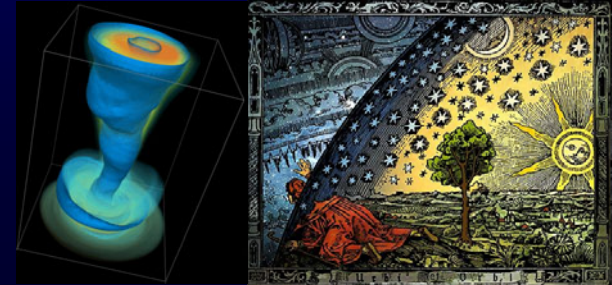
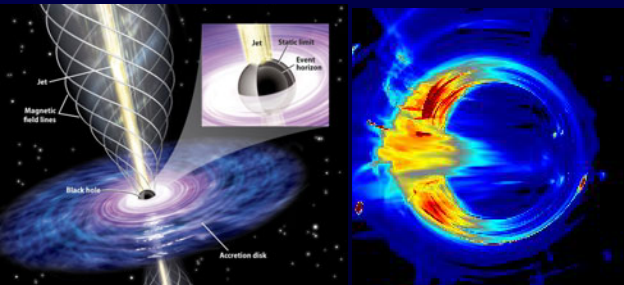


The Global Millimeter VLBI Array – Technique and Science

T.P.Krichbaum

Max-Planck-Institut für Radioastronomie
Bonn, Germany

tkrichbaum@mpifr.de



observatory staff technically involved in GMVA operation:

MPIfR: W. Alef, U. Bach, A. Bertarini, T. Krichbaum, R. Porcas, H. Rottmann, et al.

IRAM: M. Bremer, A. Grosz, S. Sanchez, M. Ruiz, et al.

OSO: M. Lindqvist, I. Marti-Vidal, J. Yang, et al.

OAN: P. de Vicente, P. Colomer, et al.

INAF: S. Buttaccio, G. Tuccari, et al.

VLBA: W. Brisken, M. Claussen, V. Dhawan, et al.

GBT: F. Ghigo, T. Minter

KVN: T. Jung, B.W. Sohn, S.S. Lee, et al.

Understand how Black Holes launch and accelerate jets

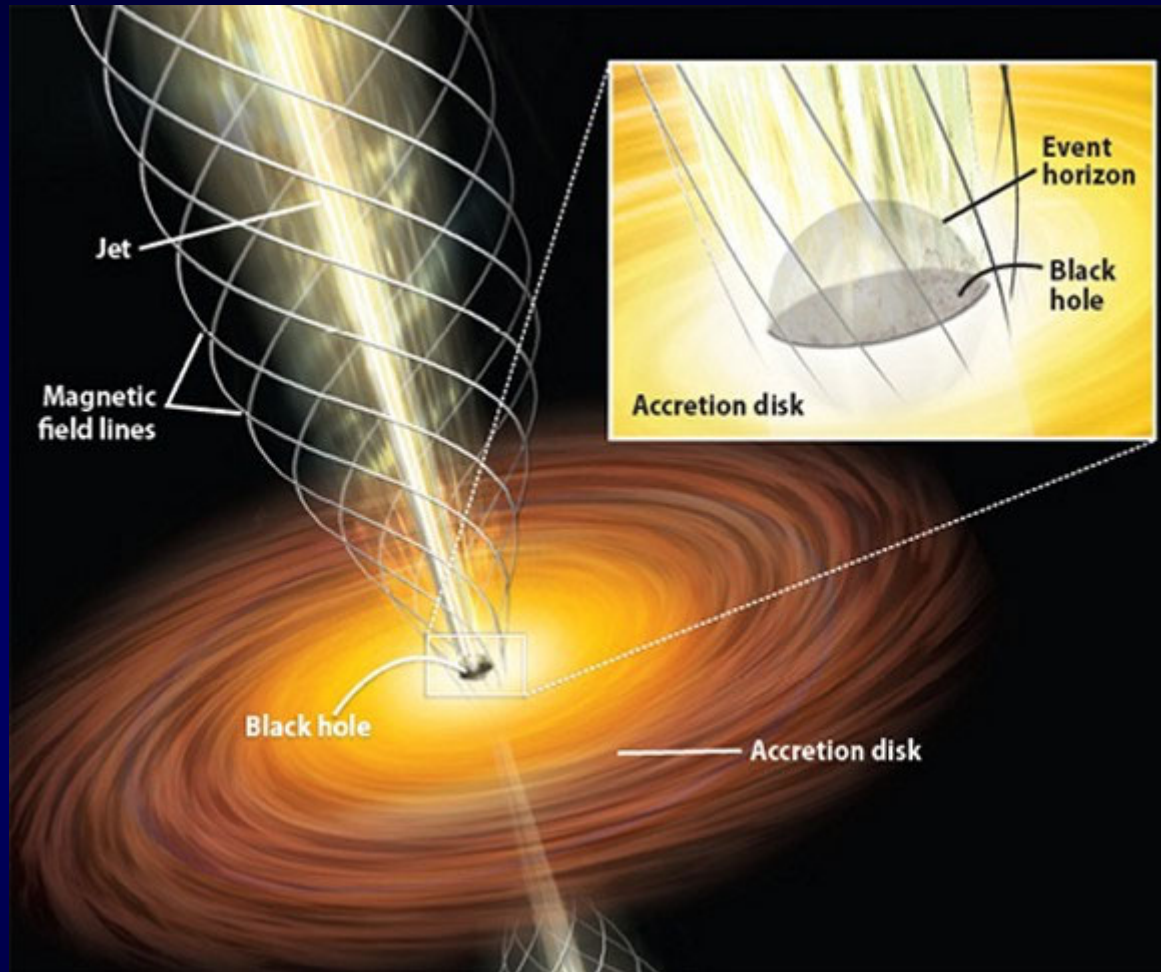
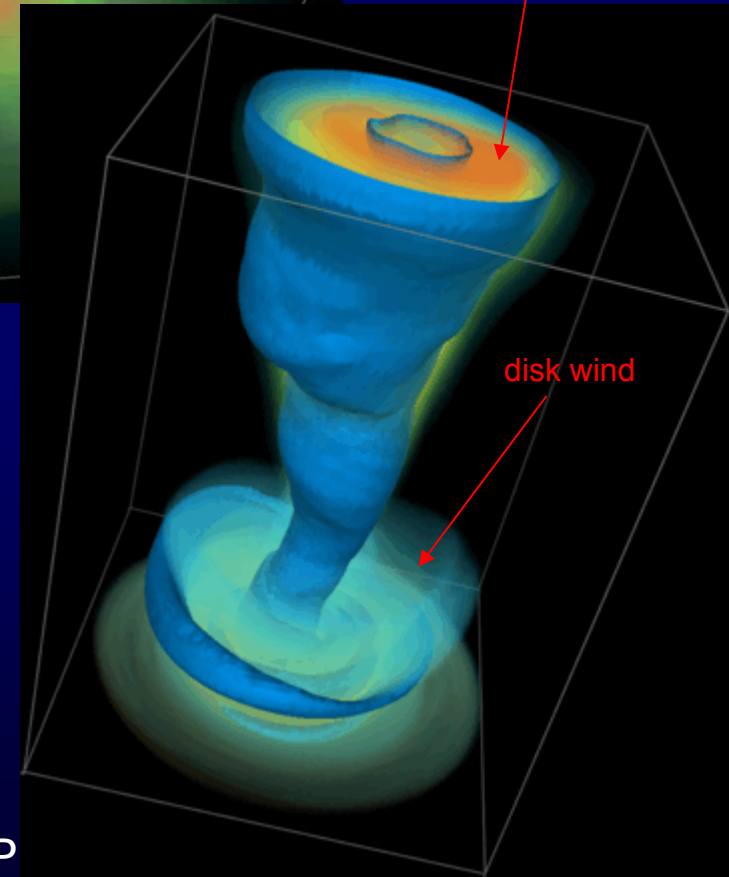
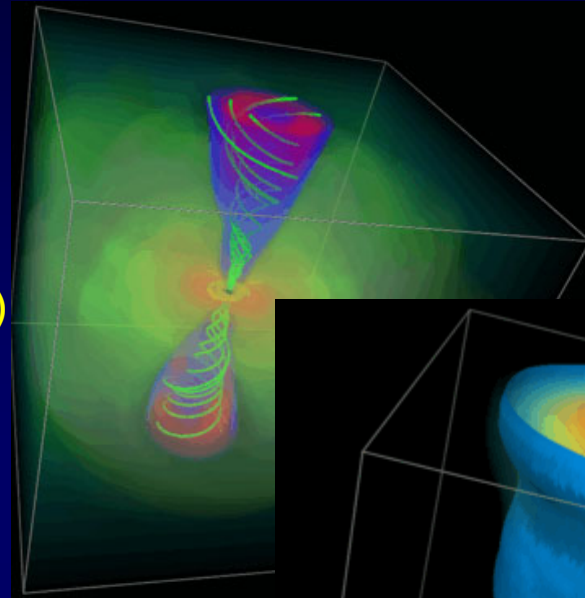


Image Credit: Astronomy/Roen Kelly

- VLBI at mm- λ overcomes opacity barrier
- mm-VLBI and space-VLBI provide required spatial resolution

Simulations: GR-MHD jets are efficient energy extractors, and remain collimated and stable

- Full 3D-GRMHD simulation of accreting and rapidly rotating BH (advection of vertical B fields)
- B-field configuration (dipole, multipole) leads to different jet speeds
- Lorentz factors of $\gamma \sim 10$ now possible (for dipole fields)
- strong collimation (< few degree)
- internal sheath/spine structure of jet
- jet outflow is stable, (kink) instabilities do not disrupt jet
- FRI/II dichotomy may be explained by initially different B-field configuration



→ need high resolution mm-VLBI monitoring in I & P

VLB-Arrays observing at mm-wavelength

- 43 GHz: VLBA(10), EVN (5), KaVa (7), HSA (12+)
- 86 GHz: GMVA(15), VLBA(8), HSA(10), KVN(3)

- 129 GHz: KVN(3), PV, PdB, SMTO,
no joined activity yet

- 230 GHz: PV, APEX, SMTO, SMA/JCMT, LMT, → EHT
planned: ALMA, SPT, NOEMA, GLT,

future:

- 350 GHz: PV, PdB, SMTO, SMA/JCMT, APEX, ALMA, SPT, KP12m

The Global Millimeter VLBI Array (GMVA)

Imaging with $\sim 45 \mu\text{as}$ resolution at 86 GHz

Baseline Sensitivities

in Europe:

20 – 150 mJy

in US with GBT:

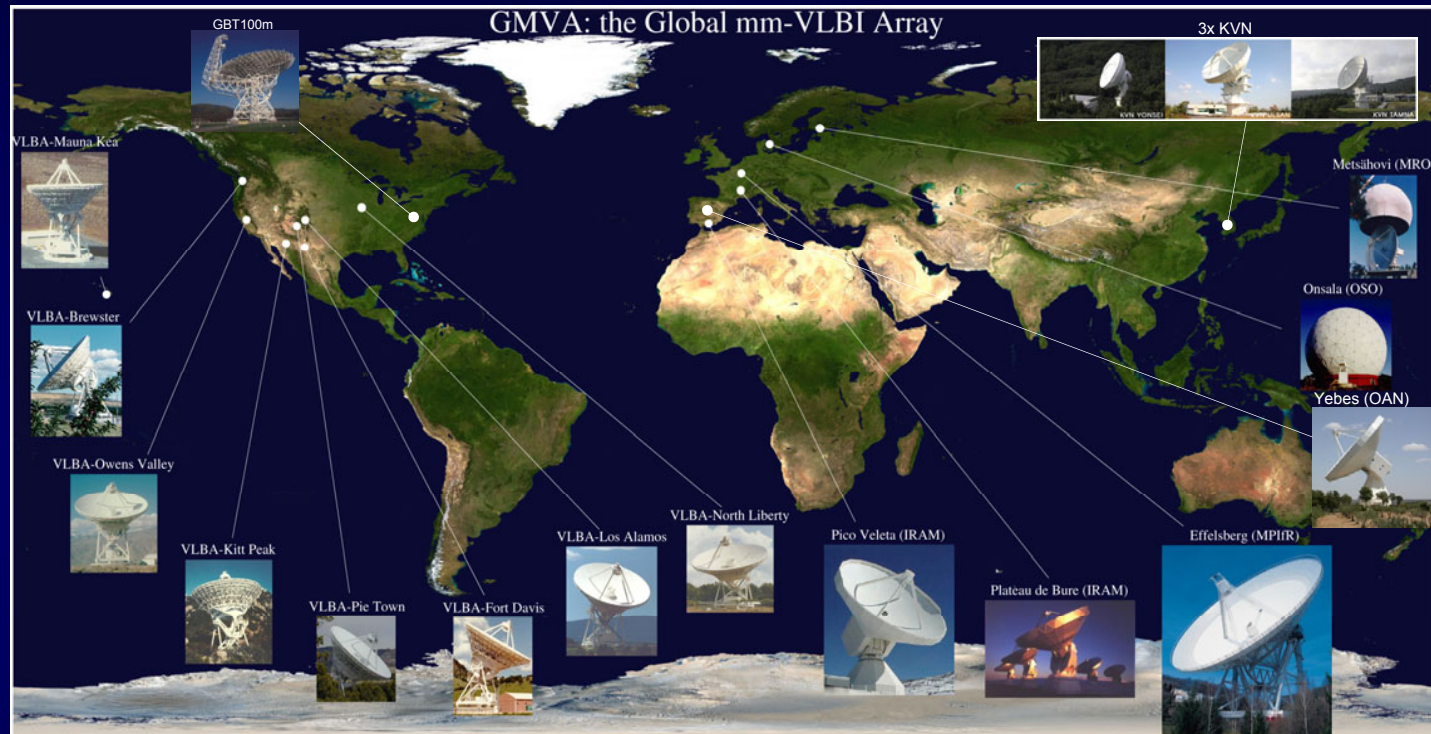
20 – 150 mJy

best transatlantic:

10 – 50 mJy

Array:

0.5 – 1 mJy / hr



(assume 7σ , 100 sec, 2 Gbps)

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

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), Yebes (40m), KVN (3 x 21m), planned: SRT, NOEMA, ...
- America: 8 x VLBA (25m), GBT (100m), planned: LMT, ALMA, ...

