Extragalatic Relativistic Jets

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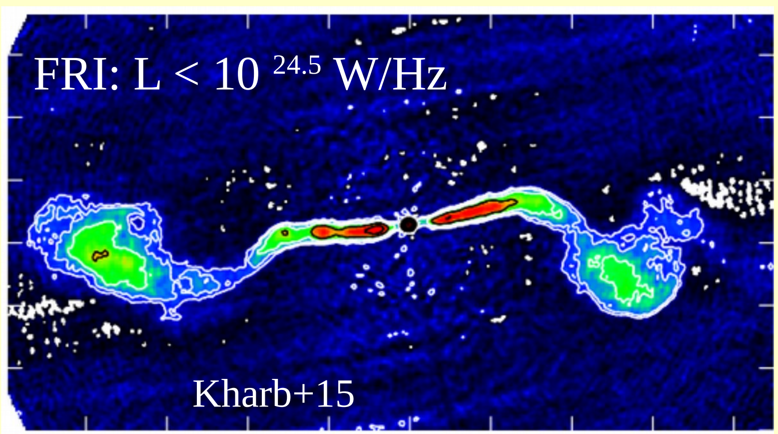
(INAF-IRA)

Outline

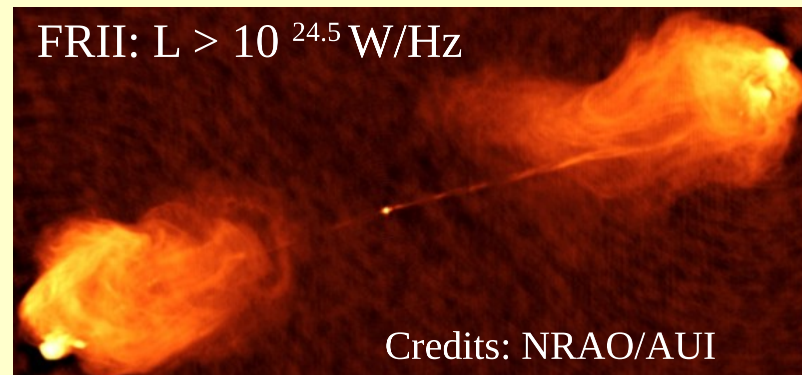
- Relativistic jets and the extragalactic γ-ray sky
- Radio and γ-ray connection
- The case of 3C 84

Relativistic jets

- Bipolar outflow of relativistic plasma produced in ~10% of AGN
- Different morphology depending on the jet power

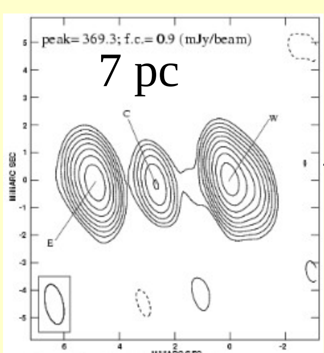


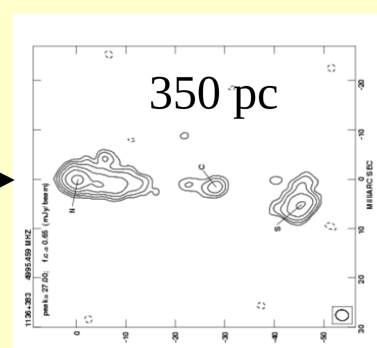
Low power: bright decollimated jets

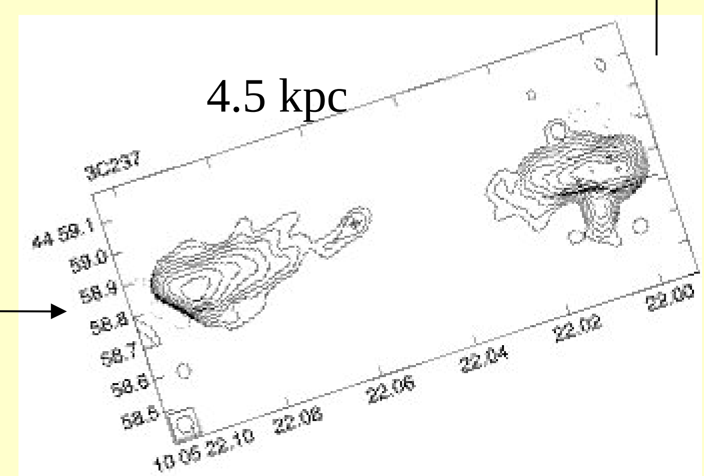


High power: weak collimated jets

- Linear size from a few pc to a few Mpc

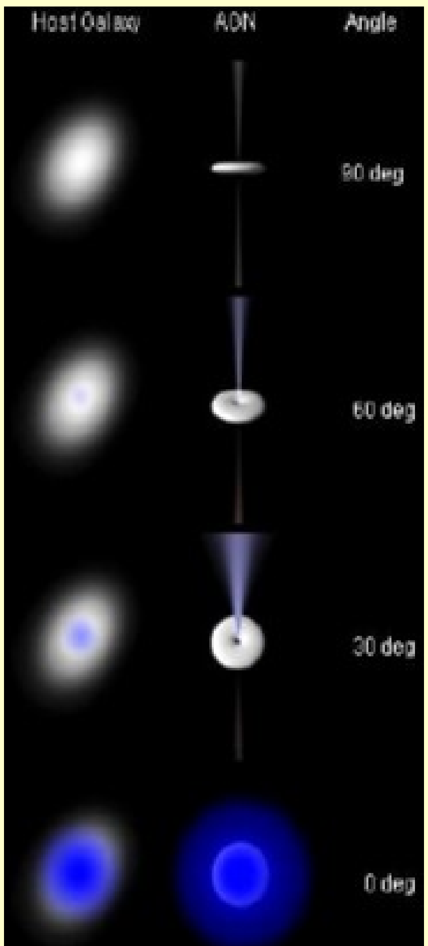


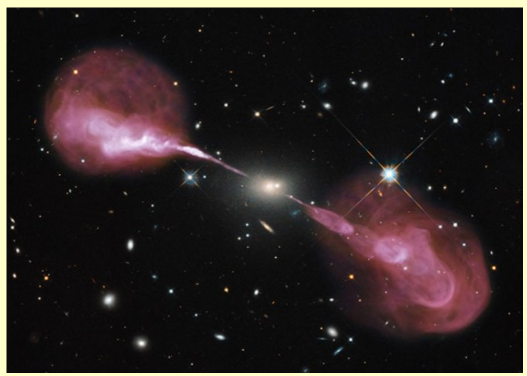


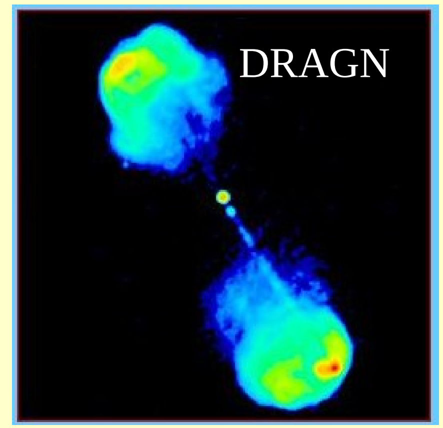


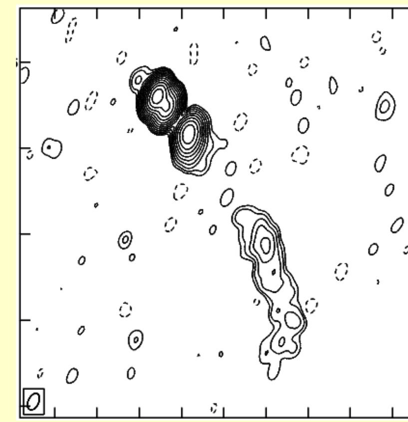
Relativistic jets: viewing angle

Depending on the viewing angle:



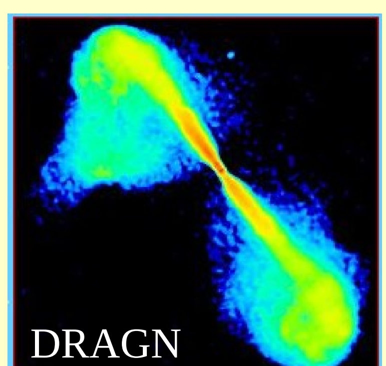


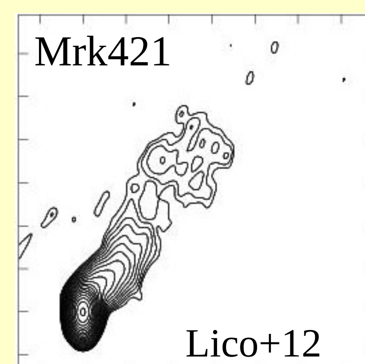




High luminosity objects: FRII → FSRQ

Low luminosity objects: FRI → BL Lacs

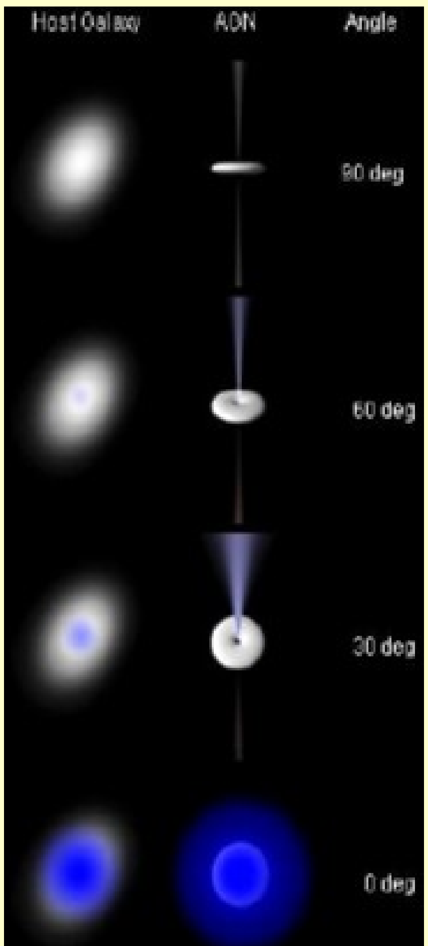


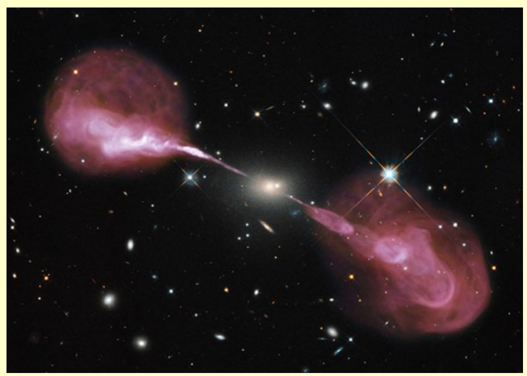


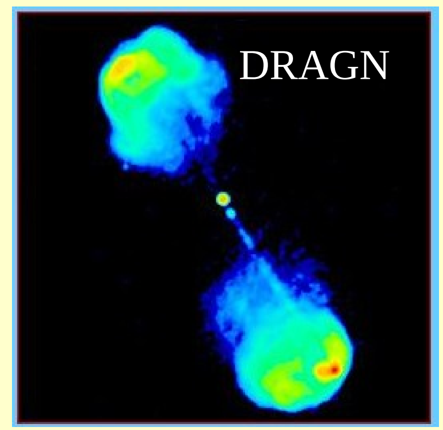
Relativistic jets: viewing angle

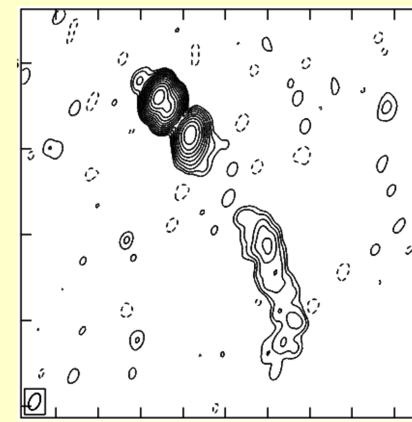
Depending on the viewing angle:

See Torresi's talk









High luminosity objects: FRII → FSRQ

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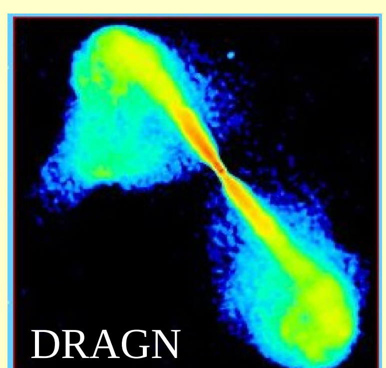
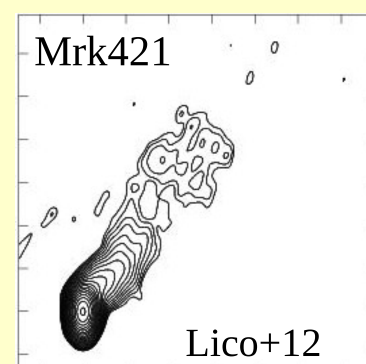




