

THE INNER JET REGION IN THE GAMMA-RAY BLAZAR MRK 501



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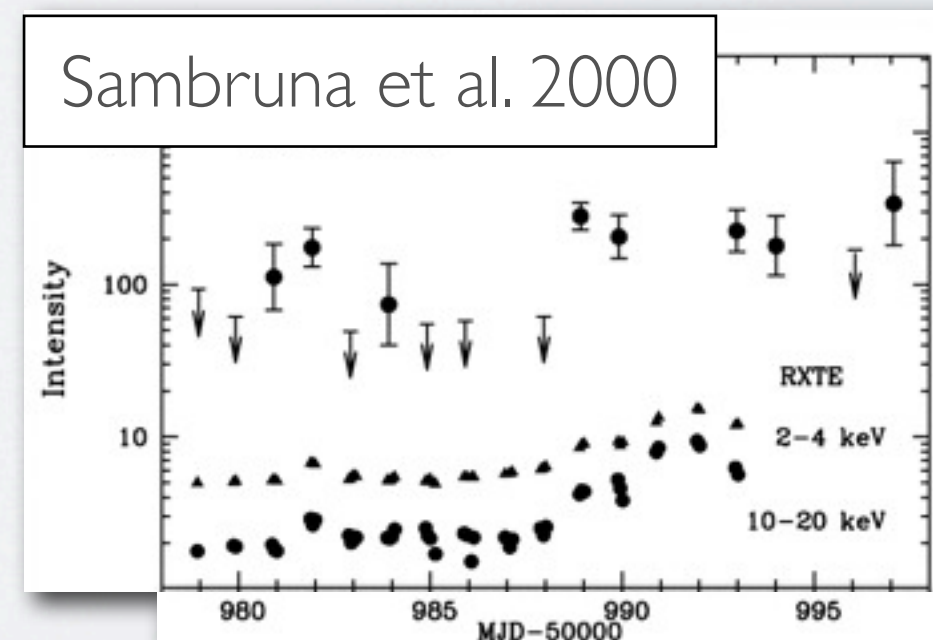
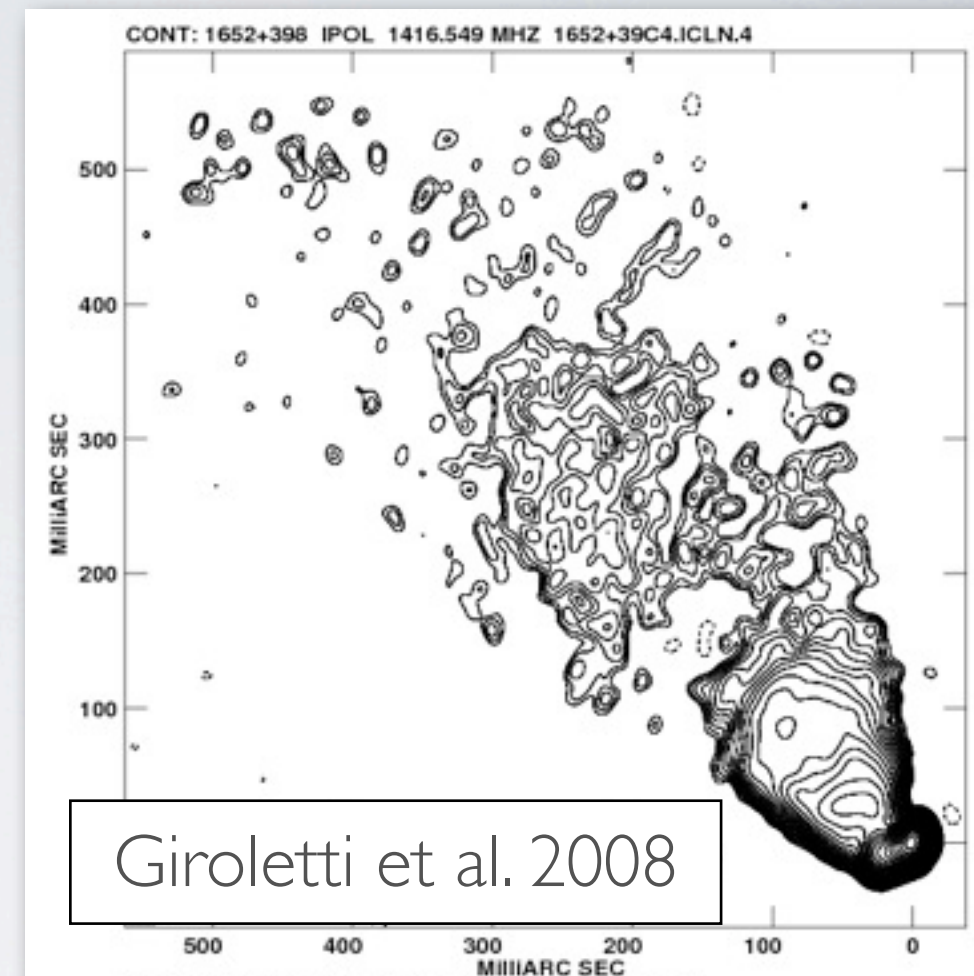
in collaboration with G. Giovannini (1), M. Kino (2), S.
Koyama (2), T. Krichbaum (3) (1 INAF/IRA, 2 NAOJ, 3 MPIfR)
and many others...

MY OUTLINE

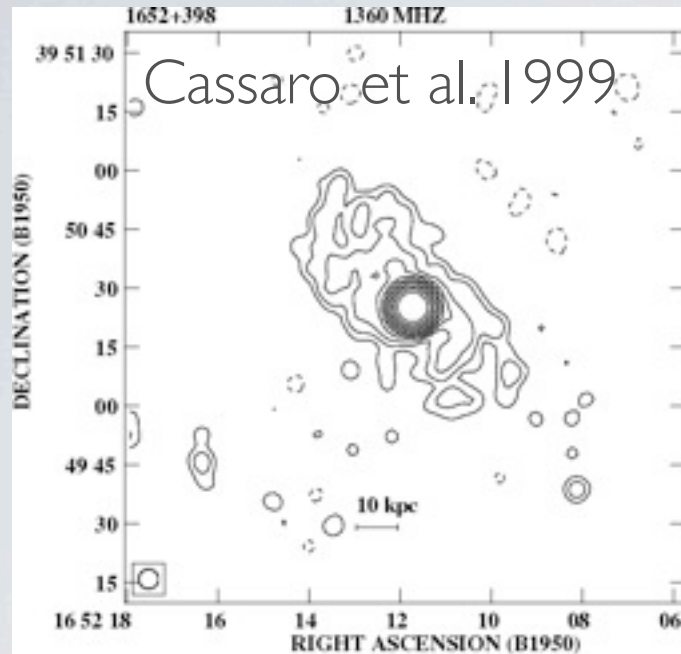
- **Source introduction:** MWL and radio background. Benefits of different strategies for achieving high resolution.
- Quick description of **VSOP results**, implications and open questions (in particular for limb brightening)
- Goals and challenges of **mm-VLBI observations**: results from 2005 and preliminary results from 2008
- Relevance for **MWL** observations and recent **Fermi campaigns**
- **Perspectives** for 2012 observations and future developments

