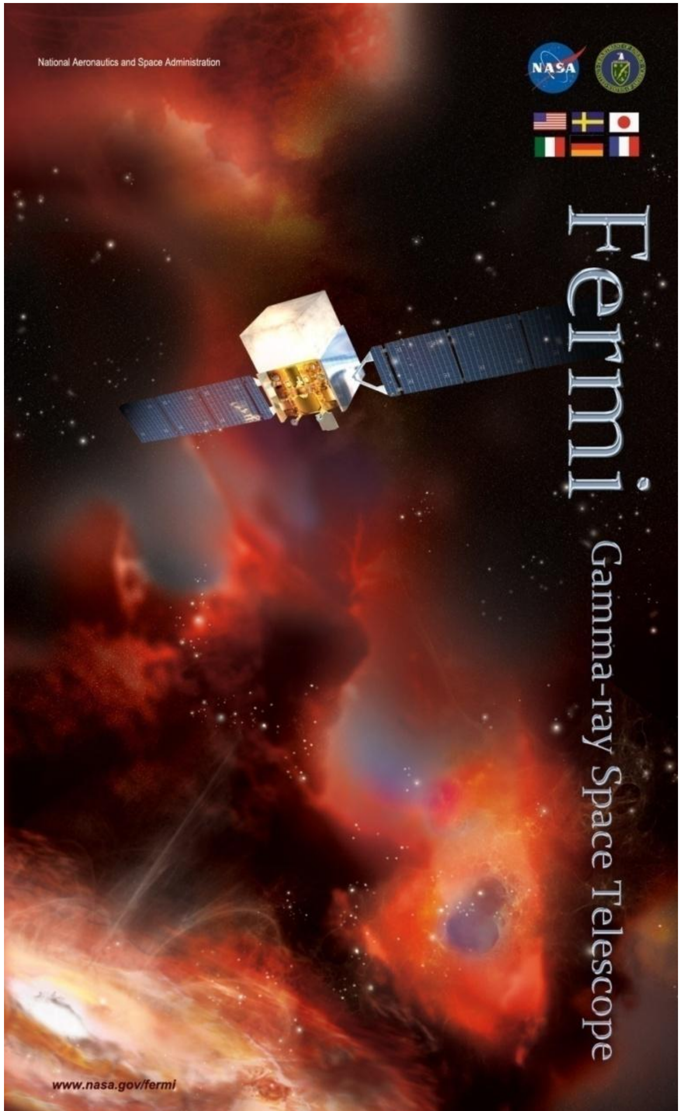


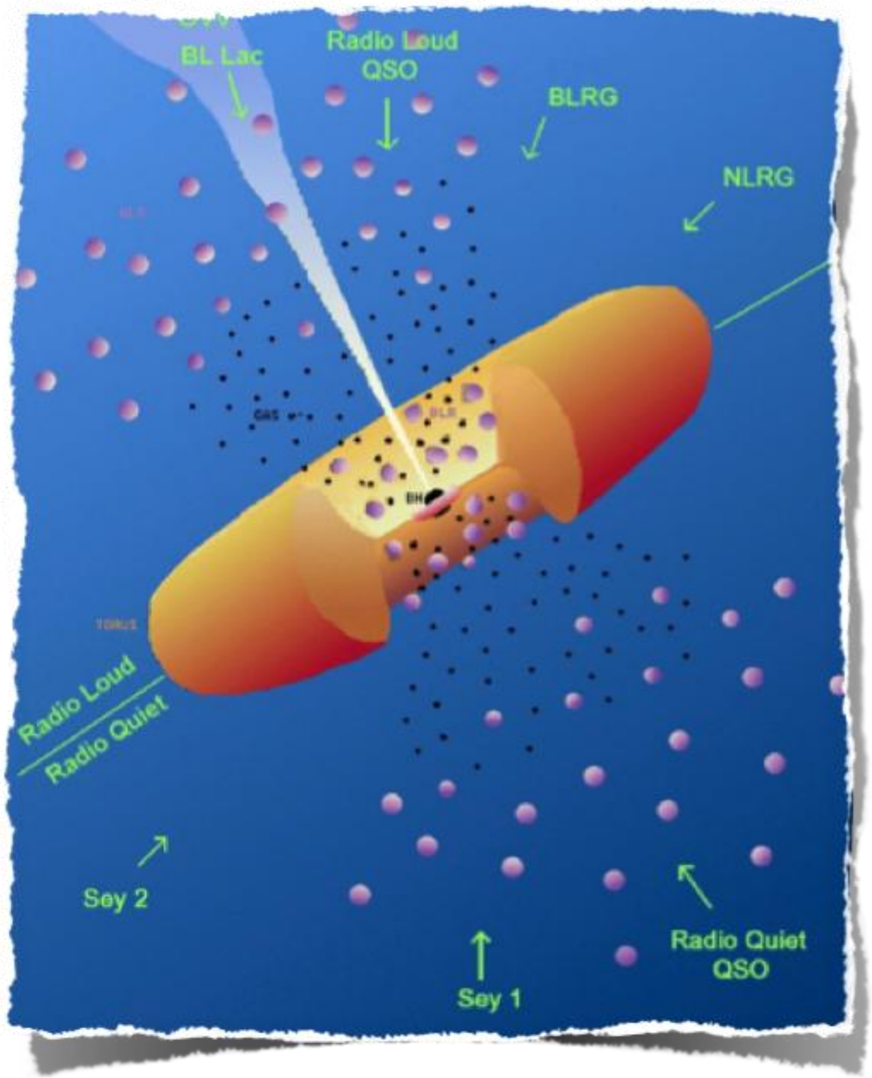
The third Fermi LAT AGN catalogue and beyond

Filippo D'Ammando

(DIFA and INAF-IRA Bologna)

on behalf of the Fermi LAT Collaboration

Different classes of AGN

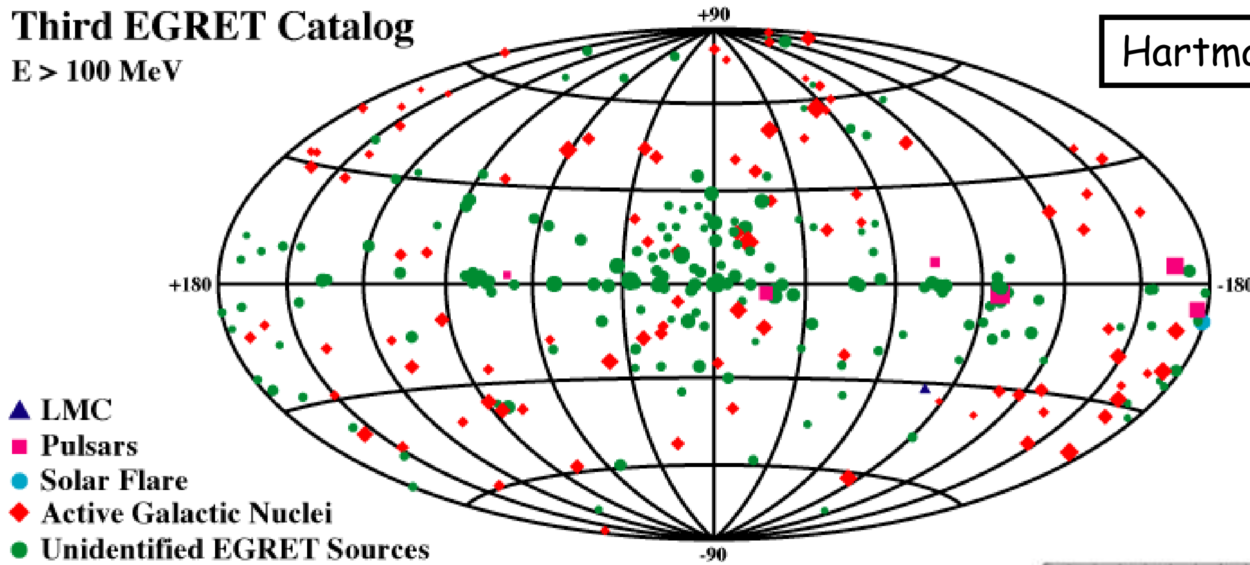


- **Quasars**
  Radio-quiet or radio-loud quasars
- **BL Lacertae Objects**
- **Radio Galaxies**
  Broad or narrow line radio galaxies (BLRGs, NLRGs)
  Fanaroff-Riley class I or II
- **Seyfert Galaxies**
  Seyfert galaxies type 1 - 2
  Narrow-Line Seyfert galaxies
- **Low-Luminosity AGN**
  Low-Ionization Nuclear Emission-Line Region Galaxies
  "Regular" spiral like Sgr A*…

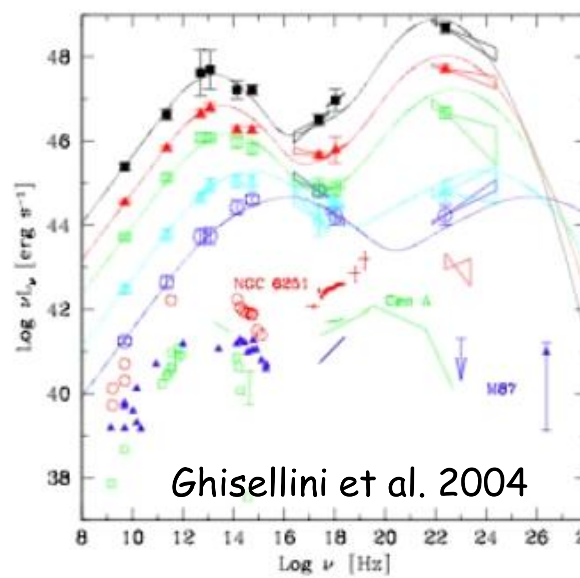
All AGN are able to emit up to the γ-ray energy domain?

EGRET Era

Hartmann et al. 1999



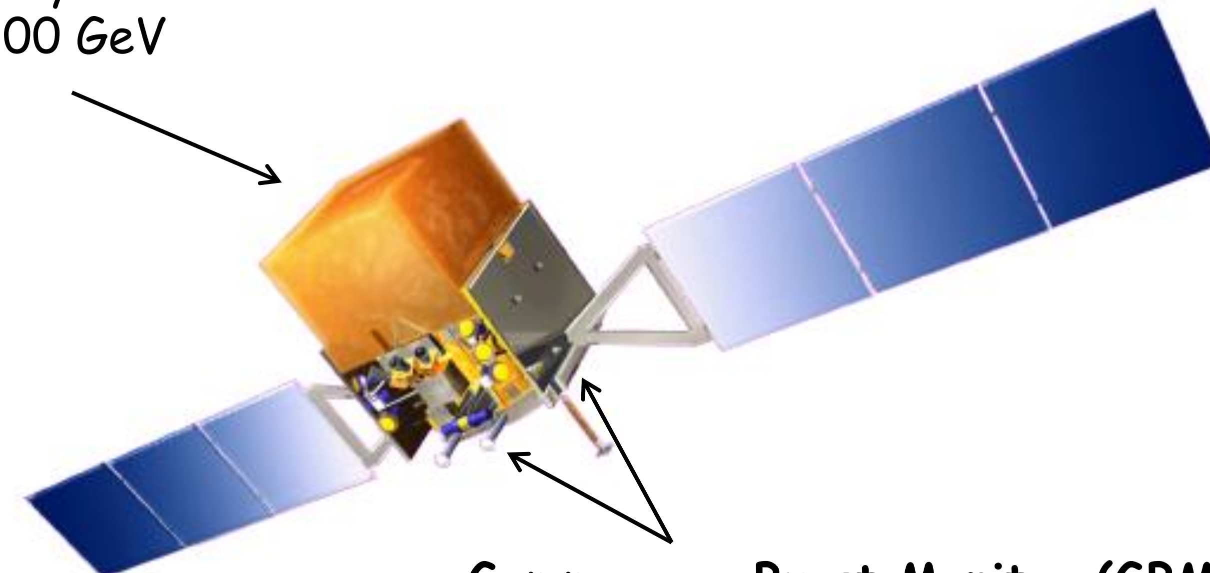
- 67 blazars detected by EGRET
- Mostly FSRQ (75% FSRQ, 25% BL Lacs)
- Only 3 *tentative* detections of radio galaxies:
  - Centaurus A
  - NGC 6251 (Mukherjee et al. 2002)
  - 3C 111 (Hartmann et al. 2008)



Ghisellini et al. 2004

The Fermi Gamma-ray Space Telescope

Large Area Telescope (LAT)
20% of the sky at any instant
from 20 MeV to >300 GeV

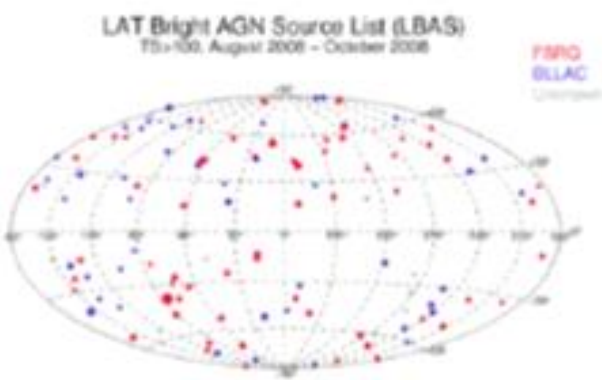


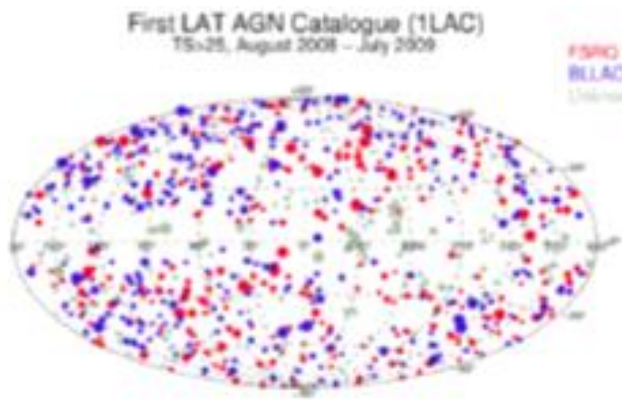
Gamma-ray Burst Monitor (GBM)
entire unocculted sky
transients from 8 keV to 40 MeV

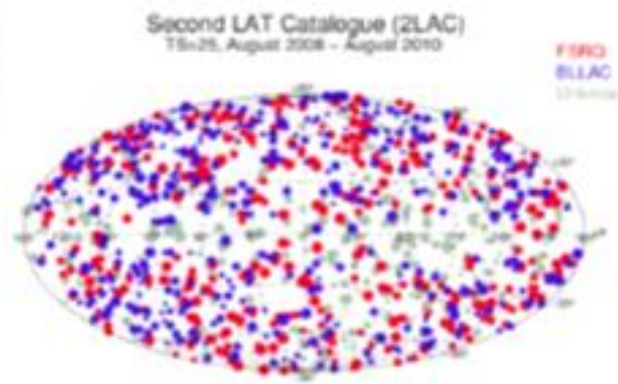
Launched from Cape Canaveral Air Station on 11 June 2008
nearly circular orbit 565 km, 25.6°

AGN and Fermi Era

3 months LAT data	11 months LAT data	24 months LAT data







LBAS-high latitude:
58 FSRQs
42 BL Lacs
6 AGNs

Abdo et al. 2009

1LAC-clean sample:
248 FSRQs
275 BL Lacs
50 Blazars with unknown type
26 AGNs

Abdo et al. 2010

2LAC-clean sample:
310 FSRQs
395 BL Lacs
156 Blazars with unknown type
24 AGNs

Nolan et al. 2012

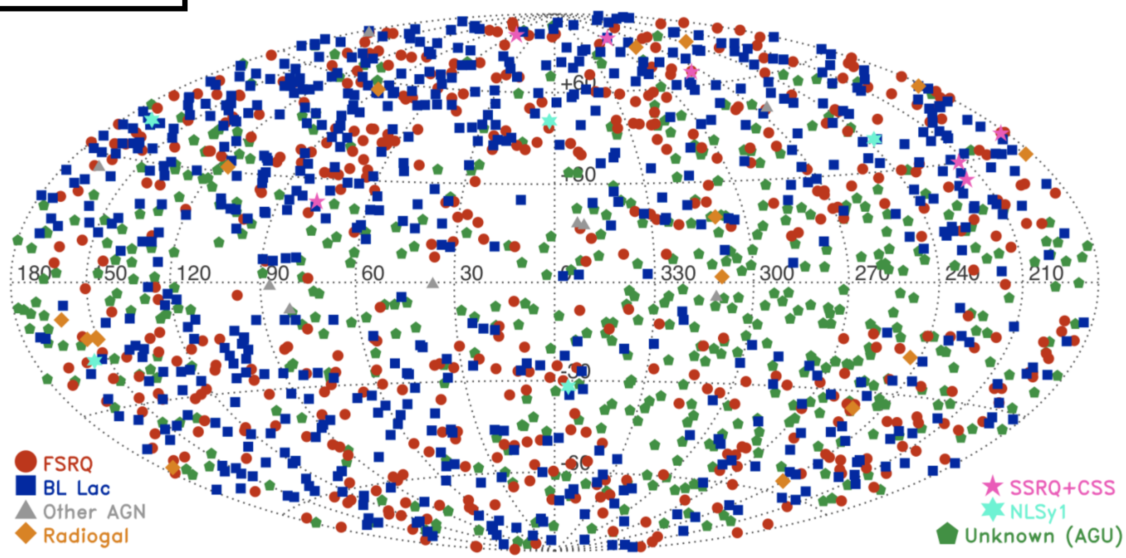
The Third LAT AGN catalog (3LAC)

Fermi Gamma-ray Space Telescope

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

BCU = Blazar candidates of uncertain type

Ackermann et al. 2015



48 months LAT data

- 1591 (1444) sources with TS>25, |b|>10° (71% more than in 2LAC)
- 182 low-latitude AGN (24 FSRQ, 30 BL Lacs, 125 BCU, 3 non-blazar AGN)