Proposal deadlines: February 1st, August 1st

3mm VLBI Array Sensitivities

Array	Stations	Baseline [mJy]	Array [mJy/hr]	12hr Map [SNR]	Comment
VLBA, 2 Gb/s	VLBA(8)	> 164	2,33	1.0e03	no HN, no SC
GMVA, 2 Gb/s	VLBA+EB+PV+PB+ON+MH	> 33	0,86	2.8e03	68 mJy VLBA-IRAM
+ Yb	present GMVA+Yebes	> 27	0,67	3.7e03	68 mJy VLBA-Yb
+ LMT + GBT	present GMVA+Yebes+LMT+GBT	> 10	0,30	8.2e03	31 mJy VLBA-GBT
+ ALMA	present GMVA+Yebes+LMT+GBT+ALMA	> 5	0,19	12.9e03	5 mJy ALMA-GBT

assuming: 512 MHz bandwidth (2 Gbit/s), t=20 sec, 7sigma fringe detection, 2 bit sampling

- Combining European mm-telescopes with the VLBA improves the angular resolution by factor ~ 2 and imaging sensitivity by a factor of $\sim 2 - 3$.
- The addition of telescopes with large collecting area (GBT, LMT, SRT, ...) gives another factor of $2 - 3$.
- Participation of ALMA leads to mJy sensitivities and will improve the overall sensitivity by a factor of $\sim 3 - 5$.
- Another factor of $\sqrt{\text{rate}/2\text{Gbps}}$ in sensitivity can be obtained via a further increase of the observing bandwidth.

GMVA Station details

- Effelsberg : RDBE or DBBC2, 3mm/7mm switch takes 0.5 hrs,
new Q-band in 2017
- Pico Veleta: dual pol, 2 independent receivers, Nasmyth mount !!, 32 Gbps upgrade
- PdBure : 5x12m, old Mk5A, limited to 1 Gbps (2 pols, each 8 x 16 MHz)
new polyfix correlator > 2017, equip. single PdB with broad band?
- Onsala : new dual polarization receiver since May 2015
- Yebes : 3mm receiver supports 1 polarization, improved surface and pointing
- Metsahovi : new 3mm dual pol receiver, 1st fringes Sep. 2015
- VLBA : continuous cal (RDBE) replacing Tsys from legacy system
- GBT : good at night time, time variable DPFU, need frequent AutoOOF
- KVN : limited to 1 Gbps, now supports 32 MHz IFs, join GMVA in 2017
- LMT : best effort availability, RDBE-S, 1 polarization per module
not yet part of GMVA, shared risk, need local contact
- Noto : only 7mm, can be combined with VLBA, YS and/or EB in switched
3mm/7mm observations

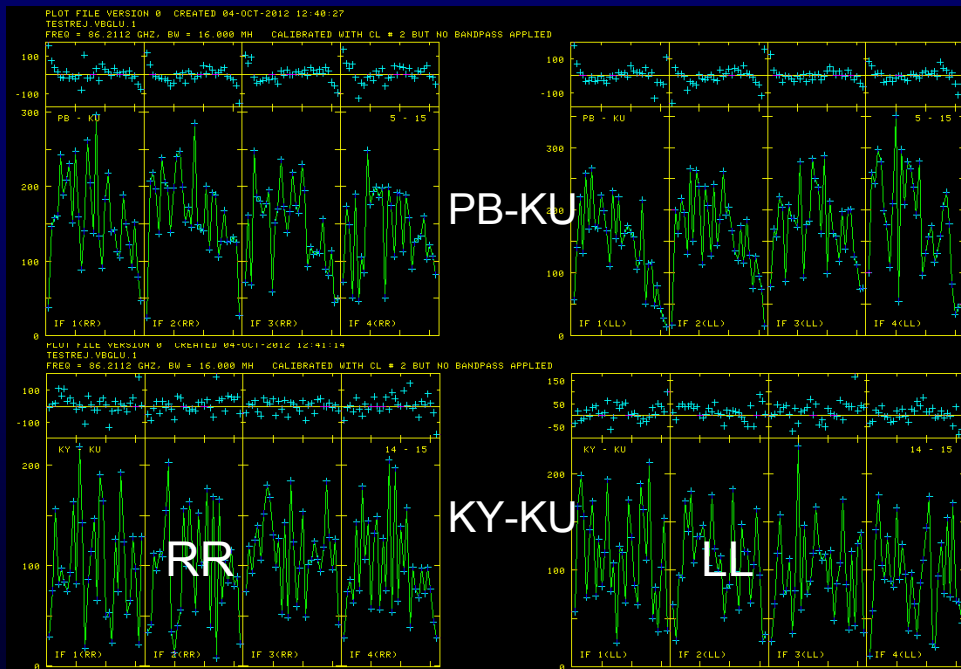
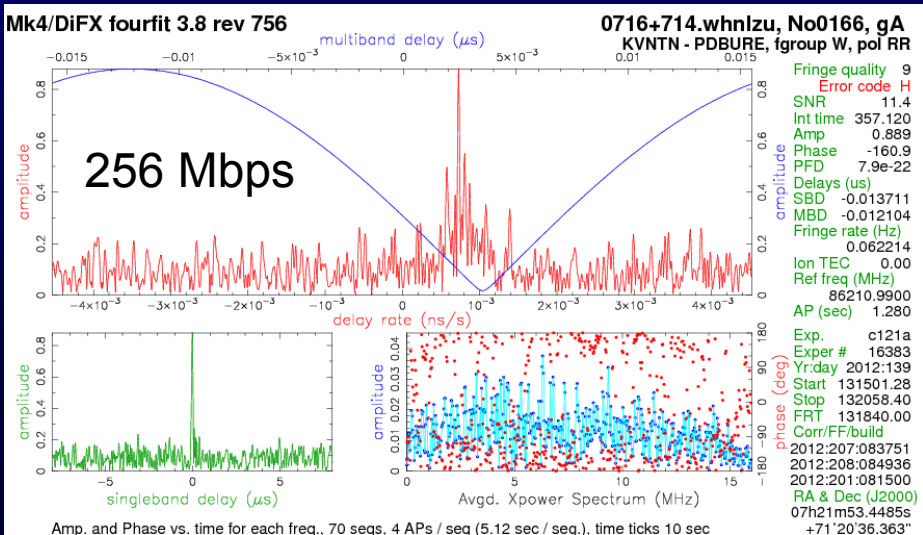
First Fringes between KVN and GMVA (86 GHz, May 2012)



3 x 21 m, baselines 305 – 478 km

0716+714

KVN – PdBI: SNR ~ 11 on 1 Jy source



86 GHz VLBI Fringes from VLBA to KVN

GMVA Session May 2015 (PFB, now 1 Gbps)

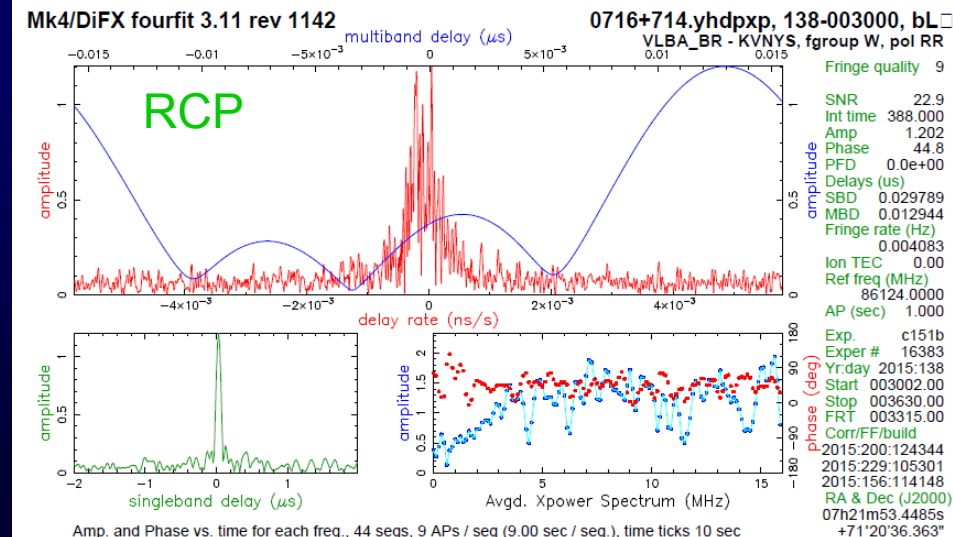
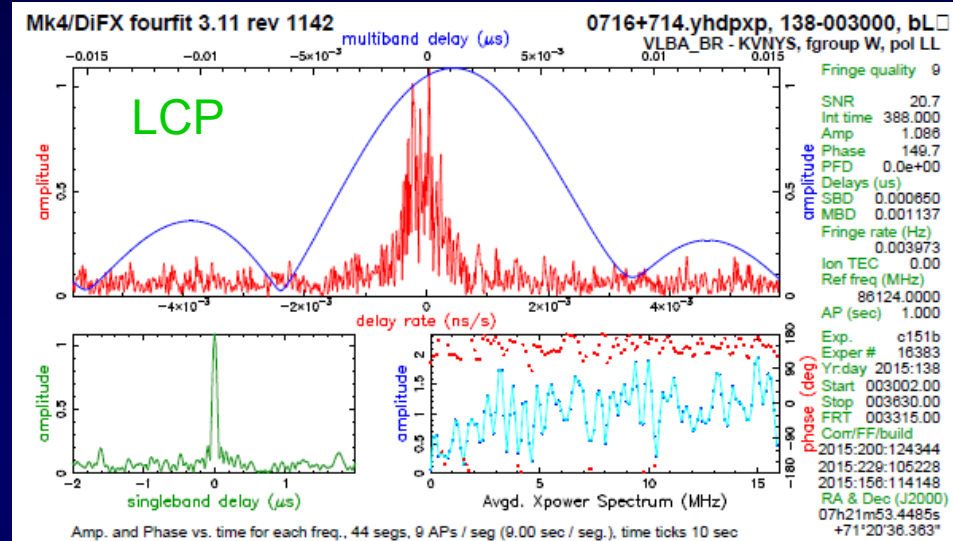


KVN Yonsei – VLBA Brewster:

$B = 7860 \text{ km}$

$\text{SNR} \sim 22$ on 0716+714 ($S_{\text{tot}} \sim 2 \text{ Jy}$)

$t_{\text{int}} = 388 \text{ sec}$, 1 Gbps





Green Bank 100m telescope participates
in GMVA 3mm VLBI observations

1st observations in Feb. 2013

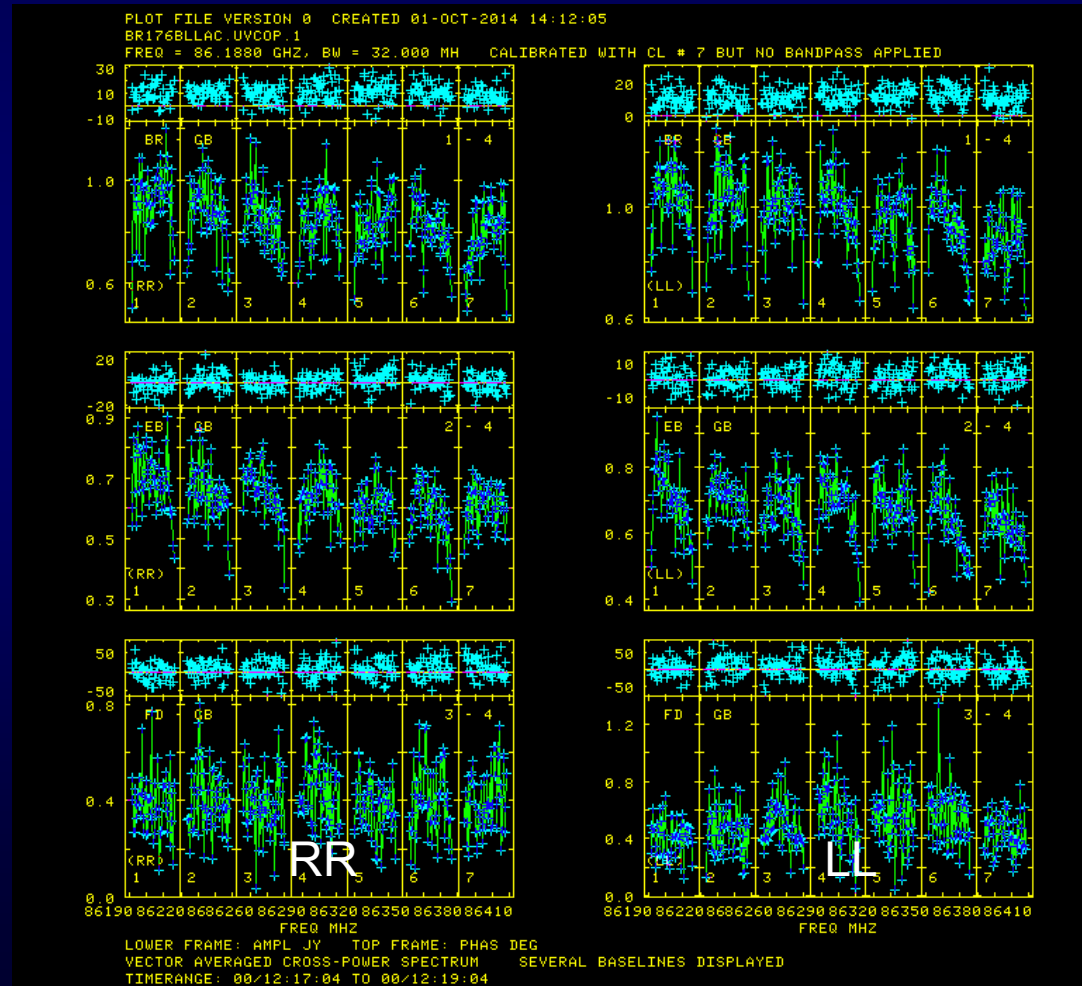
2 Gbps, 1 RDBE, PFB mode

SEFD ~ 164 K

app. eff ~ 0.26 (for $\sigma = 173$ mm)

