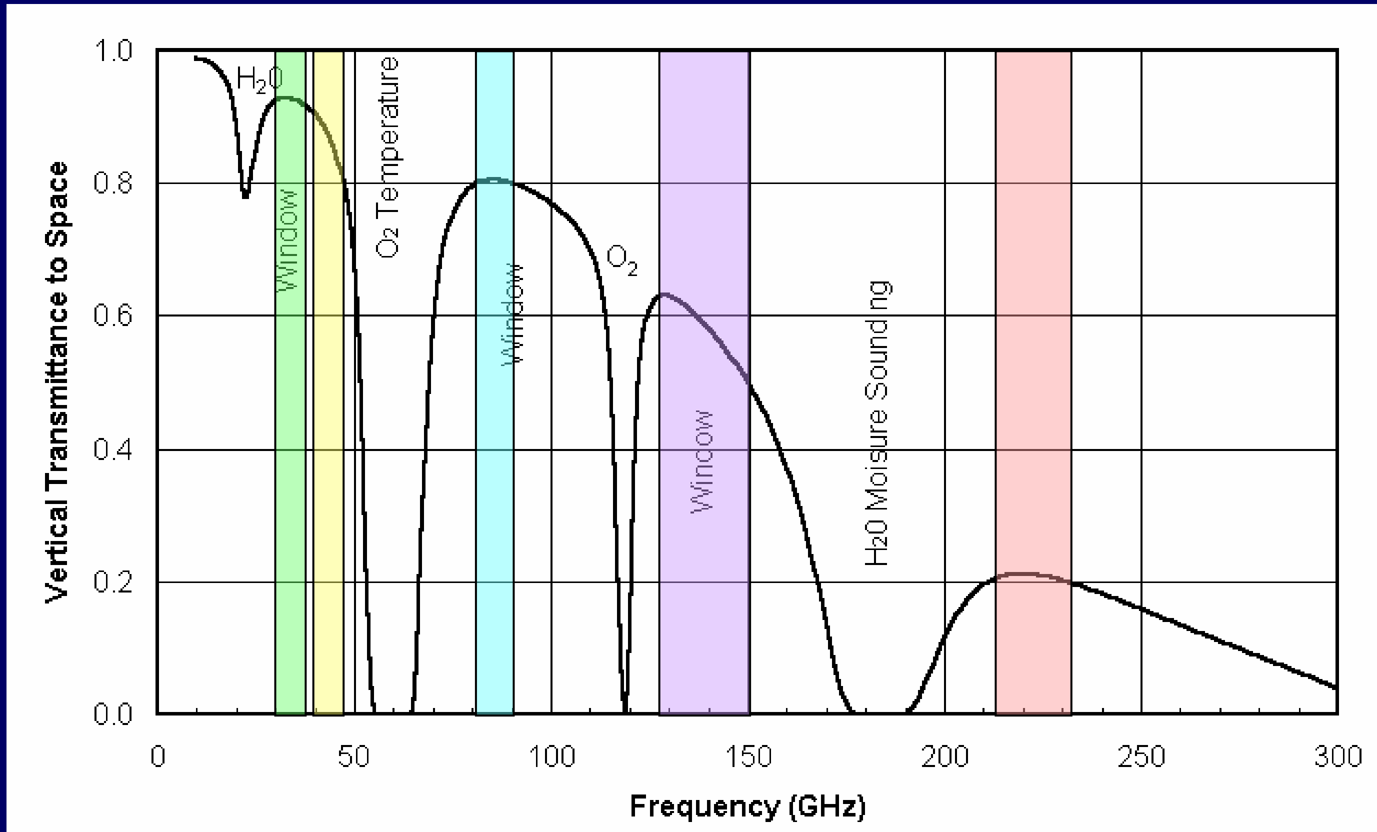
# EVN2015: High frequency VLBI in Europe

## Present status & future perspectives

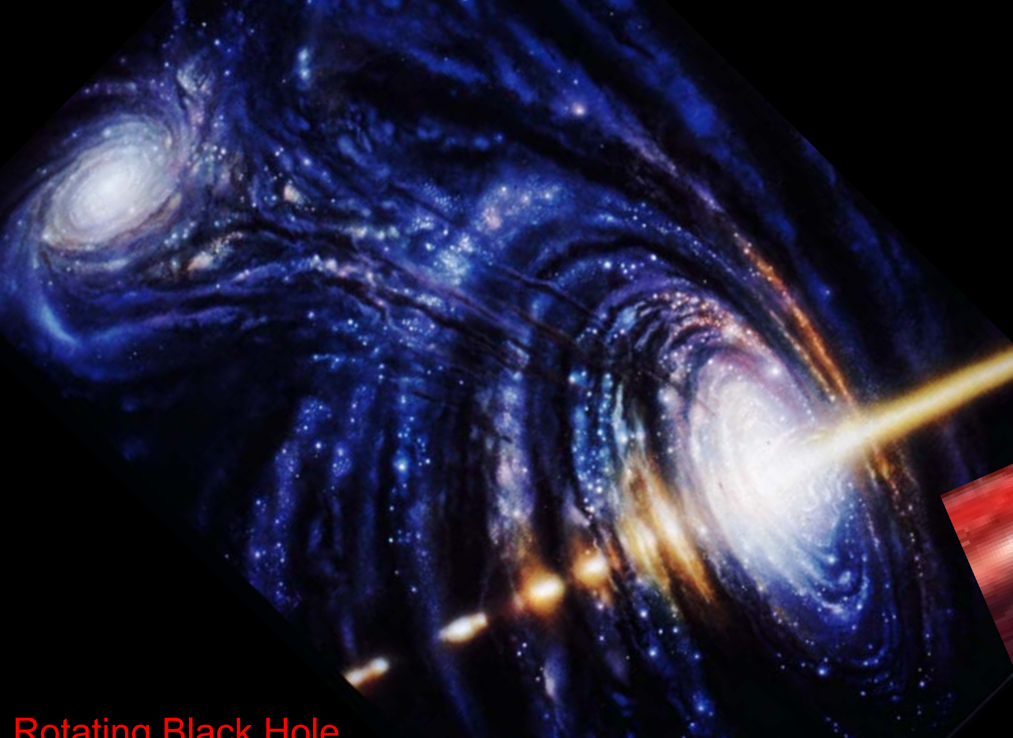
T.P. Krichbaum, MPIfR, Bonn



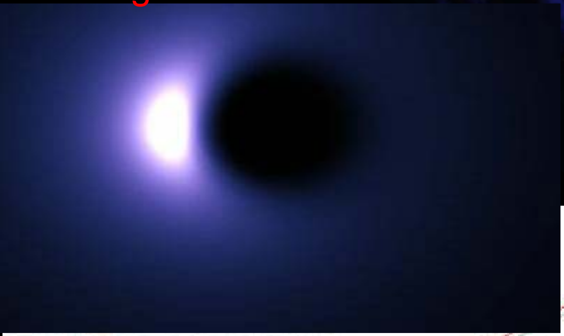

atmospheric windows support high frequency VLBI at the following bands:

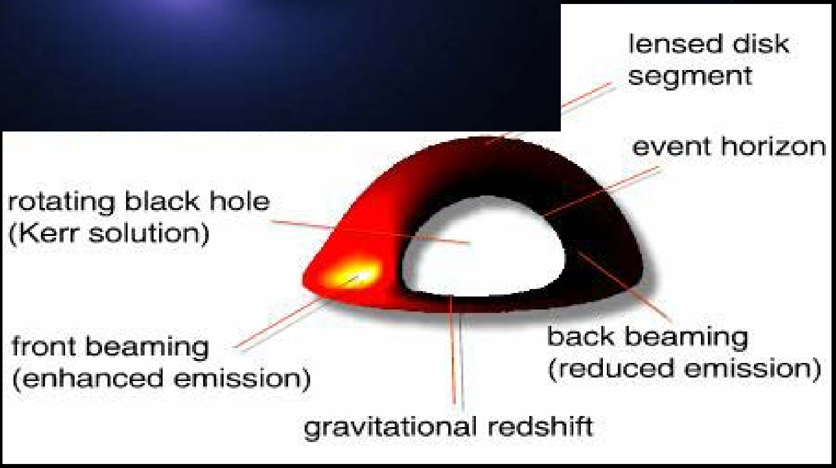
- 32-35 GHz — some preference because of low $\tau$ and future DSN observation
- 43 GHz (SiO) — already done
- 86 GHz (SiO) — already done
- 129/150 GHz — pilot studies, fringes detected
- 215/230 GHz — pilot studies, few sources detected at 20 $\mu$as

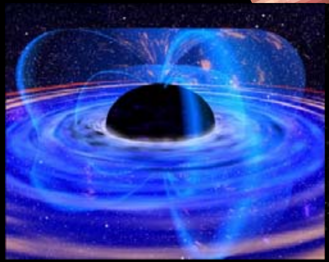
# Main Motivation: What are the procceses acting at the centers of Quasars (AGN) ? How are the powerful jets launched and accelerated ?



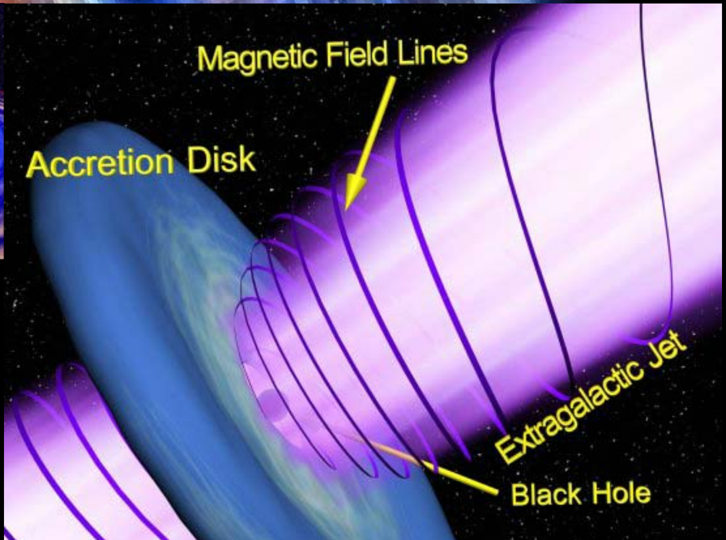
Rotating Black Hole





The Black Hole Dynamo



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- few 10$\mu$as-scale beam (3mm/1mm): few 10-100 $R_G$ in nearby SMBHs, jet nozzle
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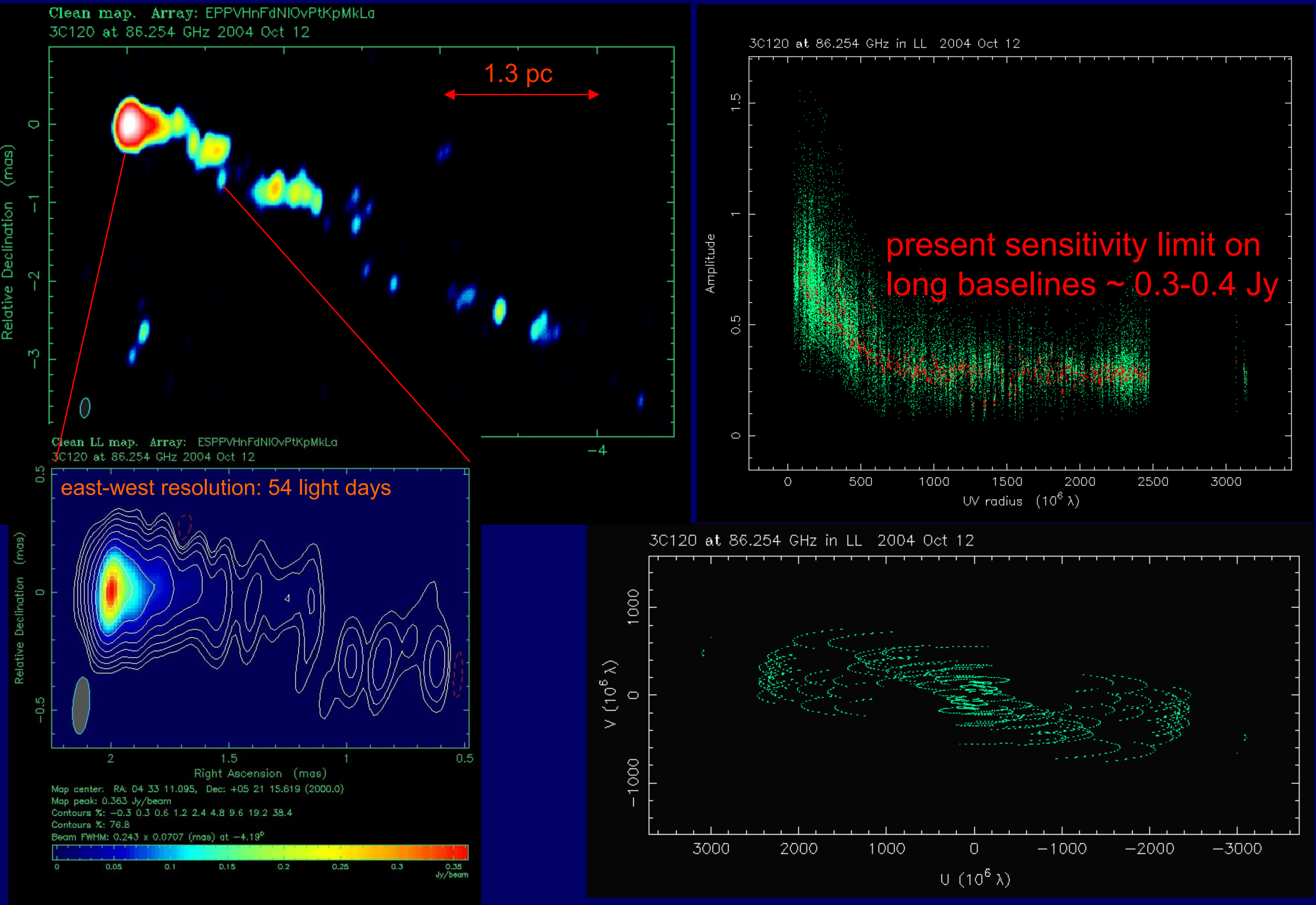
- SgrA* & M87 and alike, image event horizon, test General Relativity
- molecular lines: circumnuclear gas, interaction of jet with ambient ISM (redshifted absorption, CO, HCO+, ...)
- stars und stellar enveloppes: SiO masers, other spectral lines

# 3C120 with the full GMVA at 86 GHz, Oct. 12, 2004



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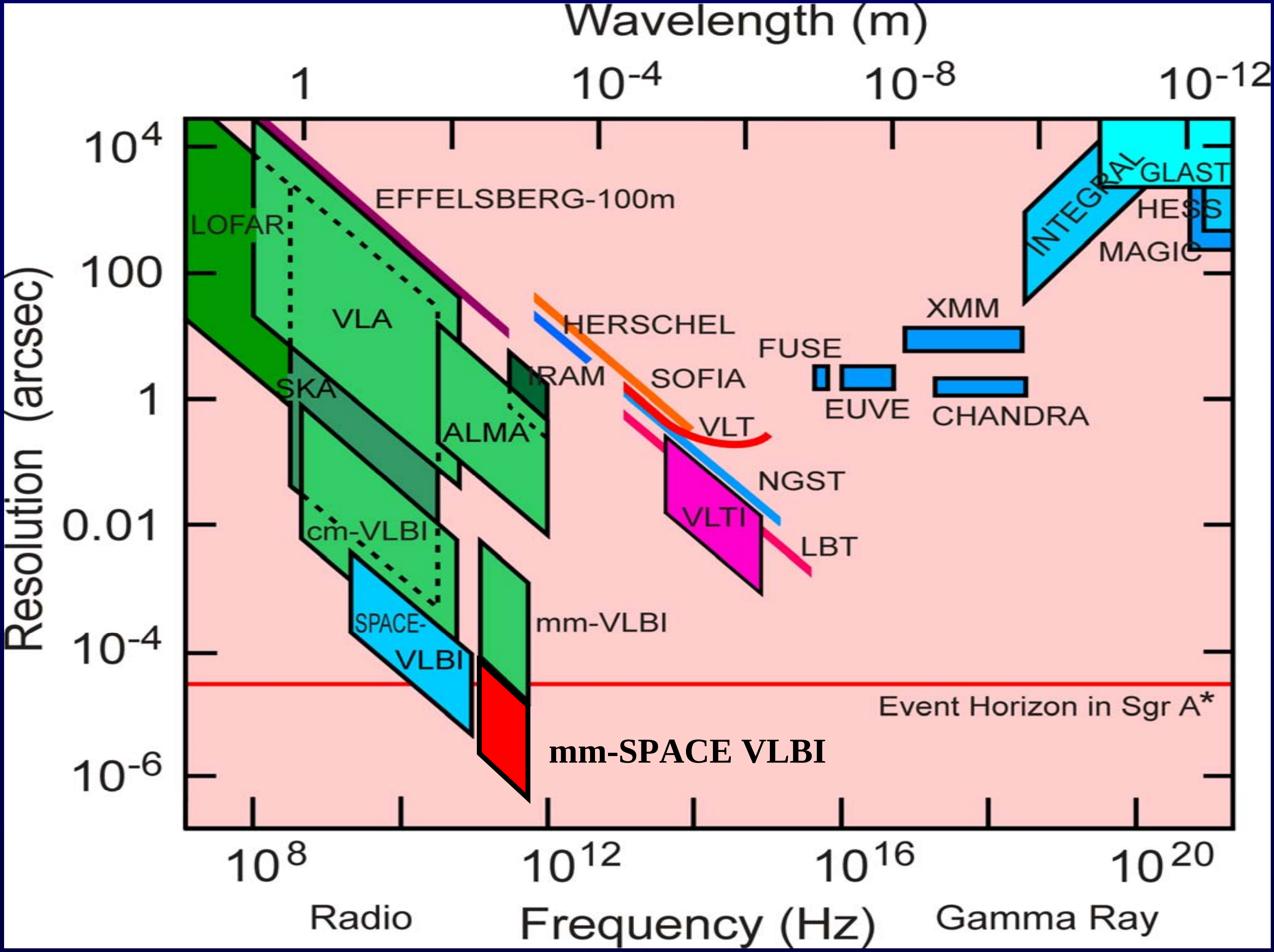
# Telescopes: now and tomorrow




Millimetre VLBI provides the highest angular resolution in Astronomy !

