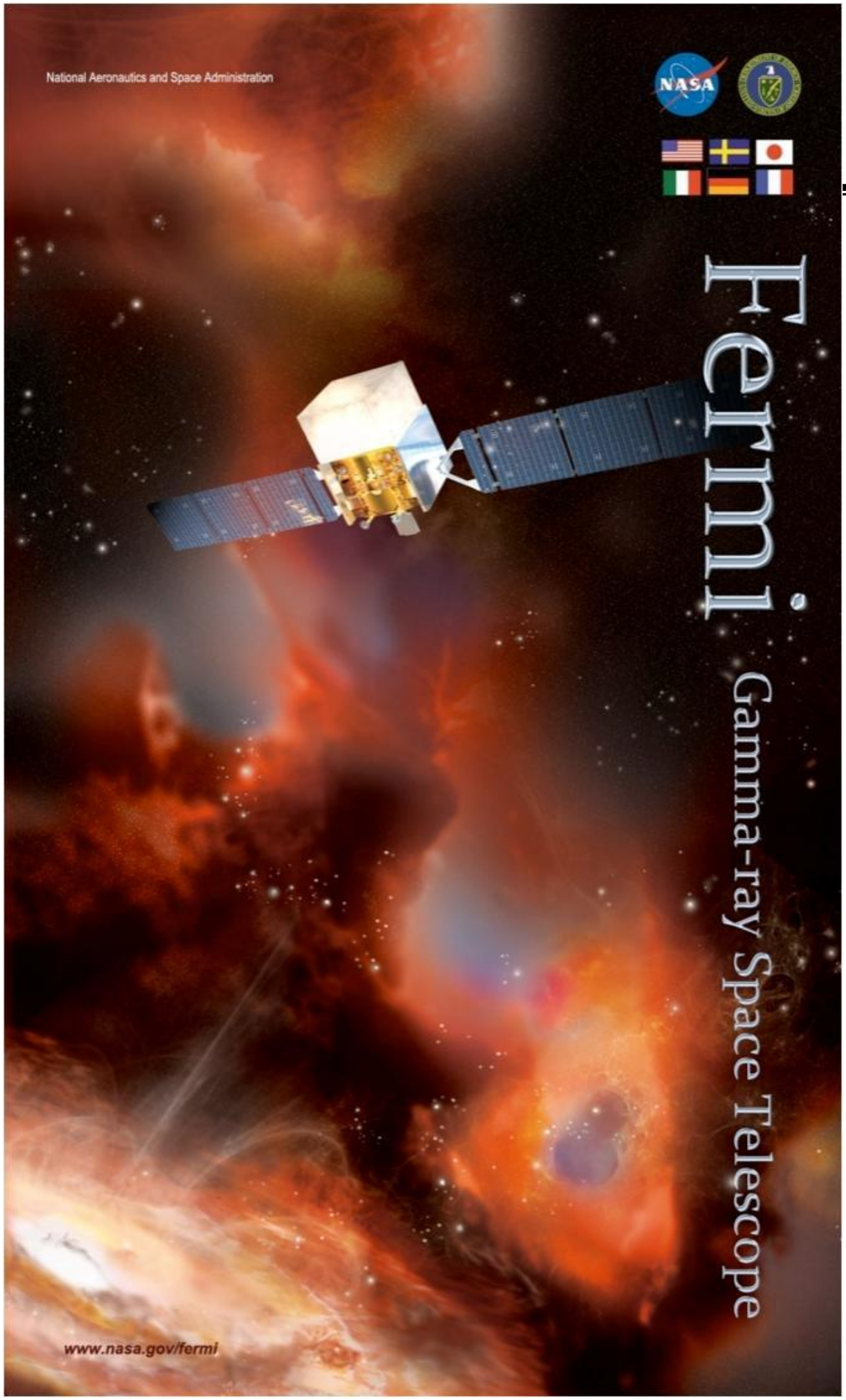

AGNs with the Fermi-LAT

Benoît Lott
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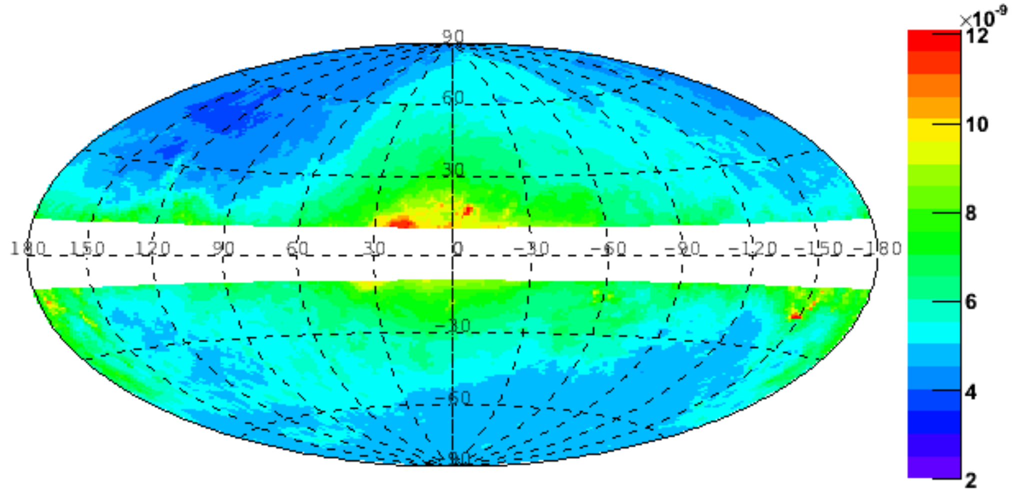
on behalf of the *Fermi*-LAT collaboration

Assets for blazar science

- unprecedented sensitivity in the GeV band
- fairly uniform at high galactic latitude
- sky scanned every 3 hours in survey mode
- alerts issued shortly after transient or new flaring sources are detected

TS=25 sensitivity map (2 yr, photon index=2.2)



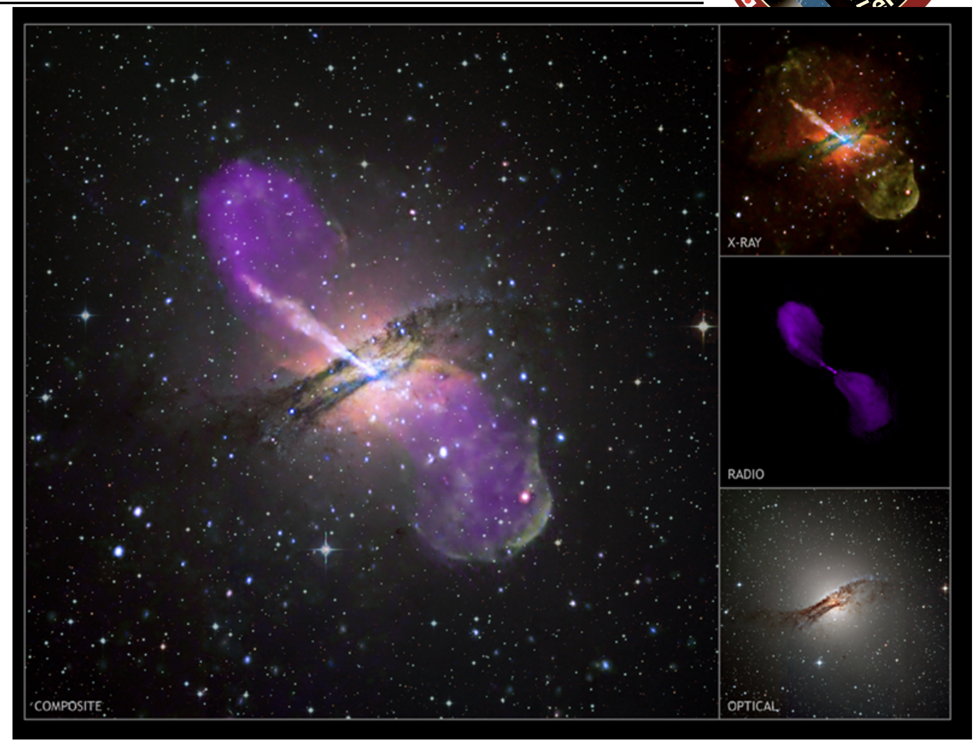
Flux(E>100 MeV) ph $cm^{-2}s^{-1}$

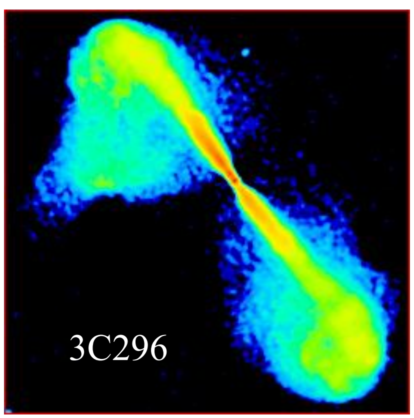
- continuous survey allows for source monitoring and variability studies on time scales ranging from months down to a few hours
- covers the little-explored 10-100 GeV domain
  - new spectral features at high energy discovered
  - identification of potential candidates of TeV sources (several discoveries)

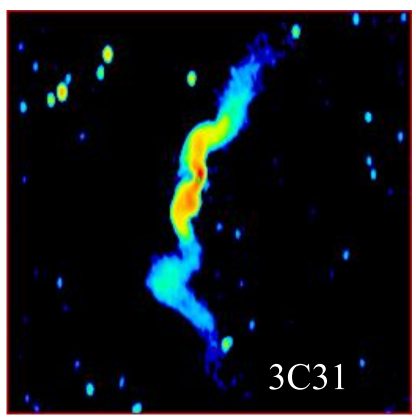
Radio galaxies

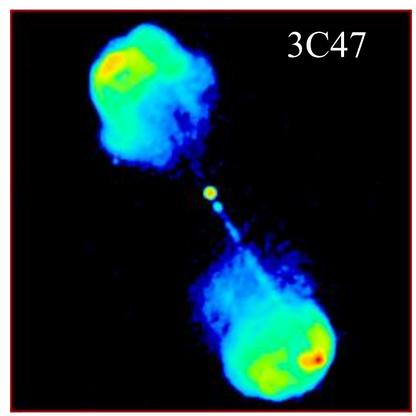
5-15% of active galaxies
Mostly of the elliptical type
Galaxies displaying extended radio lobes
(up to 10 x larger than the galaxy)

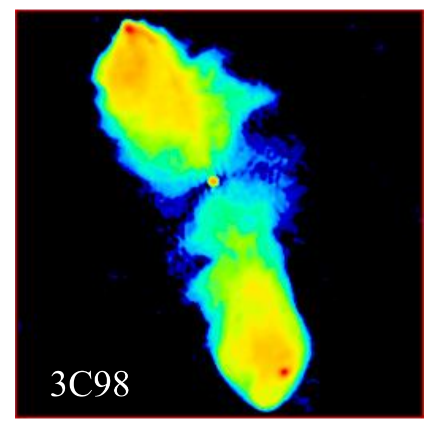
2 classes
- Fanaroff-Riley 1: large opening angle, brighter close to the core, low luminosity, close
- Fanaroff-Riley 2: highly collimated jet, lobe brightened with hot spots, luminous, distant











Unification scheme

Powered by accretion onto a central, supermassive black hole $10^{8\text{-}9}\,M_\odot$

Inner part of the disk shines very brightly: *quasar* phenomenon

Observed properties governed by angle wrt line of sight

1 pc = 3 x 10^{16} m

r_S=10^{-5} (M/$10^8\,M_\odot$) pc

Disk size: 10^{-3} pc

Base of VLBI jet: 1-10 pc

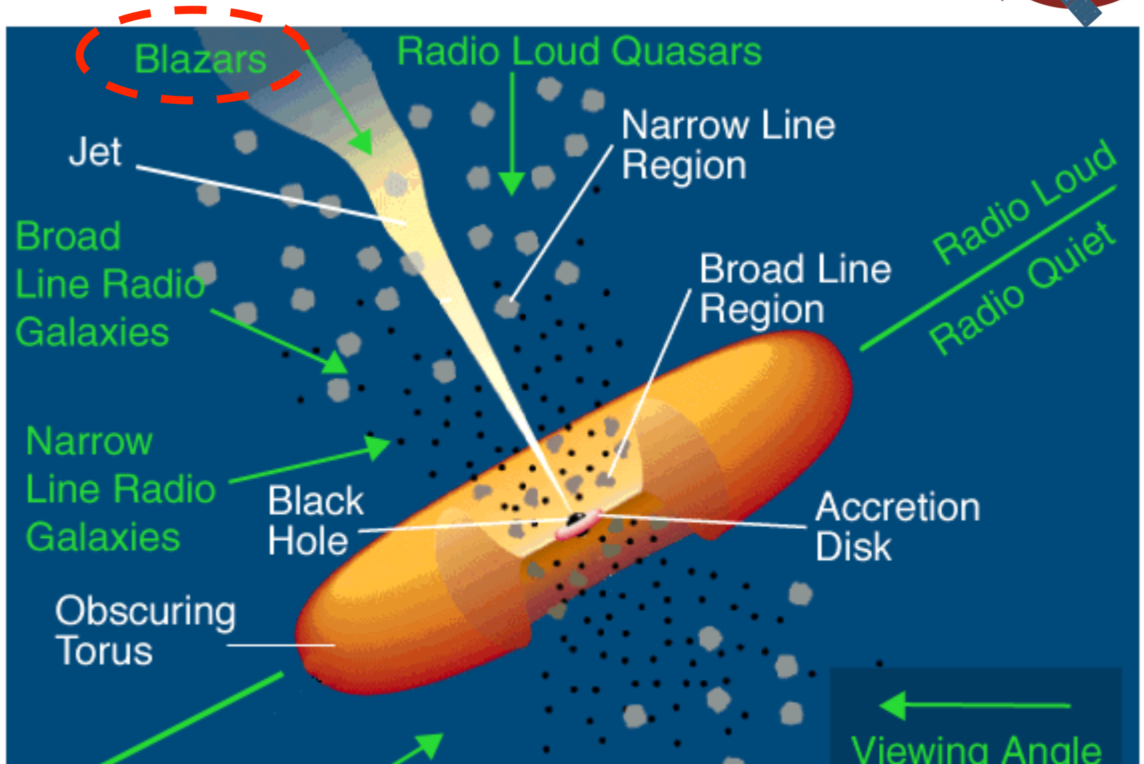
Broad-Line Region (BLR): 0.01-0.1 pc

Narrow-Line Region (NLR): 100-1000 pc

Tore: 100 pc

Galaxy diameter: 100 kpc

Radio lobes: 1 Mpc



Caution! This unification scheme is incomplete.

no explanation for differences between:

- radio-loud and radio-quiet galaxies
- FRI and FRII

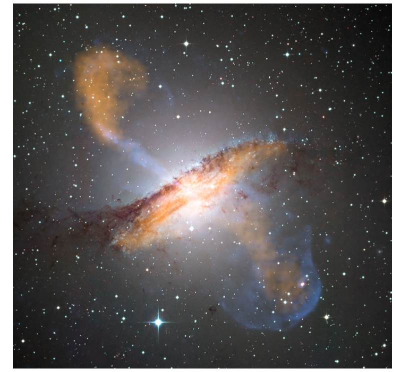
LAT-detected Radio Galaxies

For these sources, the jet is not directed toward us:

greater angle ⇒ less Doppler boosting

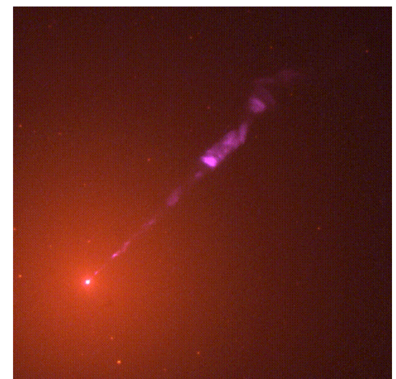
⇒ only nearby sources can be detected

These close sources can be resolved via radio interferometry (VLBI) deep down the jet, very close to the black hole.

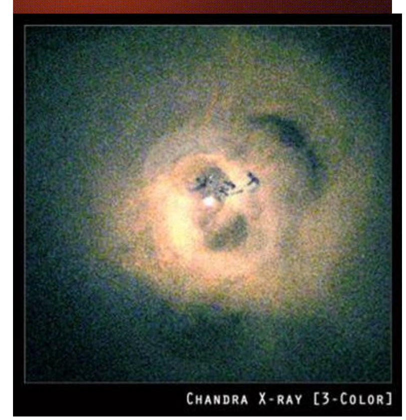


Fermi: 7 FRI radio galaxies and 4 FRII radio sources
TeV instruments 3: FRI

- Centaurus A
  - nearest radio galaxy, FRI, D=3.7 Mpc, detected by EGRET, HESS, Fermi



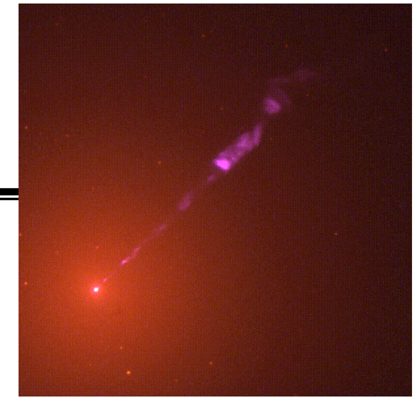
- M 87
  - giant radio galaxy, FRI, D=16Mpc
  - detected by HESS, VERITAS, MAGIC



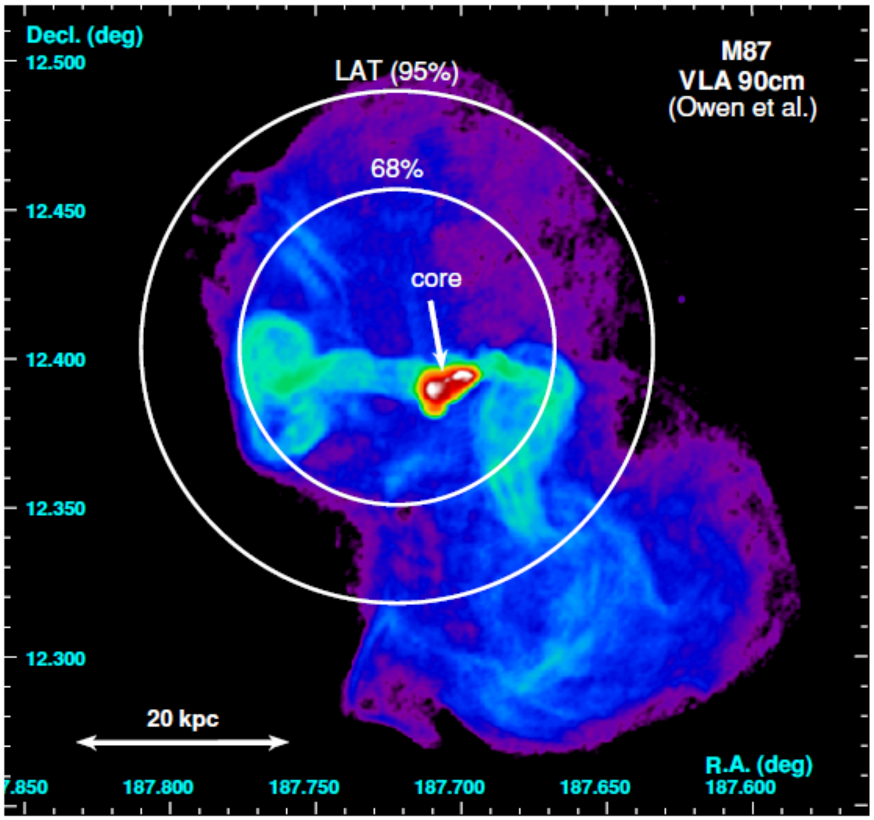
- NGC 1275
  - “cooling core” cluster
  - detected by COS-B, not by EGRET
  - now detected by Fermi, MAGIC

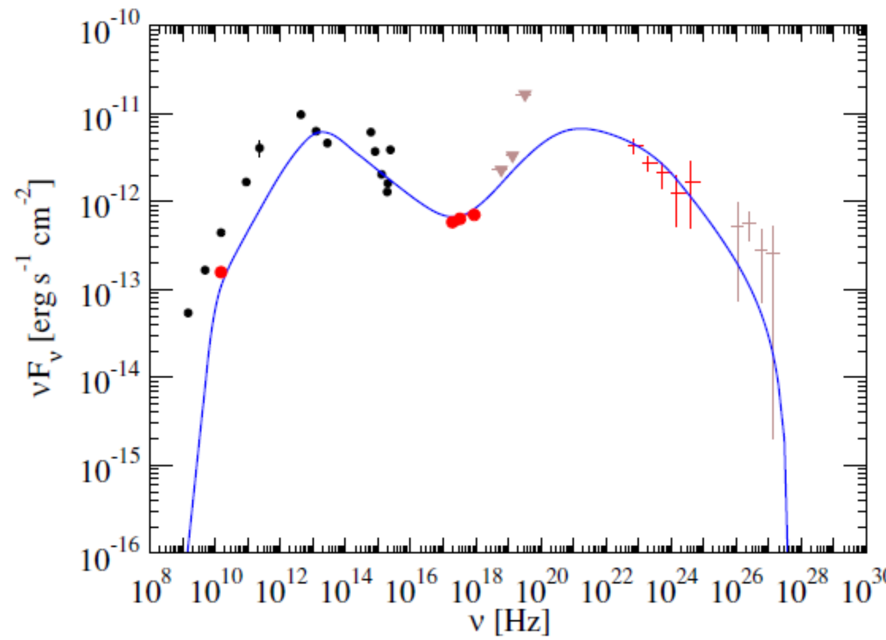
M87

giant radio galaxy, FRI, D=16Mpc
detected by HESS, VERITAS, MAGIC



Abdo et al. 09





M87 has displayed 1-day flare, challenging most models.

