The "Far Distance" Scenario for γ-ray Emission in Blazars: A View from the VLBI Observing Perspective

Iván Agudo[1,2]

[1]*Instituto de Astrofísica de Andalucía (CSIC)*

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Iván Agudo[1,2]

in close collaboration with

A. P. Marscher[2], S. G. Jorstad[2,3], V. Larionov[3,4], J. L. Gómez[1]

1 Instituto de Astrofísica de Andalucía, CSIC, Apartado 3004, 18080, Granada, Spain
2 Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA
3 Astronomical Institute, St. Petersburg State University, Universitetskij Pr. 28, Petrodvorets, 198504 St. Petersburg, Russia
4 Isaac Newton Institute of Chile, St. Petersburg Branch, St. Petersburg, Russia

[1]Instituto de Astrofísica de Andalucía (CSIC)

CSIC
Consejo Superior de Investigaciones Científicas

[2]Institute for Astrophysical Research (Boston University)

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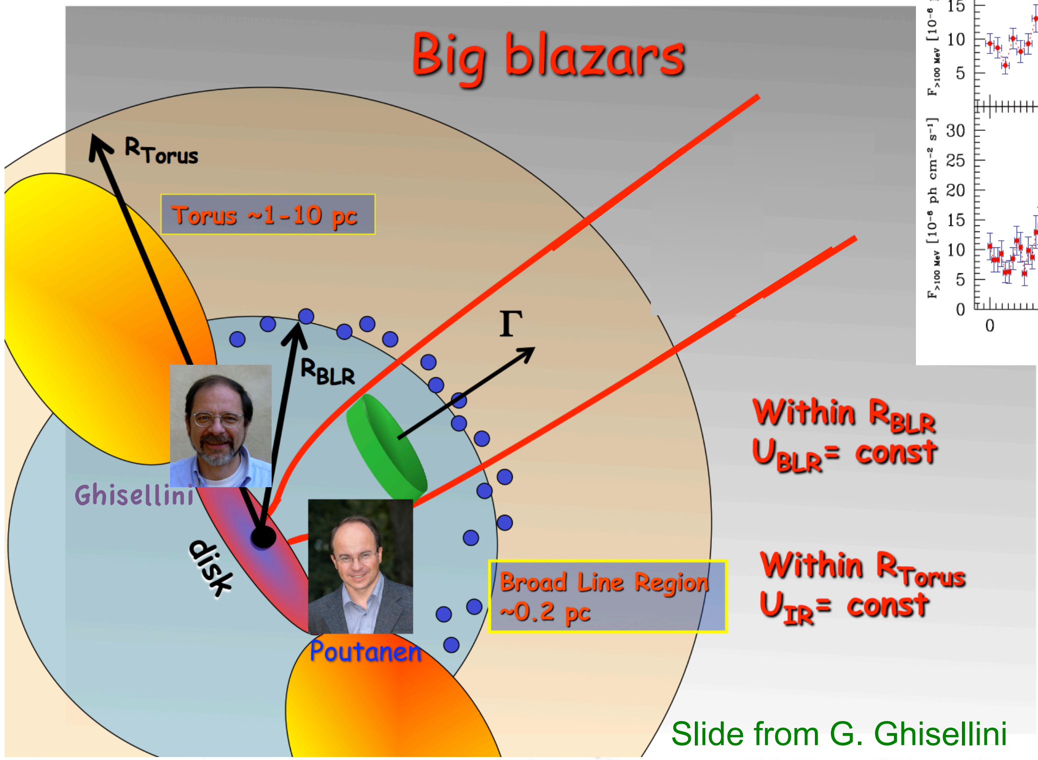
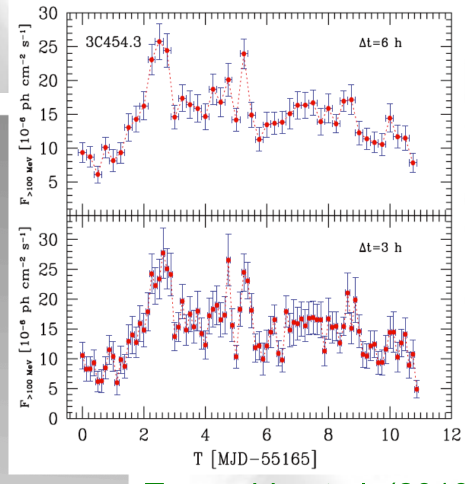
γ-ray emission sites in blazars

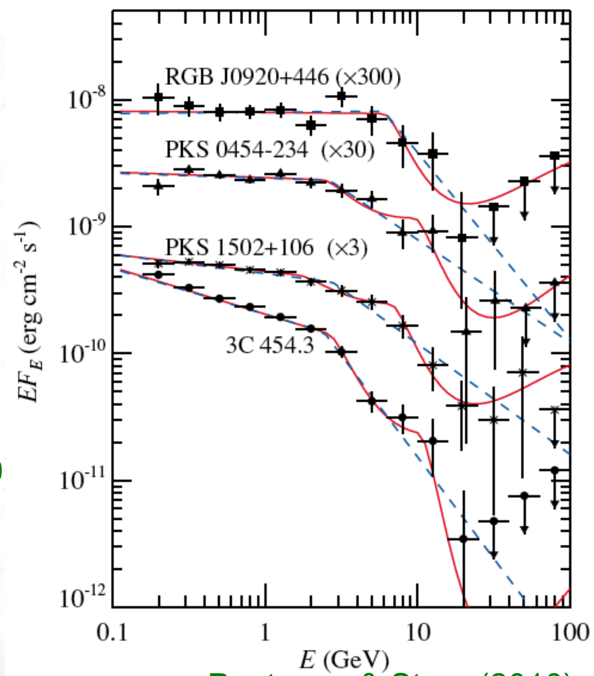
- Two main locations of the site of γ-ray emission in blazars are currently claimed. One close to the central BH (at <<1 pc, NEAR SITE, has been a preferred scenario until recently), which has been used to:
  - Explain short time-scales of γ-ray variability of a few hours (or less) reported in some blazars (Ackermann et al. 2010, Foschini et al. 2010,2011, Tavecchio et al. 2010) (Short time scales only imply small sizes of the emitting region, not a particular location)
  - Explain the sharp breaks at a few GeV seen in the γ-ray spectra of **some** blazars by opacity to pair production by (H and HeII) emission lines in the broad line region (Poutanen & Stern 2010)
  - See also Finke & Dermer (2010) who explain the break by more than one seed photon field in the BLR and up-scattering in Klein Nishina regime.



Slide from G. Ghisellini



Tavecchio et al. (2010

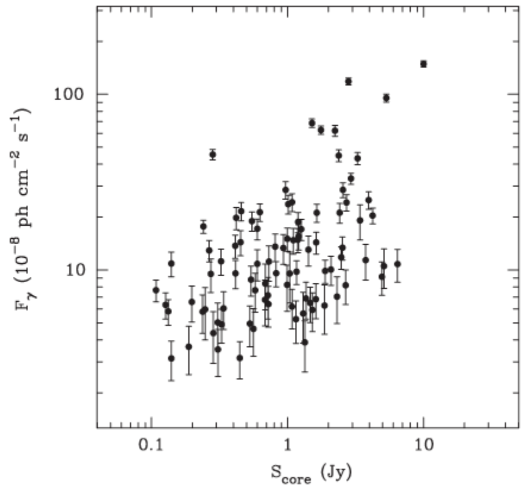


Poutanen & Stern (2010)

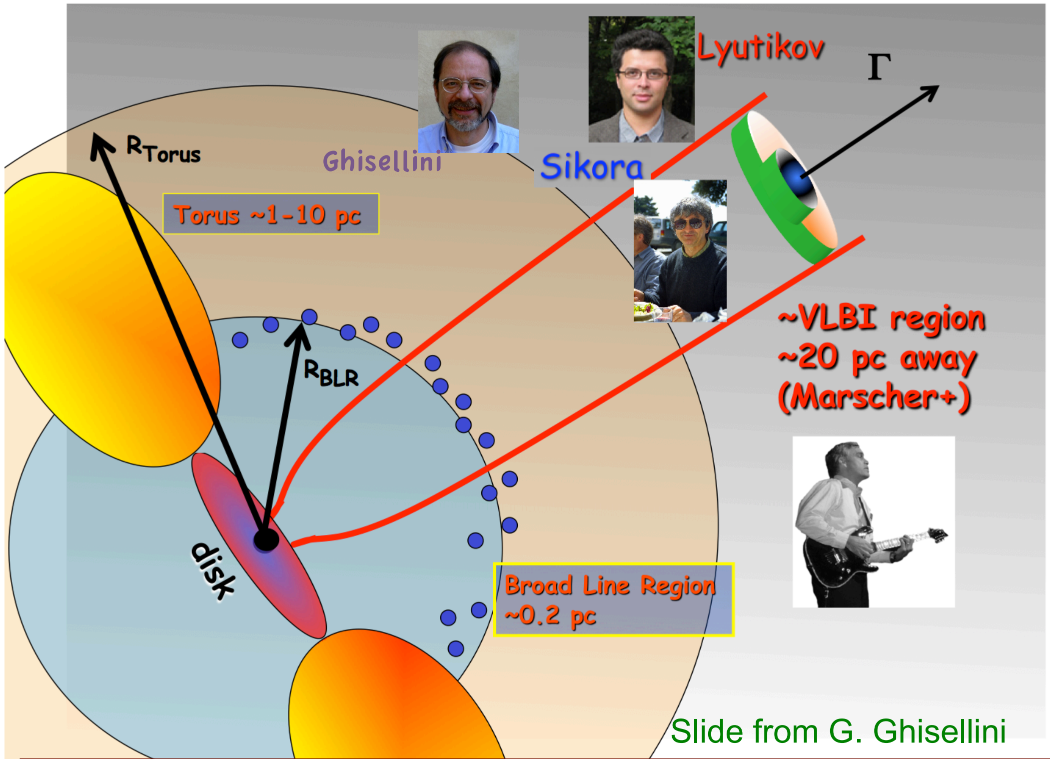
γ-ray emission sites in blazars

- The second (FAR SITE) scenario considers a region much further away from the central engine (at >>1 pc), where the photon field from the dusty torus, and synchrotron photon field from the jet itself are the most prominent photon fields. This scenario has been used to:

- Explain the correlation found between the Fermi γ-ray flux and the radio and mm flux in large blazar samples (Kovalev et al. 2009; Mahony et al. 2010; Pushkarev et al. 2010; Leon-Tavares et al. 2011; Ackermann et al. 2011; Ghirlanda et al. 2010, 2011, IA et al. subm), although these correlations alone, do not allow to infer the γ-ray emission by themselves.



