VLBI in the GLAST era – AGN studied with few 10 micro-arcsecond resolution

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(on behalf of many people involved in the GMVA)

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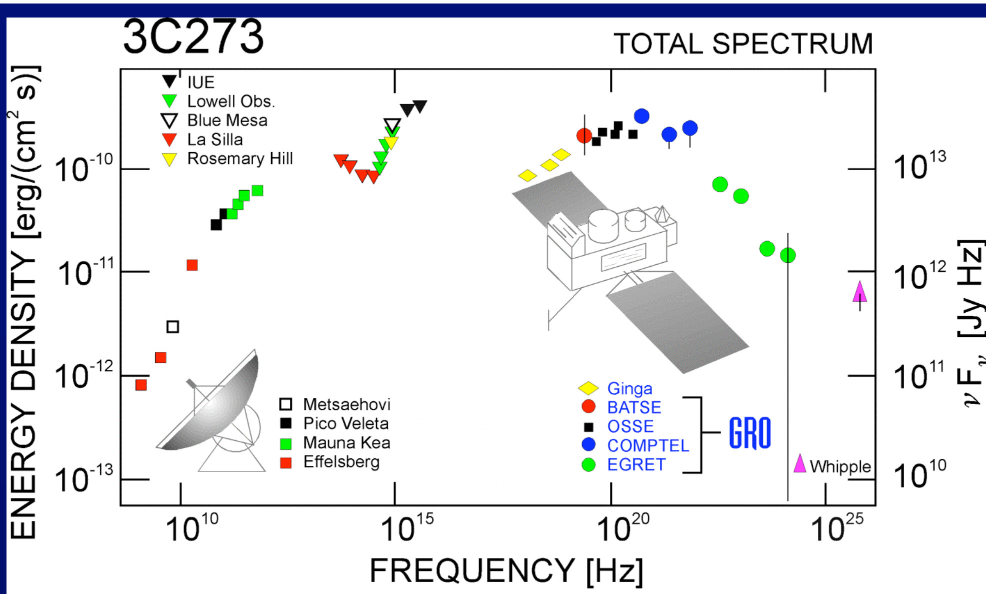
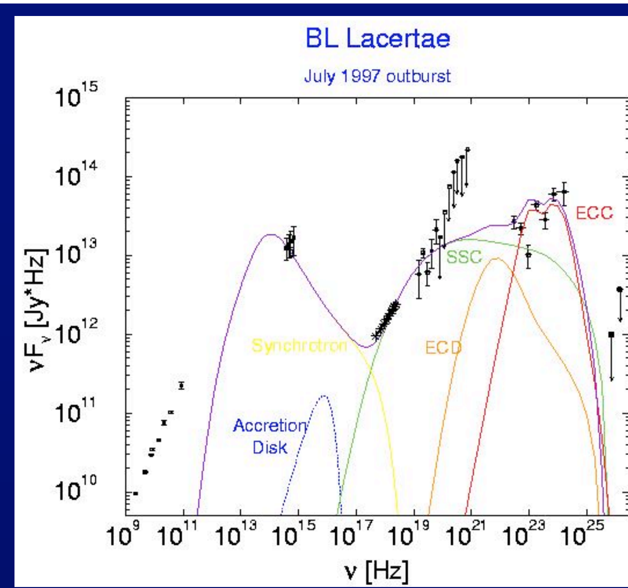
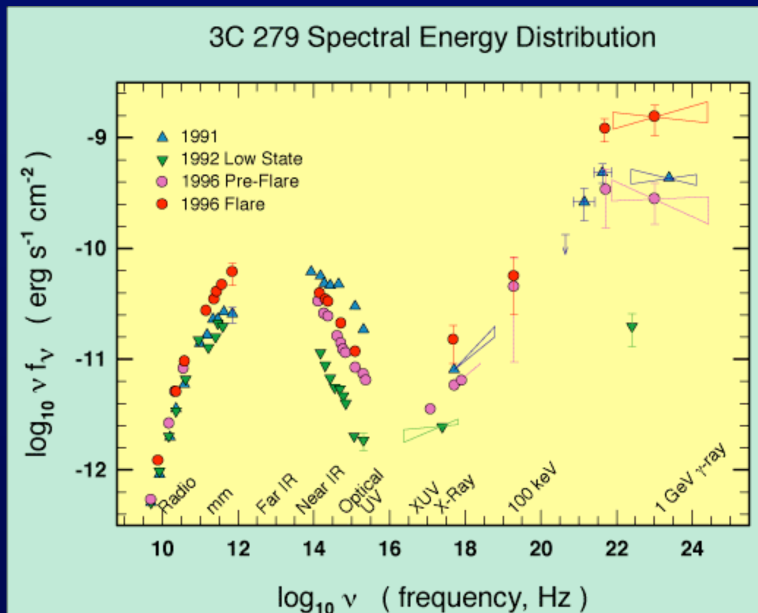
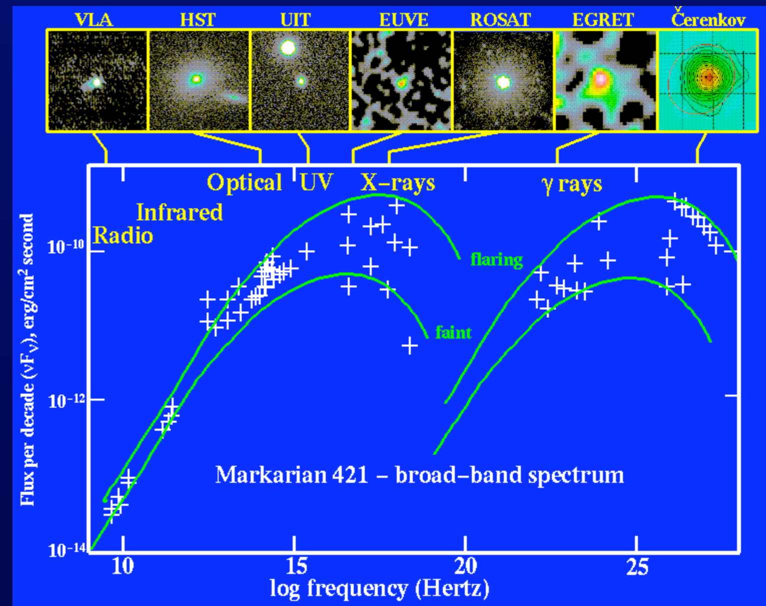


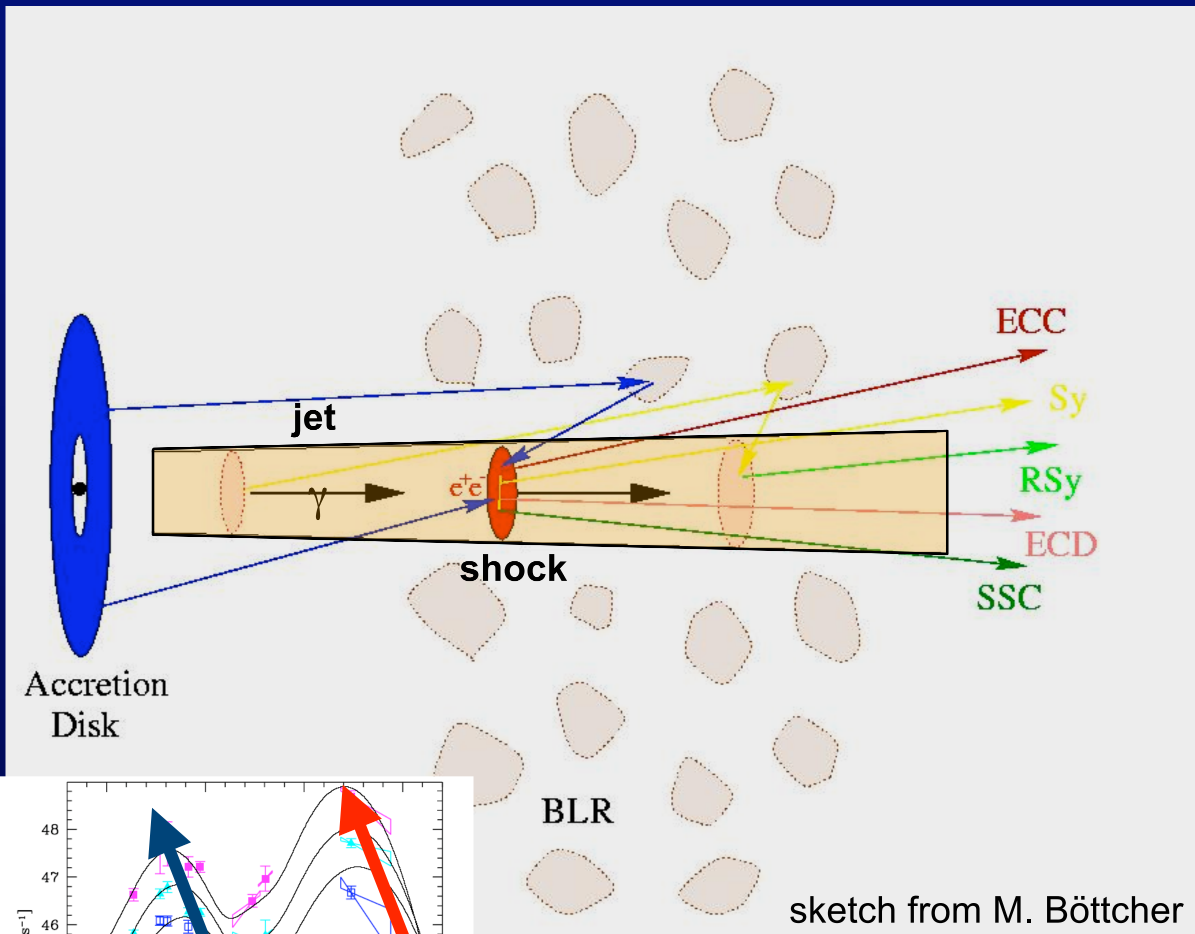






Examples of the spectral energy distribution (SED) of Blazars: Need full electromagnetic spectrum frequency coverage to study correlated variability !

The Origin of γ – rays in Blazars ?



Seed photons for inverse Compton scattering from:

ECC: External Comptonization from BLR Clouds

Sy: direct Synchrotron, shock acceleration

RSy: Reflected Synchrotron Comptonization

ECD: External Comptonization from Disk

SSC: Synchrotron Self-Compton in Jet

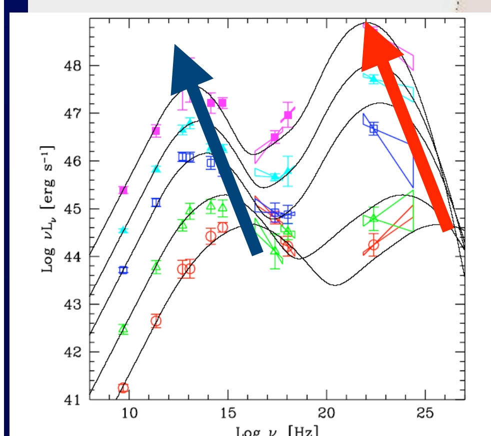
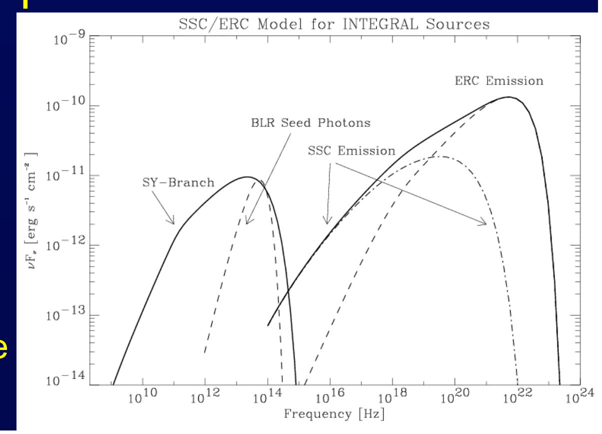
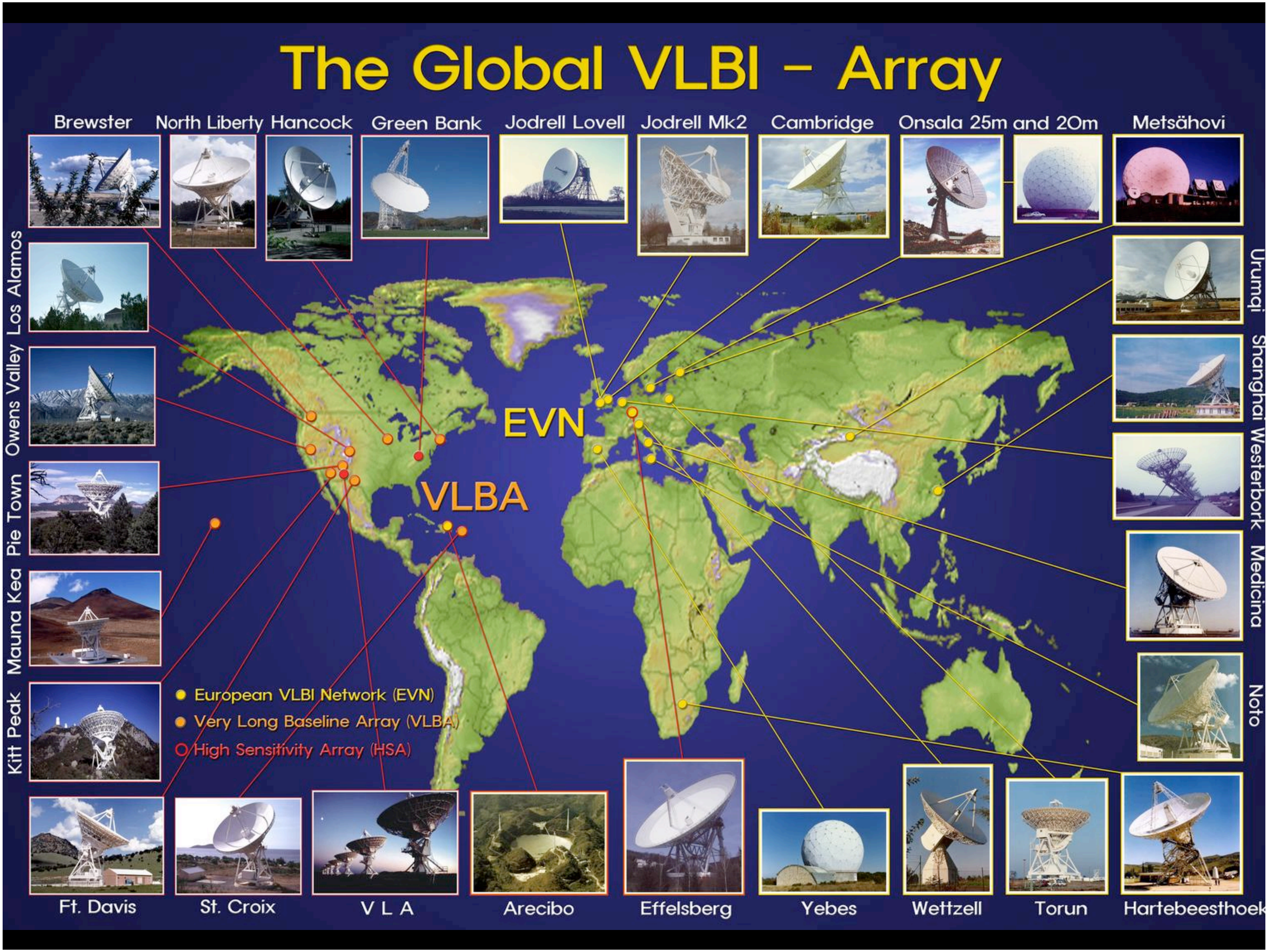