SSC parameters

s_1 =1.6, s_2 = 3.6

γ_{min} = 1, γ_{max} = 10^7, γ_b= 4 × 10^3

R = 1.4×10^{16} cm

δ= 3.9 (Γ=2.3, θ=10°)

B = 0.055 G

P_{jet}~10^{44} erg/s

Radio Galaxy: Centaurus A

nearest radio galaxy, FRI, D=3.7 Mpc,

detected by EGRET, HESS, Fermi

Table 2. Model Parameters.

Parameter	Symbol	Green[1]	Blue[2]	Violet[3]	Brown[4]
Bulk Lorentz Factor	Γ_j	7.0	$5 \to 2$	3.7	2.0
Doppler Factor	δ_D	1.0	$1.79 \to 1.08$	3.9	3.1
Jet Angle	θ	30°	25°	15°	15°
Magnetic Field [G]	B	6.2	0.45	0.2	0.02
Variability Timescale [sec]	t_v	1.0×10^5		1×10^5	1×10^5
Comoving blob size scale [cm]	R_b	3.0×10^{15}	3×10^{15}	1.1×10^{16}	9.2×10^{15}
Low-Energy Electron Spectral Index	p_1	1.8	3.2	1.8	1.8
High-Energy Electron Spectral Index	p_2	4.3		4.0	3.5
Minimum Electron Lorentz Factor	γ_{min}	3×10^2	1.3×10^3	8×10^2	8×10^2
Maximum Electron Lorentz Factor	γ_{max}	1×10^8	1×10^7	1×10^8	1×10^8
Break Electron Lorentz Factor	γ_{brk}	8×10^2		2×10^3	4×10^5
Jet Power in Magnetic Field [erg s^{-1}]	$P_{j,B}$	6.5×10^{43}	1.7×10^{41}	2.7×10^{41}	4.3×10^{38}
Jet Power in Electrons [erg s^{-1}]	$P_{j,e}$	3.1×10^{43}	3.1×10^{42}	2.3×10^{42}	7.0×10^{40}

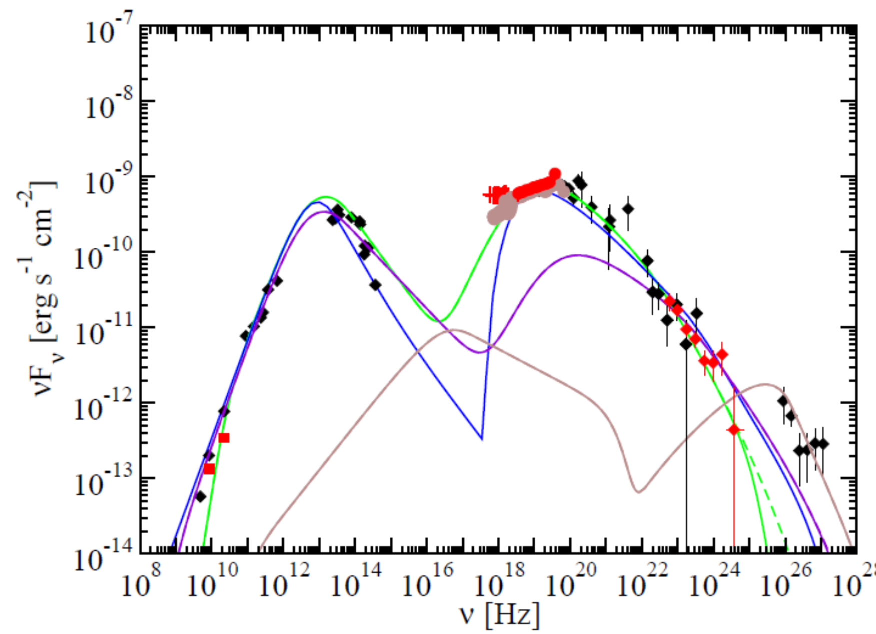
[1]SSC Model

[2]Decelerating Jet Model (Georganopoulos & Kazanas 2003)

[3]SSC Model excluding X-rays

[4]SSC Fit to HESS data only

Abdo et al. 09



Giant radio lobes of Cen A

Spans 10° in the sky, can be imaged with the Fermi-LAT

Inverse-Compton emission on Cosmic MicroWave Background or Extragalactic Background Light (IR/optical/UV)

Requires 0.1-10 TeV electrons in giant 'relic' lobes: accelerated in situ or efficient transport from center

Estimated Etot=10^{58} erg,
jet power~10^{43} erg/s,
Non-thermal/thermal plasma pressures comparable

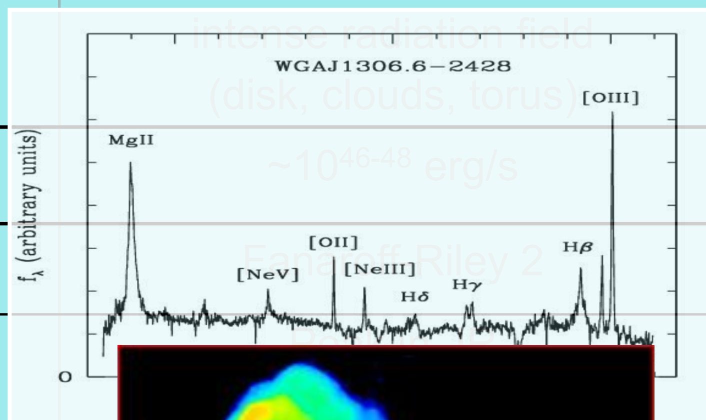
Implication for emission region/mechanism in LAT Radio galaxies?

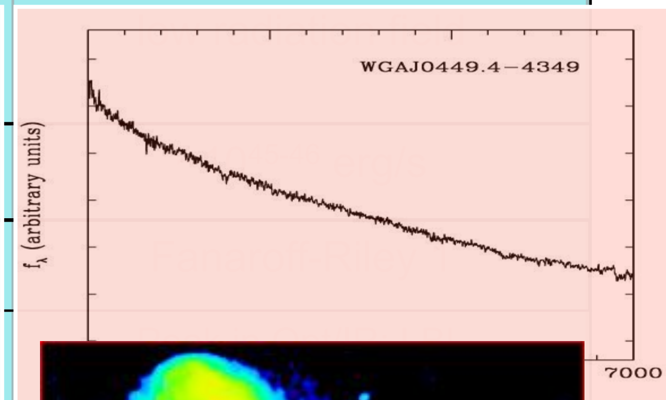
Abdo et al. Science 11

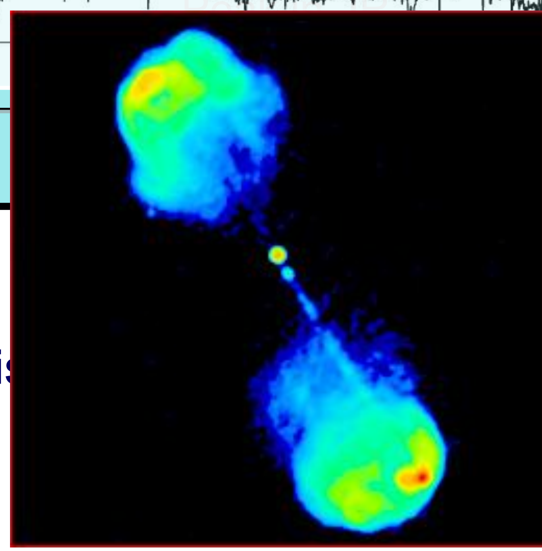
Blazar classes

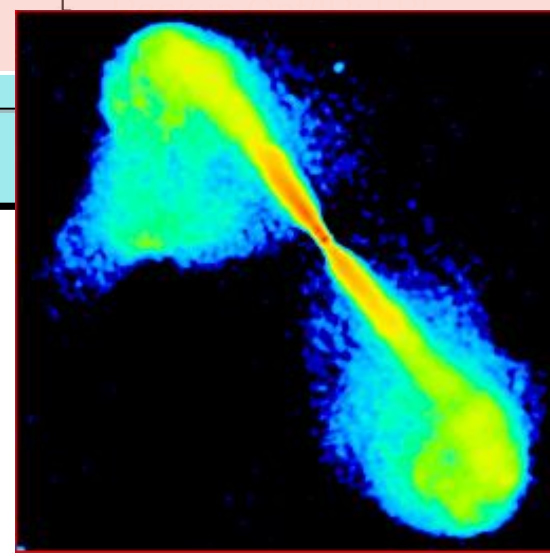
FSRQ: Flat Spectrum Radio Quasar
BL Lac: named after prototype BL Lacertae

class	FSRQs	BLLacs
Defining property	strong emission lines	nearly lineless
Environment	intense radiation field (disk, clouds, torus)	low radiation field
Power	~10^{46-48} erg/s	~10^{45-46} erg/s
Parent population	Fanaroff-Riley 2	Fanaroff-Riley 1
Synchrotron hump in SED		
Redshift		









BL Lacs redshifts are
Many redshifts are mi

Fermi Spring School 2011

Benoit Lott

Blazar Spectral Energy Distributions (SEDs)

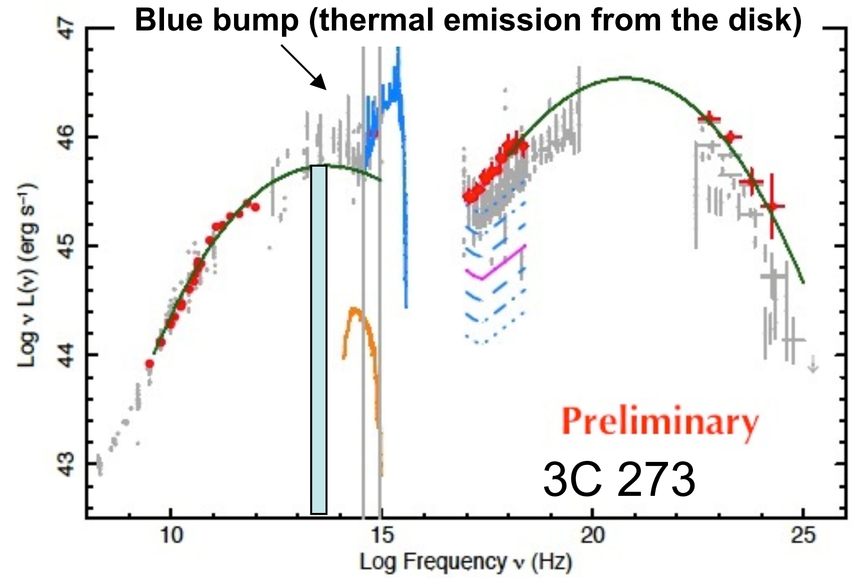
"two-hump" SEDs in $\nu F\nu$

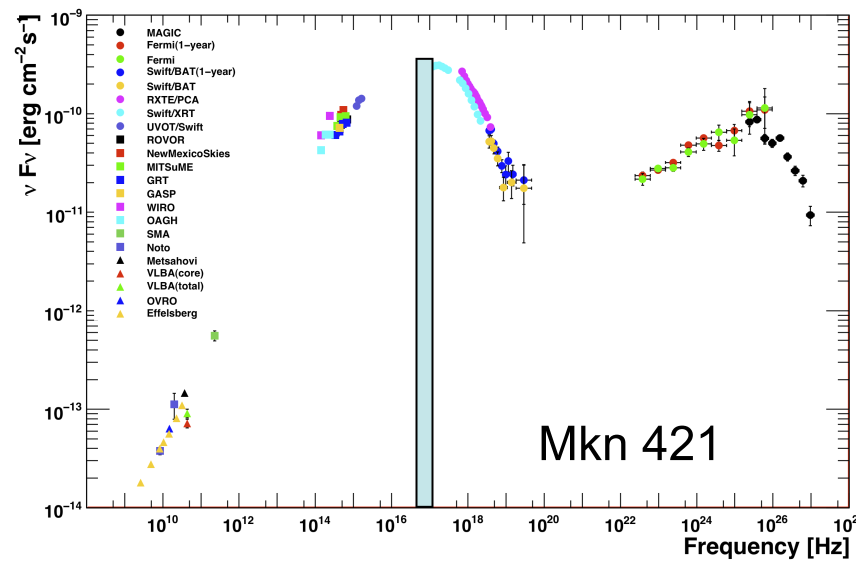
Low-energy peak: *Synchrotron*

- low-spectrum peaked (LSP/LBL) IR-optical ($\nu_{syn}<10^{14}$Hz)
- intermediate-spectrum peaked (ISP-IBL) : UV ($10^{14}<\nu_{syn}<10^{15}$Hz)
- High-spectrum peaked (HSP-HBL) : X-rays ($\nu_{syn}>10^{15}$Hz)

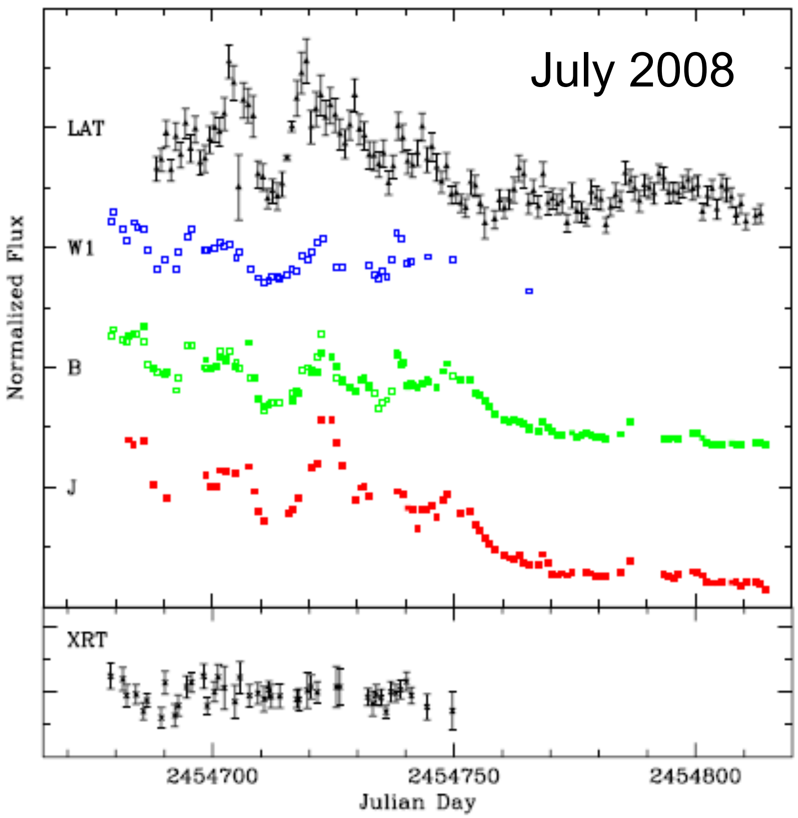
High-energy peak:

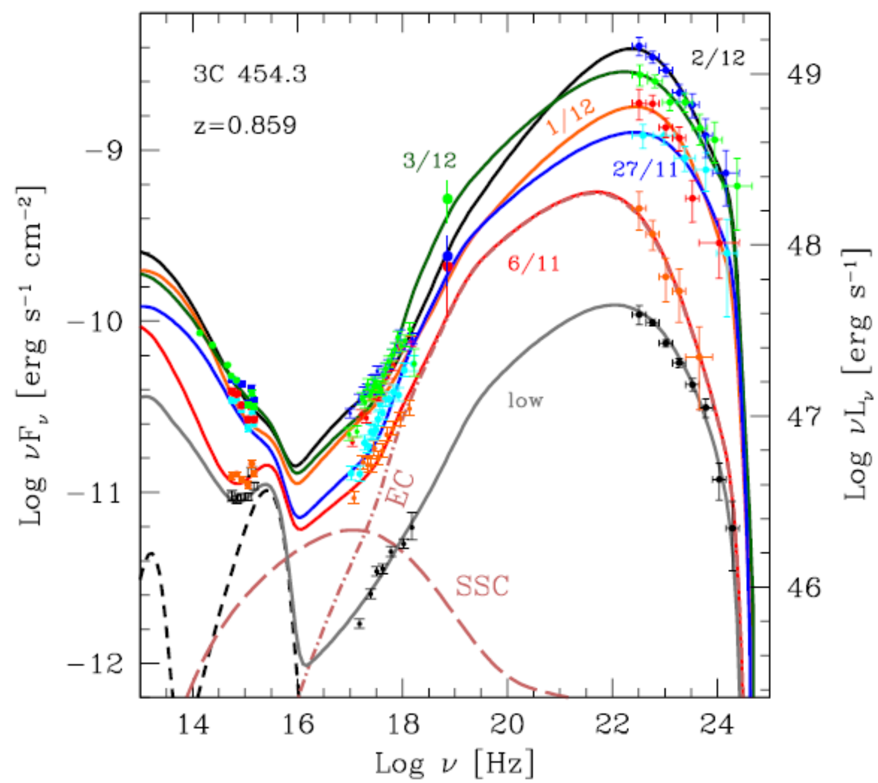
- leptonic models: *Inverse Compton* upscattering of seed photons
  - **synchrotron: "*Synchrotron Self Compton*"**
  - **External to the jet: *"External Compton"***
- Hadronic models: *photoproduction, synchrotron*…





Connecting the two humps: correlated variability





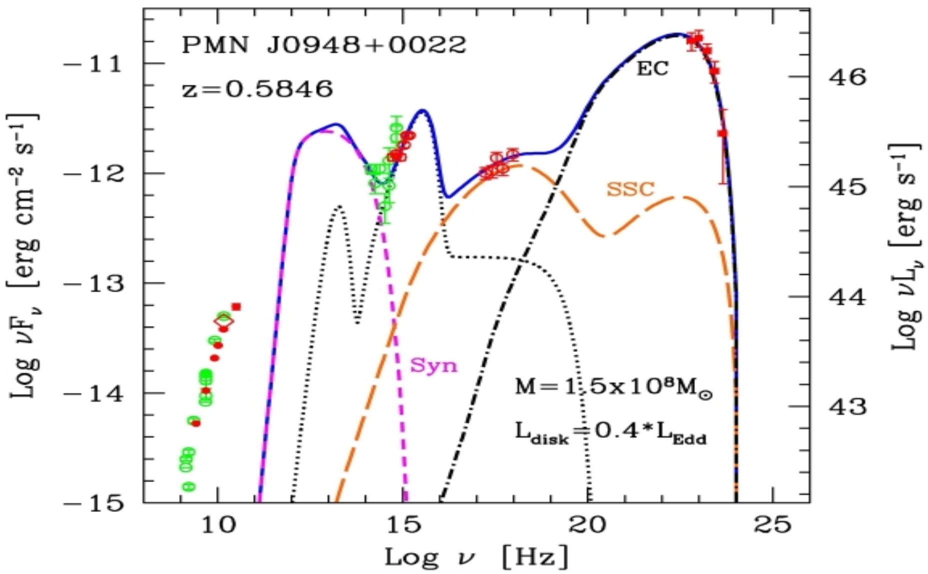
Ex: FSRQ   3C 454.3

Radio (non-blazar) Galaxies

Other class?

