

Progress on 1mm-VLBI with Apex

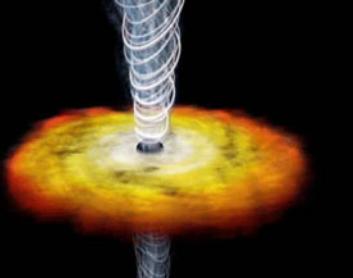
Micro-arcsecond scale imaging of black holes and jet nozzles

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(on behalf of the EHT mm-VLBI team)

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people involved:

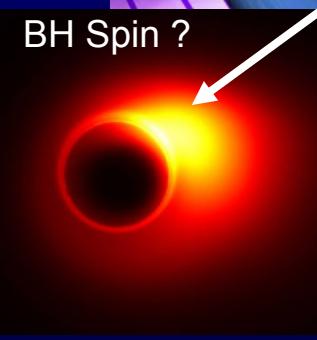
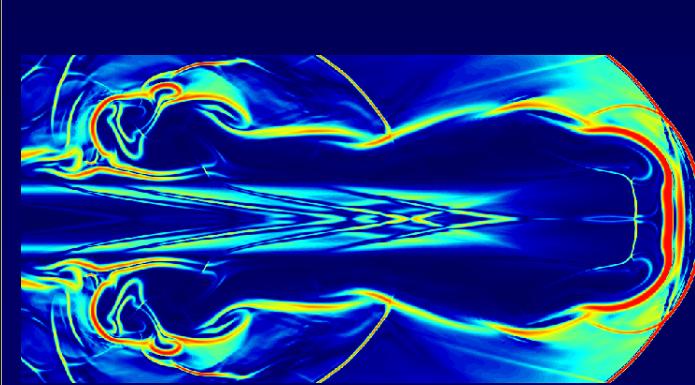
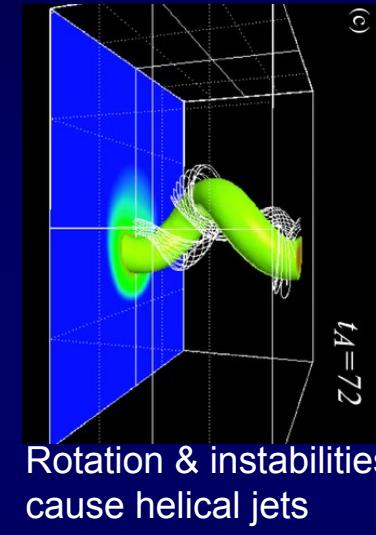
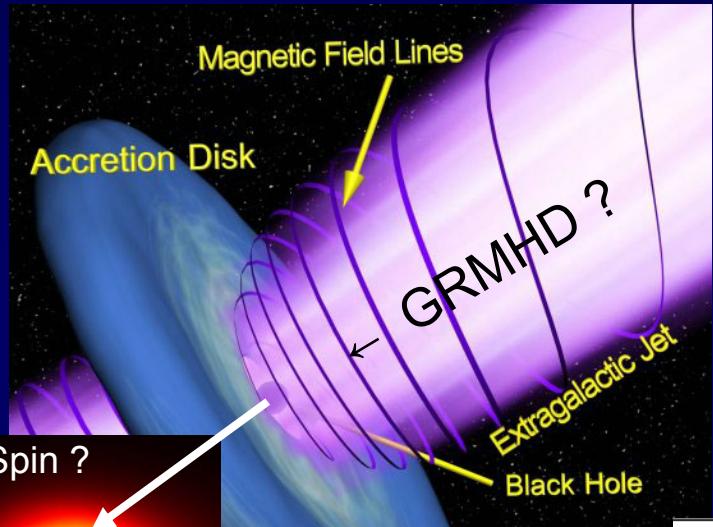
- MPIfR: W. Alef, U. Bach, A. Bertarini, T. Krichbaum,
H. Rottmann, A. Roy, J. Wagner, J.A. Zensus, et al.
- APEX: R. Güsten, K. Menten, D. Muders, and the APEX Team
- IRAM: M. Bremer, S. Sanchez, A. Grosz, K. Schuster, et al.
- OSO: M. Lindqvist, I. Marti-Vidal, H. Olofsson, M. Pantaleev, et al.
- INAF: G. Tuccari, et al.
- ESO: R. Laing, L. Testi, et al.

1mm VLBI, EHT collaboration:

- Haystack: R. Capallo, G. Crew, S. Doeleman, V. Fish, R. Lu, M. Titus, et al.
- Carma: G. Bower, R. Plambeck, M. Wright, et al.
- JCMT: P. Friberg, R. Tilanus, et al.
- SMA: R. Blundell, J. Weintraub, K. Young, et al.
- SMT: R. Freund, D. Marrone, P. Strittmatter, L. Ziurys et al.