- 467 FSRQ
- 632 BL Lacs
- 460 BCU (~50% new 3LAC sources)
- 32 non-blazar AGN

Redshift

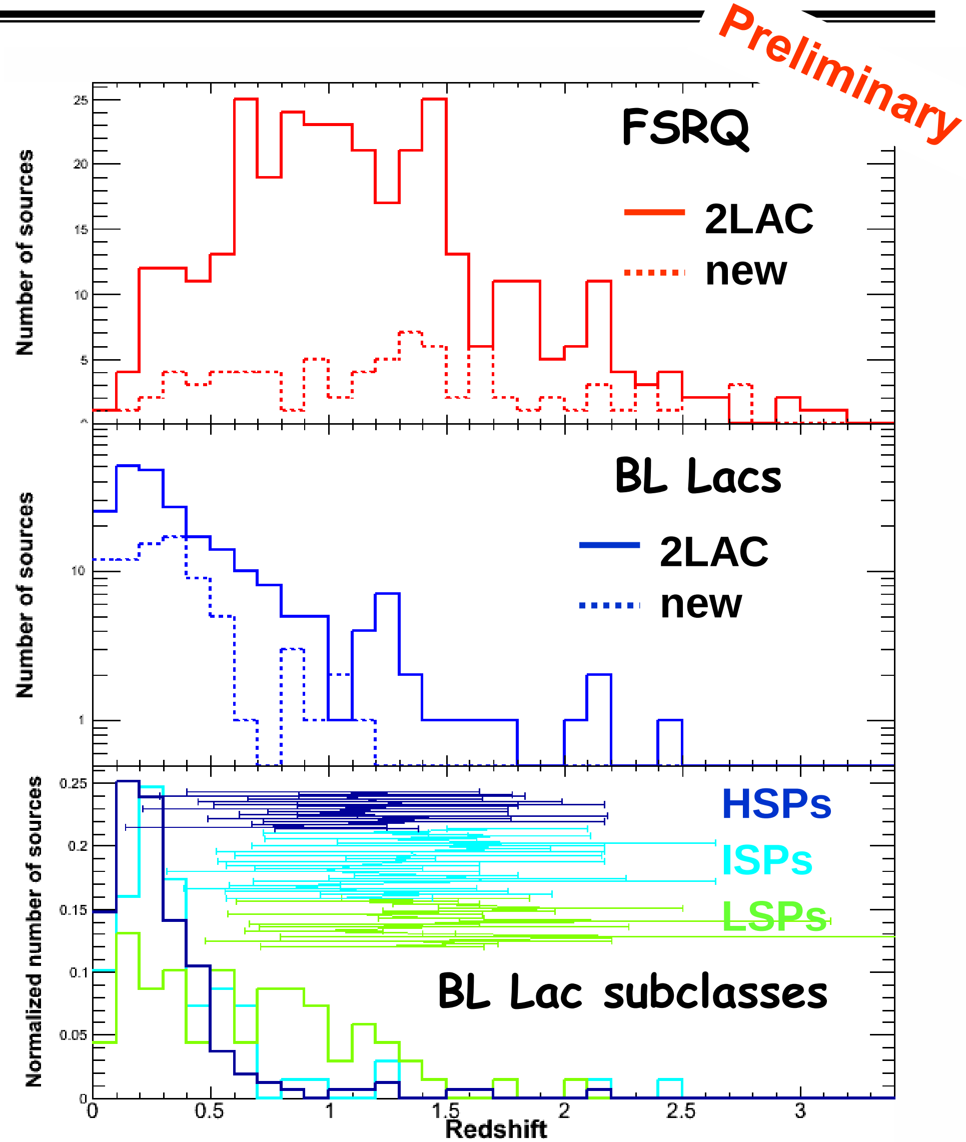
• slightly higher z for new FSRQ relative to 2LAC ones <z>=1.33 vs. 1.17 The number density of FSRQ grows dramatically up to redshift 0.5-2.0 and declines thereafter (Ajello et al. 2012)

• maximum redshift still z=3.1

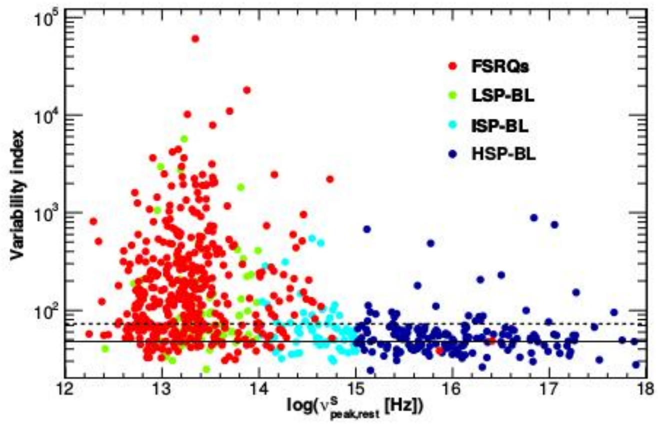
• 295/604 BL Lacs have no measured redshifts (55%, 61%, 40%) for (LSPs, ISPs and HSPs)

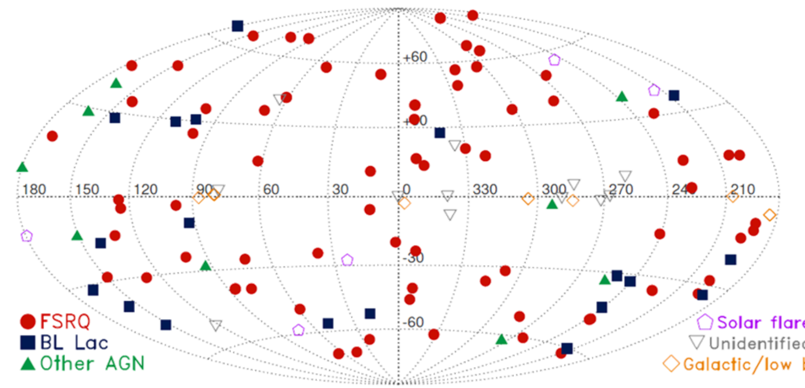
• 134 constraints from Shaw et al. (2013)

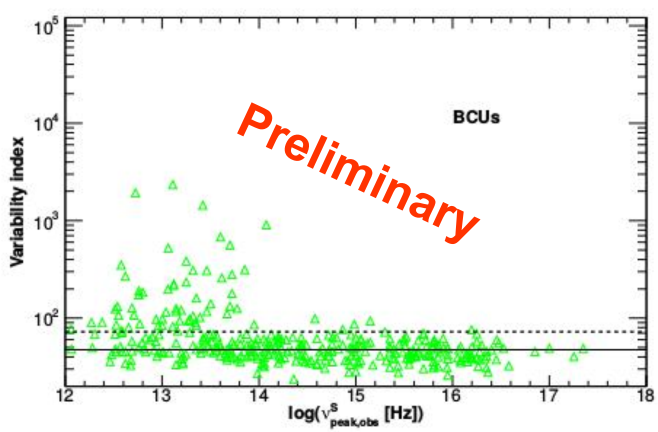
• Redshift limits for BL Lacs are not compatible with measured redshifts: measured redshifts are biased low?



Flux Variability







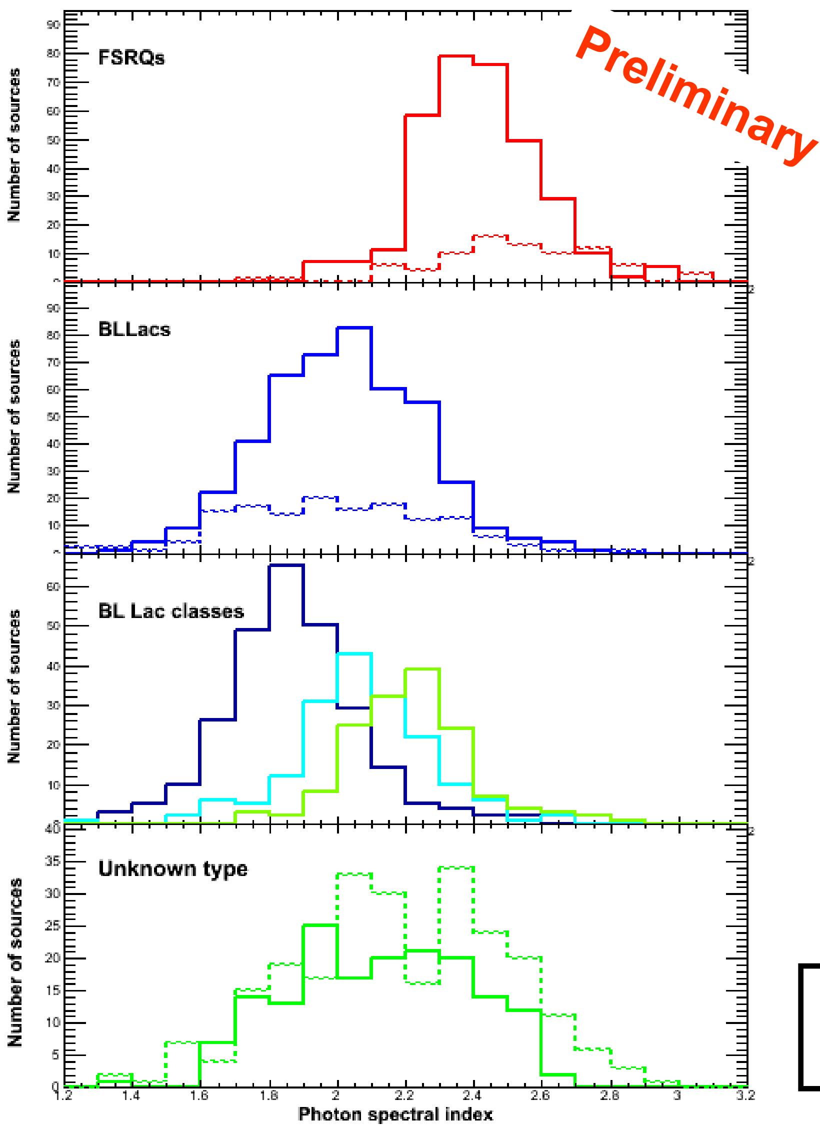
143/201 ATels for flaring AGN in 48 months:

- 71 FSRQ, 18 BL Lacs and 9 other AGN /AGU

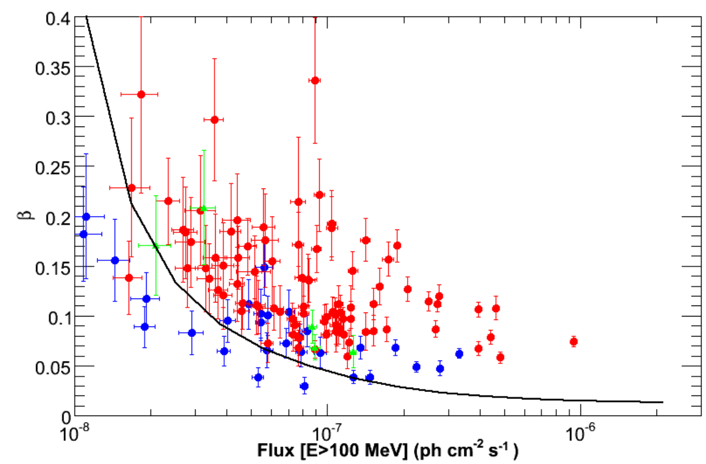
- only PKS 1915-458 (z=2.47) not in 3LAC

Fractions of sources showing significant variability :
- FSRQ: 69%
- BL Lac objects: 23% (39%, 23%, 15%) for (LSP, ISP,HSP)

Photon index and spectral curvature

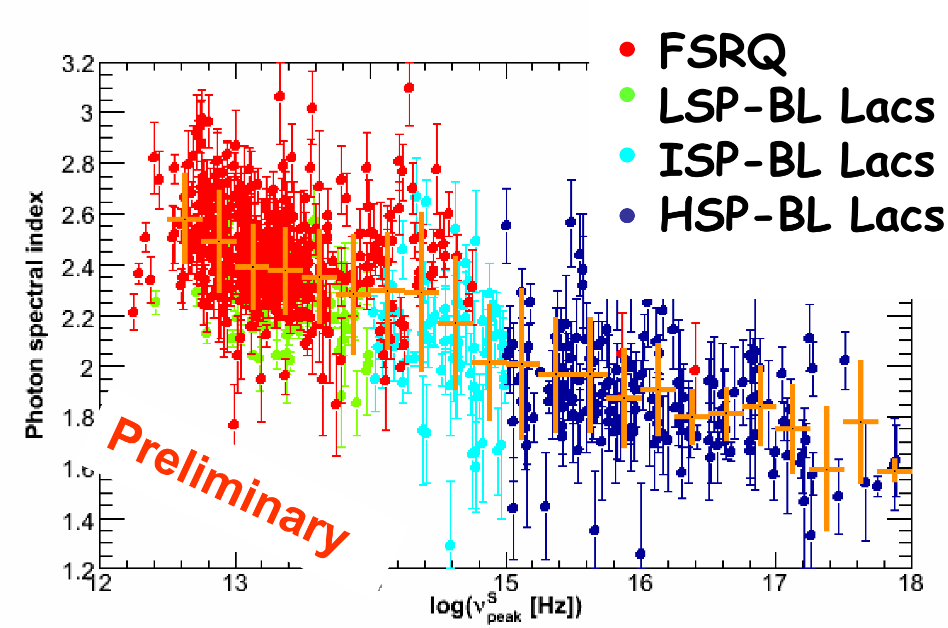


- Little overlap between FSRQ and BL Lac objects
- New FSRQ slightly softer than 2LAC ones: (<Γ> = 2.53 vs. 2.41)
- BCU spectral index distribution straddling the two classes

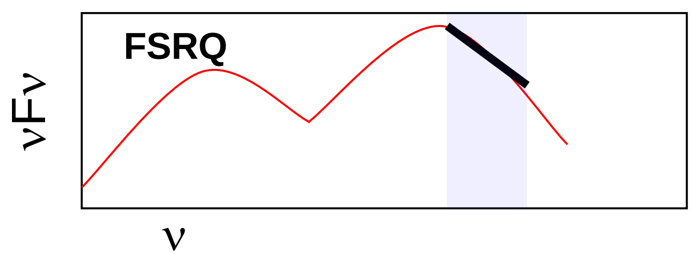


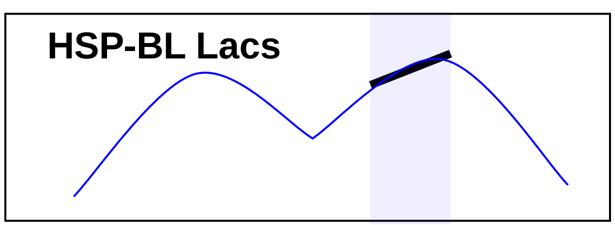
91 FSRQ (57 in 2LAC), 32 BL Lacs (12 in 2LAC) and 8 BCU showed significant spectral curvature

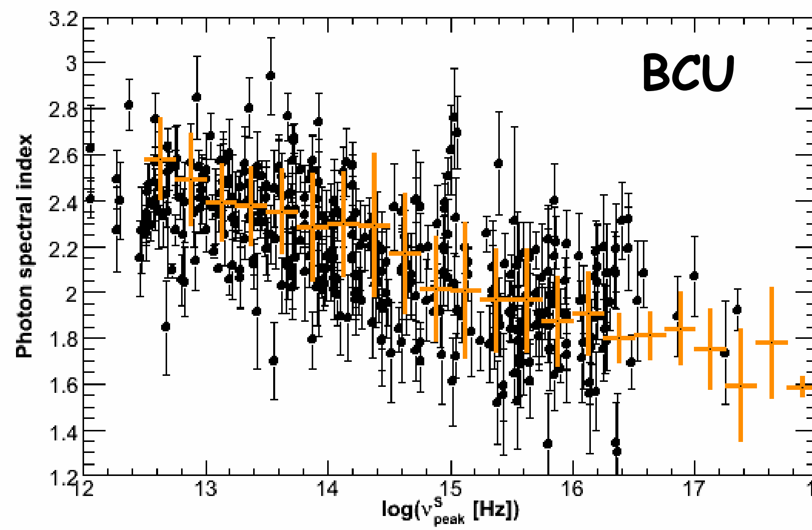
Photon index vs ν_{peak}



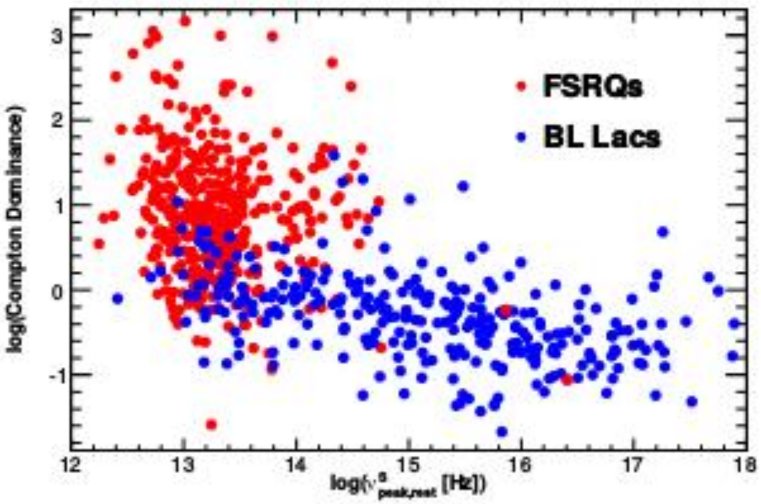
- Correlation between spectral hardness and ν_{peak} confirmed
- Same applies to BCU