Pushkarev et al. (2010)



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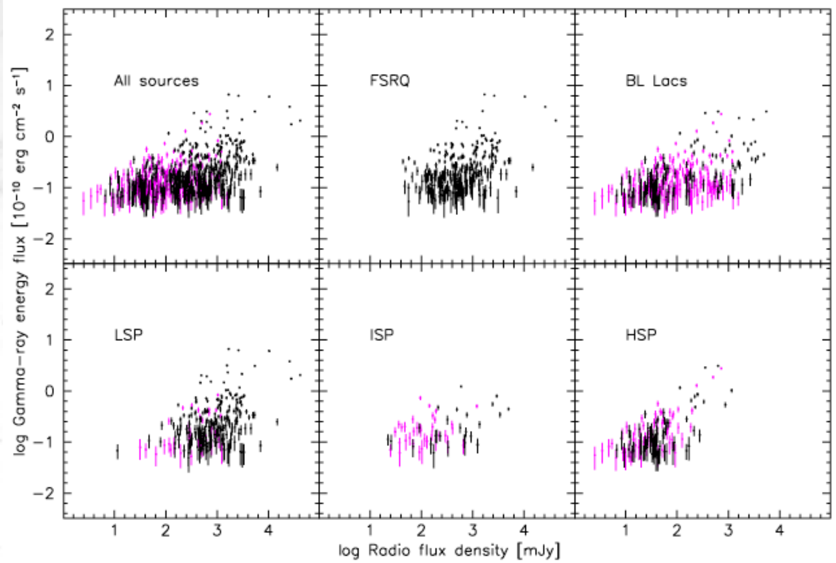

Ackermann et al. (2011)

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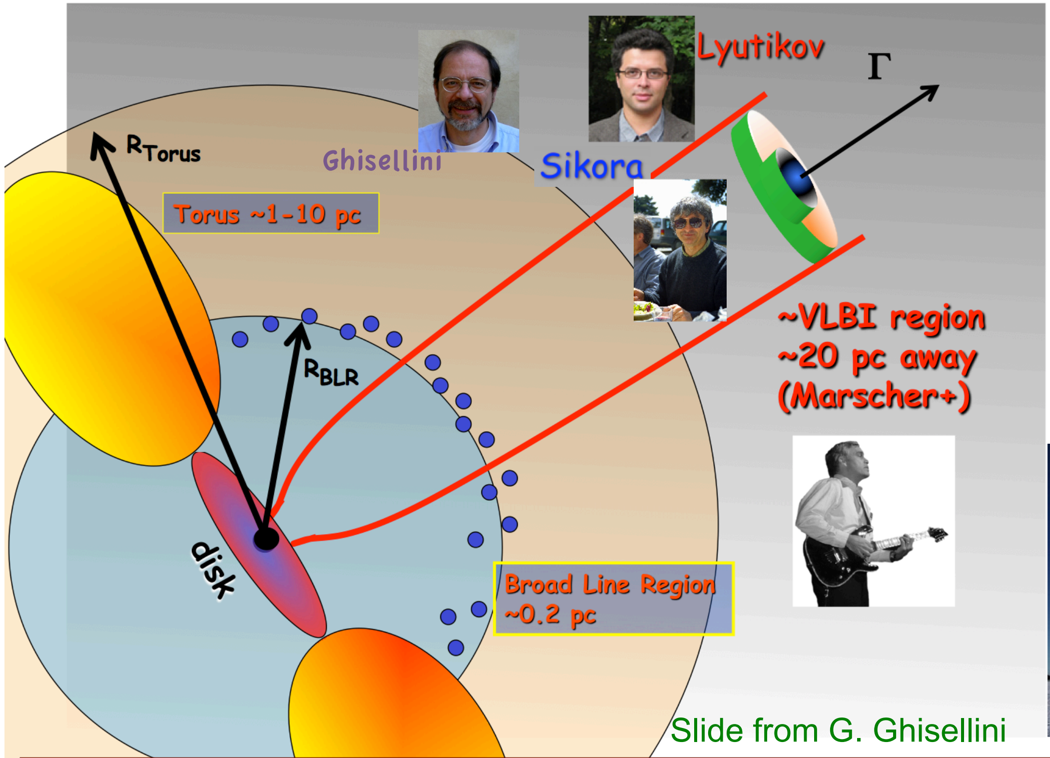

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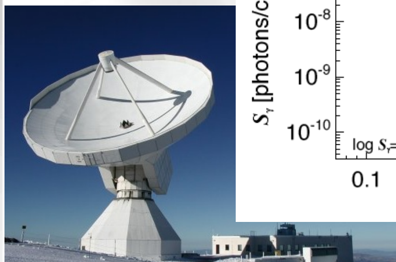
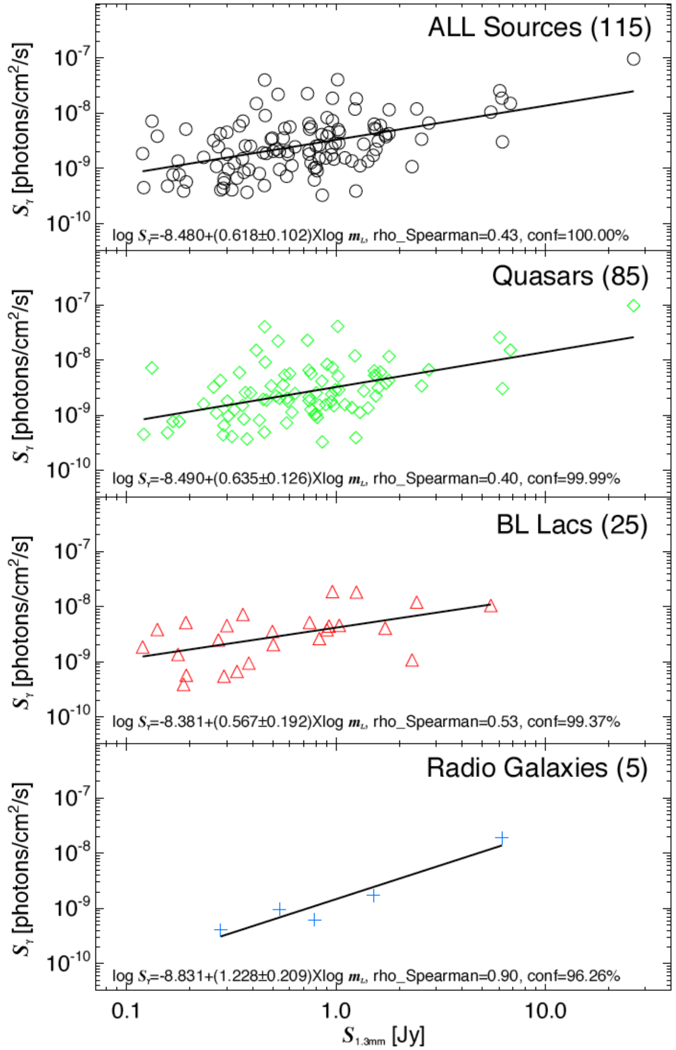


