Relativistic Jets and AGN in the Fermi Era

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on behalf of the Fermi/LAT Collaboration

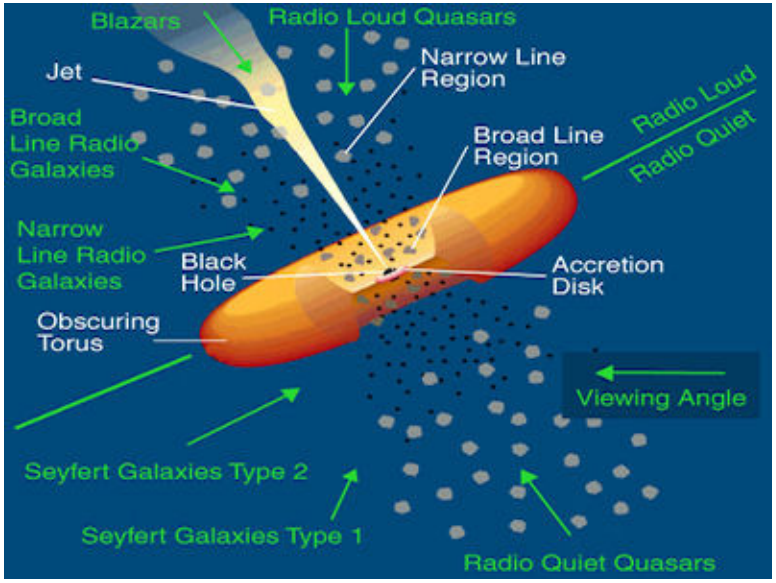
Outline of the Talk

- Active Galactic Nuclei (AGN)
- Relativistic Jets in AGN
- Fermi/LAT Instrument
- Fermi/LAT & AGN
- Conclusions

Active Galactic Nuclei

Each galaxy hosts supermassive ($M_{BH} \sim 10^6 - 10^{10}\ M_\odot$) black hole in its center, and each supermassive black hole accretes at some level from the surrounding interstellar medium. Active Galactic Nuclei are those central black holes which accrete at high rates.

AGN constitute a very diverse class of astrophysical sources. They differ in the properties of their large-scale environments, in the properties of their host galaxies, in the accretion rates and accretion fuels, in the structure and state of their circumnuclear environment, and finally in the properties of the produced outflows.

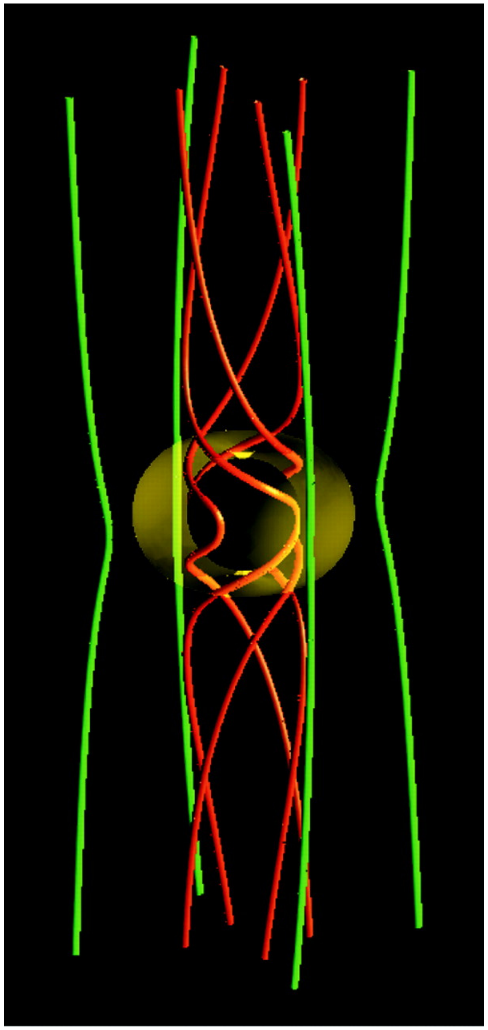


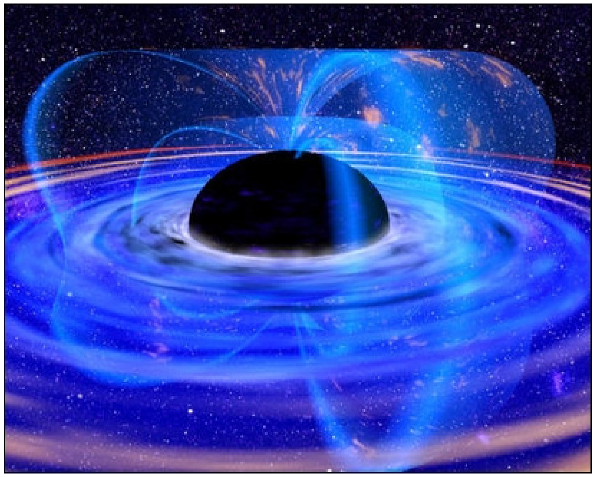
- Quasi-Stellar Objects aka Quasars ($\sim 10^{-7}$ Mpc^{-3})
  - Radio-quiet or radio-loud quasars
- BL Lacertae Objects ($\sim 10^{-7}$ Mpc^{-3})
- Radio Galaxies ($\sim 10^{-6}$ Mpc^{-3})
  - Broad or narrow line radio galaxies
  - Fanaroff-Riley class I or II
  - …any many more…
- Seyfert Galaxies ($\sim 10^{-4}$ Mpc^{-3})
  - Seyferts type 1 - 2
  - Narrow-Line Seyferts
- Low-Luminosity AGN ($> 10^{-3}$ Mpc^{-3})
  - Low-Ionization Nuclear Emission-Line Region Galaxies
  - “Regular” spiral galaxies like our Galaxy (Sgr A*)…

Relativistic Jets

Rotating black hole embedded in an external magnetic field (supported by an accretion disk) acquires a quadrupole distribution of the electric charges with the corresponding poloidal electric field. Thus, a power can be extracted by allowing currents to flow between the equator and poles of a spinning black hole above the event horizon.

Blandford & Znajek 1977 discussed how, with a force-free magnetosphere added to such a rotating black hole, electromagnetic currents are driven an the energy is released (in a form of magnetized jets) in the expense of the black hole rotational energy ("reducible mass"). This scenario was inspired by earlier developed models for young stars (Weber & Davis 1967), pulsars (Michel 1969, Goldreich & Julian 1970), and accretion disks in active galaxies (Blandford 1976, Lovelace 1976, Bisnovatyi-Kogan & Ruzmaikin 1976), and is being recently investigated further by means of GR MHD simulations (e.g., Koide et al. 2002, Komissarov 2005, McKinney & Gammie 2004).





$R_g = GM_{BH}/c^2$
$\sim 10^{14}\ (M_{BH}/10^9 M_\odot)$ [cm]

$L_{Edd} = 4\pi GM_{BH} m_p c/\sigma_T$
$\sim 10^{47}\ (M_{BH}/10^9 M_\odot)$ [erg/s]

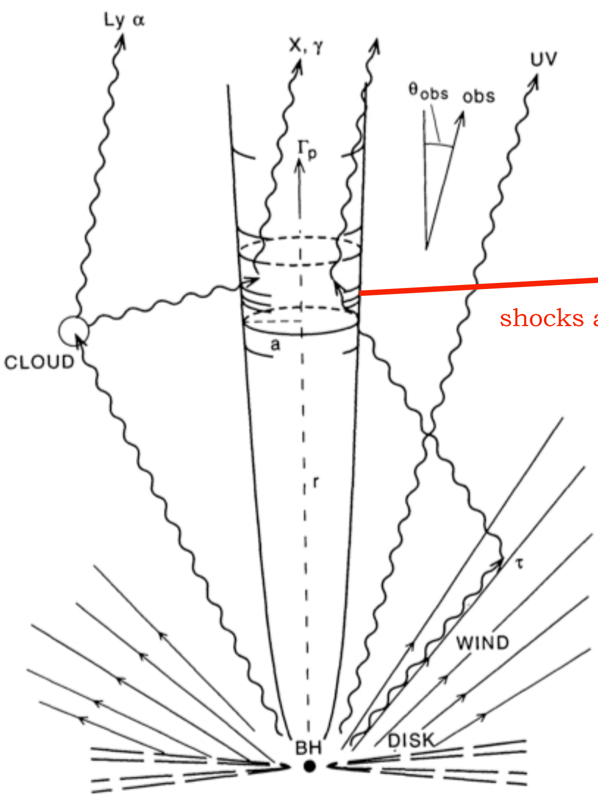
for maximally spinning black hole:

$E_{tot} \sim 0.3\ M_{BH}c^2$
$\sim 10^{63}\ (M_{BH}/10^9 M_\odot)$ [erg]

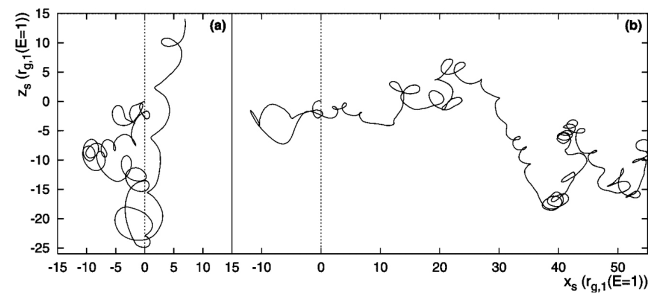
$P_{max} \sim cB^2 R_g^{\ 2}/4\pi$
$\sim 10^{46}\ (M_{BH}/10^9 M_\odot)$ [erg/s]

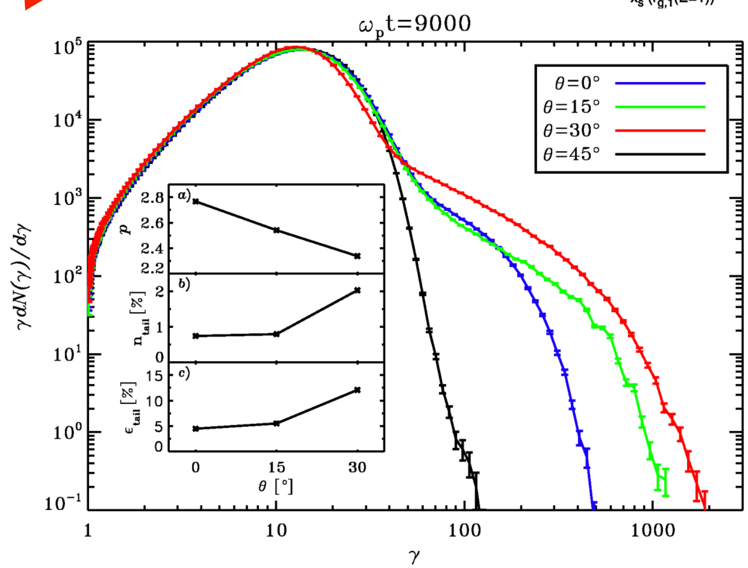
Shocks and Turbulence

Jets produced in AGN are quickly accelerated and collimated by the magnetic field, and reach terminal bulk velocities of the order of Γ_j ~ 10 - 30 at sub-pc scales (1pc ~ 3×10^{18} cm). In such relativistic magnetized outflows, shocks and turbulence driven by the intermittency of the central engine, by the magnetic reconnection, or by the jet interactions with the surrounding medium, accelerate jet particles to ultrarelativistic energies ($e^{\pm}$ up to at least 100 TeV, p^{+} possibly up to EeV). Diffusive acceleration of particles at the fronts of astrophysical shocks ("1st-ordr Fermi" process) has been discussed in the context of Galactic cosmic rays and supernova remnants (Krymski 1977, Bell 1978, Blandford & Ostroker 1978), and is being recently studied further in a relativistic regime by means of numerical simulations (MC and PIC; e.g., Hoshino et al. 1992, Niemiec & Ostrowski 2004, Sironi & Spitkovsky 2009).