Fig. 10. The average SED of the blazars studied by Fossati et al. (1998), including the average values of the hard X–ray spectra. The thin solid lines are the spectra constructed following the parameterization proposed in this paper.

standard model: $L_{ERC} / L_{SSC} \sim \delta^2 / n_e$



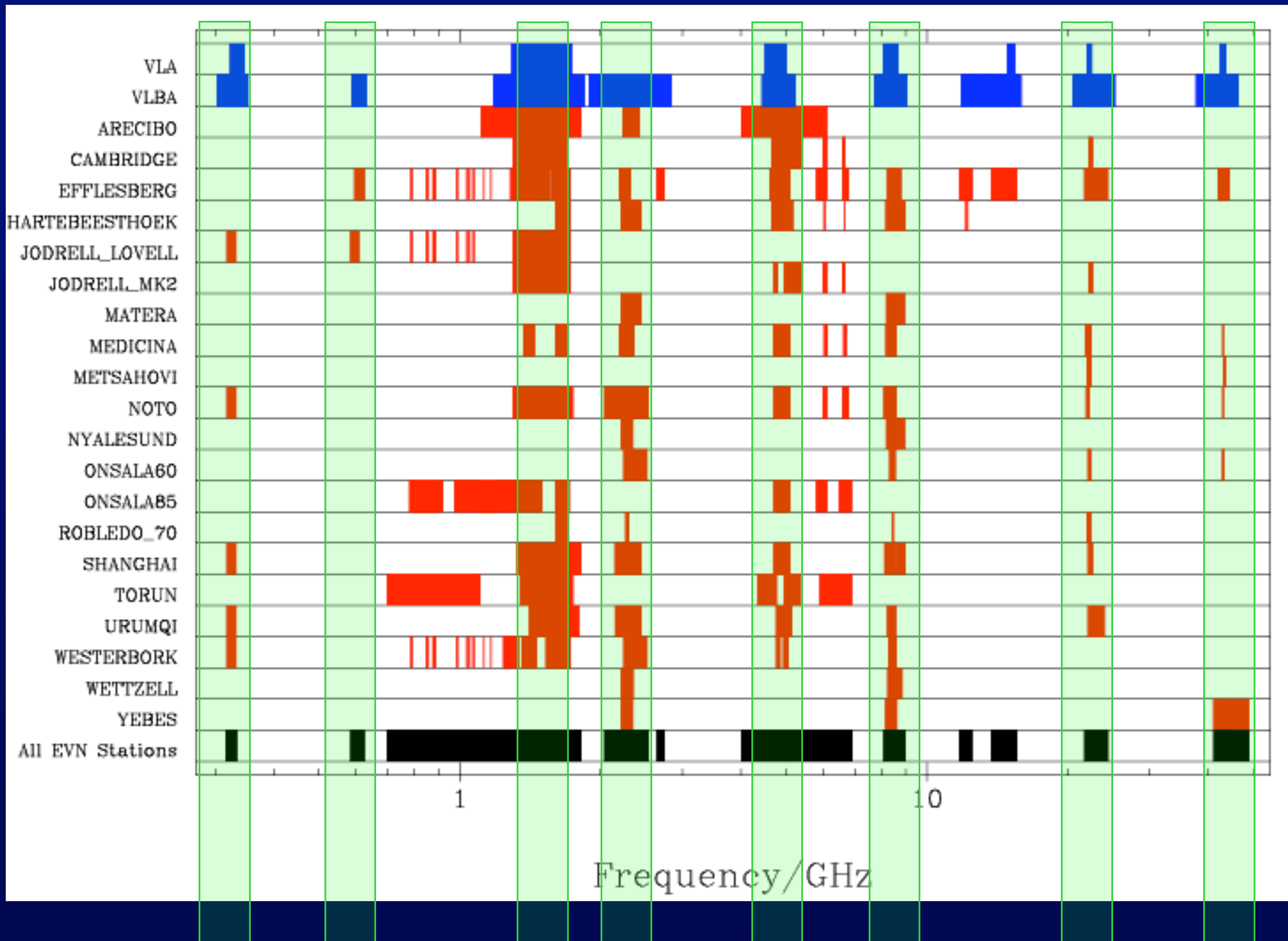

The Global VLBI - Array
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
Urumqi
Shanghai
Westerbork
Medicina
Noto
EVN
VLBA
European VLBI Network (EVN)
Very Long Baseline Array (VLBA)
High Sensitivity Array (HSA)
Ft. Davis
St. Croix
V L A
Arecibo
Effelsberg
Yebes
Wettzell
Torun
Hartebeesthoek

EVN Radio-telescopes and affiliate antennas

(SEFD's in Jy)

Station	Country	Code	Diameter	92cm	49cm	30cm	21cm	18cm	13cm	6cm	5cm	3.6cm	1.3cm	0.7cm	0.3cm
Jodrell Bank	England	Jb1	76	132	83		36	44		yes					
Jodrell Bank	England	Jb2	25				350	320		320	910		910		
Cambridge	England	Cm	32				220	212		136	900		720		
Westerbork	Netherlands	Wb	14x25m	150	90	120	30	30	60	60	1600	120			
Effelsberg	Germany	Eb	100			65	20	19	300	20	25	20	90	500	952
Medicina	Italy	Mc	32				490	600	400	170	840	320	1200		
Noto	Italy	Nt	32	980	yes	1025	820	784	770	260	yes	770	800	900	4500:
Onsala	Sweden	On85	25			900	320	320		600	1500				
Onsala	Sweden	On60	20						1110			1630	1380	1310	5858
Shanghai	China	Sh	25					540	1792	664		708	2185		
Urumqi	China	Ur	25	3020		2400	240	240	880	200		450	2950		
Torun	Poland	Tr	32			2000	250	230		220	400				
Metsahovi	Finland	Mh	14						4500			3200	2608	4500	23900
Hartebeesth.	S. Africa	Hh	26					450	380	795	680	940			
Arecibo	USA	Ar	305	12	12	3	3,5	3	3	5	5	6			
Wettzell	Germany	Wz	20						1250			750			
Robledo	Spain	Rob70	70					35	20			18	83		
Robledo	Spain	Rob34	34						150			106			
Simeiz	Ukraine	Sm	22	2000	1600			900	800	400		1200	3000		
Pico Veleta	Spain	Pv	30												710
Pl. de Bure	France	PdB	6x15m												600
VLBA	USA	VLBA	10x25m	2227	2216		296	303	330	312		350	888	1436	4000

EVN/Global VLBI: Frequency coverage



92 cm 49 cm 21/18 cm 13 cm 6 cm 3.6 cm 1.3 cm 0.7 cm

327 MHz to 43 GHz

EVN/Global VLBI: Angular Resolution

(numbers in milli-arcsec)

Array	90cm	18cm	6cm	3.6cm	1.3cm	0.7cm	0.3cm
EVN	-	15	5,0	3,0	1,00	0,55	-
EVN+Ur/Sh	30	5	1,5	1,0	0,30	-	-
EVN+VLBA	19	3	1,0	0,7	0,25	0,13	-
VLBA	21	4	1,4	0,9	0,30	0,17	0,10
GMVA	-	-	-	-	-	-	0,04

spatial scale: for $z = 1$ (ΛCDM cosmology), 1 mas = 8 pc

sub-pc scale resolution only for global VLBI at $\lambda \leq 7$mm !

The Global Millimeter VLBI Array – VLBI Imaging at 86 GHz with ~40 μas resolution

Baseline Sensitivity

in Europe:

22 – 200 mJy

in US:

100 – 140 mJy

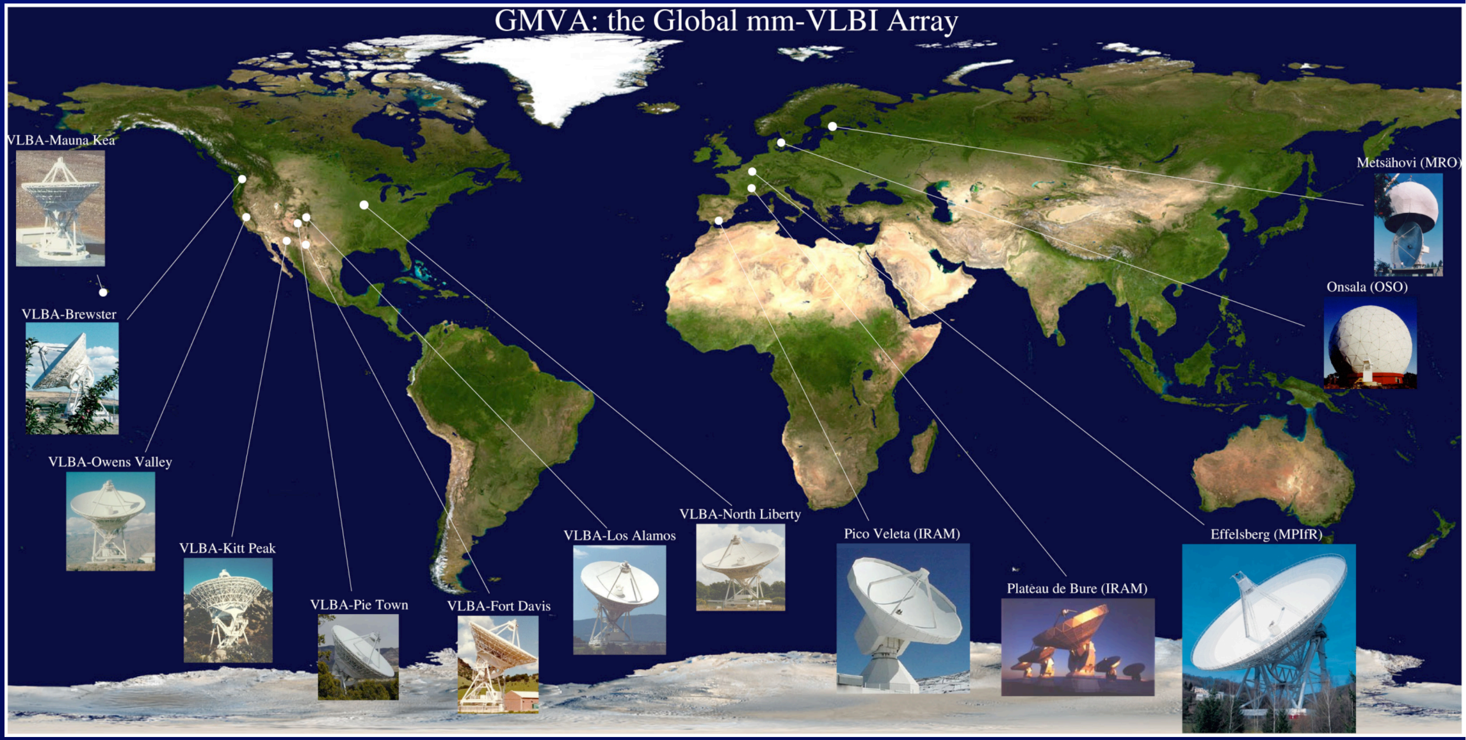
transatlantic:

40 – 70 mJy

Array:

1.1 mJy / hr

(assume 7σ, 100sec, 512 Mbps)



http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m)
- Amerika: 8 x VLBA (25m)

Proposal deadlines: February 1st, October 1st

EVN/Global VLBI: Image Sensitivities

(numbers in μJy/beam)

Array	90cm	18/21cm	6cm	3.6cm	1.3cm	7mm	3mm
EVN	248	28	29	65	254	917	-
VLBA	691	91	97	95	156	321	895
Global	170	20	21	35	121	278	-
HSA	34	7	8	9	45	84	-
GMVA	-	-	-	-	-	-	290

assumptions: 512 Mbit/s, single polarisation, 2 bit sampling, 60 min. on source

1 sigma thermal noise, natural weighting

Angular and Spatial Resolution of mm-VLBI

λ	ν	θ	z=1	z=0.01	d= 8 kpc
3 mm	86 GHz	45 μas	0.36 pc	9.1 mpc	1.75 μpc
2 mm	150 GHz	26 μas	0.21 pc	5.3 mpc	1.01 μpc
1.3 mm	230 GHz	17 μas	0.13 pc	3.4 mpc	0.66 μpc

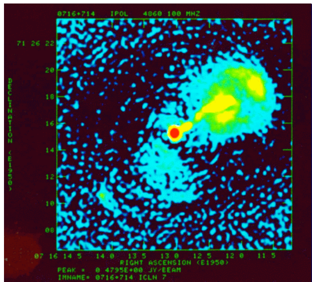
linear size: $10^3\ R_s{}^9$ $30\text{-}100\ R_s{}^9$ $1\text{-}5\ R_s{}^6$

for the nearest sources these scales correspond to a few to a few ten Schwarzschild radii, depending on distance and BH mass

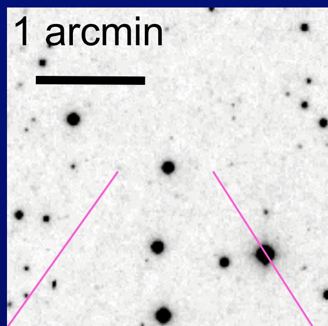
→ mm-VLBI is able to directly image jets at the vicinity of SMBHs !