IRAM 30m mm Telescope



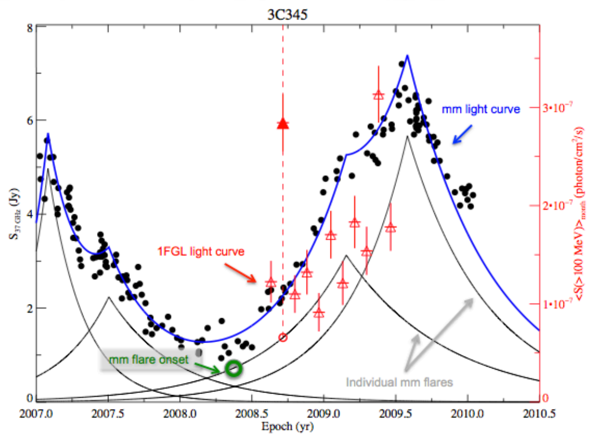
IA et al. subm

γ -ray emission sites in blazars

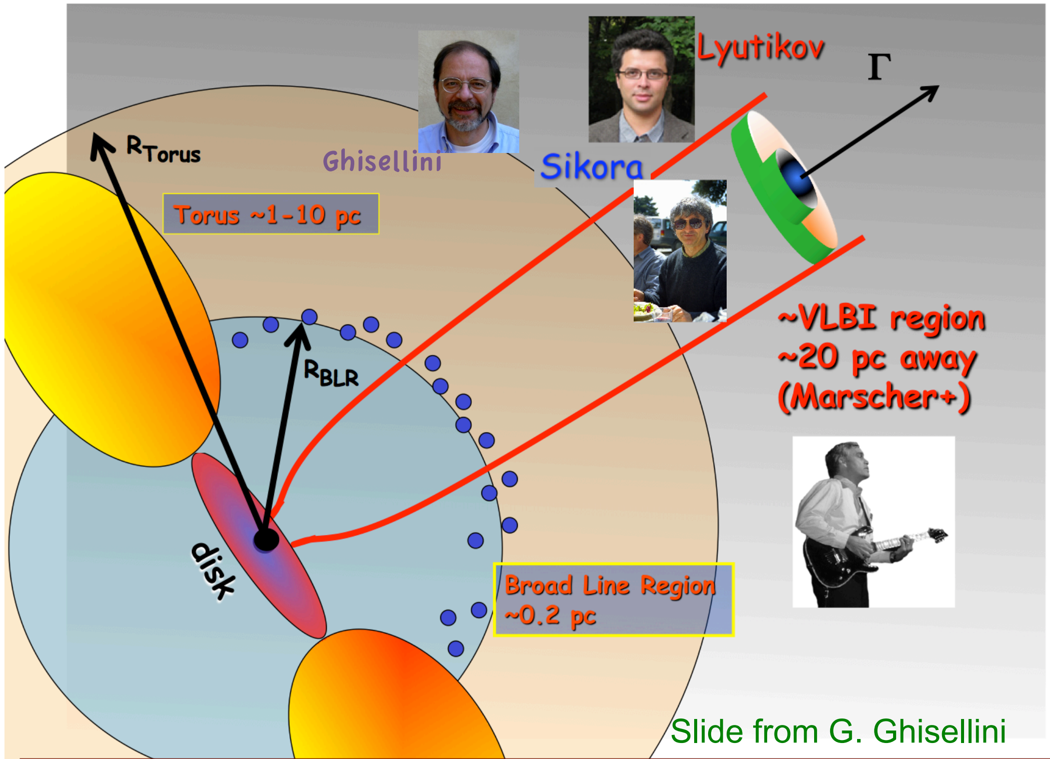
- The second (FAR SITE) scenario considers a region much further away from the central engine (at >>1 pc), where the photon field from the dusty torus, and synchrotron photon field from the jet itself are the most prominent photon fields. This scenario has been used to:

- Explain that the γ-ray flares often happens after the initial stages of a mm flare (Läteenmäki & Valtaoja 2003; Leon-Tabares et al. 2011), which they interpret as the γ-ray flare produced either at or downstream the radio core of the jet

- Explain the lack (in some cases) of broad γ-ray absorption (and Klein-Nishina) features that are expected if γ-rays are produced within the BLR (Sikora et al. 2009, Tavecchio et al. 2011, 2013).



Leon-Tabares et al. (2011)



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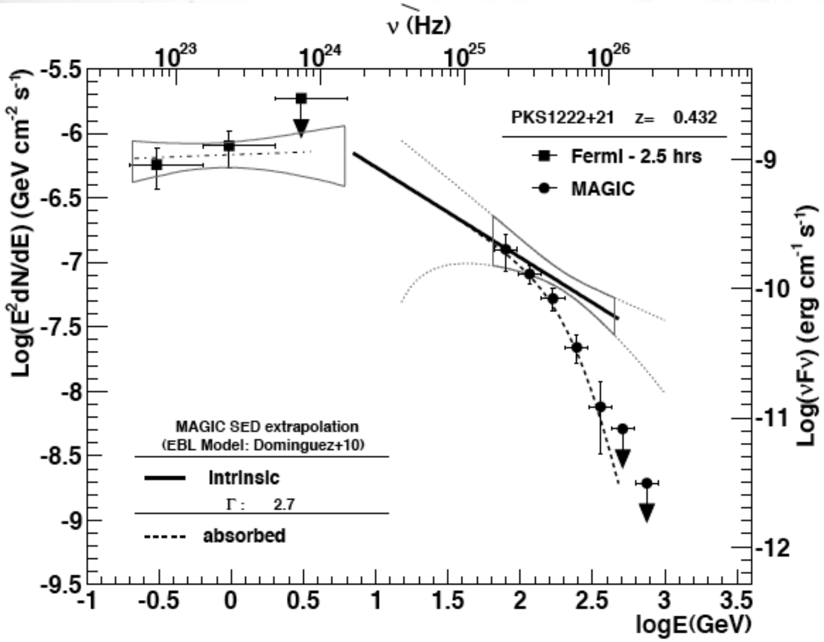
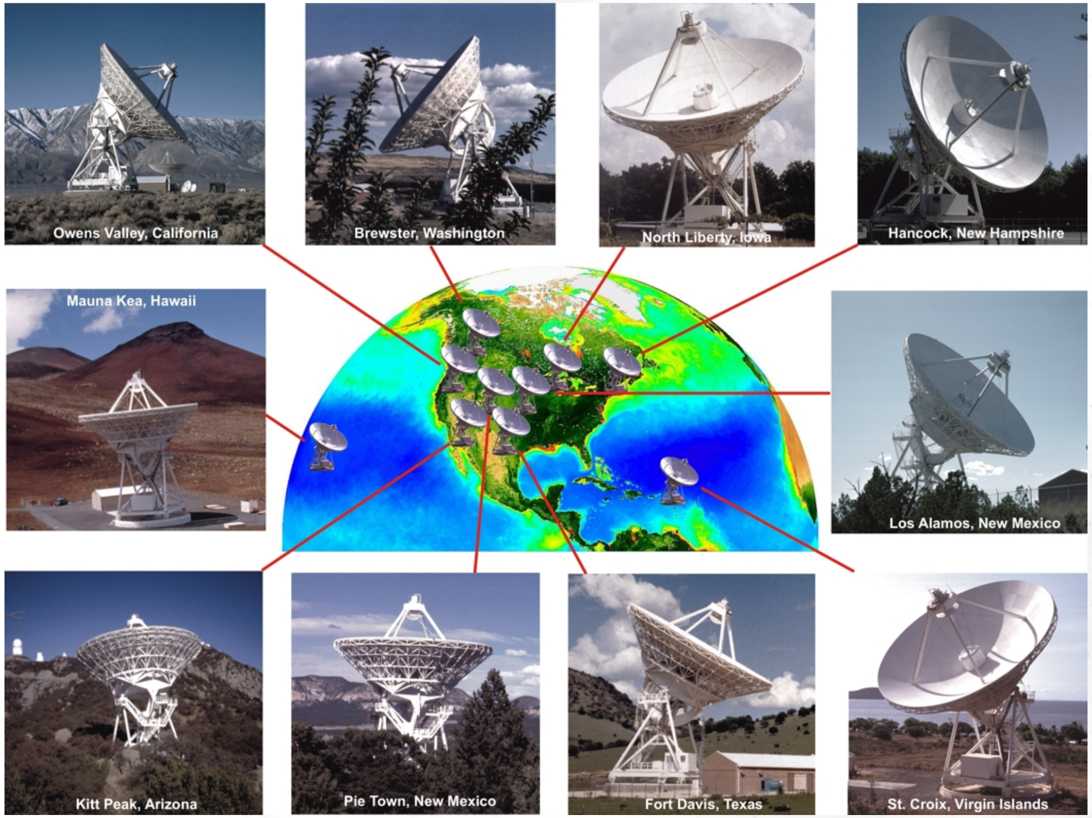
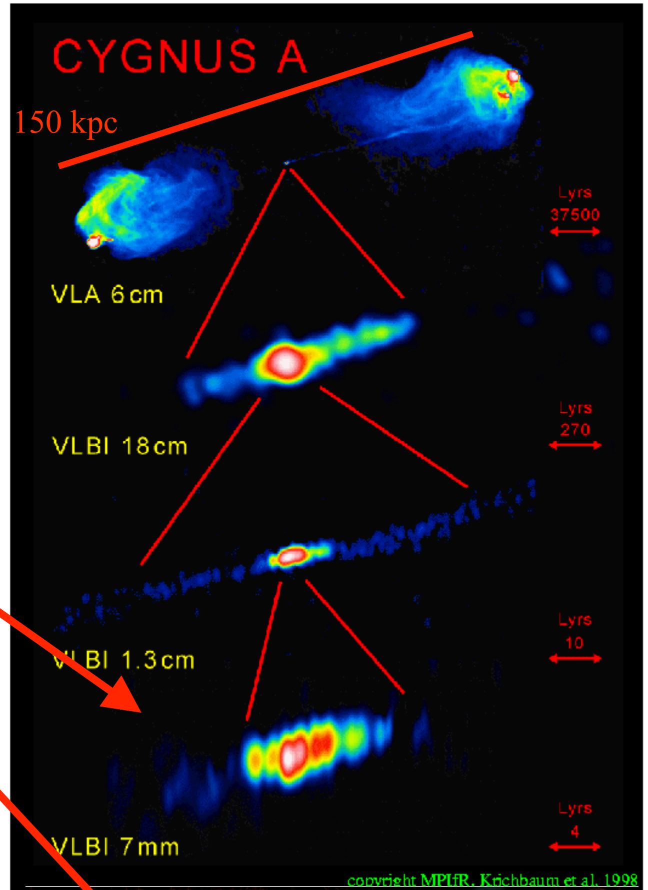


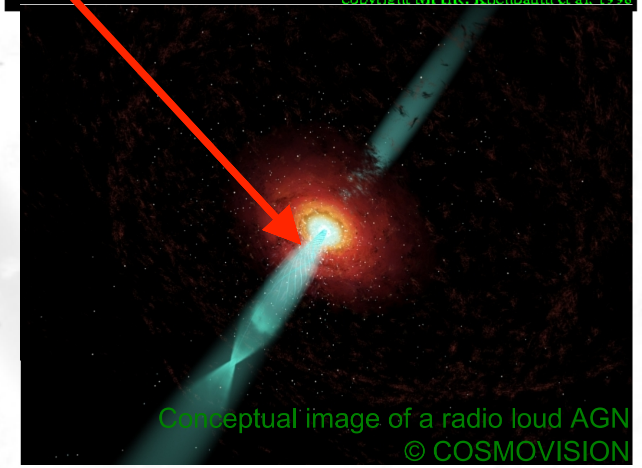
Tavecchio et al. (2011)

Very Long Baseline Interferometry (VLBI)

VLBA







- Only astronomical technique, so far, able to resolve millimeter jet structures in the sub parsec scales up to high z

- mm VLBI provides angular resolution of up to 0.1 / 0.15 milliarcsecond (~500 times better than the HST)