MARKARIAN 501

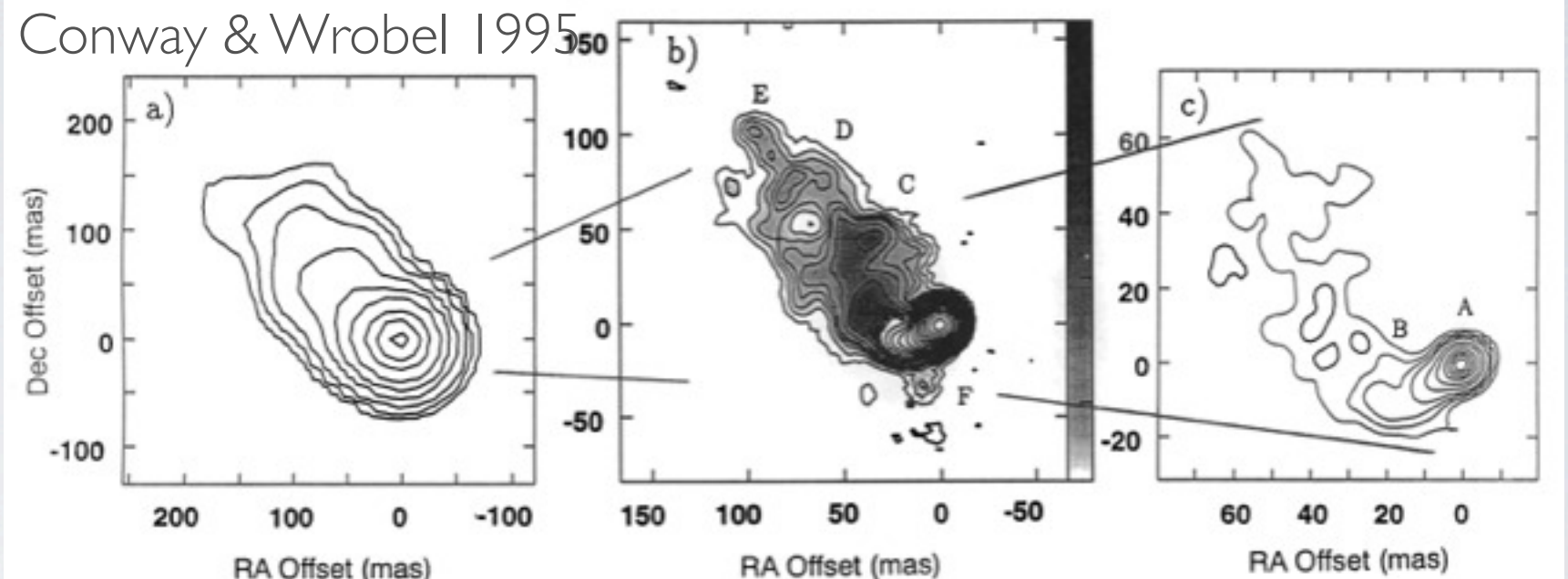
- Markarian 501 is one of the most remarkable blazars - **mostly because of its proximity**
 - a bright radio source for which VLBI provides a sub-parsec linear resolution (1 mas \sim 0.67 pc)
 - one of the first sources detected at X-ray, Very High Energy (VHE), showing very fast and correlated variability
 - one of the very few high peaked BL Lacs (HBLs) detected at MeV/GeV energy by EGRET
- **an ideal target for jet studies, with (combined) high resolution imaging & MWL spectral energy distribution (SED) modeling**



THE RADIO JET



Conway & Wrobel 1995



- Source is two-sided on kiloparsec scale, but one sided out to at least 500 pc (at the $25 \mu\text{Jy beam}^{-1}$ level)
- Jet changes position angle from 45° to 170°
- No superluminal motion detected - a surprise given the high Doppler required by high energy
- Actually, no real motion detected at all - even more a puzzle
- High angular resolution necessary for component identification and investigation of the jet structure

STRATEGIES FOR HIGH RESOLUTION OBSERVATIONS IN BLAZARS



- Short wavelengths: mm-VLBI, sensitive to inverted spectrum, self-absorbed regions near the BH

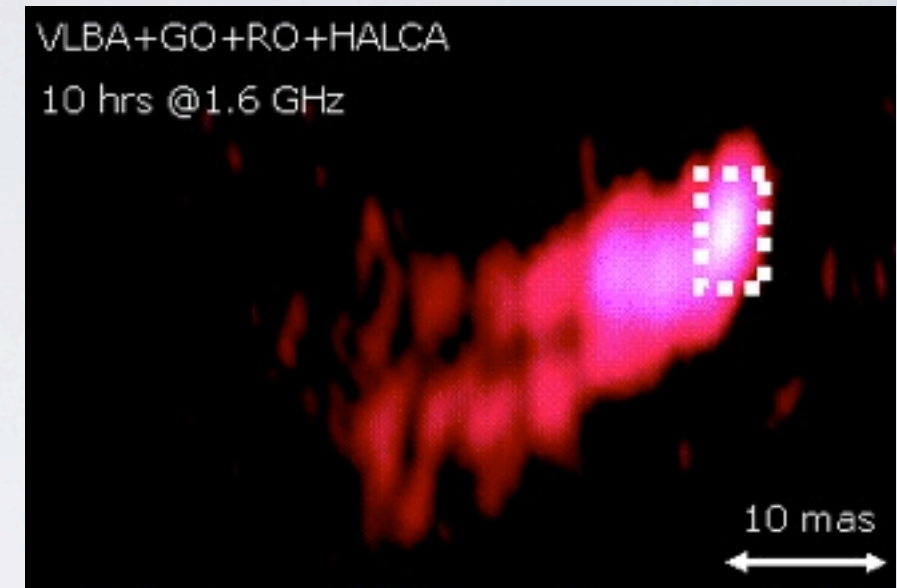
$$\theta = \frac{\lambda}{B}$$



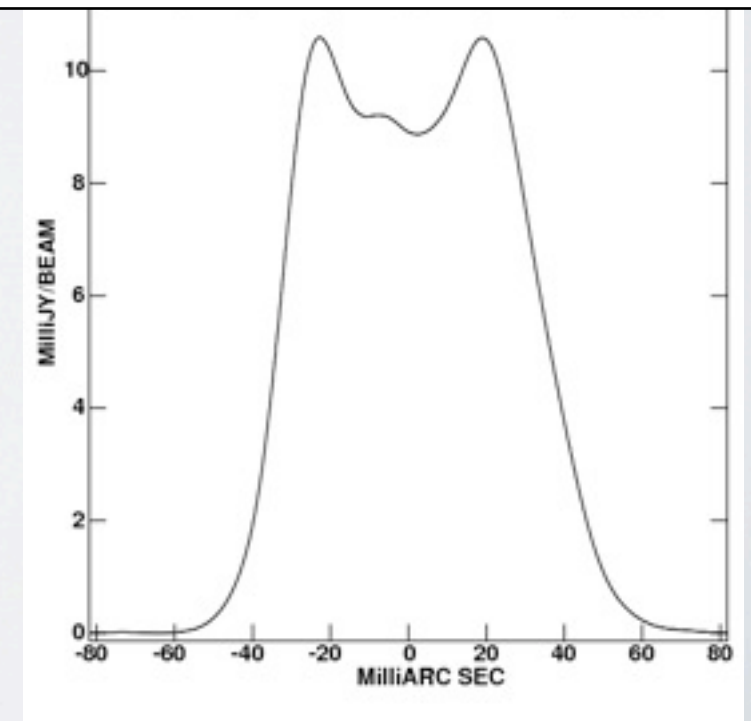
- Long baselines: space-VLBI, sensitive to steep spectrum features downstream the jet; historically, available first!