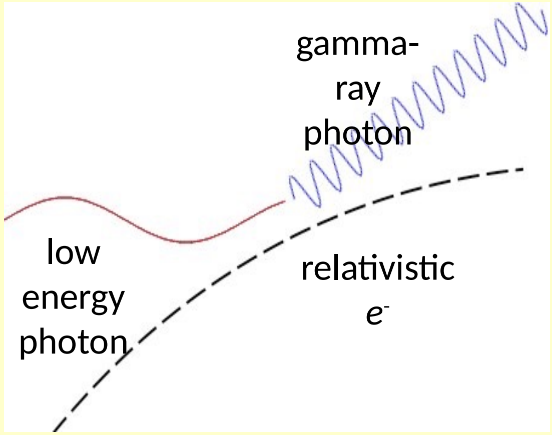
Broad-band non-thermal emission

Non-thermal emission

- Low energy: **synchrotron**

- High energy: **inverse Compton**

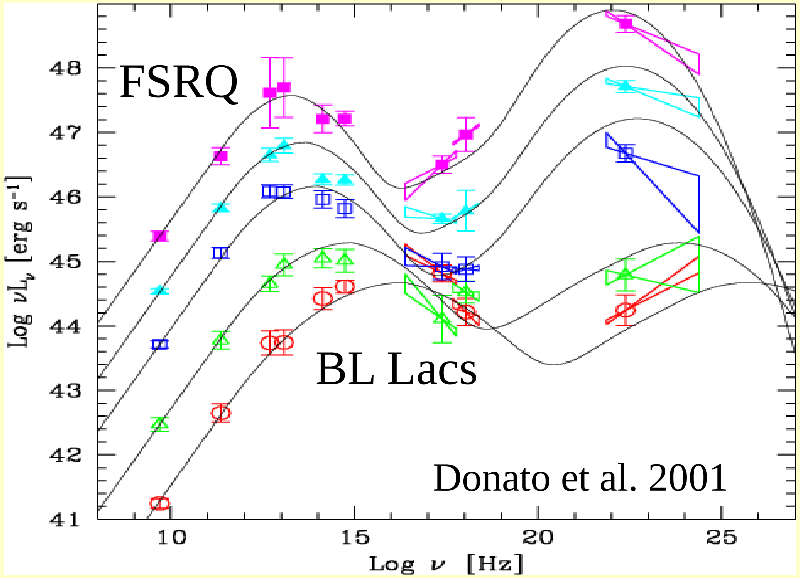
Relativistic electrons can scatter low energy photons



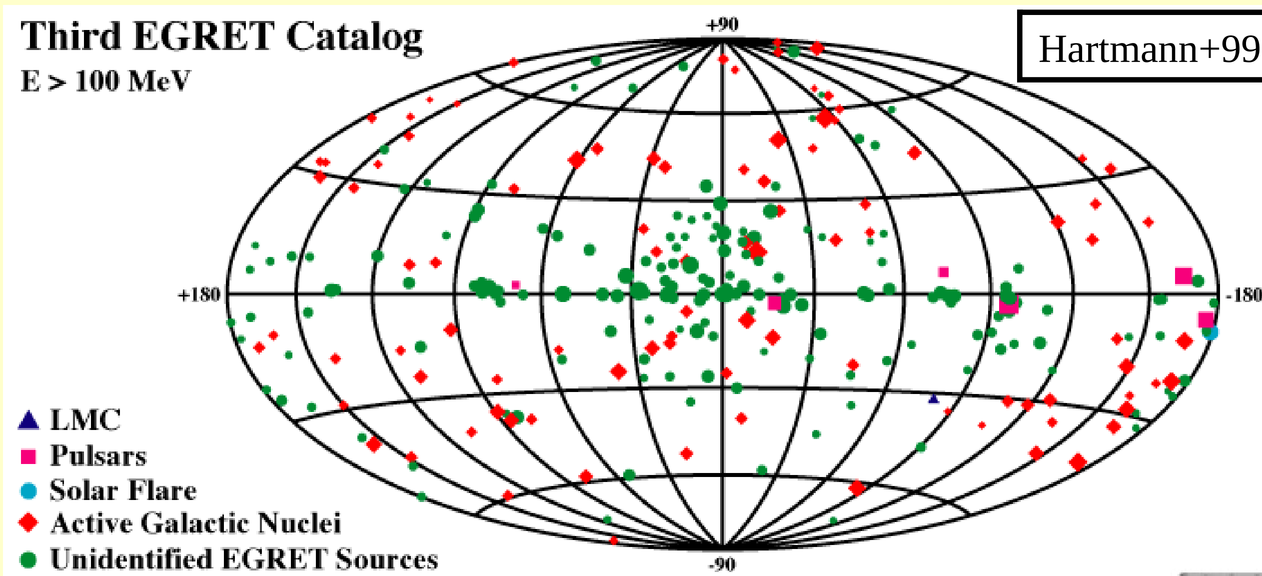
- external photons from torus, disk, BLR, CMB, EBL,... (EC)

- their own synchrotron photons (SSC)

Connection between low and high energy emission: the **blazar sequence**



The extragalactic γ-ray sky: the EGRET Era



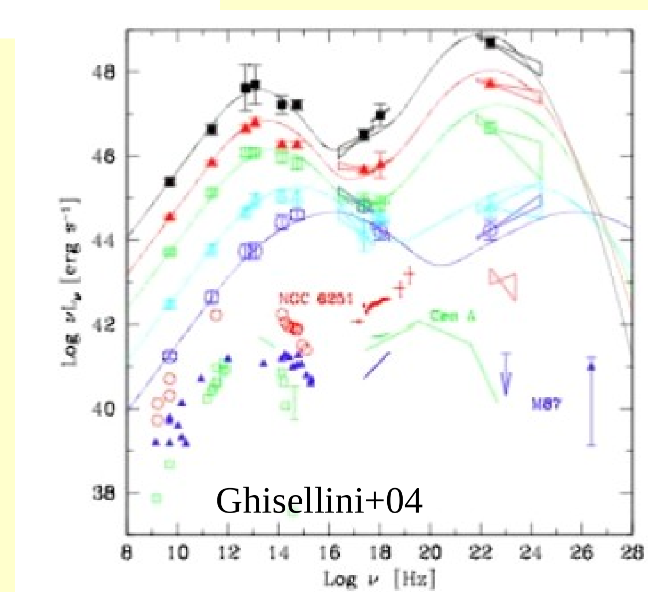
Hartmann+99

- 67 blazars detected by EGRET

- Mostly FSRQ (75% FSRQ, 25% BL Lacs)

- Only 3 *tentative* detections of radio galaxies:

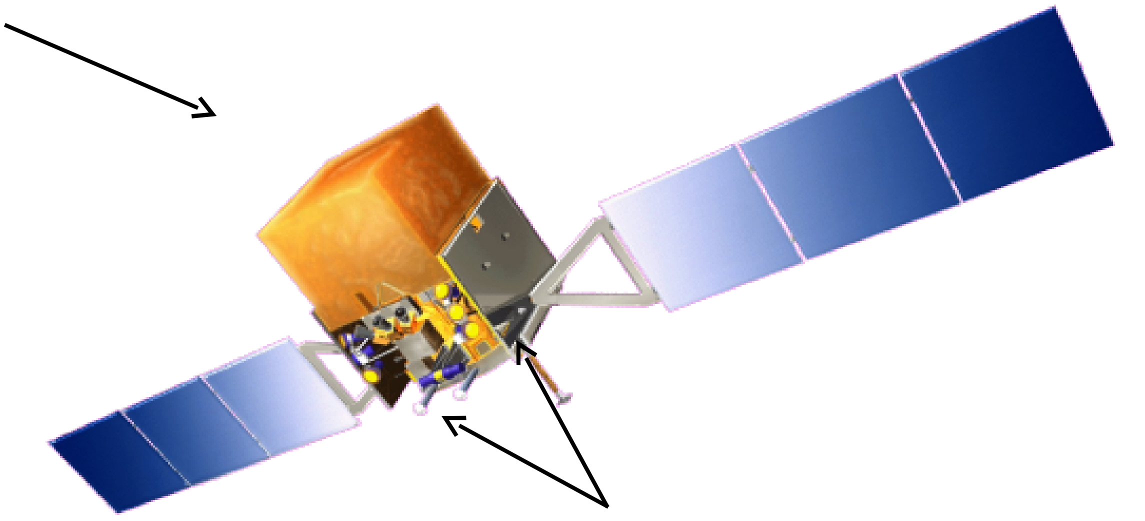
- Centaurus A
- NGC 6251 (Mukherjee+02)
- 3C 111 (Hartmann+08)



Ghisellini+04

The Fermi Gamma-ray Space Telescope

Large Area Telescope (LAT)
the first all-sky survey in γ rays, covering 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

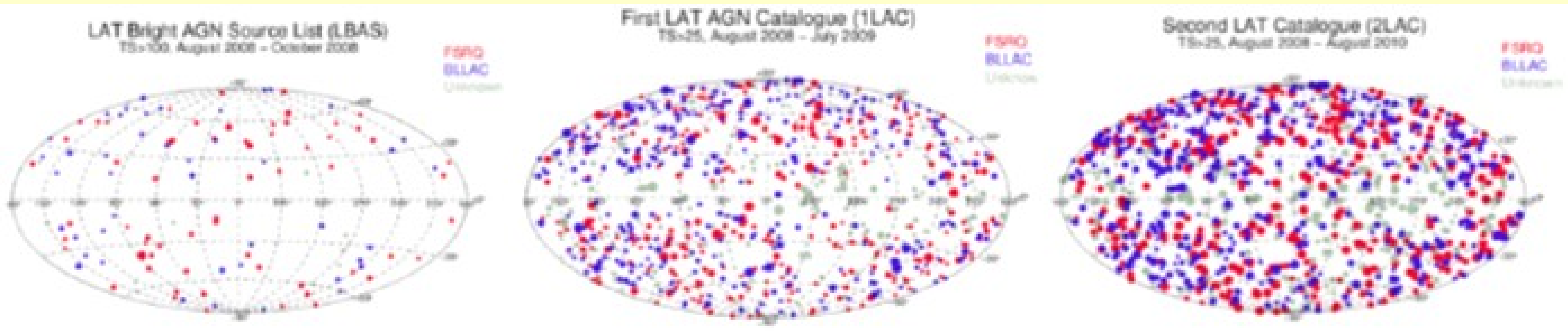
Launched from Cape Canaveral Air Station on 11 June 2008
nearly circular orbit 565 km, 25.6°

The extragalactic γ-ray sky: the Fermi Era

3-month LAT data

11-month LAT data

24-month LAT data



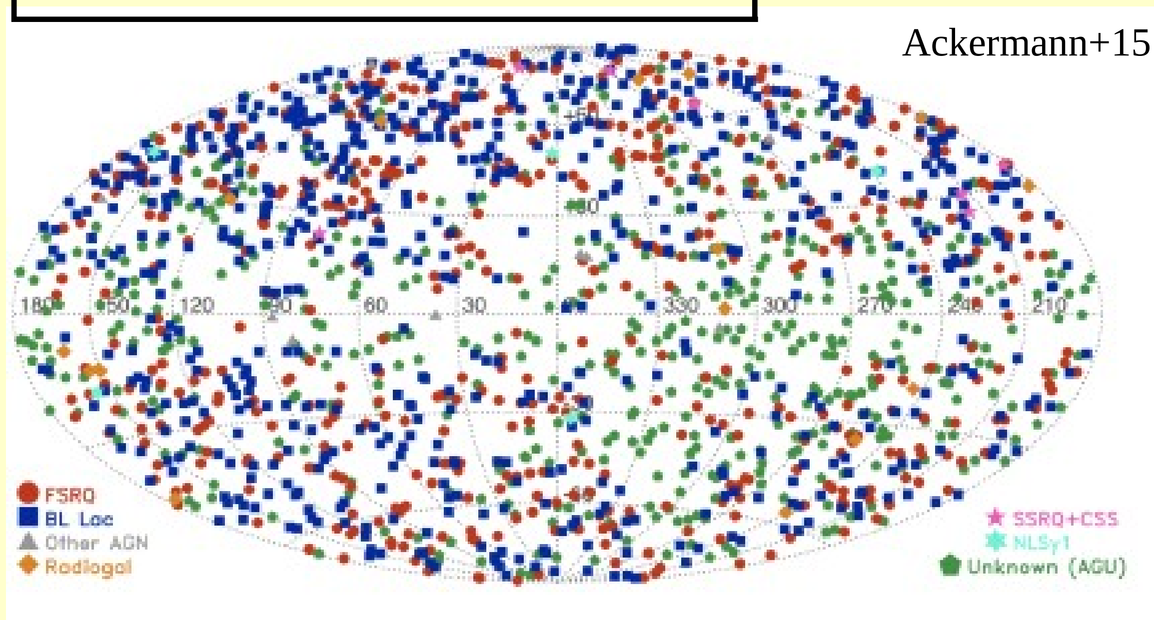
LBAS-high latitude:
58 FSRQs
42 BL Lacs
6 AGNs
Abdo+09

1LAC-clean sample:
248 FSRQs
275 BL Lacs
50 Blazars with unknown type
26 AGNs
Abdo+10

2LAC-clean sample:
310 FSRQs
395 BL Lacs
156 Blazars with unknown type
24 AGNs
Nolan+12

The Third LAT AGN Catalogue

48-month LAT data

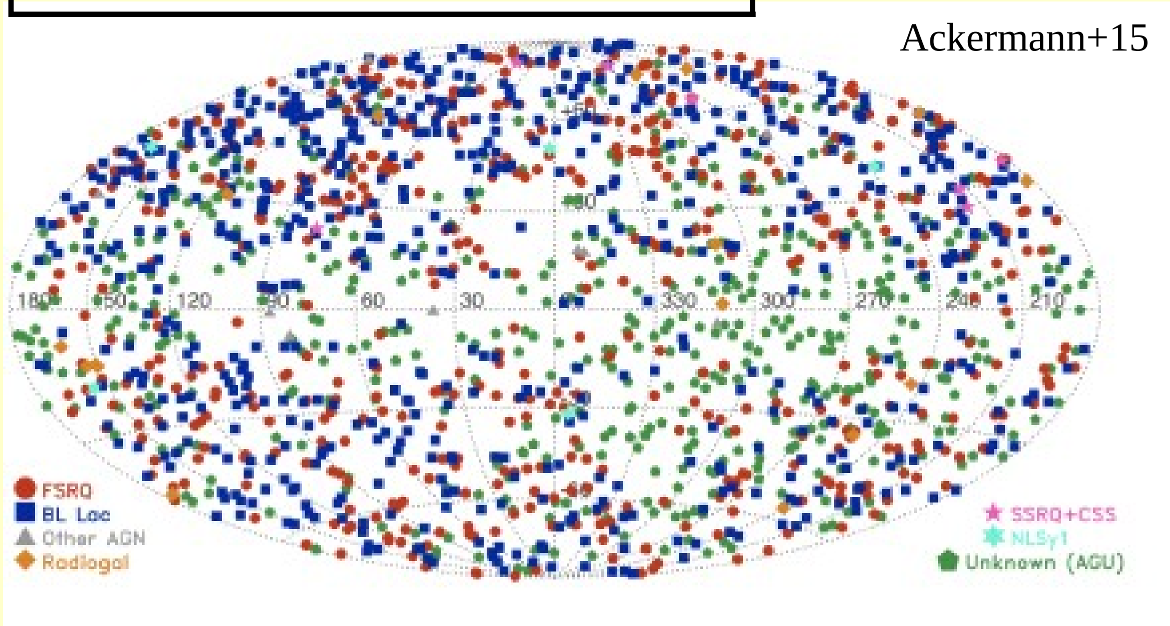


- 1591 (1444) sources with TS>25
- |b|>10°(71% more than in 2LAC)
- 182 low-latitude AGN (24 FSRQ, 30 BL Lacs, 125 BCU, 3 non-blazar AGN)

