Fermi-LAT observations of Misaligned AGN

: Towards AGN Unification

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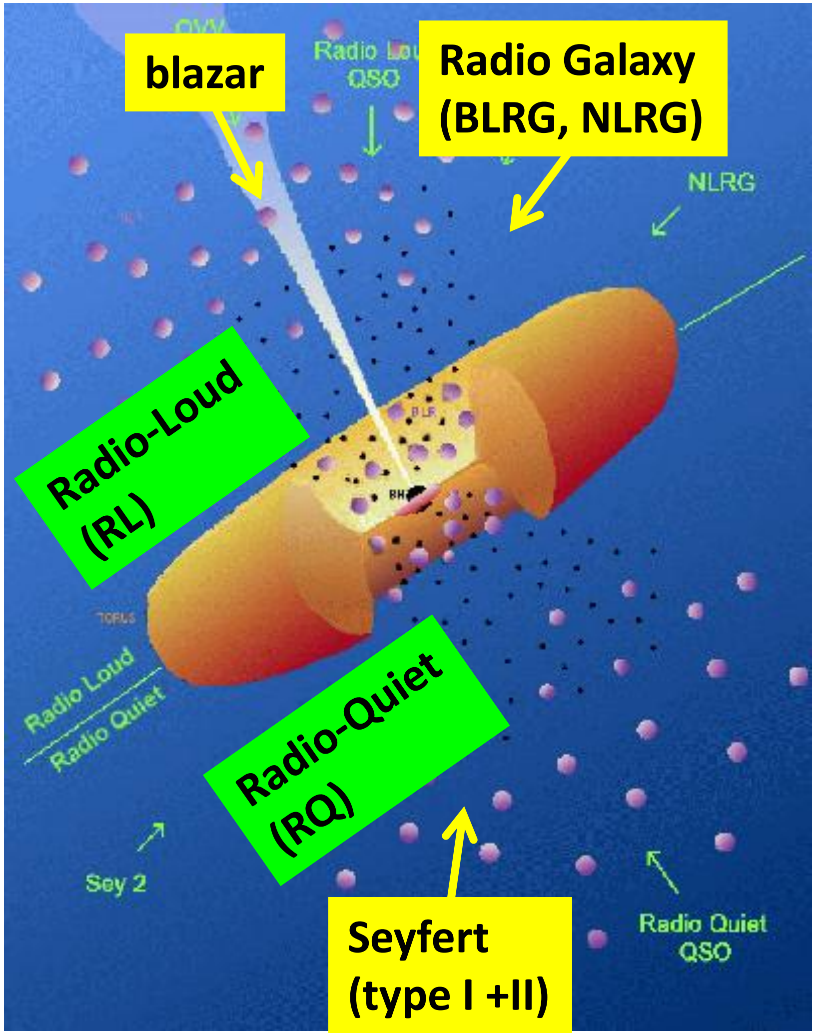
Special thanks to: **L.Stawarz, C.C.Cheung, B.Lott**,
On behalf of the Fermi-LAT collaboration

Outline

- Introduction
  - 2FGL catalog and AGN statistics
- Misaligned AGN
  - Radio Galaxies
  - Radio Lobes
  - Galactic Bubble
  - BLRGs and Seyferts - towards AGN unification
- Summary

AGN: unified view



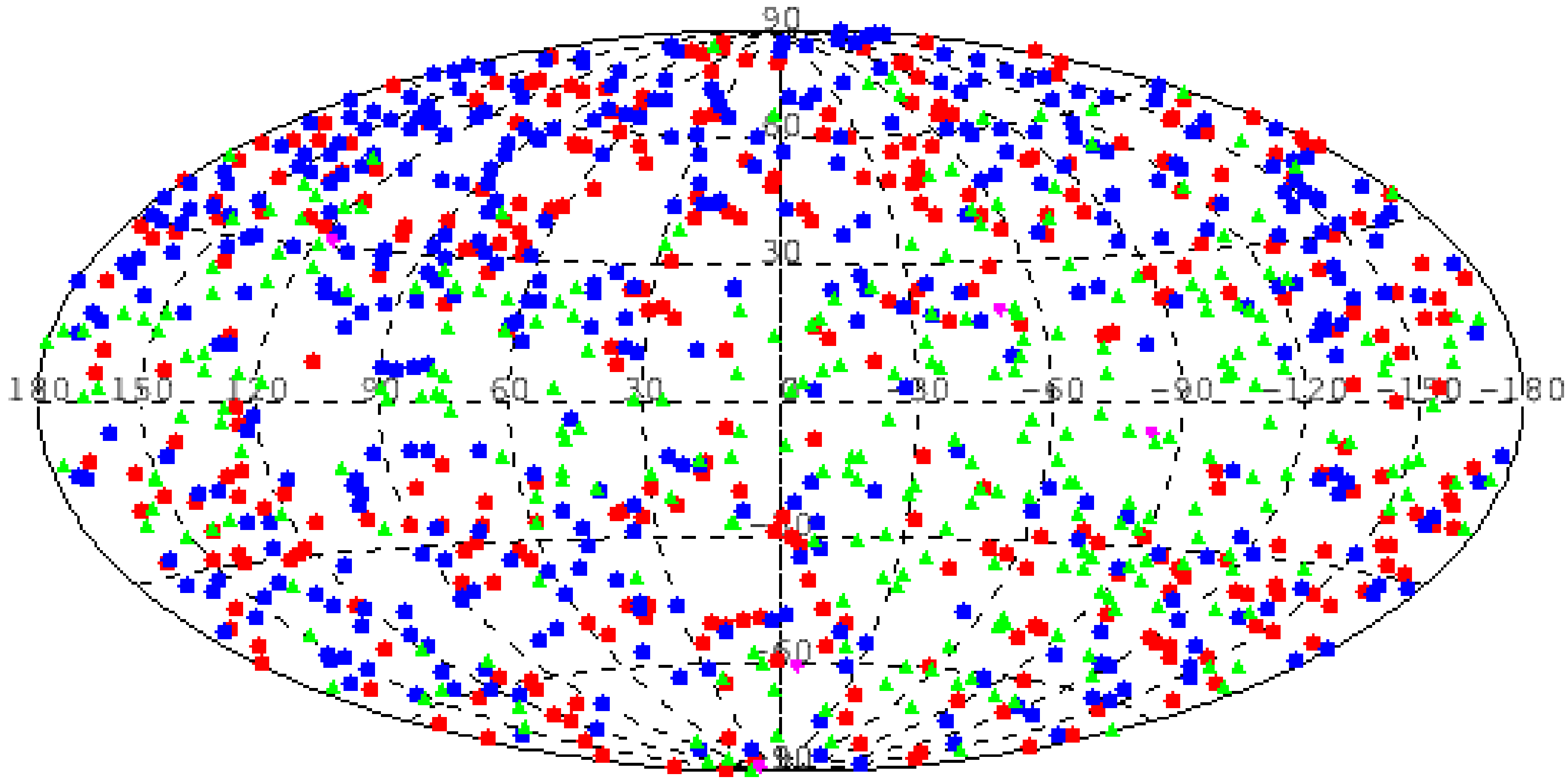
Urry & Padovani 1995 for a review

Osterbrock 1989; for local universe

- **Quasars** (~10^{-7} Mpc^{-3})
  - Radio-quiet or radio-loud quasars
- **BL Lacertae Objects** (~10^{-7} Mpc^{-3})
- **Radio Galaxies** (~10^{-6} Mpc^{-3})
  - Broad or narrow line radio galaxies (BLRGs, NLRGs)
  - Fanaroff-Riley class I or II

    … many more…
- **Seyfert Galaxies** (~10^{-4} Mpc^{-3})
  - Seyferts type 1 - 2
  - Narrow-Line Seyferts
- **Low-Luminosity AGN** (>10^{-3} Mpc^{-3})
  - Low-Ionization Nuclear Emission-Line Region Galaxies
  - "Regular" spiral like Sgr A*…

2nd LAT AGN Catalog - "2LAC"

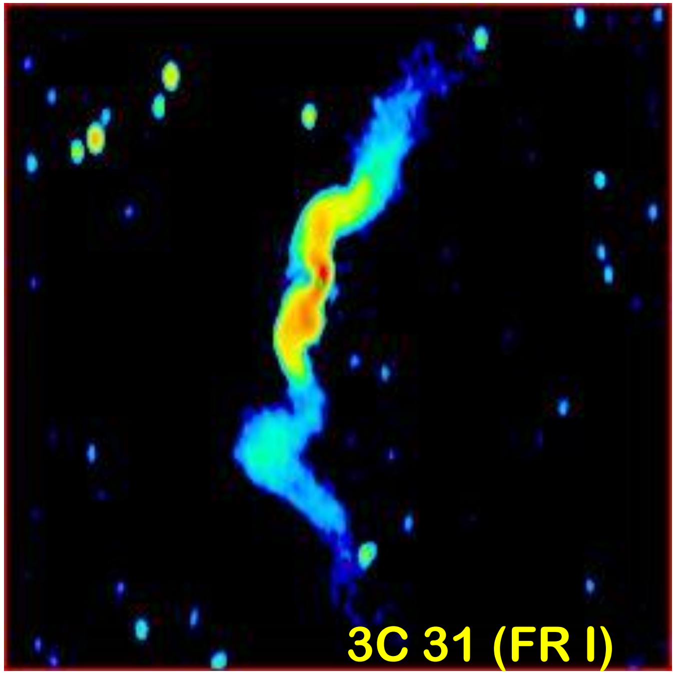


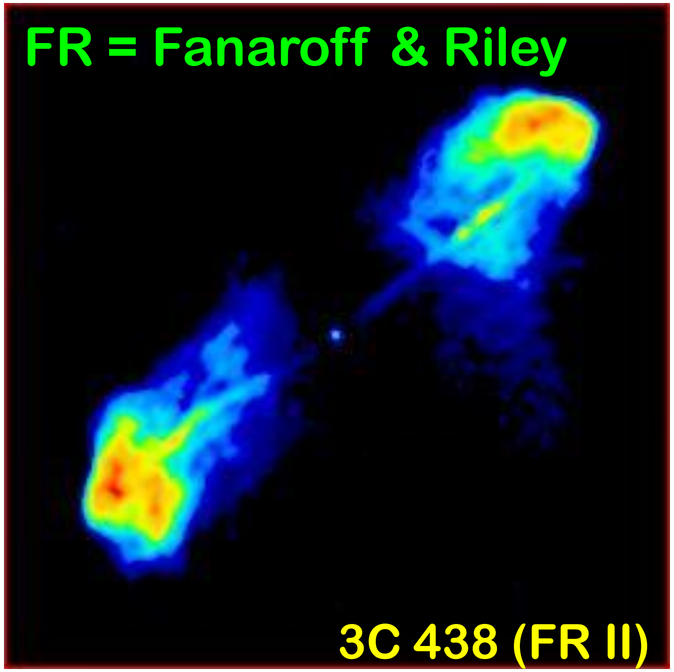
- 24 month data set
- 1749 TS>25, |b|>10° sources
- 2LAC:
- ~950 associated (P_{assoc}>80%) AGNs

Census:

- 360 FSRQs
- 420 BL Lacs (~ 60% w/ measured z)
- 160 of unknown type
- ~20 other AGNs, including RGs

Misaligned AGN (Radio Galaxies)





⟷ BL Lac?

- Low power ($10^{42\text{-}44}$ erg/s)
- Low Γ
- Core brightened
- Bending (ram pressure)
- Decelerating

⟷ FSRQ ?

- High power ($10^{44\text{-}46}$ erg/s)
- High Γ
- Edge brightened
- Collimated, straight jet
- Deceleration negligible?

Fermi-LAT detections of MAGN

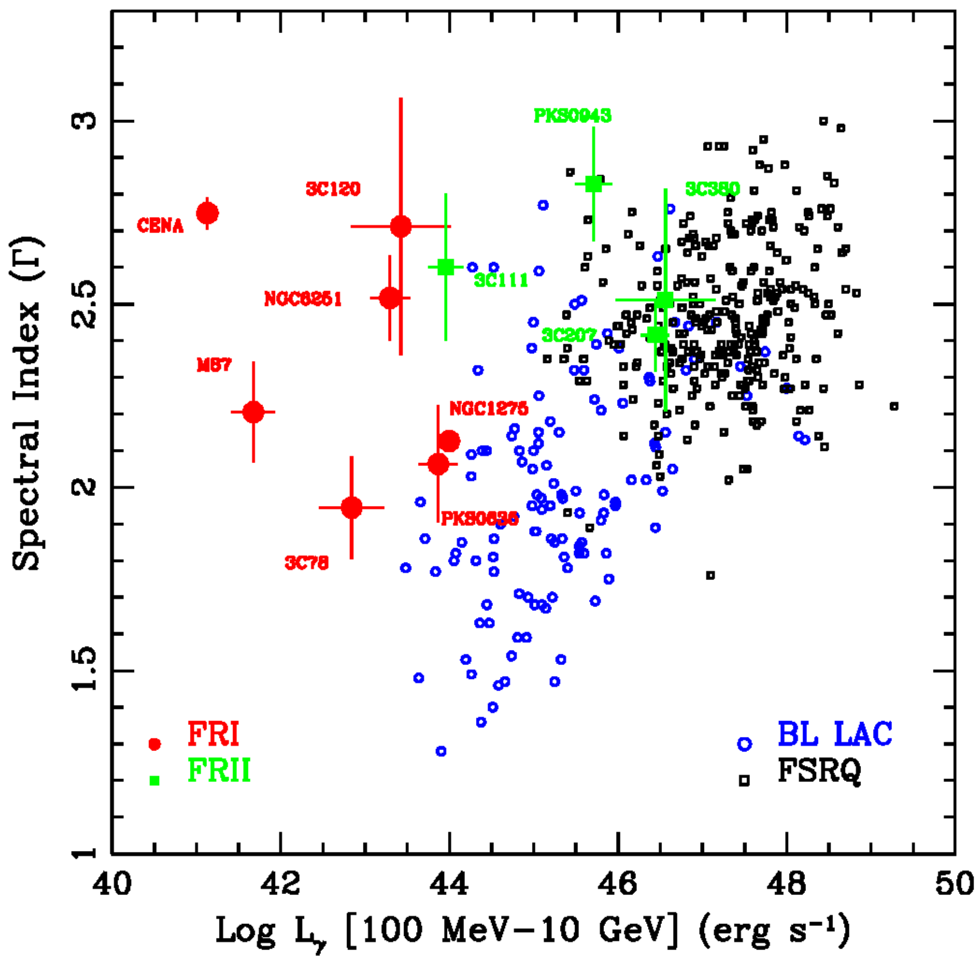
Abdo, A. A. et al. 2010, ApJ, 720, 912
(based on 15 month data)

- 7 FRI radio galaxies
- 4 FRII radio sources
  (2RGs and 2 SSRQs)

- MAGN less luminous than blazars consistent w/ the Unified Model

- FRI RGs distinct from BLLacs in the (L_{γ}, Γ) plan

- 4 Radio-Loud Narrow-Line Seyfert 1 (NLSy1)



+ Fornax A and Cen B (2FGL; preliminary)

Gamma-ray Radio Galaxies

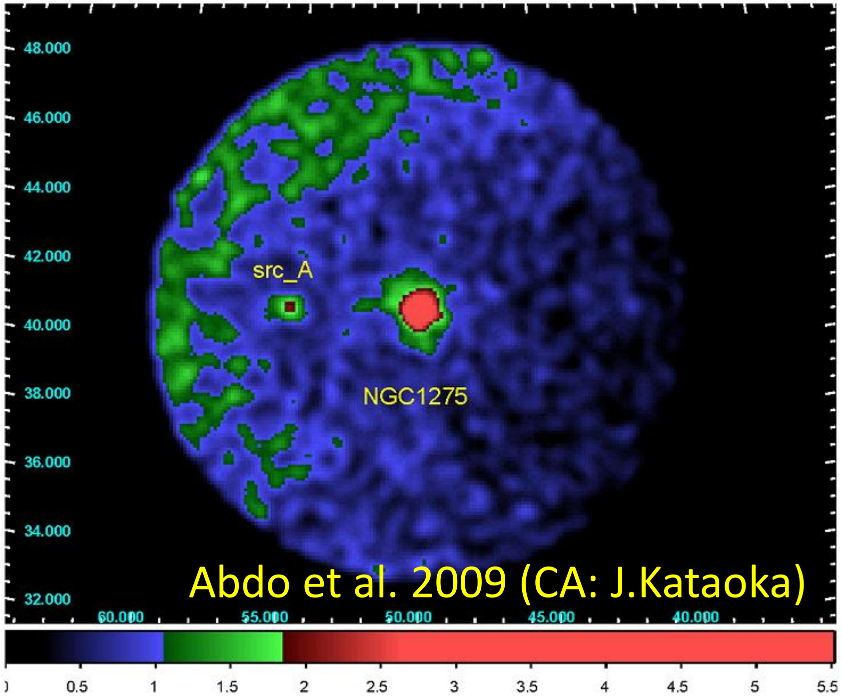
LAT provides precise γ-ray localizations, *radii* (95%) ~ 1.5 – 5' (vs. ~30' in EGRET) correspond to ~5-25 kpc for sources within 100 Mpc

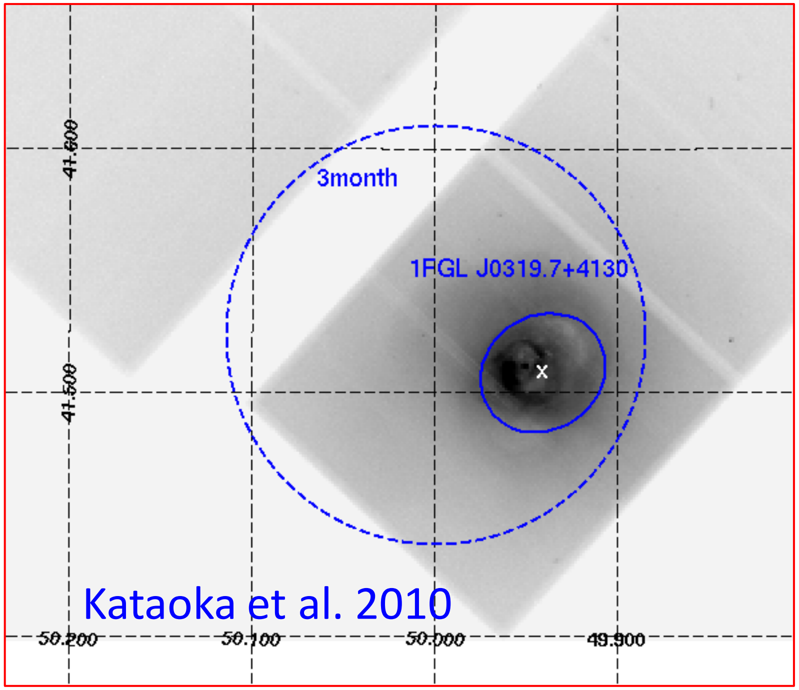
Name	D/Mpc	MeV/GeV Detection	VHE?	Note
Cen A	3.7	EGRET, LAT 2010	yes	Lobes
M87	16	LAT 2009	yes	TeV Var
Fornax A	18	LAT 2011		Preliminary
Cen B	56	LAT 2011		Preliminary
Per A	75	LAT 2009 (COS-B?)	yes**	Variable GeV + TeV
IC310	80	LAT 2010 (Neronov+)	yes	Head-tail, TeV Var?**
NGC6251	106	EGRET, LAT 2010		
3C78	124	LAT 2010		
3C120	142	LAT 2010		BLRG*
3C111	213	EGRET, LAT 2010		BLRG*

FR I > FR II

* See, Kataoka et al, 2011

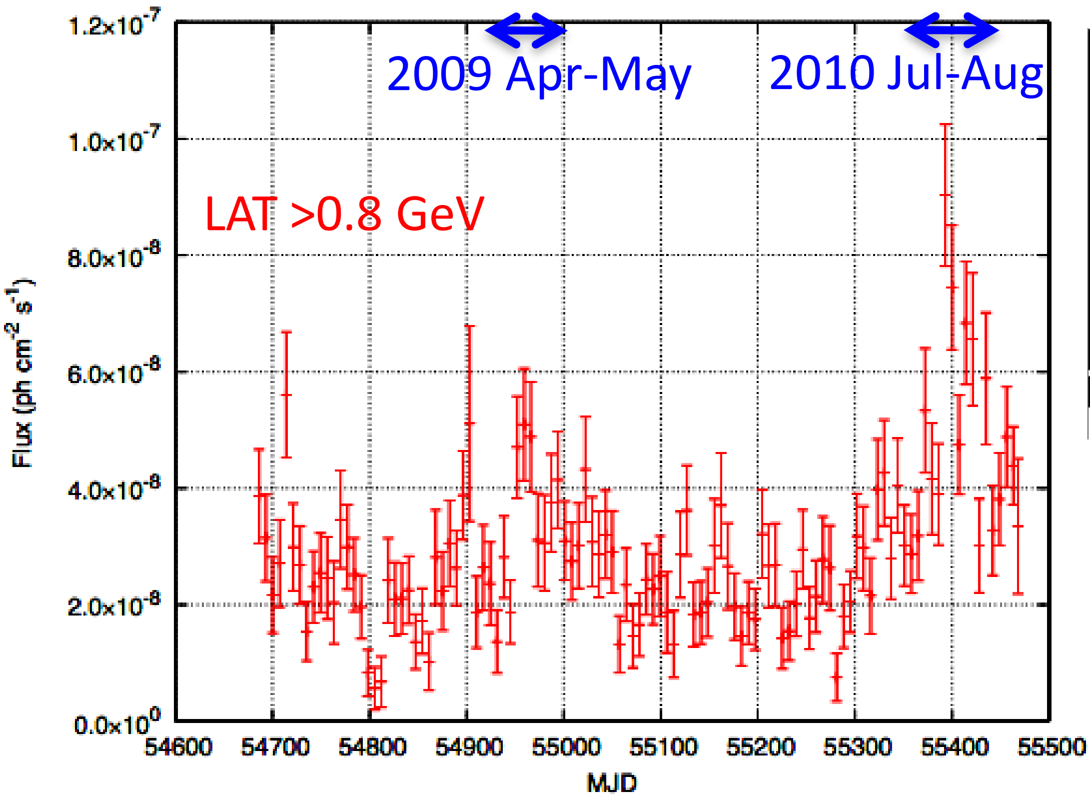
First “big” Surprise: NGC 1275



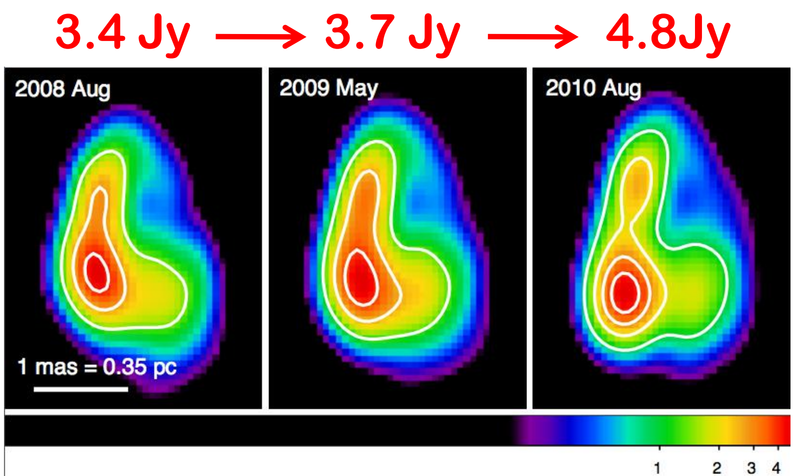


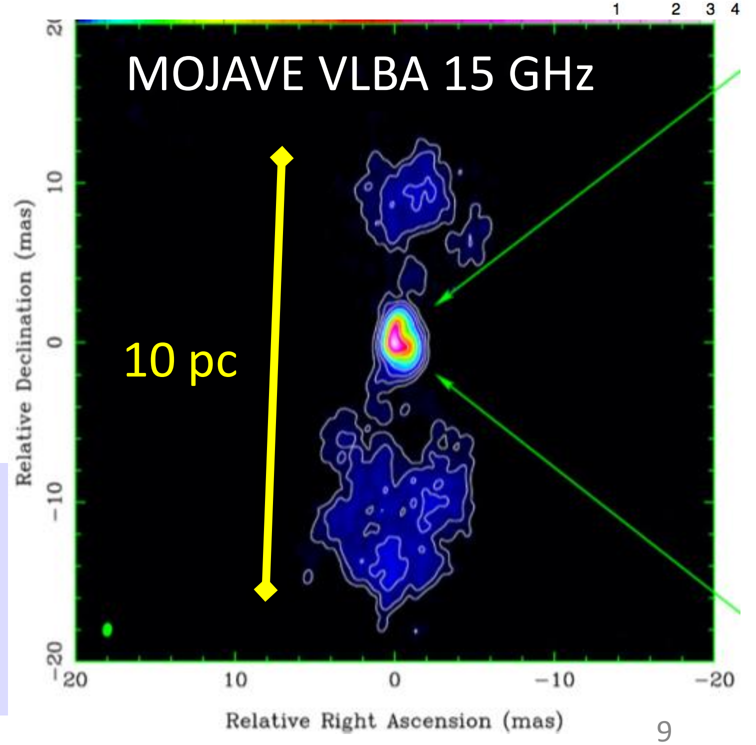
- Clear γ-ray excess exactly at the position of FR I radio galaxy 3C84 at the center of NGC 1275 in Perseus Cluster
- About an order of magnitude brighter than EGRET UL
  – significant brightening on decade time scale
- γ-rays comes from 3C84, not from Perseus cluster