# *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: $10^3\ R_s^{9}$   30-100 $R_s^{9}$   1-5 $R_s^{6}$

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass !

→ mm-VLBI is able to directly <u>image (!)</u> the vicinity of SMBHs !

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

→ many more sources if sensitivity is increased

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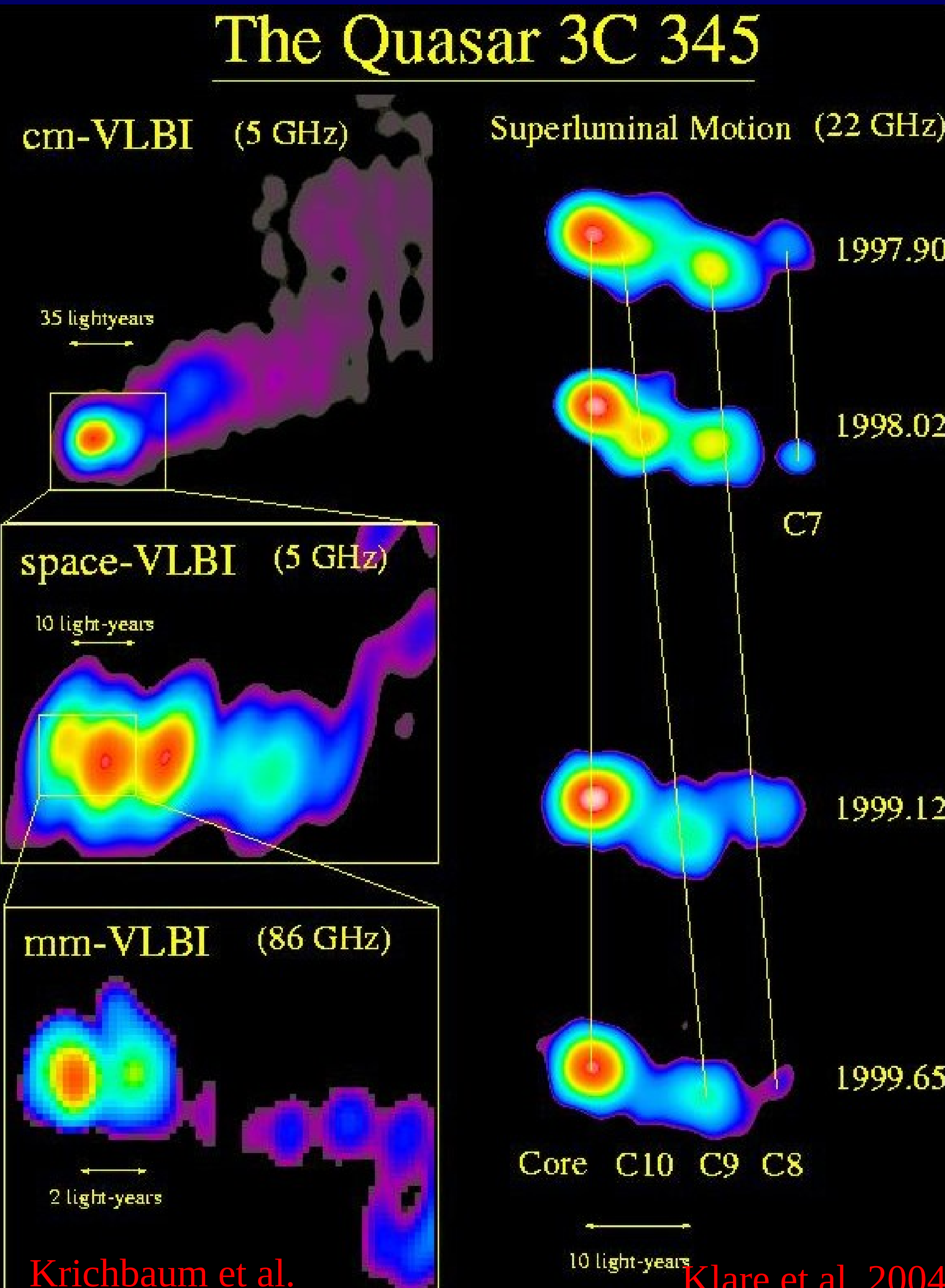
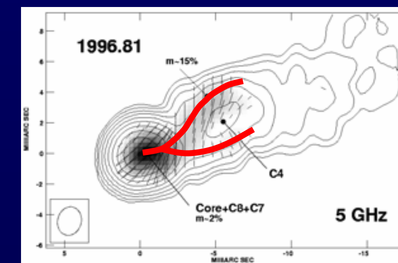
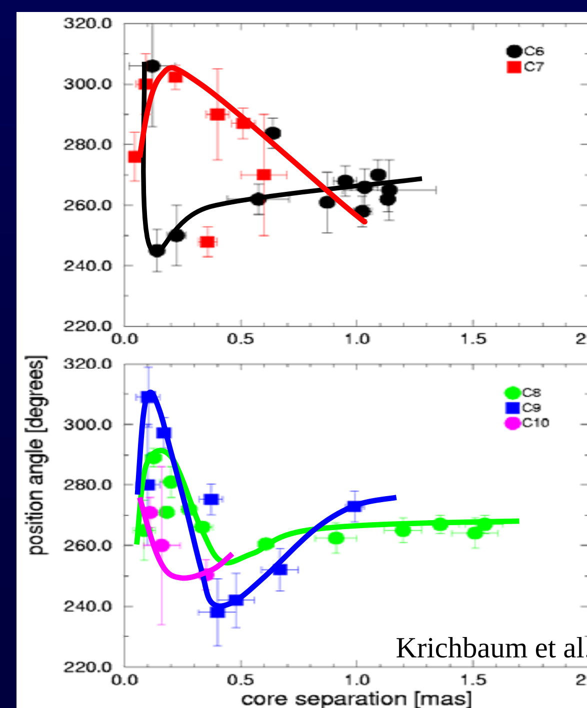
# Helical AGN-jets: need highest resolution to trace to origin




Study kinematics and helical (non-ballistic) paths with combined space-VLBI and mm-VLBI




Ros et al. 2000



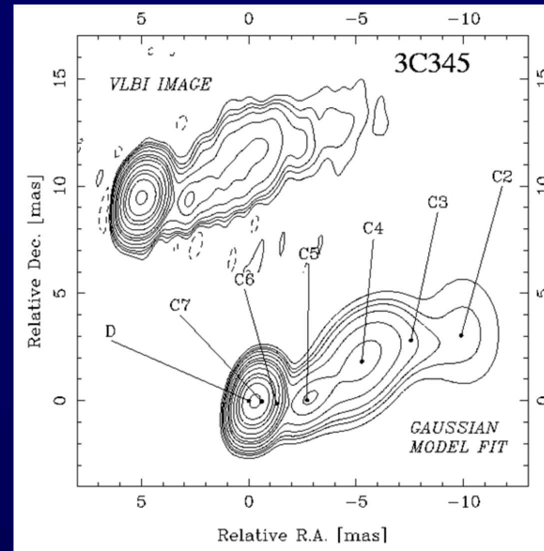
# 3C345: A Binary Black Hole ?

The assumption of a supermassive binary Black Hole in 3C345 explains:

1. observed helical trajectories of the jet components
2. flux density changes of the jet components
3. optical variability
4. morphology and evolution of the jet

This provides a new paradigm for understanding the dynamics and emission in parsec-scale jets in AGN.

(also: Gravitational Waves)

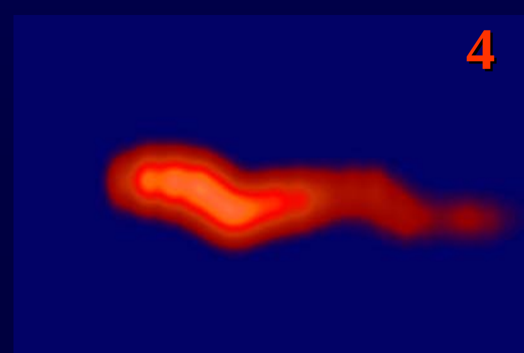


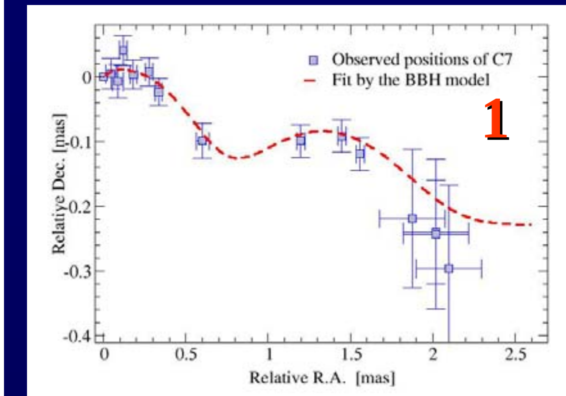

Parameters of BBH in 3C345

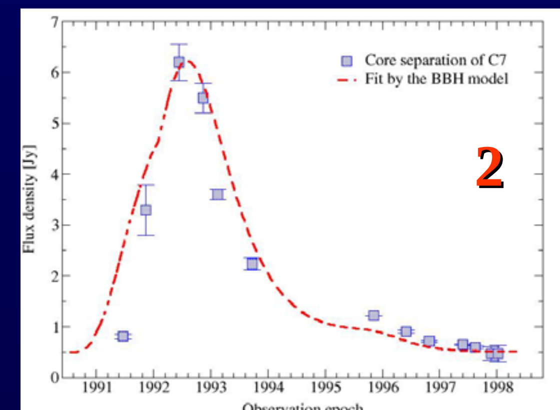
$M_1 = 1\cdot10^9\,\mathrm{M_{sol}}$, $M_2 = 5\cdot10^8\,\mathrm{M_{sol}}$

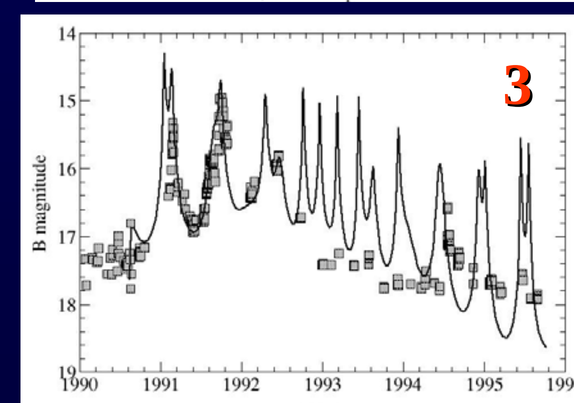
$a_{maj} = 0.63\,\mathrm{pc}\,(0.13\,\mathrm{mas})$, $e = 0.1$

$P_{orb} \approx 170\,\mathrm{years}$, $P_{prec} \approx 2500\,\mathrm{years}$




Lobanov & Roland 2002

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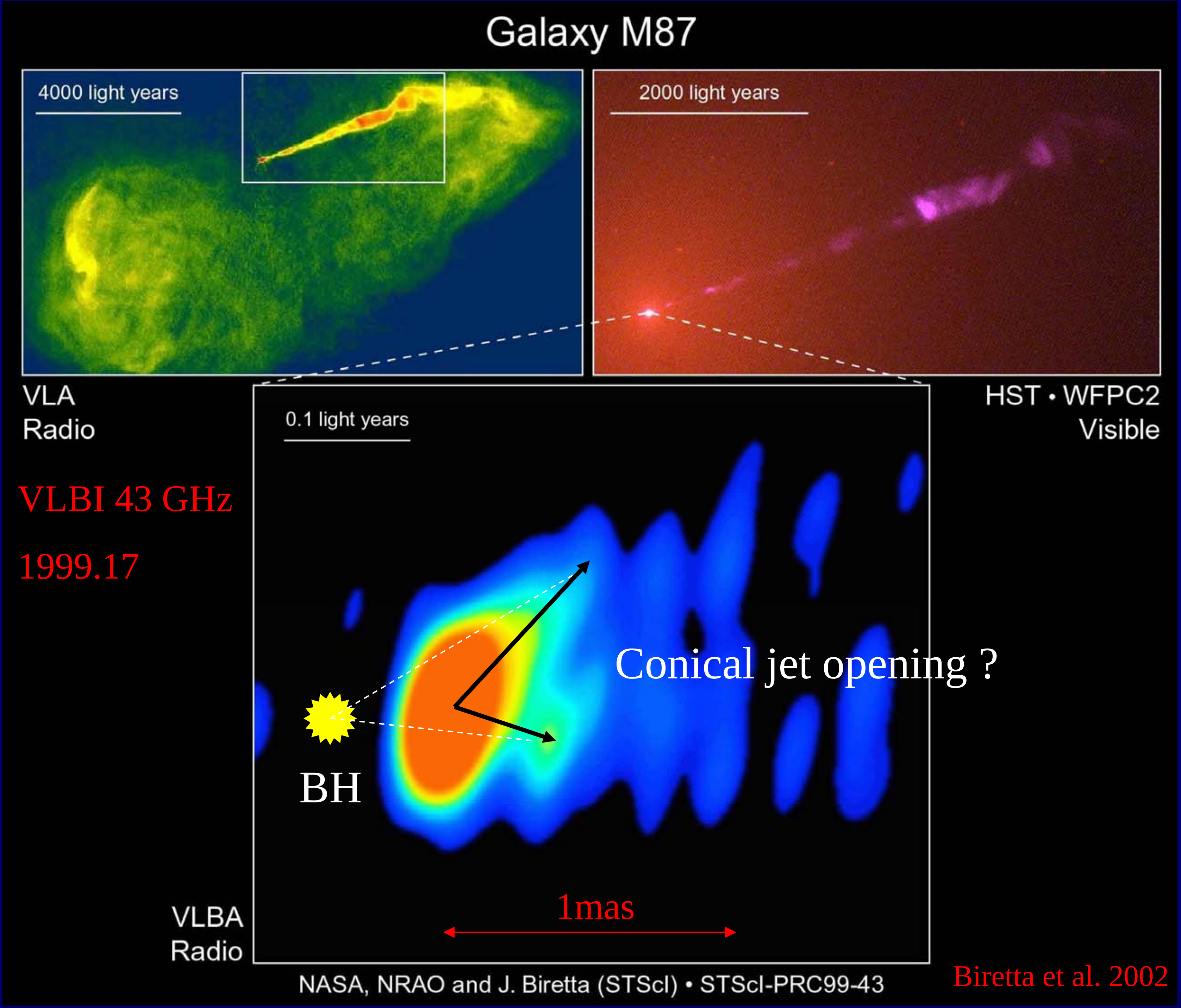
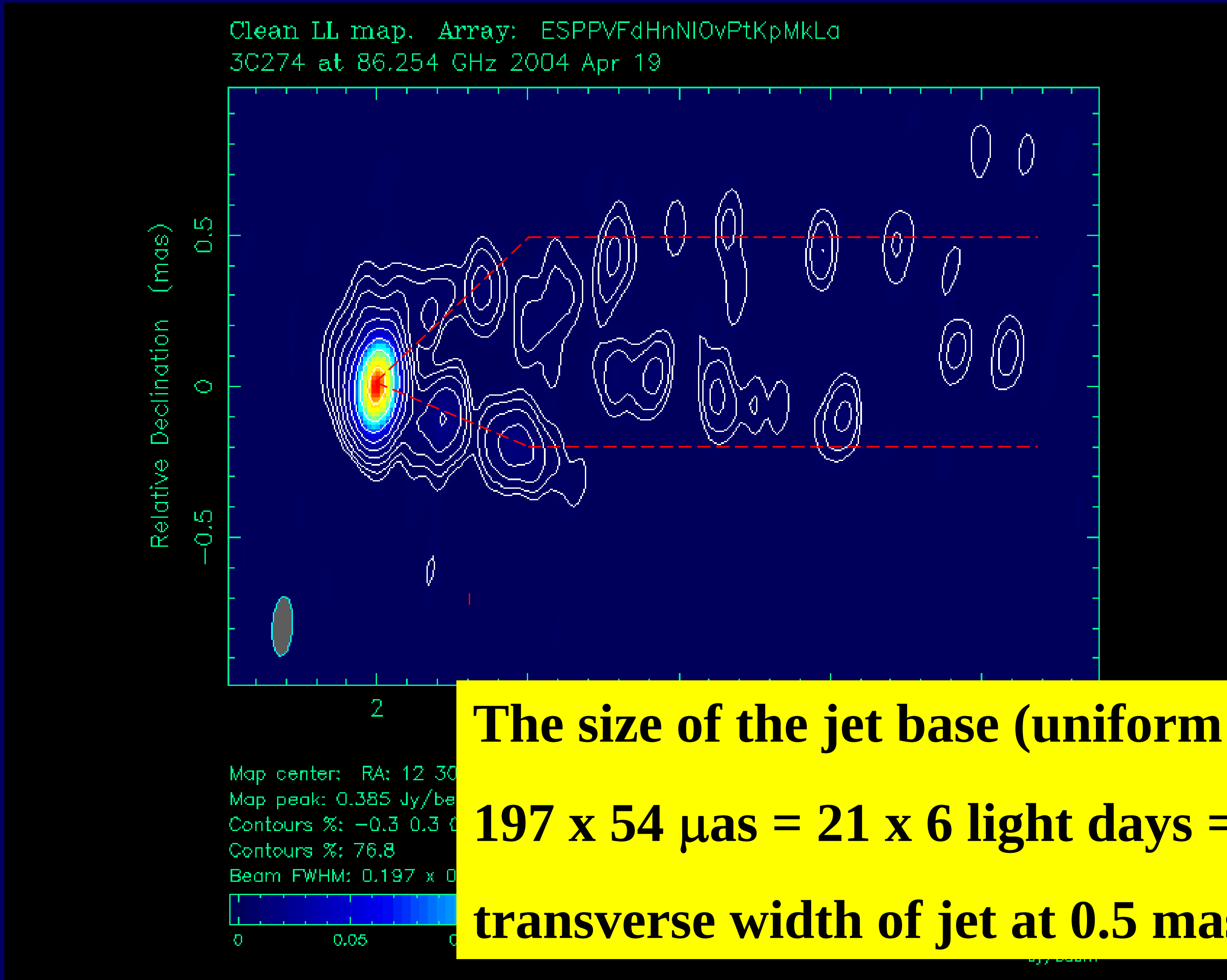

Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBI 43 GHz
1999.17
Conical jet opening ?
BH
1mas
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43
Biretta et al. 2002

# M87 at 86 GHz




Krichbaum et al. 2006

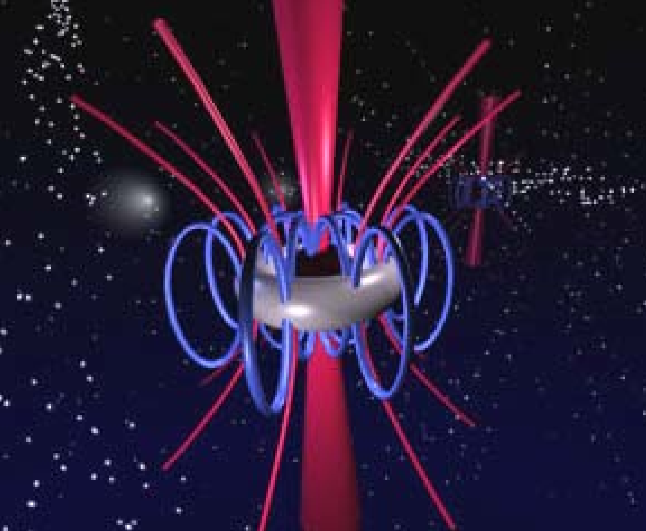
**The size of the jet base (uniform weighting):**

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

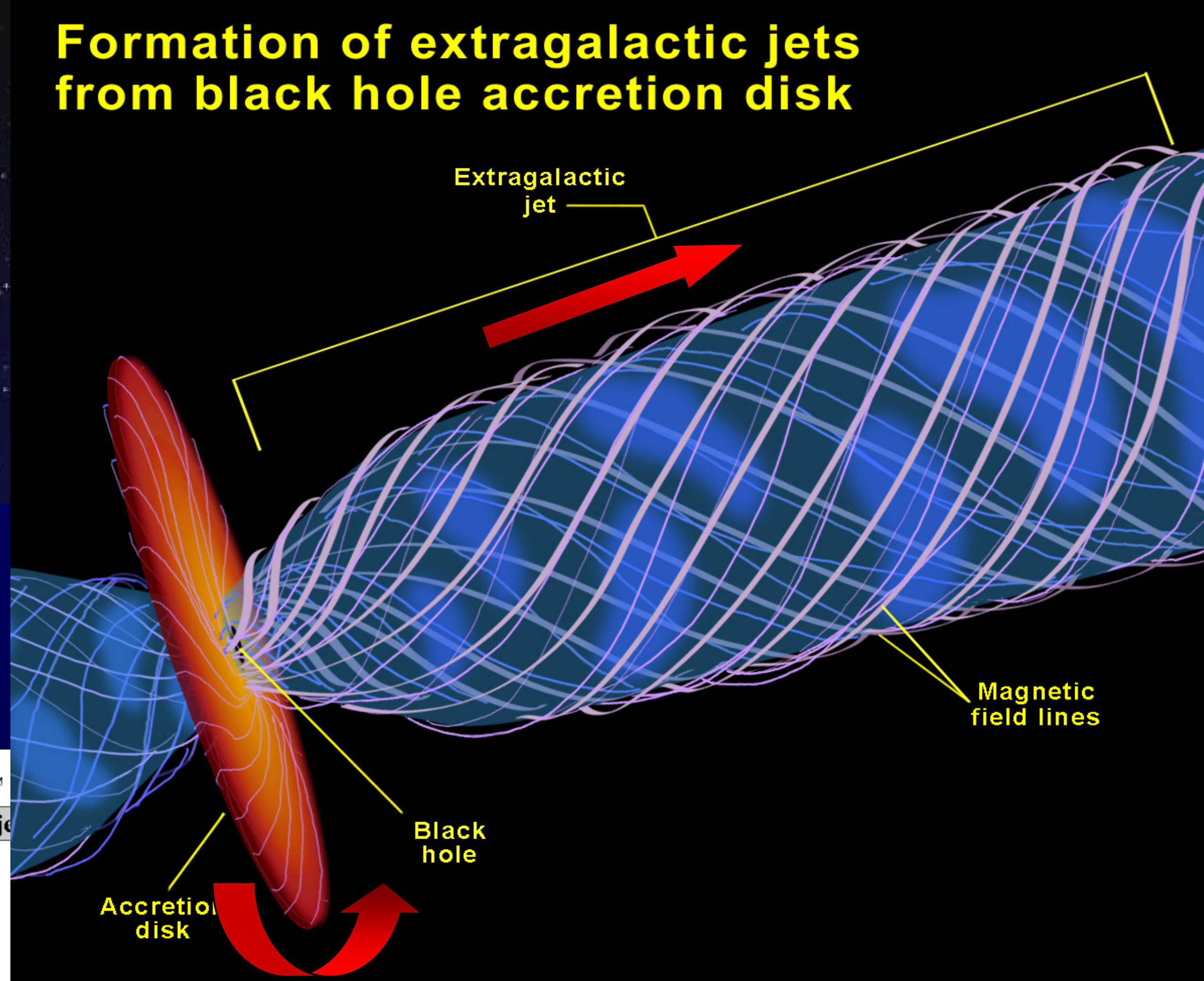
**transverse width of jet at 0.5 mas: ~174 $R_s$**

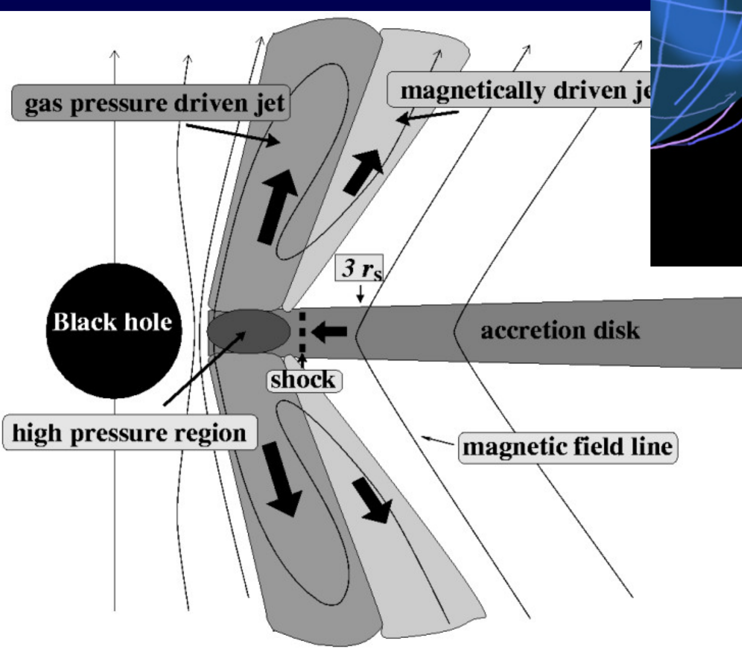
new global 3mm map of M87 observed with the GMVA in April 2004:

now with better sensitivity, data rate: 512 Mbit/s (MK5 hard disk recording)

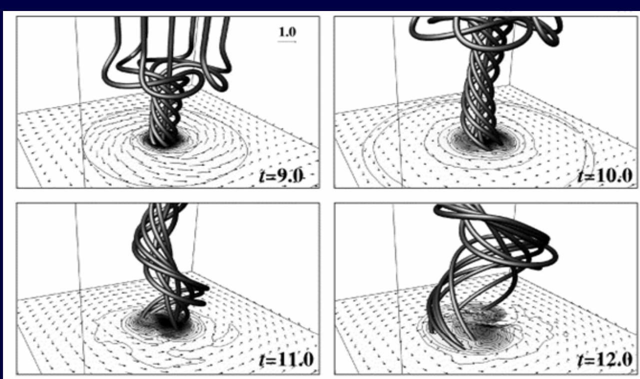


The central engine – a MHD dynamo ?




MHD simulation of a confining B-field anchored in a rotating disk



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# Position angle swing in NRAO150

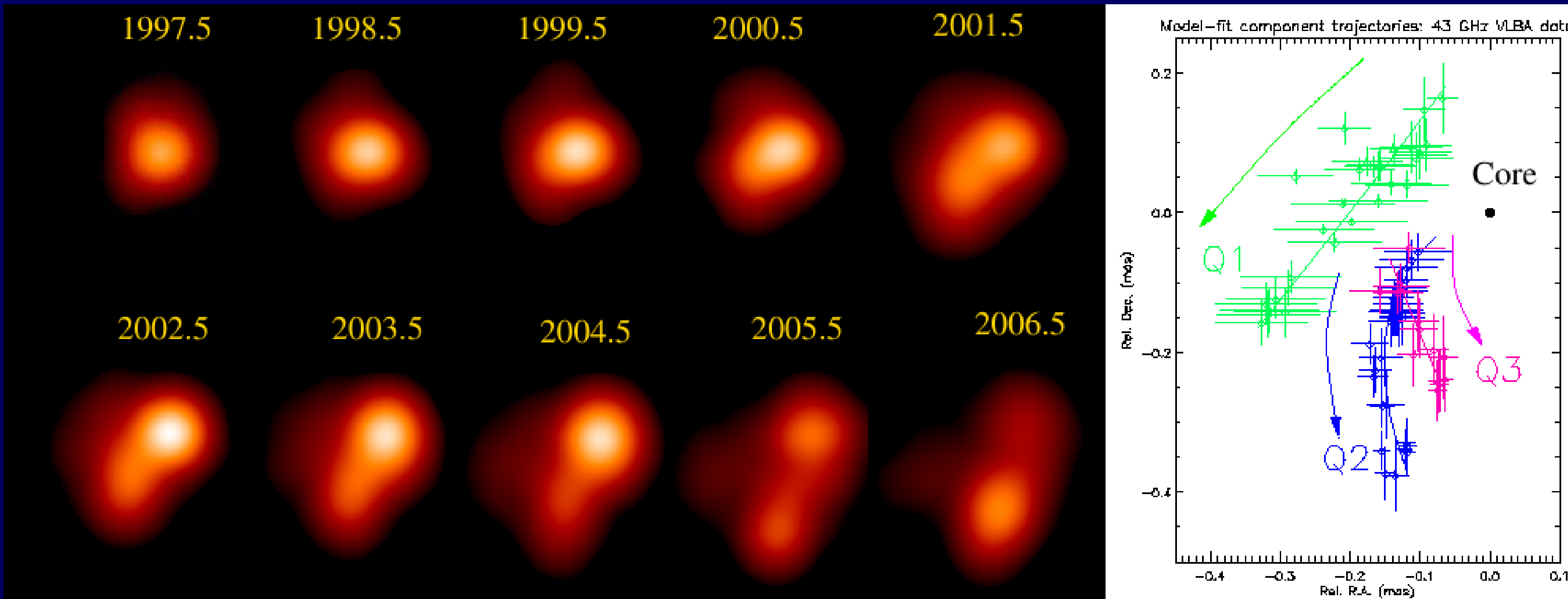
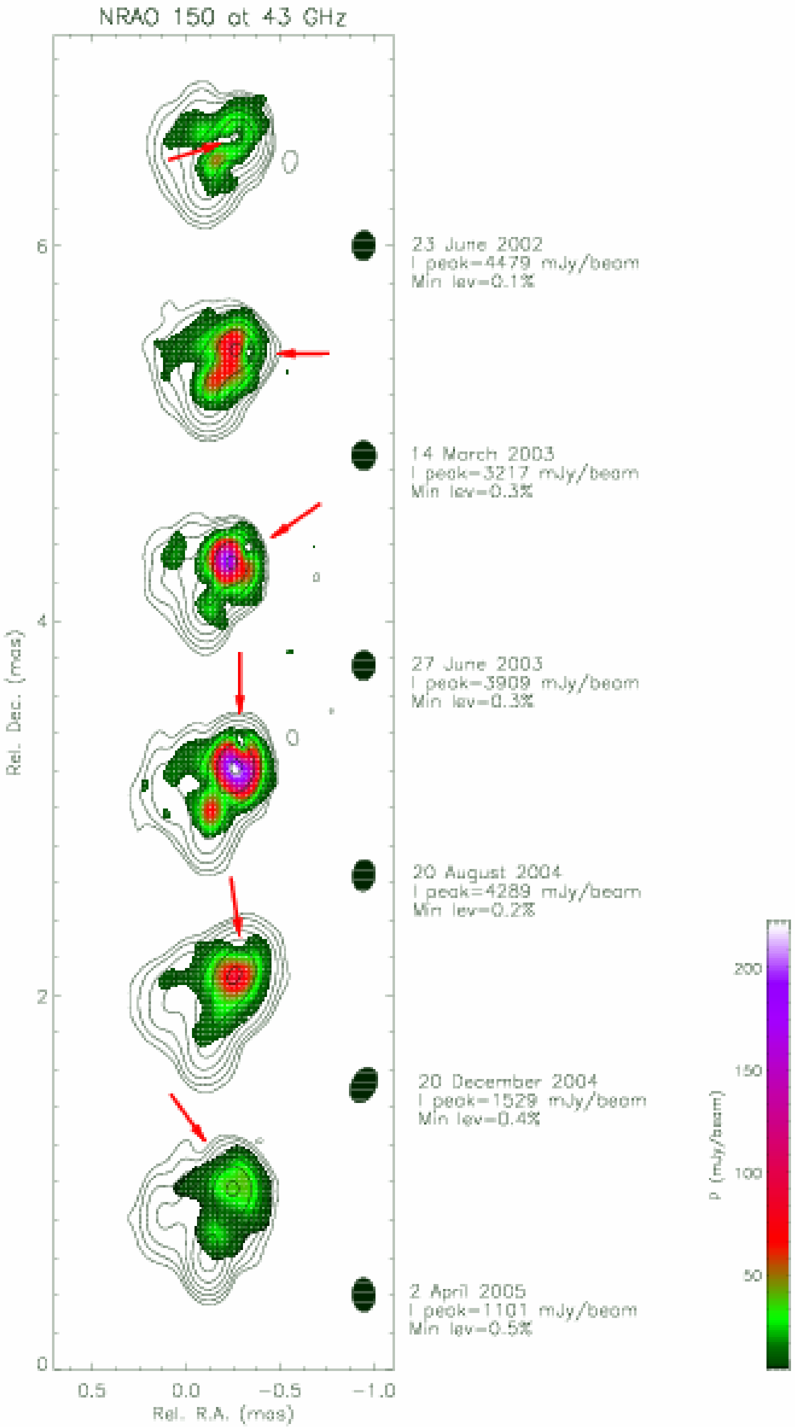