- **PMN J0948+0022, Narrow-line, radio loud Sy1** ***(contact: L. Foschini)***
  - **SED similar to FSRQ, less powerful**
  - **Radio emission is strongly variable and with flat spectrum, suggests Doppler boosting, now confirmed by LAT**
  - **More similar sources detected**

Abdo, A. A. et al. 2009, ApJ, 699, 976



Blazar/AGN populations at GeV energies (Fermi-LAT, AGILE)

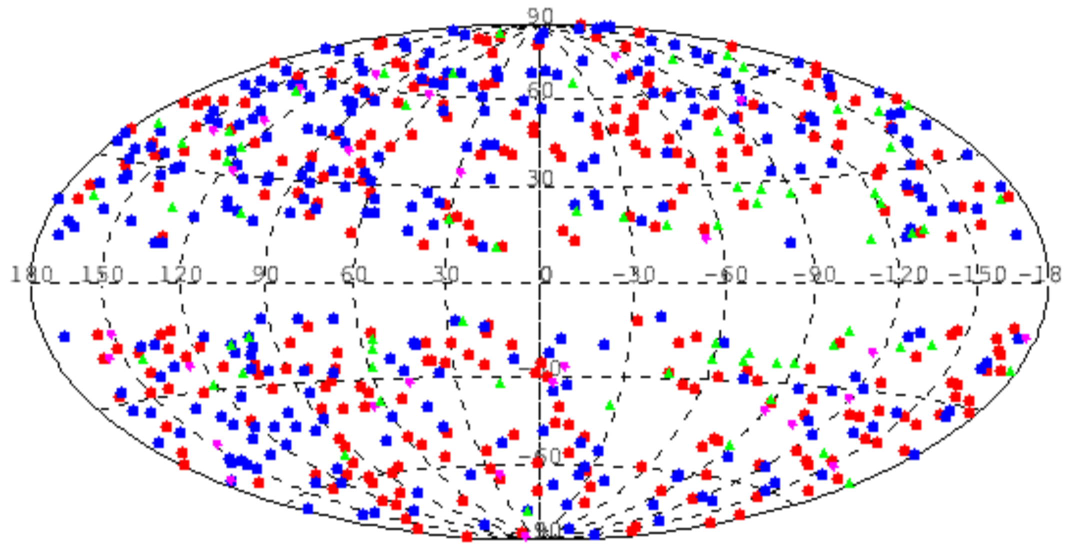
Benoit Lott

The First LAT AGN catalog (1LAC)

- 11 month data set

- 1079 TS>25, |b|>10° sources
- 1LAC: 709 sources
- 663 high-confidence (P_{assoc}>80%) AGNs

- Census:
  - **281 FSRQs**
  - **291 BLLacs (~141 with measured z)**
  - **50 of unknown type**
  - **~10 Radio galaxies**



EGRET (high confidence): ~70 blazars, 25% BLLacs

Differences between Northern Hemisphere and Southern one

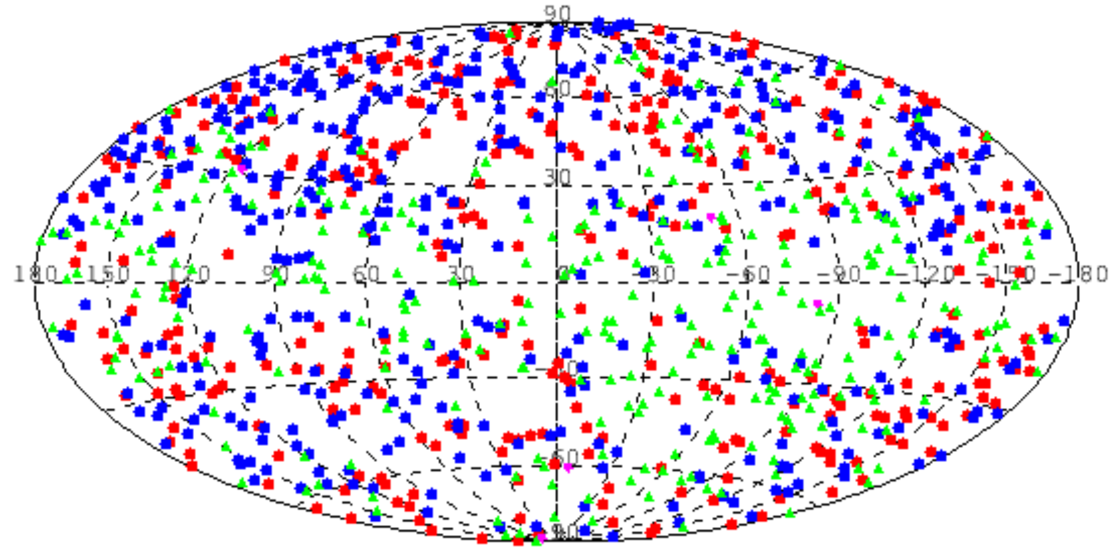
FSRQs: 4%, BLLACs: 18 %

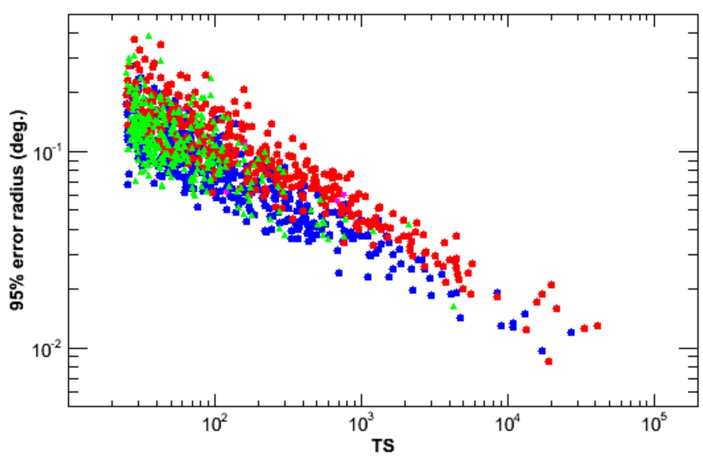
The First Catalog of Active Galactic Nuclei Detected by the Fermi LAT

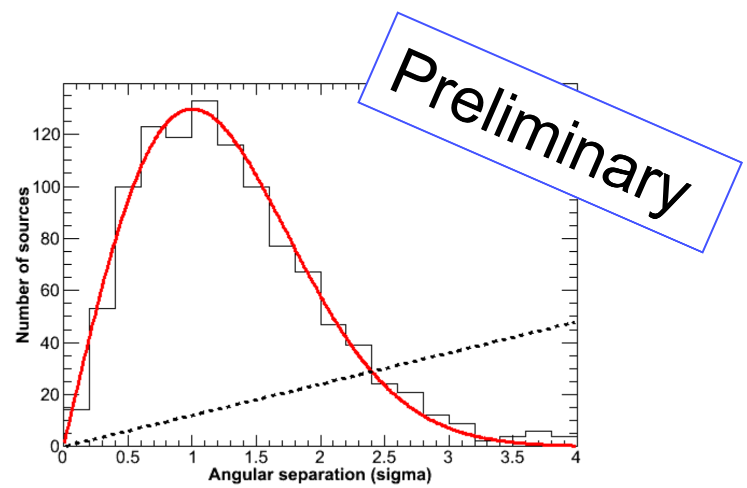
Abdo, A. A. et al. 2010

The Second LAT AGN catalog (2LAC)

- 24 month data set
- 1749 TS>25, |b|>10° sources
- 2LAC:
- ~1000 associated (P_{assoc}>80%) AGNs
- Census :
  - 360 FSRQs
  - 420 BLLacs (~60% with measured z)
  - ~200 of unknown type
  - ~20 other AGNs







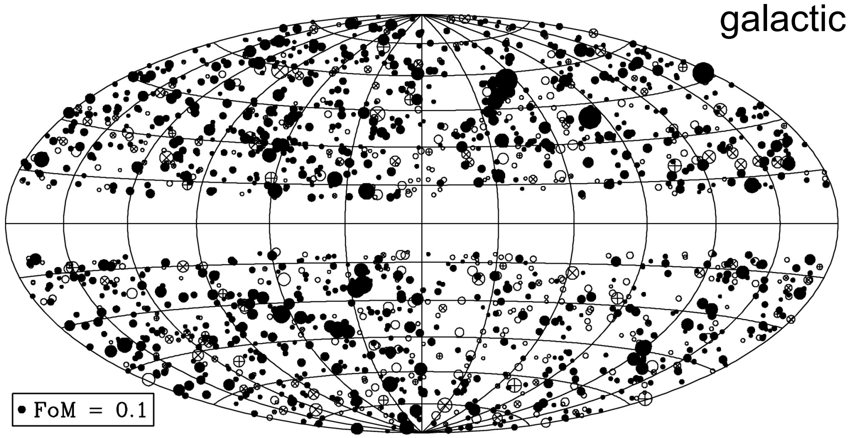
Associations

1FGL: **1049 sources with TS>25, |b|>10°**

CGRaBS (Healey et al. 08)

1627 radio sources from CRATES association based on Figure-of-Merit (spatial, radio and X spectrum) established from EGRET

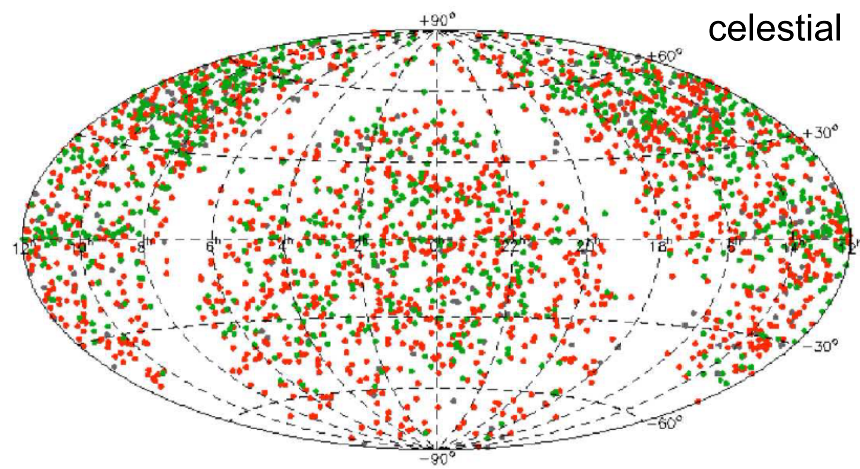
galactic



BZCat (Massaro et al. 08)

Compilation of 2500 known blazars association based on spatial coincidence (Mattox et al., 01)

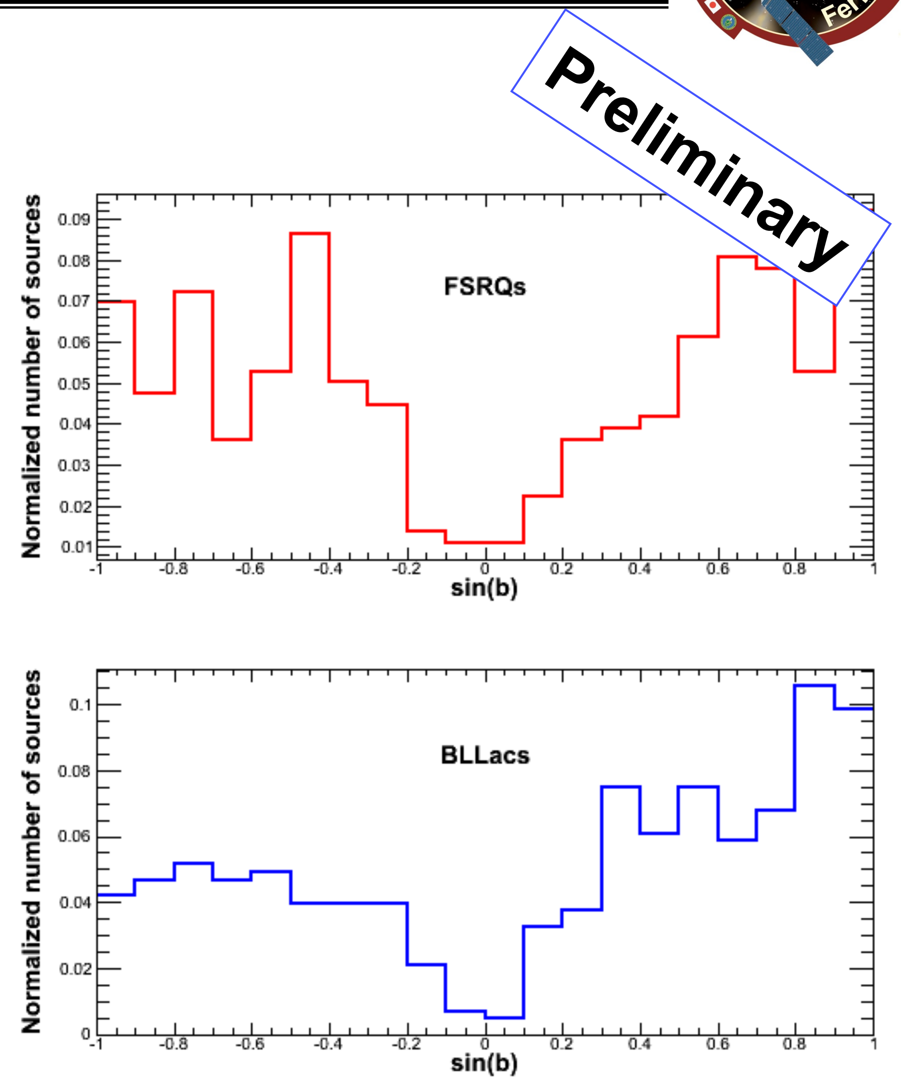
celestial



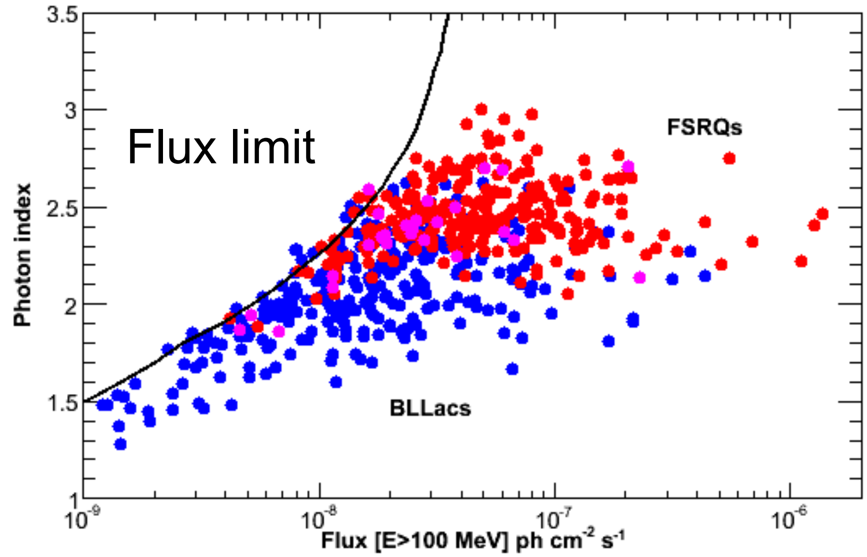
Incompleteness/Anisotropy

- BLLacs have hard spectra making them easier to detect

- Many BLLacs remain unassociated due to the incompleteness of counterpart catalogs in the Southern Hemisphere
  b>10°: ~260   b<10°: ~160



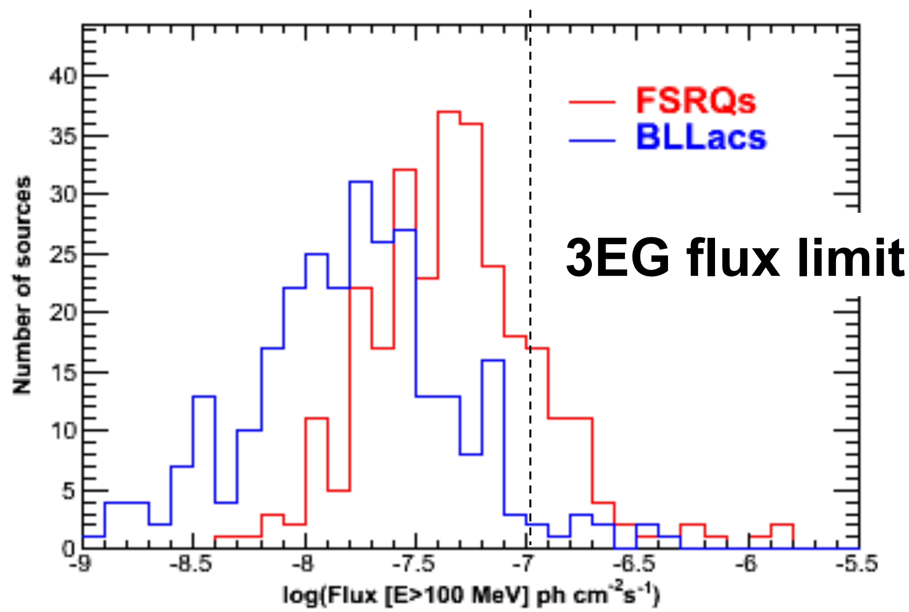
Photon index – Flux distributions



hard sources (small photon index) easier to detect

BLLAcs harder than FSRQs

Large significance but few detected photons…



Mean/Peak Flux distributions

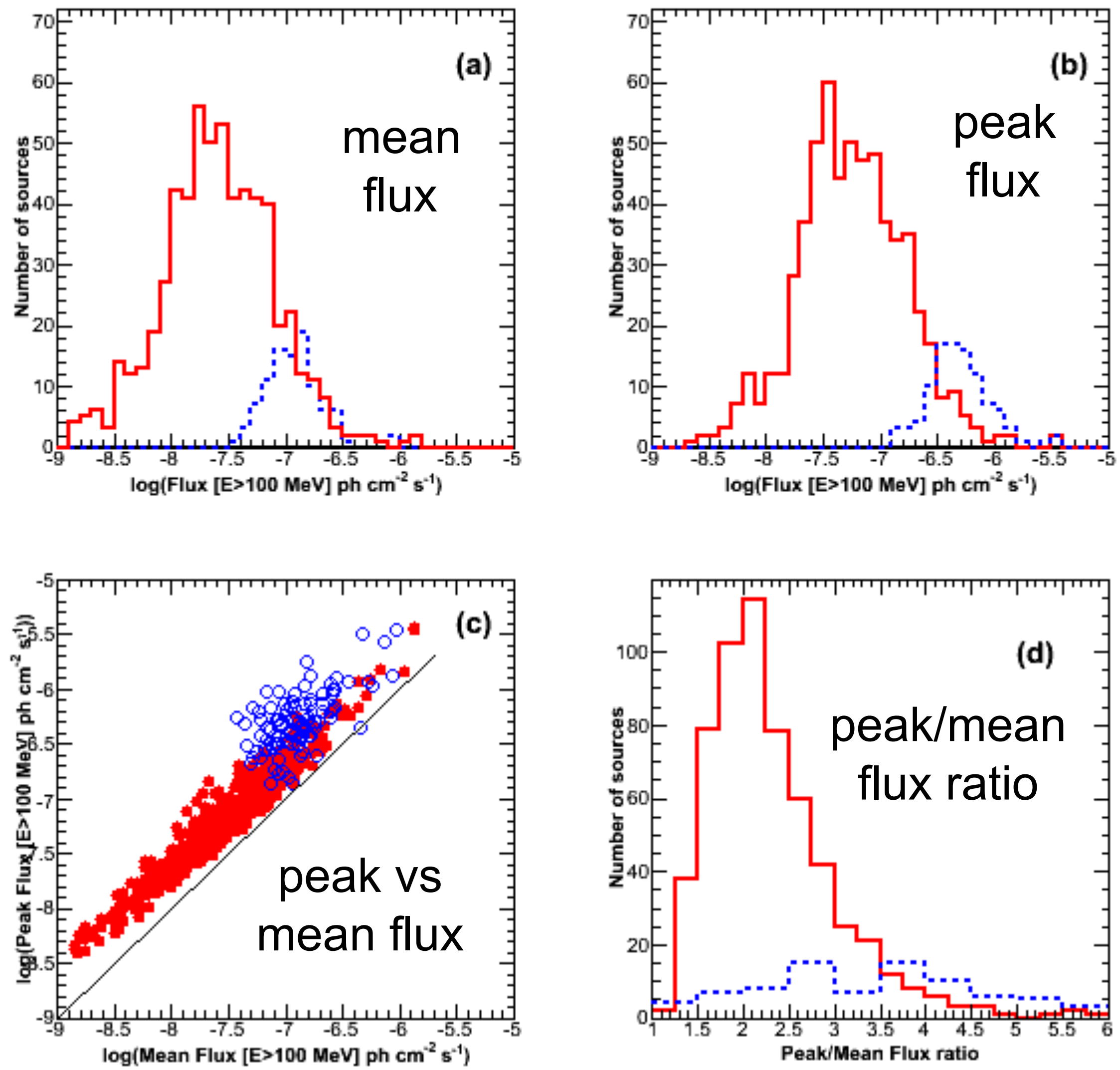
Fermi
EGRET

EGRET mean flux
« 1234 VP»