SPACE VLBI OBSERVATIONS OF MRK501

- No proper motion over 9 epochs
- compact structures are resolved in higher resolution images
- limb brightening clearly revealed by VSOP (and later confirmed on larger scales by HSA)
 - interpreted in terms of velocity structure, with a fast inner spine and a slower external shear @intermediate viewing angle
- important for theoretical jet models - e.g. Ghisellini+2005
- where is its origin?
- need even better resolution!

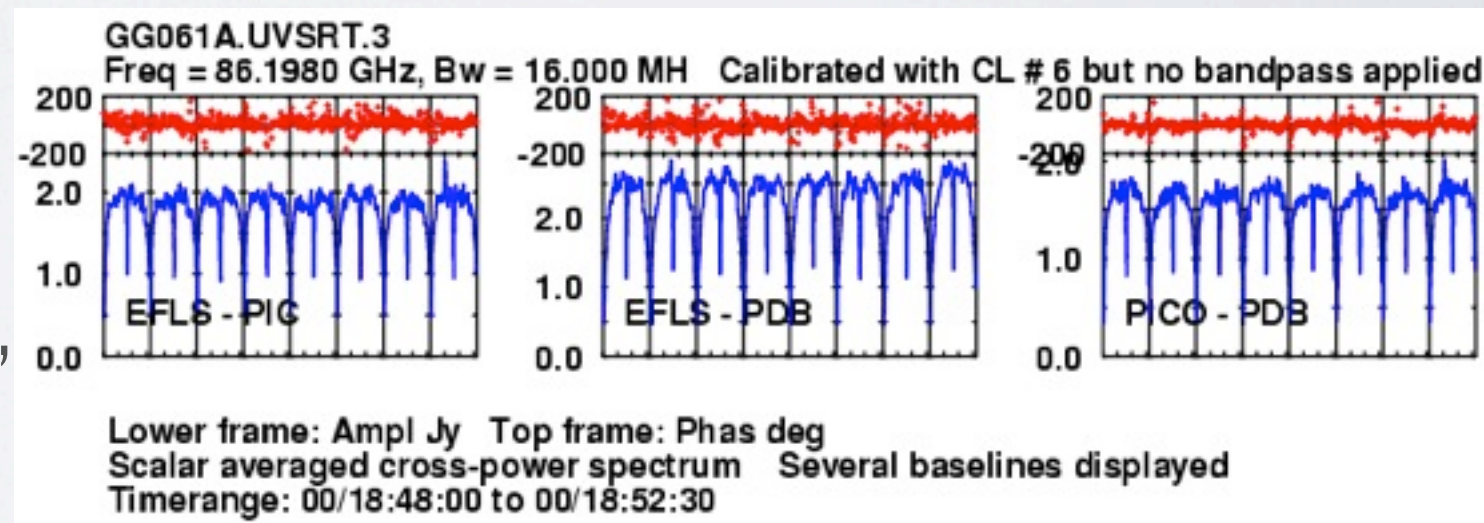


Giroletti et al. 2004, 2008



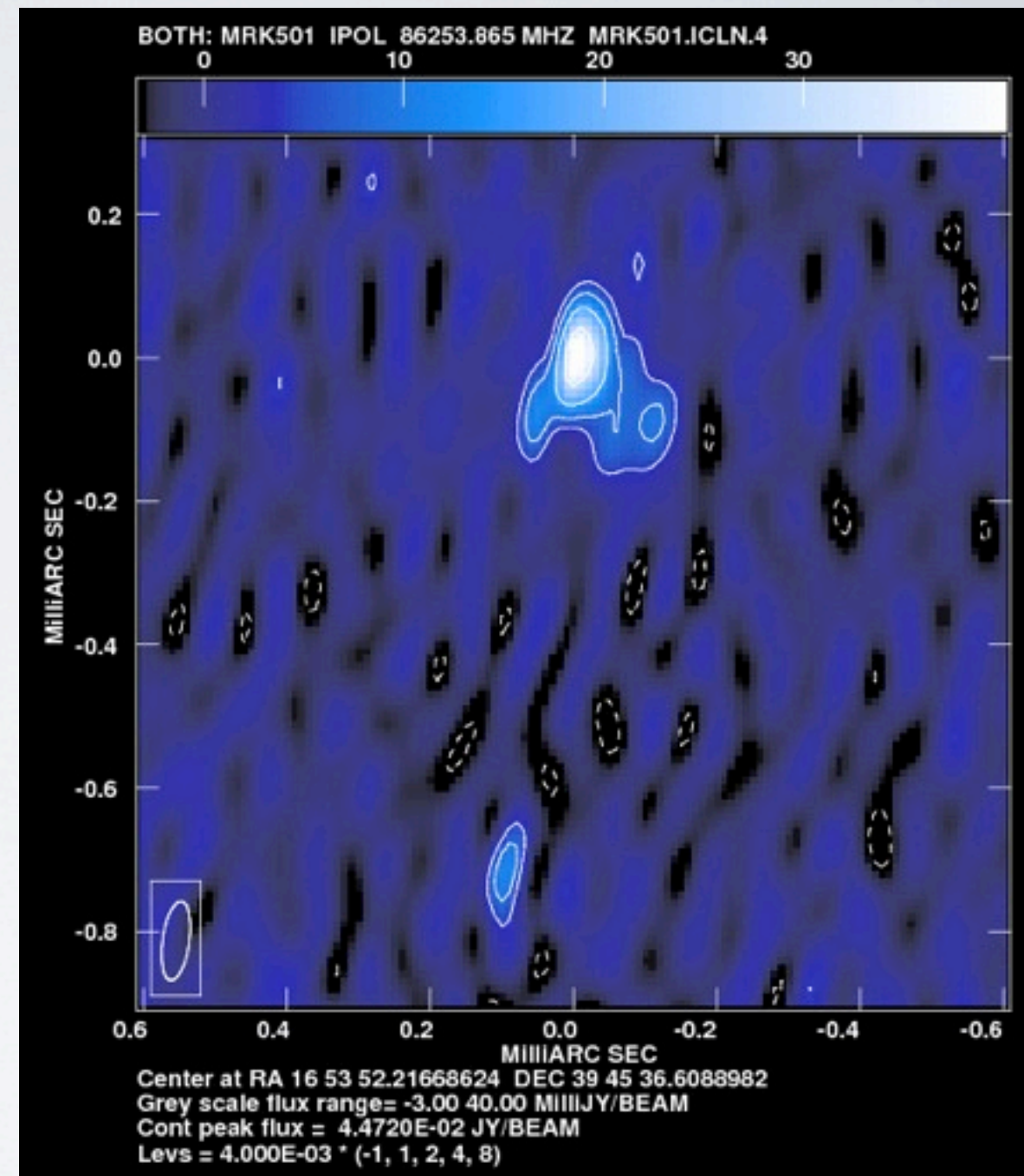
GMVA VLBI OBSERVATIONS OF MRK501

- Mrk 501 is at the threshold of the baseline sensitivity for the GMVA (0.1-0.4 Jy)
- a challenging experiment was tried in 2005. Thanks to good weather condition at Eb, PV, PdBI, actual imaging was possible
- Transatlantic fringes detected, too, resulting in resolution ~ 0.05 mas (~ 0.03 pc)