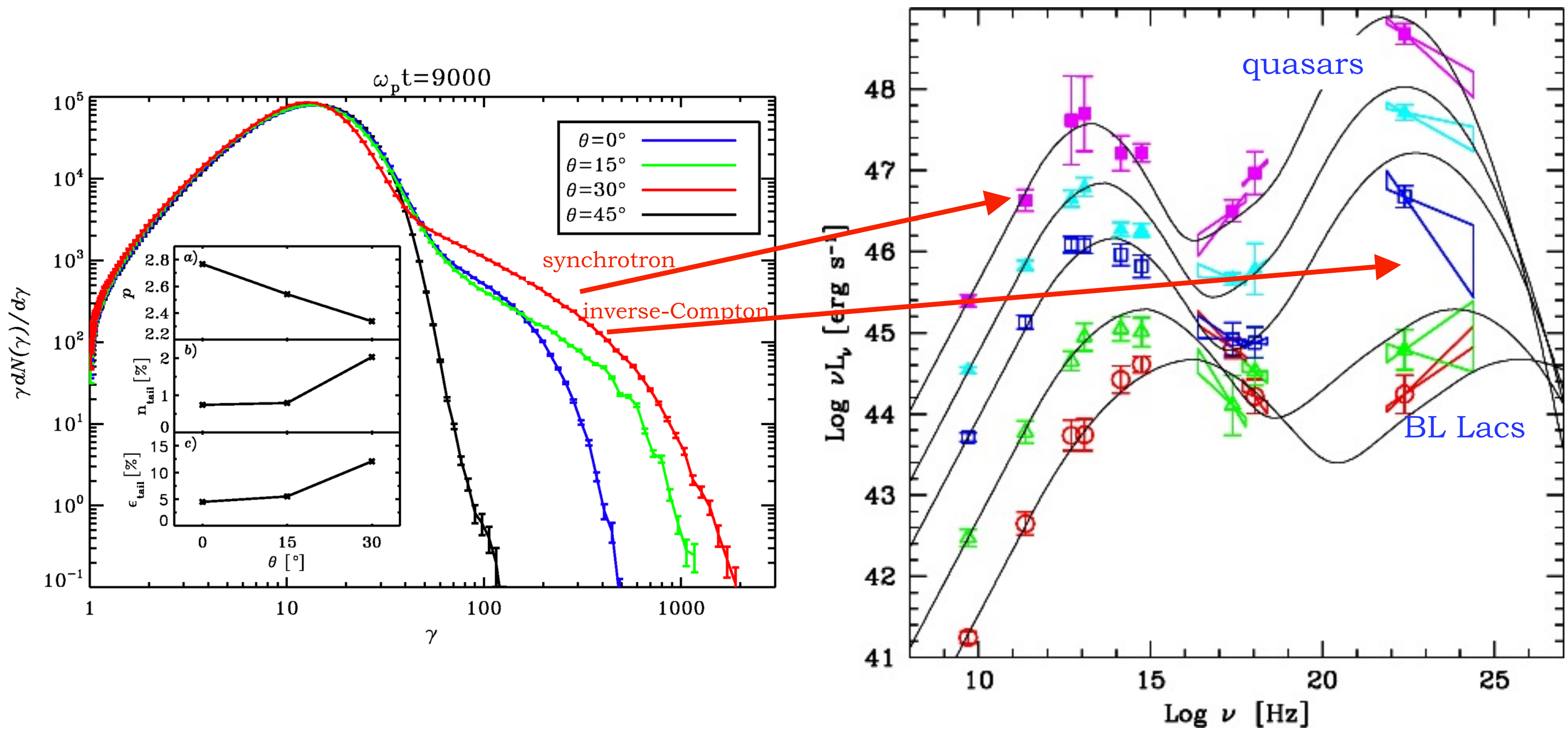


shocks and turbulence





Blazars

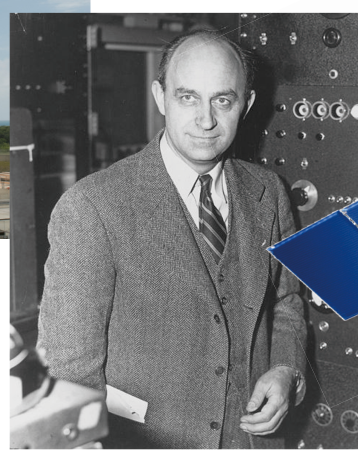


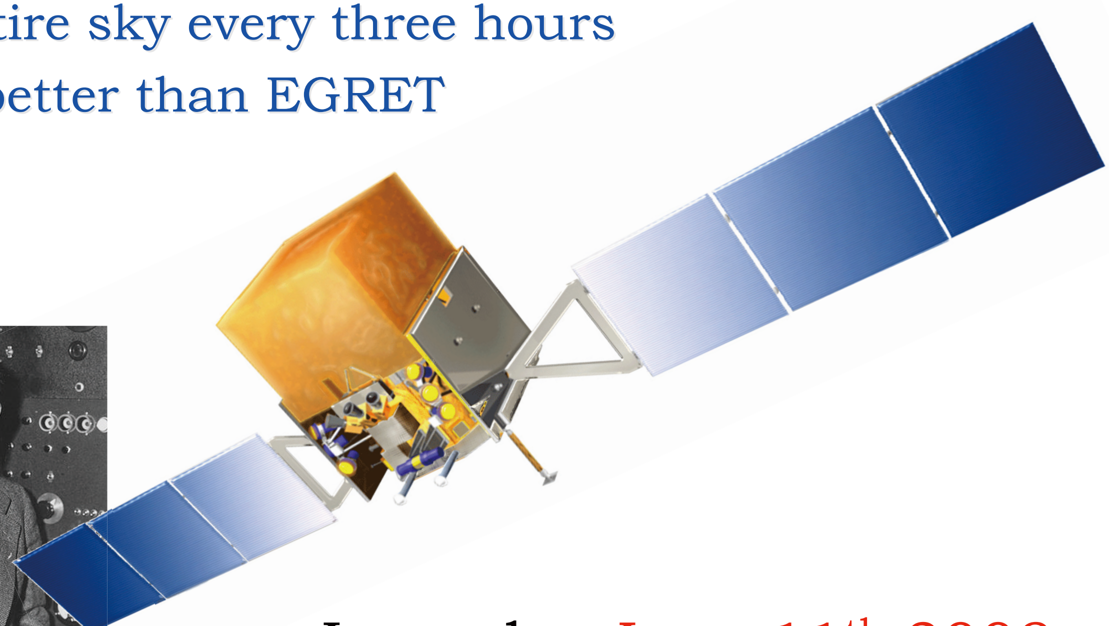
Non-thermal broad-band emission of the accelerated electrons is strongly Doppler-boosted in the observed rest frame, if a jet is viewed at angles $\theta \leq 1/\Gamma_j$, and this results in the observed luminosities $L_{obs} = \delta^4 L'$ reaching 10^{49} erg/s ("blazar sources"; here $\delta = 1/\ \Gamma_j \times [1 - \beta_j \cos\theta]$ is the Doppler factor).

As demonstrated by the previous observations with the EGRET instrument onboard Compton Gamma-Ray Observatory, most of the jet power in blazars is radiated in gamma-rays (see, e.g., Maraschi et al. 1991, Dermer & Schlickeiser 1993, Sikora et al. 1994, Ghisellini et al. 1998).

Fermi Satellite

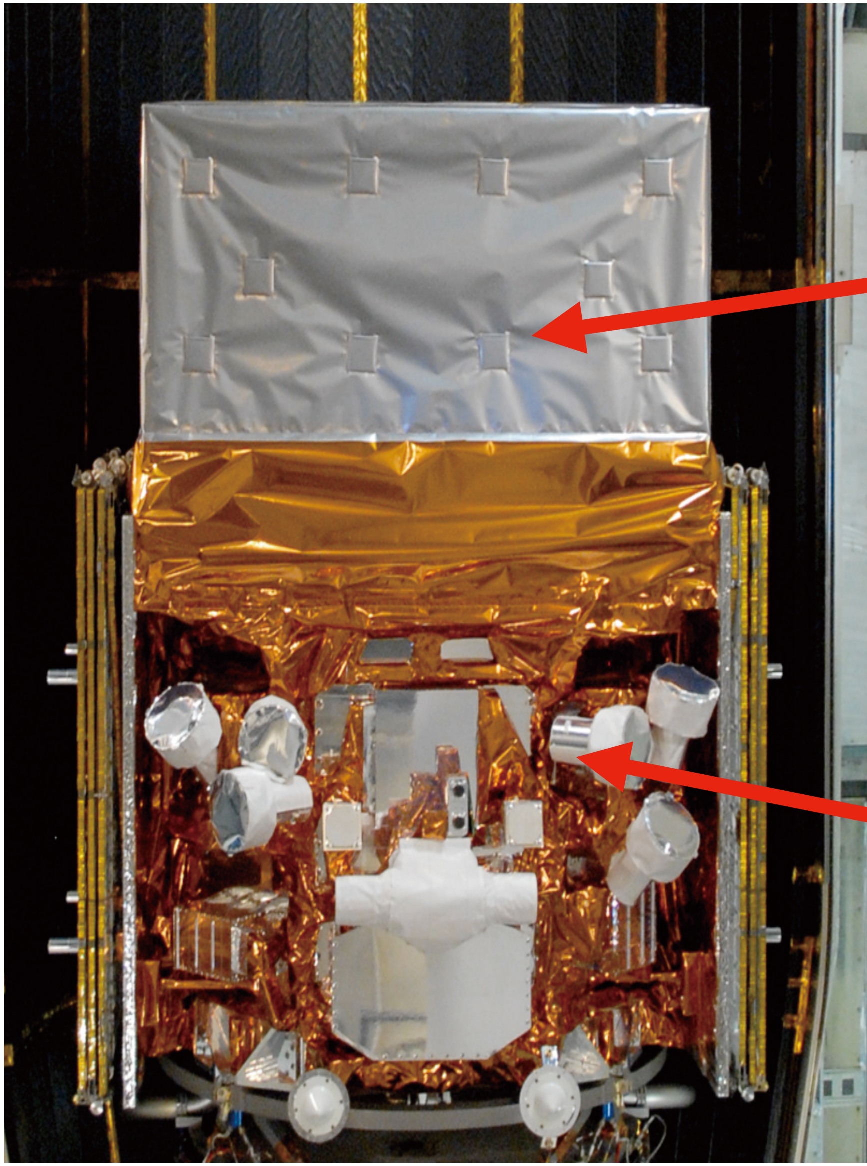
- Fermi: An International Science Mission to perform gamma-ray astronomy, with an additional X-ray detector for GRBs
  - Large Area Telescope (LAT); 20 MeV – >300 GeV
  - GLAST Burst Monitor (GBM); 10 keV – 30 MeV
- The strategy (5 years operation, 10 years goal)
  - Survey mode: entire sky every three hours
  - Sensitivity ~ 30 better than EGRET

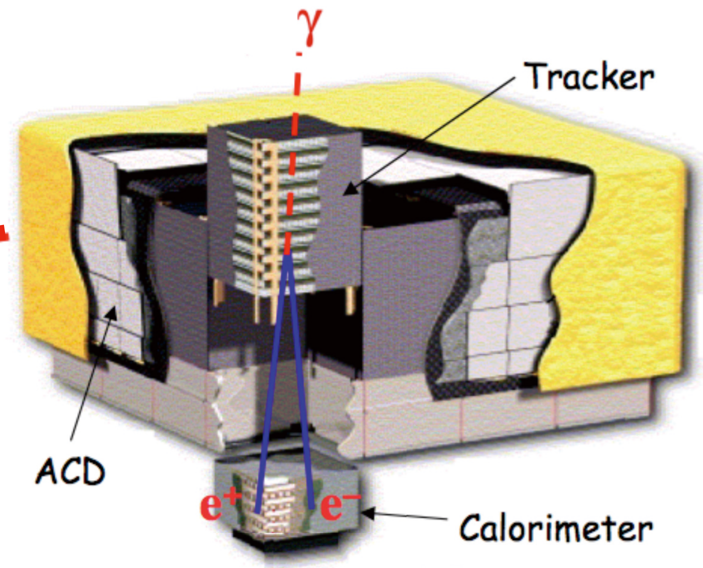




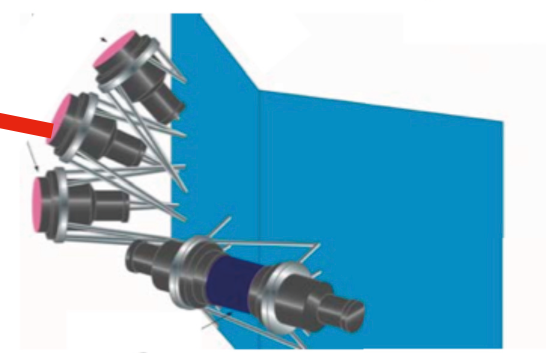
Launch: June 11^{th} 2008
Cape Canaveral

Fermi LAT and GBM





Large Area Telescope
(20 MeV – > 300 GeV)



Glast Burst Monitor
(10 keV – 25 MeV)

Fermi Collaboration

- France
  - CNRS/IN2P3, CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
  - Waseda University
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

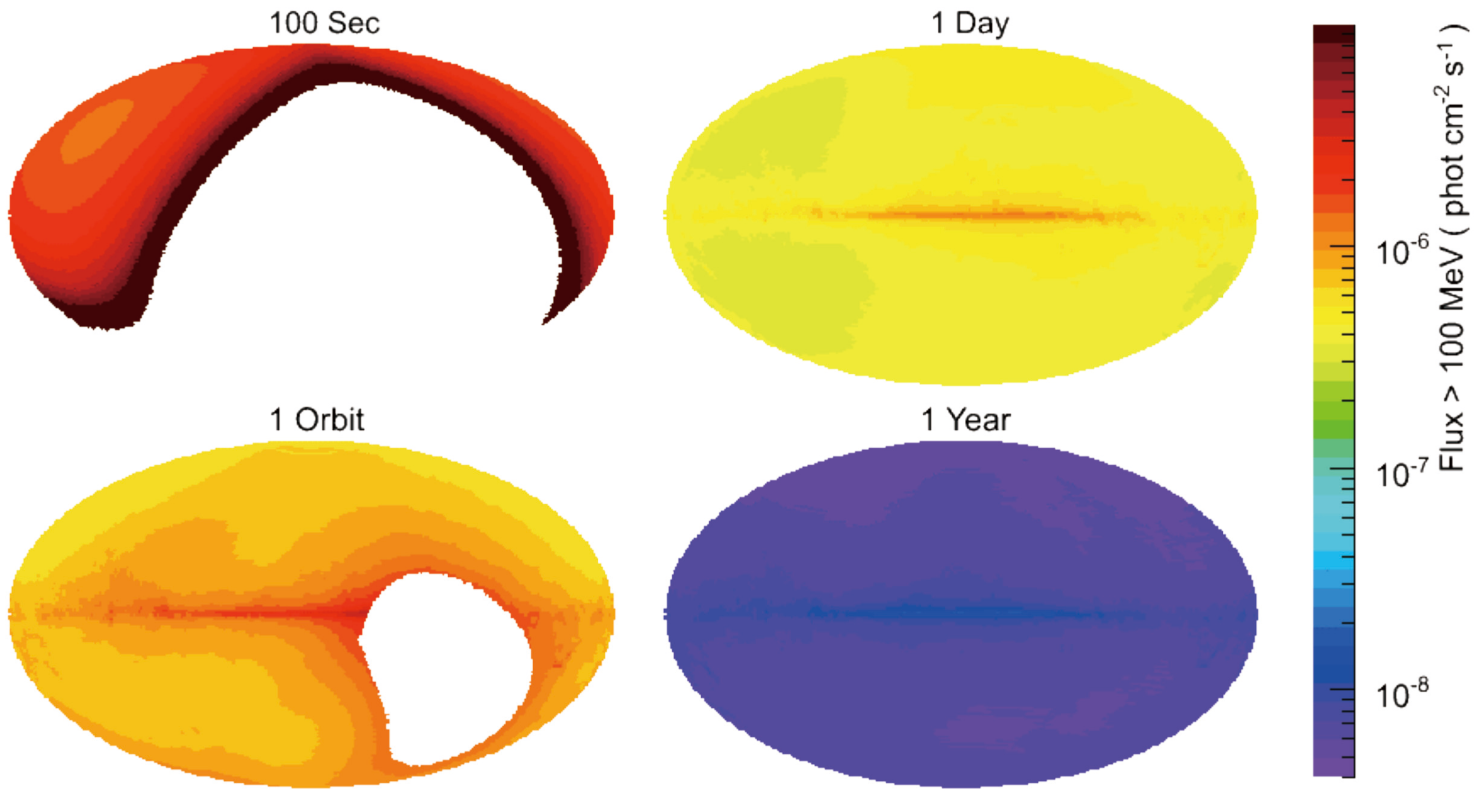
PI: Peter Michelson (Stanford)

~400 Scientific Members (including ~100 Affiliated Scientists, plus ~200 Postdocs and Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at SLAC/Stanford

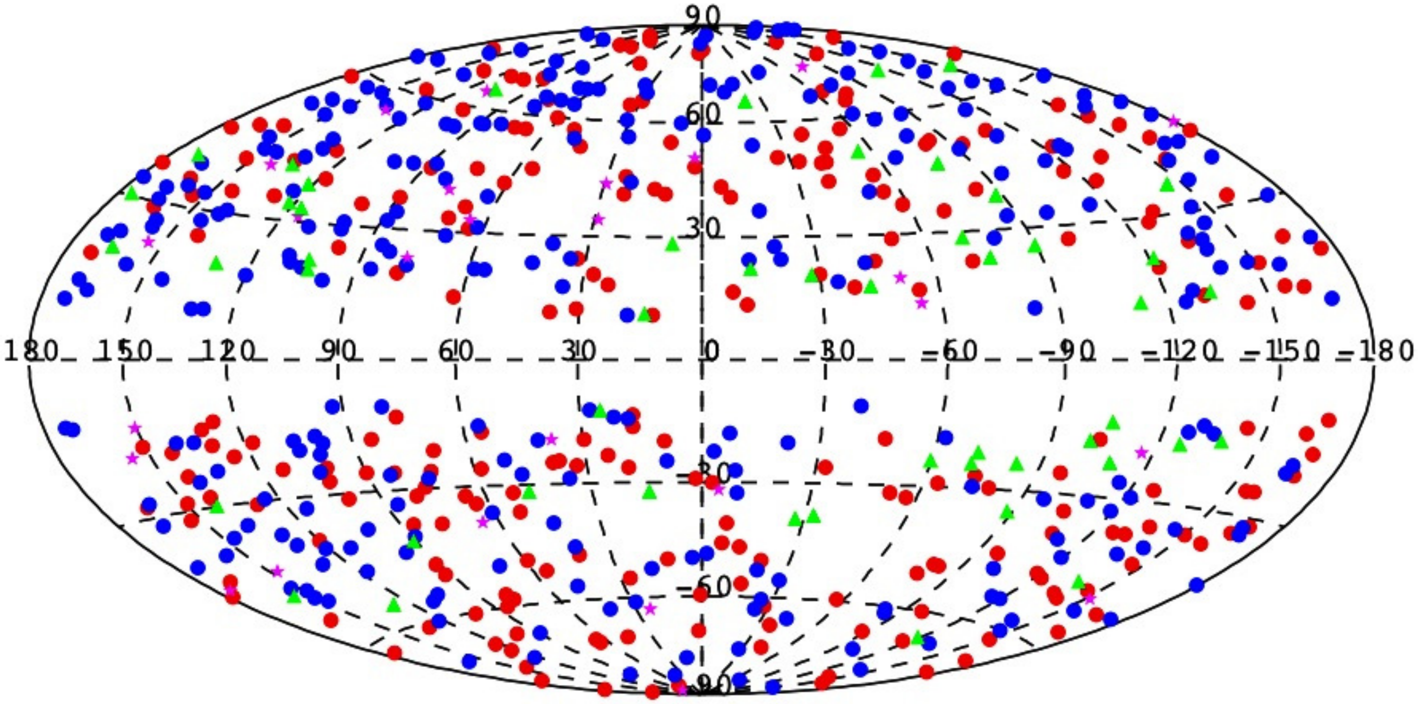
Survey Instrument LAT



Energy Resolution: ~10%
PSF (68%) at 100 MeV ~ 3.5deg
PSF (68%) at 10 GeV ~ 0.1deg
Field Of View: 2.4 sr (>20% of the sky)