Scientific Motivation:

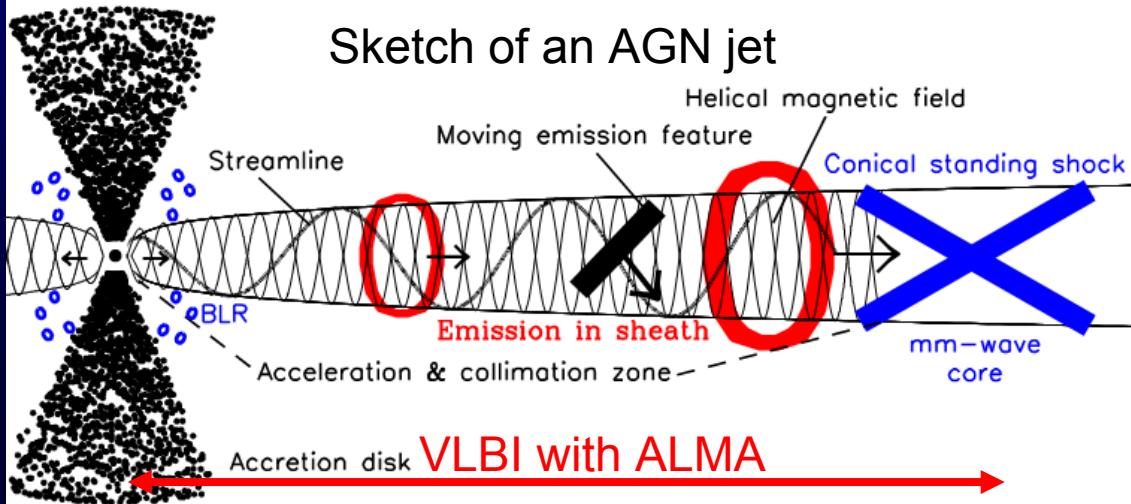
Detailed understanding of initial jet formation, acceleration and collimation. Image region around SMBHs, test GR near event horizon and test jet launching models.



Spin determines photon ring shape and jet width

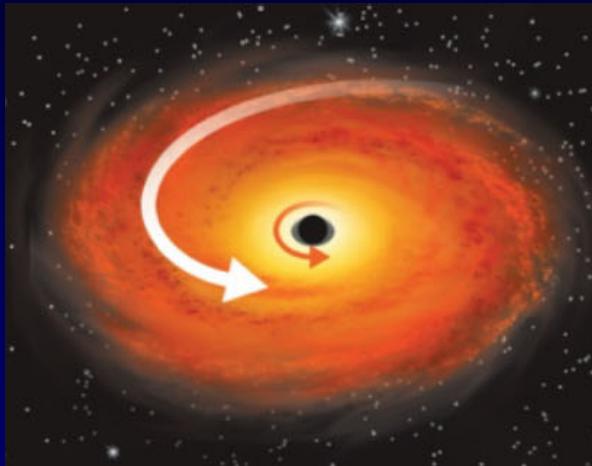
fundamental tests of BH physics

possible with mm-VLBI



The Innermost Stable Circular Orbit

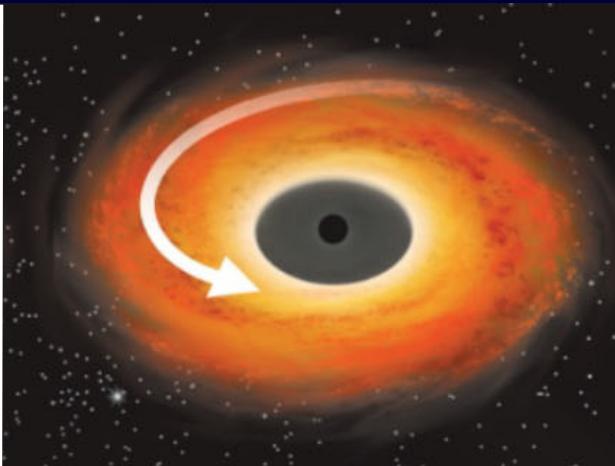
graphics: Sky & Telescope



- Maximally-spinning prograde BH (spinning in same direction as disk)

• ISCO at $R = 1 GM/c^2$

- Frame-dragging rotationally supports orbits close to BH

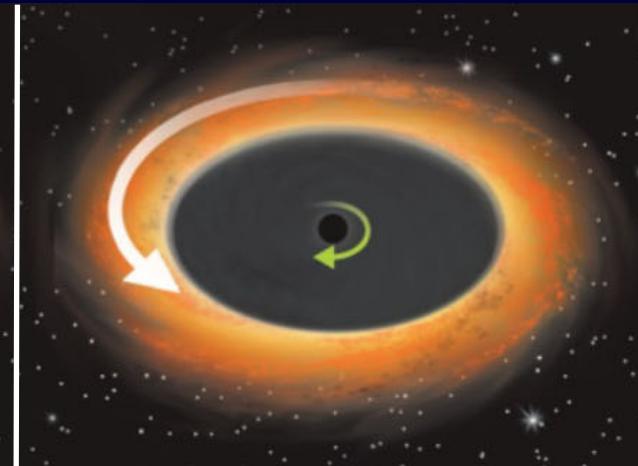


- Non-spinning BH.