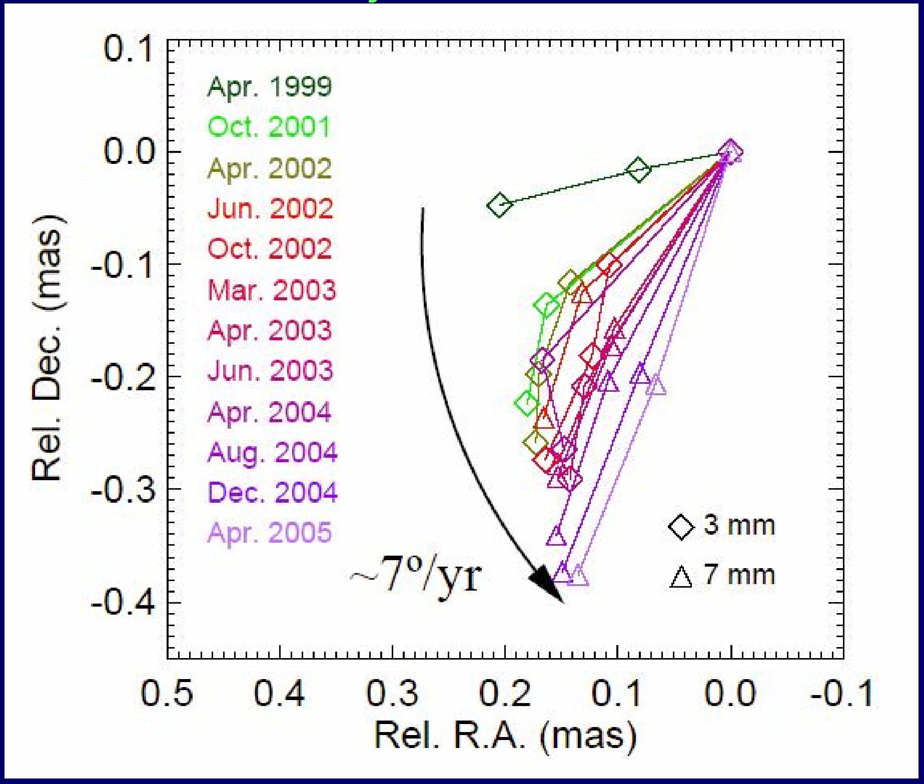

Figure 2: (Left) sequence of 43 GHz VLBA images of NRAO 150 obtained from 1997 to 2006. The projected jet rotation is evident from visual inspection. (Right) Projected trajectories of the 43 GHz model components used to fit the source structure (see Fig 1). The crosses symbolize the position errors of such components, whereas the superimposed bent lines represent the fitted trajectories of each model component (labelled in this Figure and in Fig 1). Arrows indicate the sense of motion of the jet features. All trajectories are *superluminal*, although they are *non-ballistic*. To appear in Agudo et al., A&A Letters in preparation.

Agudo et al. 2007

# Position angle swing in NRAO15 accompanied by polarisation variations




Rotation of inner jet axis:




Agudo et al. 2006, 2007, in prep.

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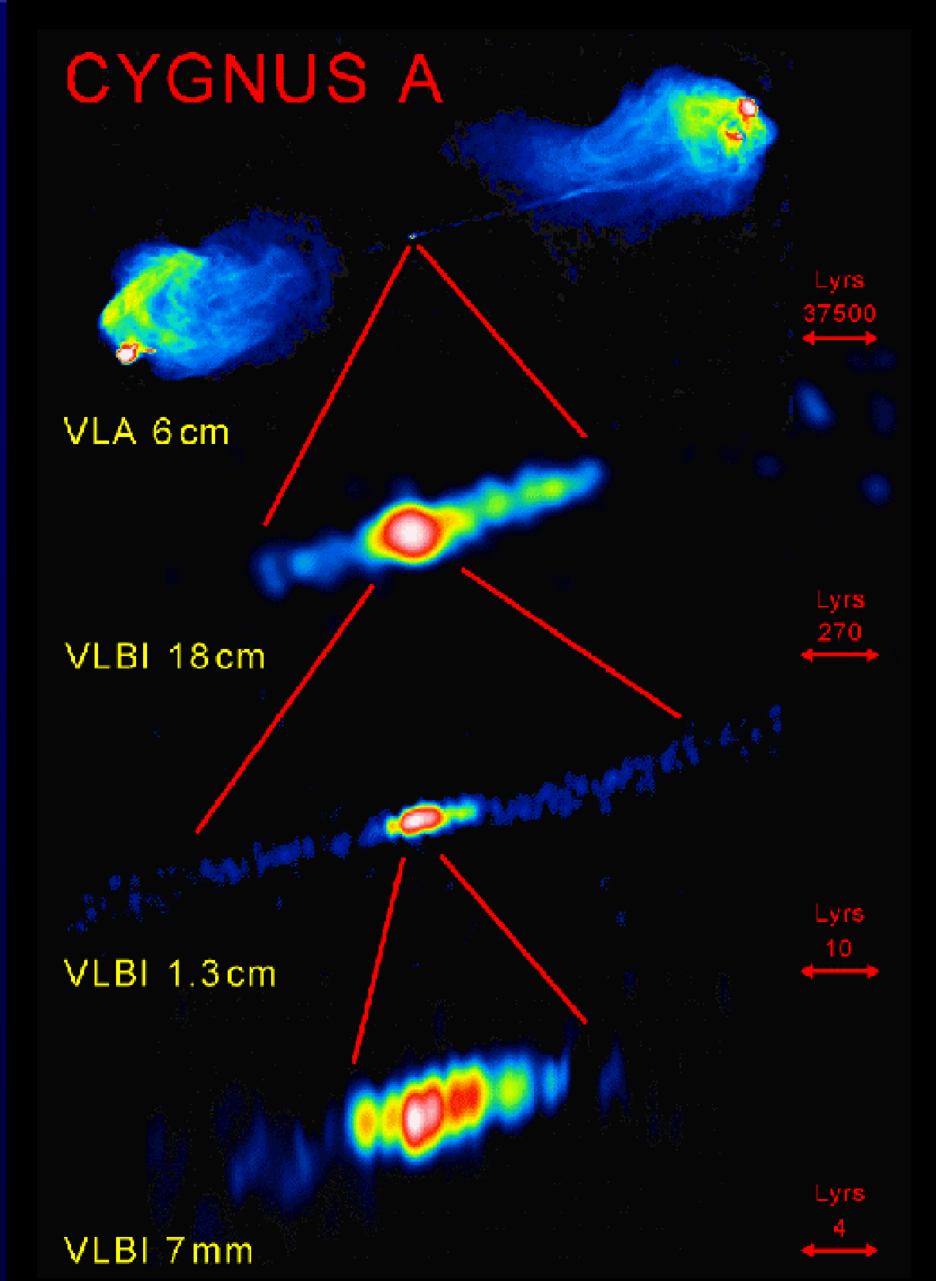
# The two-sided Jets of Cygnus A

Study of motion in two-sided jets allows one to determine the intrinsic jet speed and – at least in principle – the distance of the source (Hubble constant).

The determination of the (frequency dependent) jet-to-counter jet ratio gives insight on the absorbing accretion disk.

The distance between base of jet and counter-jet yields important size limits of the region where the jet is made and accelerated.

Towards millimeter wavelengths the foreground absorption becomes optically thin, facilitating a more direct view into the nucleus.



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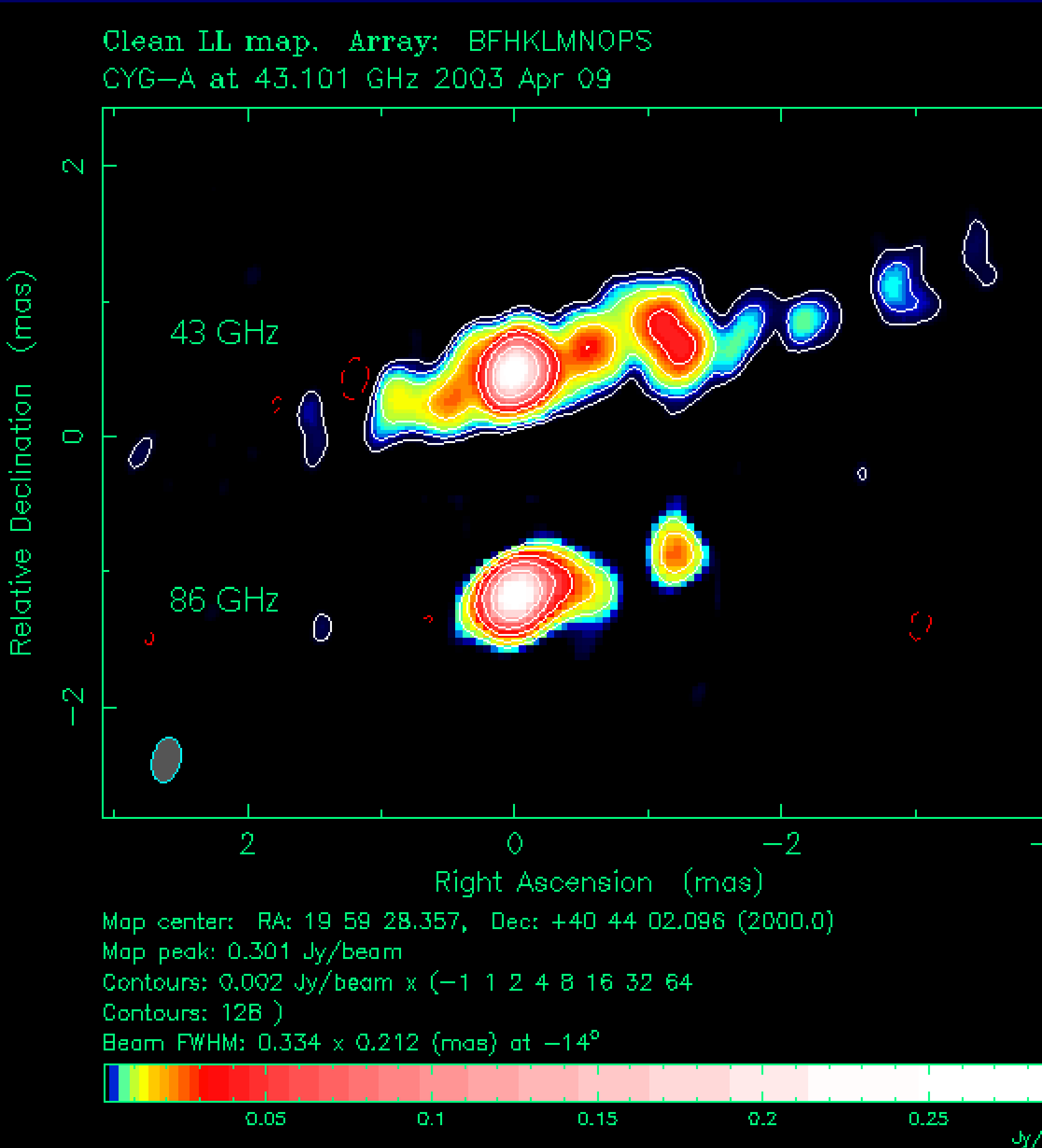
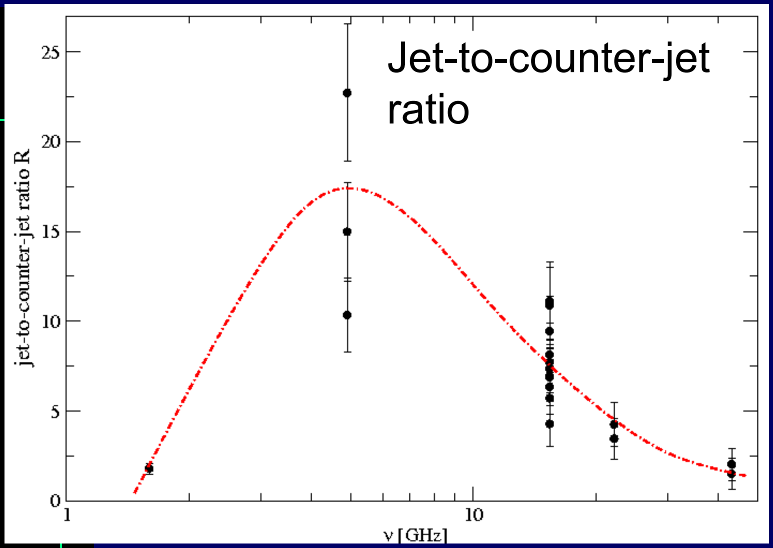
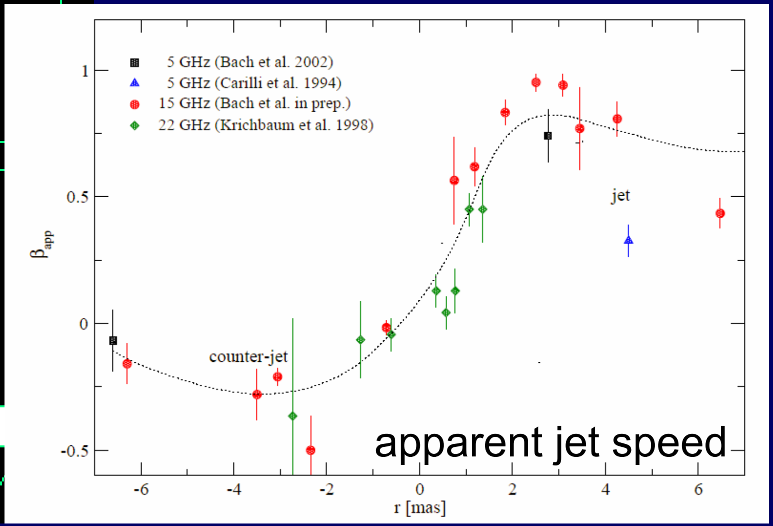



Bach et al. 2006 and in prep.