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

The Third LAT AGN Catalogue

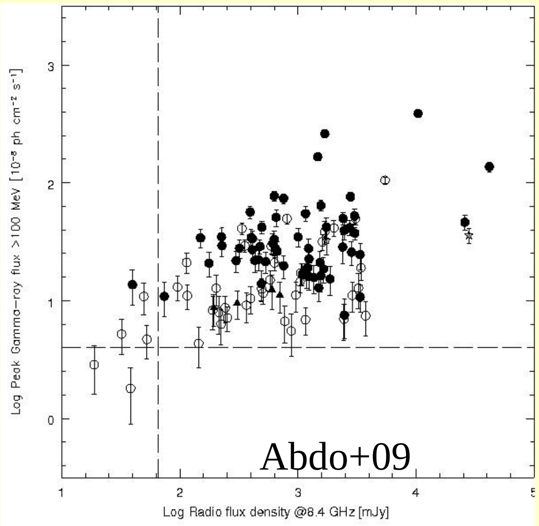
48-month LAT data



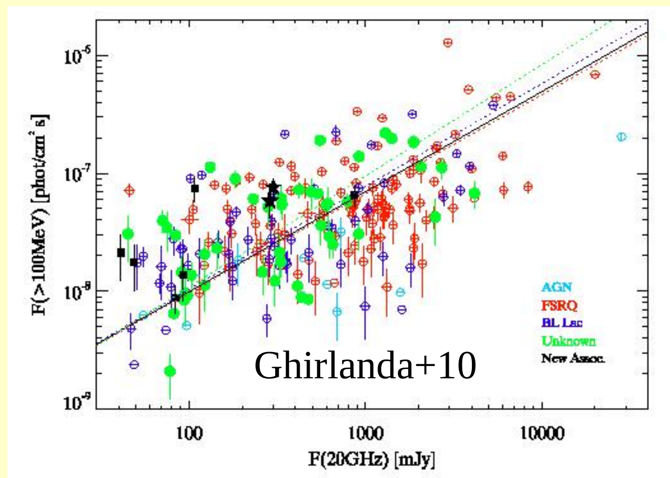
4FGL is in preparation and will be public soon!!

Radio and γ-ray correlation

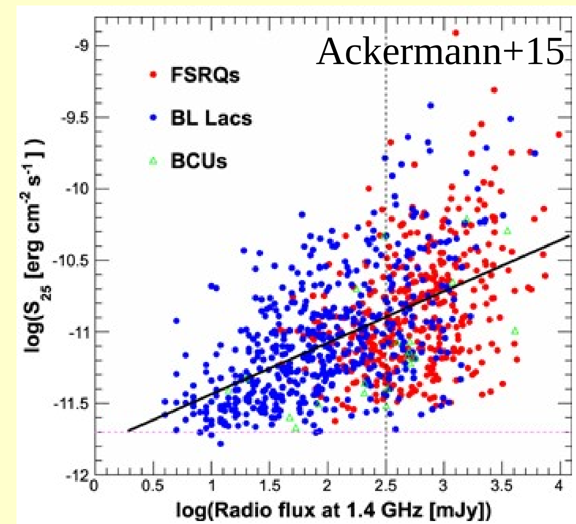
LBAS: 3-month survey
CRATES 8.4-GHz data



1LAC: 11-month survey
AT20G 20-GHz data



3LAC: 4-yr survey
1.4-GHz data



Tentative correlation

Significant (>3σ) correlation

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Note: small biased sample

Note: correlation gets stronger when considering **non-variable** Fermi sources (Mahony+10)

Radio and γ-ray correlation

LBAS: 3-month survey

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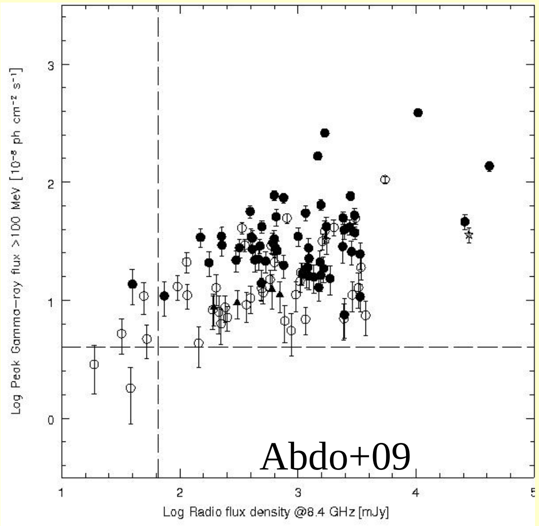
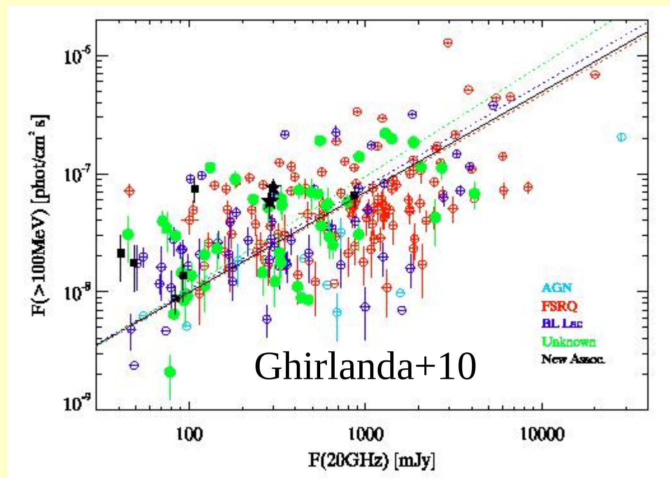


Tentative correlation

Note: small biased sample

1LAC: 11-month survey

AT20G 20-GHz data



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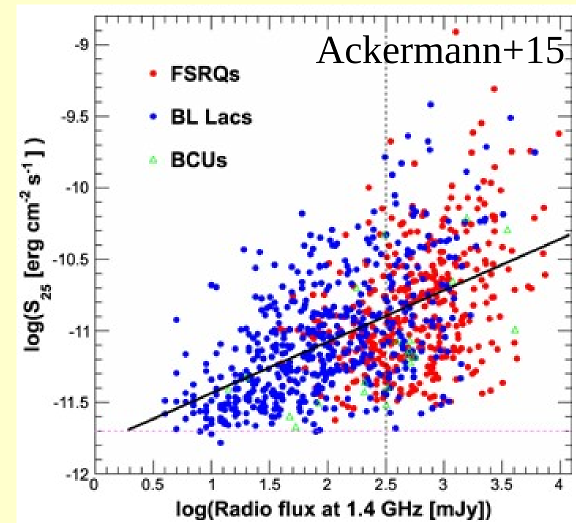
3LAC: 4-yr survey

1.4-GHz data



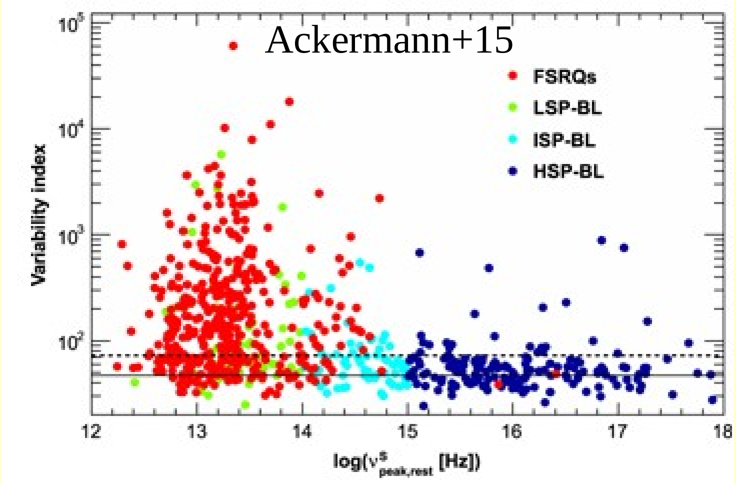
Significant (>3σ) correlation

See Lico's talk

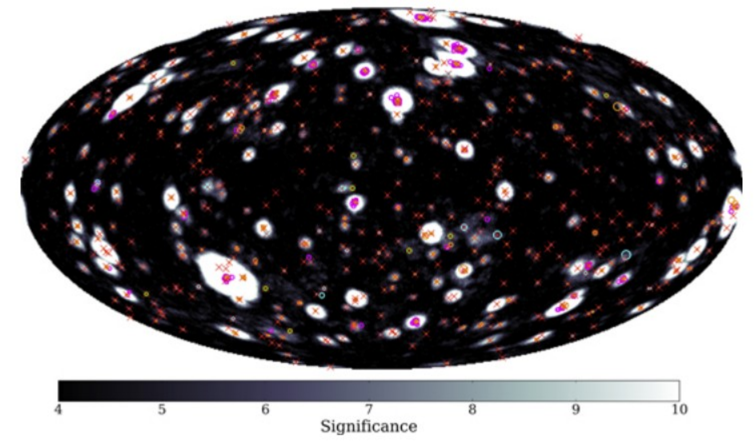
Variability

Relativistic jets viewed at small angles are highly variable at all wavelengths

A large fraction of Fermi-LAT blazars (69% FSRQ, 23% BL Lacs) are variable



2FAV Abdollahi+17



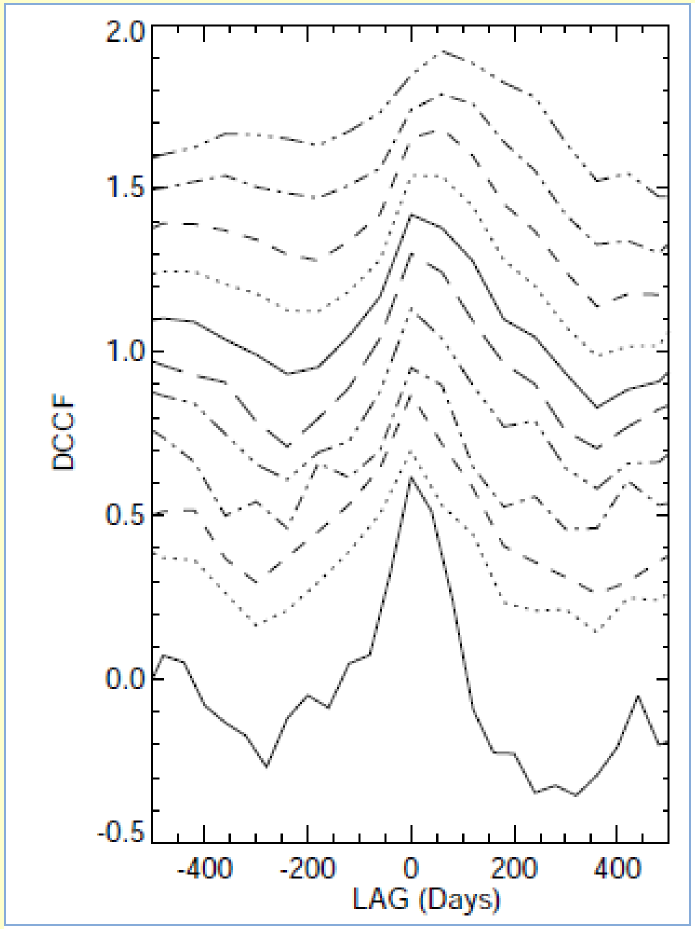
Variability timescale and the time-delay observed at different wavelength provide clues on the emitting region (size, location, seed photons) and the physics involved

Single-dish studies of large samples: F-GAMMA

Cross-correlation between the γ-ray and radio light curves of a sample of 54 Fermi blazars observed between 11 cm and 2 mm.
Additional 0.8 mm APEX data for 25 blazars.

γ-ray leads the radio variability

Fuhrmann+14



Time delay increases with frequency:

- 76±23 days at 11 cm
- 7±9 days at 2 mm

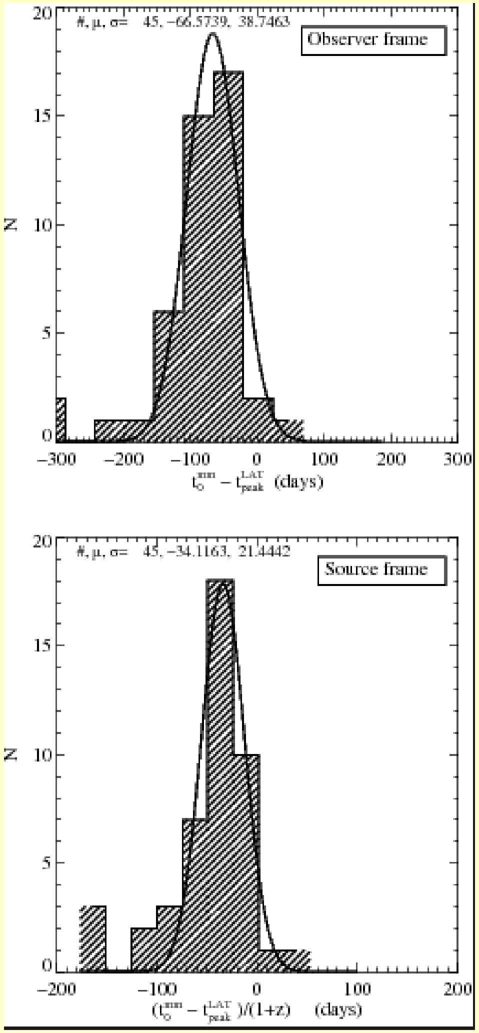
The γ-ray/radio distance decreases with frequencies:

- 9.8±3.0 pc at 11 cm
- 0.9±1.1 pc at 2 mm

Single-dish studies of large samples: Metsähovi

Cross-correlation between the radio and γ-ray light curves of a sample of 60 Fermi blazars observed at 37 GHz.