→ best candidates: Sgr A*, M87 (Cen A far south, NGC 4258 too faint)

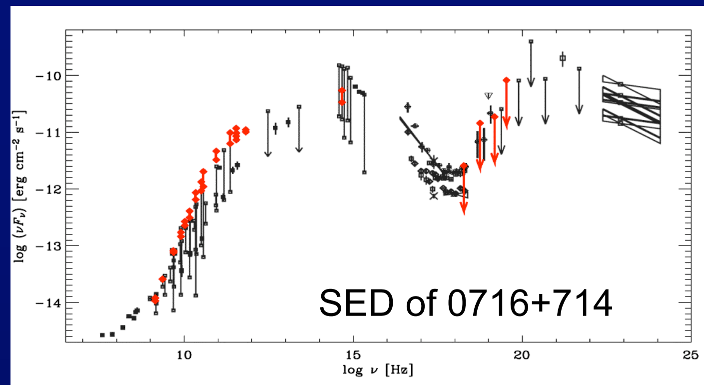
Global mm-VLBI at 150 - 230 GHz

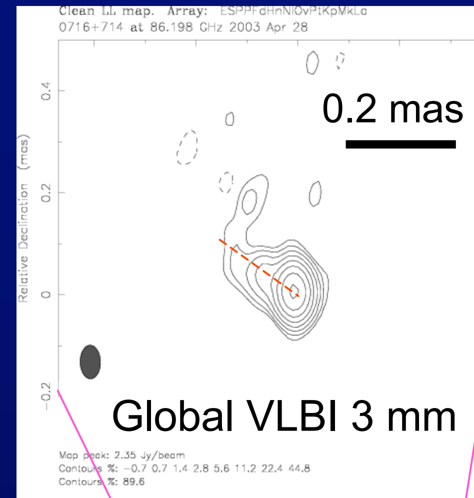


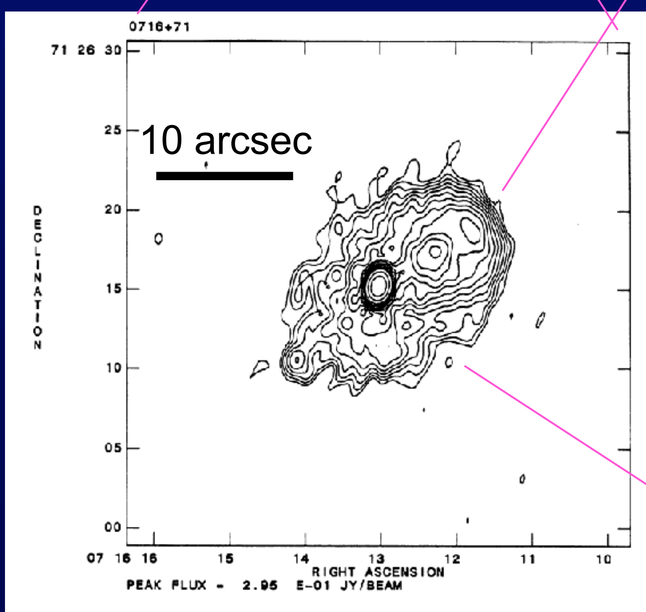
0716+714: from arcseconds to micro-arcseconds

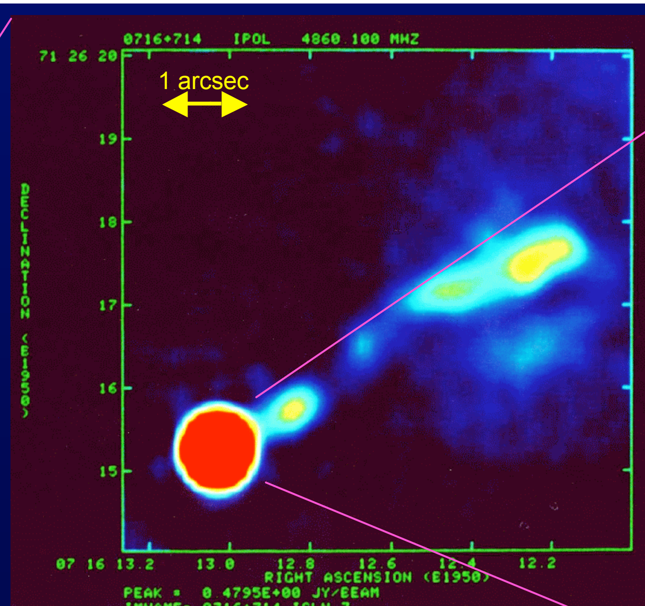


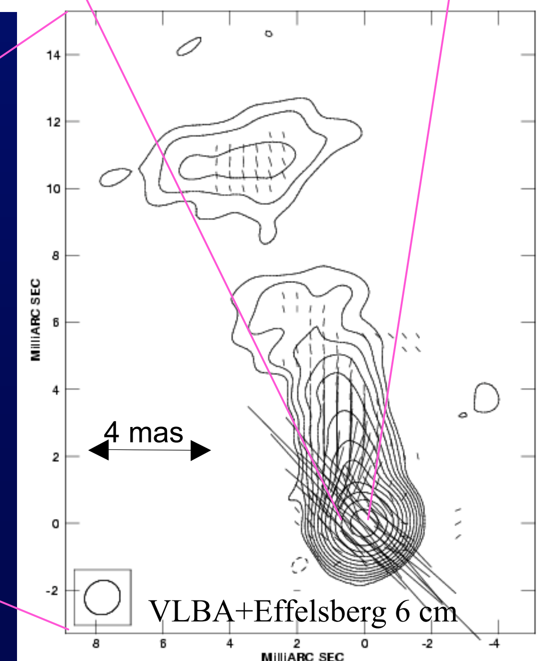
DSS (R-band)









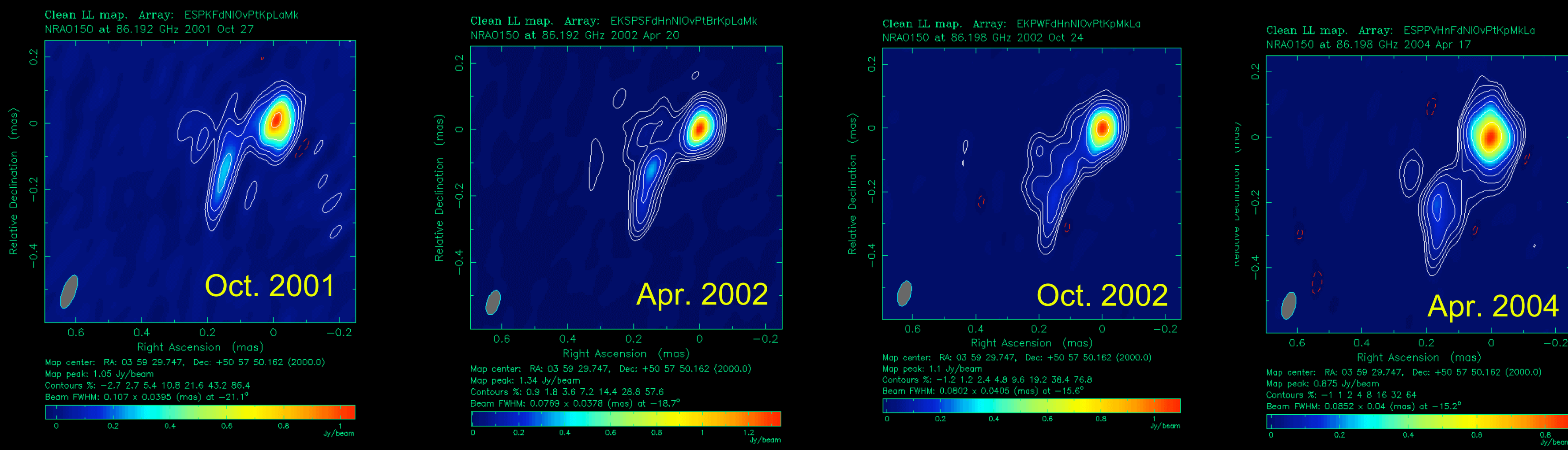


Antonucci et al. 1986 (VLA 20 cm)

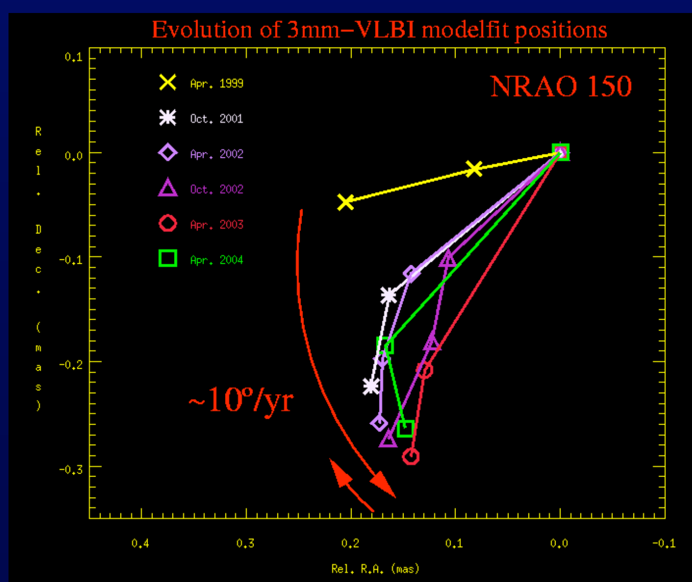
Bach et al. 2005

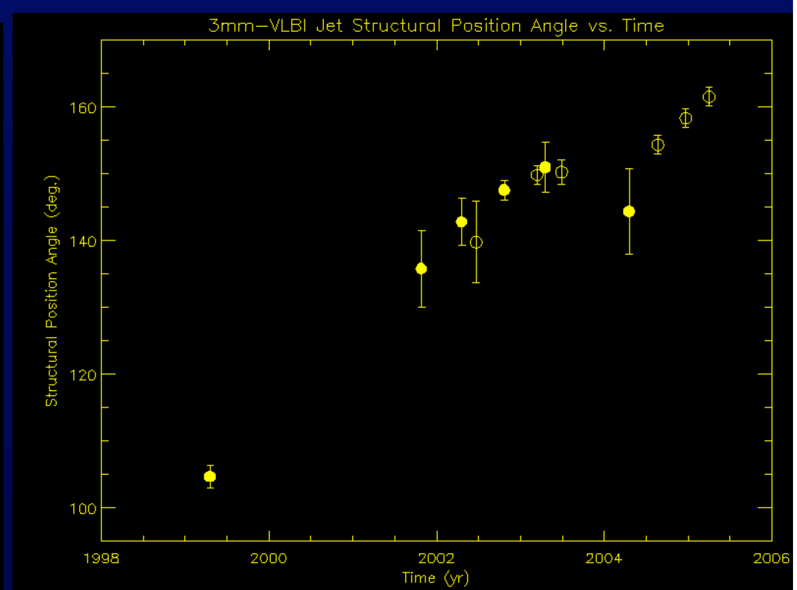
The misaligned jet of NRAO150: sub-mas scales

3 mm-VLBI images GMVA and CMVA



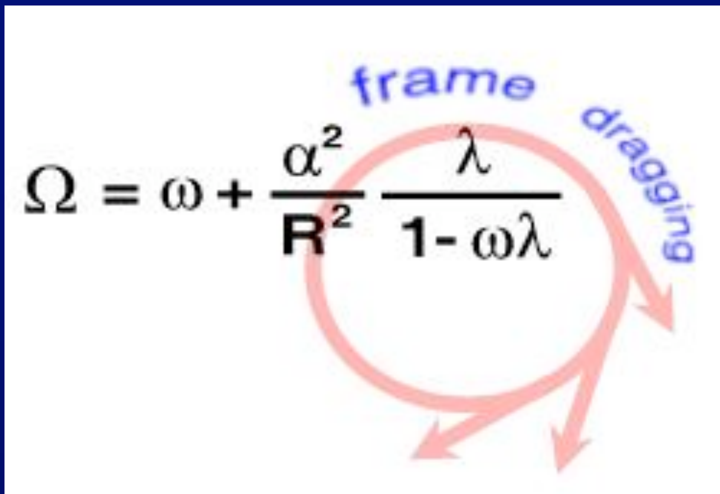
3 mm-VLBI shows jet rotation with an angular speed of ~ 10º/yr and an extrapolated period of 20-25 yrs





Agudo et al., 2006 & in preparation

Frame dragging



$$\Omega = \omega + \frac{\alpha^2}{R^2}\,\frac{\lambda}{1-\omega\lambda}$$

matter and fields are forced to rotate with the horizon

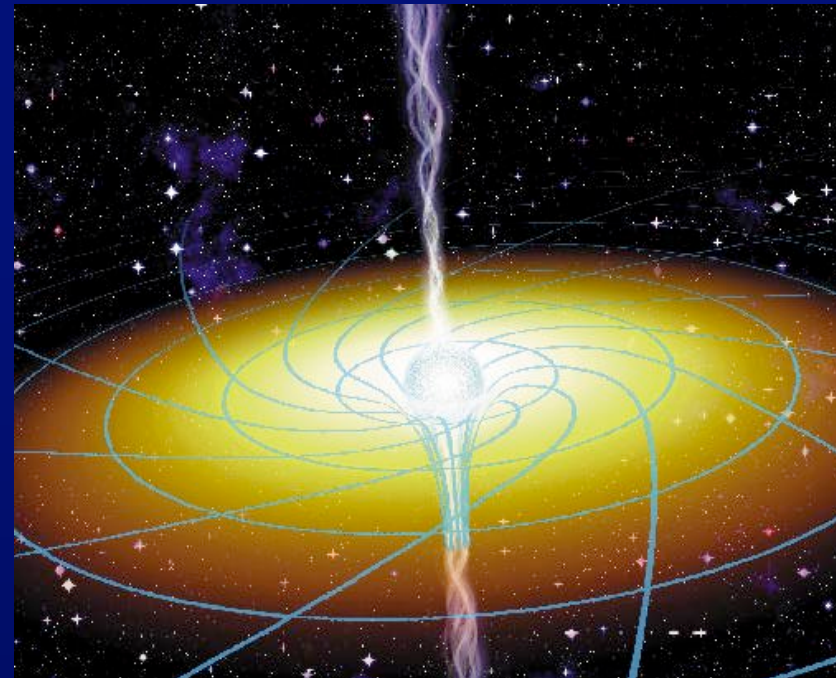
torque due to misaligne-ment of $\vec{L}$ from accr. disk and Kerr BH

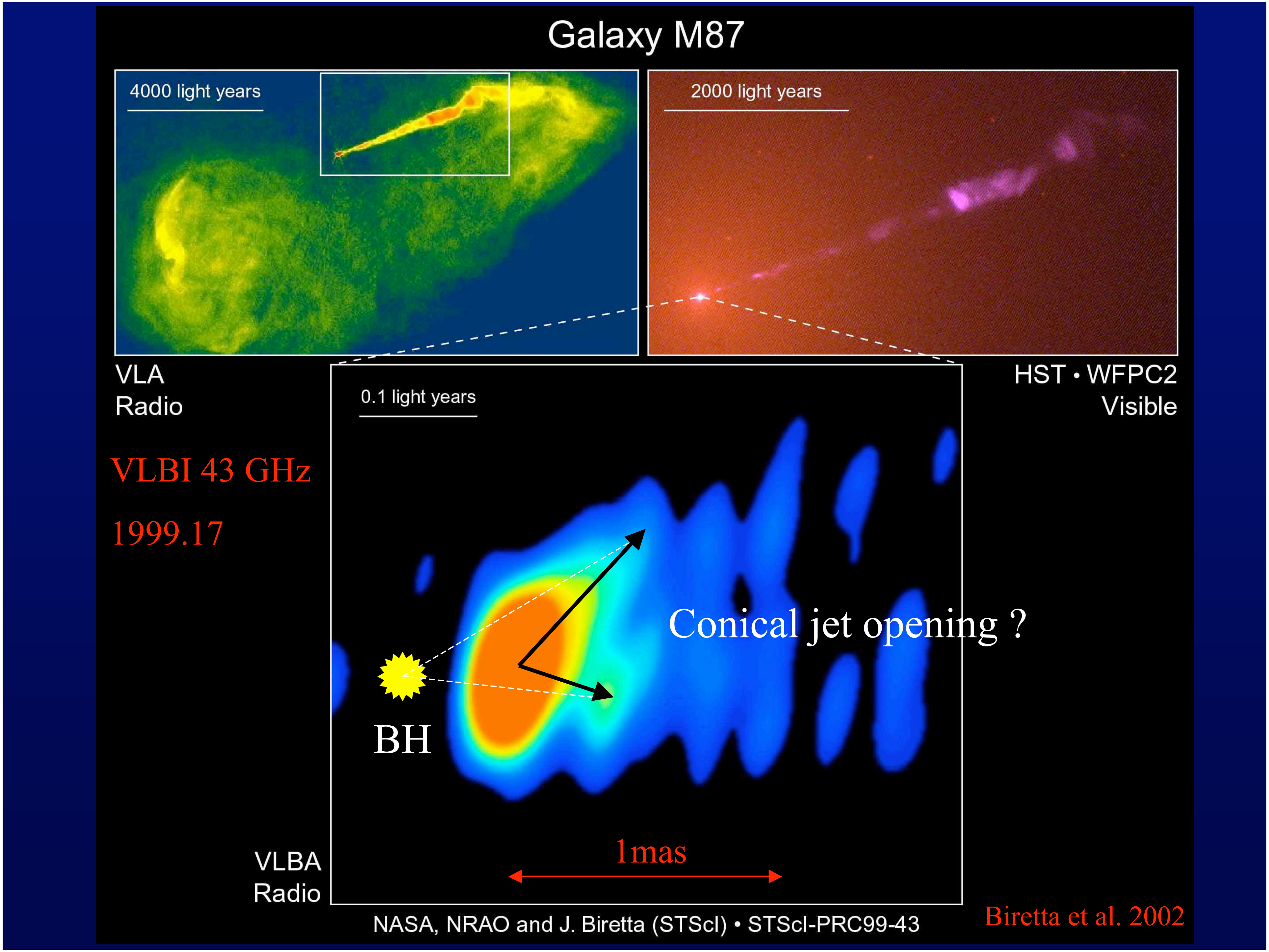
→ P =0.3 - 20 yrs can be explained

(Caproni et al., 2004)