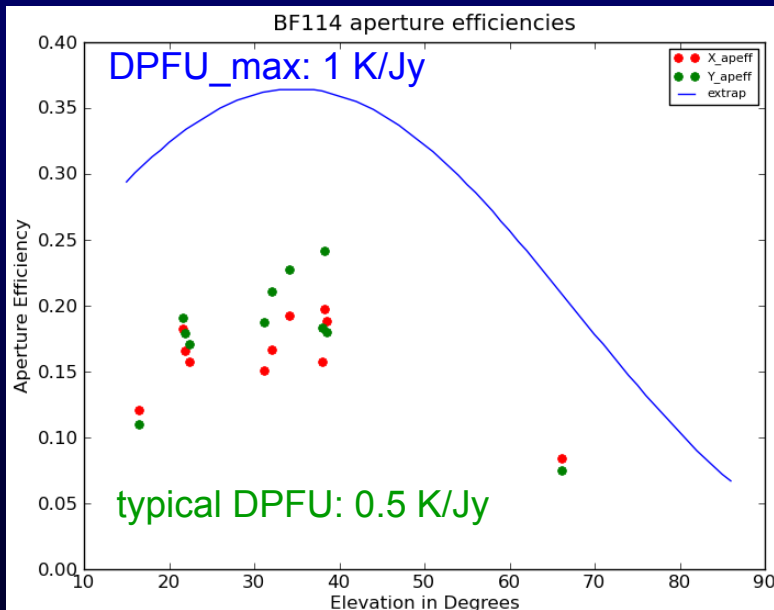
POSSM plot after FRING:

(solint 2min)

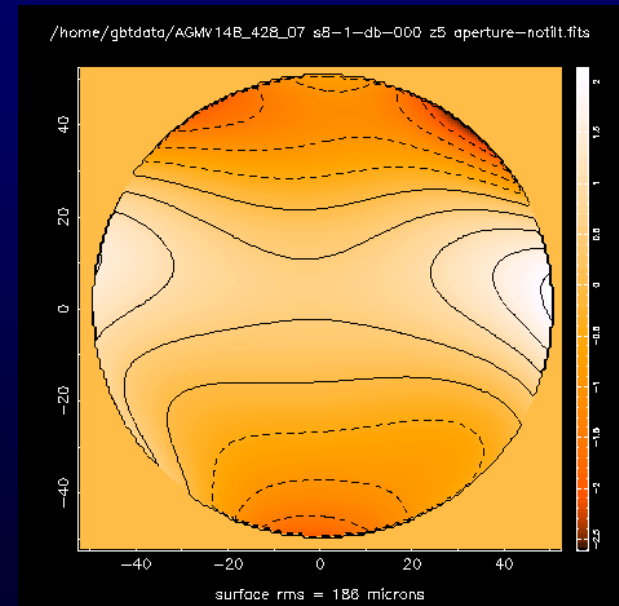


3mm VLBI with the GBT

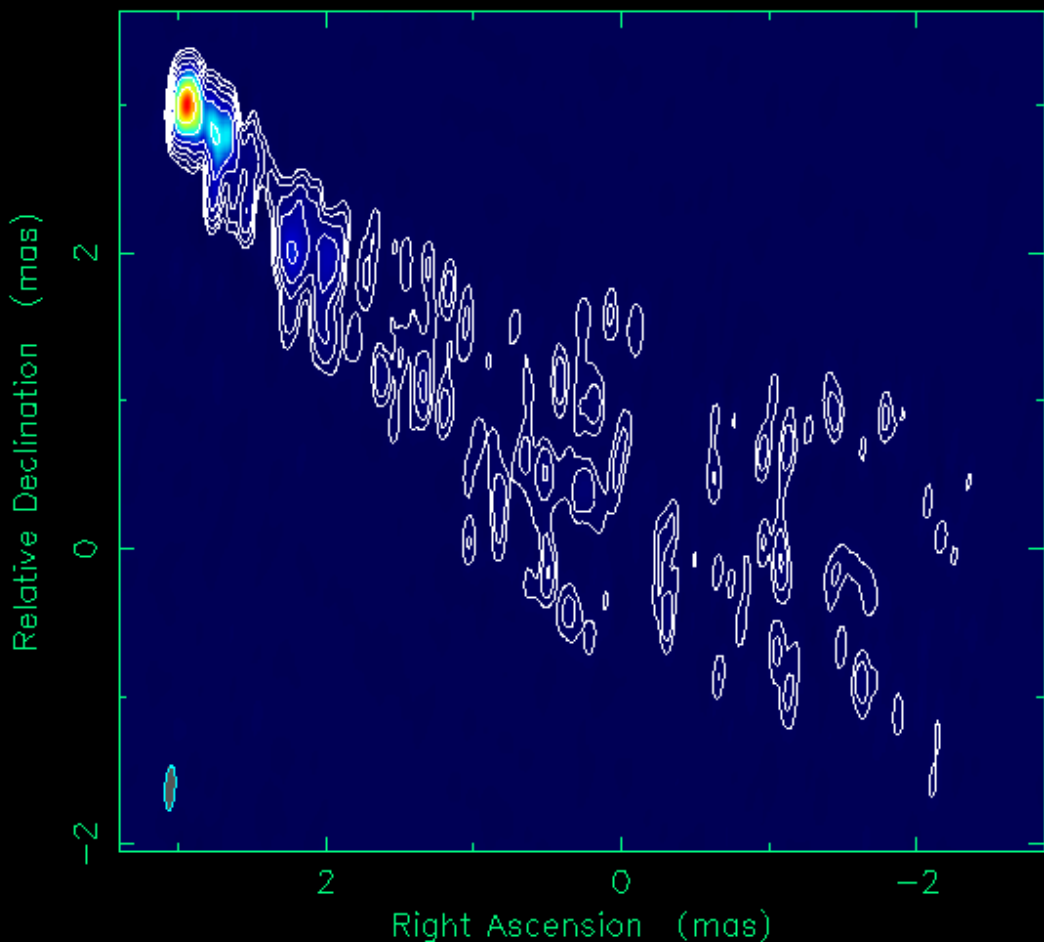
- mainly nighttime observing (+/- 2-3 hrs around sunrise/sunset)
- needs 1hr set up time, to be included in proposal
- active surface adjustment (AutoOOF) every 3-4 hrs, takes 30 min
- regular pointing every 30 mins (inserted in key file), takes 6 min
- slew time limitations (and: large slews require new pointing)
- gain elevation curve depends on actual surface rms
- effective gain can vary with time (by factor 2)



surface residuals:
(180 – 500) μm



Clean LL map. Array: BEFGKLMNOPPY
3C273B at 86.252 GHz

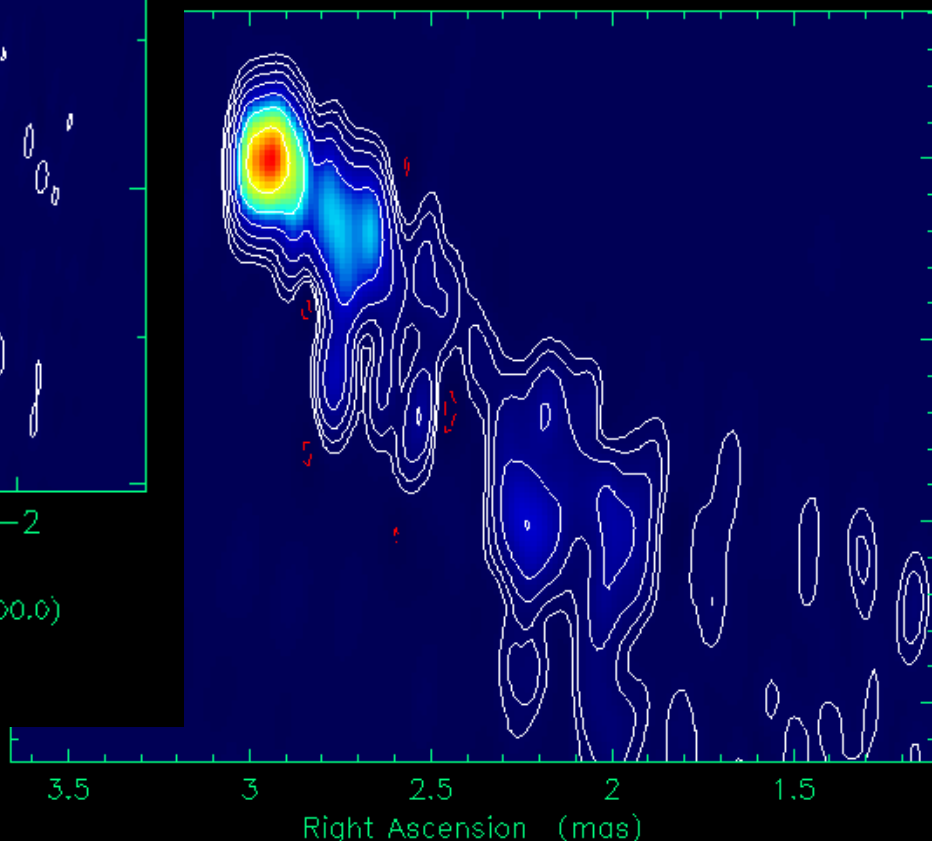


Map center: RA: 12 29 06.700, Dec: +02 03 08.595 (2000.0)
Map peak: 0.929 Jy/beam
Contours %: 1 2 4 8 16 32 64
Beam FWHM: 0.297 x 0.069 (mas) at -3.53°

Example:

3C273 at 3mm with GBT

Map. Array: BEFGKLMNOPPY
86.252 GHz



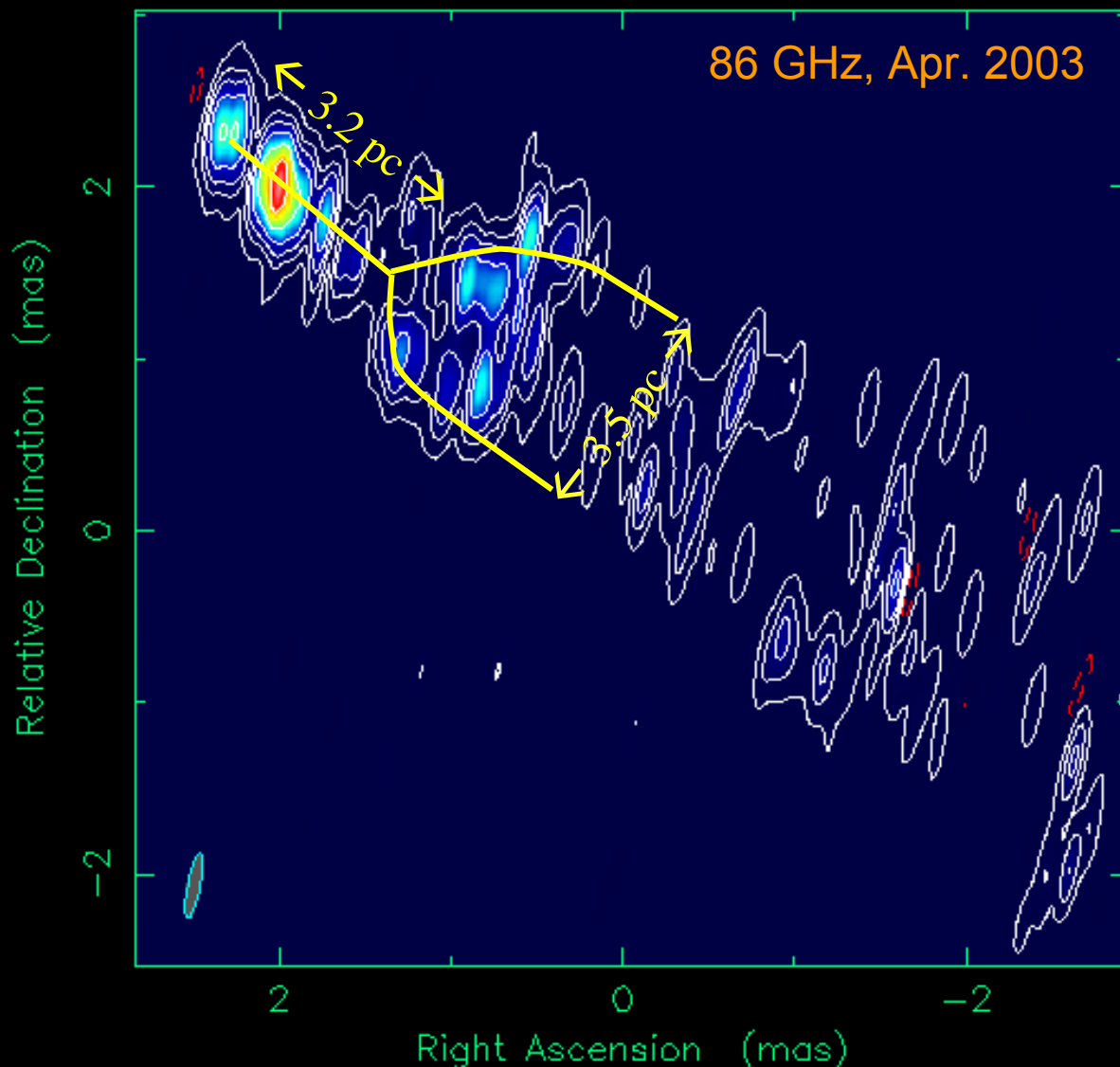
Map center: RA: 12 29 06.700, Dec: +02 03 08.595 (2000.0)
Map peak: 0.826 Jy/beam
Contours %: -1 1 2 4 8 16 32 64
Beam FWHM: 0.22 x 0.06 (mas) at -3°

GMVA(12) with GBT included

Clean LL map. Array: ESPPFdHnNIOvPtKpMkLa
3C273B at 86.222 GHz 2003 Apr 27

3C273:

persistent double rail
structure seen over a
11 yr timescale
at $r > 1\text{mas}$ ($\sim 3\text{ pc}$).