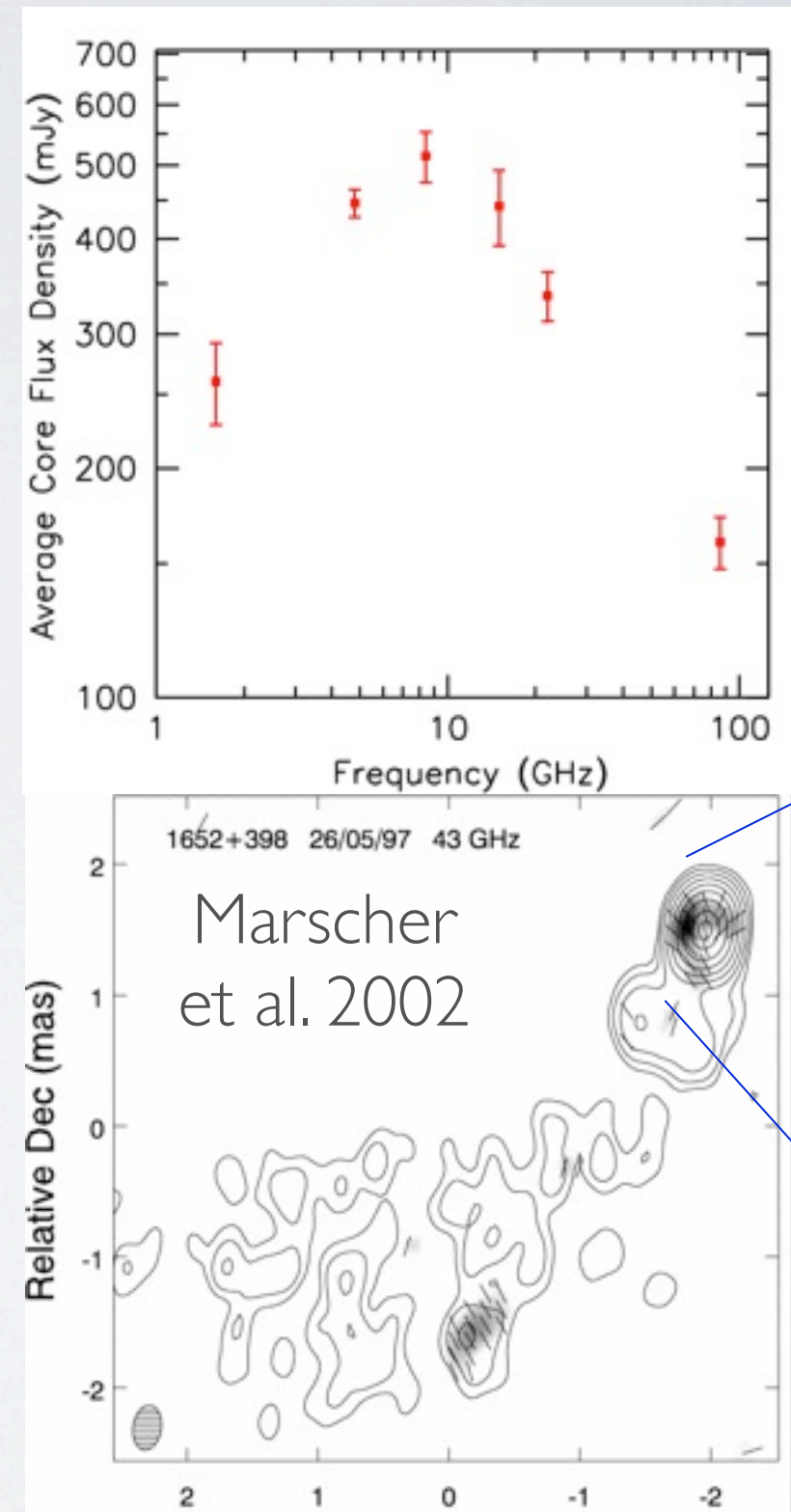
- resolution $\sim 110 \times 40 \mu\text{as}$, rms ~ 1.5 mJy/beam
- core unresolved at 86 GHz, with size smaller than 0.03 pc (gaussian fit)
- $M_{\text{BH}} = 10^9 M_{\text{sun}}$, $R_S = 10^{-4}$ pc: core size $\sim 300 R_S$
- $T_B > 4 \times 10^9$ K
- $S_t = 150$ mJy, $S_c = 45$ mJy
- limb brightening in core region?
- 10 mJy component @ 0.73 mas, PA 172°
- cleaning, model fitting, self-calibration difficult

Giroletti et al. 2008



GMVA OBSERVATIONS OF MRK 501: RESULTS FROM 2005

- steep high frequency spectrum,
turnover @ ~ 8 GHz.
 - magnetic field in the range 0.01 – 0.03 G
 - structure within the “core”
 - starting velocity and acceleration?
 - constraints from γ -ray emission? GLAST, AGILE
- jet structure
 - did we eventually find a "real" jet knot?
 - orientation, limb brightening seem to be in agreement with VLBA at 43 GHz