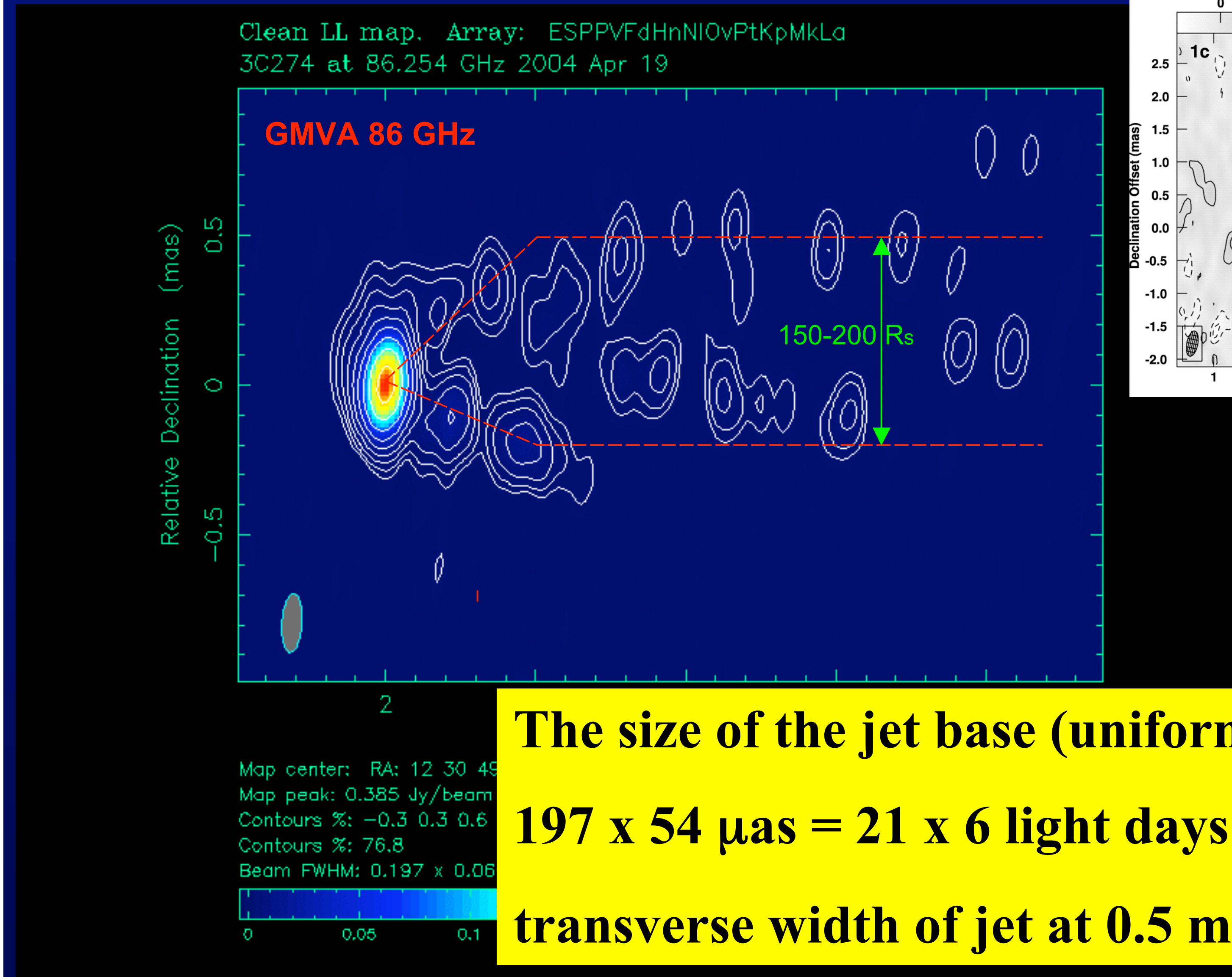
known "precessing" sources:

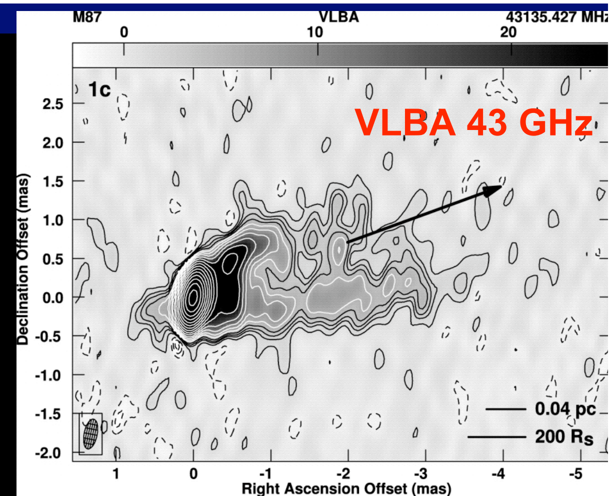
3C84	Gal
NRAO150	QSO
0716+714	BL
3C120	Gal
3C273	QSO
3C279	QSO
3C345	QSO
BLLac	BL
OJ287	BL





Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBI 43 GHz
1999.17
Conical jet opening ?
BH
1mas
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43
Biretta et al. 2002





Ly et al. 2004

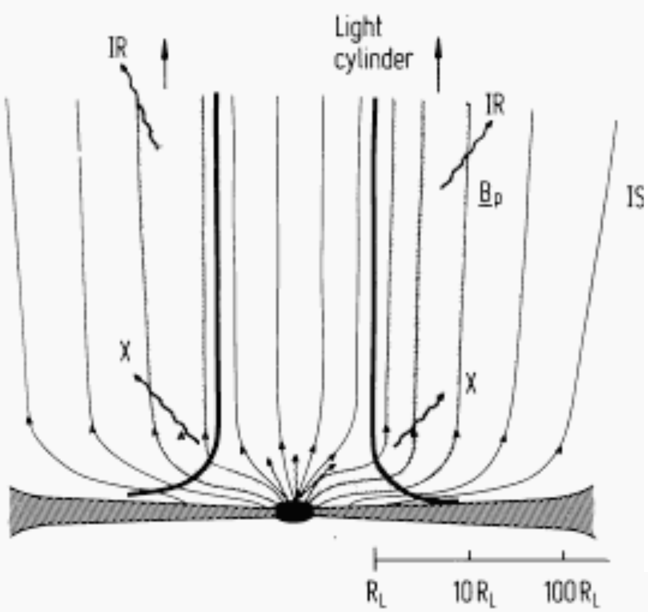
The size of the jet base (uniform weighting):

197 x 54 μas = 21 x 6 light days = <u>69 x 19</u> R_s

transverse width of jet at 0.5 mas: ~174 R_s

In M87 (and in SgrA*) global 3mm VLBI provides a spatial resolution of a few 10 Schwartzschild radii (~ 20 R_S), facilitating direct images of the vicinity of SMBHs.

The diameter of the light-cylinder determines the jet width:



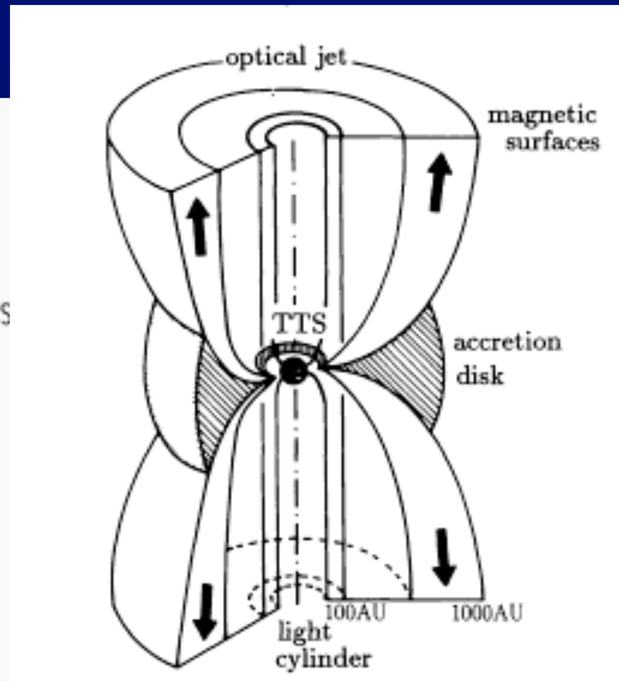
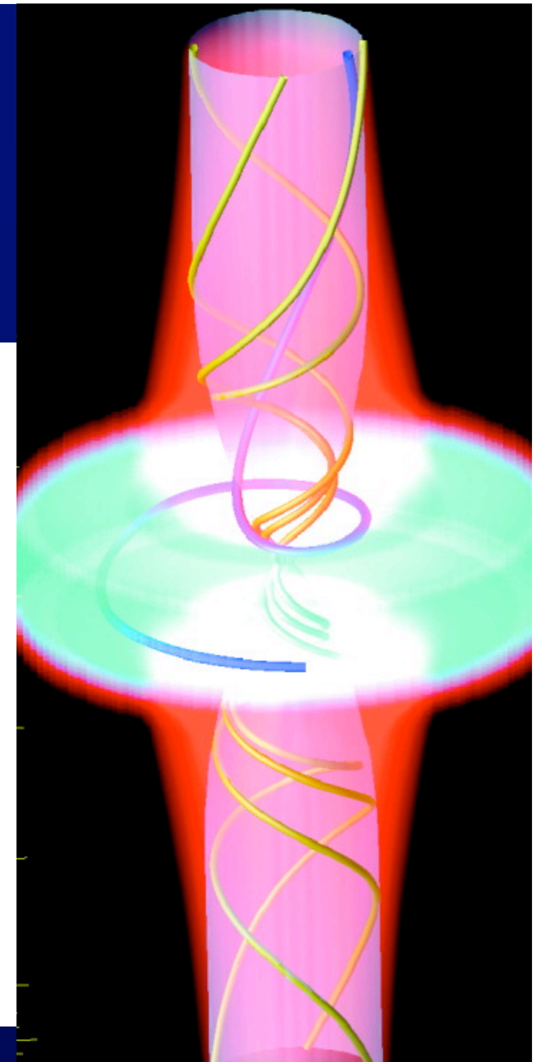


Fig. 11. The parsec-scale structure of magnetized jets in Quasars (Courvoisier and Camenzind, 1989). The central accretion disk carries a rotating magnetosphere which is strongly deformed by the presence of the light cylinder. The escaping disk-wind material is collimated outside the light cylinder by pinching forces. Stationary synchrotron emission (IR) occurs either near the light cylinder or the outer edge of the jet. The hot wind material can efficiently cool by Comptonization of the UV-flux from the inner disk and produce the hard X-ray emission (X).

Camenzind, 1990



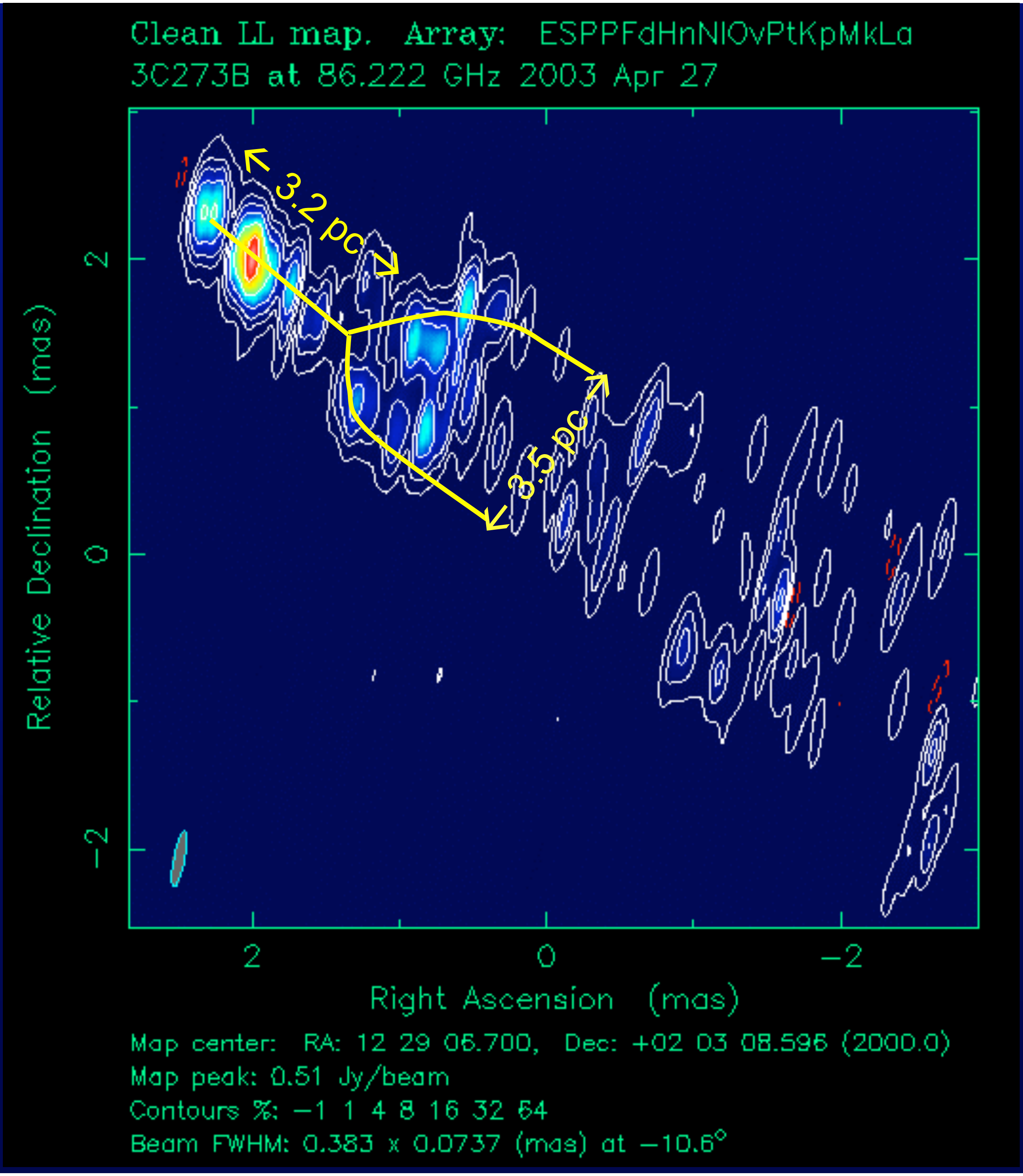
Casse & Keppens 2004

$> 40\ R_s$

jet width $\geq 2\,\gamma\,R_s$

mm-VLBI can resolve jets transversely:

A double rail structure in the jet of 3C273 – decollimation at 3 pc ?



