Relativistic jets and the Radio/γ-ray connection

M. Orienti

(INAF-IRA)

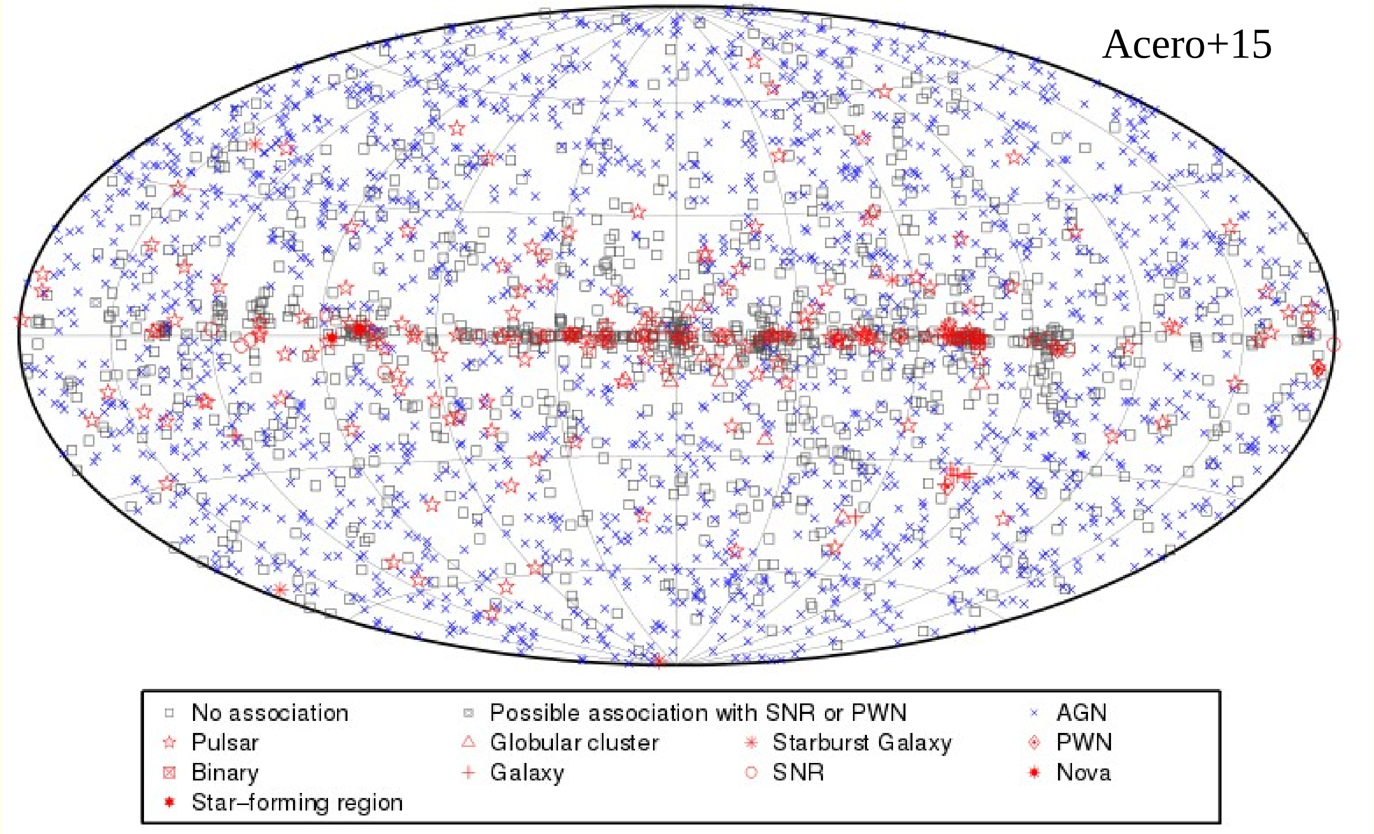
F. D'Ammando, M. Giroletti, D. Dallacasa, G. Giovannini, T. Venturi, J. Finke, K. Hada, H. Nagai, M. Ajello, et al.

Outline

- Background
- The tip of the iceberg: bright and flaring blazars
- Uncommon γ-ray emitters: what's new
- Conclusions

3FGL catalog

4 years of Fermi-LAT observations



3033 sources:

2041 associated with a low-energy counterpart

992 not associated

The extragalactic γ-ray sky

1752 (58%) extragalactic objects

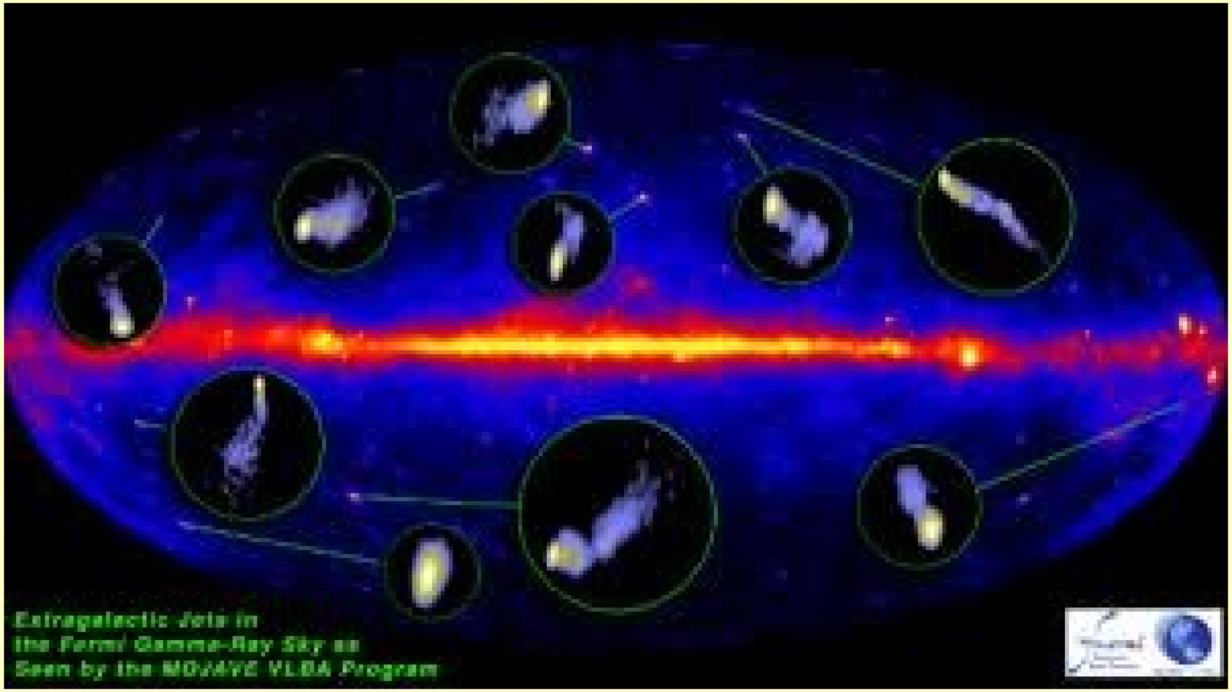
1718 (98%) blazar-like sources

15 radio galaxies

5 NLSy1

7 normal galaxies (γ-ray from cosmic rays)

Ackermann+15



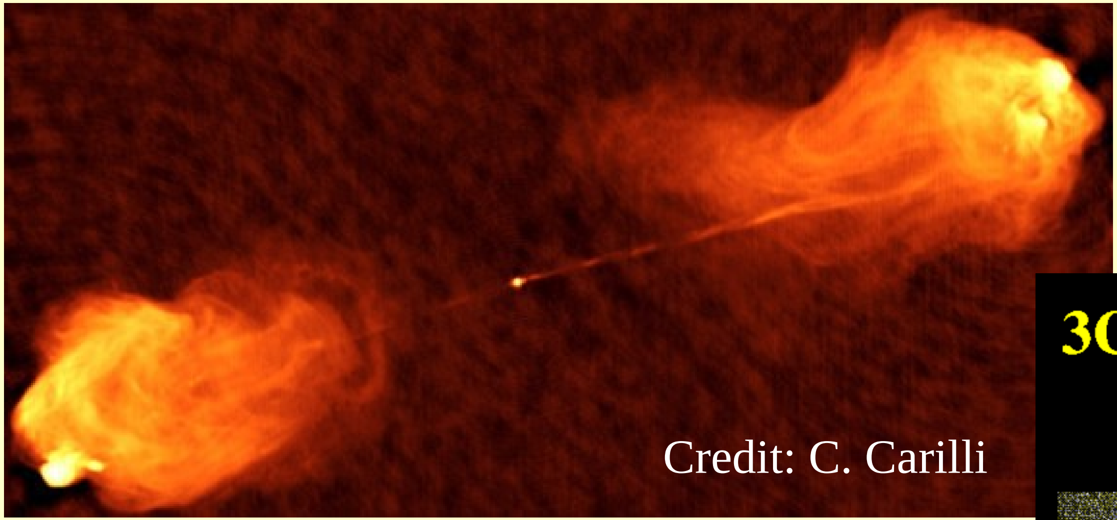
Strong γ-ray emitters:

- High radio luminosity
- Fast apparent jet speed
- High variability Doppler

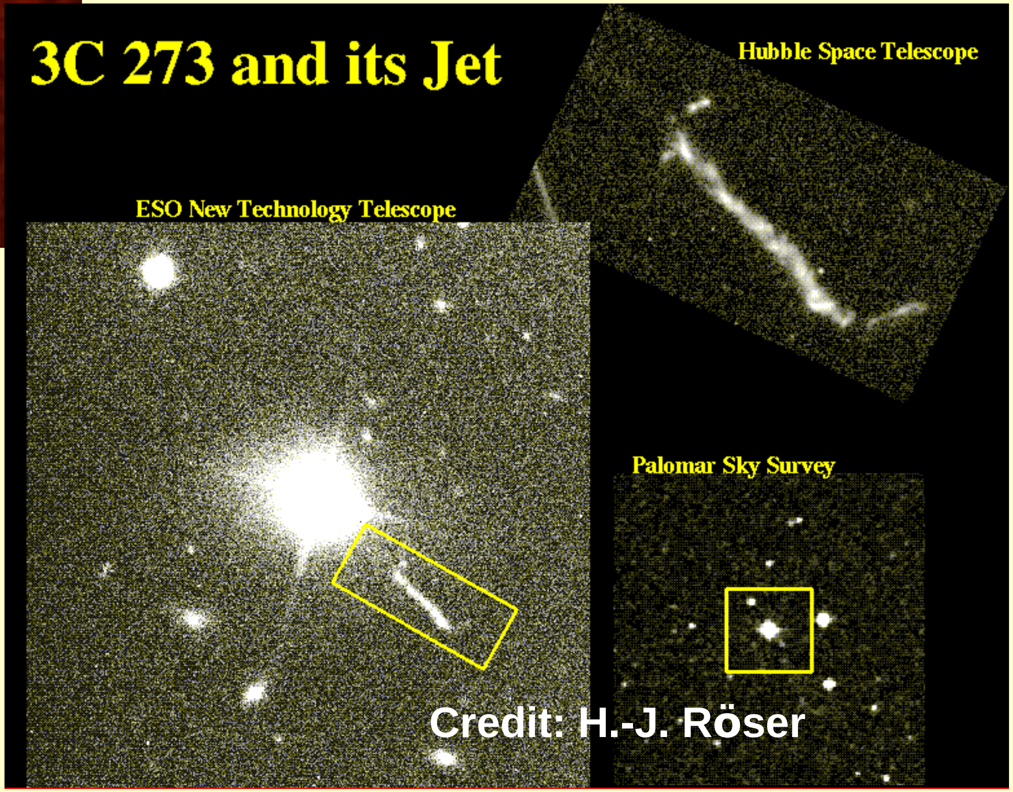
Savolainen+ 2010, Lister+ 09, Kovalev+ 2009

Extragalactic γ-ray sky dominated by radio-loud AGN

The extragalactic γ-ray sky



Only in 10% of AGN



Presence of relativistic jets

Relativistic jets

Non-thermal emission

- Low energy: **synchrotron**

Relativistic electrons can scatter low energy photons

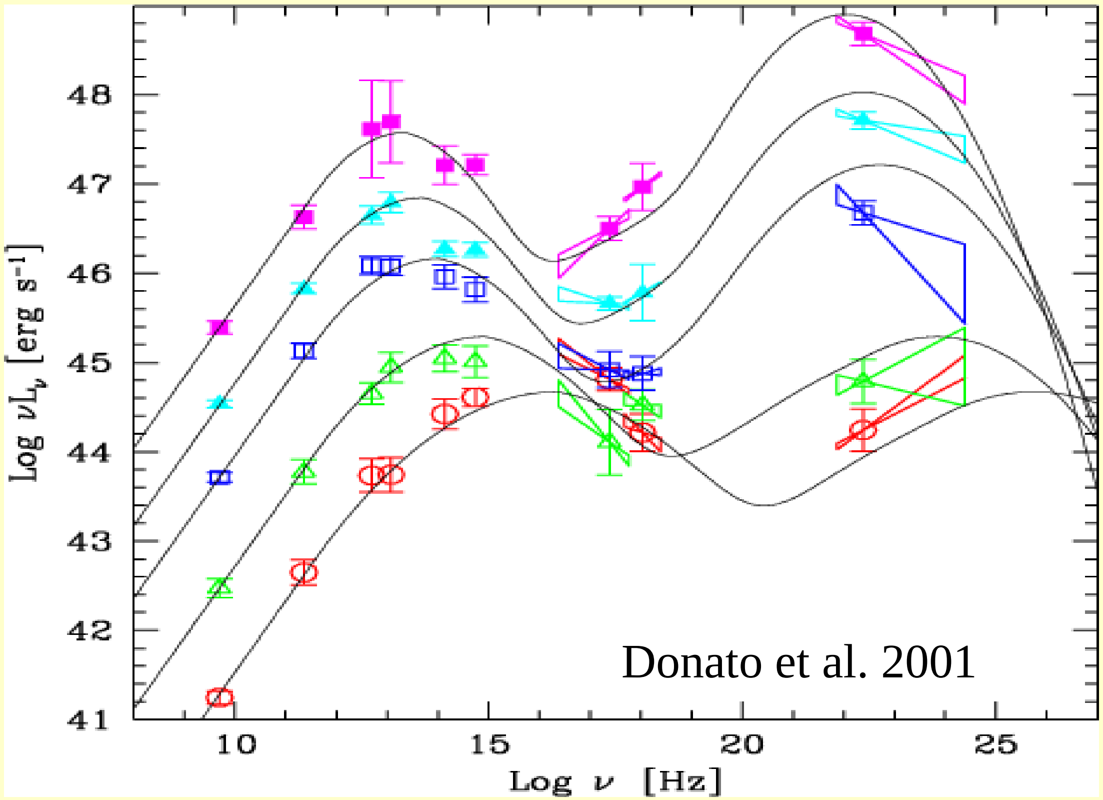
- High energy: **inverse Compton**

Seed photons:

