# Towards Millimeter-VLBI: Present status, future possibilities

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involved scientists:

IRAM: M. Bremer, P. Cox, S. Sanchez, C. Thum, H. Ungerechts, H. Wiesemeyer, et al.

MPIfR: W. Alef, U. Bach, D. Graham, T. Krichbaum, A. Lobanov, R. Porcas, A. Witzel, A. Zensus, et al.

Onsala/Sest: J. Conway, M. Lindquist, et al.

Metsähovi/Tuorla: A. Mujunen, M. Tornikoski, E. Valtaoja, K. Wiik, et al.

NRAO-VLBA: V. Dhawan, J. Ulvestad, C. Walker, et al.

IAA: I. Agudo, J.L. Gomez

KVN: S.S. Lee, B.W. Sohn

and for VLBI at 1 & 2mm:

ARO (HHT/KP): R. Freund, P. Strittmatter, L. Ziurys, et al.

MIT-Haystack: S. Doeleman, A. Rogers, A. Whitney, et al.

special thanks for providing data, partly prior to publication:

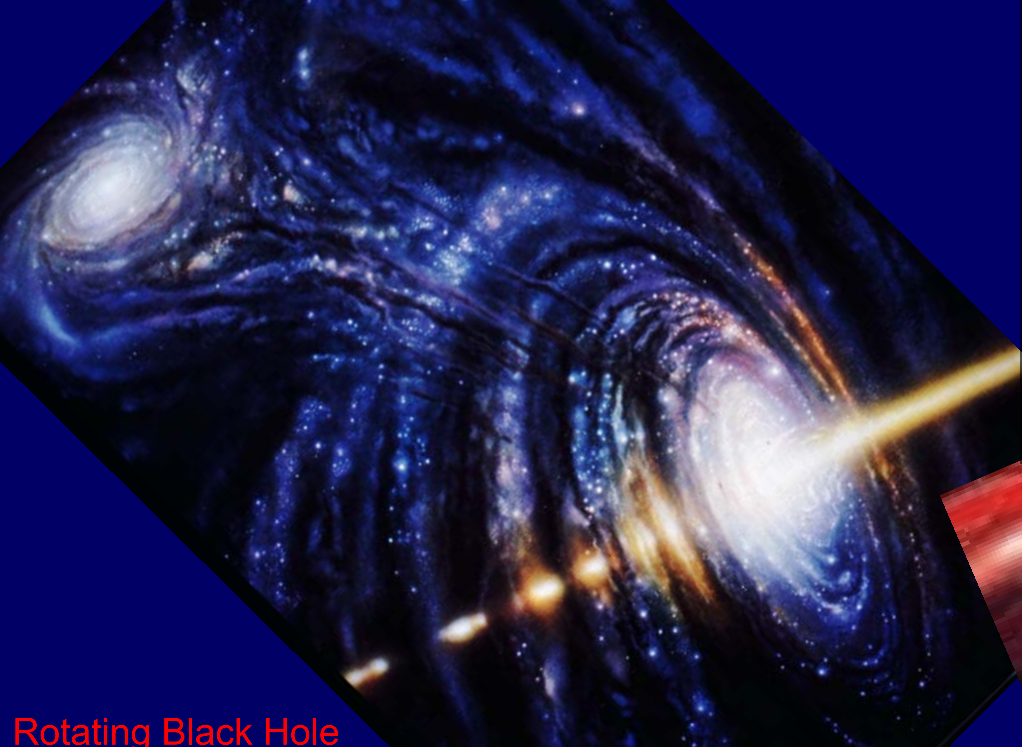
A. Marscher, S. Jorstad (Boston)

M. Gurvell (SMA)

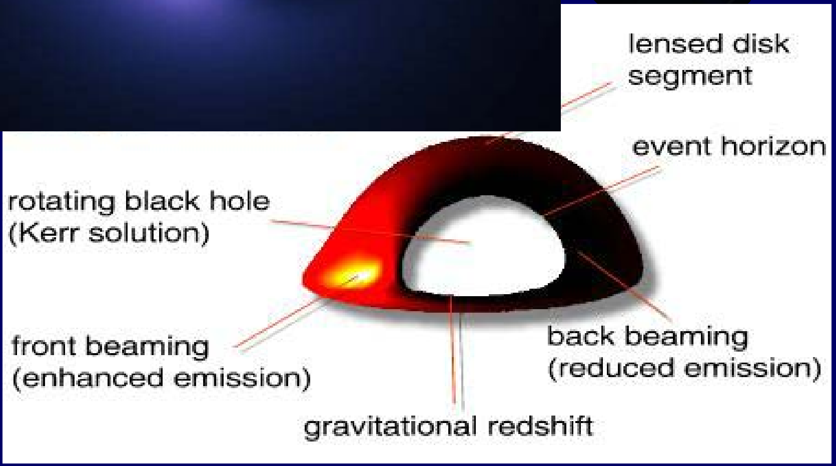
M. & H. Aller (UMRAO)

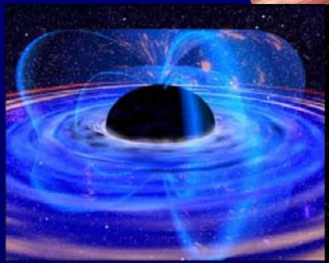
L. Fuhrmann, T. Savolainen (MPIfR)

**Main Motivation:** Which processes act at the centers of Quasars (AGN) ? How are the powerful AGN jets launched and accelerated ?

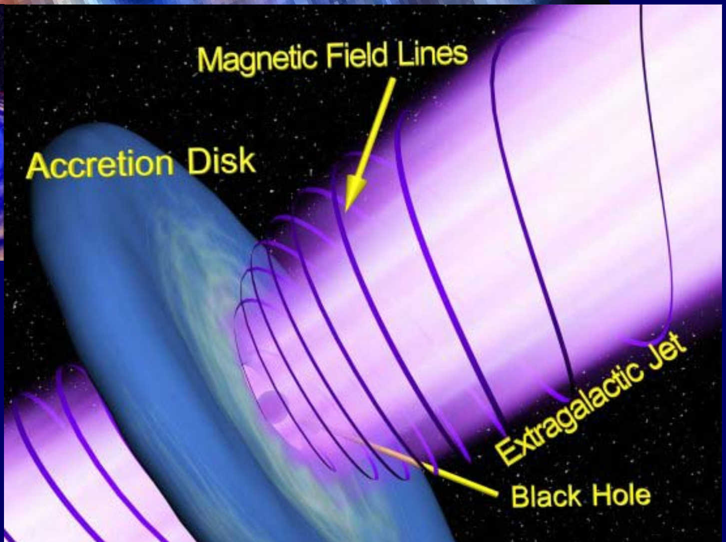


Rotating Black Hole

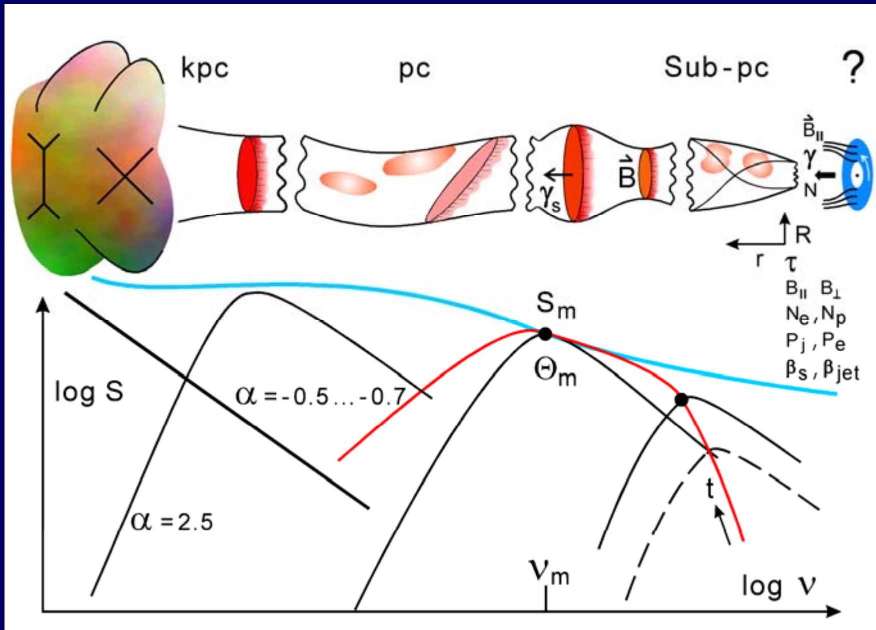


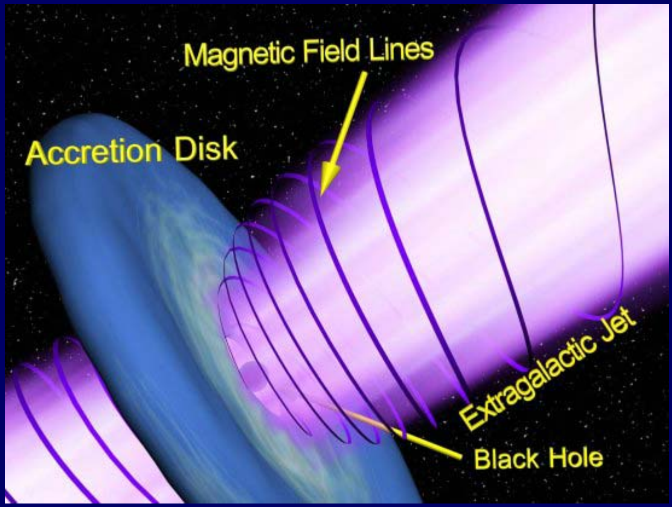



The Black Hole Dynamo



# Motivation: The basic jet model




SED: is there a blazar sequence ?

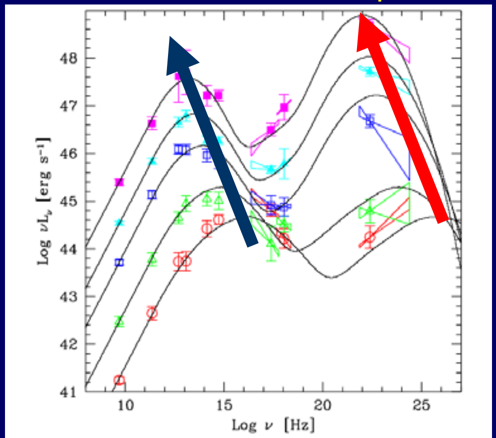



Fig. 10. The average SED of the blazars studied by Fossati et al. (1998), including the average values of the hard X-ray spectra. The thin solid lines are the spectra constructed following the parameterization proposed in this paper.

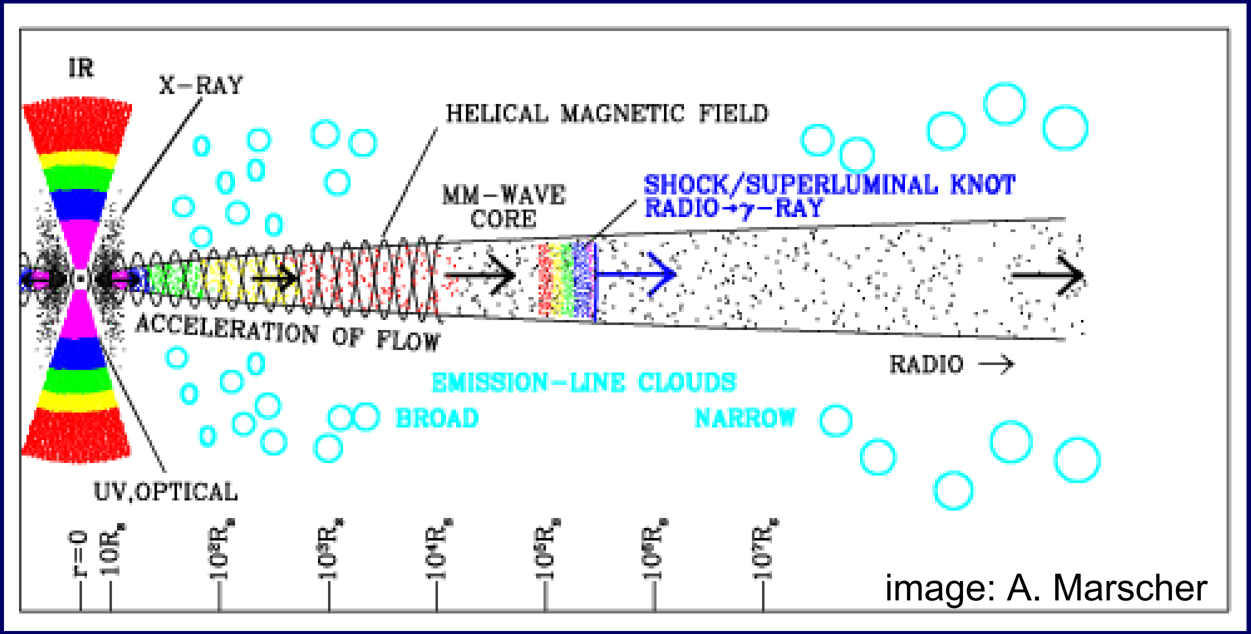
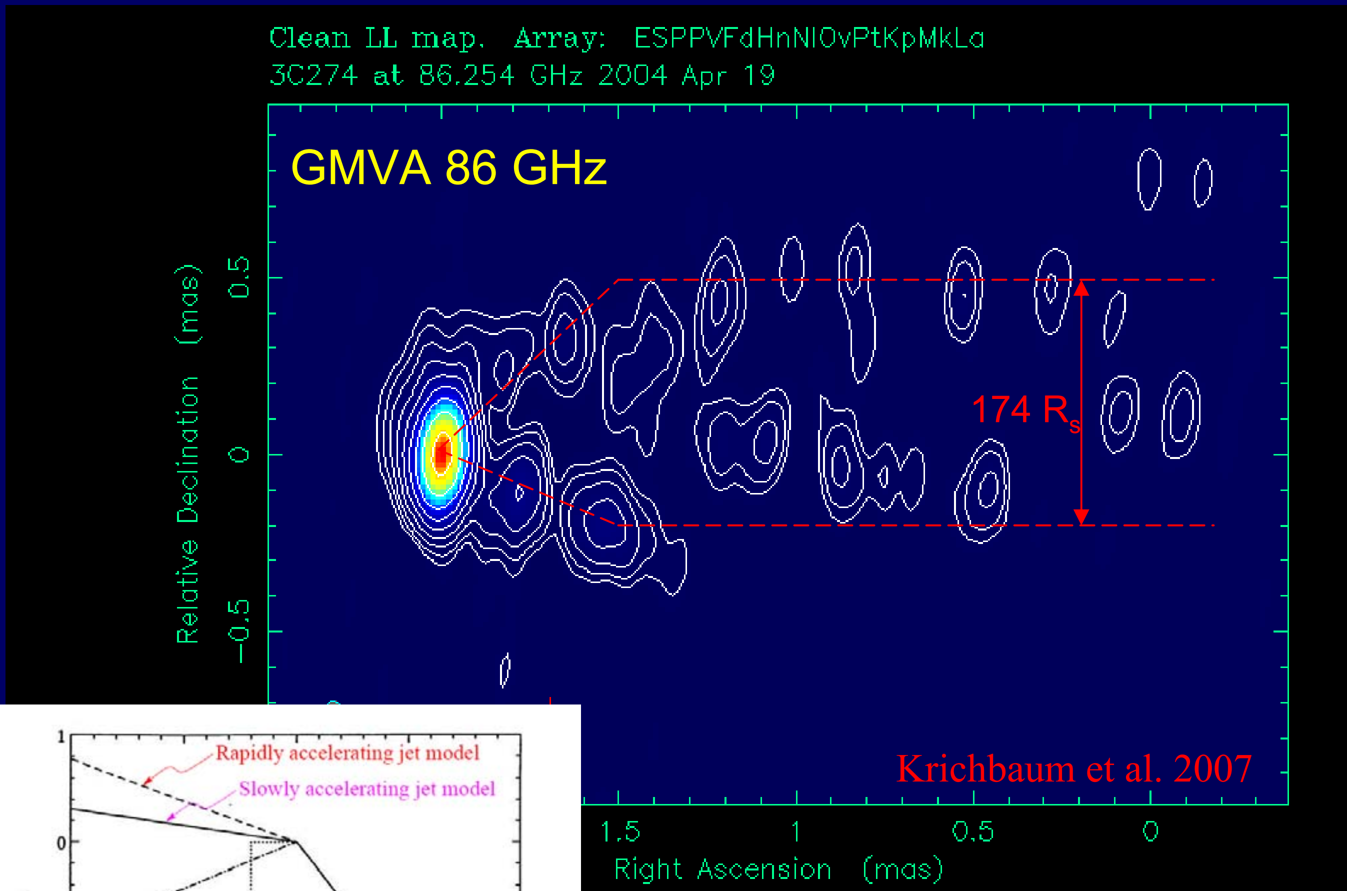
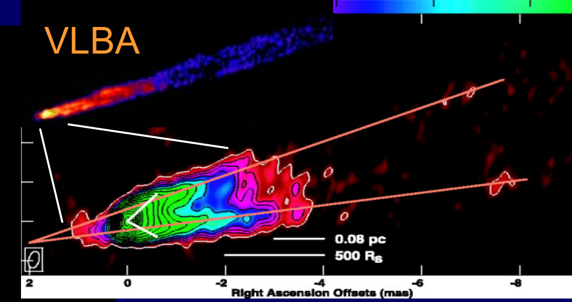
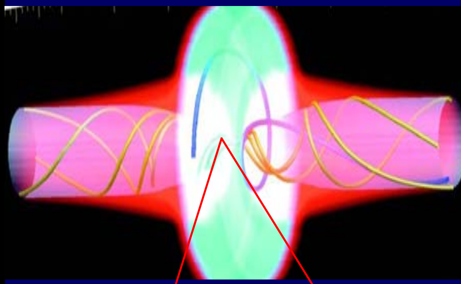
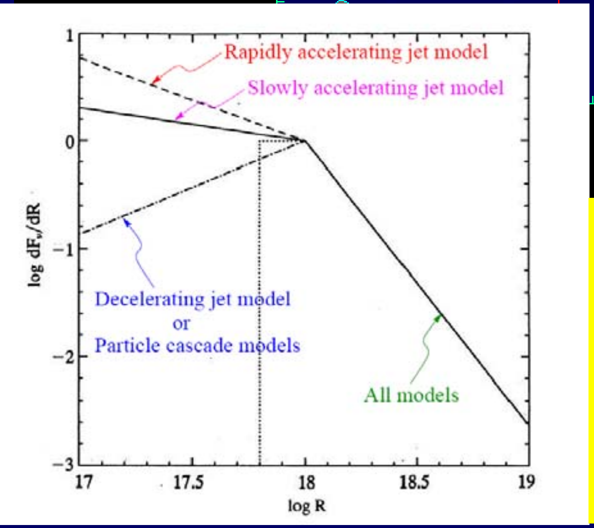



image: A. Marscher






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

**197 x 54 μas = 21 x 6 light days = 69 x 19 $R_s$**

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

Aim: Perform HDR imaging of M87 with ground and space VLBI at 43 & 86 GHz (spectral index, polarization, RM of jet base, variability).

# *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)

→ need more collecting area to image also fainter AGN (ALMA)

# What does VLBI at short millimeter wavelengths offer ?

- Study compact galactic and extragalactic radio sources with an angular resolution of a few ten micro-arcseconds (size, structure, kinematics, polarization)

- Image regions which are (self-) absorbed and therefore not observable at longer wavelength (spectrum, radiation/ energy transport, outburst – ejection relations from radio to $\gamma$ – rays).

- In detail study of central jets with smallest possible beam (transverse resolution, helical motion, precession, curvature)

- For nearby super-massive Black Holes a chance to image their immediate environment (Sgr A*, M87, etc.) with a spatial resolution of ~10 - 100 gravitational radii (accretion, orbital motion, jet-launching, General Relativity effects: space-time curvature, frame dragging + BH rotation).

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

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

100 – 300 mJy

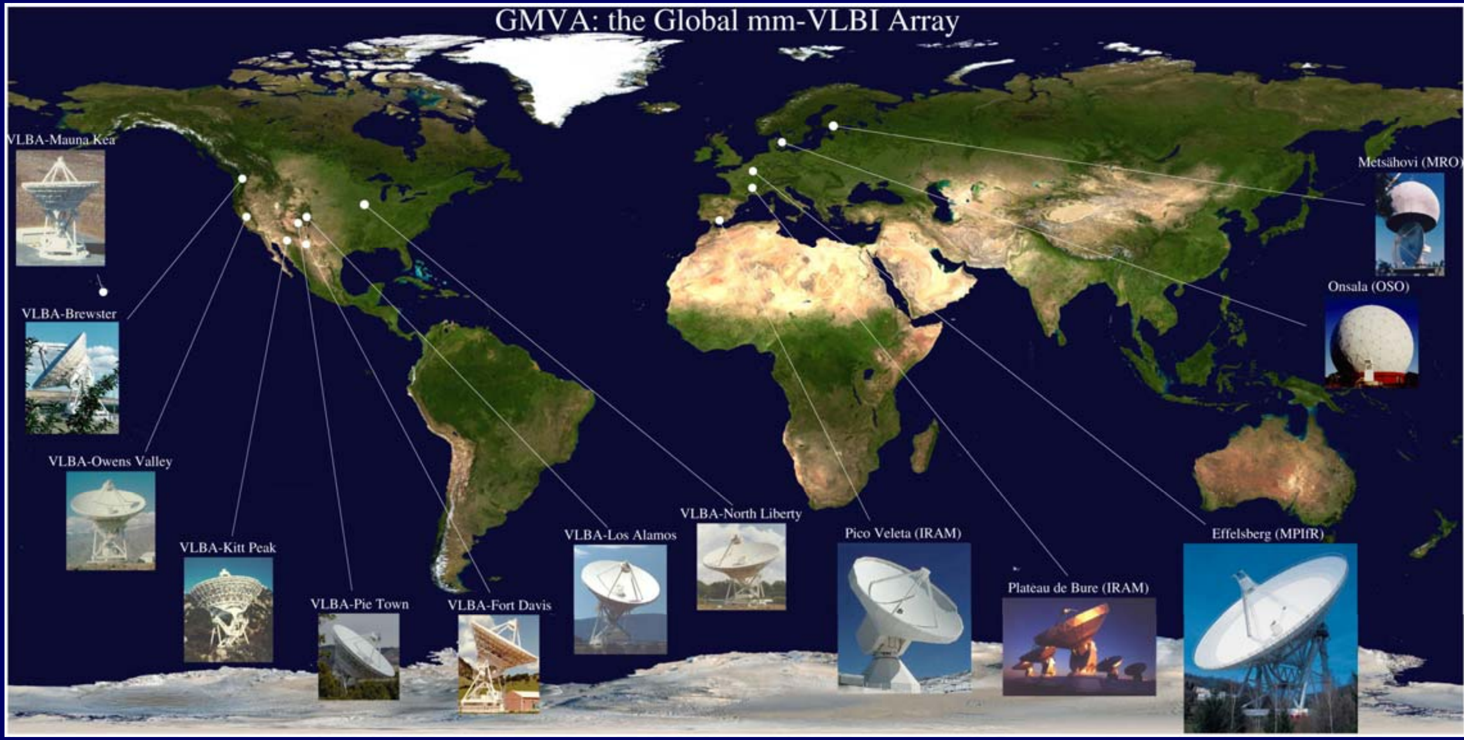
transatlantic:

50 – 300 mJy

Array:

1 – 3 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)
- USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, October 1st

# What does the GMVA offer ?

- a global 13 station VLBI array allowing high dynamic range imaging with an angular resolution of up to 40 $\mu$as at 86 GHz
- 3 – 4 times higher sensitivity than stand-alone VLBA (standard 512 Mbps recording, max. 7$\sigma$ baseline sensitivity is ~ 50-250 mJy)
- 2 epochs/year, each session ~ 3 – 5 days long (limitation by proposal pressure), single- or dual polarisation
- block schedule preparation by GMVA to optimize array calibration
- correlation at MPIfR Bonn correlator (including quality control)
- UV-FITS formated AIPS data files provided to user (MK4IN, FITLD)
- open to community by usual proposal procedures (proposal deadlines Feb. 1$^{st}$ for observation in autumn and Oct. 1$^{st}$ for observation in spring)

# GMVA Statistics

- Proposals
  - 10 proposal deadlines since October 2003 with a total of 44 submitted proposals (including Feb. 2008), many for multi-epoch monitoring covering several sessions
  - dual polarisation now requested in most proposals, spectral line (SiO masers) in 1 proposal, often strong and compact (famous) AGNs for up to 4 epochs (e.g. 3C84, 3C454.3, BL Lac, ...)
  - 15 out of the 44 so far reviewed proposals rejected, 4 approved for partial observation
- Use of the GMVA
  - Institutes and Countries of PIs of the 44 GMVA proposals:

| | |
|---|---|
| China | 2 |
| Finland | 1 |
| France | 1 |
| Germany | 20 |
| Ireland | 1 |
| Italy | 7 |
| South Korea | 2 |
| Spain | 6 |
| UK | 1 |
| USA | 4 |