$z = 0.158$

1mas ≅ 2.7 pc

Evidence for jet stratification from γ- ray observations of AGN

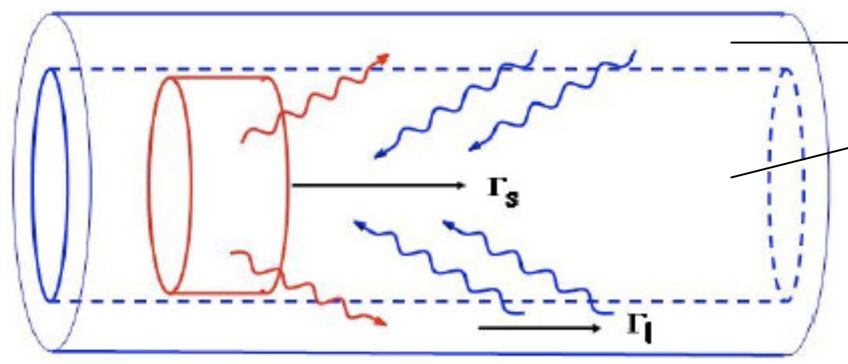


Fig. 1. Cartoon illustrating the layer+spine system.

slow layer

fast spine

transverse stratification !

need to reconcile the need of high Doppler-factors from strong TeV emission and rapid variability ($\tau_{\gamma-\gamma}$) with the lower Doppler-factors derived from the (relatively slow) superluminal motion in TeV BL Lacs.

seed photons from slow jet layer help to enhance γ–ray luminosity !

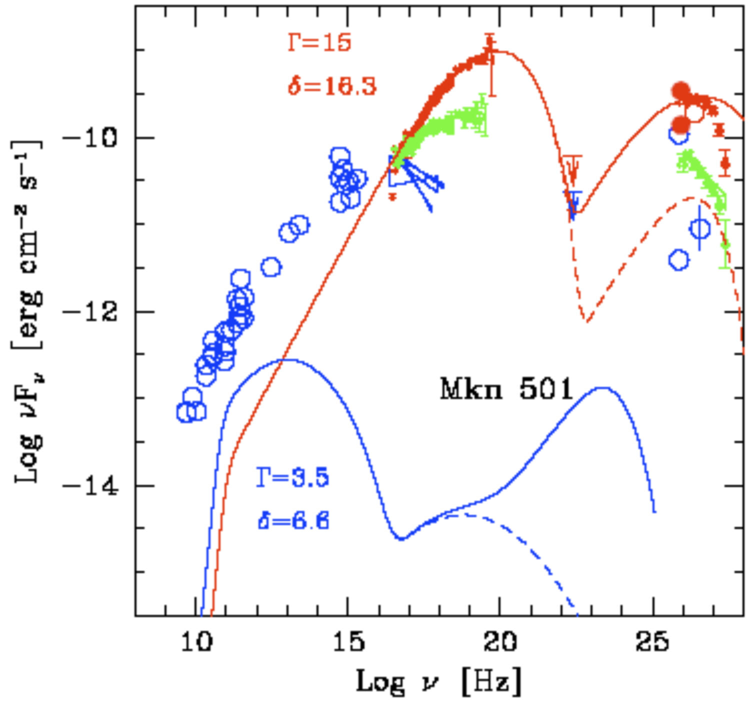
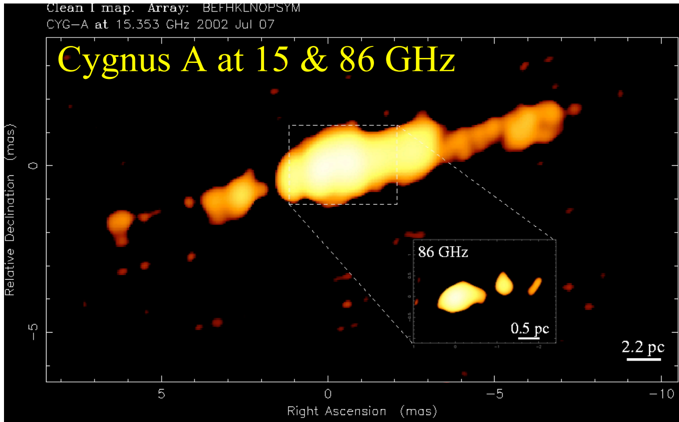


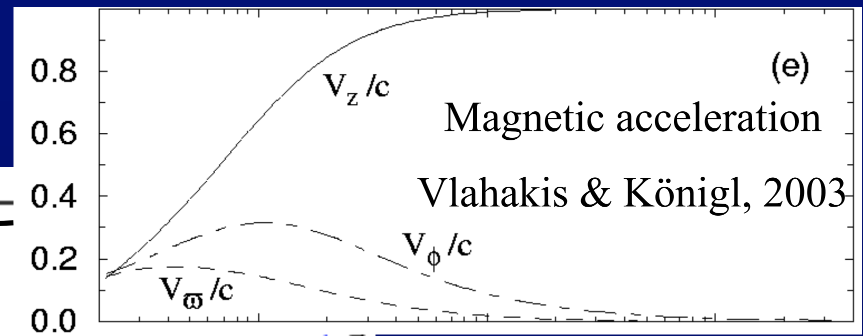
Fig. 2. Example of the SED produced by the spine-layer system, using the parameters listed in Table 1. Dashed lines correspond to the emission of the spine (layer) without taking into account the seed photons coming from the layer (spine). Data from Pian et al. (1998) and Djannati-Atai et al. (1999).

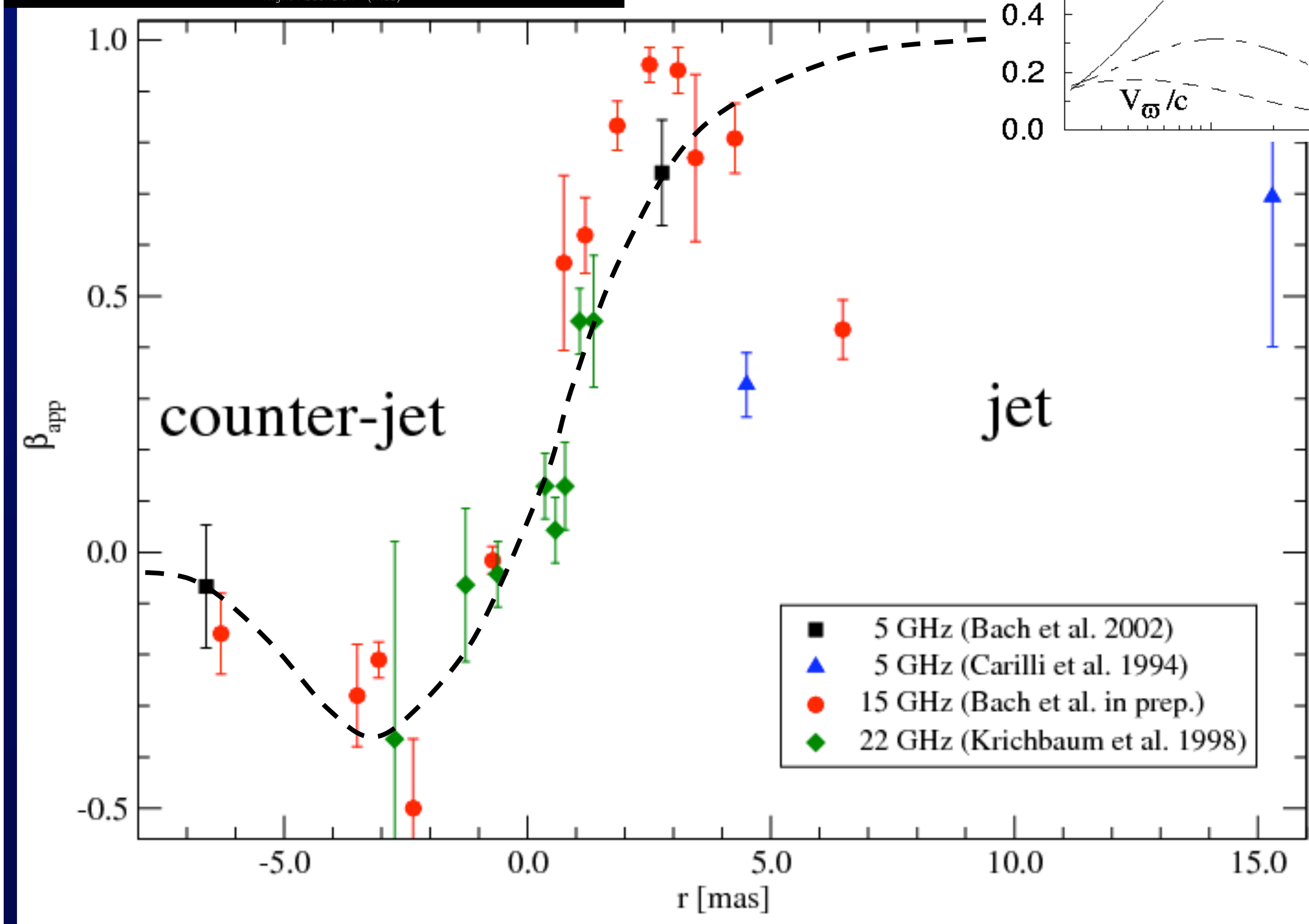
Ghisellini et al. 2005

The Jets of Cygnus A

Intrinsic jet acceleration from 0.05 c to 0.8 c







intrinsic jet speed and Lorentz-factor is not constant long jet !

Bach et al. 2004 and in prep

A prominent Gamma-Ray flare of 3C454.3 in May 2005

Pian et al., 2006, Villata et al., 2006, Fuhrmann et al., 2006, ...

M. Villata et al.: The unprecedented optical outburst of the quasar 3C 454.3 821

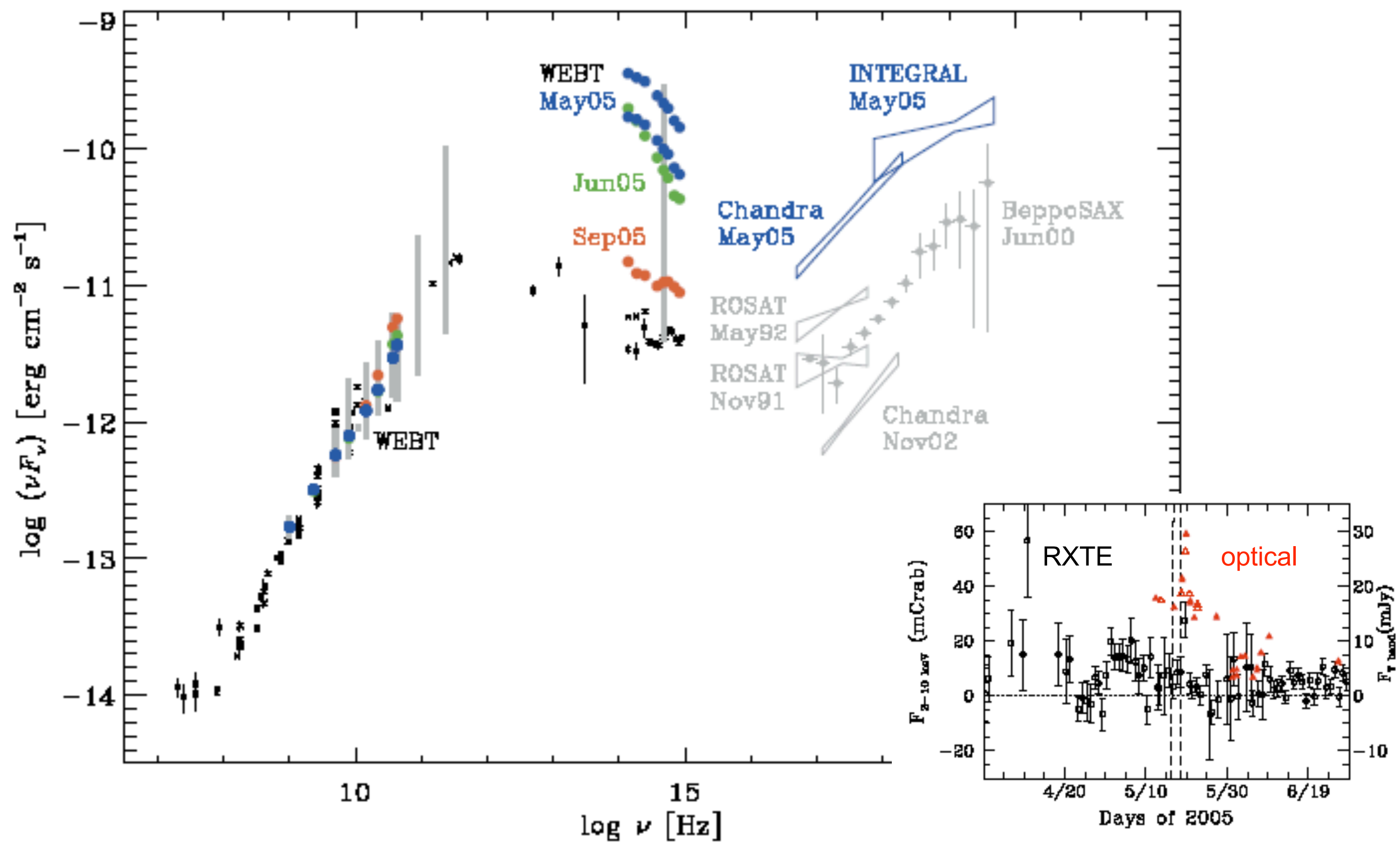
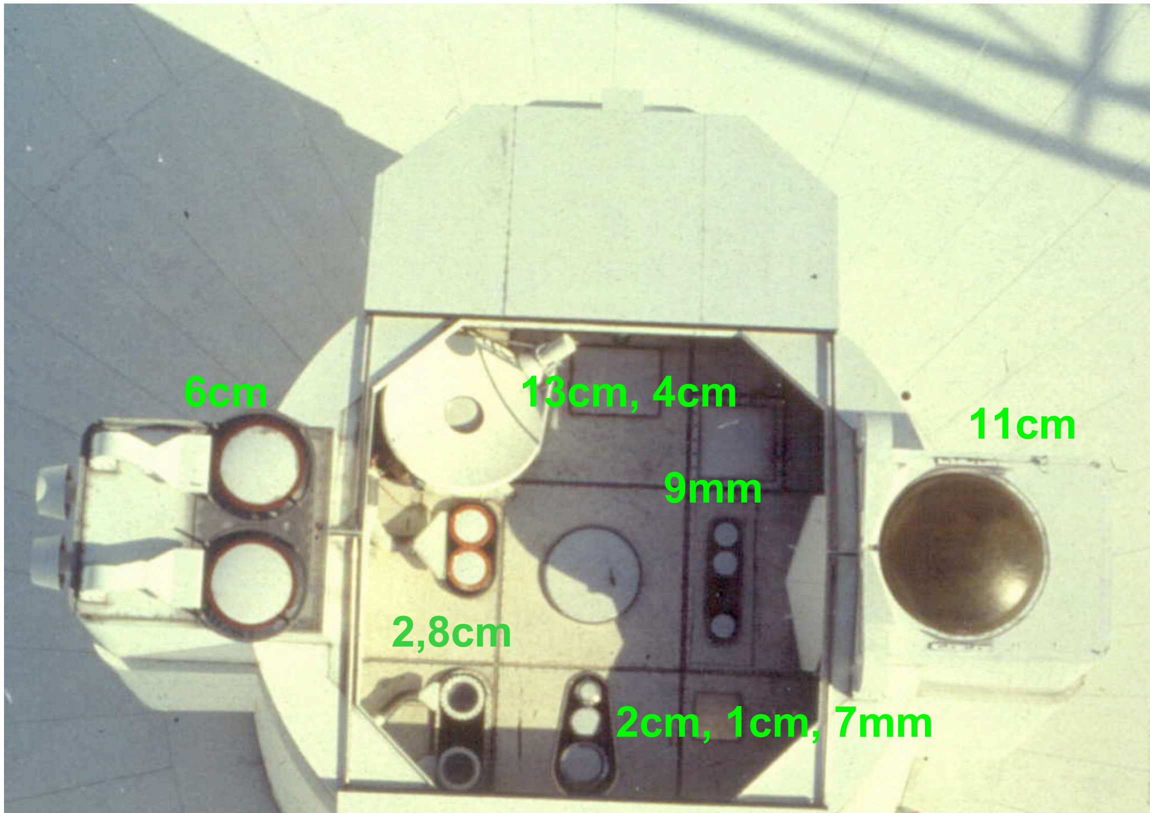