Leon-Tavares et al. 2011



Radio leads the γ-ray variability in FSRQ

Time delay between the onset of the mm flare and the peak of the γ-ray flare

- 70 days - observer frame
- 30 days - source frame

The γ-ray region should be located ~ 7.4±1.3 pc downstream along the jet:

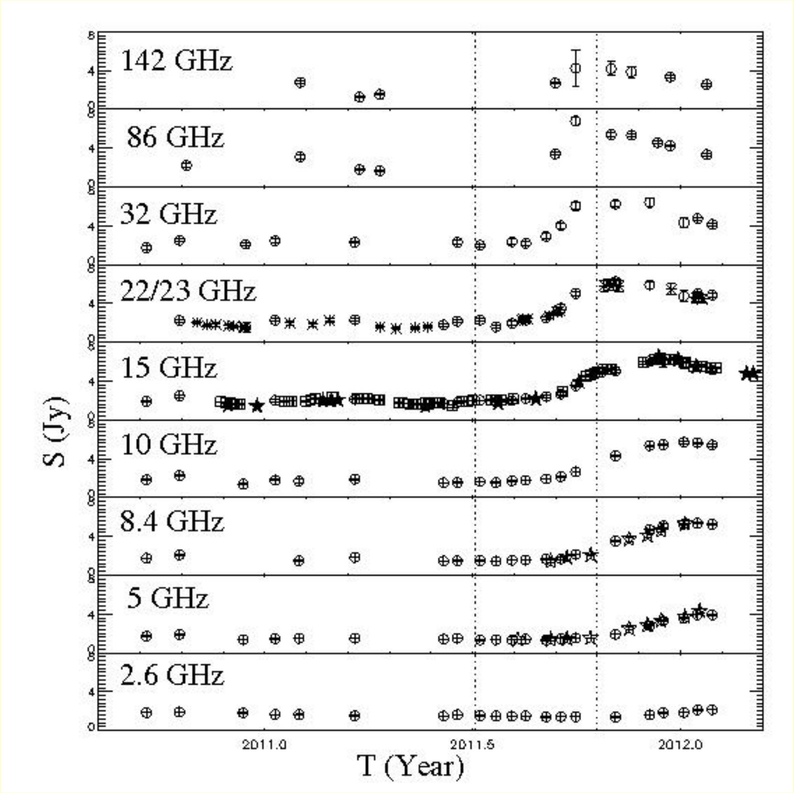
No obvious radio/γ-ray correlation in BL Lacs

Multi-ν analysis: PKS 1510-089

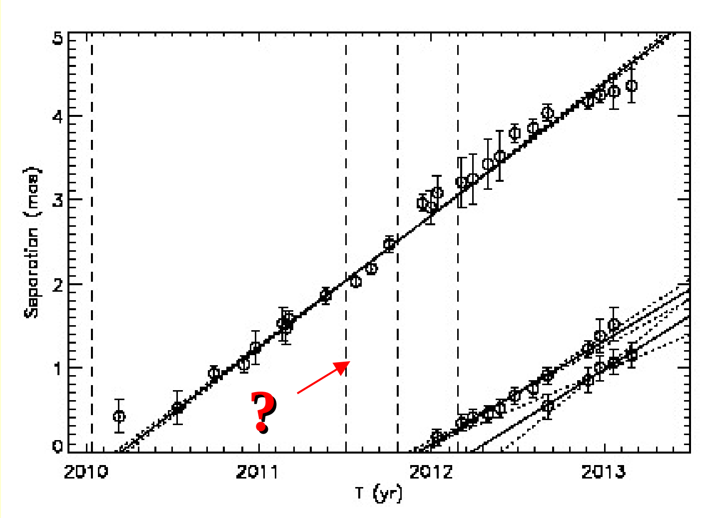
- First γ-ray flare with no obvious radio counterpart

Second γ-ray flare close in time with the mm flare

- Time lags increase with wavelength: opacity effects



Orienti+13



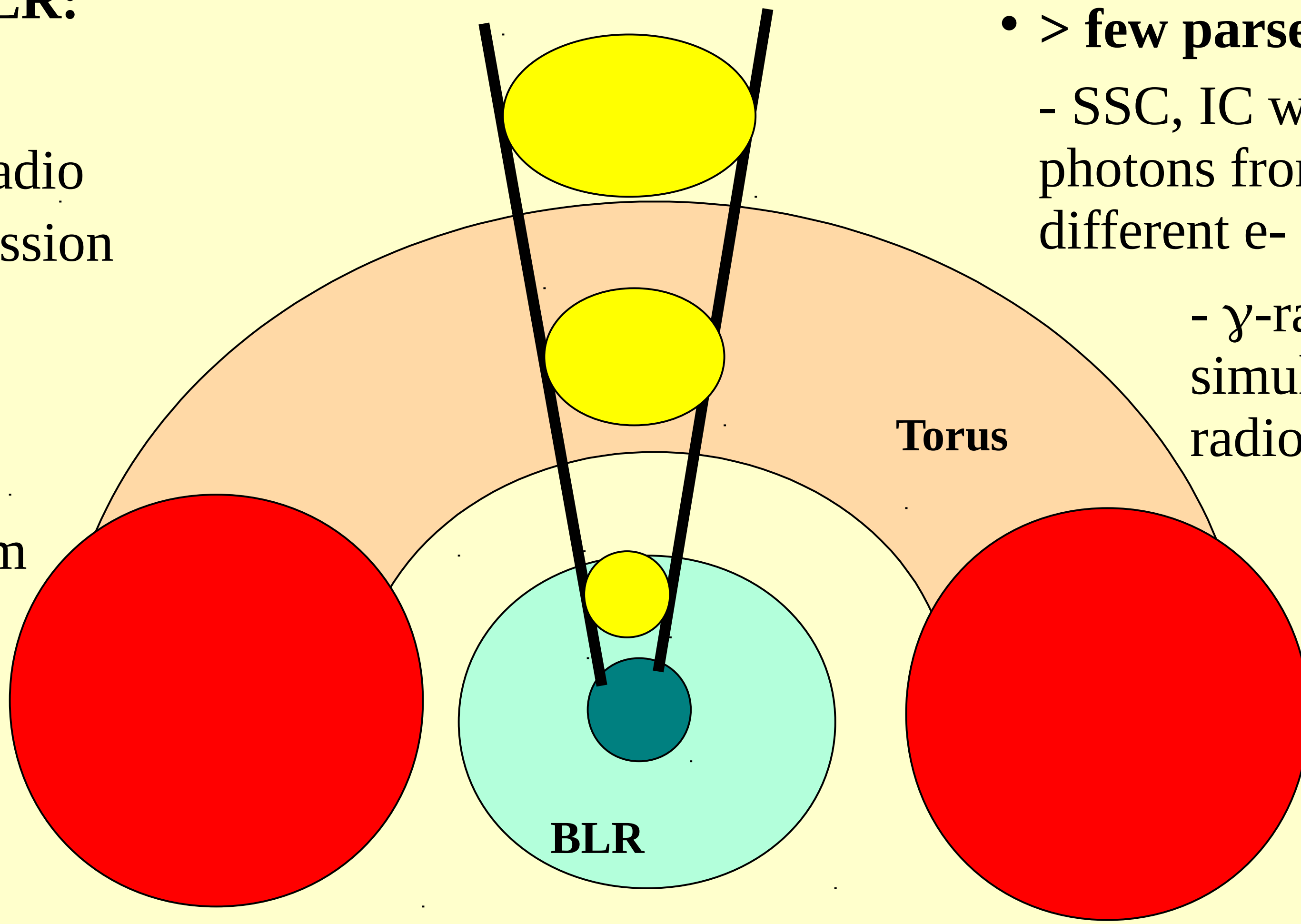
- First γ-ray flare with no ejection of superluminal components - **vicinity of BH?**

- Second γ-ray flare close in time with the ejection of a superluminal component – **at pc-scale distance?**

Open questions

Shock-in-jet model: where? how?

- **Within the BLR:**
  - IC with UV
  - γ-ray leads radio
  - No VHE emission
- **$\lesssim$ 1 pc:**
  - IC with IR
  - γ-ray and mm simultaneous
- **> few parsecs:**
  - SSC, IC with sync photons from a different e- population
  - γ-ray and mm simultaneous or radio leads γ-ray

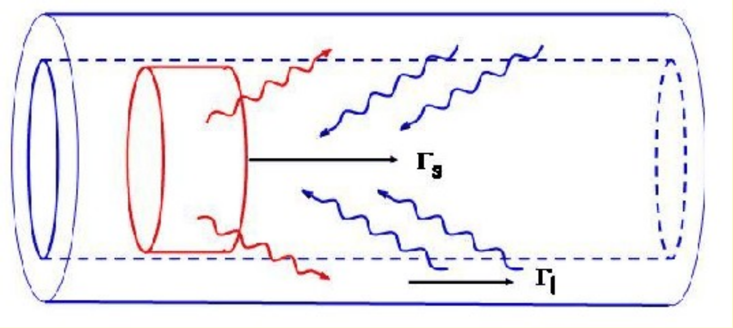


Radio/γ-ray time lag depends on the location of the shock

Not only shocks: the two-zone model

The characteristics of radio galaxies and “low-power” BL Lacs suggest a “structured jet” with a fast spine surrounded by a slower layer

Tavecchio&Ghisellini ‘08



- SSC + EC of spine (layer) photons
- No trivial radio and γ-ray correlation

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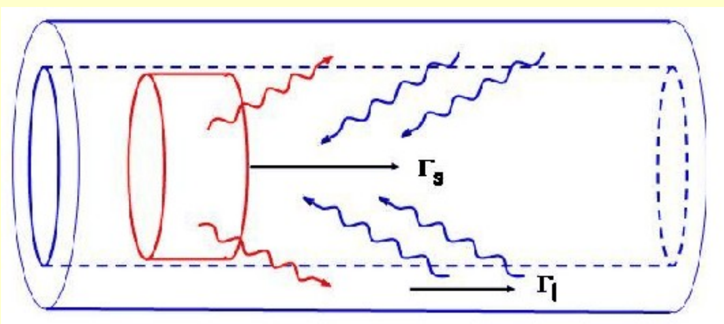

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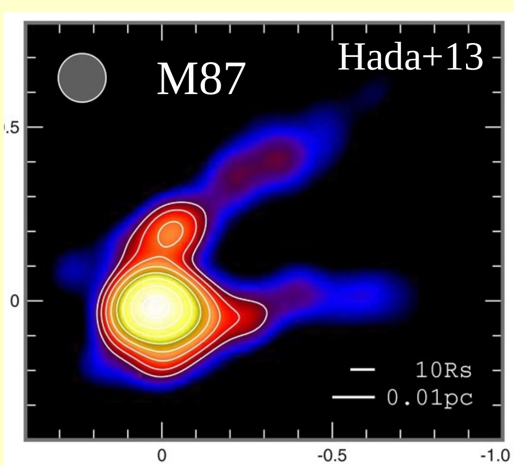
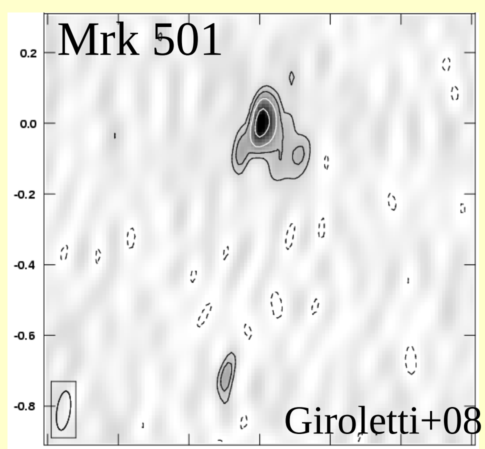
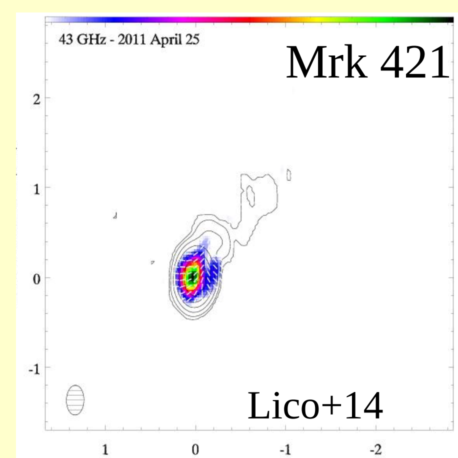
Supports from the observations: limb-brightened jet structure in FRI and BL Lacs:

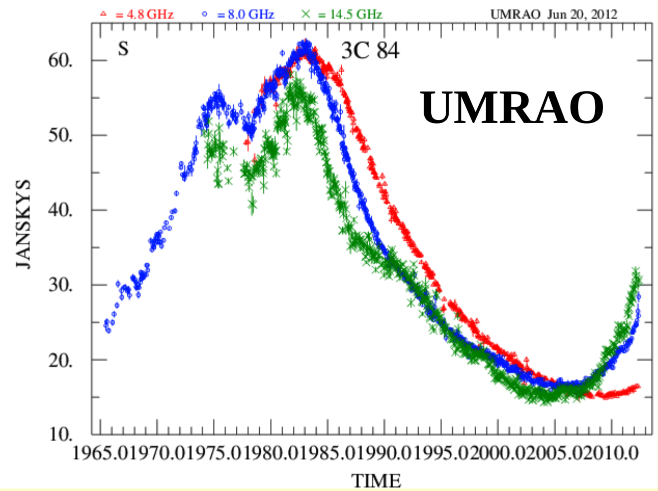


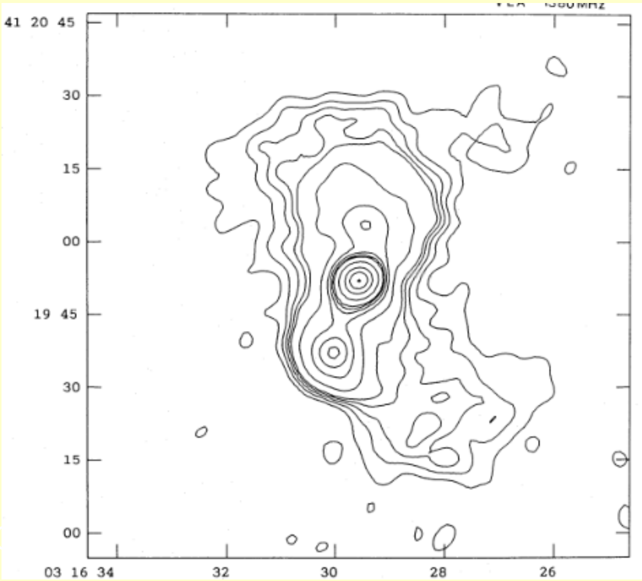


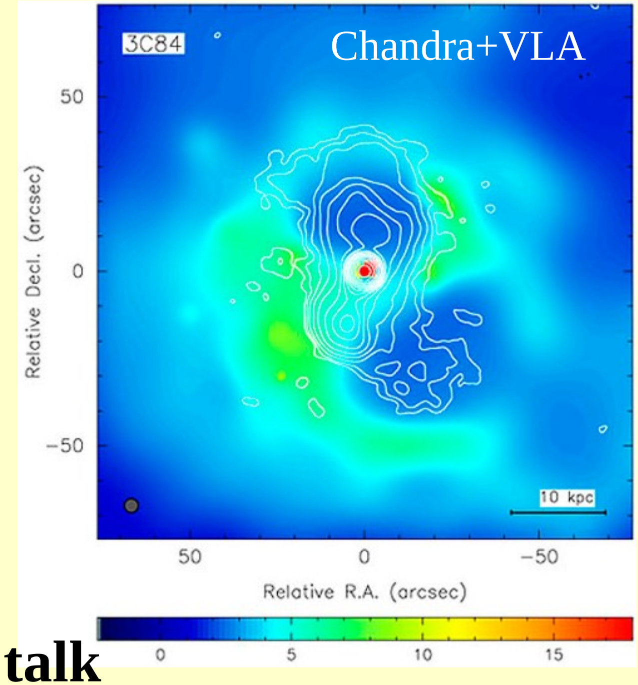


3C 84: basic information

- FRI-type galaxy
- Radio lobes fill the X-ray cavities
- Radio variability





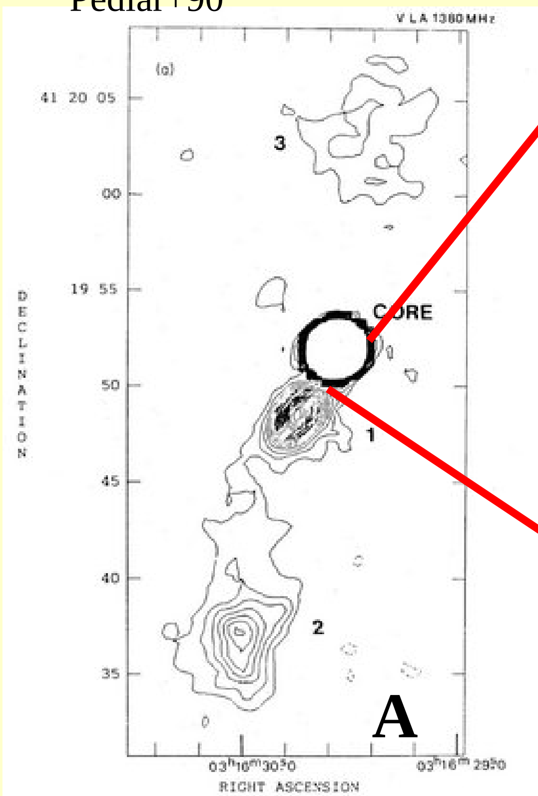


See Sanders' talk

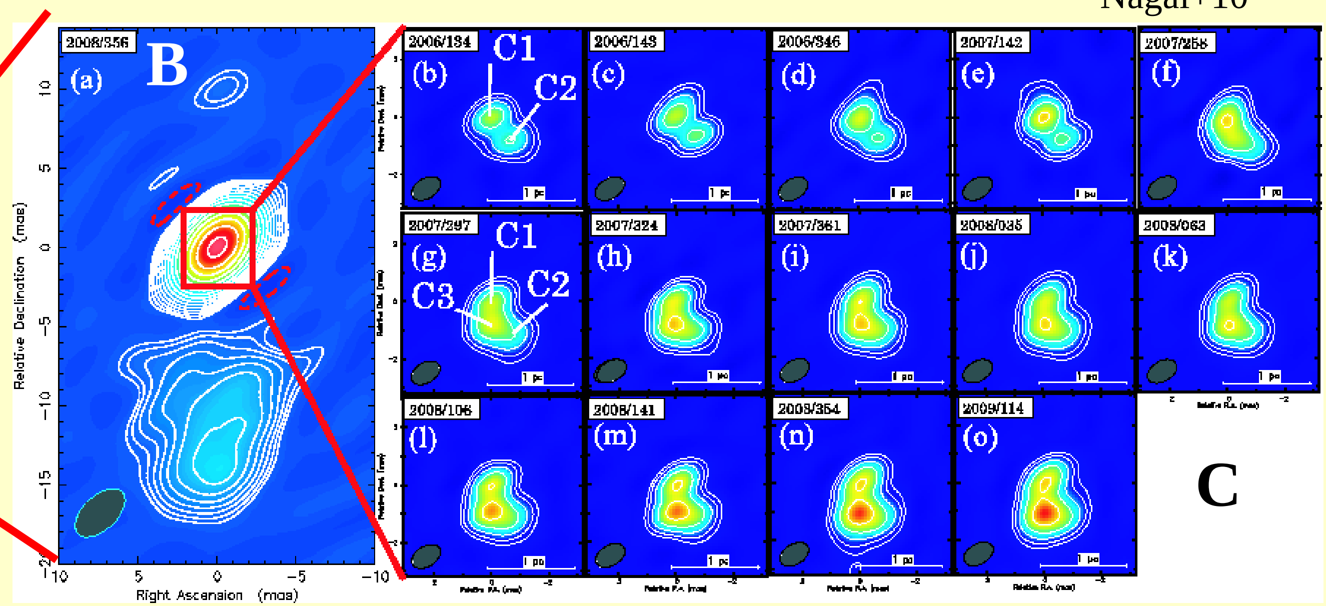
Multi-scale structure

- Recurrent radio activity
- Fast structural changes

Pedlar+90



Nagai+10

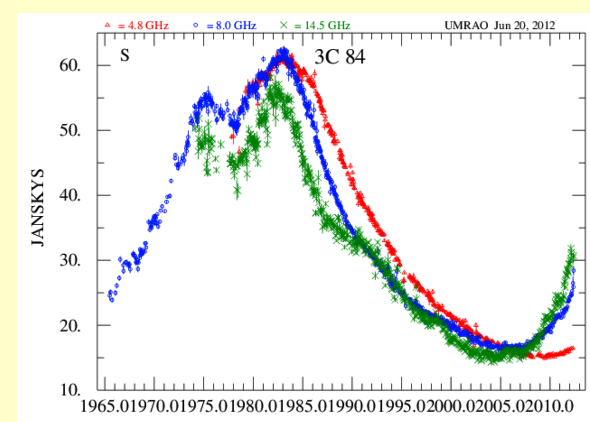


A: ~15 kpc, ~ 10^5 yr

B: ~10 pc, ~ 50 yr

C: ~1pc, ~10 yr

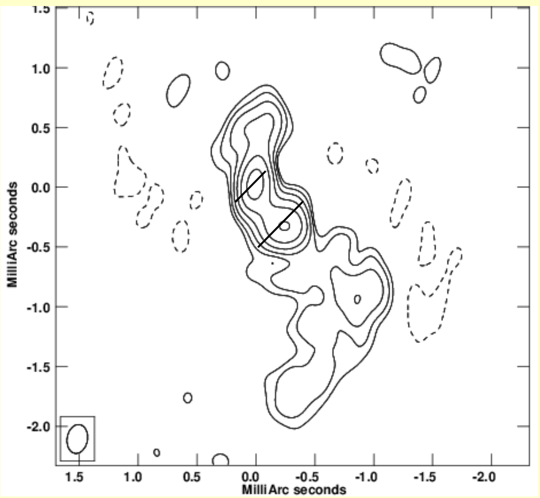
See Nagai's talk



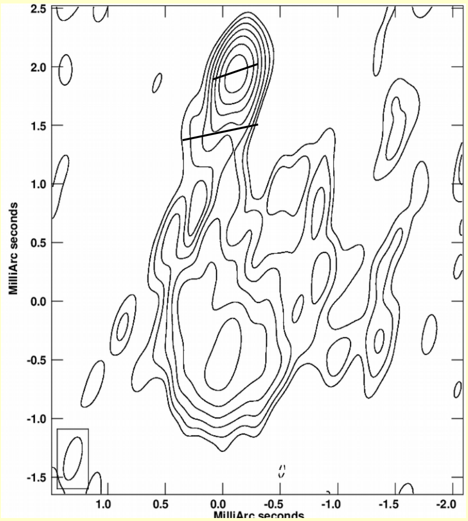
The jet structure: 1995 - 2013

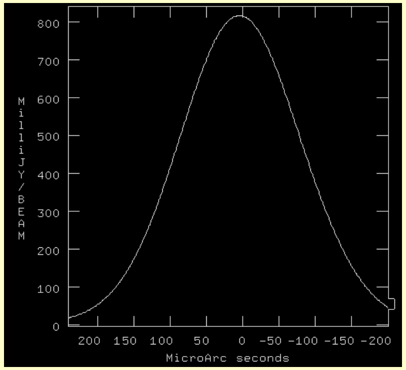
1995: ridge-brightened

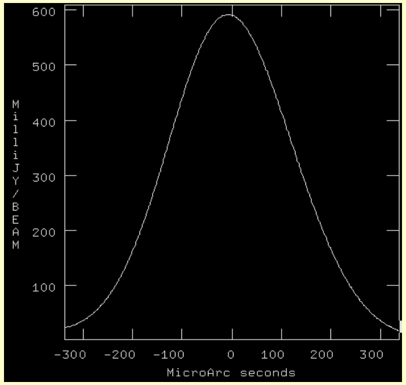
2013: limb-brightened

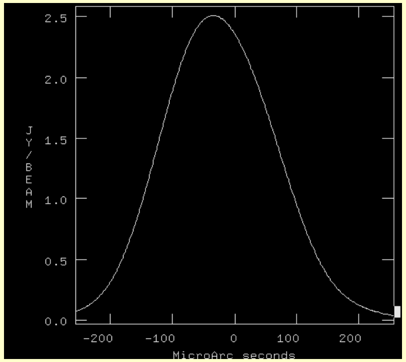


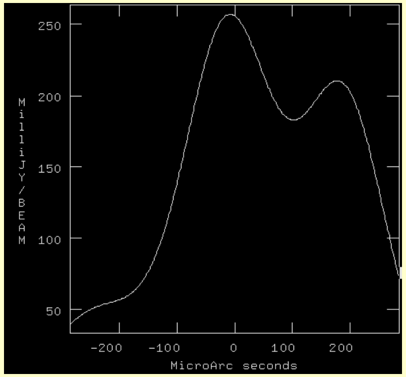
43 GHz VLBA











