# The Global 3mm VLBI Array

## mm-VLBI: Present status & future perspectives

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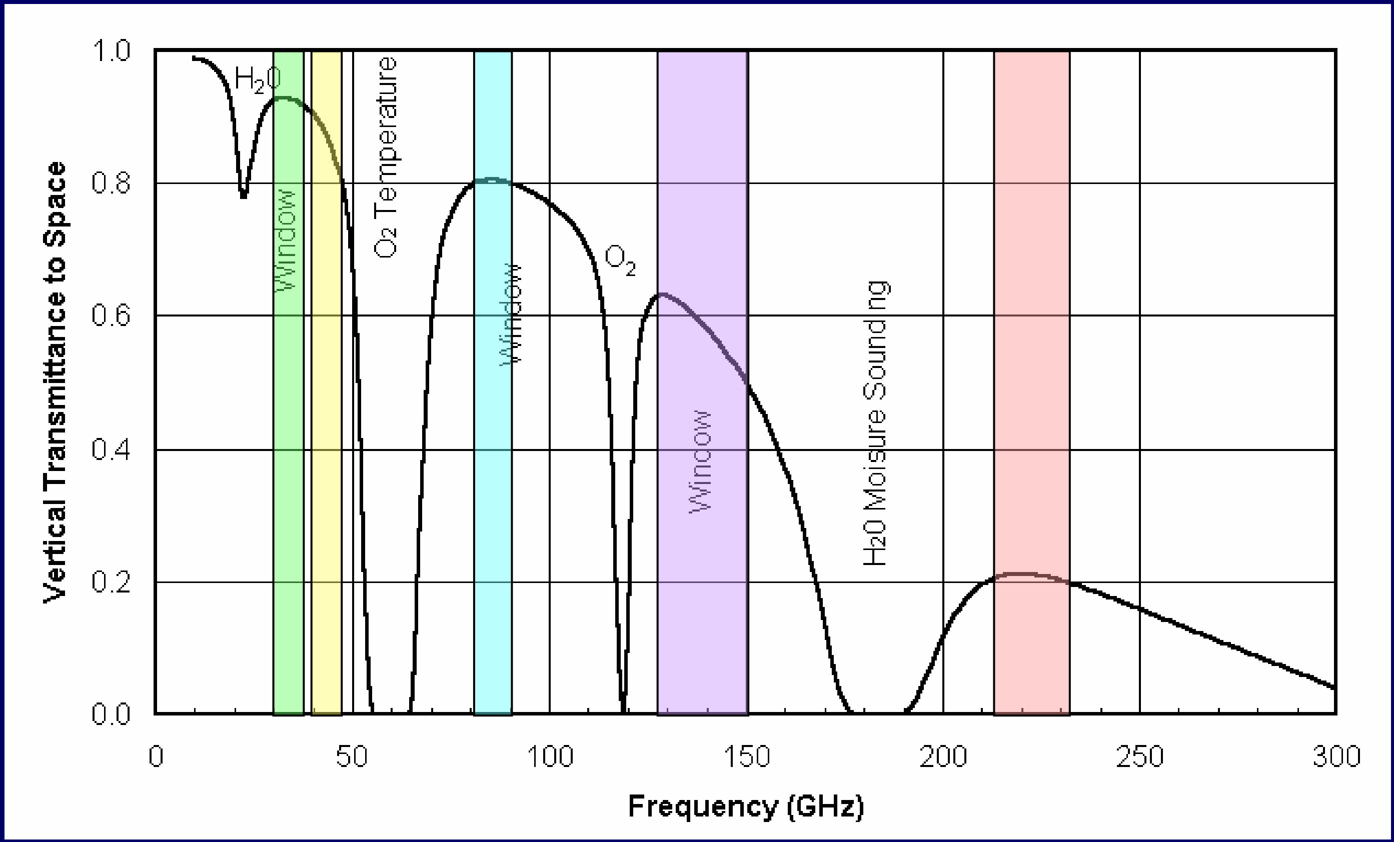
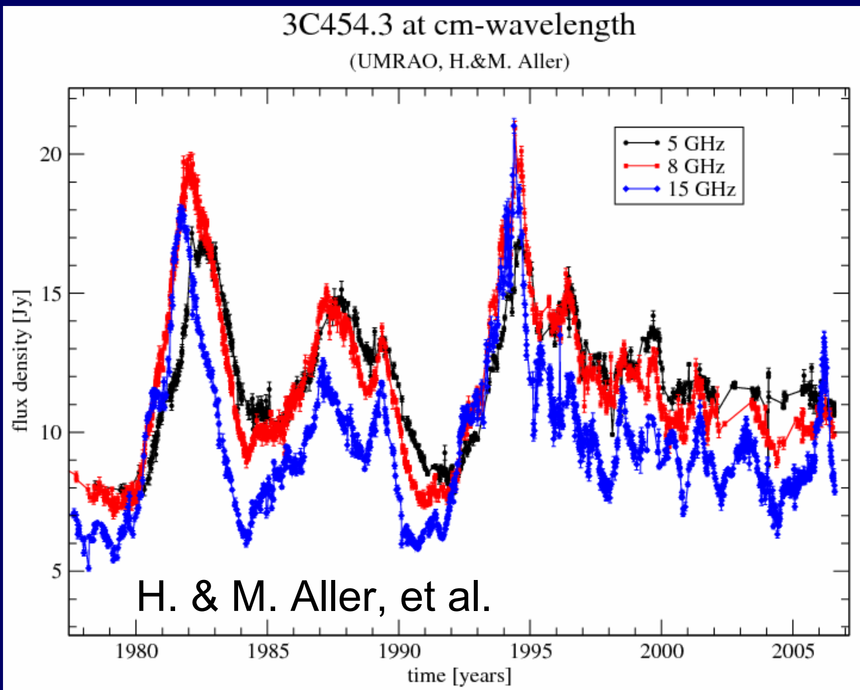
Students: Want to work on mm-VLBI ? send me an e-mail, or look at:
http://www.mpifr.de/IMPRS
http://www.mpifr.de/pdf/PhD_projects.pdf

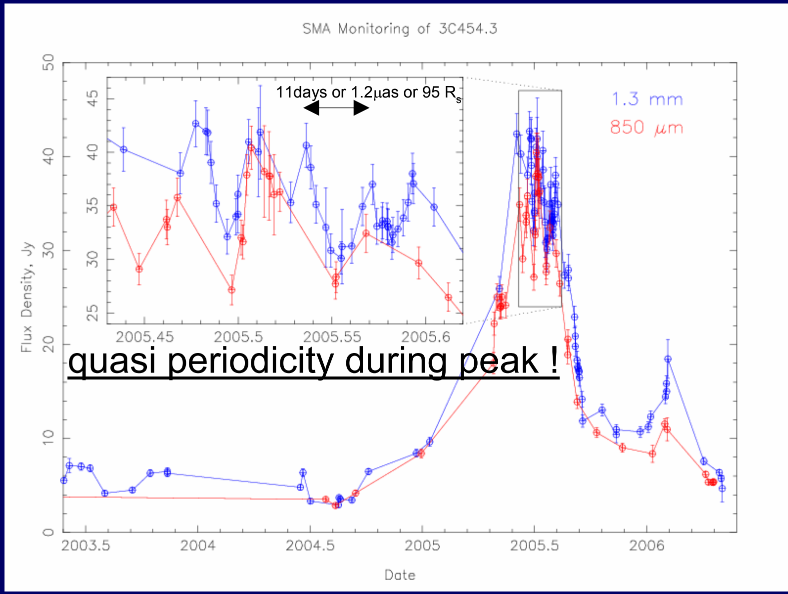



atmospheric windows support high frequency VLBI at the following bands:

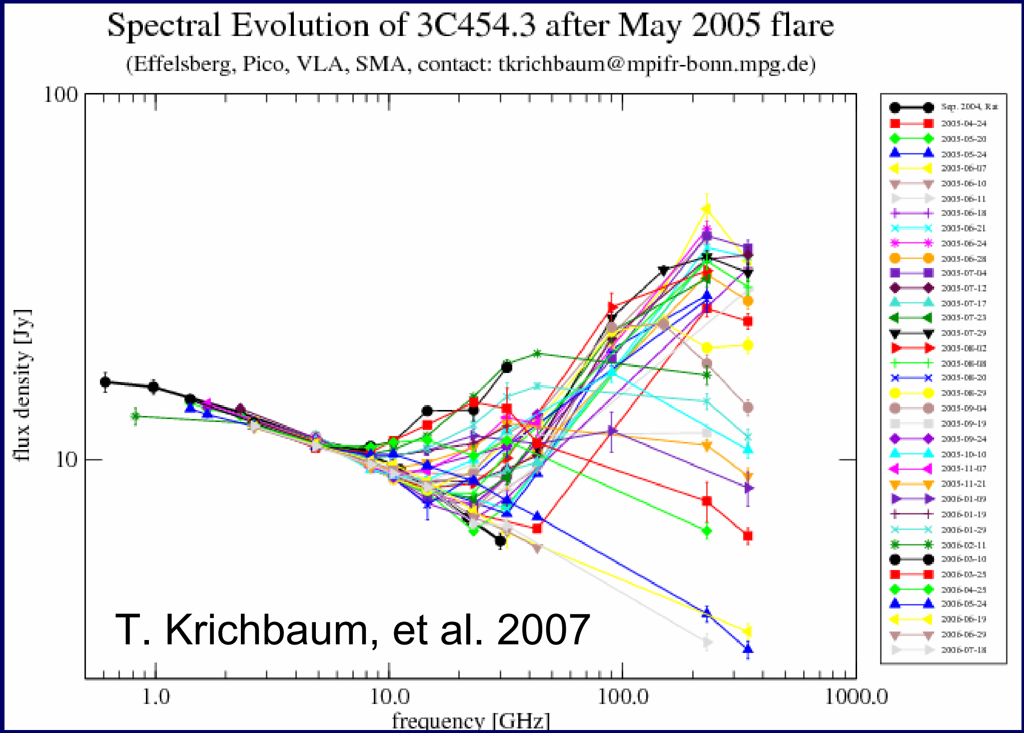
- 32-35 GHz — in principle possible, but no VLBI receivers at EVN, VLBA
- 43 GHz (SiO) — frequently done (VLBA, EVN+VLBA)
- 86 GHz (SiO) — frequently done (GMVA, VLBA)
- 129/150 GHz — pilot studies, fringes detected, both for continuum & spectral lines
- 215/230 GHz — pilot studies, few sources detected at 20 $\mu$as resolution

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




SMA data: M. Gurwell et al.




Effelsberg: 1.4 – 43 GHz

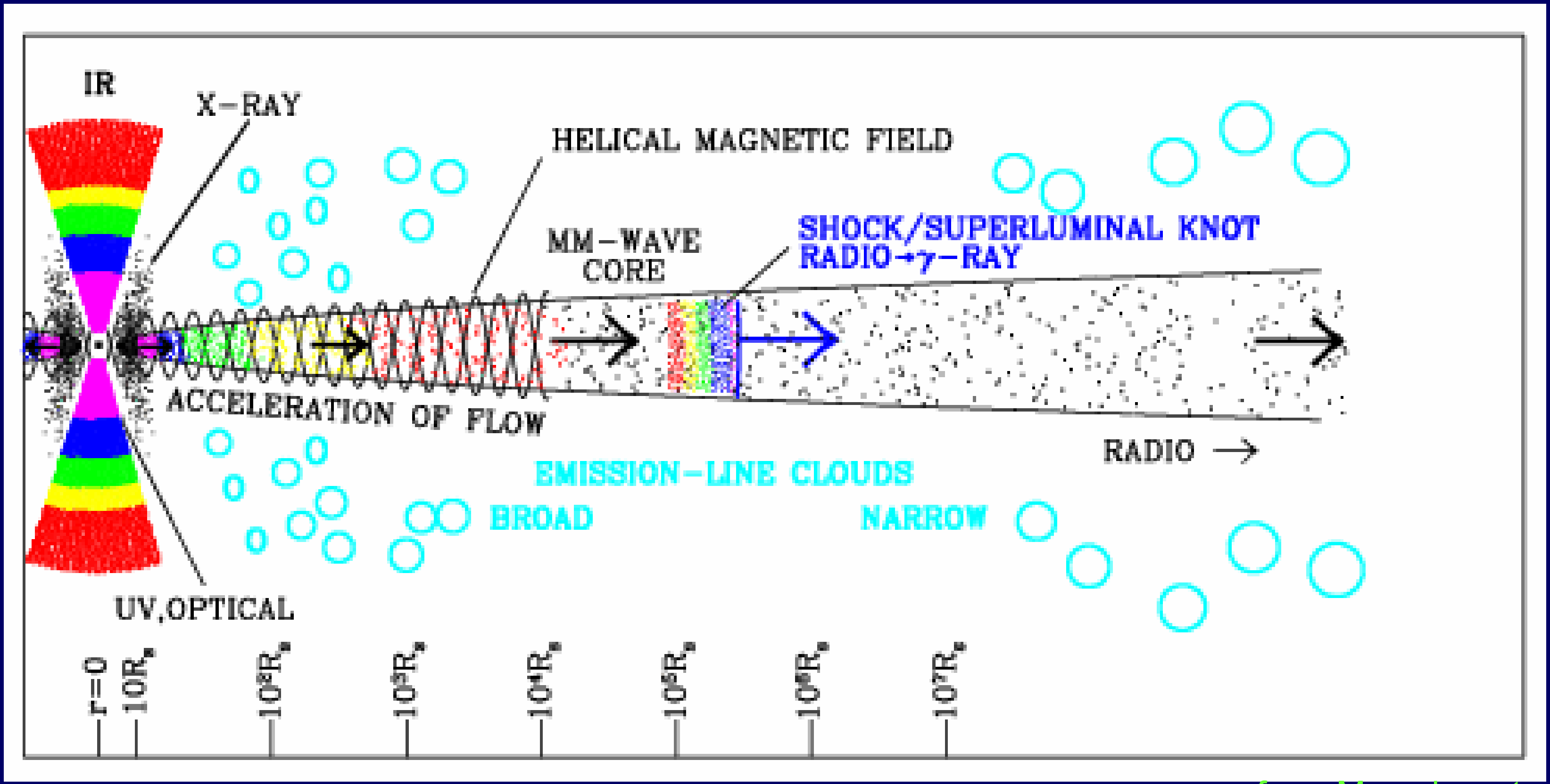
Pico Veleta: 90 – 230 GHz

SMA: 230, 350 GHz

combined data:

Krichbaum, Ungerechts, Wiesemeyer, Gurwell et al.

# Motivation: The simple jet model



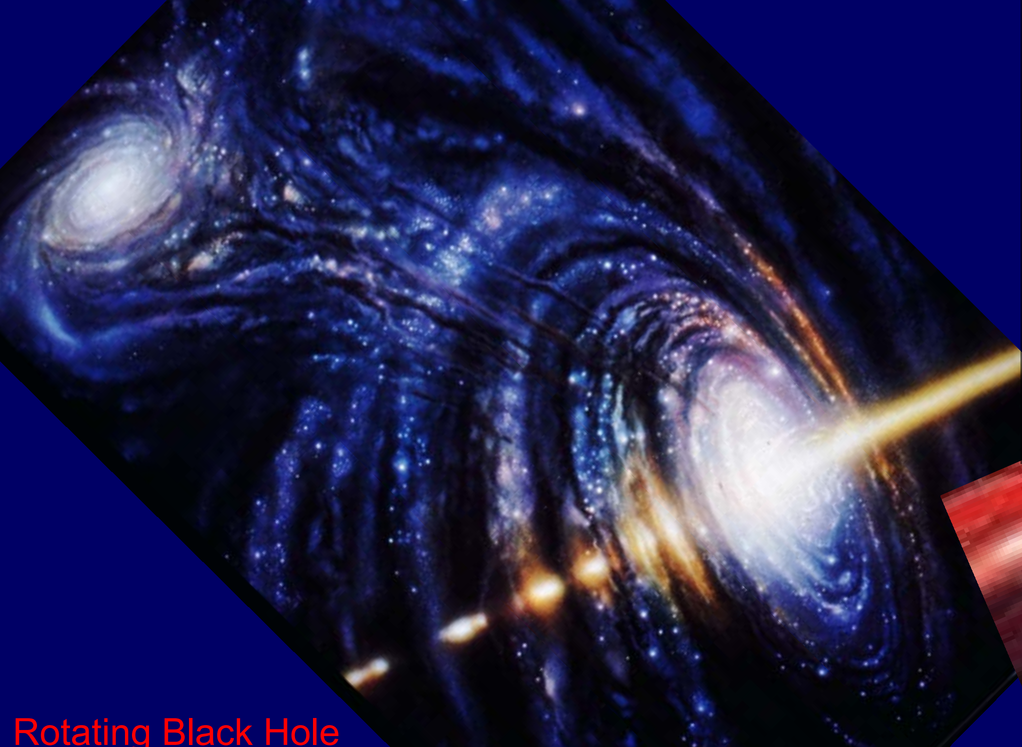

from Marscher et al.