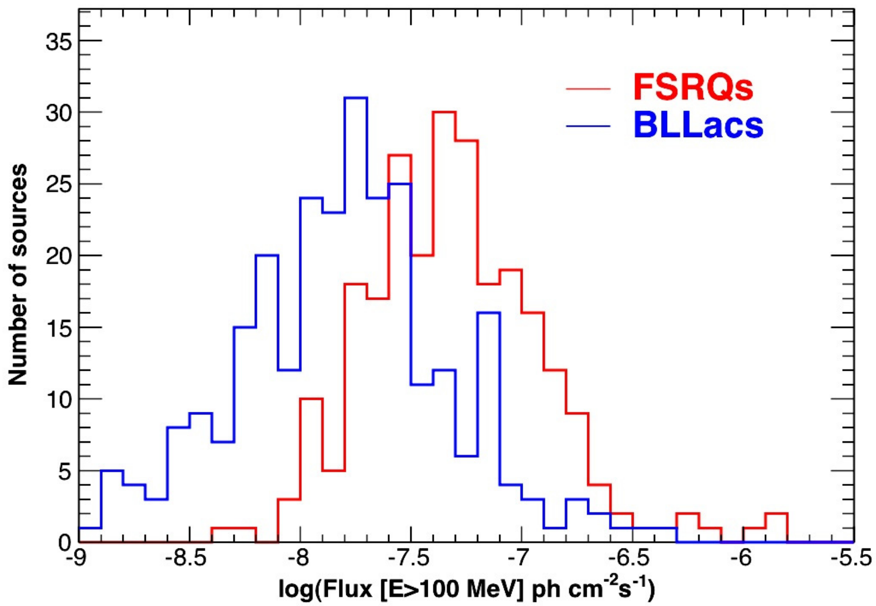
- In survey mode, the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 min exposure during this time.
- After 1 day, exposure is rather uniform (factor 2)

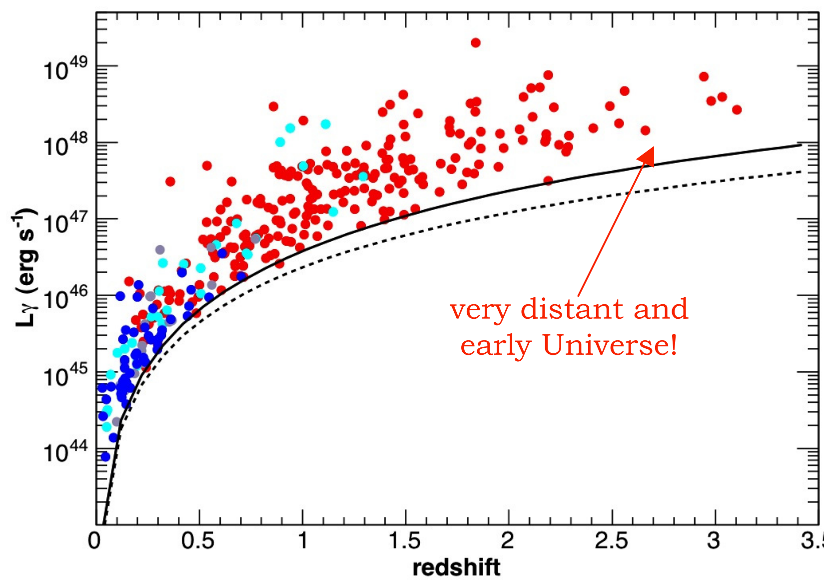
Hundreds of AGN



The first catalog of AGN detected by the Large Area Telescope (LAT) corresponds to 11 months of data collected in scientific operation mode. This First LAT AGN Catalog (1LAC) includes 671 gamma-ray sources located at high Galactic latitudes (|b|>10°) that are detected with a test statistic greater than 25 and associated statistically with AGN. Some LAT sources are associated with multiple AGN, and consequently, the catalog includes 709 AGN, comprising 300 BL Lacertae objects, 296 flat-spectrum radio quasars, 41 AGN of other types, and 72 AGNs of unknown type (Abdo et al. 2010).

Mostly Blazars

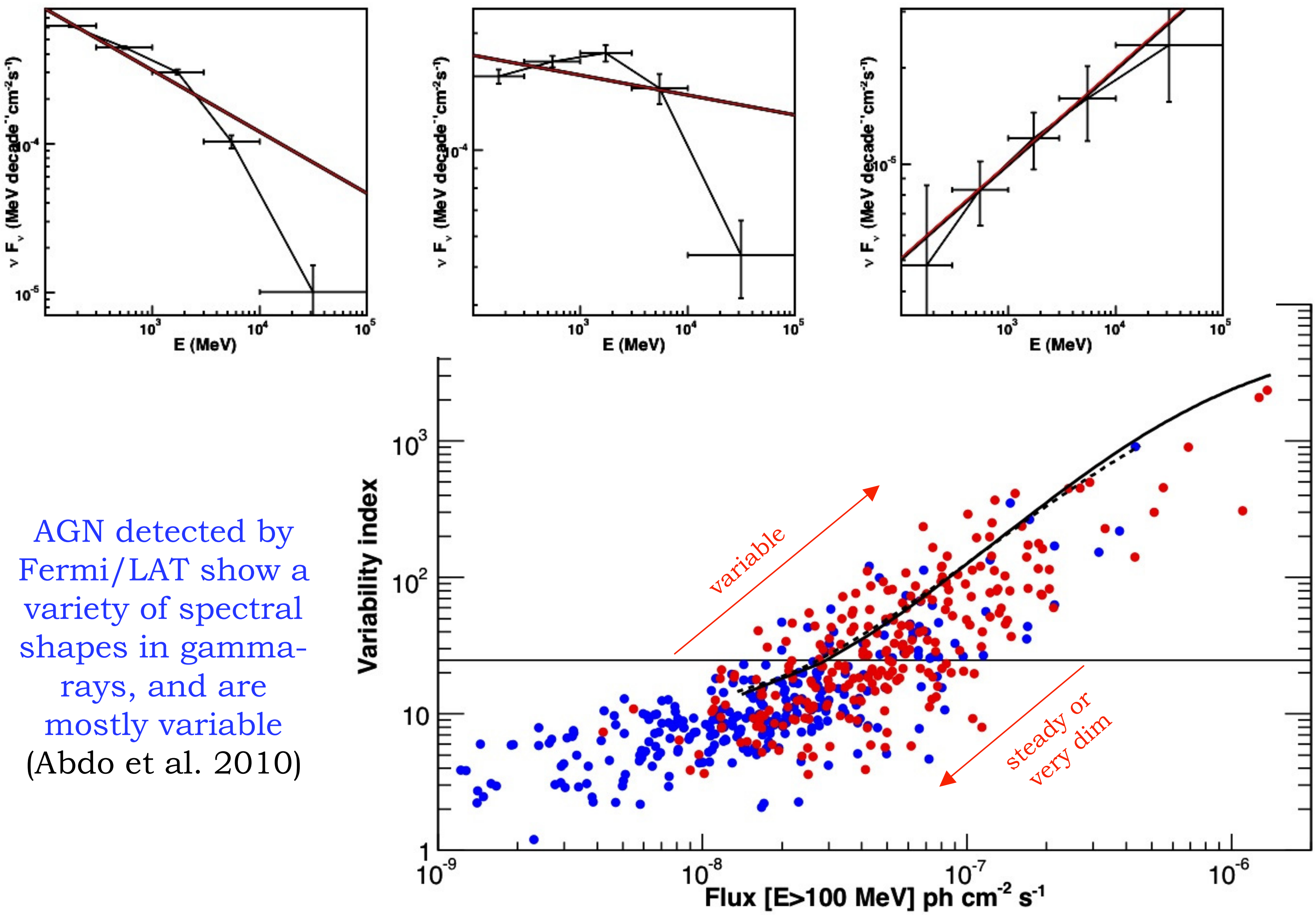




Overhelming majority of AGN detected by Fermi/LAT are blazars ("blazar" class includes Flat Spectrum Radio Quasars - FSRQs, and BL Lacertae objects - BL Lacs).

The most luminous blazars (FSRQs) are found up to redshifts of 3.5 (luminosity distances of ~30 Gpc or ~100 Gly, where the Universe was only ~10% of its age)

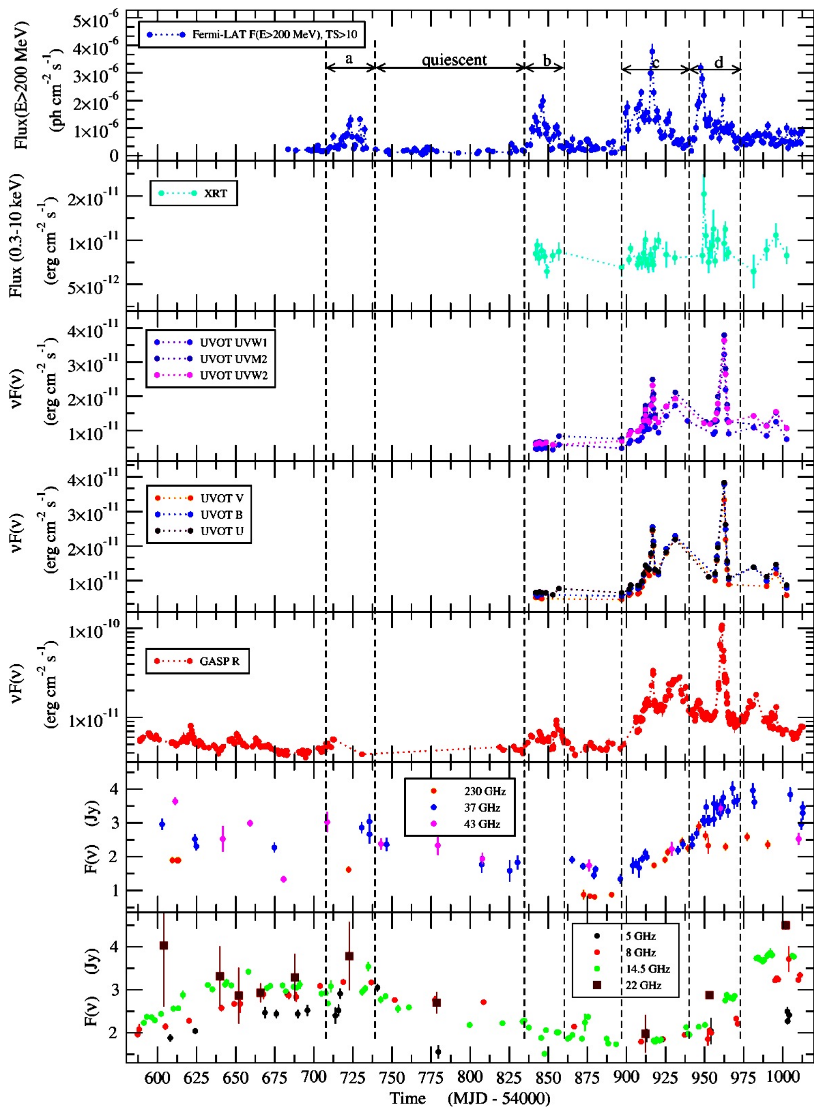
Mostly Variable

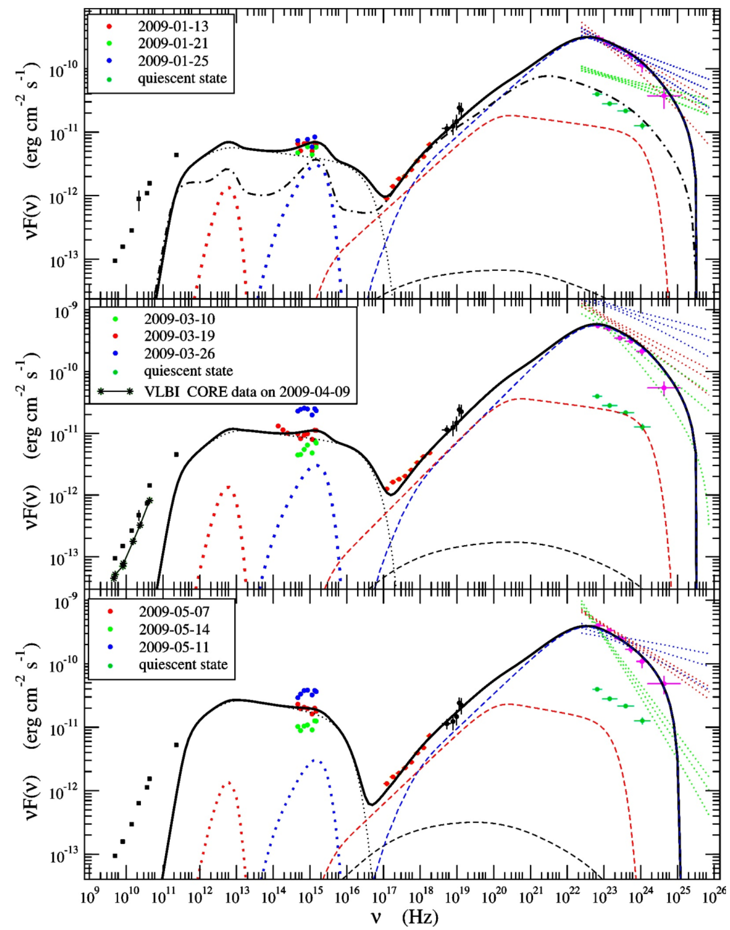


AGN detected by Fermi/LAT show a variety of spectral shapes in gamma-rays, and are mostly variable

(Abdo et al. 2010)