- Scheduled Projects: 67 (+ 6 ad hoc)
  - 10 observing sessions since April 2004
  - number of observations scheduled in each of the sessions:

| | |
|---|---|
| APR 2004 | 6 |
| OCT 2004 | 10 +1 adhoc |
| APR 2005 | 5 |
| OCT 2005 | 8 |
| MAY 2006 | 6 + 2 pol. Test |
| OCT 2006 | 4 (only PV+VLBA) |
| May 2007 | 6 +3 ad hoc |
| OCT 2007 | 7 |
| MAY 2008 | 7 |
| OCT 2008 | 7 |

## Where is the difficulty ?

- time variable weather, atmospheric opacity
- phase fluctuations and short atmospheric coherence time
- limitations of telescopes originally being designed for observations at longer wavelengths (pointing, focusing, aperture efficiency, gain-elevation curves, etc .)
- limited SNR in 8-16 MHz wide IFs (frequency synthesis)

## Solution:

more telescopes, better telescope performance, higher bandwidth,

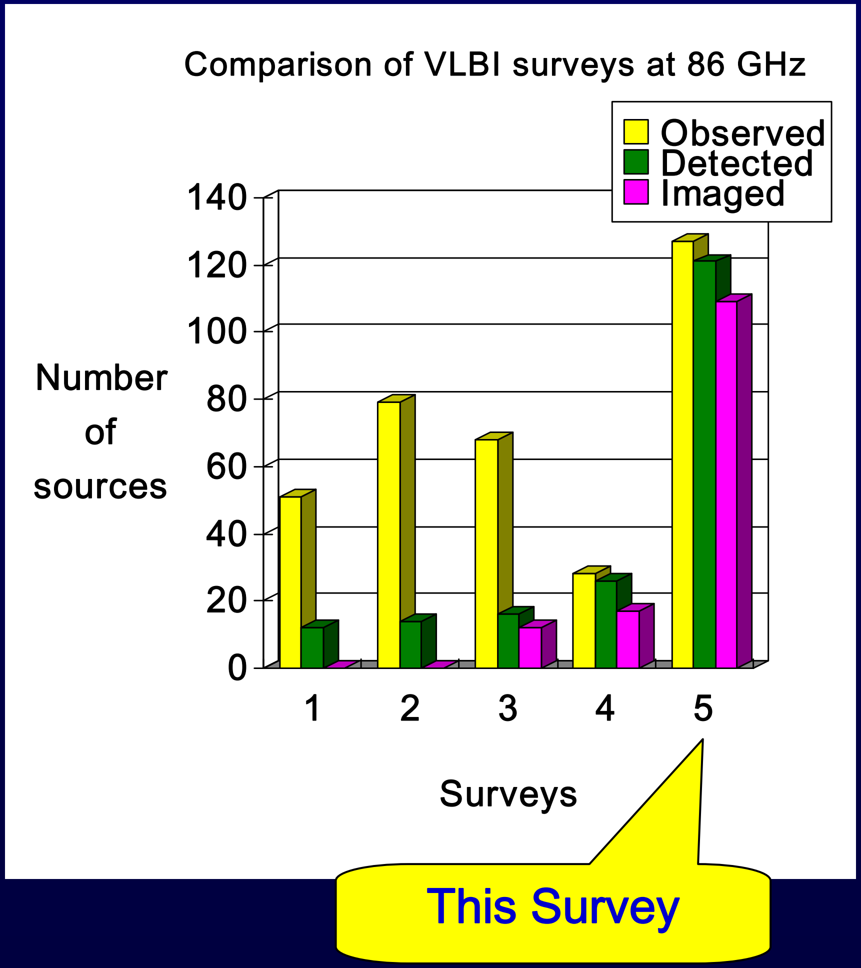
phase correction (WVR), improved fringe fitting/analysis software, and

better accuracy of: calibration, calibration, calibration, ....

# A new and comprehensive 86 GHz VLBI Survey: Comparison with previous surveys at 86 GHz

## VLBI Surveys at 86 GHz

1. Beasley et al. (1996) (N=45, 16% detect)
2. Lonsdale et al. (1998) (N=79, 14% detect)
3. Rantakyro et al. (1998) (N=67, 24% detect)
4. Lobanov et al. (2000) (N=28, 93% detect)
5. Lee et al. (2008)
   - 3~4 times better sensitivity ($S_{corr}$ >0.3 Jy)
   - larger sample (127sources) taken from surveys at lower frequencies
   - 121 (95%) sources were detected and
   - 109 (86%) sources could be imaged




S.S. Lee et al. 2008

# Results from the new 3mm VLBI survey (127 sources):

Brightness temperature decreasing with frequency ?

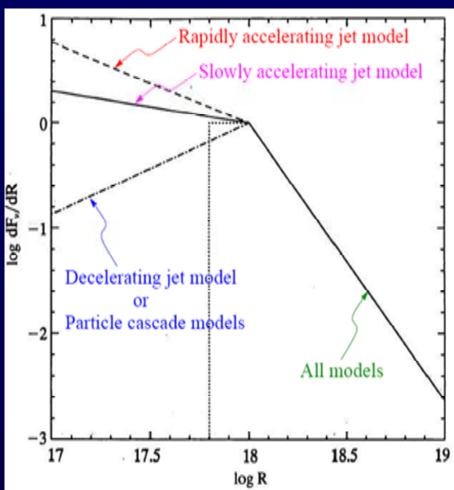
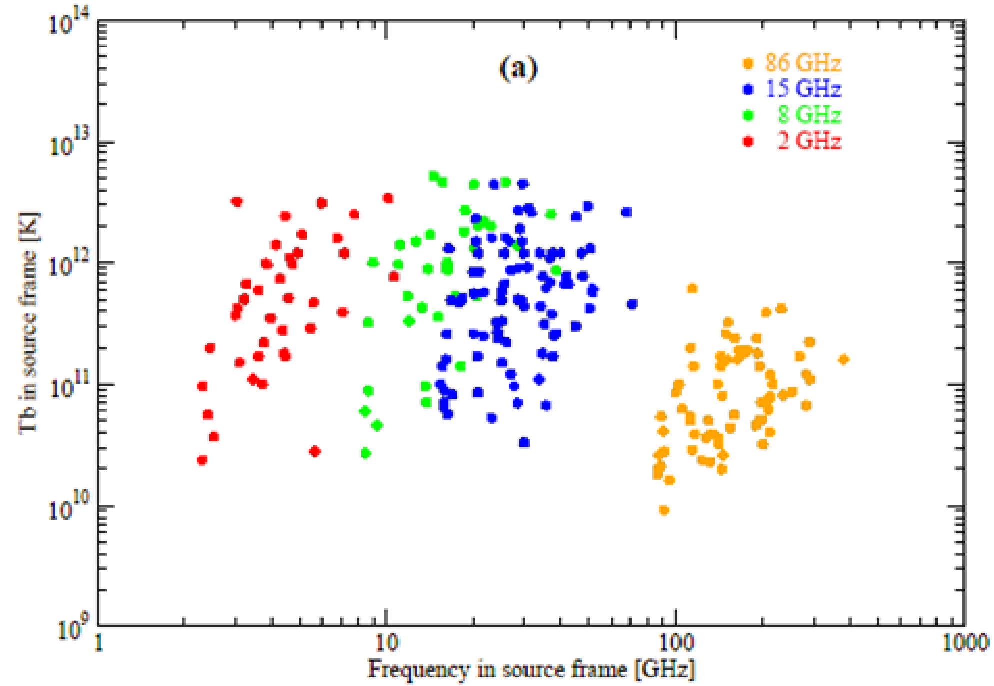
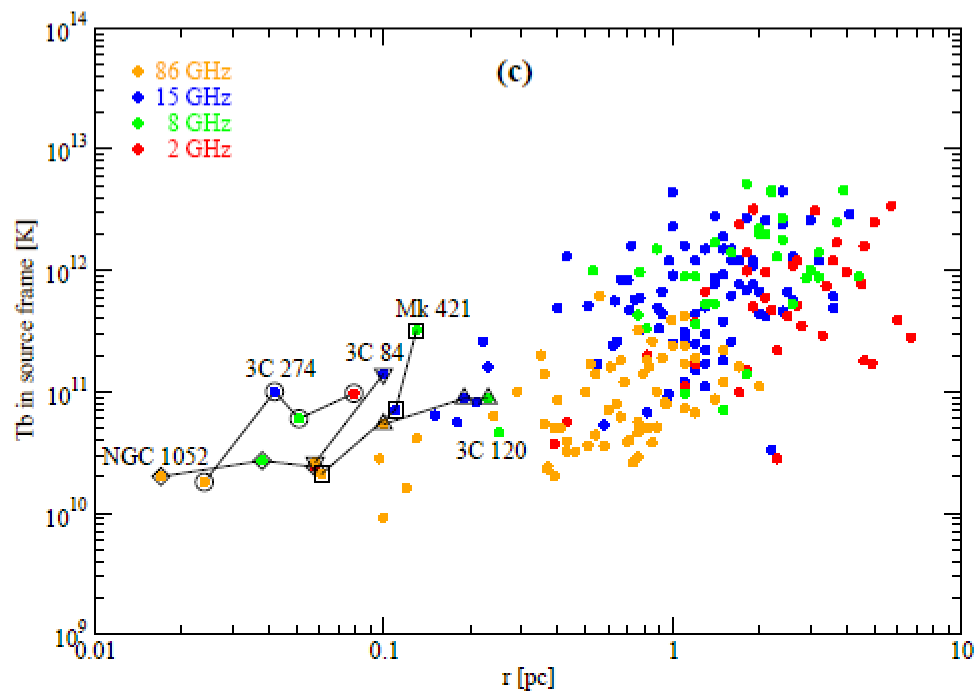



Figure from

A. Marscher (1995)

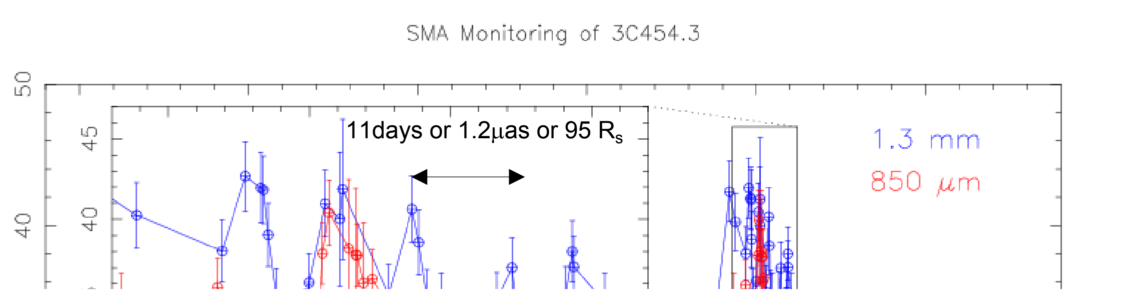
Brightness temperature increasing along jet; accelerating jets ?

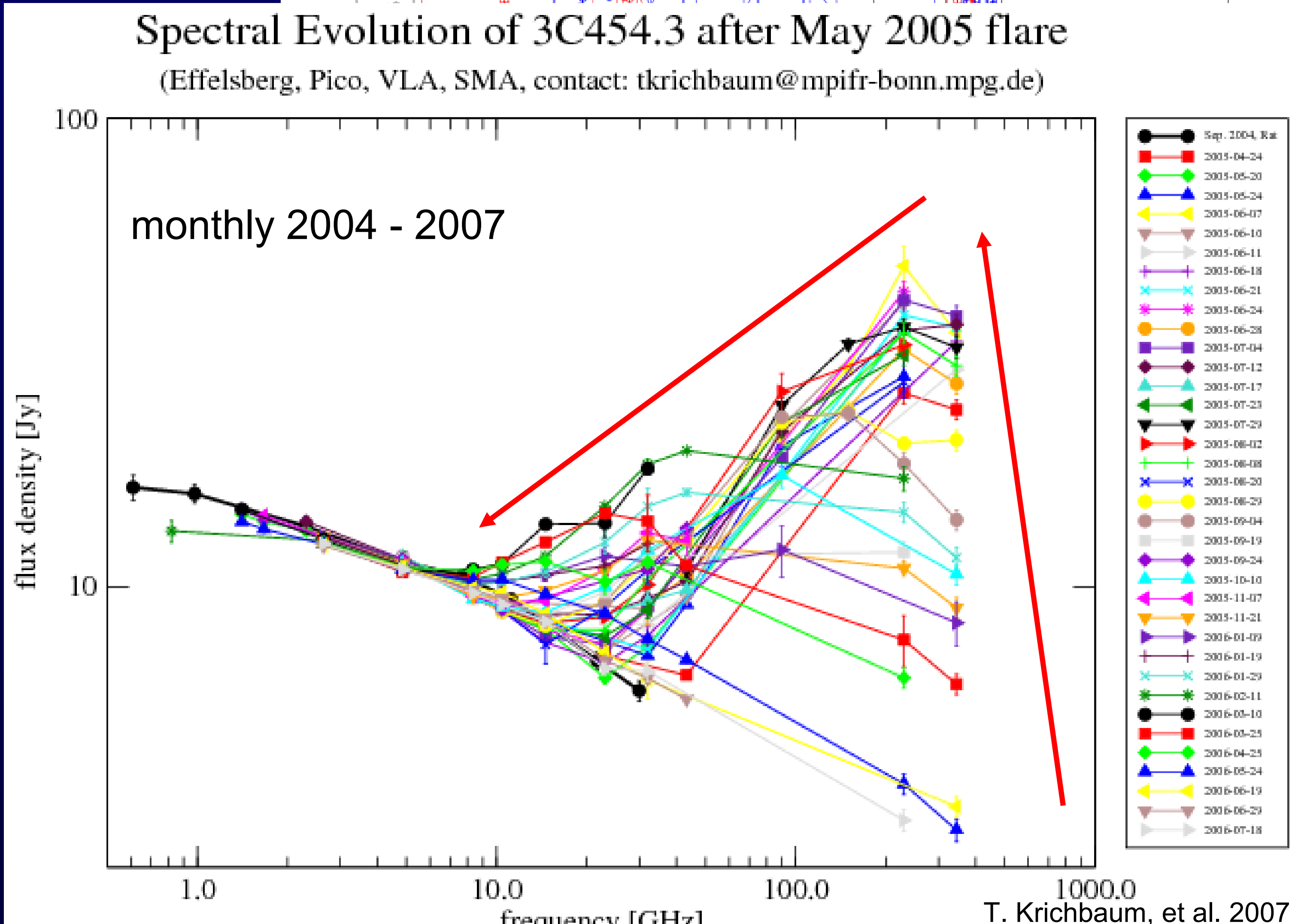



Lee et al. 2008

# Spectral variability of 3C454.3 after May 2005 Flare:




T. Krichbaum, et al. 2007

Effelsberg:

1.4 – 32 GHz

Pico Veleta:

90 – 230 GHz

SMA:

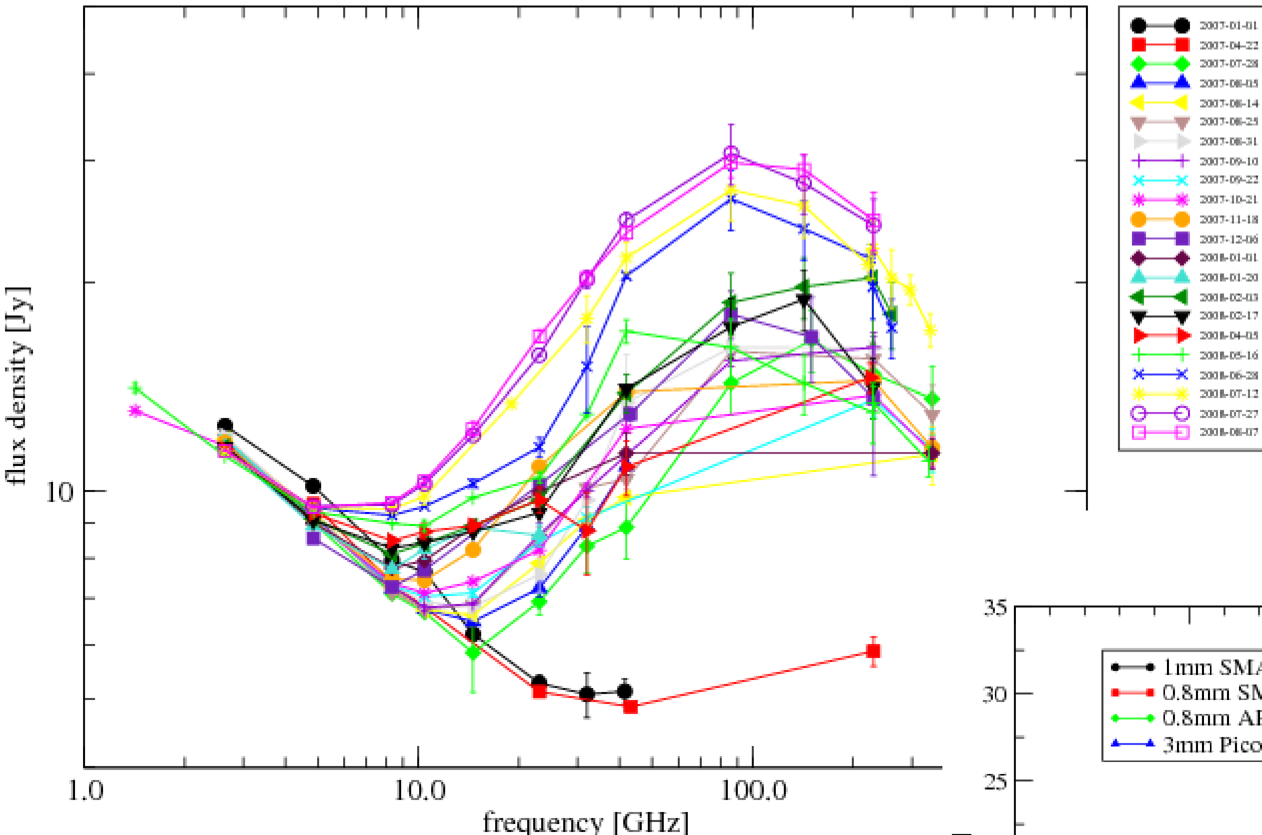
230, 350 GHz

combined data:

Krichbaum, Fuhrmann, Ungerechts, Wiesemeyer, Gurwell et al.

# Spectral Evolution of 3C454.3 after Jan. 2007

(Effelsberg, Pico, VLA, SMA, APEX)



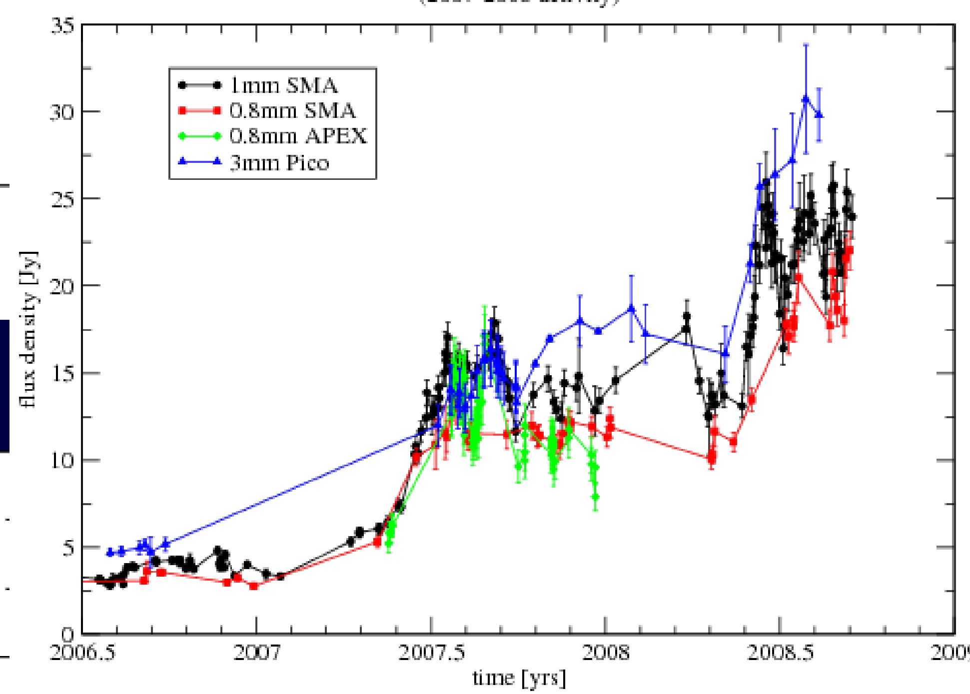

3C454.3

the story continues

new 2008 flare is even stronger than in 2007

3C454.3

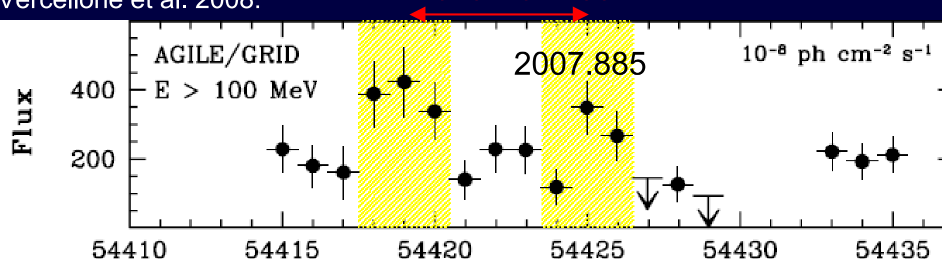
(2007-2008 activity)

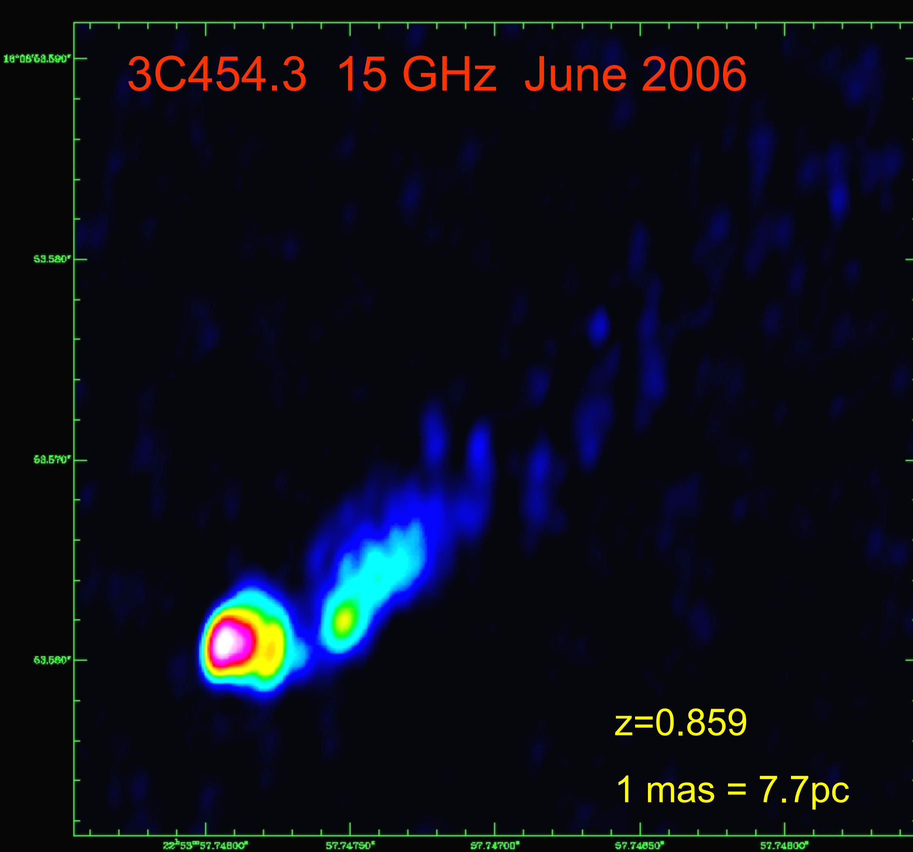



6 day oscillation, factor 2

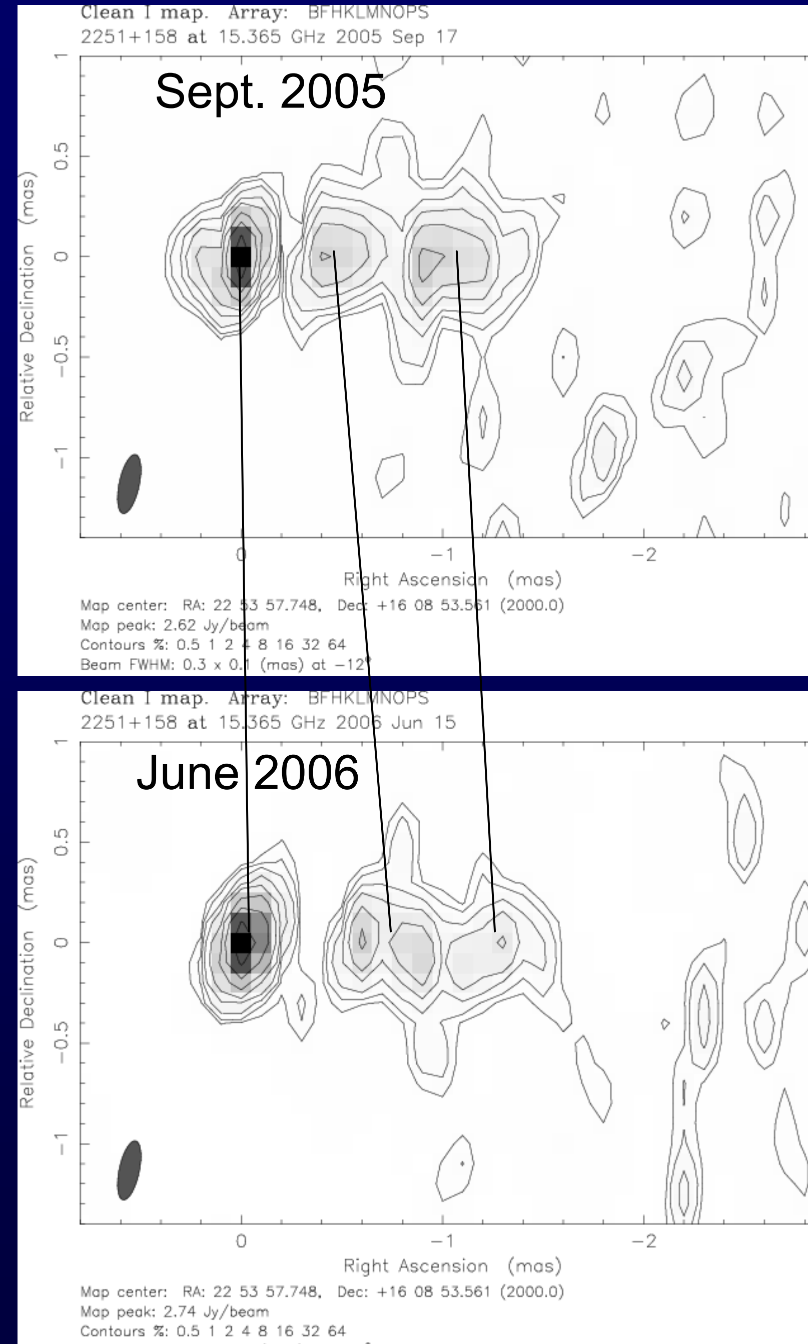
14/20 Nov.2007

Vercellone et al. 2008:





2cm survey, re-mapped

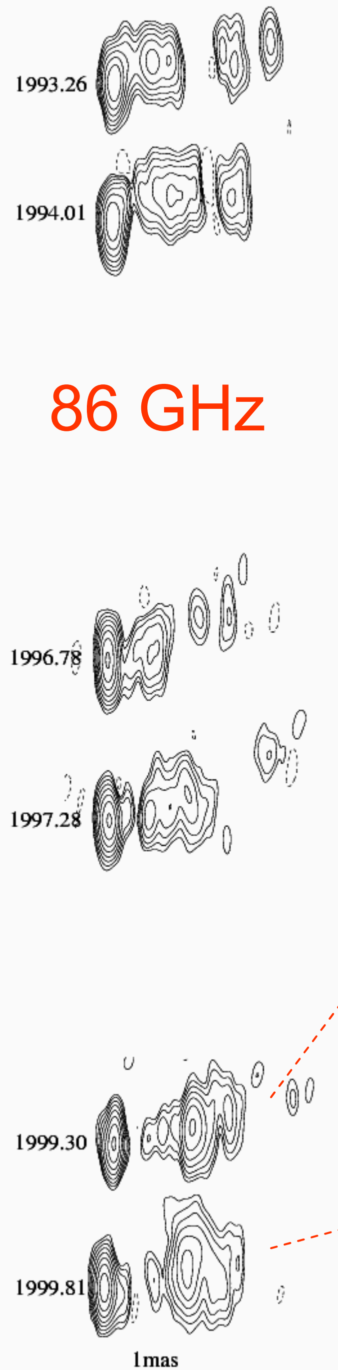



no new component near core, but:

secondary features at r=0.4 & 1.0 mas move fast:

$\mu$ = 0.27 – 0.30 mas/yr , $\beta_{app}$= 12 - 14c

at larger core separations Jorstad et al. find:
$\mu$ = 0.41 – 0.53 mas/yr, $\beta_{app}$= 19 - 25c




# 3C454.3

→ quasi simultaneous epochs allow to measure spectral properties of core and jet on sub-pc scales !

z=0.859

0.1 mas = 0.77 pc

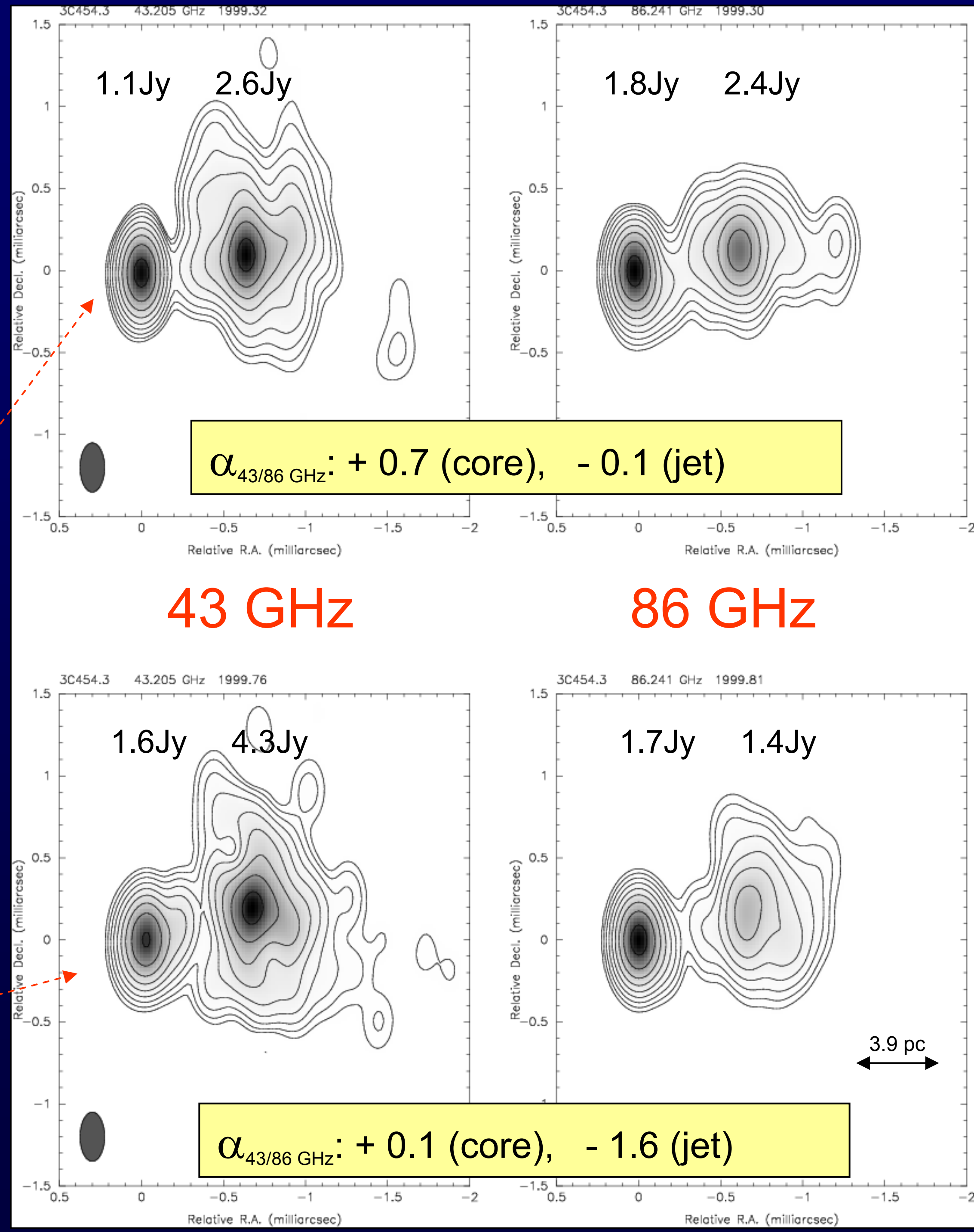
0.1 mas/yr = 4.7 c

jet speed:

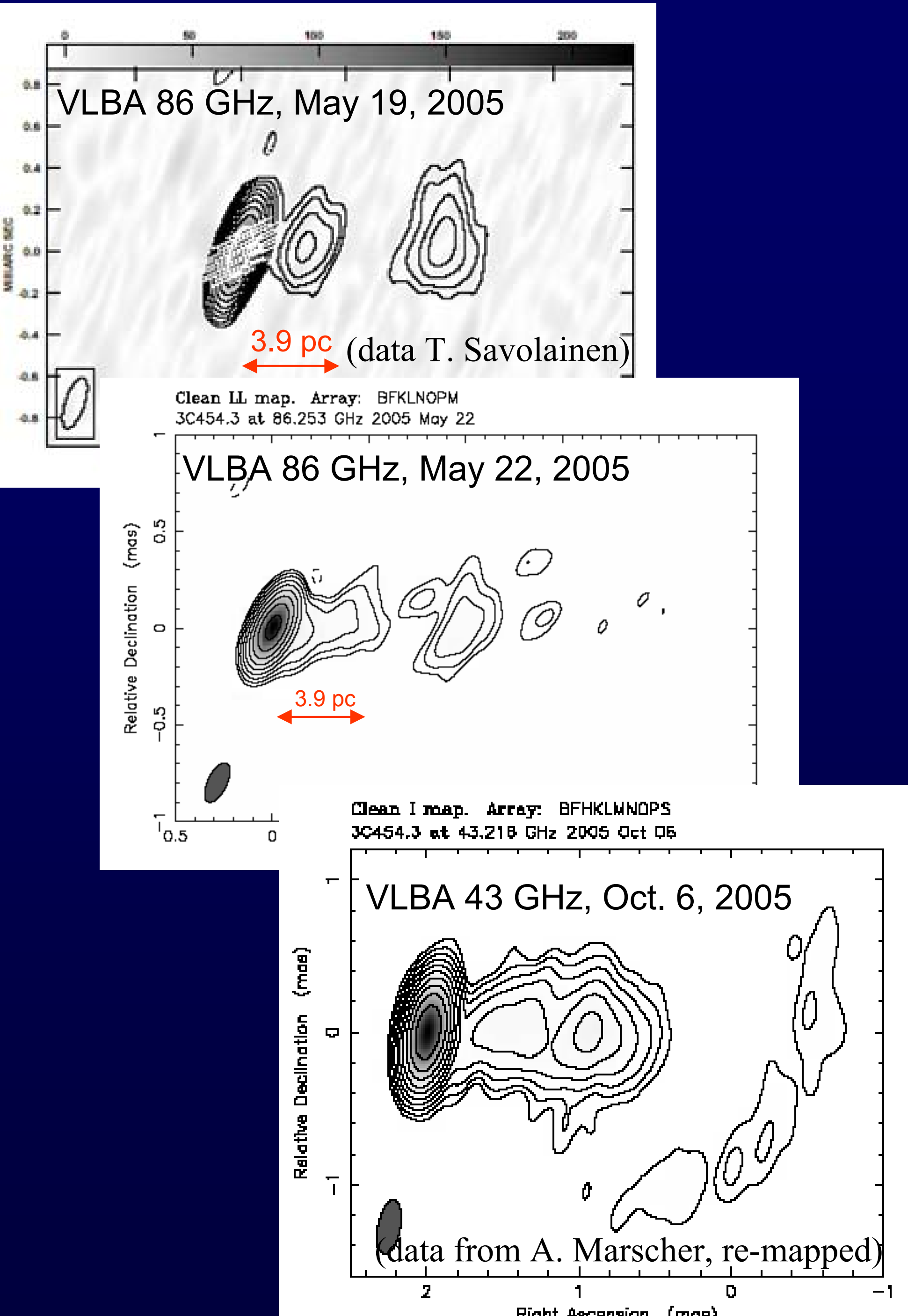
$\beta_{app}$ = 3.7 – 7

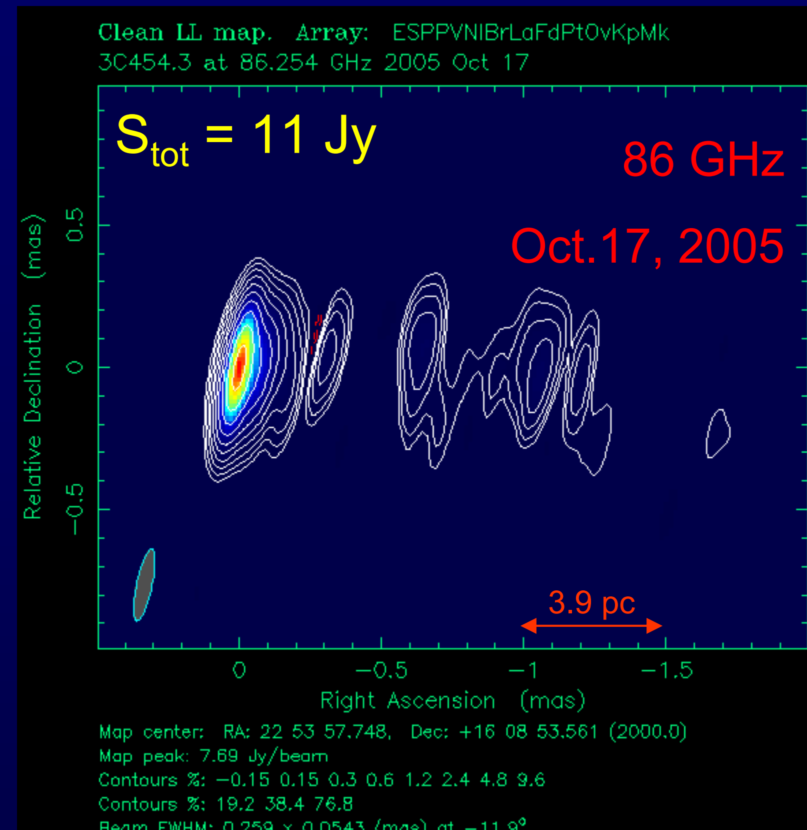
systematically lower than on outer pc-scales (acceler. caused by jet bending ?)

A. Pagels et al. 2004
7mm: A. Marscher et al.



# 86 GHz image 5 months after Outburst

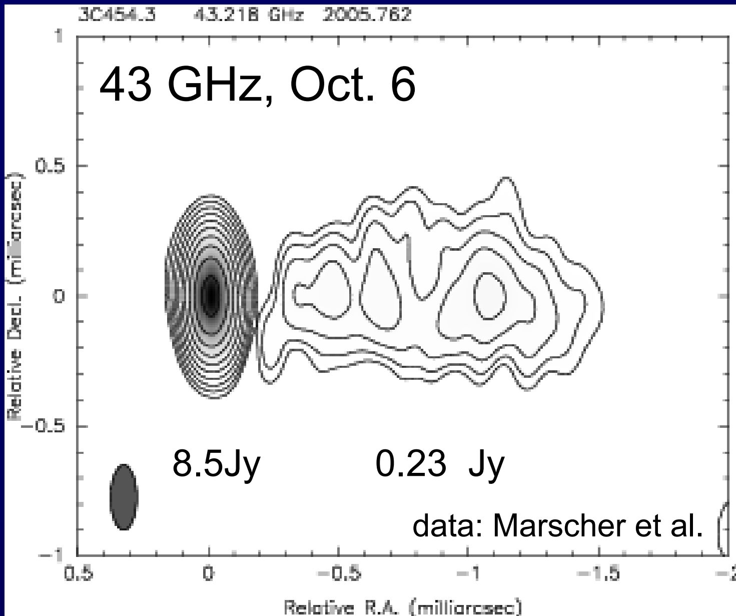


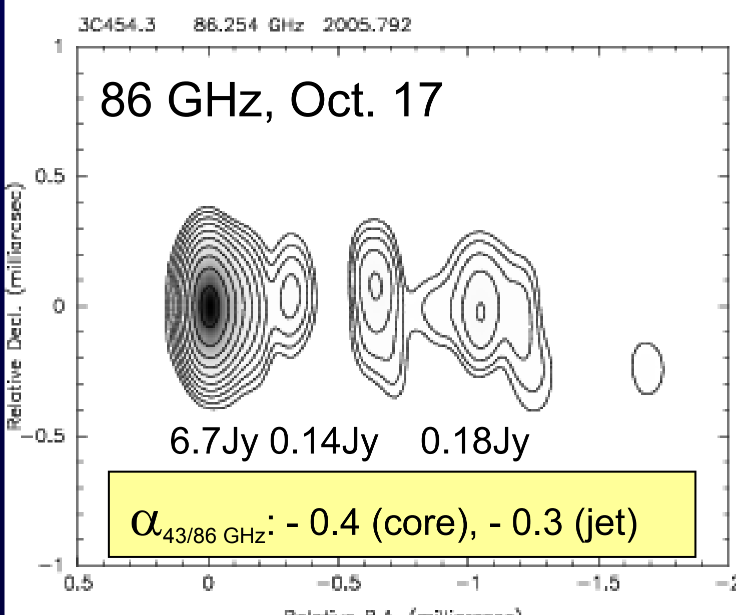

core elongation at r = 0.1-0.2 mas

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

(snap-shot type uv-coverage)




common beam 0.25 x 0.1 mas




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

43 GHz: 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)

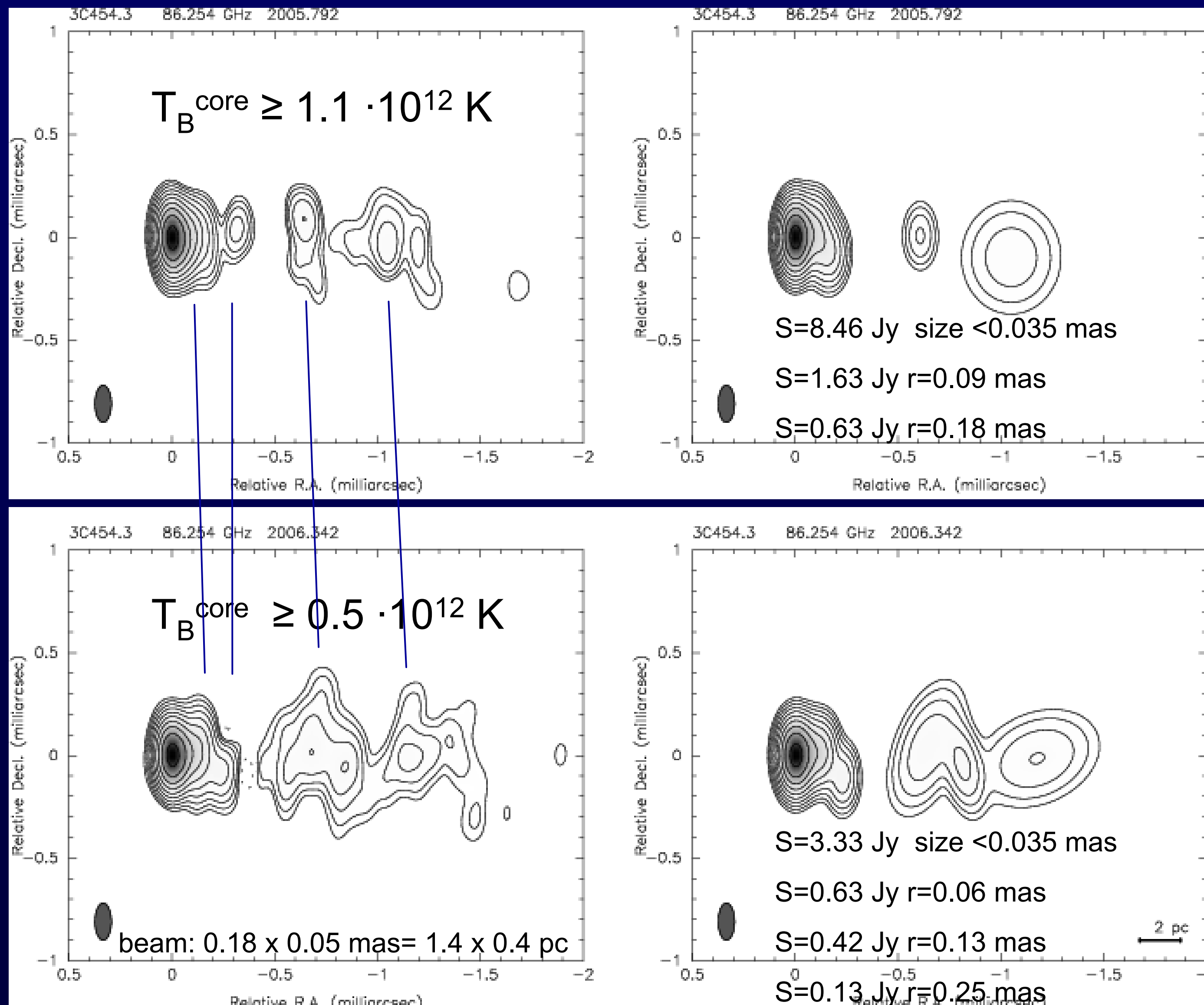
86 GHz: emission near core clearly visible
jet components at 0.6 & 1.1mas
compare well to 43 GHz image

# 3C454.3: new 3mm maps – still no motion seen

Maps | Model Fits

3mm Oct. 2005

3mm May 2006



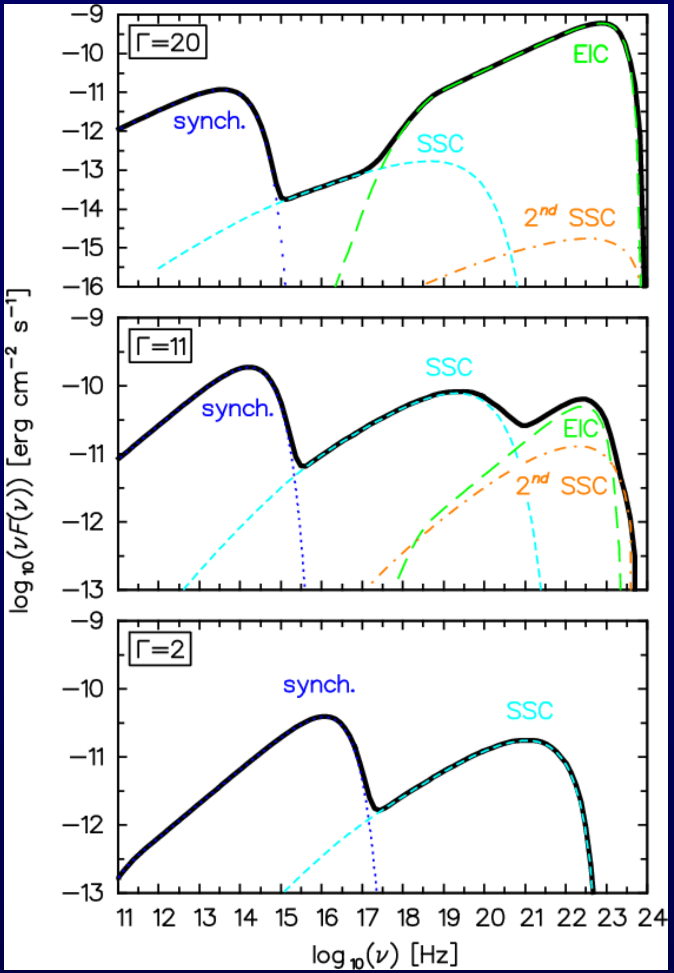

on 0.1 mas scale:

$\mu \leq 0.06$ mas/yr

$\beta_{app} \leq 3$ c

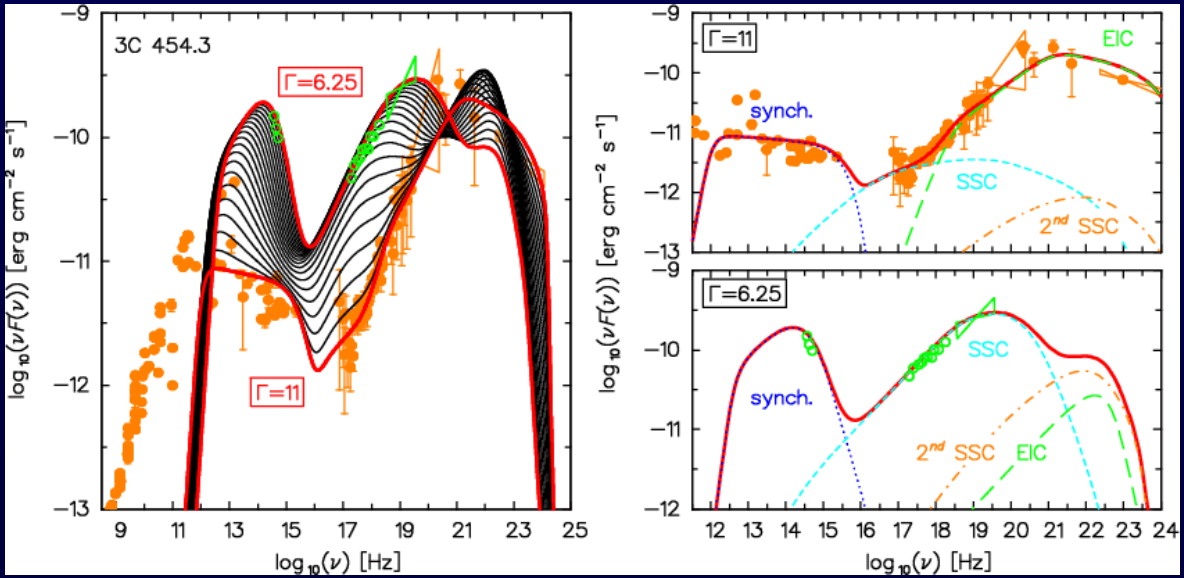
Relative importance of SSC vs. EIC component depend on core separation and jet speed.