- external photons from torus, disk, BLR... (External Compton)

- their own synchrotron photons (Synchrotron-self Compton)

Blazar sequence



Luminosity ~ $10^{49} – 10^{50}$ erg/s

Relativistic jets

Non-thermal emission

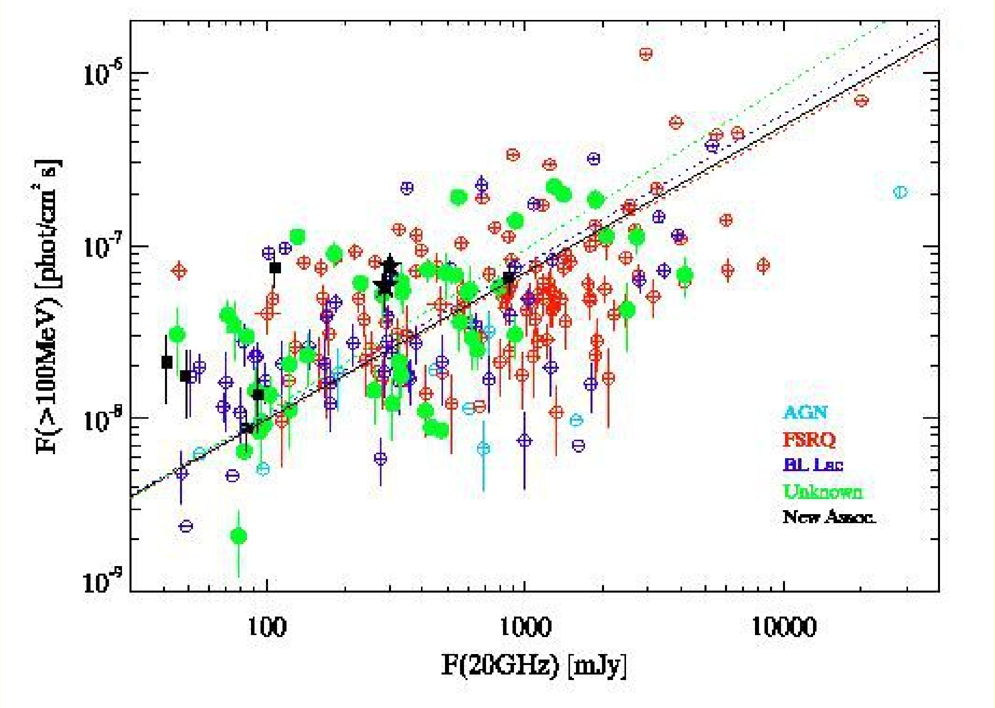
- Low energy: **synchrotron**

Relativistic electrons can scatter low energy photons

- High energy: **inverse Compton**

Seed photons:

- external photons from torus, disk, BLR... (External Compton)
- their own synchrotron photons (Synchrotron-self Compton)



Ghirlanda et al. 2010

Existence of radio-gamma correlation for both BL Lacs and FSRQ

Relativistic jets

Non-thermal emission

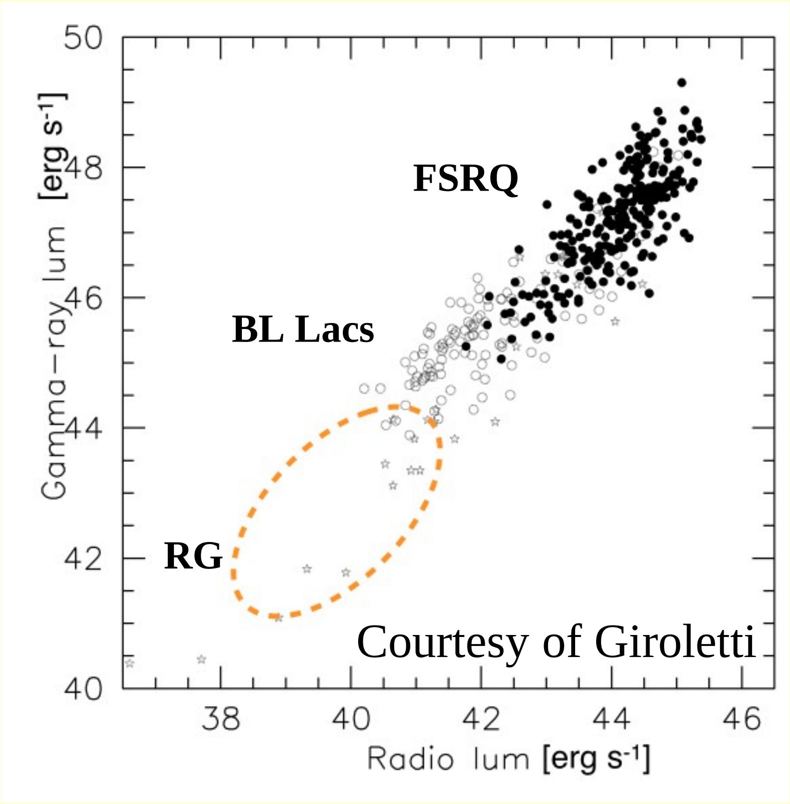
- Low energy: **synchrotron**

Relativistic electrons can scatter low energy photons

- High energy: **inverse Compton**

Seed photons:

- external photons from torus, disk, BLR... (External Compton)
- their own synchrotron photons (Synchrotron-self Compton)



Existence of radio-gamma correlation for both BL Lacs and FSRQ

Open questions

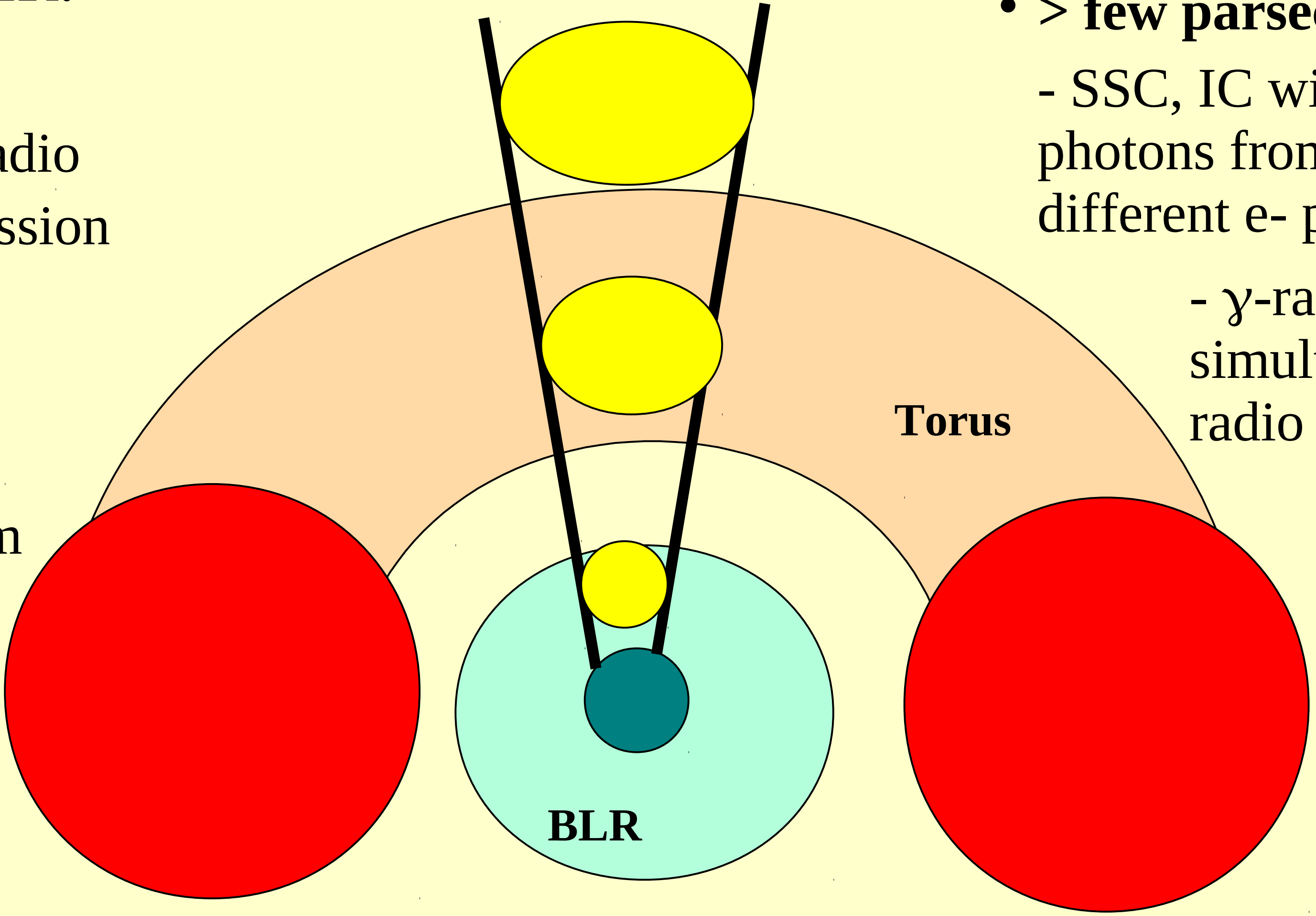
- What is the γ-ray emitting mechanism?
- Where is the region responsible for γ-ray emission?
- Shock propagation, turbulence, velocity gradient?
- What is the structure of the magnetic field in the jet?
- .....

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



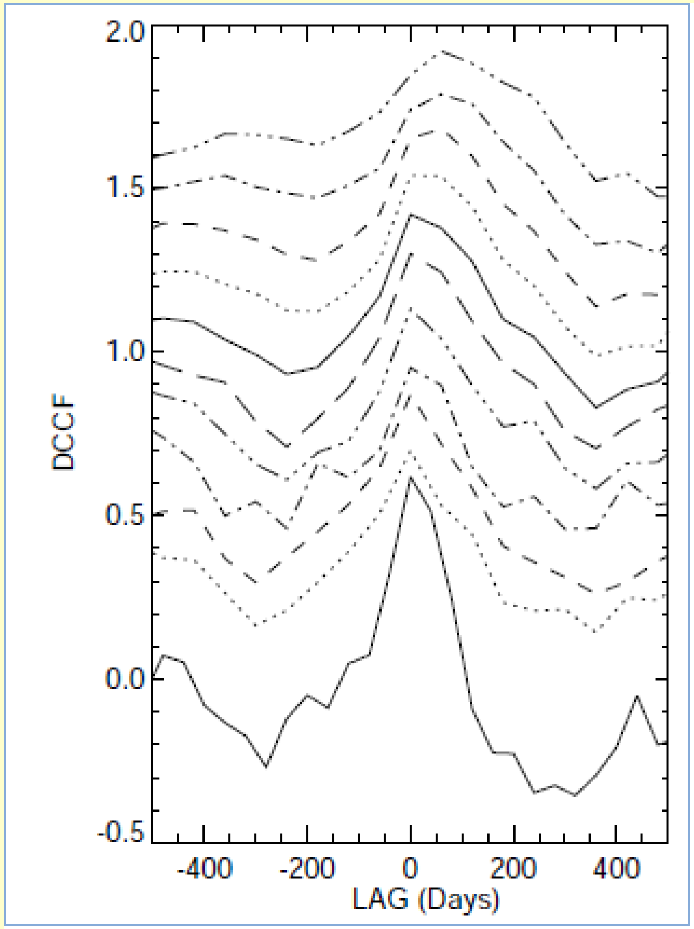
- **> few parsecs:**
  - SSC, IC with sync photons from a different e- population
  - γ-ray and mm simultaneous or radio leads γ-ray

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

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.