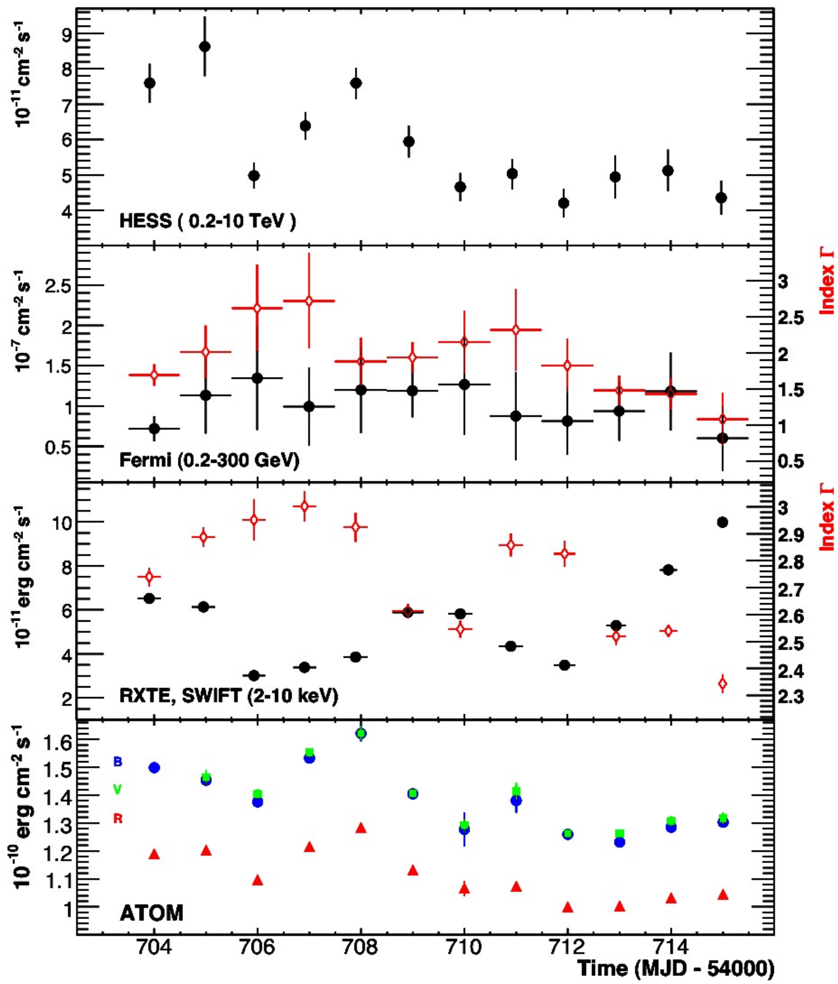
Blazars = Variable

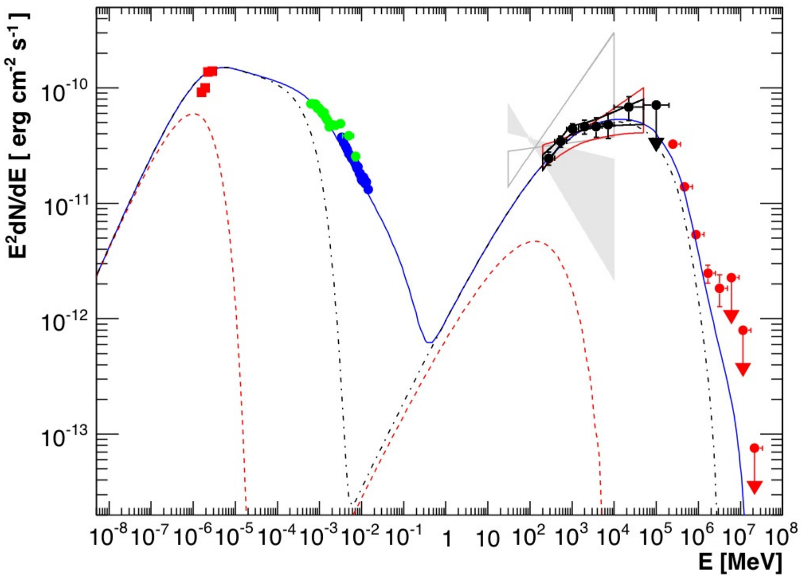




Dramatic flares of blazar sources can be observed at basically all accessible wavelengths, and are very often correlated (PKS 1510-089; Abdo et al. 2010)

Complex Variability

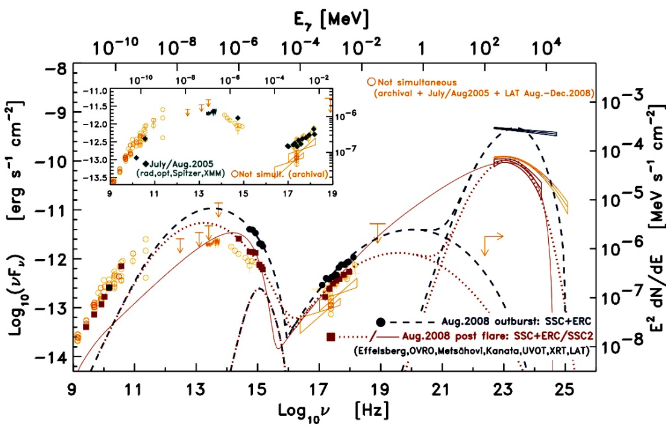


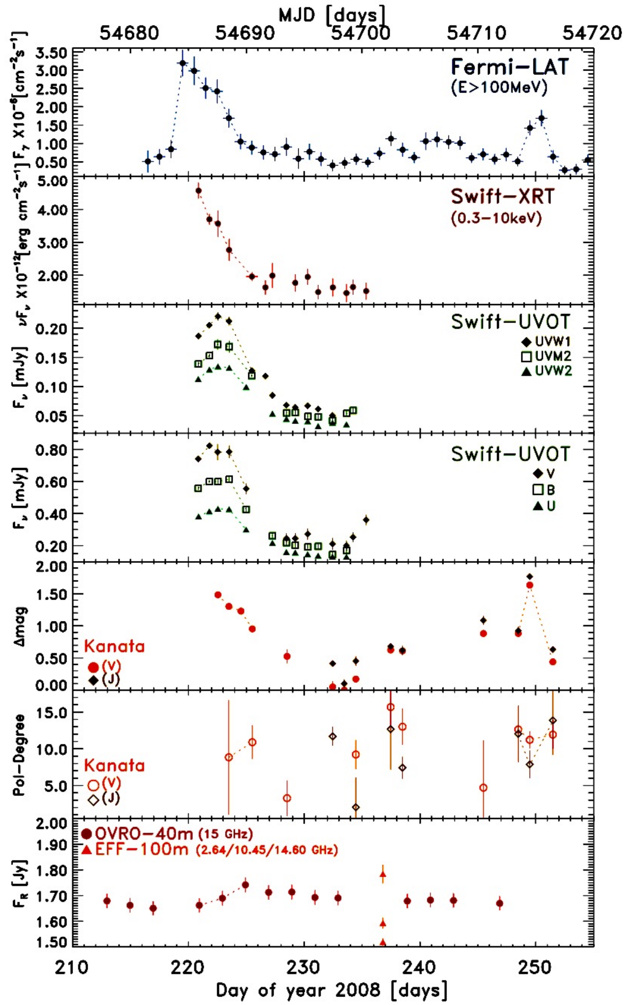


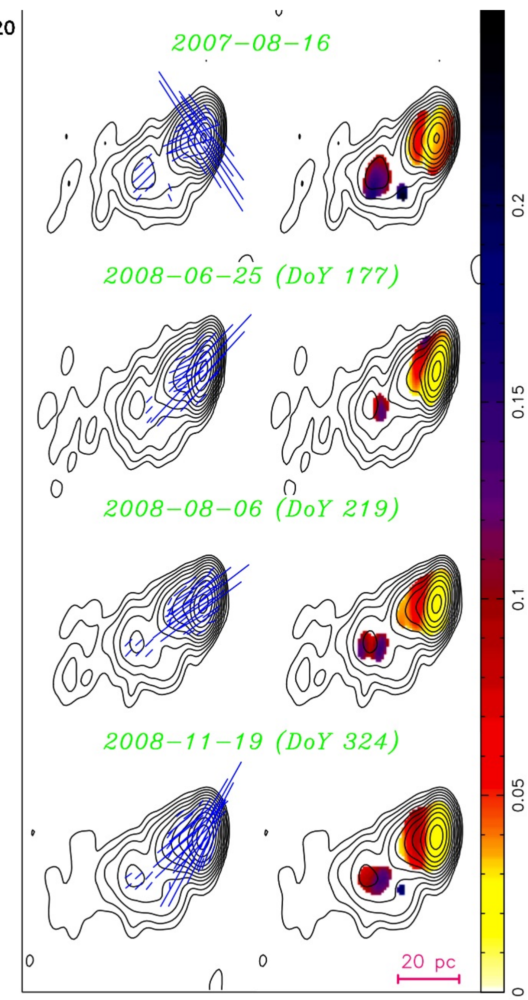
Broad-band correlations are not always the case, though… Variability timescales possibly different at different wavelengths, with the shortest ones (~200 sec) found at the observed TeV photon energies

(PKS 2155-304; Aharonian et al. 2009)

Superluminal Jets



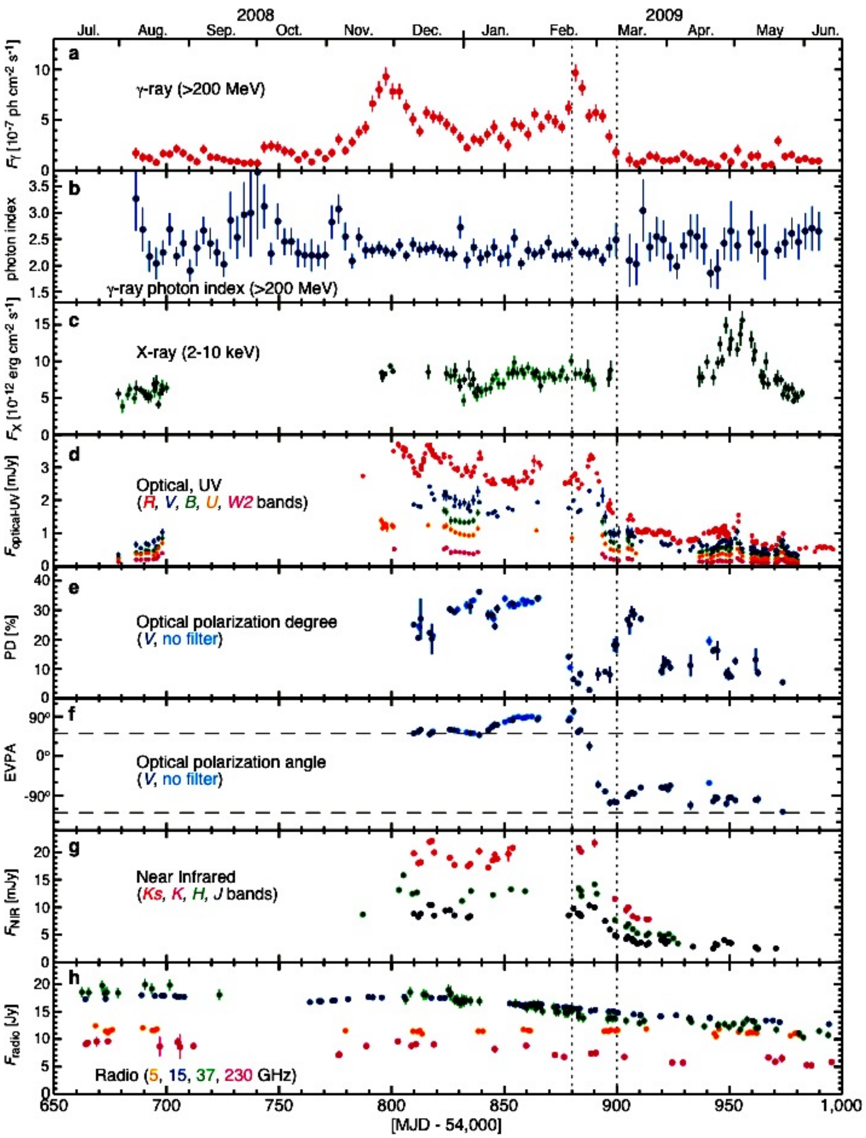


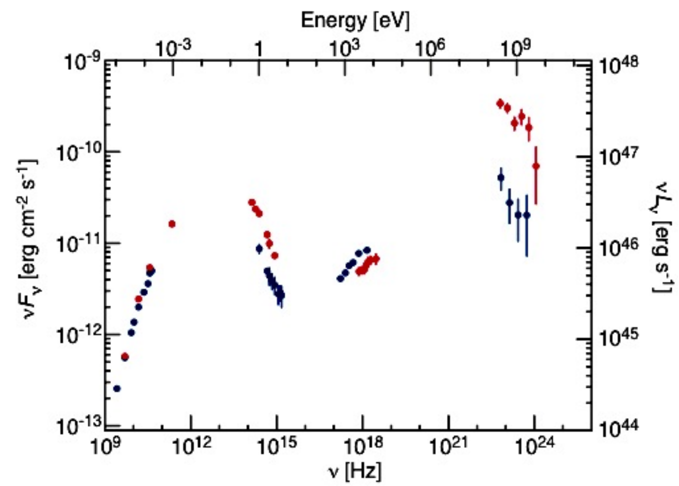


Possible association of gamma-ray flares with structural changes within the outflow (ejection of jet components with apparent superluminal velocities up to ~30c !) observed with VLBA

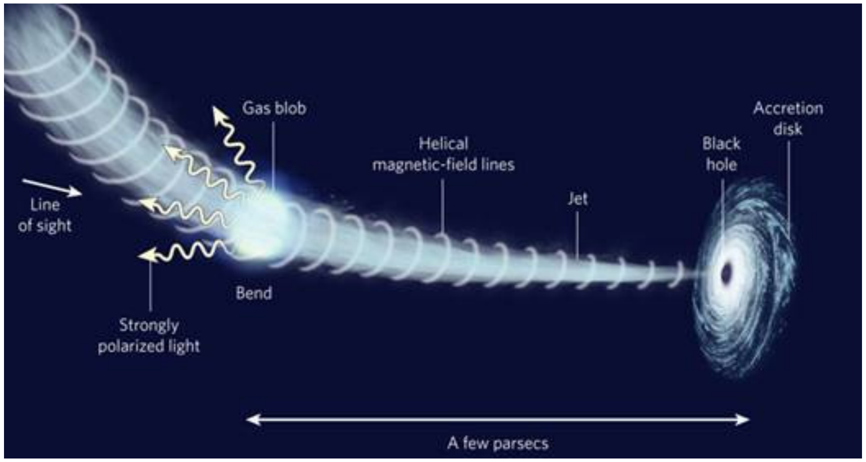
(PKS 1502+106;
Abdo et al. 2010)

Complex Jet Structure

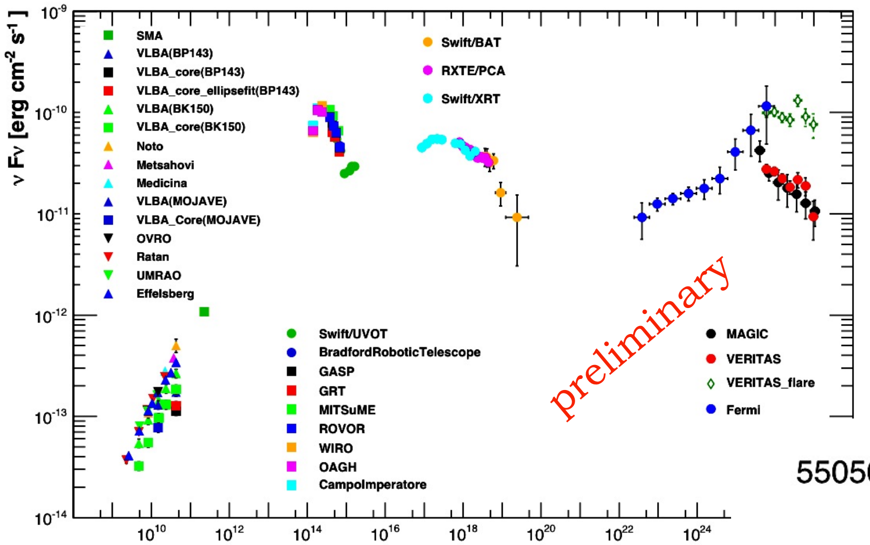




Correlation between gamma-ray flares and changes in the optical polarization angle (Kanata) gives us insight into the geometry of the unresolved blazar jets (3C 279; Abdo et al. 2010, Nature)