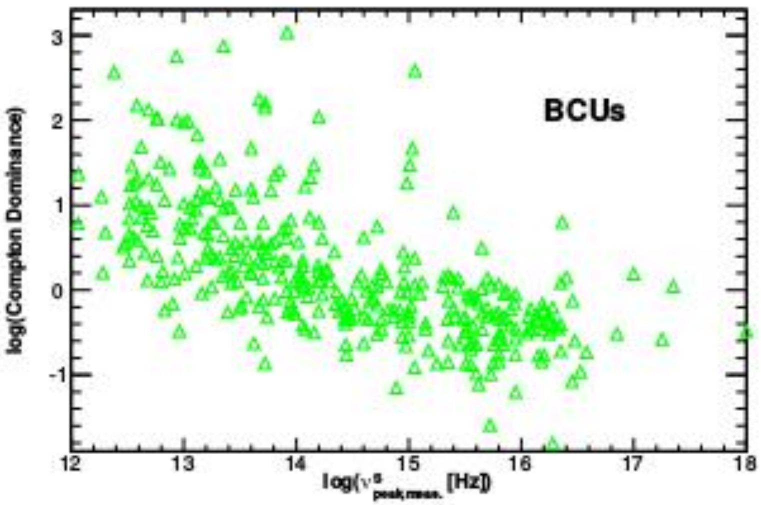


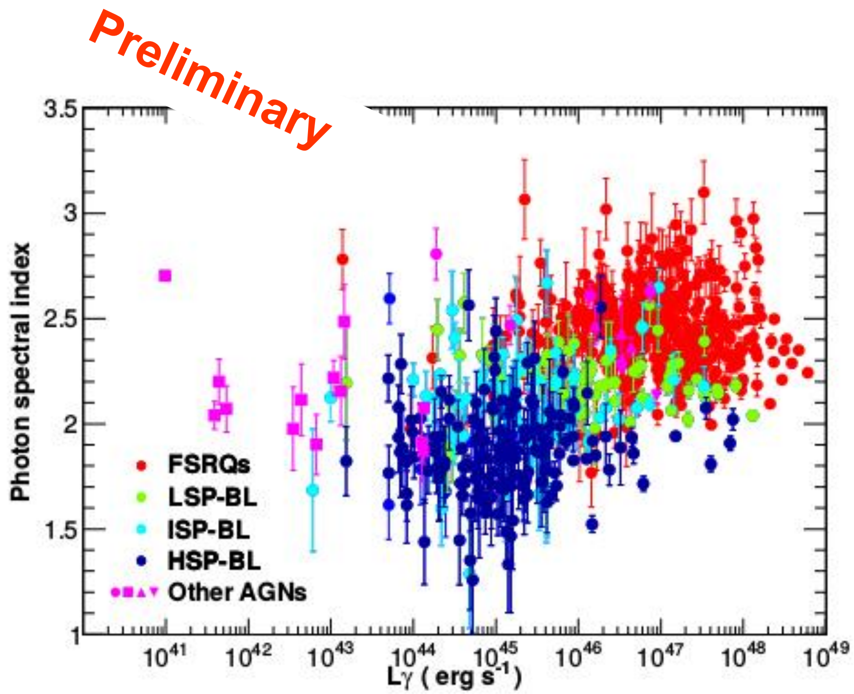




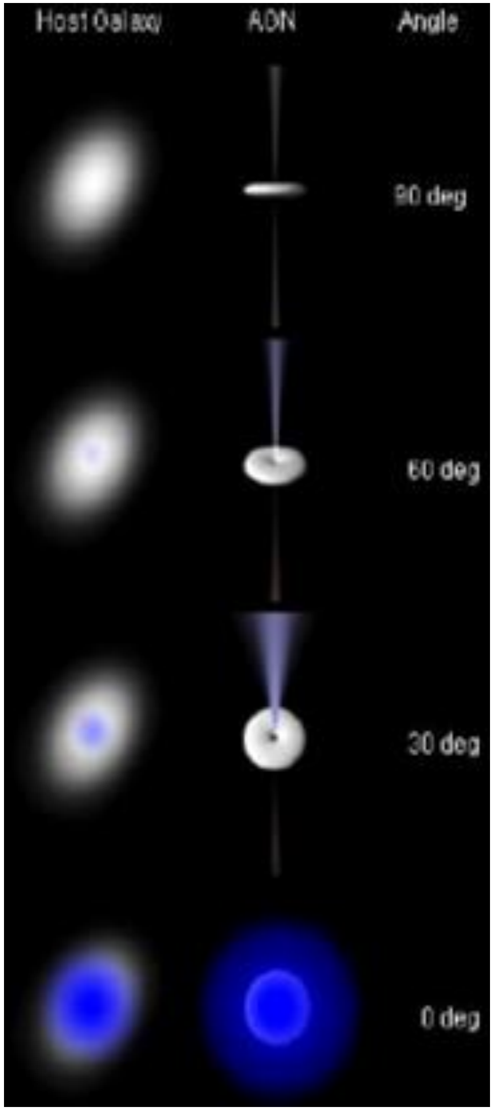
Lγ and Compton dominance







Viewing Angle and Doppler boosting



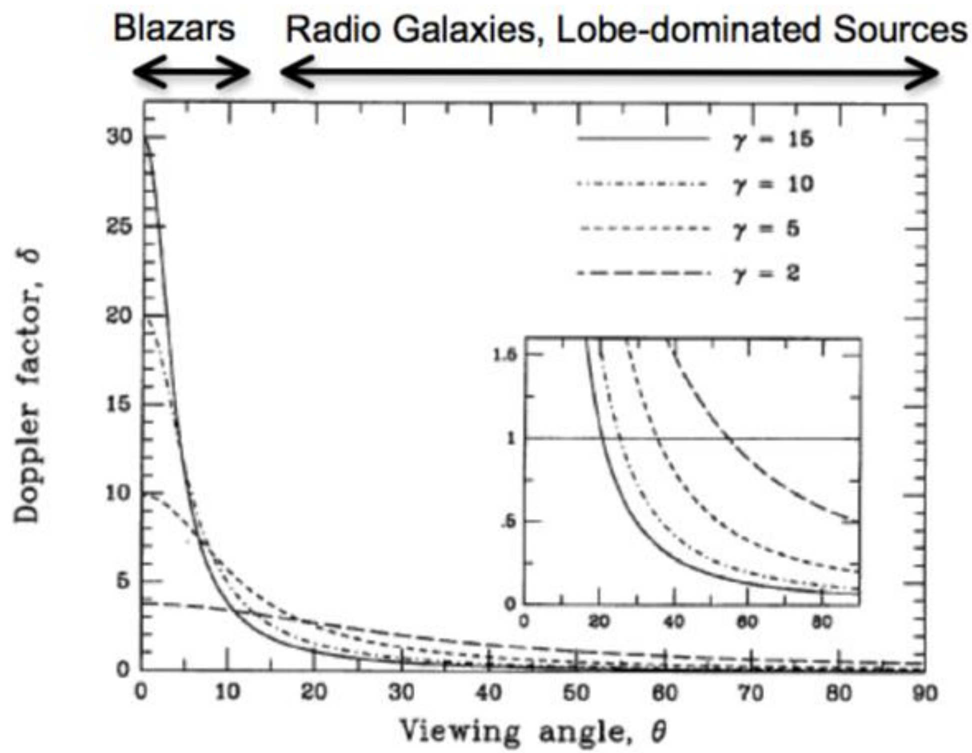
NLRG

BLRG

SSRQ

NLSy1

Blazars



Non-blazar & Misaligned AGN

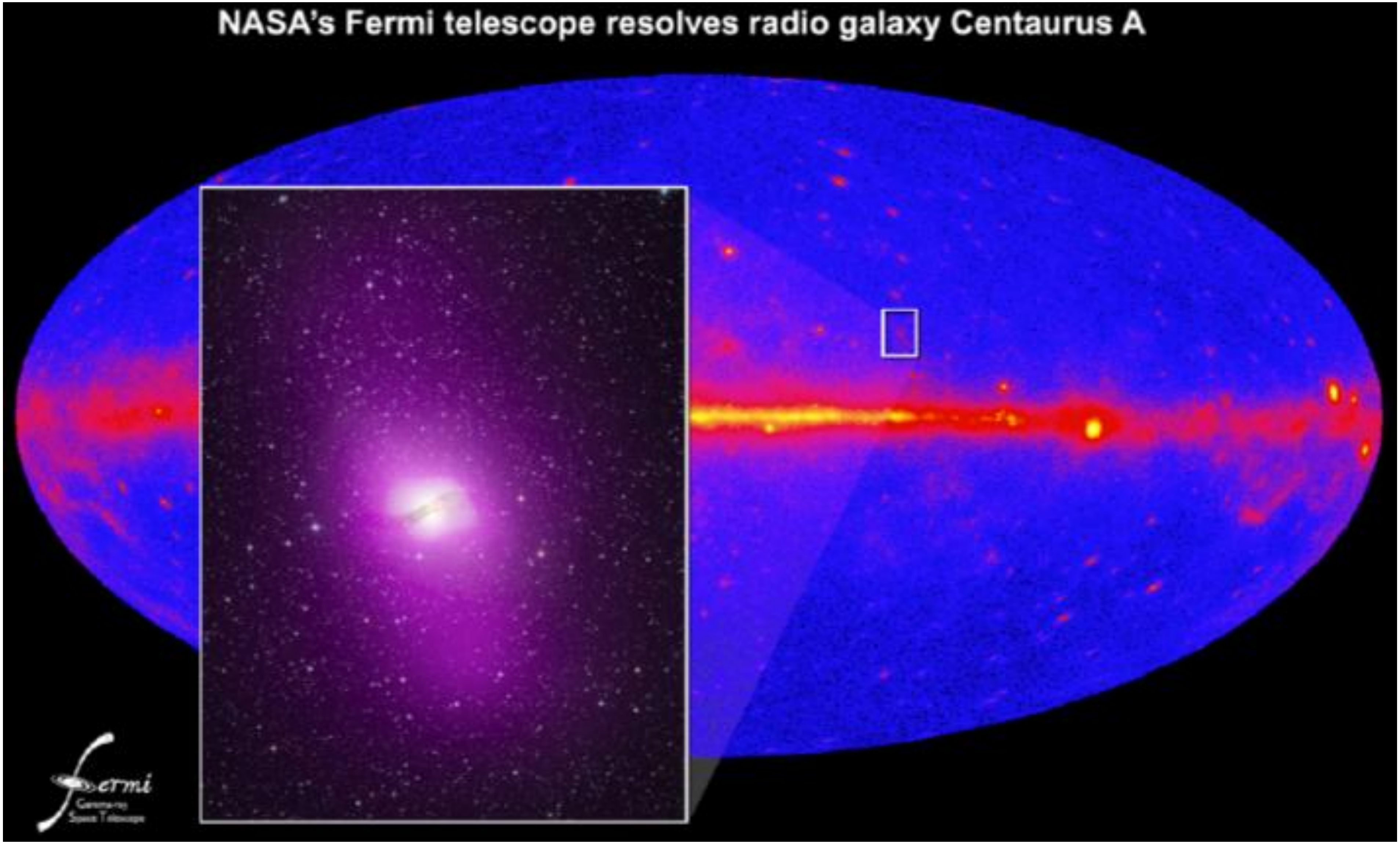
Table 5. Non-blazar objects and misaligned AGN

Name	3FGL	2FGL	1FGL	Type	Photon index	Notes
NGC 1218	J0308.6+0408*	···	J0308.3+0403*	FRI	2.07±0.11	
IC 310	J0316.6+4119*	J0316.6+4119	···	FRI/BLL	1.90±0.14	Neronov et al. (2010)
NGC 1275	J0319.8+4130*	J0319.8+4130*	J0319.7+4130*	FRI	2.07±0.01	Abdo et al. (2009c); Kataoka et al. (2010)
1H 0323+342	J0325.2+3410*	J0324.8+3408*	J0325.0+3403*	NLSy1	2.44±0.12	
4C +39.12	J0334.2+3915*	···	···	FRI/BLL?	2.11±0.17	Giovannini et al. (2001)
TXS 0348+013	J0351.1+0128*	···	···	SSRQ	2.43±0.18	
3C 111	J0418.5+3813	···	J0419.0+3811	FRII	2.79±0.08	Abdo et al. (2010e); Kataoka et al. (2011); Grandi et al. (2012)
Pictor A	J0519.2−4542*	···	···	FRII	2.49±0.18	Brown & Adams (2012); Kataoka et al. (2011)
PKS 0625−35	J0627.0−3529*	J0627.1−3528*	J0627.3−3530*	FRI/BLL	1.87±0.06	
4C +52.17	J0733.5+5153	···	···	agn	1.74±0.16	Part of a uplicate association. Most probable counterpart is a bcu III.
NGC 2484	J0758.7+3747*	···	···	FRI	2.16±0.16	quasar SDSS J075825.87+374628.7 is 0.8' away
4C +39.23B	J0824.9+3916	···	···	CSS	2.44±0.10	
3C 207	J0840.8+1315*	J0840.7+1310	J0840.8+1310	SSRQ	2.47±0.09	
SBS 0846+513	J0849.9+5108*	···	···	NLSy1	2.28±0.04	
3C 221	J0934.1+3933	···	···	SSRQ	2.28±0.12	
PMN J0948+0022	J0948.8+0021*	J0948.8+0020*	J0949.0+0021*	NLSy1	2.32±0.05	
PMN J1118-0413	J1118.2-0411*	···	···	agn	2.56±0.08	
B2 1126+37	J1129.0+3705	···	···	agn	2.08±0.13	Part of a duplicate association. Most probable counterpart a BLL.
3C 264	J1145.1+1935*	···	···	FRI	1.98±0.20	
PKS 1203+04	J1205.4+0412	···	···	SSRQ	2.64±0.16	
M 87	J1230.9+1224*	J1230.8+1224*	J1230.8+1223*	FRI	2.04±0.07	Abdo et al. (2009d)
3C 275.1	J1244.1+1615	···	···	SSRQ	2.43±0.17	
GB 1310+487	J1312.7+4828*	J1312.8+4828*	J1312.4+4827*	agn	2.04±0.03	
Cen A Core	J1325.4−4301*	J1325.6−4300	J1325.6−4300	FRI	2.70±0.03	radio core
Cen A Lobe	J1324.0−4330e	J1324.0−4330e	J1322.0−4515	FRI	2.53±0.05	giant lobes detected (Abdo et al. 2010b)
3C 286	J1330.5+3023*	···	···	SSRQ/CSS	2.60±0.16	
Cen B	J1346.6−6027	J1346.6−6027	···	FRI	2.32±0.01	Katsuta et al. (2013)
Circinus	J1413.2−6518	···	···	Seyfert	2.43±0.10	Hayashida et al. (2013)
3C 303	J1442.6+5156*	···	···	FRII	1.92±0.18	
PKS 1502+036	J1505.1+0326*	J1505.1+0324*	J1505.0+0328*	NLSy1	2.61±0.05	
TXS 1613−251	J1617.3−2519	J1617.6−2526c	···	agn	2.59±0.10	Part of a duplicate association. Most probable counterpart is a bcu II.
PKS 1617−235	J1621.1−2331*	J1620.5−2320c	···	agn	2.50±0.23	
NGC 6251	J1630.6+8232*	J1629.4+8236	J1635.4+8228*	FRI	2.22±0.08	
3C 380	J1829.6+4844*	J1829.7+4846*	J1829.8+4845*	SSRQ/CSS	2.37±0.04	
PKS 2004−447	J2007.8−4429*	J2007.9−4430*	J2007.9−4430*	NLSy1	2.47±0.09	

9 (12) FR I
3 FR II
7 SSRQ

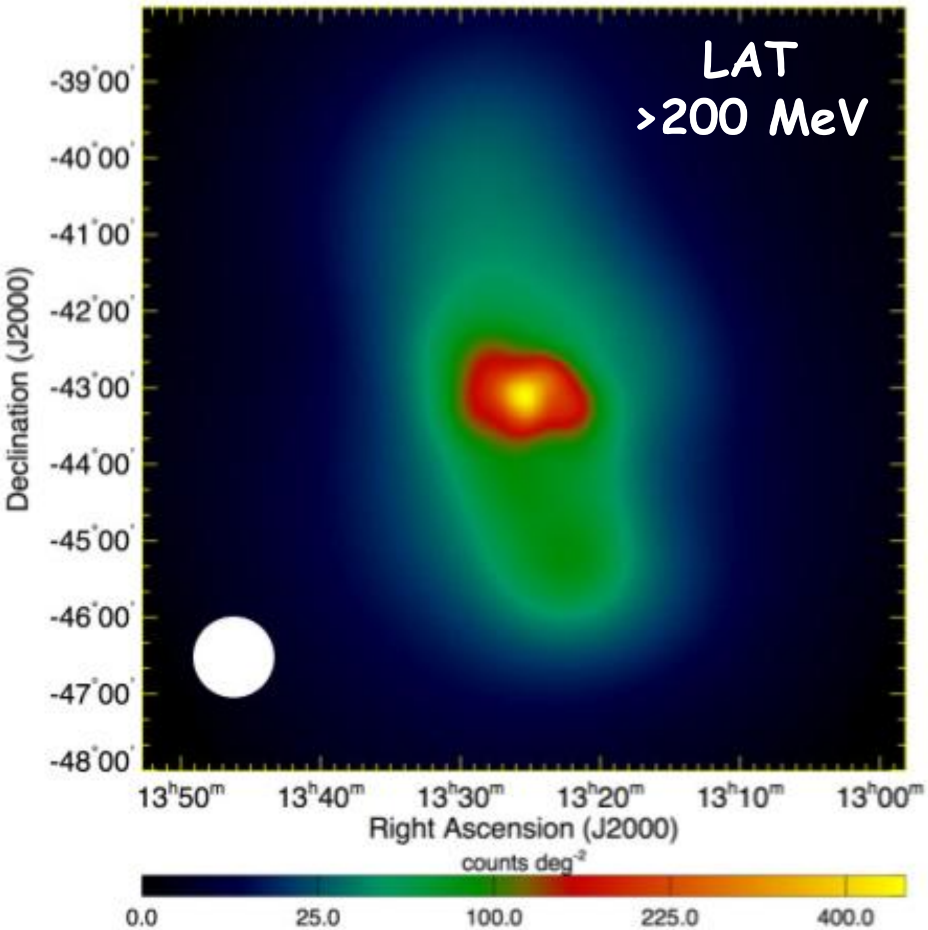
1 Seyfert
5 NLSy1
1 CSS (?)
6 AGN

Centaurus A

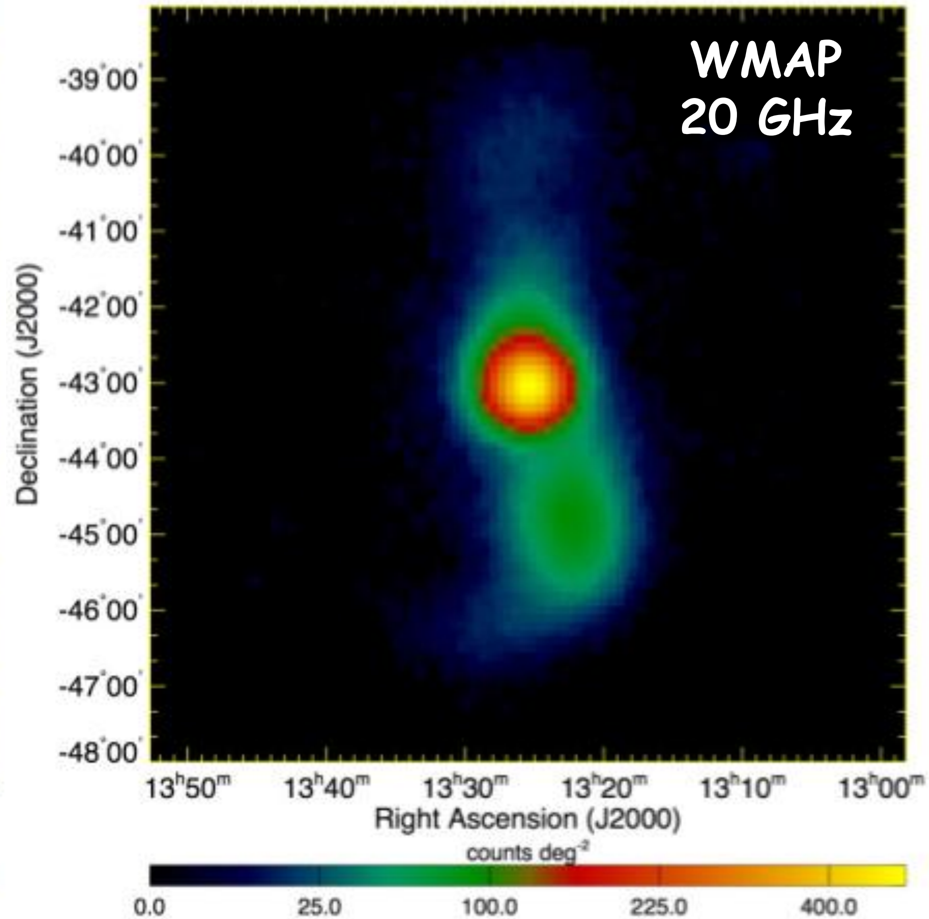

NASA's Fermi telescope resolves radio galaxy Centaurus A
Fermi
Gamma-ray
Space Telescope

First γ-ray Imaging of Cen A Giant Lobes

Over ½ of the total >100 MeV observed LAT flux in the lobes



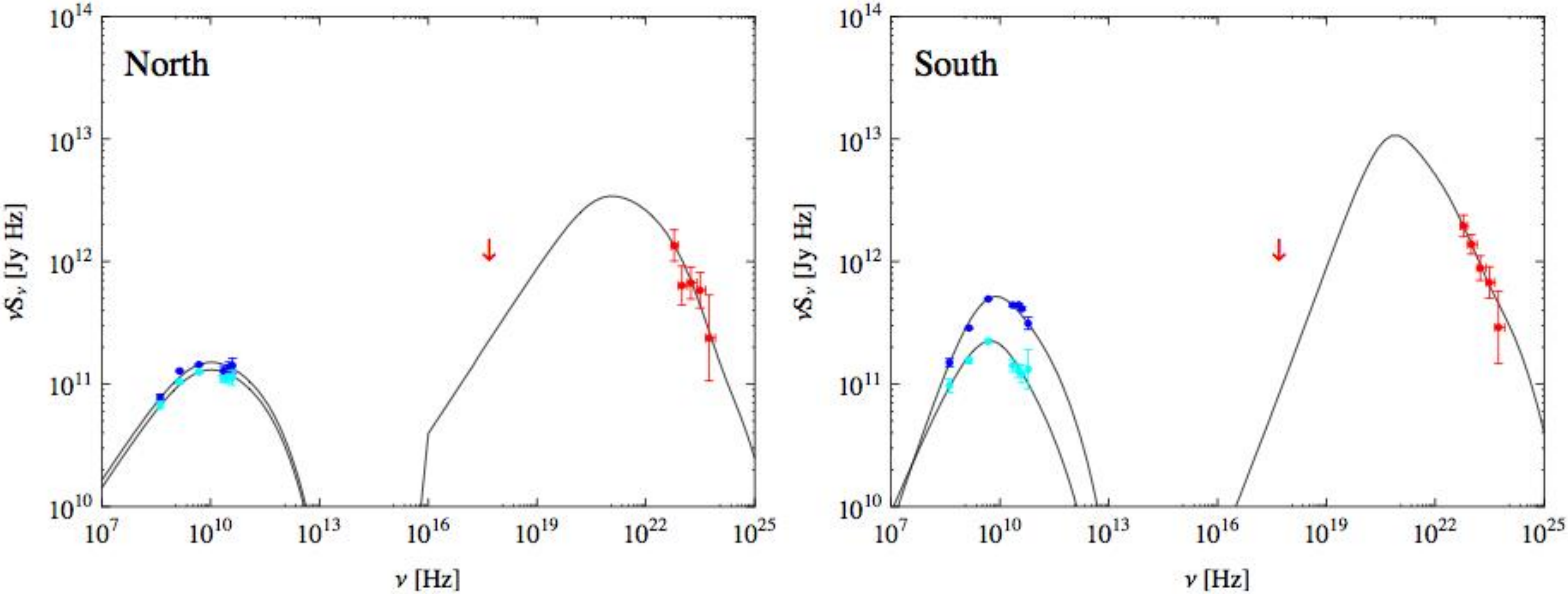
Background & point sources subtracted



From Nils Odegard (GSFC)