Fuhrmann+14



γ-ray leads the radio variability

Time delay increases with frequency:

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

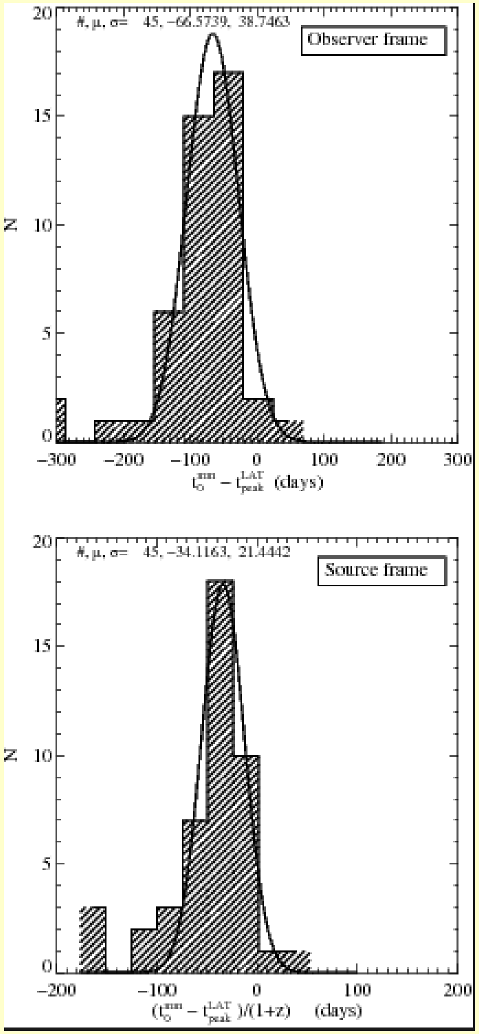
The γ-ray/radio distance decreases with frequencies:

- 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+11



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

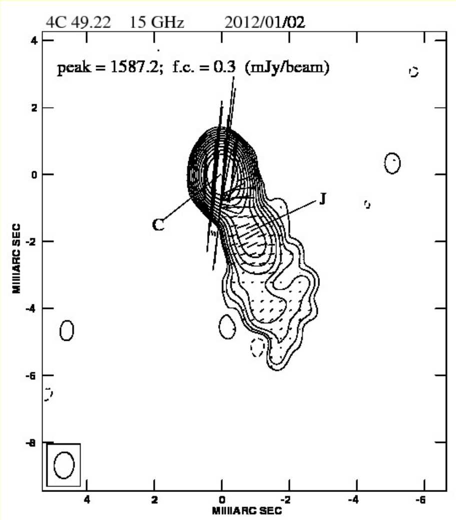
The γ-ray region should be located ~ 7.4±1.3 pc downstream along the jet:

No clear radio/γ-ray correlation in BL Lacs

How can we answer (or try to..)?

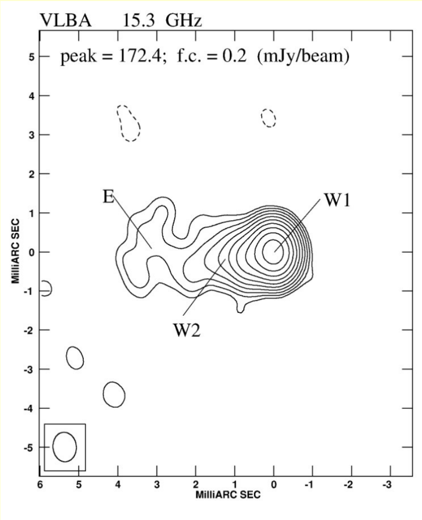
High-resolution + multifrequency + multiepoch + polarimetry

Multi-epoch VLBI observations of flaring sources



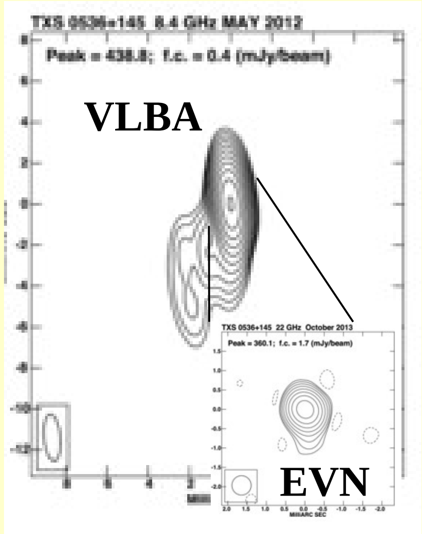
Cutini+14

FSRQ



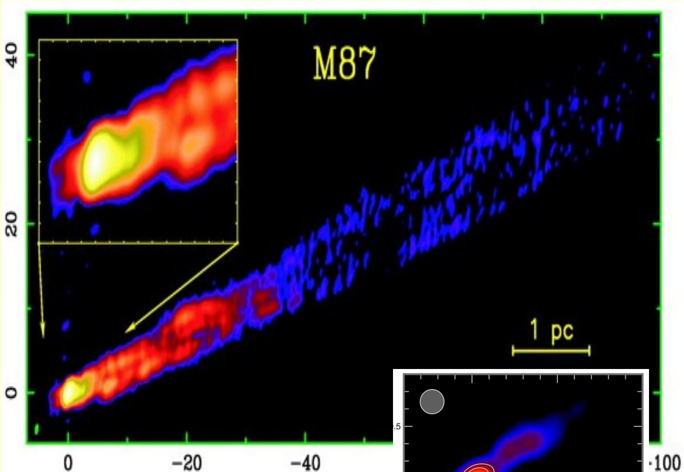
D'Ammando+13

NLSy1



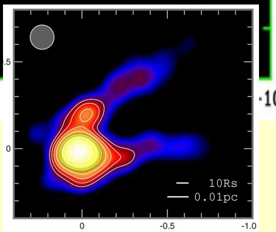
Orienti+14

High-z FSRQ



Kovalev+07

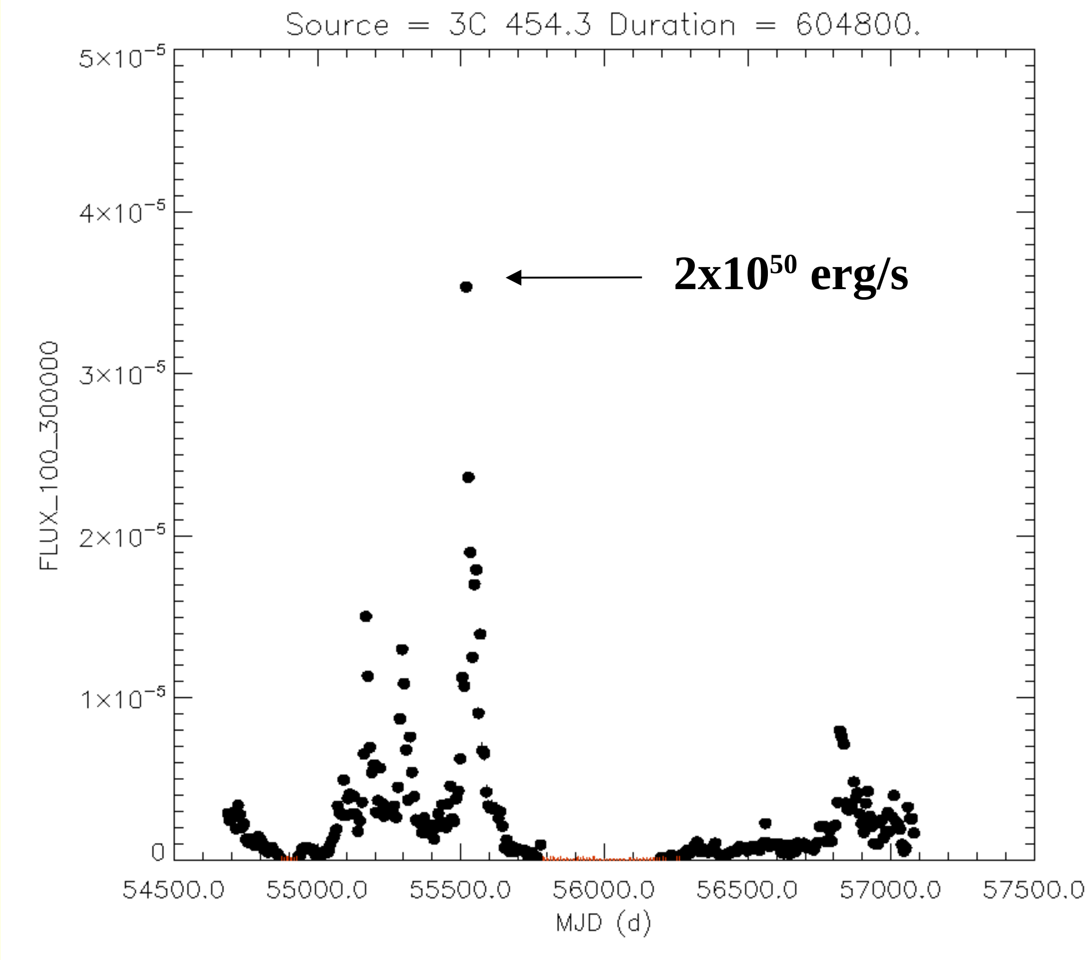
RG



Hada+13

The brightest blazar: 3C 454.3

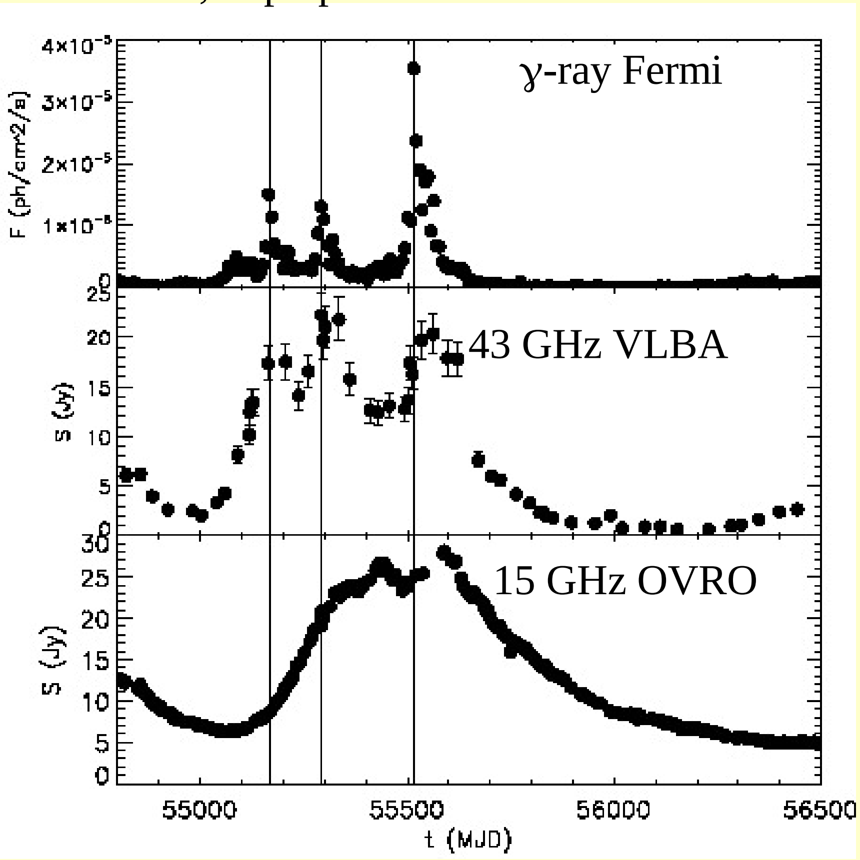
The most active blazar in gamma rays during the first 3 years of Fermi.



An ideal candidate for studying the radio/γ-ray connection

Radio and γ-ray light curves

Orienti, in prep



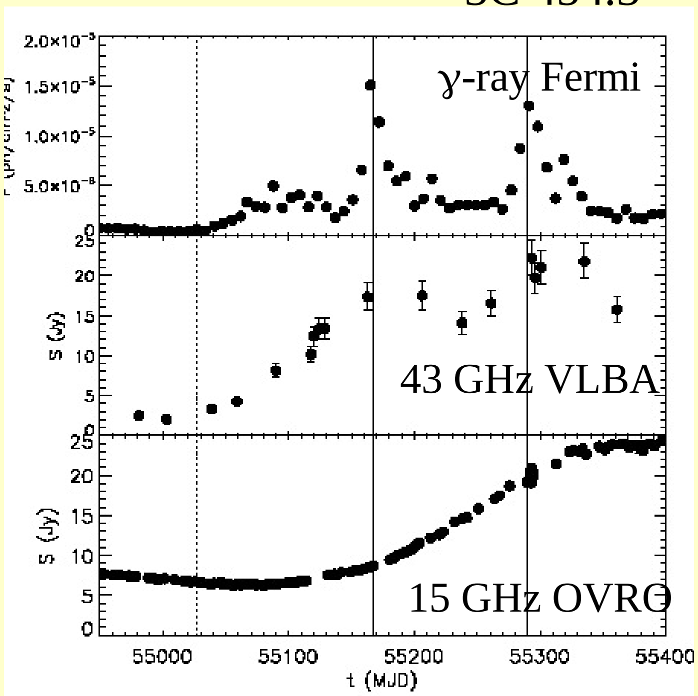
The rise of the mm flux density precedes the γ-ray flare

γ-ray produced pc away from the core

γ-ray region opaque to cm emission

The γ-ray region

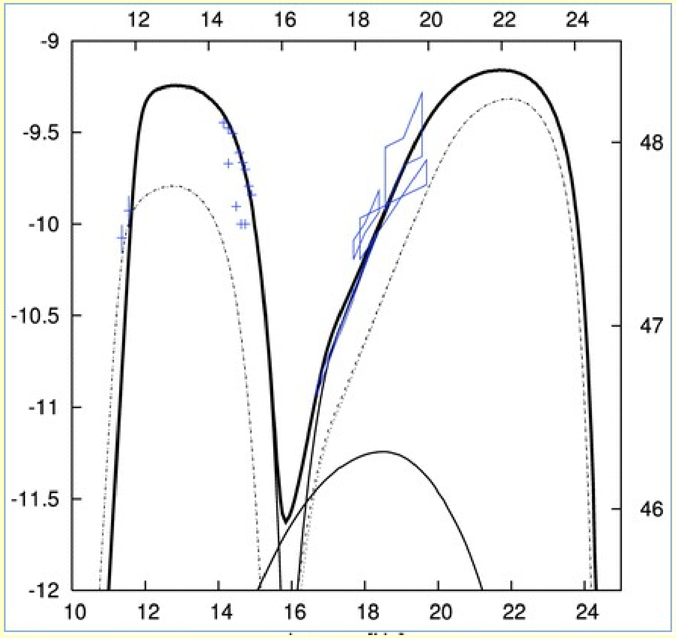
3C 454.3



The increase of **γ-ray and mm emission** seems **simultaneous**. At 15 GHz it is delayed by about 2 months.