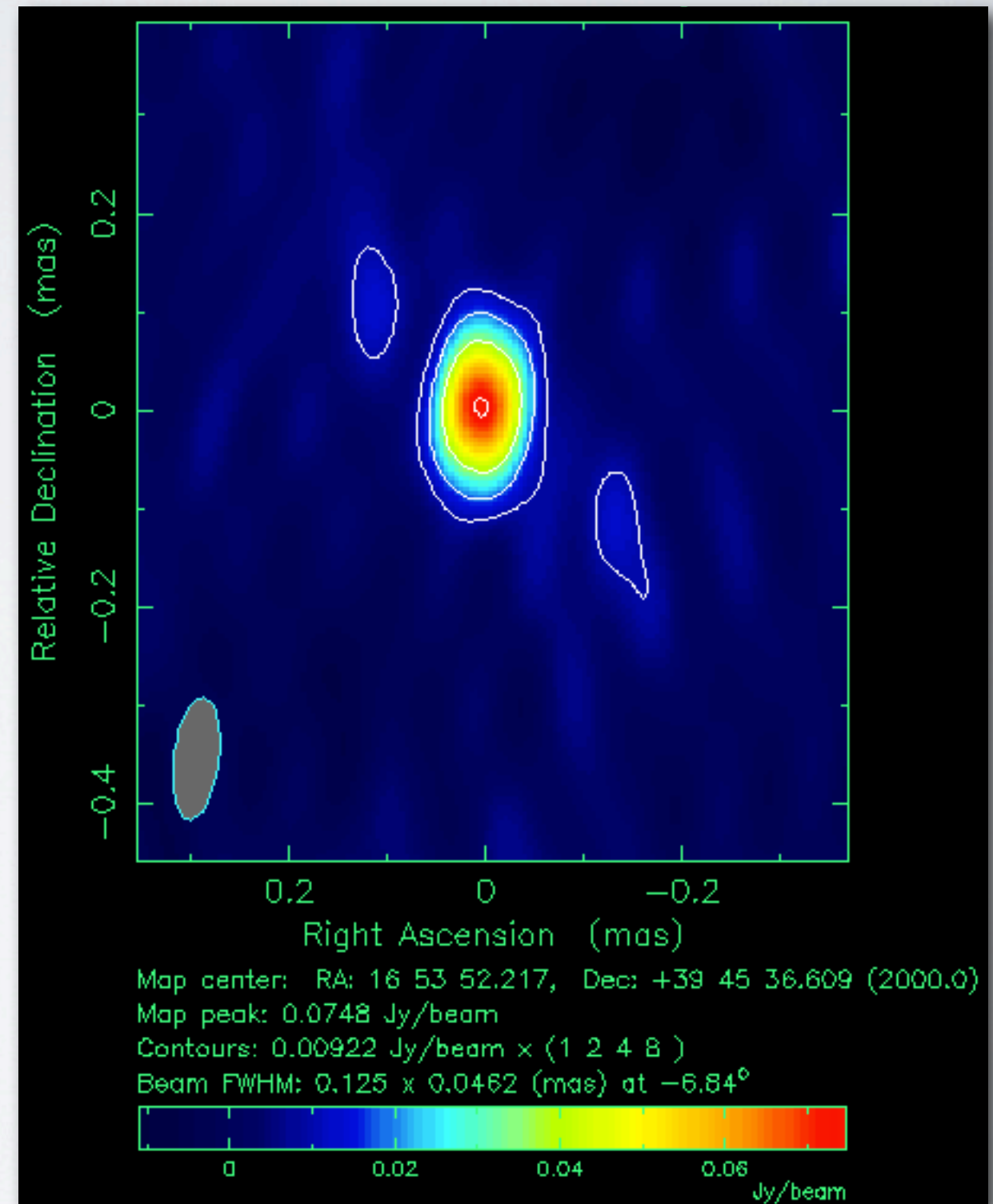


OPEN QUESTIONS

- Confirmation of limb brightening, jet knot
- MWL connection: Fermi and VHE observatories interested in the source, and triggering lots of other MWL facilities
- New observations awarded for May 2008, during big MWL campaign, with mixed success
 - very bad weather at Pico Veleta and other stations
 - Fermi launch delayed, so a big piece of SED is missing

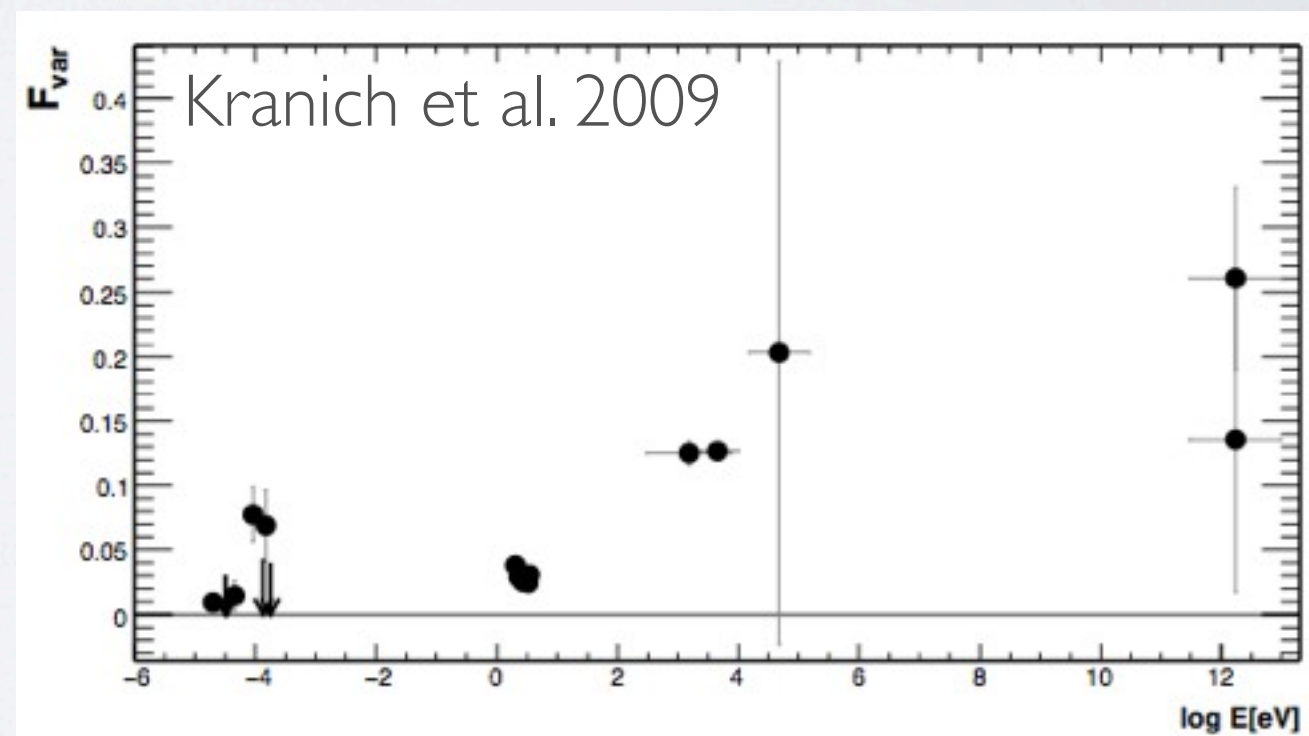
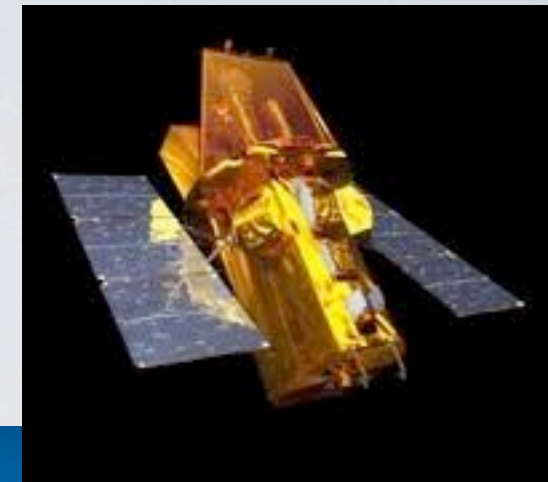
GMVA OBSERVATIONS OF MRK 501: THE 2008 DATA