- Accretion disk still rotates!

• ISCO at $R = 6 GM/c^2$

- No frame-dragging: orbits cease to spiral in and instead plunge toward BH inside ISCO



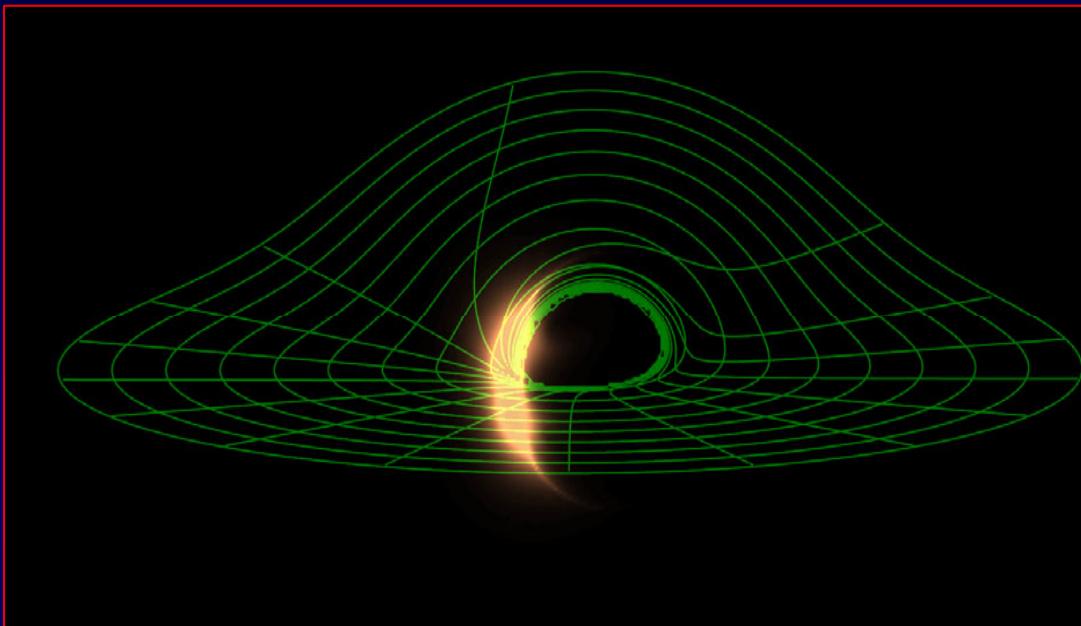
- Maximally-spinning **retrograde** BH (spinning in opposite direction as disk)

• ISCO at $R = 9 GM/c^2$

- Frame-dragging acts in opposition to disk angular momentum, causing orbits to plunge farther out

