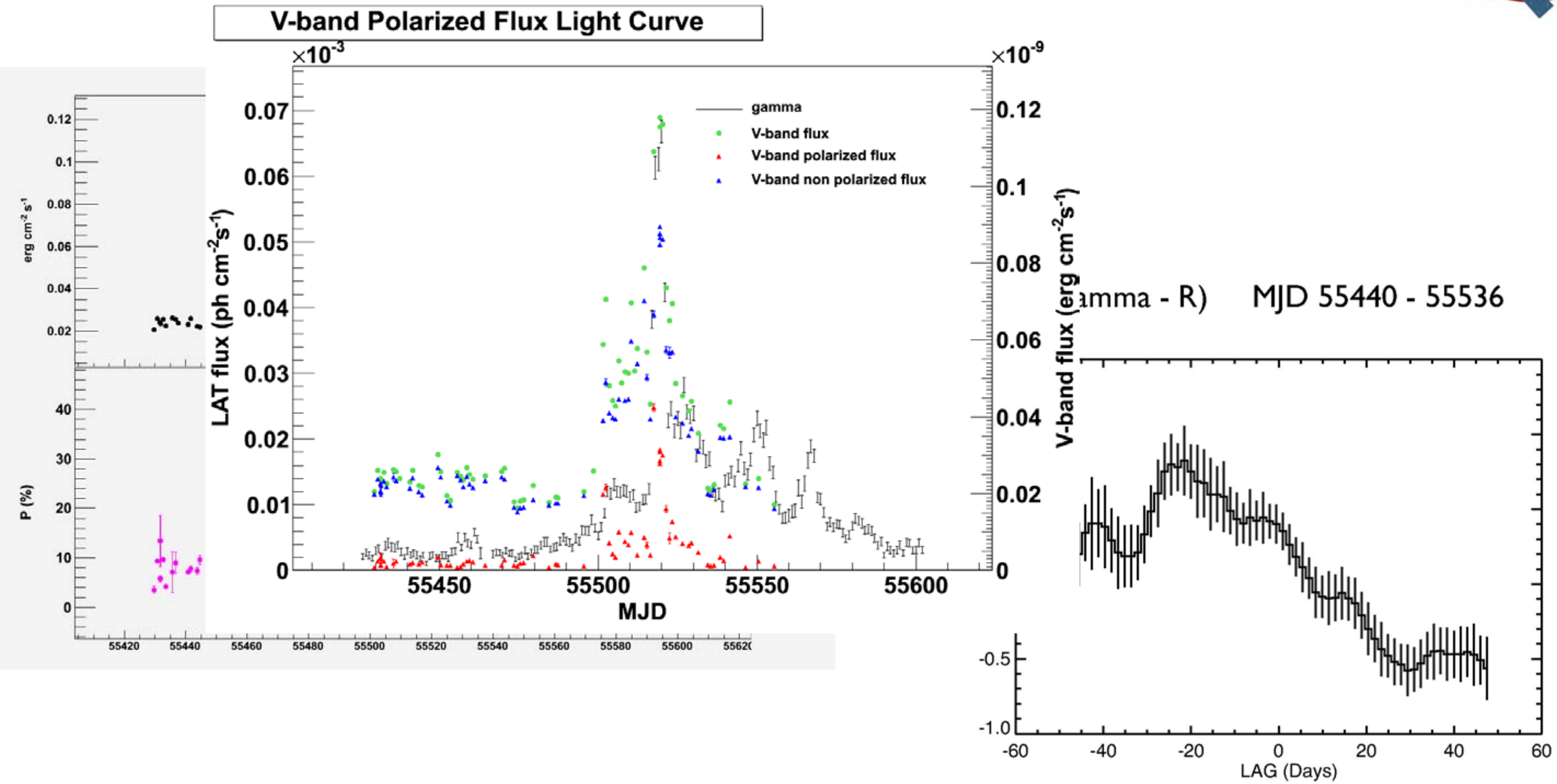
• MW correlations essential! In summary:

* Radio flux relatively steady –

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

* Optical is 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


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
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
55450
55500
55550
55600
0.12
0.1
0.08
0.06
0.04
0.02
erg cm^-2 s^-1
P (%)
40
30
20
10
55420
55440
55460
55480
55500
55520
55540
55560
55580
55600
amma - R)
MJD 55440 - 55536
-0.5
-1.0
-60
-40
-20
0
20
40
60
LAG (Days)