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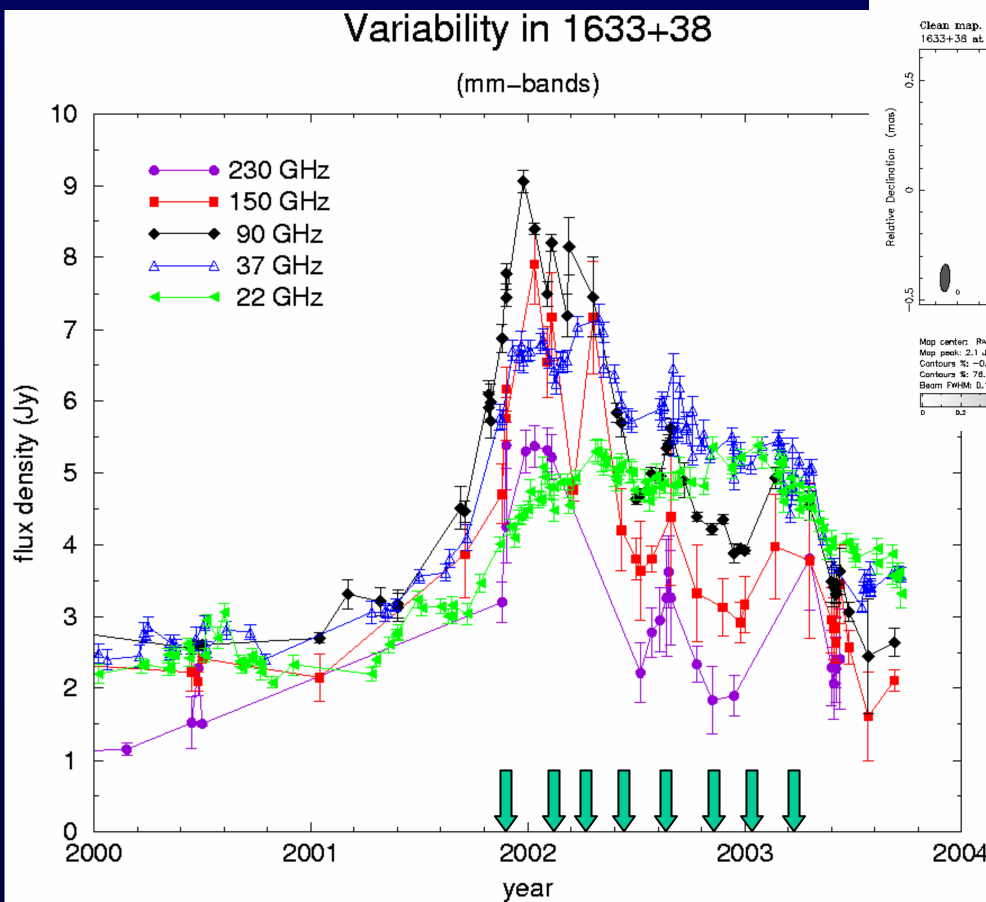
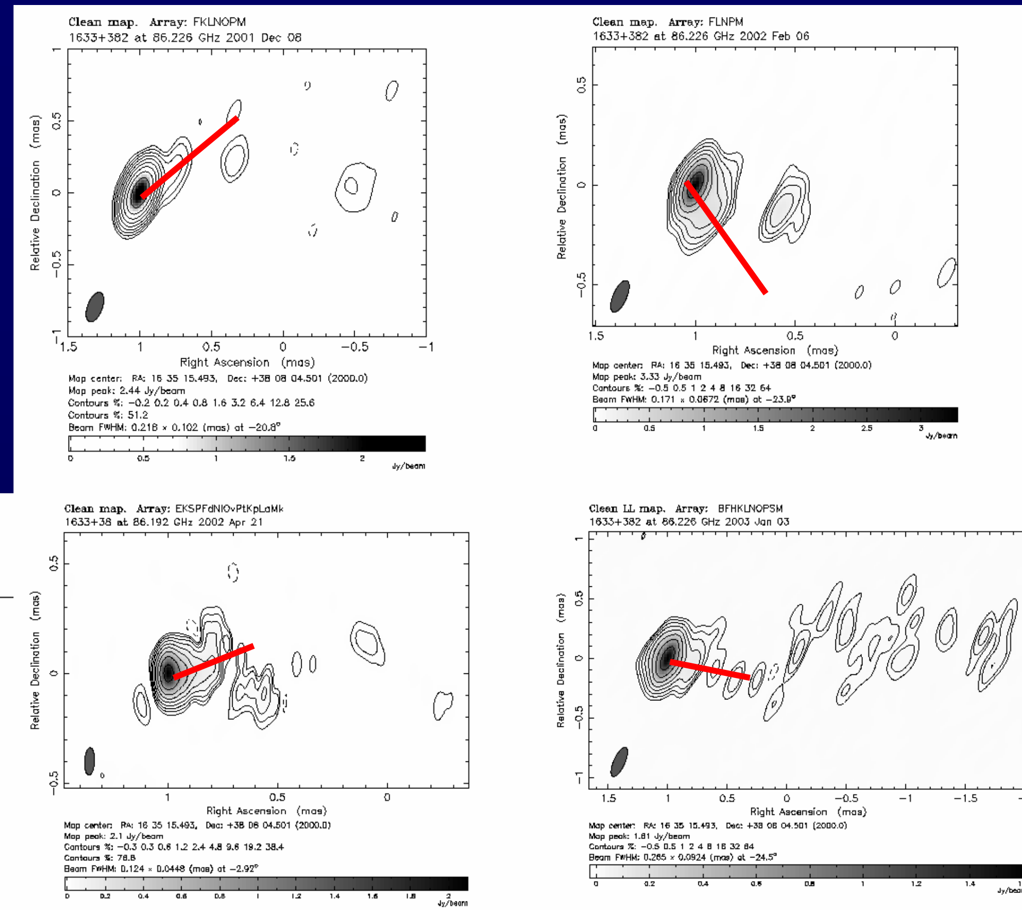
# Monitoring of the gamma-ray quasar 1633+382 after a major mm-flare




Prelim. 3mm-VLBI images reveal changes of the orientation at the jet base on timescales of only 2-3 months !

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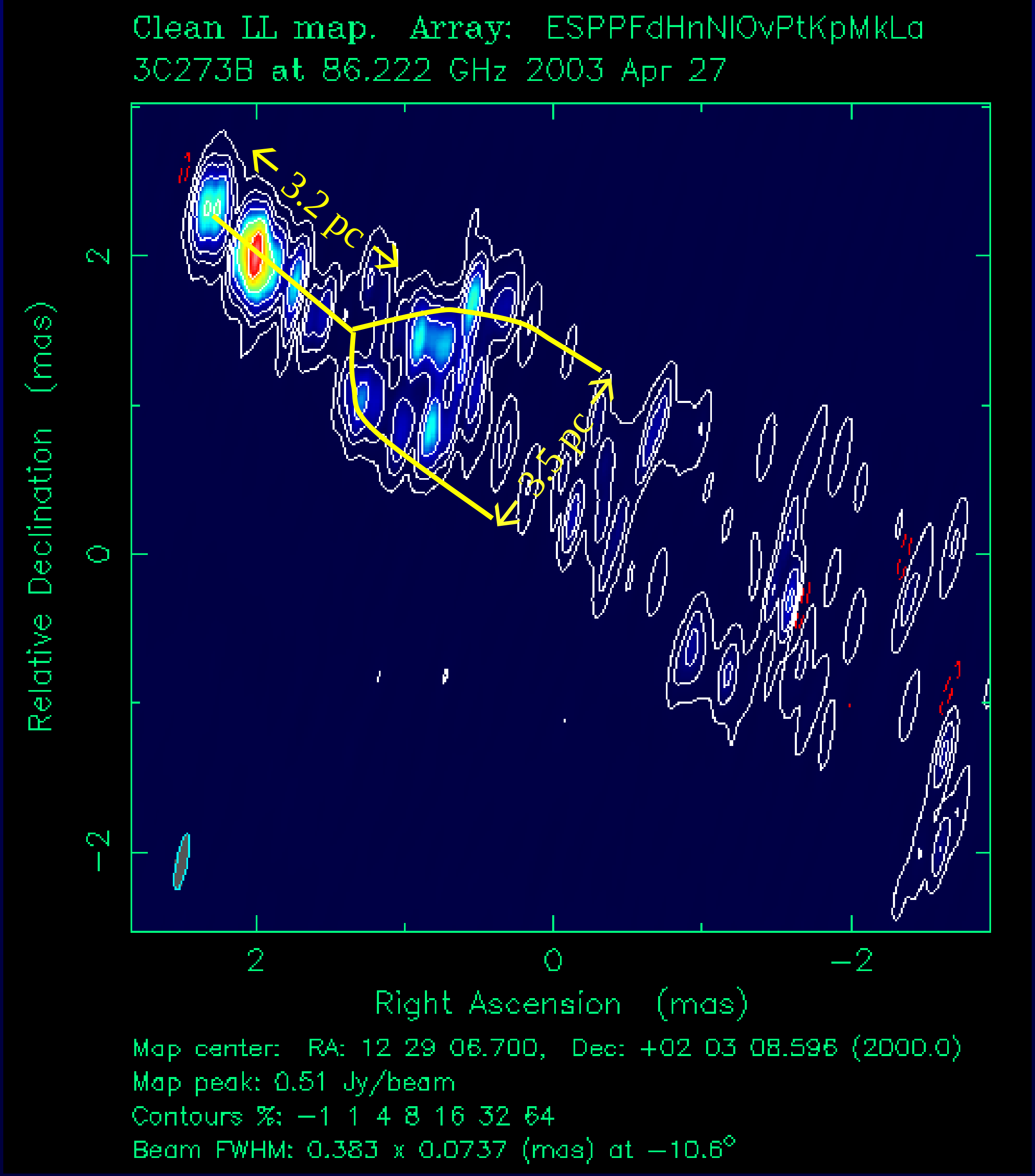
mm-VLBI can resolve jets transversely:

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



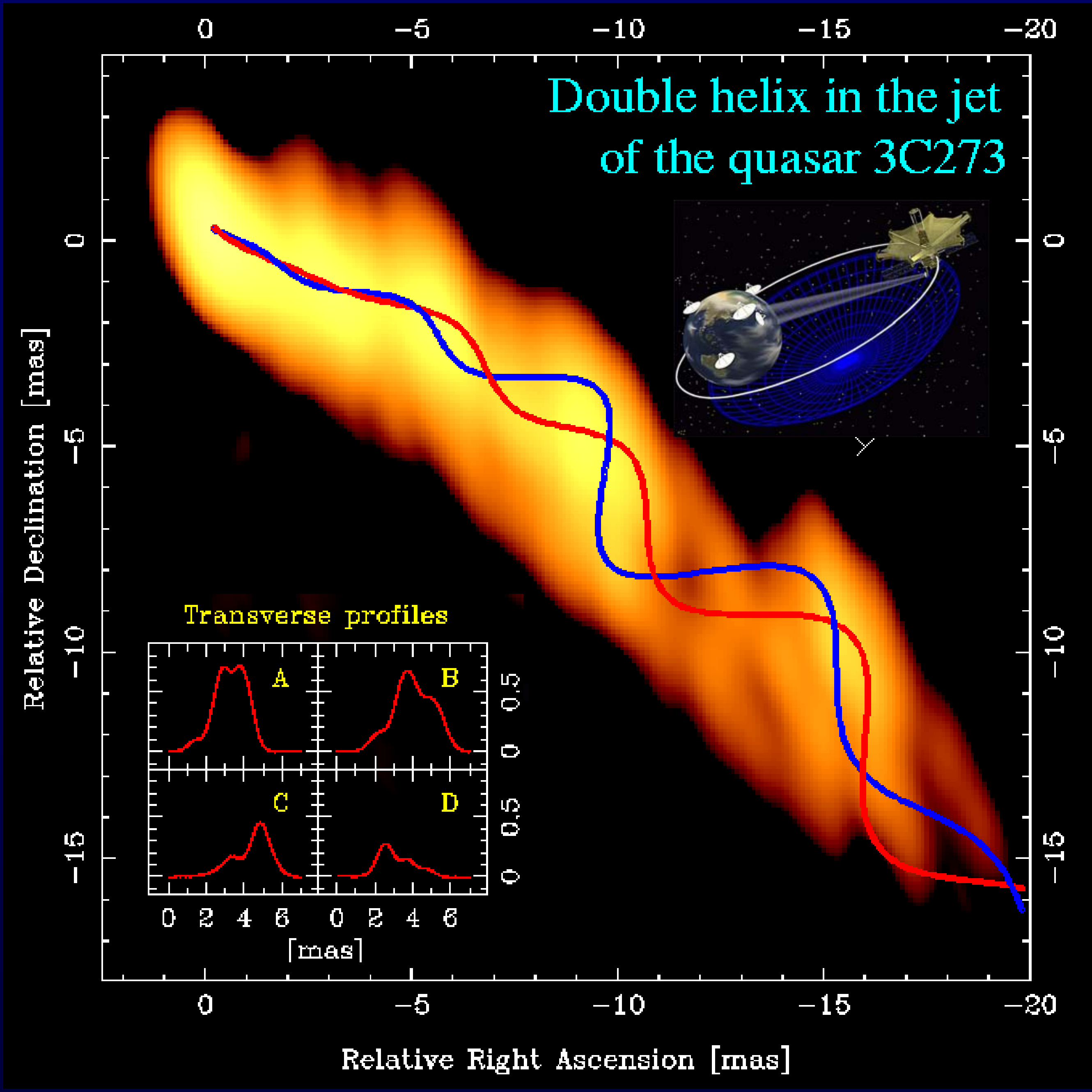

$z = 0.158$

1mas $\cong$ 2.7 pc

Plasma instabilities become visible are when jets are trans-versially resolved.

For more detailed studies need dynamic range > few 1000: 1

Future: mm-VLBI and mm-Space-VLBI (VSOP2, ARISE) will show this in AGN jets also at z > 0.2.




Lobanov and Zensus 2002

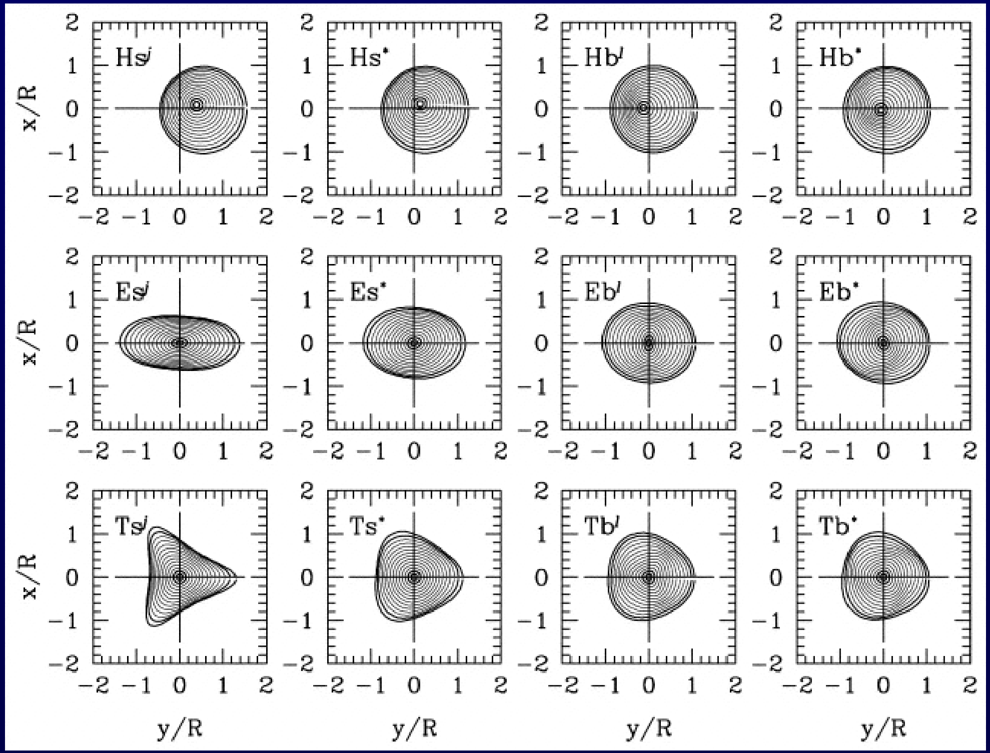
# Kelvin Helmholtz Instabilities in Jets: a tool to measure the physical parameters (p, ρ, γ, M) of the relativistic flow

Hardee, 2000, ApJ 533, 176

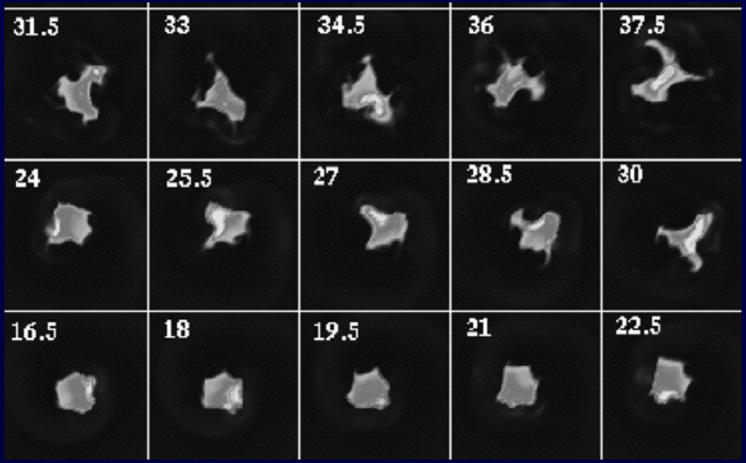
helical surface & body modes

elliptical surface & body modes

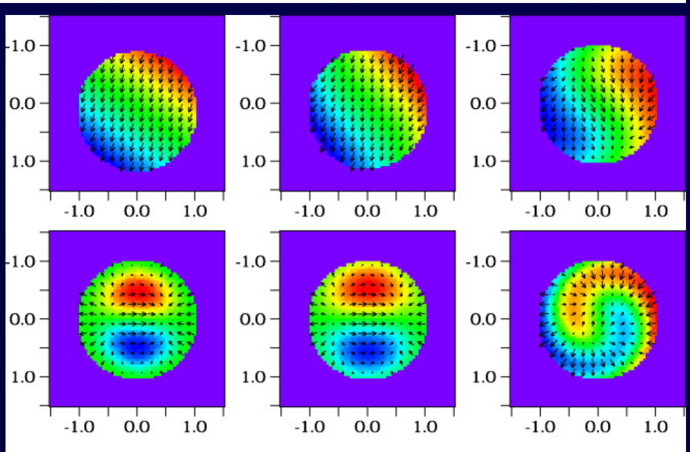
triangular surface &body modes




transverse cross-sections - density:




internal pressure:

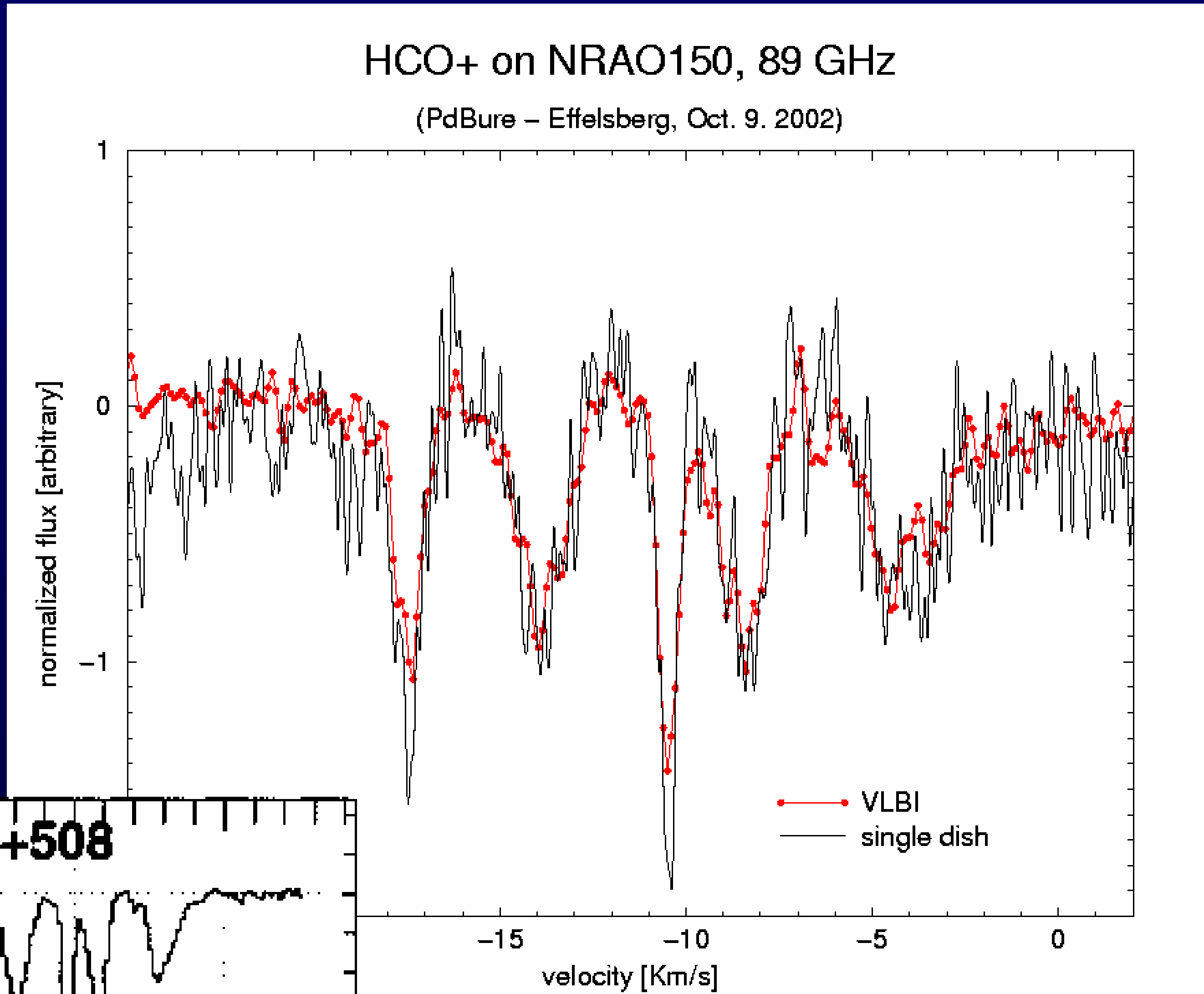


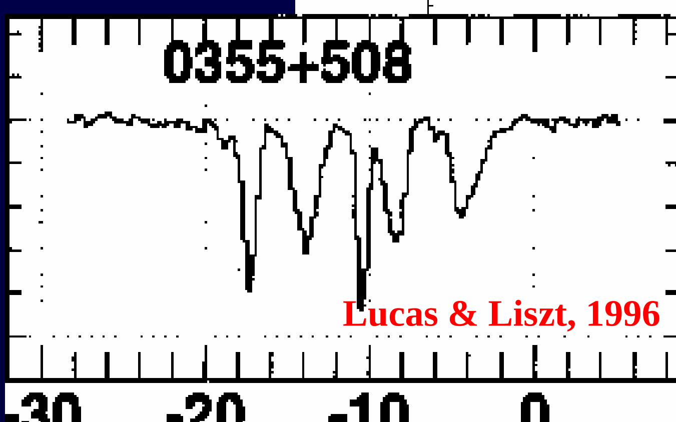

Hardee et al , 2001

# What does Millimetre-VLBI offer:

- determine structure and kinematics in I & P at the centres of compact galactic & extragalactic radio sources
- jets: how launched, collimated, accelerated, polarimetry → particle composition, B-topology
- resolution ~$\lambda$/D, increase D→ space VLBI, decrease $\lambda$→ mm-VLBI penetrates opacity barriere
- 50-100 $\mu$as-scale beam (7mm/3mm): high positional accuracy for kinematical studies, short obs. intervals
- few 10$\mu$as-scale beam (3mm/1mm): few 10-100 $R_G$ in nearby SMBHs, jet nozzle
- inner regions: helical motion, precession
- inner regions: detect absorbing torus, measure jet-to-counterjet ratio and speed → geometry, unified schemes
- variability: more pronounced at mm-$\lambda$, detect new jet plasma close to place of creation, early evolutionary stages (outburst-ejection relation ?)
- spectra: multi-$\lambda$ studies (cm/space VLBI) → radiation transport, shock-physics, broad-band SEDs
- transverse resolution of jets: instabilities (KH, MHD), driver: BP or BZ process, spin of BH ?
- SgrA* & M87 and alike, image event horizon, test General Relativity
- molecular lines: circumnuclear gas, interaction of jet with ambient ISM (redshifted absorption, CO, HCO+, ...)
- stars und stellar enveloppes: SiO masers, other spectral lines

# VLBI detection of galactic absorption against NRAO150

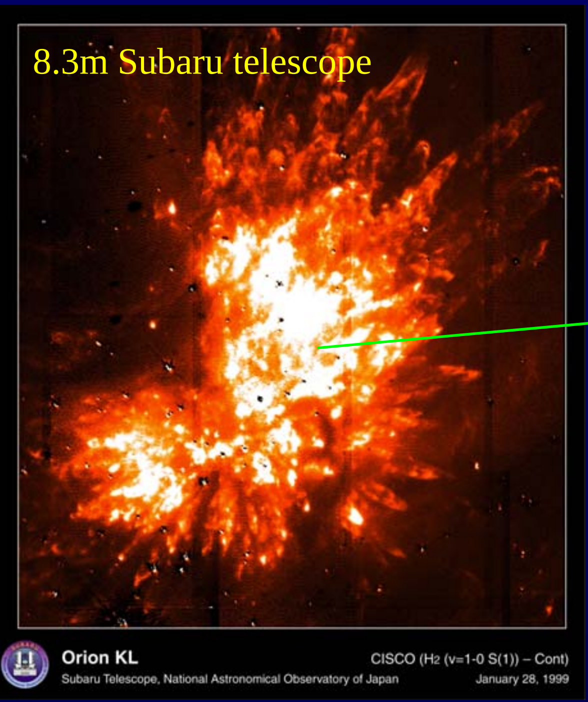


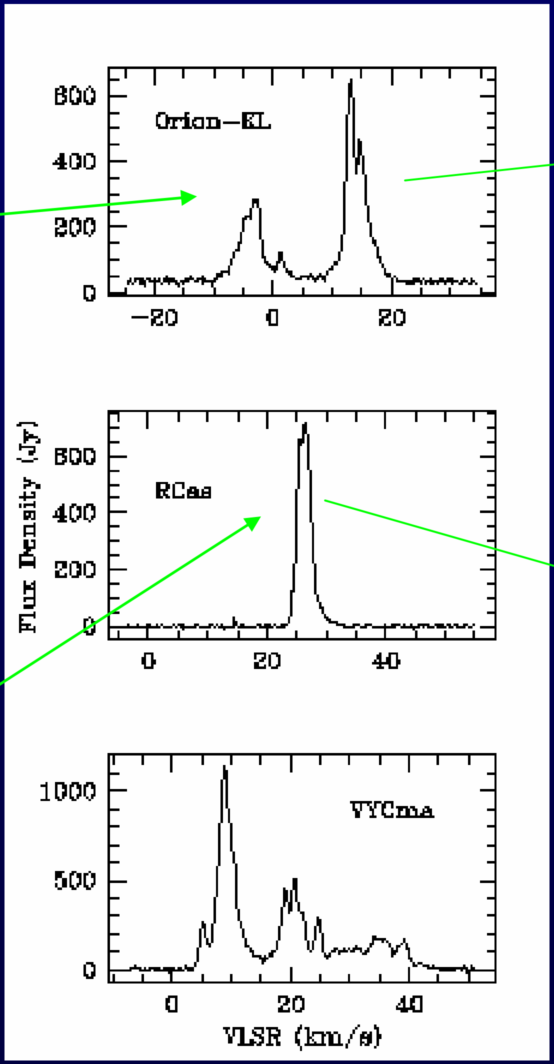



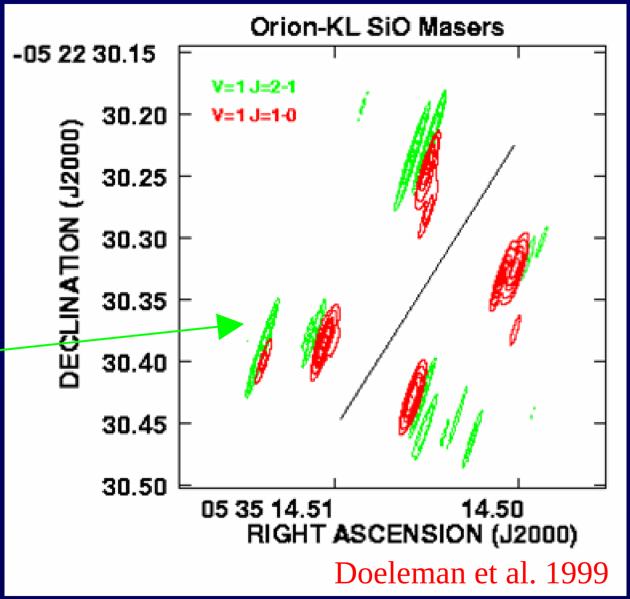

Greve et al. 2003

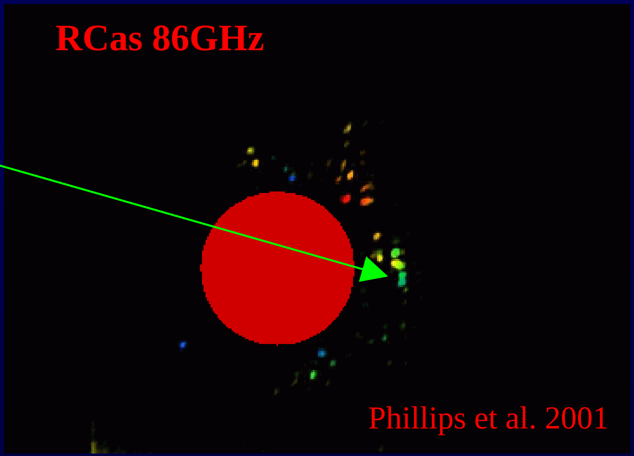
many more sources are possible !

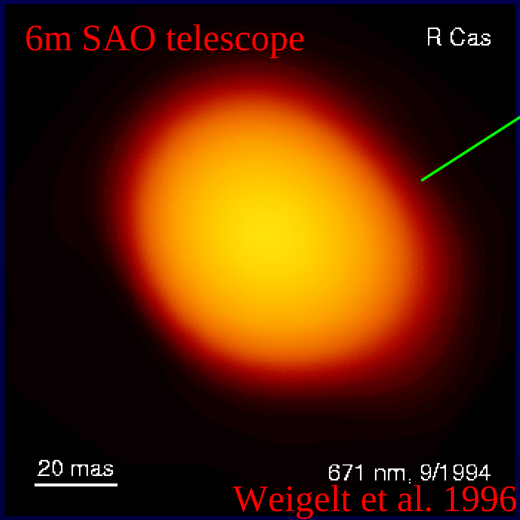
# SiO Maser at 43 and 86 GHz



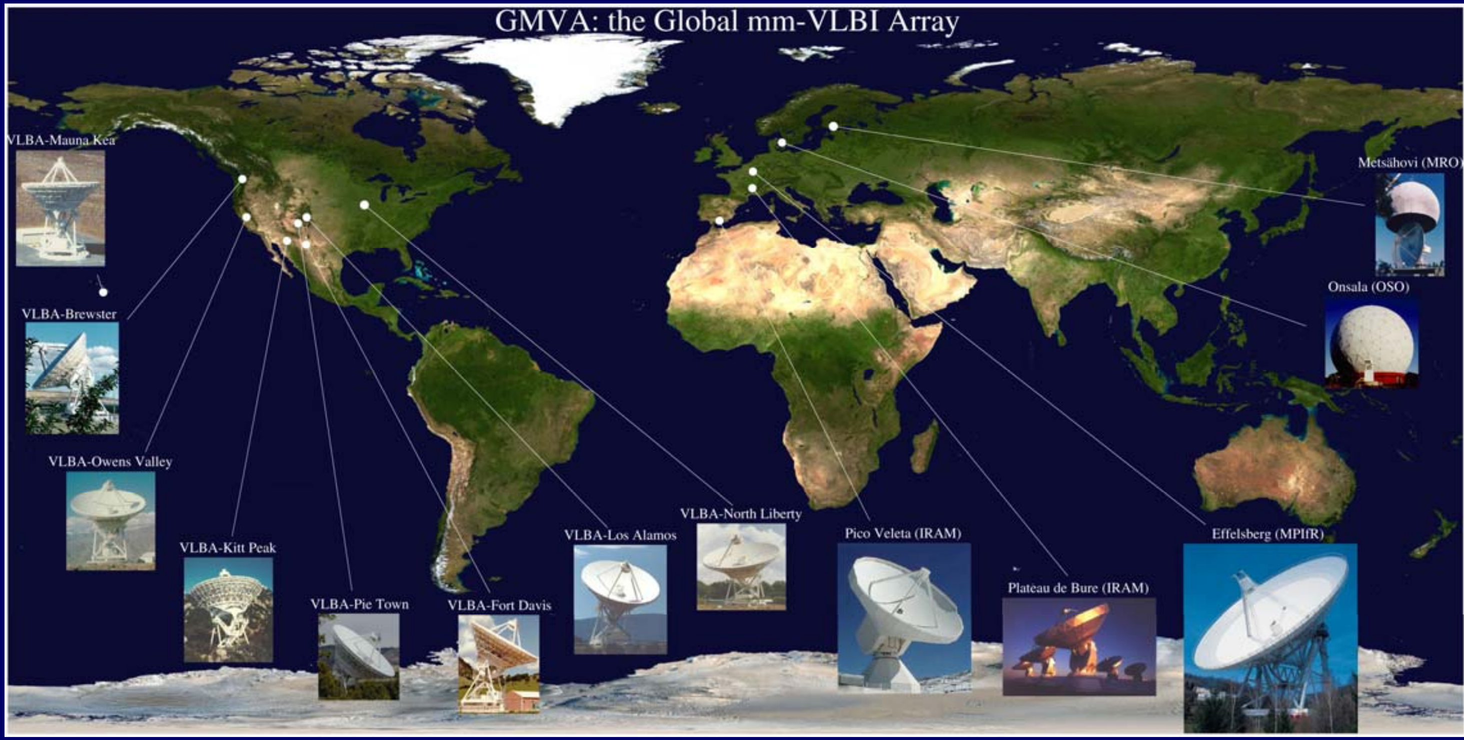



# The Global Millimeter VLBI Array – VLBI Imaging at 86 GHz with ~40 μas resolution




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

# Global VLBI at 3mm: Existing and possible future antennas

- need more sensitivity
- need more stations to allow better self – calibration
- need southern antennas for low declinatioin sources

| Station | Country | Diameter [m] | Zenith Tsys [K] | Gain [K/Jy] | App.Eff. % | SEFD [Jy] |
|---|---|---|---|---|---|---|
| Effelsberg | Germany | 80 | 130 | 0.14 | 8 | 930 |
| Plateau de Bure | France | 35 | 120 | 0.21 | 60 | 570 |
| Pico Veleta | Spain | 30 | 120 | 0.14 | 55 | 715 |
| Onsala | Sweden | 20 | 300 | 0.049 | 43 | 6100 |
| Metsähovi | Finland | 14 | 400 | 0.017 | 30 | 23500 |
| VLBA(8) | USA | 25 | 100 | 0.036 | 20 | 2800 |
| | | | | | | |
| Hopefully soon: | | | | | | |
| GBT | Va, USA | 100 | 150 | 1.0 | 35 | 150 |
| Noto | Italy | 32 | 150 | 0.05 | 20 | 3000 |
| Yebes | Spain | 40 | 150 | 0.22 | 50 | 680 |
| Nobeyama | Japan | 45 | 150 | 0.17 | 30 | 880 |
| | | | | | | |
| Future: | | | | | | |
| CARMA | Ca ,USA | 35 | 150 | 0.14 | 50 | 1070 |
| LMT | Mexico | 50 | 150 | 0.43 | 60 | 350 |
| ALMA | Chile | 50x12 | 100 | 1.8 | 70 | 55 |