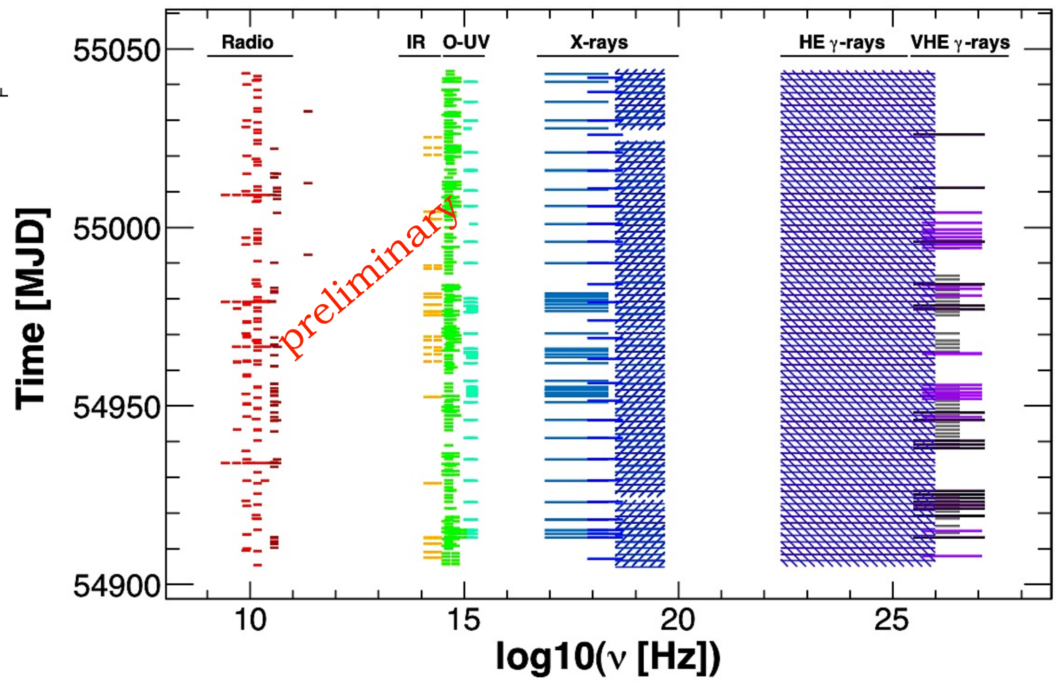


Multiwavelength Campaigns

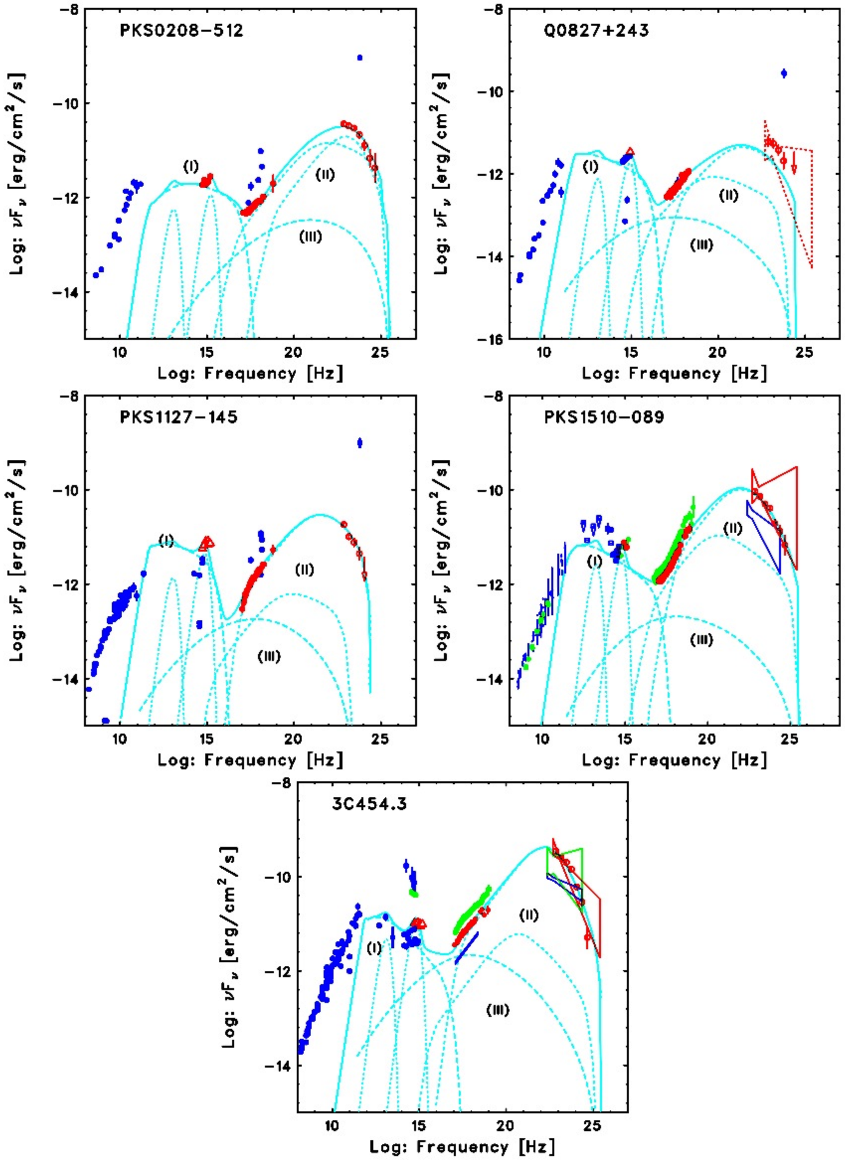


Plenty of truly multiwavelenght and truly simultaneous data to come…
These data will allow us to constrain several hardly known parameters of relativistic jets in AGN
(Mrk 501; Abdo et al., submit.)

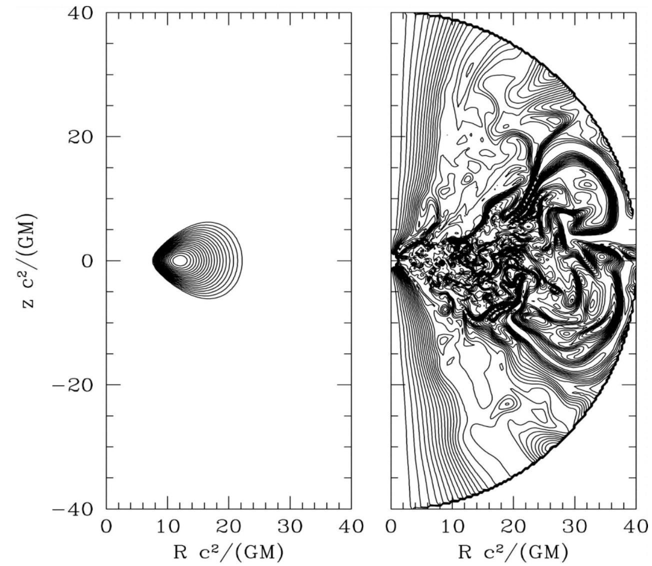
Magnetic field	$B = 0.015$ G
Emission region size	$R = 1.3 \times 10^{17}$ cm
Jet Doppler and bulk Lorentz factors	$\Gamma = \delta = 12$
Equipartition parameter	$\eta_e \equiv U'_e/U'_B = 56$
Minimum electron energy	$\gamma_{min} = 600$
Intrinsic electron break energy	$\gamma_{br,1} = 4 \times 10^4$
Cooling electron break energy	$\gamma_{br,2} = 9 \times 10^5$
Maximum electron energy	$\gamma_{max} = 1.5 \times 10^7$
Low-energy electron index	$s_1 = 2.2$
High-energy electron index	$s_2 = 2.7$
Electron index above the cooling break	$s_3 = 3.65$
Mean electron energy	$\langle\gamma\rangle \simeq 2400$
Main variability timescale	$t_{var} \simeq 4$ day
Comoving electron energy density	$U'_e \simeq 5 \times 10^{-4}$ erg cm^{-3}
Comoving magnetic field energy density	$U'_B \simeq 0.9 \times 10^{-5}$ erg cm^{-3}
Comoving energy density of synchrotron photons	$U'_{syn} \simeq 0.9 \times 10^{-5}$ erg cm^{-3}
Comoving electron number density	$N'_e \simeq 0.26$ cm^{-3}
Luminosity of the host galaxy	$L_{star} \simeq 3 \times 10^{44}$ erg s^{-1}
Jet power carried by electrons	$L_e \simeq 10^{44}$ erg s^{-1}
Jet power carried by magnetic field	$L_B \simeq 2 \times 10^{42}$ erg s^{-1}
Jet power carried by protons[a]	$L_p \simeq 3 \times 10^{43}$ erg s^{-1}
Total jet kinetic power	$L_j \simeq 10^{44}$ erg s^{-1}
Total emitted power	$L_{em} \simeq 10^{43}$ erg s^{-1}
Isotropic synchrotron luminosity	$L_{syn} \simeq 10^{45}$ erg s^{-1}
Isotropic SSC luminosity	$L_{ssc} \simeq 2 \times 10^{44}$ erg s^{-1}



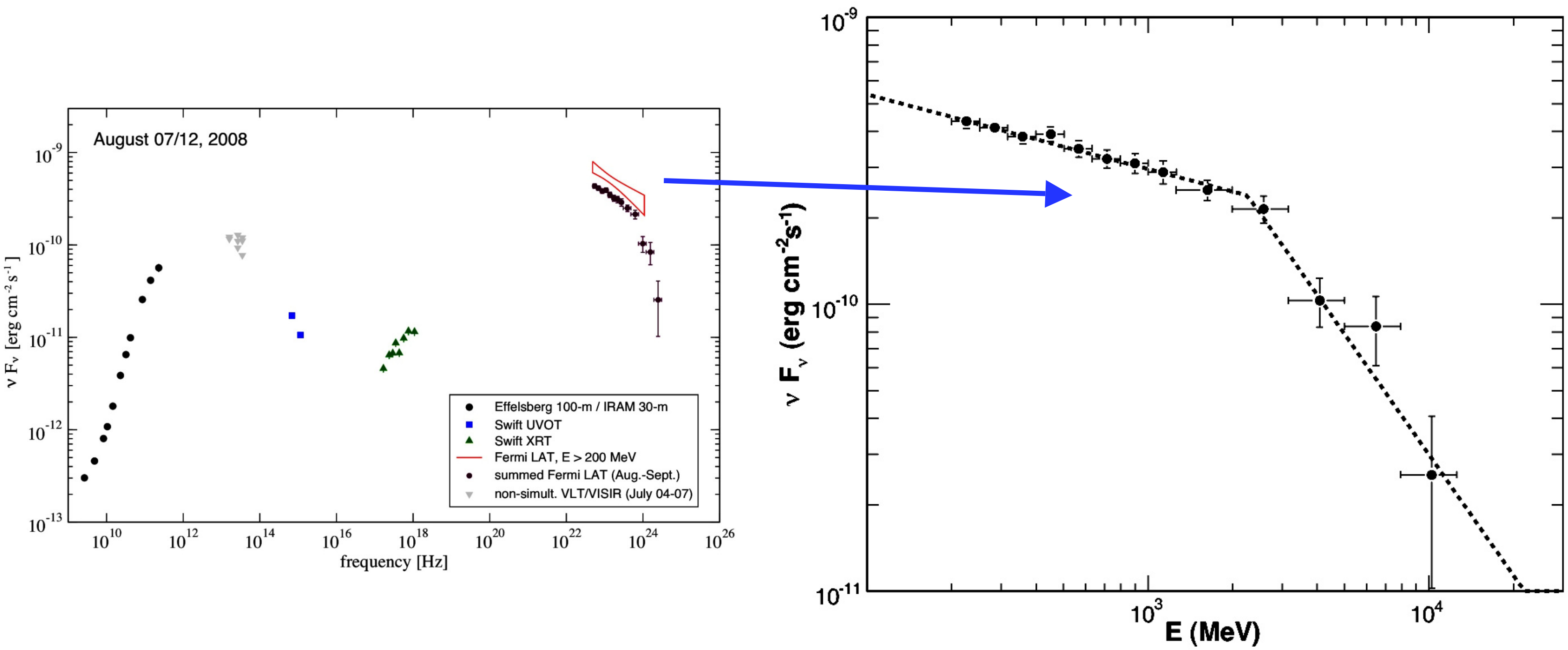
Why Variable?



Modeling of simultaneous gamma-ray and X-ray (Suzaku) data for powerful quasars suggests that the difference between the low and high-activity states in luminous blazar sources is due to the different total kinetic power of a jet, and therefore intermittent (modulated) activity of the central engine (supermassive black hole and the accretion disk; Abdo et al. 2010). This regards rather long-timescale variability (months/years). The origin of short-timescale variability remains elusive.



Spectral Breaks



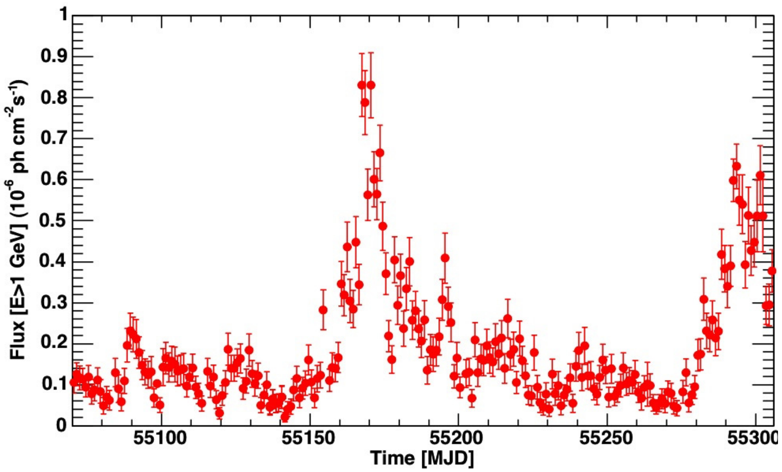
Fermi/LAT discovered that gamma-ray spectra of luminous blazars are typically of a broken power-law form, with spectral breaks located typically around the observed photon energies of few GeV.