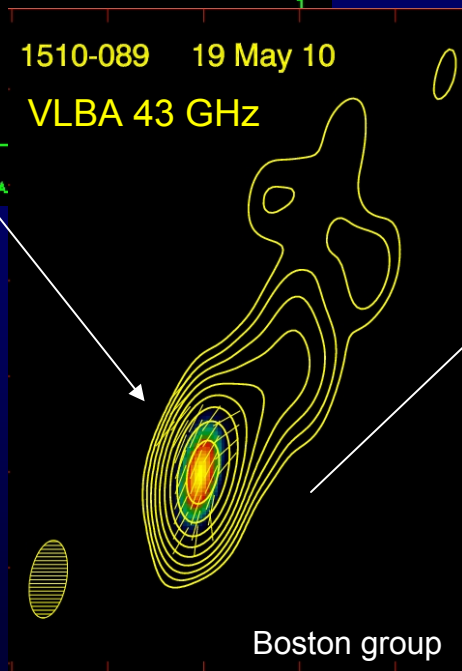
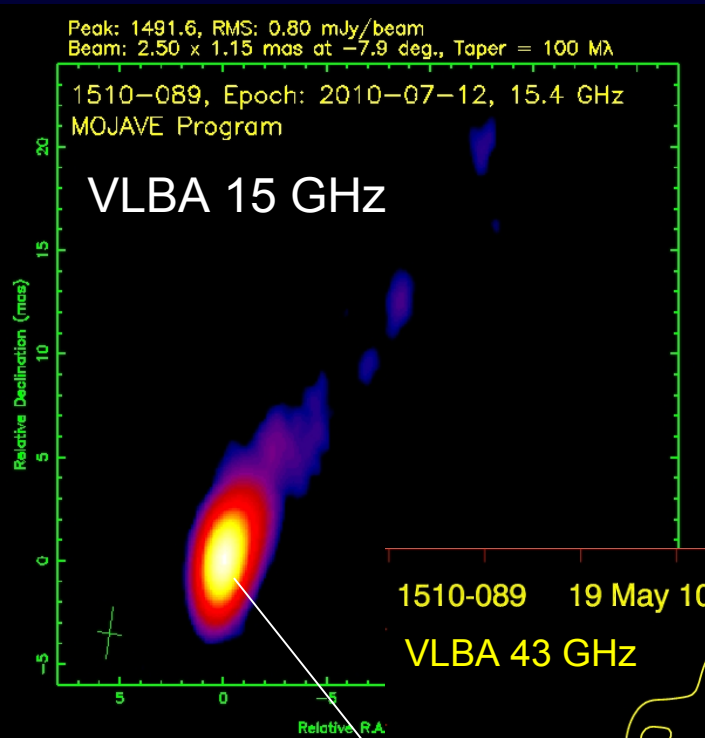


$z = 0.158$

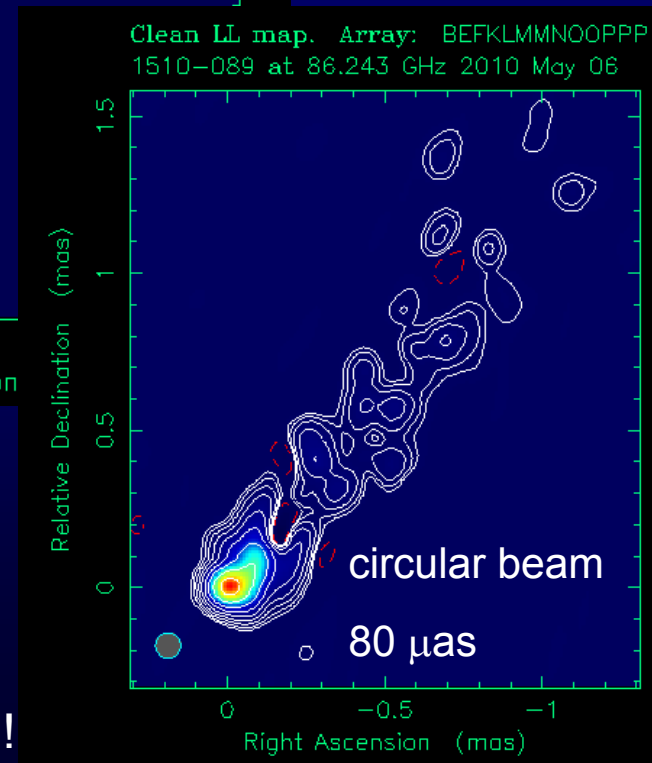
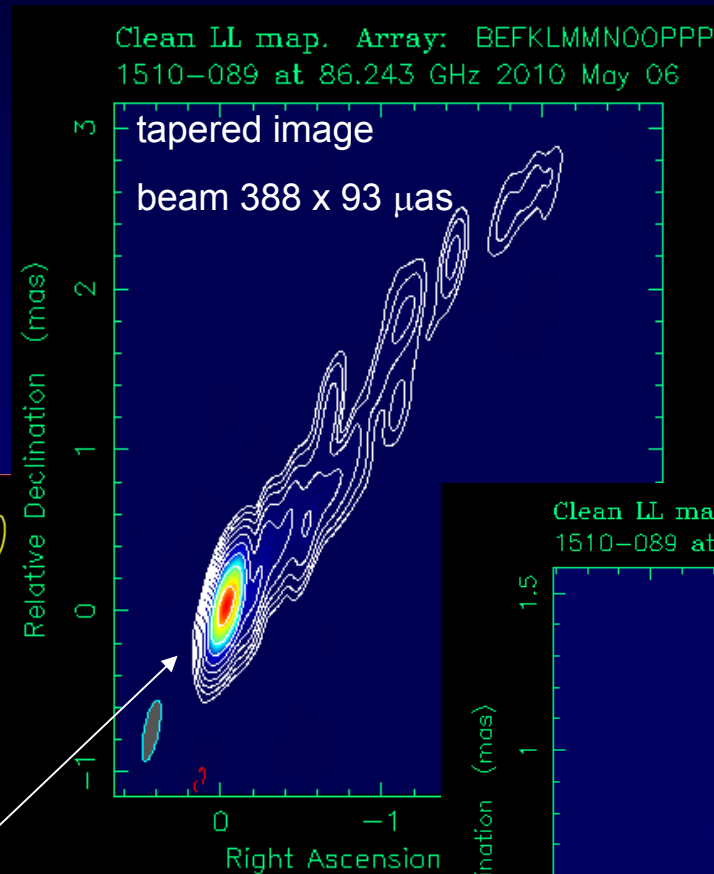
$1\text{mas} \cong 2.7\text{ pc}$

Map center: RA: 12 29 06.700, Dec: +02 03 08.596 (2000.0)
Map peak: 0.51 Jy/beam
Contours %: -1 1 4 8 16 32 64
Beam FWHM: 0.383 x 0.0737 (mas) at -10.6°

1510-089 observed with the GMVA in May 2010



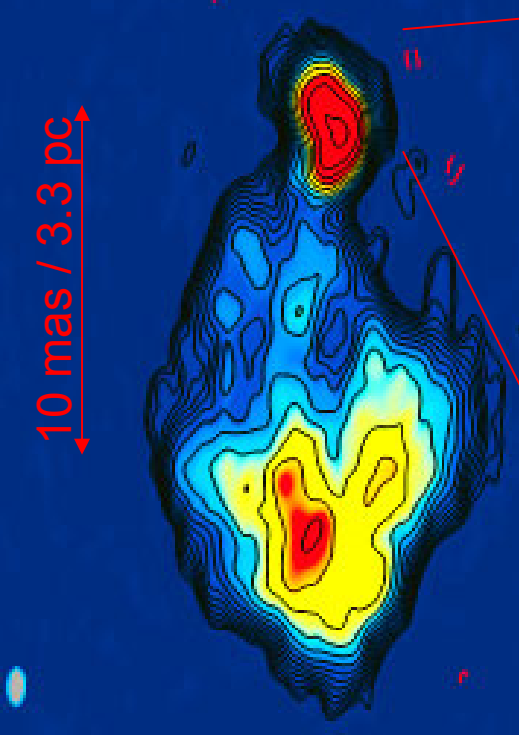
GMVA 86 GHz



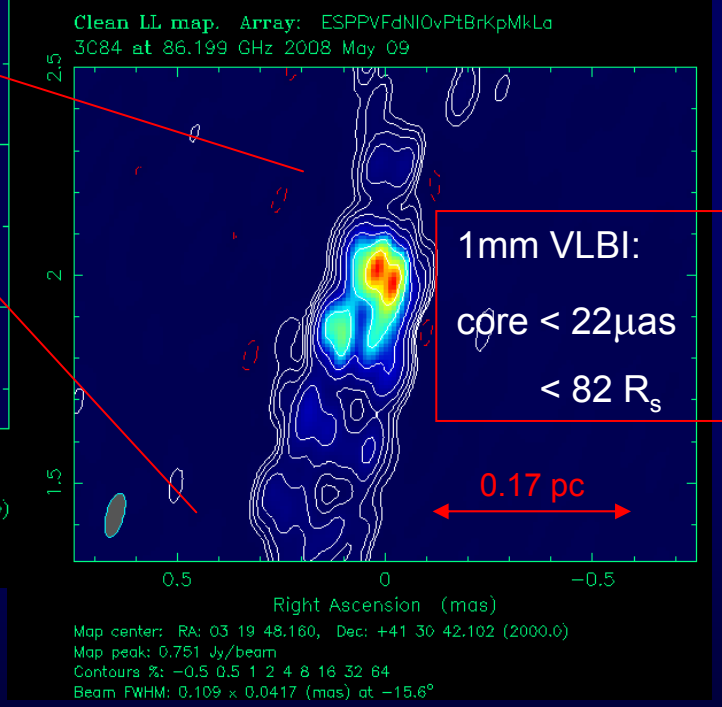
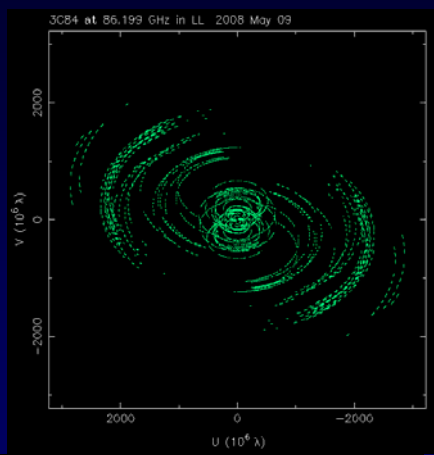
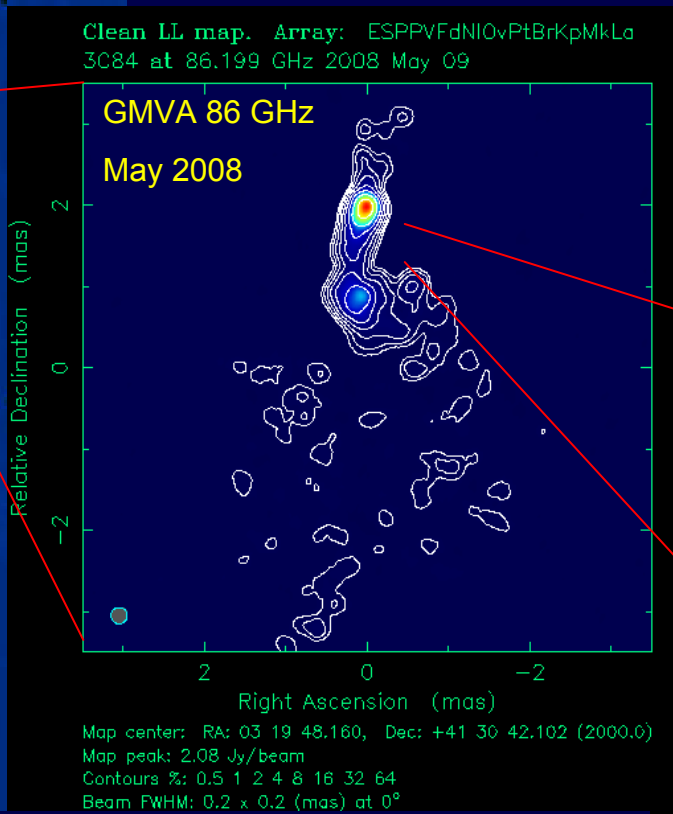
possible bi-furcation at jet base similar to 3C345 and M87 !