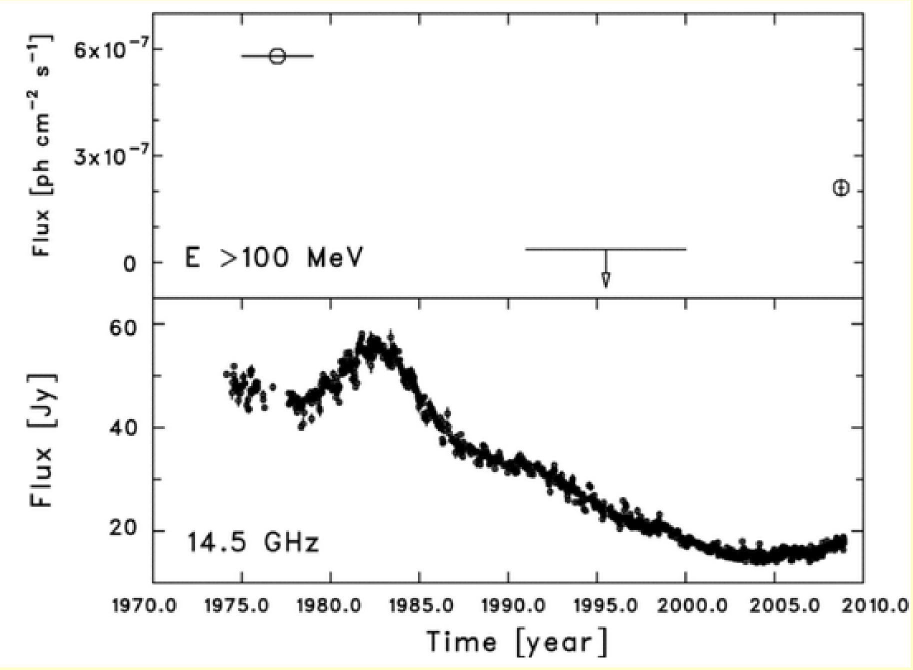
Change in the jet PA

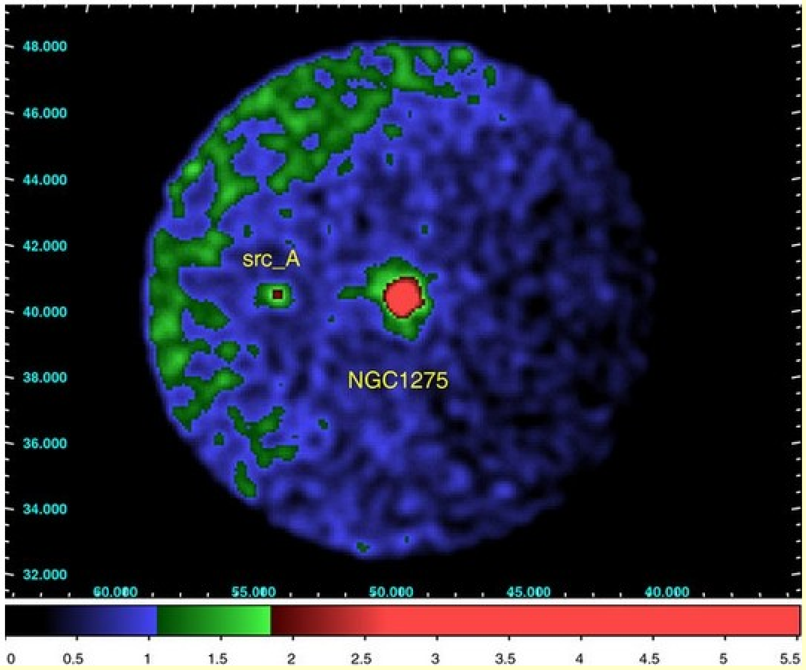
See Giovannini’s talk

The gamma-ray emission

- Possible detection by COS B at energies > 70 MeV
- No γ-ray detection by EGRET
- γ-ray emission detected in four-month Fermi-LAT observations

Abdo+09



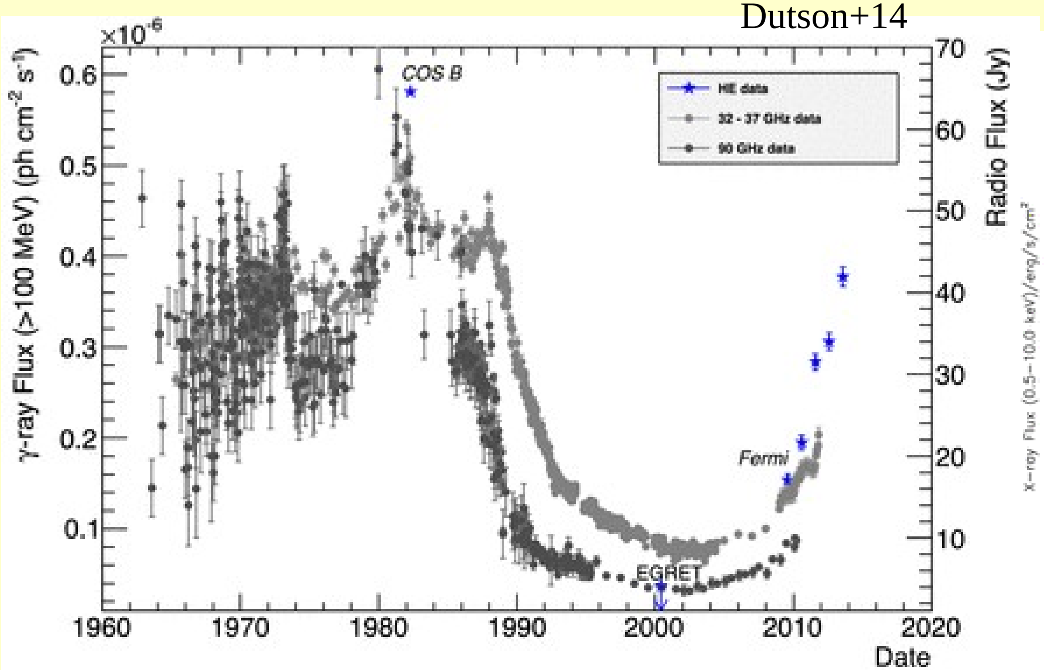


Variation over years/decades → R < 0.3 pc

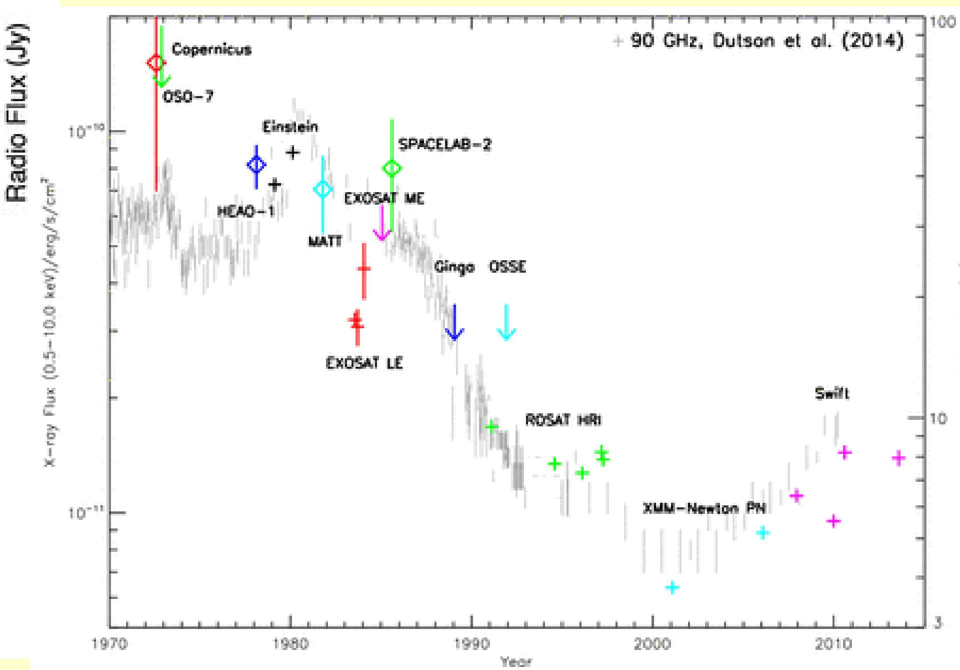
The gamma-ray emission

- Possible detection by COS B at energies > 70 MeV
- No γ-ray detection by EGRET
- γ-ray emission detected in four-month Fermi-LAT observations

Dutson+14

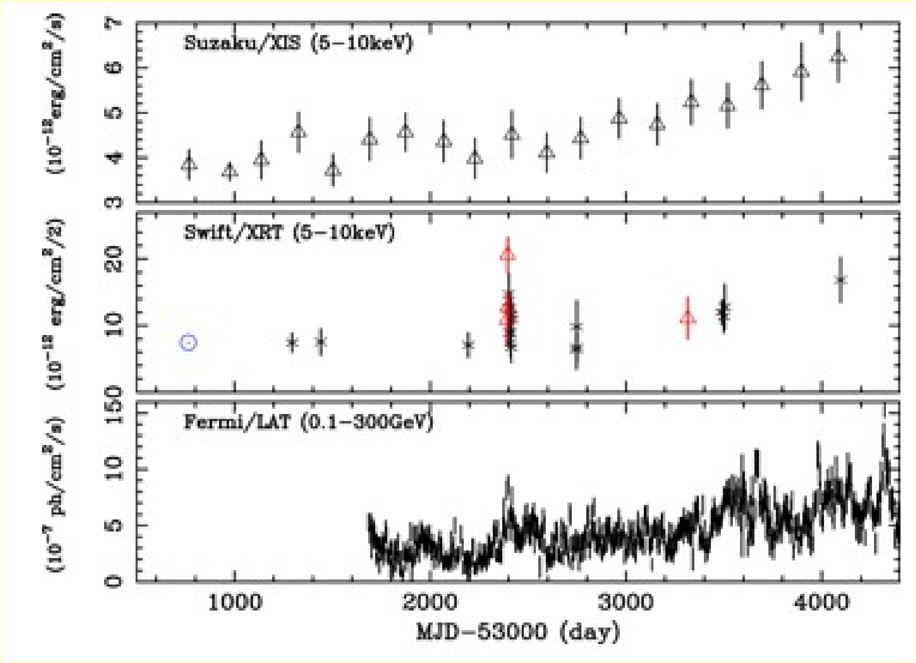


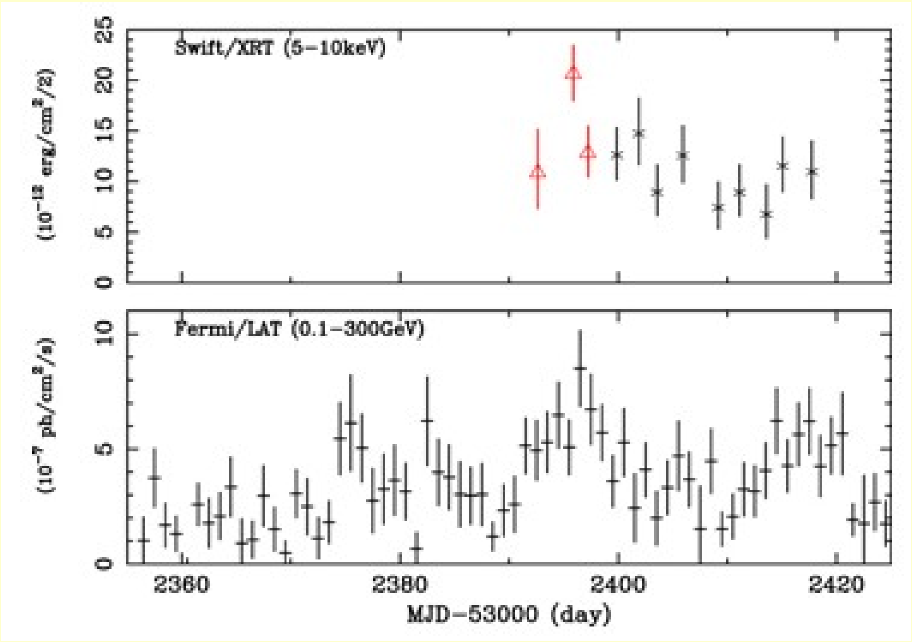
Fabian+15



High and low activity stages in radio and high energies (X-rays and γ-rays).

The gamma-ray and X-ray emission





Fukazawa+18

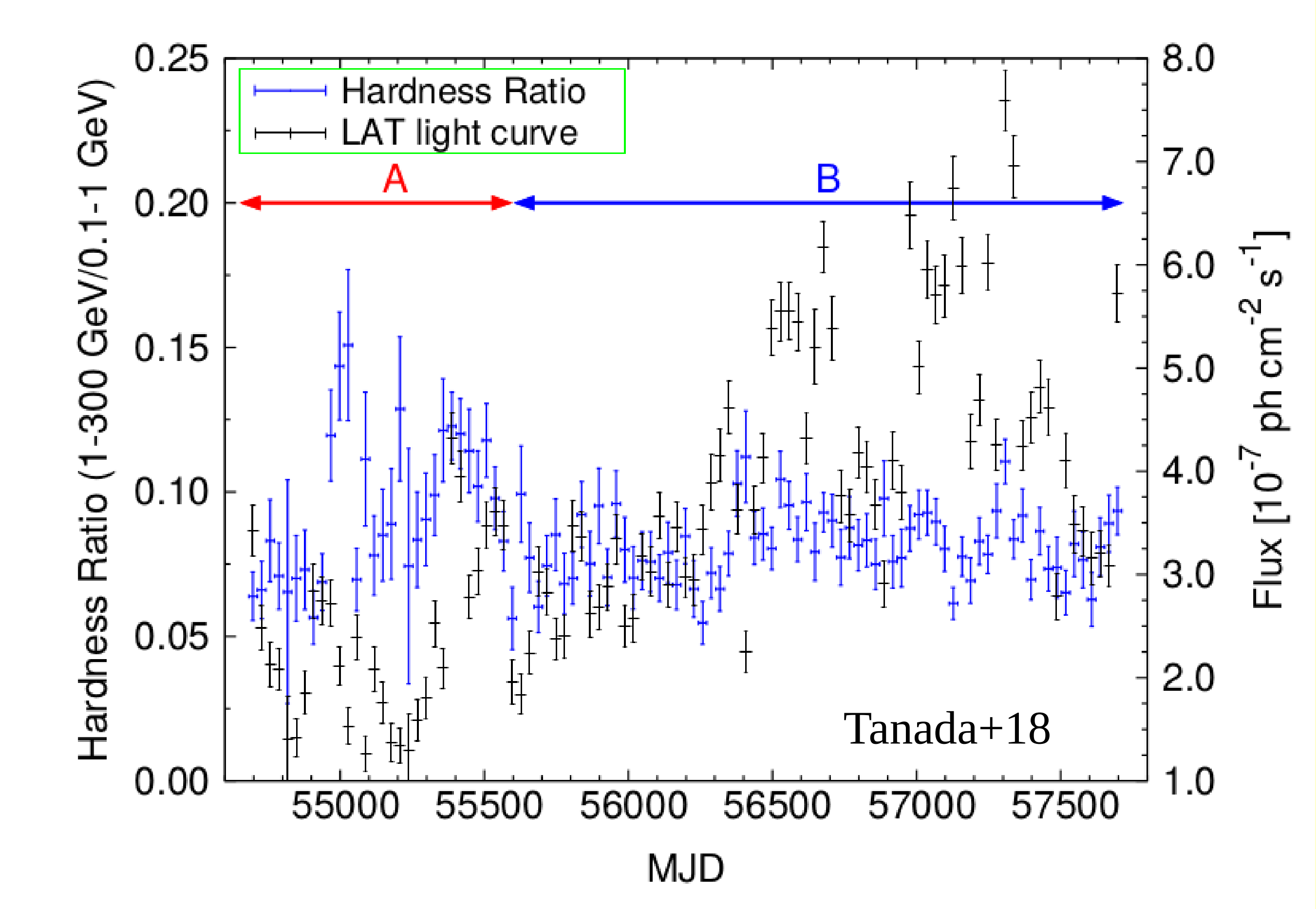
Correlated X-rays and γ-rays variability on short and long timescales.