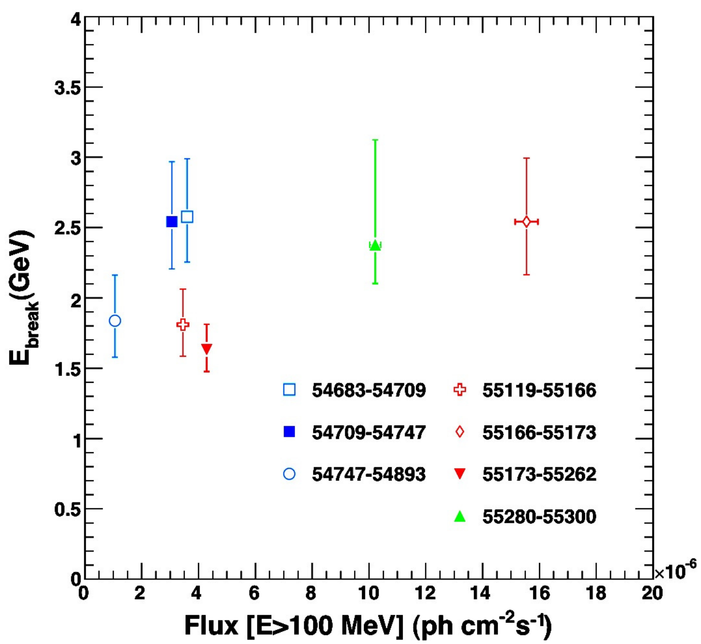
For example, a fit between 200 MeV and 300 GeV gives photon indices

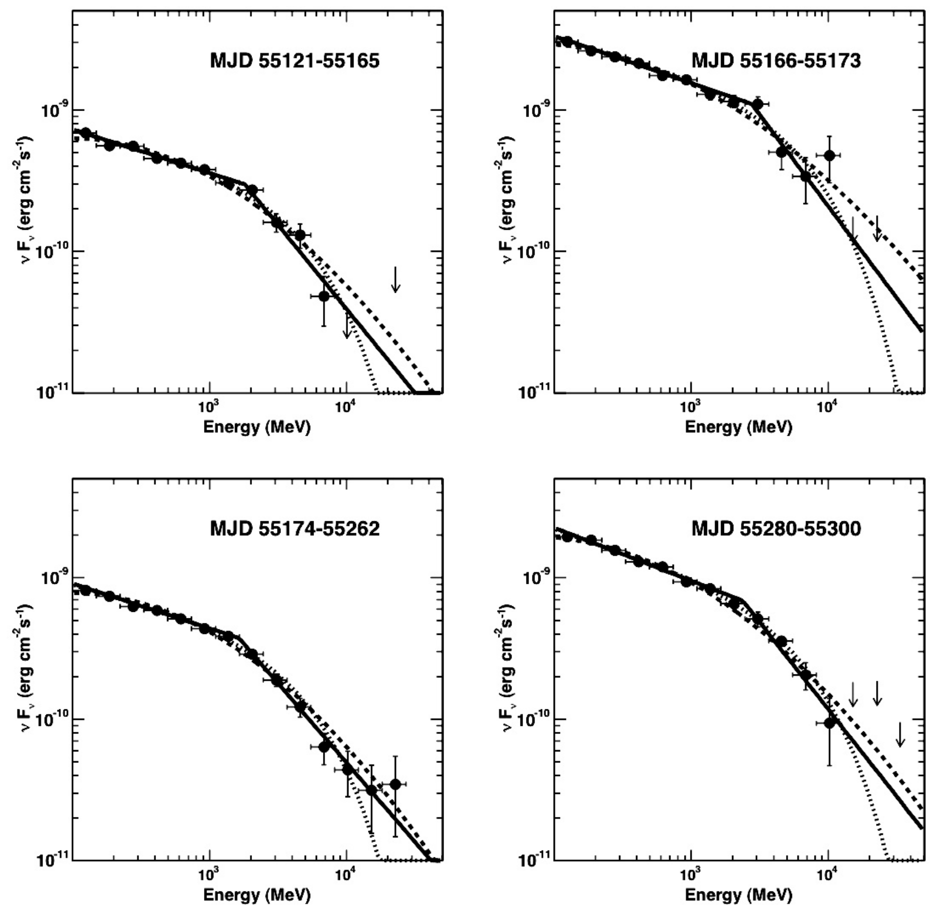
Γ_1 = 2.27±0.03, Γ_2 = 3.5±0.3, E_{br} = 2.4±0.3 GeV

(3C 454.3; Abdo et al. 2009)

What Is It Telling Us?







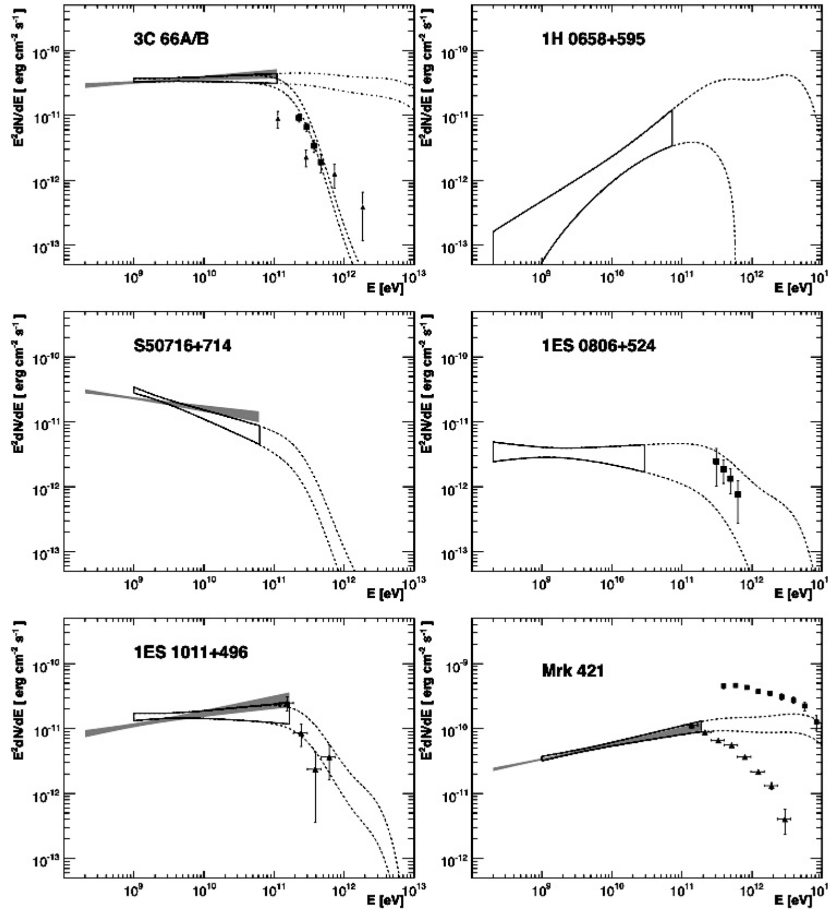
Despite dramatic (3h) variability with flares up to L(>0.1GeV) ~ 3×10^{49} erg/s, the gamma-ray spectrum seems stable

(3C 454.3; Ackermann et al. 2010; see also the talk by Y. Tanaka)

GeV/TeV Connection

Table 1. AGN detected at TeV energies.

Name	α_{J2000}	δ_{J2000}	Type[a]	z	Ref
Blazars:					
RGB J0152+017	$01^h 52^m 39.6^s$	$+01^\circ 47' 17''$	HBL	0.080	1
3C 66A	$02^h 22^m 39.6^s$	$+43^\circ 02' 08''$	IBL	0.444[b]	2,3[c]
1ES 0229+200	$02^h 32^m 48.6^s$	$+20^\circ 17' 17''$	HBL	0.140	4
1ES 0347-121	$03^h 49^m 23.2^s$	$-11^\circ 59' 27''$	HBL	0.188	5
PKS 0548-322	$05^h 50^m 40.8^s$	$-32^\circ 16' 18''$	HBL	0.069	6
RGB J0710+591	$07^h 10^m 30.1^s$	$+59^\circ 08' 20''$	HBL	0.125	7
S5 0716+714	$07^h 21^m 53.4^s$	$+71^\circ 20' 36''$	LBL	0.300	8
1ES 0806+524	$08^h 09^m 49.2^s$	$+52^\circ 18' 58''$	HBL	0.138	9
1ES 1011+496	$10^h 15^m 04.1^s$	$+49^\circ 26' 01''$	HBL	0.212	10
1ES 1101-232	$11^h 03^m 37.6^s$	$-23^\circ 29' 30''$	HBL	0.186	11
Markarian 421	$11^h 04^m 27.3^s$	$+38^\circ 12' 32''$	HBL	0.031	12
Markarian 180	$11^h 36^m 26.4^s$	$+70^\circ 09' 27''$	HBL	0.046	13
1ES 1218+304	$12^h 21^m 21.9^s$	$+30^\circ 10' 37''$	HBL	0.182	14
W Comae	$12^h 21^m 31.7^s$	$+28^\circ 13' 59''$	IBL	0.102	15
3C 279	$12^h 56^m 11.2^s$	$-05^\circ 47' 22''$	FSRQ	0.536	16
PKS 1424+240	$14^h 27^m 00.4^s$	$+23^\circ 48' 00''$	IBL	...	17
H 1426+428	$14^h 28^m 32.7^s$	$+42^\circ 40' 21''$	HBL	0.129	18
PG 1553+113	$15^h 55^m 43.0^s$	$+11^\circ 11' 24''$	HBL	$0.09-0.78$	19
Markarian 501	$16^h 53^m 52.2^s$	$+39^\circ 45' 37''$	HBL	0.034	20
1ES 1959+650	$19^h 59^m 59.9^s$	$+65^\circ 08' 55''$	HBL	0.048	21
PKS 2005-489	$20^h 09^m 25.4^s$	$-48^\circ 49' 54''$	HBL	0.071	22
PKS 2155-304	$21^h 58^m 52.1^s$	$-30^\circ 13' 32''$	HBL	0.117	23
BL Lacertae	$22^h 02^m 43.3^s$	$+42^\circ 16' 40''$	LBL	0.069	24,25[c]
1ES 2344+514	$23^h 47^m 04.8^s$	$+51^\circ 42' 18''$	HBL	0.044	26
H 2356-309	$23^h 59^m 07.9^s$	$-30^\circ 37' 41''$	HBL	0.167	27
Others					
3C 66B	$02^h 23^m 11.4^s$	$+42^\circ 59' 31''$	FR1	0.02106	28
M 87	$12^h 30^m 49.4^s$	$+12^\circ 23' 28''$	FR1	0.004233	29
Centaurus A	$13^h 25^m 27.6^s$	$-43^\circ 01' 09''$	FR1	0.00183	30



Emission above 100 GeV photon energies can be detected from the ground by the Imaging Atmospheric Cherenkov Telescopes (Whipple, CANGAROO, Magic, HESS, VERITAS)

Extrapolations of Fermi spectra to the TeV regime with the absorption of very high-energy gamma-rays taken into account (Abdo et al. 2009)

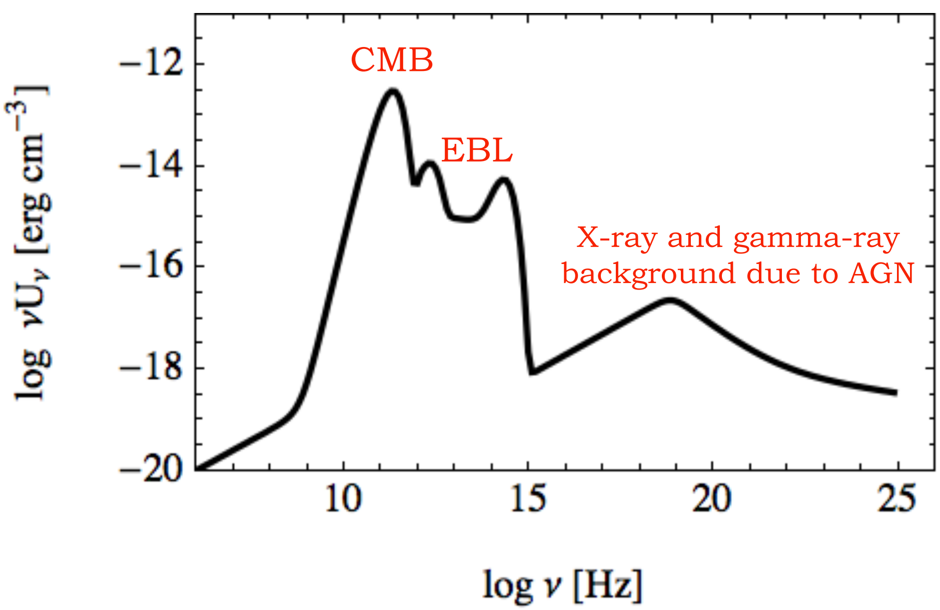
Absorption of Gamma-rays

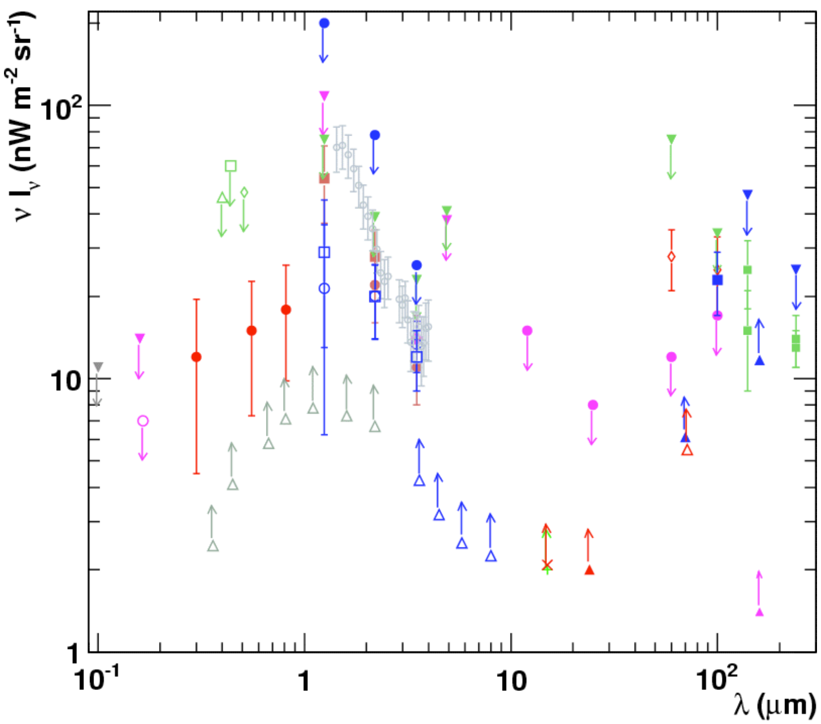
The Universe is not transparent to very high-energy gamma-rays (Nikishov 1962, Gould & Schreder 1966)! This is because of a photon-photon pair production involving extragalactic background radiation, and in particular Extragalactic Background Light at optical and near-infrared frequencies (EBL: 0.1-1000 μm). As a result, only relatively local sources ($z < 0.2$) can be detected at TeV photon energies. Direct measurements of EBL are however difficult due to strong foreground emission. EBL spectral shape reflects star and dust formation history, and therefore probes galaxy evolution models. Even small uncertainties in the absorbing photon number density, $n_0(\varepsilon_0) \propto \tau_{\gamma\gamma}(\varepsilon_0)$, translate to large uncertainties in the gamma-ray attenuation.