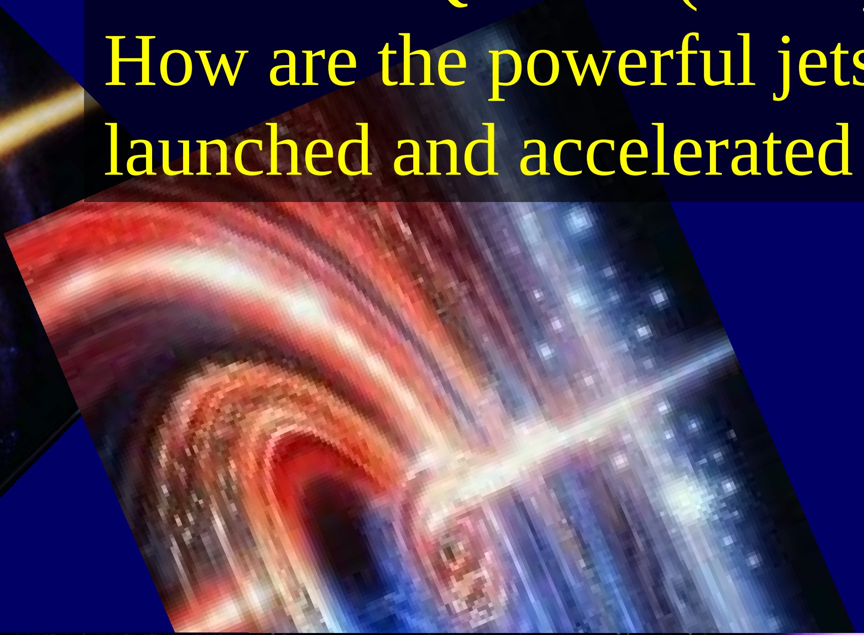
angular resolution: ~ wavelength / antenna separation = $\lambda$ / D

decrease $\lambda$ : mm-VLBI

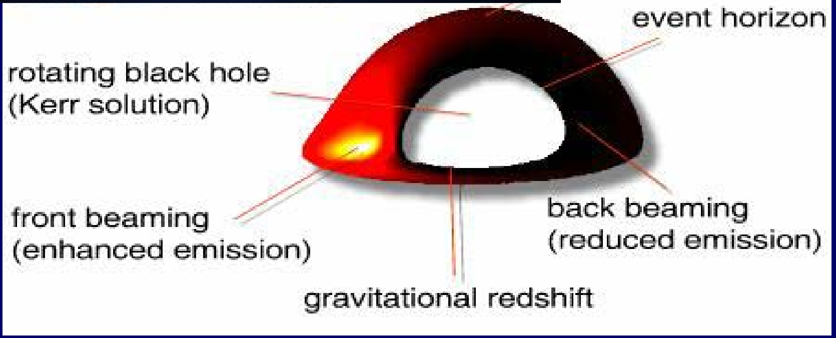
increase D : space-VLBI

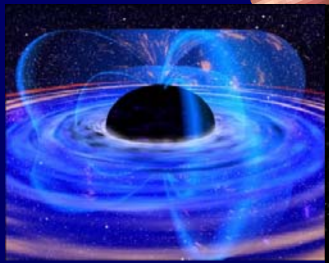
# Main Motivation: What are the processes acting at the centers of Quasars (AGN) ? How are the powerful jets launched and accelerated ?



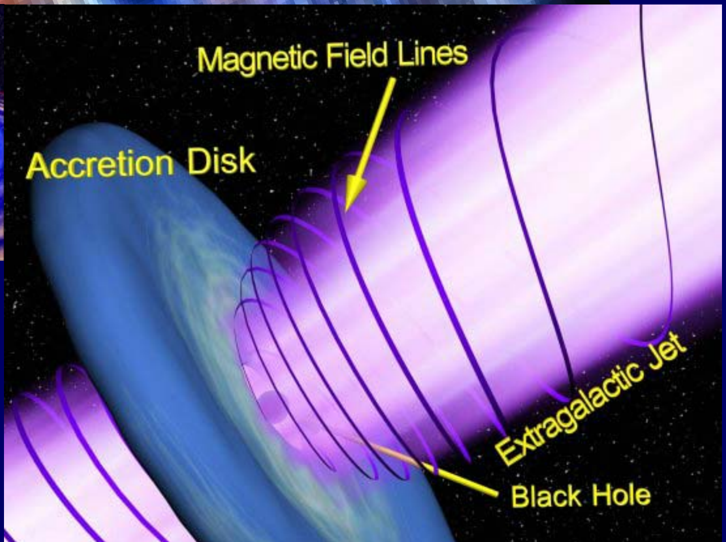


Rotating Black Hole

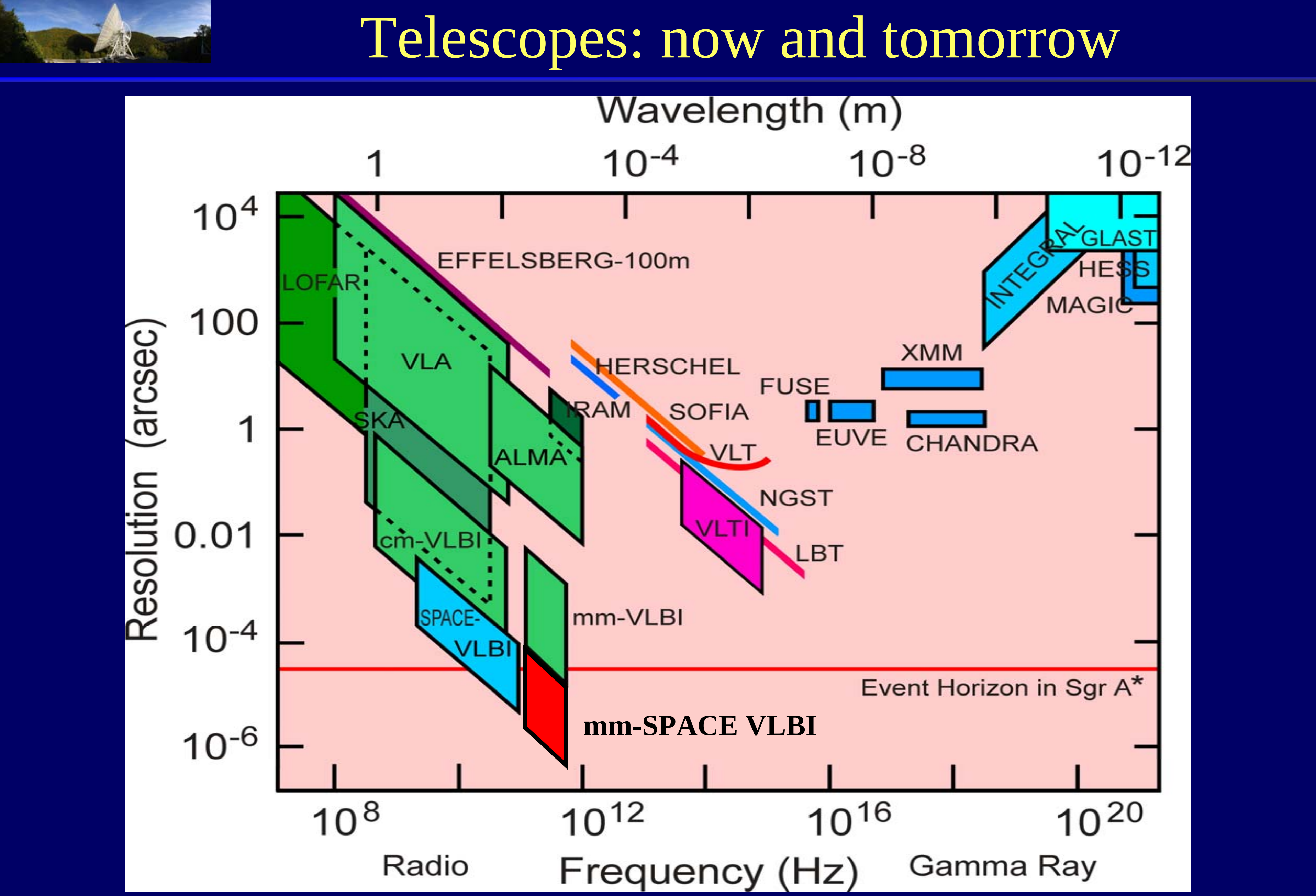


The Black Hole Dynamo



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

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

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

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

→ if ALMA is added one can image virtually all AGN with S > few mJy

# The Global Millimeter VLBI Array – VLBI Imaging at 86 GHz with ~40 $\mu$as resolution

Baseline Sensitivity

in Europe:

50 – 300 mJy

in US (VLBA):

250 – 350 mJy

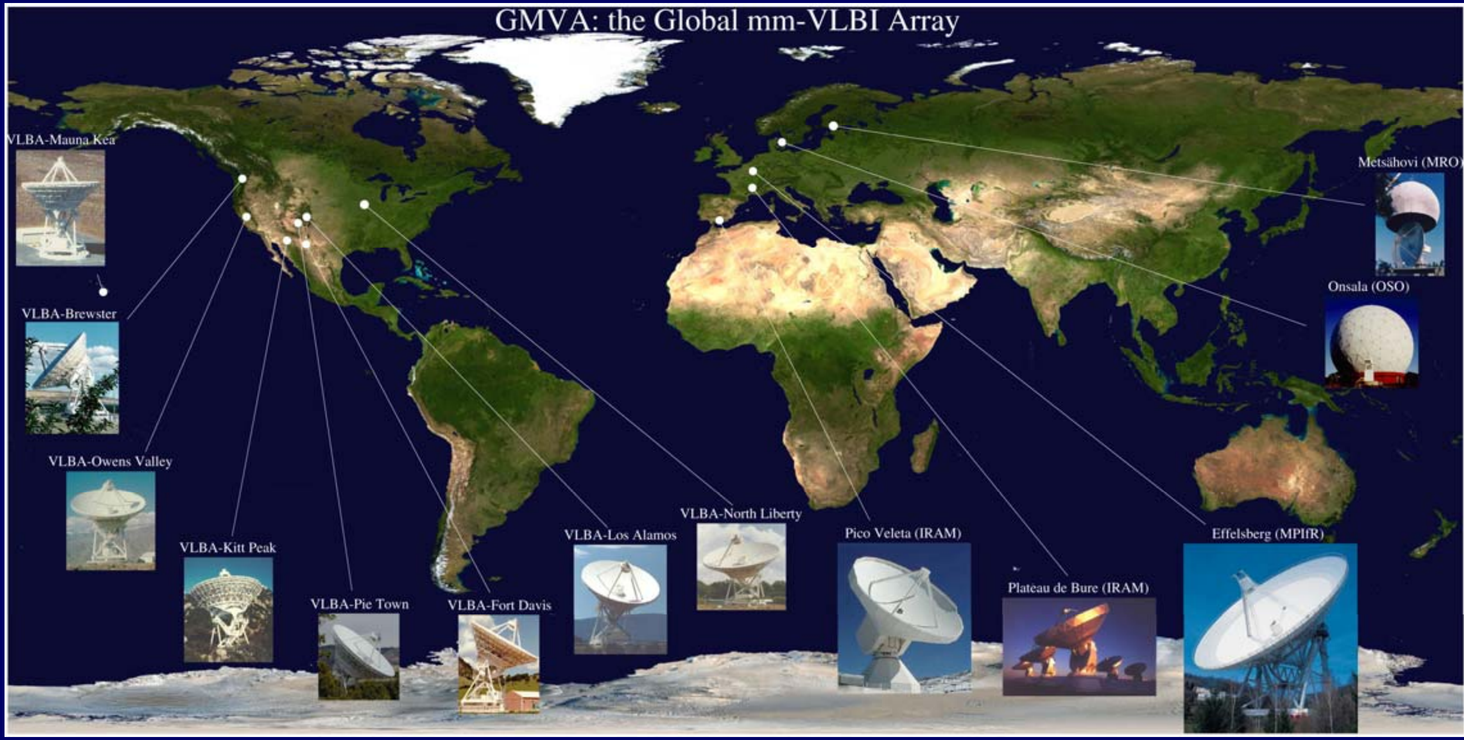
transatlantic:

80 – 350 mJy

Array:

2 – 4 mJy / hr

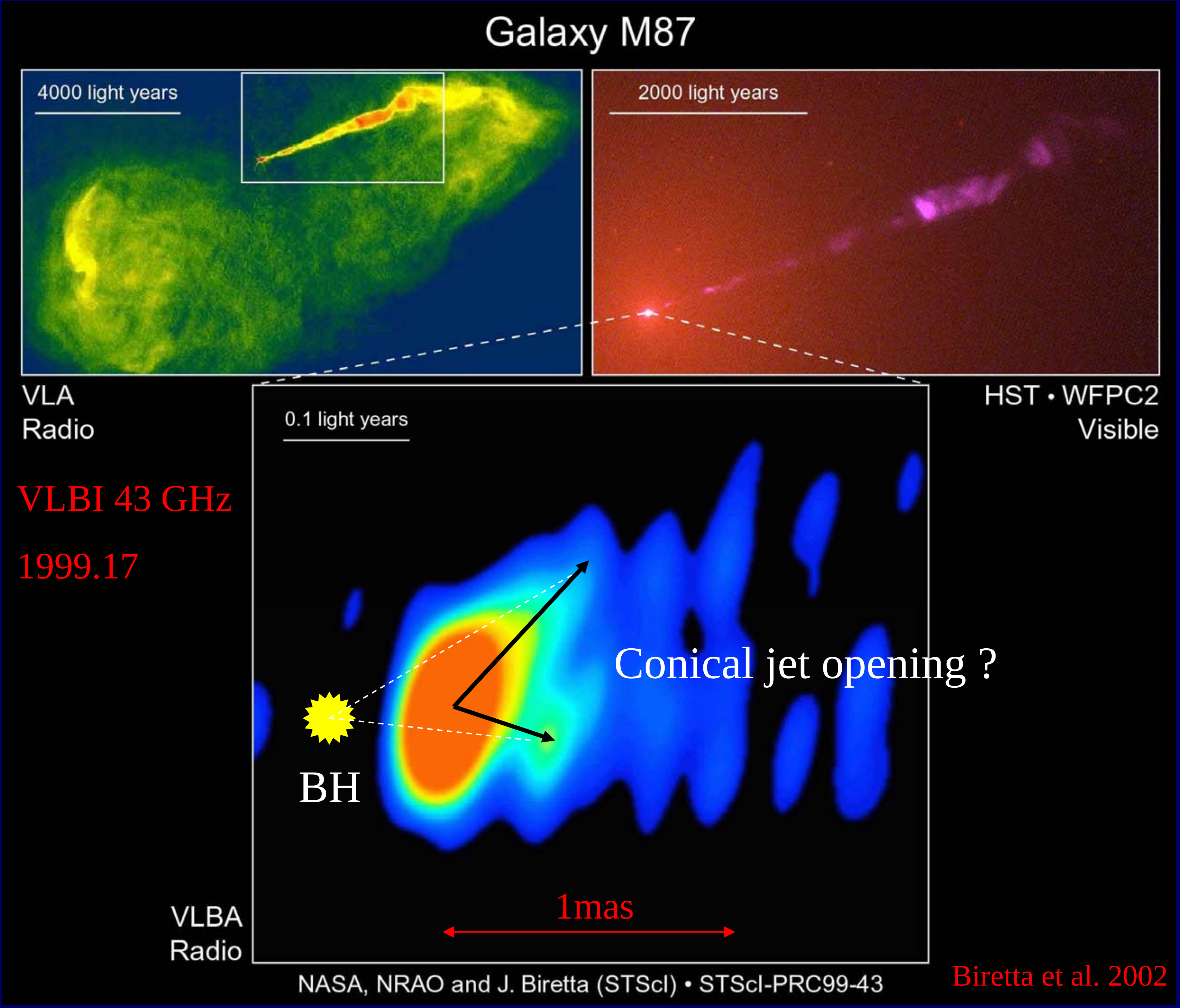
(assume $7\sigma$, 100sec, 512 Mbps)




http://www.mpifr.de/div/vlbi/globalmm

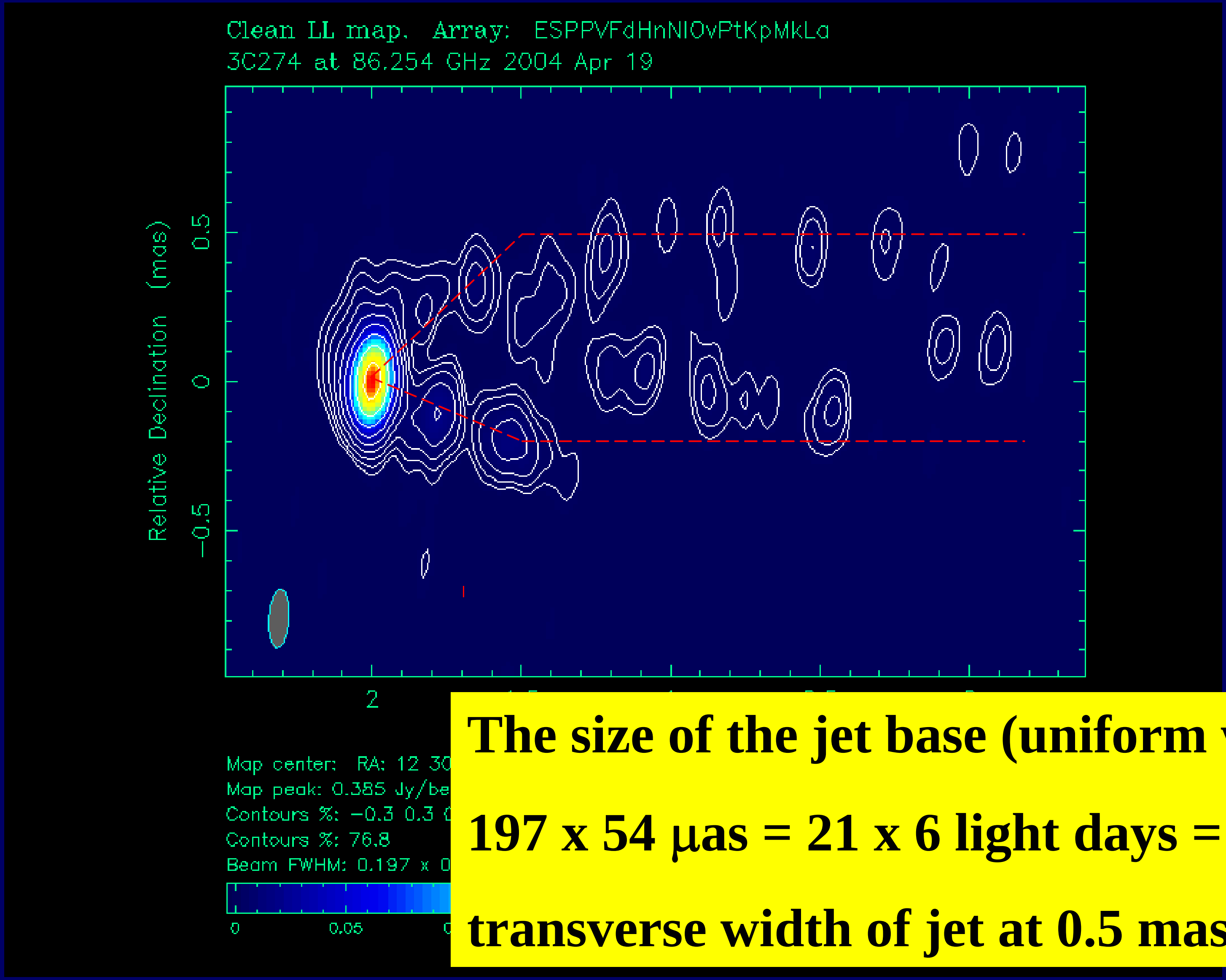
- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m)
- USA: 8 x VLBA (25m)

Proposal deadlines: February $1^{st}$, October $1^{st}$



Galaxy M87
4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
VLBI 43 GHz
1999.17
0.1 light years
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