- Long-term: change of the emission region → C3-jet structure
- Short-term: injection of fresh particles accelerated in a shock → core

Hodgson+18, Tanada+18

See Fukazawa's talk

Fermi-LAT monitoring of 3C 84

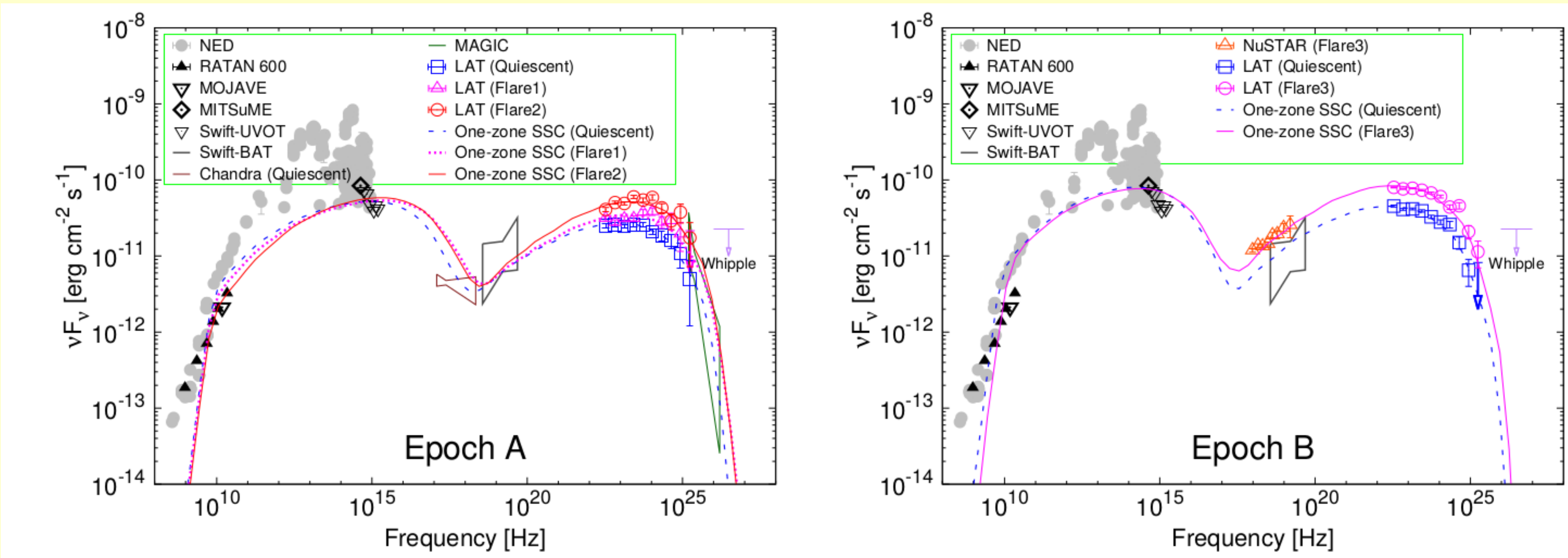


Change in the hardness ratio around begin of 2011

A: injection of high-energy electrons

B: change of the Lorentz factor and/or angle to our line of sight

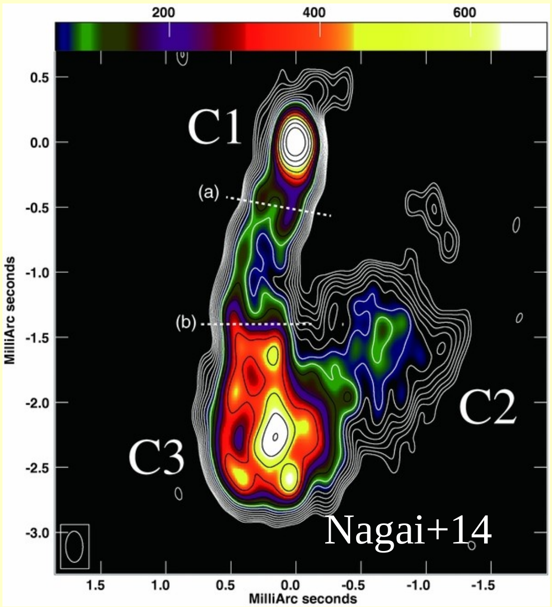
SED modeling: SSC



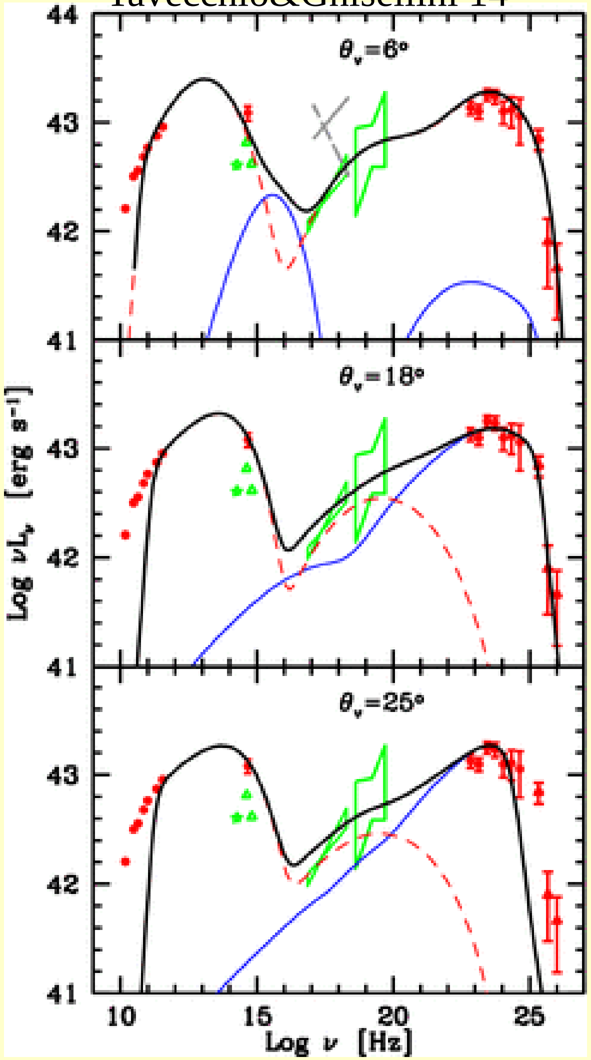
Tanada+18

Epoch	State	R [cm]	B [G]	K [cm^{-3}]	n	$\gamma_{\rm min}$	$\gamma_{\rm brk}$	$\gamma_{\rm max}$	δ	$\Gamma_{\rm b}$	θ [°]
A	Quiescent	0.8×10^{18}	0.04	45	2.6	10.0	0.8×10^{3}	2.5×10^{5}	2.7	2.0	20
	Flare 1	0.7×10^{18}	0.04	50	2.6	10.0	1.0×10^{3}	4.0×10^{5}	2.7	2.0	20
	Flare 2	0.6×10^{18}	0.04	50	2.6	10.0	1.8×10^{3}	3.5×10^{5}	2.7	2.0	20
B	Quiescent	1.0×10^{18}	0.04	48	2.6	10.0	0.8×10^{3}	1.0×10^{5}	2.7	2.0	20
	Flare 3	0.4×10^{18}	0.04	270	2.6	10.0	0.7×10^{3}	1.0×10^{5}	3.6	3.3	16

Spine-layer scenario: 3C 84



Tavecchio&Ghisellini 14



Spine-layer model well reproduces the SED with θ~18°.

θ> 20° unlikely due to strong internal absorption.

Limb-brightened structure may be the observable manifestation of a structured jet.

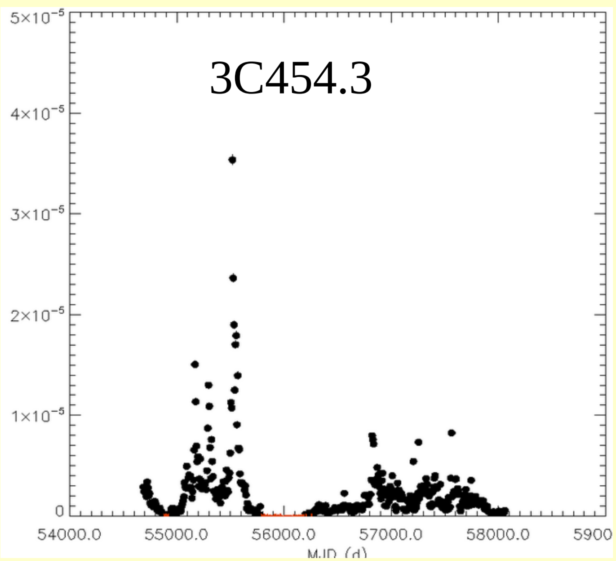
Summary

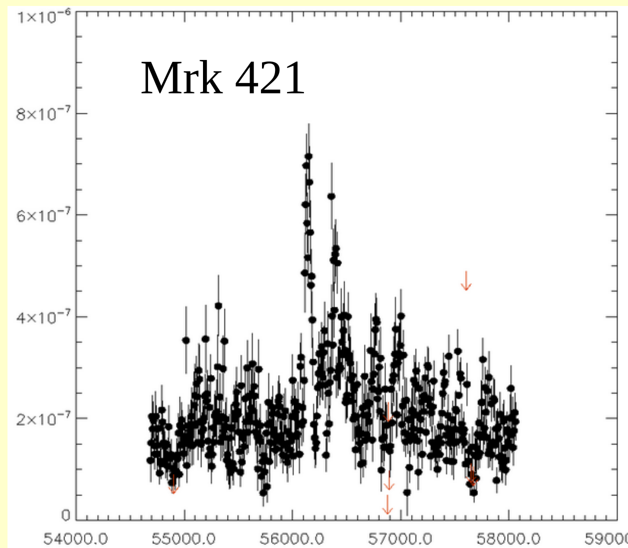
- Radio-loud AGN dominate the γ-ray sky
- Empical correlation between radio and γ-ray emission
- Time lags are usually present between radio and γ-ray variability
- 3C 84 shows changes in radio structure and γ-ray emission on long and short time scales
- Now the jet has a clear limb-brightened structure, opposite to the ridge-brightened structure observed in the '90
- High-energy emission may come from different regions

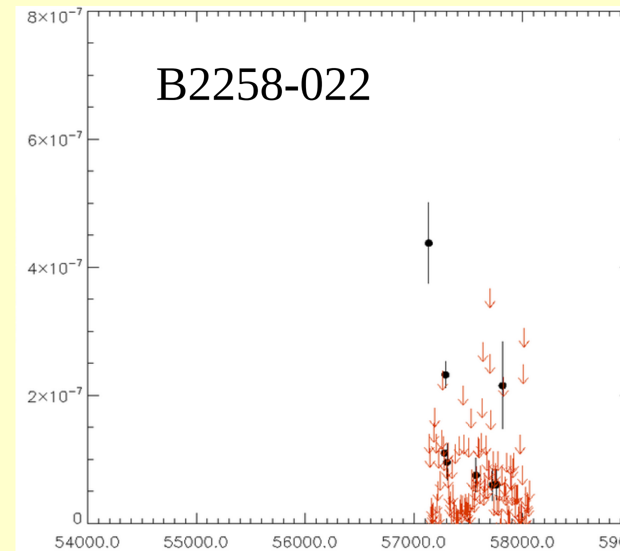
BACK UP SLIDES

Fermi-LAT Variability

Fermi-LAT scans the full sky every 3 hr and is a golden mine for flare hunters!