Co-spatiality of γ-ray and mm emission produced on pc scale

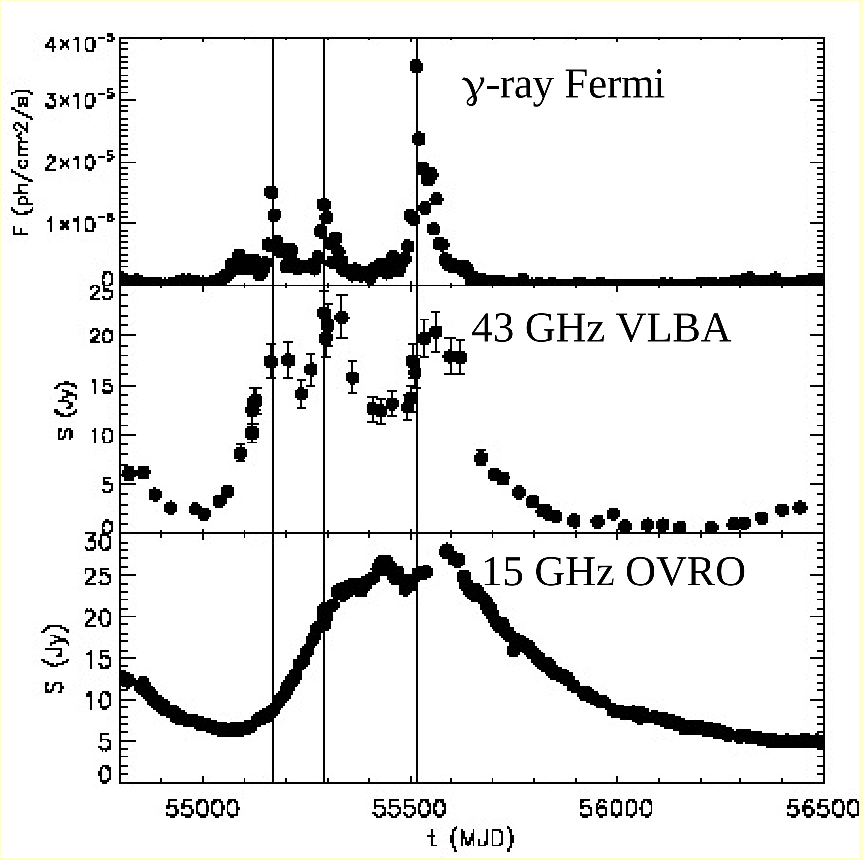
- IR photons from the dusty torus
- Synchro photons from different e^- population

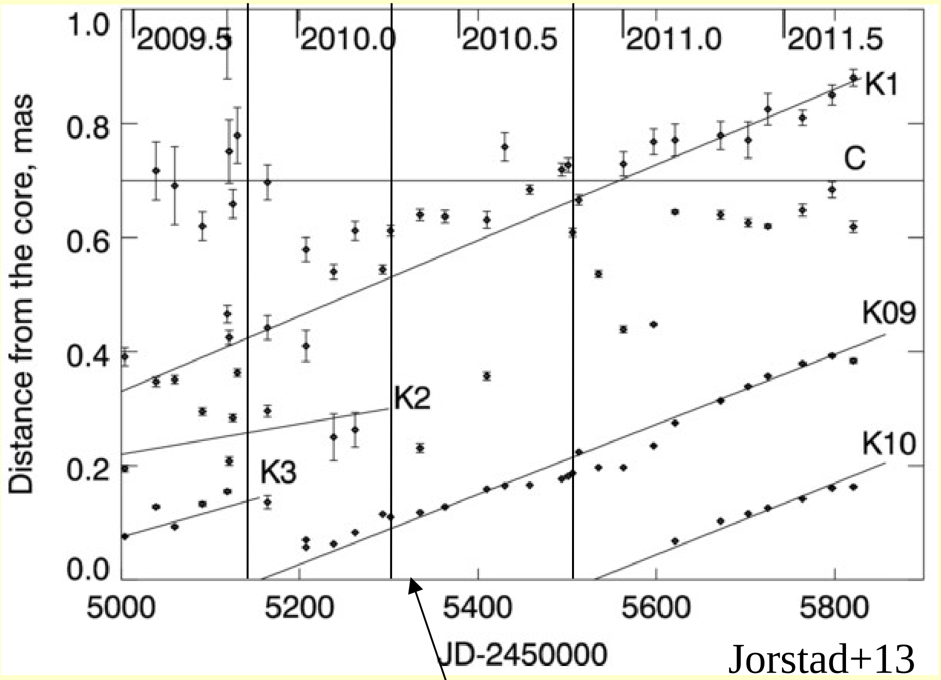


Sikora+08

Reconfinement shock in toroidal magnetic field + IR photons

Superluminal motion



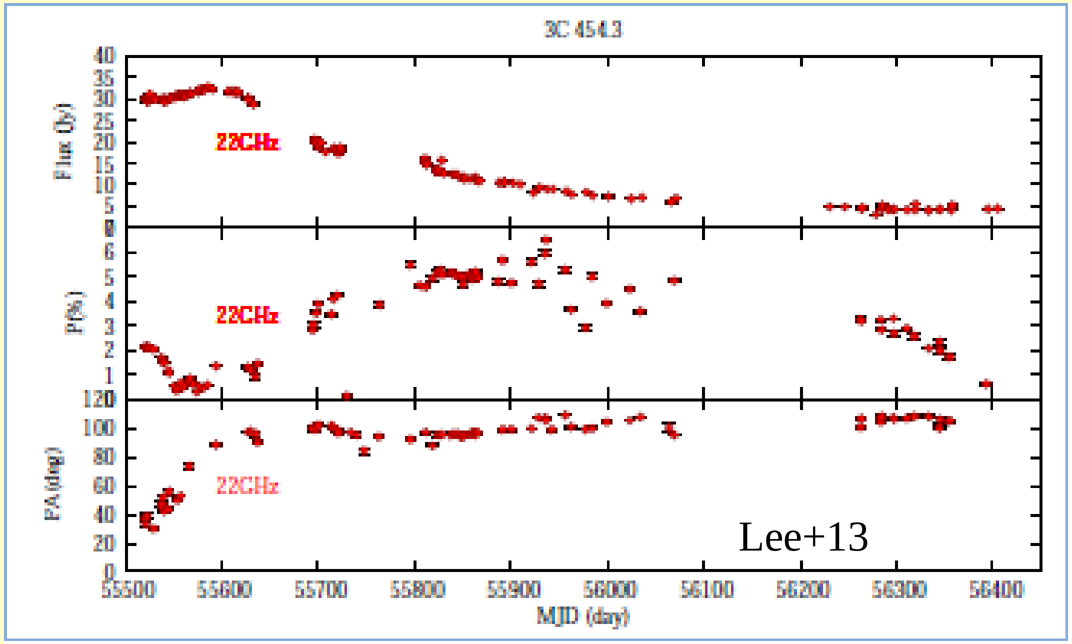


Some γ-ray flares without knot ejection

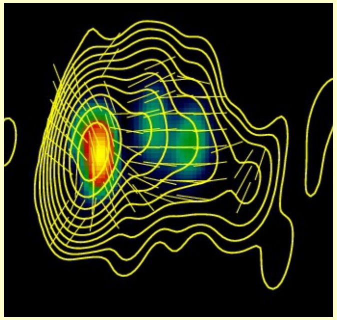
Superluminal knot is the observable manifestation of a propagating shock

Usually ejected close to a γ-ray flare

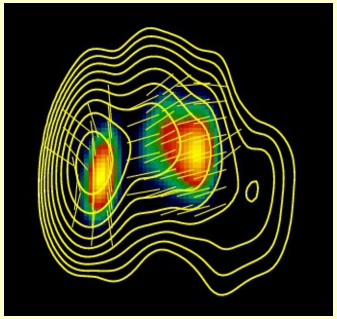
Magnetic field



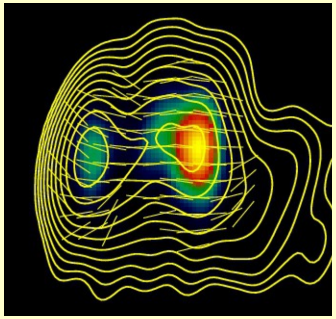
Jorstad+13



Mar 11



Apr 11



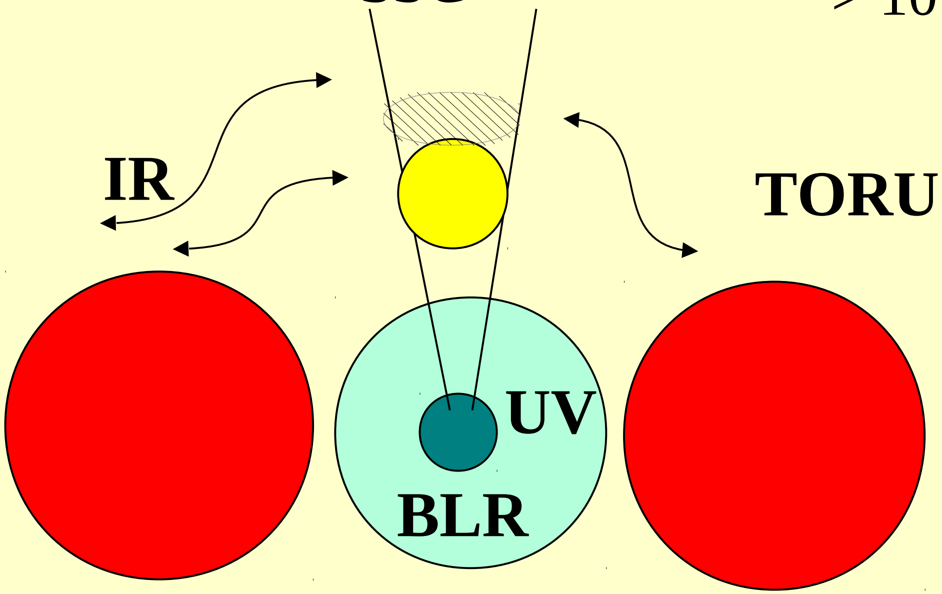
Jul 11

- Single dish: EVPA rotates of about 90°

- VLBI: Flux and polarization dominated by the knot ejected in Dec 2009 interacting with a stationary shock

Knot EVPA parallel to the jet axis, as expected for internal shock or reconfinement shock in a **toroidal magnetic field** (e.g. Sikora+08)

Observational clues



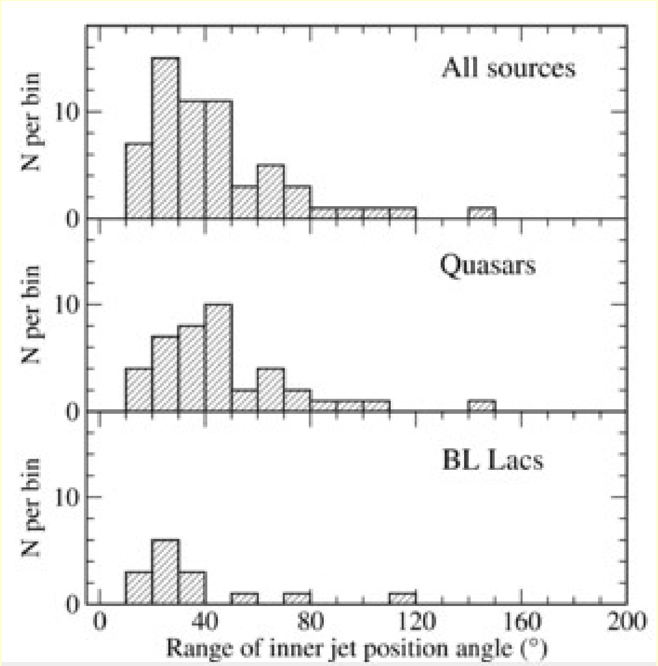
WHERE?	WHO?	HOW?
• pc scale	Internal shock	IR from torus
• > 10 parsec	Reconfinement shock	SSC
	Standing conical shock	Synchro from different e^- population