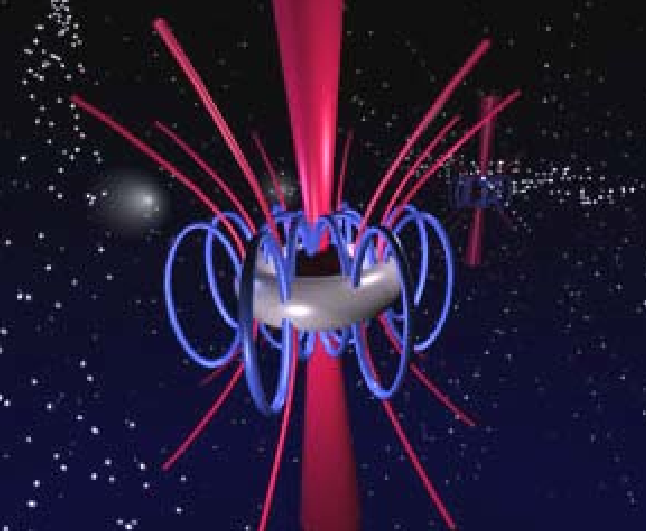
**The size of the jet base (uniform weighting):**

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

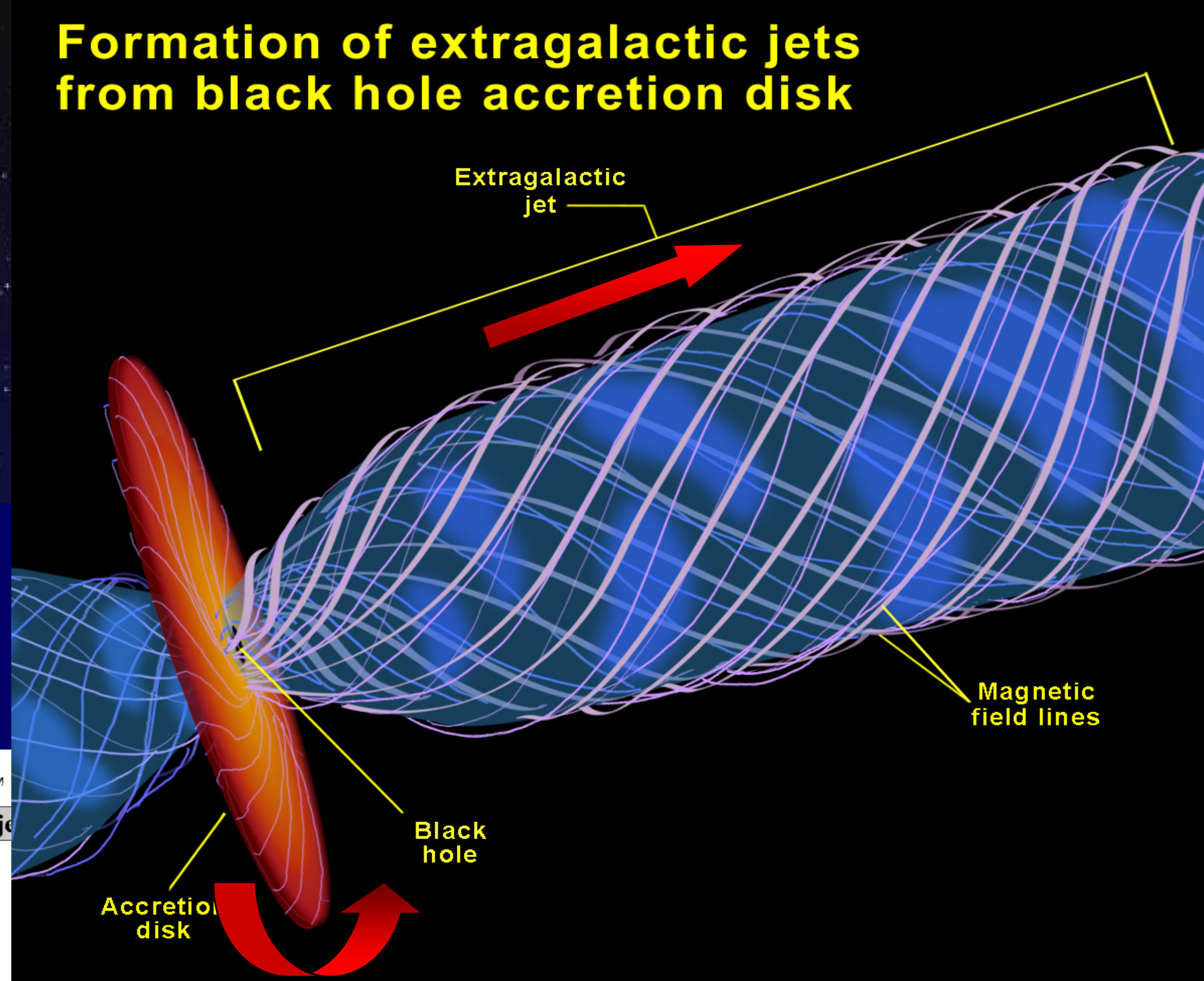
**transverse width of jet at 0.5 mas: ~174 $R_s$**

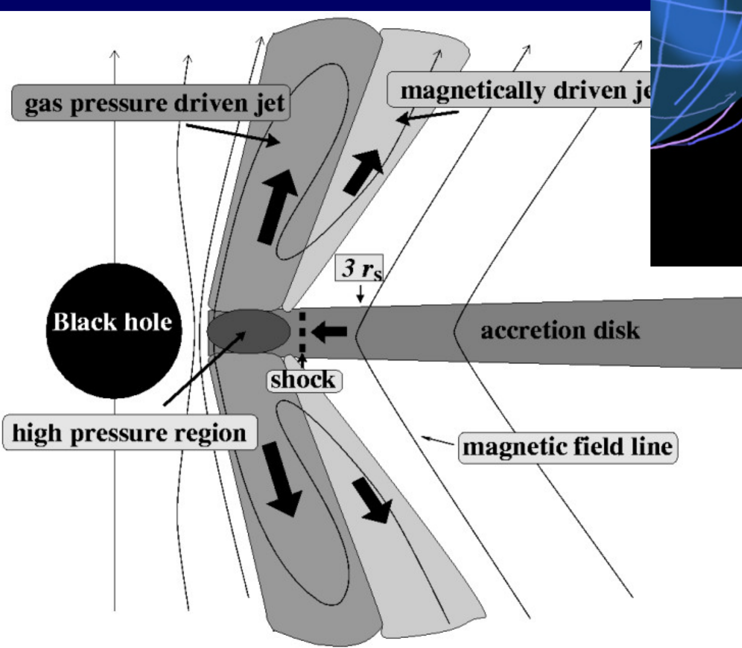
new global 3mm map of M87 observed with the GMVA in April 2004:

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

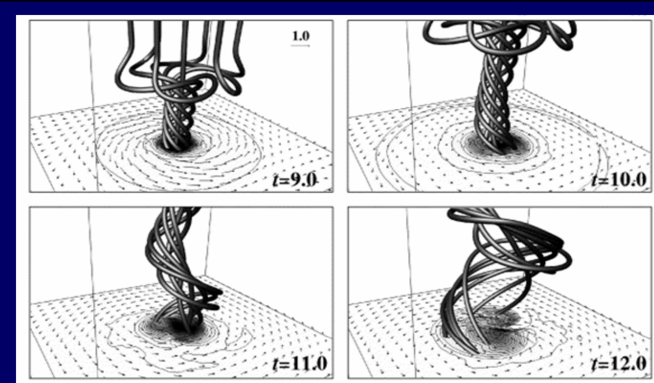


The central engine – a MHD dynamo ?



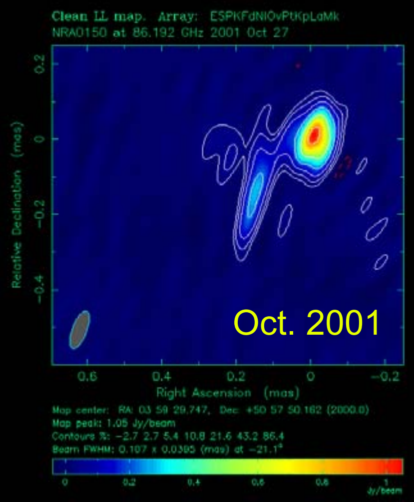



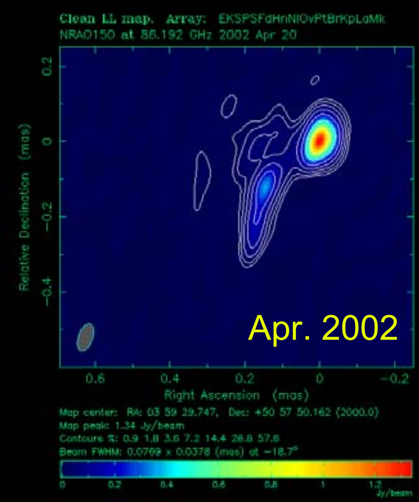

MHD simulation of a confining B-field anchored in a rotating disk

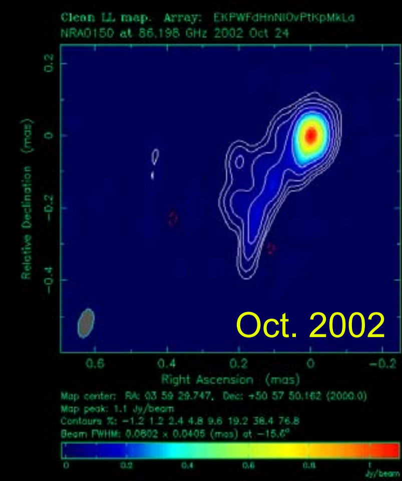


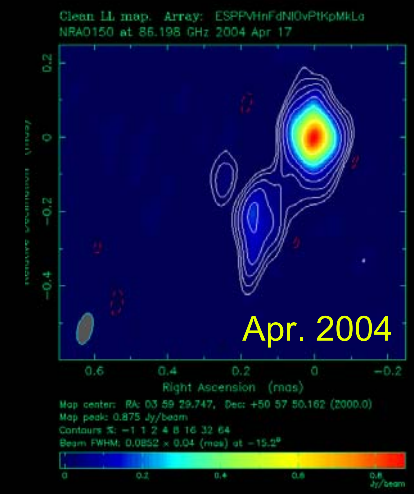
# The swinging jet of NRAO150: sub-mas scales

3 mm-VLBI images GMVA and CMVA

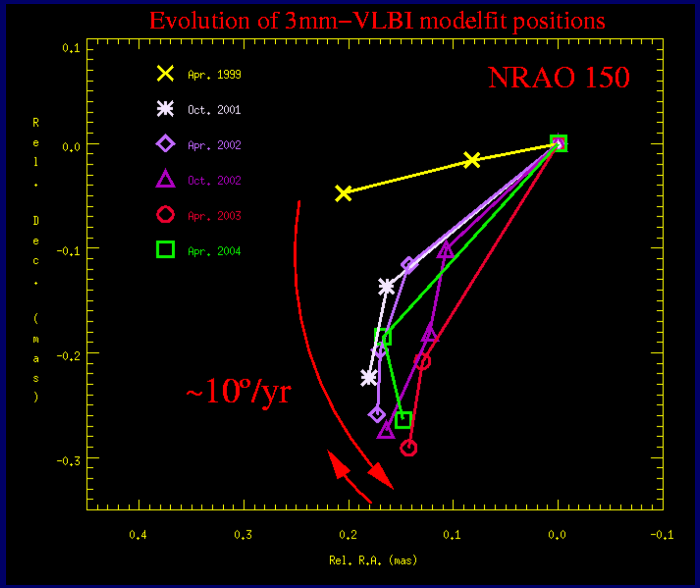


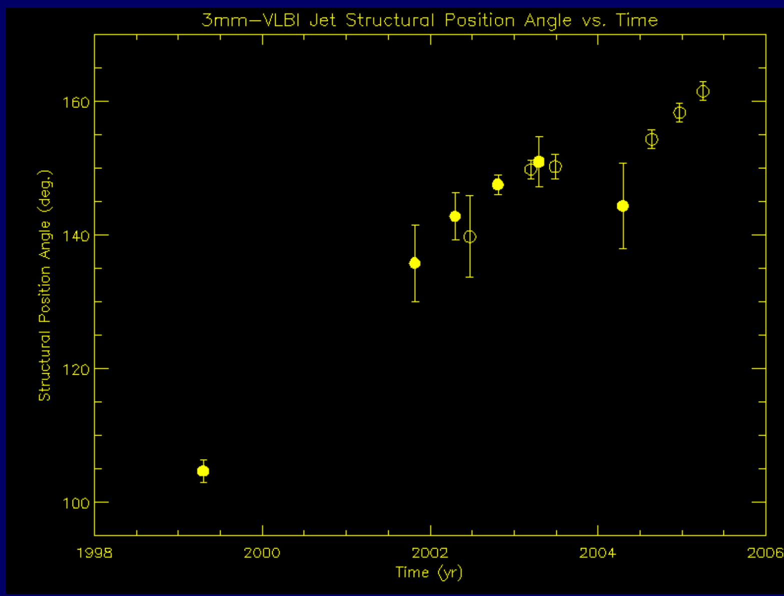



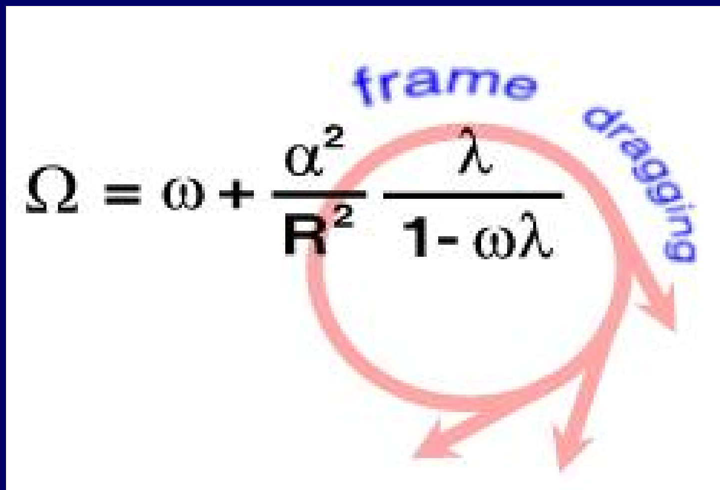

3 mm-VLBI shows jet rotation with an angular speed of ~10º/yr and an extrapolated period of 20-25 yrs



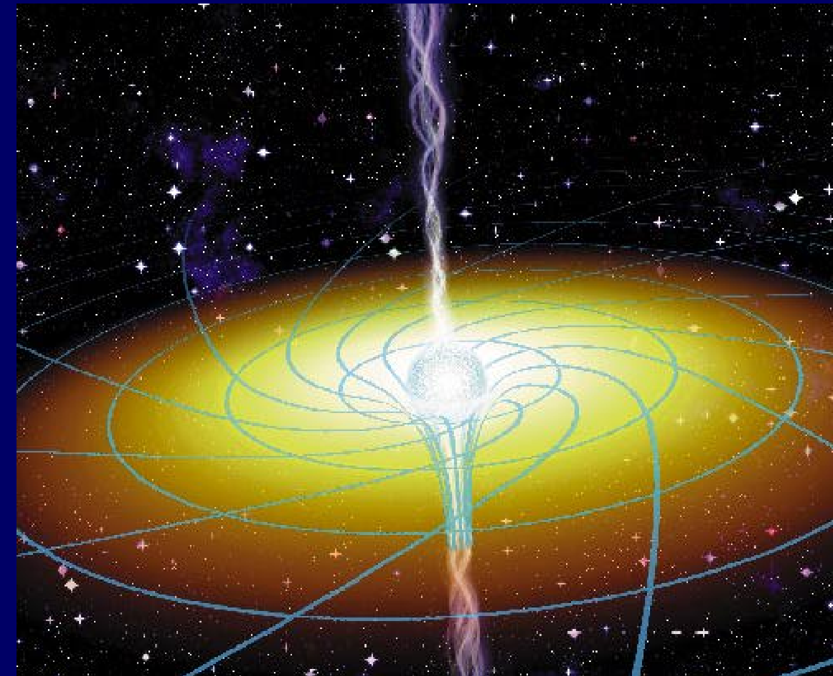




Agudo et al., in preparation

# Are GR-effects the main jet driver ?




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



matter and fields are forced to rotate with the horizon

torque due to misaligne-ment of L from accr. disk and Kerr BH

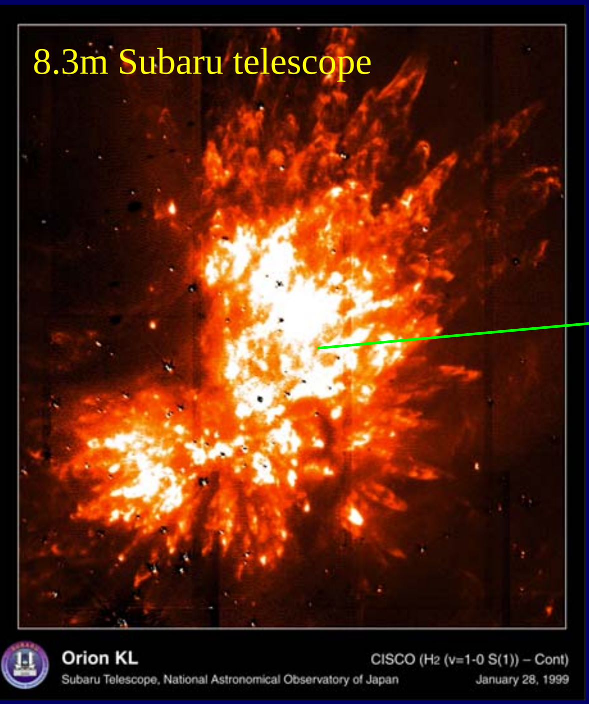
→ P =0.3 - 20 yrs appear possible

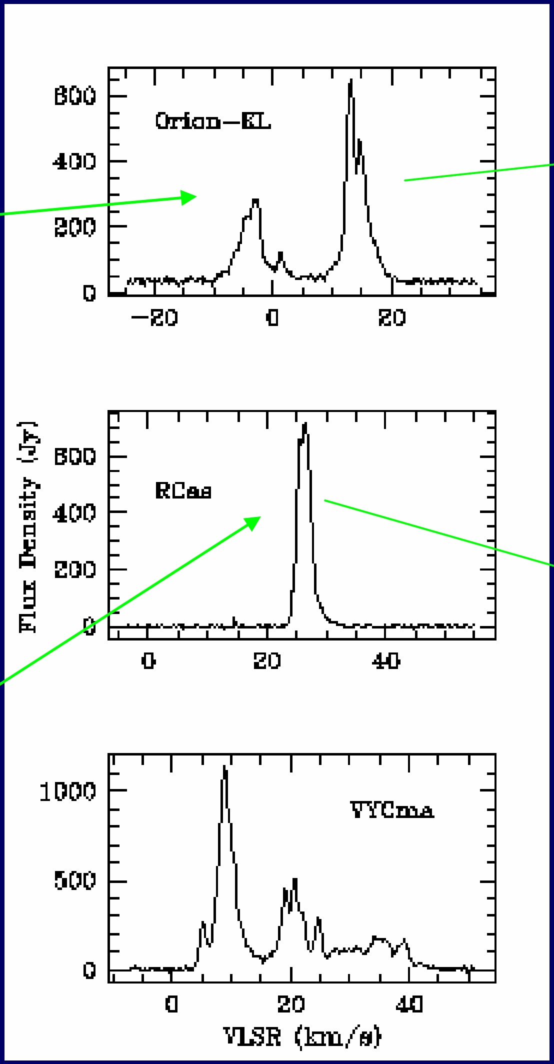
(Caproni et al., 2004)