- New 3mm observations on 8 May 2008 with standard GMVA
- Despite difficult observing conditions, Mrk501 is detected, again, with $S \sim 75$ mJy
- High S/N on Eu-Eu baselines, good S/N on VLBA-VLBA baselines, mixed results on Eu-VLBA baselines: the source is significantly resolved



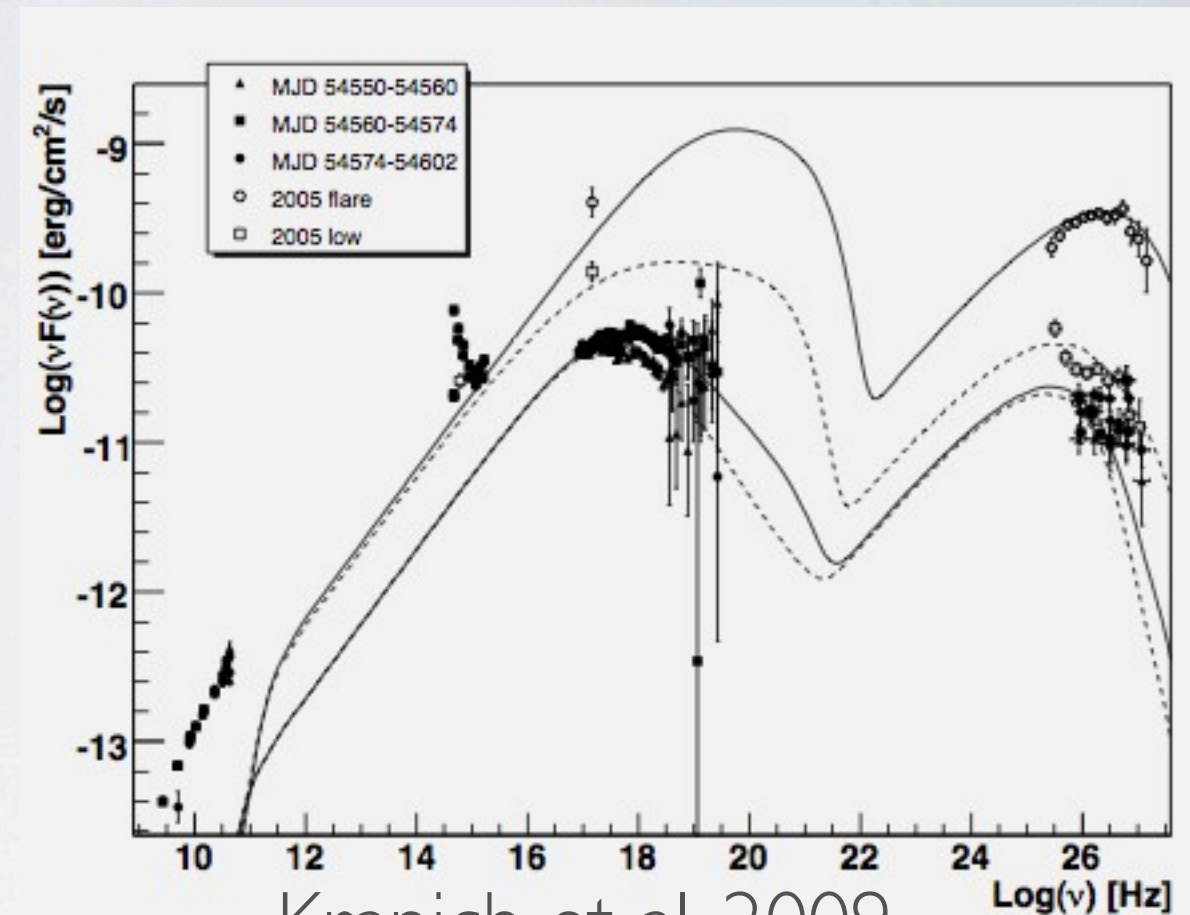
THE 2008 MWL CAMPAIGN

- Even if Fermi was not flying, the MWL campaign took place
- Observations in radio (Effelsberg, IRAM, Medicina, Metsahovi, Noto, RATAN-600, VLBA), optical (KVA), UV (Swift/UVOT), X-rays (RXTE/PCA, Swift/XRT and Swift/BAT) and γ -rays (MAGIC, Whipple, VERITAS)
- Data taken between March 25 and May 16, 2008 (Fermi was then launched on June 11)
- Mrk 501 was in a low state (VHE flux of $\sim 20\%$ Crab); nevertheless, significant flux variations observed in X-rays and γ -rays, with increased variability going from radio to γ -ray energies.



2008 MWL CAMPAIGN RESULTS

- SED during the two different emission states well described by a homogeneous one-zone synchrotron self-Compton model. The high emission state was satisfactorily modeled by increasing the amount of high energy electrons with respect to the low emission state.