Assuming constant jet energy, a high $\gamma$ 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 $\Gamma = 6$.

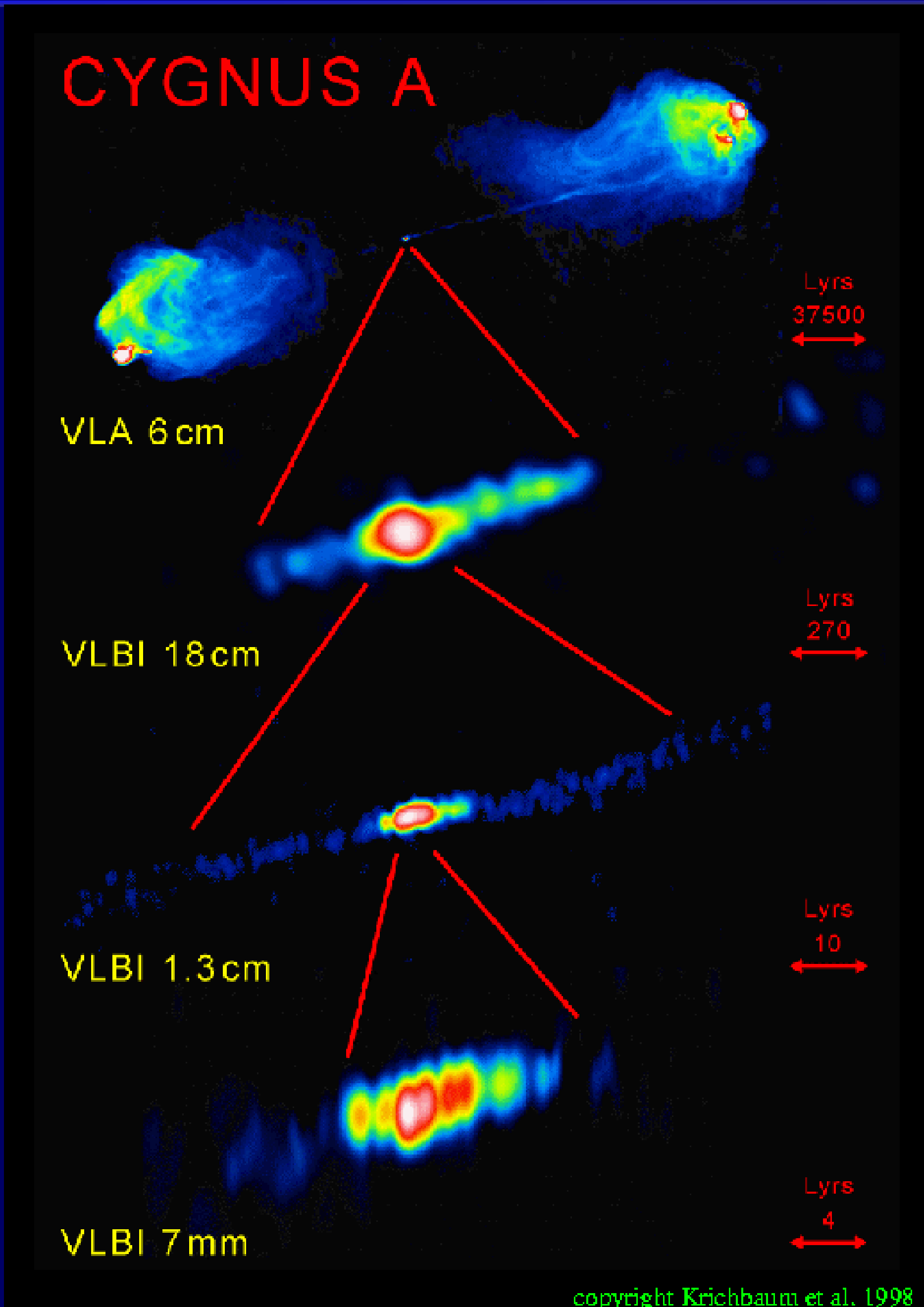
# The two-sided Jets of Cygnus A

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.

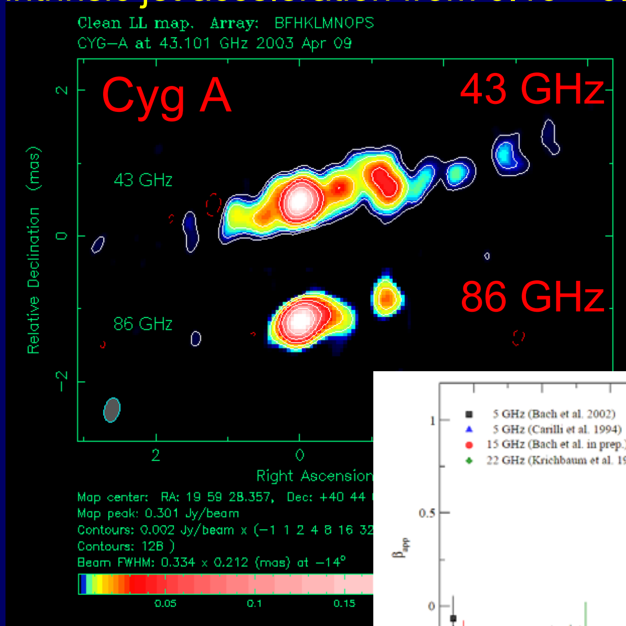
The distance between base of jet and counter-jet yields important size limits of the region where the jet is made and accelerated.

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

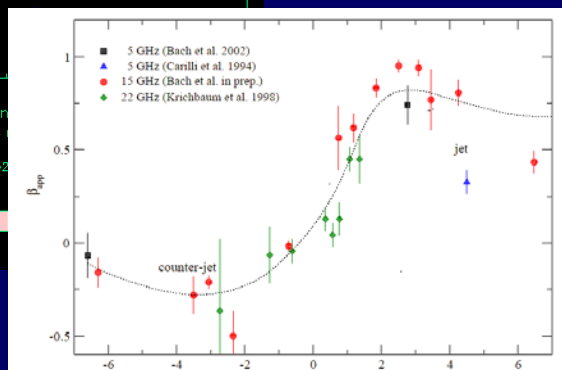


# The Jets of Cygnus A: Acceleration and Absorption

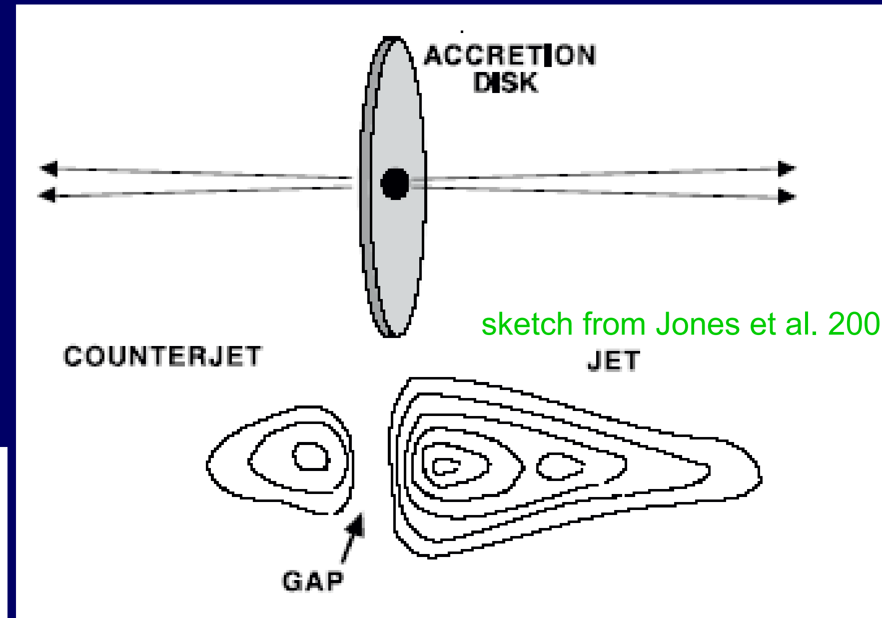
intrinsic jet acceleration from 0.1c – 0.7c

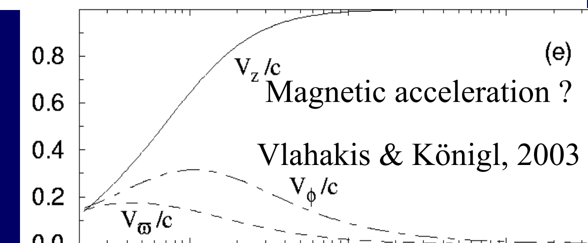



Bach et al. 2006



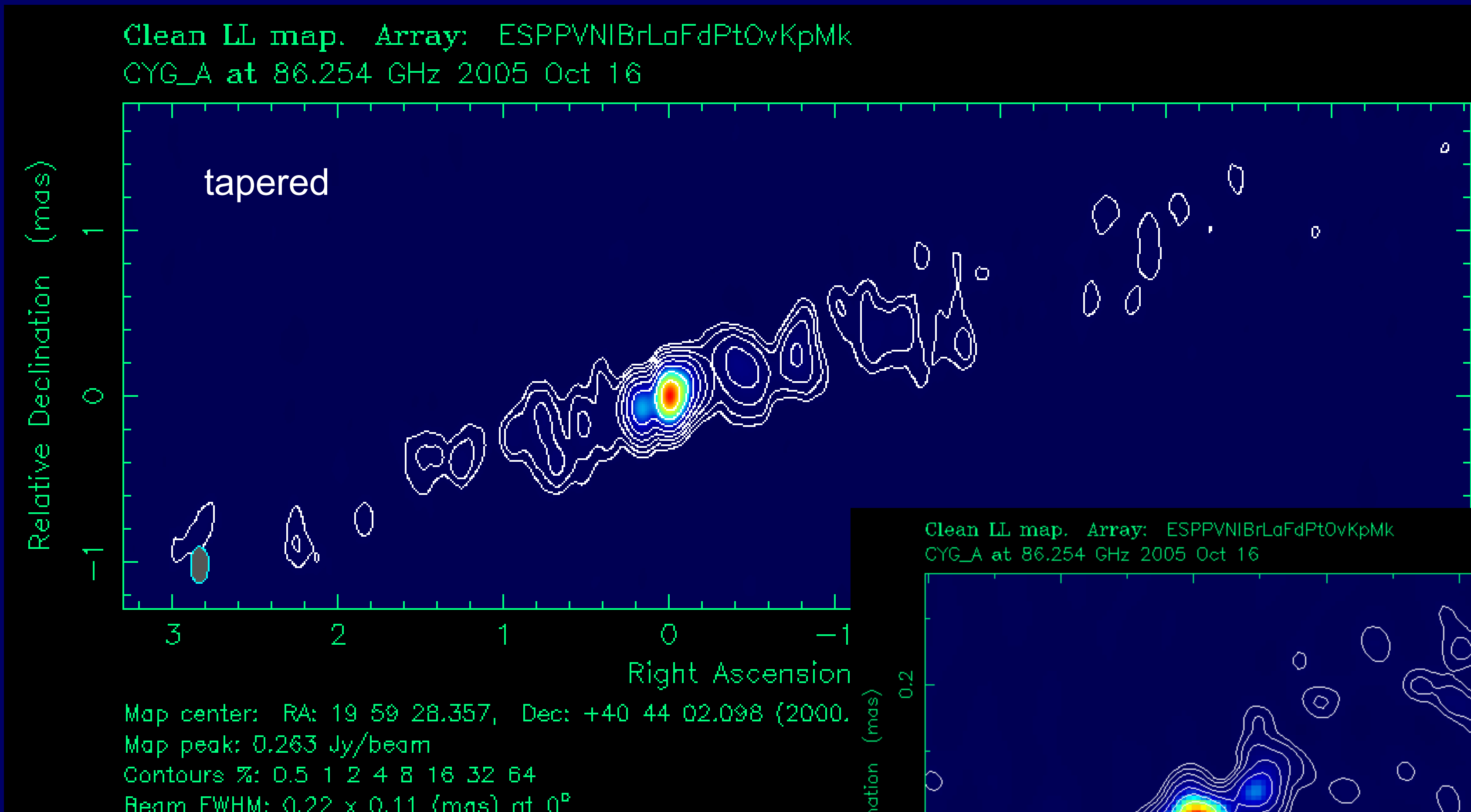

jet acceleration from 0.1c – 0.7c

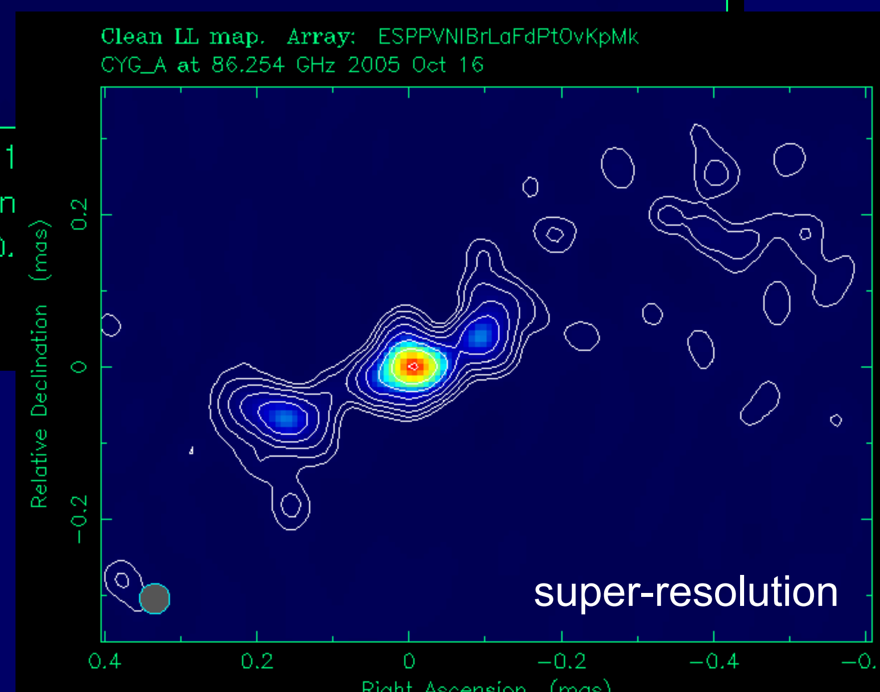



- size of gap depends on jet-launching process and thickness of disk
- need highest frequencies and highest resolution to penetrate opaque absorber and resolve the jet base and image the disk.
- expect free-free absorbtion of counter-jet, which is seen through the disk
- need multi-frequency VLBI monitoring from ground (7mm, 3mm) and space (7mm)

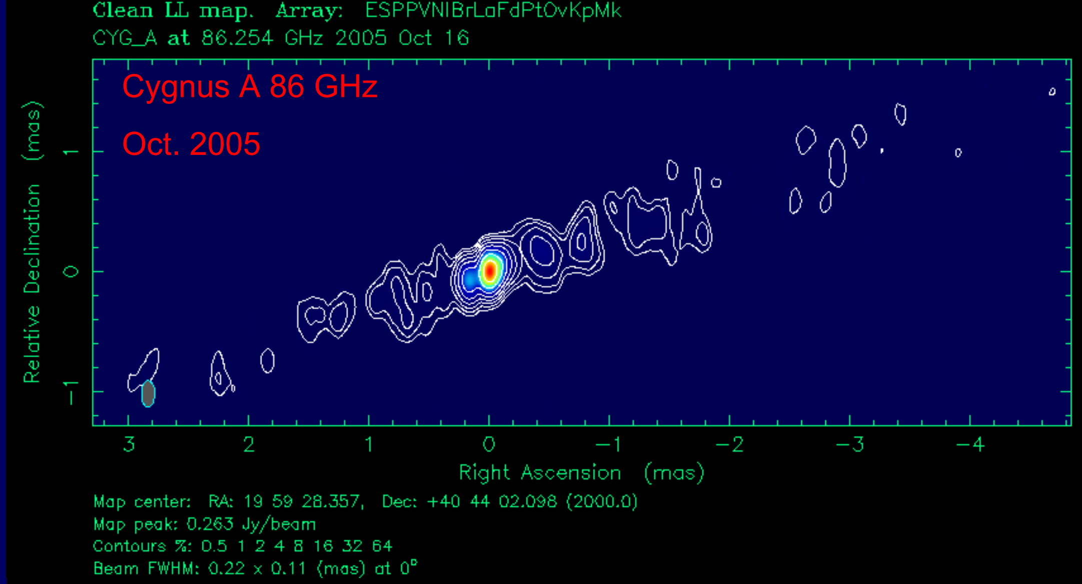
# Jet and Counter-jet of Cygnus A at 86 GHz

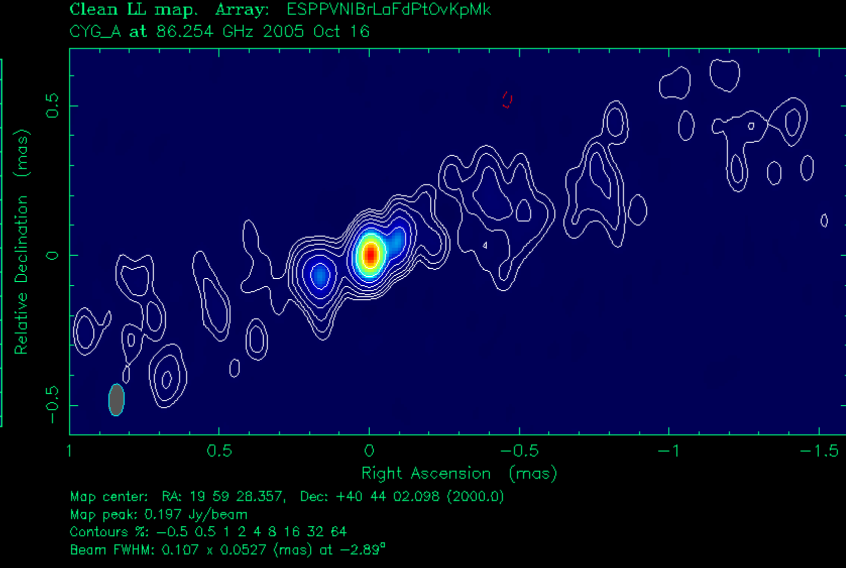


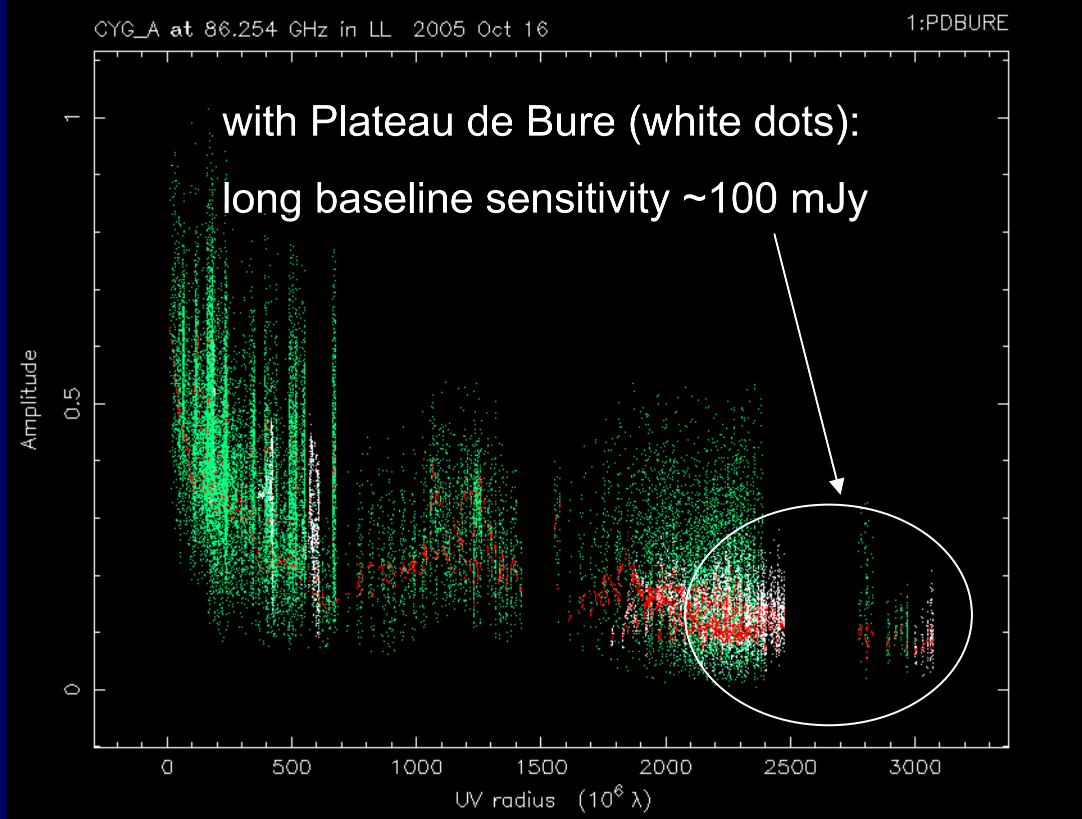



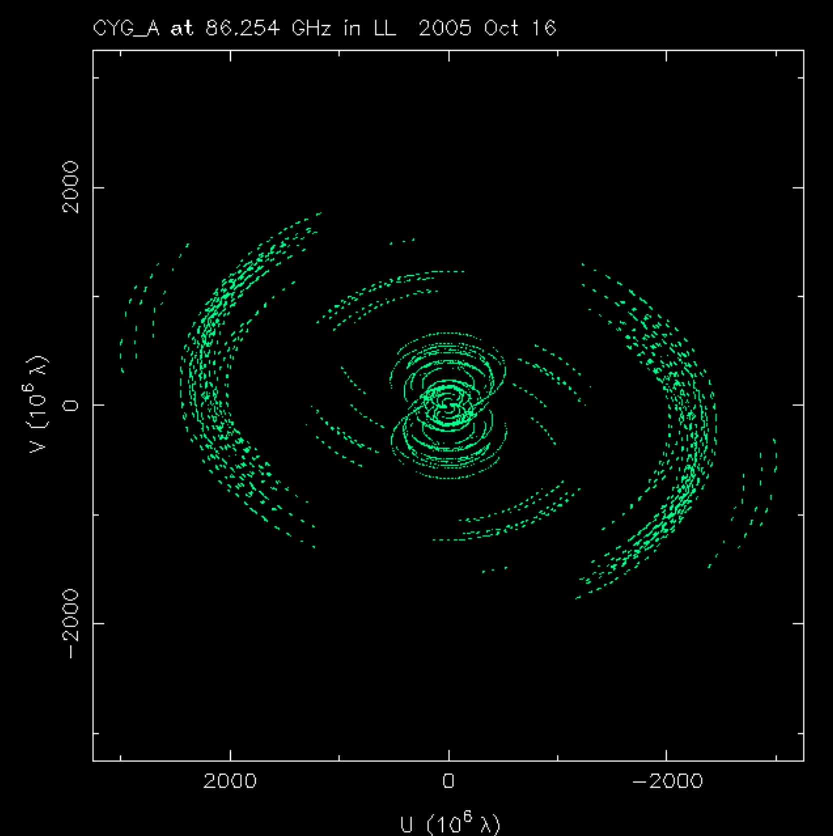

0.1 mas ↔ 0.11 pc ↔ 440 $R_s$[9]

core size: ≤ 46 μas or 203 $R_s$[9]