86 GHz GMVA images of 3C84: the jet base is transversely resolved !

VSOP 5 GHz
Aug 2001

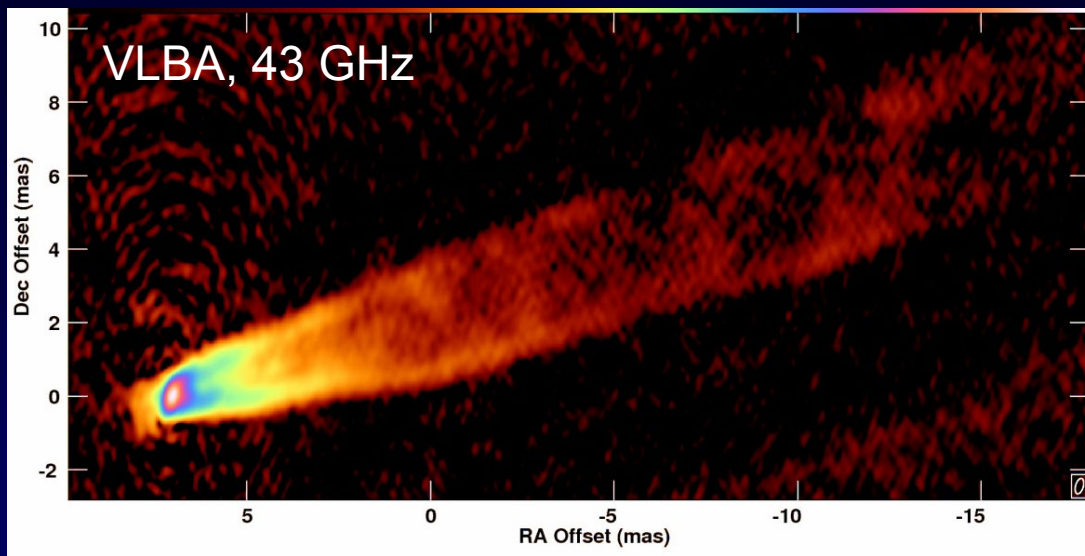


transversely resolved !



Asada et al. 2006

Nuclear region and sub-mas jet base resolved: 42 μ as corresponding to a linear scale of 16 lightdays or 142 R_s in units of the central SMBH → also Radioastron @22 Ghz !

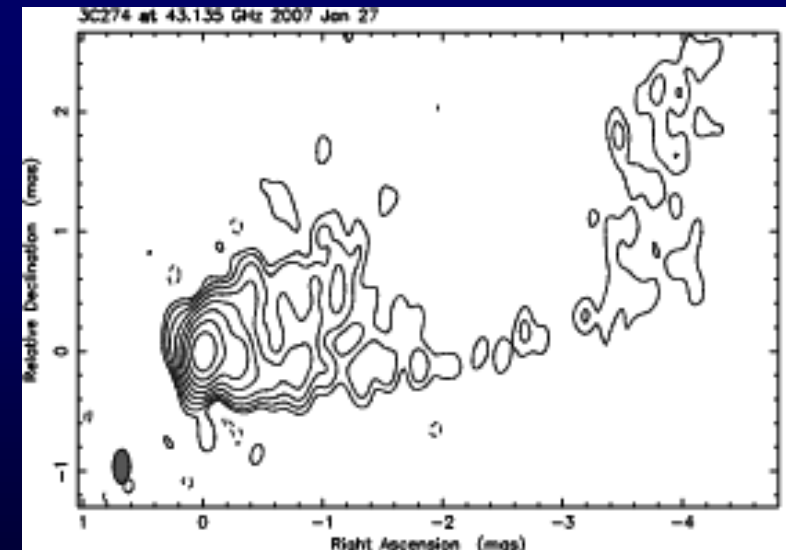


The jet of M87 at mm-wavelength

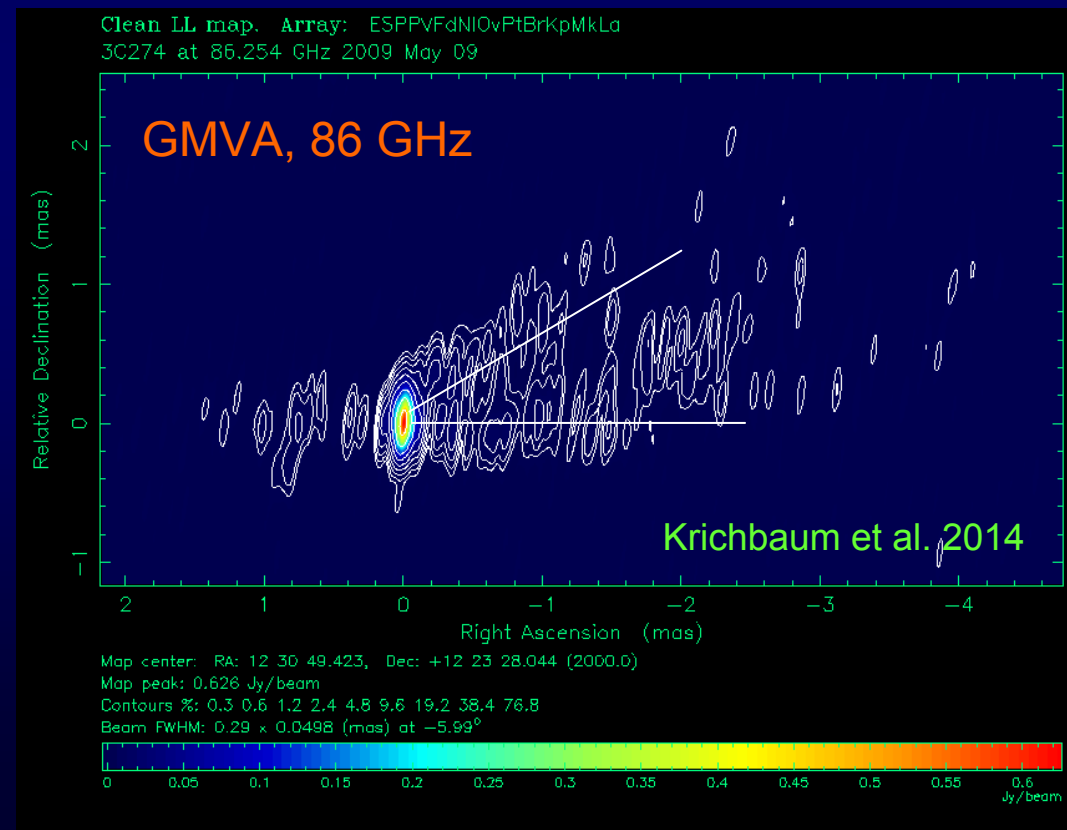
Edge brightened conical jet, at 86 GHz southern rail always appears brighter

Walker et al. 2008

VLBA, 43 GHz

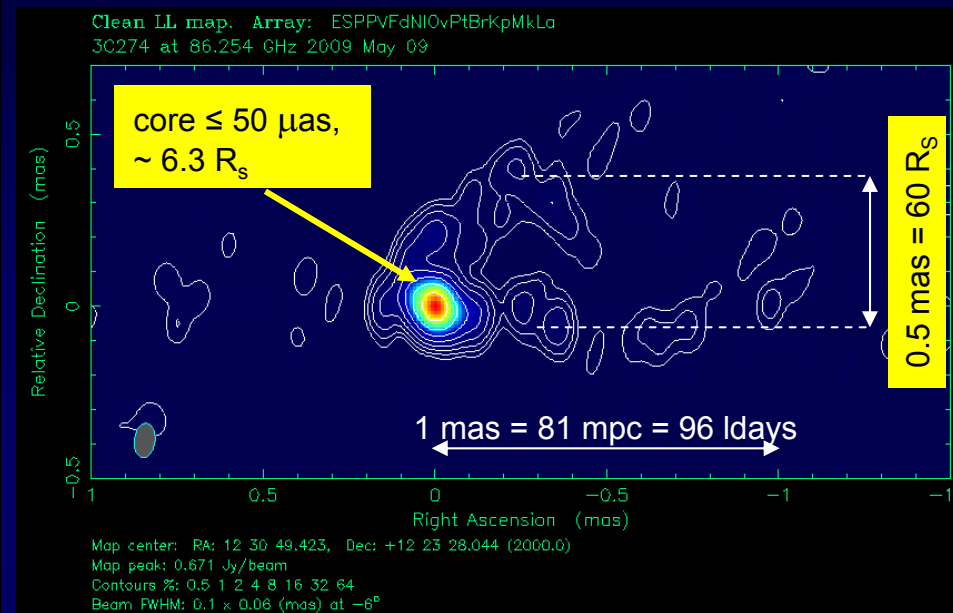
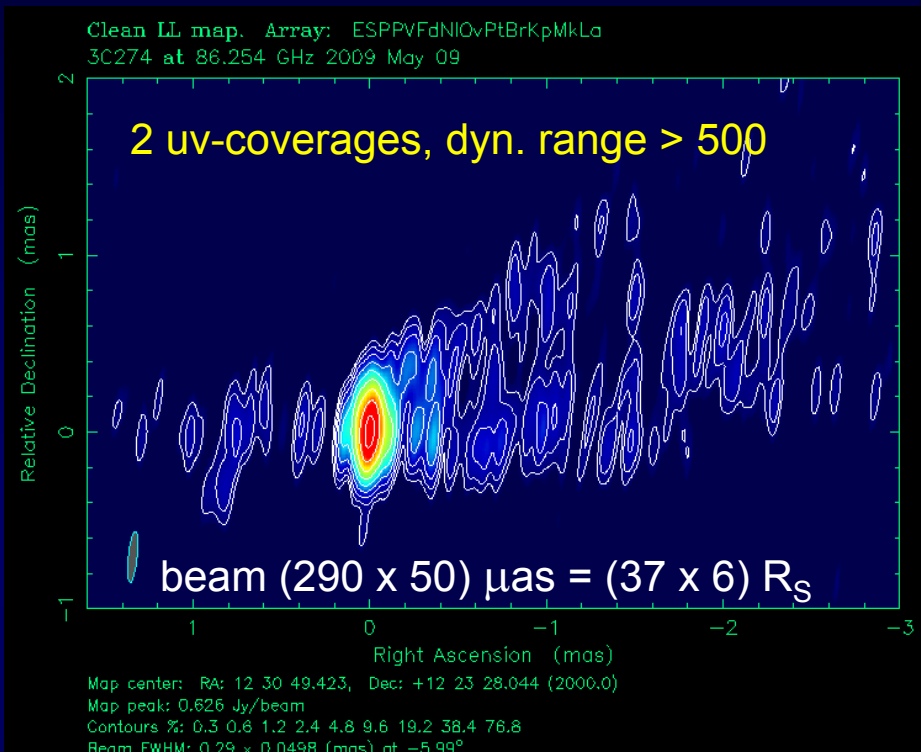