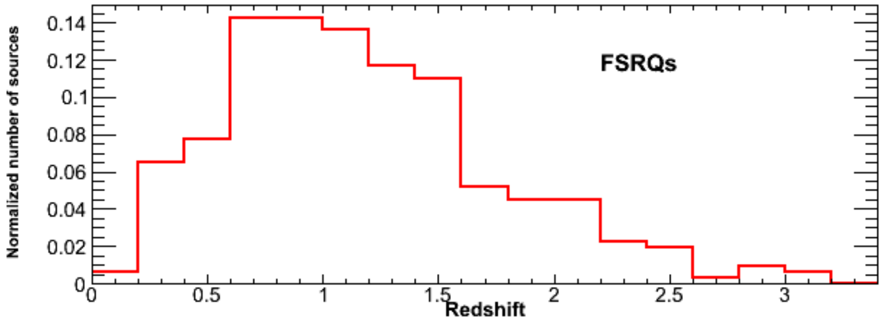
EGRET peak flux:
maximum in 2-w VPs

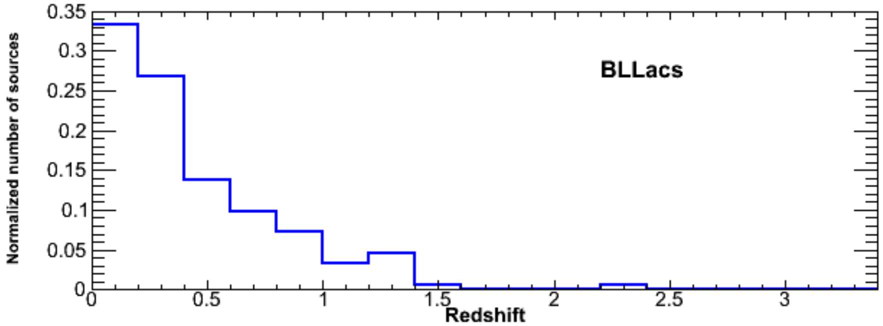
Fermi mean flux:
11-m averaged

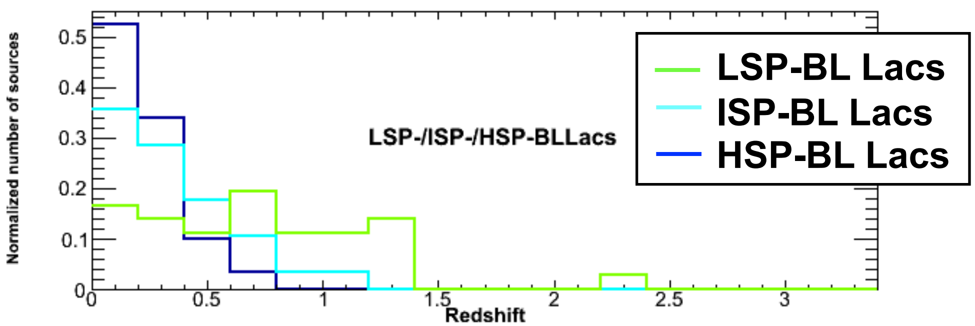
Fermi peak flux:
maximum in 1-m periods



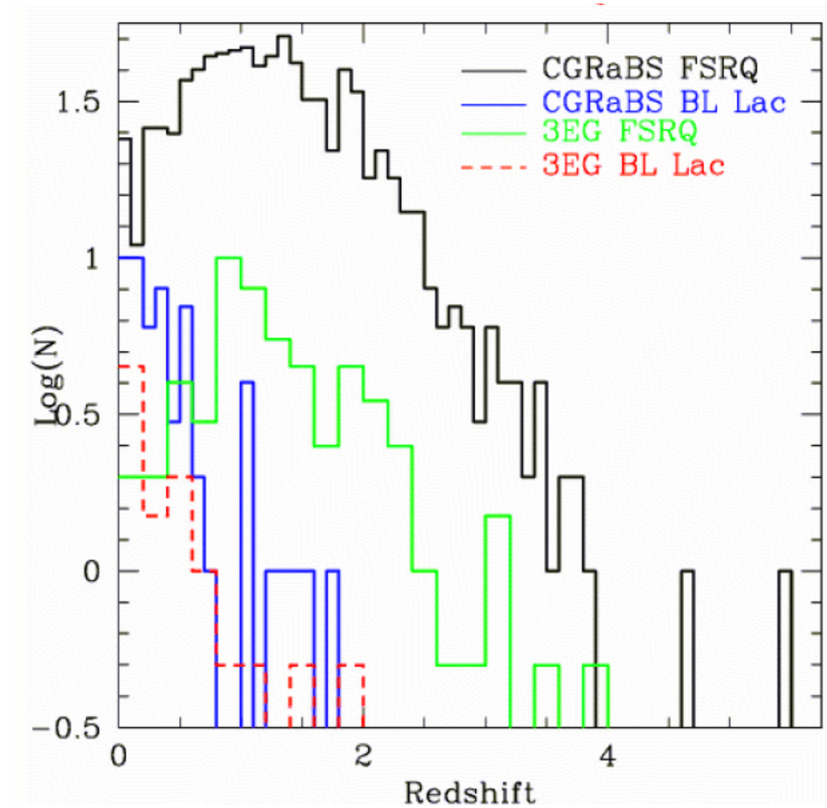
Redshift distributions







z_{max} for FSRQs: 3.1
(BAT: 40% of FSRQs are at z>2)



Redshift versus luminosity

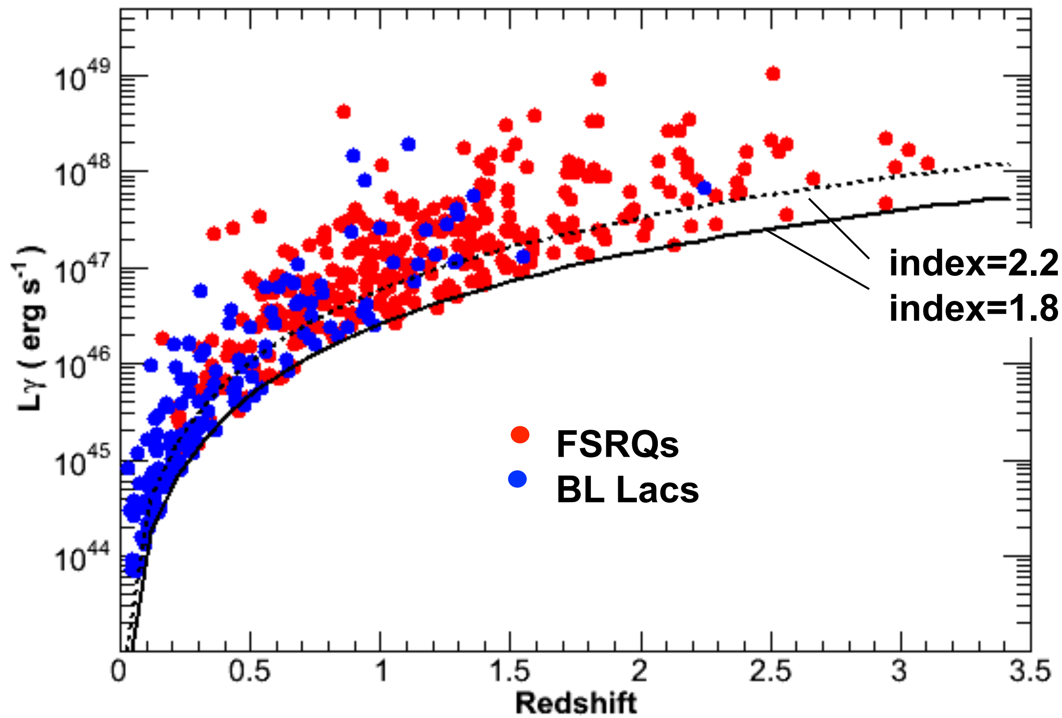
$$L_\gamma = 4\pi d_L^2 \frac{S(E_1,E_2)}{(1+z)^{2-\Gamma}}$$

d_L: luminosity distance
$S(E_1,E_2)$: energy flux between E_1(100 MeV) and E_2 (100 GeV)

Only bright sources are visible at large distance
Malmquist bias

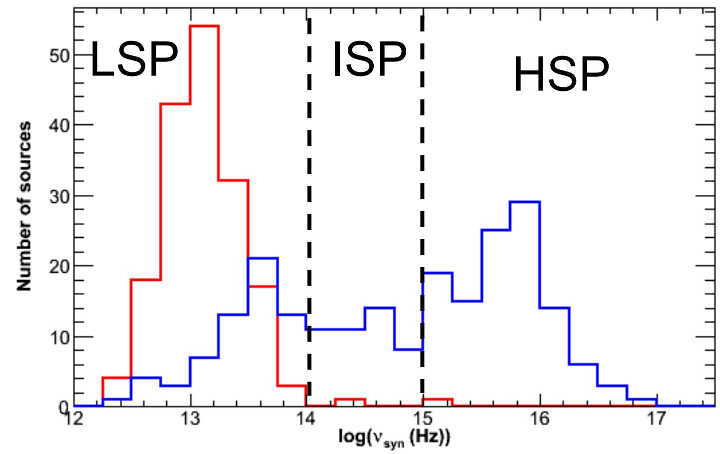
Distant HSPs at constant luminosity couldn't be detected

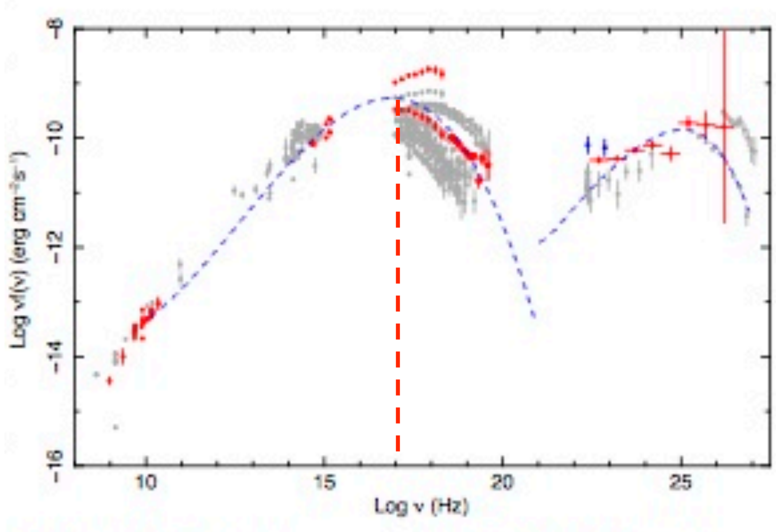
Cautionary note:
only half of the BLLacs have measured redshifts

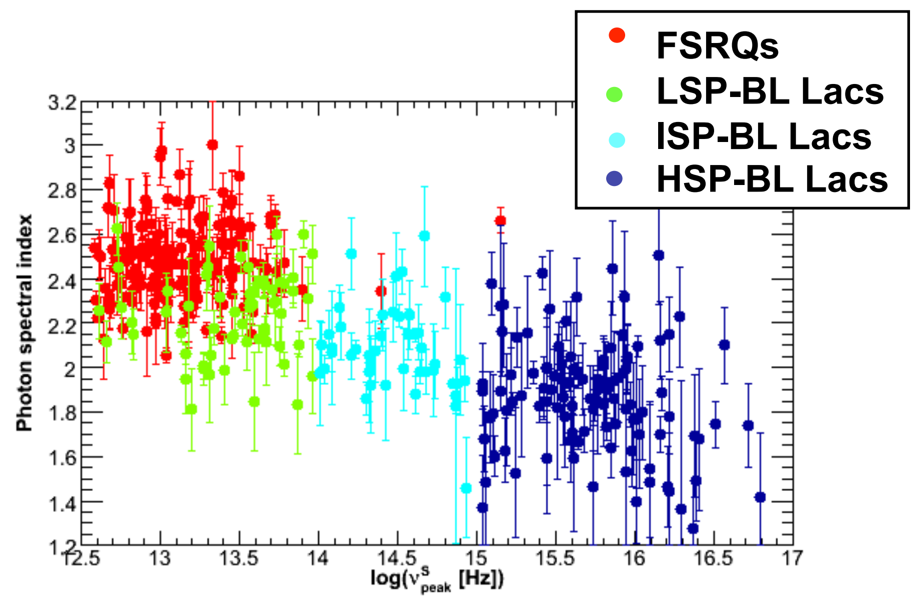


Synchrotron-peak locations

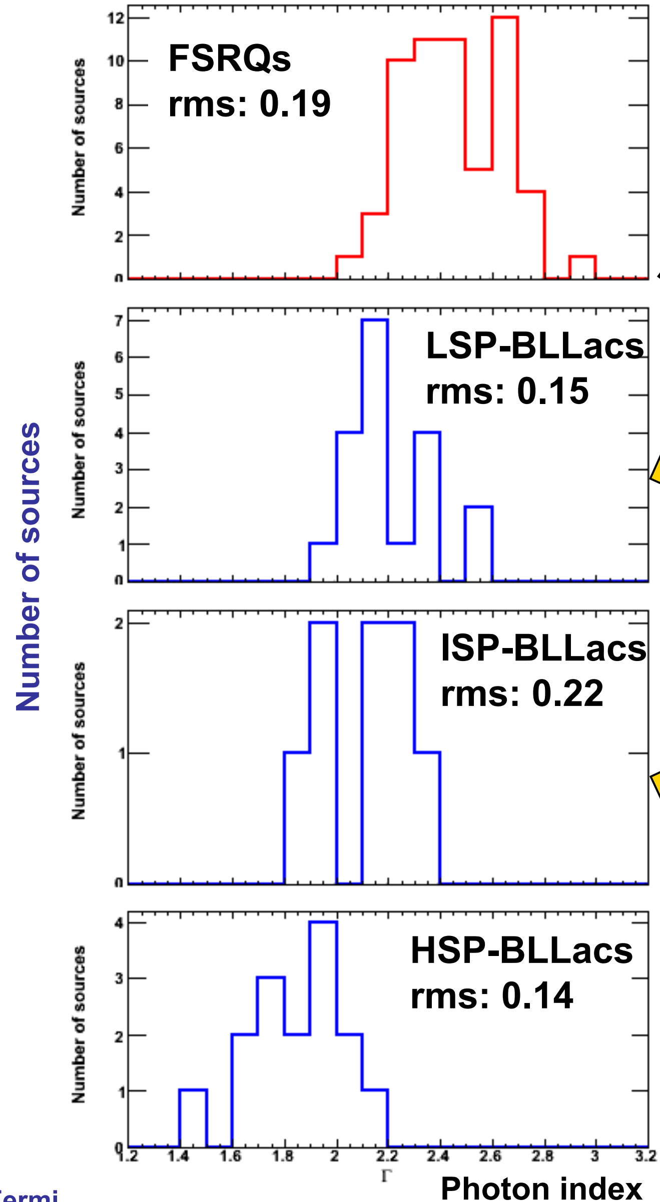
SED-based classification:
Determination of the position of the synchrotron peak
FSRQs are all low-frequency peaked and have soft gamma-ray spectra
BLLacs are more diverse



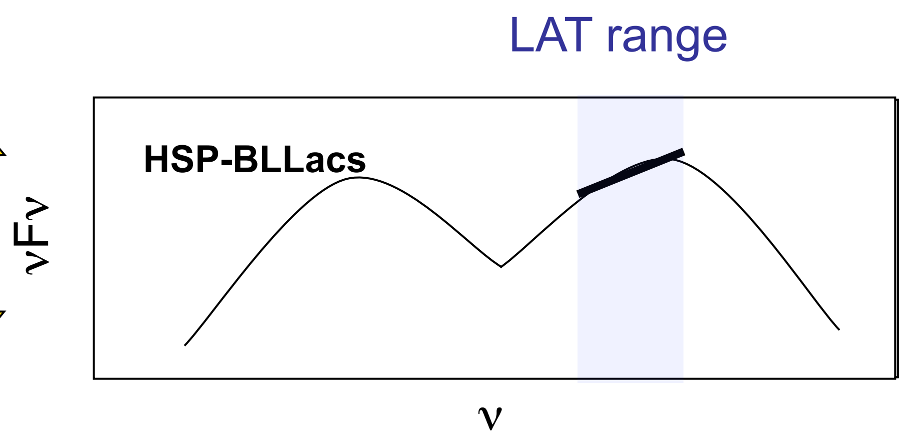




Photon index distributions in LBAS



Photon index determined with the first 6-month data set

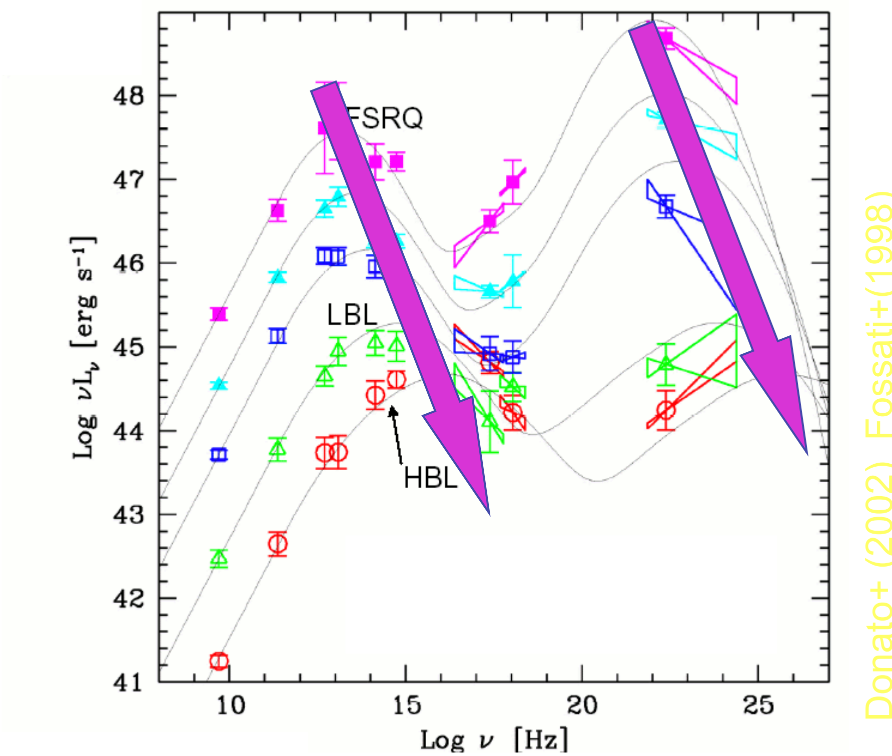


- Strong correlation between photon index and blazar class
- Narrow distributions point to a small numbers of parameters driving the blazar SEDs

Blazar Sequence: « Grand Unification » Between BLLacs and FSRQs?