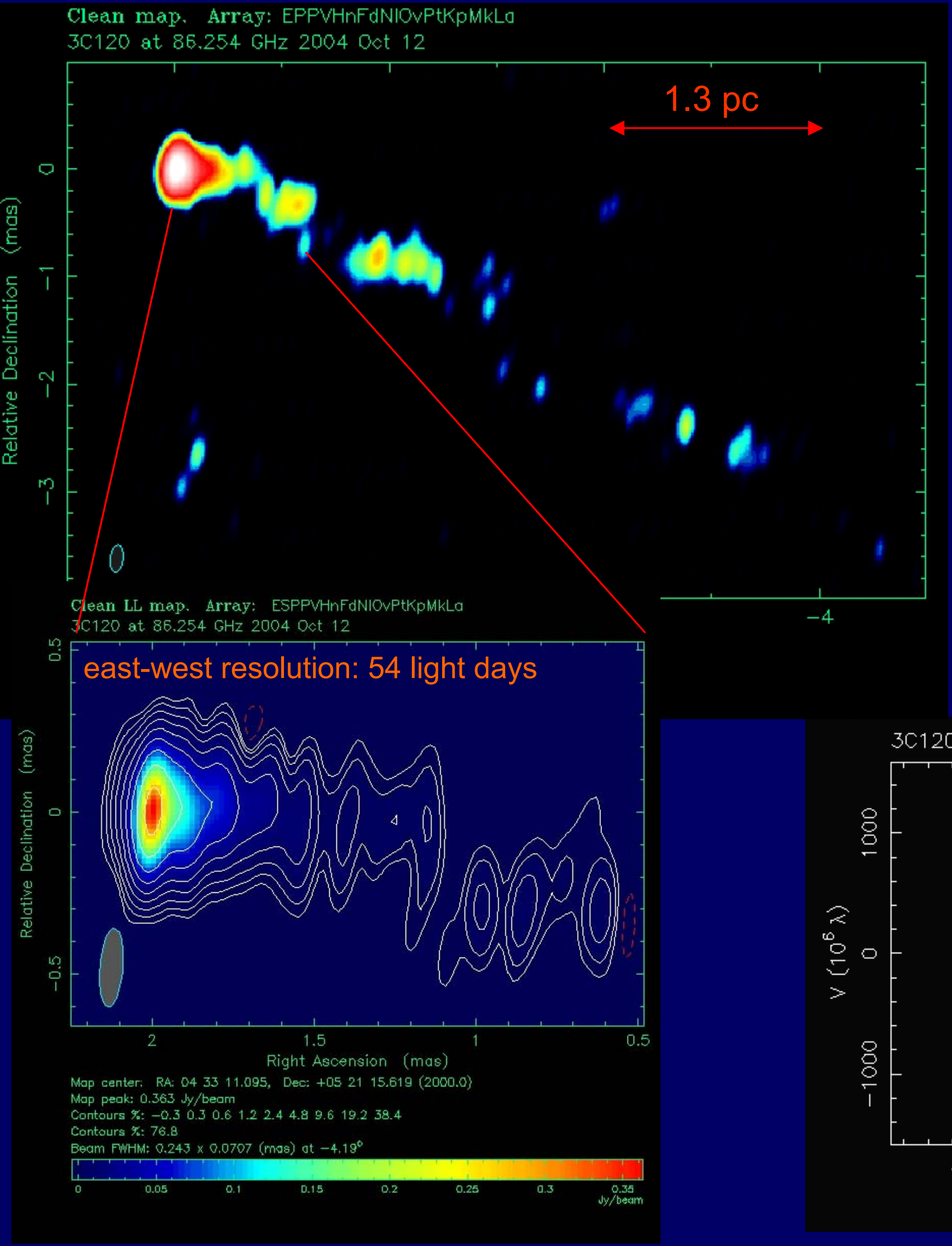

Clean LL map. Array: ESPPVNIBrLaFdPtOvKpMk
CYG_A at 86.254 GHz 2005 Oct 16
Cygnus A 86 GHz
Oct. 2005
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 19 59 28.357, Dec: +40 44 02.098 (2000.0)
Map peak: 0.263 Jy/beam
Contours %: 0.5 1 2 4 8 16 32 64
Beam FWHM: 0.22 x 0.11 (mas) at 0°

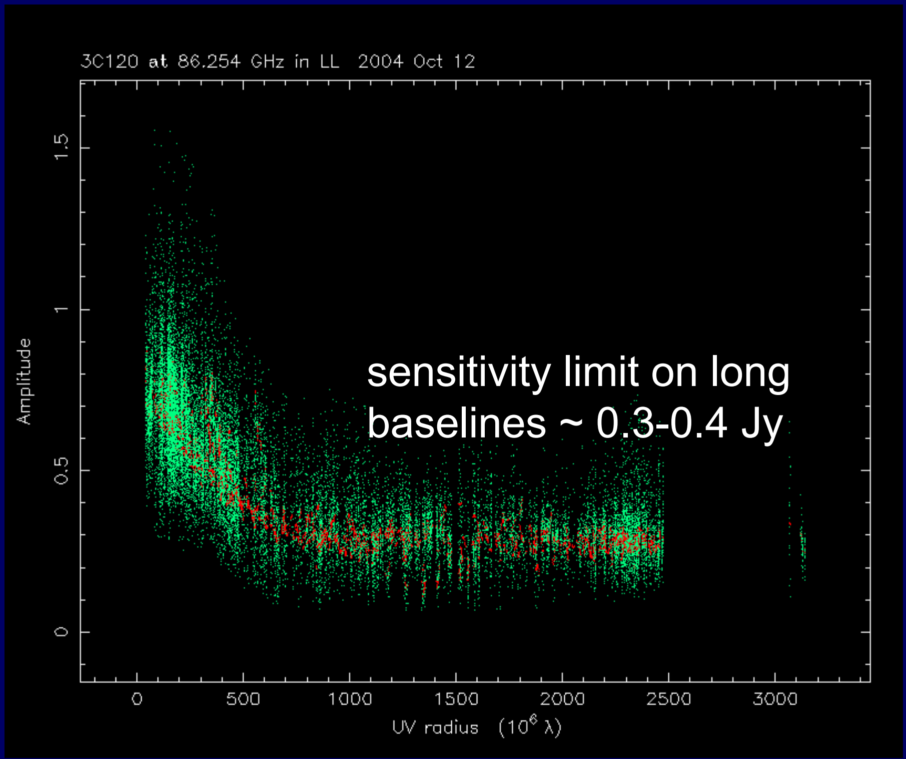

Clean LL map. Array: ESPPVNIBrLaFdPtOvKpMk
CYG_A at 86.254 GHz 2005 Oct 16
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 19 59 28.357, Dec: +40 44 02.098 (2000.0)
Map peak: 0.197 Jy/beam
Contours %: −0.5 0.5 1 2 4 8 16 32 64
Beam FWHM: 0.107 x 0.0527 (mas) at −2.89°

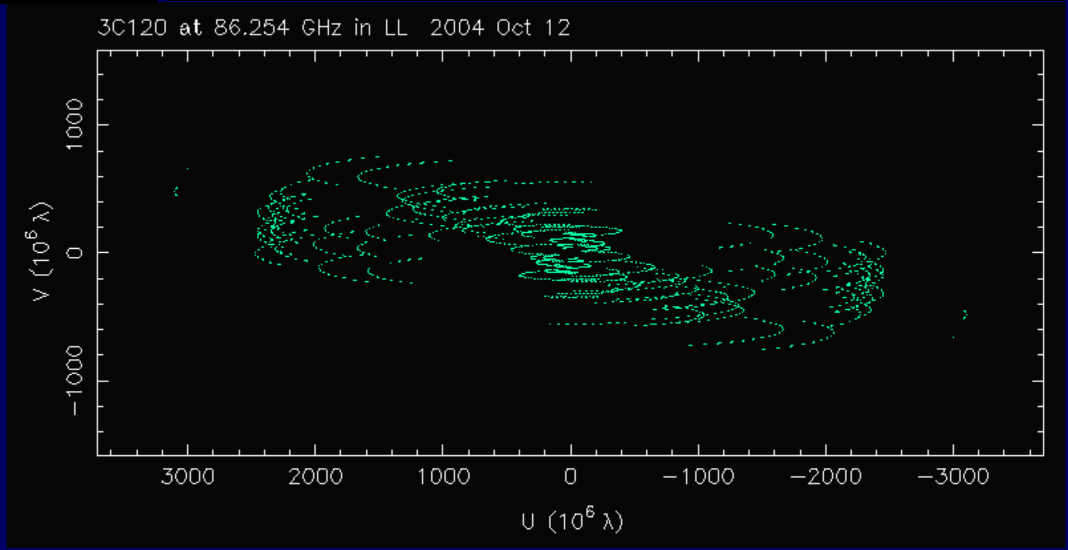

CYG_A at 86.254 GHz in LL 2005 Oct 16
1:PDBURE
with Plateau de Bure (white dots):
long baseline sensitivity ~100 mJy
Amplitude
UV radius (10^6 λ)


CYG_A at 86.254 GHz in LL 2005 Oct 16
V (10^6 λ)
U (10^6 λ)

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



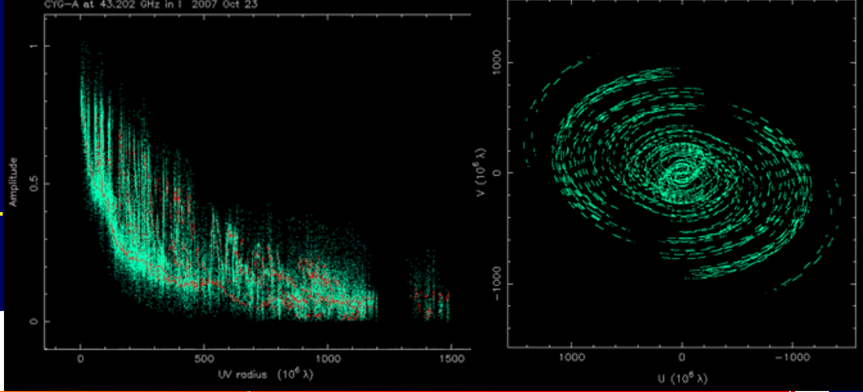



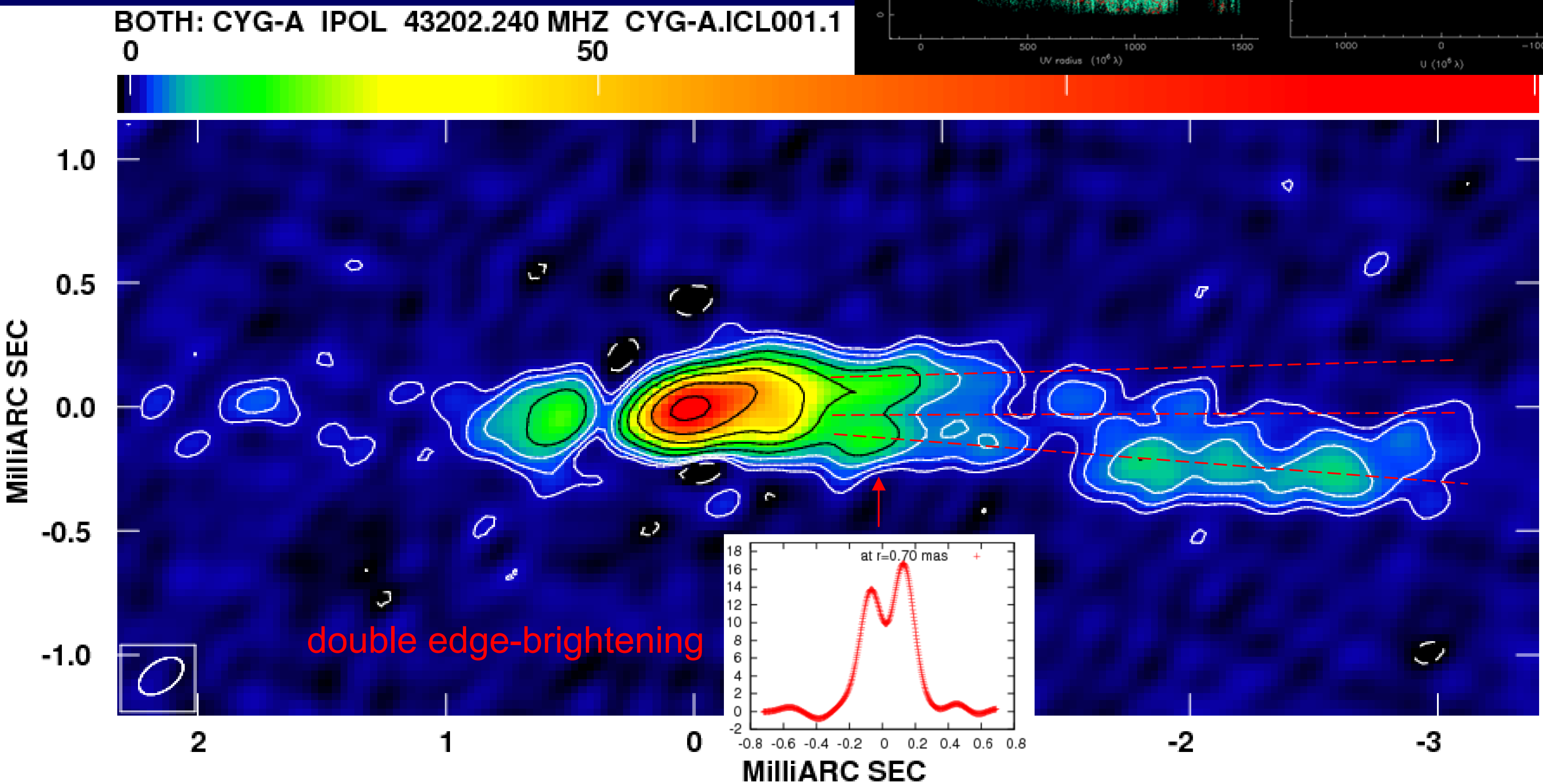



# Global VLBI image of Cygnus A

# (43 GHz, Oct. 2007)

13 Stations: Ef, On, (Nt), VLBA(9, no SC), VLA(1), GBT



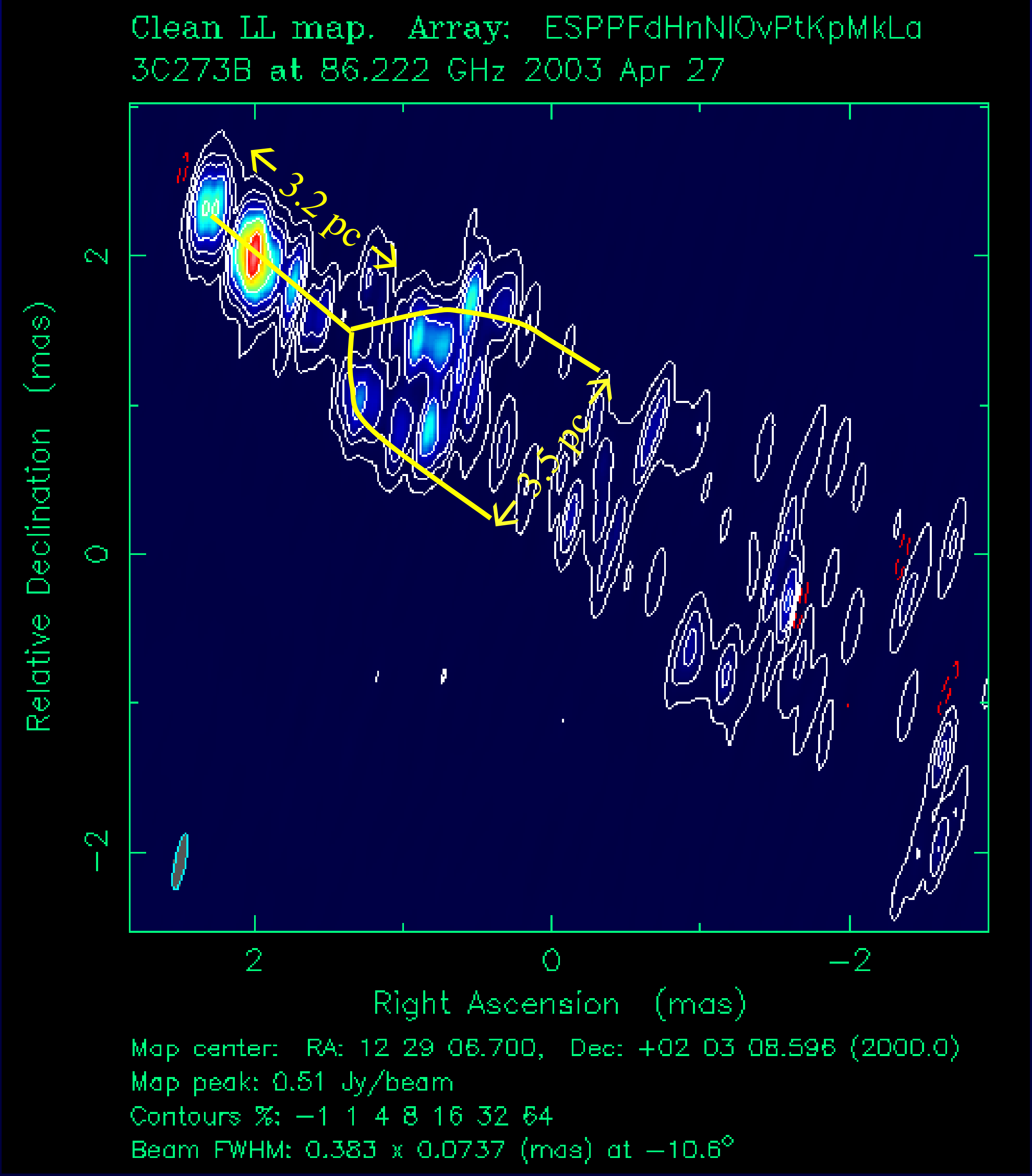




Center at RA 19 59 28.35649900 DEC 40 44 02.0972799
ROT -15.000
Grey scale flux range= -1.0 150.0 MilliJY/BEAM
Cont peak flux = 1.6619E-01 JY/BEAM
Levs = 1.041E-03 * (-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512)

see poster by U. Bach et al.

mm-VLBI resolves jet transversely:

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




$z = 0.158$

1 mas $\cong$ 2.7 pc

# The Jets of Cygnus A at 43 GHz and 86 GHz

gap between jet

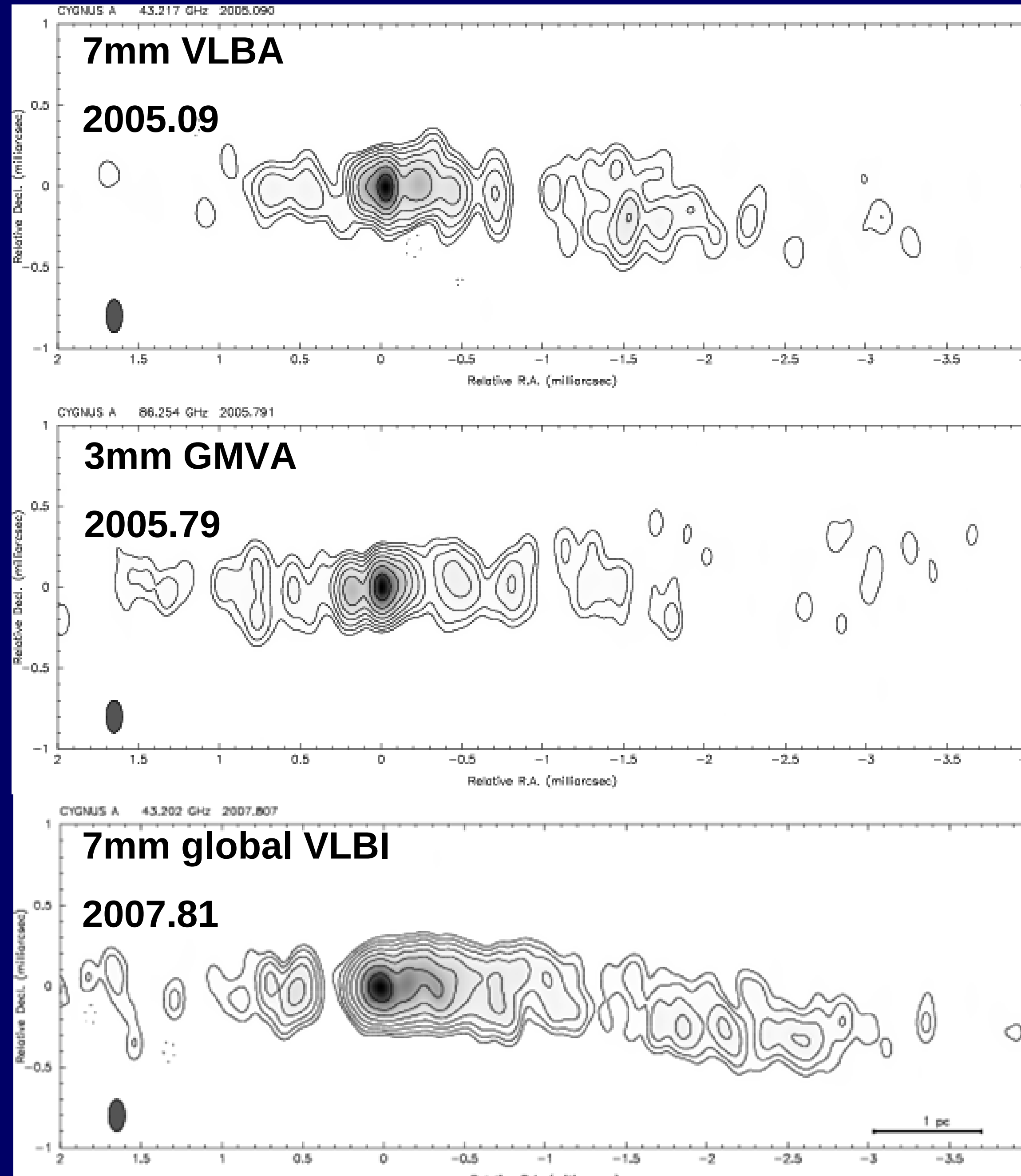
and counterjet:

at 43 GHz: ≈ 0.5 mas

~ 2200 $R_s$

at 86 GHz: ≤ 0.2 mas

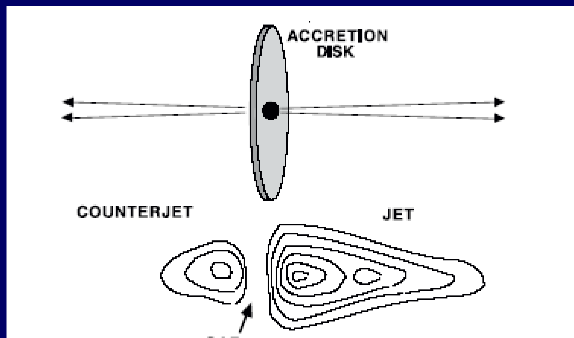
~ 880 $R_s$




convolved with common

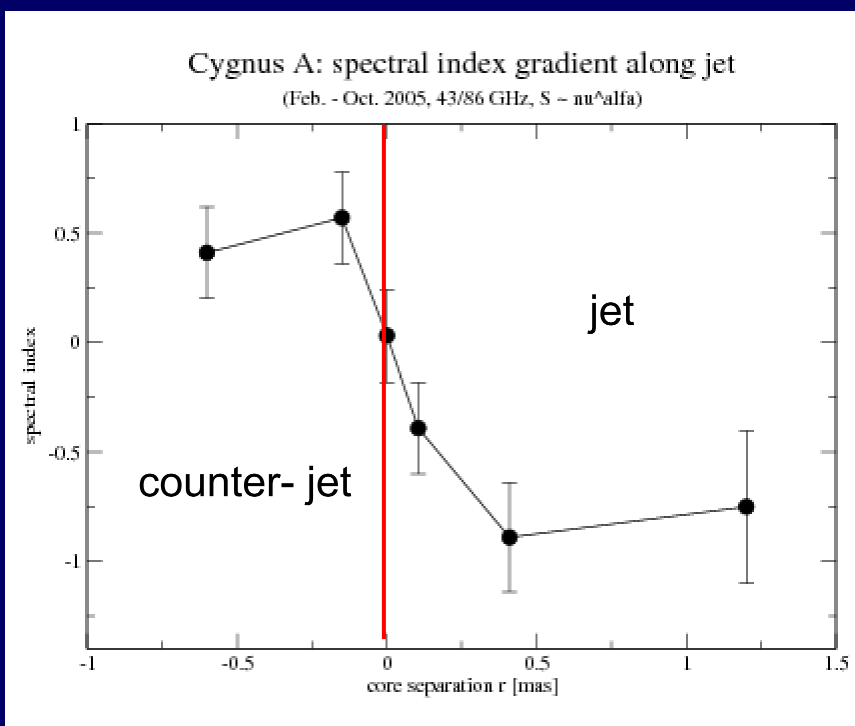
beam of size 0.2 x 0.1 mas

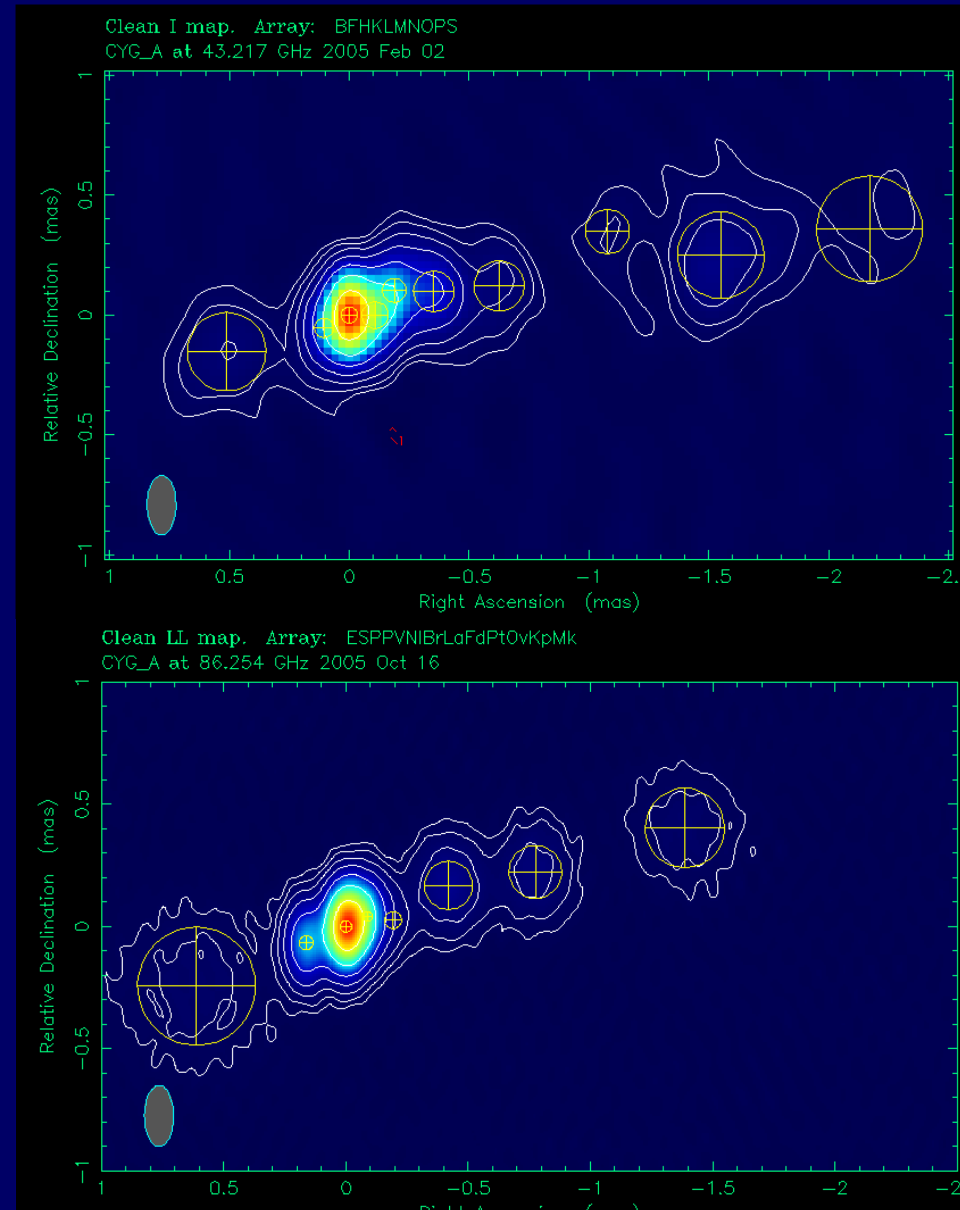
# The spectral index distribution on sub-mas scales