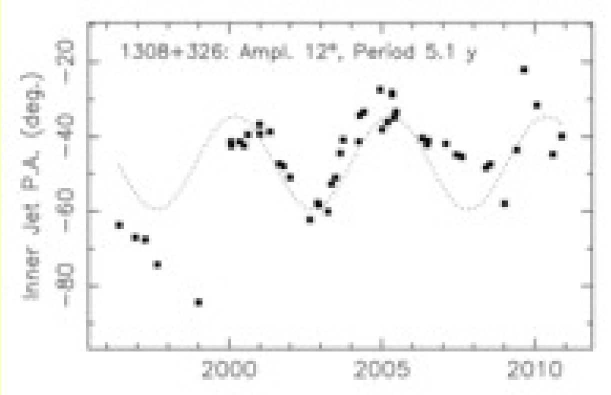
The γ-ray region

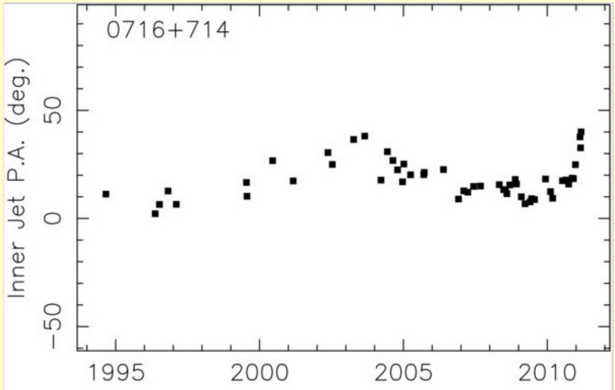
Pc-scale distance → Causality argument < 10^{16} cm

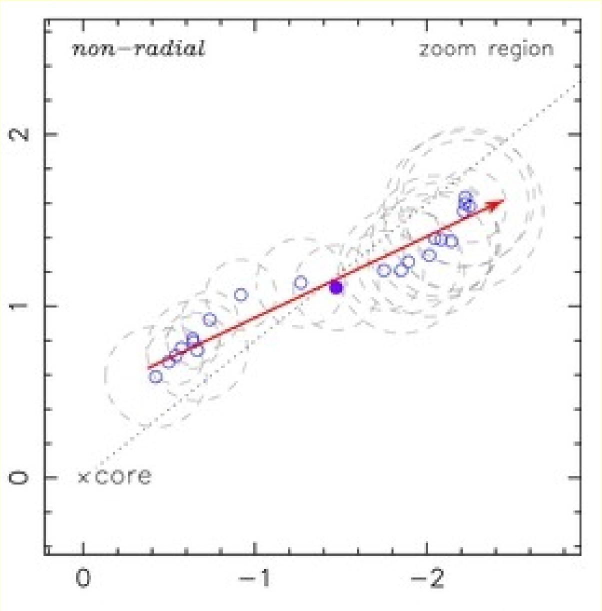
Large changes in the inner jet position angle → Jet knot occupies only a fraction of the jet cross-section

Lister+13



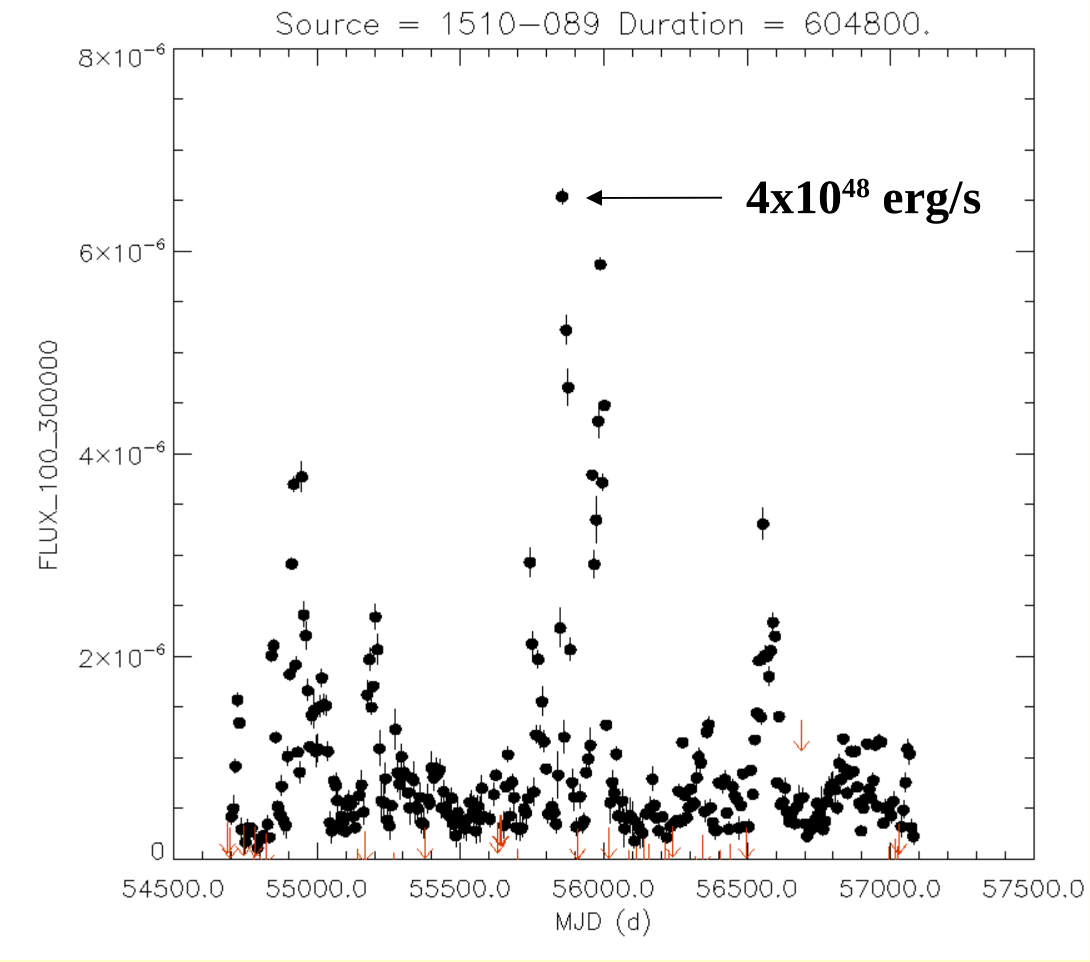






A very active blazar: PKS 1510-089

Many bright γ-ray flares. Superluminal knots ejected ~ every year

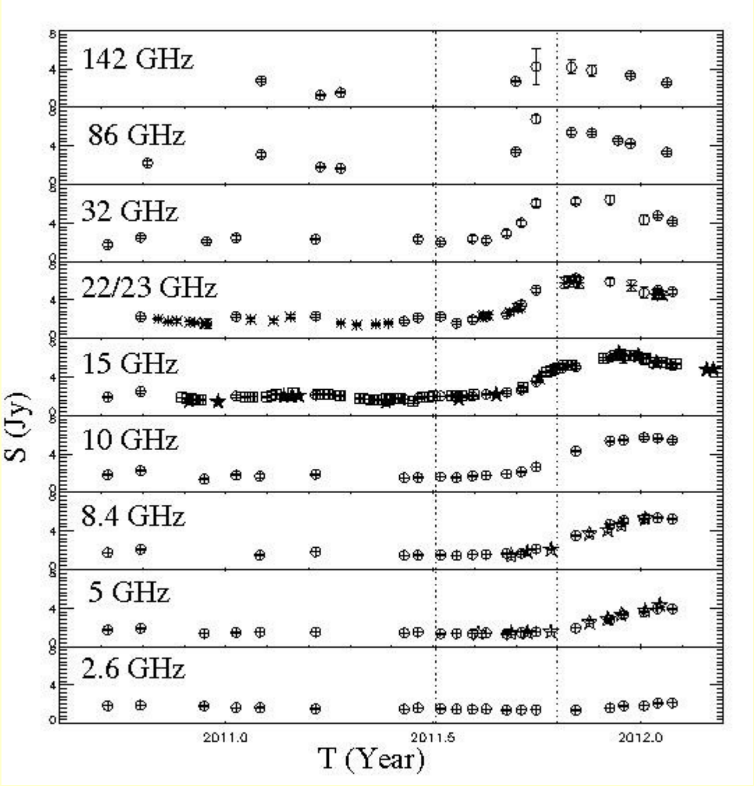


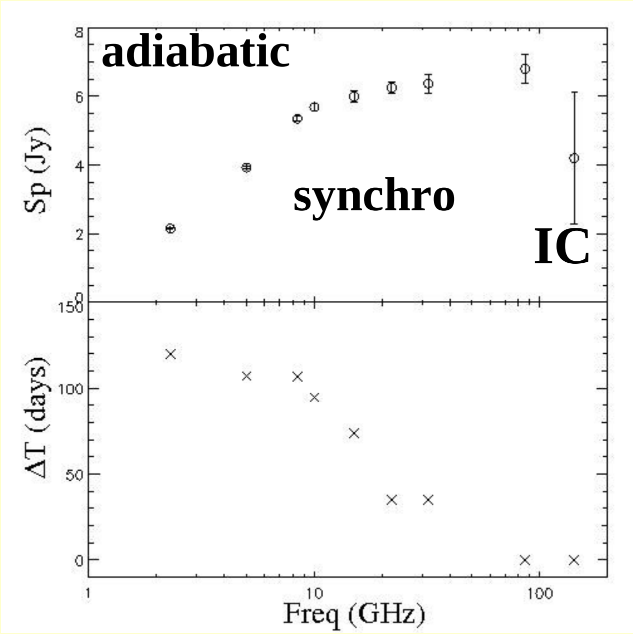
A FSRQ Detected above 100 GeV!

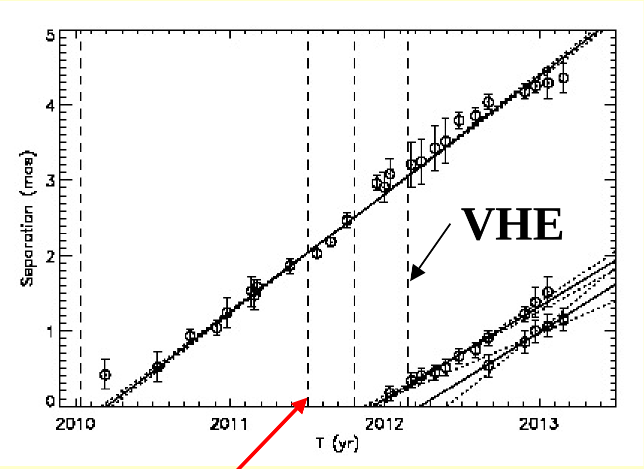
Shock stages

Multifrequency: schock stages + VLBI: Detection of superluminal knots

Orienti+13 PKS 1510-089





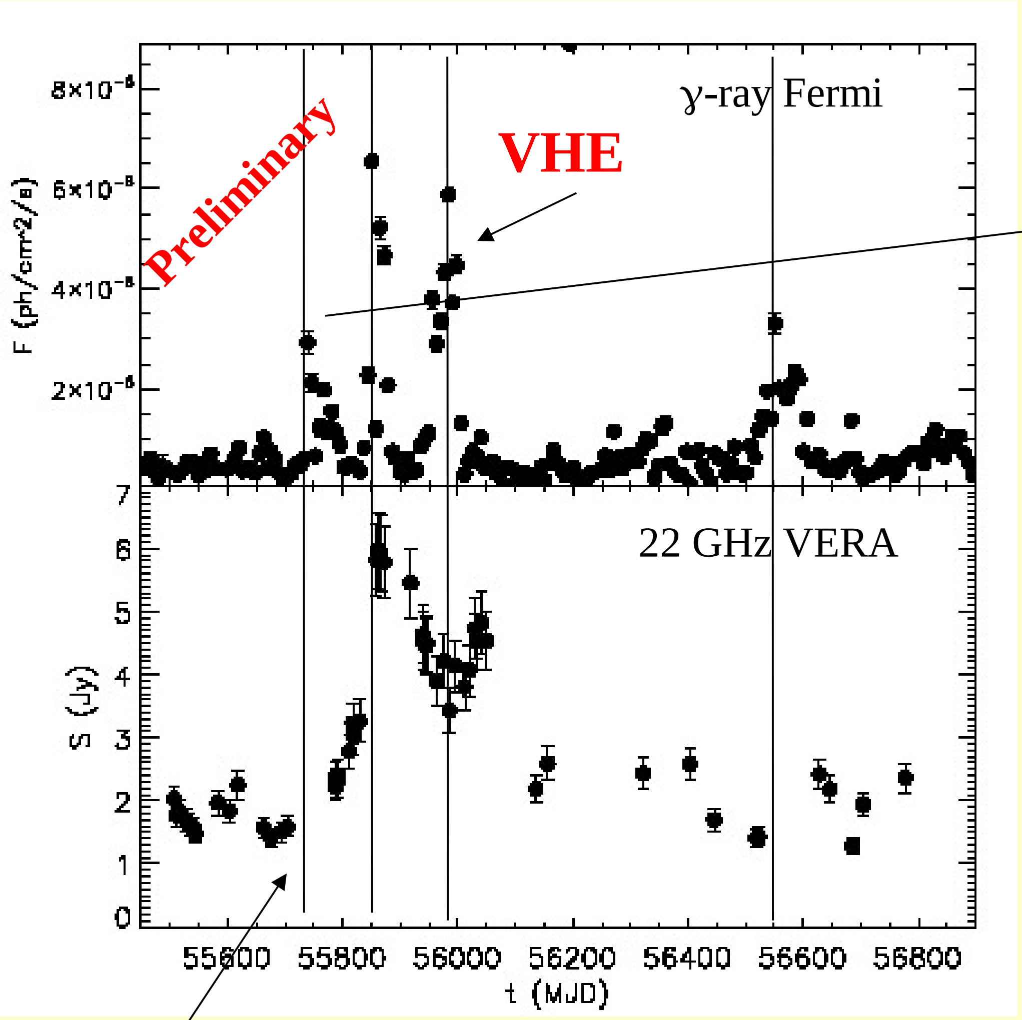


Peak flux density depends on the shock stage.