NGC 1275: Variability



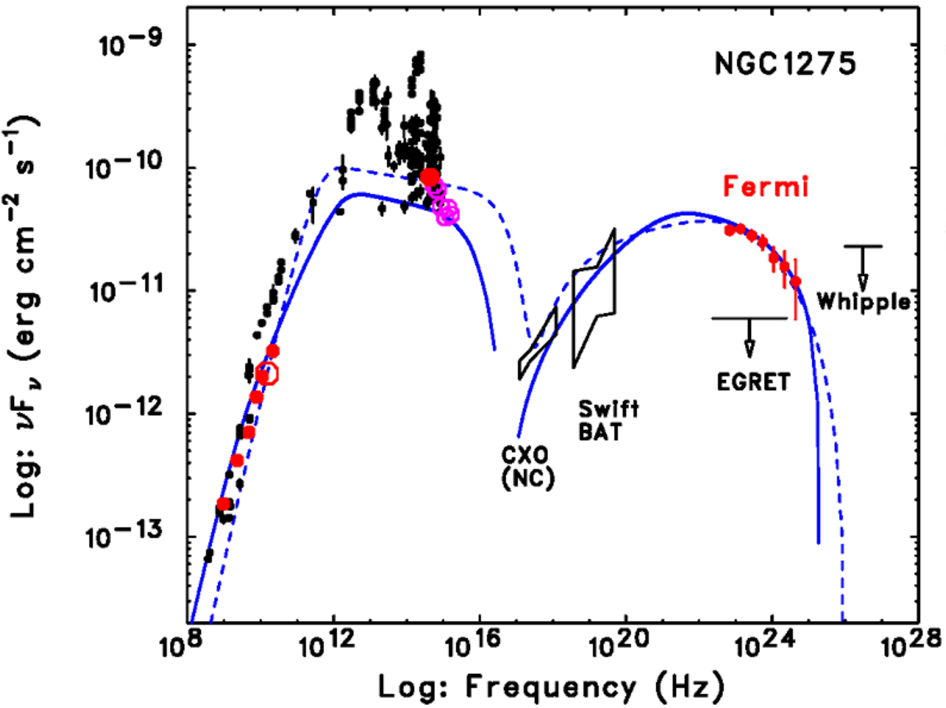
Brown & Adams 2011

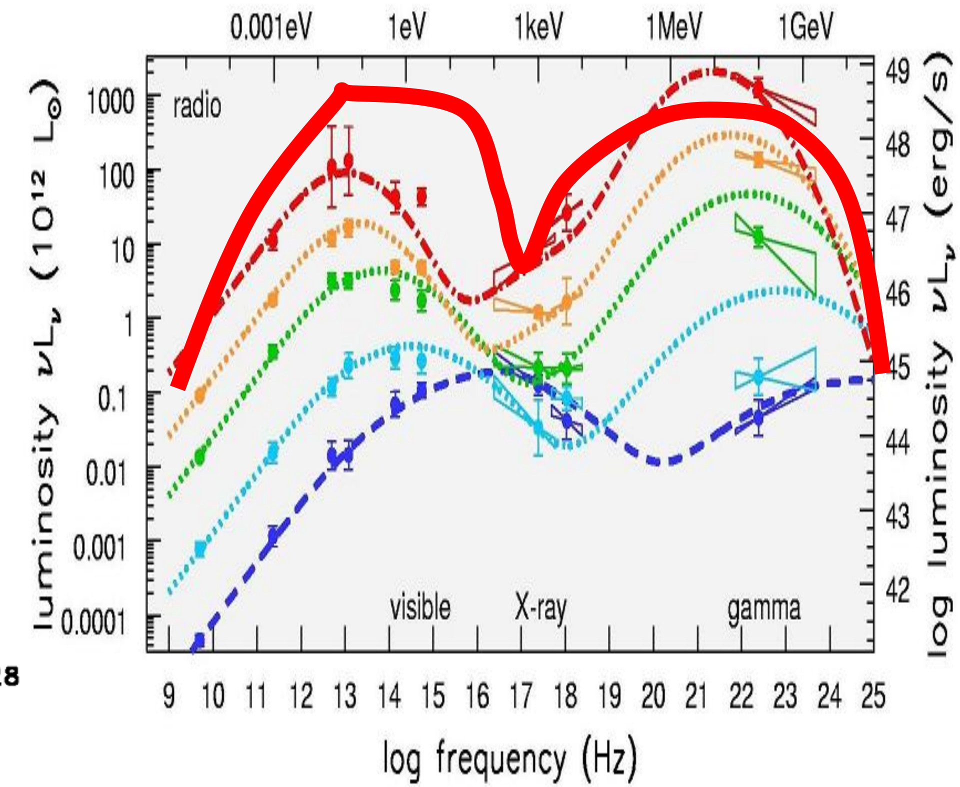




- **Flaring in 2009 with >GeV hardening** (Kataoka et al. 2010)
- **Brighter flare in 2010** (Donato+ Atel 2737) **with VHE detection by MAGIC (in prep)**

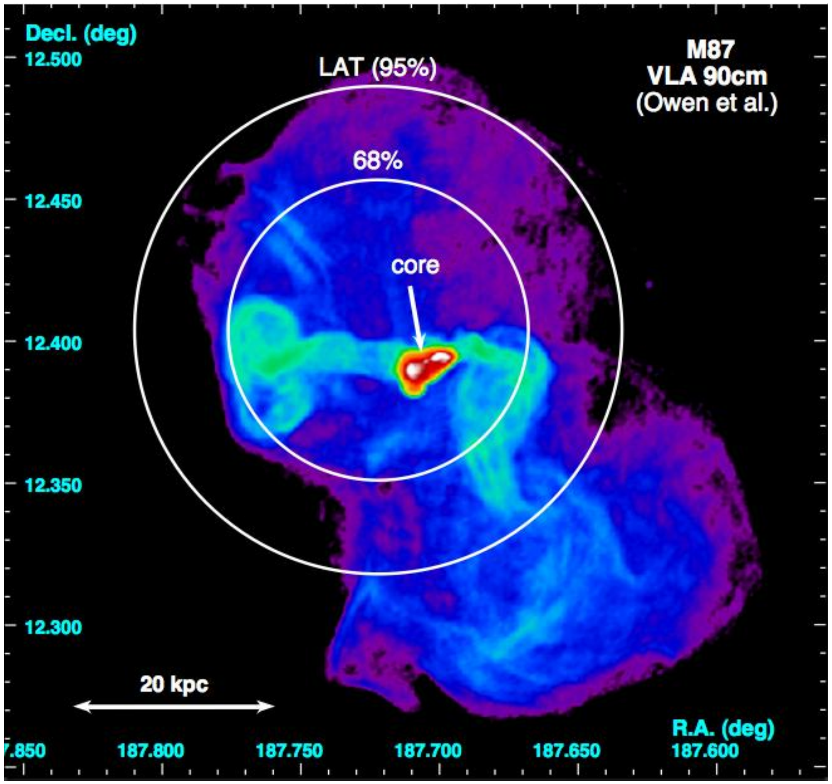
NGC 1275: SED



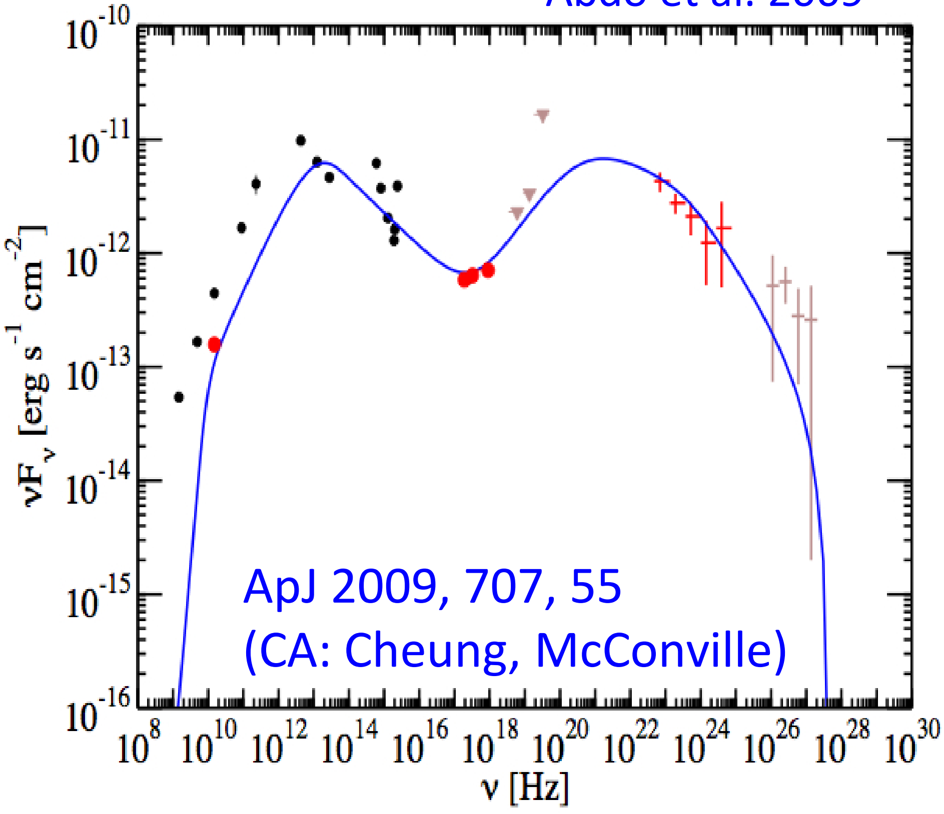


- One zone SSC fit the data, but $\delta \sim$ 2-3 (viz $\delta \sim$10 for blazars)
- Jet power close to the power required to inflate the lobes against the pressure of the hot cluster gas : (0.3-1.2)x 10^{44} erg/s
- Maybe, jet emission dominated not by a "spine" ($\Gamma_j \sim 10$), but by the slower jet "boundary layers"? ($\Gamma_j \sim$ a few)

M87 nucleus: GeV-TeV connection



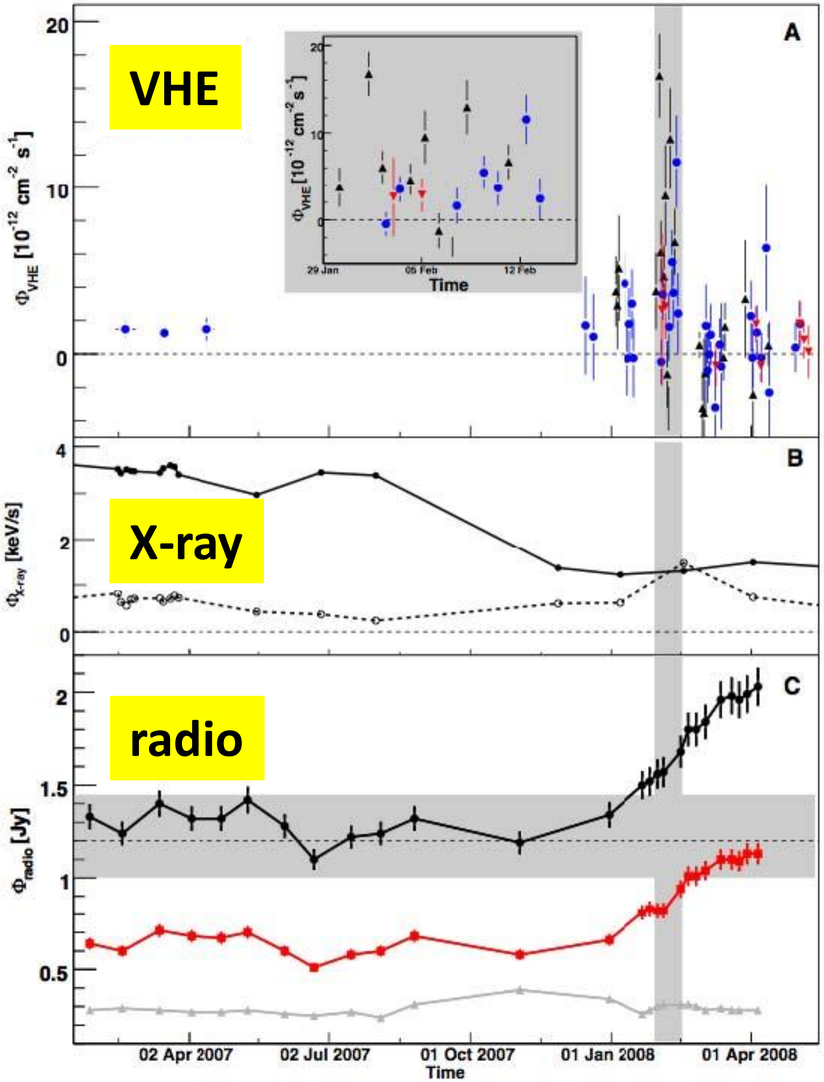
Abdo et al. 2009



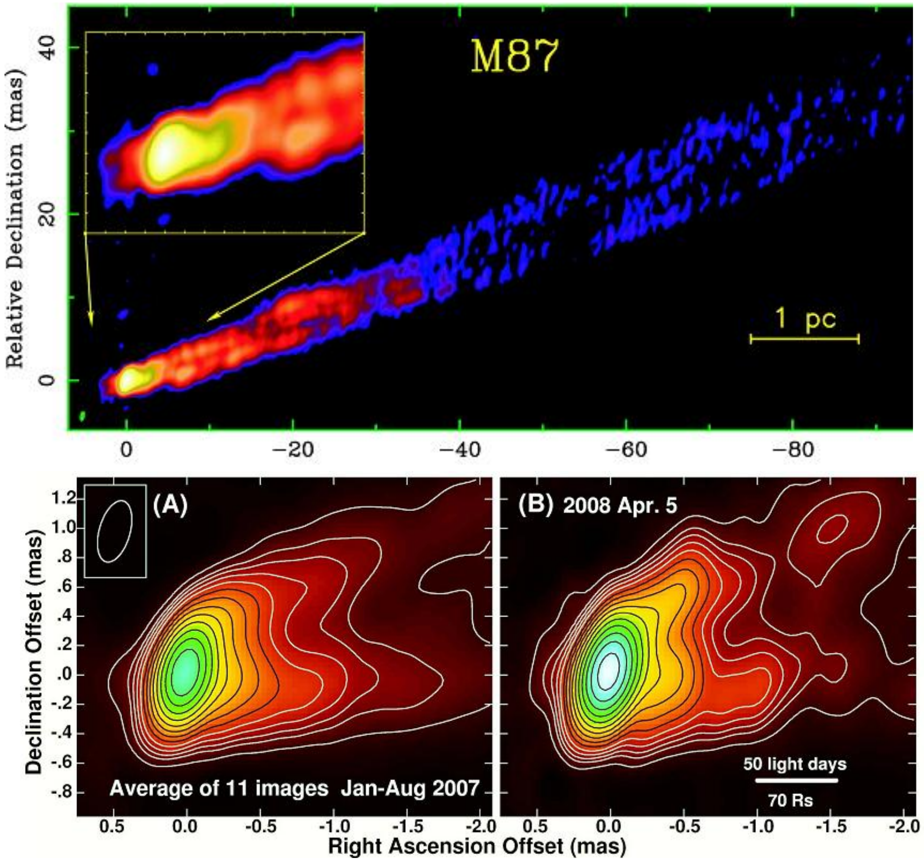
- Comparable with previous EGRET UL of 2.18×10^{-8} ph/cm^2/s
  - no significant variability on decade time scale?
- LAT spectrum smoothly connects with low-activity level of the TeV emission. Again, only mild beaming required : $\delta \sim 2 - 4$

Note: Limb-brightened jet

Kovalev+ 2007

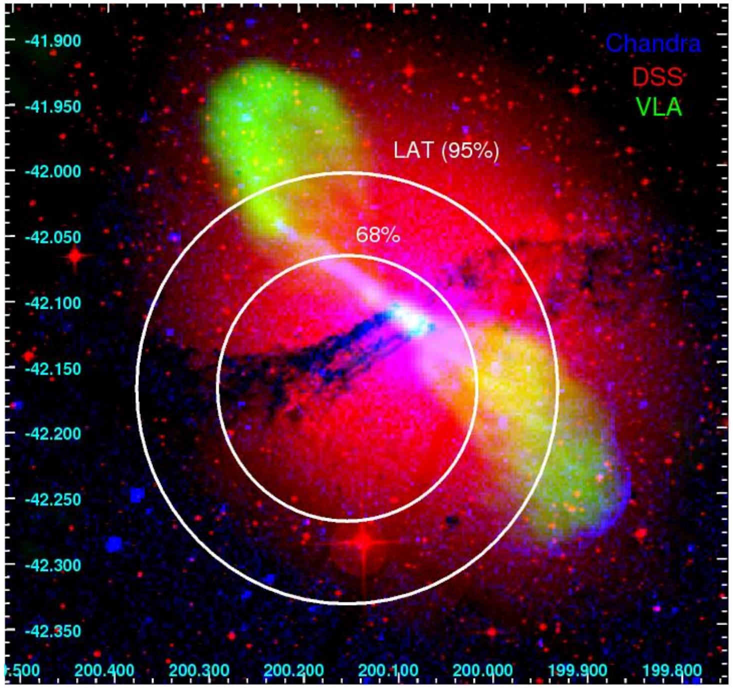


Acciari+ 2010

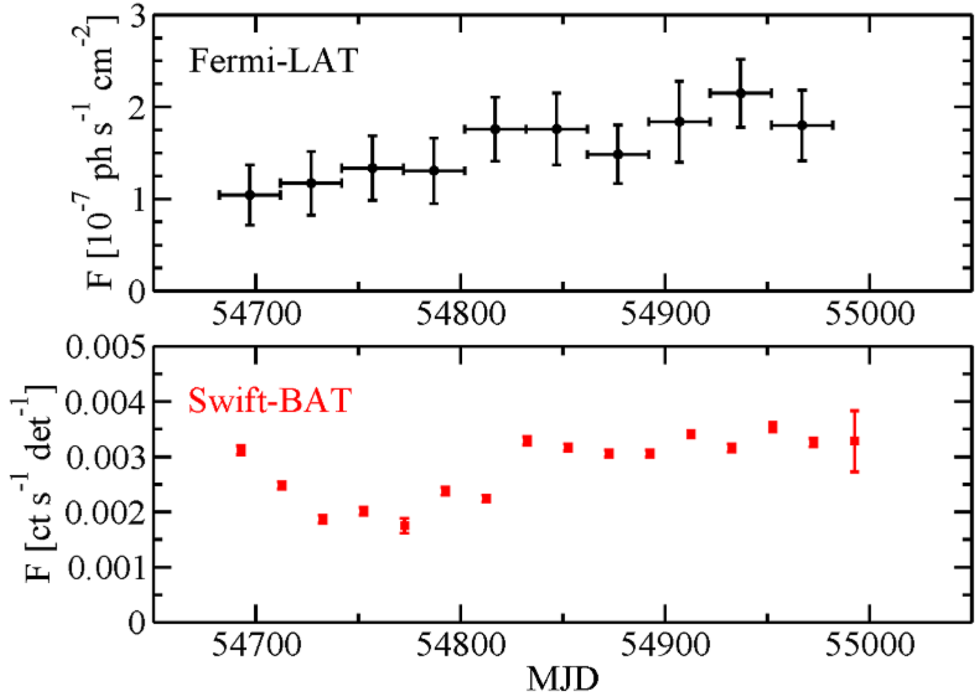


- Jet on ~100 pc scale resolved: "Limb-brightened" jet.
- Ejection of a new-radio knot triggered TeV flare?