Nakamura & Asada 2013



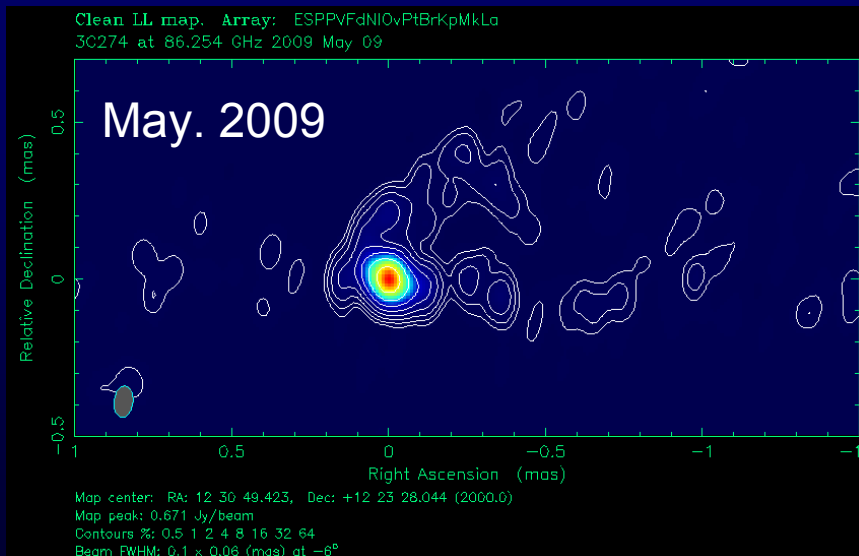
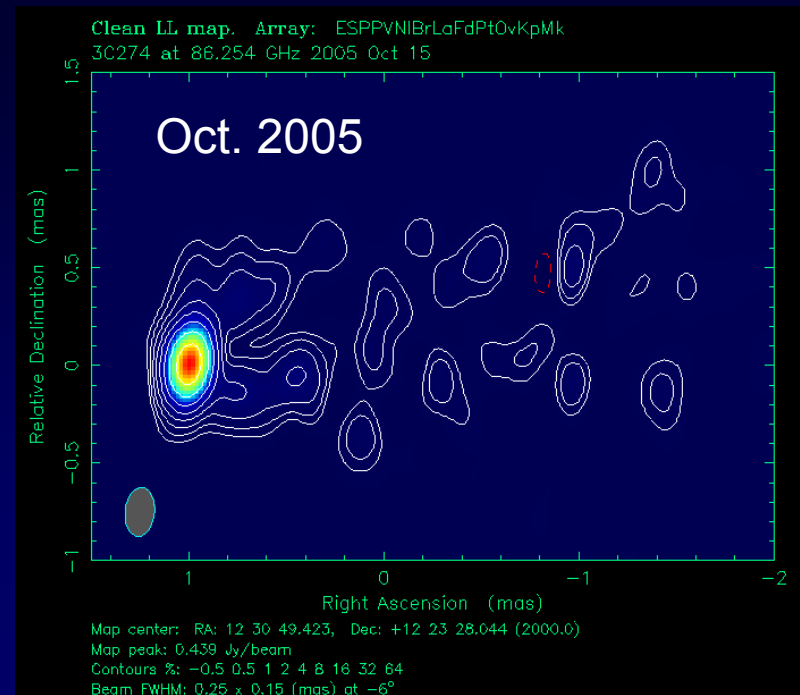
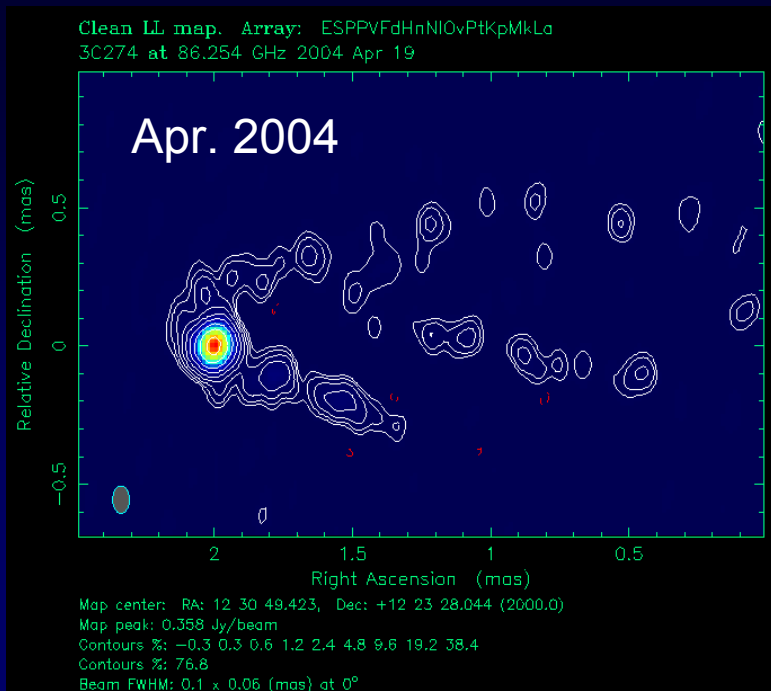
New 86 GHz GMVA images of M87 jet reveal counter-jet

(3mm, May 2009)



Krichbaum et al. 2014

- first time that counter-jet is seen at 3mm
- peak $T_B \sim 2 \cdot 10^{10}$ K at core
- core size $\leq 6 R_s$, expected size of photon ring $41.3 \mu\text{as}$ ($5.2 R_s$)
- jet width $\sim 60 R_s$ at $r = 0.3$ mas ($\sim 40 R_s$)
- brightest peak located in southern filament, but not at jet apex ??



slightly super-resolved
3mm maps of M87

some variability but
basically consistent
structure over years

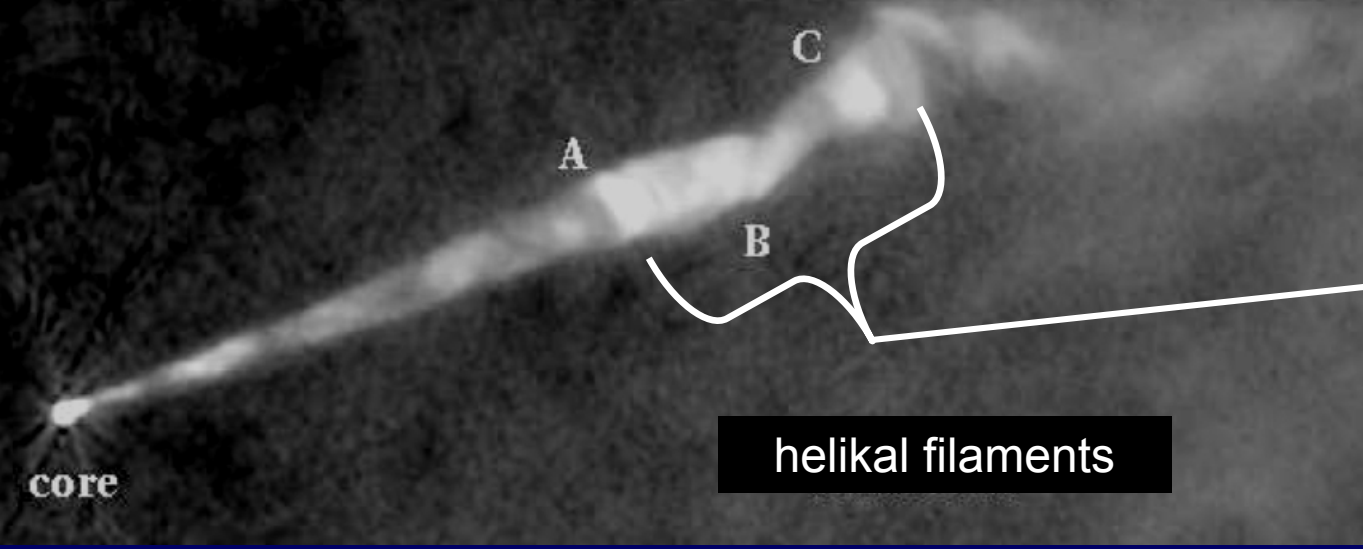
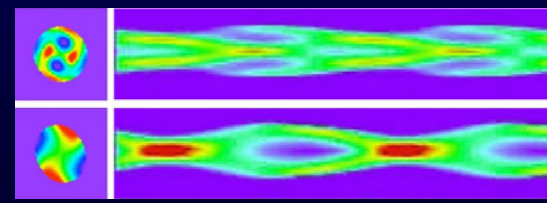
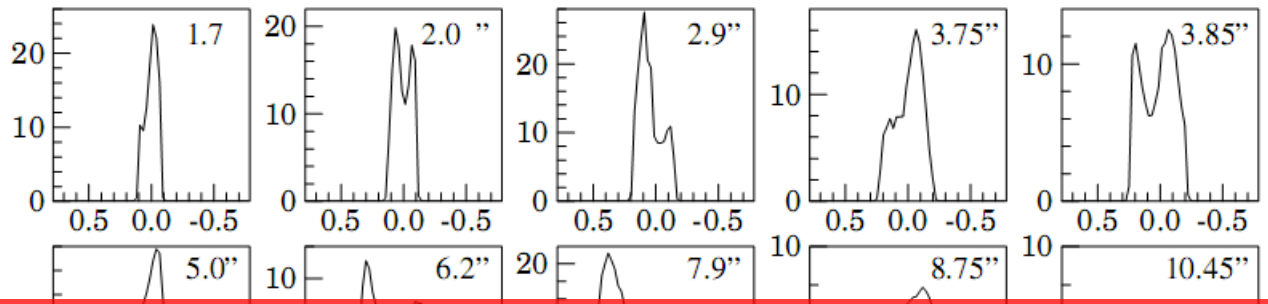
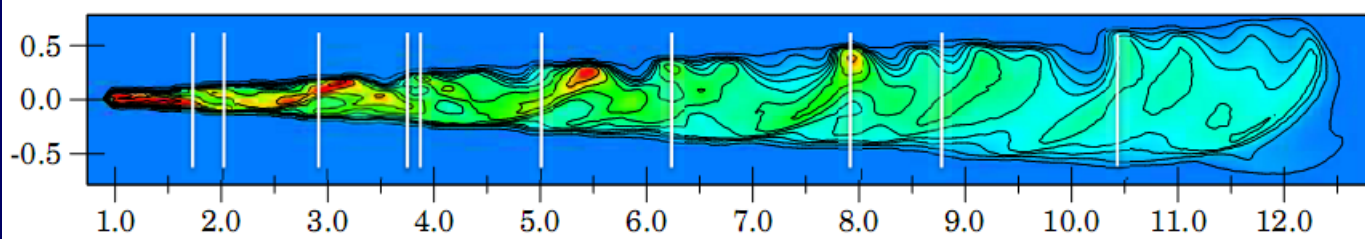


FIG. 3.—Gray scale image of the jet from feature A through C

Kelvin-Helmholtz Instabilities

Elliptical body mode and double peaked transverse jet-profiles



HDR mm-VLBI imaging resolves jet transversely and traces cause of instability to origin