Interpretation of the 1mm VLBI size measurement

gravitationally lensed image of accretion disk



Broderick & Loeb 2008

orbiting hot spot / instability

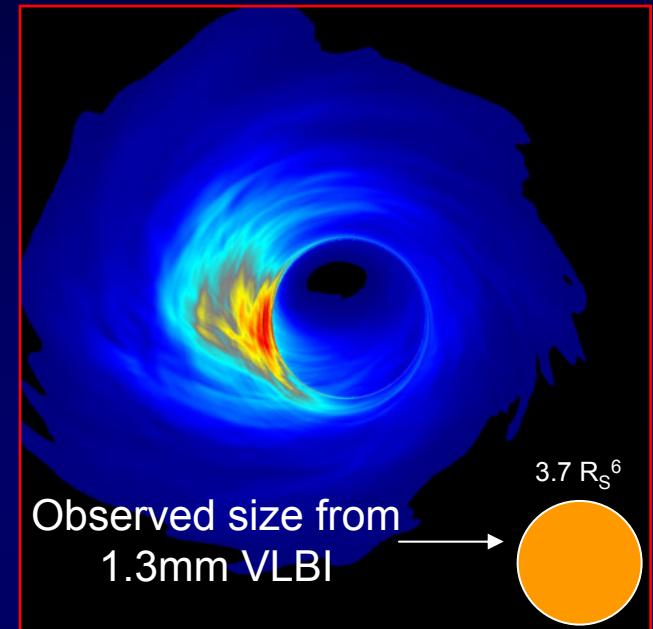


image credit: Noble & Gammie

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

observed size: $43 (+14/-8) \mu\text{as}$