Cen A nucleus (I)

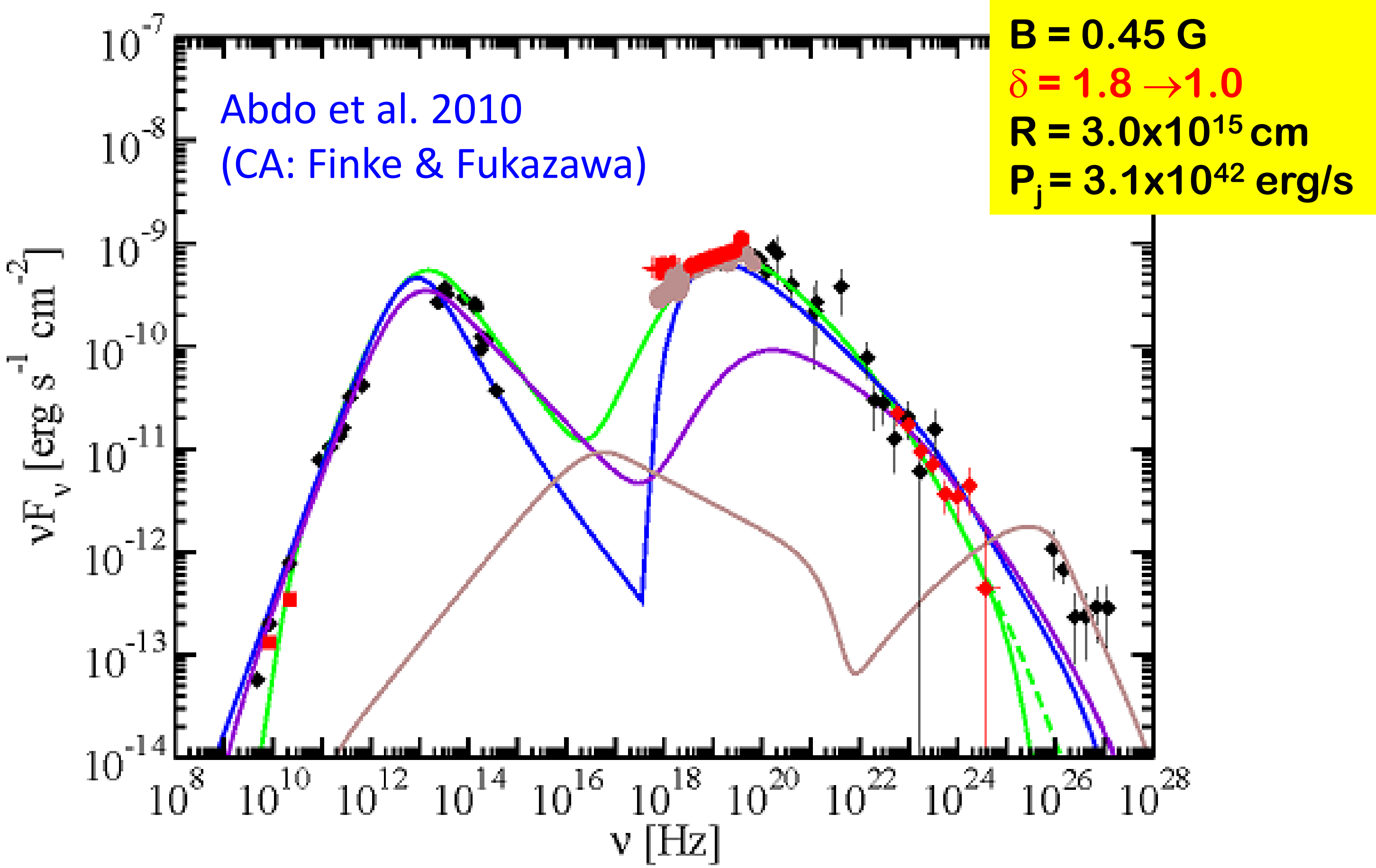


Abdo et al. 2010 (CA: Finke, Fukazawa)



- Steep LAT spectrum of $\Gamma = 2.67 \pm 0.10$, with detectable variability (apparently correlated with Swift-BAT)
- A single, one-zone SSC fit the MW data from radio to GeV, but fails to explain non-simultaneous HESS data
- γ-rays may be originated from slower portion of the jet, i.e., sheath

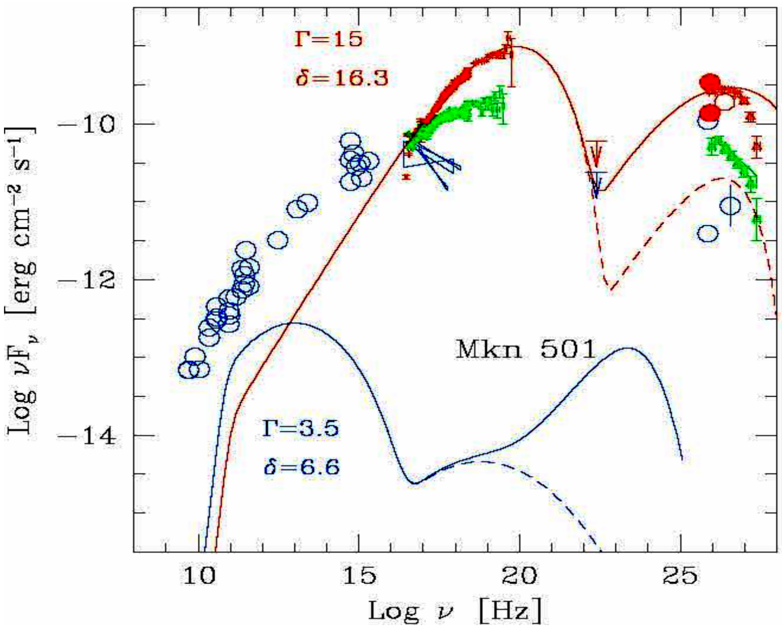
Cen A nucleus (II)

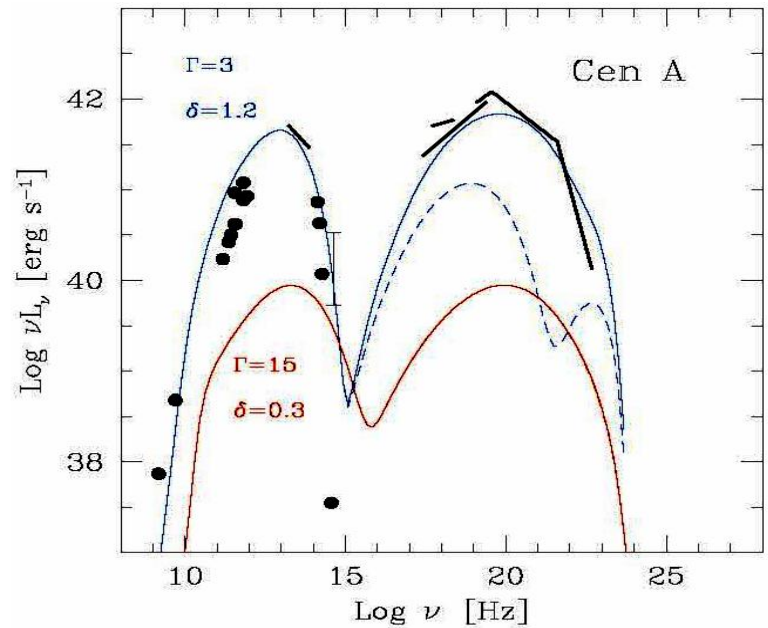


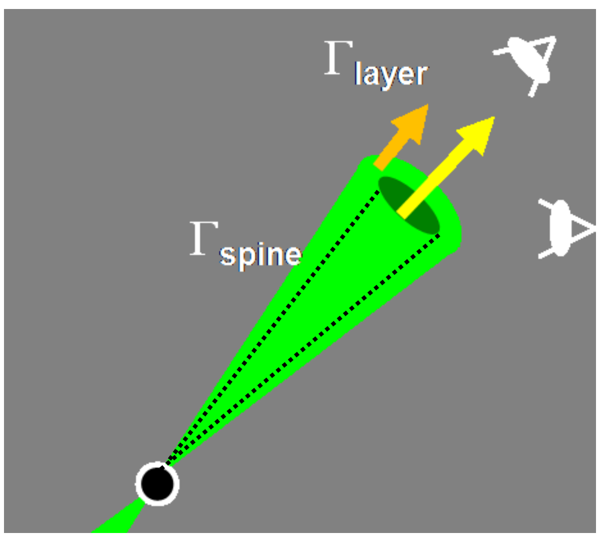
The green curve is a synchrotron/SSC fit to the entire data set. The dashed green curve shows this model without γγ attenuation. The violet curve is a similar fit but is designed to under fit the X-ray data, and the brown curve is designed to fit the HESS data while not over-producing the other data in the SED. The blue curve is the decelerating jet model fit (Georganopoulos & Kazanas 2003).

Stratified Jet?

Laing & Bridle 02, Chiaberge 00+ Ghisellini+ 05







- RGs may/should be “mis-aligned” blazars
  - low power **FR I** — **BL Lacs**
  - high power **FR II** — **FSRQs**
- SED modeling on-going

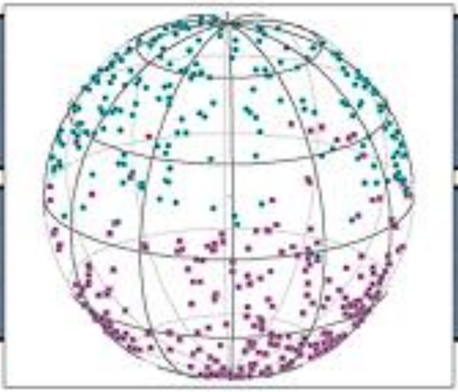
Spine dominated ….. **Blazars**
Layer dominated ….. **RGs**

FRI vs FR IIof 4 Radio Samples

© P. Grandi

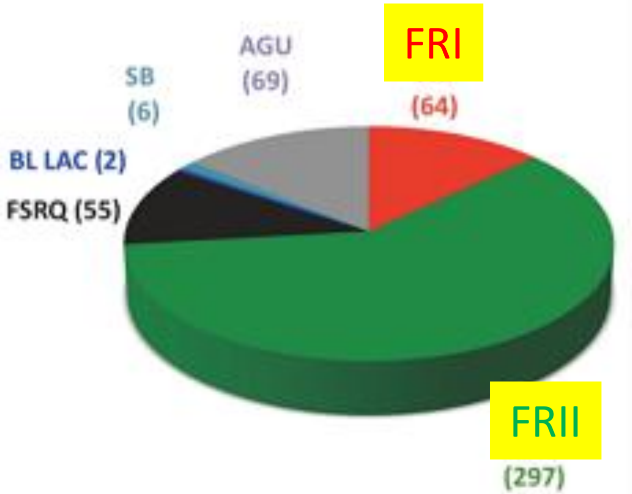
3CRR sample ν =178 MHz
F> 10.9 Jy
173 sources

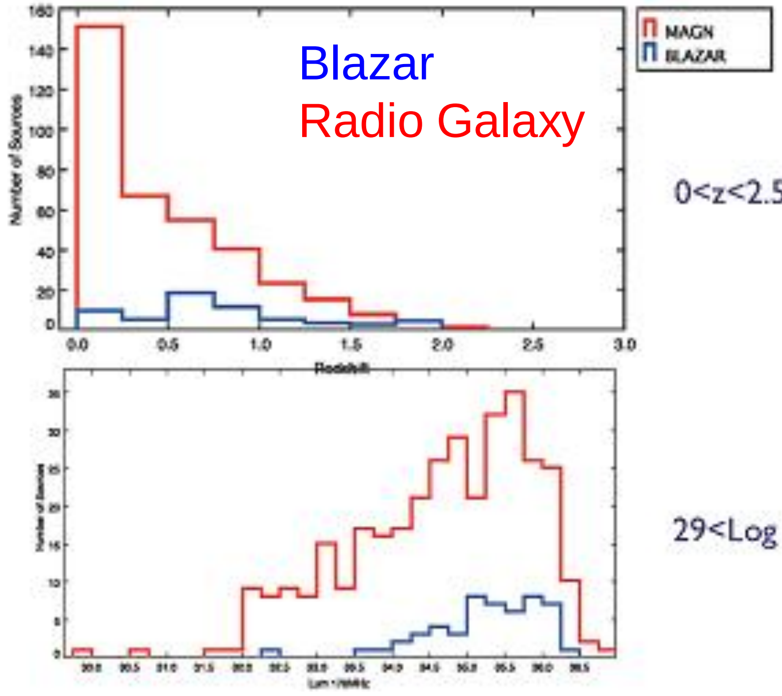
3CR sample ν =178 MHz
F> 9 Jy
113 sources



Molonglo Southern 4Jy sample MS4ν =408 MHz
F> 4 Jy
228 sources

2Jy sample declination+10° and redshift z<0.7
ν =2.7 GHz
F> 2 Jy
88 sources





0<z<2.5

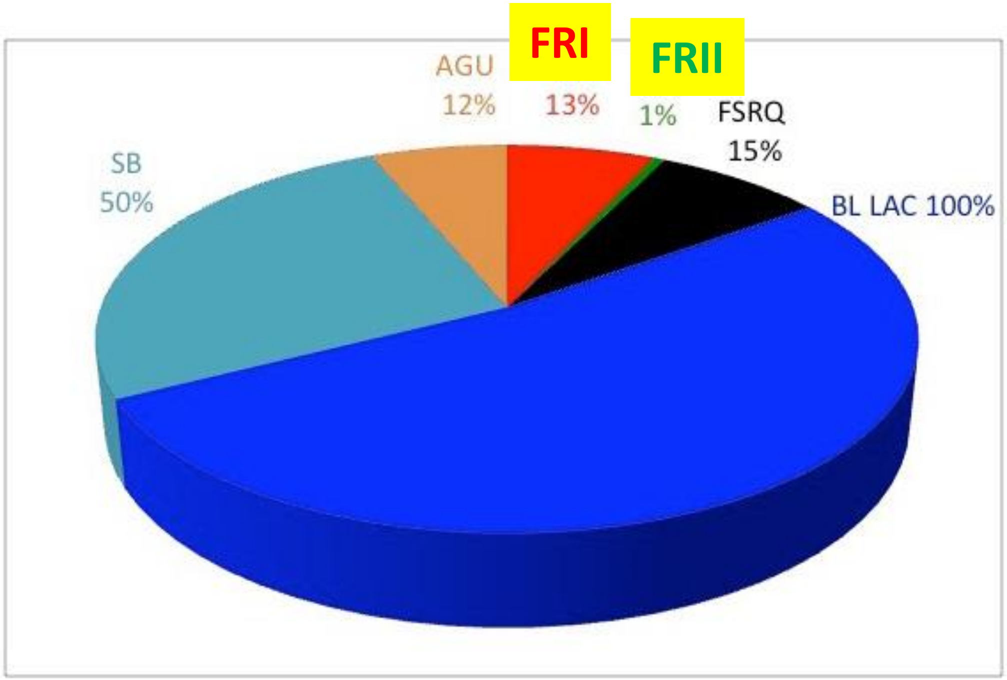
29<Log ($L_{178\ MHz}$)<37 erg s^{-1}

Rate of LAT Detected AGNs

© P. Grandi

15 and 24 months of sky survey

preliminary

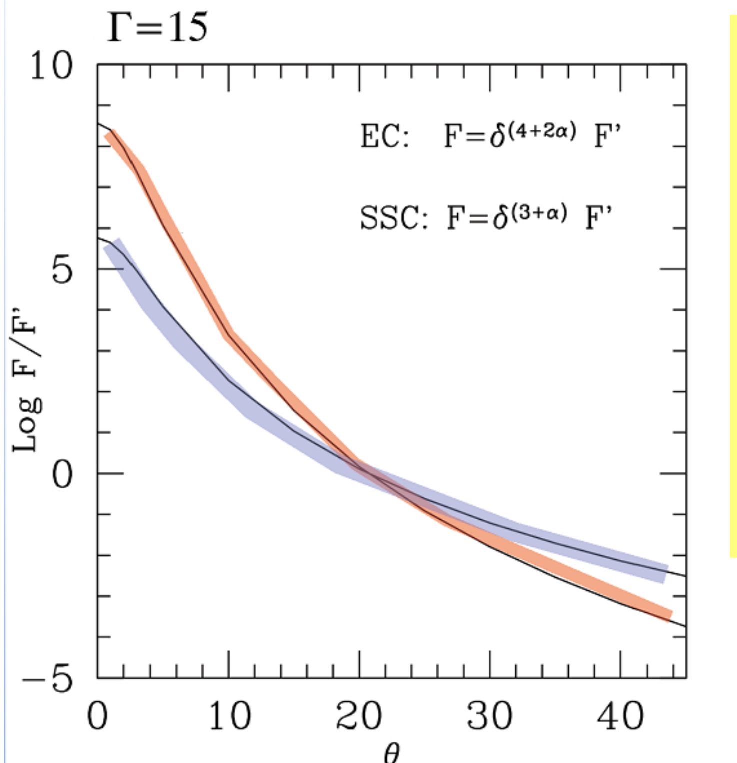


FRII are the less detected objects

The γ-ray elusiveness of FRIIs has been also confirmed by a dedicated study of Broad Line Radio Galaxies (Kataoka et al. 2011, ApJ In press)

Stratified Jet – FR I and FR II

© P. Grandi

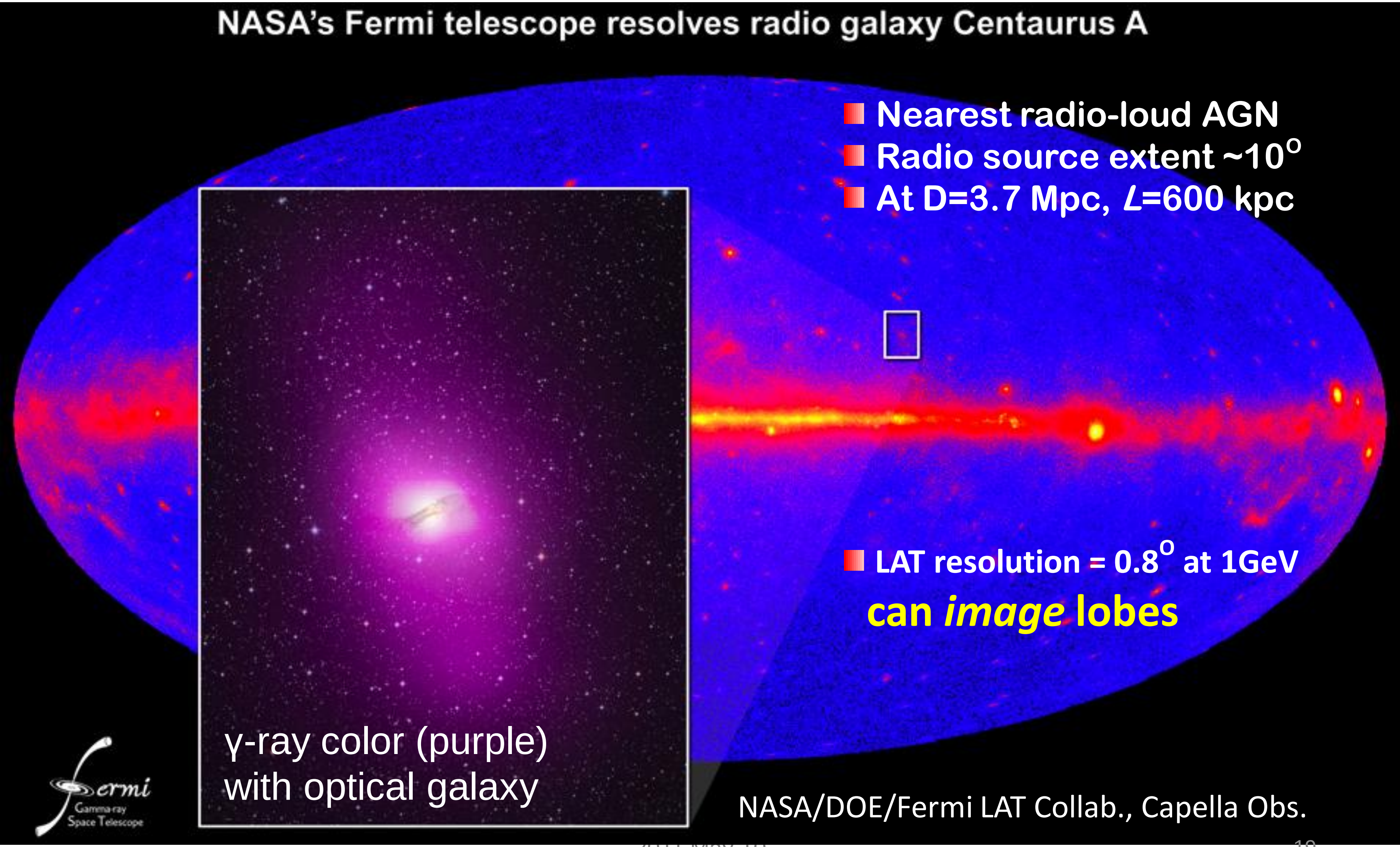


γ-ray emission in FRII jets is dominated by the inner fast collimated regions. Two effects could be contribute to reduce the number of FRIIs observed by Fermi:

i) the absence/reduction of feedback between different jet layers (particularly efficient mechanism in FRI with large inclination angles)

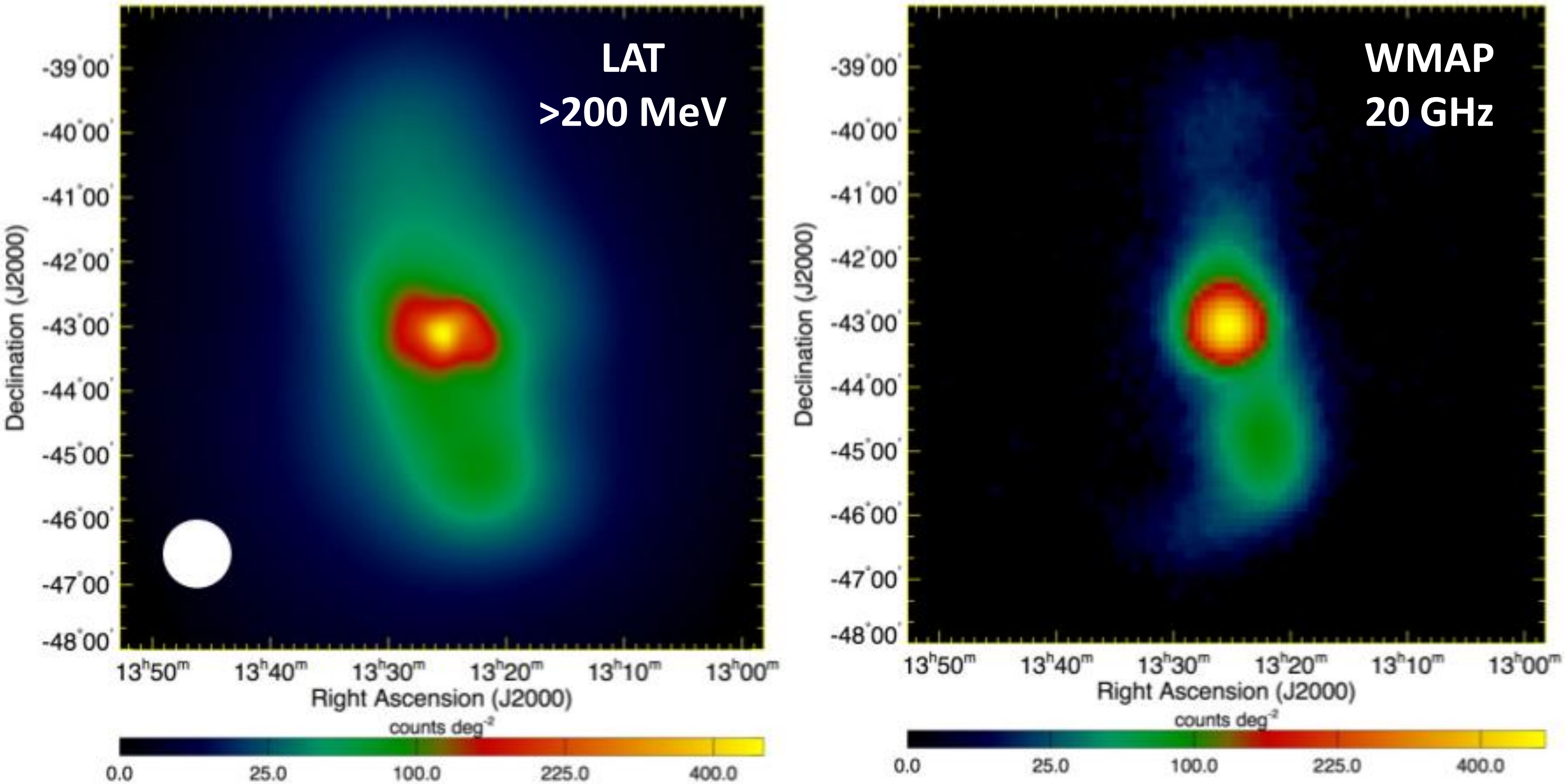
ii) the γ-ray narrower beaming cone of External Compton scattering (EC) when compared to that of the synchrotron-self processes (SSC).