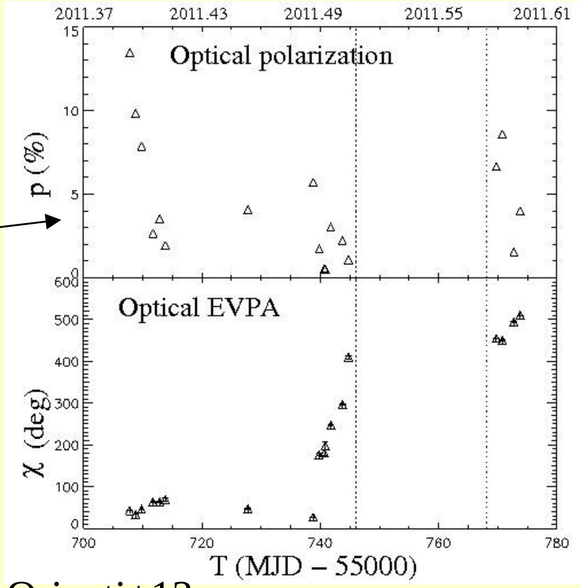
Not all γ-ray flare close in time with the ejection of superluminal knots

The **γ-ray and mm flare** seems **simultaneous**. Delayed at longer λ → Cospatiality in a pc-scale region

Polarization: core component



No radio counterparts



Orienti+13

Optical flare close to the γ-ray flare

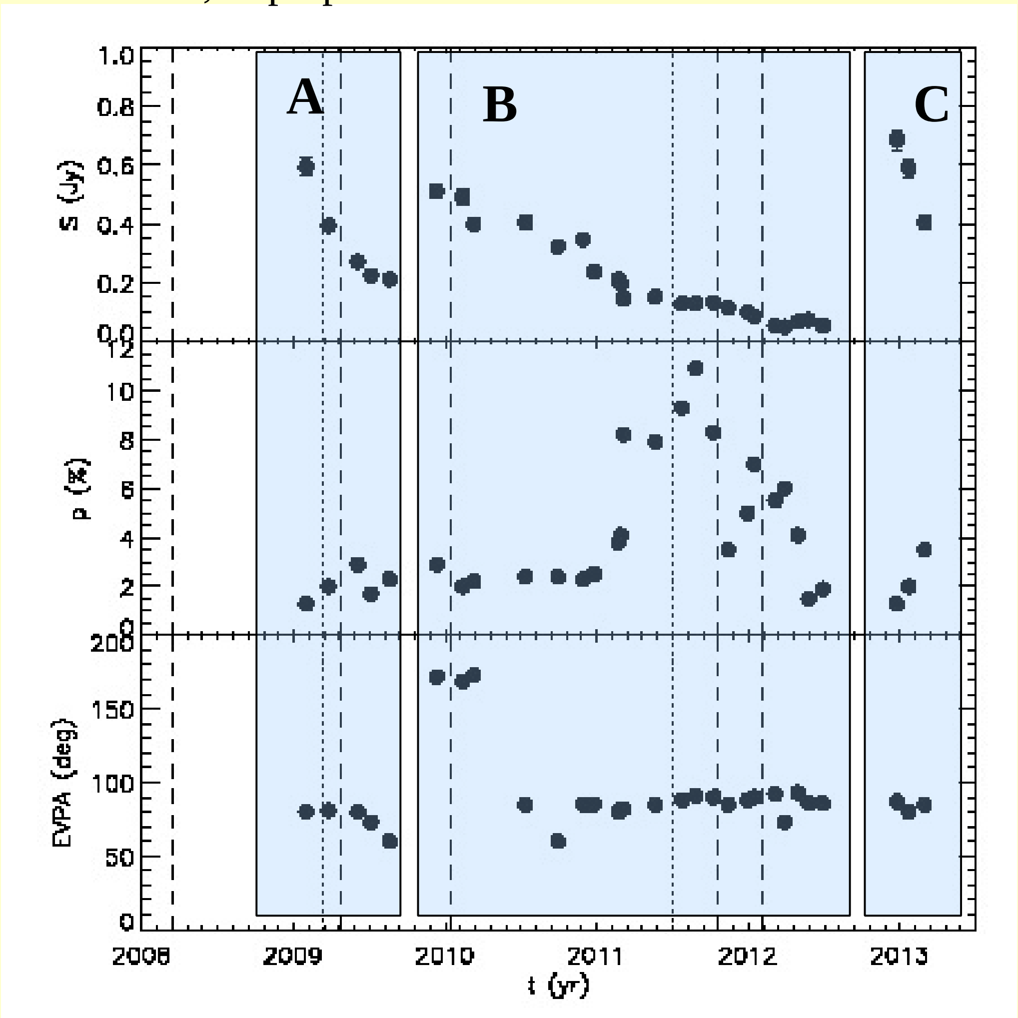
Optical EVPA rotates ~380° in 7 days

Shock within the BLR moving in a helical magnetic field

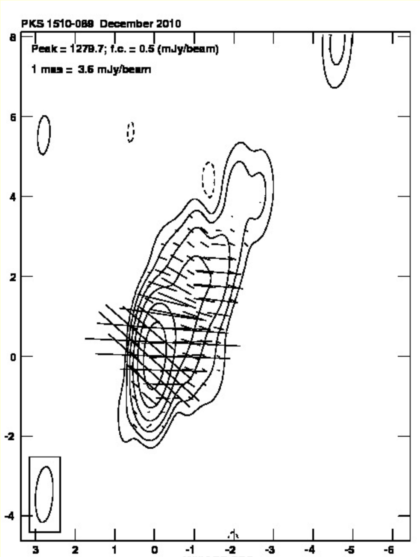
The interaction with a standing shock at pc-scale distance may produce the second huge flare

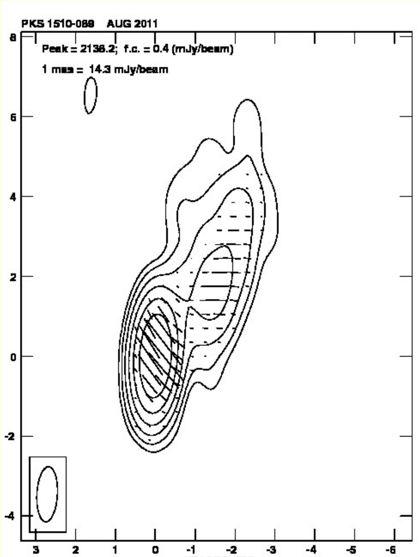
Polarization: jet component

Orienti+, in prep



As the knot emerges from the core its EVPA aligned to ~ 80°

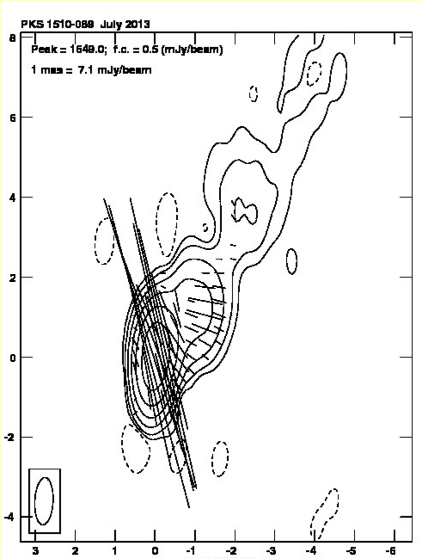




EVPA of the knots is roughly ⊥ to the jet axis.

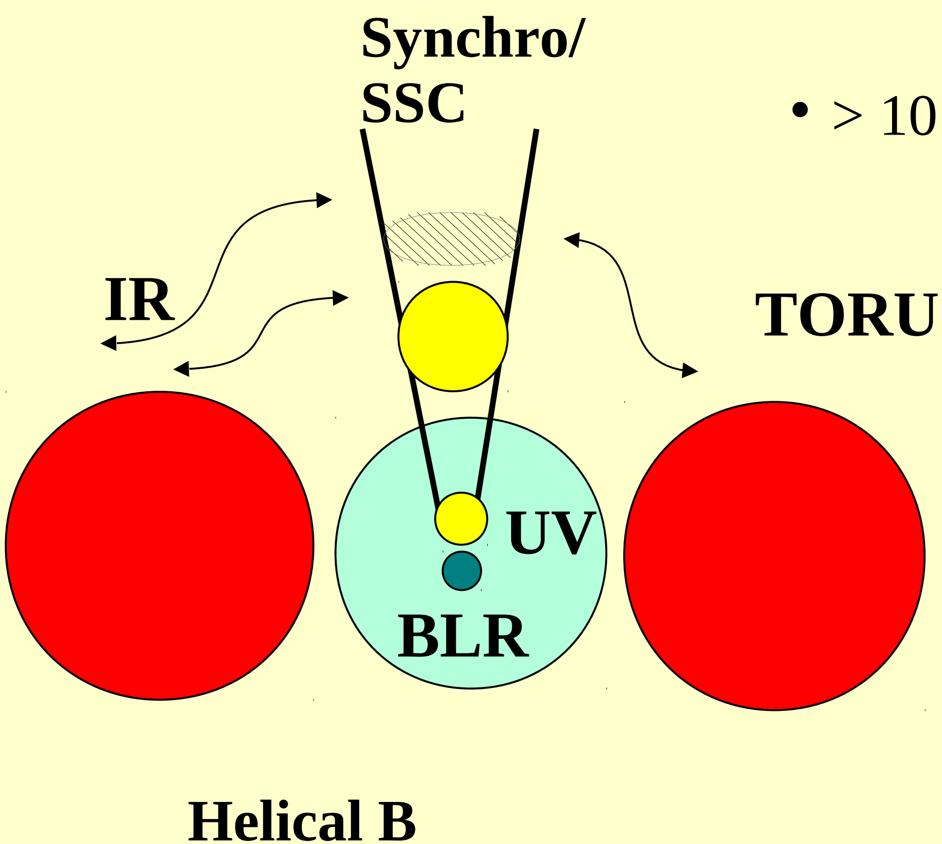
Oblique shock?

Reconfinement shock in a chaotic B?



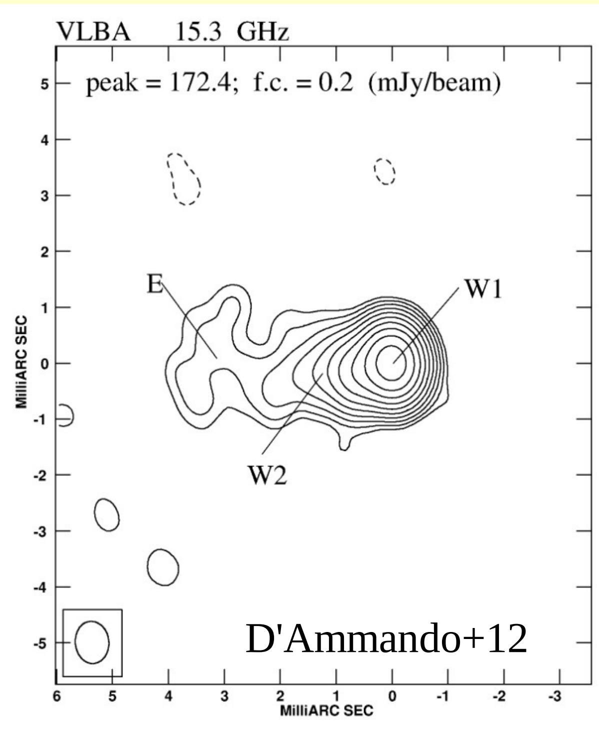
Observational clues

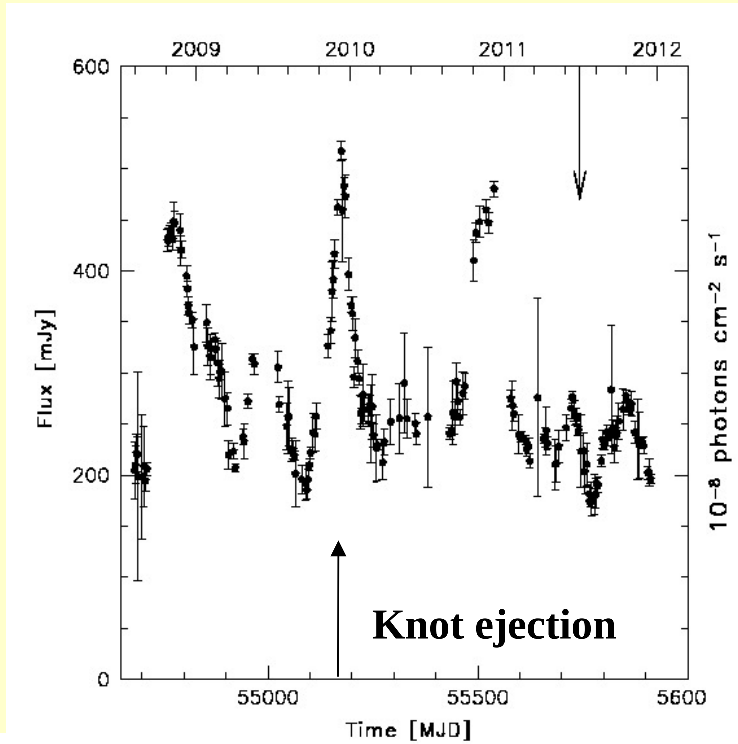
WHERE?	WHO?	HOW?
• < pc	Magnetic field reconnection	UV/optical from BLR
• pc scale	Internal shock	IR from torus
• > 10 parsec	Reconfinement shock	SSC
	Standing conical shock	Synchro from different e^- population