deconvolved : $37 \mu\text{as}$

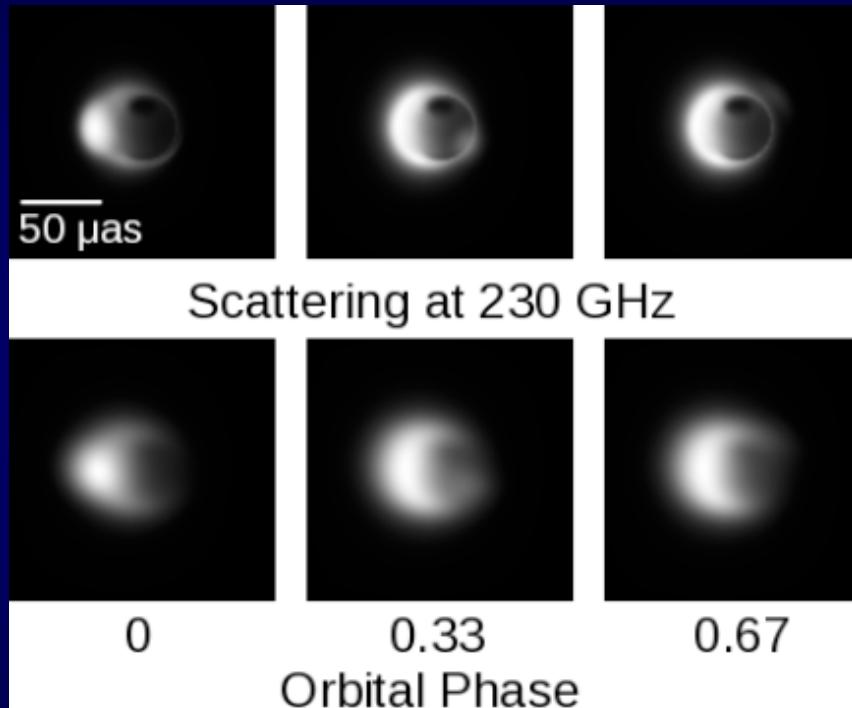
intrinsic : $3.7 R_s$

Observed size is smaller than expected size of accretion disk

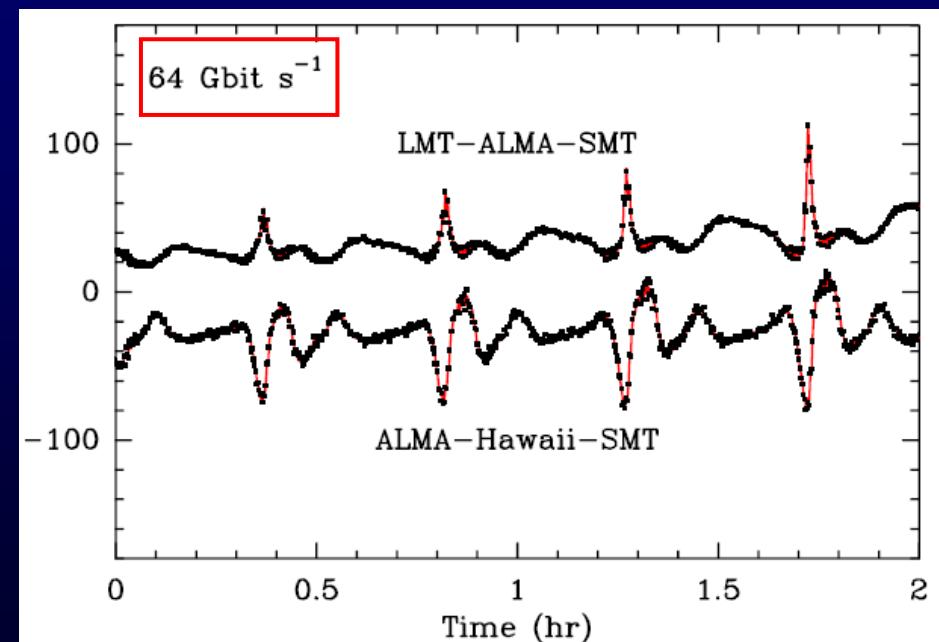
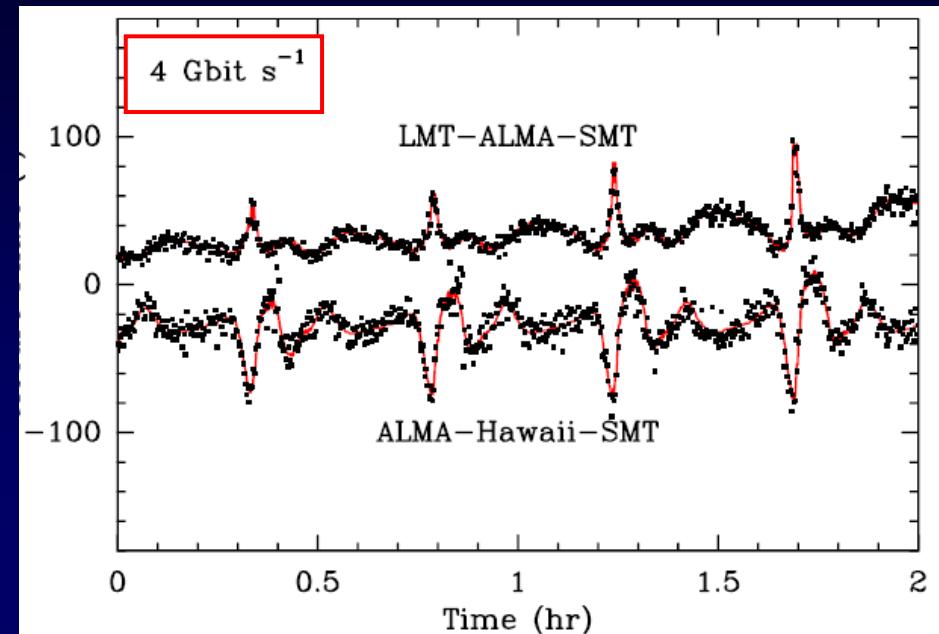
→ emission from hot spot or width of crescent shaped photon ring ?