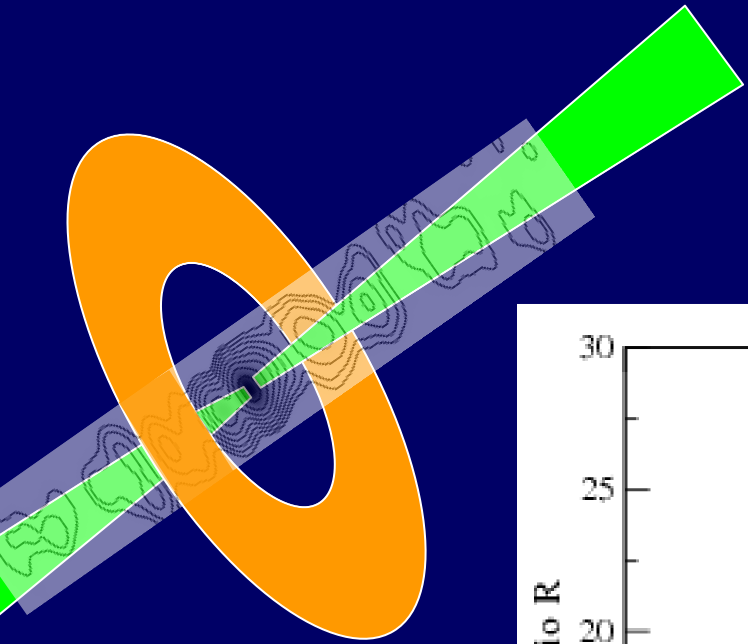
sketch from Jones et al. 2000

inverted spectrum on counter-jet side

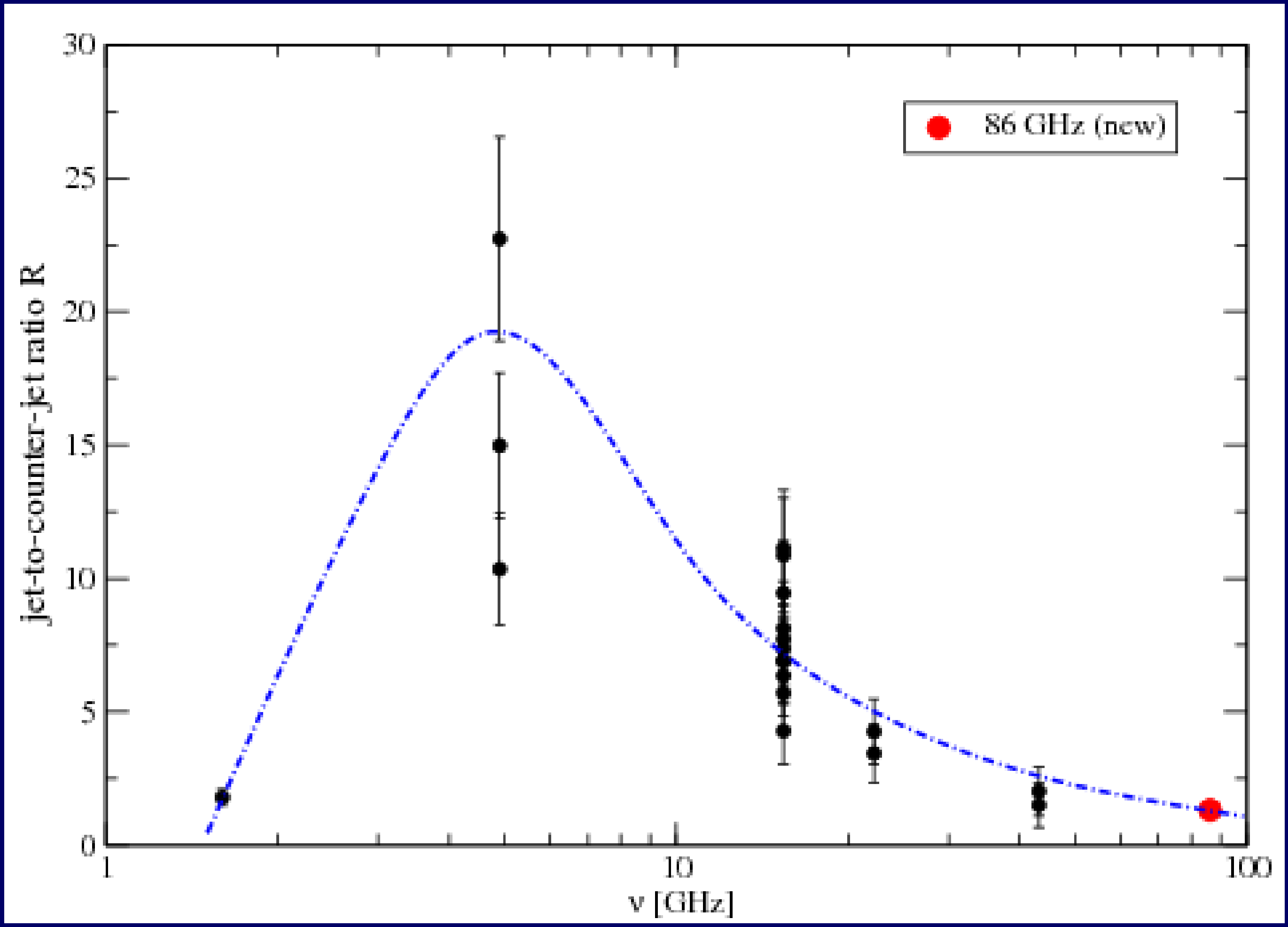


# New: Jet-to-Counterjet Ratio determined at 86 GHz



$R_{86\ GHZ} = 1.32 +/- 0.12$




inner edge: 0.3 mas

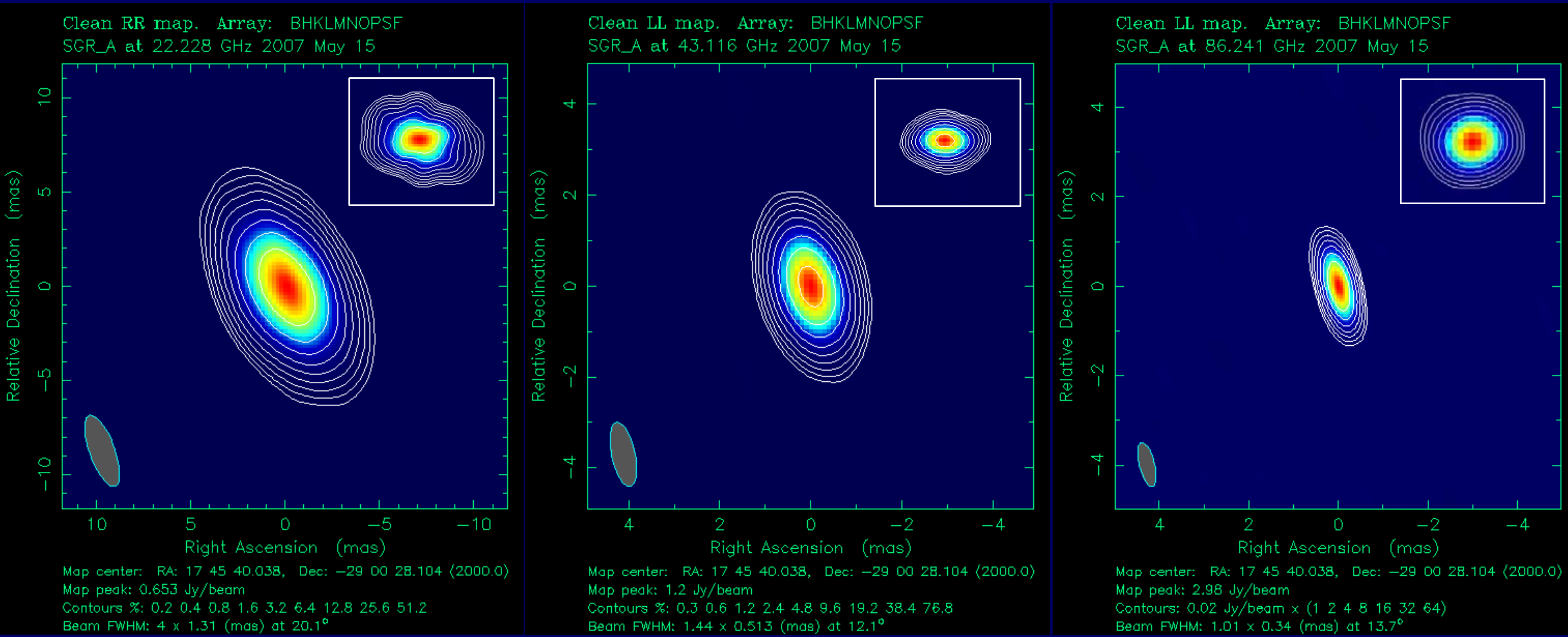
(0.3 pc)

outer edge: 4-5 mas

(4-5 pc)

# 22 / 43 / 86 GHz VLBA observations

# (May 15 – 24, 2007, 10 epochs)



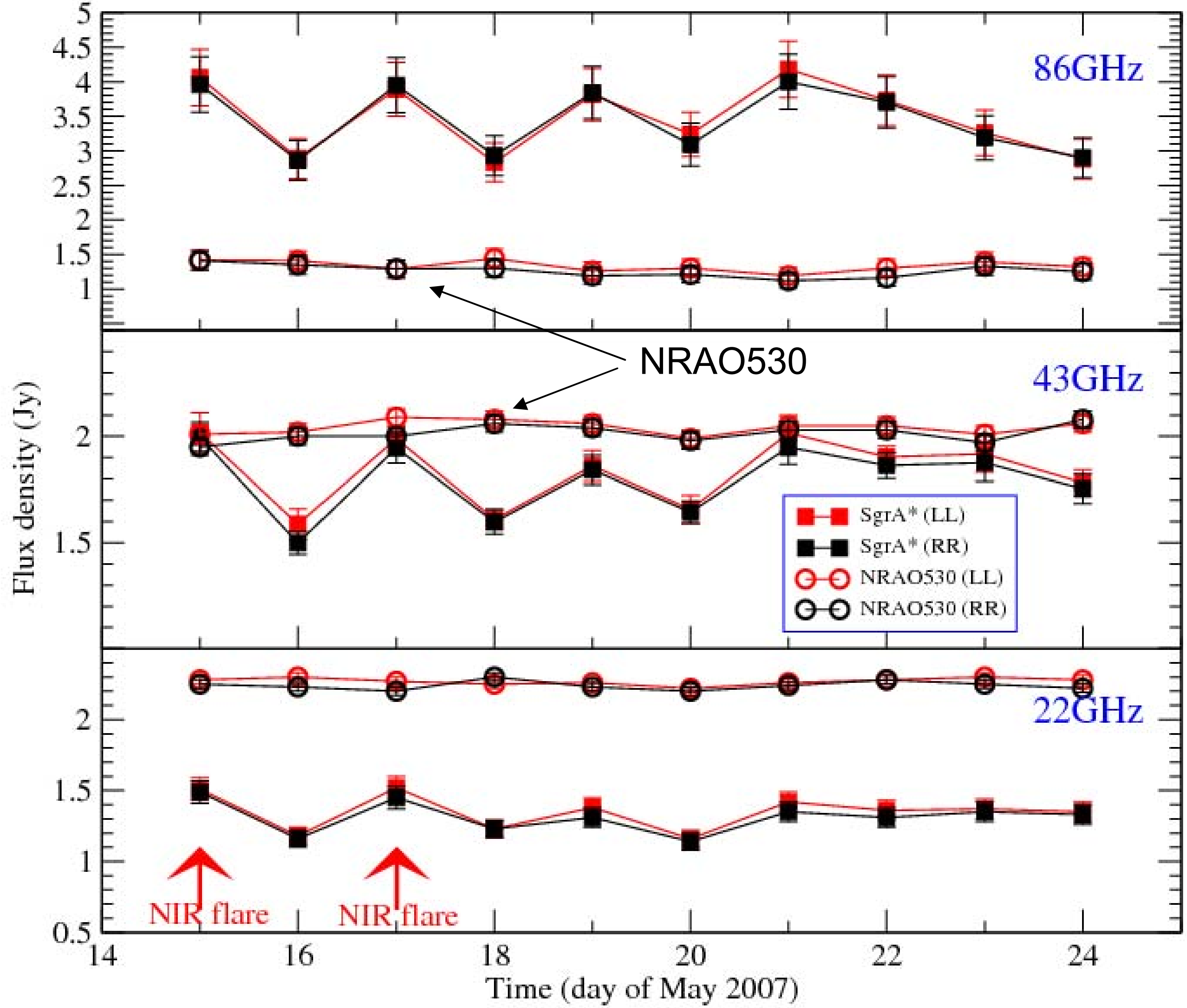

R.Lu et al. 2008

beam:4.0×1.31 mas @20° | beam: 1.44×0.51mas @12° | beam:1.01×0.34 mas @13.7°

22 GHz | 43 GHz | 86 GHz

part of a coordinated X-ray, NIR, mm, VLBI campaign

# Variation of the VLBI flux density of Sgr A*'s versus time



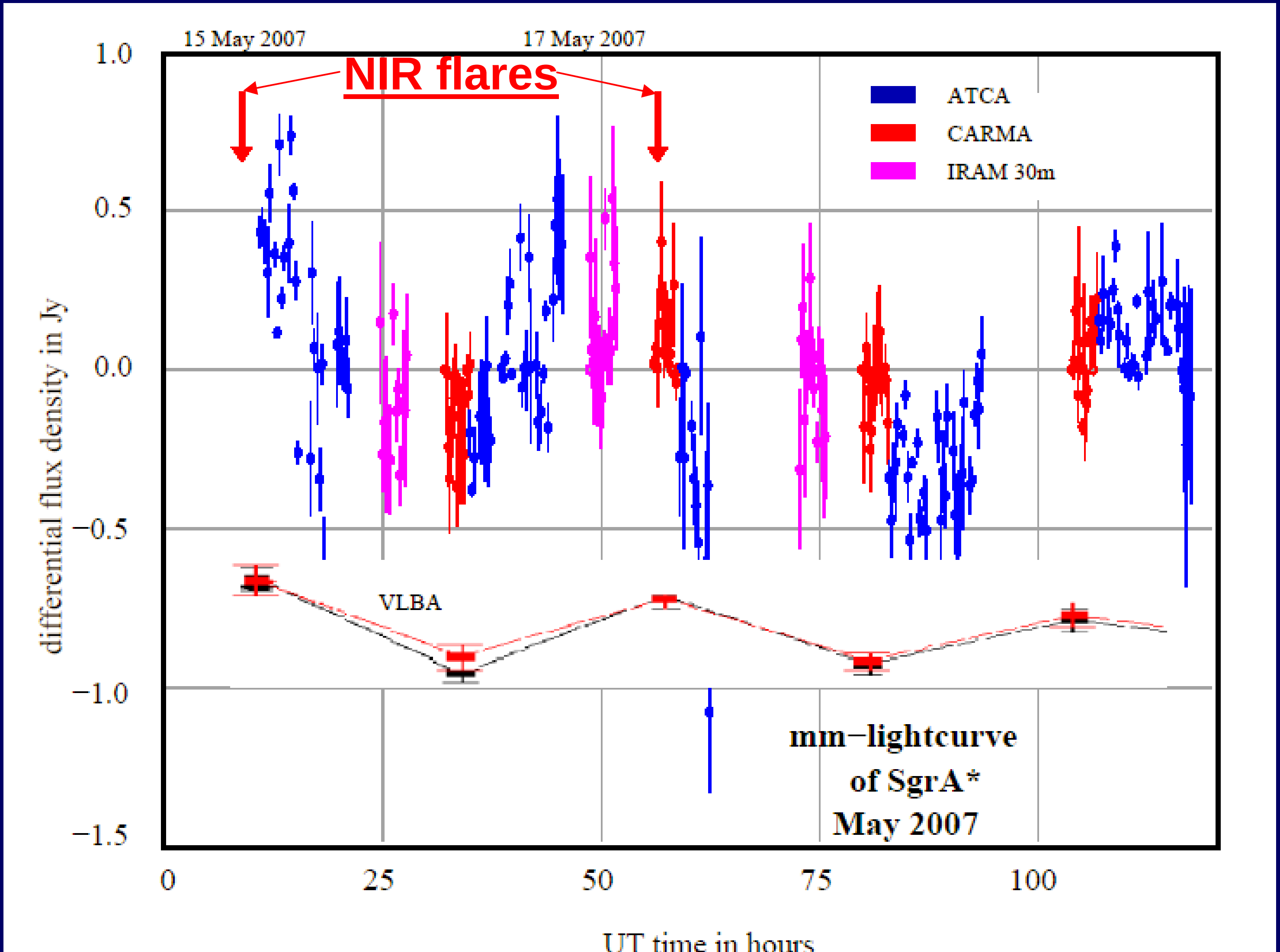

3mm:
$\Delta S/S_{SgrA^*}$ = 15%
$\Delta S/S_{NRAO530}$ = 7%

7mm:
$\Delta S/S_{SgrA^*}$ = 10%
$\Delta S/S_{NRAO530}$ = 2%

13mm:
$\Delta S/S_{SgrA^*}$ = 9%
$\Delta S/S_{NRAO530}$ = 1%

R.Lu et al. 2008

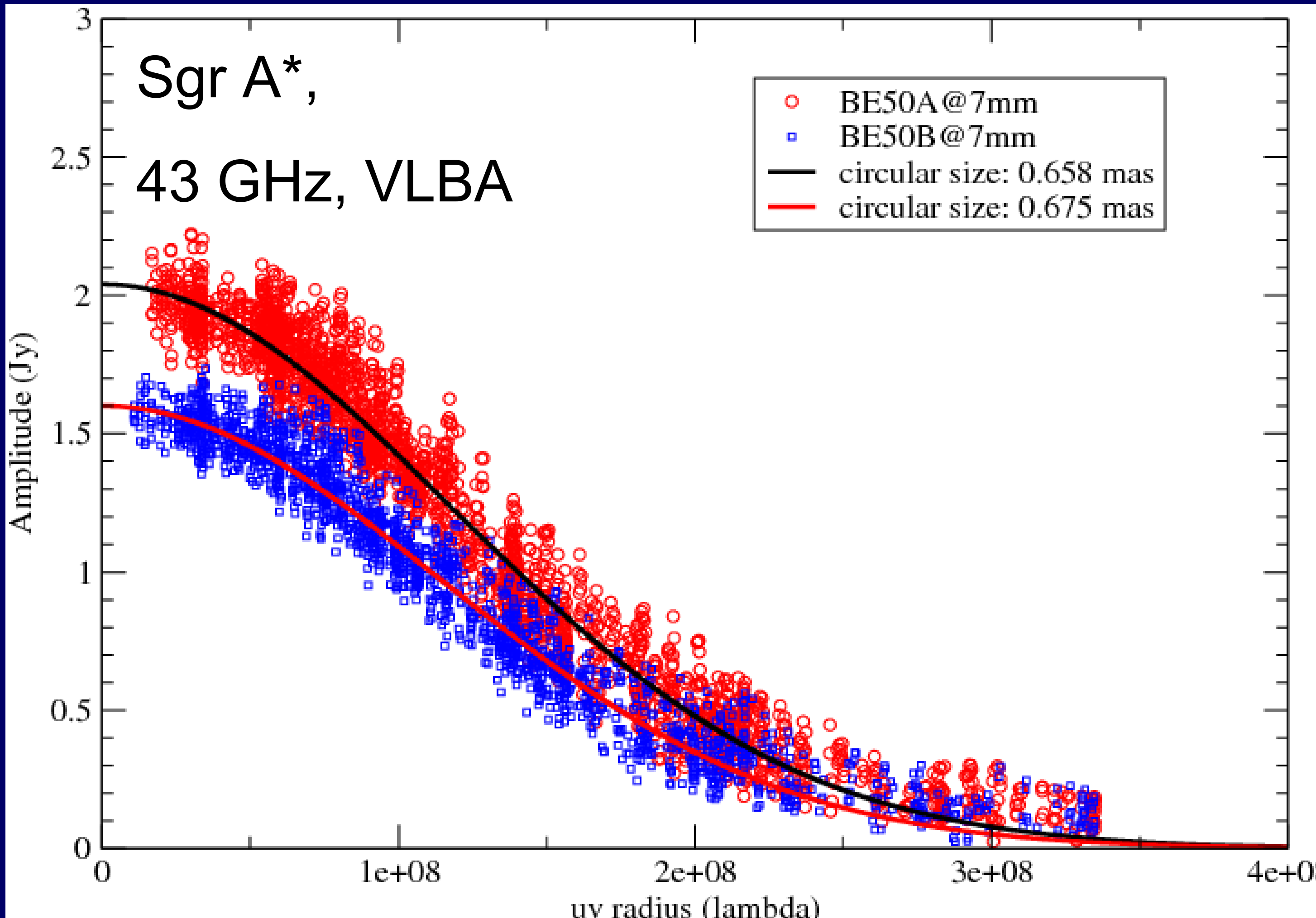
# Total flux density versus VLBI flux density




Kunneriath et al. 2008

prelim. composite light curve from ATCA (86 GHz), Carma (100 GHz) and Pico Veleta (230 GHz)