Fig. 4. Spectral energy distribution of 3C 454.3 showing contemporaneous radio, near-IR, optical, and X-ray (Chandra and INTEGRAL) data during May 15–20, 2005. Previous data are also plotted for comparison, together with two other spectra from the WEBT campaign (see text for further details).



picture: MPIfR, Bonn

View of the secondary focus cabin (apex) of the MPIfR 100 m Radiotelescope at Effelsberg, Germany.

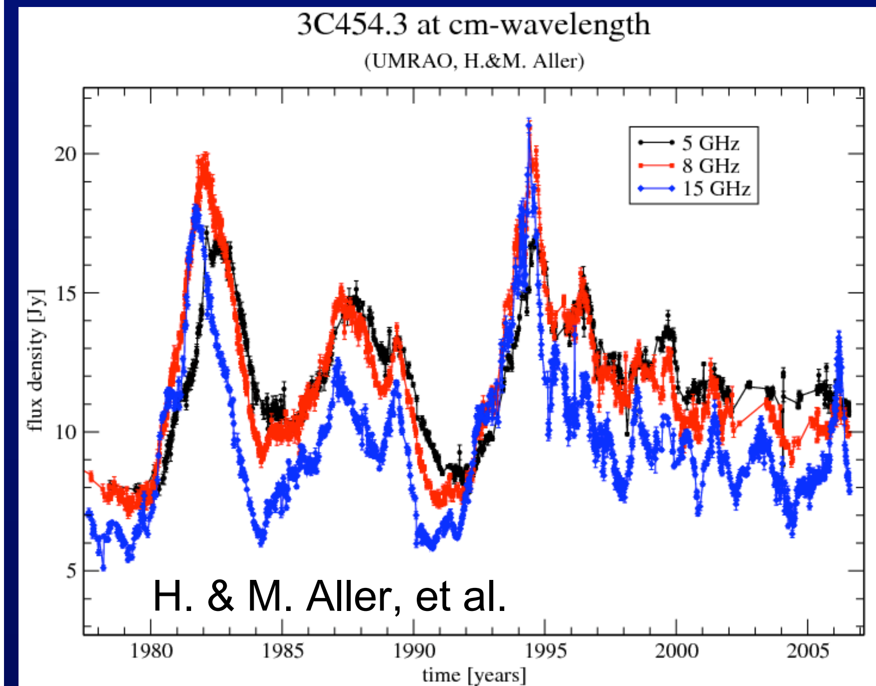
flexible change of receivers, ranging from 2.7 GHz (11 cm) to 43 GHz (7 mm) within 20 – 30 sec switching time.

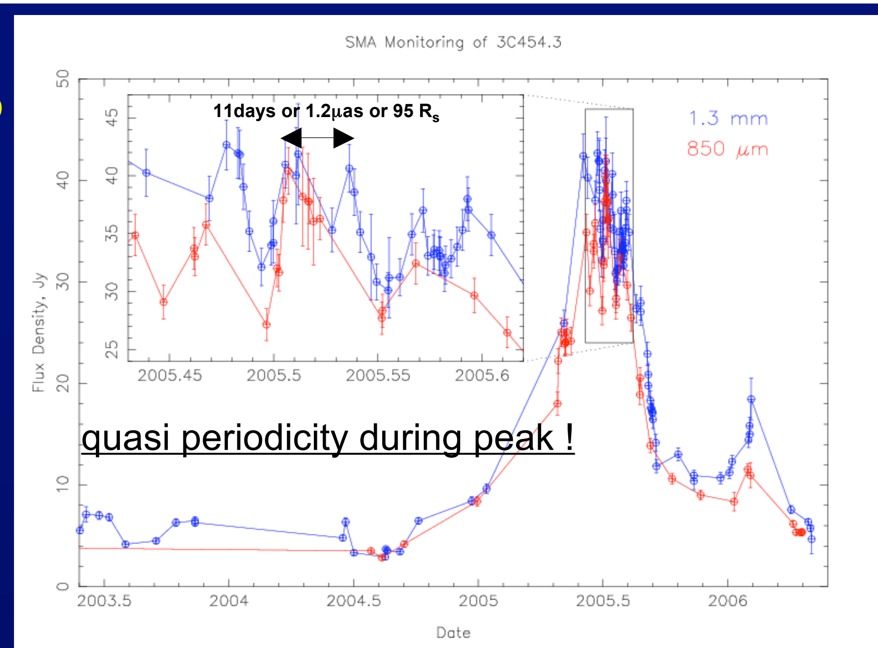
apex cabin closed for observations with prime focus receivers

Secondary Focus Cabin of 100m RT

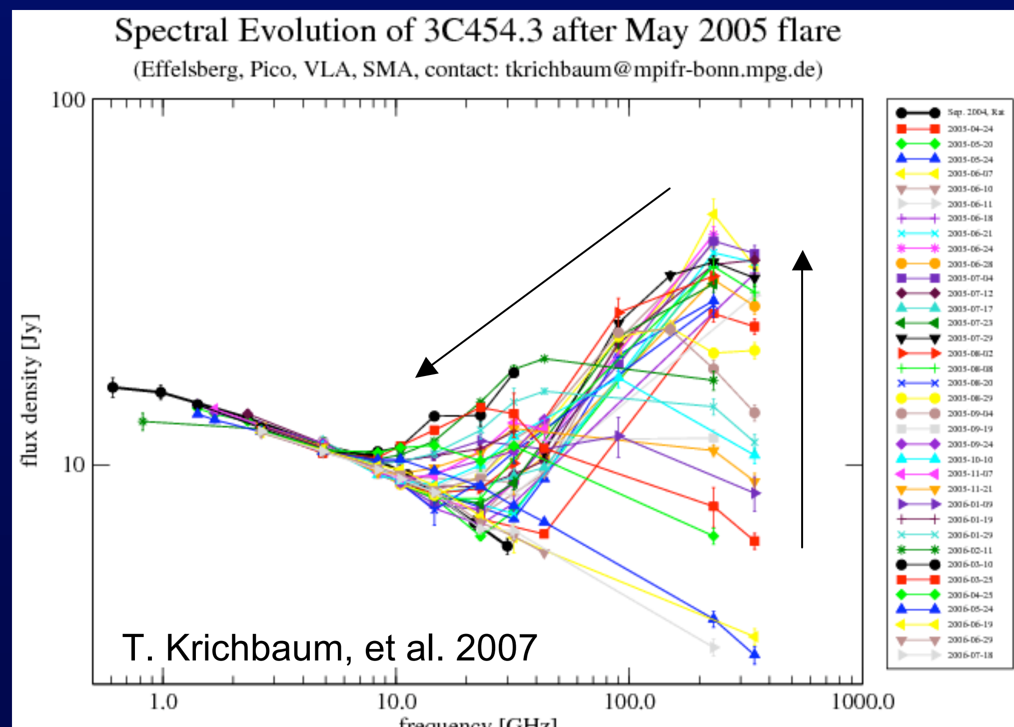
Max-Planck-Institut für Radioastronomie

Spectral variability of 3C454.3 after 2005 Flare:





SMA data: M. Gurwell et al.



90 – 230 GHz

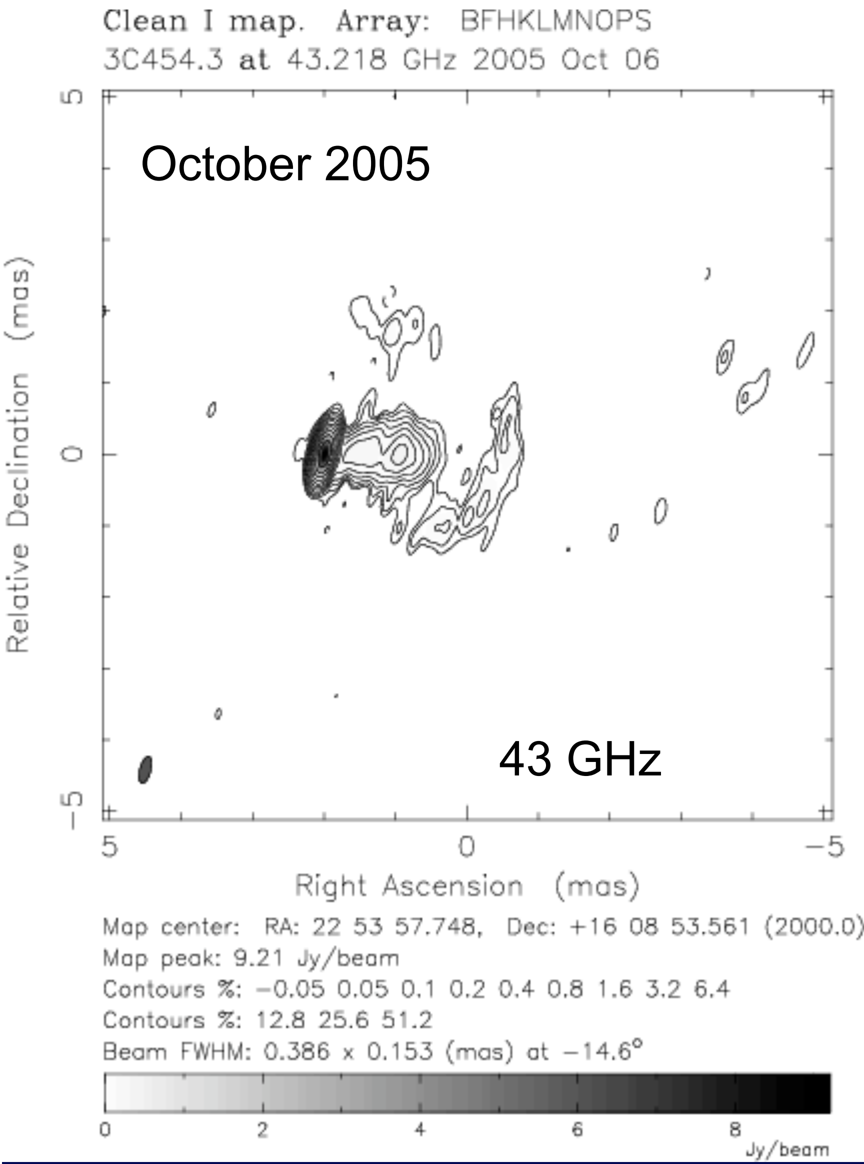
SMA:

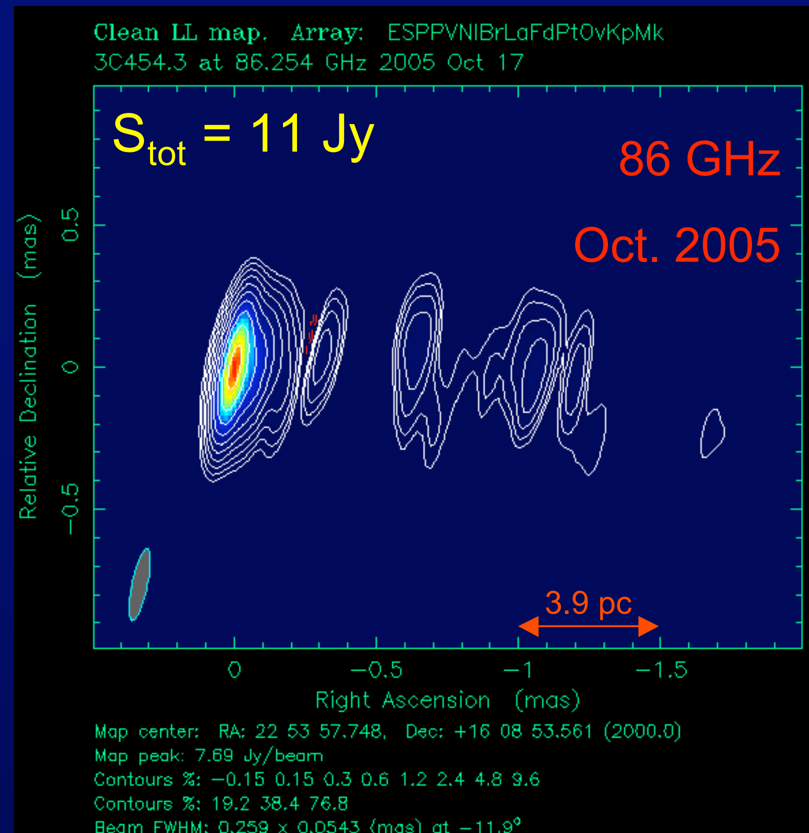
230, 350 GHz

on the right, combined data:

Krichbaum, Ungerechts, Wiesemeyer, Gurwell et al.