Time resolving BH orbits and determination of ISCO

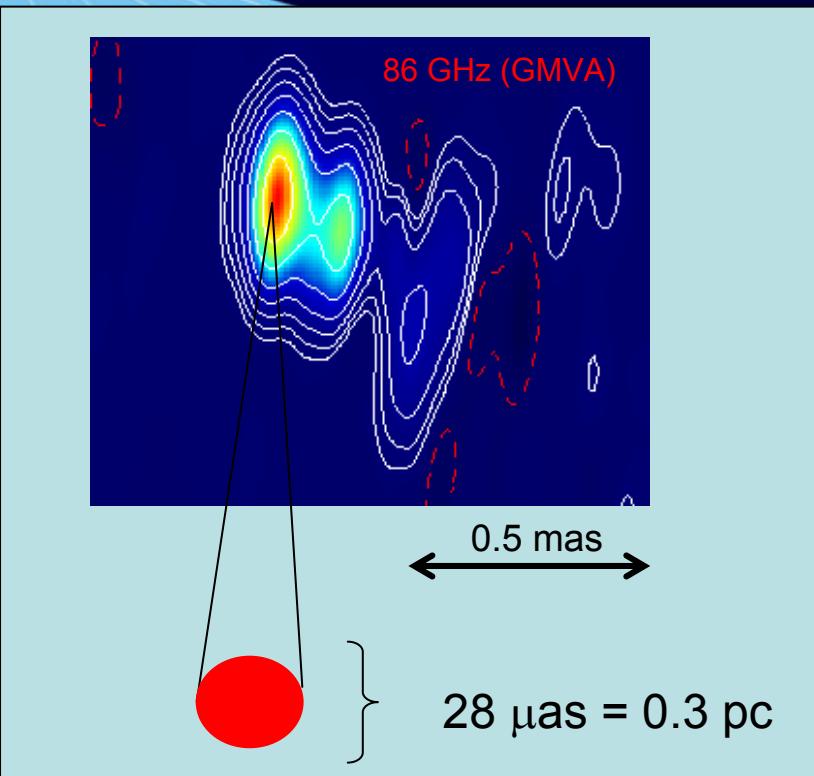
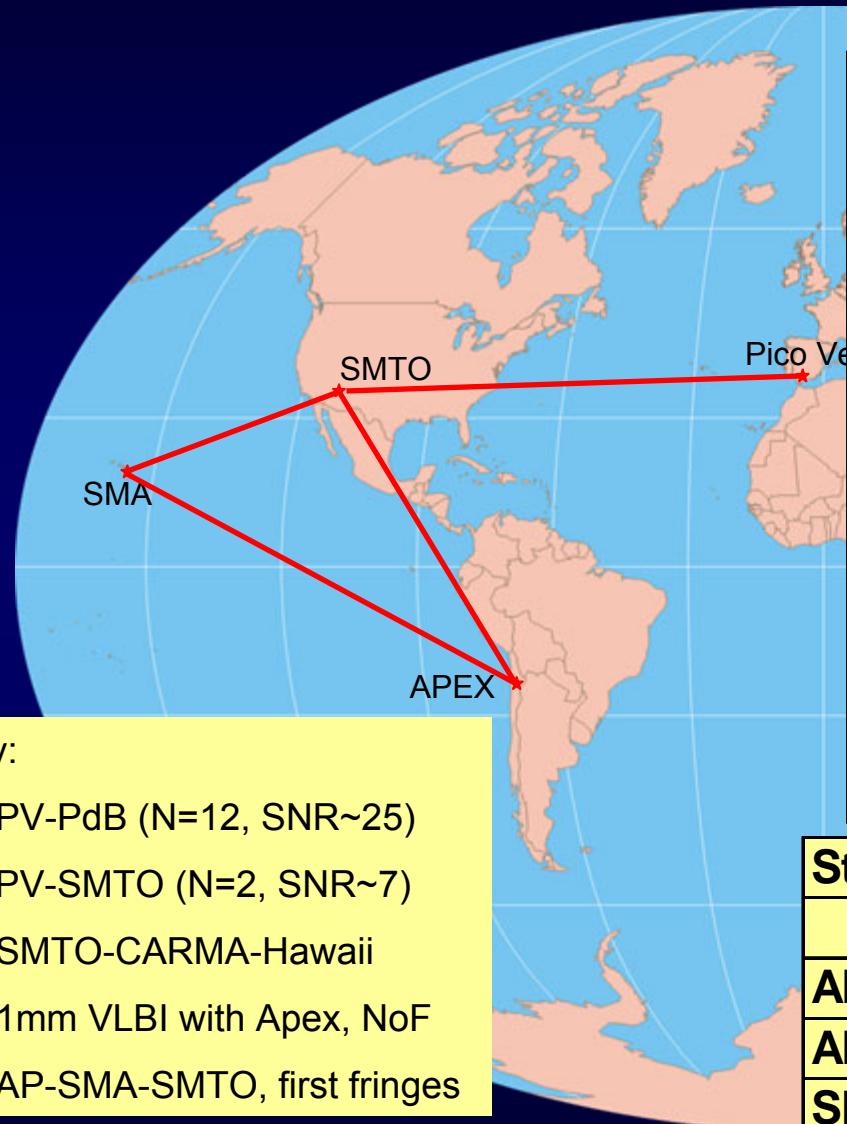
use closure phase to detect quasi-periodic variations from BH orbit