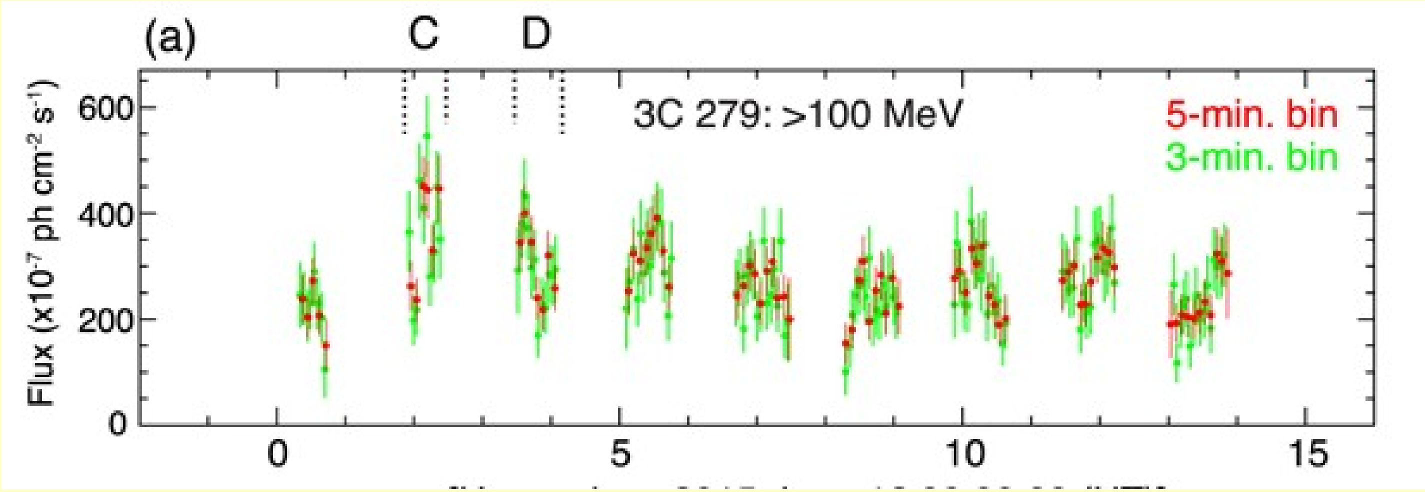
Public light curves for ~150 sources that underwent a flare in -rays:

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

Pushing further: Fermi-LAT ToO

Sub-orbital light curve of 3C 279

Ackermann+16



First time that a **doubling time < 5 min** was observed in the GeV band

Very compact region of ~100 Rs from central engine in a conical jet

Gamma-ray beyond BLR

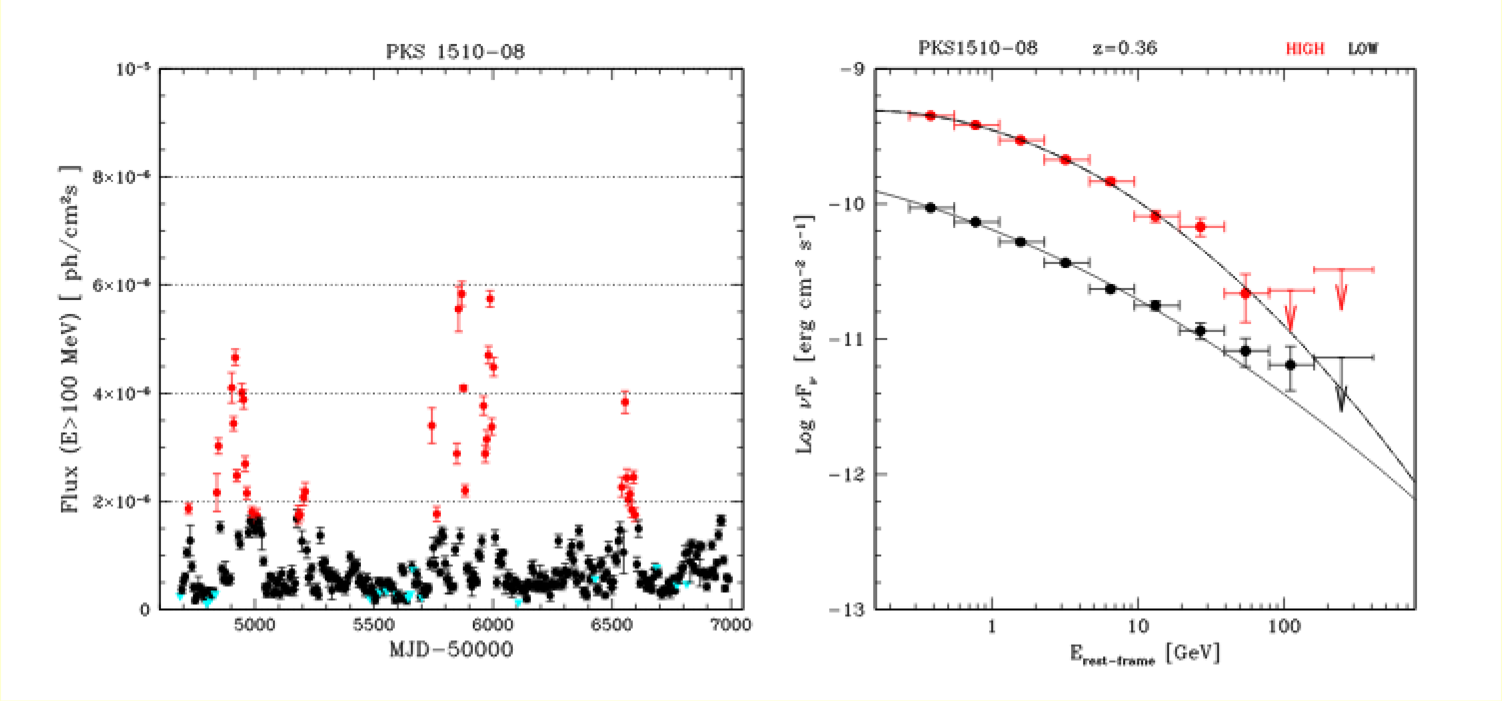
Analysis of 7.3 yr Fermi-LAT data of 106 FSRQ

2/3 no absorption at E > 20 GeV

1/3 curvature at E > 20 GeV, but can be intrinsic

No BLR absorption in both high and low-activity states

Costamante+18



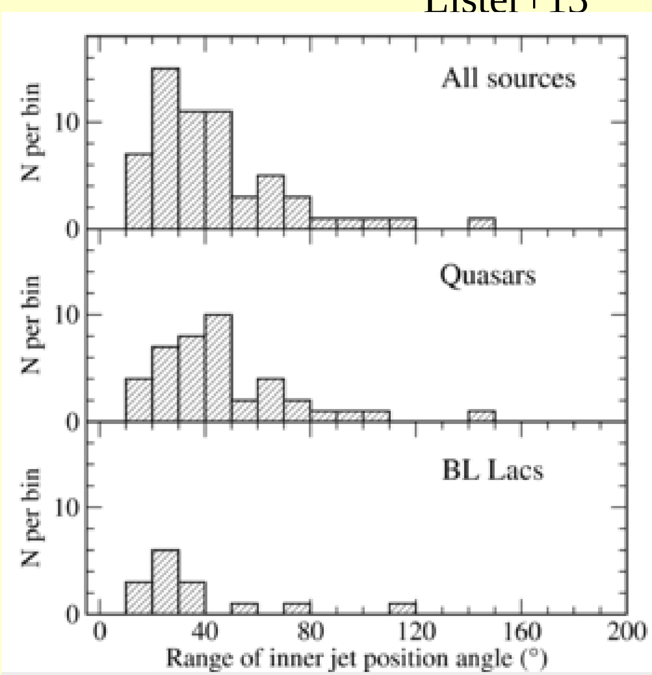
On average, Gamma-ray emission produce outside the BLR

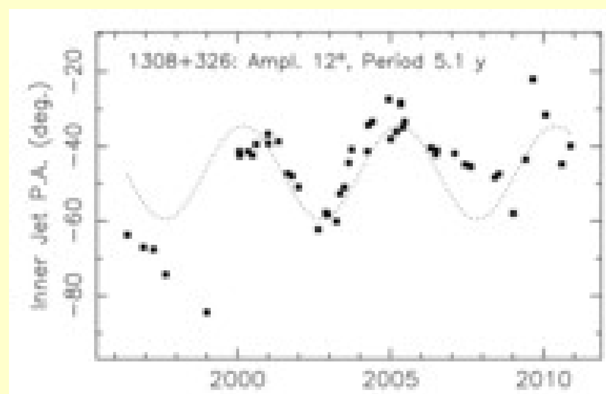
The γ-ray region

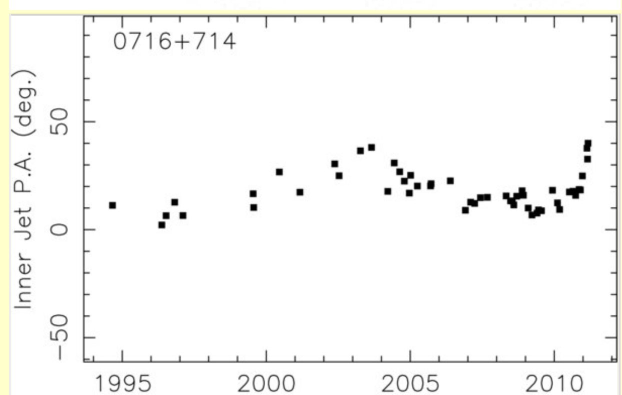
Pc-scale distance → Causality argument < 10^{16} cm

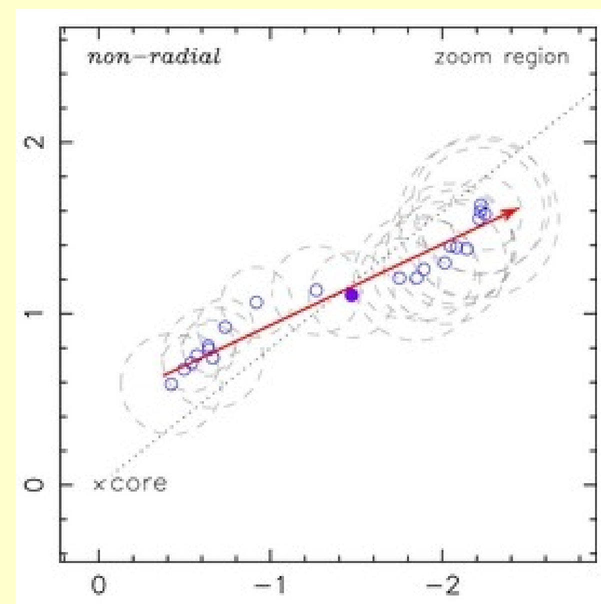
Large changes in the inner jet position angle → Jet knot occupies only a fraction of the jet cross-section

Lister+13



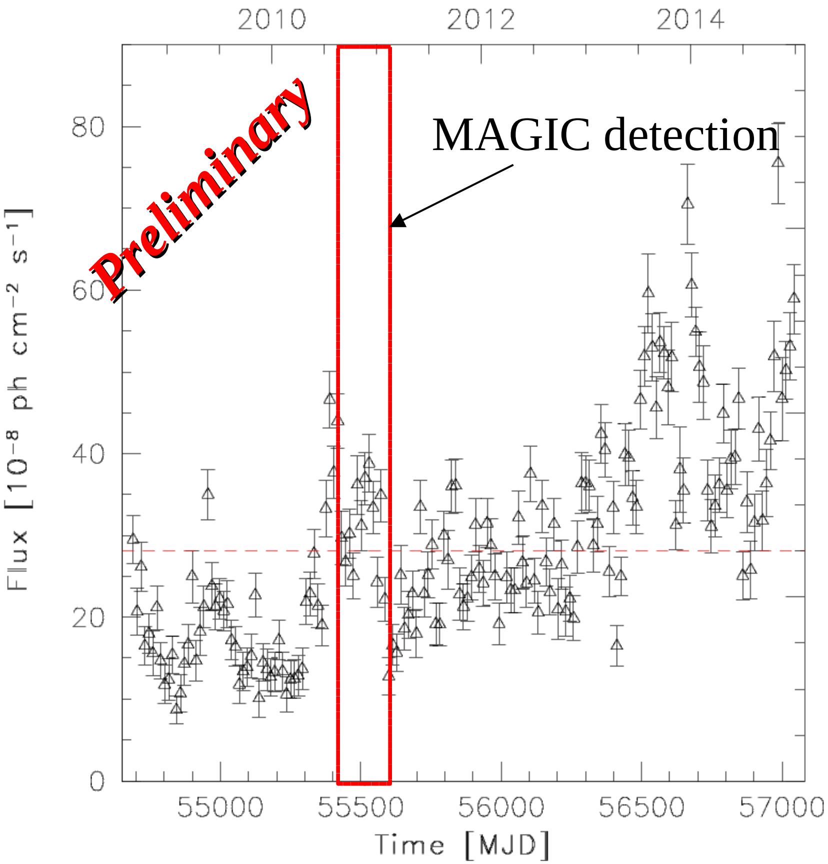






Flux variability

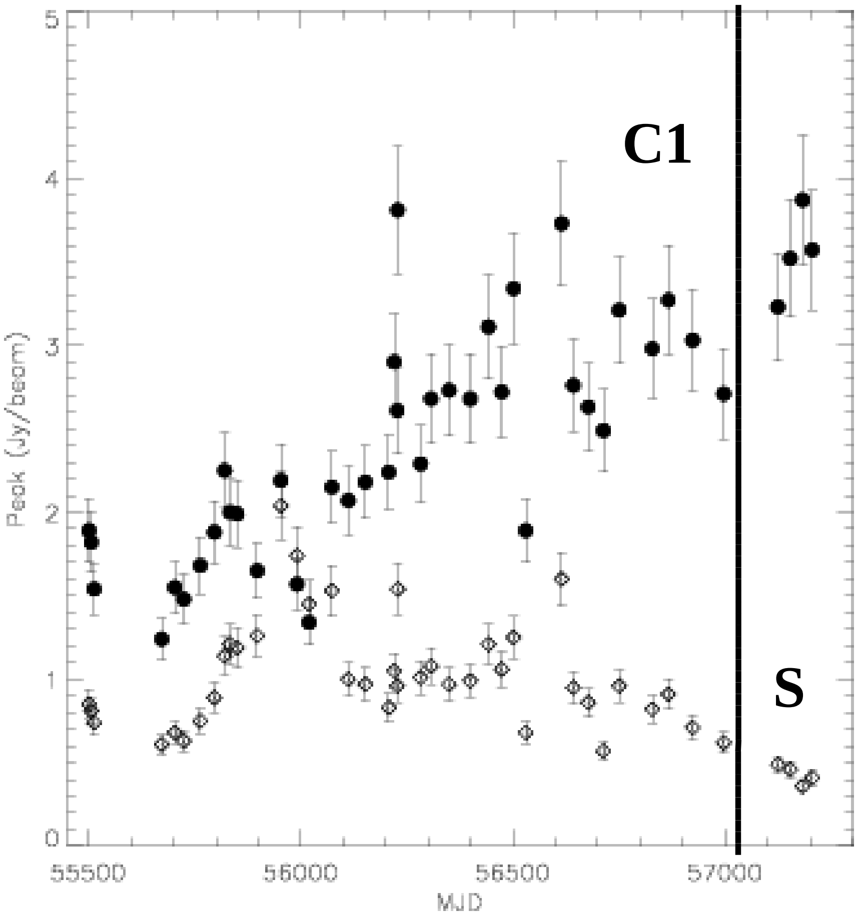
Fermi-LAT light curve



Two-week time bins

E > 100 MeV

43 GHz VLBA



BU Blazar group