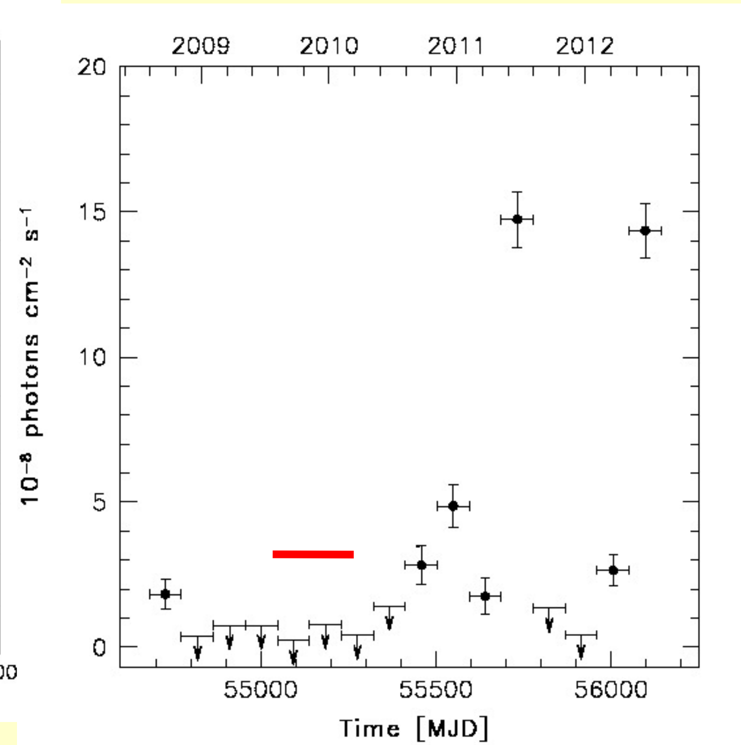


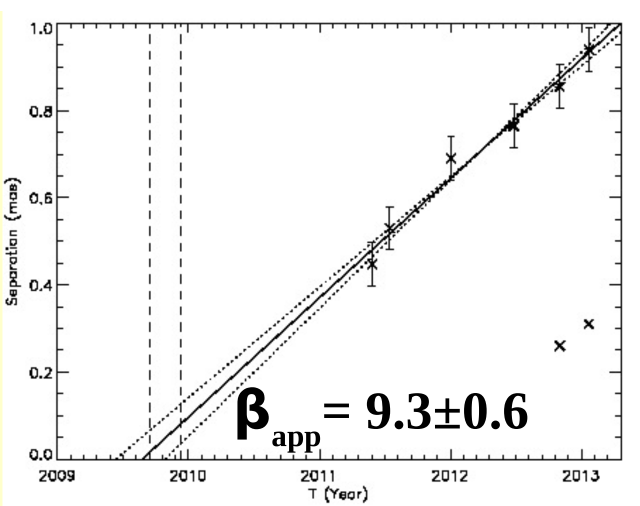
Different flares from different regions along the same jet

SBS0846+513: relativistic jet in NLSy1









No γ-ray flare detected close in time with the ejection of a new jet component.

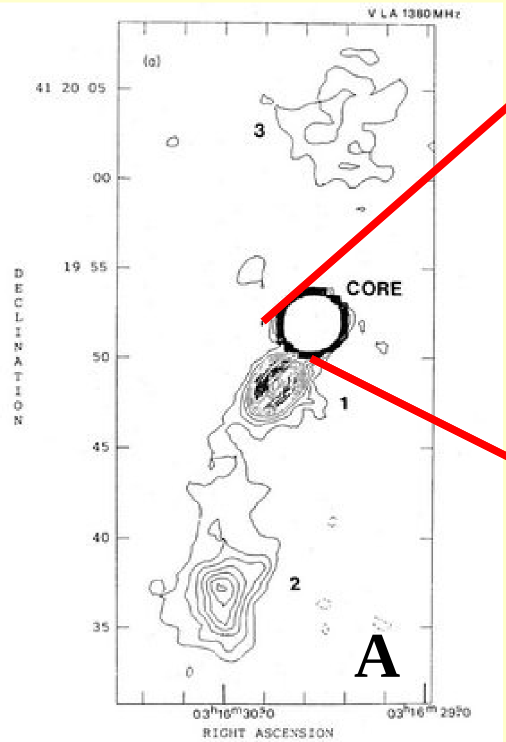
No seed photons?

No clear radio/γ-ray connection

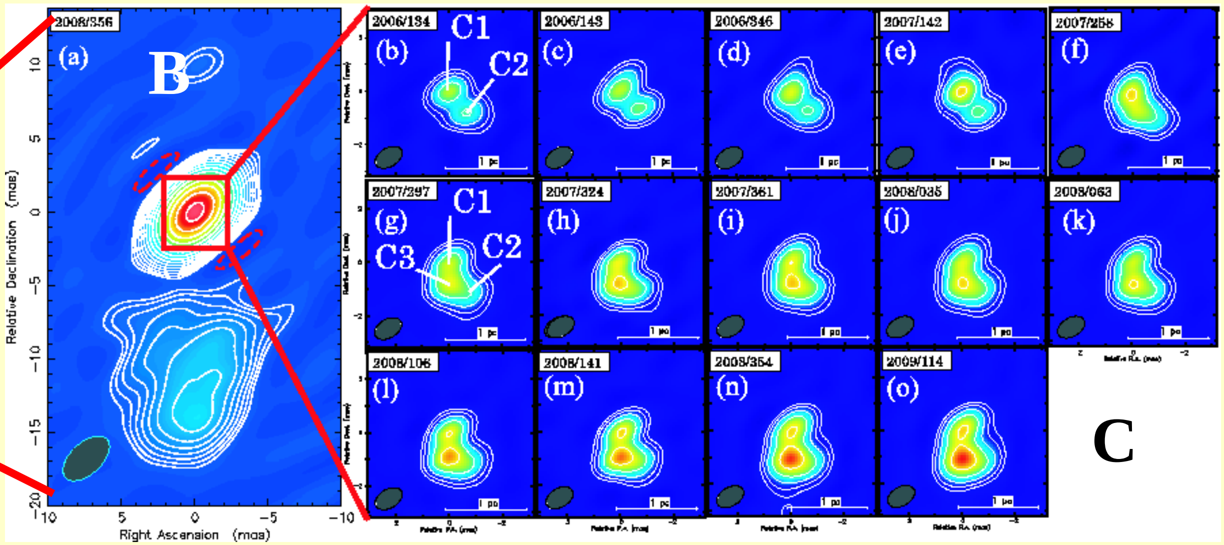
The radio galaxy NGC 1275

3C 84 is a nearby z=0.0176 radio galaxy with recurrent radio activities.

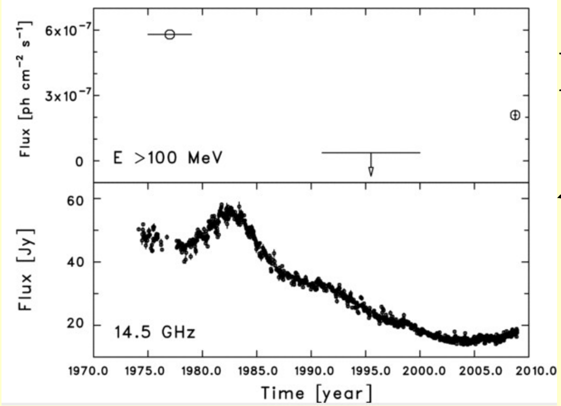
Pedlar+90



Nagai+10



Abdo+09



A: ~10 kpc, t_{syn} ~ 10^5 yr

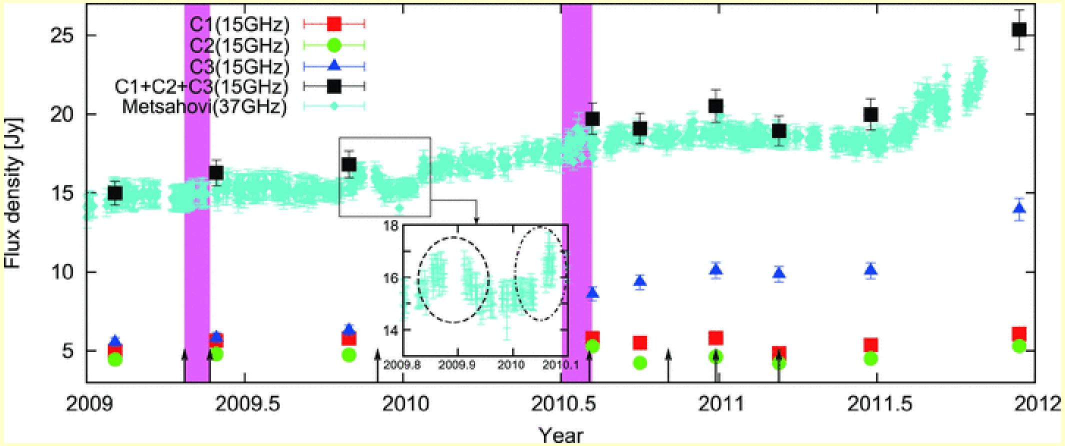
B: ~10 pc, ~ 50 yr, 1959?

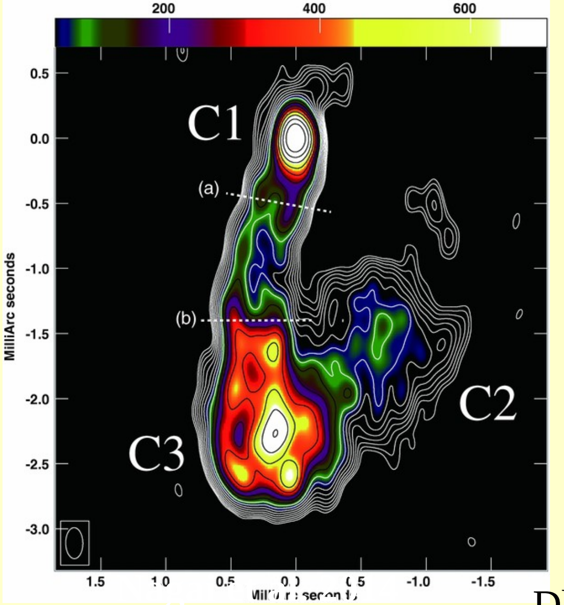
C: ~1pc, ~5 yr, 2005?

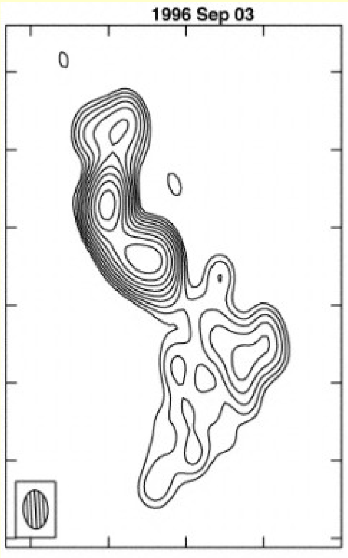
Detected by *Fermi* with luminosity 7 times higher than EGRET limit

γ-ray variability, origin < 1 pc?

The trigger: two zone model – 3C 84







Dhawan et al. 1996

Detected at VHE by MAGIC

No radio/γ-ray correlation

No superluminal component

Limb-brightened when γ-ray-loud

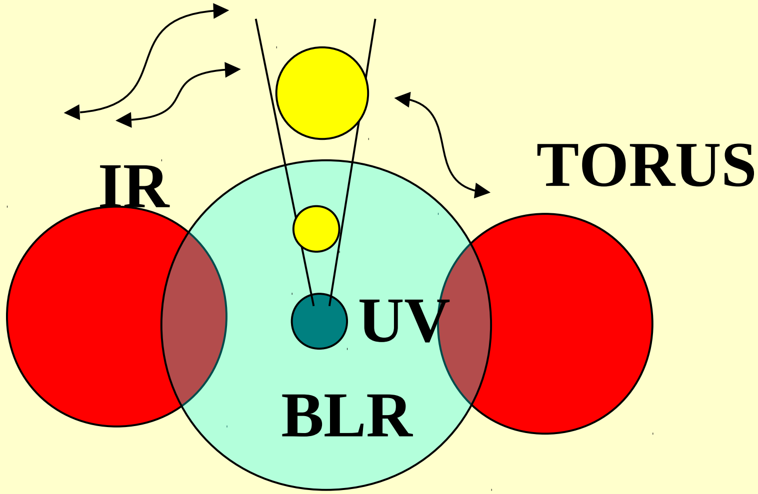
Edge-darkened when γ-ray-quiet

SED NOT consistent with one-zone region, e.g. shock

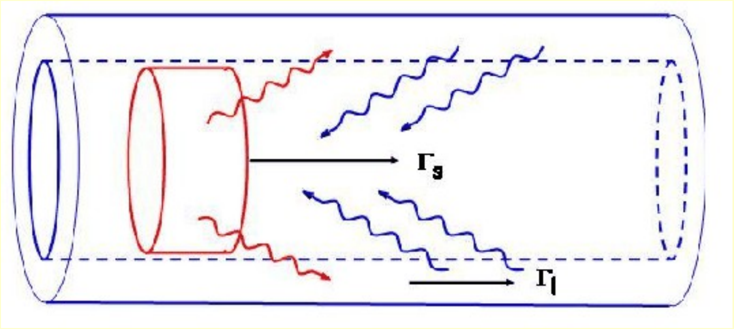
SED consistent with a spine-layer model

Tavecchio & Ghisellini 2014

Open questions



Ghisellini+08



WHERE?	WHO?	HOW?
• Sub-pc scale	Magnetic field reconnection	UV, optical from BLR
	Internal shock	
• pc scale		IR from torus
	Reconfinement shock	
• > 10 parsec	Standing conical shock	Synchro from different e^- population
• Two-zone model	Velocity gradient	Synchro from different e^- population

Not only jets

What about high-z γ-ray blazars?