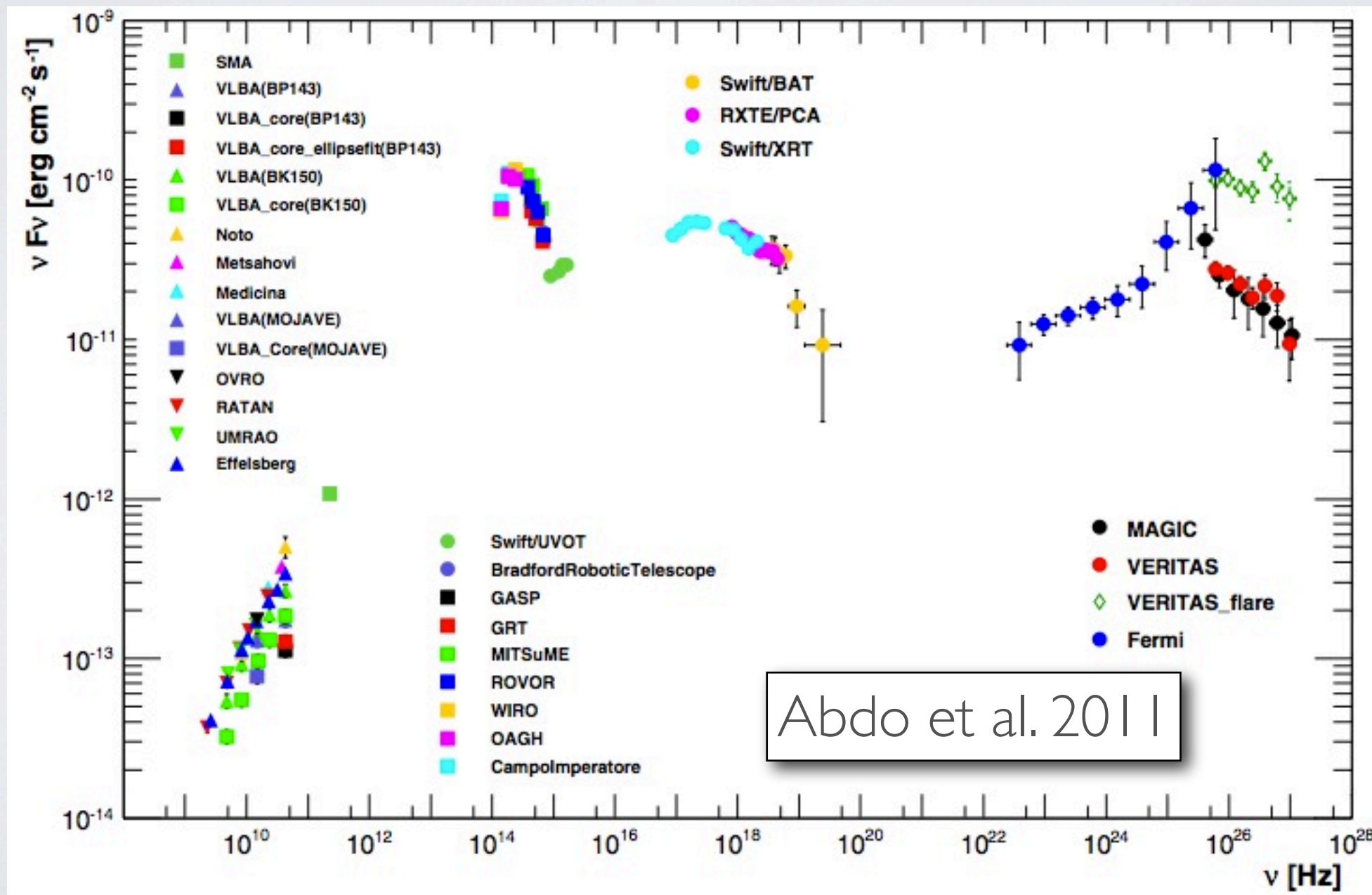
Kranich et al. 2009

- The size of the emitting region matches well with the GMVA resolution!

	2008 high state	2008 low state	2005 high	2005 low
γ_{break}	$2.6 \cdot 10^5$	$2.2 \cdot 10^5$	$1.0 \cdot 10^6$	$1.0 \cdot 10^5$
n_1	2.0	2.0	2.0	2.0
n_2	3.9	4.2	3.9	3.2
B [G]	0.19	0.19	0.23	0.31
K [cm ⁻³]	$1.8 \cdot 10^4$	$1.8 \cdot 10^4$	$7.5 \cdot 10^4$	$4.3 \cdot 10^4$
R [cm]	$3 \cdot 10^{15}$	$3 \cdot 10^{15}$	$1 \cdot 10^{15}$	$1 \cdot 10^{15}$
δ	12	12	25	25

FOLLOWING CAMPAIGNS: 2009

- Fermi-LAT led MWL campaign in 2009 March 15—August 1, with participation from many observatories



2009 MWL CAMPAIGN RESULTS AND PROSPECTS...

- Gamma ray flux \sim a few $\times 10^{-8}$ ph cm $^{-2}$ s $^{-1}$; no outstanding flare but \sim 30d time scale variability
- Gamma ray photon index between 1.52 ± 0.14 and 2.51 ± 0.20 ; average of 1.78 ± 0.03 and no correlation with flux
- Broadband SED well described by 1-z SSC with total jet power of 10^{44} erg s $^{-1}$, i.e. $\sim 10^{-3}$ L $_{\text{Edd}}$.
- Continued observations needed (more constraints, short and long term variability, different physical states, ...): campaign extended in 2010, 2011, and 2012
- **New Mrk501 GMVA observations this May! ...looking forward to the results**

PERSPECTIVES FOR ALMA AND VLBI

- Sensitivity on long baselines is clearly an issue in Mrk 501
- Source is significantly resolved: a sensitive station with long baselines and good weather is essential for success
- Mrk 501 is a special source because of its proximity, but it's only the tip of the iceberg of a huge population of TeV blazars
- These objects are all rather weak radio sources, and CTA will greatly enlarge the interest in them