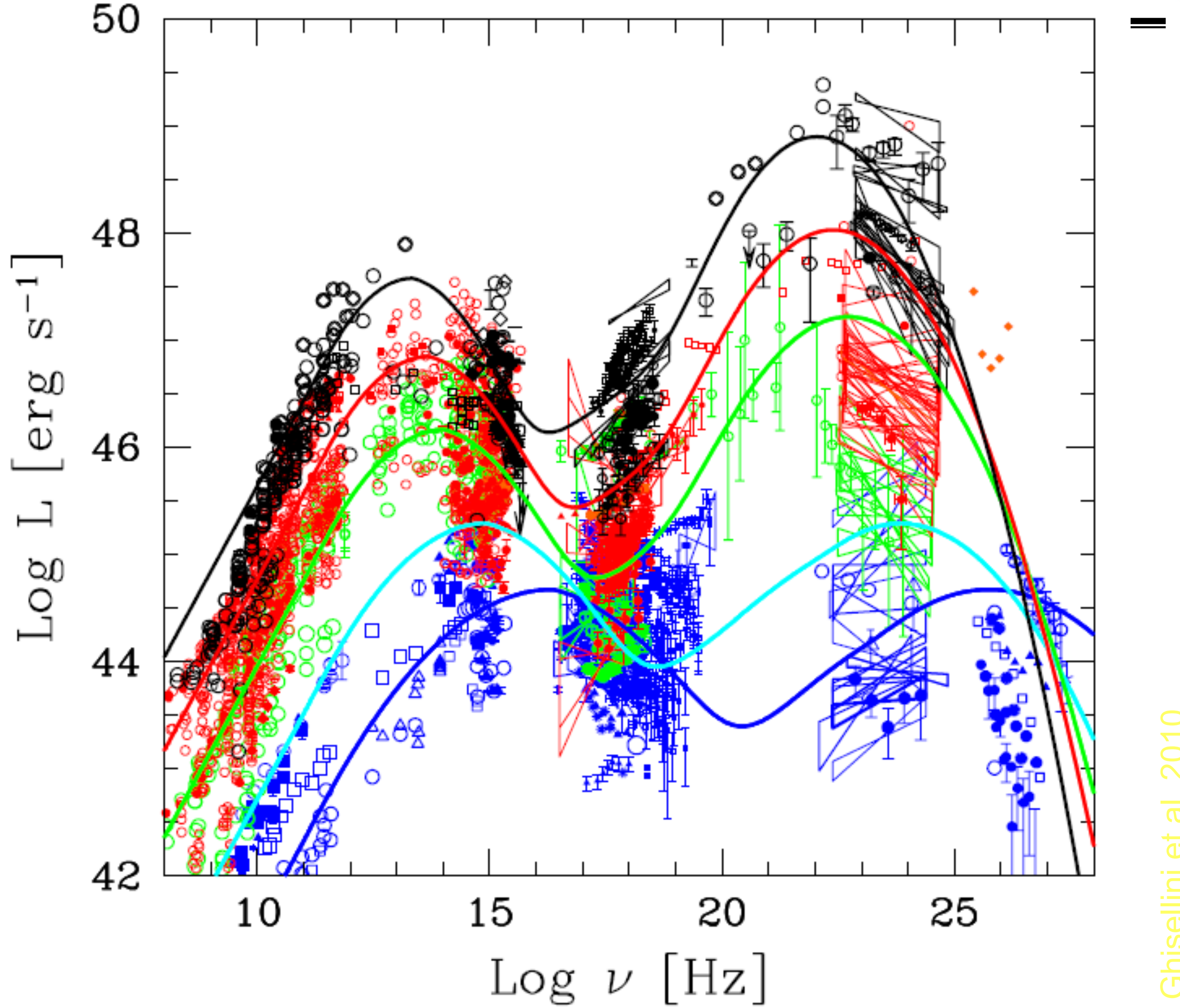
Average SEDs of blazars binned according to radio luminosity
126 blazars in total
28 with a spectral index measured by EGRET

- $\nu_{peak} \propto L^{-1}$
- $\nu_{HE} / \nu_{LE} = cst$
- $L_{HE} \propto L_{radio}$



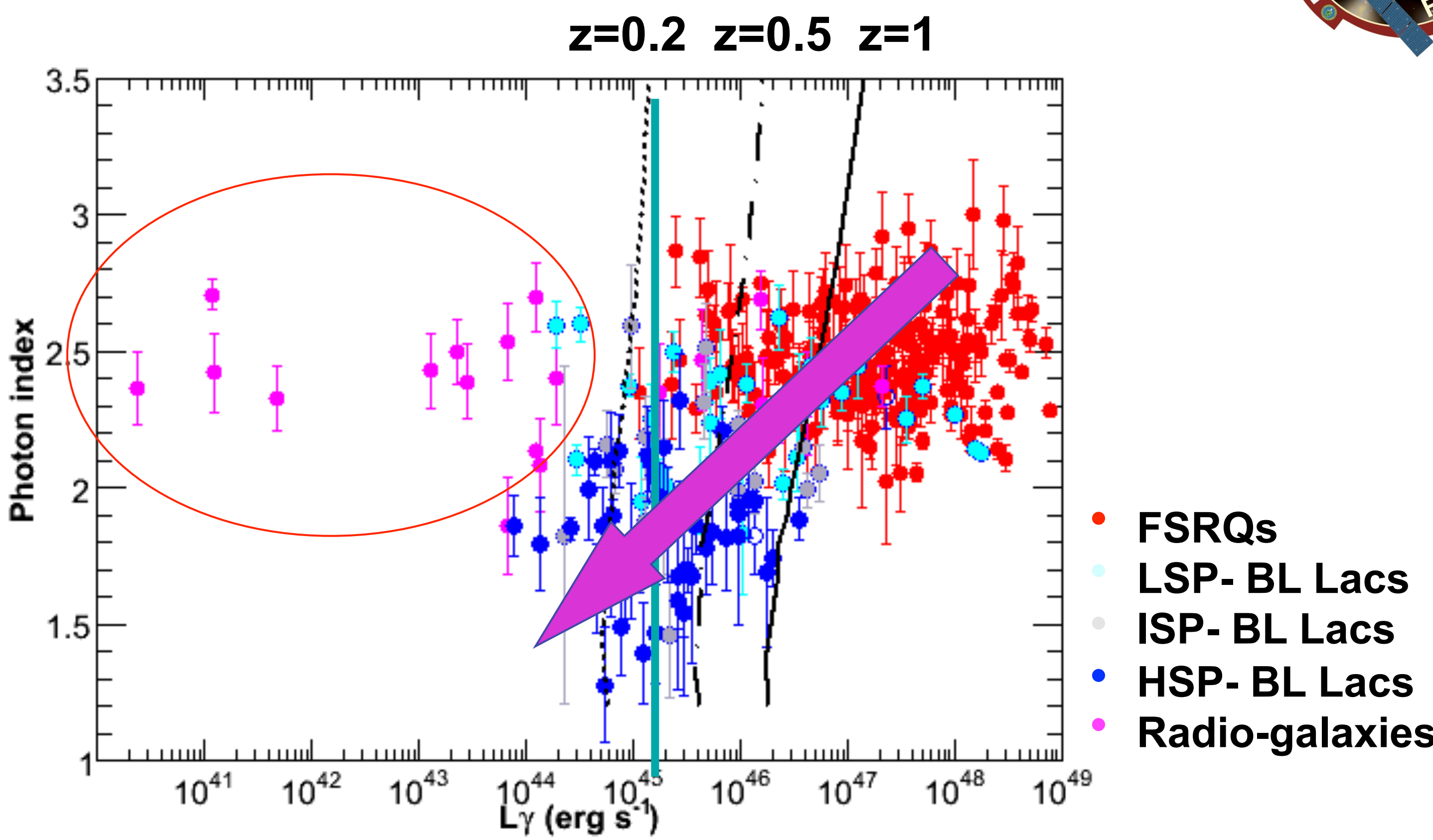
Implies a correlation between
- photon index in the Fermi band and position of the synchrotron peak
- luminosity and photon index in the Fermi band

Many severe selection biases!
Some outliers found
Many BLLacs without redshift



50
48
46
44
42
Log L [erg s^{-1}]
10
15
20
25
Log ν [Hz]
Ghisellini et al. 2010

Luminosity vs photon index



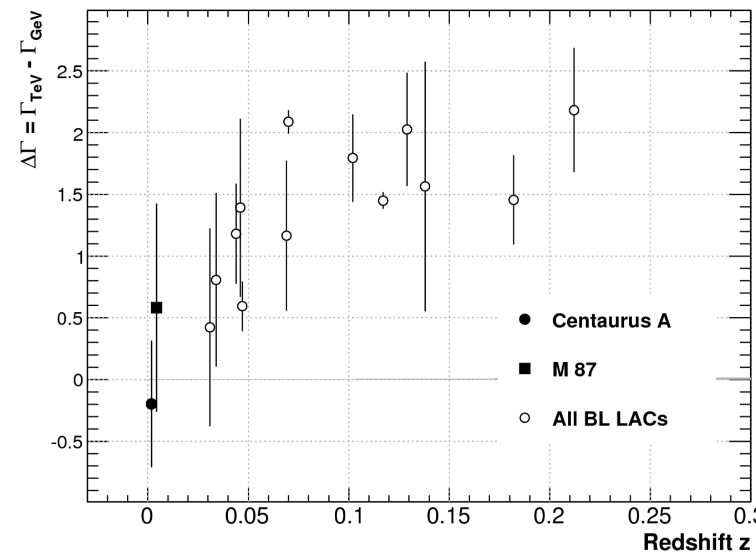
Reduced accretion rate? Difference in BH spin?

Beware that the correlation does not hold for FSRQs alone.

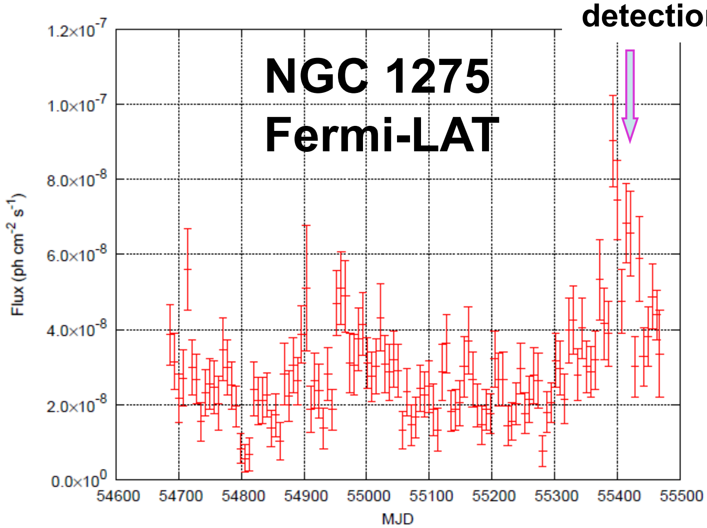
GeV/TeV connection

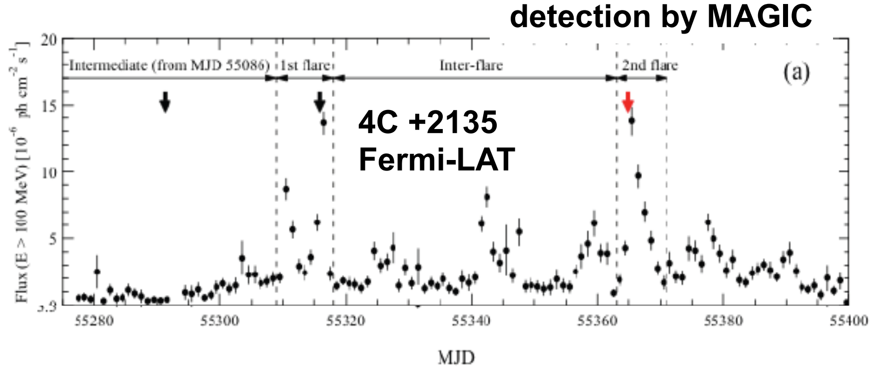
« GeV-TeV connection »

- 90% of TeV blazars detected with Fermi
  ~10 TeV sources detected with the help of Fermi
- long integration times are required in the GeV band (difference in sensitivity)
- very few TeV sources show significant sign of variability in the GeV band ⇒ difficult to measure short-term correlated variability between the two bands
- trend in Γ_{TeV}-Γ_{GeV} due to EBL attenuation?



Abdo et al. 2009





Benoit Lott

PKS2155-304 in quiescent state

SSC parameters

s_1 =1.3, s_2 = 3.2, s_3 = 4.3

γ_{min} = 1, γ_{max} = $10^{6.5}$

γ_{b1}= 1.4 × 10^4, γ_{b2} = 2.3 × 10^5

N_{tot} = 6.8 ×10^{51}

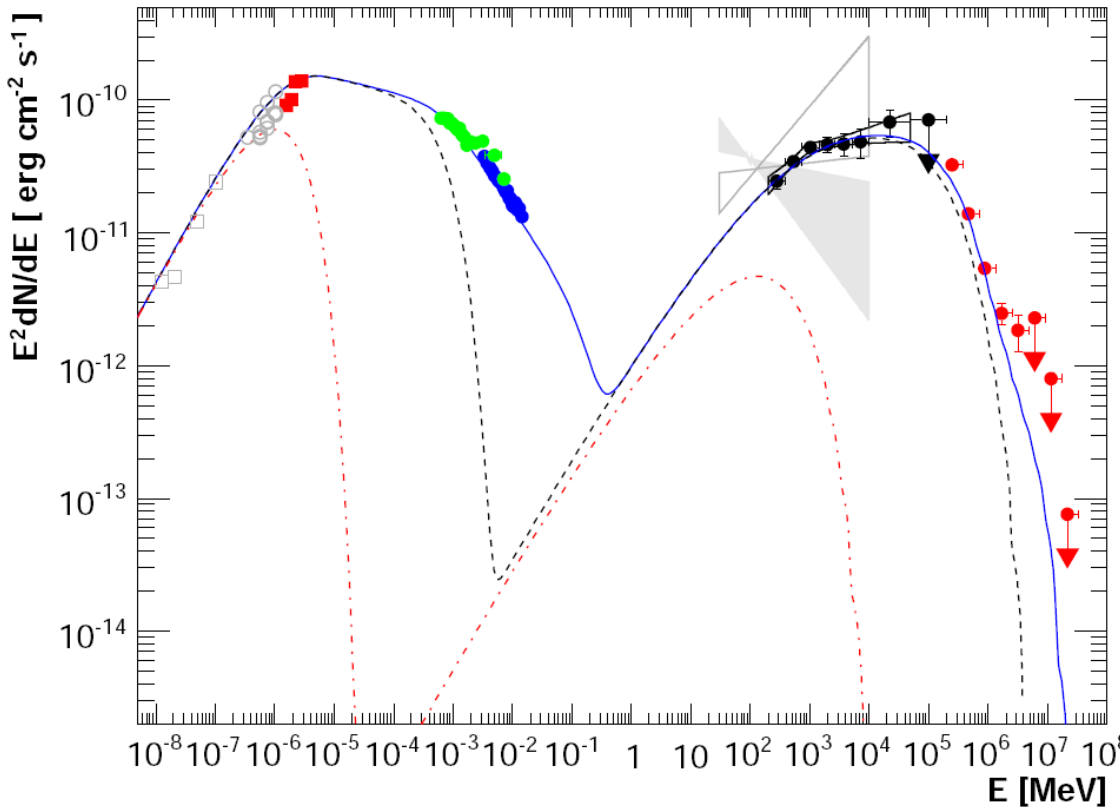
R = 1.5×10^{17} cm

δ= 32

B = 0.018 G

Important Klein-Nishina effects

Correlated variability more complex than that predicted by SSC



Aharonian, F. et al. 2009, ApJL, 696, L150

SEDs of TeV HBLs

SEDs are often well reproduced by SSC models

X-ray and TeV gamma-ray fluxes usually strongly correlate ⇒« one-zone »

Significant deviations of timing cross-correlations from those expected by SSC are failrly common though

Ex: MW campaign on Mrk501

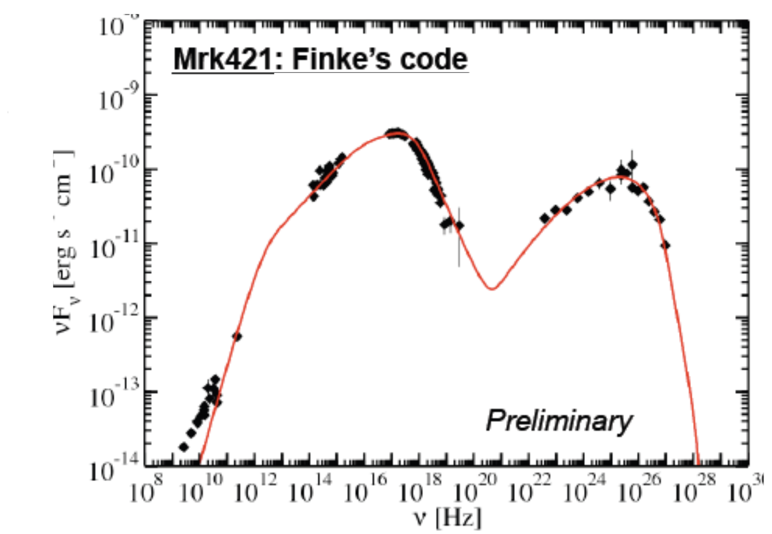
$s_1 = 2.2$, $s_2 = 2.7$, $s_3 = 3.5$

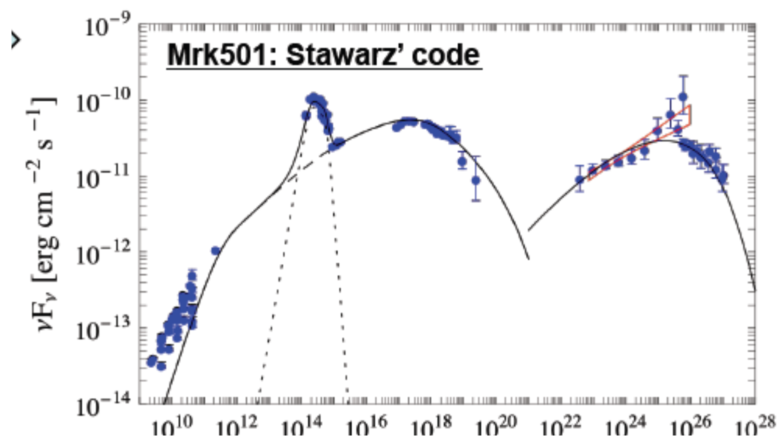
$B = 0.015$ G, $R = 1.3\times10^{17}$ cm

$\delta = 22$, $\eta_e = 130$, $\gamma_{min} = 300$, $\gamma_{b1} = 3\times10^4$

$\gamma_{b2} = 5\times10^5$, $\gamma_{max} = 3\times10^6$

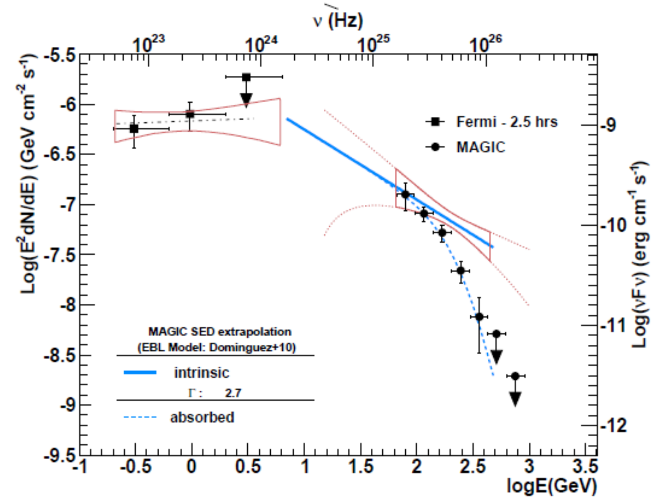
Abdo, A. A. et al. 2011, ApJ, 727

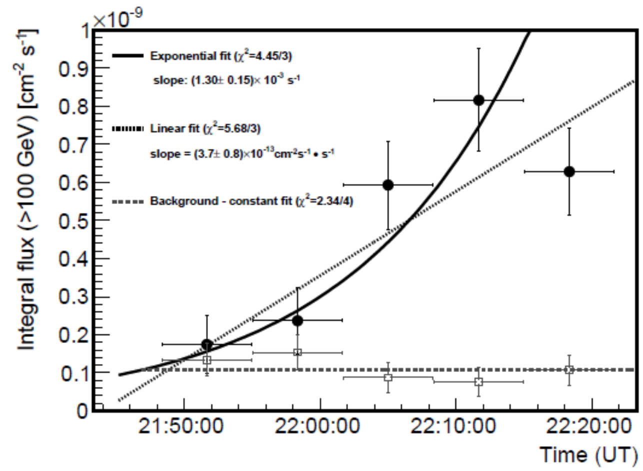




A TeV FSRQ: 4C +2135 (z=0.432)

- Two other FSRQS detected at TeV: 3C279 (z=0.549), PKS1510-08 (z=0.36)
- Detected by MAGIC
- Very hard in the Fermi-band
- 10 min variability in TeV
- Emission within BLR seems ruled out
- Hadronic component?