Spine-sheath structure in relativistic jet simulations

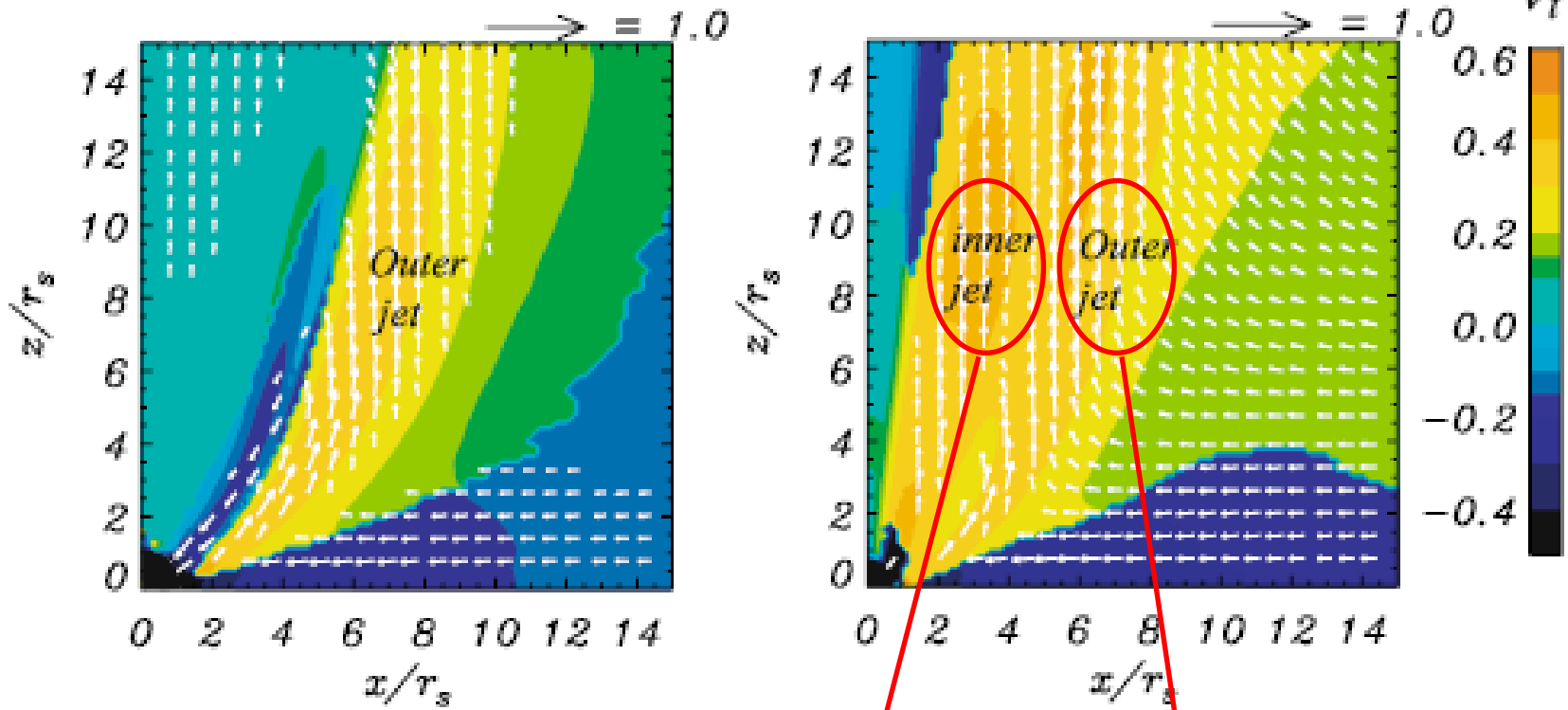
total velocity plots

non rotating BH

rapidly rotating BH

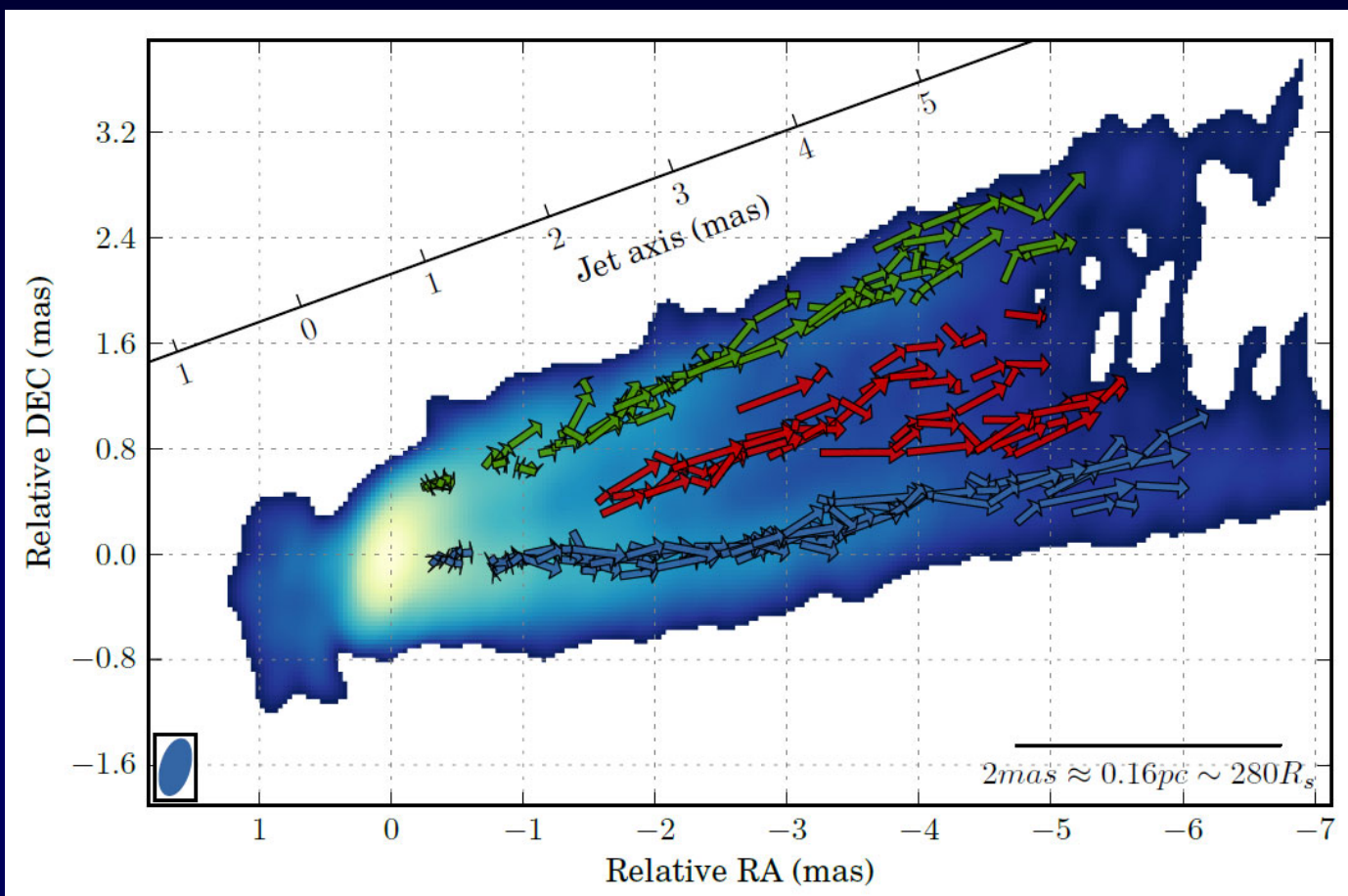
(e) $a=0.0, b_0=0.05$
 $time/\tau_s = 275.$

(f) $a=0.95, b_0=0.05$
 $time/\tau_s = 200.$



Jets from fast spinning BHs develop a slower inner and faster outer jet sheath
at $v=0.2 - 0.6 c \rightarrow$ jet edge-brightening and stratification on $\leq \sim 10 R_S$ scales

M87 – Strong evidence for a stratified jet flow from VLBA 43 GHz monitoring



wavelet based
image analysis

data:
43 GHz VLBA
(C. Walker et al.)

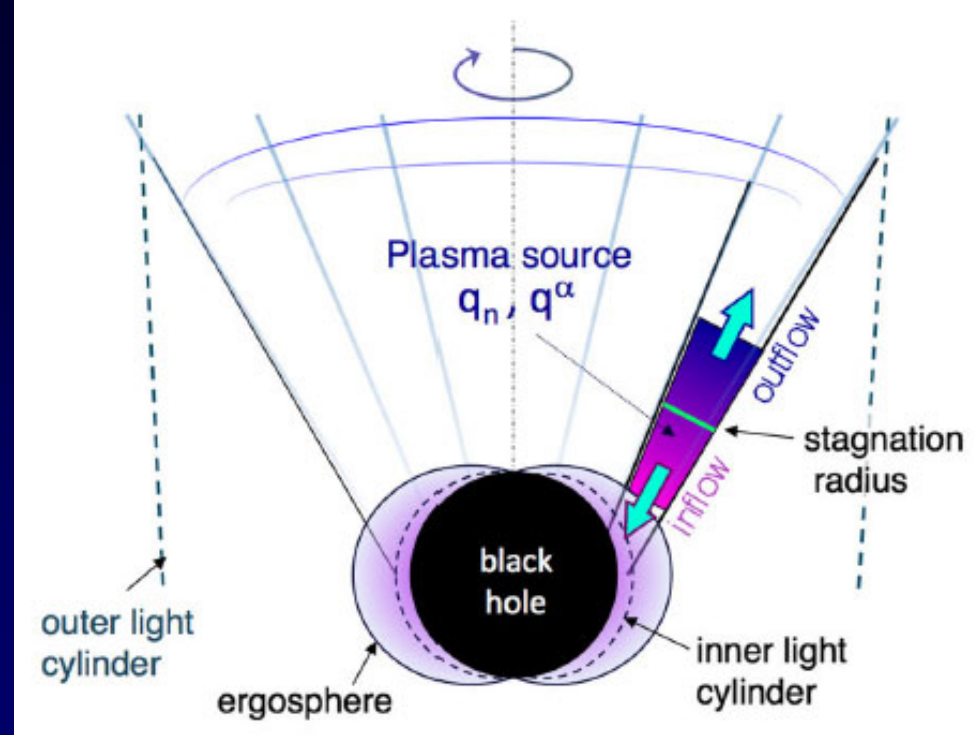
Mertens & Lobanov 2014, Mertens+ 2015

apparent acceleration on sub-pc scales (0.2 – 1.5c)
comparable velocity in spine/sheath
differential Doppler-boosting

Magneto-hydrodynamic plasma flows in Kerr space time

complex stratified and *filamentary structures* expected near BH variable on 1-1000 ISCO timescales

need high dynamic range multi-color and multi-epoch polarimetric submm VLBI imaging



Globus & Levinson 2013 (Phys. Rev. D)

McKinney, Tschekhovskoy, Blandford, 2012 & 2013



Magnetic fields and plasma jets are shaped by **Birkeland currents**

→

- stratified (multi-velocity) structures at jet base
- helical and rotating jet filaments

Competing Jet Models

synchrotron self-absorbed conical jet plus relativistic shocks (Blandford-Königl jet)

stratified (MHD) jet with moving hot spots/shocks or filamentary patterns

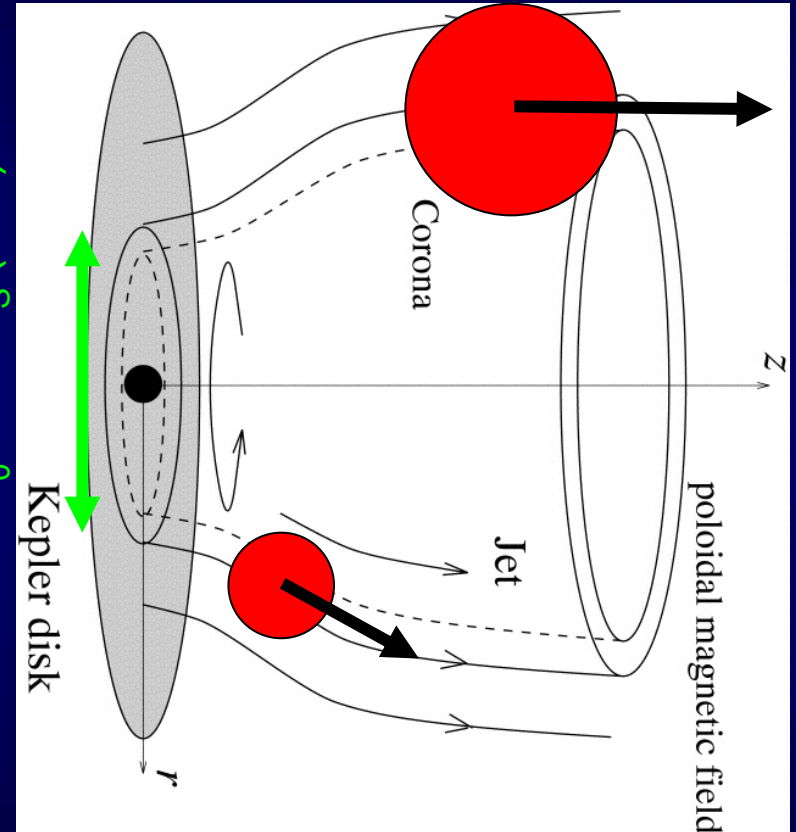
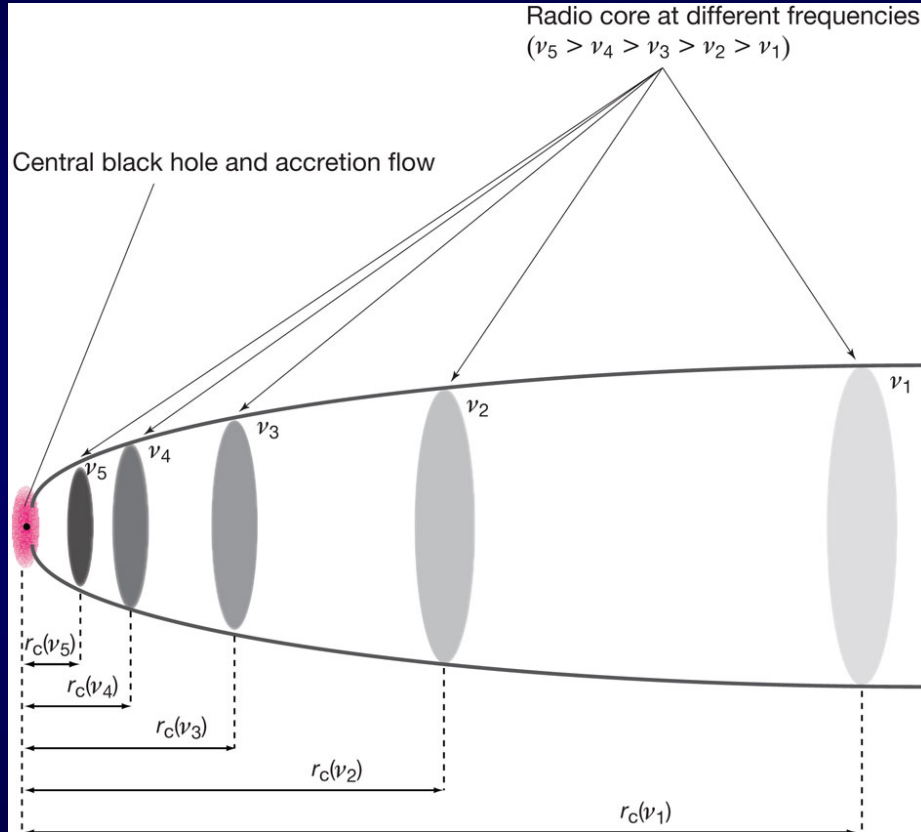


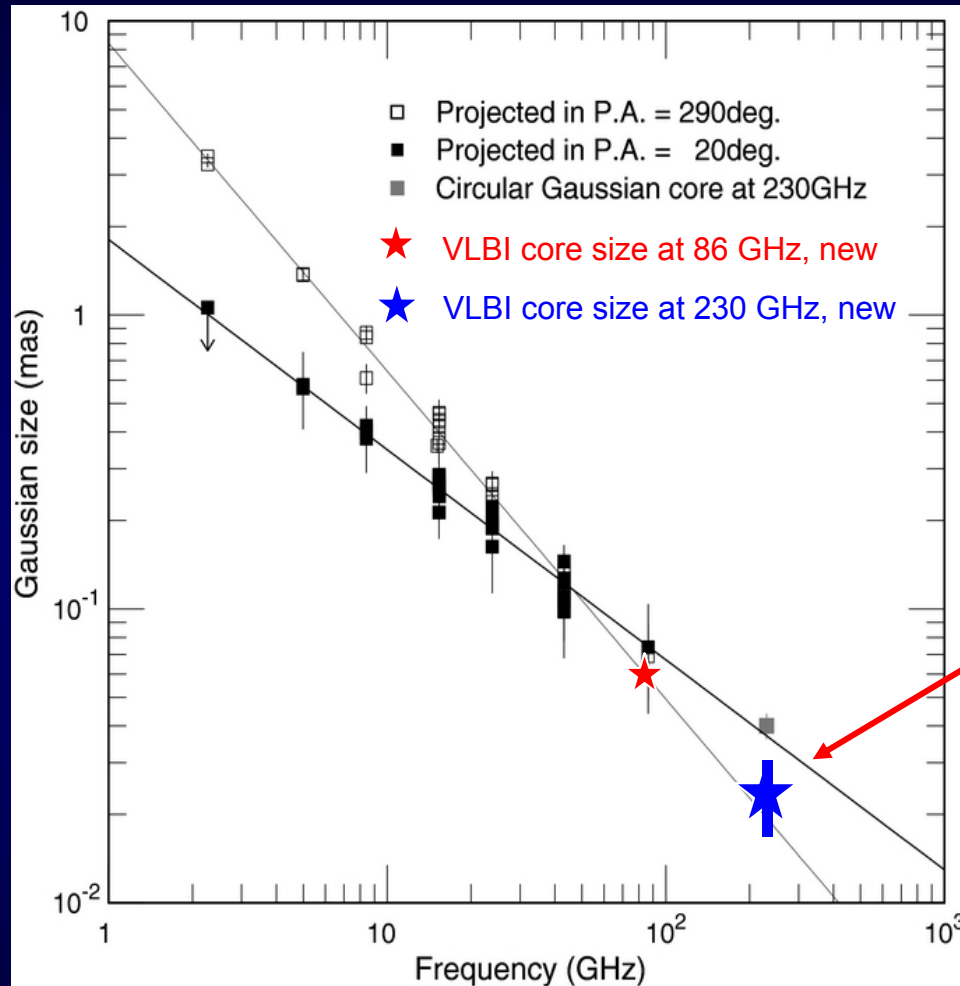
Figure from Hada et al. 2011, Nat.