# Visibility variations on two consecutive days

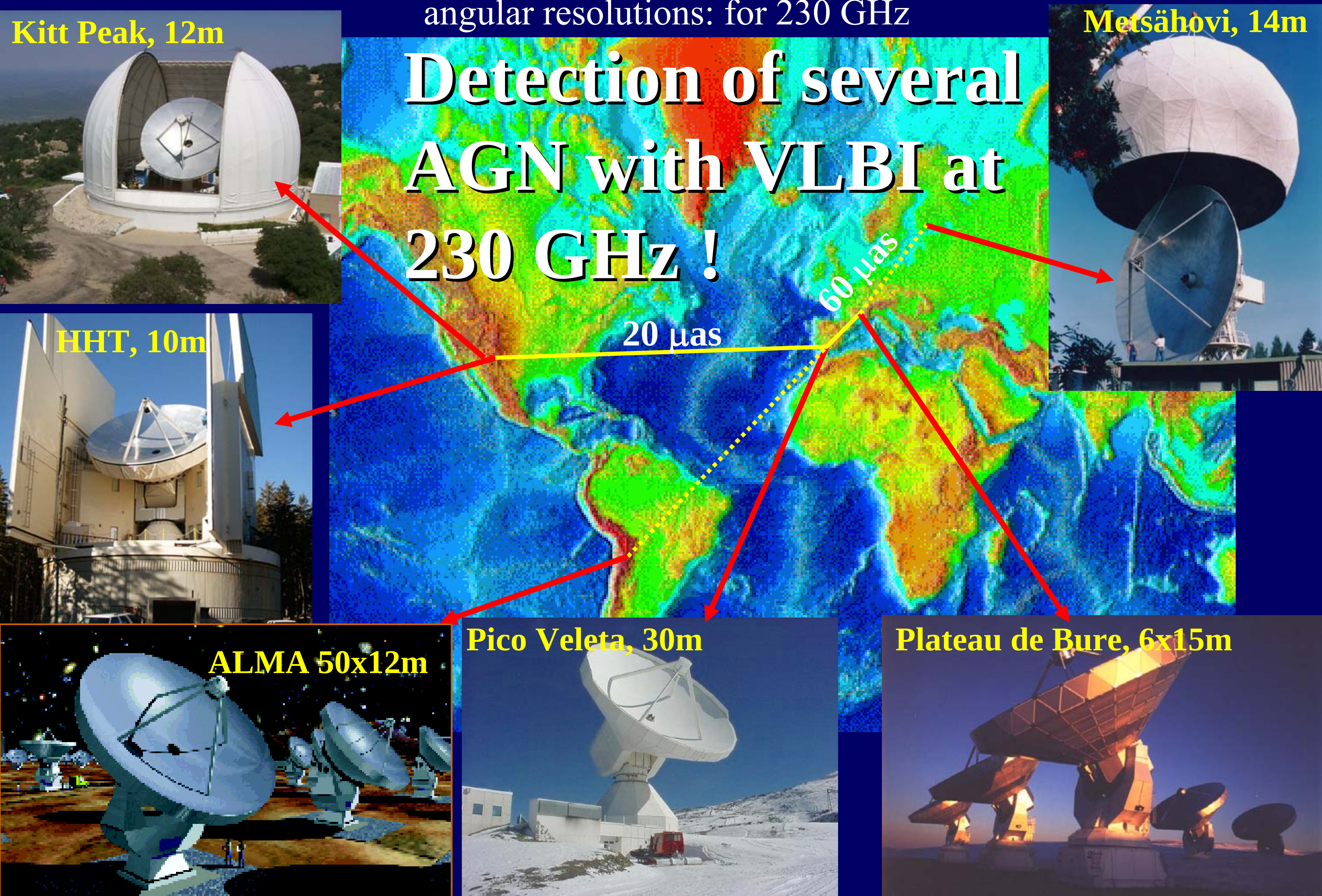



R.Lu et al. 2008

a 30% flux change, no significant change of size

# Global mm-VLBI at 150 - 230 GHz

angular resolutions: for 230 GHz



# Signal-to-Noise ratios for the 230 GHz detections in 2003 (PV –PdB – HHT baselines):

short baselines: SNR : ≤ 25

long baseline: SNR : 6 – 7

Two sources detected at 6.4 Gλ:

3C454.3 and 0716+714

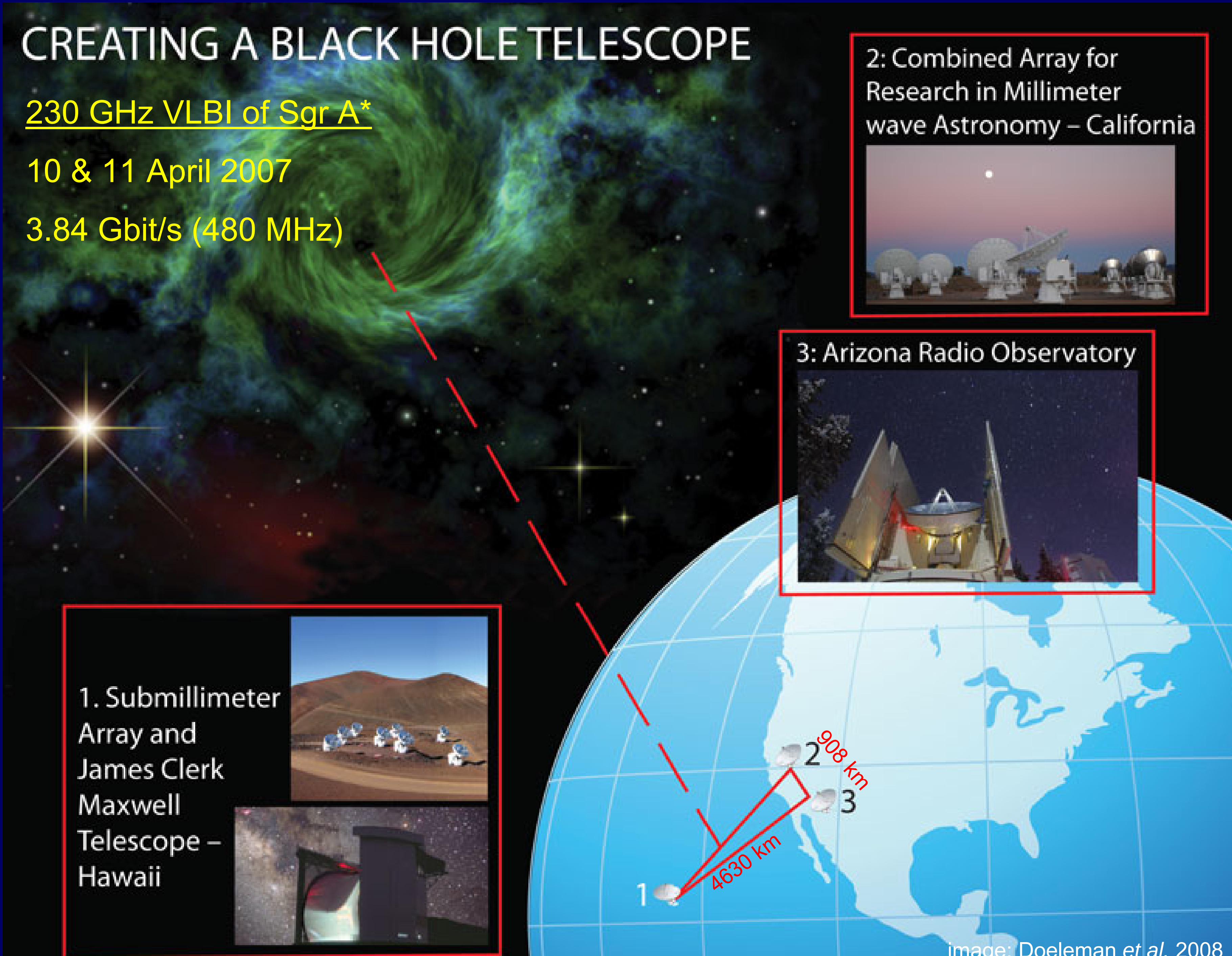
for 3C454.3 (z = 0.859)

$\nu' = 428$ GHz , life time $B\,\gamma^2 = 3.6\ 10^5$ ,

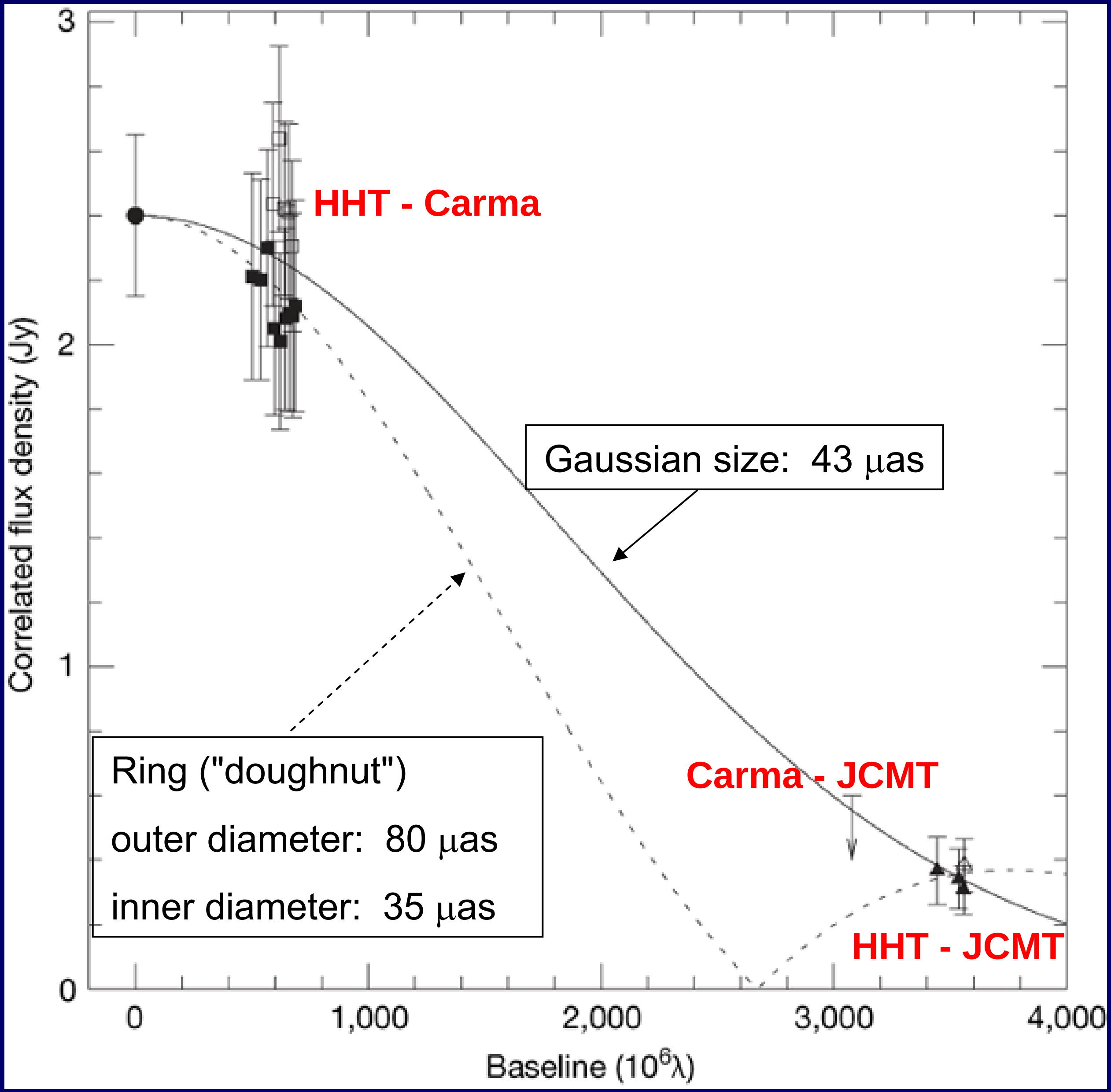
$\theta \leq 16\ \mu as = 0.1\ pc = 1050\ R_S^{9}$ ,

SSA: $B \leq 1$ G $\rightarrow\ \gamma > 600$

| Source | PdBI - PV | HHT - PV |
|---|---|---|
| NRAO150 | 10.7 | |
| 3C120 | 8.2 | |
| 0420-014 | 24.9 | |
| 0736+017 | 7.1 | |
| 0716+714 | 6.8 | 6.4 ? |
| OJ287 | 10.4 | |
| 1055+018 | | |
| 3C273 | 8.2 | |
| 3C279 | 9.6 | |
| NRAO530 | | |
| SgrA* | | |
| 3C345 | | |
| 1633+382 | | |
| 1749+096 | | |
| 2013+370 | | |
| BL Lac | 9.0 | |
| 2145+067 | | |
| CTA102 | | |
| 3C454.3 | | 7.3 |

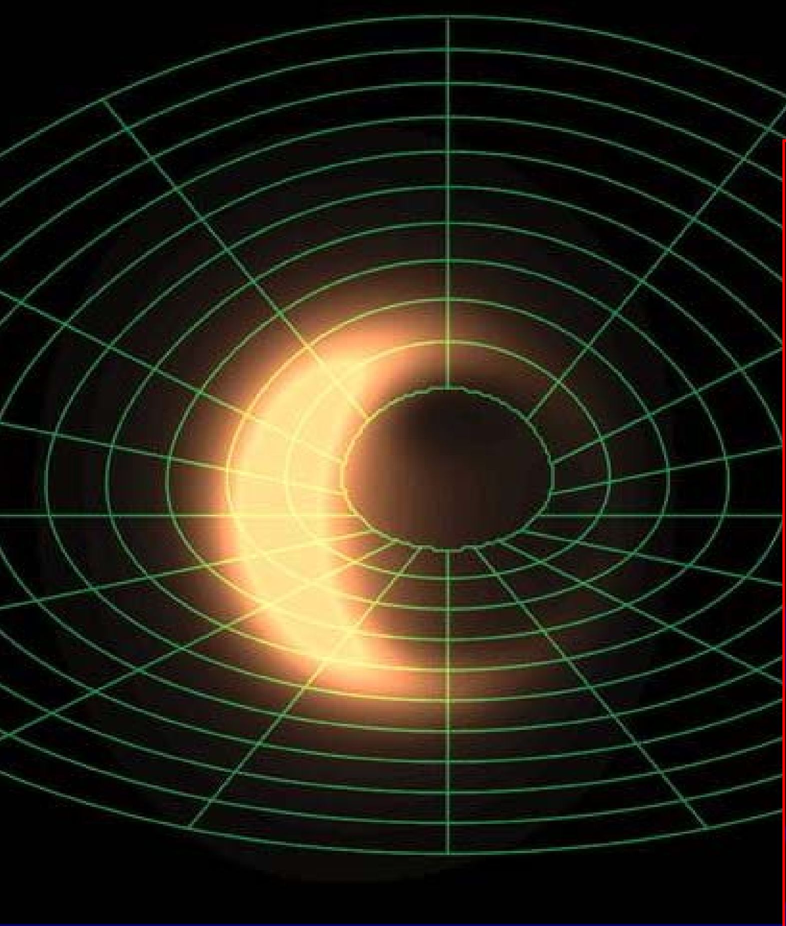

CREATING A BLACK HOLE TELESCOPE
230 GHz VLBI of Sgr A*
10 & 11 April 2007
3.84 Gbit/s (480 MHz)
2: Combined Array for Research in Millimeter wave Astronomy – California
3: Arizona Radio Observatory
1. Submillimeter Array and James Clerk Maxwell Telescope – Hawaii
1
2
3
908 km
4630 km
image: Doeleman et al. 2008

# Fitting the size of SgrA* with 1.3mm wavelength VLBI.

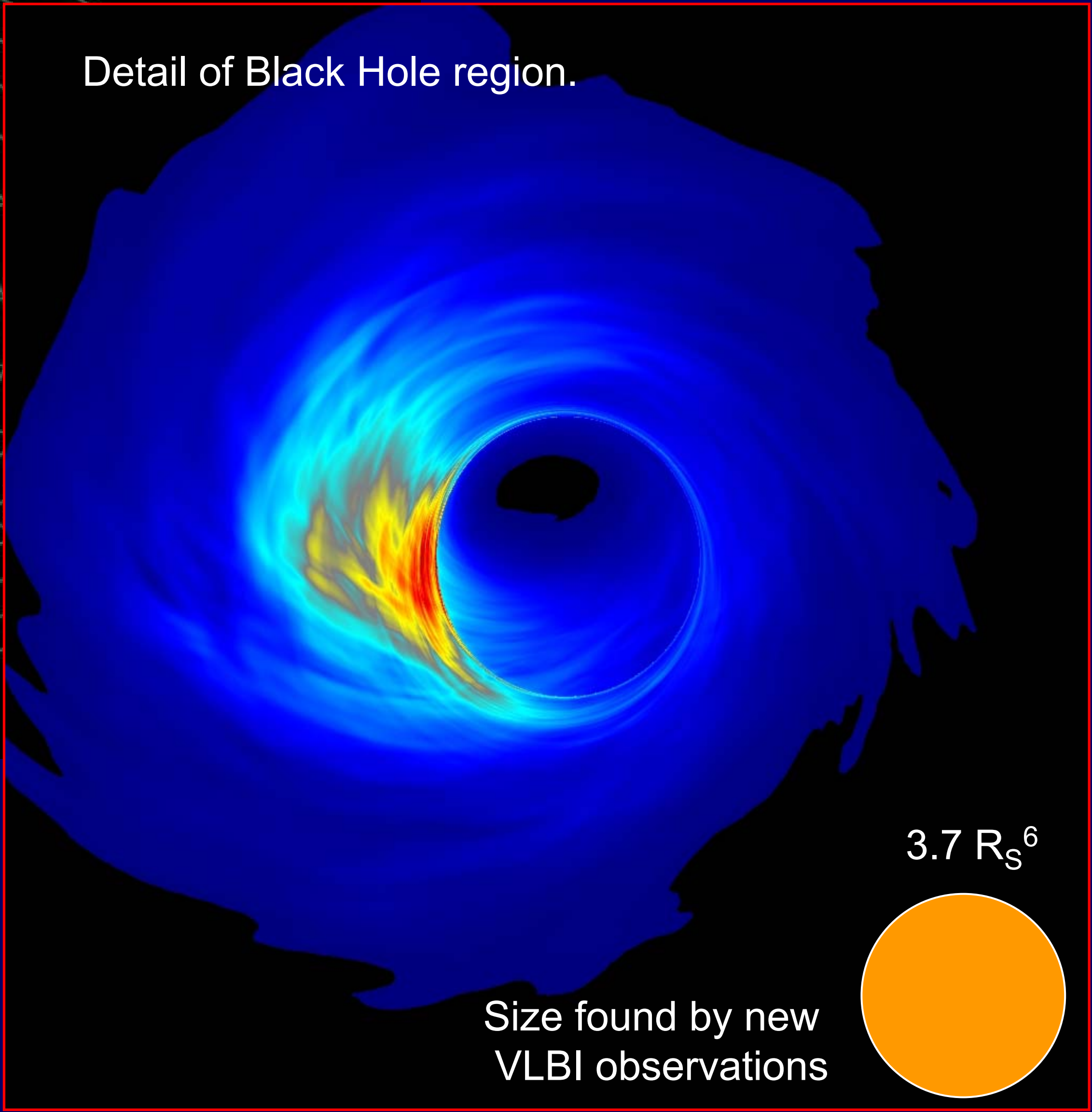



Doeleman et al. 2008, Nature 455, 78-80

# The shadow of the Black Hole in curved Space Time



Credit: Avery Broderick (CITA) & Avi Loeb (CfA)




observed size: 43 μas

deconvolved: 37 μas (3.7 $R_S$[6])

Doeleman *et al. Nature* **455**, 78-80 (2008)

image cedit: S. Noble (Johns Hopkins), C. Gammie (University of Illinois)

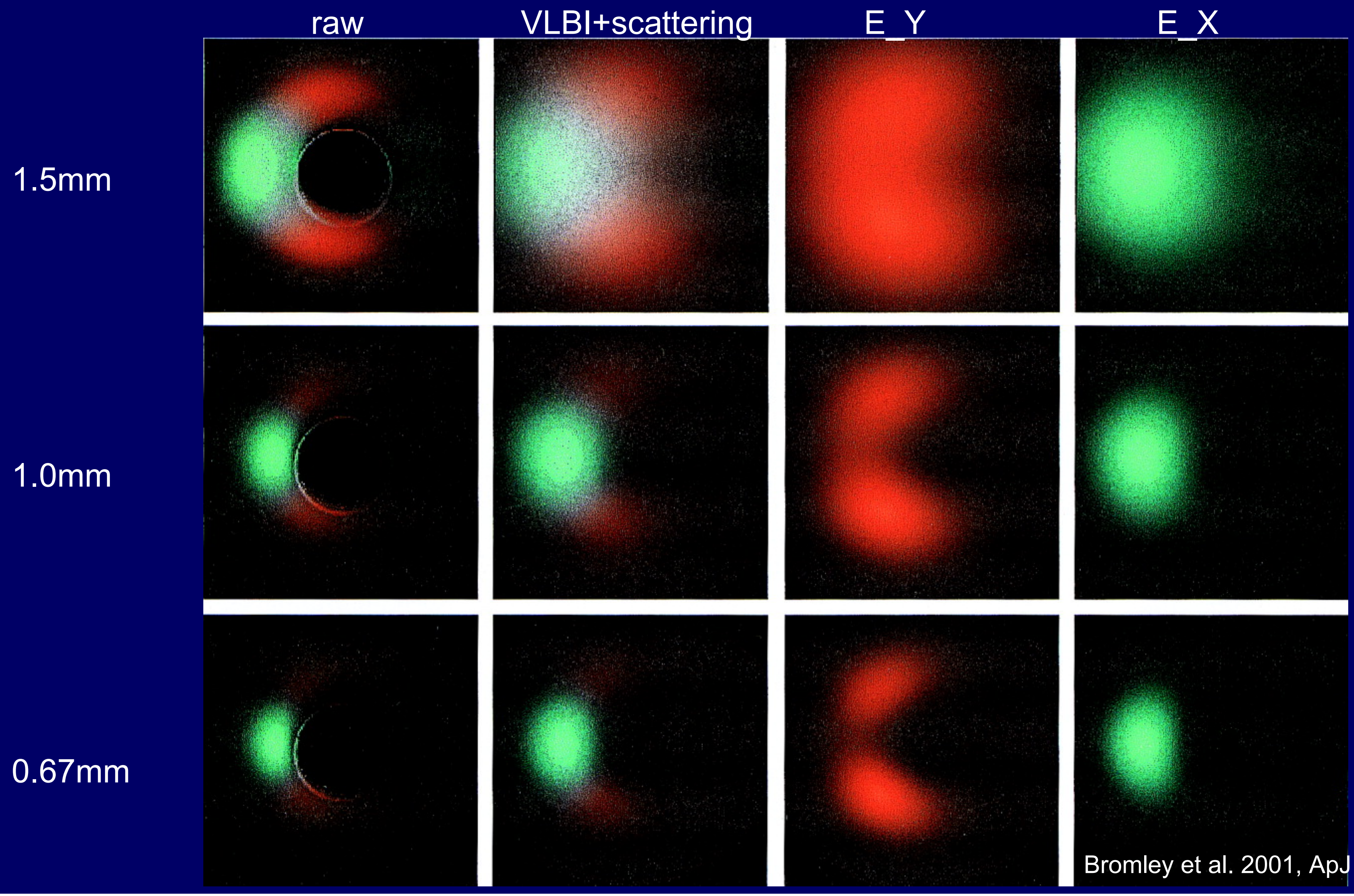
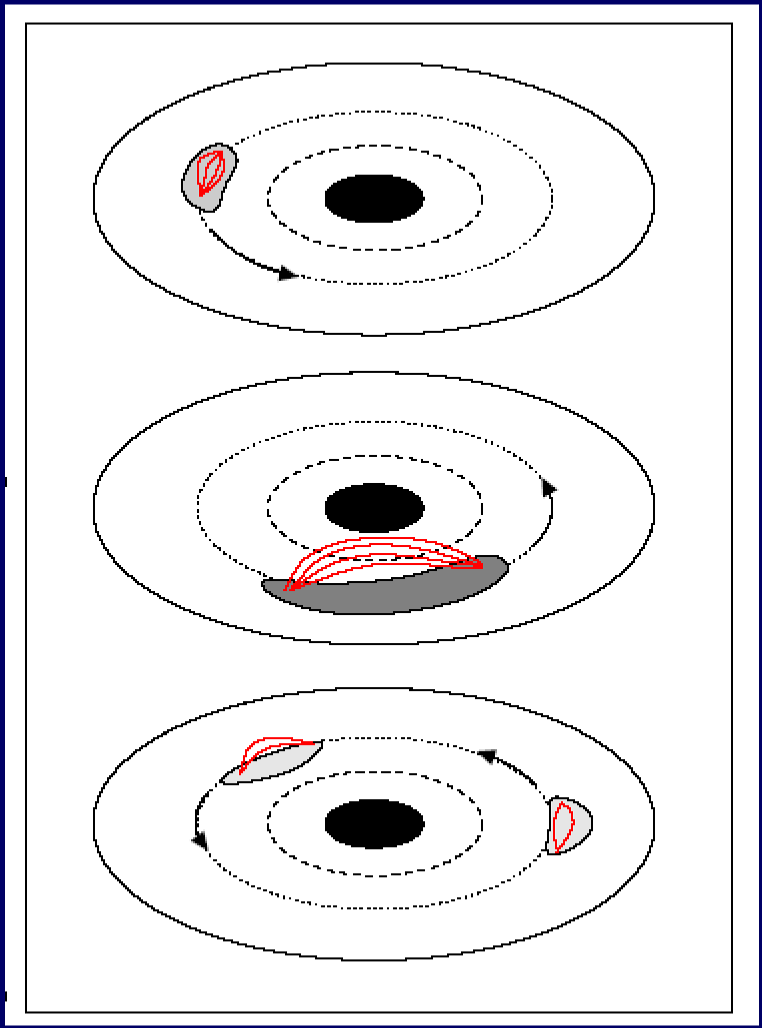
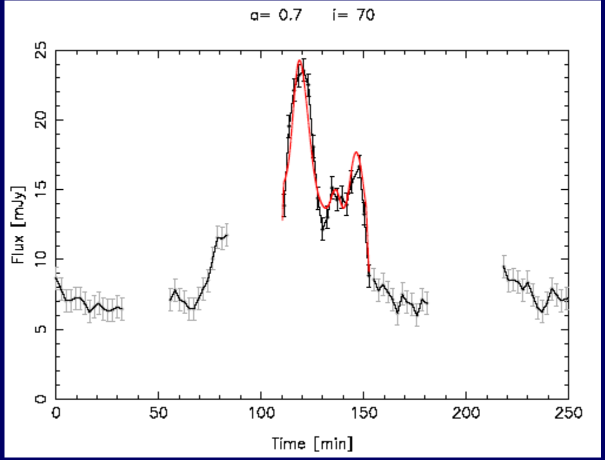



FIG. 2.—Polarization maps at three wavelengths near the peak of the millimeter-to-submillimeter emission from Sgr A*. The top row shows emission at 1.5 mm, the middle row is at 1 mm, and the bottom row corresponds to 0.67 mm. The images in each row show the raw ray-tracing output (*first column on the left*) and an image blurred to account for finite VLBI resolution and interstellar scattering (*second column*). The two rightmost columns give the vertical and horizontal components of the polarized emission. Throughout, red pixels designate vertically polarized light, and cyan corresponds to horizontal polarization. The pixel brightness in all images scales linearly with flux.