Early VLBI studies of γ-ray blazars

- Jorstad et al. (2001a) monitored 42 γ-ray bright blazars with the VLBA at 22 and 43 GHz from 1993 to 1997 to determine jet proper motions and ejections that could be related to the γ-ray behavior observed by EGRET.
- They showed that apparent superluminal motions in γ-ray sources were much faster than for the general population of bright compact radio sources.
- They also found an apparent correlation between VLBI core flux density and γ-ray flux
- Both results have been confirmed by recent work with Fermi data (e.g. Kovalev et al. 2009; Lister et al. 2009; Pushkarev et al. 2010)

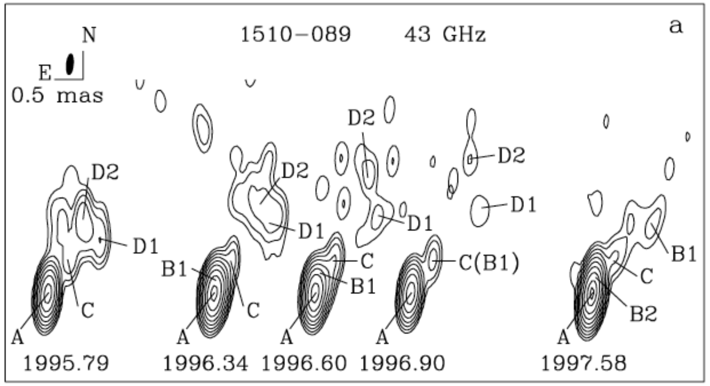


Fig. 26a

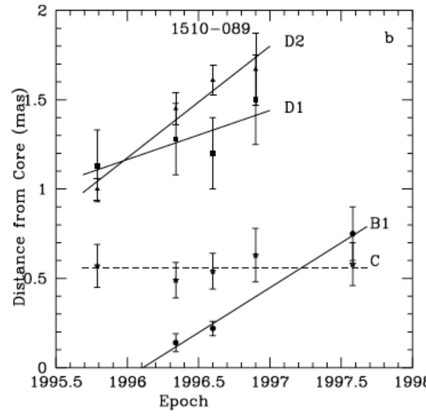
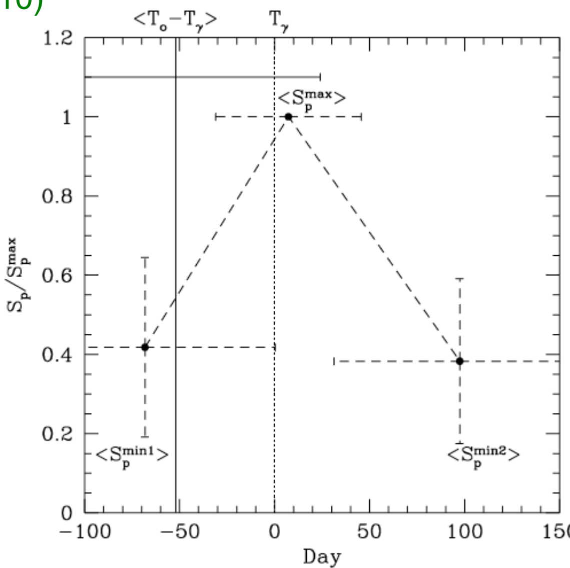


Fig. 26b

Jorstad et al. (2001a)

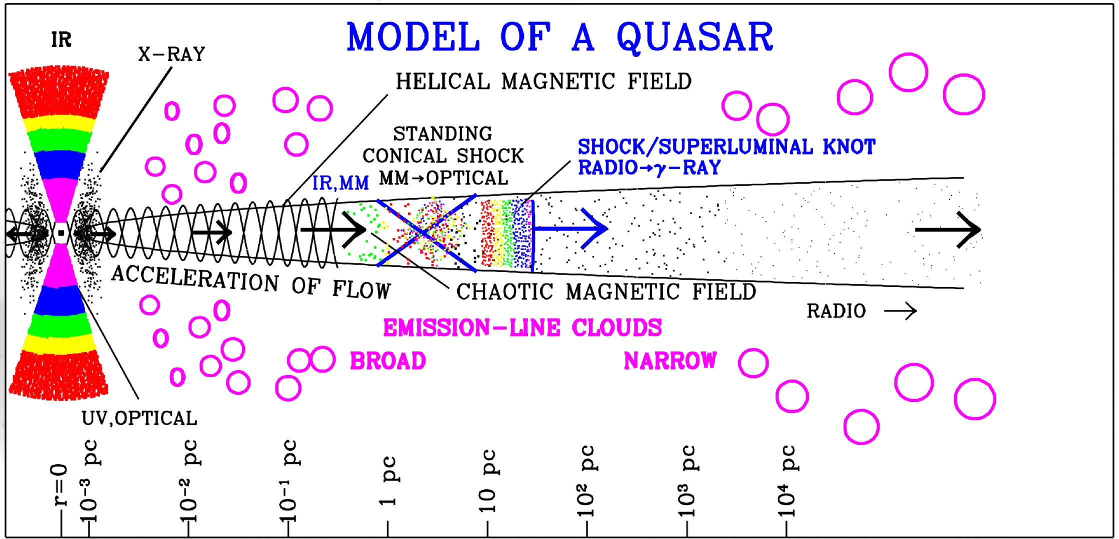


Jorstad et al. (2001b)

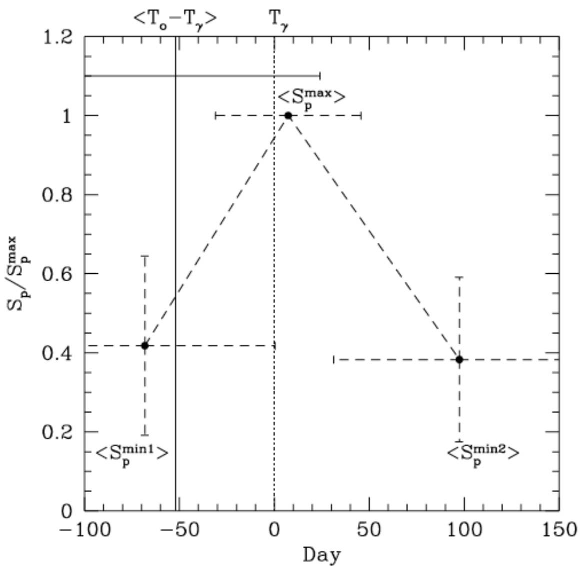
- Jorstad et al. (2001b) suggested that the γ-ray events are produced by superluminal radio knots.
- General pattern found: A disturbance causes the appearance of a superluminal component near the time of minimum polarized flux density. A gamma-ray fare follows, occurring almost simultaneously with the local maximum of the polarized radio flux density. During the gamma-ray outburst the polarized flux density nearly doubles and returns to the initial quiescent state.

Early VLBI studies of γ-ray blazars

- Strong argument in favor of the FAR SITE scenario.
- Jets in powerful blazars are in general not efficient synchrotron radio-mm emitters up to >>1 pc from the central engine, so if γ-ray and radio events are exactly time coincident they must be located where radio events are already visible



Conceptual image of a quasar emission and structure
© A. Marscher



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- Jorstad et al. (2001b) suggested that the γ-ray events occur in the superluminal radio knots.
- General pattern found: A disturbance causes the appearance of a superluminal component near the time of minimum polarized flux density. A gamma-ray fare follows, occurring almost simultaneously with the local maximum of the polarized radio flux density. During the gamma-ray outburst the polarized flux density nearly doubles and returns to the initial quiescent state.

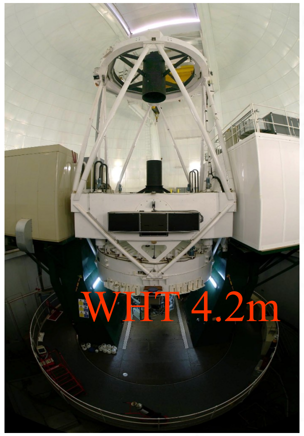
Current MWL studies

- The Boston University Blazar Group monitors (since 2007) 36 of the brightest γ-ray blazars with monthly 7mm polarimetry with the VLBA (at better than 0.15 milliarcsecond resolution)

Contribution from Spain

3 & 1 mm photo-polarimetry:

- POLAMI (Polarimetric AGN Monitoring with the IRAM-30m-Telescope)
- MAPI (Monitoring AGN with Polarimetry at the IRAM-30m-Telescope)
- >700 observing hours so far (started on mid 2007)



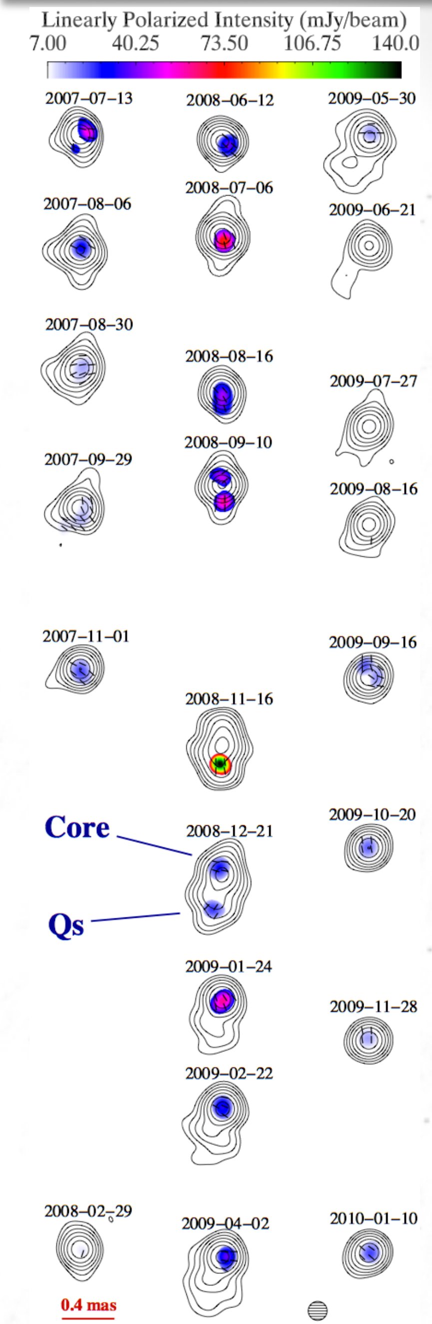
Near IR photo-polarimetry:

- Monitoring with the 4.2m William Herschel Telescope (ORM)
- 8 observing nights so far (started in March 2011)

Optical photo-polarimetry:

- MAPCAT (Monitoring AGN with Polarimetry at the Calar Alto 2.2m Telescope)
- >500 observing hours so far (started on mid 2007)

A new case: the BL Lac Object AO 0235+164



31 monthly VLBA 7mm pol. Images

0.15 mas resolution

2007 to 2010

From BU Blazar monitoring

Fermi-LAT data from mid 2008 (2 day bins)

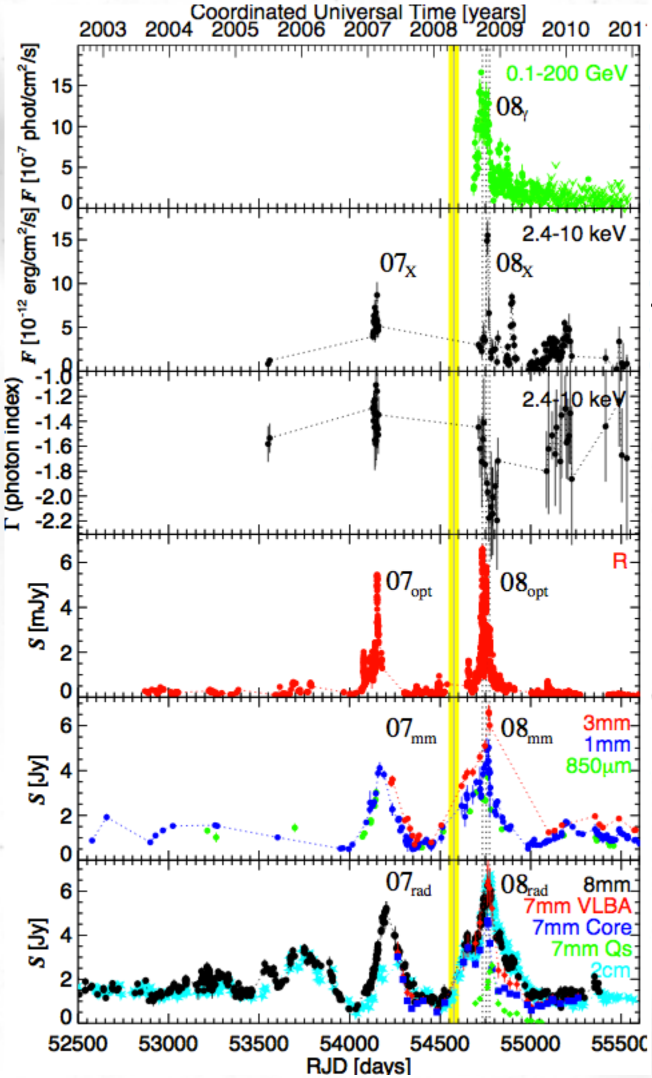
SWIFT-XRT and RXTE data from 2005

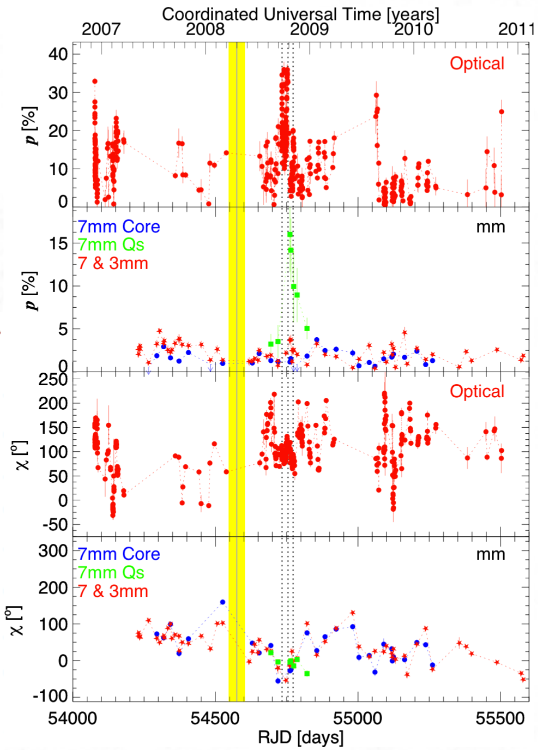
1200 optical points from 11 telescopes

SMA (1 & 0.8 mm) light curves from 2008

8mm light curve from the Metsahovi radio observatory

Light curves from the brighter VLBI jet features (the Core & Qs)





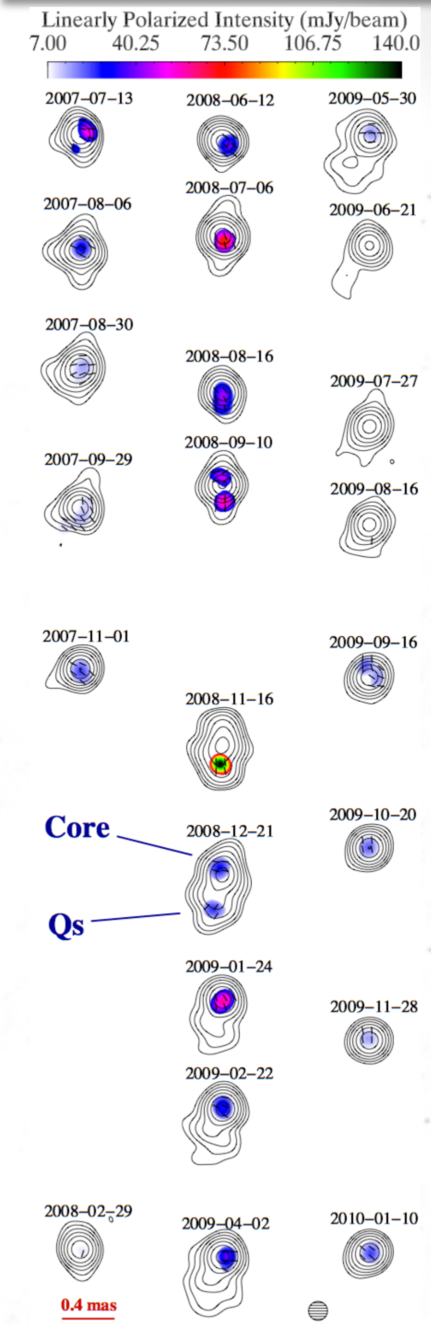
I, p & χ curves from:

7mm VLBA strong features

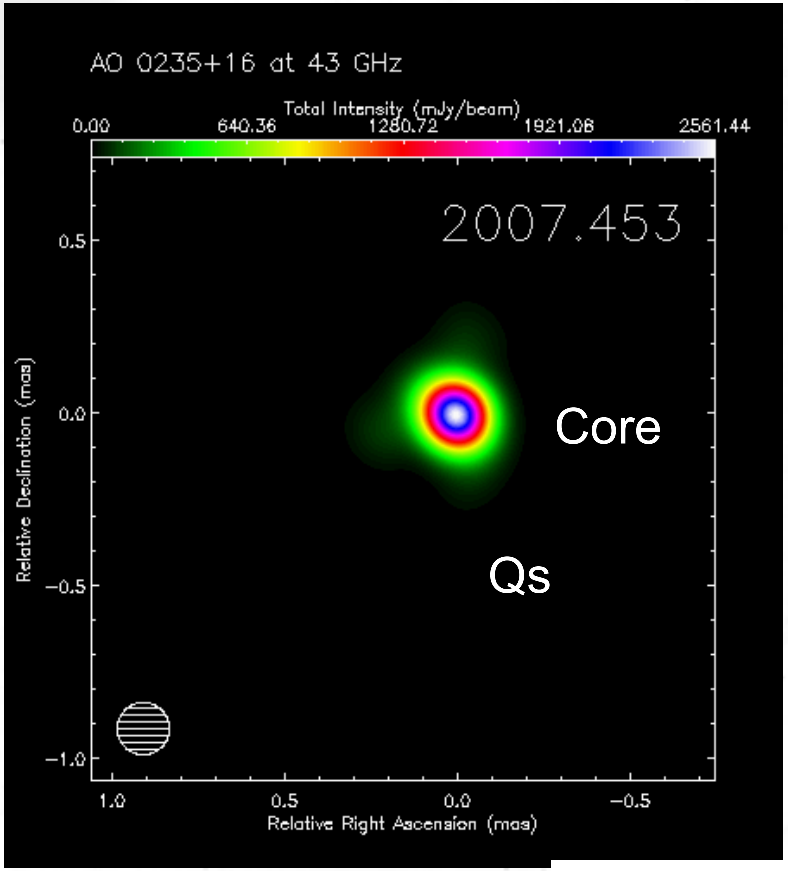
3mm IRAM 30m Tel. (from 2008)