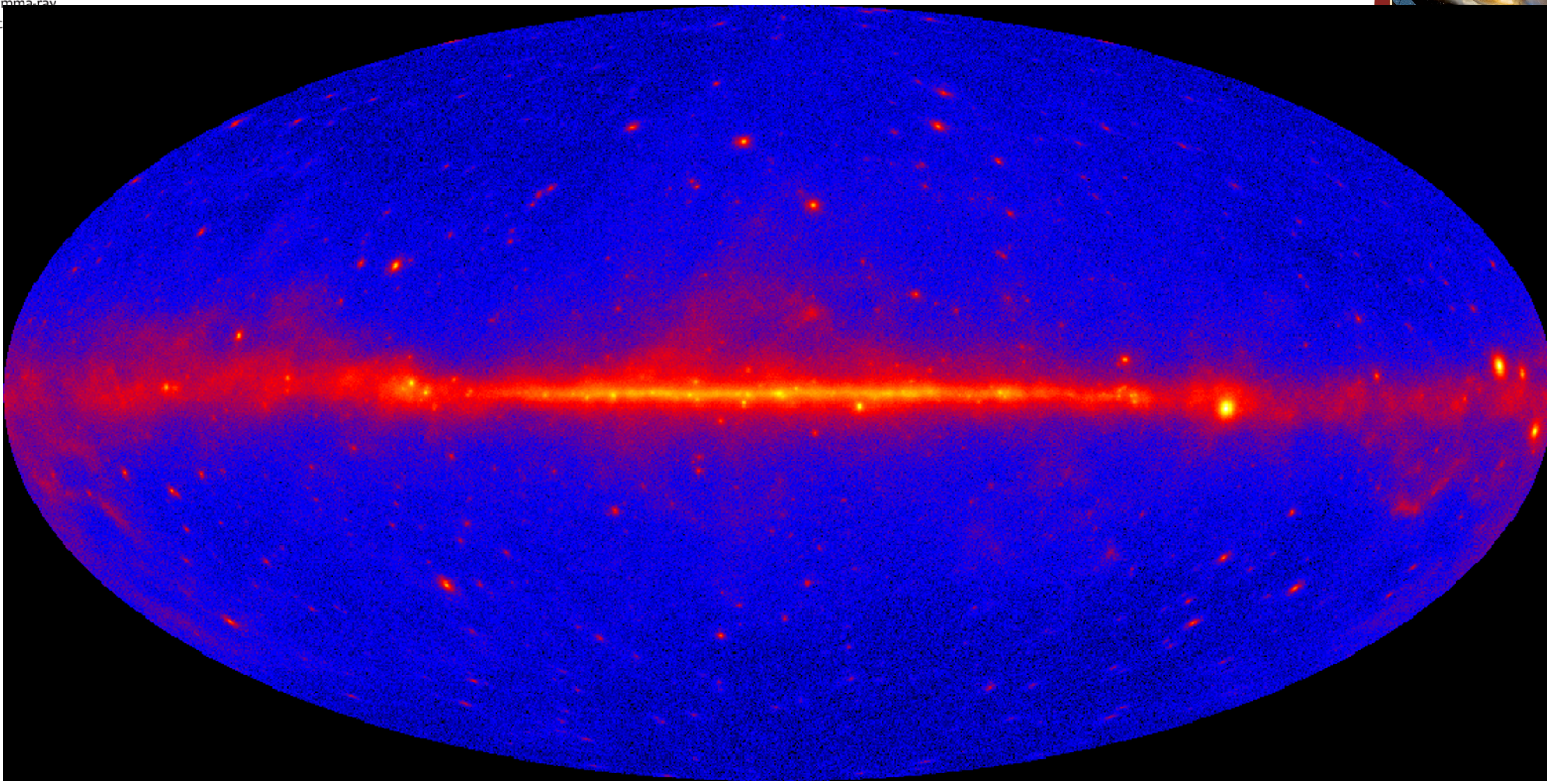




J. Aleksic et al., ApJL 2011, 730 L8

Log N-Log S
Contribution to
Extragalactic Diffuse Background

Extragalactic Diffuse Background



Diffuse component is due to:

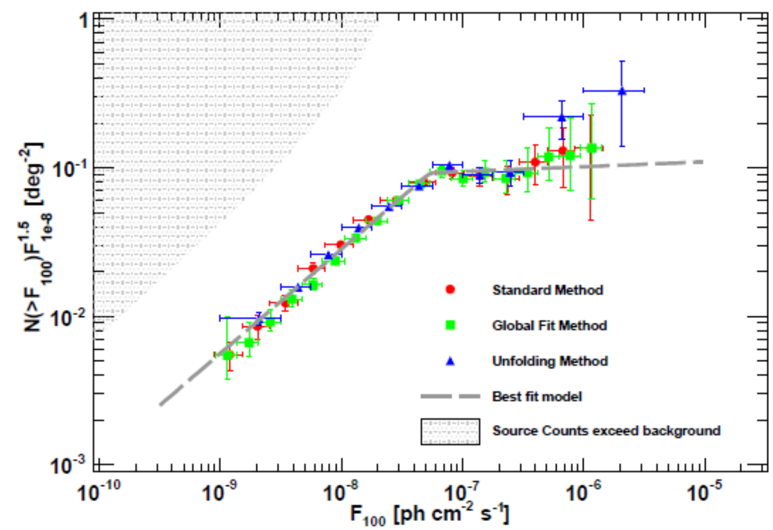
- Galactic Diffuse Emission
- *Extragalactic Diffuse Background* (EDB,isotropic)
- Instrumental background (~isotropic)

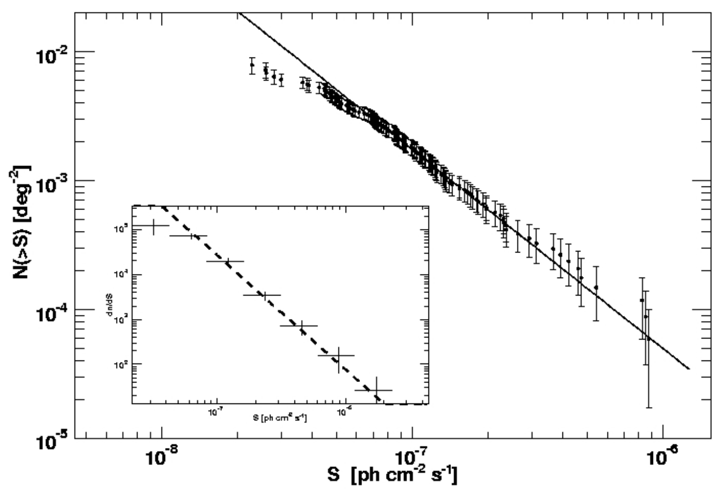
EDB estimated at high galactic latitude with tight cuts on events to reject instrumental background to the largest possible extent

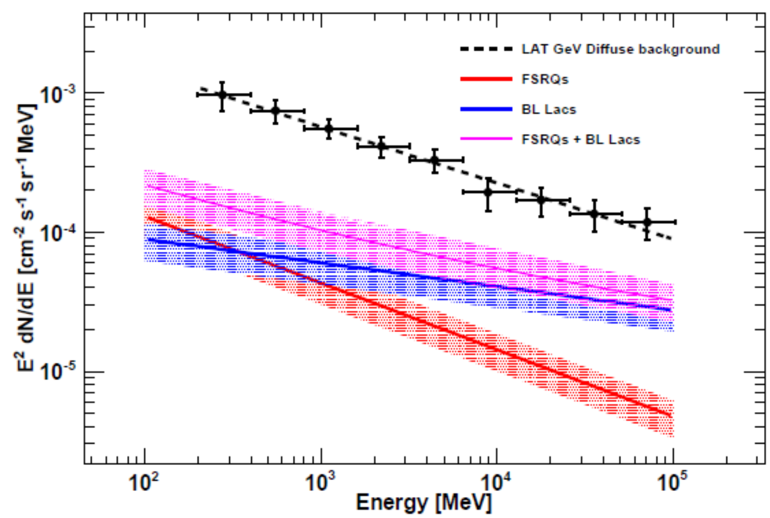
Log N - Log S / Contribution to EGB

- F_{100}> $5x10^{-8}$ ph cm^{-2} s^{-1}:
  FRSQ density: 6 x 10^{-3} deg^{-2}
  BL Lac density: 2 x 10^{-3} deg^{-2}
- F_{100}> 10^{-9} ph cm^{-2} s^{-1}:
  blazar density: 0.12 ±0.3deg^{-2}
- Break in Log N-Log S around
  F_{100} = 10^{-7} ph cm^{-2} s^{-1}
- Contribution of blazars
  to gamma-ray extragalactic
  diffuse background =16±7%

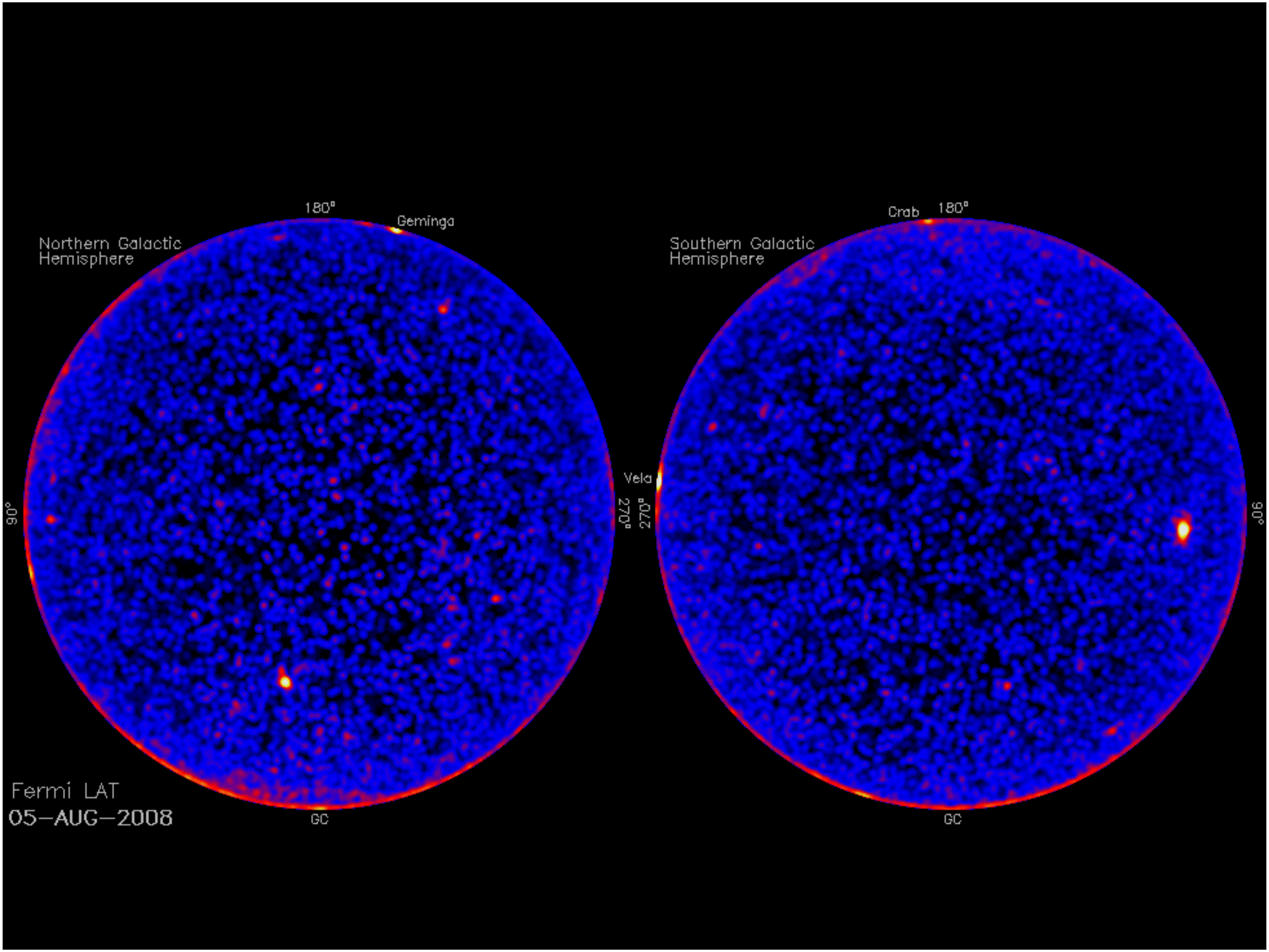
Abdo, A. A. et al. 2010, ApJ, 720, 435





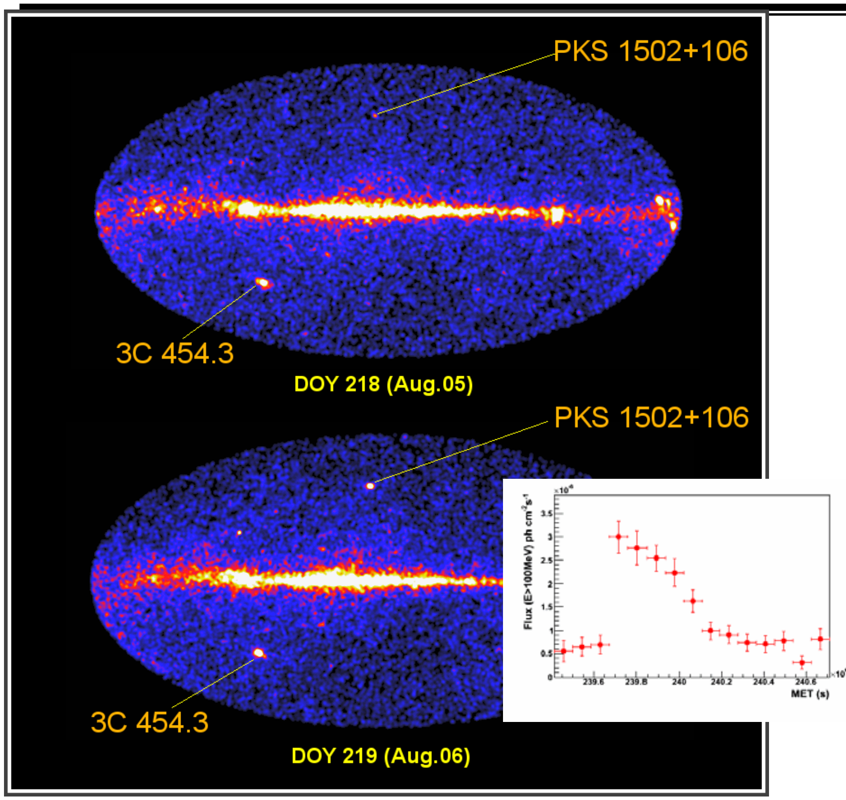


Variability



180°
Geminga
Northern Galactic
Hemisphere
90°
270°
Vela
GC
Fermi LAT
05-AUG-2008
Crab
180°
Southern Galactic
Hemisphere
270°
90°
GC

Fermi's variable sky



~130 Astronomers telegrams

~120 about AGNs

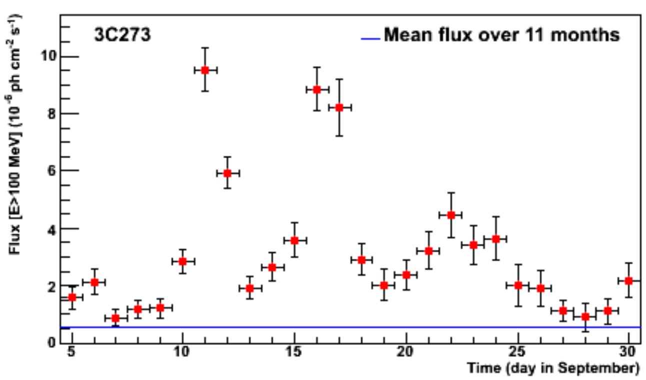
alert threshold:

F[E>100 MeV]~10^{-6} ph cm^{-2} s^{-1}

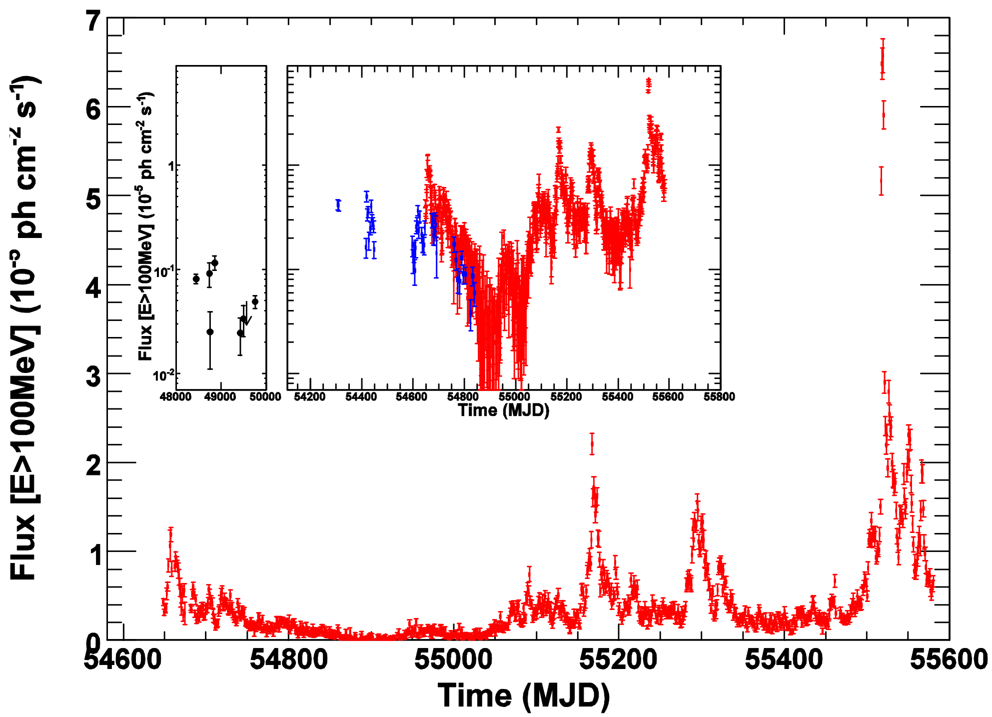
Other considerations:

- Significant flux rise wrt average
- TeV detectability
- Event rarity

http://www-glast.stanford.edu/cgi-bin/pub_rapid



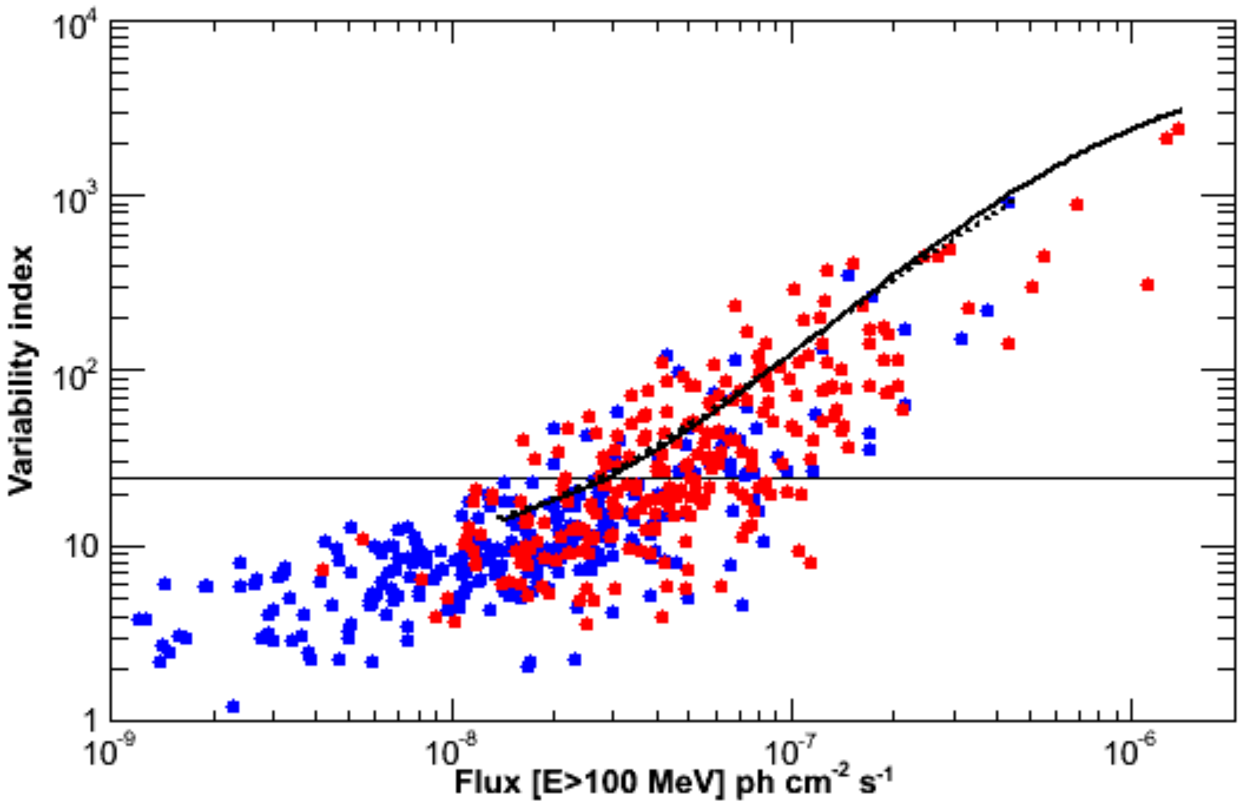
Flare Advocates issue alerts and feed the Fermi blog