86 GHz image 5 months after Outburst





43 GHz (data from A. Marscher, re-mapped)

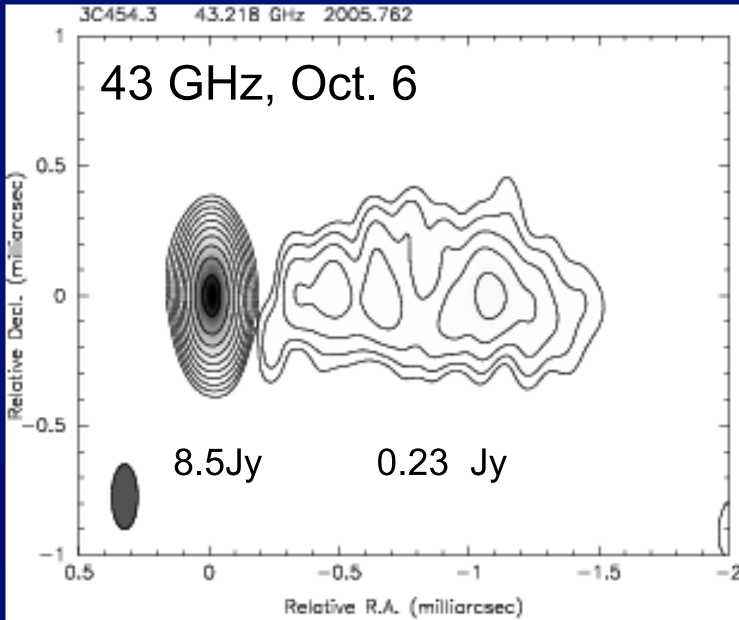
86 GHz (GMVA, this paper)

core elongation at r = 0.1-0.2 mas

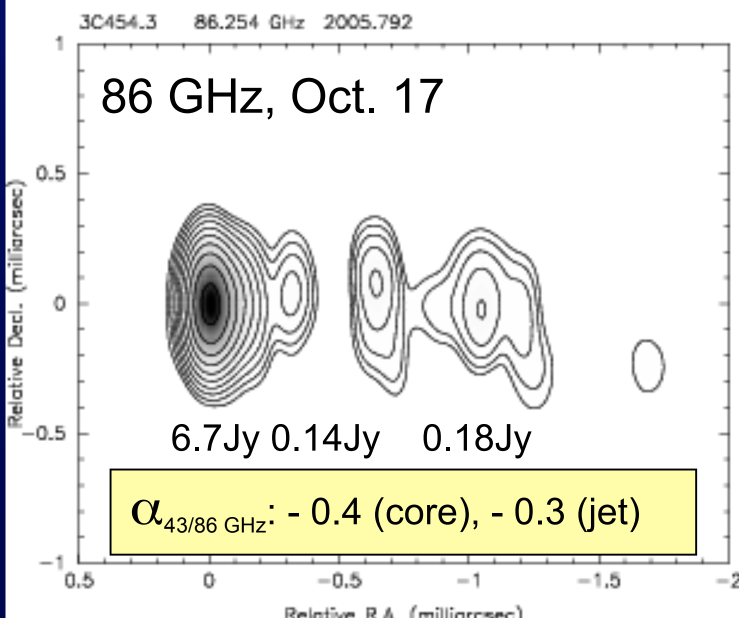
highest resolution: 54 μas or 0.42 pc or 4274 R_s[9]

(problem: limited uv-coverage)

Quasi-simultaneous mm-VLBI observations of 3C454.3 after outburst



common beam 0.25 x 0.1 mas



<u>43 GHz:</u> no emission near core

known jet emission at 0.3 -1.4 mas

conclusion:

strong absorption in the 0.1-0.3 mas region,

i.e. on the 1-2 pc scale

spectral index : +1.1 .... + 2.6 (range of uncertainty)

<u>86 GHz:</u> emission near core clearly visible

jet components at 0.6 & 1.1mas

compare well to 43 GHz image

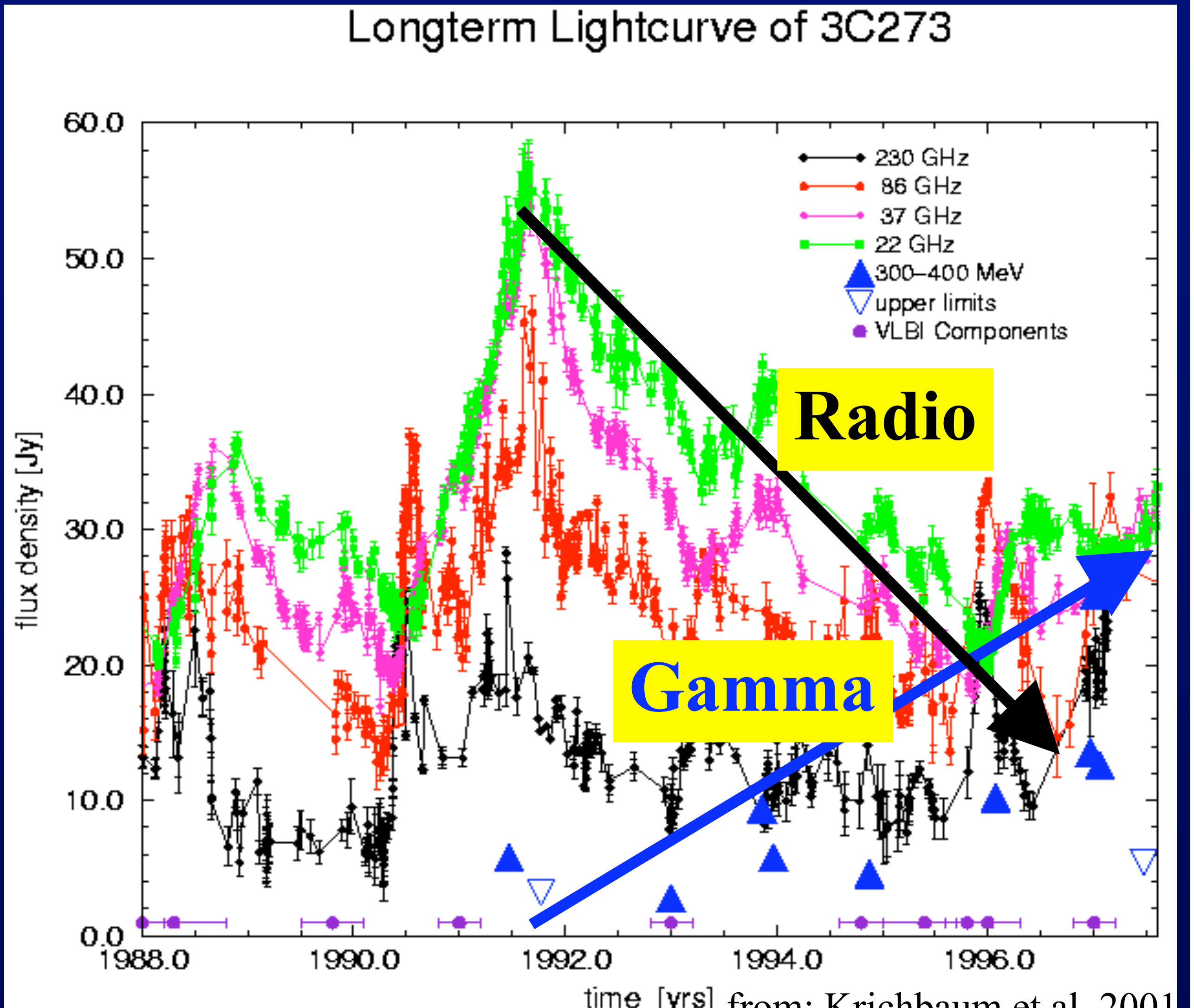
Variability and Outburst-Ejection relations

Long-term VLBI studies of 3C273:

Superluminal jet components appear about once per year.

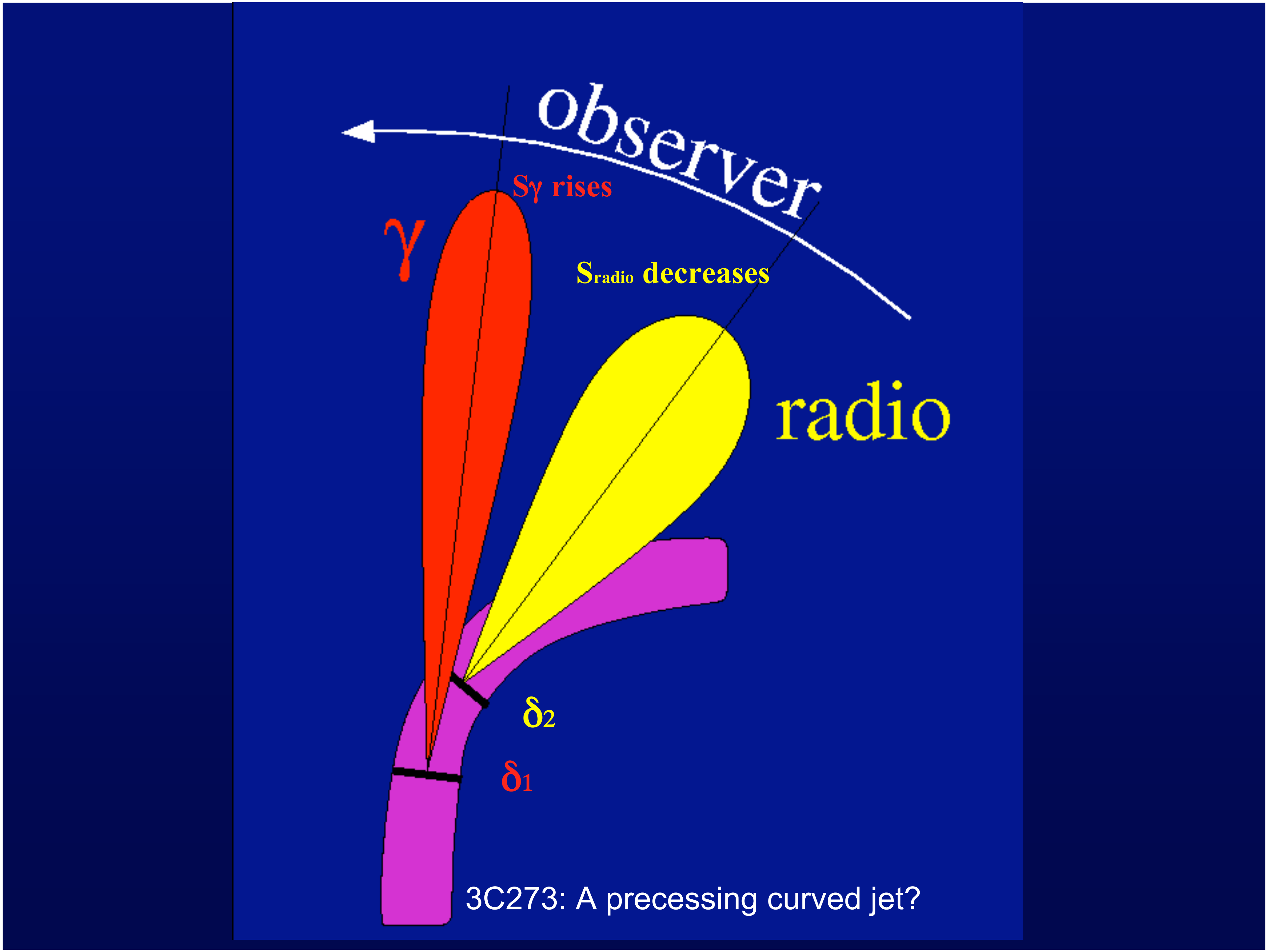
Most jet components appear at the time of the <u>ONSET</u> of a mm-flare.

High gamma-ray fluxes are measured at the <u>ONSET</u> or during the <u>RISE</u> of the mm-flares.



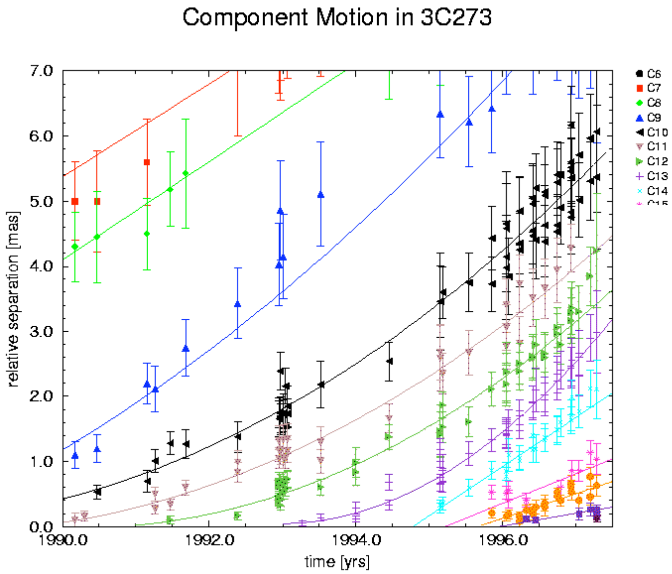
from: Krichbaum et al. 2001

Coordinated flux density variability and VLBI monitoring is essential !



observer
Sγ rises
γ
Sradio decreases
radio
δ2
δ1
3C273: A precessing curved jet?

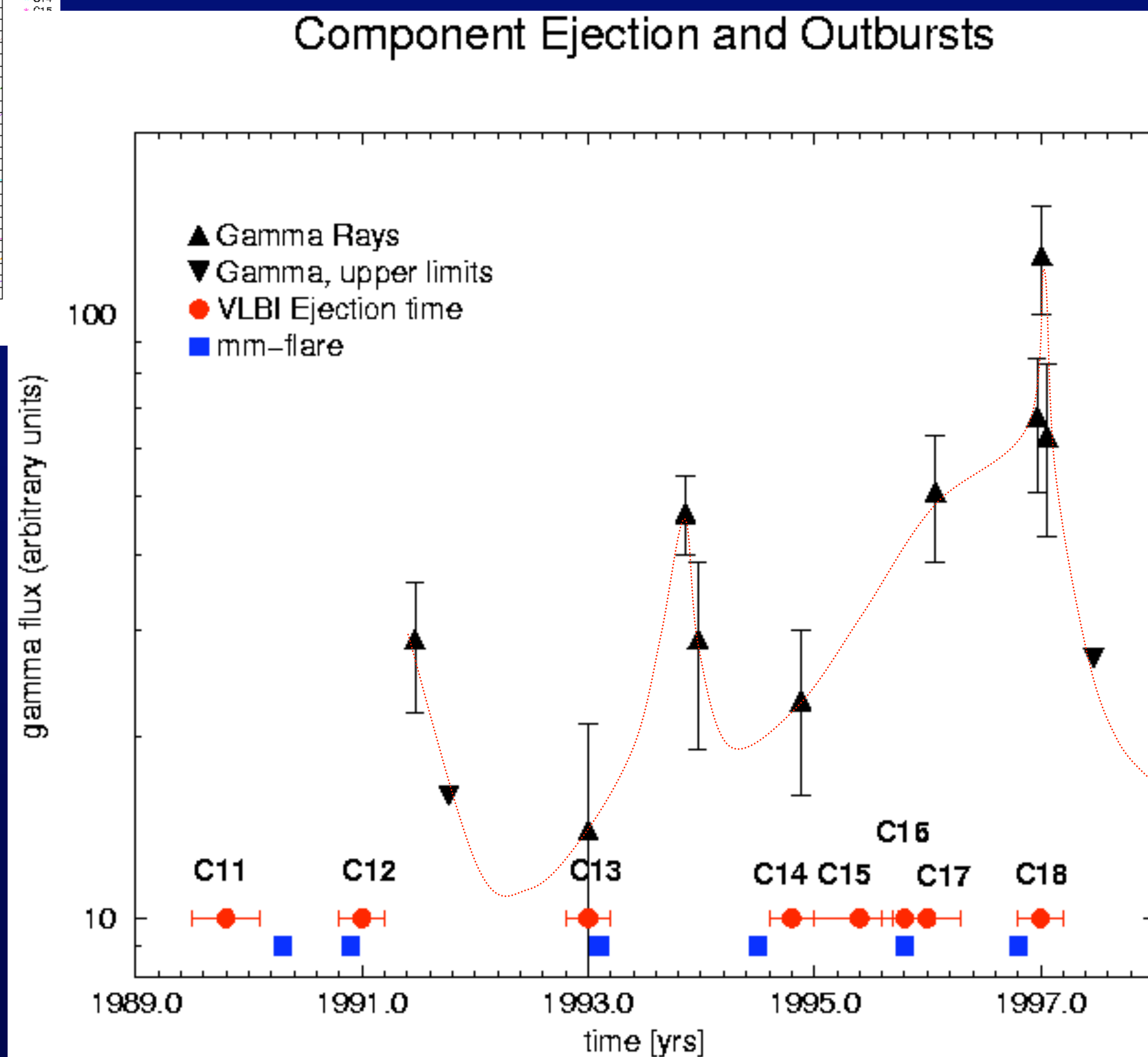
3C273: mm- to γ-ray variability and VLBI



but:

γ-ray variability curve is not well sampled !