Optical measurements from several telescopes in 3 continents

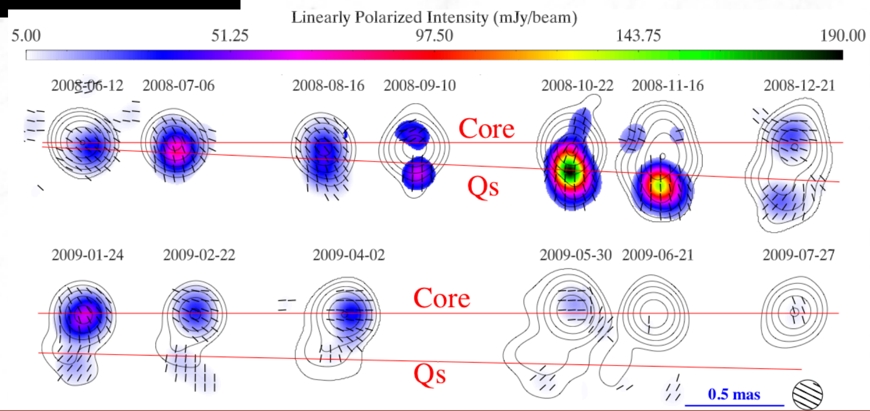
7 mm Jet Structure and Kinematics



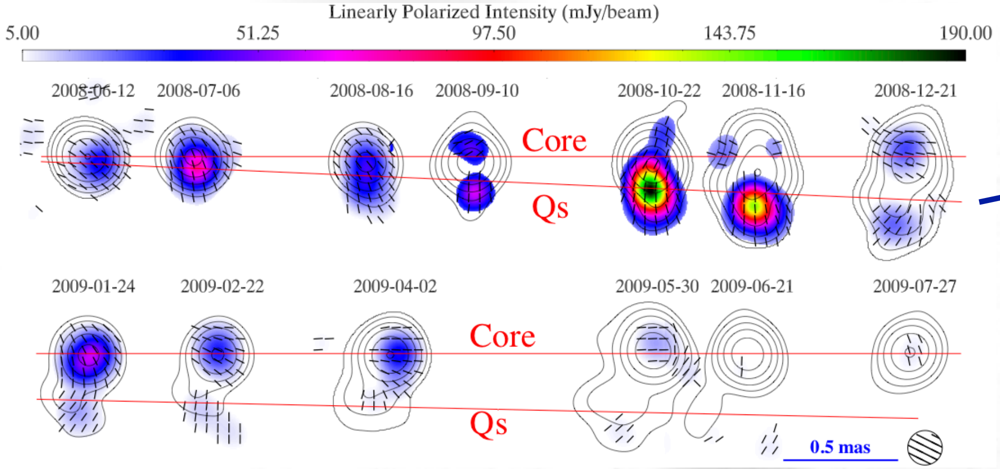
AO 0235+164 VLBA 43GHz total intensity images



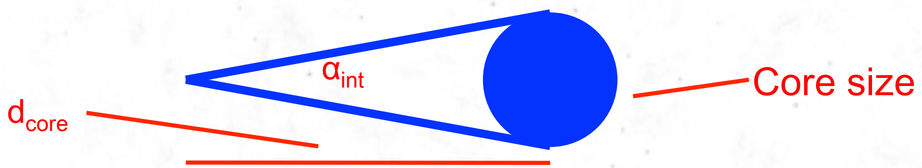
- We model the brightness distribution of every image with a small set of circular (1 or 2) Gaussian components
- Our model fits distinguish the core (brighter one) and a second bright and moving emission region (Qs).
- Qs, the brightest moving jet feature detected so far: β_{app} = (12.6 ± 1.2) c.



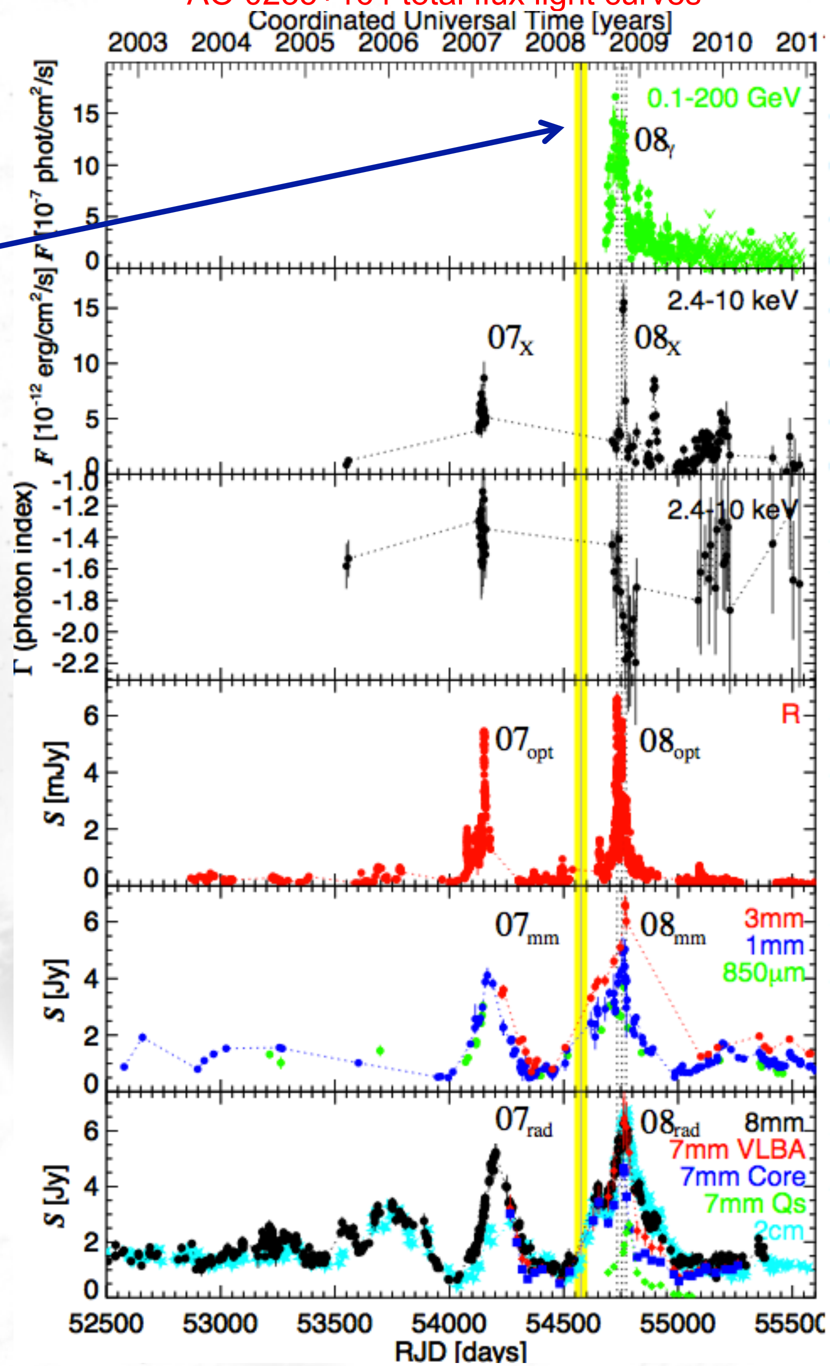
Flare in the Qs Jet Region at 1 mm and 7 mm



- Qs was ejected from the core in 2008.30 ± 0.08, at the start of the extreme radio and mm outburst
- Qs is the brighter 7mm superluminal knot ever seen in AO 0235+164, and radio/mm flares are the only outbursts after the ejection of Qs.
- The rarity of such events strongly implies that they are physically related.
- The jet half-opening-angle of 0235+164 ($\alpha_{int}/2 \leq 1.25^o$, Jorstad et al. 2001; Piner et al. 2006) and the FWHM of the core measured from our 31 VLBA images (0.054 ± 0.018 mas) give $d_{core} \geq 12$ pc from the vertex of the jet cone