last stable orbit radius: $1 \rightarrow 6 R_s$ for BH spin $a = 1 \rightarrow 0$

still unclear of what is seen at 1mm, need complementary imaging with GMVA

M87's core size is smaller than previously thought

1mm VLBI
March 2013:
detection of
M87 on APEX
baselines



Krichbaum et al. 2014

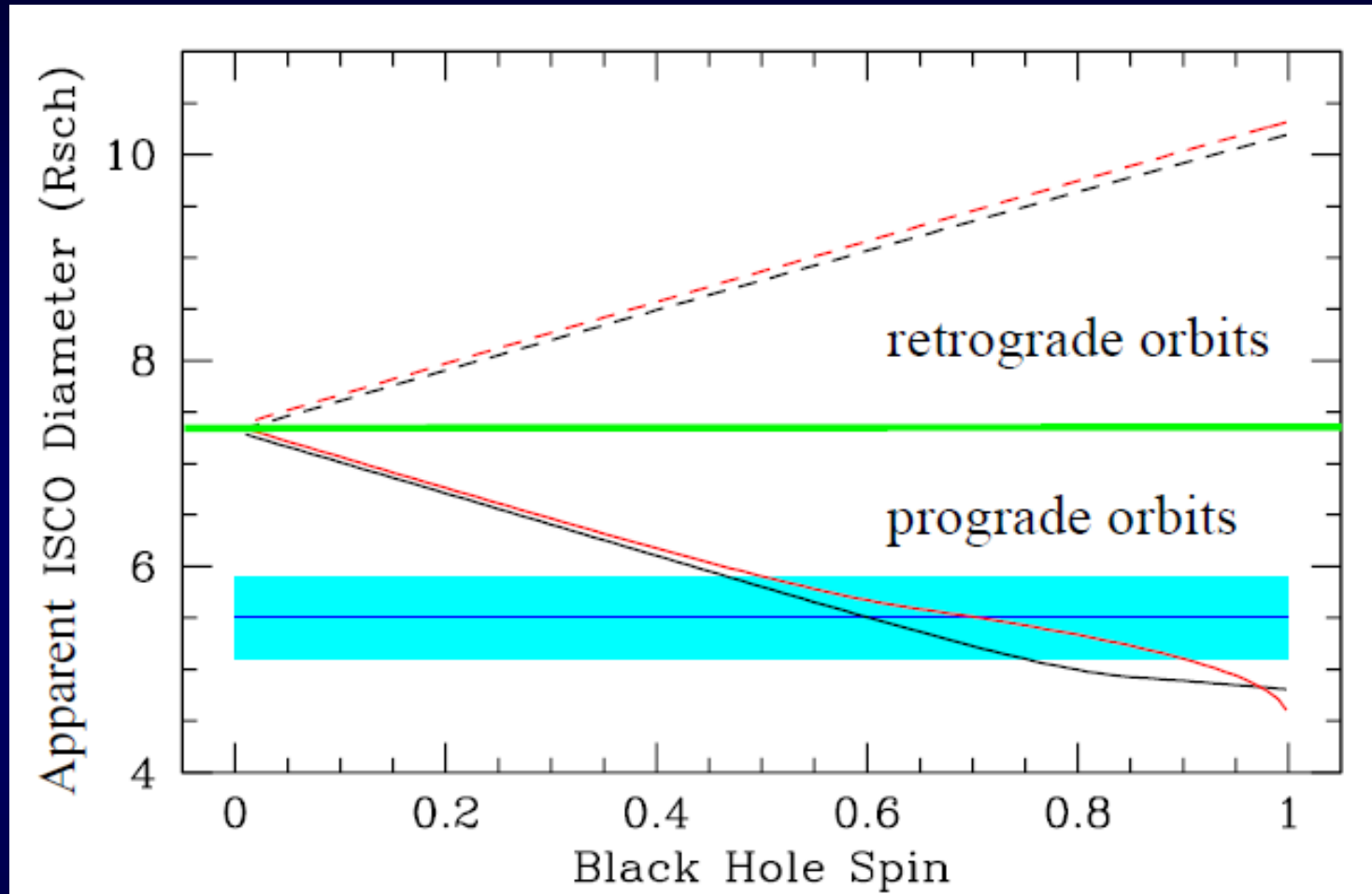
new data point
core size:

23 μ as or
2.9 R_s

This is smaller
than the
photon ring for
an $a=1$ BH !

APEX baselines are more N-S oriented, than the E-W orientation of the US-array:
the above numbers may measure the N-S jet width or sheath rather than the core !

M87: core size and BH spin



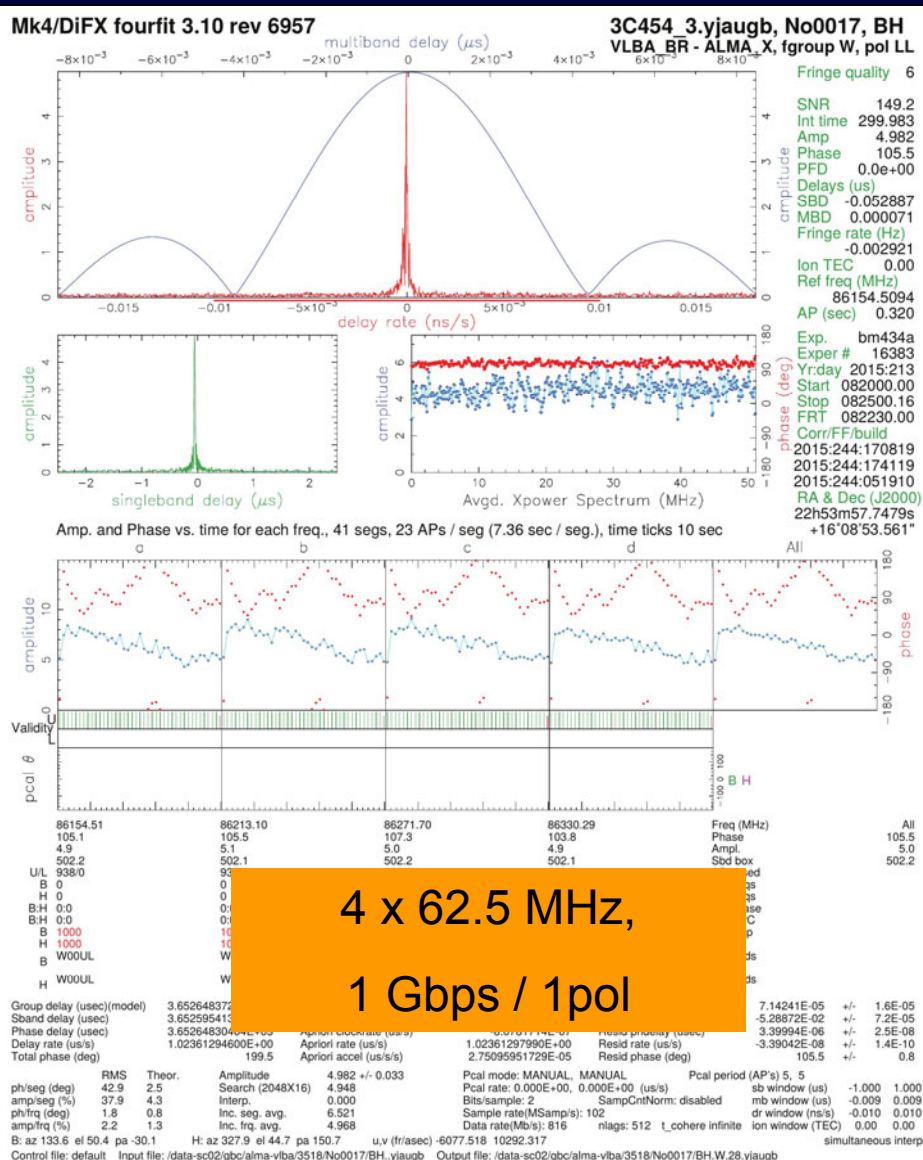
if measured VLBI size relates to ISCO -> non-zero BH spin and prograde disk rotation

First VLBI fringes with phased ALMA at 86 and 230 GHz

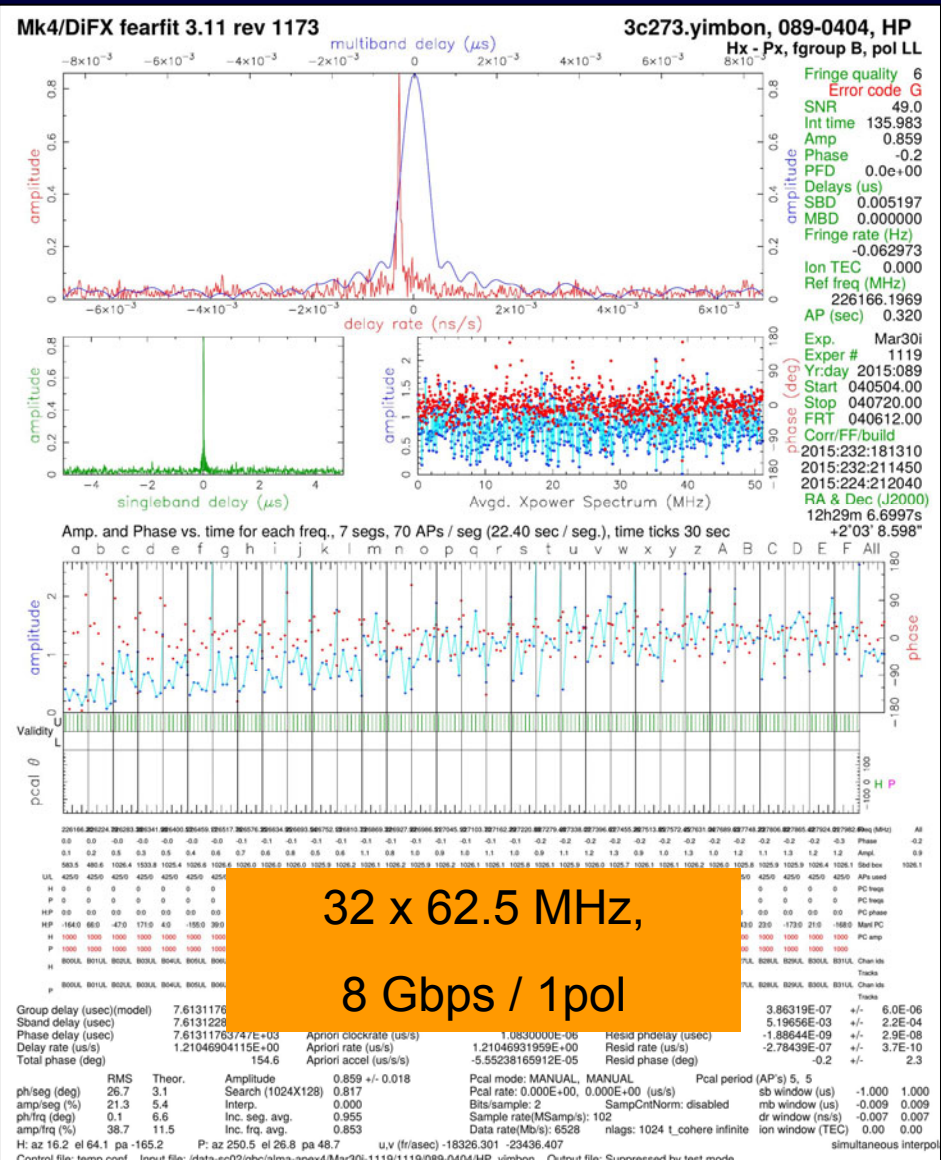
(Aug. 2015)

ALMA-VLBA @ 86GHz

ALMA-PicoVeleta @ 230GHz



4 x 62.5 MHz,
1 Gbps / 1pol



32 x 62.5 MHz,
8 Gbps / 1pol

credit: APP collaboration !

VLBI with the phased ALMA telescope will boost sensitivity and imaging capabilities of mm-VLBI



image: C. Padilla@ALMA

mm VLBI with phased ALMA is technically feasible!

Summary and Outlook

- the Origin of Jets in AGN can be studied at 7mm, 3mm and now also at 1mm
- 3mm and 7mm VLBI is almost standard (< 2 Gbps), VLBI @ 1mm is non-standard (16 Gbps in 2015, aim at 64 Gbps)
- participation of large collecting area dishes now provide much higher sensitivity (IRAM, GBT, Effelsberg, Yebes, soon: LMT, ALMA, ...)
- the VLBA provides important uv-coverage and frequency agility (43/86 GHz)
- calibration limitations due to weather are overcome by maximizing the antenna numbers, which facilitates the use of closure amplitudes (need $N > 12$)
- more advanced methods in global-fringe fitting are still desirable to overcome limitations set by the atmosphere (incoherent averaging, phase transfer, etc.)
- a further increase of the observing bandwidth beyond 2 Gbps at 3mm/7mm is highly desirable (ALMA: 32 Gbps)
- dual/multi frequency phase transfer capabilities are not yet in place
- a denser time sampling is necessary to better trace rapidly evolving sources
- 1.3 mm-VLBI (EHT) is limited and requires complementary global 7 & 3 mm VLBI (better uv-coverage, sensitivity, beam size within a factor of 2)