Sensitivity depends on observing bandwidth: will increase data rates from 4 Gbps to 64 Gbps



Fringe detection with APEX at 230 GHz (May 7, 2012)



History:

- 1995: PV-PdB (N=12, SNR~25)
- 2002: PV-SMTO (N=2, SNR~7)
- 2007: SMTO-CARMA-Hawaii
- 2011: 1mm VLBI with Apex, NoF
- 2012: AP-SMA-SMTO, first fringes

Station	Station	Length (km)	Resolution (μ as)
APEX	SMA	9447	28,4
APEX	SMTO	7174	37,4
SMTO	SMA	4627	58,0



existing station

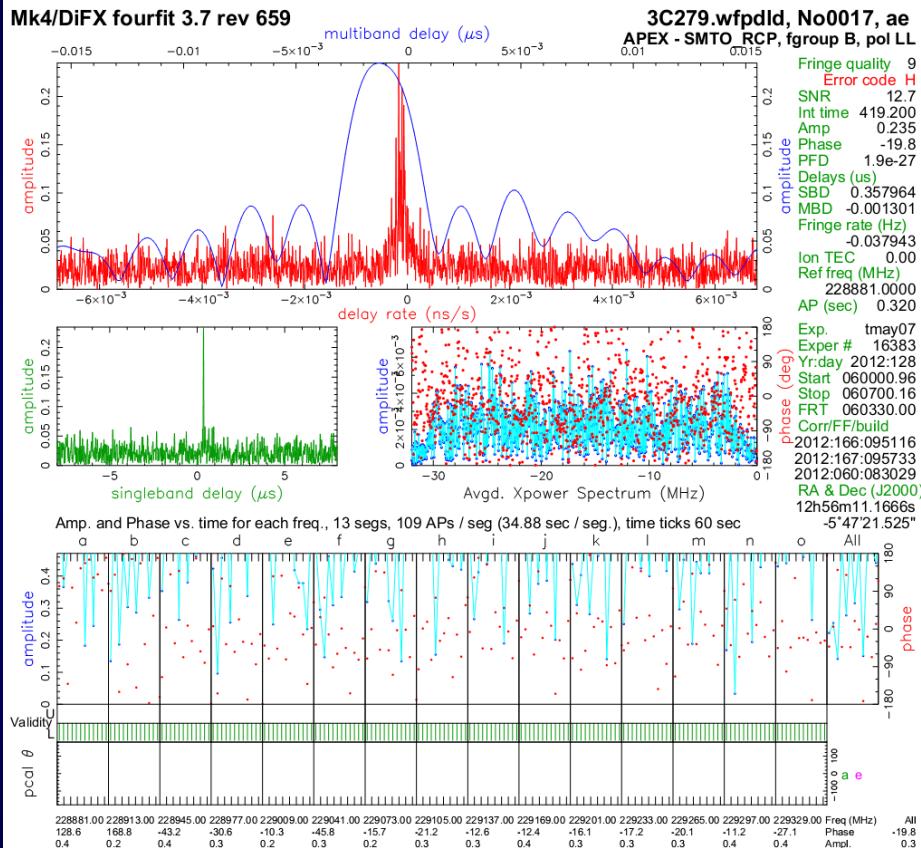


1mm fringes established

First VLBI fringes with APEX at 230 GHz

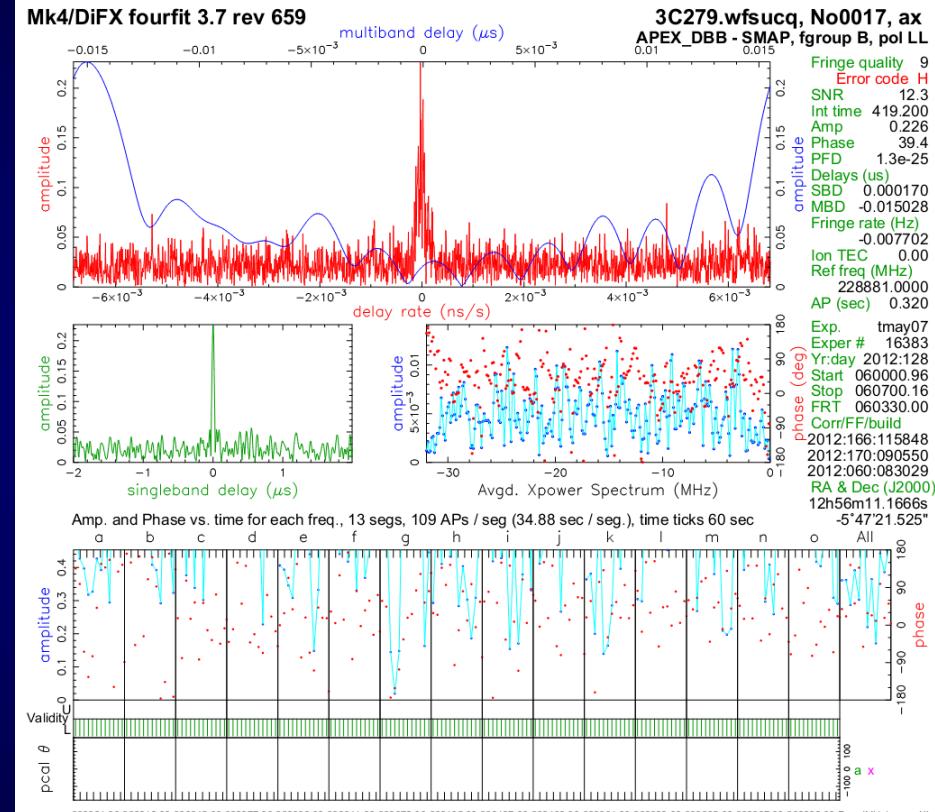
(May 7, 2012)