Only a few high-z blazars (64 in the 3FGL)

Faint and soft sources

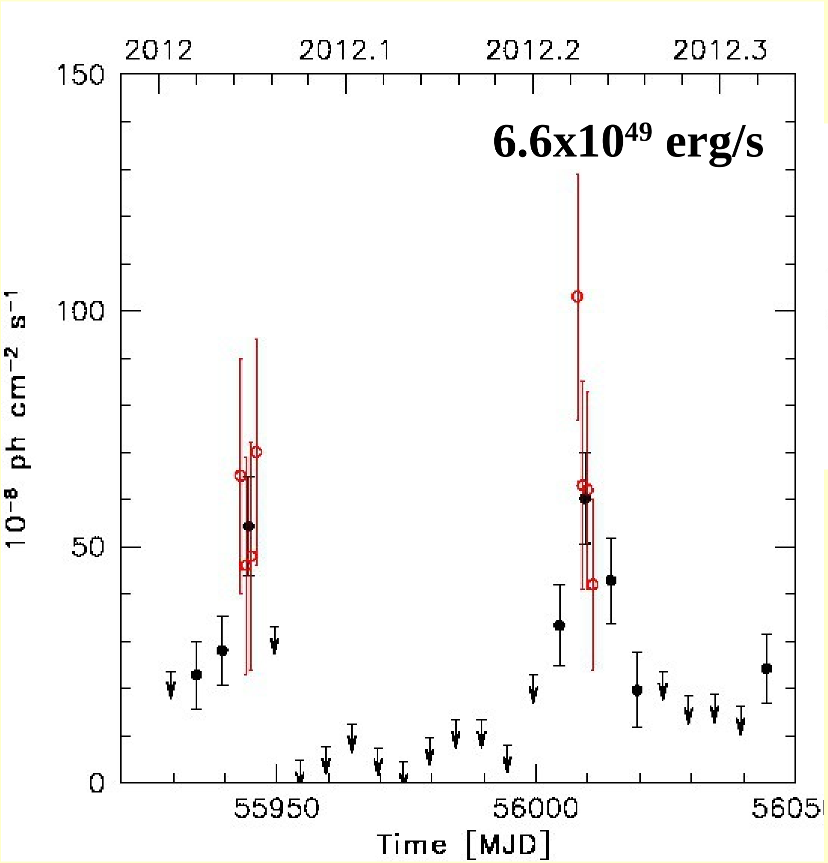
They become very luminous and harder during flares

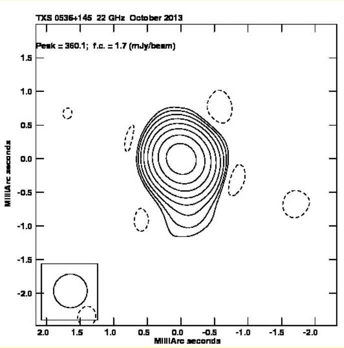
Extragalactic Background Light studies!

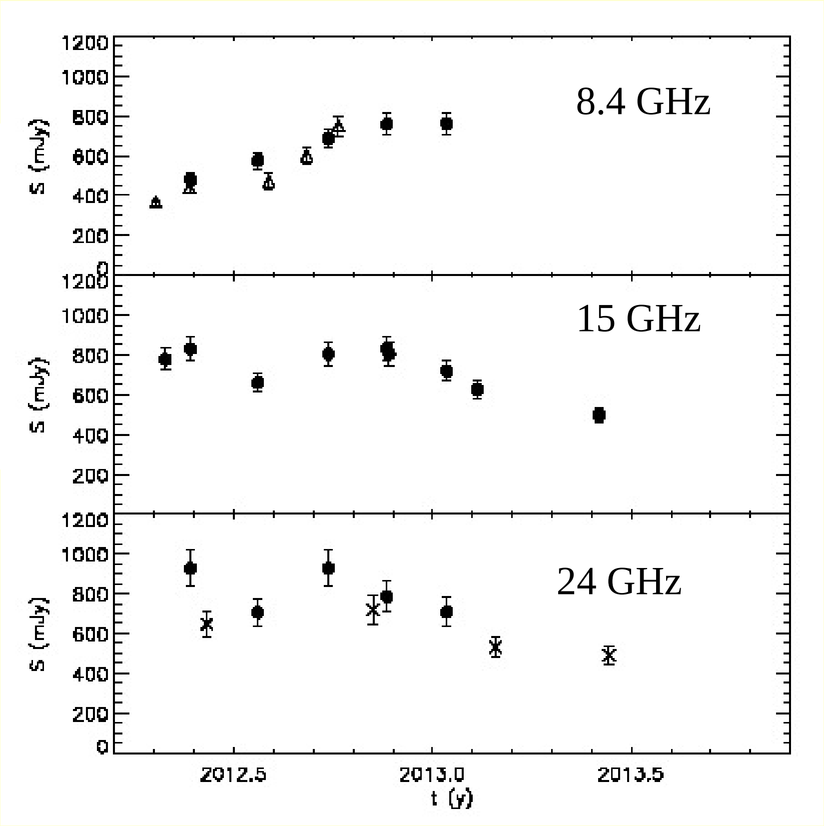
High-z blazar TXS 0536+145 (z=2.69)

Radio delayed by 4-5 months (obs frame)

Orienti+14



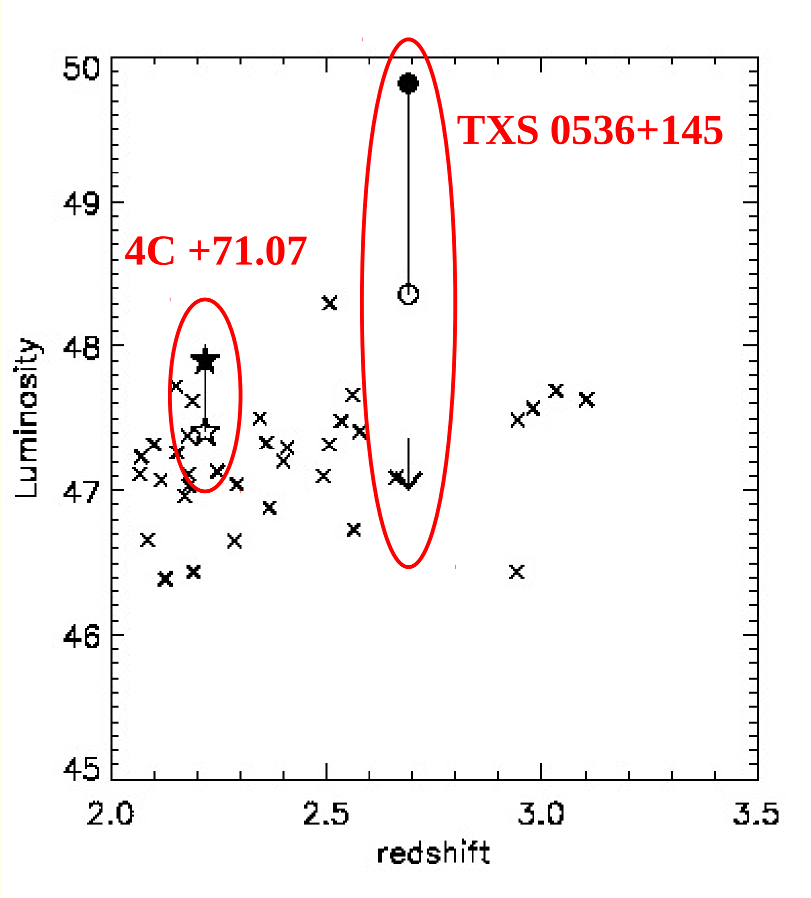




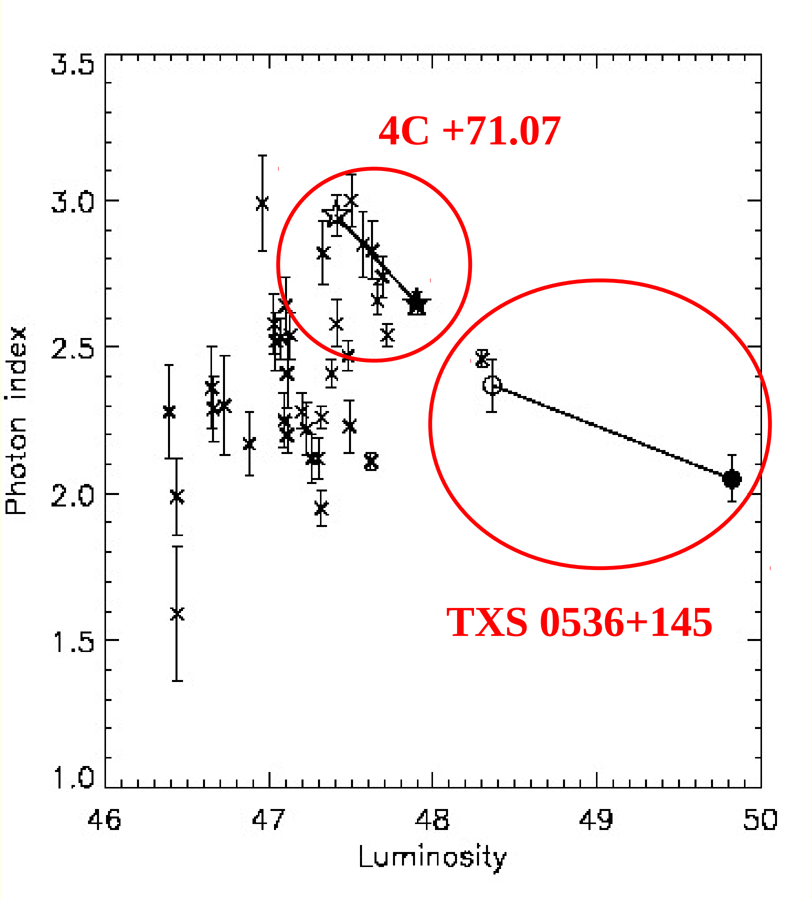
It is the γ-ray flaring blazar at the highest redshift detected so far

High-z γ-ray blazars and the EBL

Lγ - z



Γ - Lγ



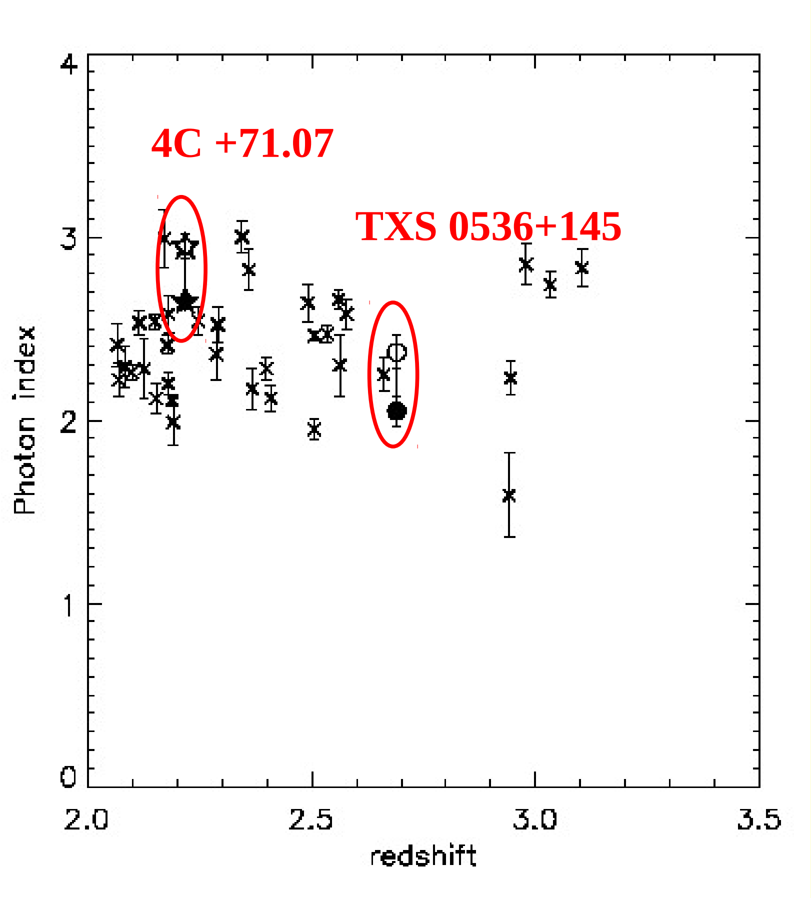
TXS 0536+145 and the EBL

Γ - z

Spectral hardening:

Average Γ = 2.37± 0.09

Flare Γ = 2.05± 0.08



At z = 2.69, the optical depth τ ~ 1 should be at 40 Gev (Finke 2010)

The highest photon energy is 11.2 GeV, compatible with the EBL models.

Summary

γ-ray sky dominated by blazar population

Connection between radio and γ-ray emission

Flaring γ-ray emission from different region of the jet

The trigger: shock-in-jet or velocity gradient

Change in the jet structure

High-z blazars and the EBL