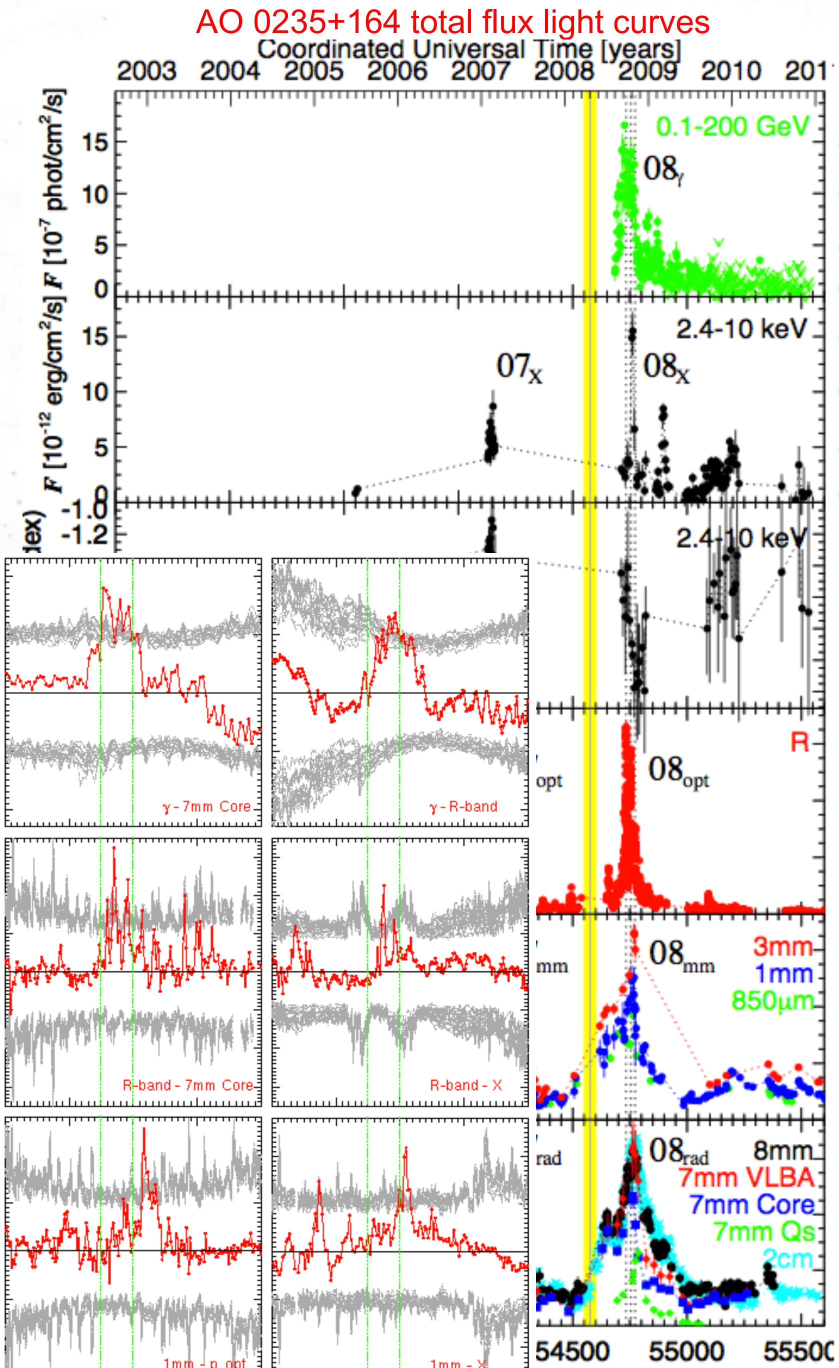


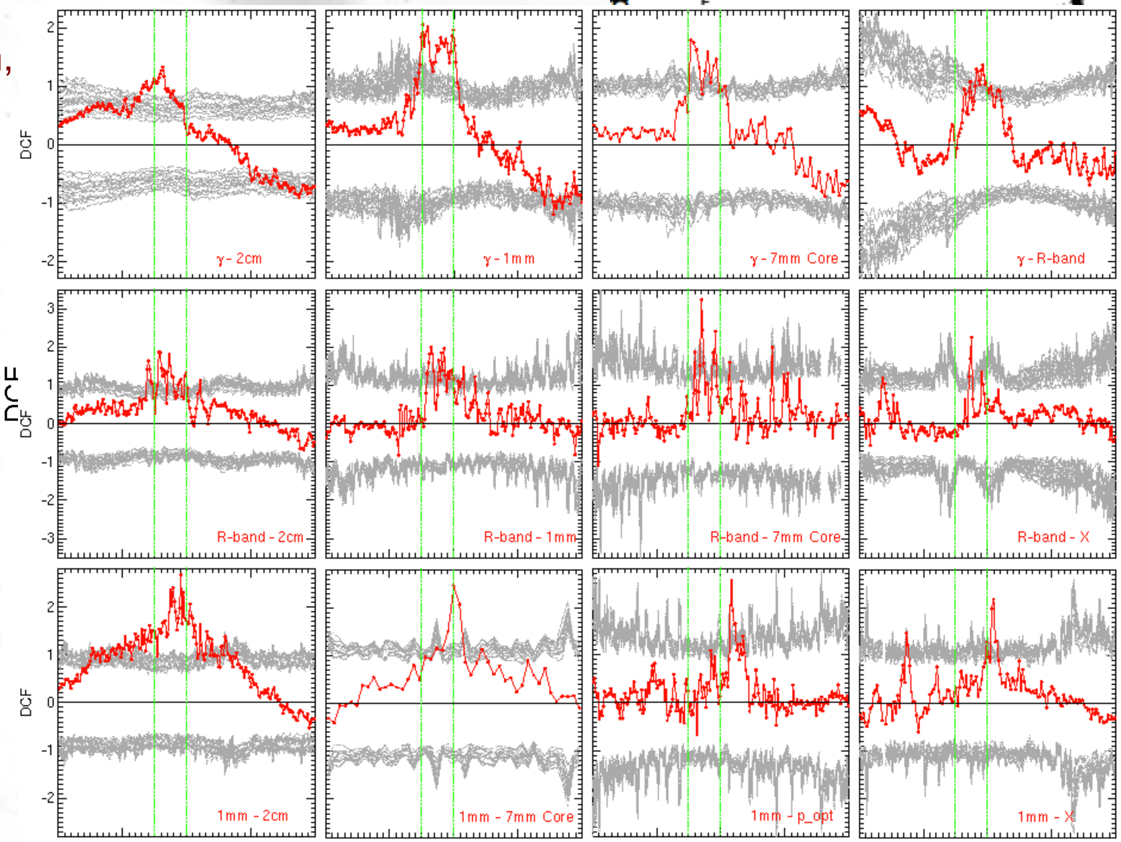
AO 0235+164 total flux light curves



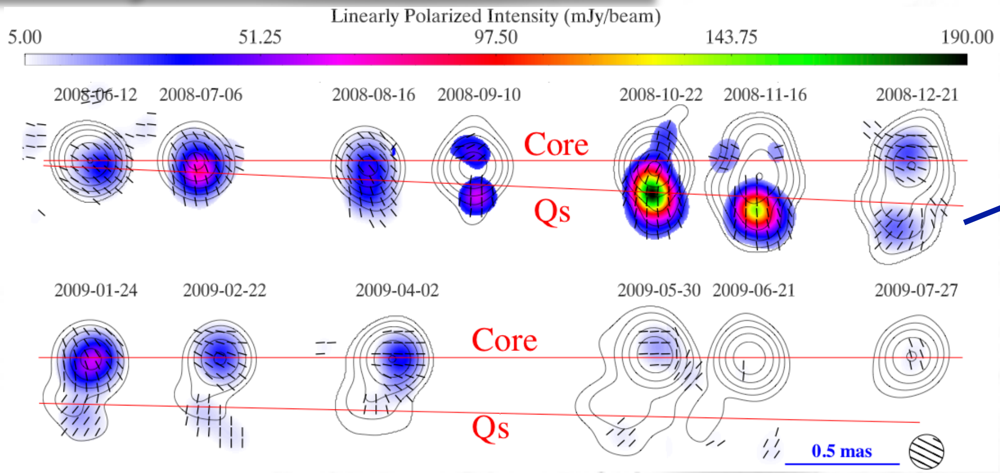
γ-ray Flares

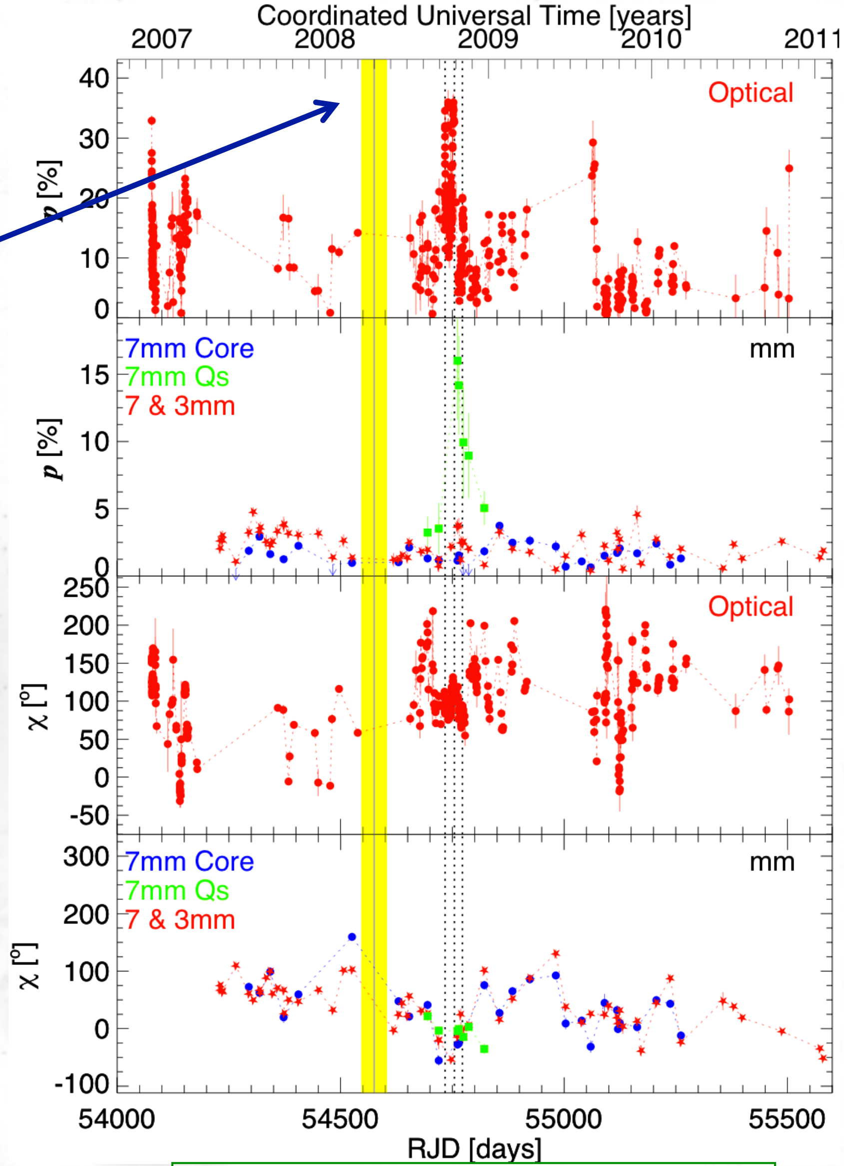
- The radio and mm flares took place during optical, X-ray, and γ -ray counterparts
- The discrete correlation function (DCF; Edelson & Krolik 1988) between the γ-ray and 1mm light curve shows a prominent peak
- Our Monte Carlo simulations of stochastic variability confirm, at 99.7% confidence, the correlation between highly luminous γ-ray and millimeter flares in 2008
- Correlation of γ-ray and 2cm, 7mm (core), optical light curves is of similarly high significance.
- As well as the correlation of the optical light curve with the one at X-rays and the optical polarization degree evolution
- Probability that a random γ-ray flare occur contemporaneously with an optical and a mm flare by chance is only 5 x10^{-4}





Variability of Linear Polarization





- Extremely high, variable optical polarization, p_{opt}~35%, during the sharp optical and γ-ray flares
- The mm and 7mm core linear polarization remain ~5%, whereas Qs shows and extremely high linear polarization degree ~16% at about exactly the time of the optical outburst
- This gives the unambiguous confirmation for the connection and co-spatiality of all these series of events along the spectrum from γ-rays to radio wavelengths.

IA et al. (2011b, ApJL,735, L10)

- All these events have been located at (or beyond) the VLBI core, and hence the γ-ray emission should have been produced at more than 12 pc from the central black hole.