# Stations in Europe capable of mm-VLBI

| | | | | | available receivers | | | |
|---|---|---|---|---|---|---|---|---|
| **Station** | **Location** | **Diameter** *[m]* | **Surface** *[mm]* | **adaptive** | **7mm** | **3mm** | **2mm** | **1mm** |
| existing and working: | | | | | | | | |
| Effelsberg | Germany | 100 | 0,400 | secondary | y | y | bad | bad |
| Pico Veleta | Spain | 30 | 0,065 | no | n | y | y | y |
| Plateau de Bure | France | 6x15 | 0,067 | no | n | y | y | y |
| Onsala | Sweden | 20 | 0,130 | no | y | y | | bad |
| Metsahovi | finland | 14 | 0,100 | no | y | y | y | bad |
| near future: | | | | | | | | |
| SRT | Italy | 64 | 0,200 | yes | y | y | ? | bad |
| Yebes | Spain | 40 | 0,150 | no | y | y | ? | bad |
| Noto | Italy | 32 | 0,400 | secondary | y | ? | bad | bad |
| possible candidates: | | | | | | | | |
| Simeiz | Ukraine | 22 | 0,250 | no | n | n | bad | bad |
| Cambridge | England | 32 | 0,300 | no | n | n | bad | bad |
| DSN HEF | Spain | 32 | 0,480 | no | n | ? | bad | bad |
| HartRAO | S. Africa | 26 | 0,5-1,0 | no | n | bad | bad | bad |
| Torun | Poland | 32 | 0,4-1,0 | no | n | bad | bad | bad |
| Medicina | Italy | 32 | 0,700 | no | ? | bad | bad | bad |
| Ventspils | Latvia | 32 | 1,300 | no | ? | bad | bad | bad |

# Noto performance at 43 GHz:

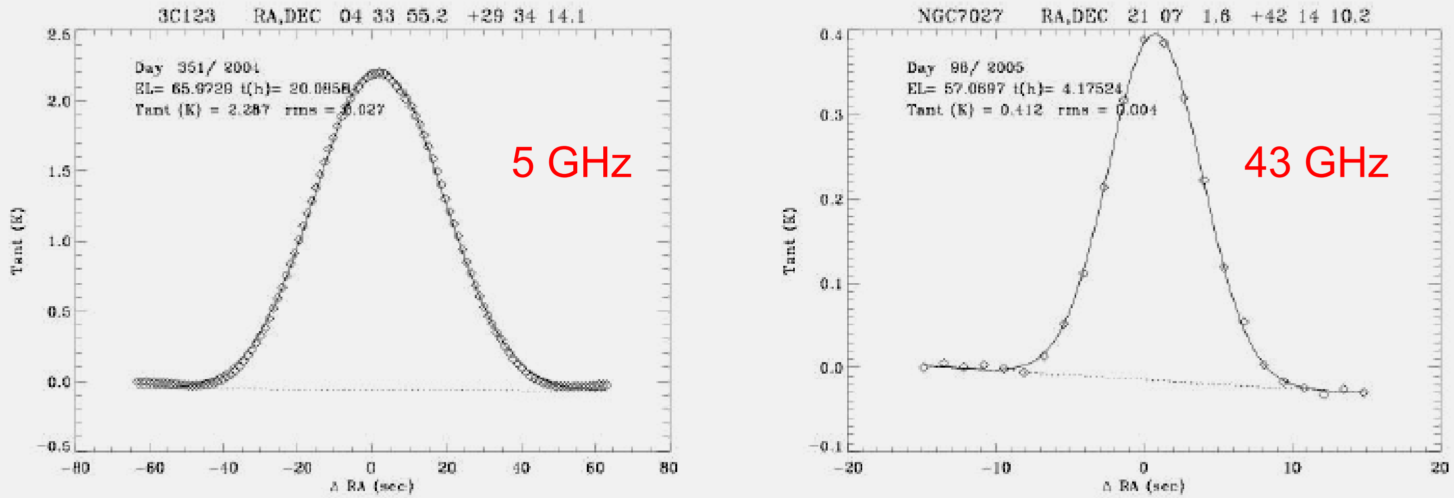
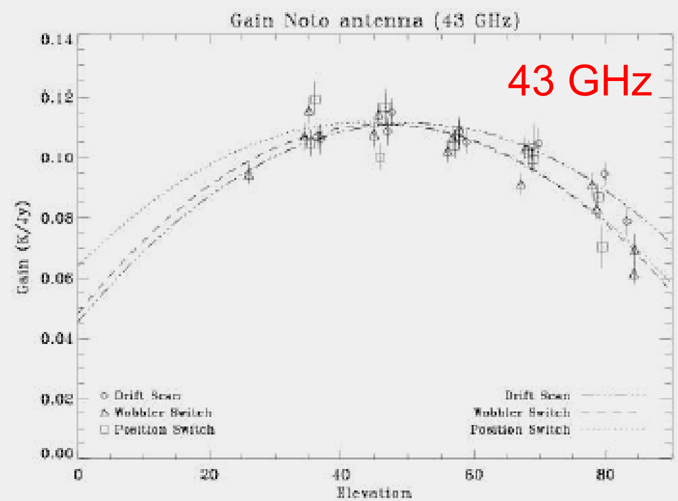



**Fig. 2.** Examples of drift scans: in the left panel a drift scan at 5 GHz; in the right panel a drift scan at 43 GHz.



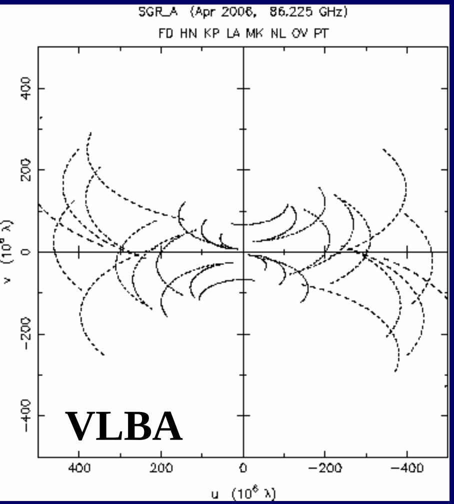

**Surface accuracy:**

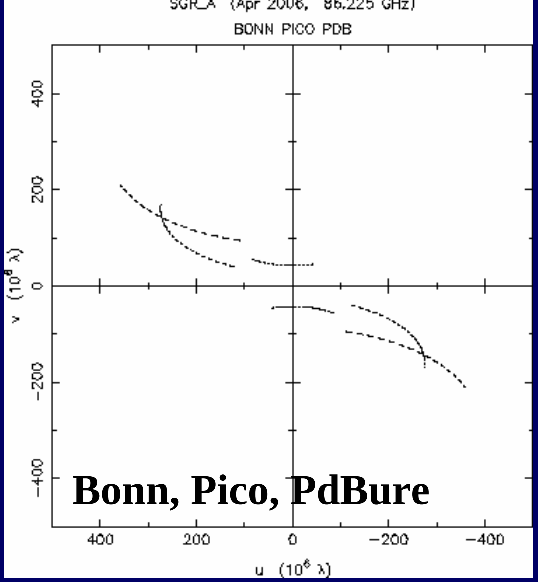
at 5 GHz: 0.17 K/Jy $\rightarrow \eta_A = 0.6$

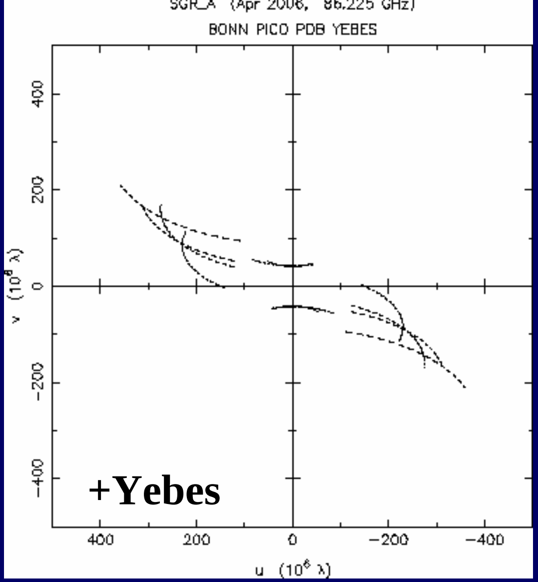
at 43 GHz : 0.10 K/Jy $\rightarrow \sigma = 0.4$ mm

**Fig. 3.** Left panel: gain measures at 43 GHz for the different acquisition methods analyzed. Right panel: gain curves of the Noto antenna at 22 GHz with (filled symbols) and without (open symbols) atmospheric corrections.

Leto et al. 2006

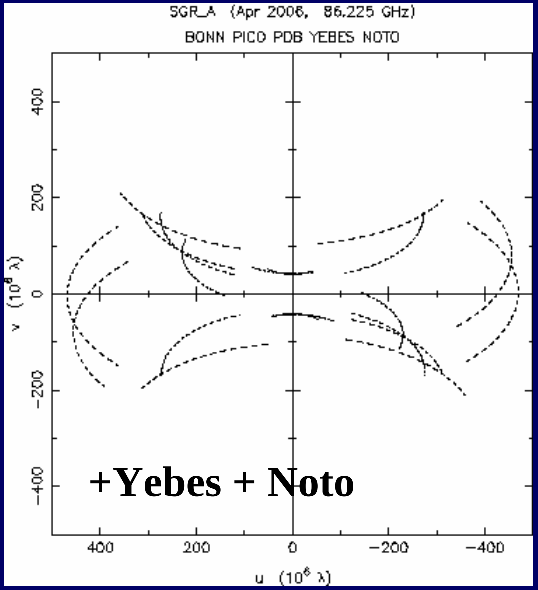


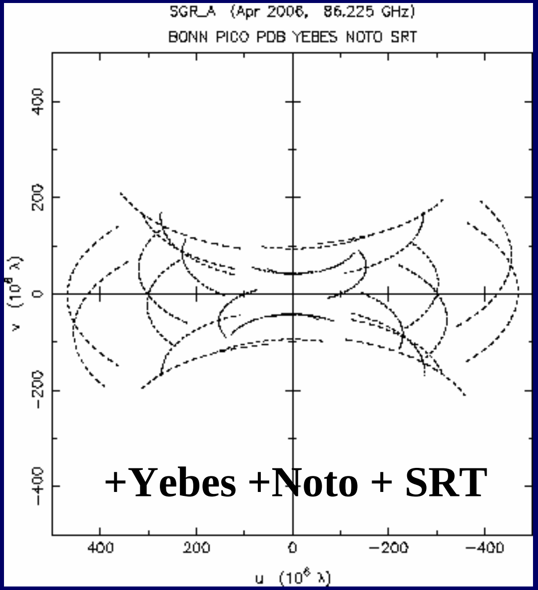




example for Sgr A*:

improve the uv-coverage and sensitivity by adding antennas in southern Europe at 22, 43 GHz and eventually also at 86 GHz.




Noto, Yebes and the SRT could enormously improve the image quality at 7 & 3mm !

# „European“ 3mm VLBI imaging of SMBH in SgrA* -

## Sensitivity of present and near future antennas

| Station | Country | Diameter | Zenith Tsys | Gain | App.Eff. | SEFD |
|---|---|---|---|---|---|---|
| | | [m] | [K] | [K/Jy] | [%] | [K] |
| Effelsberg | Germany | 80 | 130 | 0.14 | 7 | 930 |
| Plateau de Bure | France | 6x15 | 120 | 0.20 | 65 | 600 |
| Pico Veleta | Spain | 30 | 120 | 0.14 | 55 | 860 |
| Yebes | Spain | 40 | 150 | 0.18 | 40 | 830 |
| Noto | Italy | 32 | 150 | 0.04 | 15 | 3800 |
| SRT | Sardinia | 64 | 150 | 0.35 | 30 | 430 |
| APEX (if at 3mm) | Chile | 12 | 100 | 0.03 | 70 | 3400 |

for comparision: VLBA SEFD= 4800

Bonn/Pico/Bure 25 mJy

IRAM/Apex 60 mJy

IRAM/Noto 90 mJy

VLBA/VLBA 180 mJy

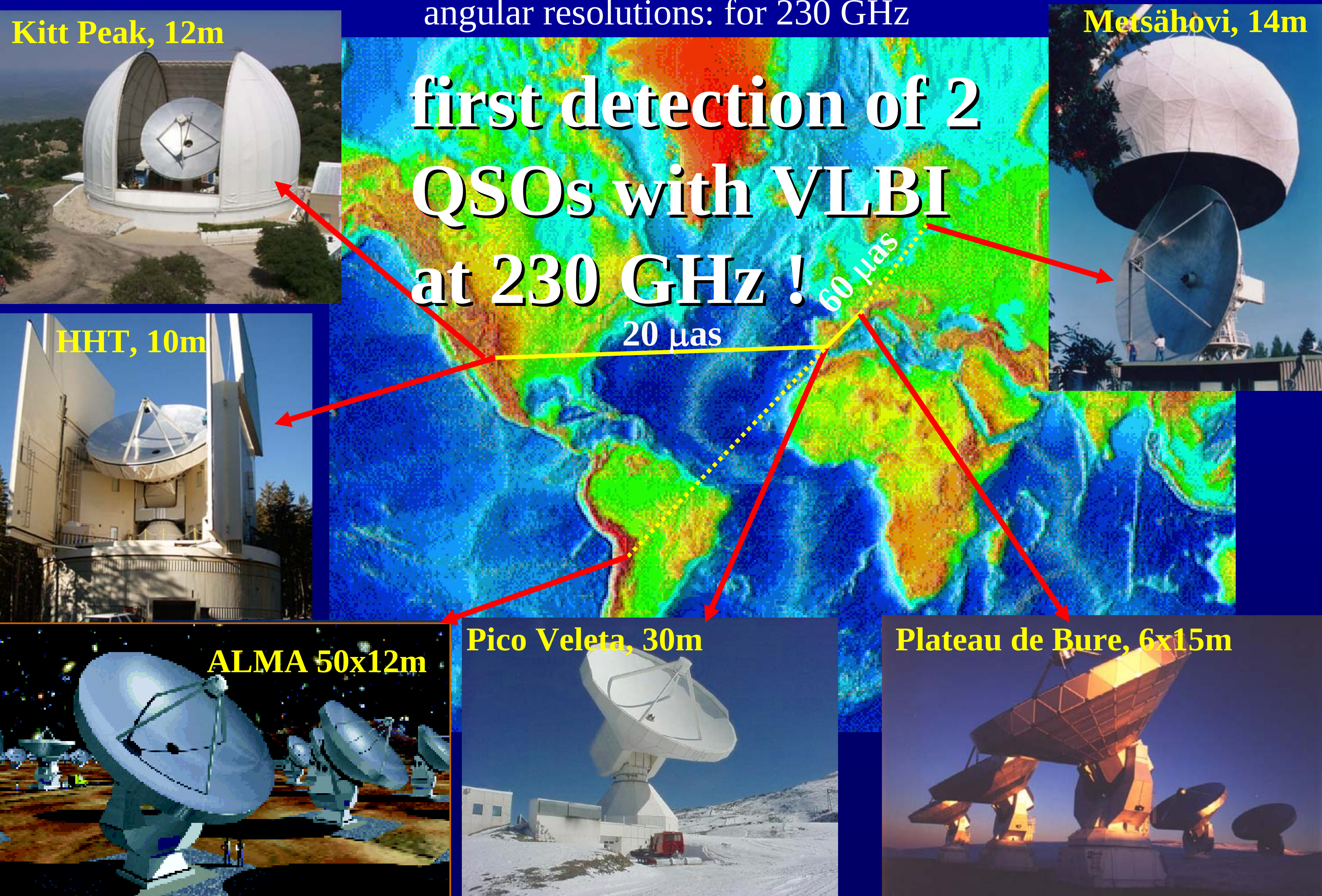
IRAM/ALMA 2 mJy

IRAM/SRT 20 mJy

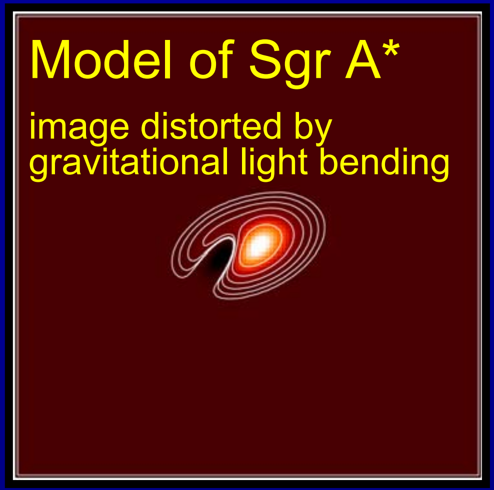
assume future data rate of 4 Gbps (Mark5B+)