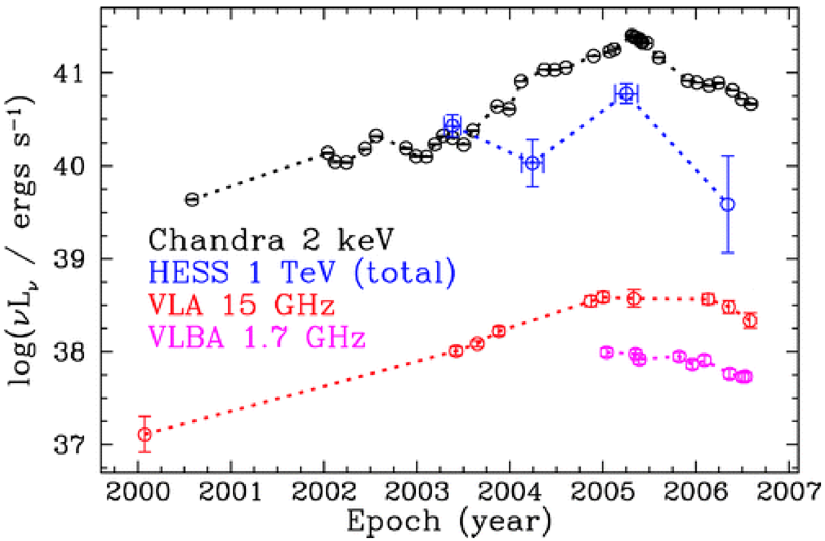
Abdo et al. 2010

Inverse Compton γ-ray Emission



- The γ-ray emission from lobes is due to IC (CMB+EBL), with B ~ 0.9 μG in both lobes, near equipartition
- t_{cool} < R/c for GeV emitting electrons: acceleration all over the volume

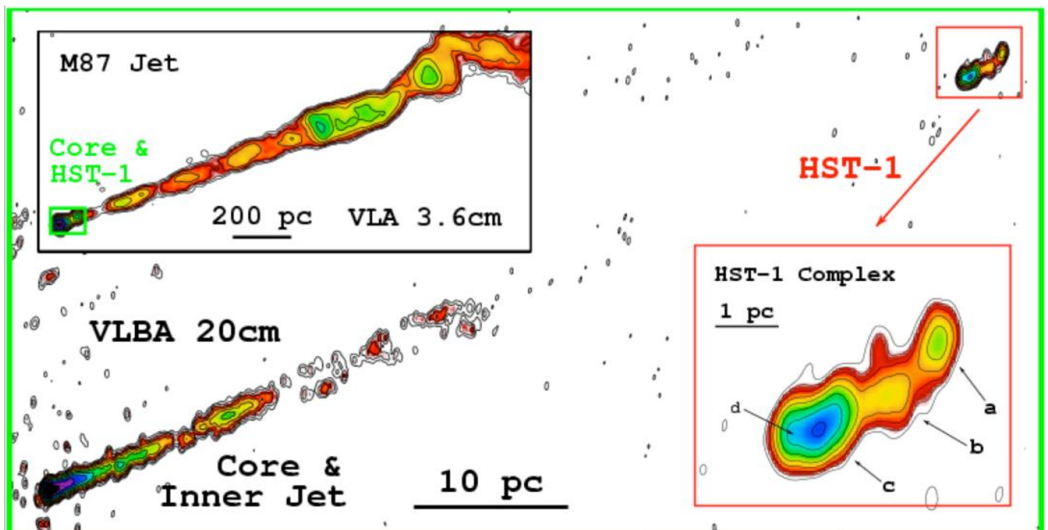
Dissipation zone in M87: far away...

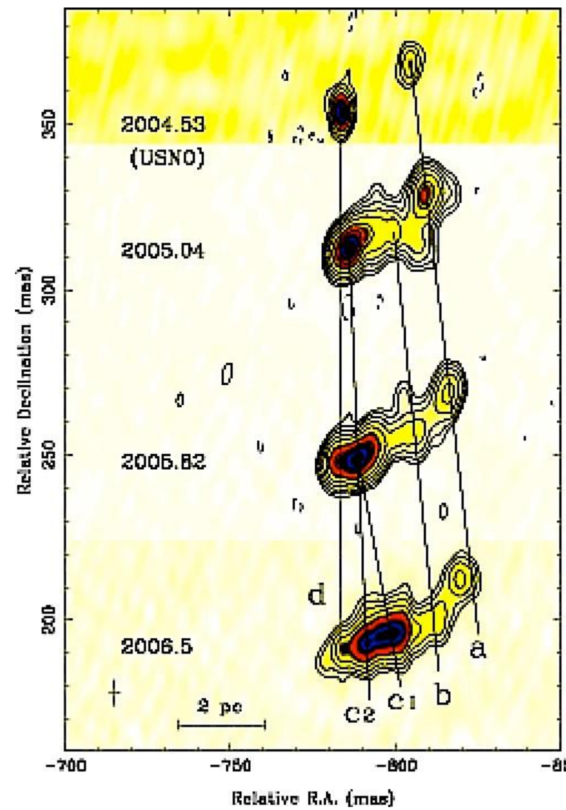


After a huge flare, the unresolved and stationary knot HST-1 in M87 jet ejected superluminal blobs moving down the outflow

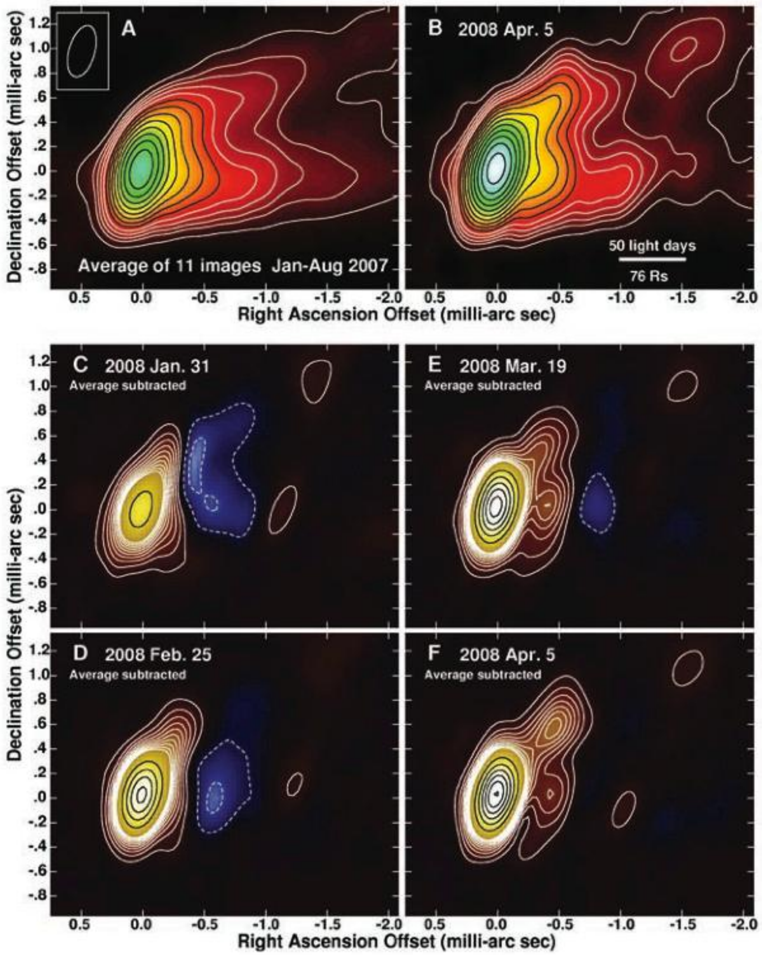
Why does the HST-1 knot behave like a central engine? Is the gamma-ray emission produced in HST-1 as well?

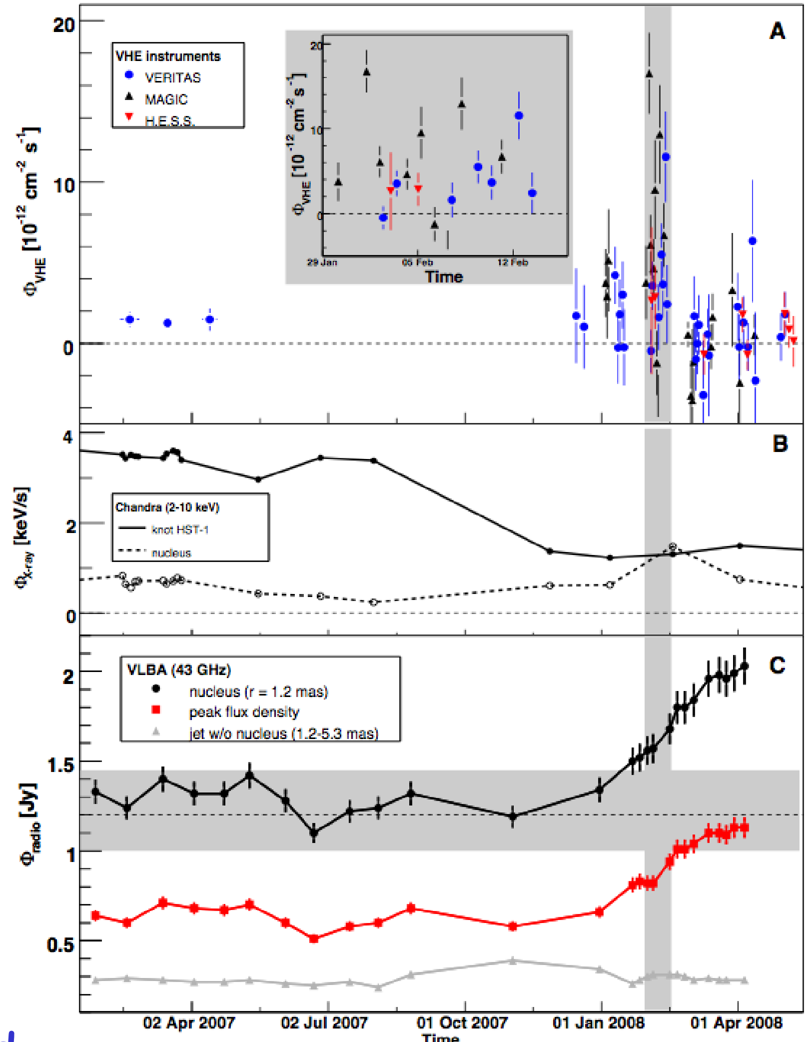
Cheung et al. 2007





...or closer to the SMBH?

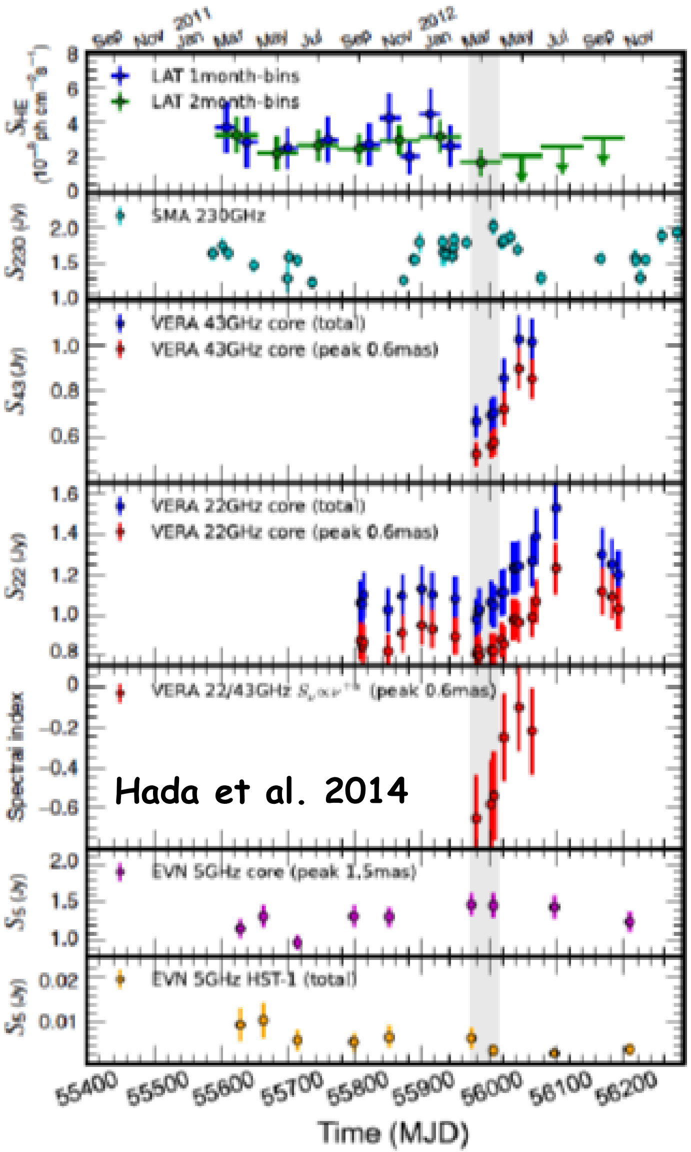


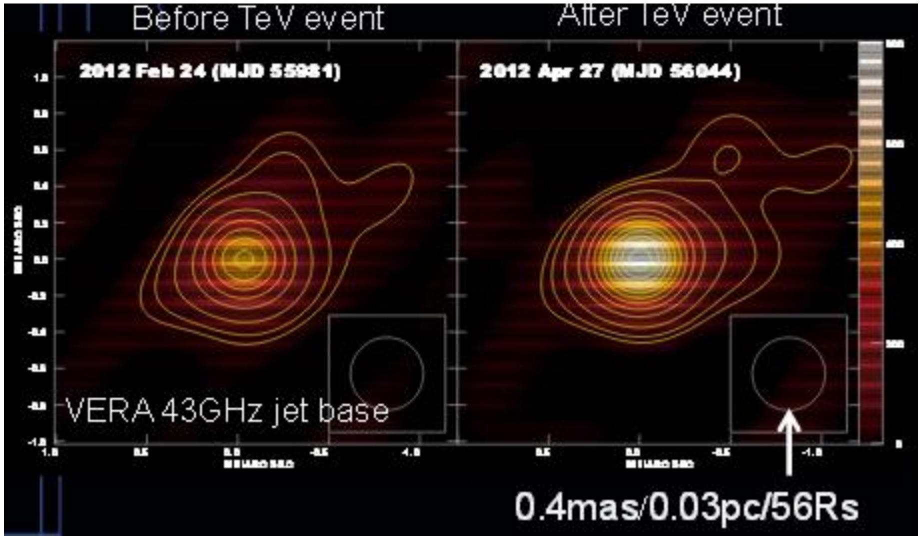


The observed γ-rays may be instead produced in the innermost part of the M87 jet

Acciari et al. 2009 [HESS, MAGIC & VERITAS]

TeV flare from M87 in 2012



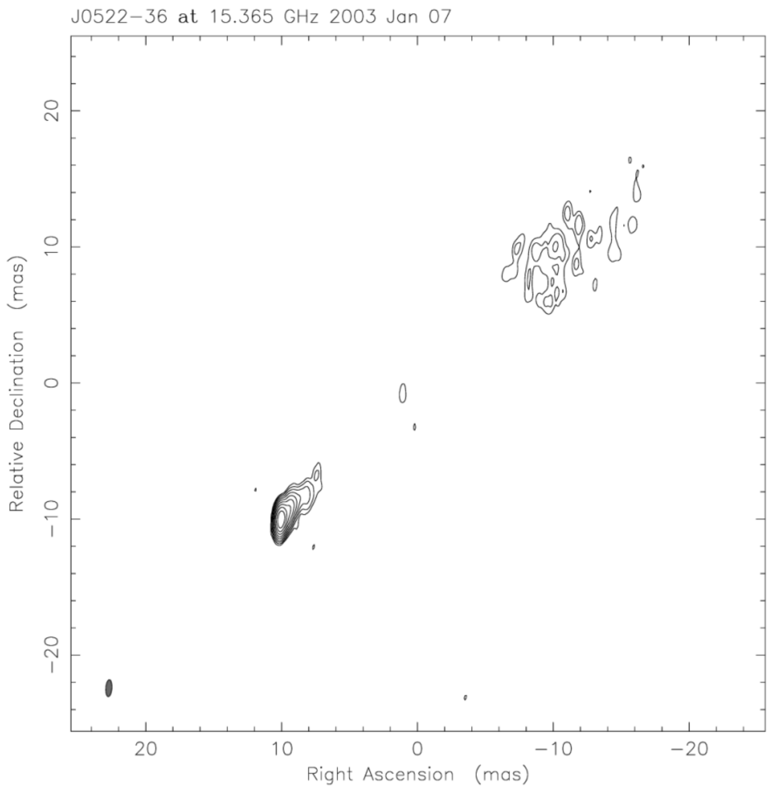


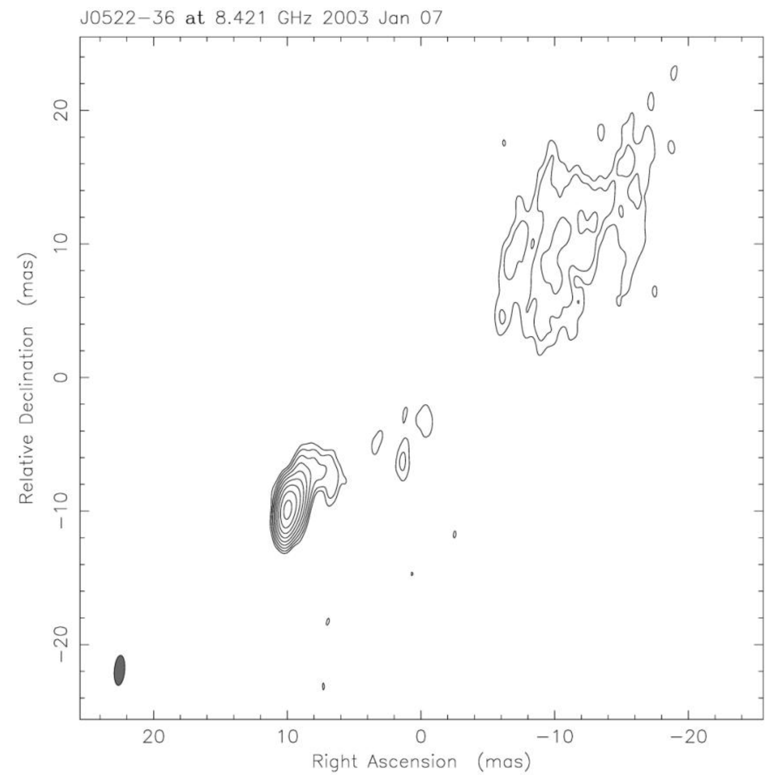
- Remarkable flux increase (~70%) from the radio core (22/43GHz) coincidentally with the TeV event

- HST-1 remained quiescent

- LAT light curves - no significant enhancement, but a possible state change after the TeV event?