Cen A lobe: γ-ray imaging (I)



Cen A lobe: γ-ray imaging (II)

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

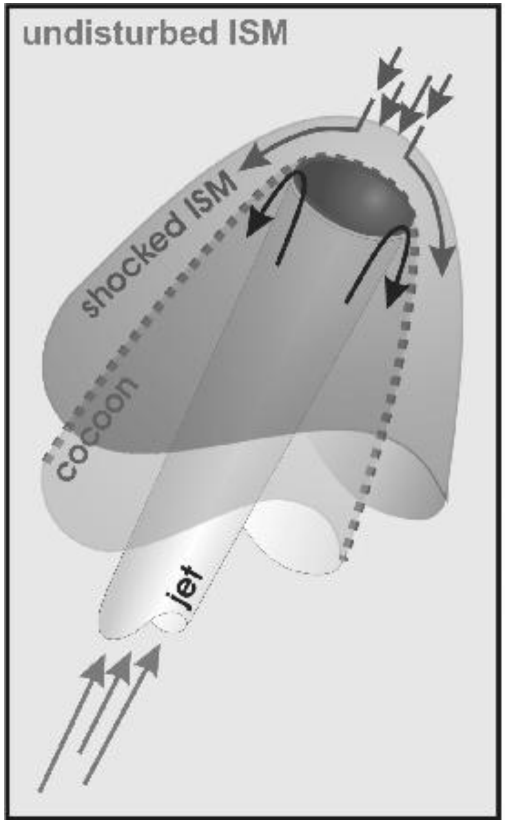


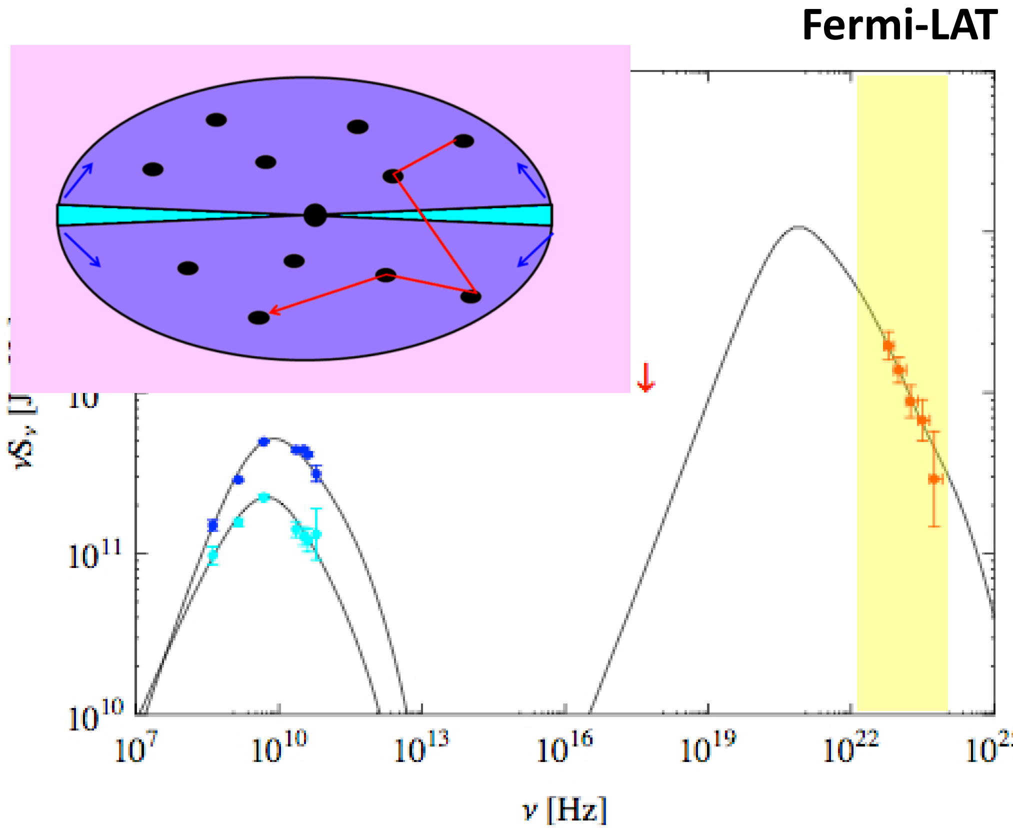
Background & point sources subtracted

From Nils Odegard (GSFC)

2010 Science, 328, 725 (CA: Cheung, Fukazawa, Knodlseder, Stawarz)

Why important? – (I) acceleration



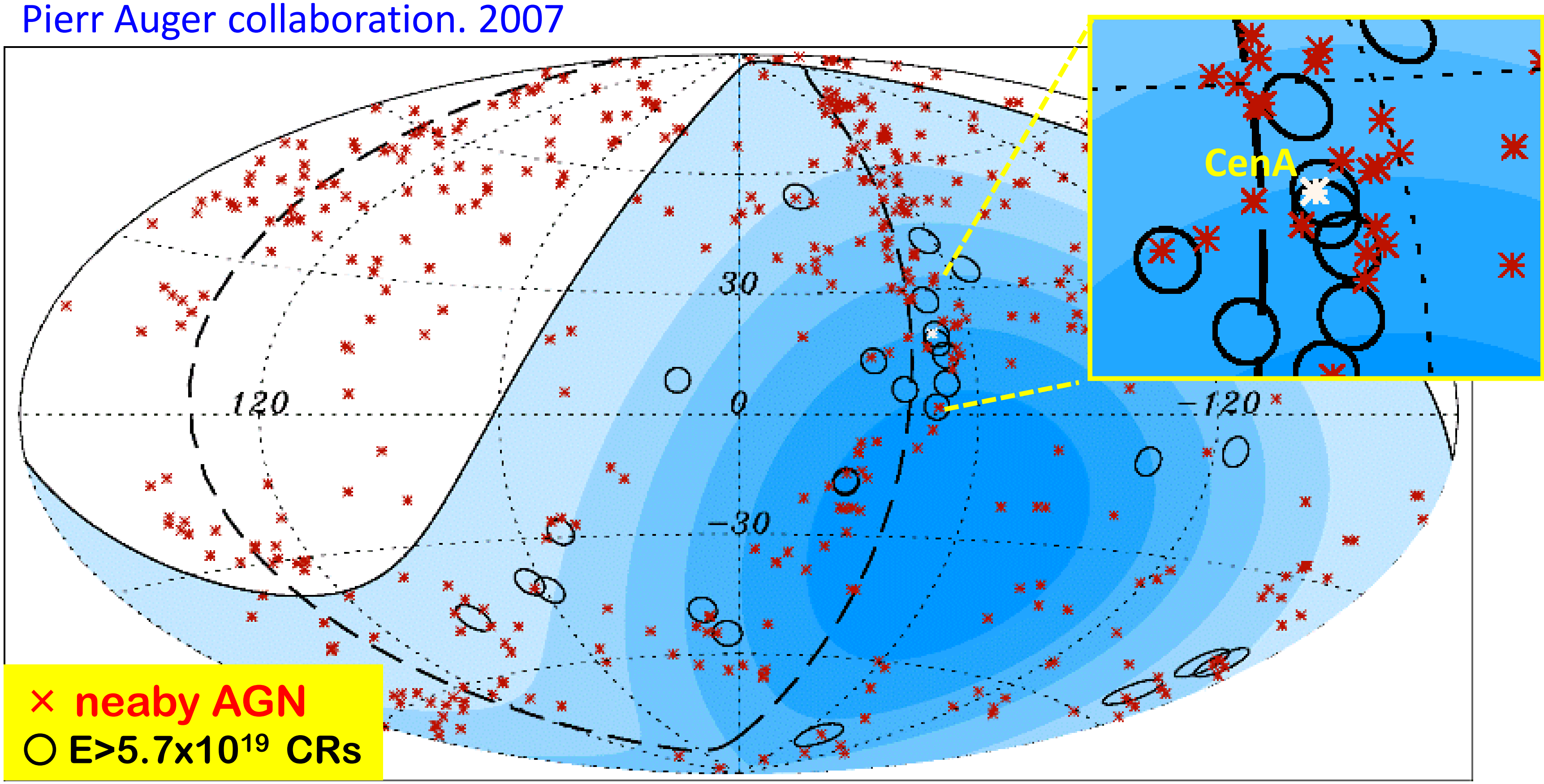


- Good IC (CMB+EBL) fits of LAT spectra with **B ~ 0.9 μG in both lobes.** (close to equipartition: $U_e \sim U_B$)
- $t_{cool} < R/c$ for GeV emitting electrons: **acceleration all over the volume.**

⇨ **Stochastic acceleration like Fermi-II ?**

Why important? – (II) relation to CRs

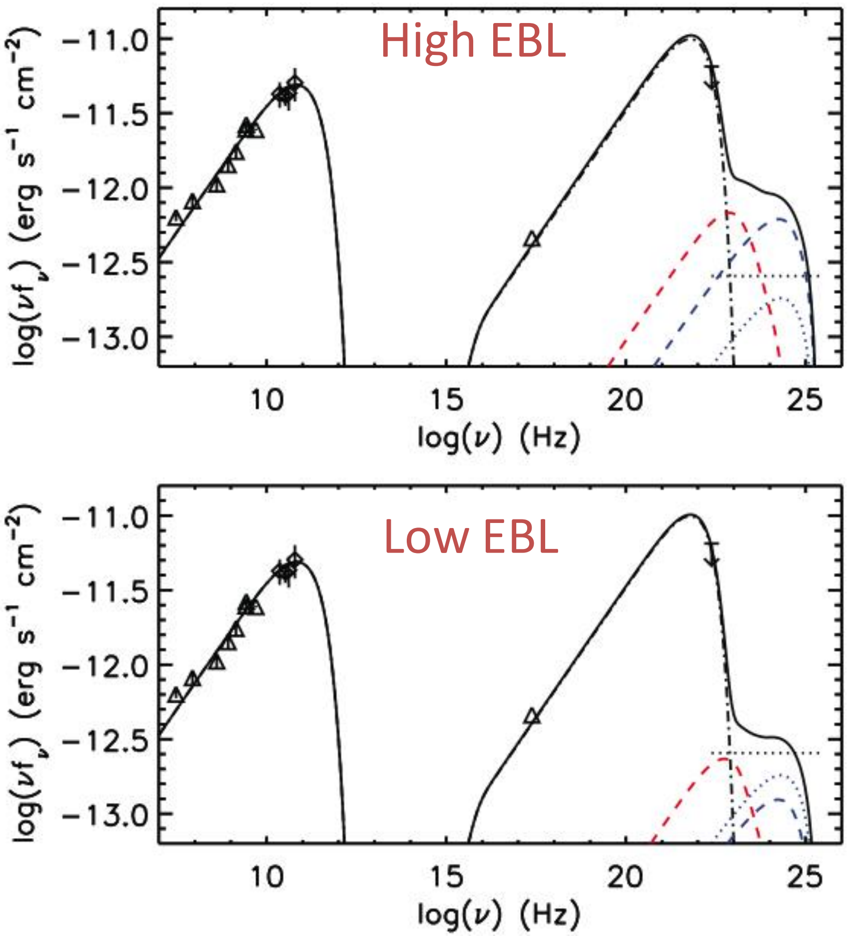
Pierr Auger collaboration. 2007



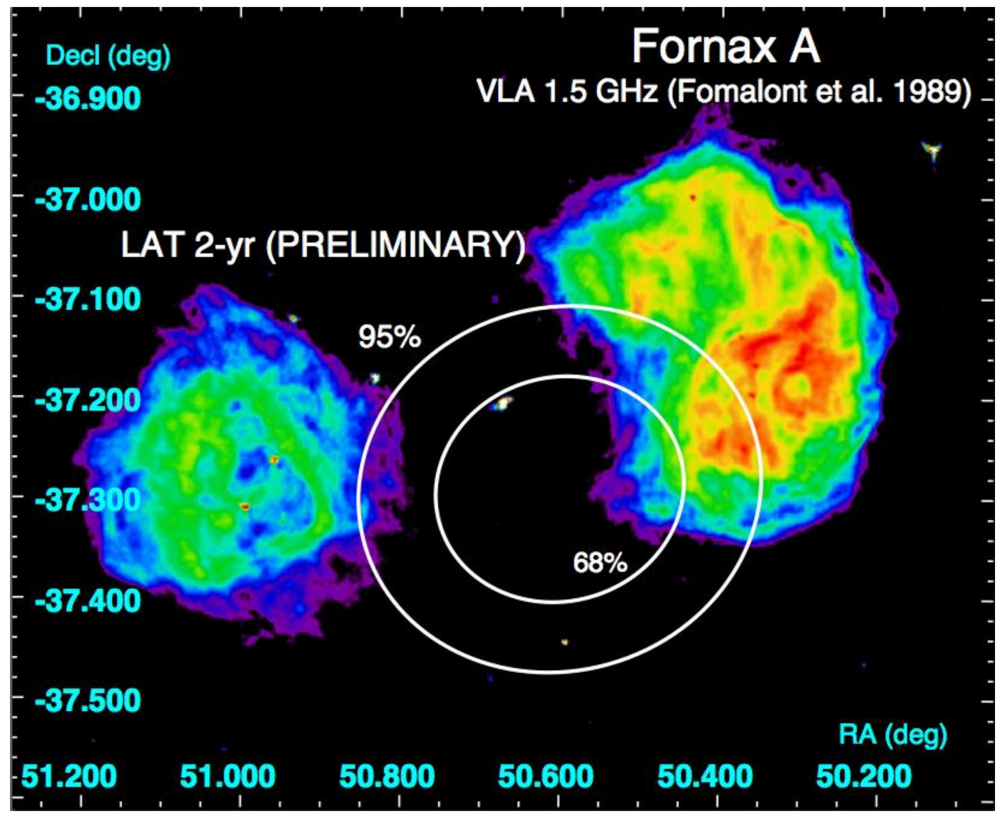
- Anisotropic distribution of $E > 5.7 \times 10^{19}$ eV Cosmic Rays
- Highest energy CRs may be accelerated in nearby AGN (see, also in this context, Hardcastle et al. 2009)

IC γ-rays from Fornax A lobe?

IC/X-ray lobe B-field ~1.5 μG (Feigelson et al. 1995, Isobe et al. 2006)



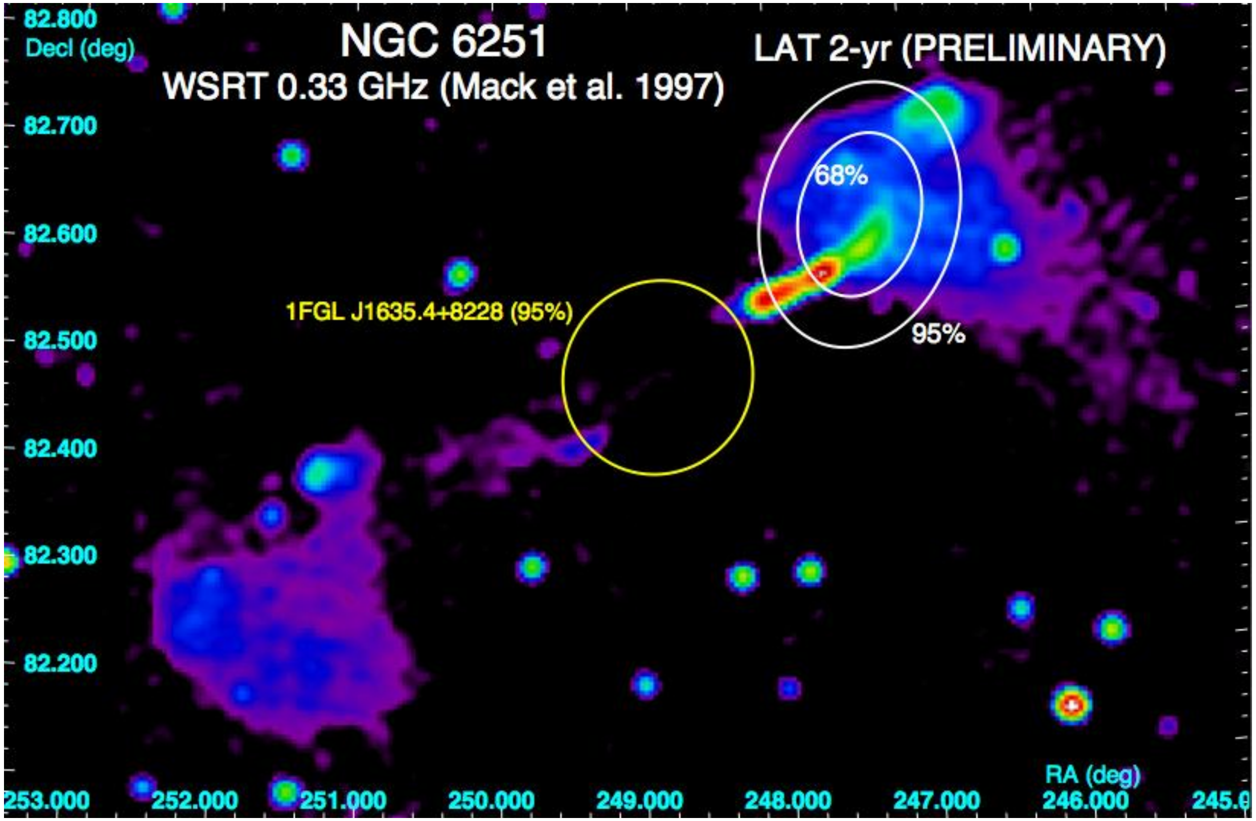
Georganopoulos et al. (2008)



LAT 68% and 95% confidence ellipse on radio image

LAT team leads: McConville, Georganopoulos

IC γ-rays from NGC6251 lobe?

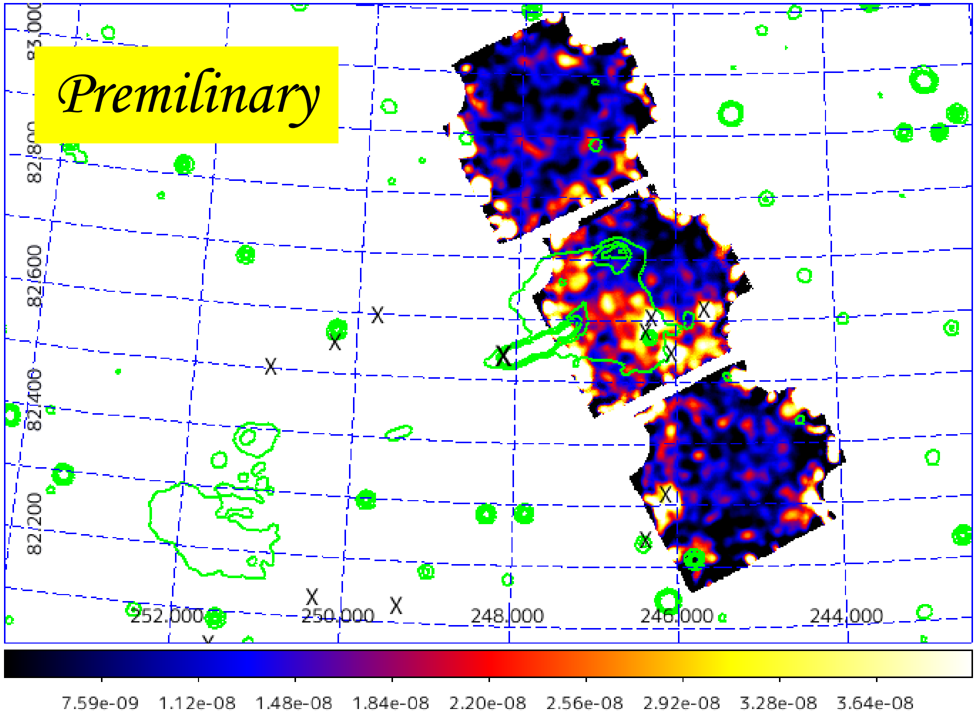


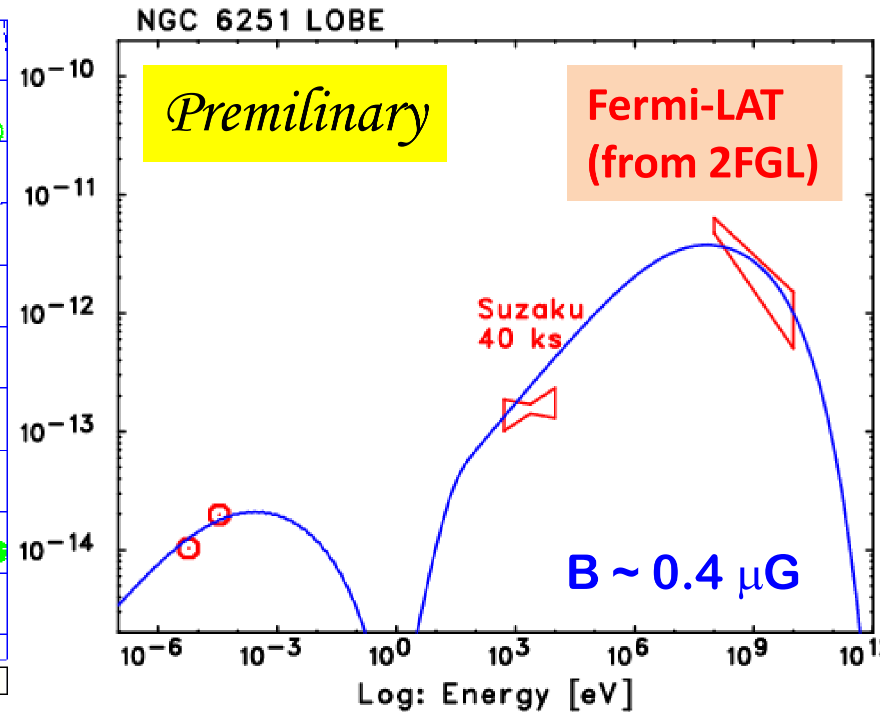
LAT 68% and 95% confidence ellipse on radio image

1FGL/15-month LAT analysis in 2010 ApJ 720, 912 (CA: P. Grandi) also Migliori et al., submitted

- **Associated with 3EG J1621+8203 (Mukherjee et al. 2002) with large error circle**
- **Large radio galaxy (1.2 deg ~ 1 Mpc) so LAT capable of spatially separating lobe from AGN emission**
- **Lobe equipartition B-field ~0.3 μG (Mack et al. 1996); cf. ~1 μG for Cen A**