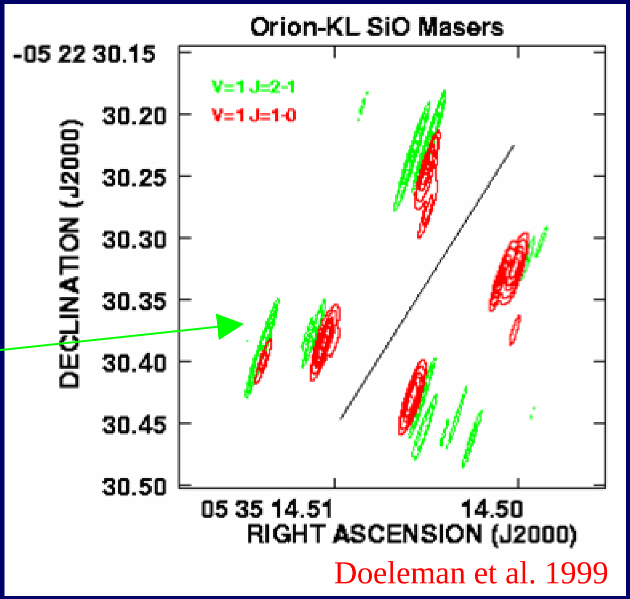
**known „precessing“ sources:**

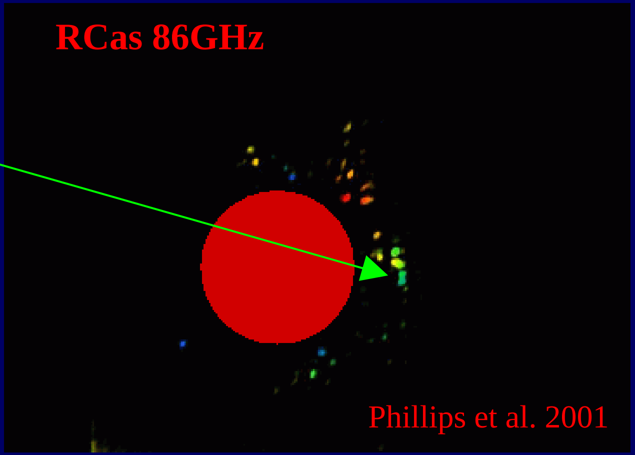
| | |
|---|---|
| 3C84 | Gal |
| NRAO150 | EF |
| 0716+714 | BL |
| 3C120 | Gal |
| 3C273 | QSO |
| 3C279 | QSO |
| 3C345 | QSO |
| BLLac | BL |

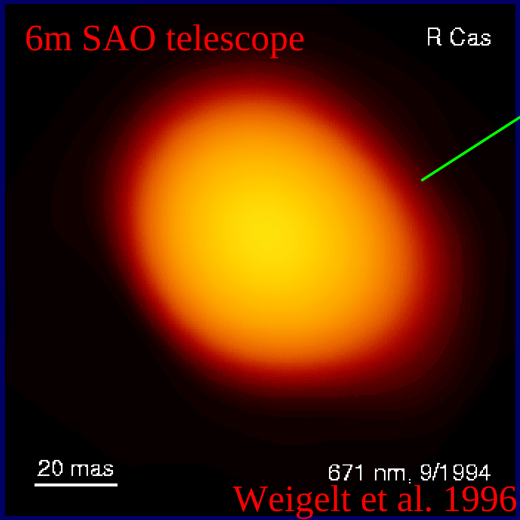
# SiO Maser at 43 and 86 GHz



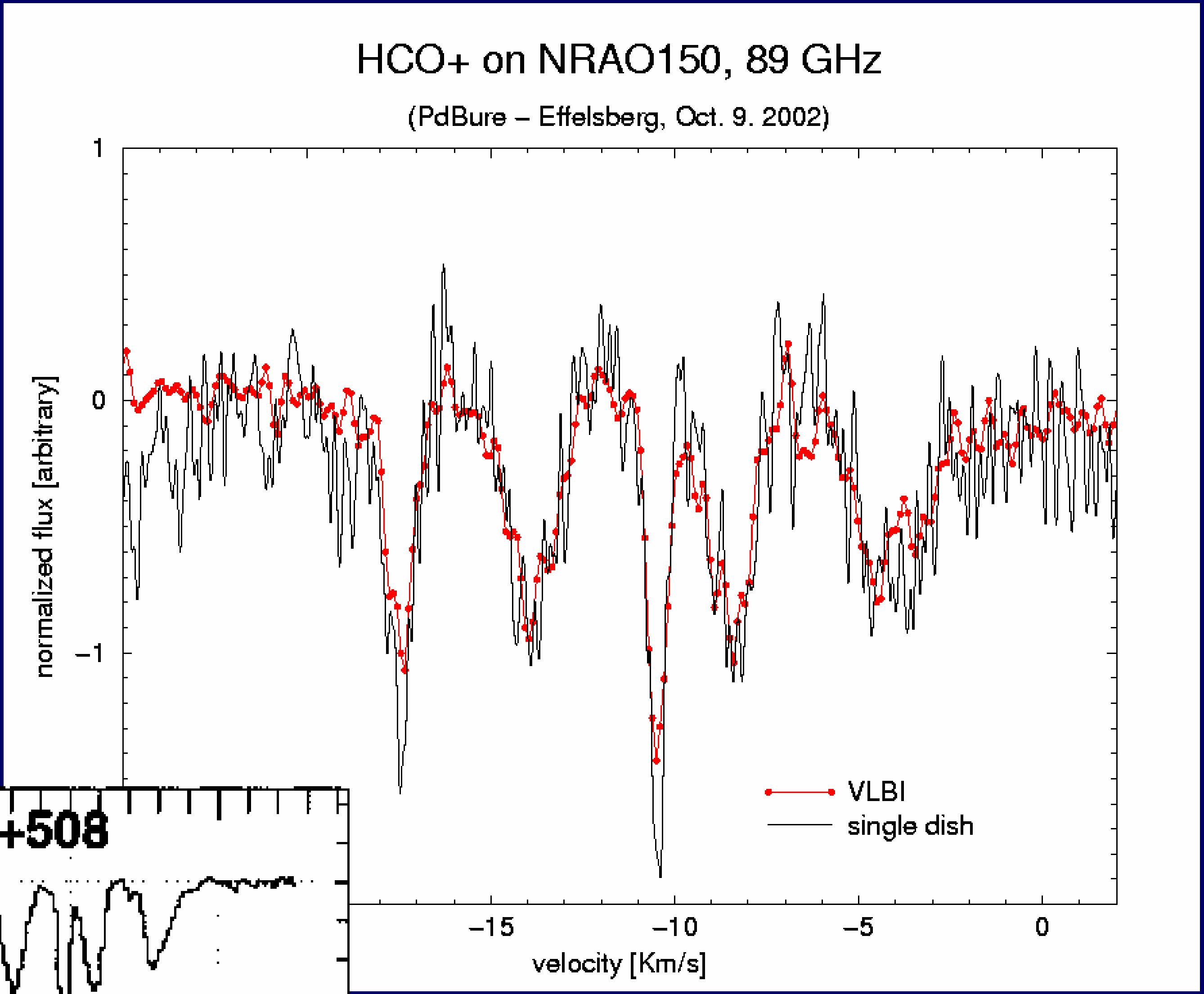



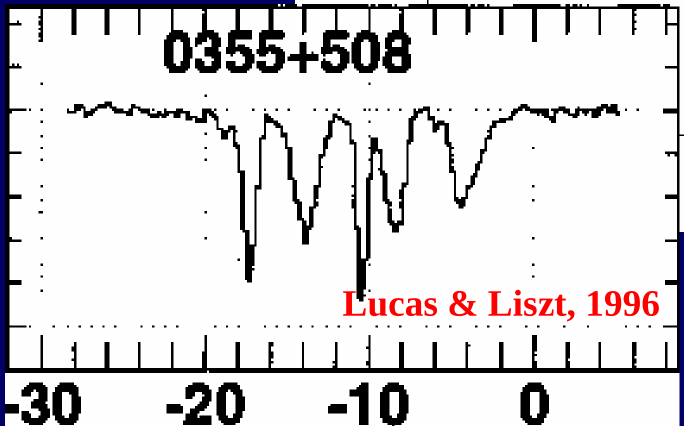



# VLBI detection of galactic absorption against NRAO150




Greve et al. 2003

many more sources are possible !

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

<u>Baseline Sensitivity</u>

in Europe:

<u>50 – 300 mJy</u>

in US:

<u>250 – 350 mJy</u>

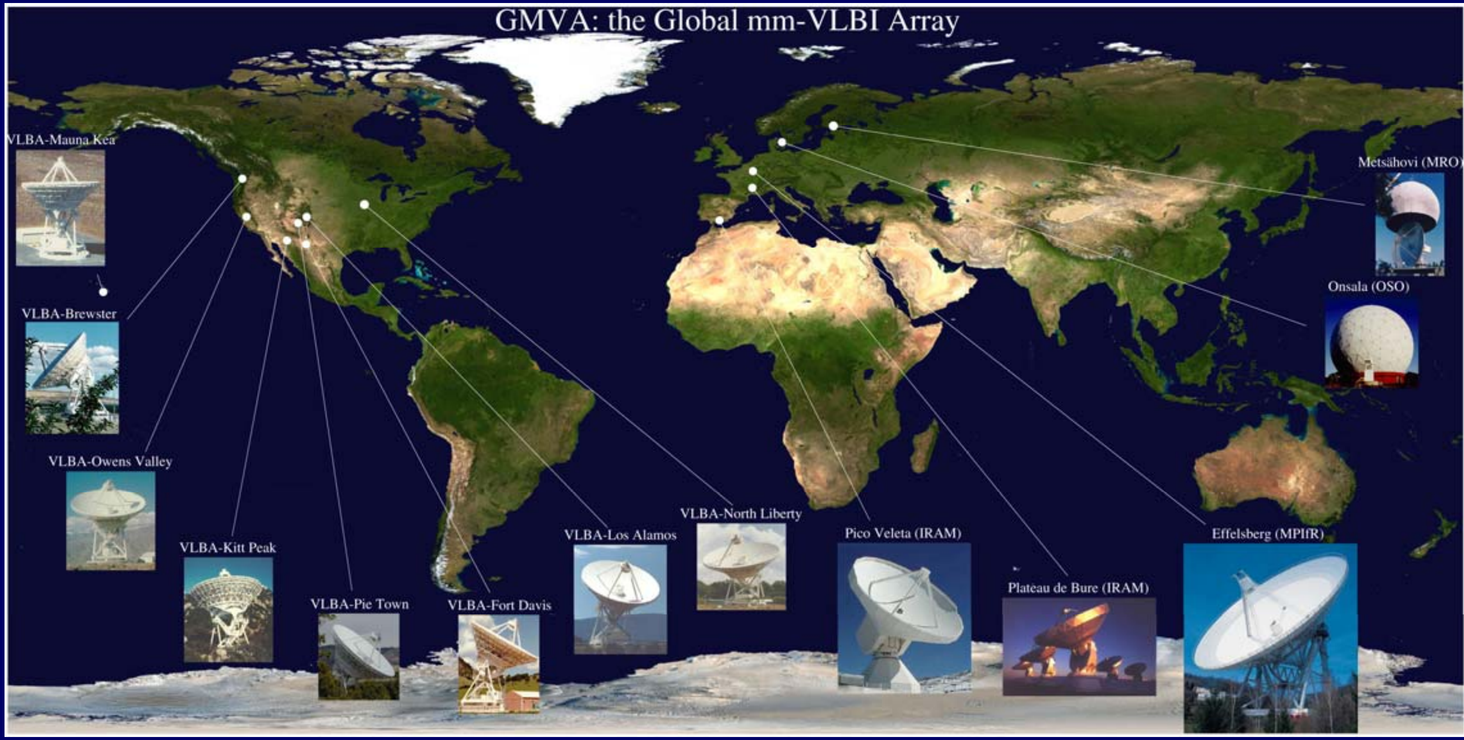
transatlantic:

<u>80 – 350 mJy</u>

Array:

<u>2 – 4 mJy / hr</u>

(assume 7σ, 100sec, 512 Mbps)




http://www.mpifr.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

# EVN/Global VLBI: Angular Resolution

(numbers in milli-arcseconds)

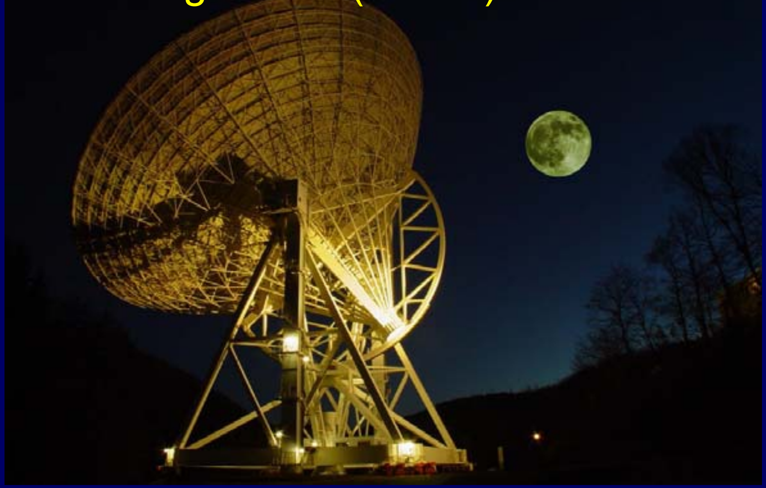
| Array | 90cm | 18cm | 6cm | 3.6cm | 1.3cm | 0.7cm | 0.3cm |
|---|---|---|---|---|---|---|---|
| EVN | - | 15 | 5,0 | 3,0 | 1,00 | 0,55 | - |
| EVN+Ur/Sh | 30 | 5 | 1,5 | 1,0 | 0,30 | - | - |
| EVN+VLBA | 19 | 3 | 1,0 | 0,7 | 0,25 | 0,13 | - |
| VLBA | 21 | 4 | 1,4 | 0,9 | 0,30 | 0,17 | 0,10 |
| GMVA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

spatial scale: for z =1 ($\Lambda$CDM cosmology), 1 mas = 8 pc

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

# Enhanced 3mm VLBI sensitivity by including the 3 largest European mm-telescopes:

Effelsberg 100 m (MPIfR)



Plateau de Bure, 6 x 15 m (IRAM, France)

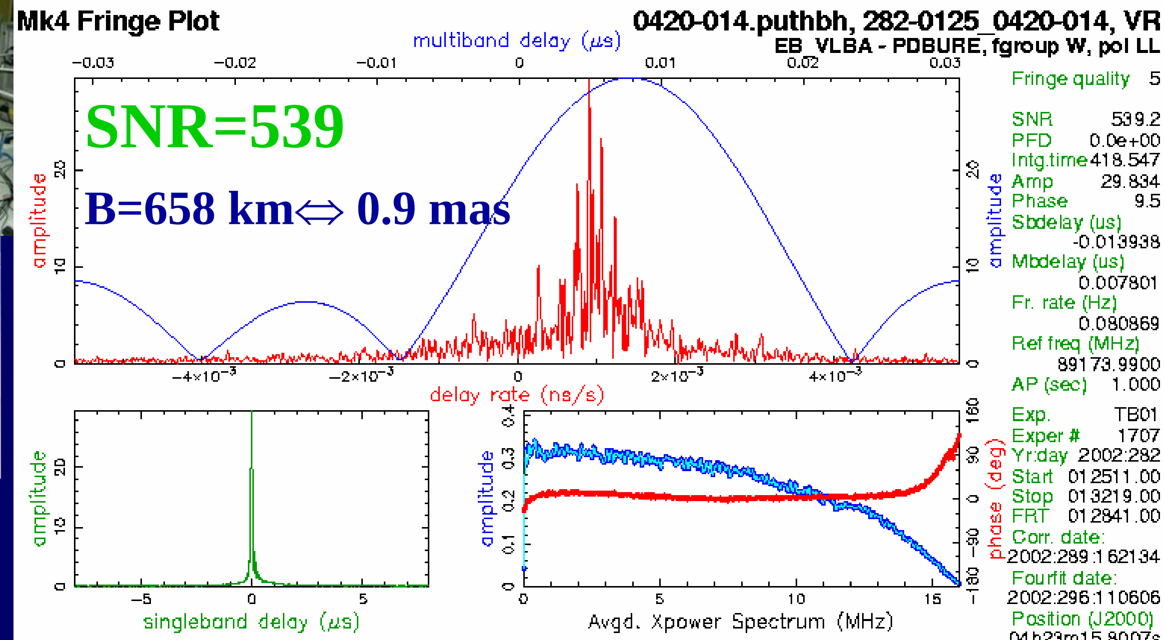
Baseline lengths (km):

| | PdB | PV |
|---|---|---|
| EB | 658 | 1700 |
| Pdb | | 1146 |

fringe spacing: 0.4 – 1.1 mas,

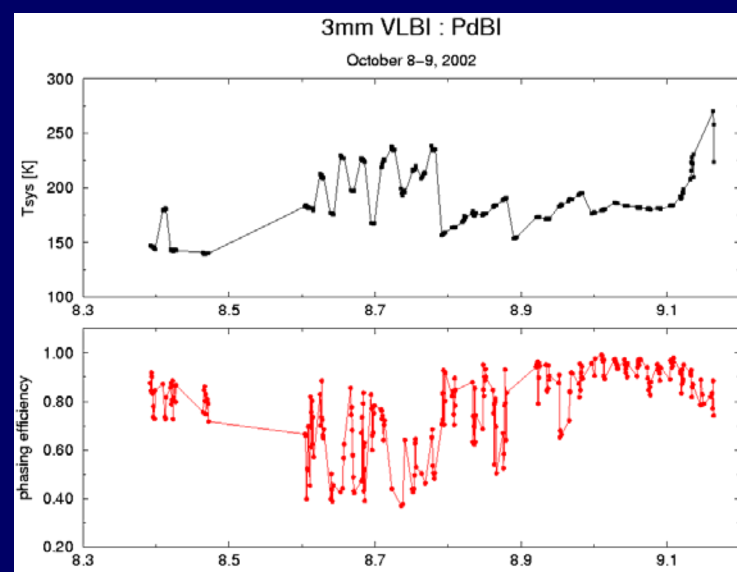
sensitivity > 40 -70 mJy (7$\sigma$, 512 Mbps)