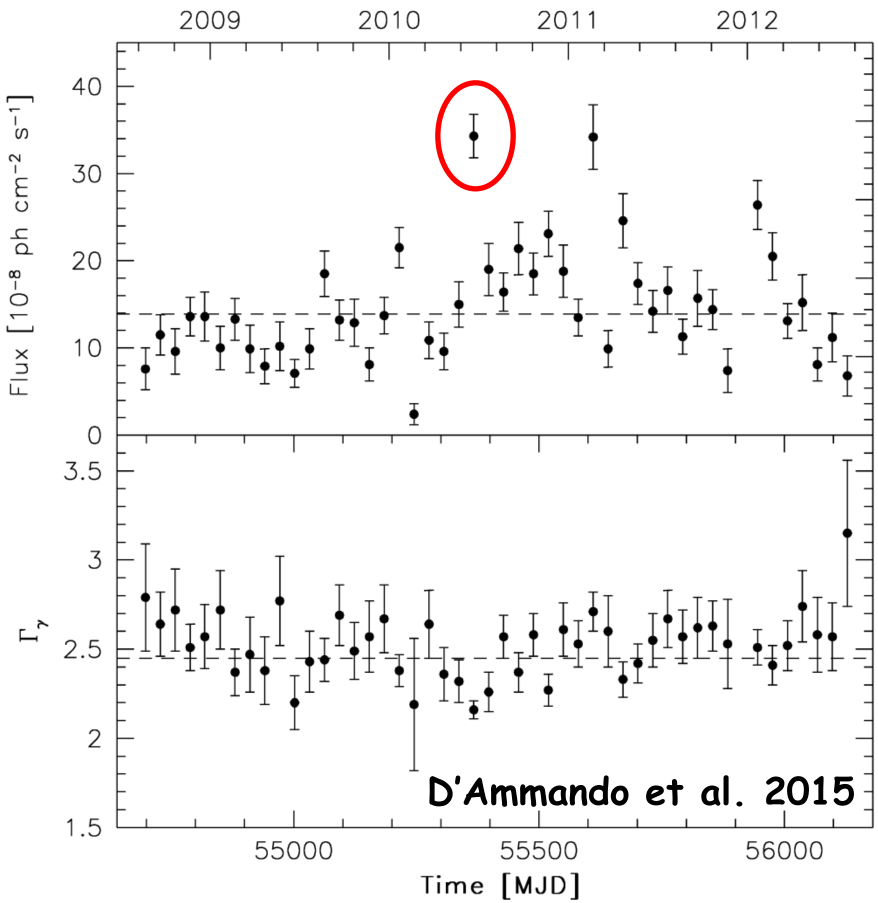
VLBA observations of PKS 0521-36



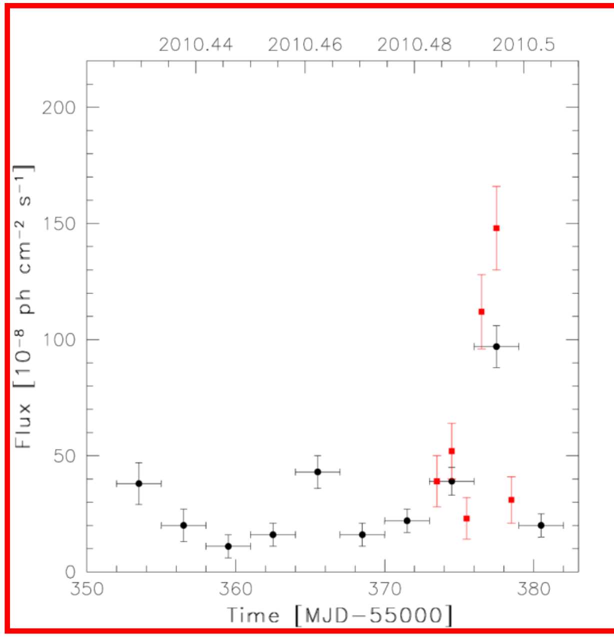


On pc-scales the AGN PKS 0521-36 shows a knotty structures similar to M87 and 3C 120. The brightness profile along the jet axis decreases rapidly with increasing distance from the core, but it then steeply rises again at ~30 mas

γ-ray flaring activity from PKS 0521-36



2008 August – 2012 August
[1-month time bin]



The broad emission lines in optical and UV and the steep radio spectrum indicate for PKS 0521-36 a possible classification as an intermediate object between BLRG and SSRQ

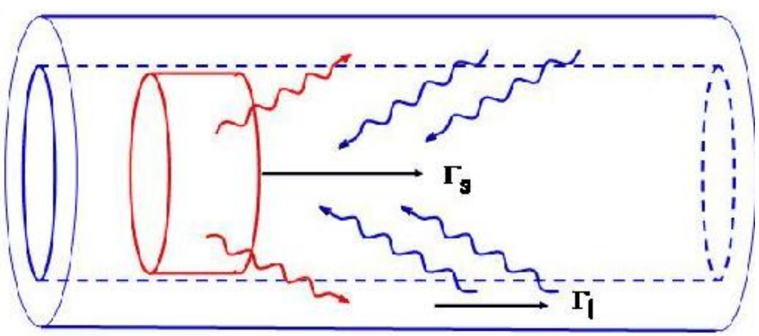
The flaring activity detected by Fermi-LAT between 2010 June and 2012 February is very intriguing

Nature of the source

- How to reconcile the knotty jet structure observed in radio with the high activity observed in gamma rays?

- Emitting jet not closely aligned to the line of sight. Is it possible to model the SED of the gamma-ray flare with a low Doppler factor as suggested in the past for this source?

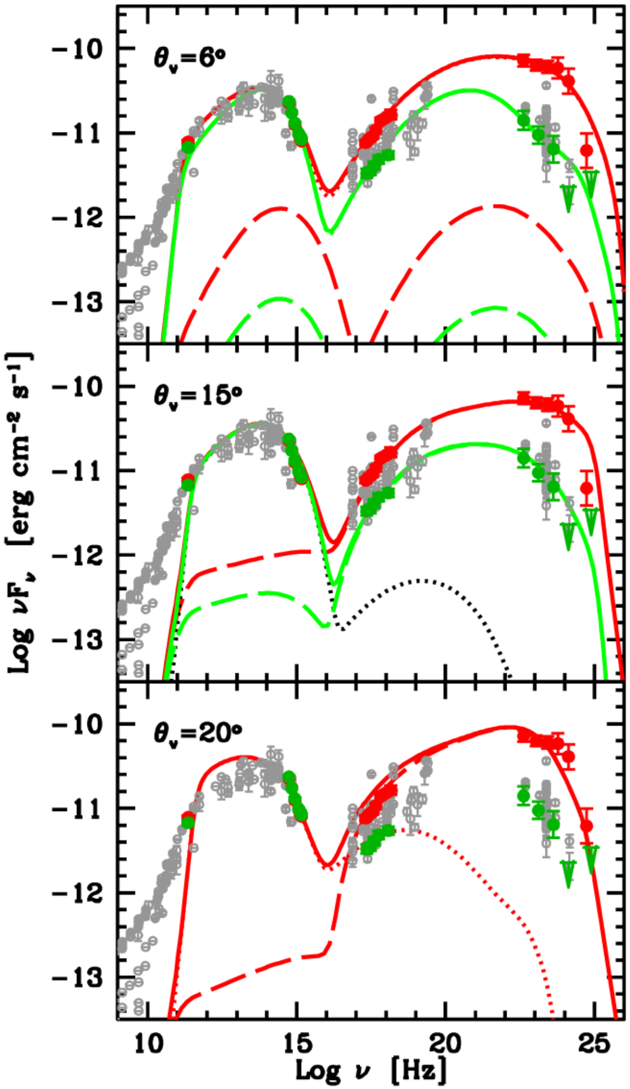
- Structured jet with spine or layer region active in different epochs?



RGs may/should be "misaligned" blazars
- low power FR I ⟷ BL Lacs
- high power FR II ⟷ FSRQs

SED modeling
- Spine dominated ….. Blazars
- Layer dominated ….. RGs

Structured jet scenario for PKS 0521-36



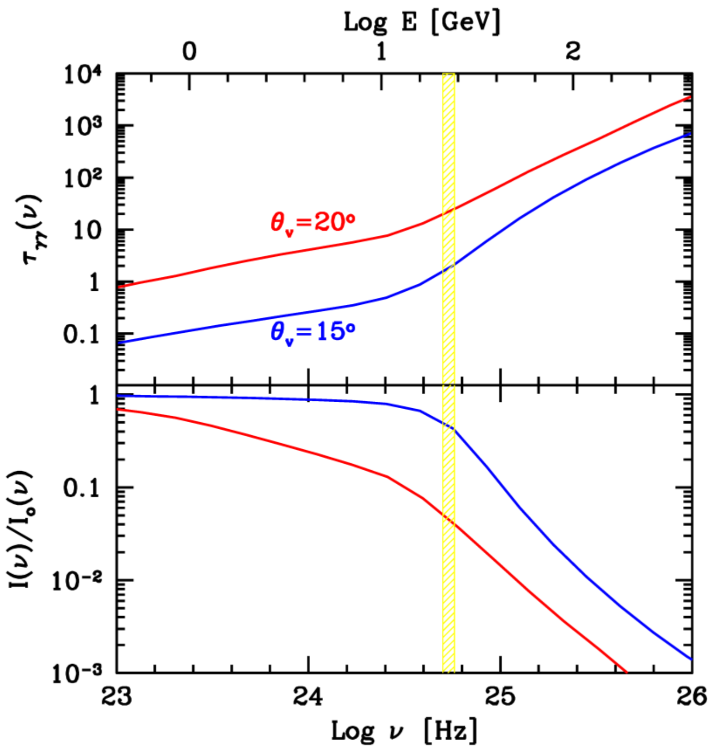
We applied a spine-layer model to a low activity state (green) and a high activity state (red) SED assuming three different viewing angles: 6°, 15°, and 20°. We obtain a good fit for the first two cases

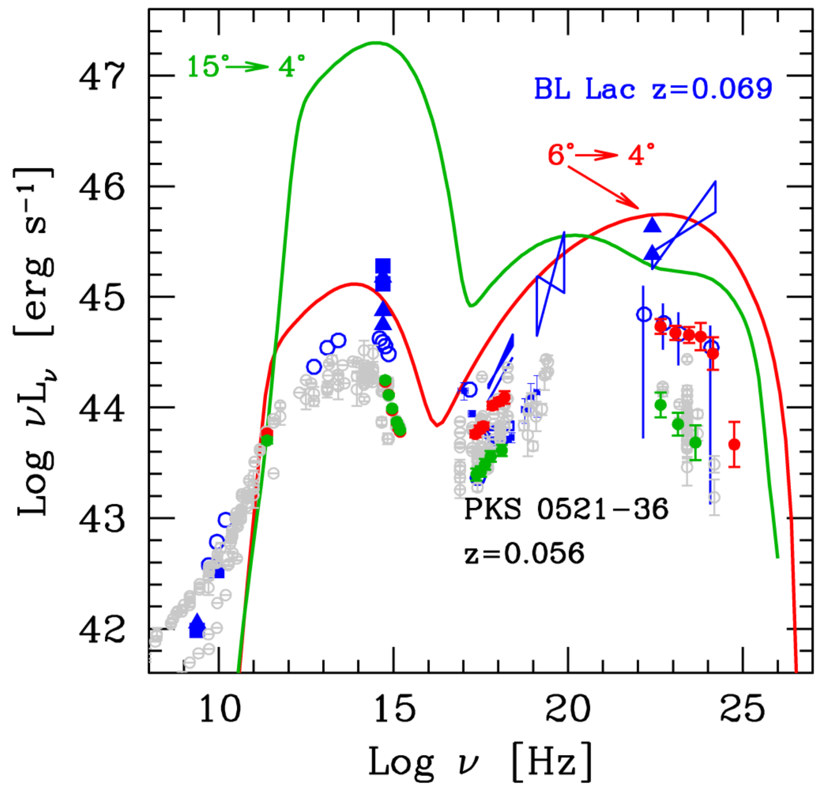
For relatively small angles the spine emission largely dominates the SED

For larger angles the only suitable solution is that the low-energy bump is dominated by the synchrotron emission of the spine, and the IC bump by the IC emission of the layer

D'Ammando et al. 2015, MNRAS, 450, 3975

SED modelling of PKS 0521-36

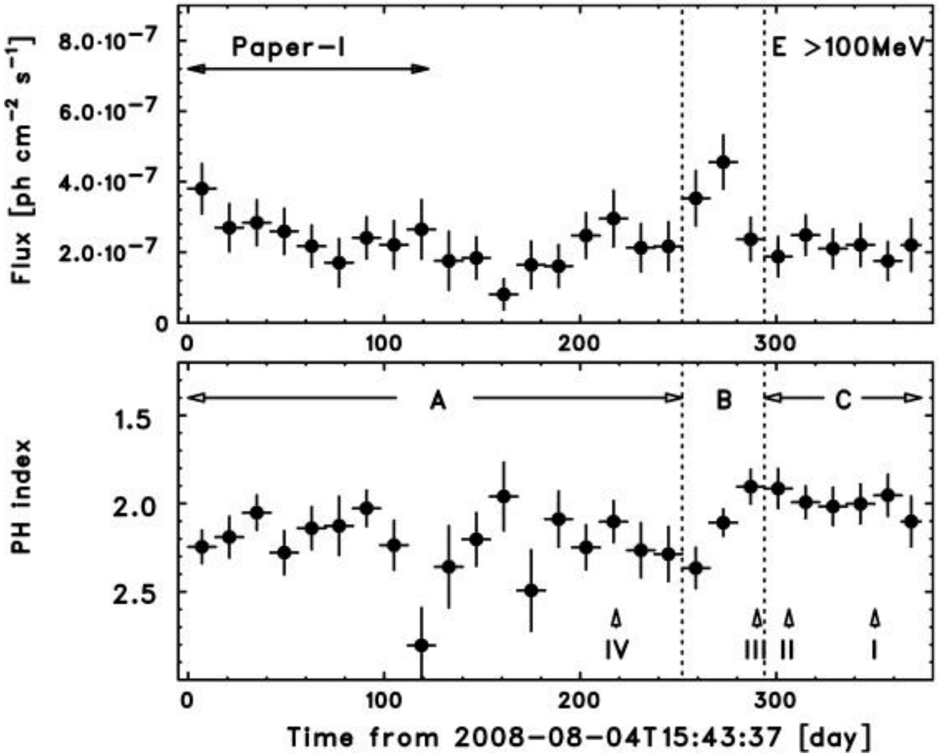




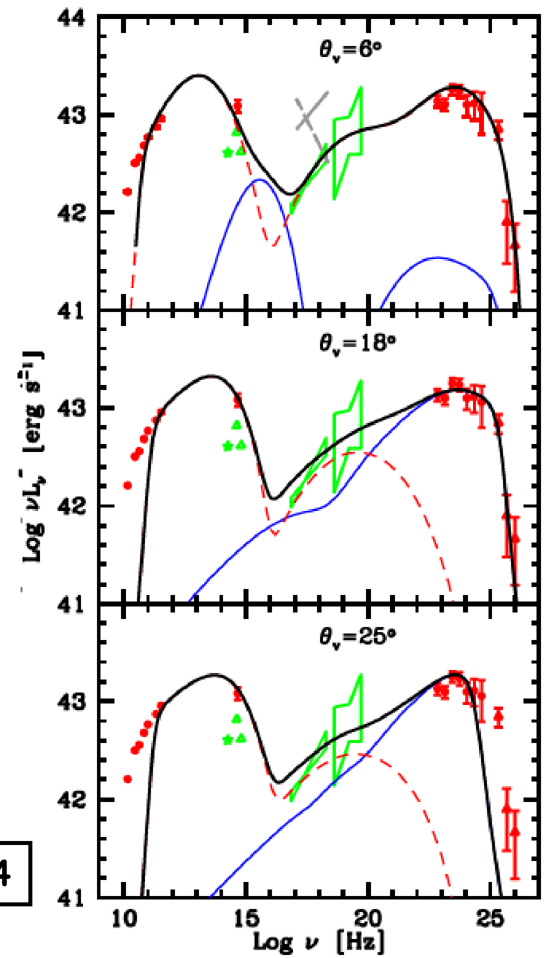
The case for θ = 20° requires a large intrinsic luminosity. In that case the optical depth reaches 1 at about 1 GeV

Once observed at a small angle, the SED obtained with θ = 15° does not resemble that of a blazar, in contrast to the unification scheme for radio galaxies and blazars

NGC 1275: LAT observations



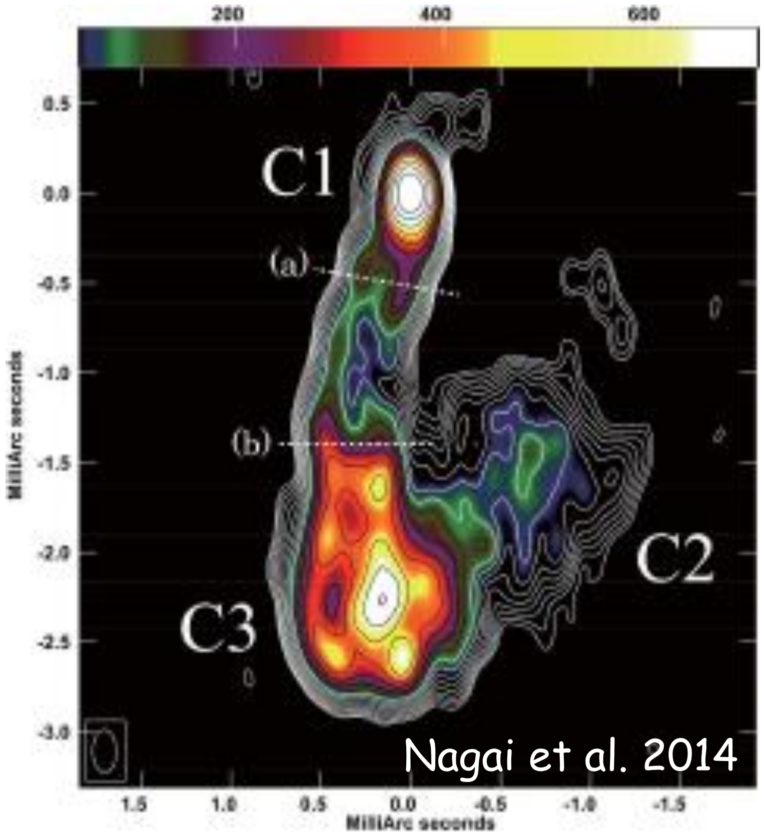
Kataoka et al. 2010



Tavecchio & Ghisellini 2014

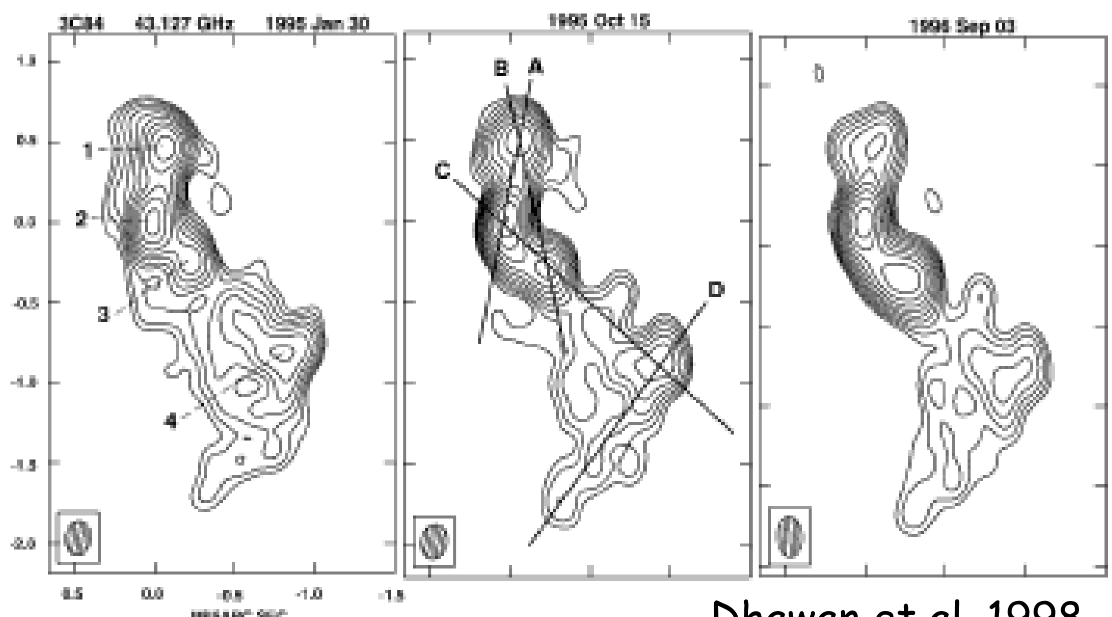
- About an order of magnitude brighter than EGRET UL – significant brightening on decade time scale
- Flux doubling on monthly time-scale: ≈ 0.1 pc jet emission region