NGC 6251 lobe: X-ray follow-up

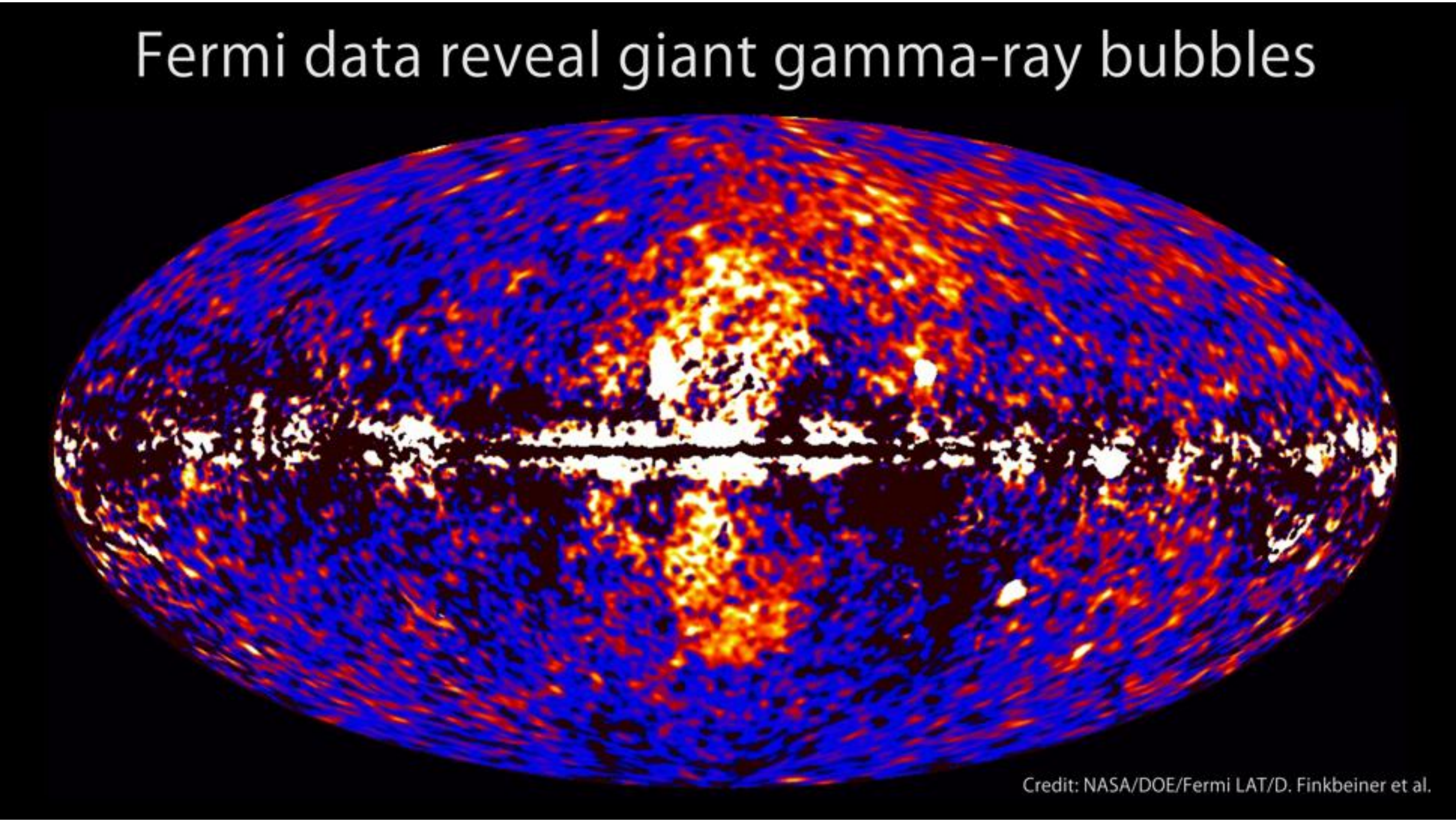




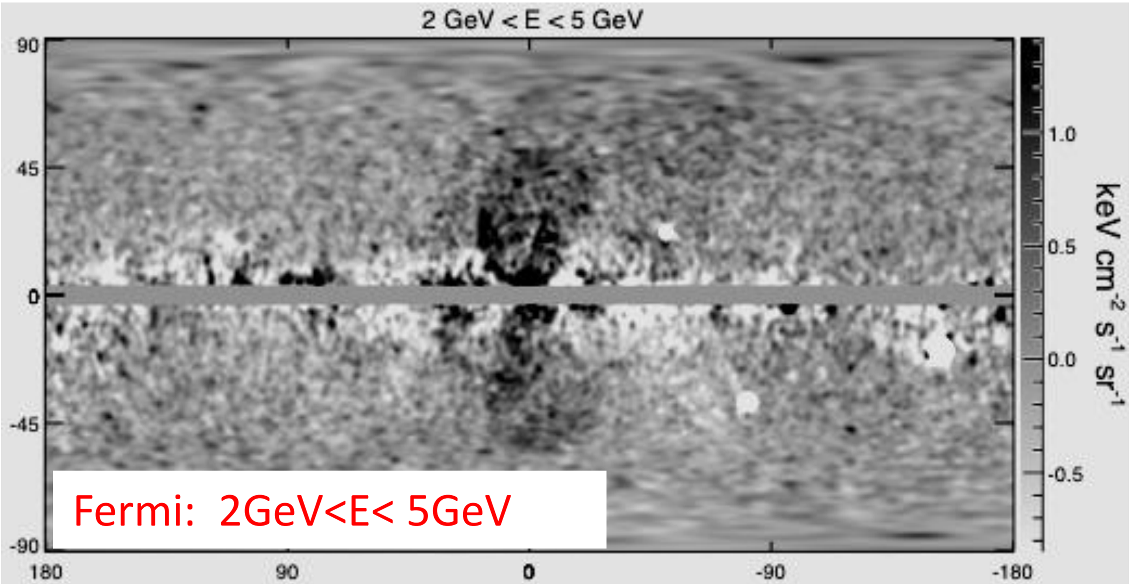
Takeuchi, Kataoka et al. in prep (2011)

- **Suzaku follow-up observations of NGC 6251 lobe region (ON/Off src; 40 ksec each)**
- **After removing all suggestive background, there still remained some diffuse X-ray emission, but relation to gamma-ray lobe is still under investigation**

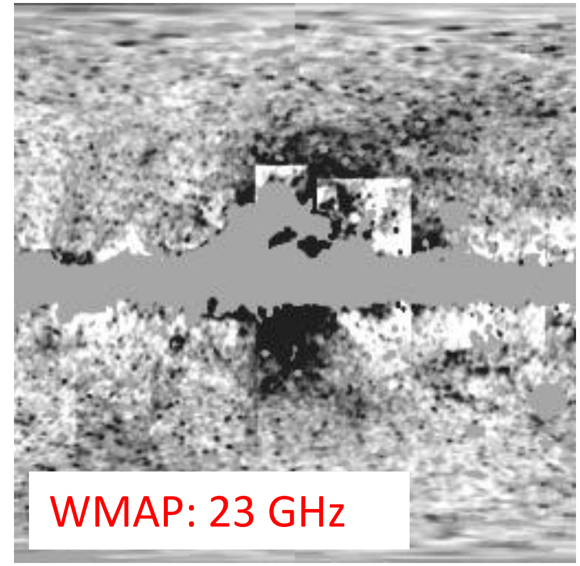
Galactic Haze: nearest γ-ray lobe

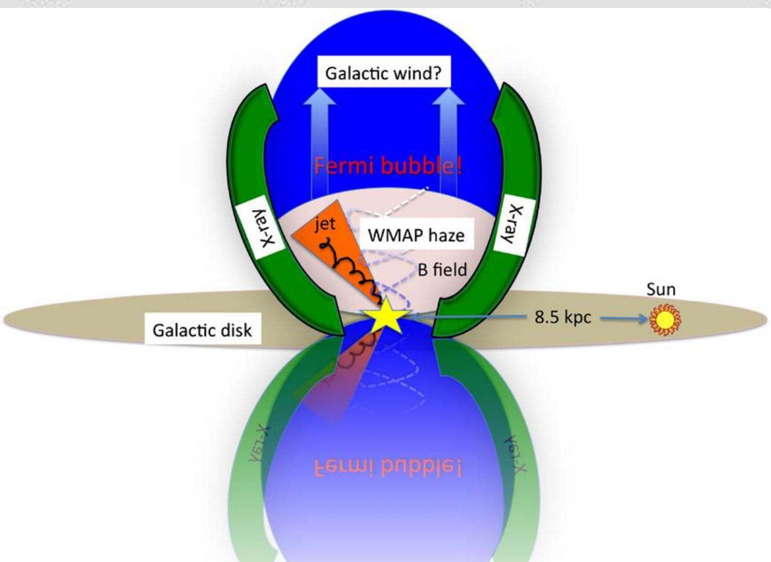


Origin of “γ-ray bubble”



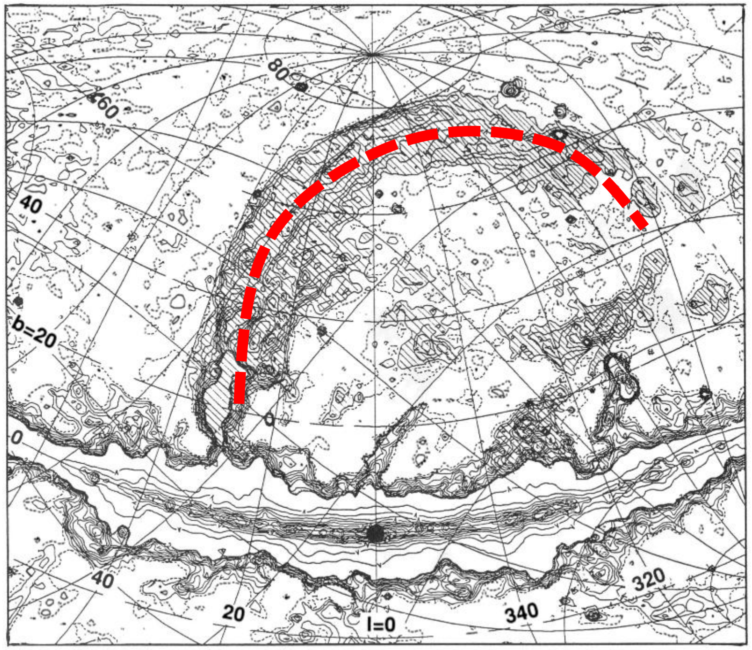
Su et al. 2010

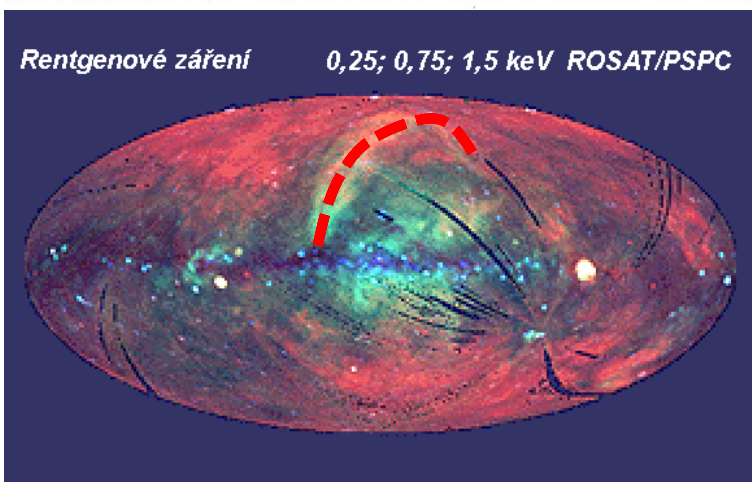




- **Fermi-LAT reveals large γ−ray bubbles, extending 50° above/below Gal. plane**
- **Correlated w/ WMAP haze, suggesting IC/CMB in origin**
- **Similar to Radio Lobe in AGN - past activity of Sgr A* ?**

Past Activity of Sgr A* (1)

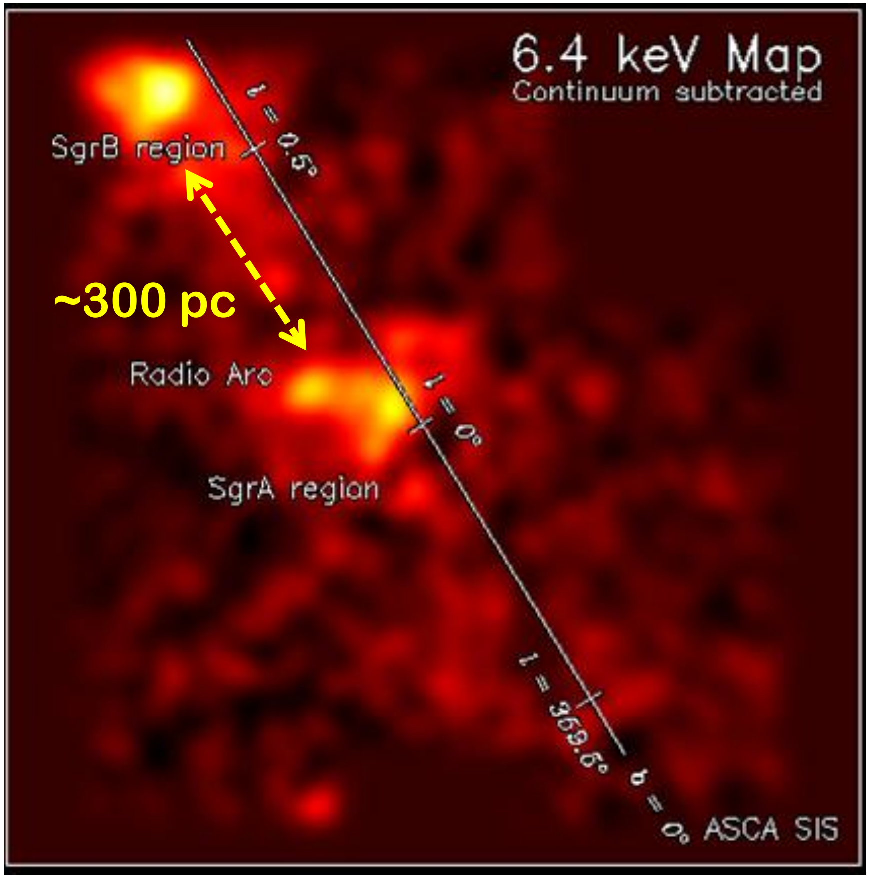


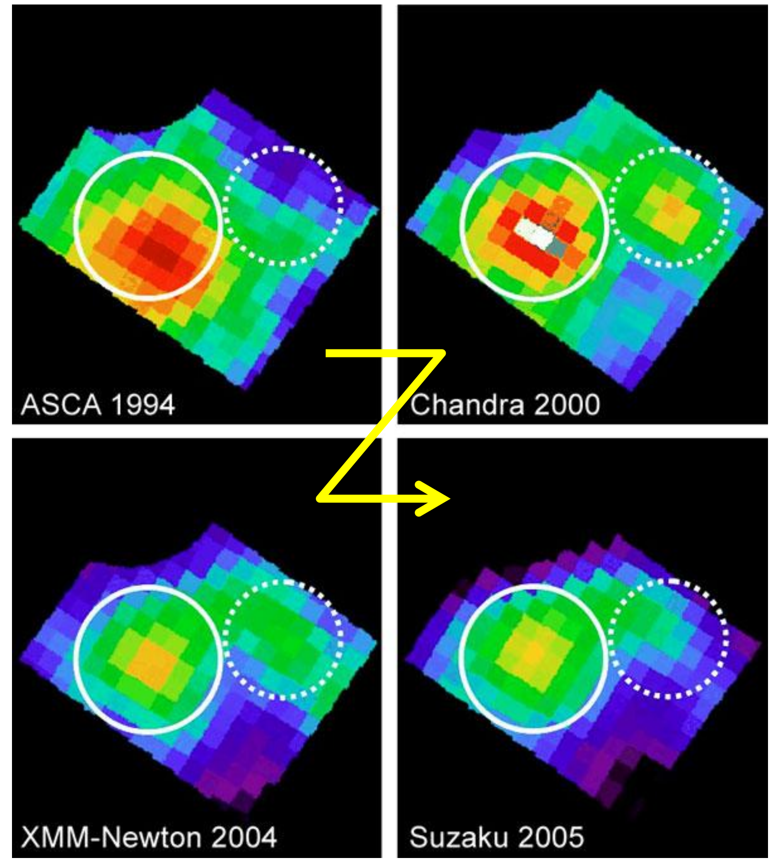


- **"Ω Lobe" is a well-known structure in radio** (Haslam +82; see also Haslam +74, Sofue 77, 84, 94, 00)
- **Proposed to be related to an explosion which took place around the Galactic Center ~ 10 Myr ago (with the total energy $E_{tot} \sim 10^{55}$ - 10^{56} erg), and which formed a shock in the interstellar medium**
- **Two scenarios have been proposed:**
  - **explosion was driven by the central starburst (Sofue 77)**
  - **jet-like activity of SMBH (Oort 77)**
- **Similar structure is seen in X-ray, known as "North Polar Spur"**

Past Activity of Sgr A* (2)

Koyama et al. 2008





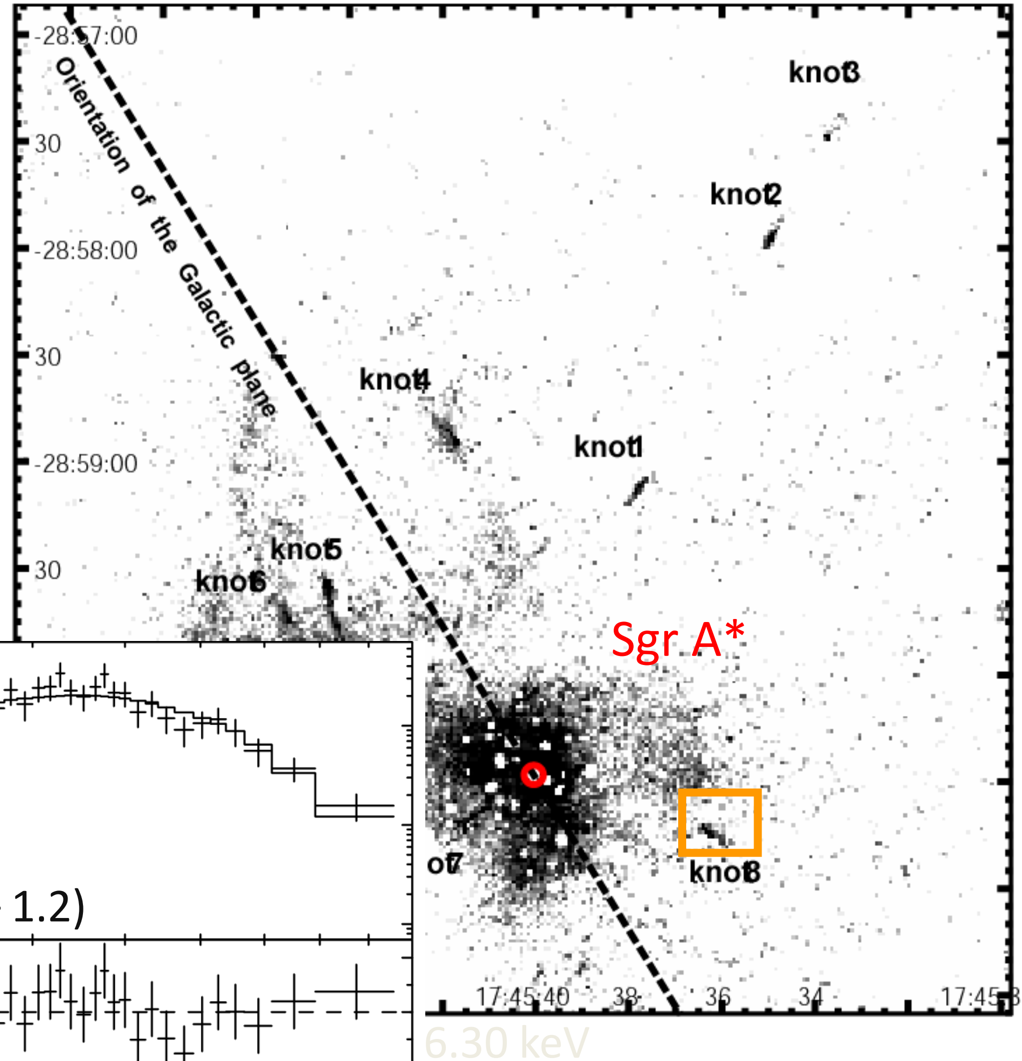
- X-rays from Sgr A* take 300 years to reach a large molecular cloud Sgr B2, suggesting Sgr A* must be much brighter in the past.
- Indeed, brightness of Sgr B2 faded substantially in just 5 years!

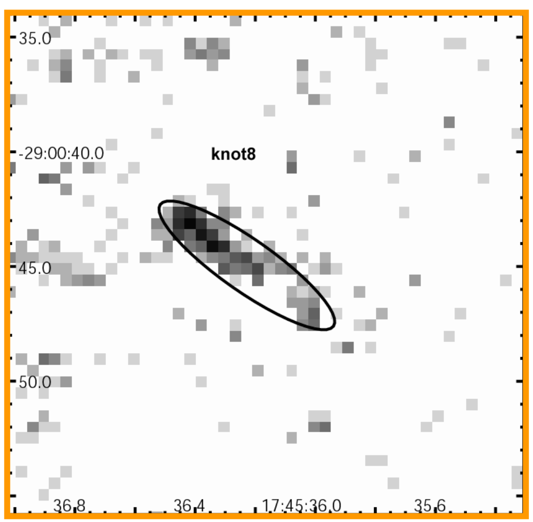
Past Activity of Sgr A* (3)

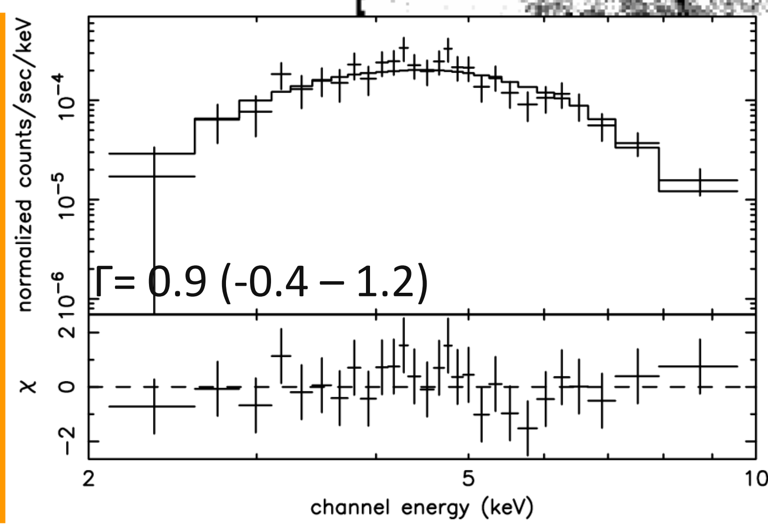
Senda et al. in prep

- About ~10 knotty structures
- knot1-3… aligned on a straight line
- Non-thermal PL spectra
- Similar geometry, size, direction

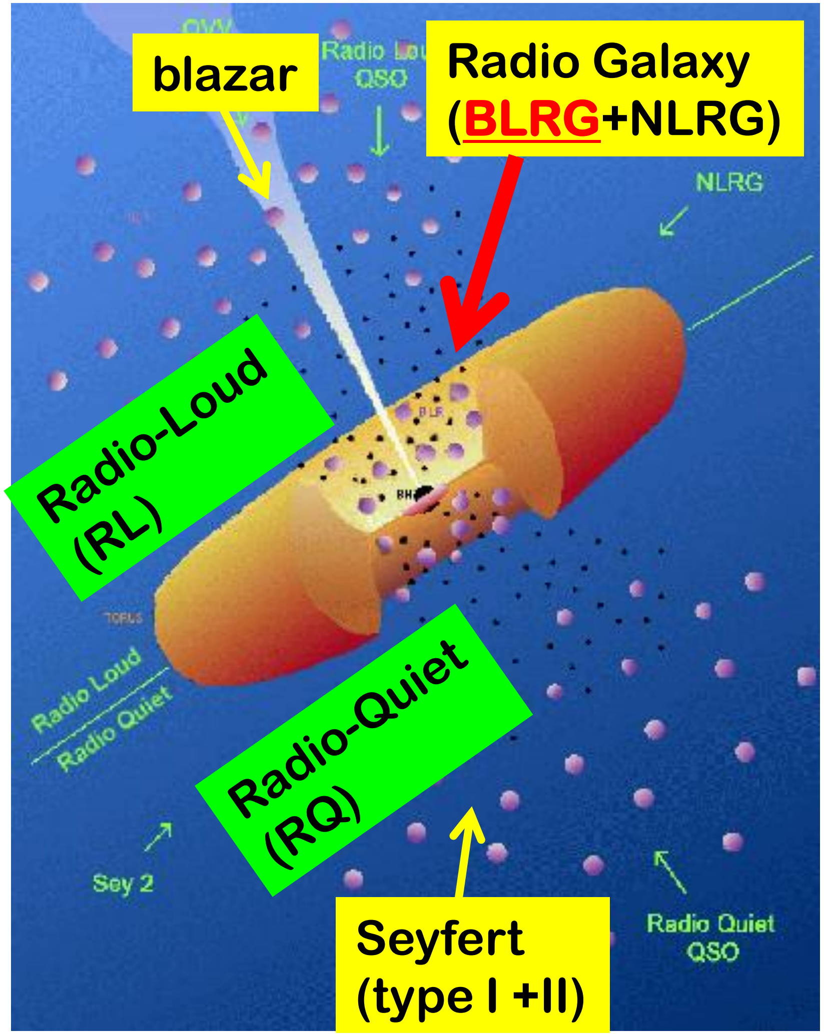
-> Evidence for past Jet activity in the center of our Galaxy?