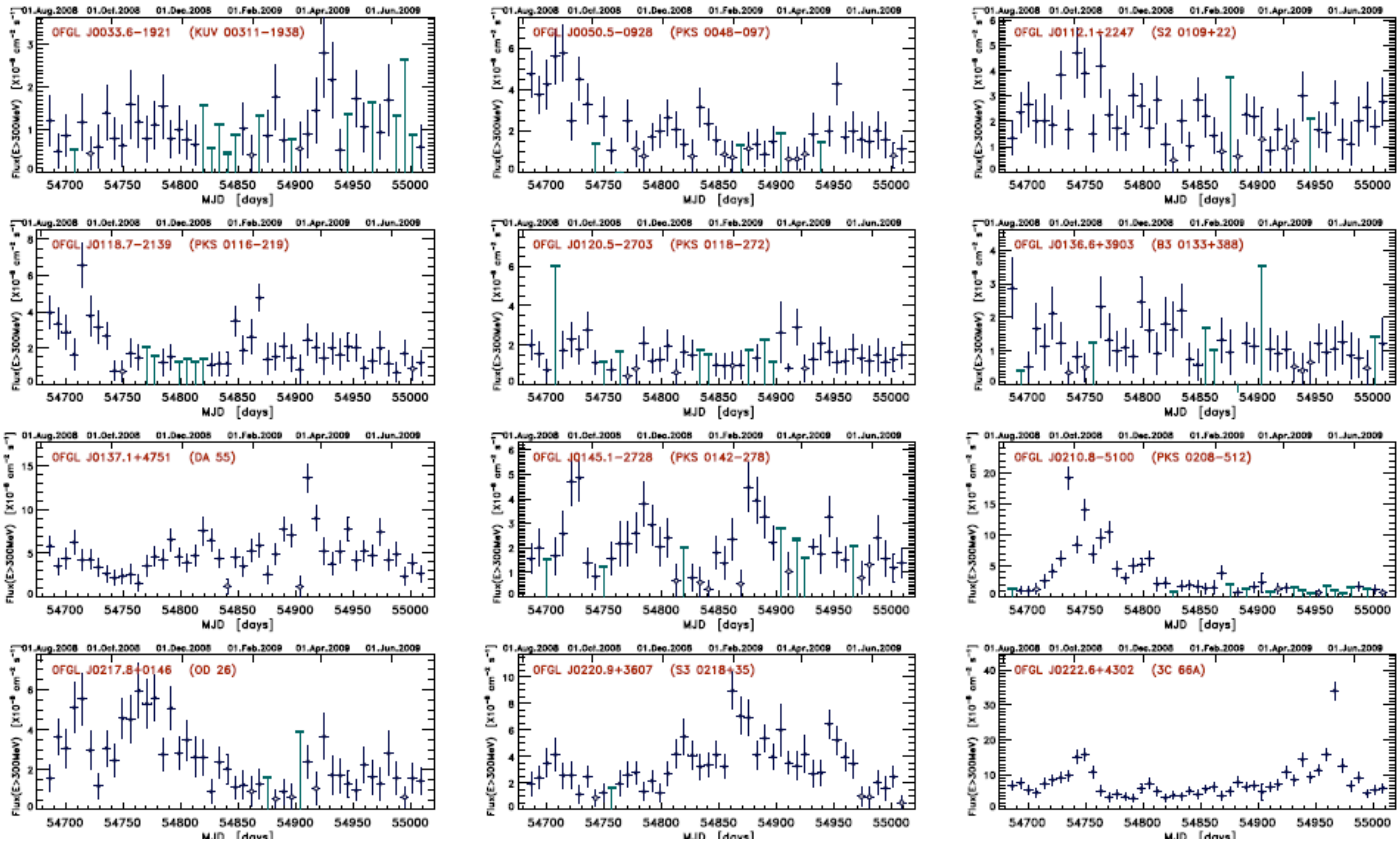

Flux [E>100MeV] (10^{-5} ph cm^{-2} s^{-1})
Time (MJD)
0
1
2
3
4
5
6
7
54600
54800
55000
55200
55400
55600
Flux [E>100MeV] (10^{-5} ph cm^{-2} s^{-1})
1
10^{-1}
10^{-2}
48000
49000
50000
54200
54400
54600
54800
55000
55200
55400
55600
55800
Time (MJD)

Variability index

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

based on monthly light curves (11 months)

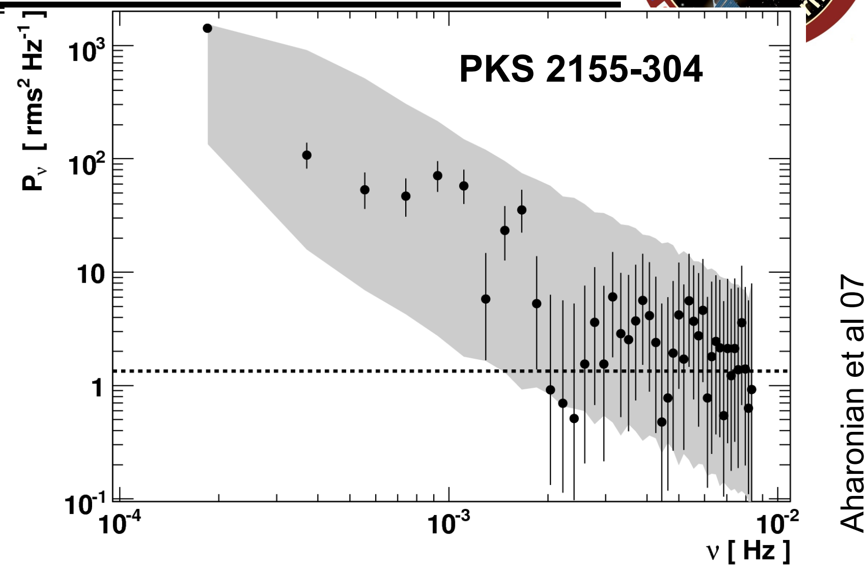


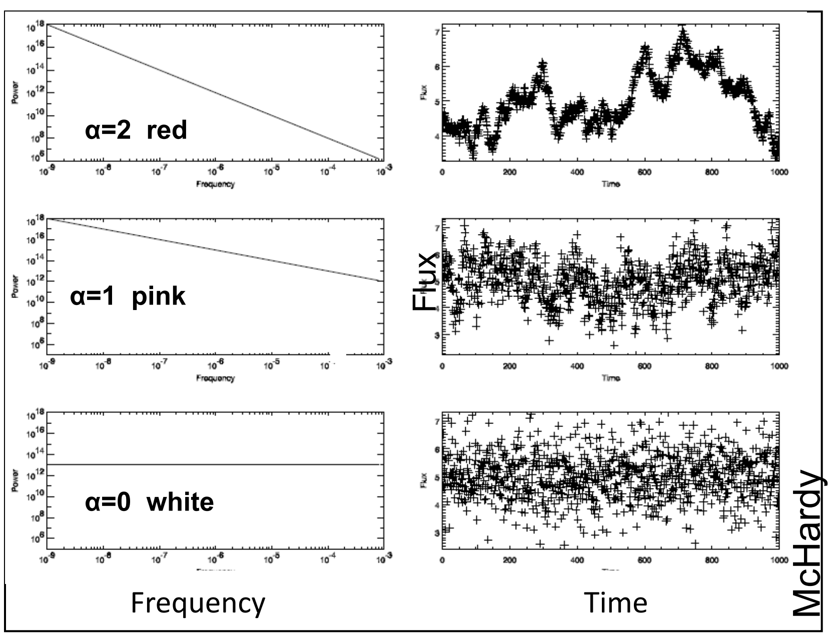

01.Aug.2008 01.Oct.2008 01.Dec.2008 01.Feb.2009 01.Apr.2009 01.Jun.2009
0FGL J0033.6-1921 (KUV 00311-1938)
0FGL J0050.5-0928 (PKS 0048-097)
0FGL J0112.1+2247 (S2 0109+22)
0FGL J0118.7-2139 (PKS 0116-219)
0FGL J0120.5-2703 (PKS 0118-272)
0FGL J0136.6+3903 (B3 0133+388)
0FGL J0137.1+4751 (DA 55)
0FGL J0145.1-2728 (PKS 0142-278)
0FGL J0210.8-5100 (PKS 0208-512)
0FGL J0217.8+0146 (OD 26)
0FGL J0220.9+3607 (S3 0218+35)
0FGL J0222.6+4302 (3C 66A)
54700 54750 54800 54850 54900 54950 55000
MJD [days]
Flux(E>300MeV) [x10^{-6} cm^{-2} s^{-1}]

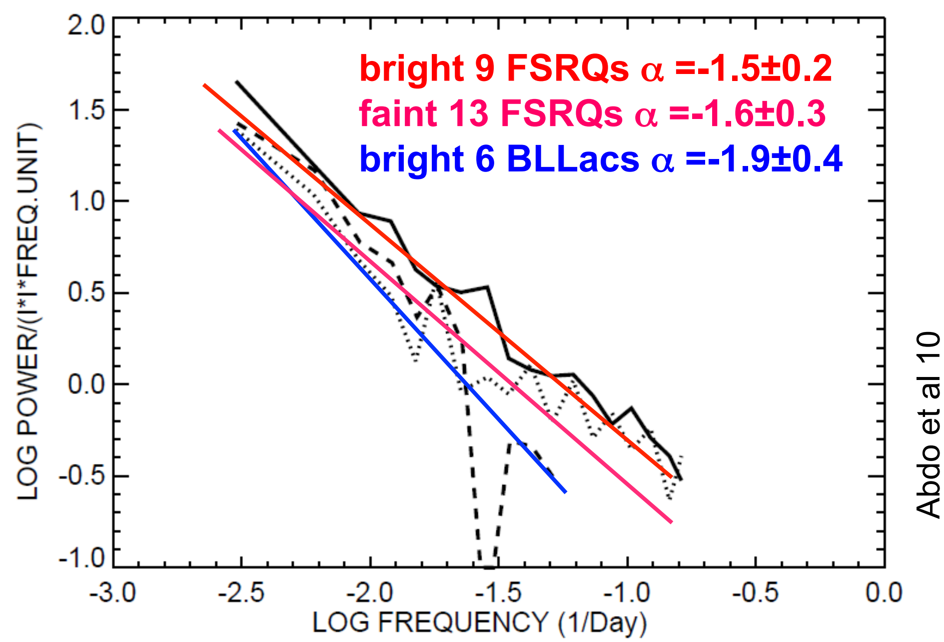
Power density spectrum

$$|F_N(\nu)|^2 = \left(\sum_{i=1}^{N} f(t_i)\cos(2\pi\nu t)\right)^2 + \left(\sum_{i=1}^{N} f(t_i)\sin(2\pi\nu t)\right)^2$$

PDS ~ 1/freq$^{-\alpha}$ with α between 1 (« flicker », « pink-noise ») and 2 (« shot noise », «Brownian») with peak around 1.6-1.7 (similar to optical or radio)

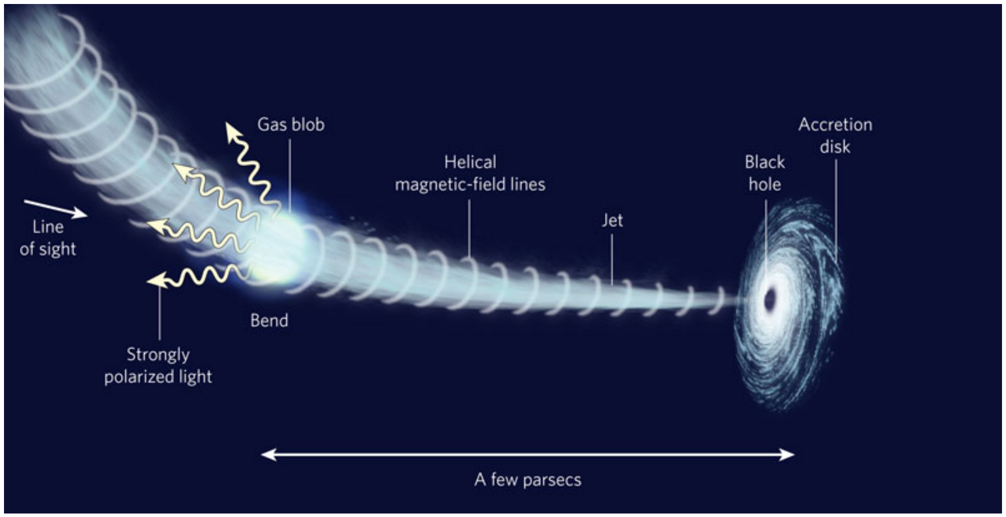


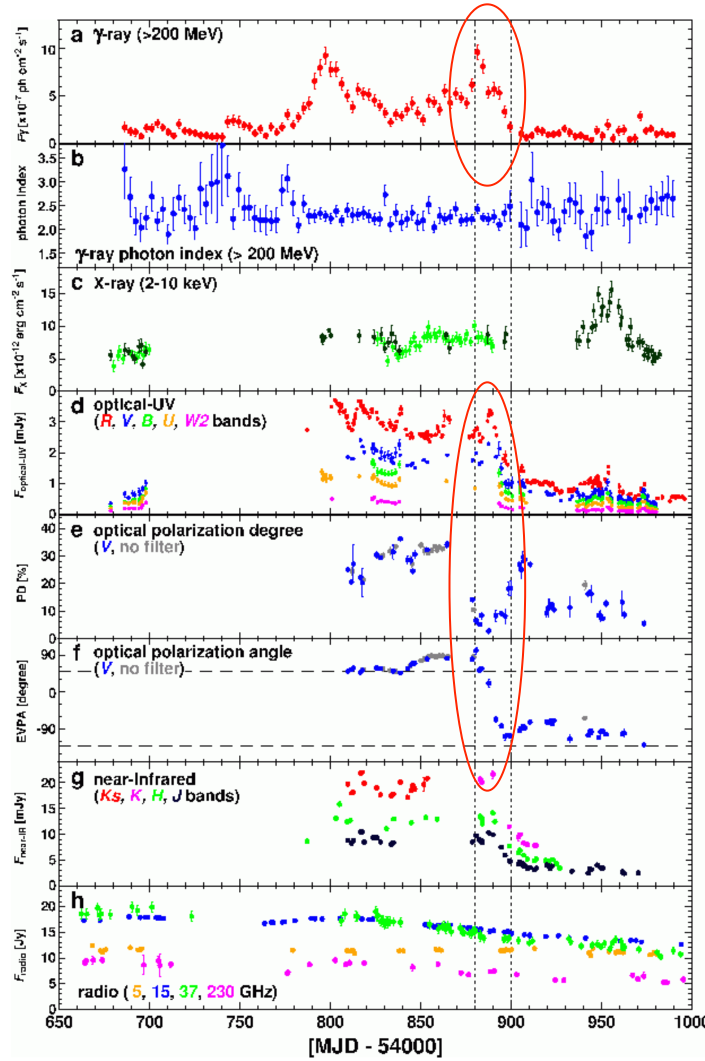




Fermi Spring School 2011

3C 279





Flare due to variation of Doppler factor angle wrt ligne of sight ($I(\nu) \propto \delta^3 I'(\nu')$)

- bent jet
- wobbling jet
- helical path of blob along the jet

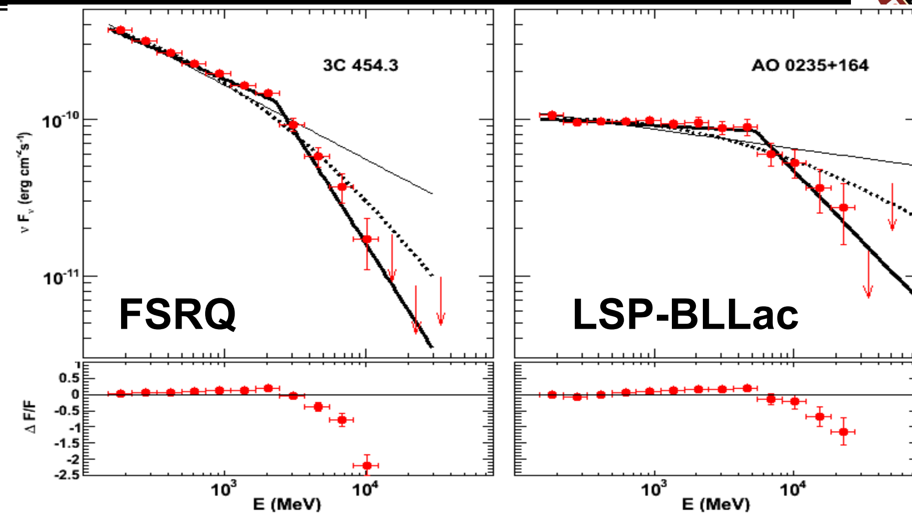
Provide explanation for the observed polarisation swings

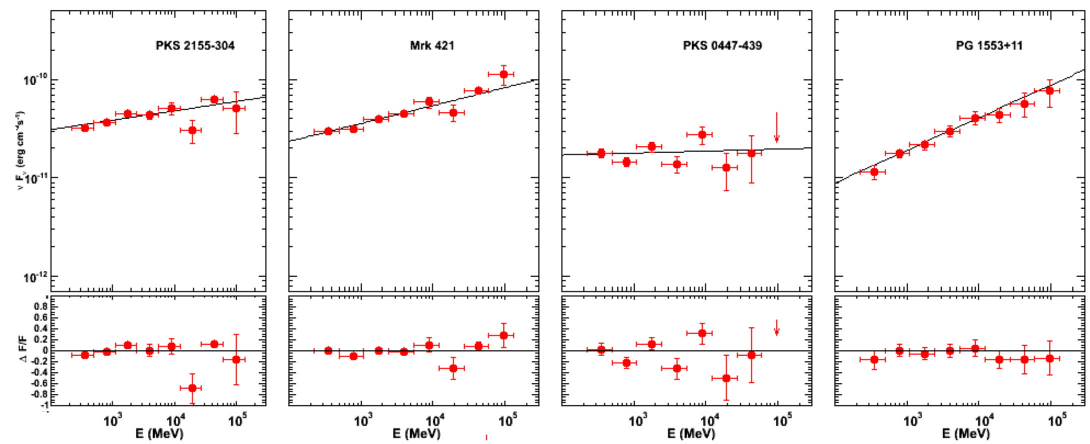
Abdo et al. 10

Spectral distributions

Curved spectra

- General feature in FSRQs and many LSP-BLLacs
- Absent in HSP-BLLacs
- Broken power law model seems to be favored
- $\Delta\Gamma \sim 1.0 > 0.5 \rightarrow$ not from radiative cooling
- Possible explanations:
  - feature in the underlying particle distribution
  - Klein-Nishina effect
  - γ-γ absorption effect
- Implications for EBL studies and blazar contribution to extragalactic diffuse emission

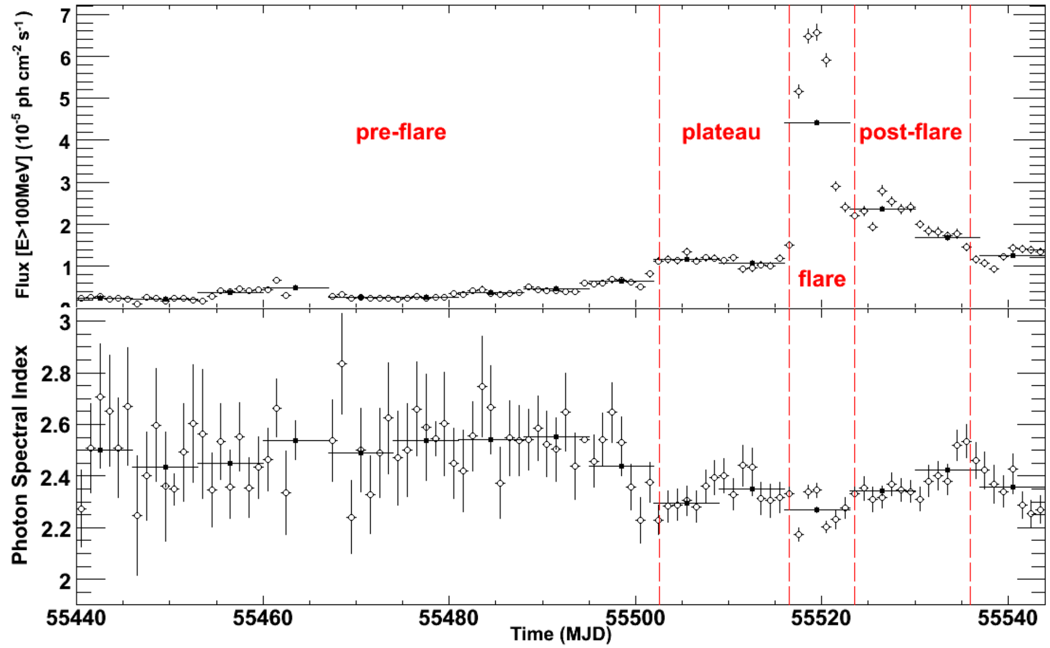




HSB-BLLacs

daily/weekly light curves

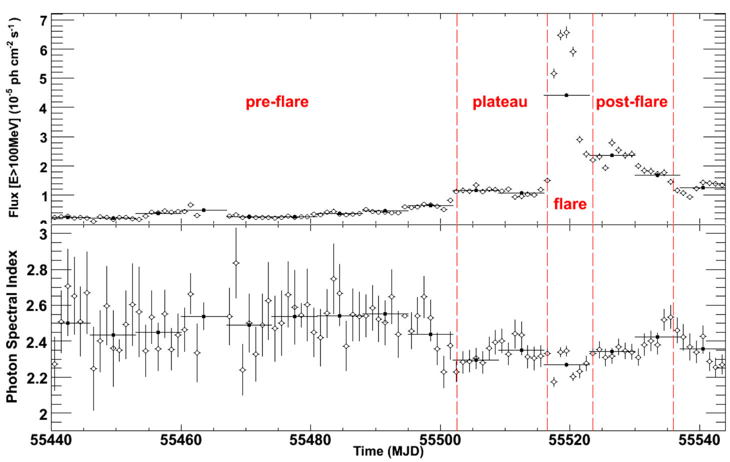
- 5-day long outburst
- peak daily F[E>100 MeV] : $(66\pm 2) \times 10^{-6}$ ph cm^{-2} s^{-1}
- 13-day long plateau
longer in duration and higher in flux than previous ones
characteristic behavior for this source!
- onset of plateau marked by weak but significant hardening Γ=2.50 ±0.02 to 2.32 ±0.03