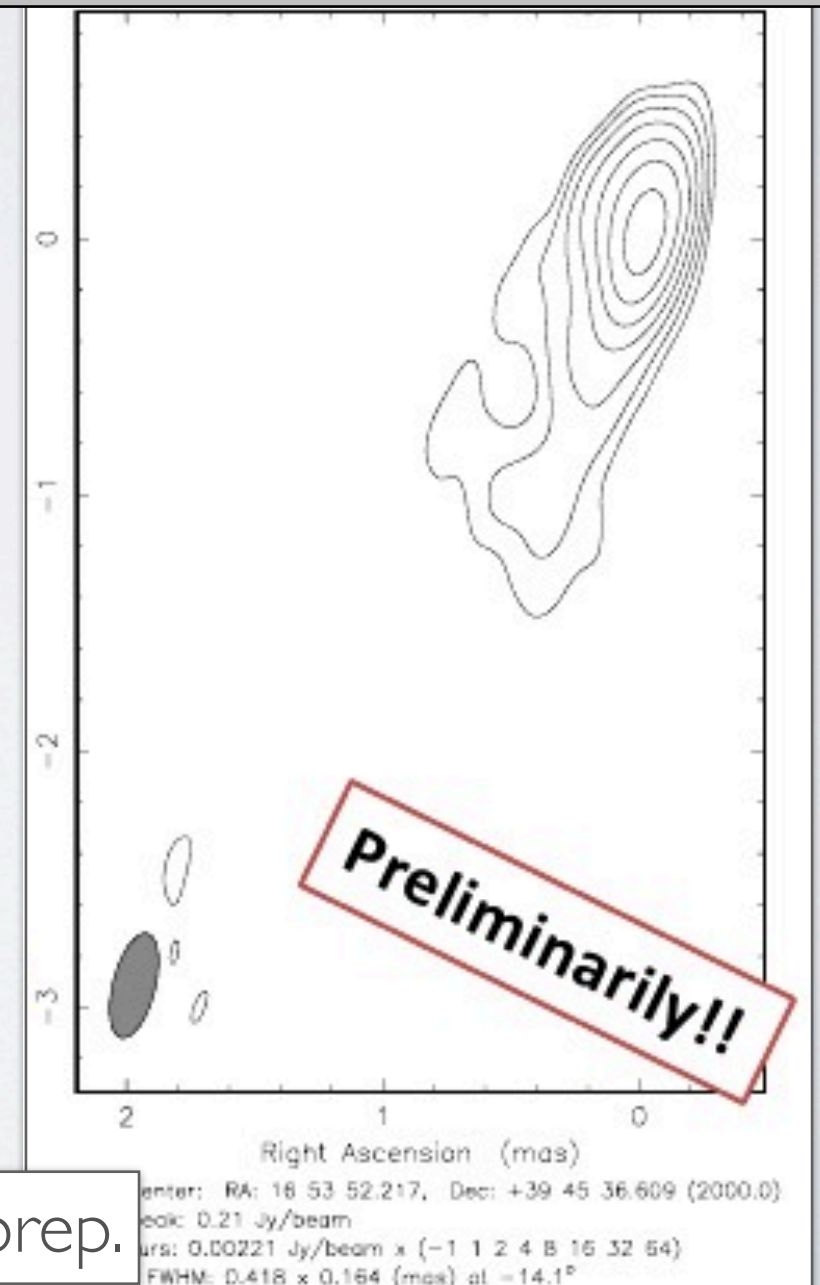


PROBING RADIAL POSITION WANDER OF MRK 501 CORE WITH VERA & VLBA 7MM

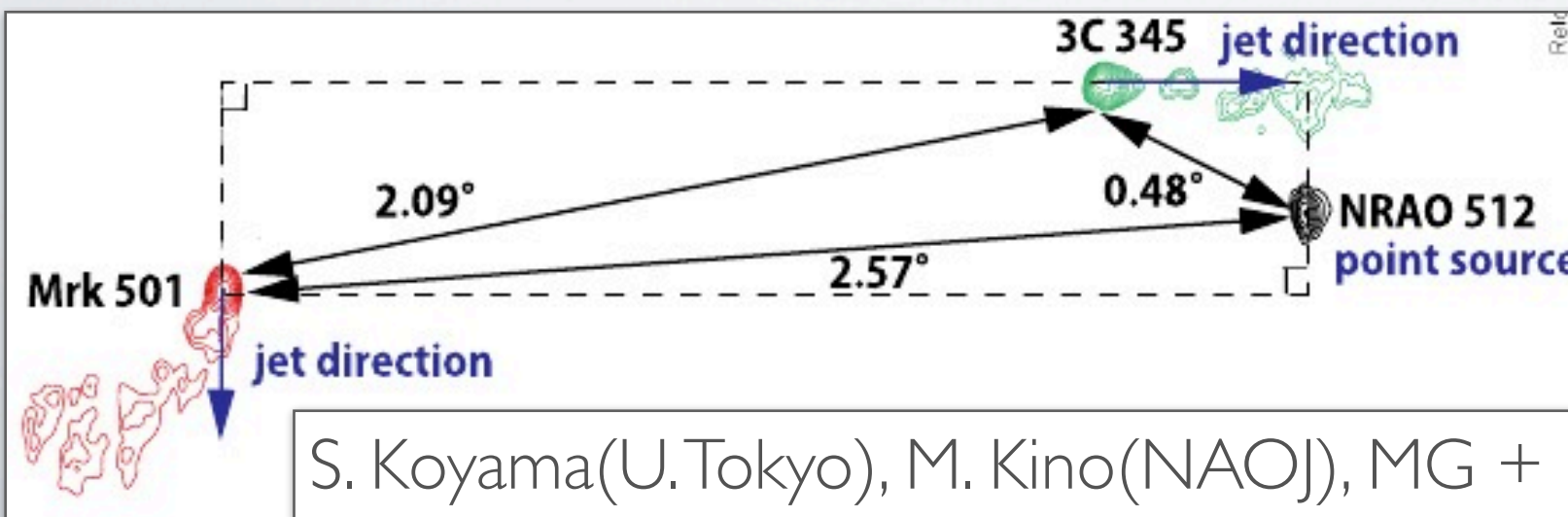
Summary of our observations

- VERA observation
 - 2010 Oct.~2012 Feb.
 - 14 epochs (under analysis; S. Koyama Ph.D. thesis)
- VLBA observation
 - 2012 Feb.~
 - 4 epochs (under analysis)
 - 2 epochs (planning)

'fringe-fitting' image of Mrk 501 at VLBA 7mm



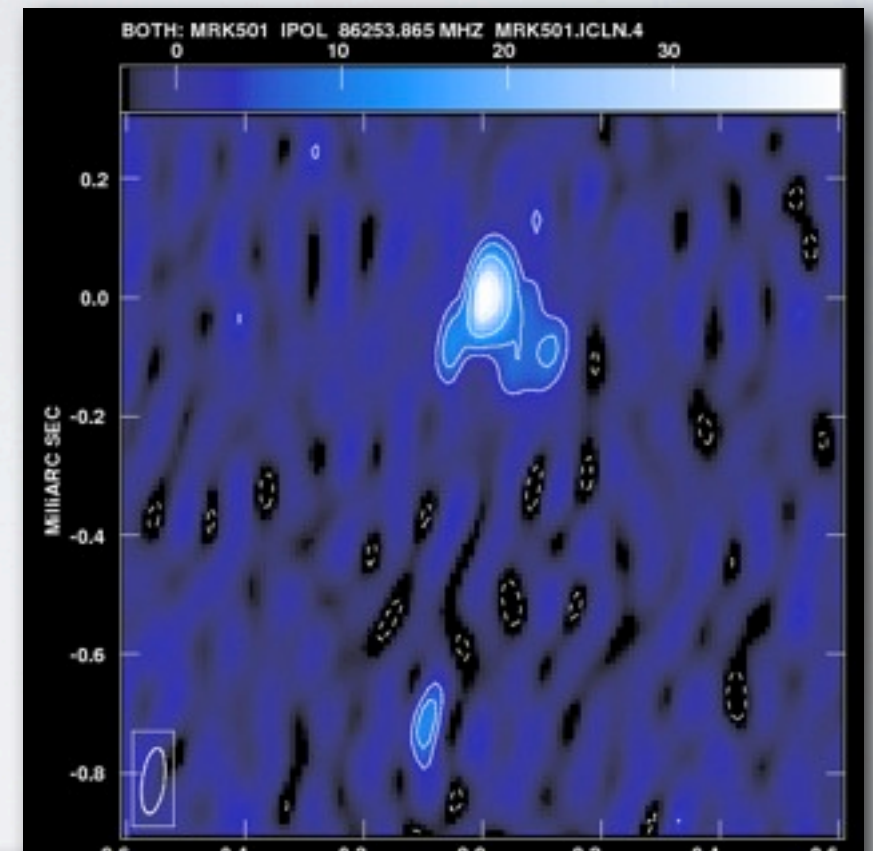
Configurations of Mrk 501 & calibrators



S. Koyama(U.Tokyo), M. Kino(NAOJ), MG + in prep.

CONCLUSIONS

1. Current Global mm-VLBI array can routinely detect and image sources at ~ 0.1 Jy flux density level, e.g. Mrk 501
2. Connection to MWL and high energy properties is possible but has significant limits with current resources
3. Inclusion of ALMA would greatly improve our capabilities for blazar modeling (more sources, better time coverage, higher fidelity, ...)



REFERENCES

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- Kranich et al. 2009, arXiv:0907.1098
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ABSTRACT

- We observed Mrk501 with the Global Millimeter VLBI Array (GMVA) in 2005 and 2008. The source was expected to be at the sensitivity threshold for the GMVA, given its flux density of a few 100's mJy. We successfully detected the source in both observations. In the first run, we detected a tentative structure of limb brightening within the $\sim 1000 R_S$ region. In the second epoch, despite the bad weather and a lower final image fidelity, we still detect the source on transatlantic baselines. Since the source was observed during a MWL (radio to TeV) campaign, our data provide for the first time the possibility to study the Spectral Energy Distribution at the highest possible resolution with simultaneous data. Indeed, the GMVA resolution matches the emission size required by SED modeling and provide useful independent constraints on the jet parameters.