Photon-photon annihilation:

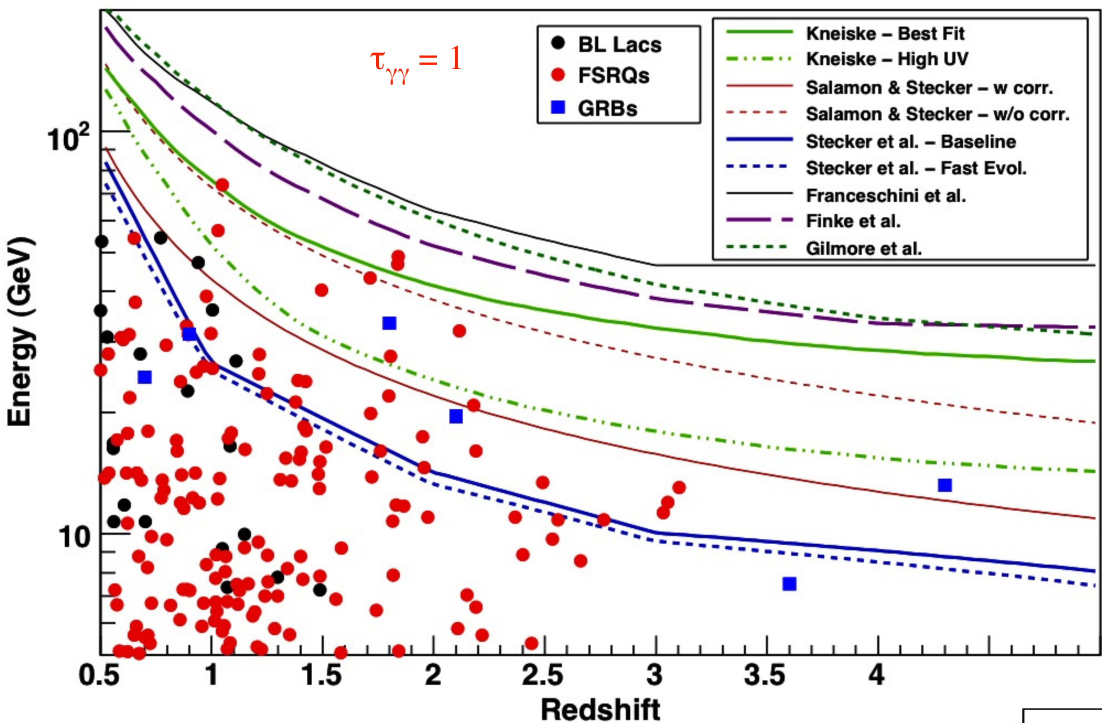
$\langle\sigma_{\gamma\gamma}\rangle \sim 0.2\ \sigma_T \times \delta(\varepsilon\varepsilon_0/m_e^2c^4 - 1)$

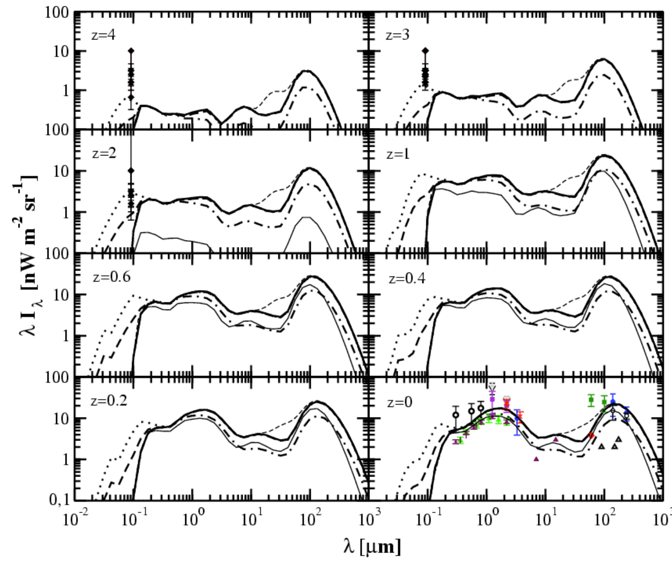
$S_{obs}(\varepsilon) = S_{int}(\varepsilon) \times \exp[\tau_{\gamma\gamma}(\varepsilon)]$

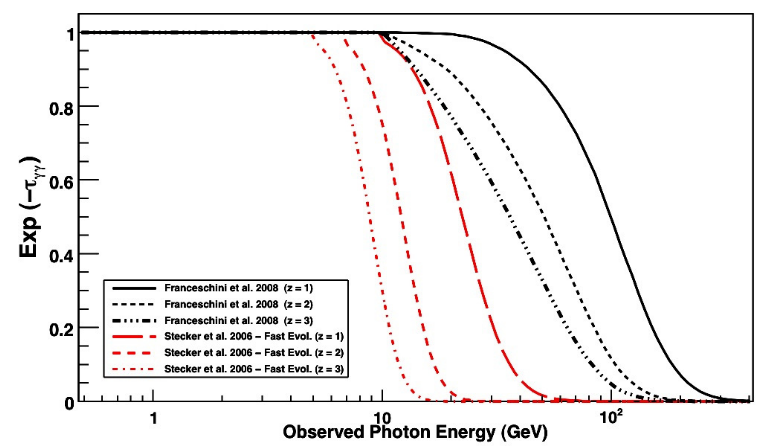




Constraining EBL





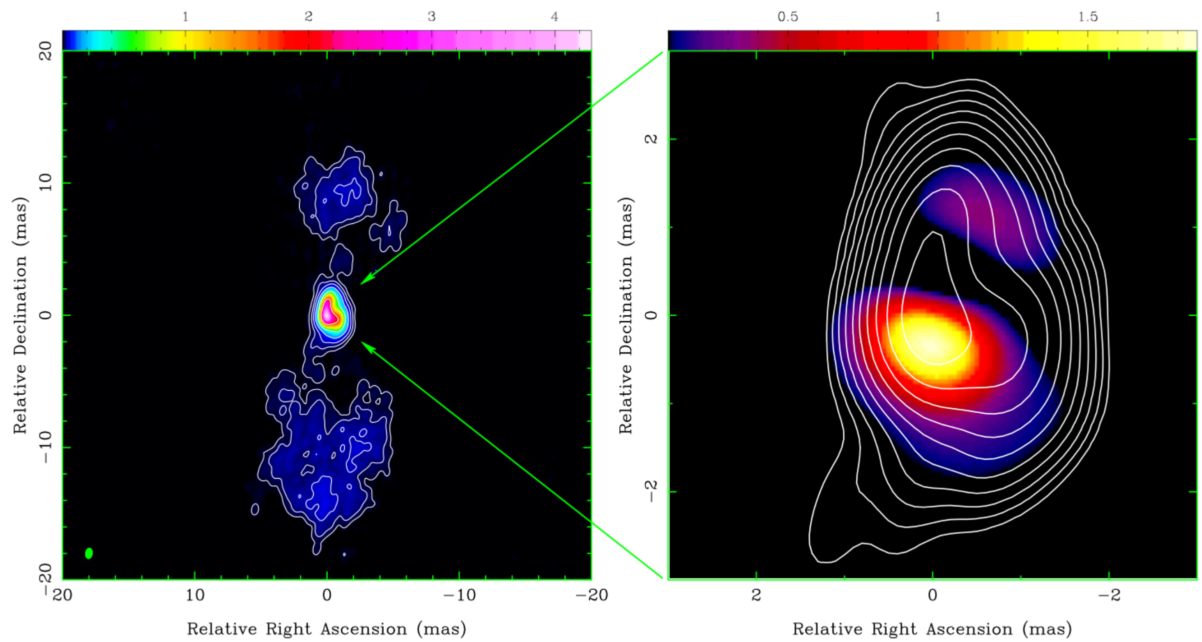


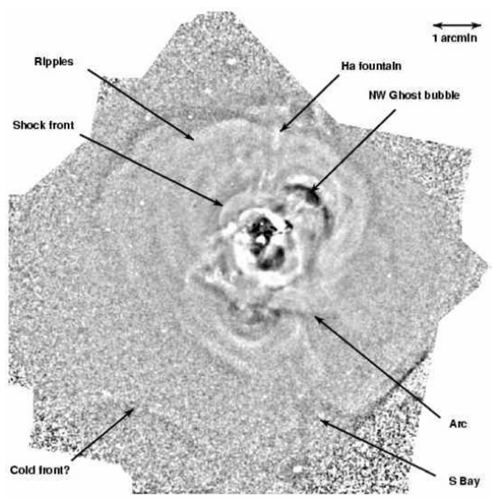
With the impressive photon and source statistics, Fermi/LAT can constrain hardly known but important spectral shape of EBL

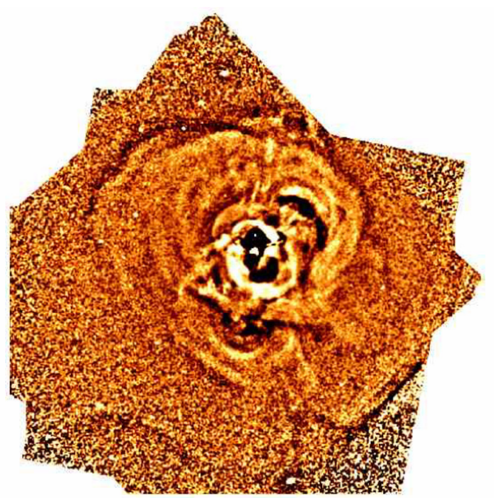
(Abdo et al. 2010)

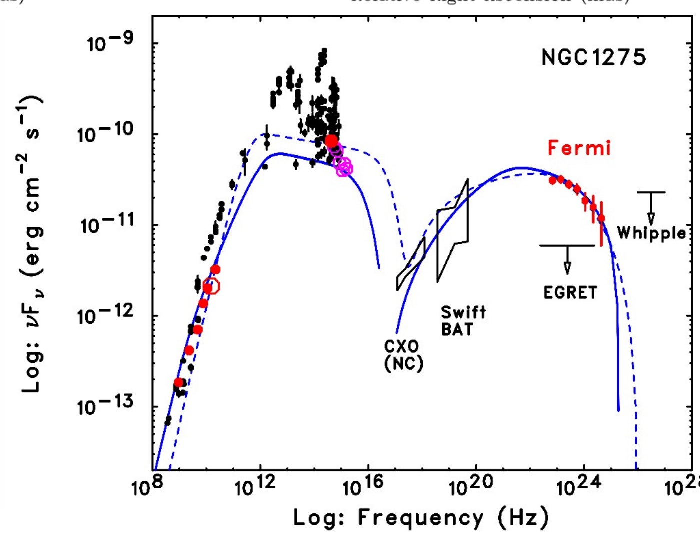
Radio Galaxies: A New Class

NGC 1275 =
Perseus A
(Abdo et al. 2009,
Acciari et al. 2009,
Kataoka et al. 2010)
Source located in
the center of a
cluster of galaxies