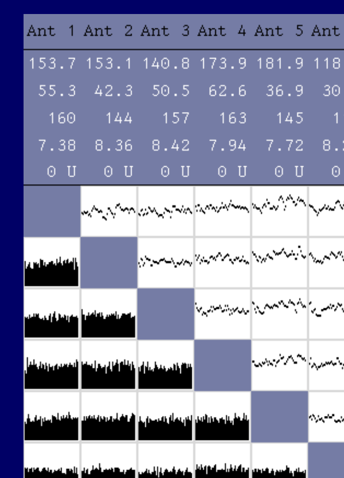
Pico Veleta 30 m (IRAM, Spain)




| Source | S_tot | SNR(scan) |
|---|---|---|
| 0420-014 | 8,9 | 77-539 |
| NRAO150 | 7,6 | 122 |
| NRAO530 | 5,9 | 26 |
| SgrA* | | 18 |
| 1633+38 | 4,6 | 132-210 |
| 2145+067 | 6,7 | 158-236 |
| 3C454.3 | 6,1 | 39-119 |

# Oct. 2002: all 6 antennas of the Plateau de Bure interferometer phased for 3mm-VLBI



# EVN/Global VLBI: Image Sensitivities

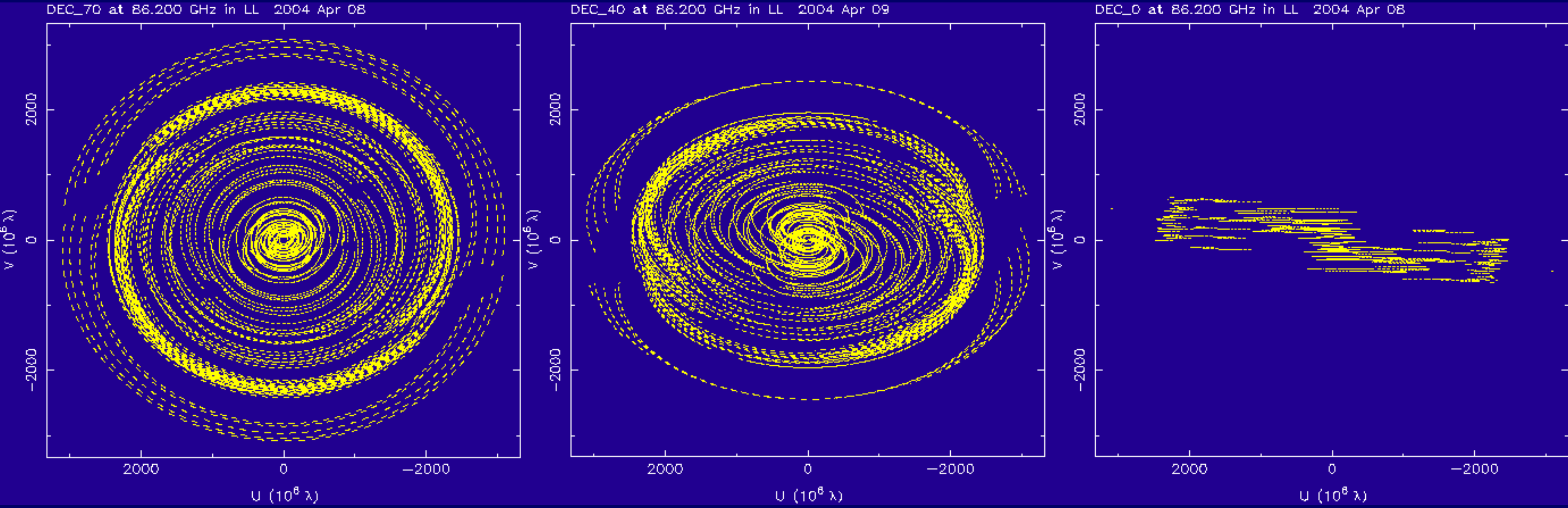
(numbers in μJy/beam)

| 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

# Typical uv-coverages of the Global 3mm VLBI Array



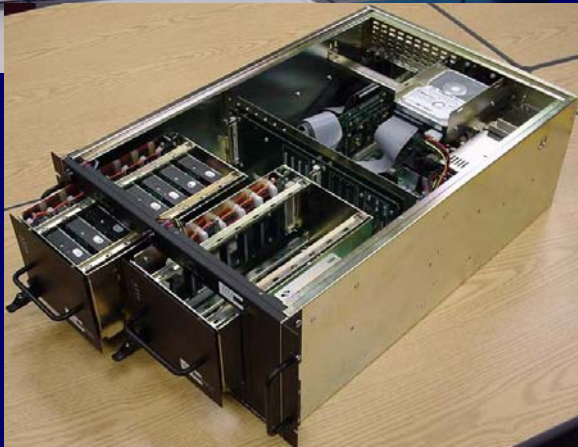

Dec. +70 Dec. +40 Dec. 0

# The VLBI Correlator in Bonn

Max-Planck-Institut für Radioastronomie

- Station based XF design
- 10 stations, 1 Gbit/s/station
- correlate all baselines at once or 8 with full polarisation
- VLBA; MKIV; MKV soon
- 1 or 2 bit recording
- continuum: 32 lags, 16 IFs
- spectral line: $\leq$ 4096 lags
- output rate ~500 kB/s
- interface to AIPS (MK4IN)

**available 24 hrs/day; up to 50% available for mm-VLBI !**



New MK5A hard disk (8 x 300 GB) recorders with data rate of up to 1 Gbit/s

# 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 (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)

# Where is the difficulty ?

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

## Solution:

better telescopes, more bandwidth, phase correction (WVR)

but now: calibration, calibration, calibration, ....

## Detection threshold for VLBI:

Defining the system equivalent flux density $\mathrm{SEFD_i}$ [Jy] of the i-th antenna of an interferometer

$$\mathrm{SEFD_i} = \frac{\mathrm{T^i_{sys}}}{\mathrm{g_i}}$$

one obtains for a single VLBI baseline between antenna i and antenna j the $1\,\sigma$-detection threshold $\sigma_{ij}$ [Jy]:

$$\sigma_{ij} = \frac{1}{\eta_c} \cdot \sqrt{\frac{\mathrm{SEFD_i} \cdot \mathrm{SEFD_j}}{2 \cdot \Delta\nu \cdot \tau_{\mathrm{integ}}}}$$

where the factor $\eta_c$ corrects for the correlator losses due to sampling ($\eta_c = 0.64$ for 1-bit smapling, $\eta_c = 0.88$ for 2-bit sampling), $\Delta\nu$ is the observing bandwidth [Hz] and $\tau_{\mathrm{integ}}$ is the coherent integration time [sec]. In practice, the solution interval for fringe fitting could be $5 - 10$ times longer than the coherence time.

100 m telescope: $T_{sys}$ = 100 K, $\eta$=0.5 → g = 1.4 K/Jy

SEFD = 100/1.4 Jy = 71 Jy

VLBI of two 100m RT 's: $\sigma$ = 0.4 mJy (for $\Delta\nu$=256 MHz, $\tau$=100 sec)

Rayleigh-Jeans law: $S = \frac{2kT}{\lambda^2}\Omega_A = \frac{2kT}{A_{eff}};$

$$A_{eff} = \eta_A A_{geom}$$

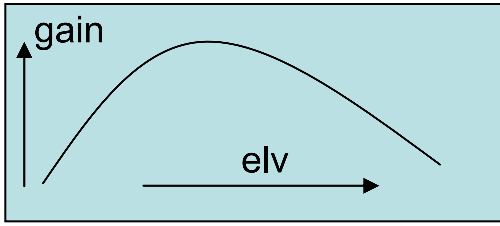
**Antenna Calibration:**

An antenna i of diameter $D_i$ [m] and aperture efficiency $\eta_A$ [%] measures for a source of flux density S [Jy] an antenna temperature $T_A$ [K]. The gain of the antenna $g_i$ [K/Jy] is then given by:

$$g_i = \frac{T_A}{S} = 2.845 \cdot 10^{-4} \cdot \eta_A^i \cdot {D_i}^2$$

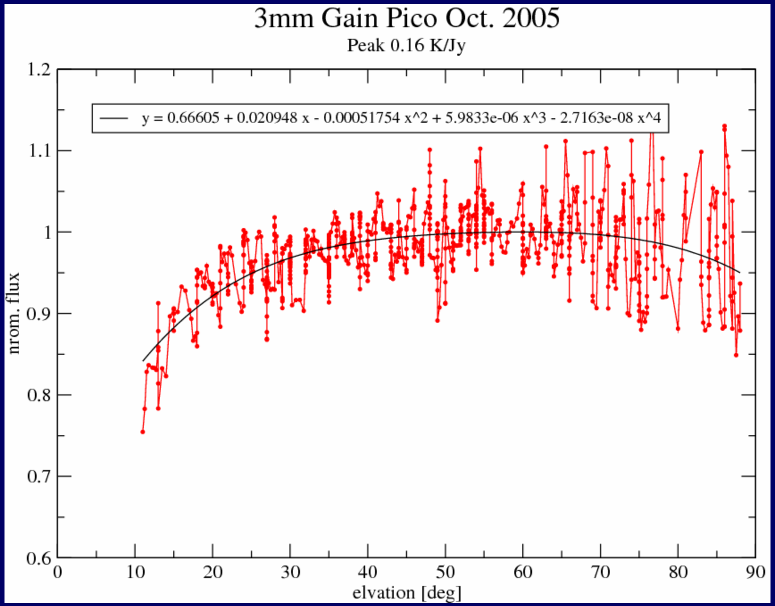
The aperture efficiency $\eta_A$ and therefore the gain $g_i$ are for most antennas elevation dependent, with a maximum typically at $30 - 45°$ elevation. The gain therefore often is given as a (polynomial) function of elevation $g_i = f(elv)$ or zenit angle $g_i = f'(z)$. If $f(elv)$ or $f'(z)$ are the gain curves normalized to 1 at their peak, the gain is often given as:

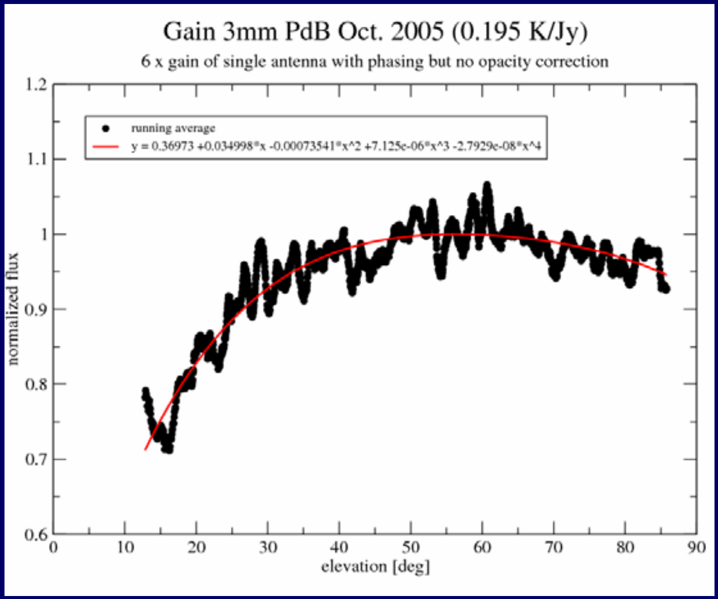
$$g_i = \mathrm{DPFU} \cdot f(elv) = \mathrm{DPFU} \cdot f'(z)$$

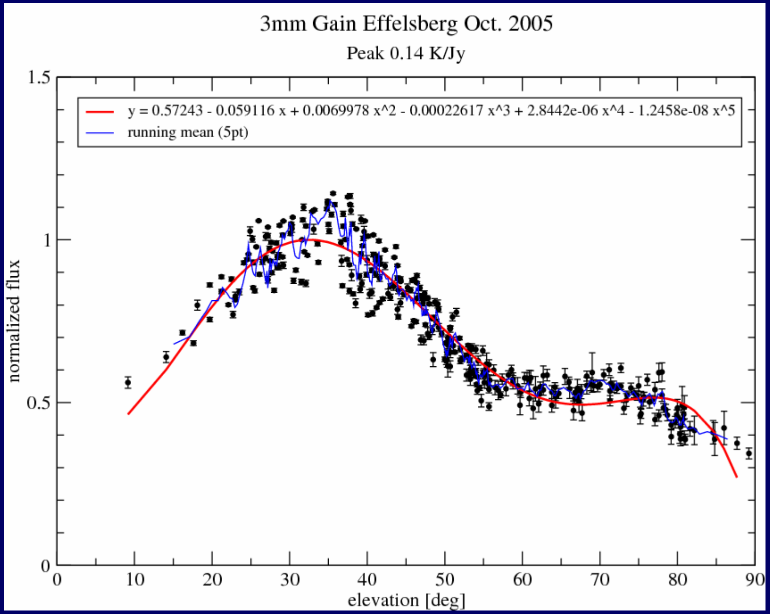


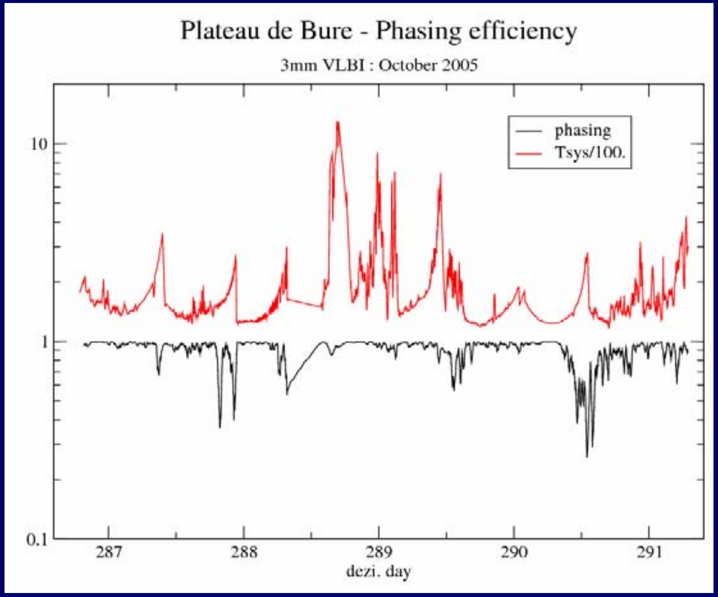

with the peak gain being called DPFU (degrees per flux unit). In practice on measures the gain, or the aperture efficiency, using sources of known brightness (primary calibrators), which at mm-wavelengths could be the planets (e.g. Mars, Uranus), some minor planets (e.g. Ceres), planetary nebula (e.g. NGC 7027), compact H II regions (e.g. K3-50 A), etc.

# Calibration : Antenna gain – elevation curves

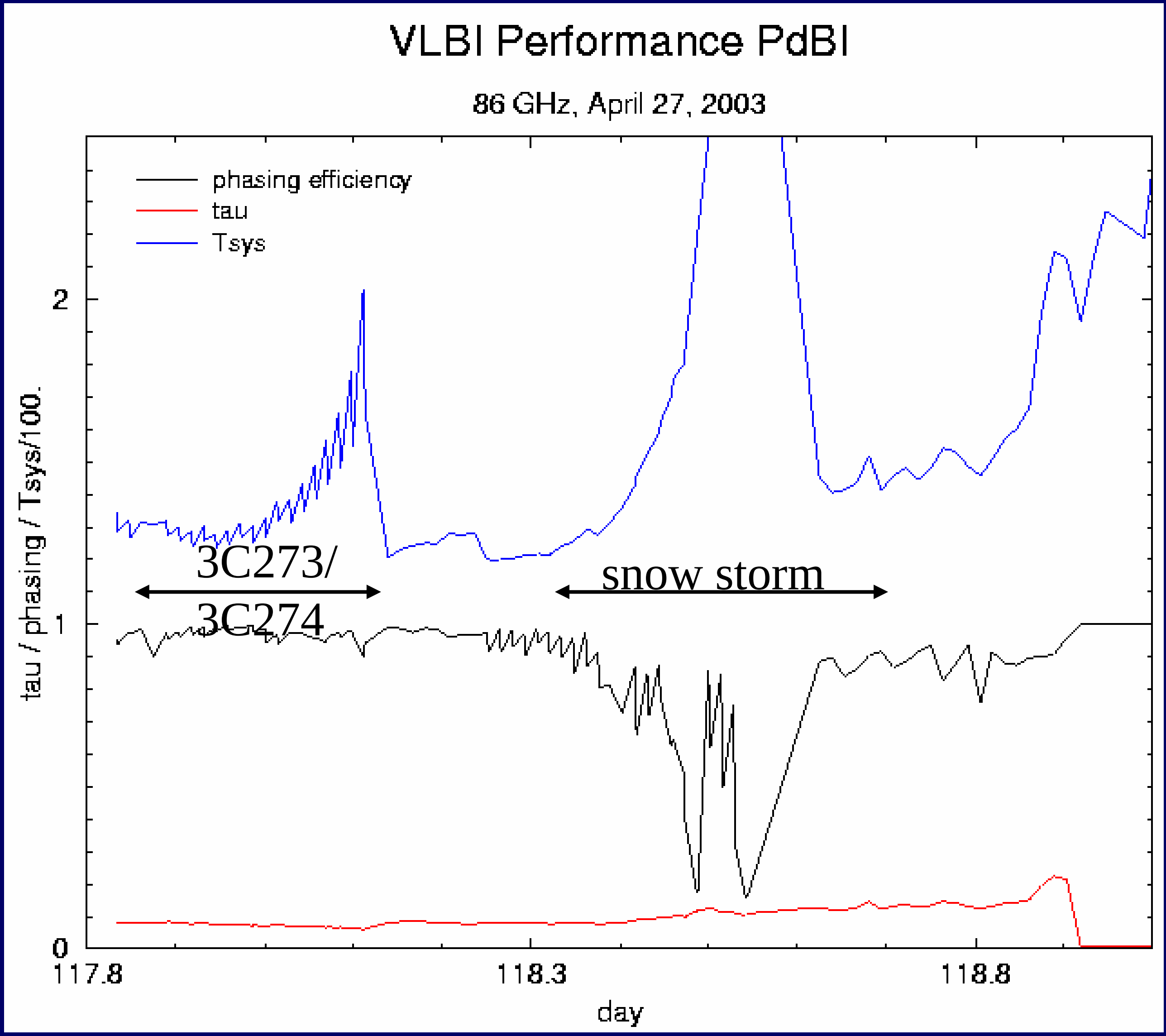


# Correcting the phasing efficiency of the IRAM interferometer




VLBI at PdBure:

MKV disk recording

256 Mbit/s

$T_{sys}$ = 125 – 130 K

$\tau$ = 0.07 – 0.15

phasing eff. $\geq$ 0.9

## Atmospheric attenuation and opacity:

Observing the "empty sky" at a given elevation $elv$ yields an observed antenna temperature

$$T_A = T_{\rm Rx} + T_{\rm Atm} \cdot \eta_l \cdot (1 - e^{-\frac{\tau_0}{\sin(elv)}}) + T_{\rm amb}(1 - \eta_l)$$

where $T_{\rm Rx}$ is the receiver temperature, $T_{\rm Atm}$ is the effective temperature of the atmosphere, $T_{\rm amb}$ is the ambient temperature, and $\eta_l$ is the feed efficiency (typically $\eta_l = 0.9$). The atmospheric opacity is given by $\tau = \tau_0 A$, where $\tau_0$ is the zenit opacity and the airmass is approximated by

$$A \simeq \frac{1}{\sin(elv)}.$$

The atmospheric zenit opacity is usually determined from tipping scans $T_{\rm sys} = f(elv)$, which measure the system temperature as a function of elevation (sky dip). For $A < 3$ the following linearization allows an easy deterimination of $\tau_0$ and $T_{\rm Rx}$ from a fit of a straight line to $T_{\rm sys}$ versus $A$

$$T_{\rm sys} = T_{\rm Rx} + T_{\rm Atm} \cdot \tau_0 \cdot A = T_{\rm Rx} + T_{\rm Atm} \cdot \frac{\tau_0}{\sin(elv)}$$

Opacity fit done either manually or with AIPS task "APCAL" (opac; dofit 1)

# Correction for atmospheric absorption in AIPS: APCAL

Task APCAL: writes a new SN-table

OPCODE: 'opac' or 'grid'

SOLINT: several hours

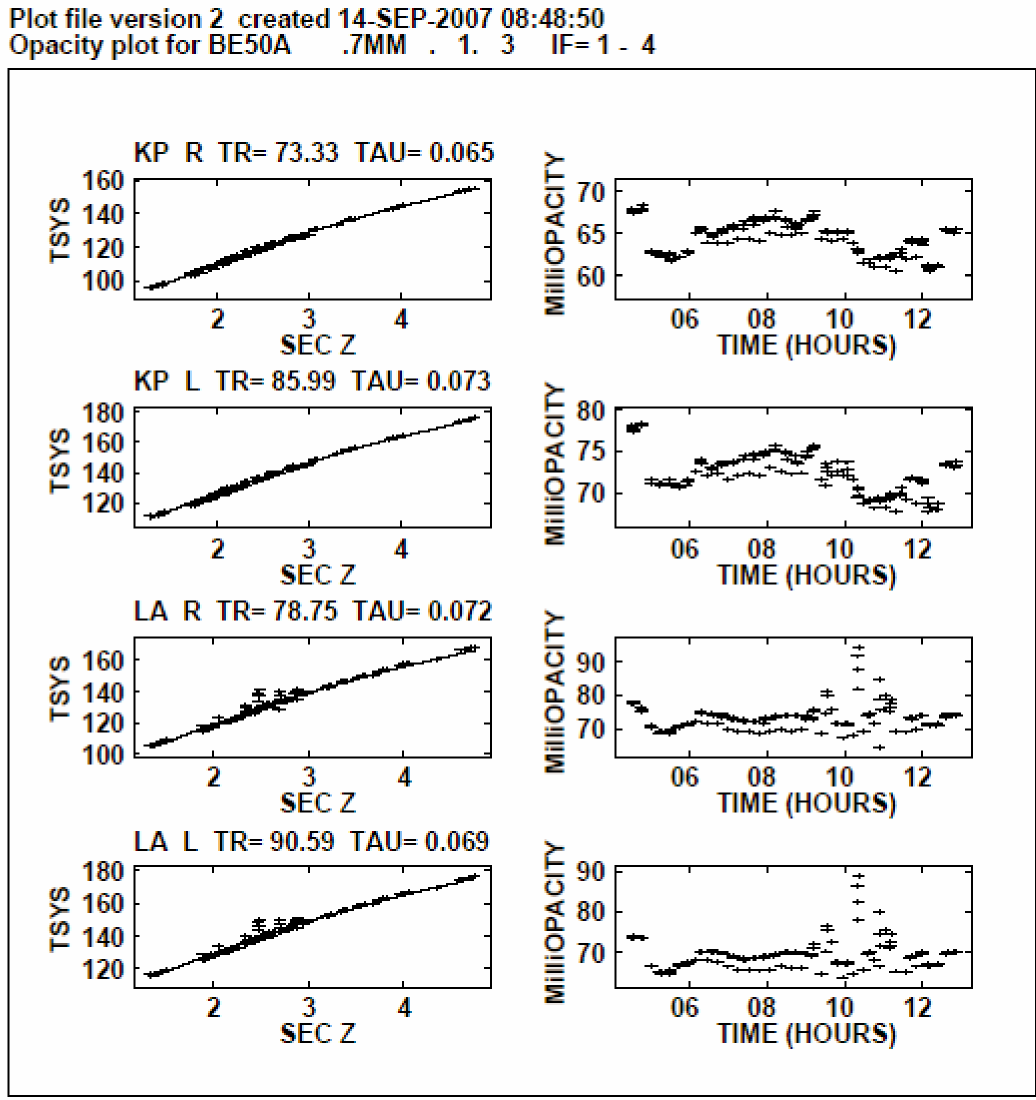
TRECVR: reasonale start value, eg. 100

TAU0: reasonable start value, eg. 0.08

DOFIT: 1 (or 0 if TRECVR and tau0 are known)

Weather table or ASCII file if available

| Stat. | Pol. | Receiver Temp. | | Zenit Opacity | |
|---|---|---|---|---|---|
| BR | RCP 0/ 8h 1m | Trec (K): | 64.61 | Zen. opac.: | 0.077 |
| BR | LCP 0/ 8h 1m | Trec (K): | 77.17 | Zen. opac.: | 0.112 |
| HN | RCP 0/ 8h 1m | Trec (K): | 104.89 | Zen. opac.: | 0.140 |
| HN | LCP 0/ 8h 1m | Trec (K): | 95.70 | Zen. opac.: | 0.144 |
| KP | RCP 0/ 8h 1m | Trec (K): | 73.33 | Zen. opac.: | 0.065 |
| KP | LCP 0/ 8h 1m | Trec (K): | 85.99 | Zen. opac.: | 0.073 |
| LA | RCP 0/ 8h 1m | Trec (K): | 78.75 | Zen. opac.: | 0.072 |
| LA | LCP 0/ 8h 1m | Trec (K): | 90.59 | Zen. opac.: | 0.069 |
| MK | RCP 0/ 8h 1m | Trec (K): | 59.83 | Zen. opac.: | 0.033 |
| MK | LCP 0/ 8h 1m | Trec (K): | 67.51 | Zen. opac.: | 0.036 |
| NL | RCP 0/ 8h 1m | Trec (K): | 71.03 | Zen. opac.: | 0.172 |
| NL | LCP 0/ 8h 1m | Trec (K): | 61.28 | Zen. opac.: | 0.187 |
| OV | RCP 0/ 8h 1m | Trec (K): | 85.46 | Zen. opac.: | 0.067 |
| OV | LCP 0/ 8h 1m | Trec (K): | 88.08 | Zen. opac.: | 0.066 |
| PT | RCP 0/ 8h 1m | Trec (K): | 75.54 | Zen. opac.: | 0.063 |
| PT | LCP 0/ 8h 1m | Trec (K): | 74.11 | Zen. opac.: | 0.060 |
| SC | RCP 0/ 8h 1m | Trec (K): | 89.40 | Zen. opac.: | 0.179 |
| SC | LCP 0/ 8h 1m | Trec (K): | 93.60 | Zen. opac.: | 0.182 |
| FD | RCP 0/10h 2m | Trec (K): | 74.33 | Zen. opac.: | 0.089 |
| FD | LCP 0/10h 2m | Trec (K): | 77.14 | Zen. opac.: | 0.105 |




Note: don' forget to set source fluxes with SETJY before running APCAL

The measured flux density $S_{\mathrm{meas}}$ of a source needs to be corrected for atmospheric absorption. The true flux density $S_{\mathrm{true}}$ (referring to 'outside' the atmosphere) is therefore given by

$$S_{\mathrm{true}} = S_{\mathrm{meas}} \cdot e^{\tau} \simeq S_{\mathrm{meas}} \cdot e^{\frac{\tau_0}{\sin(elv)}}$$

Similarly, the effective system temperature, which is finally used for the calibration of the mm-VLBI data, is given by

$$T_{\mathrm{sys}}^{\mathrm{eff}} = T_{\mathrm{sys}} \cdot e^{\tau} = T_{\mathrm{Rx}} \cdot e^{\frac{\tau_0}{\sin(elv)}} + T_{\mathrm{Atm}}(e^{\frac{\tau_0}{\sin(elv)}} - 1)$$

The zenith opacity $\tau_0$ depends on the height of the observatory above sea level and at 3 mm ranges under best conditions from $\tau_0 = 0.03$ for Mauna Kea to $\tau_0 = 0.07$ for Effelsberg. In typial observing conditions opacities are in the range $\tau_0 = 0.05 - 0.15$.

## Planets as primary calibrators at 86 GHz

| Planet | $T_B$ [K] | $\alpha$ | comment |
|---|---|---|---|
| Merkur | 500 | 0 | $T_B = 359 + 147 \cdot \cos(\xi + 17)$ |
| Venus | 359 | -0.35 | |
| Mars | 210 | 0 | $T_B \propto \sqrt{\frac{1.524}{r}}$; $T_B = 210 + 10 \cdot \cos(\xi + 10)$ |
| Jupiter | 174 | 0 | own emission |
| Saturn | 151 | 0 | rings |
| Uranus. | 136 | -0.35 | |
| Neptun | 128 | -0.35 | |

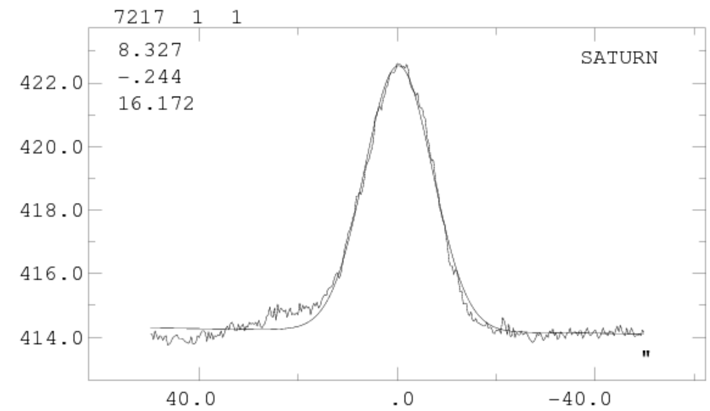
Note: All $T_B$ have to be corrected by -2.7 K because of CMBR, (cf. Altenhoff et al. 1994, AA, 281, 161).

*Calculation of flux density from known brightness temperature:* At a wavelength $\lambda$, the flux density $S_\lambda$ [Jy] of a blackbody of brightness temperatur $T_B$ [K] filling a solid angle $\Omega_s$, is given in the Rayleigh-Jeans limit:

$$S_\lambda = \frac{2k\Omega_s T_B}{\lambda^2} \cdot C$$

with Boltzmann's constant $k = 1.38 \cdot 10^{-23}$ [$\mathrm{JK}^{-1}$] and $C$ the normalized solid angle correction. For planetary disks, $C$ can be calculated as follows (Ulich et al. 1980):

$$C = \frac{1 - e^{-x^2}}{x^2}$$




with

$$x = \sqrt{4 \ln 2} \cdot \frac{R}{\theta_{\mathrm{HPBW}}}$$

and

$$\Omega_s = 2\pi[1 - \cos(R)] \simeq \pi R^2$$

where $R$ is the geometric mean of the polar and equitorial planetary diameter, and $\Omega_s$ the corresponding solid angle. $\theta_{\mathrm{HPBW}}$ is the size of the Gaussian beam of the telescope. This approximation is only valid for $R \lesssim 2\theta_{\mathrm{HPBW}}$.

In the case of an elliptical Gaussian brightness profile the correction $C$ is given by:

$$C_g = \sqrt{[1 + (\frac{\phi_1}{\theta_1})^2][1 + (\frac{\phi_2}{\theta_2})^2]}$$

where $\phi_S = \phi_1 \times \phi_2$ is the elliptical source size, and $\theta_{\mathrm{HPBW}} = \theta_1 \times \theta_2$ is the elliptical beam size.

# Brightness temperatures of planetes

| | 31 | 90 | 113 | 150 | 227 | 279 | 337 | 392 | 808 | Ghz |
|---|---|---|---|---|---|---|---|---|---|---|
| Mercury | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | 500 | K |
| Venus | 466 | 367 | 339 | 294 | 294 | 294 | 294 | 294 | 294 | |
| Mars | 194 | 207 | 209 | 212 | 214 | 216 | 217 | 217 | 221 | |
| Jupiter | 152 | 172 | 172 | 172 | 172 | 172 | 172 | 162 | 144 | |
| Saturn | 133 | 149 | 145 | 137 | 136 | 136 | 135 | 136 | 115 | |
| *Uranus: | 136 | 136 | 122 | 112 | 94 | 92 | 88 | 84 | 64 | |
| *Neptune | 127 | 127 | 114 | 110 | 92 | 85 | 84 | 79 | 61 | |
| Pluto | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | |
| Callisto | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | |
| Ganymede | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | 125 | |

References: Ulich 1981 A.J.,86,1619,Griffen 1986 Icarus 65,244;Hildebrand 1985 Icarus,64,64;Orton 1986,Icarus 67,289;Muhleman&Berge 1991

Note: Brightness temperatures at intermediate frequencies are obtained by linear interpolation.

For Uranus and Neptune, we use the empirical fit to the Uranus temperature spectrum (Griffin & Orton 1993 Icarus 537), in the 0.35-3.3 mm region:

$$T_{Uranus} = a_0 + a_1 \lg\lambda + a_2 (\lg\lambda)^2 + a_3 (\lg\lambda)^3 \; K \quad (2)$$

where $a_0$=-795.694, $a_1$=845.179, $a_2$=-288.946, $a_3$=35.200, $\lambda$ in micrometers.

The neptunian brightness temperature , between 0.35 and 3.3 mm is given by (Griffin & Orton 1993 Icarus 537):

$$T_{Neptune} = a_0 + a_1 \lg\lambda + a_2 (\lg\lambda)^2 + a_3 (\lg\lambda)^3 \; K \quad (3)$$

where $a_0$=-598.901, $a_1$=655.681, $a_2$=-229.545, $a_3$=28.994, $\lambda$ in micrometers.

http://sma1.sma.hawaii.edu/planetvis.html

http://cfa-www.harvard.edu/~cqi/mircook.html#htoc49

# Future: where are we going ?

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

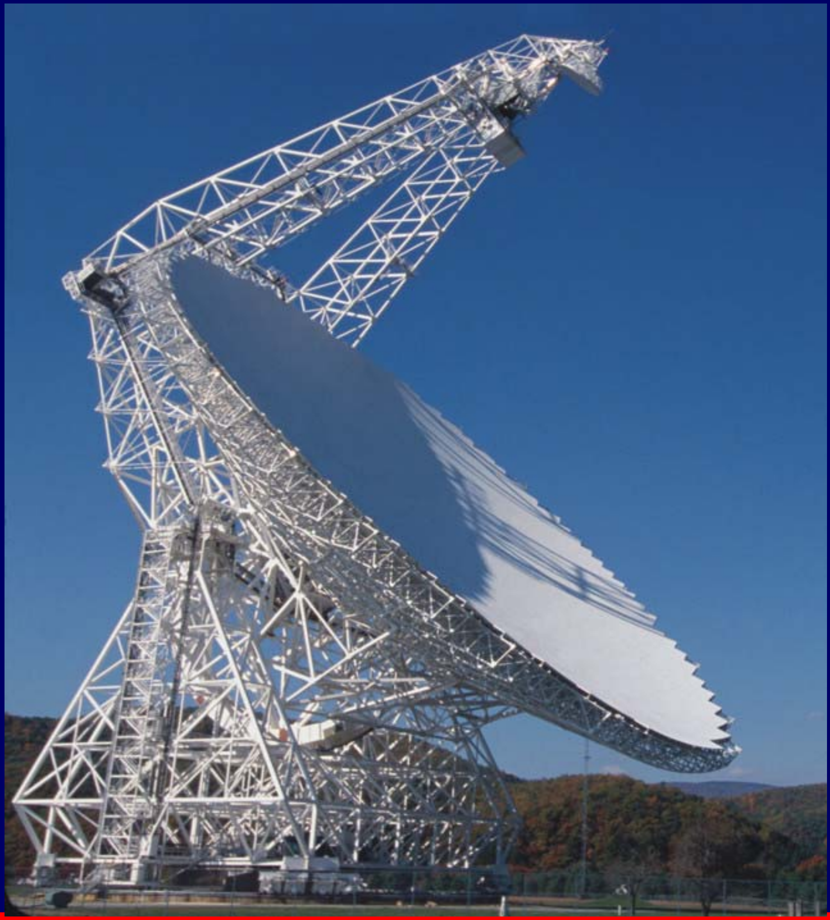
now →

- 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 |

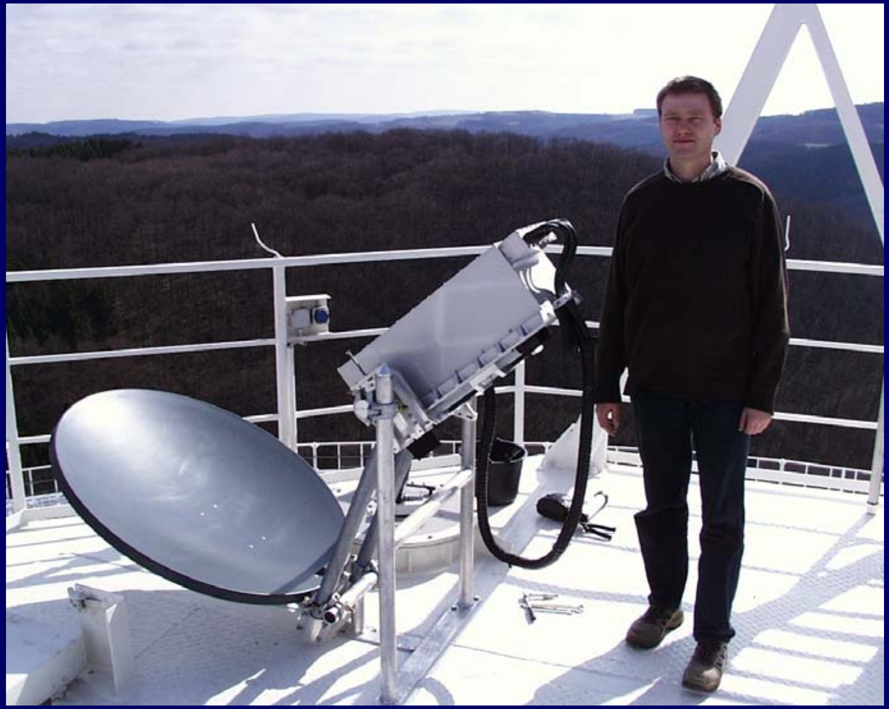
# plus the GBT, asap :