(3C279 showed γ-ray variations on time scales of a few days !)



Krichbaum et al. 2001

Component Ejection Times and Outbursts

Id.	Ejection Time [yrs]	Gamma Flare Time of Max.	Onset of Flare (mm-radio)
C6	1980.0± 0.3		1980.6
C7	1982.4± 0.4		1982.3
C8	1984.6± 0.2		1984.2
C9	1988.0± 0.2		1987.8
C10	1988.3± 0.5		1988.0
C11	1989.8± 0.3		1990.3
C12	1991.0± 0.2	1991.47	1990.9
C13	1993.0± 0.2	1993.00	1993.1
		1993.86	
C14	1994.8± 0.2	1994.88	1994.3
C15	1995.4± 0.4		
C16	1995.8± 0.2	1996.08	1995.8
C17	1996.0± 0.3		
C18	1997.0± 0.2	1997.02	1996.8

$$t_0^{\mathrm{VLBI}} - t_0^{\mathrm{mm}} = 0.1 \pm 0.2$$
$$t_0^{\gamma} - t_0^{\mathrm{mm}} = 0.3 \pm 0.3$$

This suggests:

$$t_0^{\mathrm{mm}} < t_0^{\mathrm{VLBI}} \leq t_0^{\gamma}$$

Krichbaum et al. 2001

In 3C273 Gamma – ray flares, mm – flares and times of VLBI component ejections correlate.

Gamma – rays escape from the VLBI jet at about 1000-2000 Schwarzschild radii !

$$for\ \beta_{app} \approx 4\ near\ core \Rightarrow$$

$$and\ \ r_{\gamma}\ the\ separation\ \ at\ r(\tau_{\gamma\gamma} = 1)$$

$$r_{\gamma} \leq 0.1\, mas = 6 \cdot 10^{17}\, cm = 2000\, R_s$$

Are γ–ray detected blazars faster ?

apparently yes !

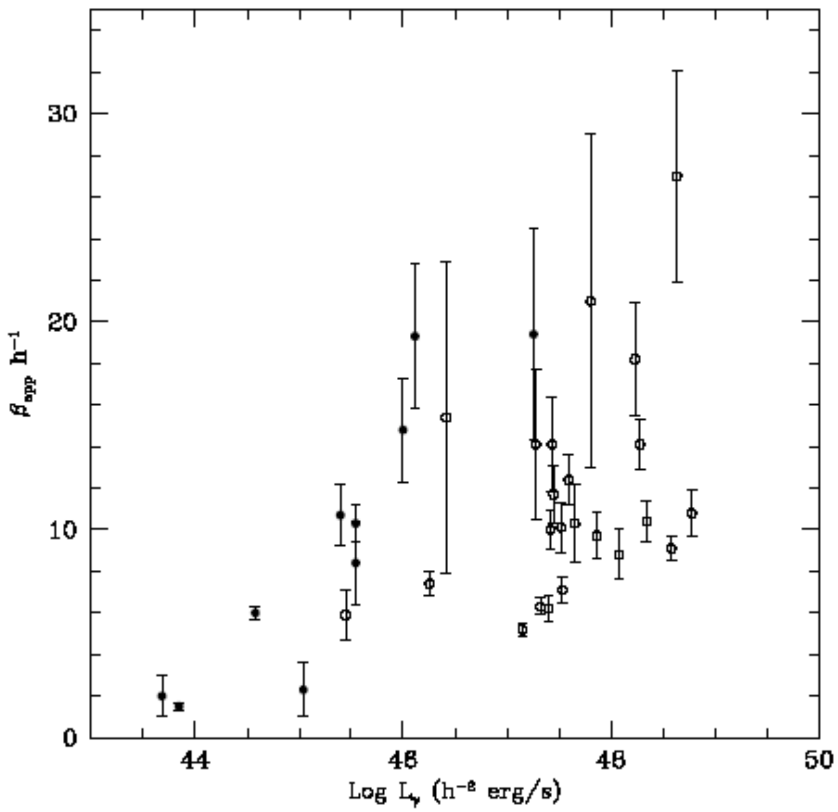


Fig. 42b.— Dependence of apparent speed of jet components on the γ-ray luminosity; open circles correspond to quasars, filled circles to BL Lac objects. In the case of multiple moving components the highest speed obtained at 3 or more epochs is used.

22/43 GHz VLBA: Jorstad et al. 2001

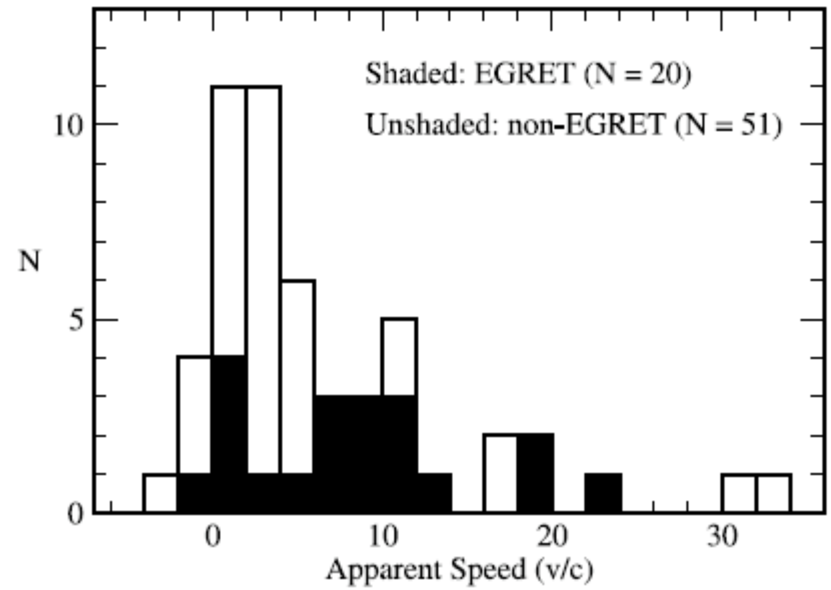


FIG. 10.—Histogram of the brightest component speed in EGRET-detected and non–EGRET-detected sources for our representative flux density–limited sample.

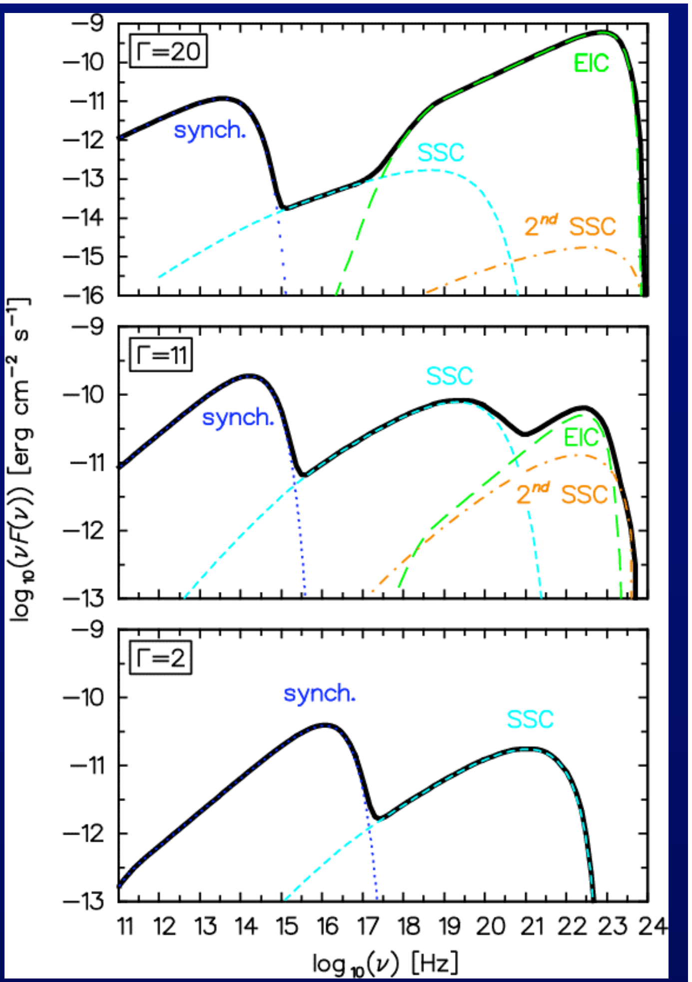
2cm survey: Kellermann et al. 2004

$\beta_{app} = 8.0 \pm 1.6$ for 20 sources detected by EGRET

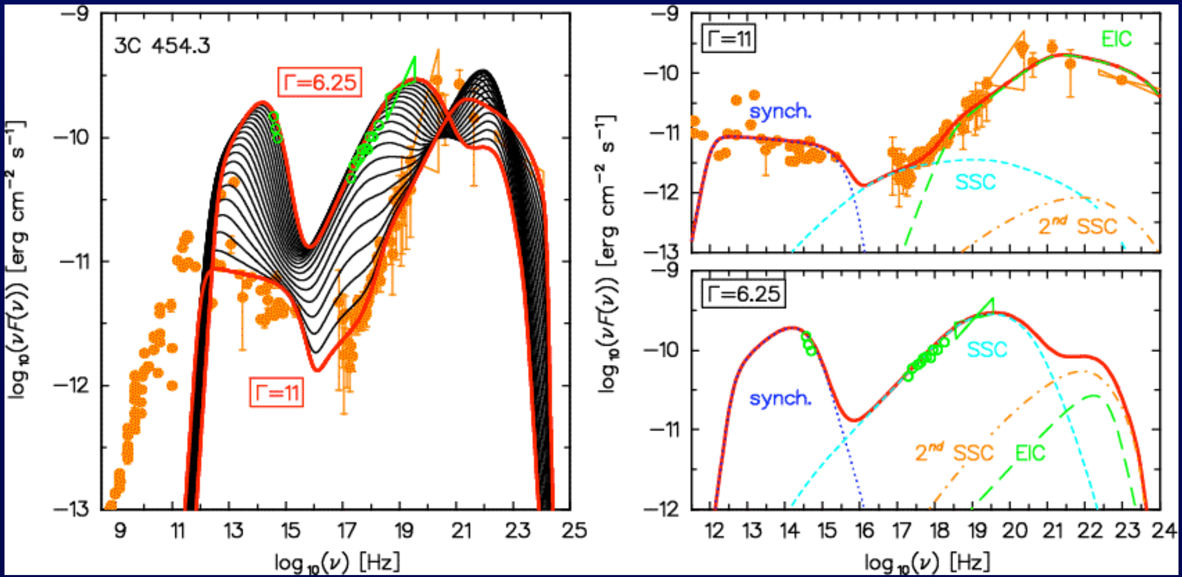
$\beta_{app} = 3.9 \pm 1.1$ for 51 sources not EGRET detected but: relative importance of SSC vs. EIC component depend on core separation and jet speed.

Assuming constant jet energy, a high γ shifts the radiation zone to larger core-separations, causing reduced SSC flux.

higher X – ray flux for jets with lower Lorentz-factors !



Katarzynski & Ghisellini, 2007



application to broad-band flare of 3C454.3 in April 2005 suggests low jet $\Gamma = 6$.

Gamma-ray emission in AGN originates from the base of relativistic jets, and is therefore Doppler-beamed and highly variable in intensity and spectral shape.

Main Mechanism: Inverse Compton scattering with synchrotron electrons

origin of seed photons controversial (SSC, ERC, RSC)

better understanding of physical conditions and emission mechanisms needed (δ, γ_e, B, n_e, ep or e^-e^+, R, ... ?)

VLBI, and in particular mm-VLBI can provide:

- morphology from pc down to sub-pc scales (>0.04 mas, few 10-1000 R_S)
- stringent limits to sizes (brightness temperature, energy density, magnetic field)
- shape and structure of jet (opening angle, bending, stratification, shocks)
- via monitoring: kinematics (β,γ) and geometry (δ, θ) (radial dependence of δ ?)
- after outbursts: detection of moving jet components in very early evolutionary stages (complemented by multi-frequency flux monitoring)
- in combination with cm-VLBI spectral properties of for core & jet components (ν_m, B)

Scheduling and logistical constraints

EVN: 3 sessions per year, mainly 18/21cm, 5/6cm, 1.3cm once per year

1.3cm/7mm seldomly because of low proposal pressure, data rates ≤ 1024 Mbit/s

eEVN: several sessions/yr, 2 week response, only 18 or 6 cm,

6 stations (Wb, Jb, Cm, On, Mv, Tr), Eb coming end 2007, data rates ≤ 256 Mbit/s

VLBA: flexible time allocation, rapid frequency switching, data rates ≤ 512 Mbit/s

VLBA+Effelsberg: flexible, broad frequency coverage (1.4 – 86 GHz), ≤ 512 Mbit/s

HSA: up to 100 hrs per trimester, no 43 GHz in summer (is this reasonable?), ≤ 512 Mbit/s

Global VLBI: same as EVN, 3 sessions per year, need increased proposal pressure to schedule 1.3cm/7mm more frequently, ≤ 512 Mbit/s

GMVA: 3mm, global (3xEVN + 2xIRAM +8xVLBA), 2 sessions per year (spring/autumn) of up to 10 days, depending on proposal pressure, ≤ 1024/512 Mbit/s in Europe/USA

VLBA+MPIfR+IRAM: flexible 3mm VLBI similar to VLBA+Eb, not yet established, need MOU !

END