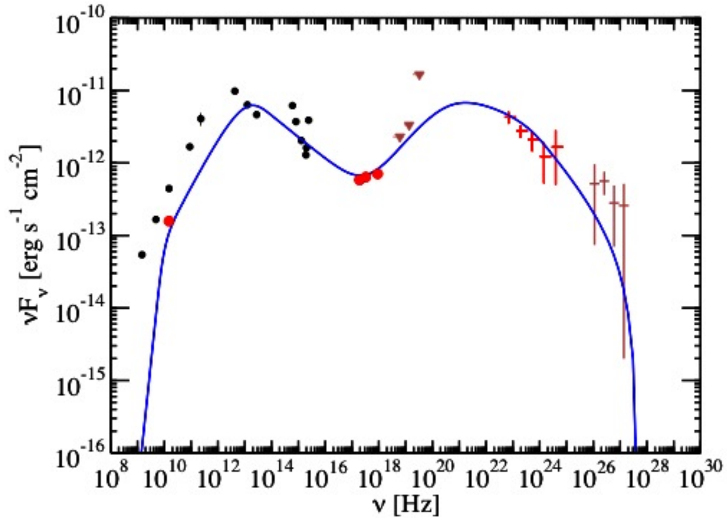


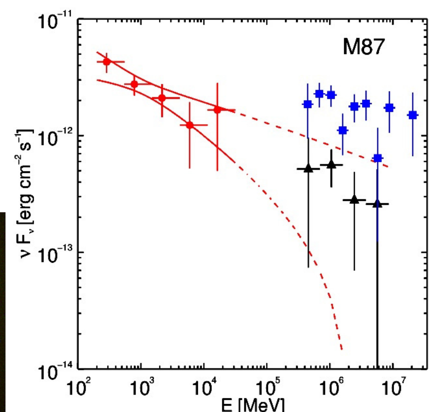


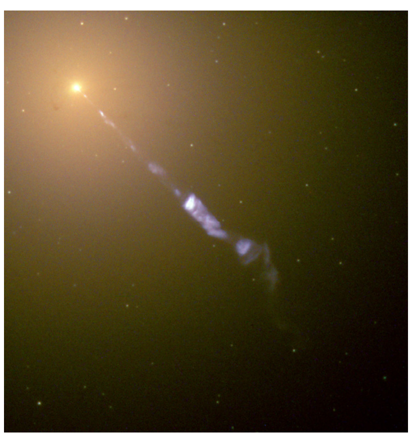


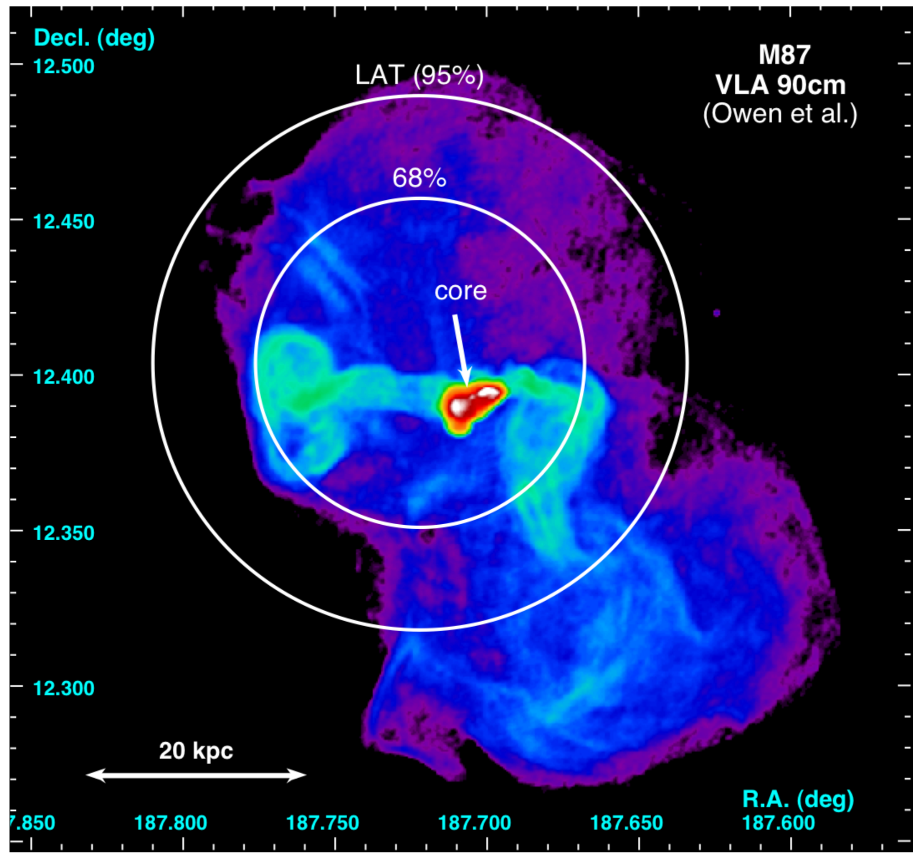


Radio Galaxies: Famous Ones





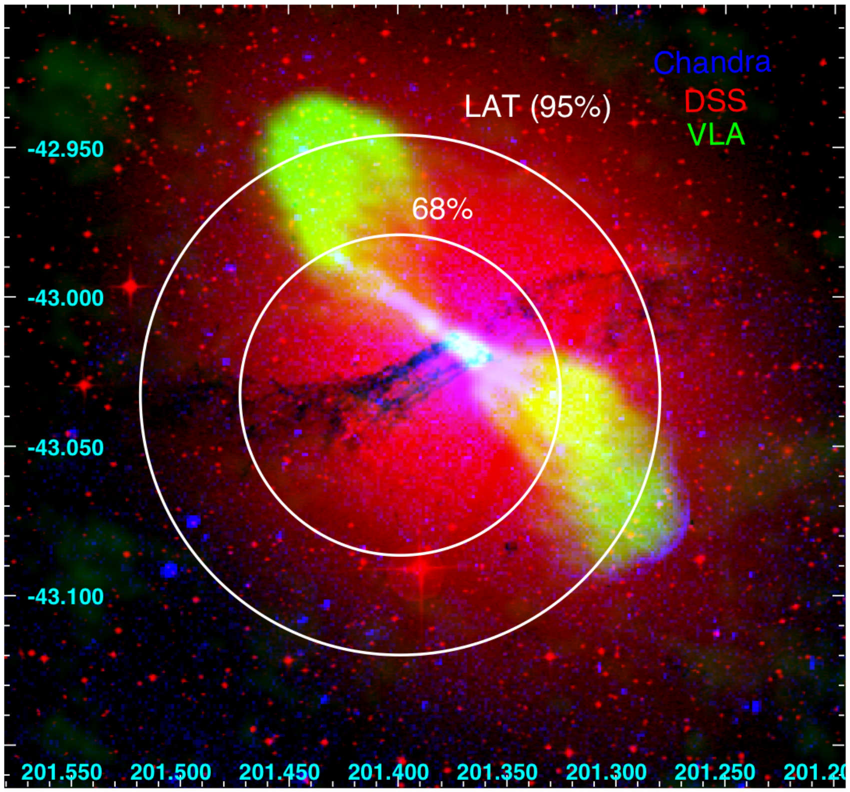


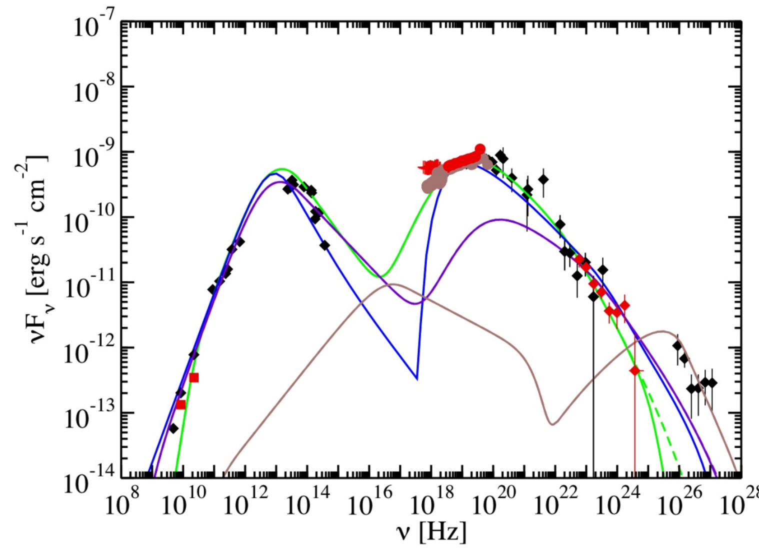


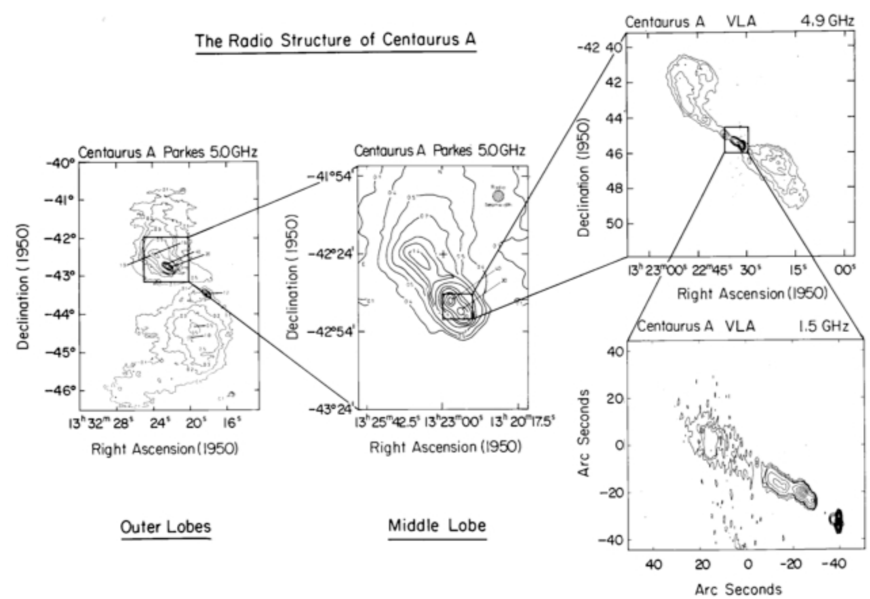
M 87 = Virgo A (Abdo et al. 2009)

First jet ever discovered (Curtis 1918)

Radio Galaxies: Our Neighbors

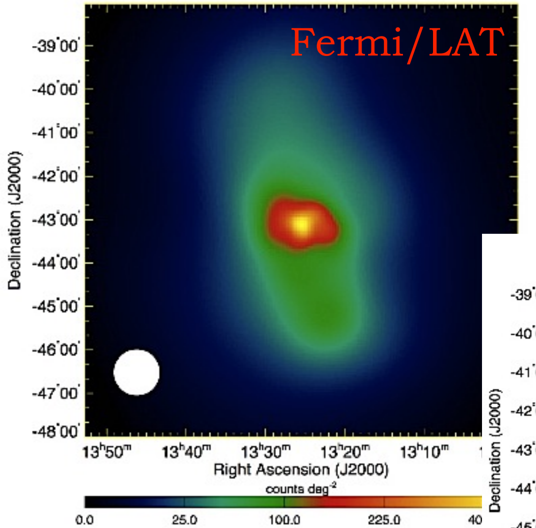


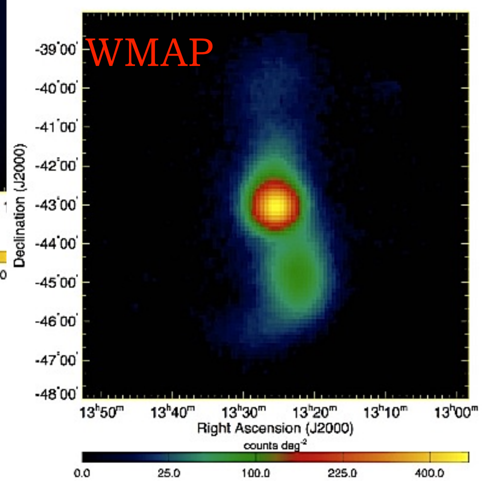


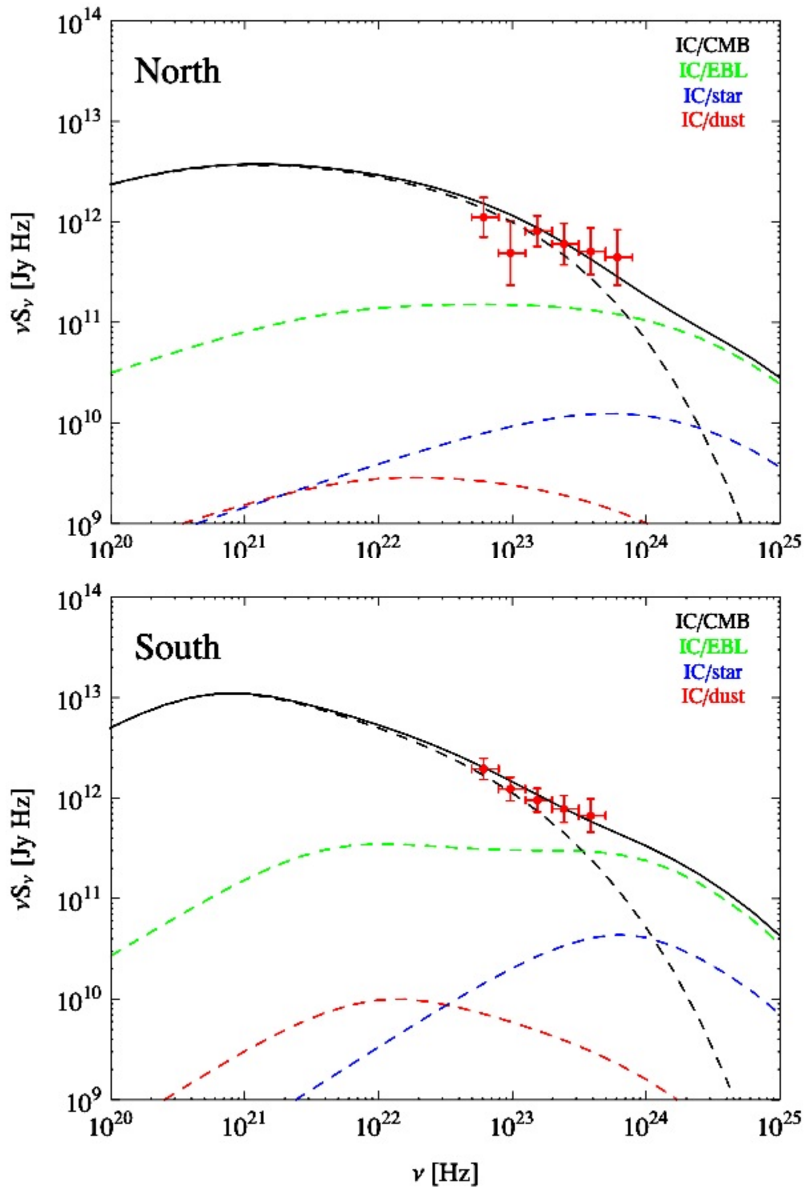


Centaurus A:
only 3.4 Mpc away!
(Abdo et al. 2010)
Very complex radio structure

Resolving Giant Lobes







Fermi/LAT (similarly to WMAP) resolved giant lobes of Centaurus A radio galaxy (~8 deg on the sky, ~1 Mpc physical size)

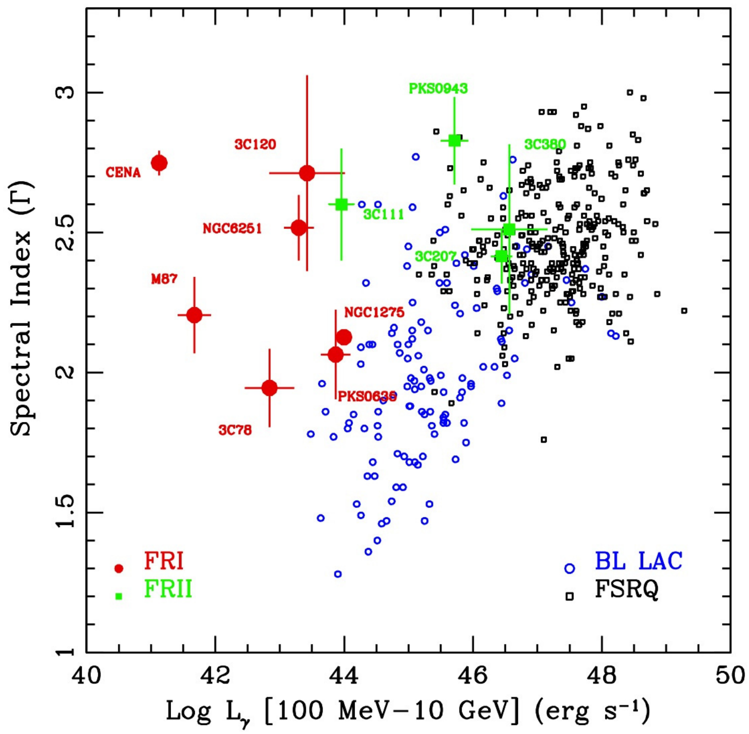
The observed gamma-ray emission is well modeled as being due to inverse-Comptonization of cosmic background radiation by relict ultrelativistic electrons injected into the giant lobes by jets ~100 Myr ago

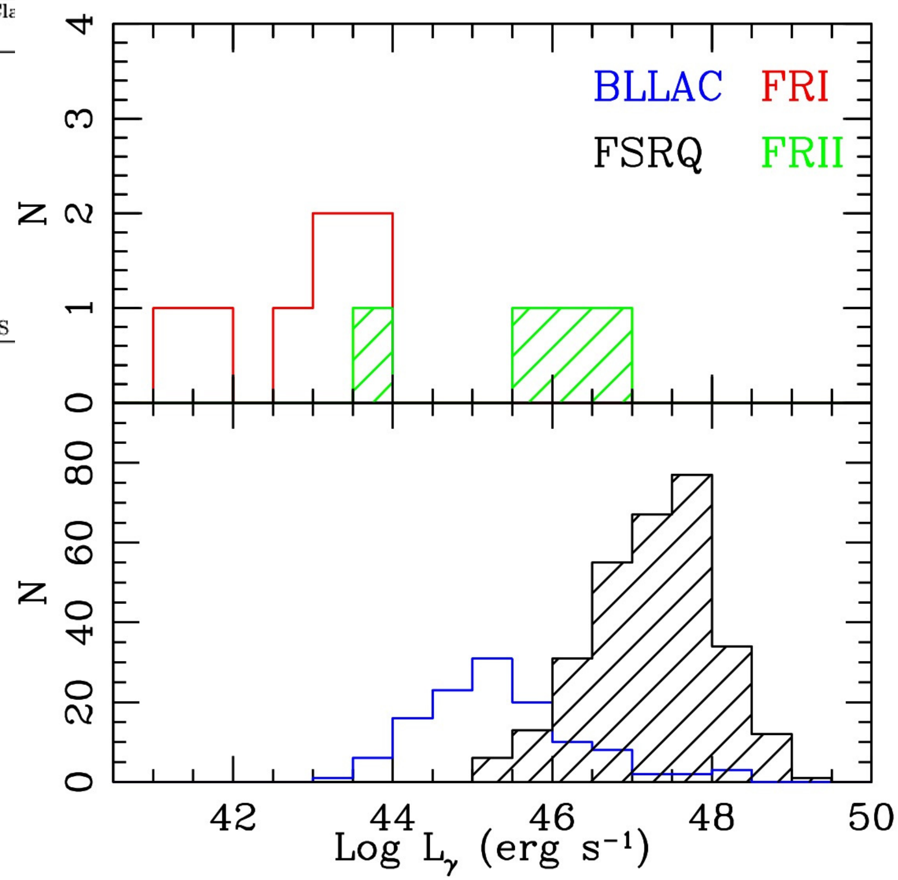
(Abdo et al. 2010, Science)

“Misaligned Blazars”

Table 1: The Sample

Object	1FGL Name	RA (J2000)	Dec (J2000)	Redshift	Cla Radio
3C 78/NGC 1218	1FGLJ0308.3+0403	03 08 26.2	+04 06 39	0.029	FRI
3C 84/NGC 1275	1FGLJ0319.7+4130	03 19 48.1	+41 30 42	0.018	FRI
3C 111	1FGLJ0419.0+3811	04 18 21.3	+38 01 36	0.049	FRII
3C 120		04 33 11.1	+05 21 16	0.033	FRI
PKS 0625-354	1FGLJ0627.3−3530	06 27 06.7	−35 29 15	0.055	FRI[b]
3C 207	1FGLJ0840.8+1310	08 40 47.6	+13 12 24	0.681	FRII
PKS 0943-76	1FGLJ0940.2−7605	09 43 23.9	− 76 20 11	0.27	FRII
M87/3C 274	1FGLJ1230.8+1223	12 30 49.4	+12 23 28	0.004	FRI
Cen A	1FGLJ1325.6-4300	13 25 27.6	− 43 01 09	0.0009[c]	FRI
NGC 6251	1FGLJ1635.4+8228	16 32 32 .0	+82 32 16	0.024	FRI
3C 380	1FGLJ1829.8+4845	18 29 31.8	+48 44 46	0.692	FRII/CSS





Relativistic jets in radio galaxies are viewed at larger inclinations (than in blazars); hence their lower observed gamma-ray luminosities
(Abdo et al. 2010)

Conclusions

• AGN (and blazars in particular) are fascinating objects providing the best insight into relativistic plasma and high energy astrophysics in general

• AGN dominate the gamma-ray sky

• Fermi/LAT is extremely well suited instrument for studying AGN at GeV photon energies

• After two years of the Fermi/LAT operation, an unprecedented amount of data regarding AGN has been collected

• New examples and classes of gamma-ray - emitting AGN are being discovered continuously

• Multiwavelength studies and cross-field collaboration will enable a better understanding of AGN in a near future