# Orbiting hot spot model

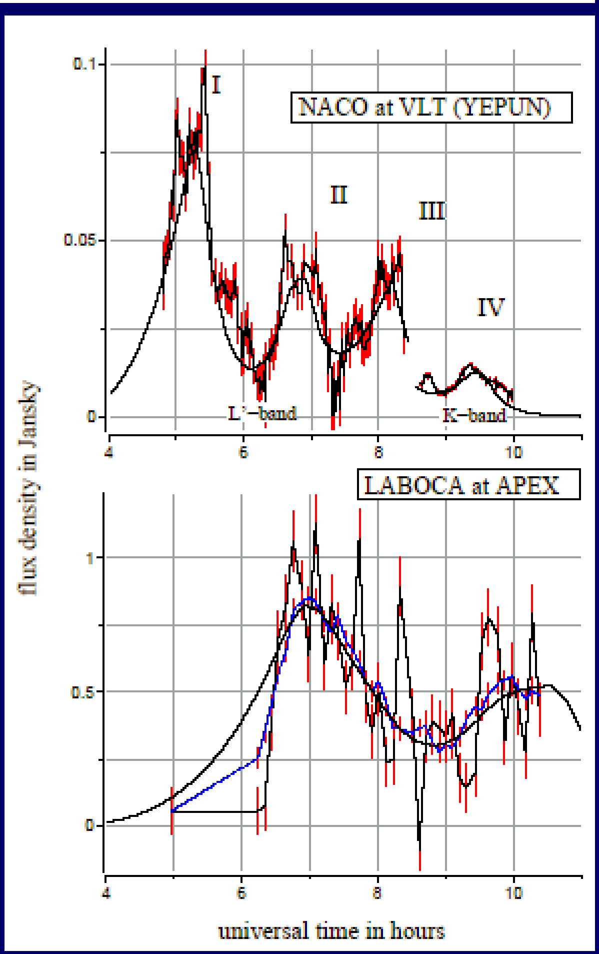





May 15, 2007

infrared

($K_s$ band)




June 3, 2008

infrared

(L' and K band

sub-mm

(345 GHz)

Zamaninasab et al. 2008

Eckart et al. 2008

Eckart et al. 2008b

# Modulation of the closure phase by orbiting hot spots around a rotating BH

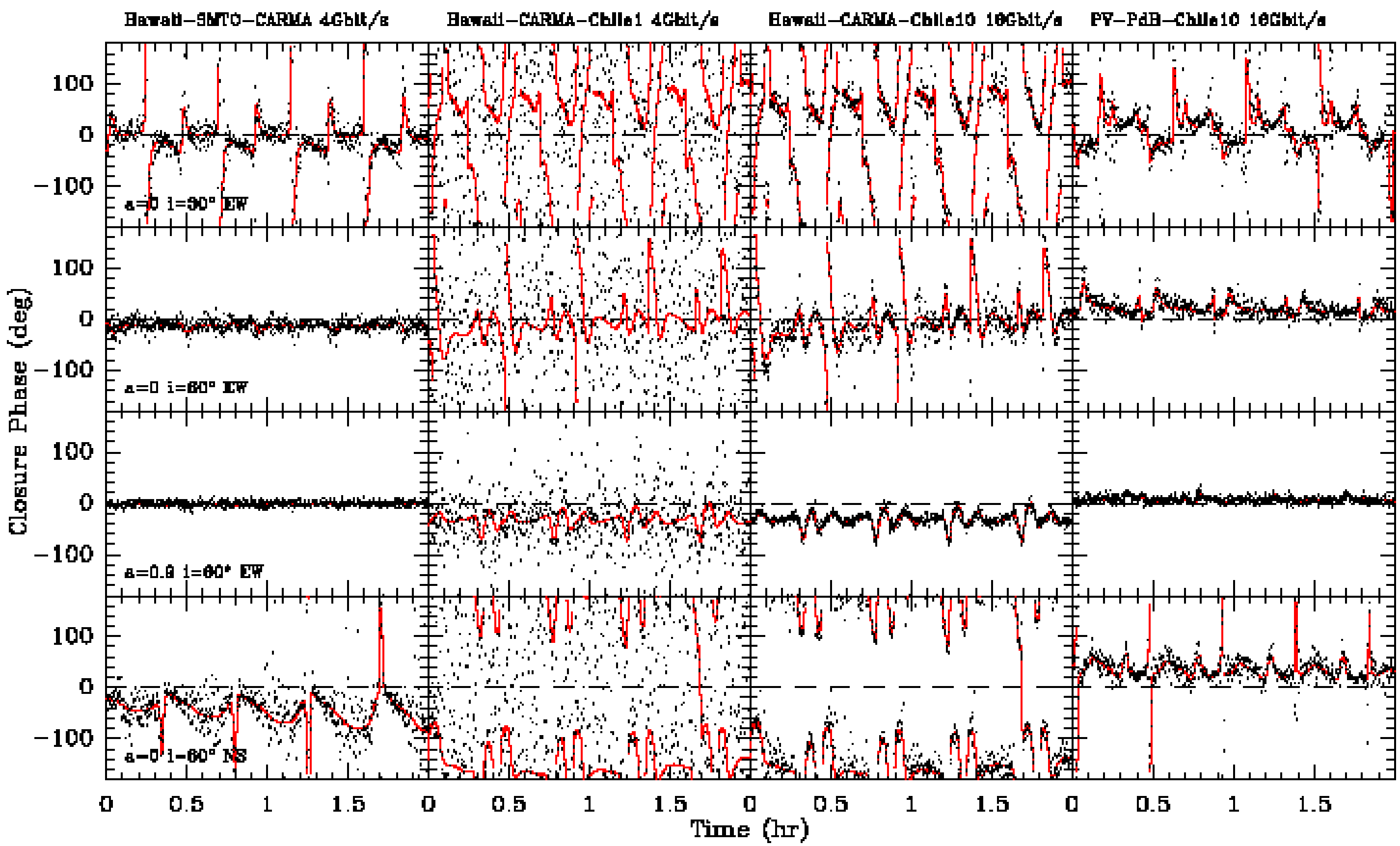



Figure 1: Simulated data at 230 GHz (points), with noiseless models in red. Models are denoted by black hole spin ($a$ = 0 or 0.9 times maximal), inclination of spin axis to line of sight, and projected major axis orientation. The hotspot orbits at the innermost stable circular orbit for $a = 0$ and a comparable radius at $a = 0.9$. Two hours of data, corresponding to 4.5 periods, are shown. The second and third columns illustrate why Chile-10 may be important.

Fish et al. 2008

# mm-VLBI with European telescopes -

## Sensitivity of present and near future antennas (3mm)

| 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 | 90 | 0.22 | 65 | 409 |
| Pico Veleta | Spain | 30 | 90 | 0.14 | 55 | 640 |
| Yebes | Spain | 40 | 120 | 0.18 | 40 | 660 |
| 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+)

# Soon: New 40m OAN-Yebes telescope joins global 3mm-VLBI

$T_{RX}$ ~ 50 K, BW: 600 MHz

dual polarisation

H-maser available

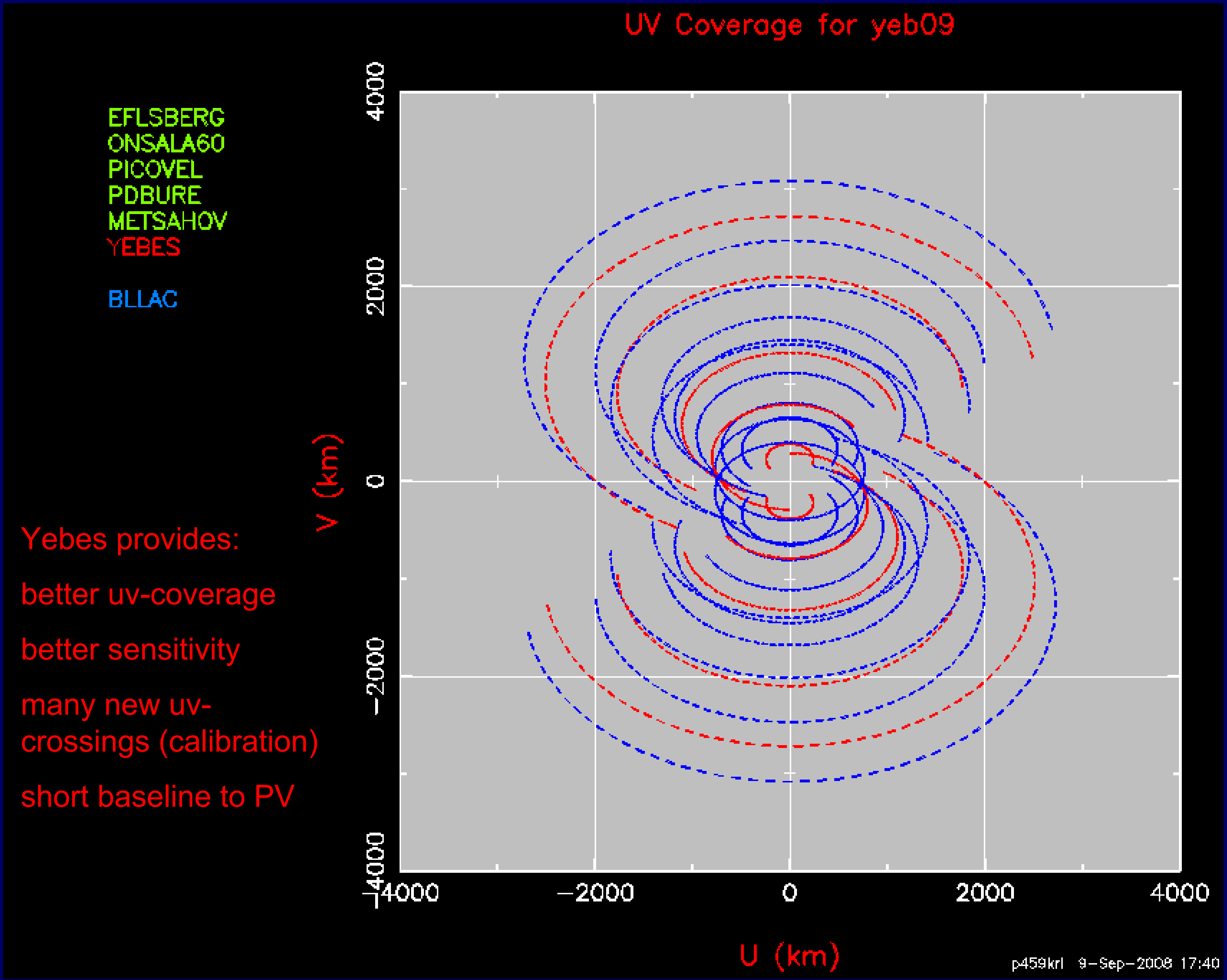
VLBI recording terminal available

K-band fringes in May 2008

mount: ALT/AZ, Nasmyth-Cassegrain focus

surface 150 $\mu$m, aperture efficiency: 0.40-0.45, gain: ~0.2 K/Jy

expected SEFD: ~600 Jy (for comparison PV: 600 Jy)



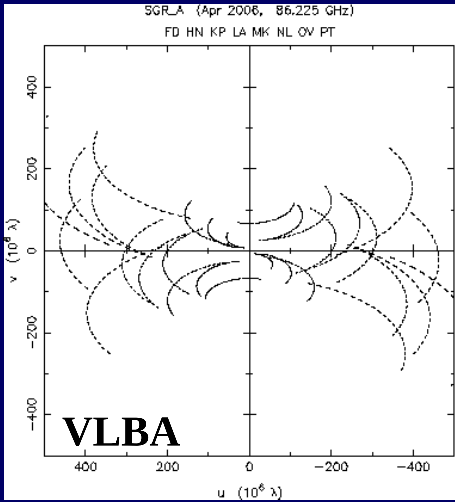

Yebes provides:

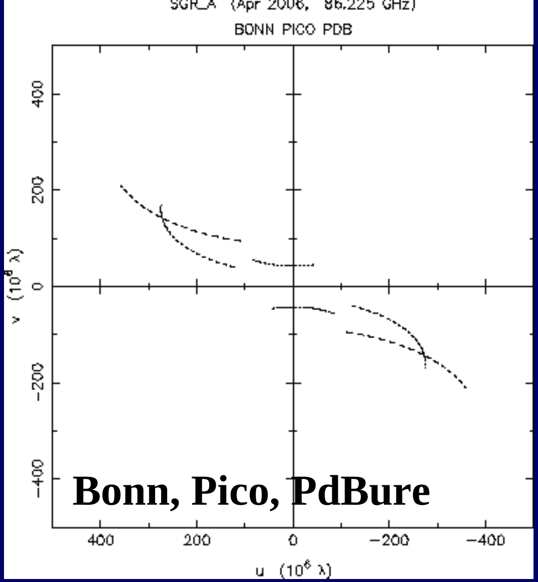
better uv-coverage

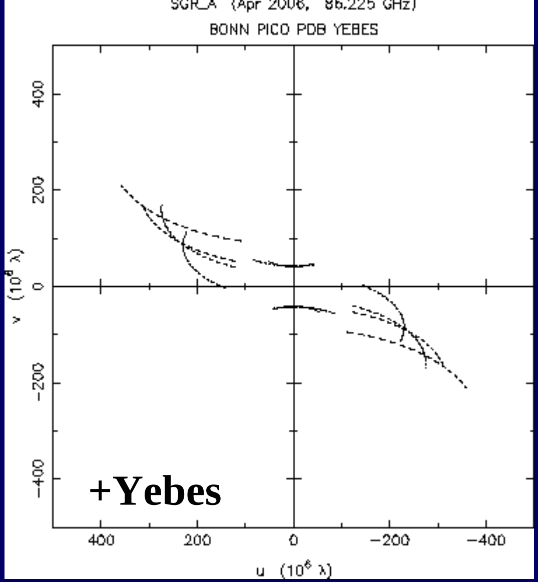
better sensitivity

many new uv-crossings (calibration)

short baseline to PV

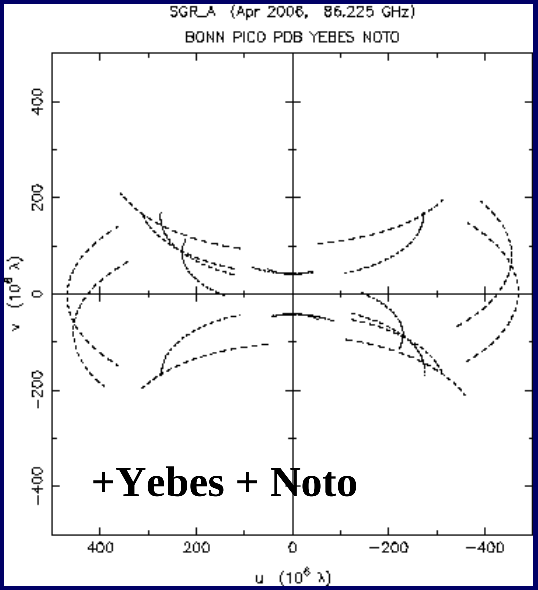


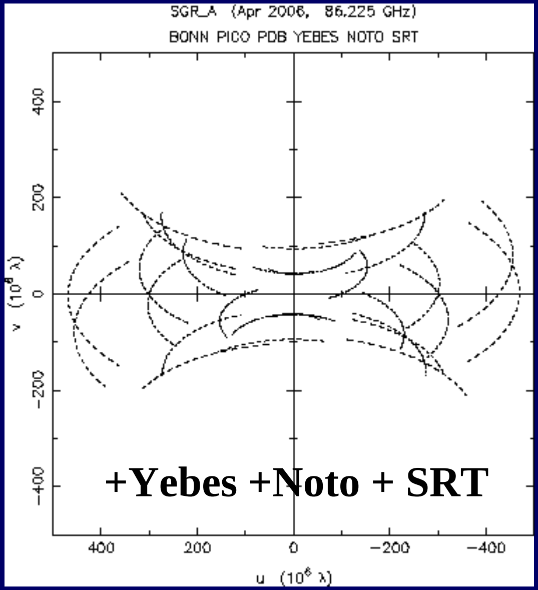




mm-VLBI and flux monitoring of Sgr A*:

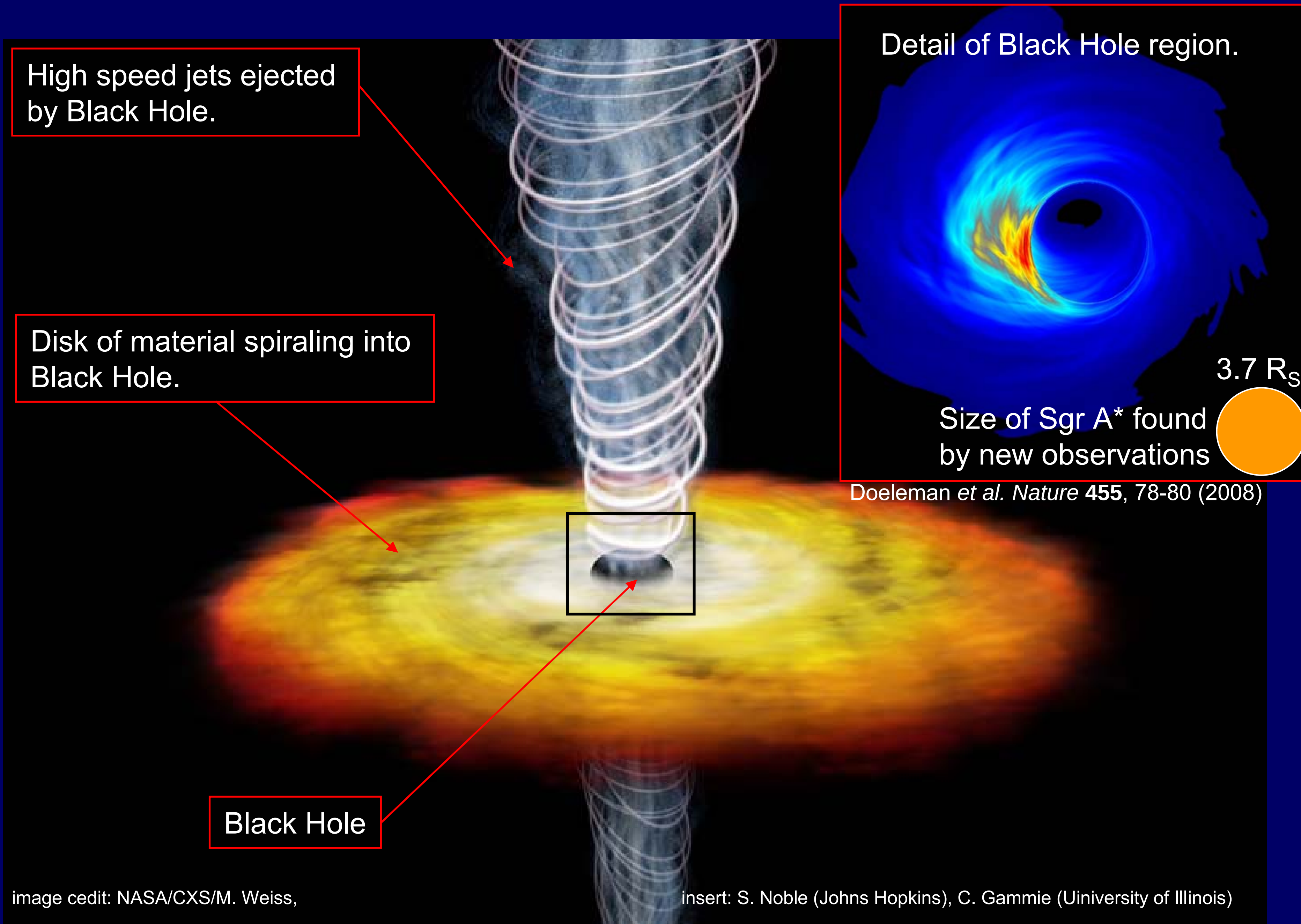
need to improve the uv-coverage and sensitivity in Europe at 43/86 GHz !




Noto, Yebes and the SRT will dramtically improve the image quality at 3mm !

# mm-VLBI: Probing the edge of Black Holes




Doeleman *et al. Nature* **455**, 78-80 (2008)

image cedit: NASA/CXS/M. Weiss, insert: S. Noble (Johns Hopkins), C. Gammie (Uiniversity of Illinois)

# Conclusions

- The Global 3mm VLBI Array (GMVA) provides up to 40 μas resolution and 50 – 300 mJy baseline sensitivity and 2.3 mJy/hr for mapping → *Just USE IT !*
- recent improvements on station performance (PdB) and recording technology (MK5, ≥1Gbit/s) allow to survey hundreds of AGN (aim: source statistics, jet formation, etc.)
- mm-VLBI is ideally suited to image AGN in their earliest evolutionary stages and after major flares (radio to TeV). More frequent observations are required to study the kinematics.
- At 3mm, nearby SMBHs (M87, SgrA*) can be imaged with unsurpassed spatial resolution of a few 10 Schwarzschild radii (M87 has a jet, SgrA* not).
- The small observing beam of mm-VLBI is ideal to study jet curvature, jet precession, counter-jets and transverse resolution effects (e.g. 3C345, NRAO150, M87, Cygnus A).
- SgrA* is smaller than 3.7±1.5 $R_S$; need global 1mm VLBI with transcontinental baselines (PV- PdB, + HHT, SMA, CARMA, APEX, ALMA,...) to image GR effects near a SMBH.
- Global VLBI at 2mm & 1.3mm is now technical feasible. The increase of observing bandwith (4 Gbit/s at present), will lower the detection threshold to < 100 mJy, allowing to image many compact sources with micro-arcseconds resolution at $\nu = \nu_{Rest}$ (1+z) !
- A mm-VLBI AGN monitoring is needed in support of satellite missions like GLAST, Herschel and Planck.
- The combination of global 3mm VLBI with VSOP2 at 7mm gives matching beams.

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

- enlarge the number of mm-stations, improve the uv-coverage and collecting area of the existing arrays; 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 + GBT+ expandedEVN (Yebes, Noto, SRT, ....)
at 3 mm – GMVA + Apex + CARMA + GBT, LMT, ..., ALMA
at 1 mm – PdB/PV + HHT + JCMT/SMA + CARMA + APEX, ..., ALMA

- equip more stations with modern (MMIC, HEMT) receivers operating at mm-bands (32?, 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 (absorption line vlbi)

- 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)

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

- perform mm-VLBI observations more frequently (at least 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, need 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 a mm-antenna on the southern hemisphere mm-antenna, preferably at European longitudes (i.e. in North or South Africa), a southern mm-antenna is also usefull to better uv-connect ALMA with Europe.
- involve East Asia (Korea, China, Japan)