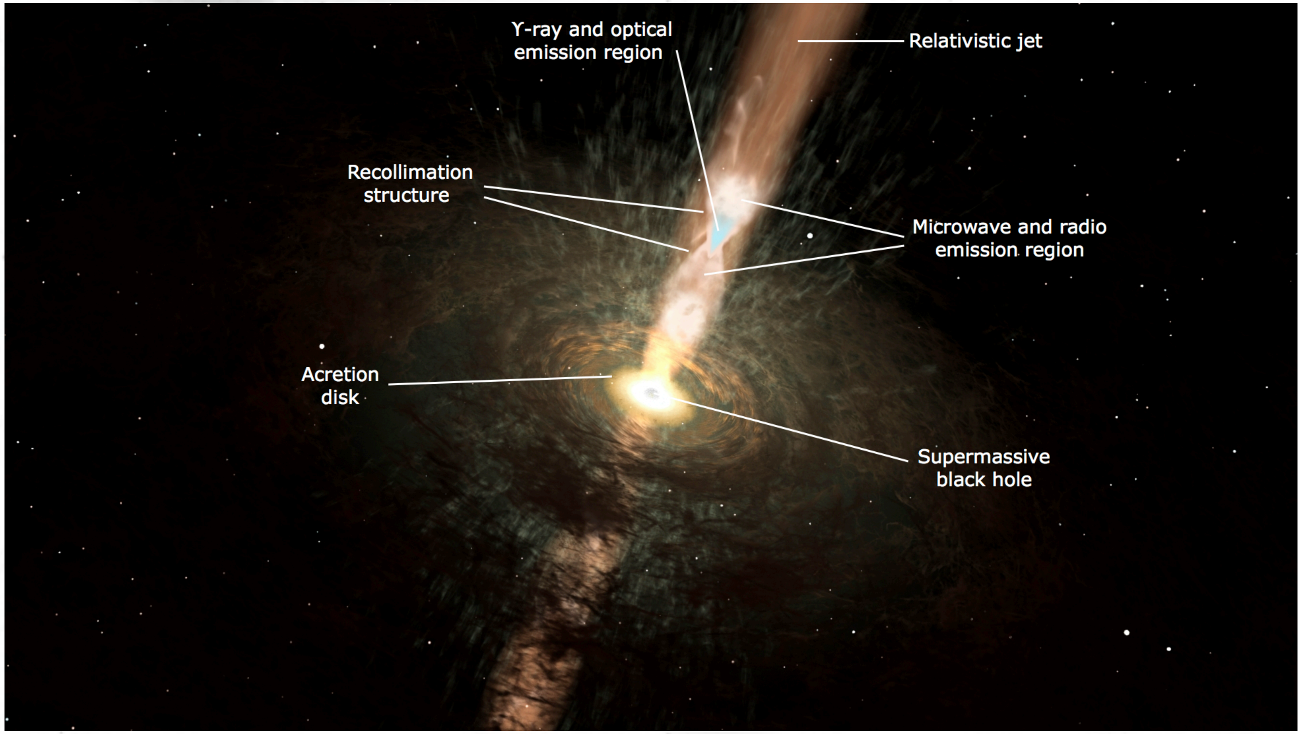
γ–ray emission consistent with SSC model

- In general, the γ-ray IC emission may arise from either the SSC process or IC scattering of optical-IR radiation from the dusty torus photon field.
- The Broad Line Region cannot be a possible source of photons (too close to the BH).
- Emission from the dusty torus has not been detected thus far in BL Lac objects such as AO 0235+164,
- Which allow us to propose the SSC mechanism (seed synchroton photons from the jet itself) for this source

Proposed model for the multi spectral-range emission

AO 0235+164: IA et al. (2011b, ApJL,735, L10)

- Scenario where radio, mm, optical flares produced at the 7mm core (conical shock) by particle acc in a moving blob (Qs) when it crosses a standing shock. Qs also contributes to flares
- Shortly after, γ-ray flares are produced by inverse Compton scattering of these optical-IR photons (SSC)
- The multi spectral range variability properties of AO 0235+164 cannot be easily explained by the External Compton (EC) scenario, hence further favoring the SSC mechanism



The case of BL Lac object OJ287

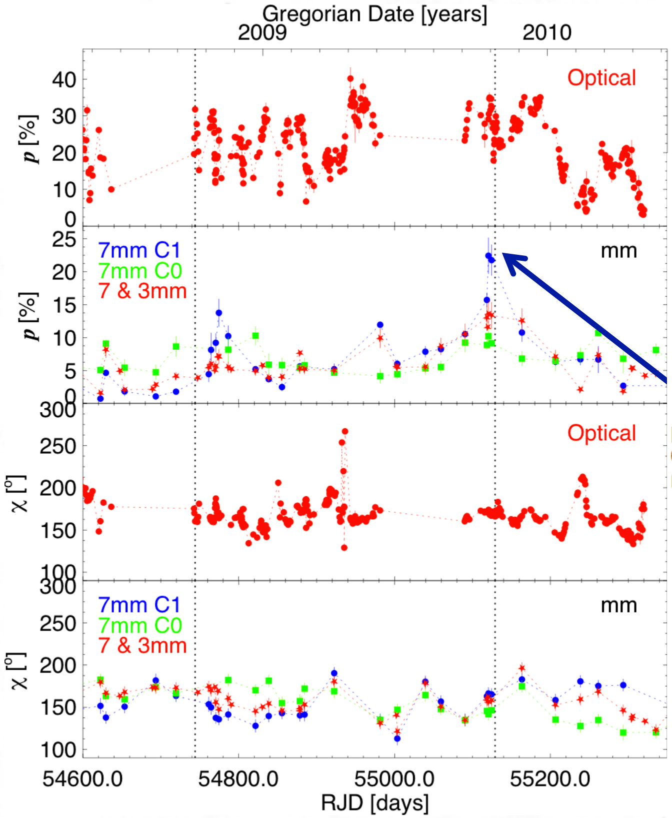
IA et al. (2011a, ApJL,726, L13)

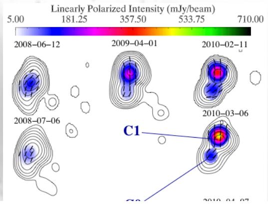
- Two kinds of events in the mm range are related at high confidence to the reported γ-ray outbursts (A_γ and B_γ).:

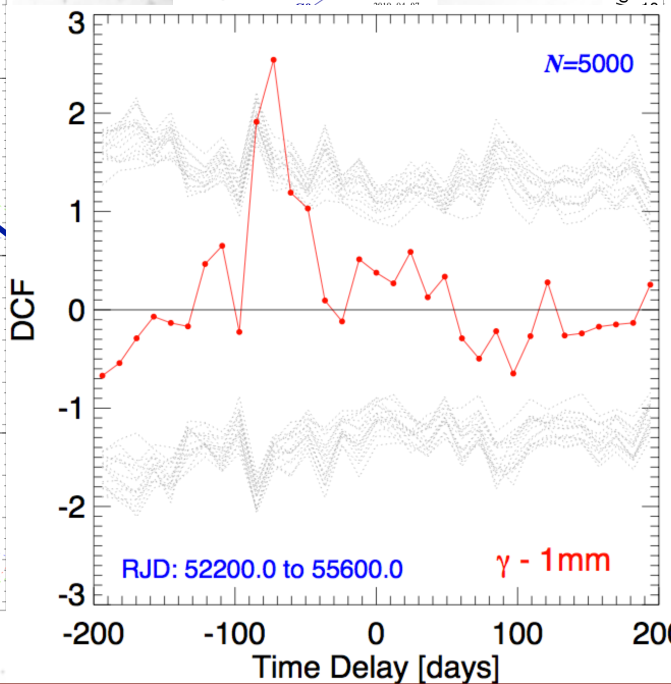
  (1) The early rising phases of the two most luminous 1mm flares ever detected in OJ287 (A_{mm} and B_{mm})

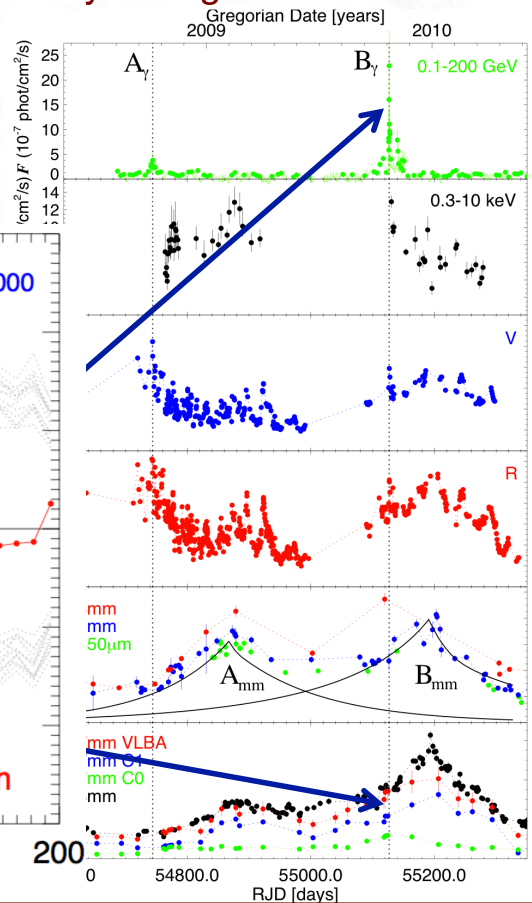
  (2) The two sharp increases to unprecedented levels of linear polarization (~14% and ~22%) in bright jet feature C1 <u>> 14 pc from the central engine.</u>

- The exceptionally high polarization of C1 during γ-ray flare B_γ provides extremely strong evidence that the event occurred in C1.









Common conclusions for the cases of AO 0235+164 and OJ287

- In contrast to other models assuming γ-ray emission to come from <<1pc from the central AGN engine,
- γ–ray flares have been located >12pc from the BH ***for the case of BL Lac object AO 0235+164 & OJ287***
- These results are not essentially based on a particular emission model. They come from the analysis of observational data, and hence they represent a robust evidence in favor of the FAR ZONE γ-ray emission scenario
- γ–ray flares are difficult to reproduce in the EC(dust, BLR, disc) models. We favor the SSC mechanism.