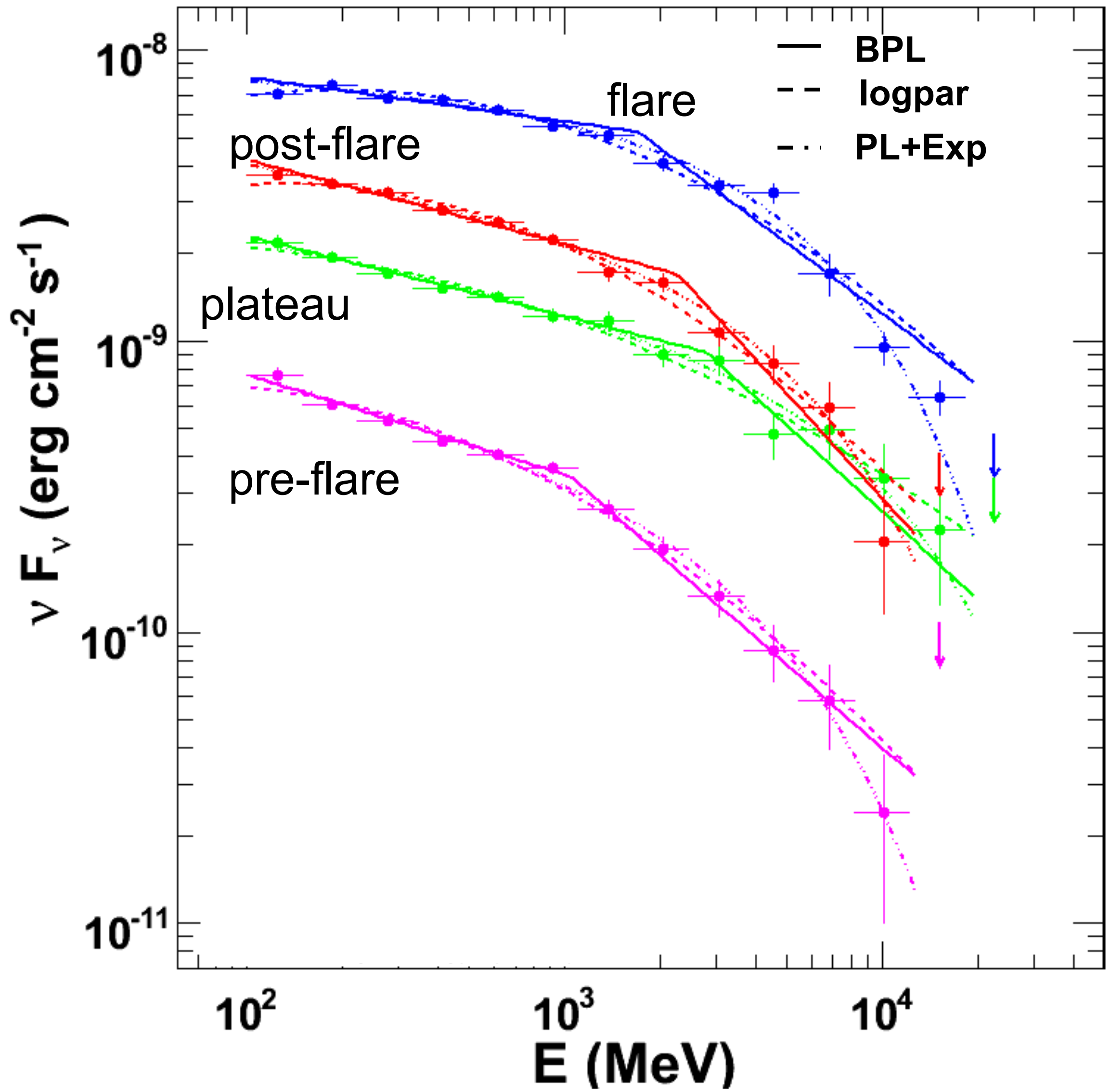


- decrease in flux by a factor of 3 in 4 days
- slowly decaying activity around 20 x 10^{-6} ph cm^{-2} s^{-1}

γ-ray νFν

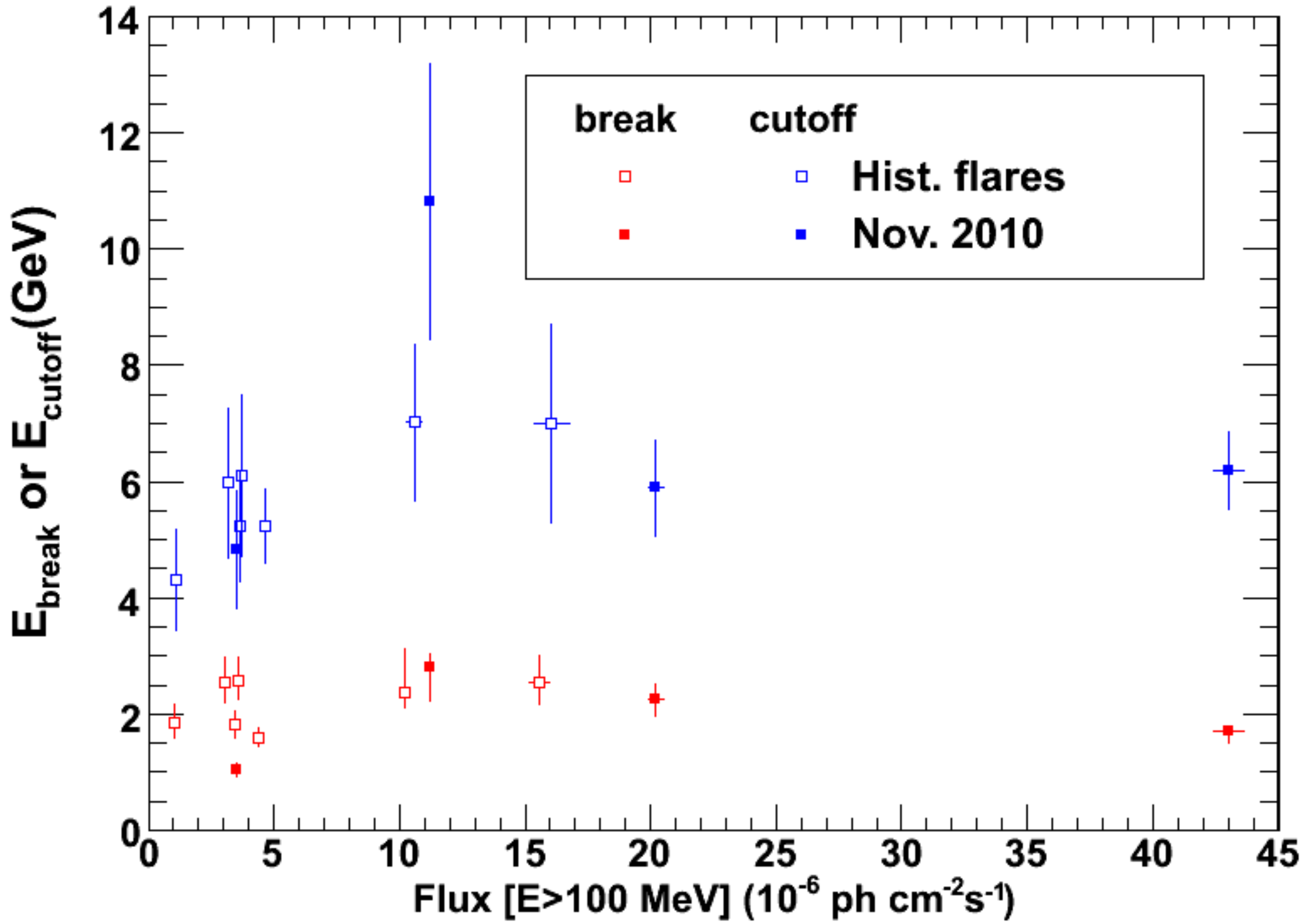
- preflare and plateau: BPL and PL+expcutoff give similar quality fits
- logparabola significantly worse
- none of tested functions gives a good fit for the flare period





Benoit Lott

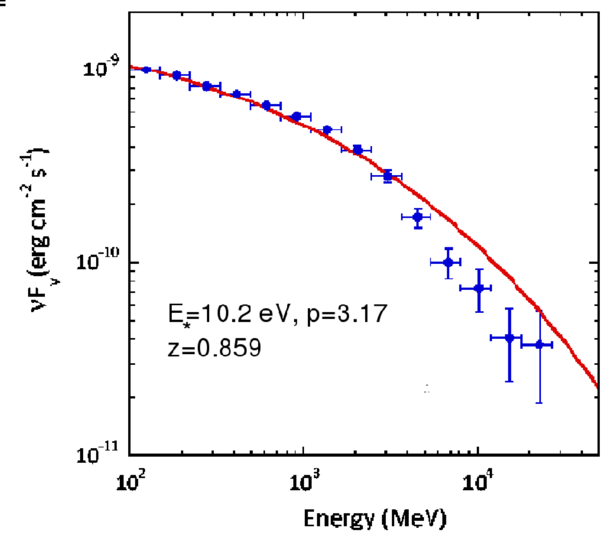
Evolution of energy break with flux

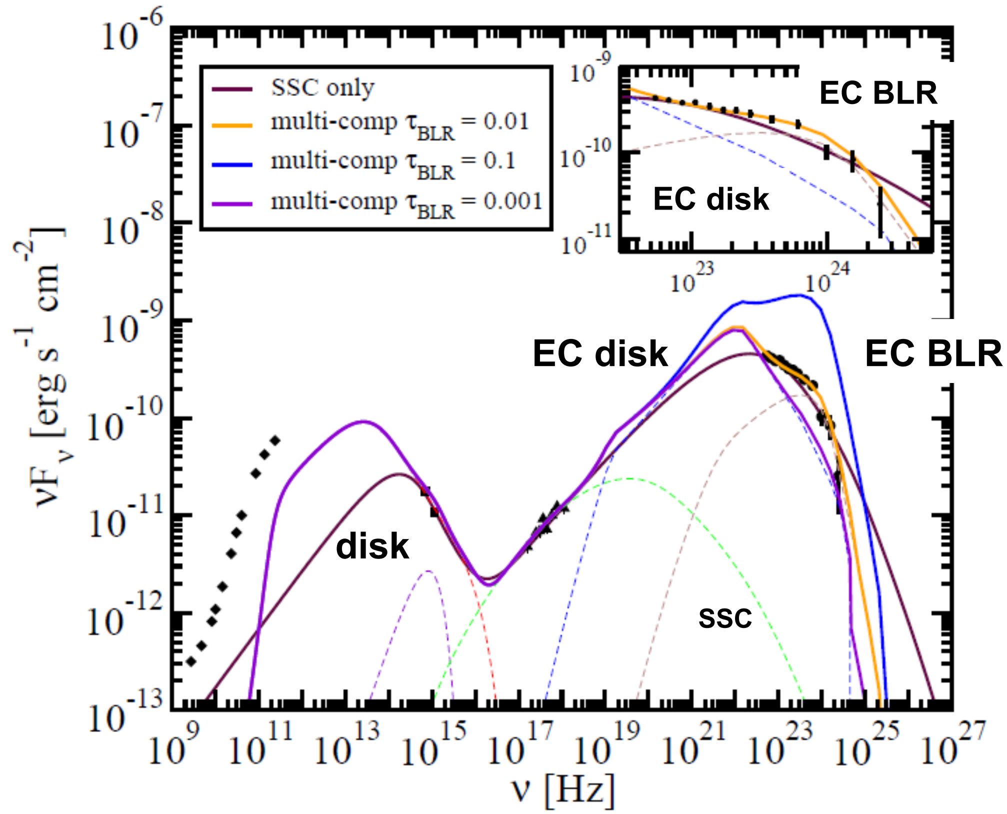


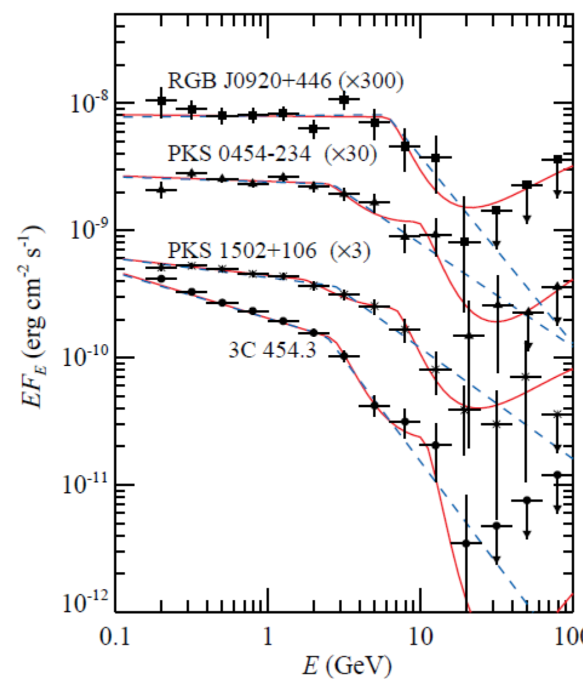
Constant break-energy issue

- $\gamma\gamma$ 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

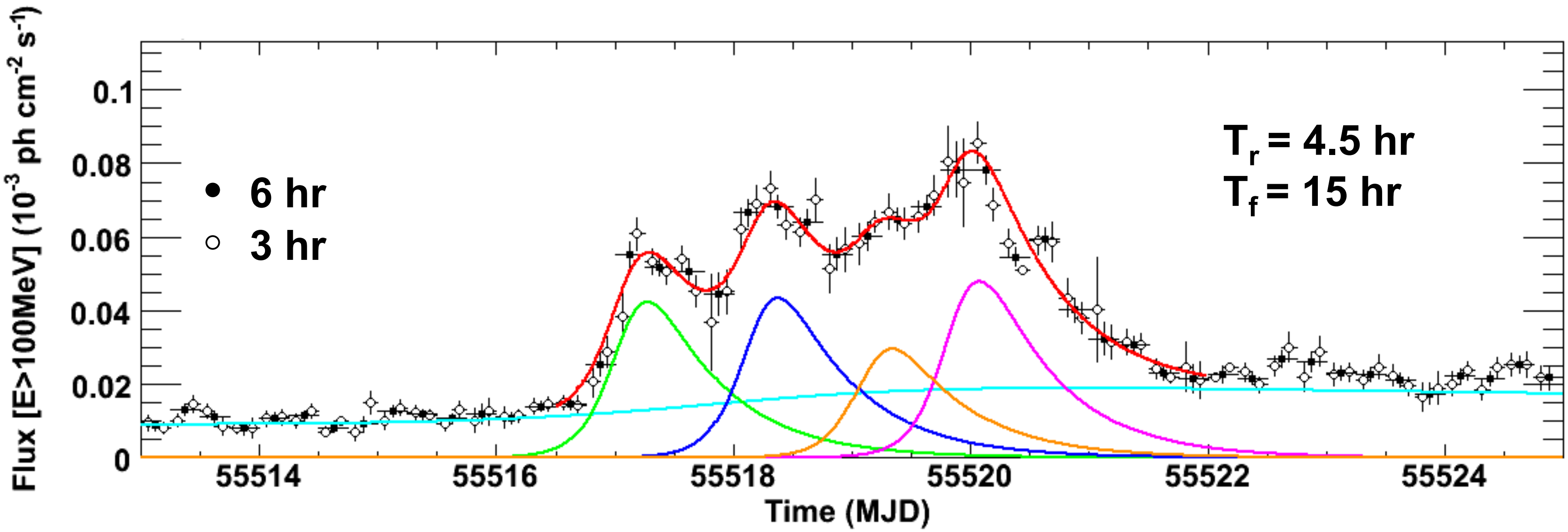
Some sources with breaks in the GeV domain (4C+21.35, S5 0715+71) have been detected at TeV energies







High-resolution light curve

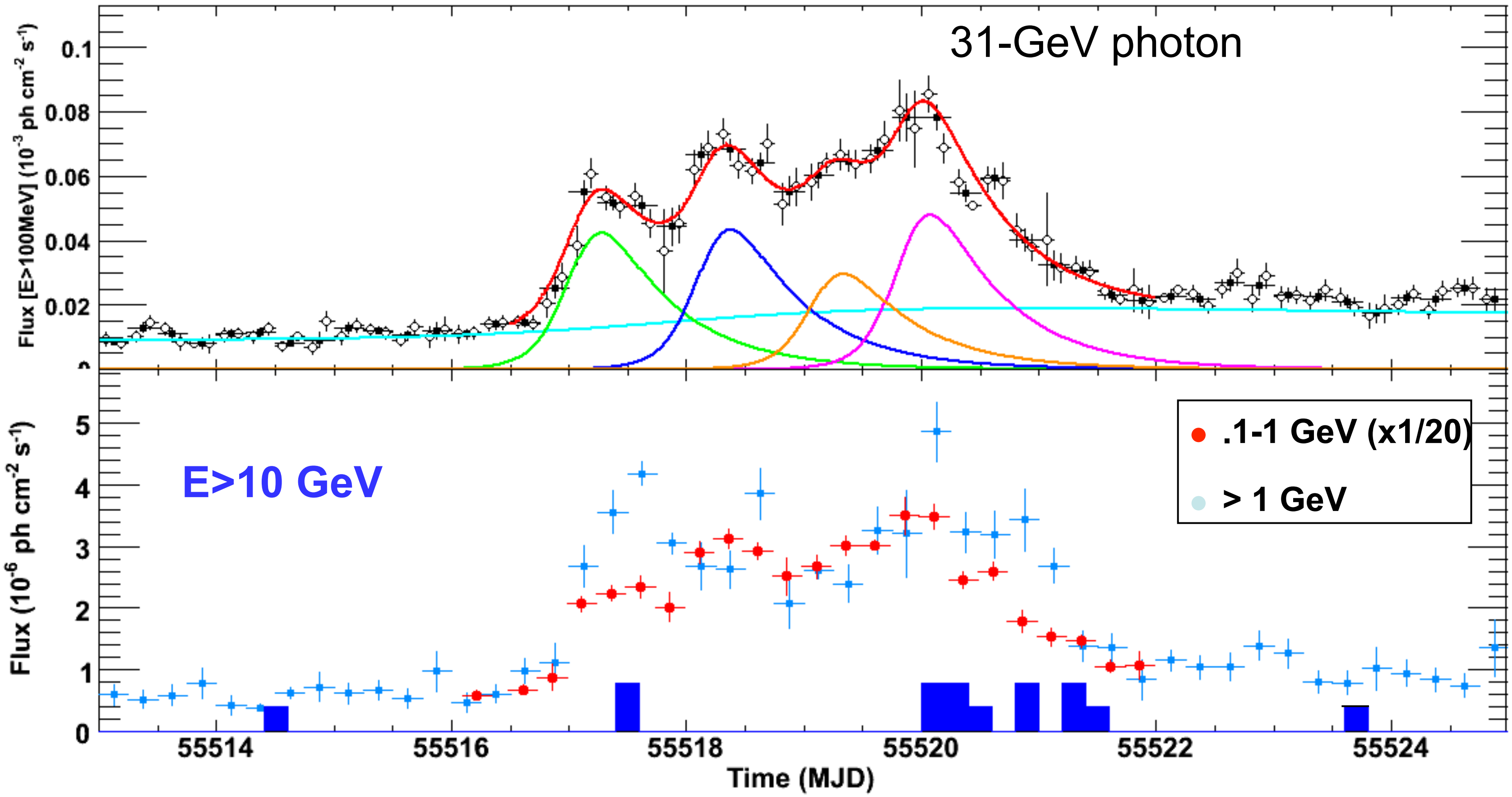


- 3-hr peak: F_{100}= (85 ± 5) x 10^{-6} ph cm^{-2} s^{-1}
- most luminous AGN yet observed, isotropic L_γ = (2.1 ± 0.2) x10^{50} erg s^{-1}
- 4x flux increase in ~12 hr: ~ 6 hr doubling time
- 4 subflares fitted with same T_r (4.5 hr) and same T_f (15 hr)

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

- dL/dt ~ 10^{46} erg s^{-2} largest ever measured for a blazar (dwarfs PKS2155-304, Mrk 501…)
  >> L_{Edd}/cR_s (3 x 10^{43} erg s^{-2}) as predicted in Eddington-limited accretion scenario (Elliot & Shapiro 74)

Highest-energy photons



Clear « hard-lag » effect during the flare

- **transparency to $\gamma\gamma$ absorption due to:**
  - **increased Lorentz factor ?**
  - **plasma blob of larger size?**
- **radiating hadrons requiring more time to accelerate?**

Conclusions

- Fermi has enabled major progress in blazar science
- >1000 sources discovered
- monitoring will continue
- unfortunately, little overlap with CTA (2018) is foreseen