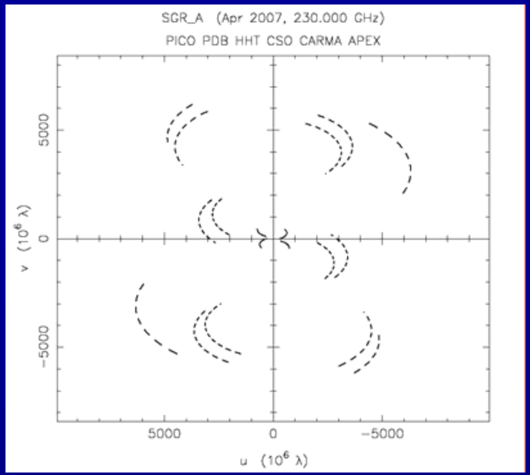
# Global mm-VLBI at 150 - 230 GHz

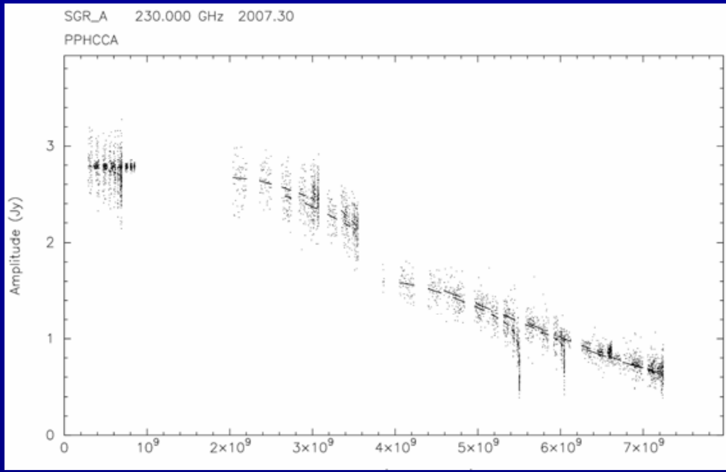
angular resolutions: for 230 GHz

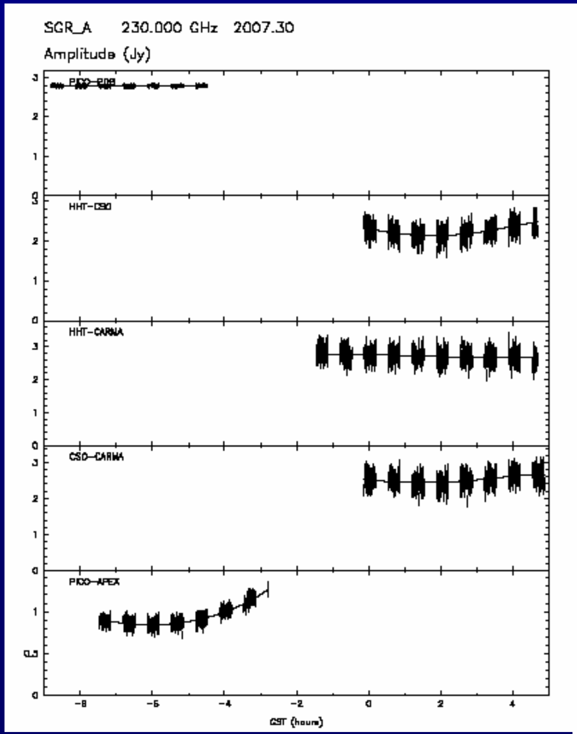


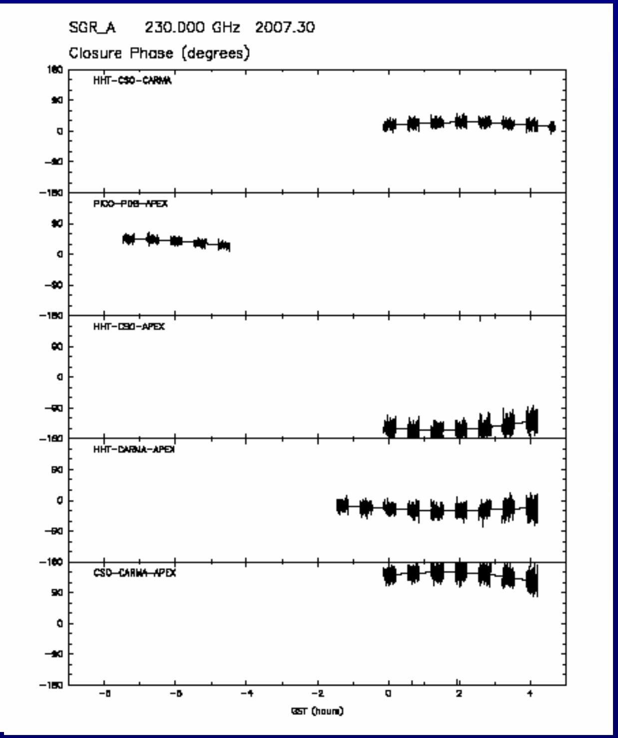
# Simulation of 230 GHz VLBI of Sgr A* with IRAM (Pico Veleta, Plateau de Bure), HHT, CSO/SMA, CARMA

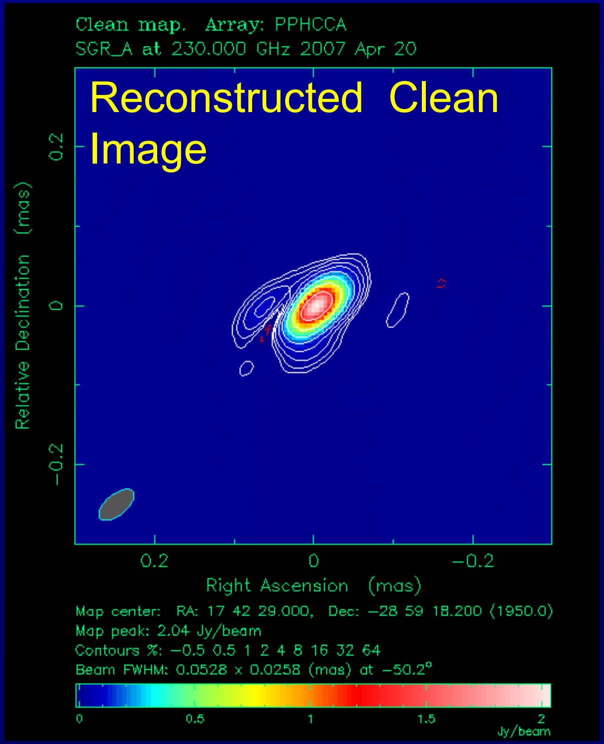


# Steps towards improved mm-VLBI in Europe (1)

- enlarge the number of mm-stations, improve the uv-coverage and collecting area of the array; adjust telescope surfaces where possible, search partner stations outside Europe to maximize baseline lengths

***World array***: at cm – (e)VLA + (e)Merlin + EVN + VLBA
at 7mm – (e)VLA +VLBA + expandedEVN (Yebes, Noto, SRT, ....)
at 3/1 mm – PdB/PV + CARMA + ALMA + ... Apex, HHT, SMA, LMT, ...

- equip more stations with modern (MMIC, HEMT) receivers operating at mm-bands (34, 43, 86 GHz), add beam-switch and dual-polarization, include frequency agility to facilitate antenna pointing/calibration

- consider building multi-frequency systems (i.e 22/43/86 GHz) for frequency phase referencing, correction of atmospheric phase variations (central receiver lab?)

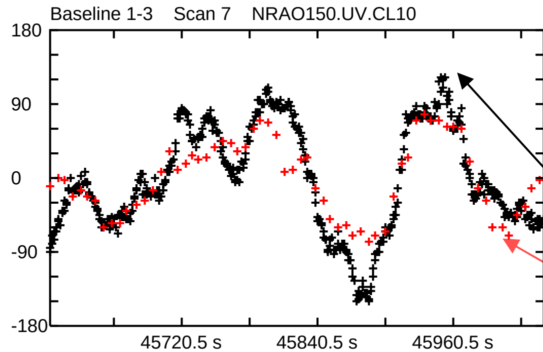
- improve sensitivity by going to larger bandwidth (rates > 2-4 Gbps); provide DBBCs to all stations, provide larger bandwidths for individual IF-channels to maximize continuum sensitivity and detectability of broad (> 1000 km/s) spectral lines

- improve the antenna calibration accuracy by dedicated flux measurements, determination of antenna gain vs. elevation, time and temperature, apply atmospheric corrections (WVR, opacity via GPS)

# VLBI Phase Correction Demo

NRAO 150
Pico Veleta - Effelsberg
86 GHz VLBI
2004 April 17

No phase correction

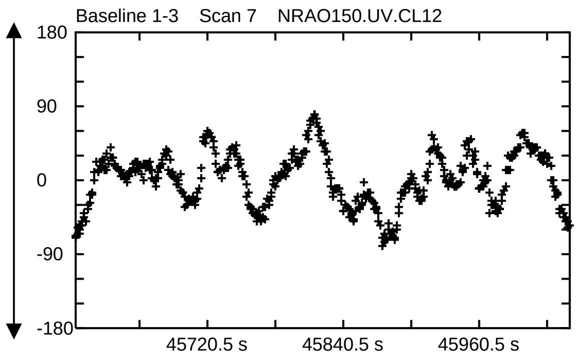



VLBI phase

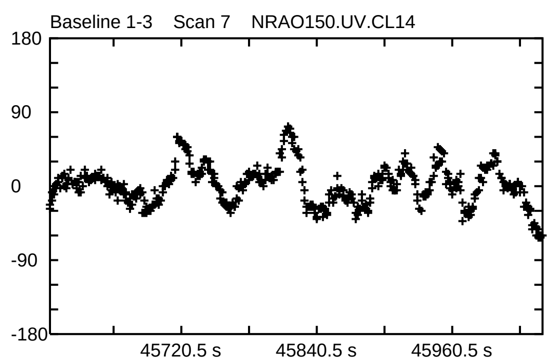
WVR phase

EB phase correction

path
3.4 mm

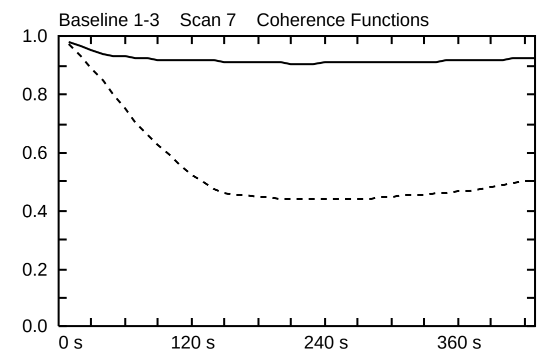



EB+PV phase correction




420 s

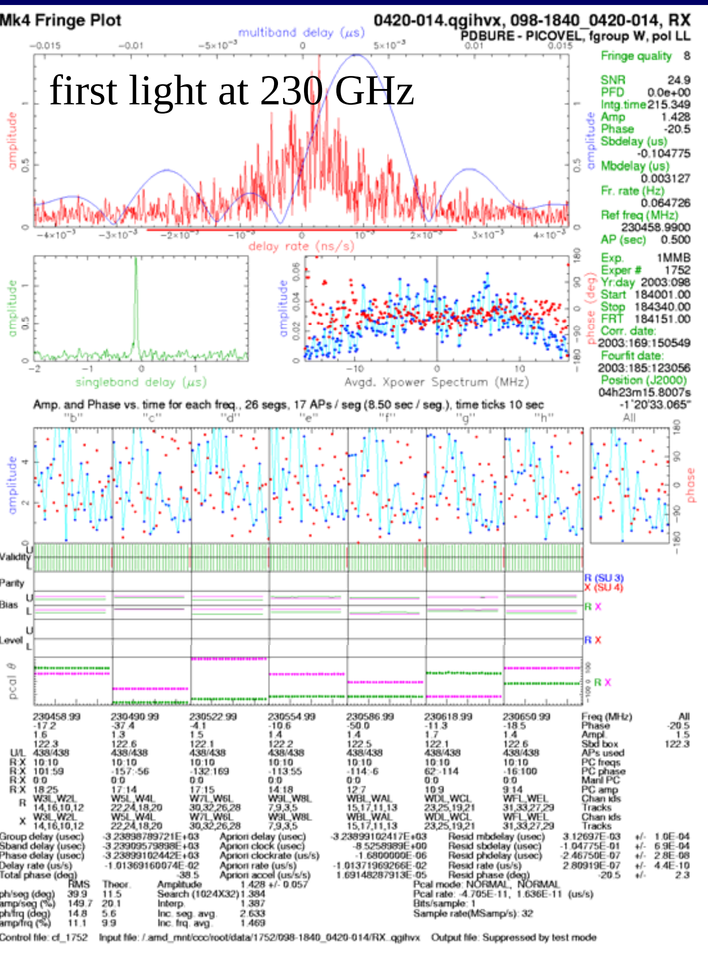
Coherence function before & after




- Path rms reduced 1.0 mm to 0.34 mm
- Coherent SNR rose 2.1 x

A. Roy et al.

# The Future :Water Vapor Radiometry and Phase Correction

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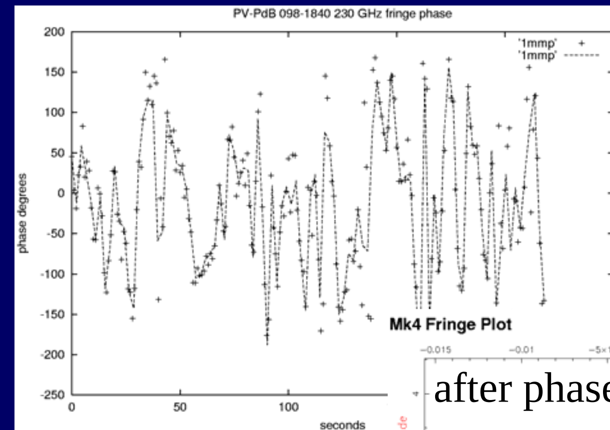


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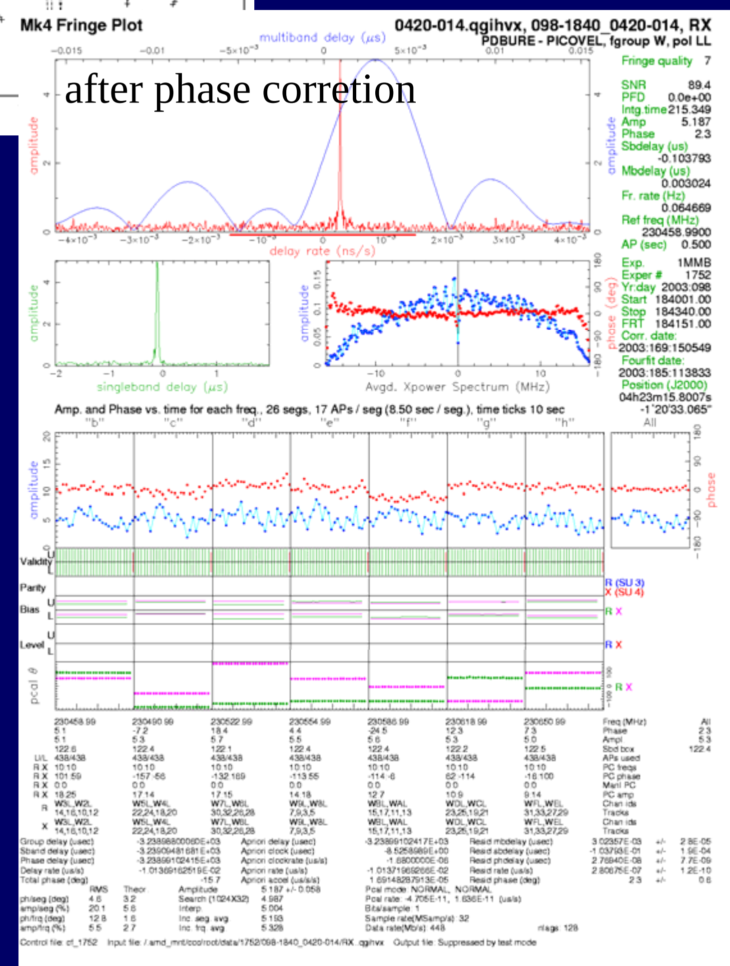


0420-014

Pico – PdB

230 GHz

April 2003

from SNR= 25 → to SNR = 89 !

# Steps towards improved mm-VLBI in Europe (2)

- perform mm-VLBI observations more frequently (once per month)

- identify and support stations for regular flux and polarization monitoring; fluxes and EVPAs are a MUST for the scientific interpretation. Flux monitoring also stimulates ToOs

- check array performance by eVLBI, rapid response to source activity in the mm-bands

- development of fringe fitting and post-correlation software (global fringe fitting, incoherent segmentation, FRING, phase correction methods)

- advertise more aggressively array capabilities, attract more users, improve the user support

- advertise a southern hemisphere mm-antenna at European longitudes (i.e. in North or South Africa), need additional partner stations for European mm-VLBI, also to better uv-connect ALMA with Europe (move SEST to HartRAO ?)