Toward AGN unification; BLRGs



Urry & Padovani 1995 for a review

- A long debated problem in our understanding of SMBHs is to unify different types of AGN

- Broad line radio galaxies (BLRGs) are ideal targets, since they exhibit both the disk-related "Seyfert-like" and the jet-related "Blazar-like" radiative signature, without being obscured by large amounts of gas
  (e.g., Wozniak+98, Grandi+02, Kataoka+07, Grandi & Palumbo 08, Sambruna+09 …)

- Our primary goals are to examine the γ-ray properties of BLRGs as potential γ-loud AGN, in a broad context of AGN unification scheme

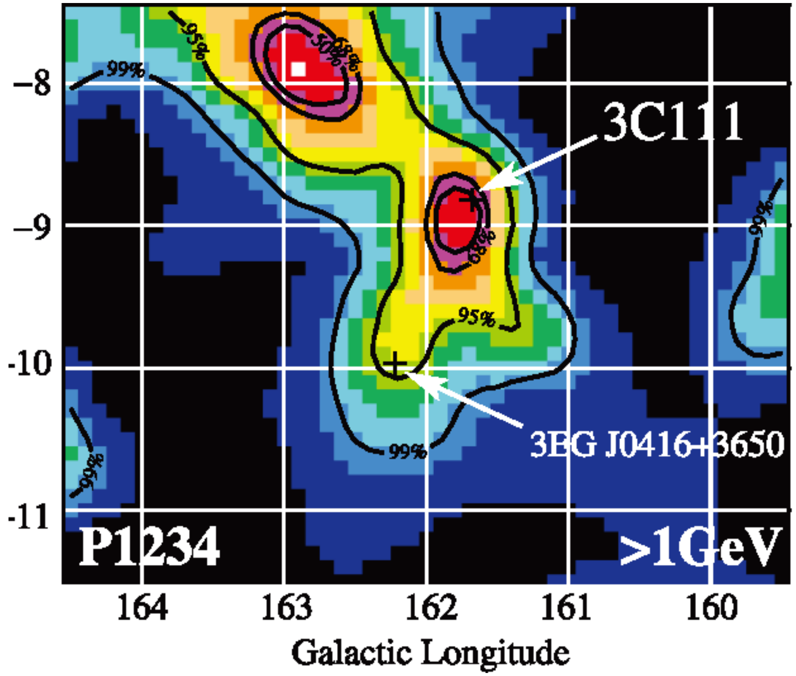
Fermi-LAT observations; samples

- All the BLRGs observed by modern X-ray astronomy satellites, for which data are available at energies above 2 keV
- A representative sample of Sy-1 galaxies with known radio fluxes and BH mass

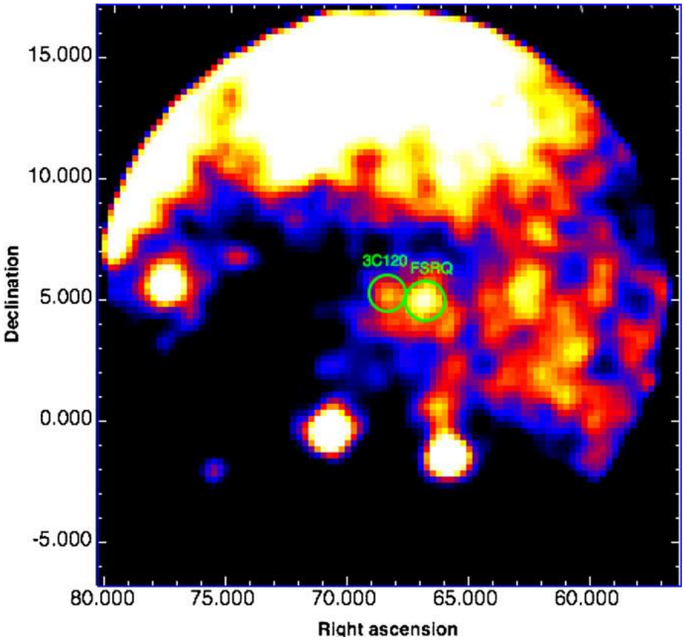
→ 18 BLRGs + 9 Sy-1s of high-accretion-rate

- Already known γ-ray sources: 3C111, 3C120 … and more ???

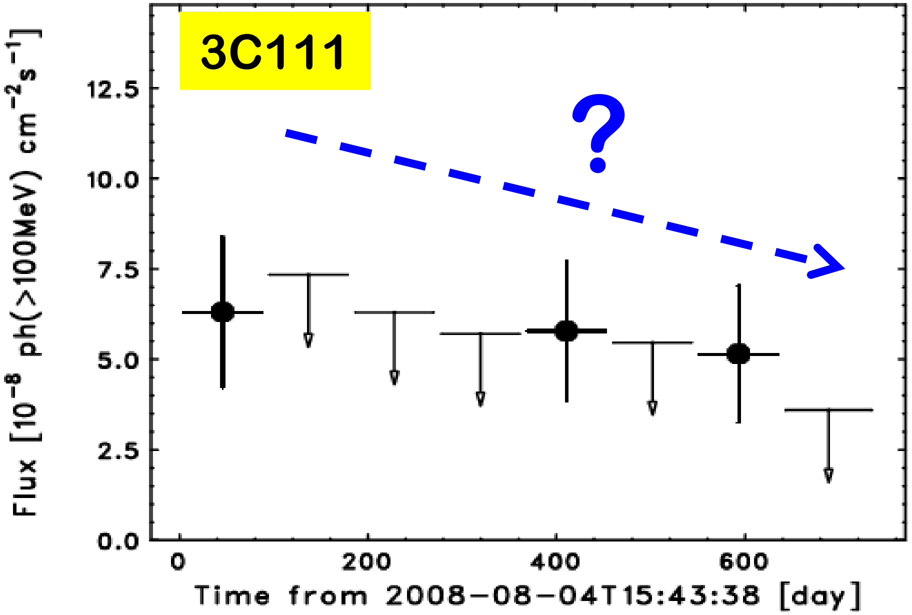
Hartman+ 2008 (EGRET), Abdo+ 2010

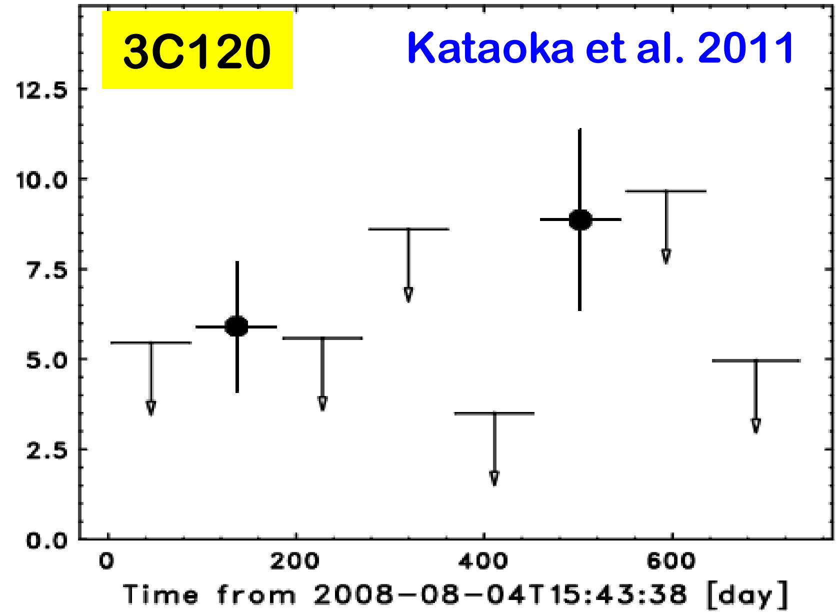


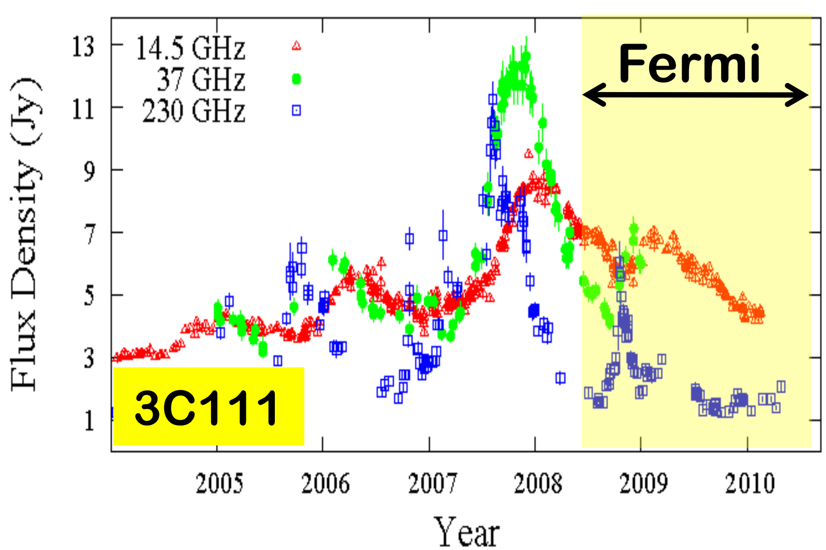
Abdo+ 2010 (Fermi-LAT)



Analysis of 2yr Fermi-LAT data

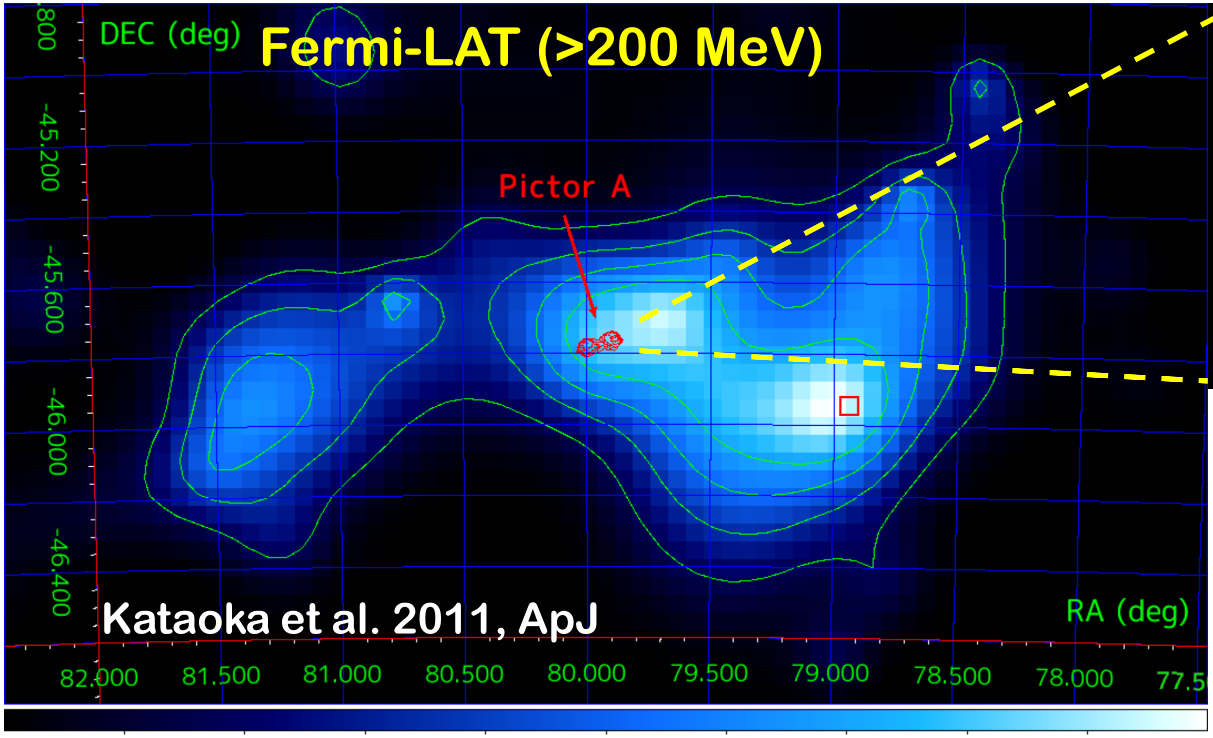


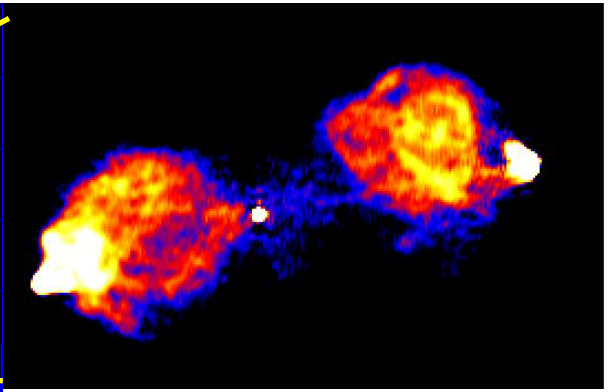




- No statistically significant detection except for 3C111 and 3C120
- 1/20 of EGRET flux for 3C111. γ-ray emission is most obvious during first 6-month, coinciding with a bright sub-mm flare (Chatterjee+2011)

Pictor A; another candidate

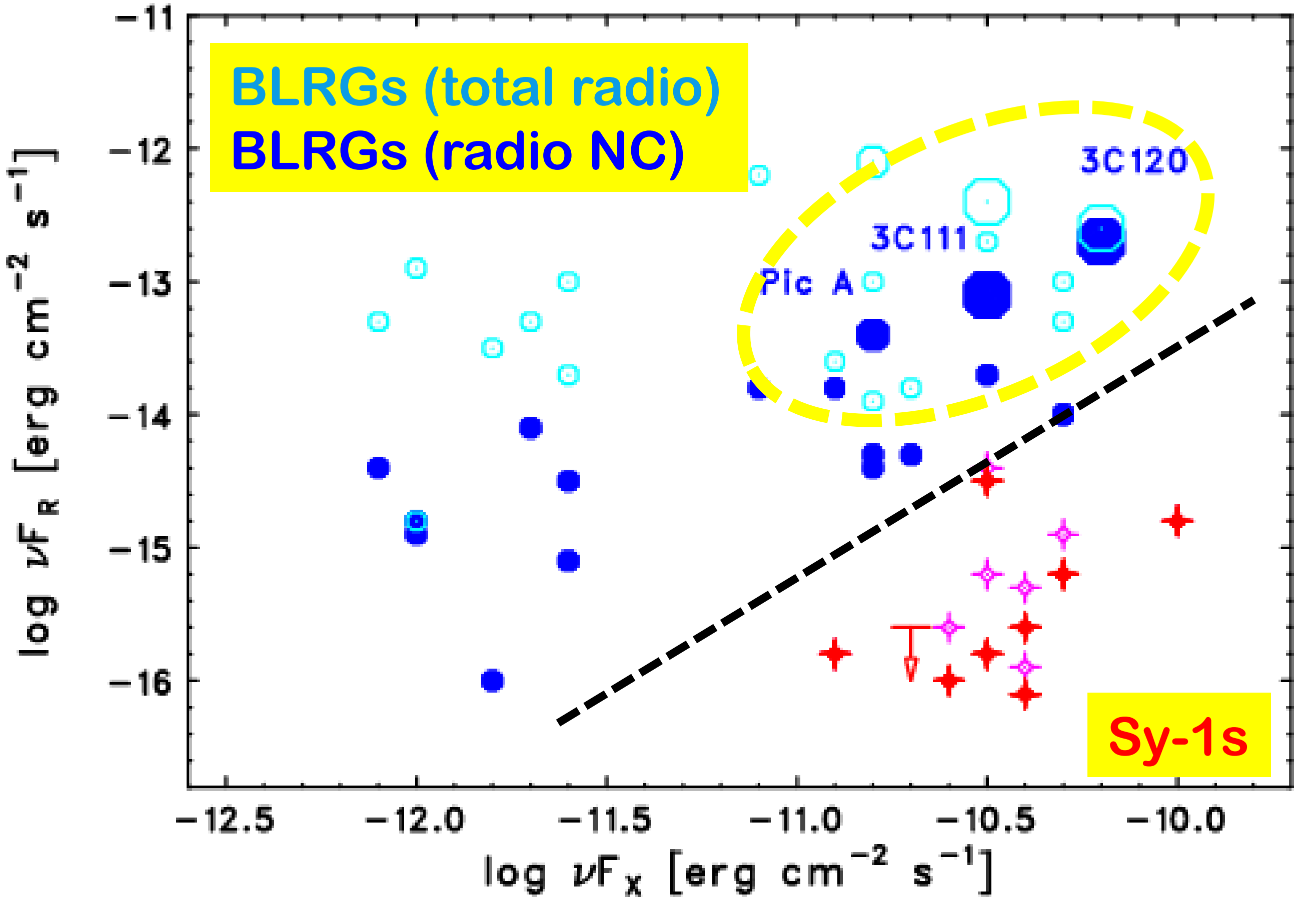




1.4GHz radio image of Pictor A radio galaxy (Perley et al. 1997)

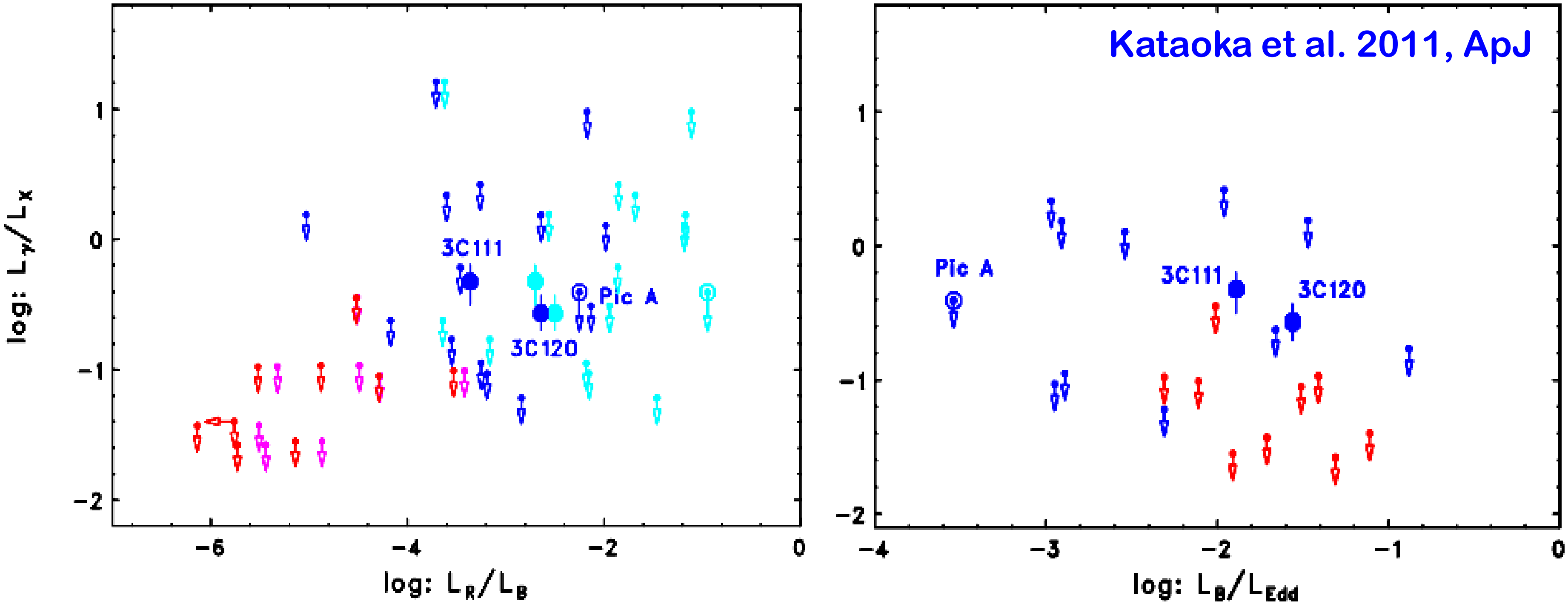
- Fermi-LAT TS map centered on Pictor A, showing the presence of multiple γ-ray peaks in the field. The peak near the center of the map (TS=20) is almost exactly coincident with the position of Pictor A
- Although not yet detected, formal detection (TS >25) of this source by Fermi-LAT in the near future is quite likely

Which BLRGs are detected in GeV ?



- What appears to differentiate 3C111 and 3C120 (and possibly Pictor A) from the sources not yet detected in γ–rays is the strong nuclear flux density in the radio

Multi-wavelength Diagnostic Planes

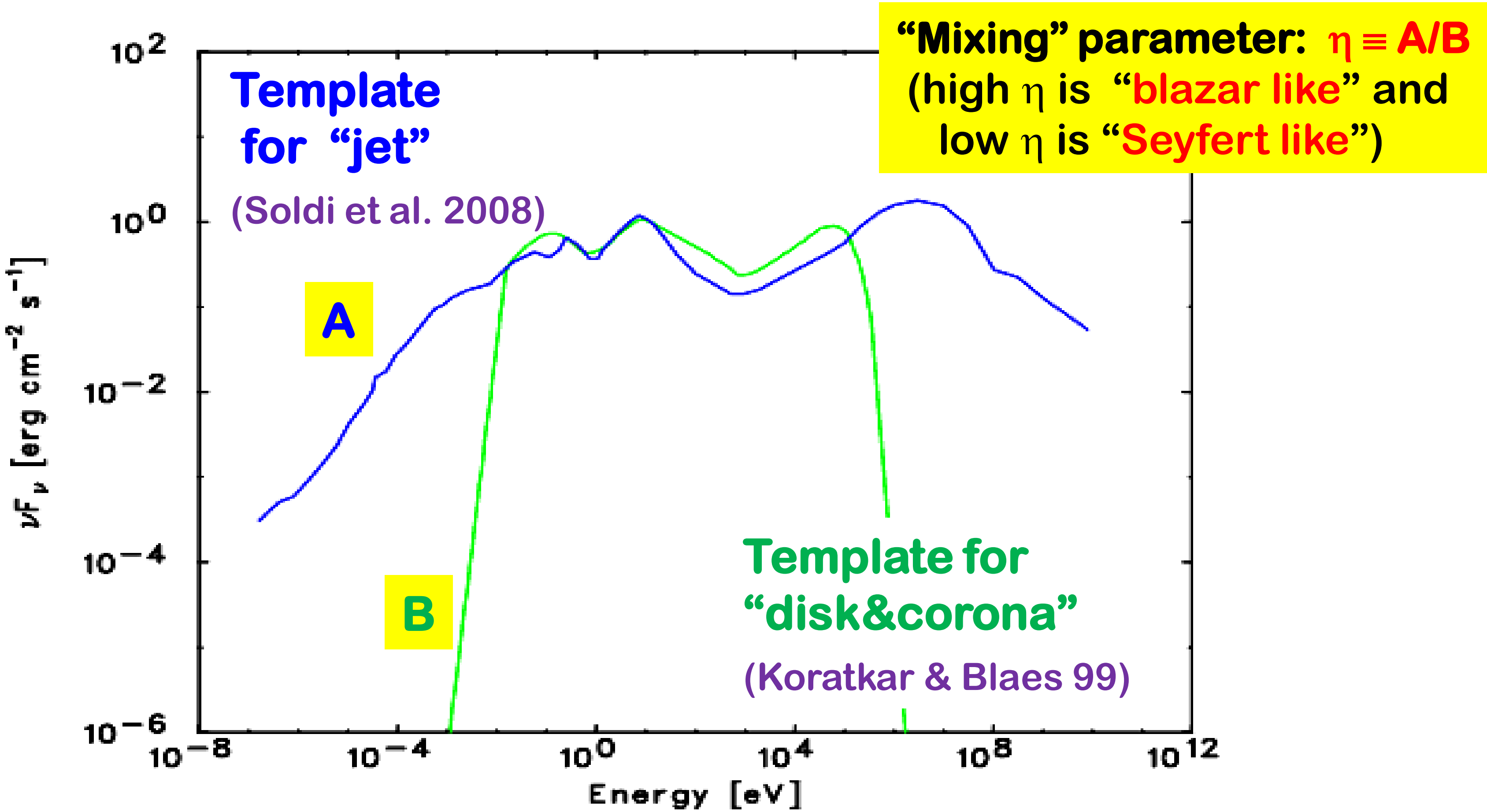


"Radio-loudness"
(≈ jet efficiency)

"Eddington Ratio"
(≈ accretion rate)

- Brightest GeV sources (3C111, 3C120 & Pictor A) do *not* stand out in these diagnostic planes. Most important parameter for GeV detection is radio nuclei power/flux!