NGC 1275: limb brightening



Nagai et al. 2014

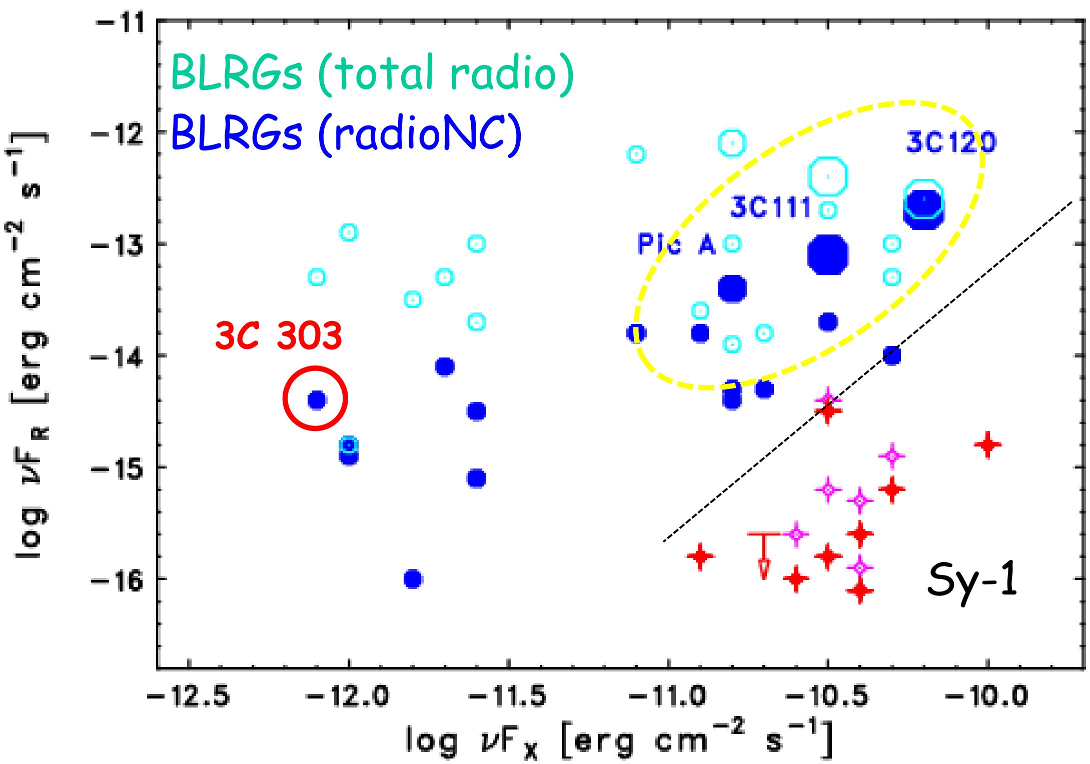
From 1990s to 2013 the jet structure changed from ridge-brightening to limb-brightening. This change in apparent transverse structure might be caused by the change in the transverse velocity structure

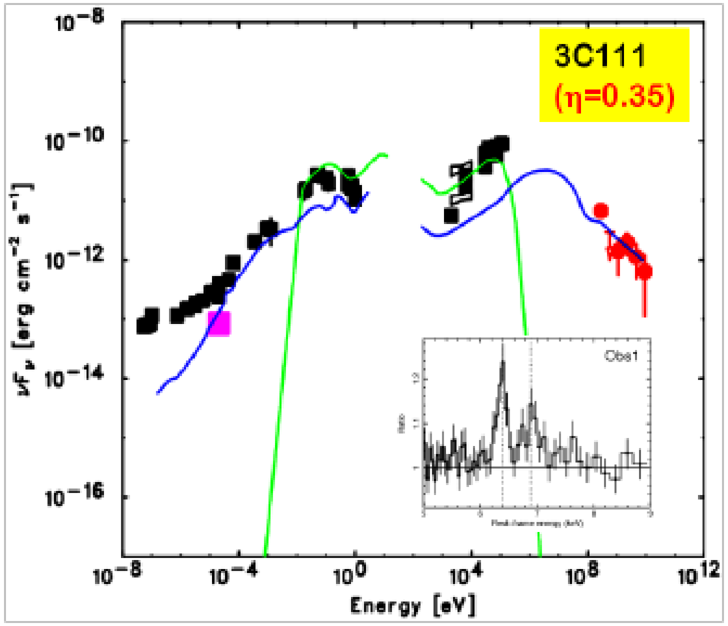


Dhawan et al. 1998

In the context of a structured jet, this transition may be related to the γ-ray time variability on the timescale of decades

Which BLRG are detected in gamma?

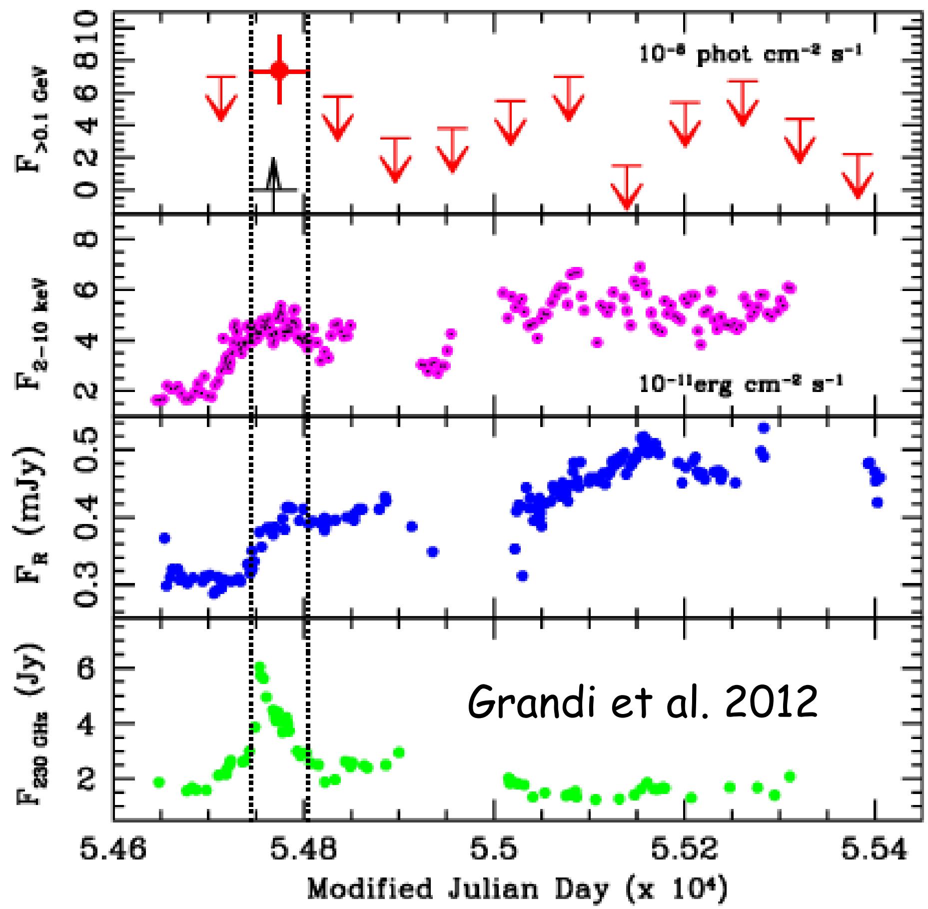


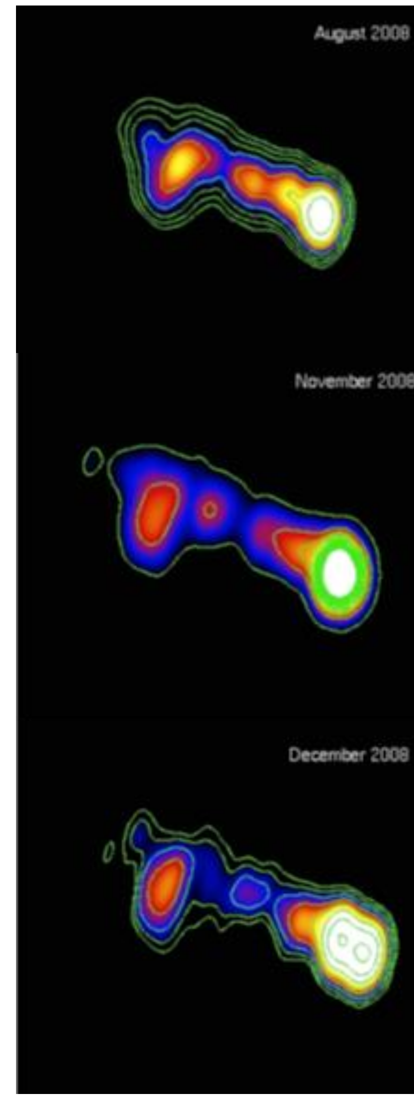


Kataoka et al. 2011

- Overall SEDs are well described by a combination of **"disk emission"** and ***"non-thermal jet emission"***
- Usually LAT-detected BLRG shows the **strongest radio nuclear flux**
- GeV emission is most likely dominated by the beamed radiation of relativistic jets as blazars

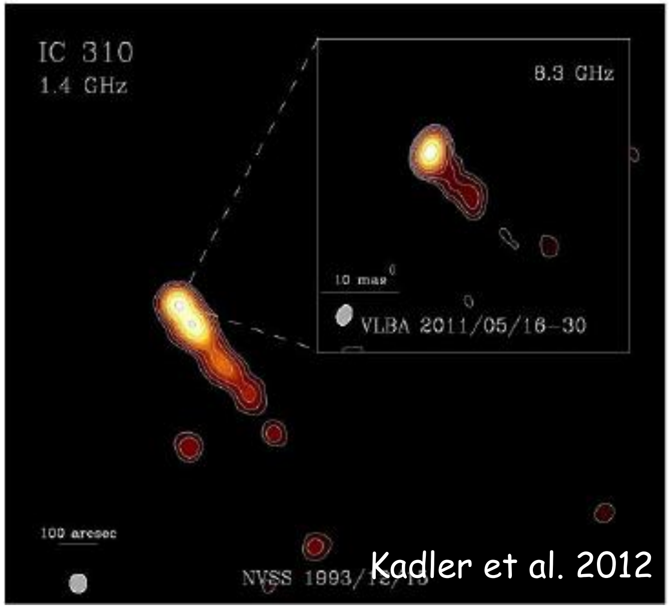
3C 111





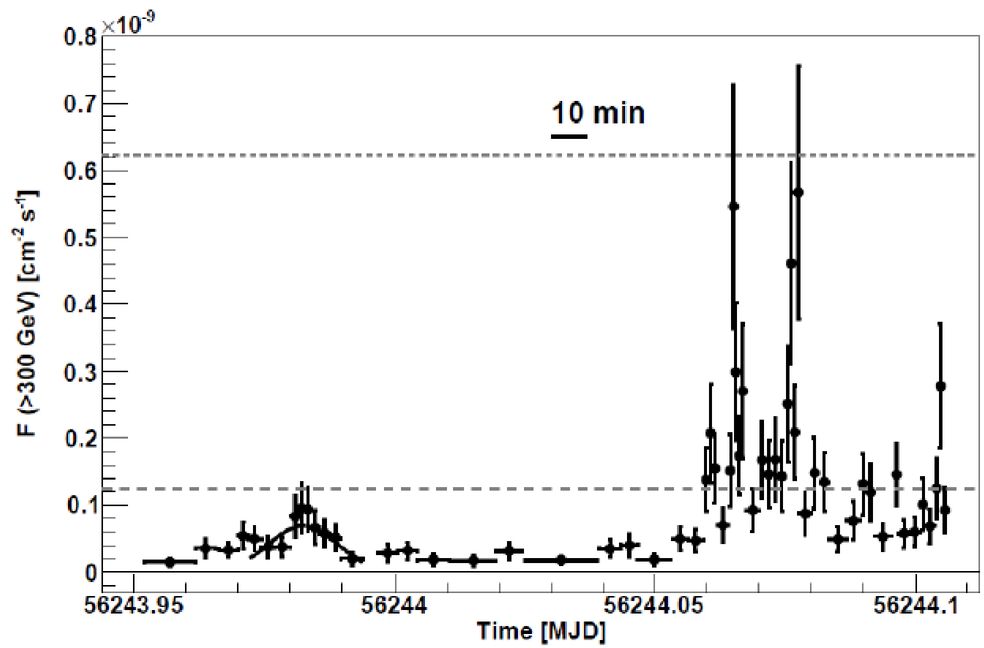
Increase of mm, optical, X-ray activity in 2008 Sep-Nov coincident to a LAT detection , suggesting co-spatiality of the event. A size of the gamma-ray emitting region R≲0.1 pc was inferred

IC 310: radio galaxy or blazar?



VLBI reveals a pc-scale inner structure, with a one-sided core-jet structure oriented along the same position angle as the kpc scale structure. Low luminosity FR I? BL Lac?

Aleksic et al. 2014

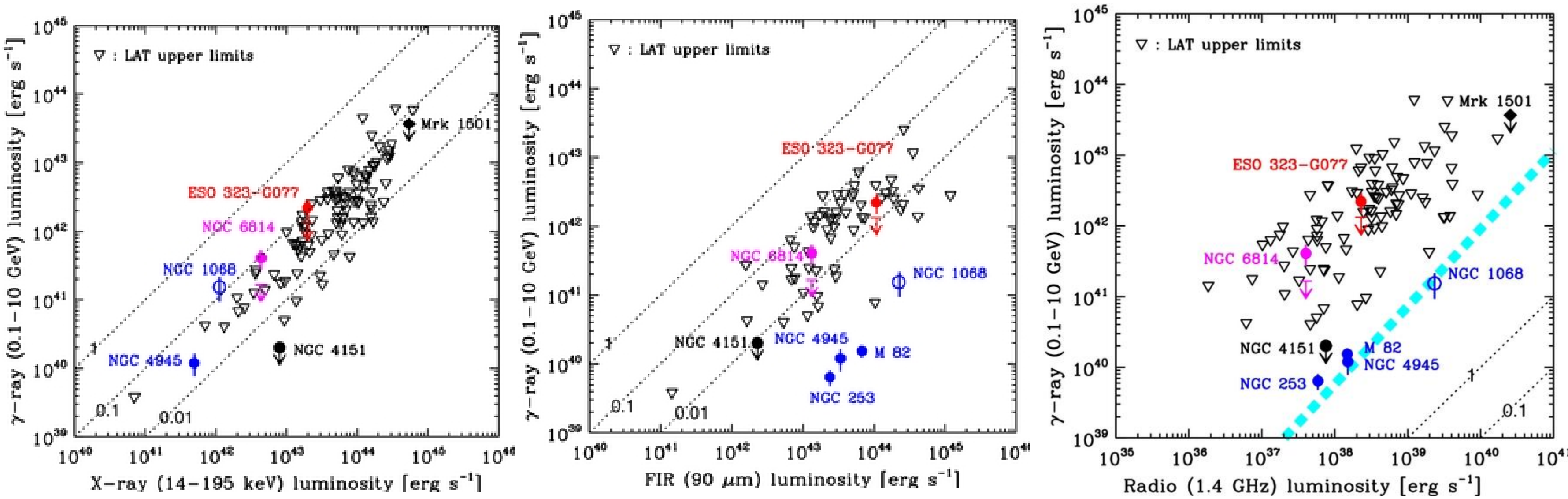


At VHE very fast variability was observed, with a flux doubling time scale < 4.8 min, suggesting particles accelerated in an extremely narrow region located near the event horizon of the BH and permeated by strong electric fields

Seyfert galaxies

120 hard X-ray selected radio-quiet Seyferts without strong starburst activity to constrain the high-energy emission mechanisms

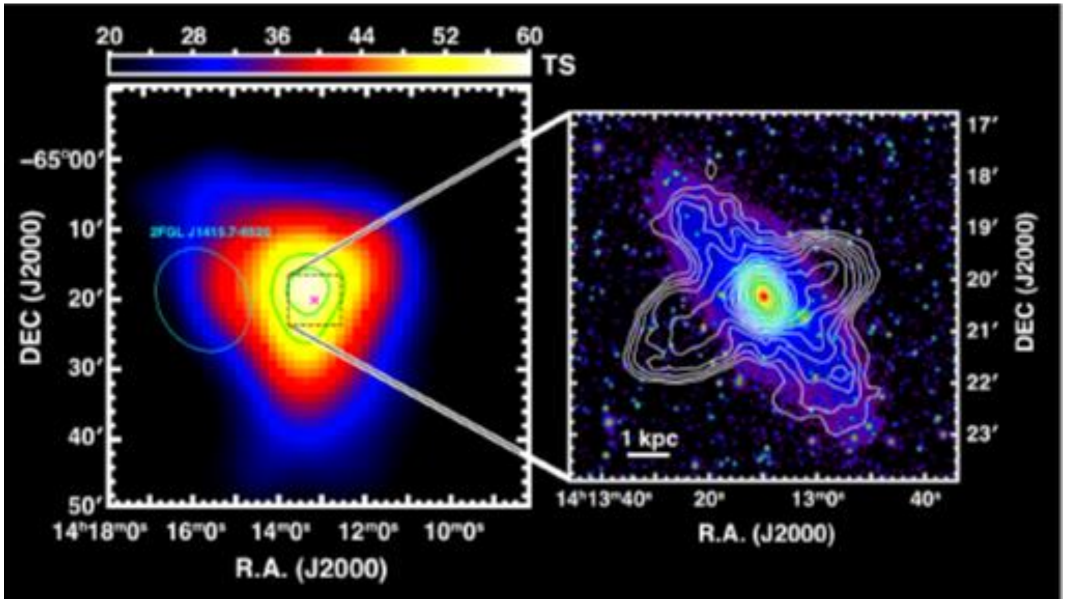
Ackermann et al. 2012



No detections, with ESO 323-G077 and NGC 6814 not confirmed

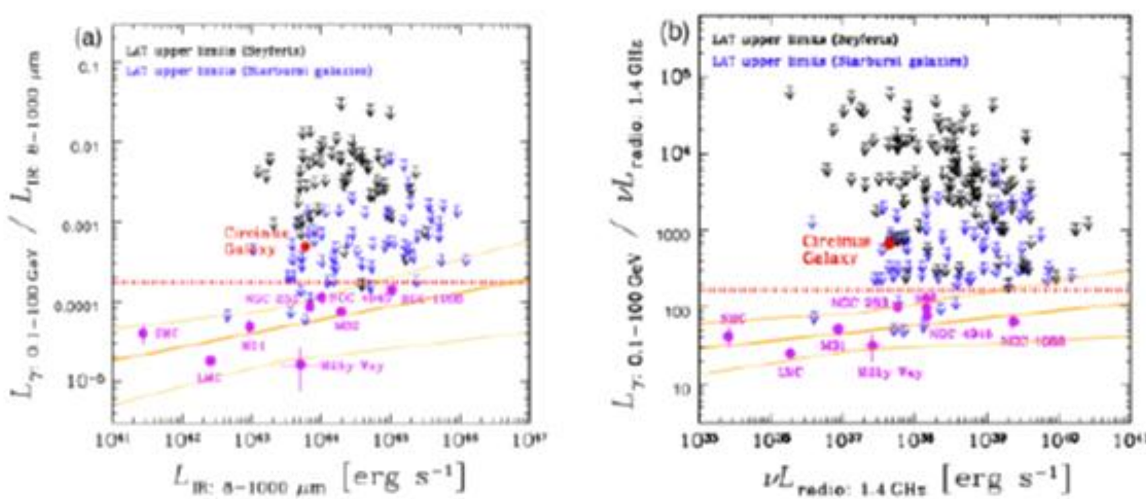
L_γ / L_X < 0.1 -0.01: Seyfert are not prominent γ-ray emitters