| | SEFD[Jy] |
|---|---|
| Effelsberg | 950 |
| Pico Veleta | 710 |
| Plateau de Bure | 500 |
| GBT | 150 |



need GBT to enhance VLBA baseline sensitivities via global fringe fitting

# VLBI Phase Correction with the Effelsberg water vapor radiometer (WVR)

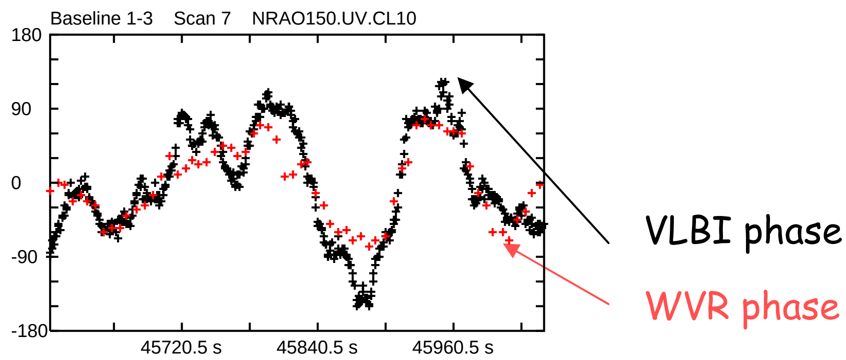
A. Roy
U. Teuber
H. Rottmann
R. Keller

Max-Planck-Institut für Radioastronomie

# VLBI Phase Correction Demo

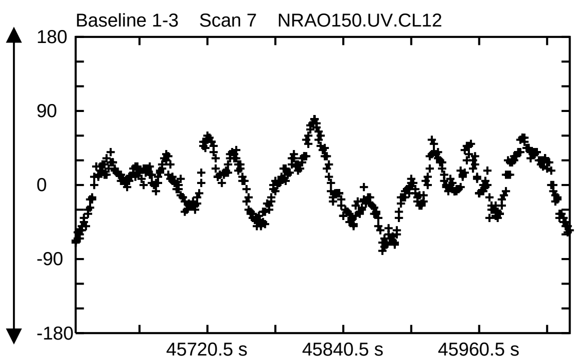
NRAO 150
Pico Veleta - Effelsberg
86 GHz VLBI
2004 April 17

## No phase correction

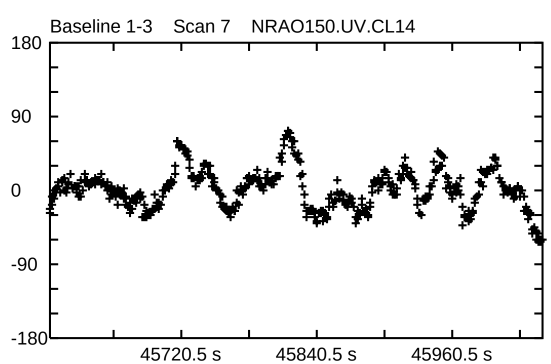



## EB phase correction

path
3.4 mm

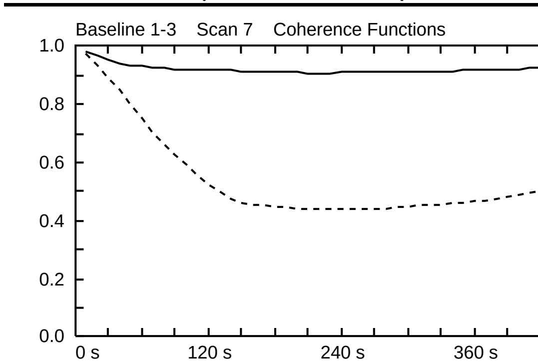



## EB+PV phase correction




420 s

## Coherence function before & after



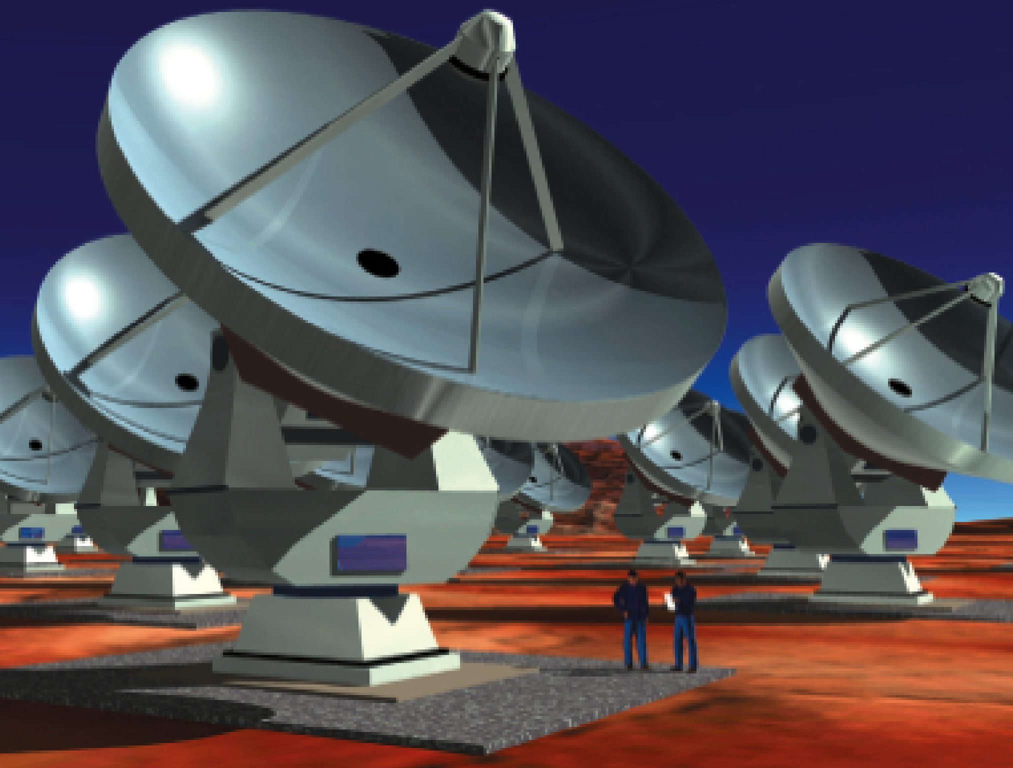

- Path rms reduced 1.0 mm to 0.34 mm
- Coherent SNR rose 2.1 x

A. Roy et al.

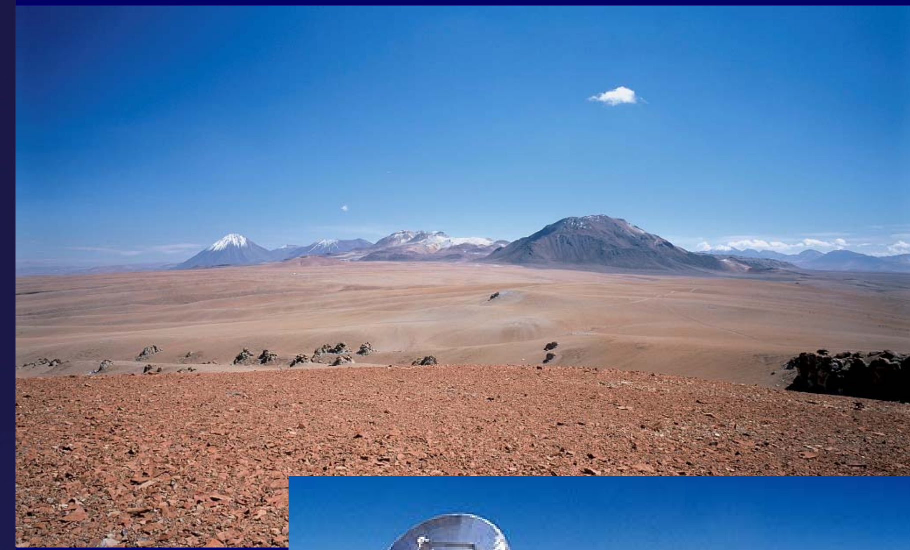
# ALMA

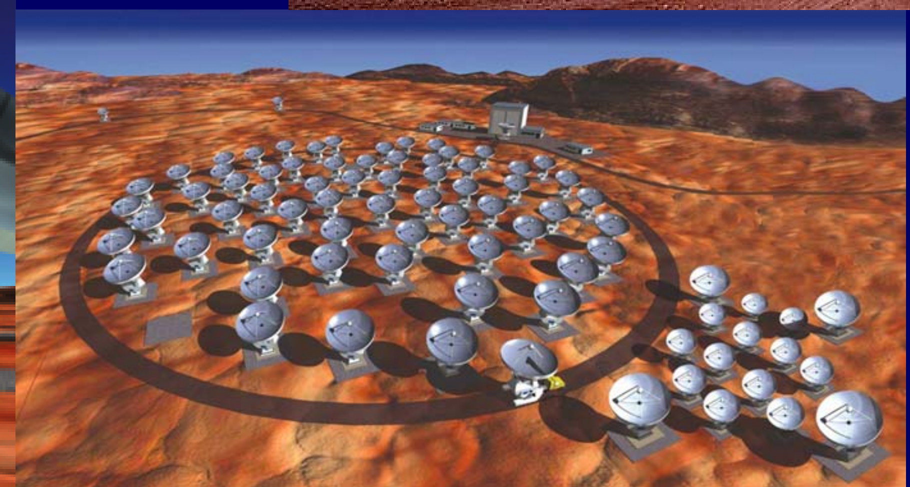
## ATACAMA LARGE MILLIMETER ARRAY

(50 antennas with 12 m diameter)



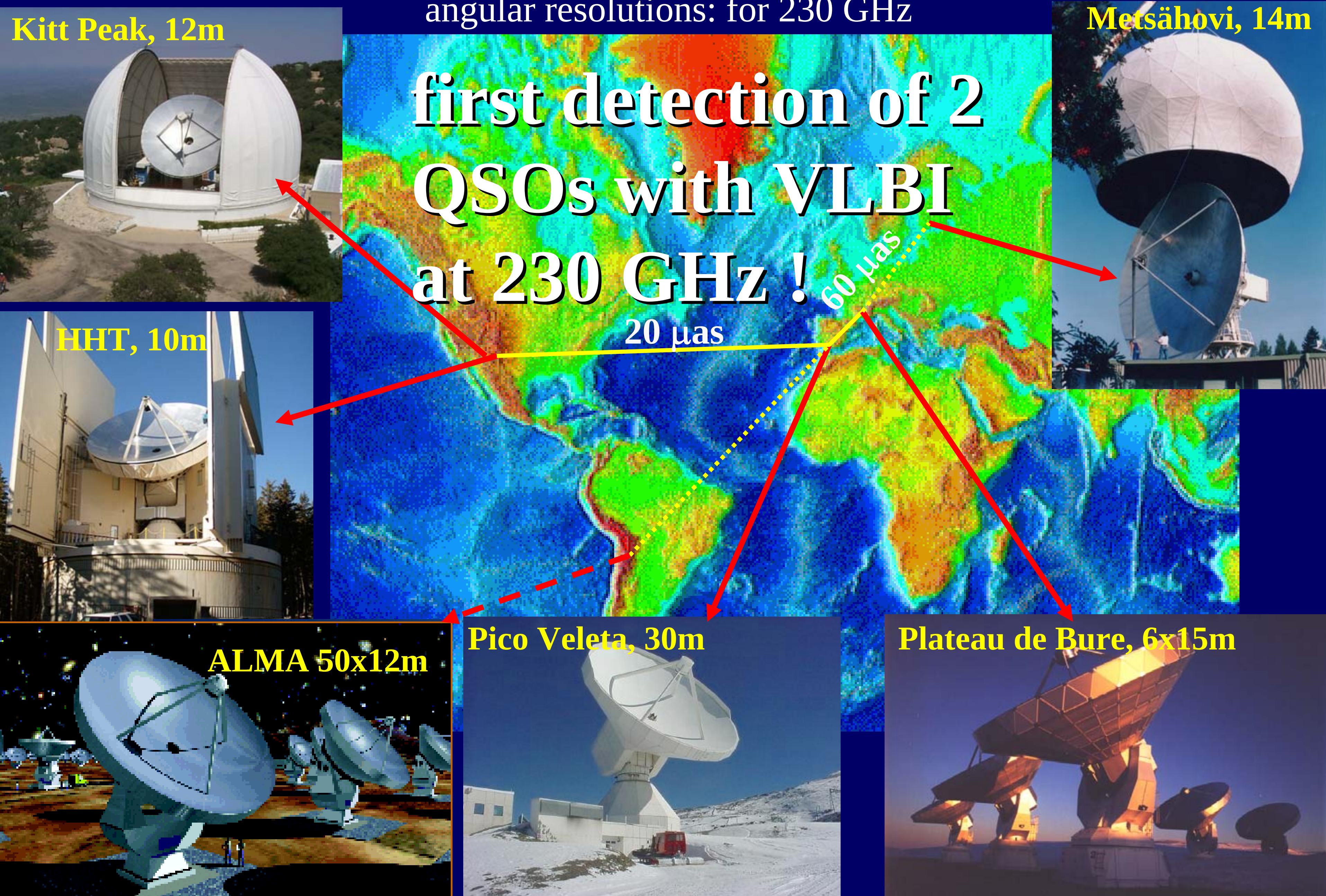
Chajnantor Plateau (5100 m)

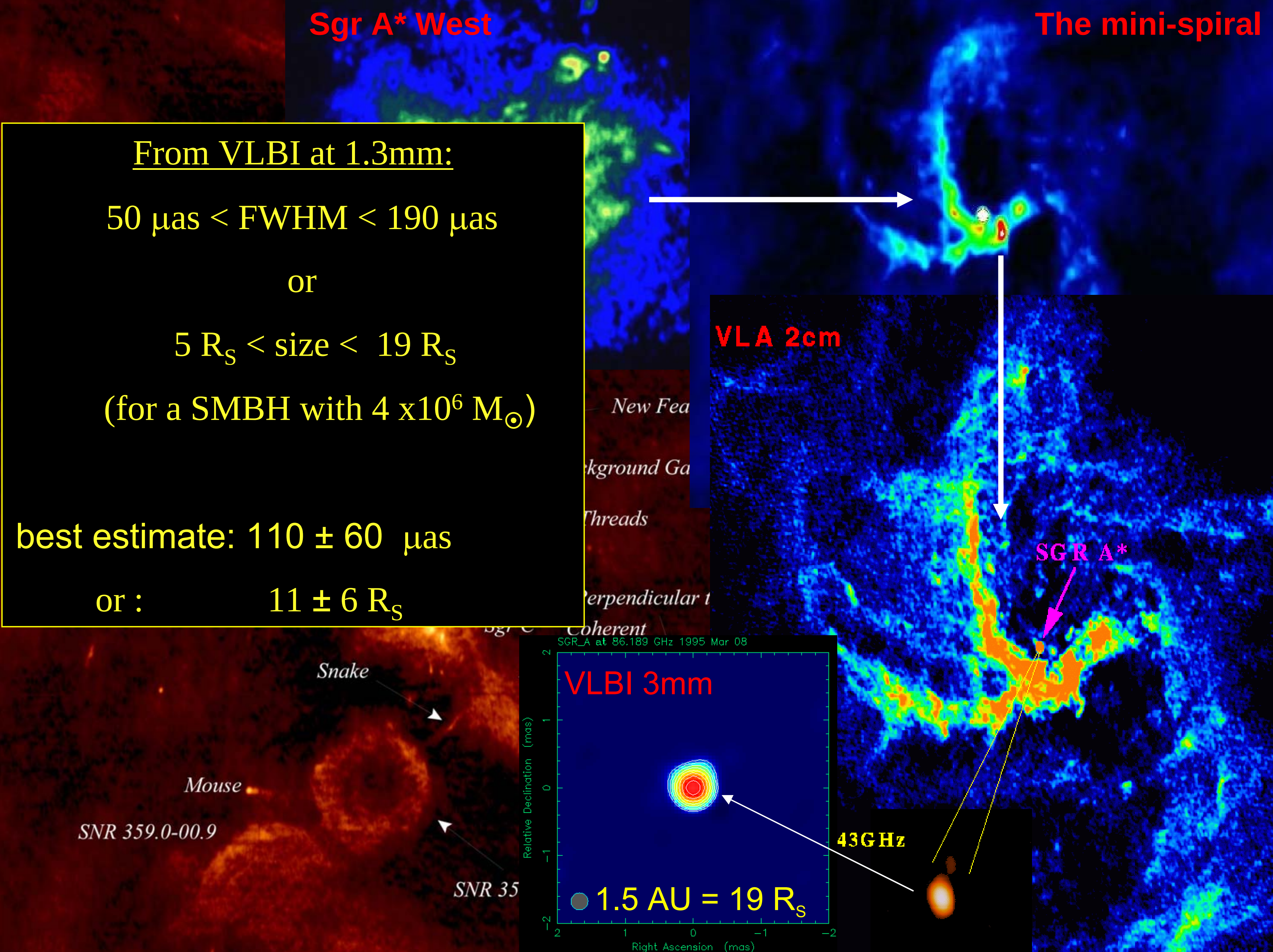




# Global mm-VLBI at 150 - 230 GHz

angular resolutions: for 230 GHz



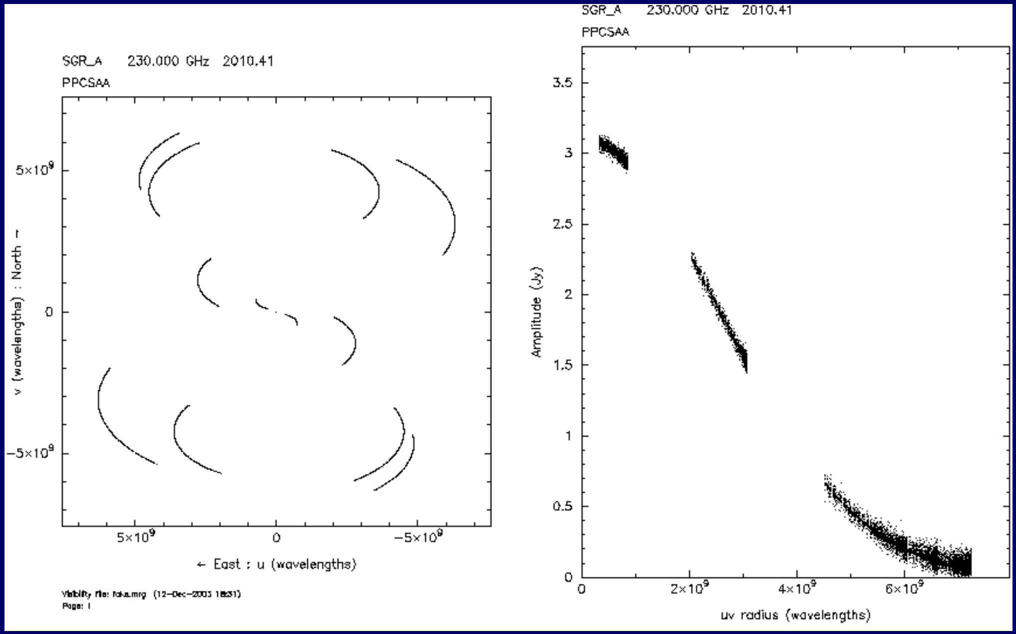

Sgr A* West
The mini-spiral
From VLBI at 1.3mm:
50 μas < FWHM < 190 μas
or
5 R_S < size < 19 R_S
(for a SMBH with 4 x10^6 M_⊙)
best estimate: 110 ± 60 μas
or : 11 ± 6 R_S
VLA 2cm
SGR A*
SGR_A at 86.189 GHz 1995 Mar 08
VLBI 3mm
1.5 AU = 19 R_S
Relative Declination (mas)
Right Ascension (mas)
43GHz
Snake
Mouse
SNR 359.0-00.9