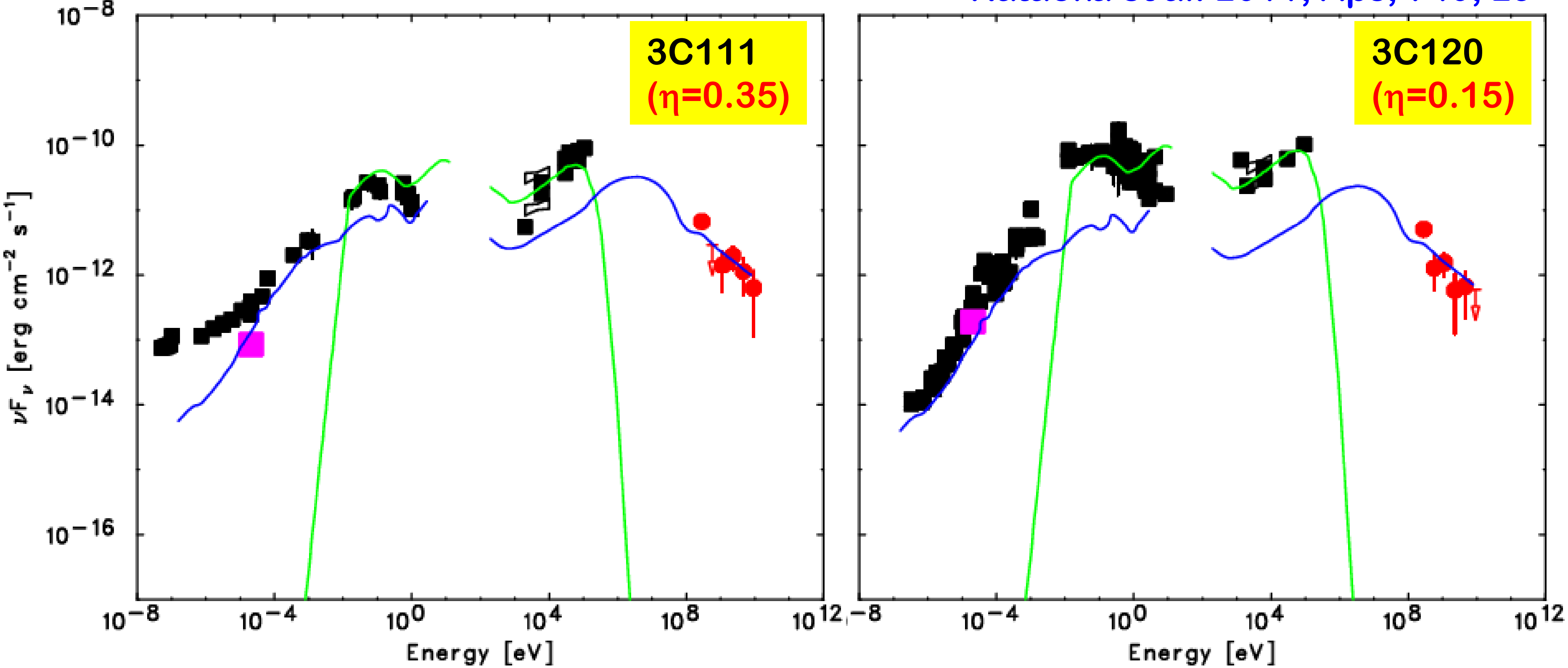
A “Hybrid” model: jet+disk



- Using “templates” for a blazar (3C273) and Sy-1 SEDs, we try to disentangle the jet and the accretion disk contributions to the broad-band emission spectra of BLRGs

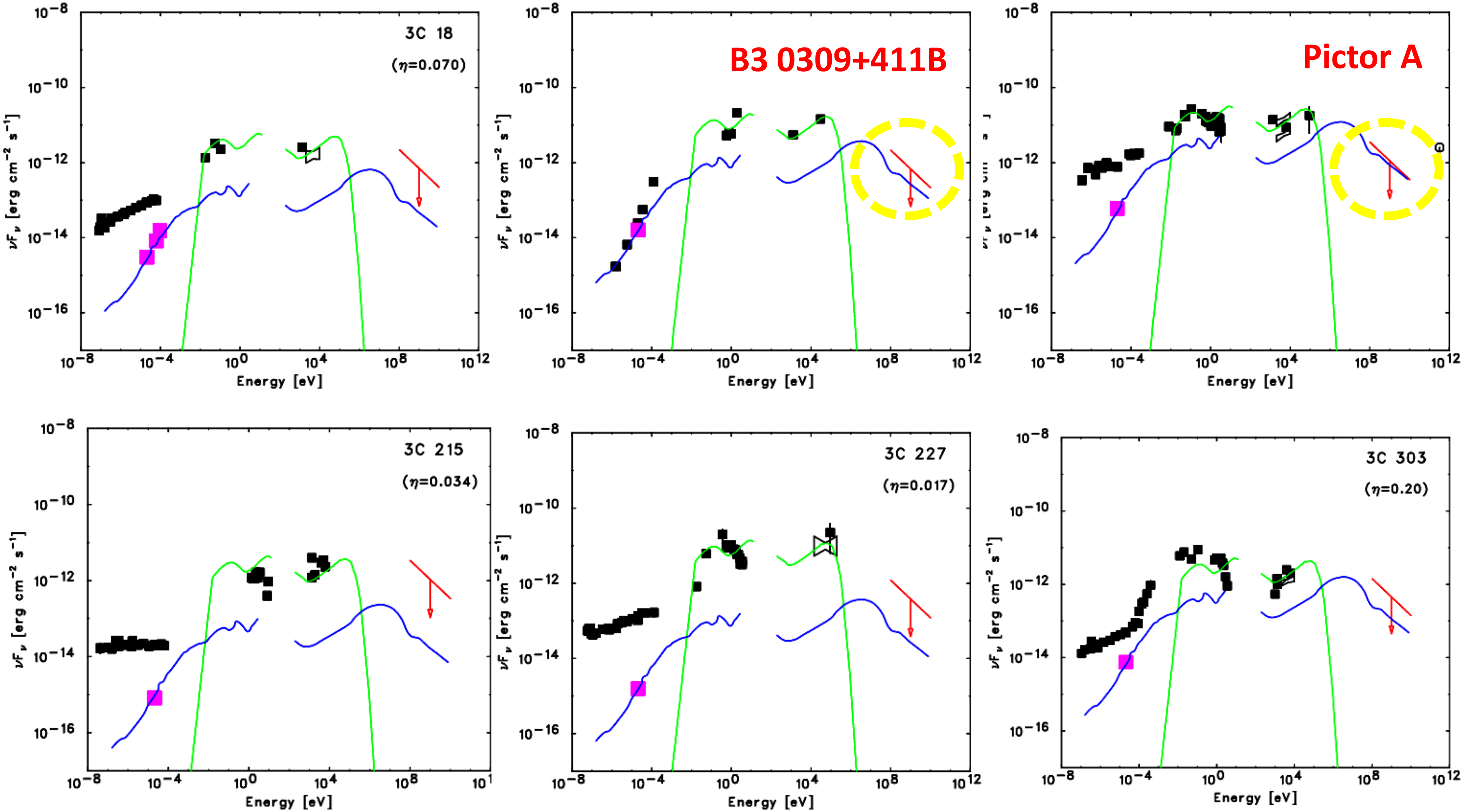
Application to SEDs: 3C111, 3C120

Kataoka et al. 2011, ApJ, 740, 29

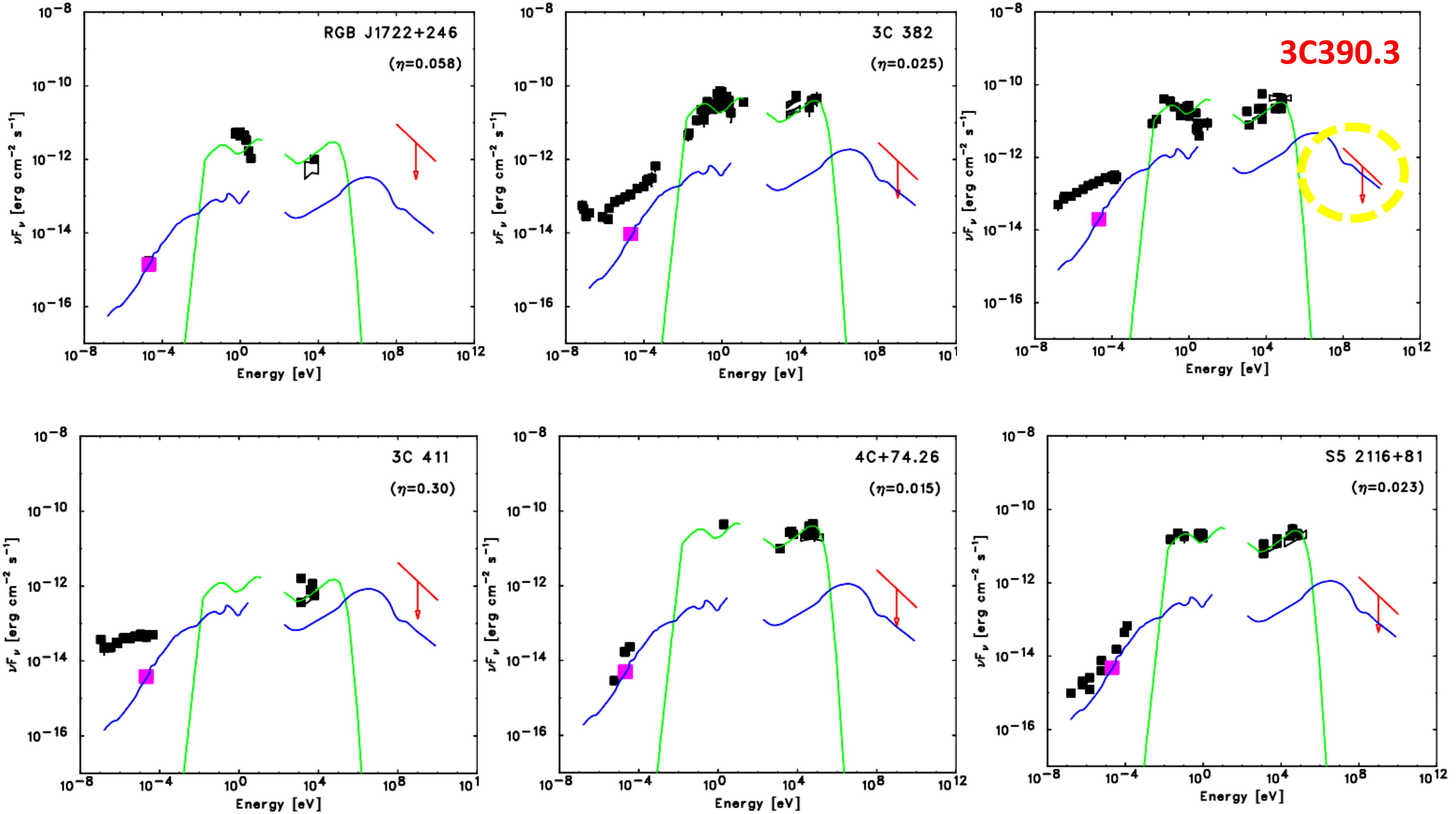


- Total observed luminosities of the accreting matter and of the nuclear jets in BLRGs are roughly comparable ($\eta \sim 0.1$-1), while that of the Sy-1 is very small ($\eta < 0.001$)

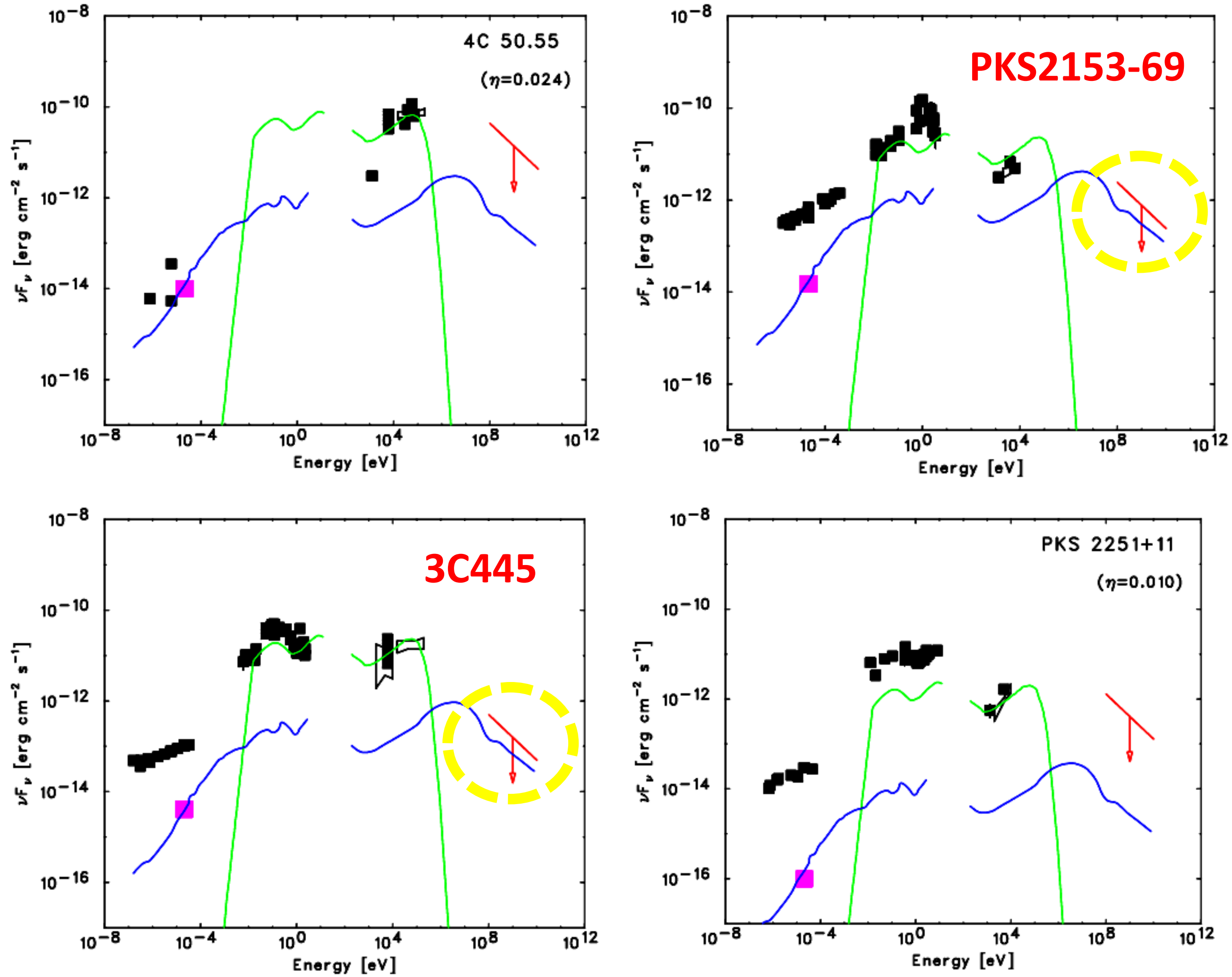
Application to SED: BLRGs(1)



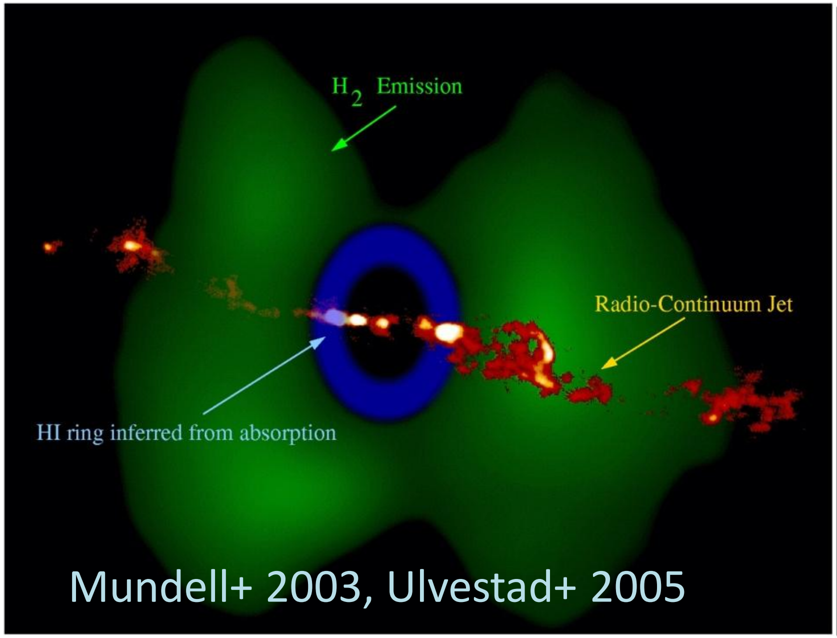
Application to SED: BLRGs(2)

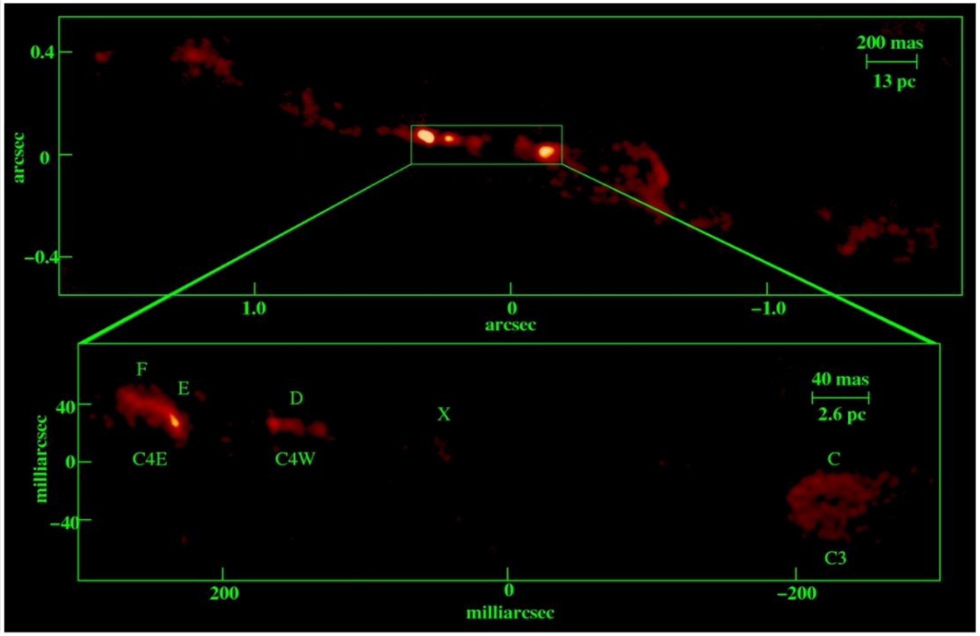


Application to SED: BLRGs(3)



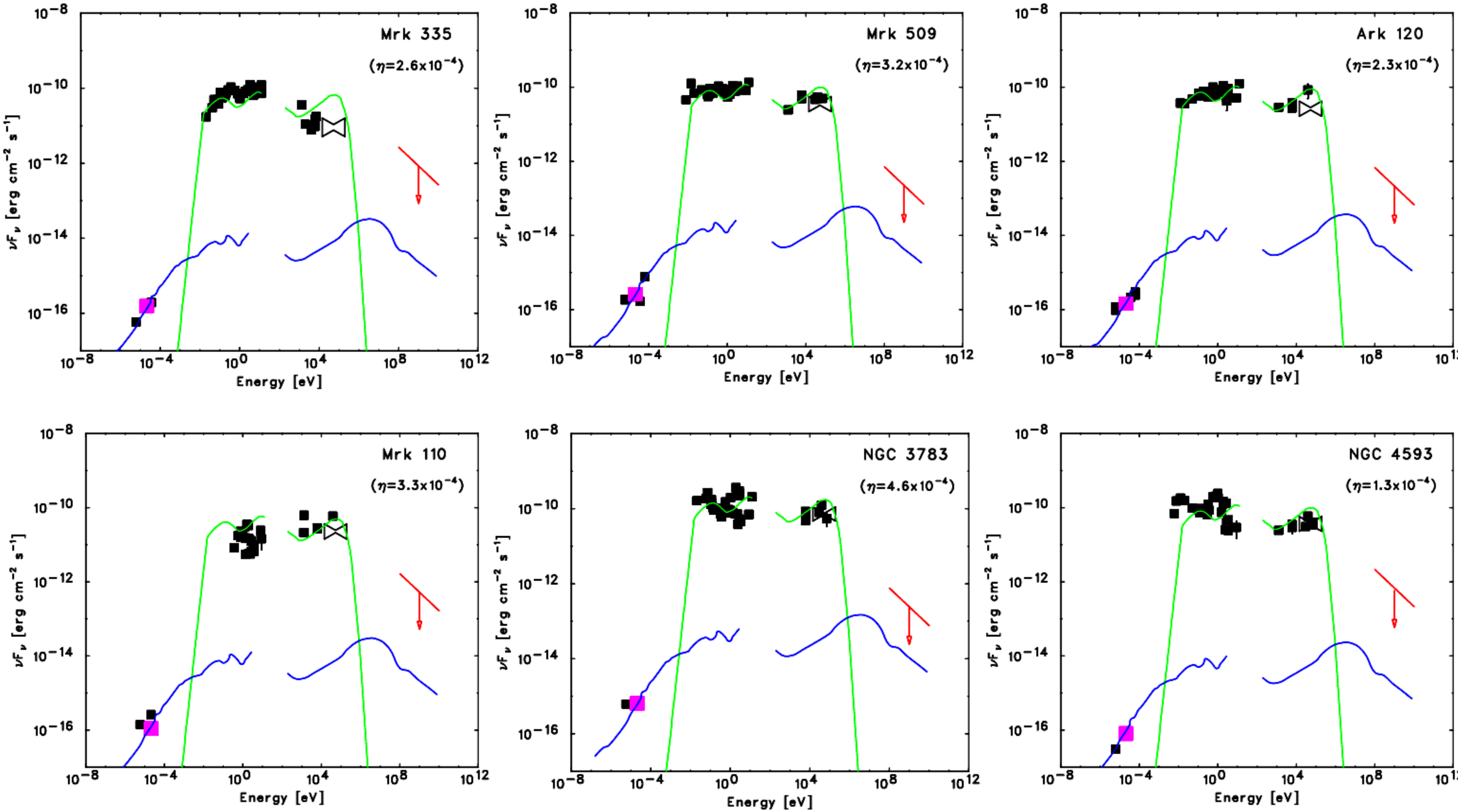
How about “Seyferts”?