Circinus galaxy



Circinus is well located inside of LAT 68 c.l. region

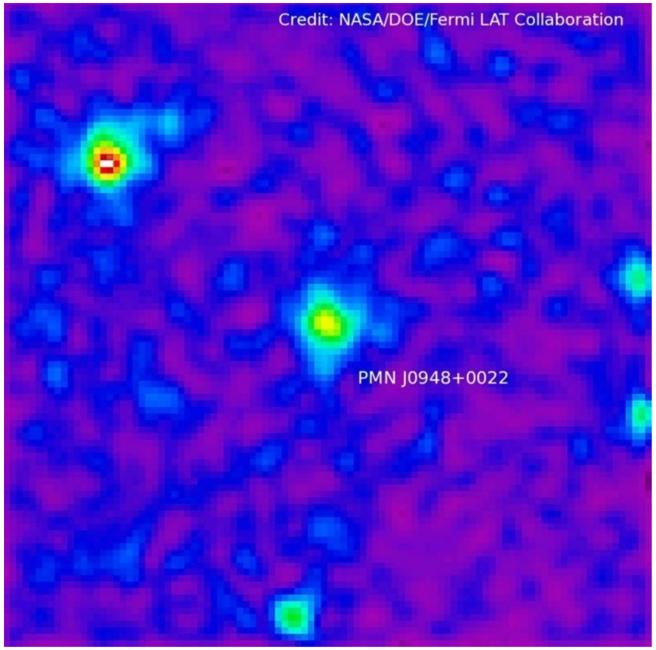
Circinus Galaxy shows higher L_γ/L_{IR} and L_γ/L_{radio}. This γ-ray luminosity exceeds the value expected from cosmic rays interaction in the interstellar medium and IC radiation from radio lobes



Gamma-ray emitting NLSy1s

- Before the launch of the *Fermi* satellite, only blazars and radio galaxies were known to be γ-ray emitting AGNs
- *Fermi*-LAT first 4 years of operation (1FGL, 2FGL, 3FGL) confirmed that the known extragalactic γ-ray sky is dominated by blazars but…

…the first detection of a γ-ray emitting narrow-line Seyfert 1 galaxy, PMN J0948+0022, during the first months of LAT observations was a great surprise!



Confirmation of the presence of relativistic jets also in NLSy1

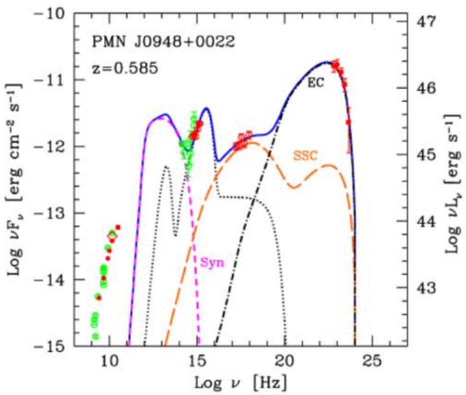
NLSy1s are thought to be hosted in **spiral/disc galaxies**, the presence of a relativistic jet in some of these objects seems to be in contrast to the paradigm that the formation of relativistic jets could happen only in elliptical galaxies (e.g. Boettcher & Dermer 2002, Marscher 2010)

Narrow-line Seyfert 1s and *Fermi*-LAT

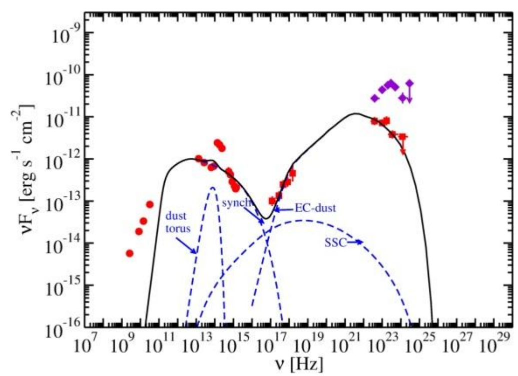
Fermi Gamma-ray Space Telescope

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

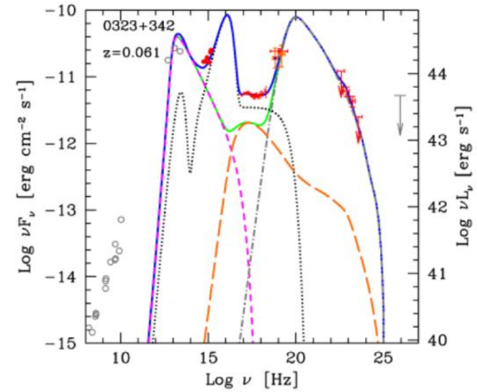
6 narrow-line Seyfert 1s were detected with TS > 25

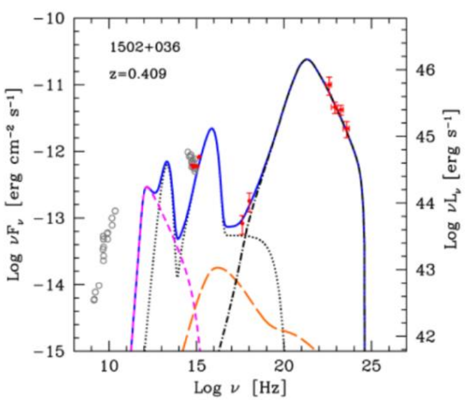


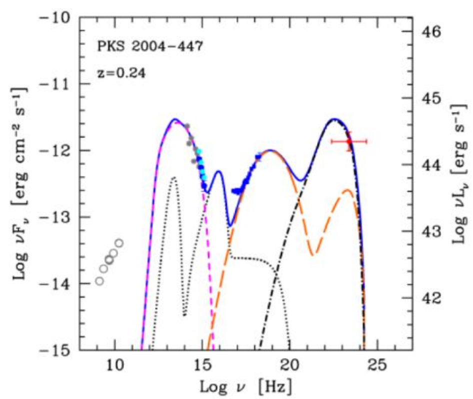
See also Foschini et al. 2012, 2014



D'Ammando, Orienti, Finke et al. 2012





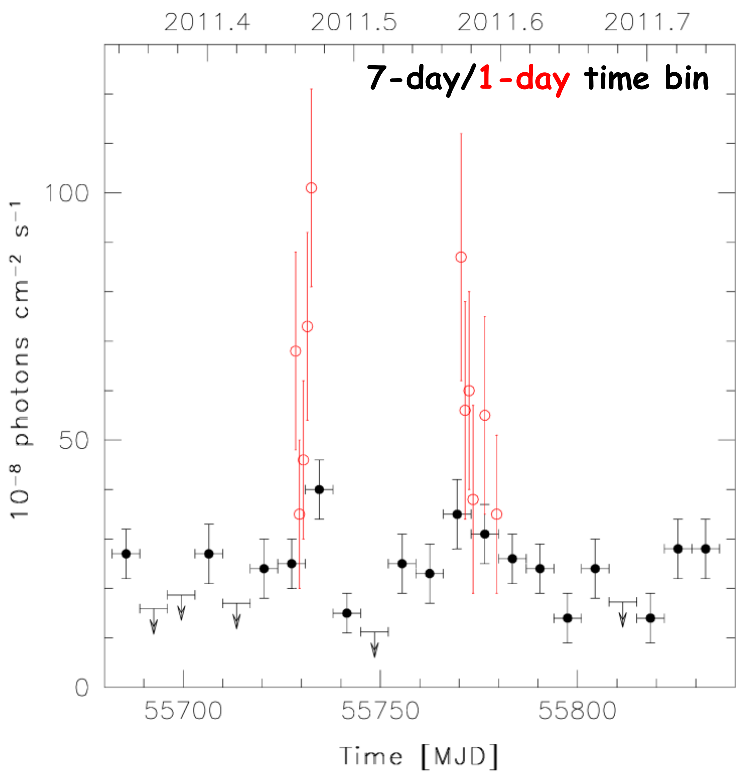


Abdo et al. 2009 (CA: L. Foschini)

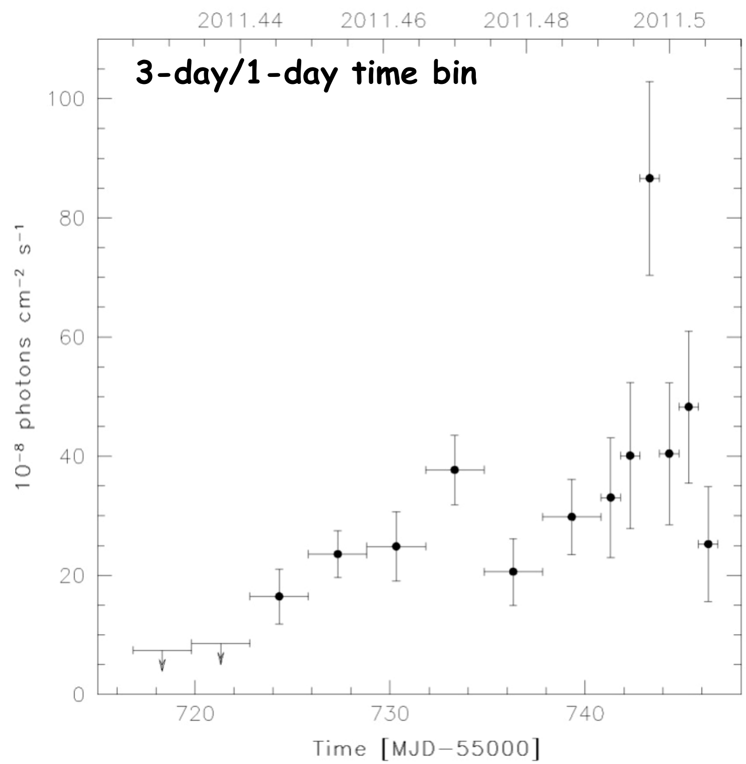
- 1H 0323+342
- SBS 0846+513
- PMN J0948+0022
- PKS 1502+036
- PKS 2004-447
- **FBQS J1644+2619**
  (D'Ammando et al. 2015)

NLSy1s are flaring gamma-ray sources!

PMN J0948+0022



SBS 0846+513

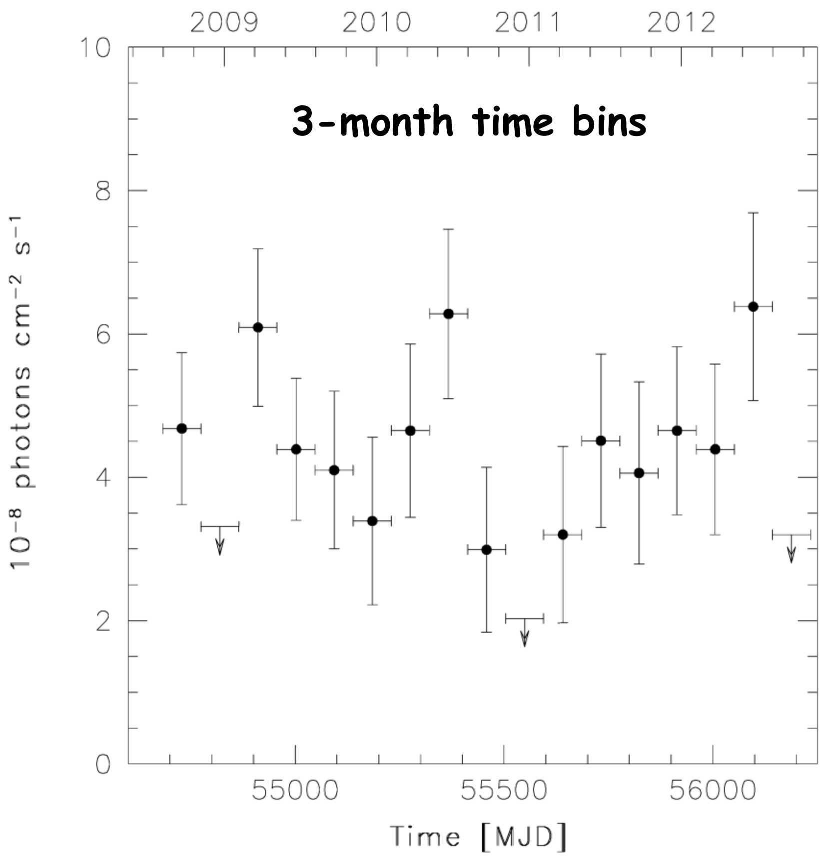


D'Ammando et al. 2014, MNRAS, 438, 3521

D'Ammando et al. 2012, MNRAS, 426, 317

PMN J0948+0022, SBS 0846+513, and 1H 0323+342 (ATel #5344) showed different flaring episodes with an apparent isotropic gamma-ray luminosity of ***~10^{48} erg s^{-1}, comparable to that of the bright FSRQs***

The ordinary life of PKS 1502+036



PKS 1502+036 was detected by LAT over 51 months (2008 August 4 - 2012 November 4) with TS = 314, an average flux (0.1-100 GeV) of (4.0 ± 0.4)e-8 ph cm^{-2} s^{-1} and a photon index Γ = 2.60 ± 0.06

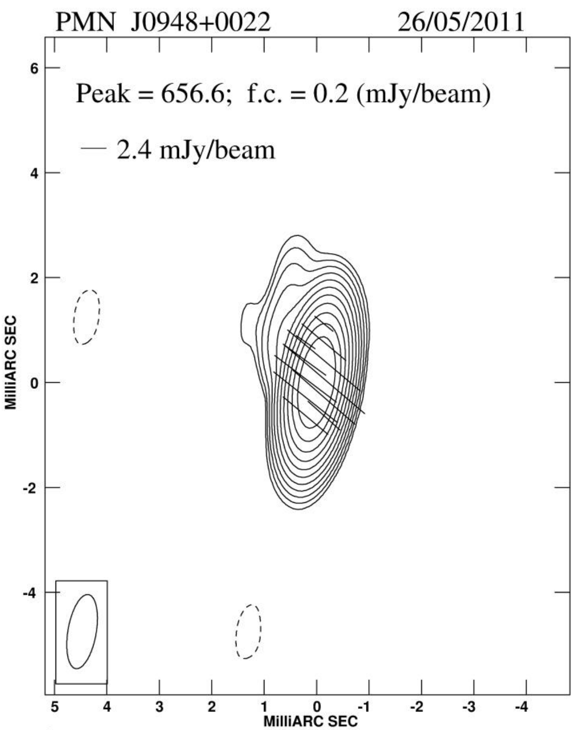
No significant flux variability was observed, with only a few detections on weekly time scales and a peak value of (18 ± 6)e-8 ph cm^{-2} s^{-1}

D'Ammando, Orienti, Doi, et al. 2013a, MNRAS, 433, 952

Core-jet structures in gamma-ray NLSy1s

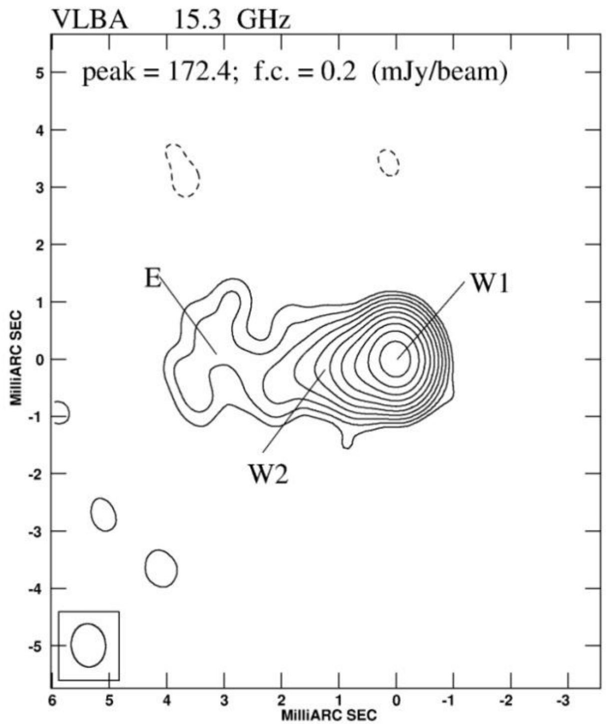
Core-jet structure on parsec scale resolved with the VLBA

PMN J0948+0022



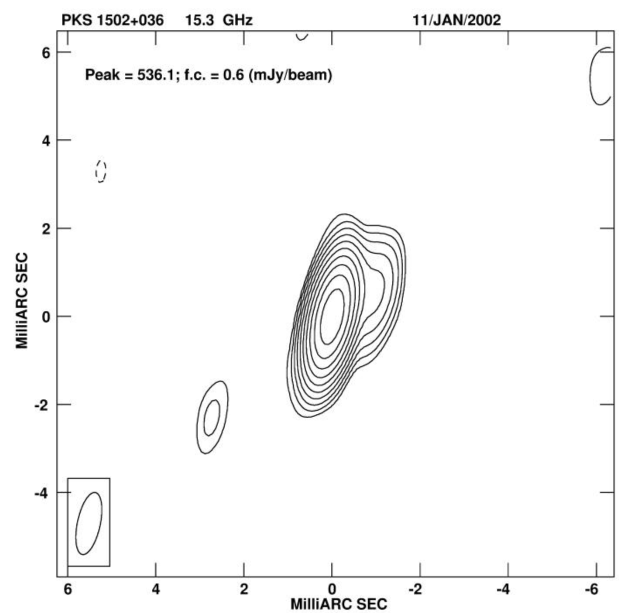
D'Ammando et al. 2014

SBS 0846+513



D'Ammando et al. 2012

PKS 1502+036



D'Ammando et al. 2013a

Proper motion of gamma-ray NLSy1s

Fermi Gamma-ray Space Telescope

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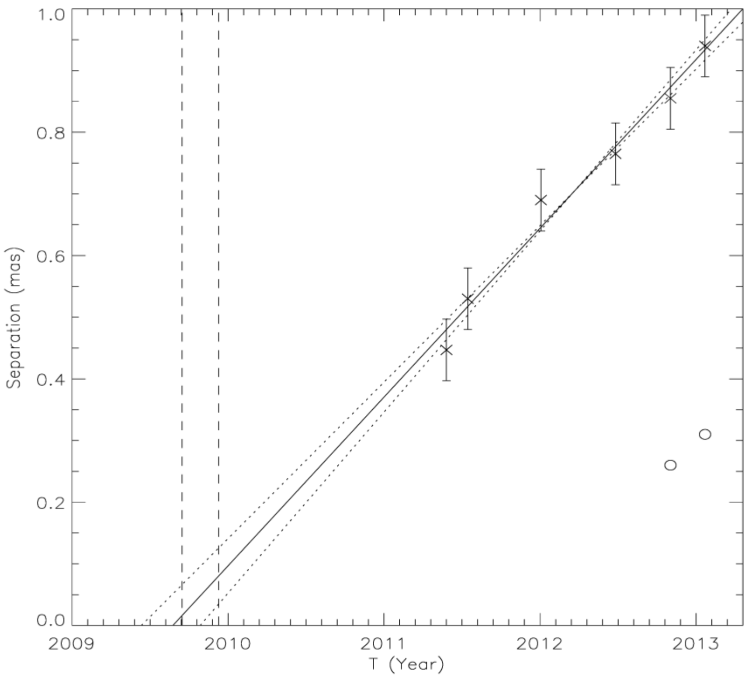
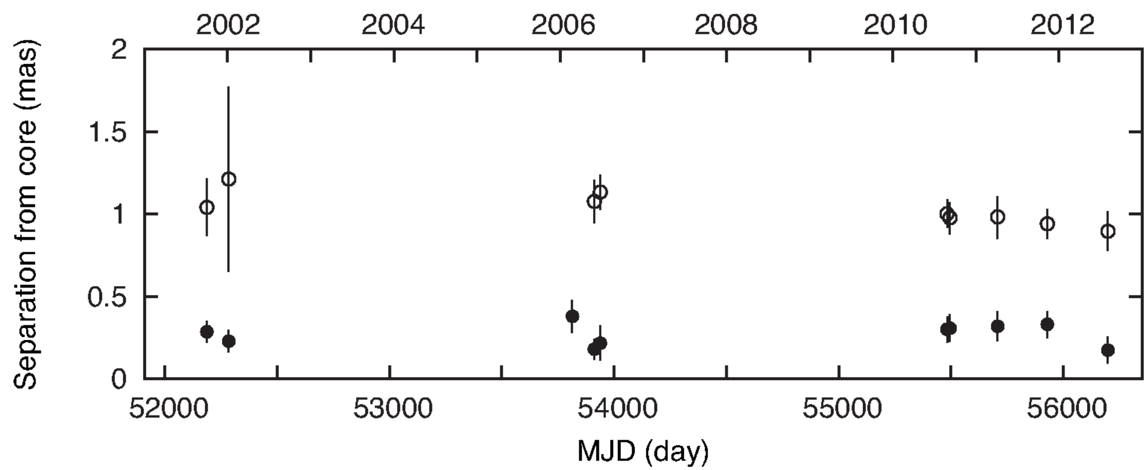