# Simulation of 1 mm VLBI of SgrA*

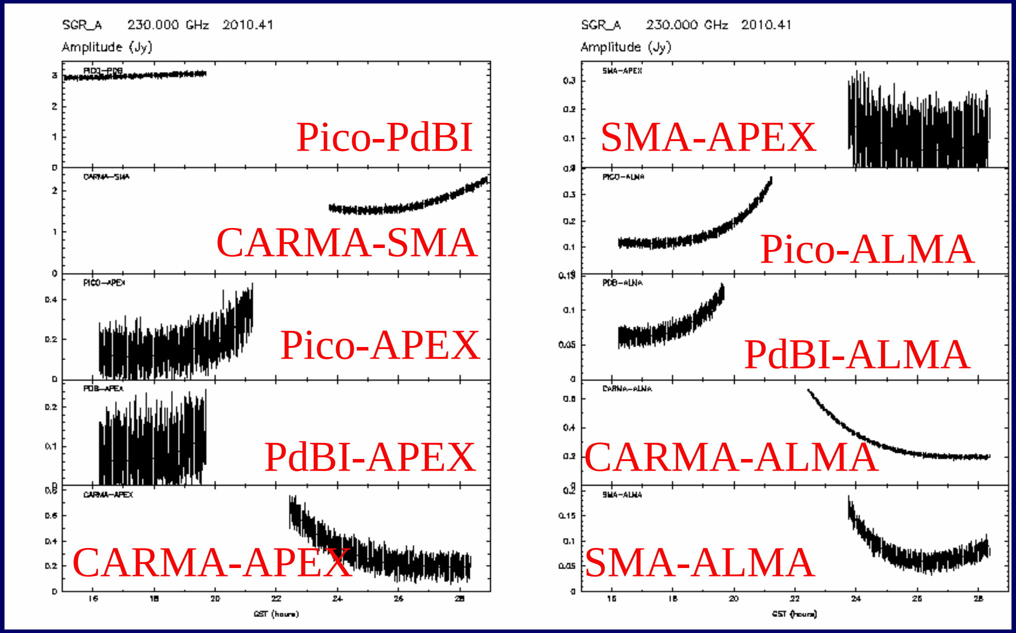
Pico Veleta, Plateau de Bure, SMA,CARMA, APEX, ALMA

point source of size: 0.030 mas

uv-coverage:




visibilities:



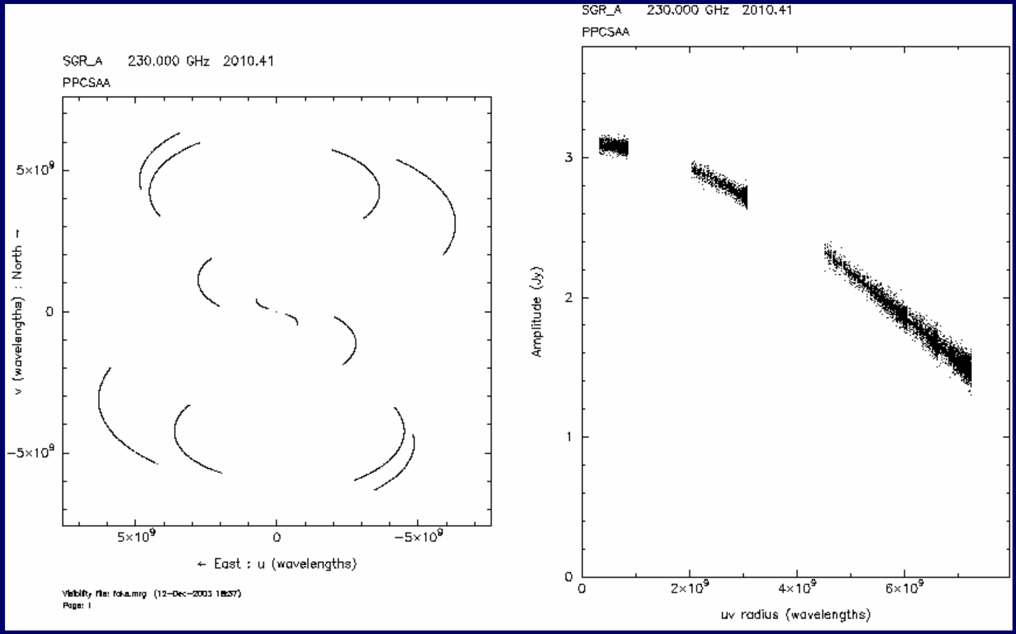

intrinsic size 4.5 $R_S$

# Simulation of 1 mm VLBI of SgrA*

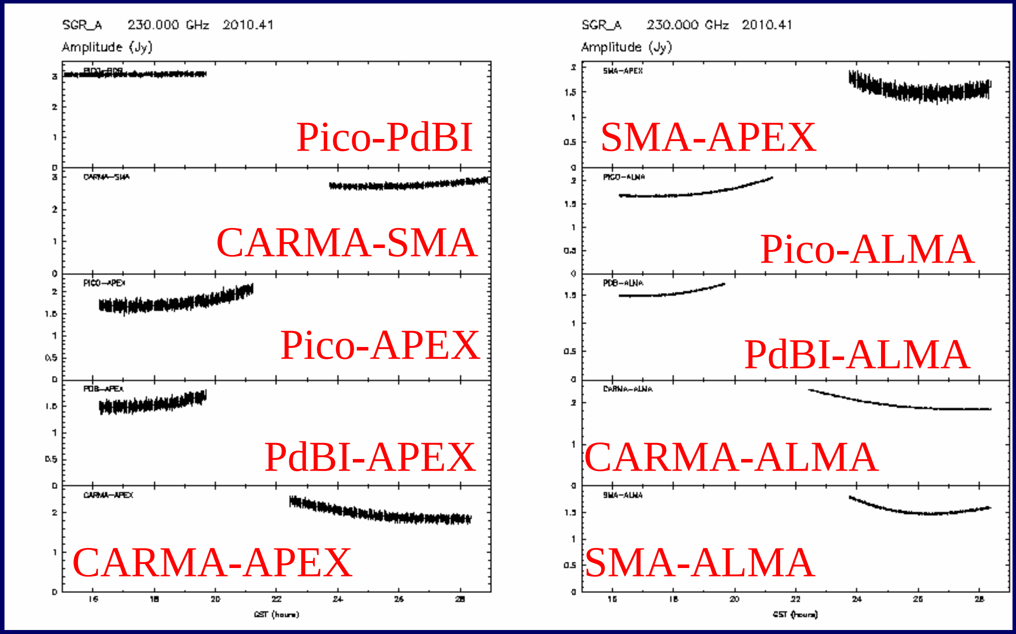
Pico Veleta, Plateau de Bure, SMA,CARMA, APEX, ALMA

point source of size: 0.013 mas

uv-coverage:




visibilities:




intrinsic size 2 $R_S$

# Future 1mm-VLBI – Detection Limits

## (7σ in [mJy])

| | Pico | CARMA | Kitt Peak | HHT | SMA | APEX | ALMA |
|---|---|---|---|---|---|---|---|
| PdBure | 76 | 66 | 214 | 207 | 100 | 132 | 17 |
| Pico | — | 80 | 260 | 252 | 122 | 161 | 21 |
| CARMA | — | — | 226 | 220 | 105 | 139 | 18 |
| Kitt Peak | — | — | — | 715 | 344 | 455 | 59 |
| HHT | — | — | — | — | 333 | 441 | 57 |
| SMA | — | — | — | — | — | 212 | 28 |

**assume: 1 Gbit/s, 10 s coherence time, 2 bit sampling**

expected detection limits:

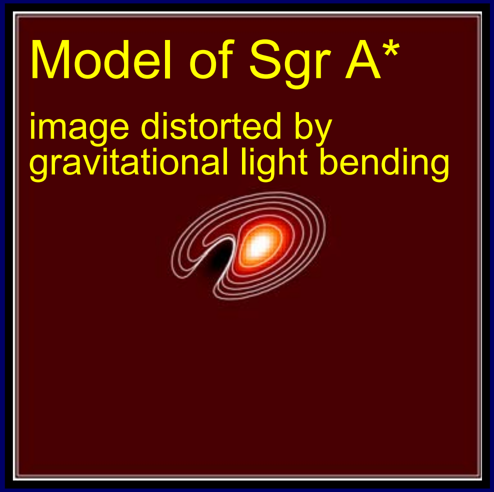
Pico–HHT–KP: 250 mJy

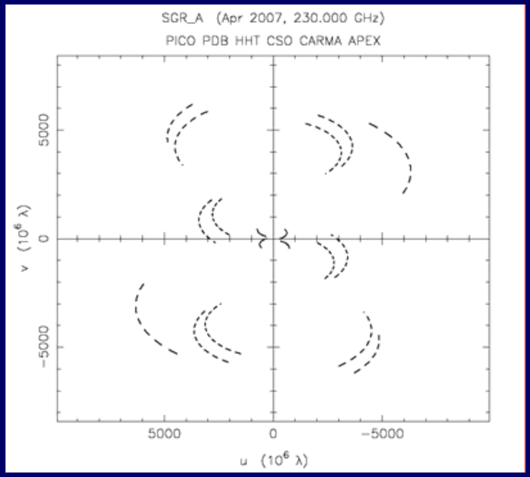
plus P.de Bure /Carma: ≥ 70 mJy

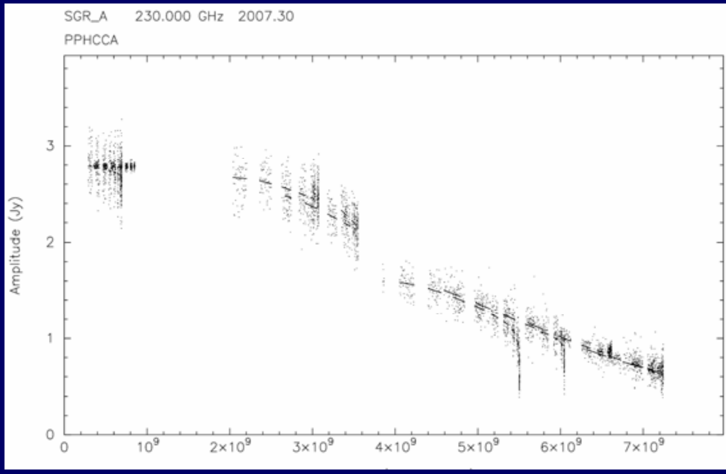
plus ALMA : ≥ 17 mJy

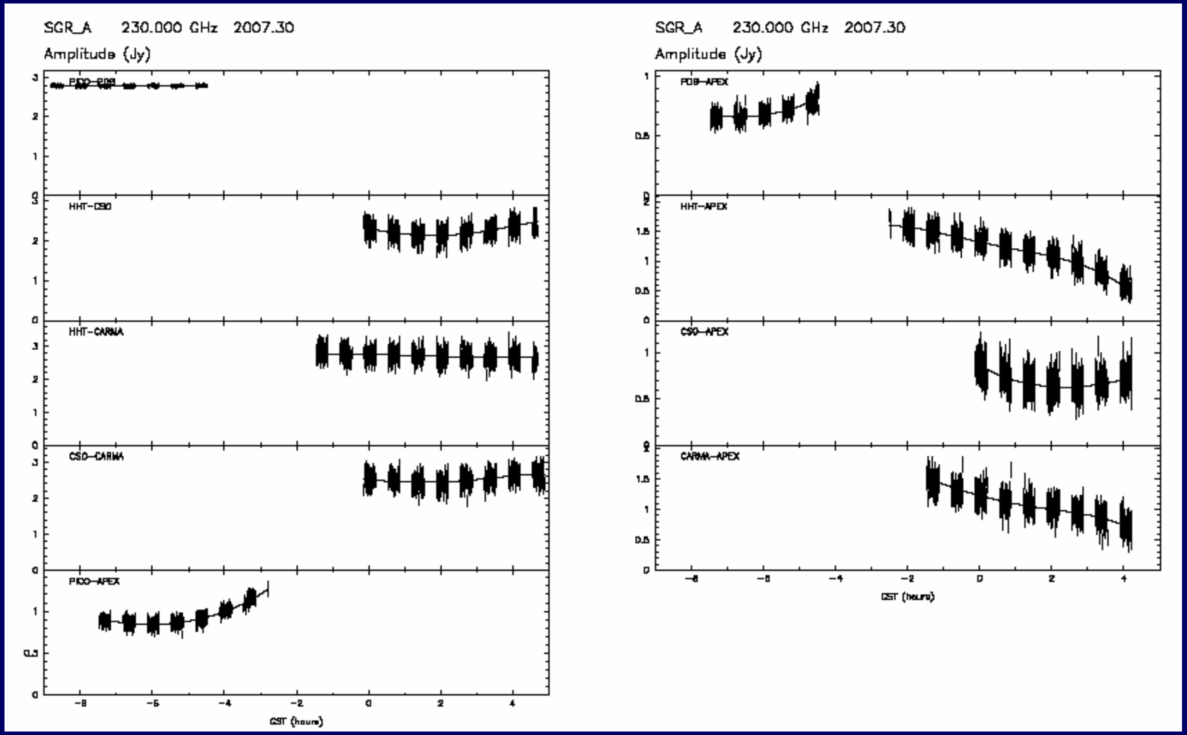

numbers will improve if WVR + phasecorr. is applied

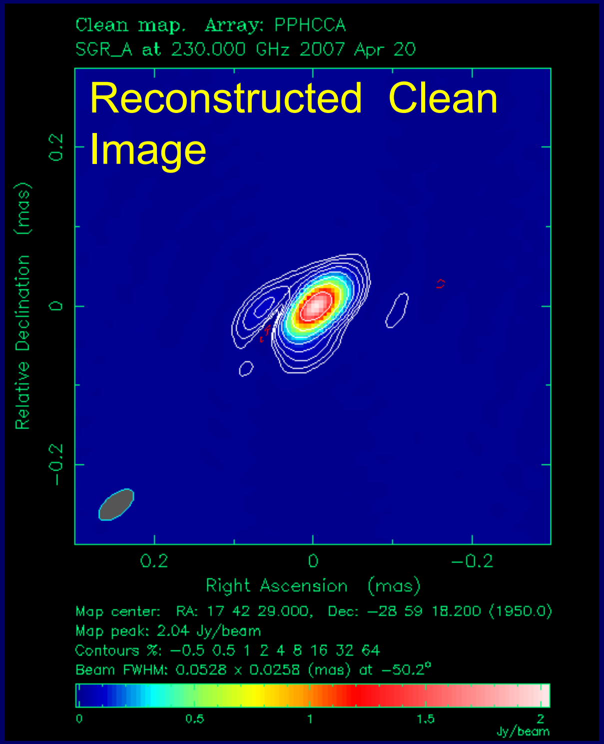
# Simulation of 230 GHz VLBI of Sgr A* with IRAM (Pico Veleta, Plateau de Bure), HHT, CSO/SMA, CARMA



# Conclusions

- The Global 3mm VLBI Array (GMVA) provides up to 40 μas resolution and 50 – 300 mJy  baseline sensitivity.
- Scheduling, observing, correlation and export into AIPS FITS are done in a user-friendly manner by experts in contact with P.I. → *Just make use of  it !*
- more than ~130 continuum sources are doable, not counting spectral line observations.
- more sensitivity expected when adding other telescopes (GBT, CARMA, LMT, ALMA) and when VLBA supports 1Gbit/s recording. The application of atmospheric phase corrections (WVRs) and further increased recording bandwidths (> 2 Gbps) will help to push the sensitivity to the mJy – level.
- Global VLBI at 2mm & 1.3mm is already technical feasible. The further increase of bandwith (2-4 Gbit/s) should facilitate imaging of compact sources with a resolution of  10 - 20 micro-arcseconds at $\nu = \nu_{Rest}$ (1+z) ! (e.g. for z=3 and ν=345 GHz, $\nu_{Rest}$= 1 THz ).
- mm-VLBI monitoring is needed in support of GLAST, Herschel and Planck. The GMVA provides good sensitivity and the smallest observing beam in Astronomy.