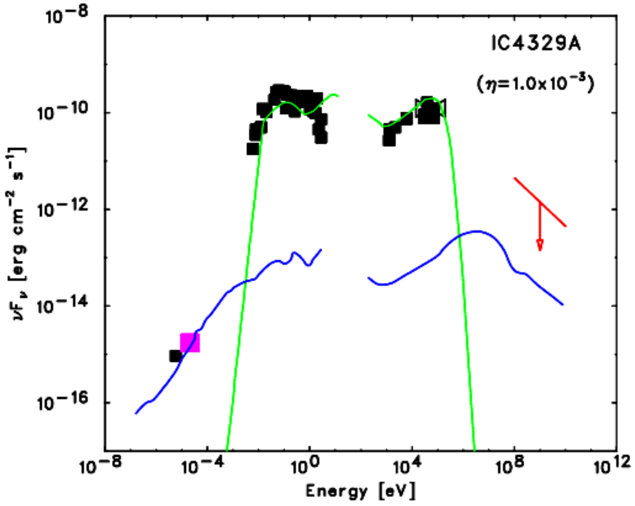


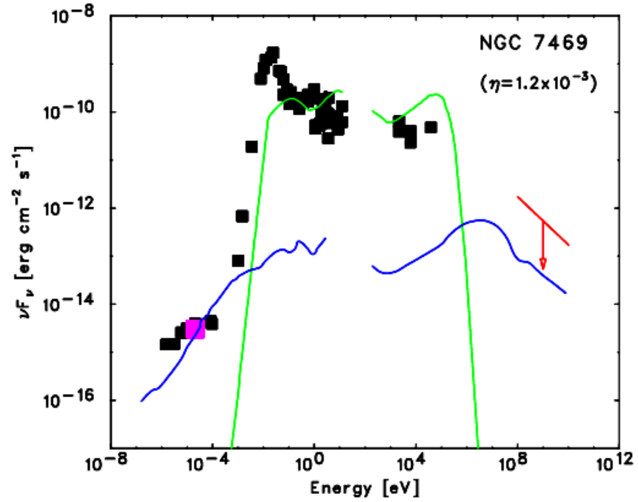
- 240-pc jet in NGC 4151 (Seyfert 1.5) is two-sided and highly collimated (diameter < 1.4 pc)
- Knotty morphology seems to be related to shocks formed as the jet interacts with small ISM clouds
- $L_R \sim 10^{37}$ erg/s. No evidence for relativistic bulk velocities (knots’ velocities < 0.03c at 0.1-10 pc scales)

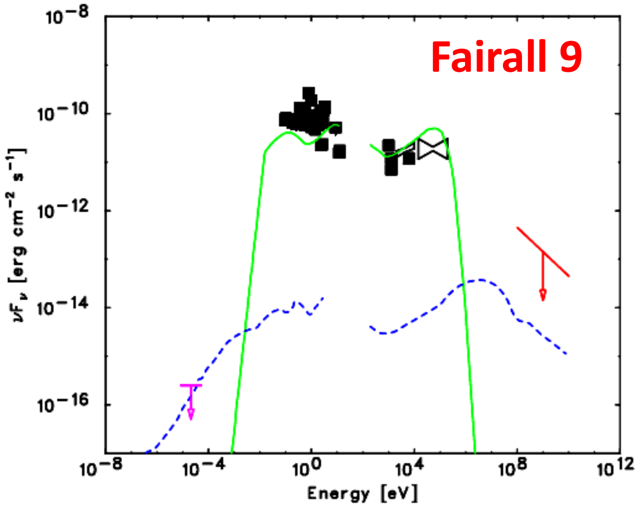
Application to SED: Sy-1s(1)



Application to SED: Sy-1s(2)

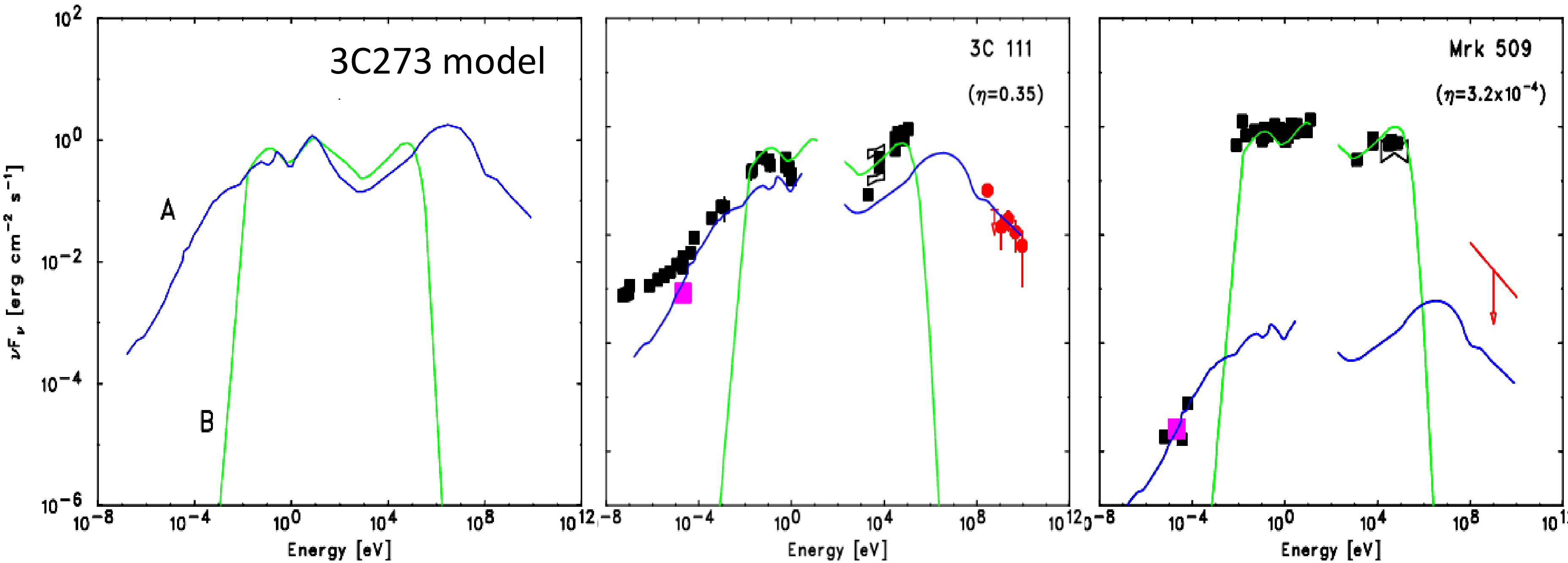






- Note, radio emission from **Fairall 9 is not** detected and thus only upper limit is provided in the SED.

Mixing “Jet” and “Disk” components



Blazars: η ~1

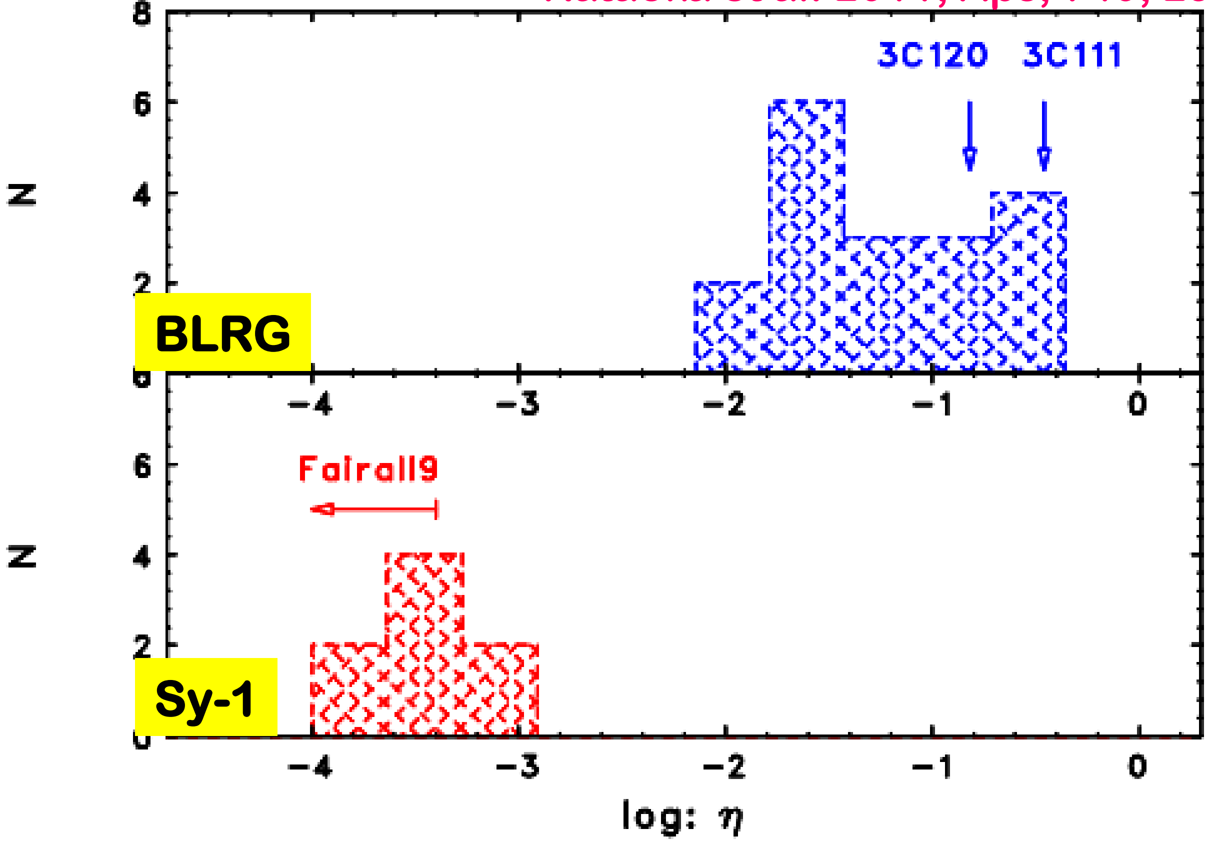
BLRGs: η ~0.1

Sy-1s: $\eta < 0.001$

- **Conversion efficiency of accretion matter to the jet determine whether the object can be “radio-loud ” or “radio-quiet”**
- **Probably, this conversion efficiency is tightly related with a rotation of the central BH**

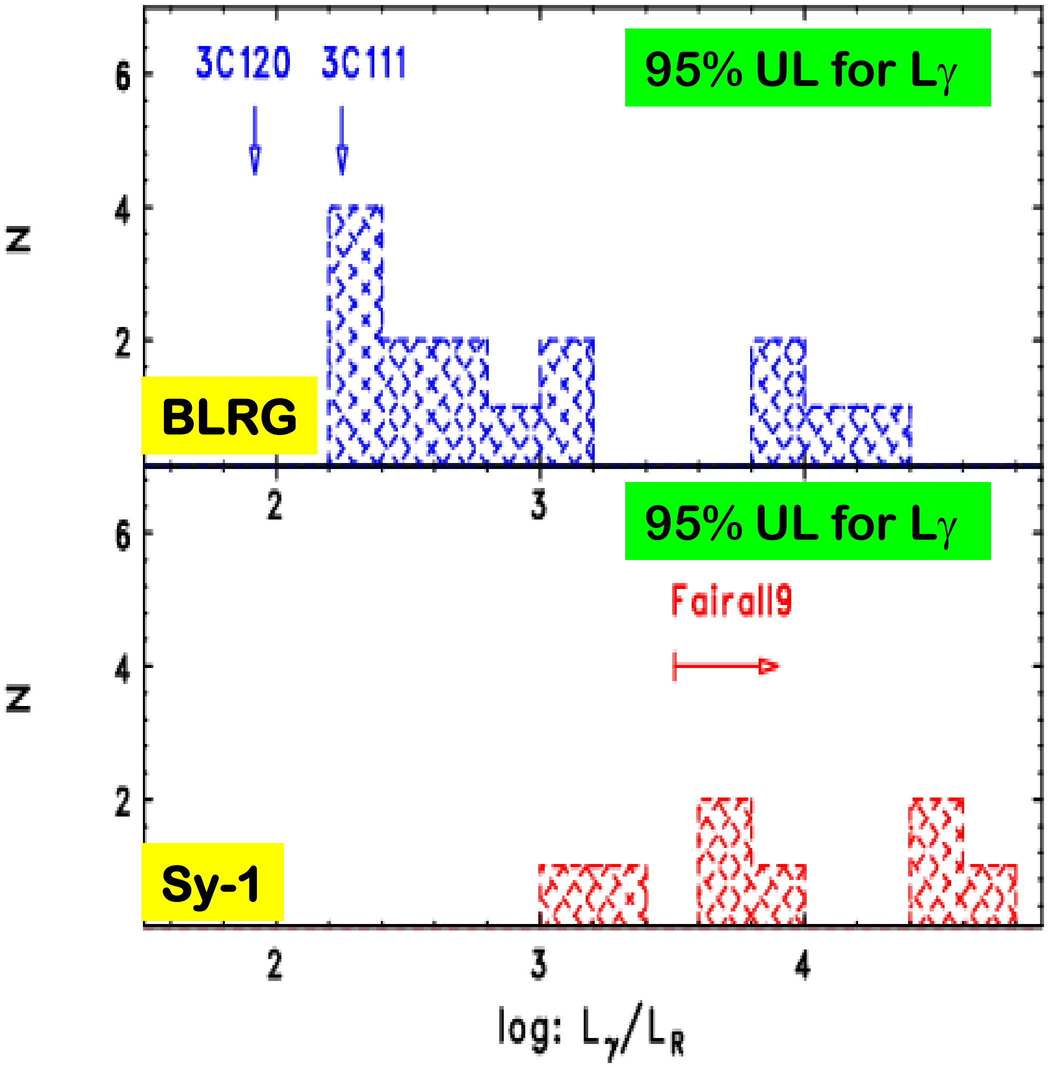
"Disk vs Jet" contribution

Kataoka et al. 2011, ApJ, 740, 29



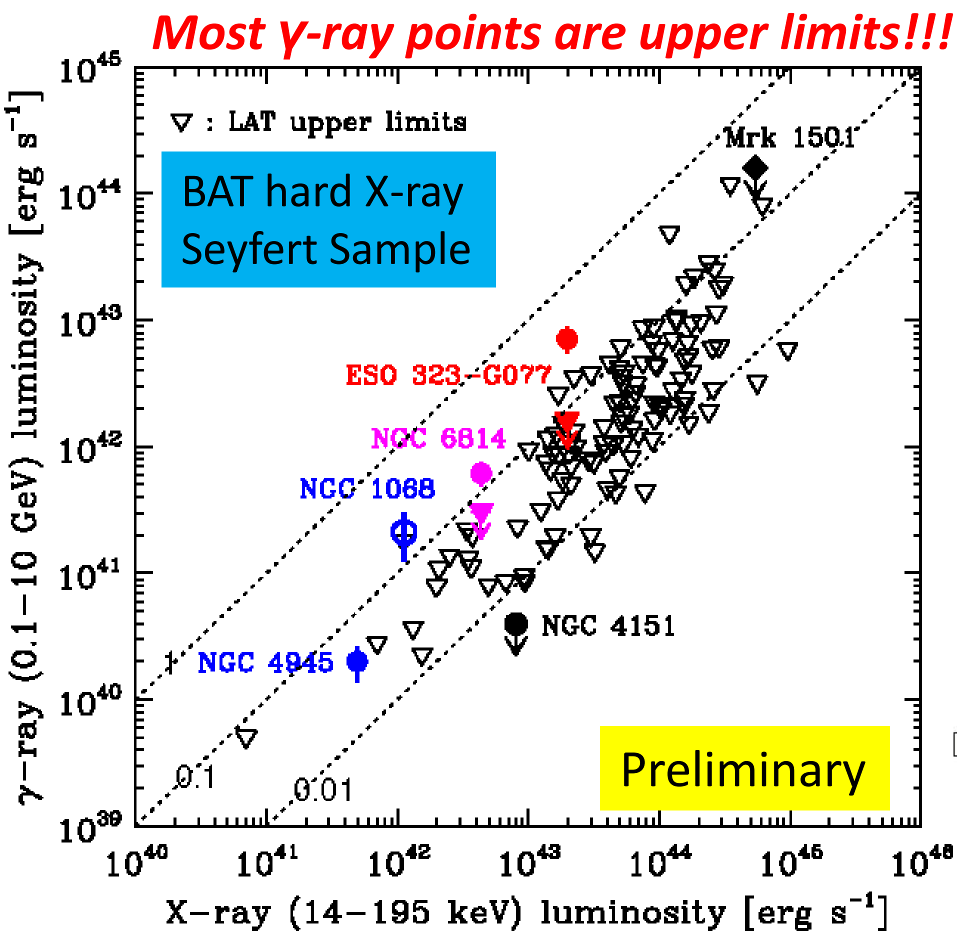
- Distribution of mixing parameter η for BLRGs and Sy-1s. Relative contribution of the nuclear jets to the accreting matters is > 1 % for BLRGs, whilst < 0.1 % for Sy-1 galaxies

Future LATdetection; more thought

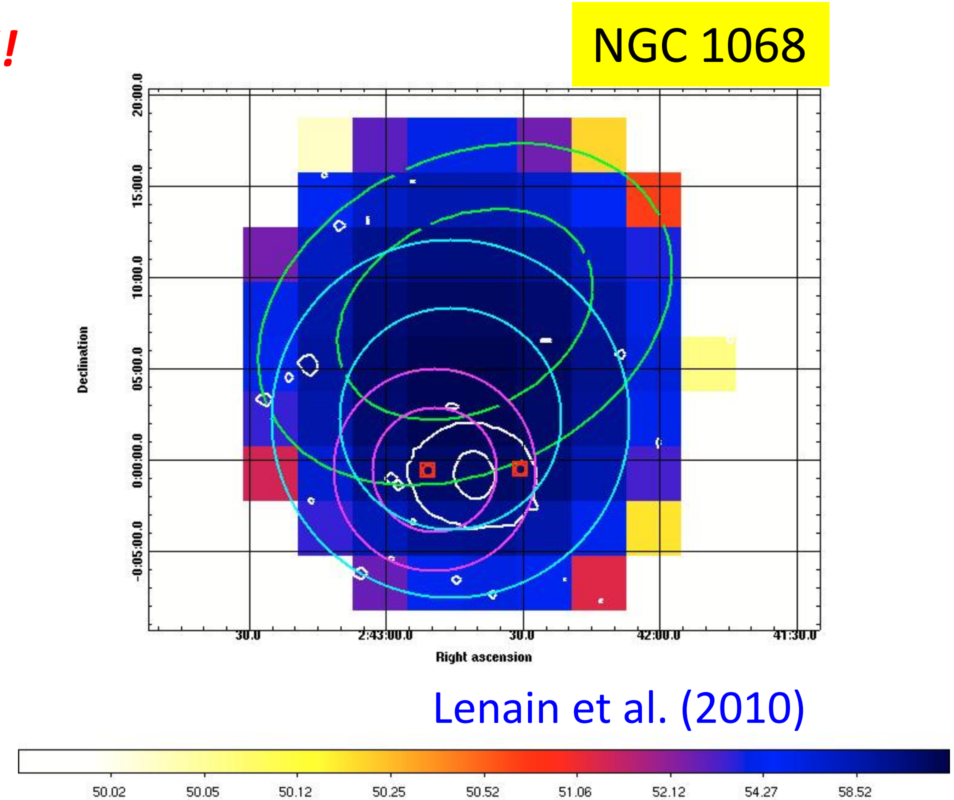


- The γ-ray-to-radio energy flux ratios for the two BLRGs (and of Pictor A) detected by Fermi LAT are of the order of 100, while the corresponding UL for all other objects are much above this value
- BLRGs are in principle γ-ray loud, but their detections in γ-rays are at present just limited by the sensitivity of Fermi-LAT

AGN related γ-rays from Seyferts?

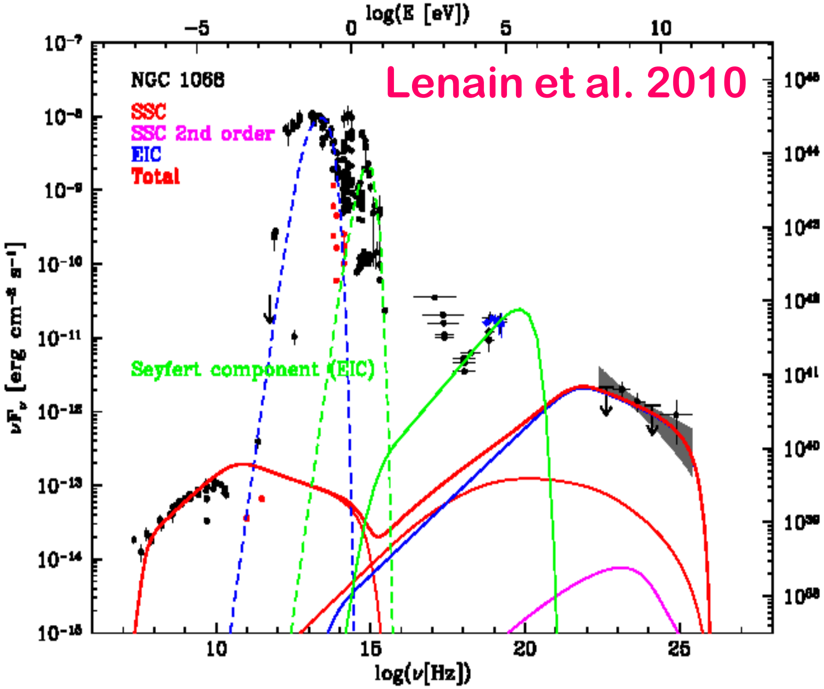


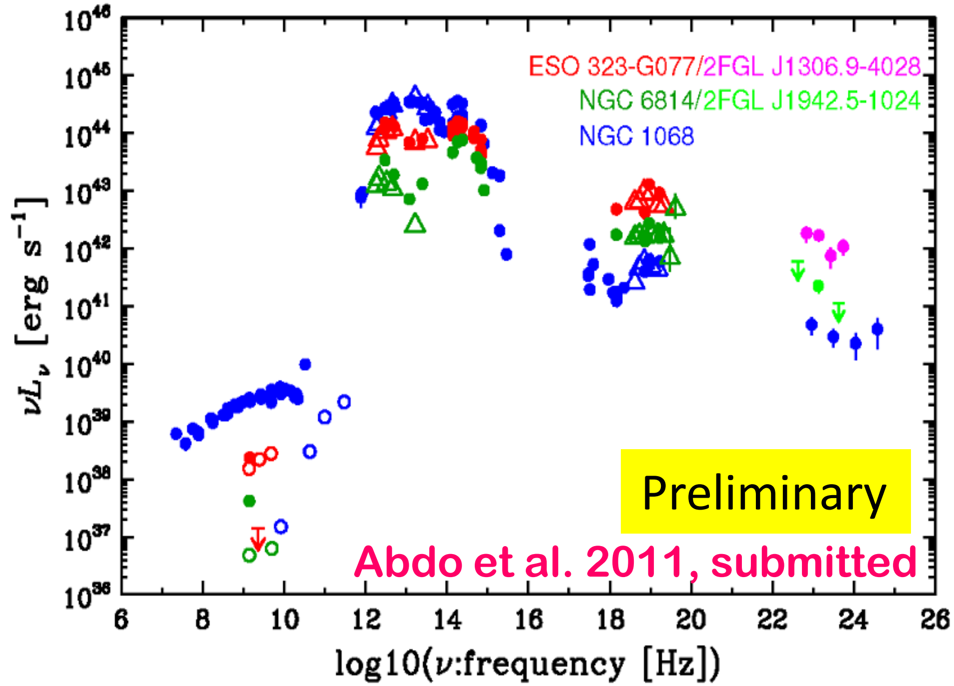
**CA: Bechtol , Hayashida, Madjeski, Stawarz (ApJ, submitted)*



- **Most BAT Seyfert sample provides only UL**
- **But, γ-ray emission already detected from a few Sy-2s?**

γ-ray Emission from Sy?





- "Jet model" applied in Lenain et al. (2010)
- Both γ-ray detcted Sy-2s, **NGC 1068 and NGC 4945**, strong **starburst activity.** Therefore, it may be possible that observed γ-ray is due to SB rather than non-thermal jet emission
- Same applied for possible association of ESO 323-G077, NGC 6814

Conclusion

- After 3 years of successful operation, Fermi-LAT provided various new insights into the physics of AGN Jets

- Not only blazars, but misaligned radio galaxies are now being important γ–ray source population. In this context, observations and detections of several BLRGs are particularly important to test the AGN unification scheme
(i.e., viewing angle, radio-loud/quiet classification)

- Further new surprise is the detection of γ-ray lobe, both in our Galaxy as well as in nearby radio galaxy. The γ-ray imaging of these extended lobes may provide clues to the high energy cosmic-ray acceleration in extragalactic sources