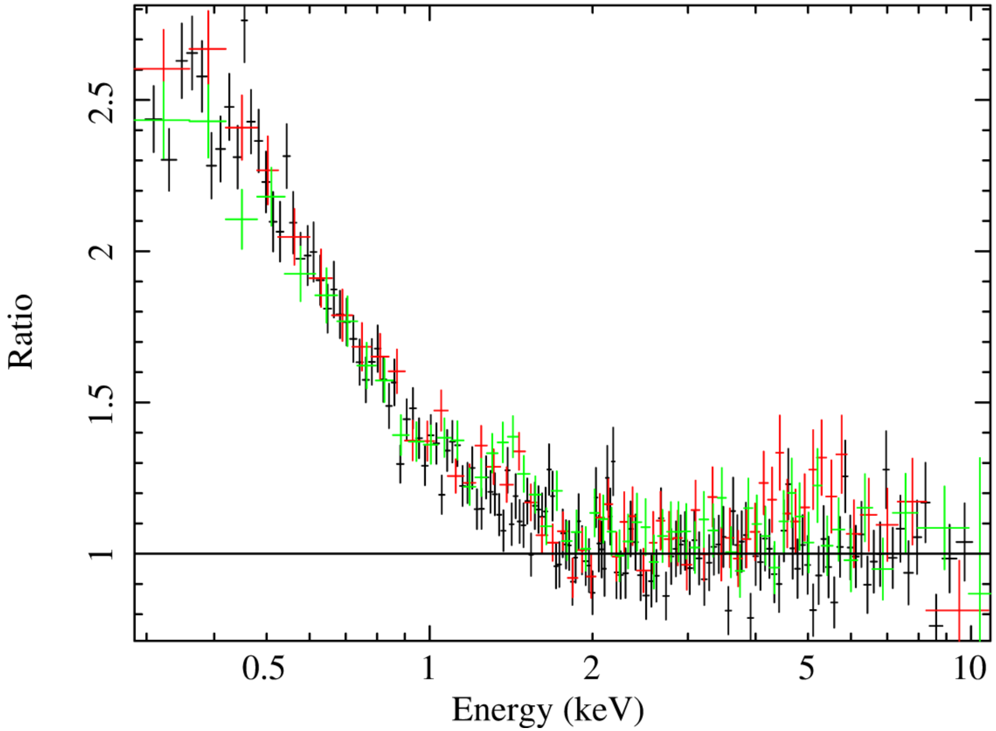
With 6-epoch MOJAVE data for SBS 0846+513 we obtained an apparent velocity of the jet knot **(9.3±0.6)c**, suggesting **the presence of boosting effect as well as in blazars**. The time of ejection is **T_0 = 24 August 2009**, likely connected with a radio flare. *No significant gamma-ray activity was detected in that period*

D'Ammando et al. 2013b, MNRAS, 436, 191

No significant proper motion was detected for the jet components of PKS 1502+036



XMM observation of PMN J0948+0022



Γ = 1.88 $\pm$ 0.01 in the 0.3-10 keV energy range, χ^2_{red} = 1.87 (1254)

A simple power law in 2-10 keV provides a good fit Γ = 1.48$\pm$0.03

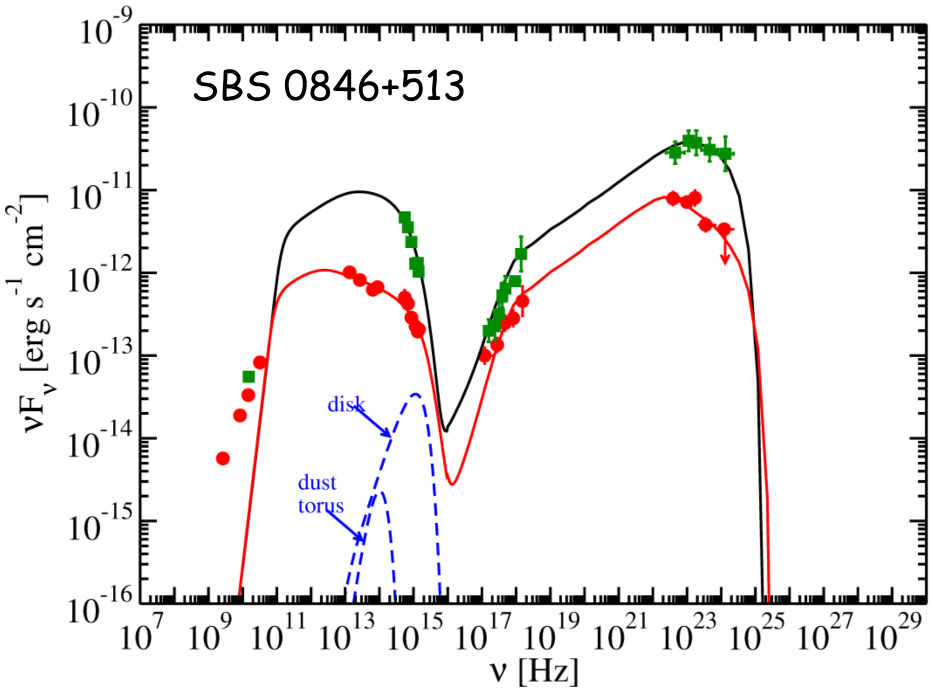
A clear soft excess was observed, notwithstanding the non-thermal jet emission!

D'Ammando et al. 2014

A broken power-law provides an acceptable fit, χ^2_{red} = 1.10 (1252), with a break at energy E_{break} = 1.72$\pm$0.10 keV and photon indices Γ_1= 2.14$\pm$0.03 and Γ_2 = 1.48$\pm$0.04. The emission above 2 keV is dominated by the jet component, with no detection of an Iron line in the spectrum and a 90% upper limit on the EW of 19 eV

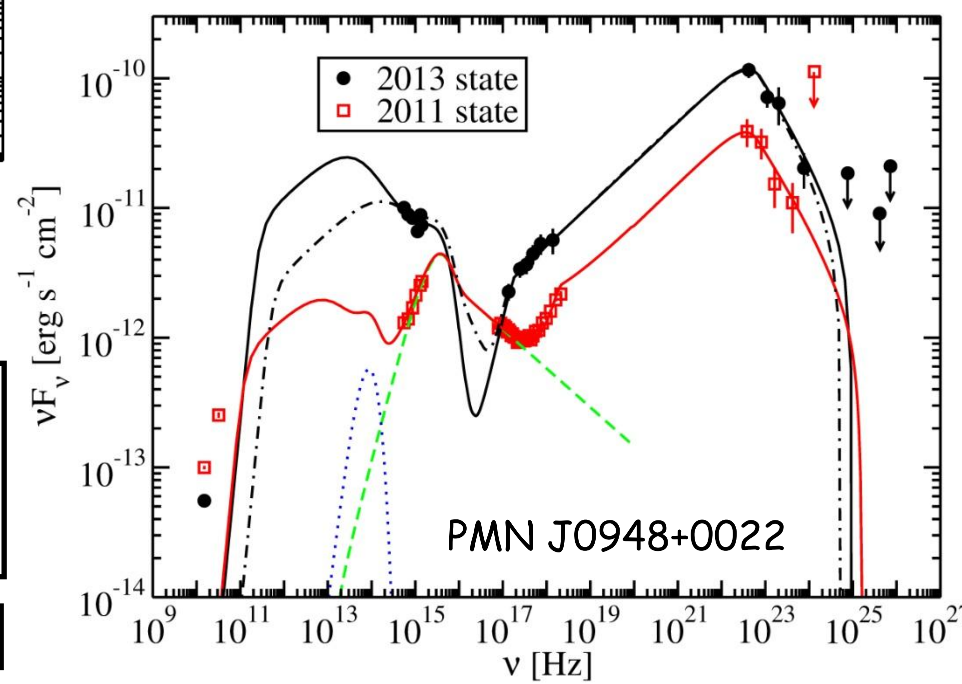
The soft component can be also fitted with a black body model with kT ~ 0.18 keV. Such a high temperature is inconsistent with the standard accretion disk theory

SED modeling of NLSy1s



The quiescent and flaring state, modelled by EC (dust), could be fitted by changing the electron distribution parameters as well as the magnetic field

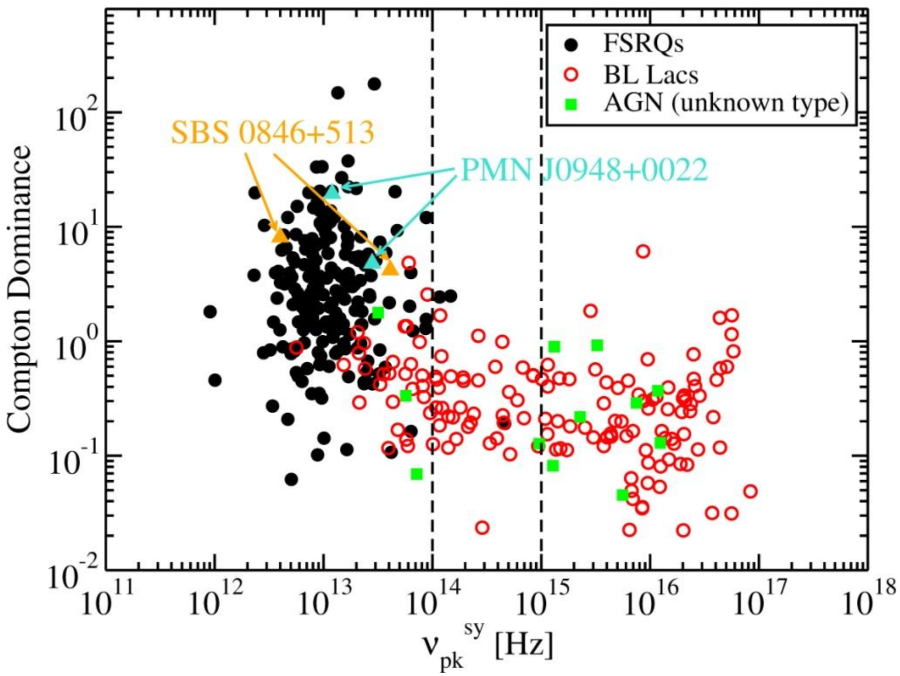
D'Ammando et al. 2013b



The 2013 flaring state may be modelled by EC (dust) or EC (BLR). In the latter, the source is far from the equipartition favouring the EC (dust) model.

D'Ammando et al. 2015

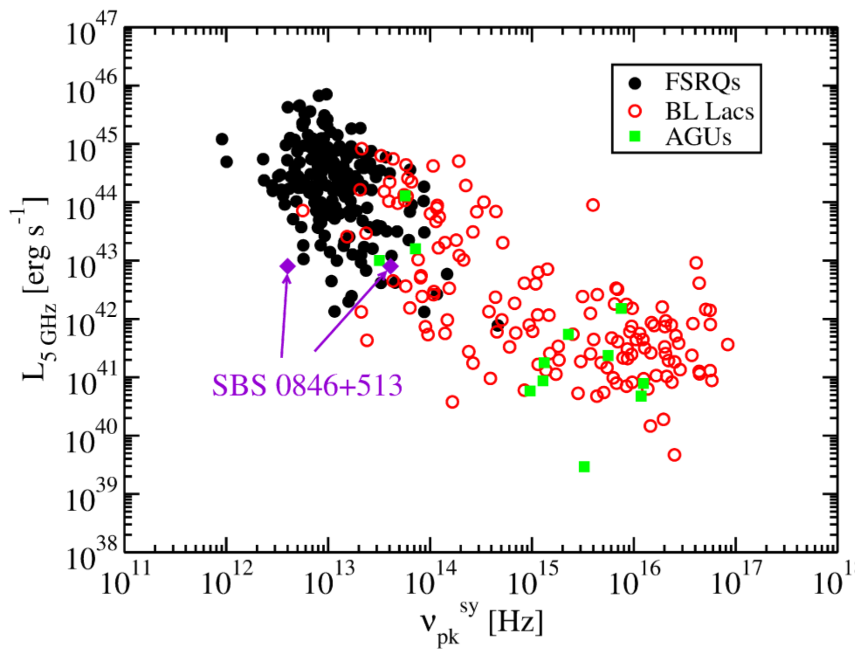
Comparison with γ-ray blazars



SBS 0846+513 and PMN J0948+0022 showed a Compton dominance typical of FSRQs during both the low and high activity state

D'Ammando et al. 2015

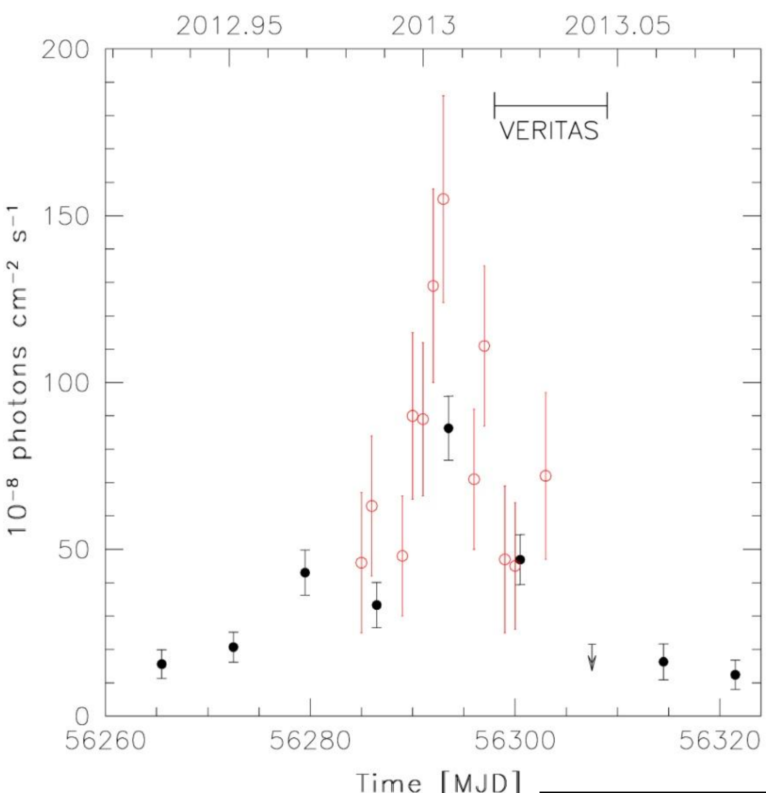
Figures adapted from Finke 2013

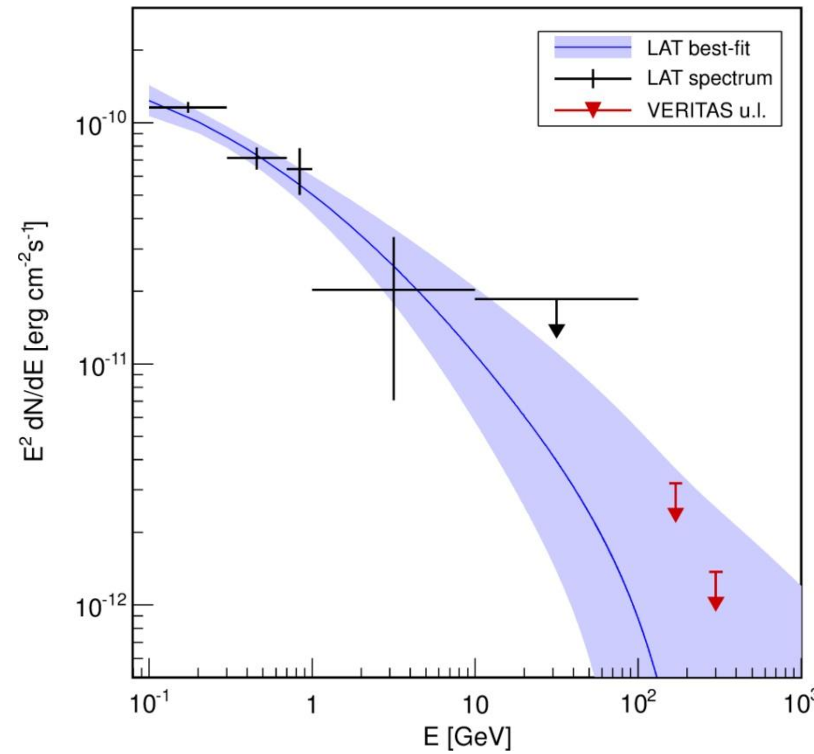


In the "classical" blazar sequence plot SBS 0846+513 seems to lie in the FSRQ region

D'Ammando et al. 2013b

NLSy1 as VHE emitting sources?





D'Ammando et al. 2015, MNRAS, 446, 2456

Following the most powerful flaring activity from PMN J0948+0022, the detection of VHE emission from this NLSy1 was attempted by VERITAS. Future observations with the Cherenkov Telescope Array (CTA) will constrain the level of gamma-ray emission at 100 GeV or below.

Summary

• The 3LAC is a major improvement over the 2LAC: many more associations thanks to improved methods, and reduced uncertainties due to longer exposure and analysis refinements

• Fermi-LAT confirmed that misaligned AGN are a class of γ-ray emitting source, including different flavours (FR I, FR II, BLRG, SSRQ, Seyfert)

• Some "misaligned AGN" showed blazar-like behaviour (e.g. strong and rapid variability), suggesting a relatively small viewing angle

• Structured jet models may be a good representation of these misaligned AGN, in accordance with some observational evidence

• Six NLSy1 have been detected in gamma-ray so far. At least three NLSy1 showed intense γ-ray flares, thus NLSy1 can host relativistic jets as powerful as blazars. Are these sources peculiar also among the NLSy1?

• The discovery of relativistic jets in a class of AGN thought to be hosted by spiral galaxies was a great surprise but are gamma-ray NLSy1 not in classical spiral galaxies?