3C279 and MK5C, DBE & DBBC, 1.92 Gbit/s, 480 MHz bandwidth



APEX – SMTO (Arizona): SNR 12.7

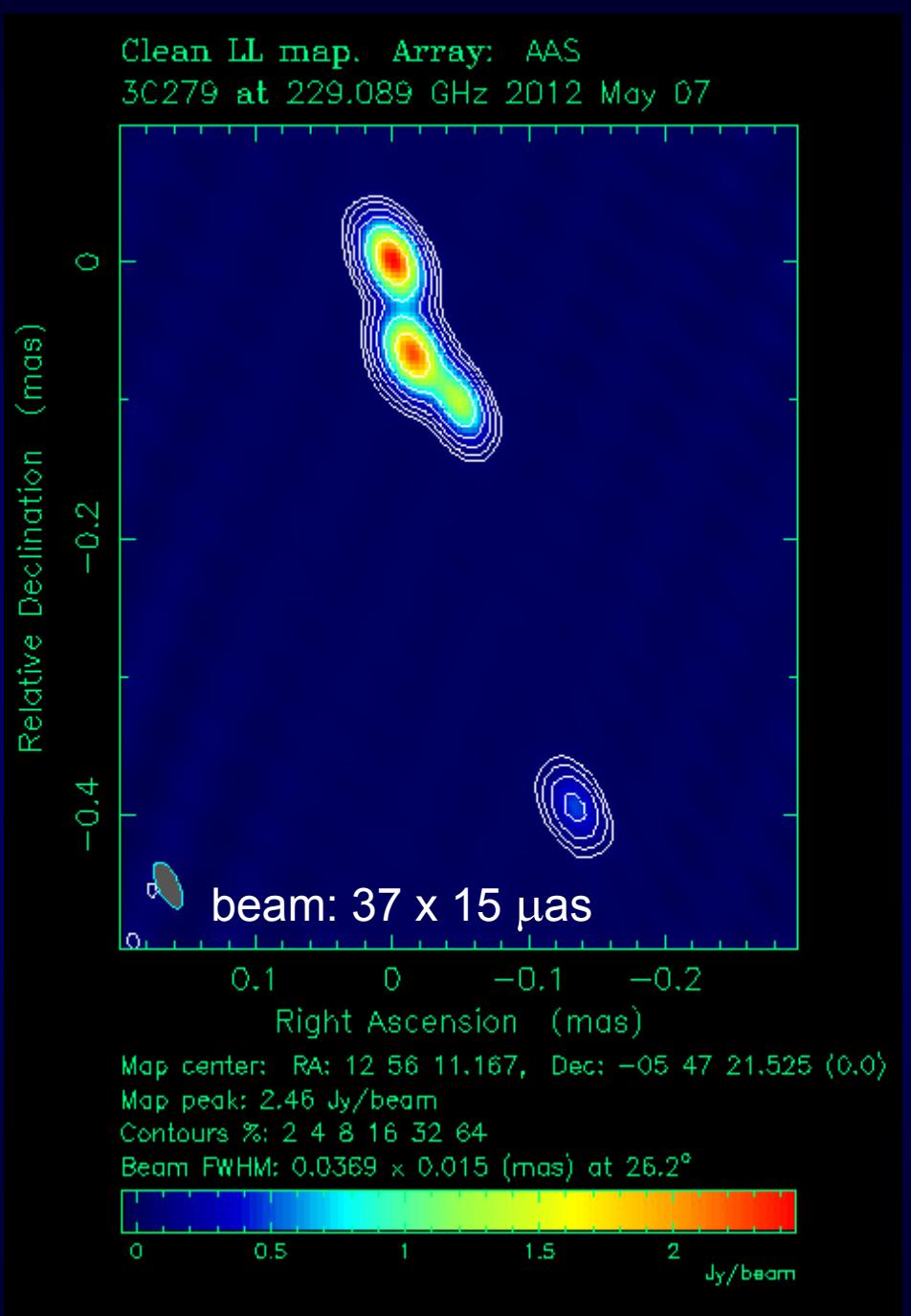
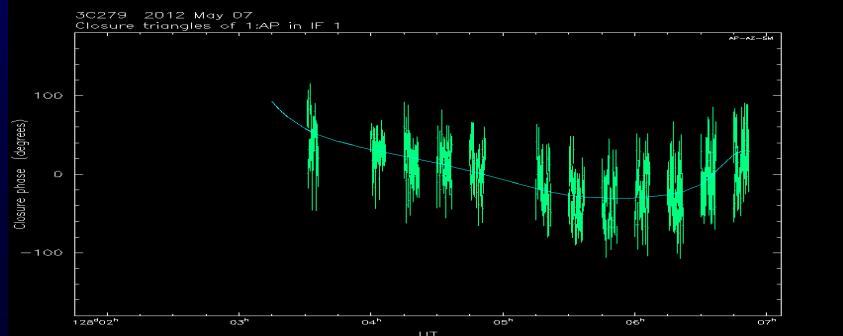
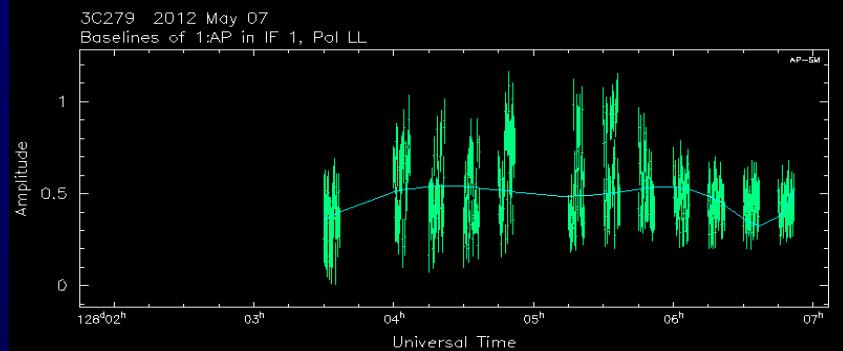
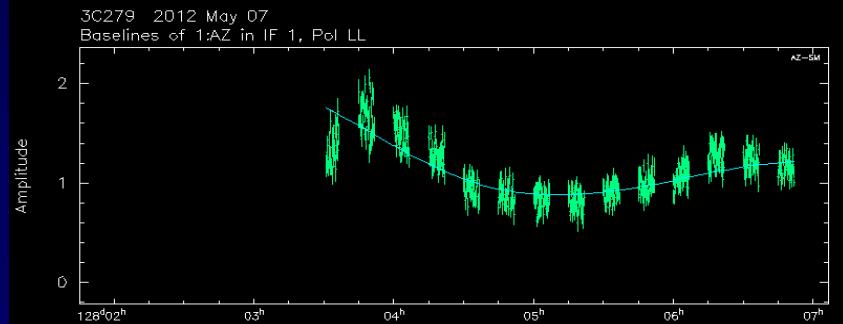
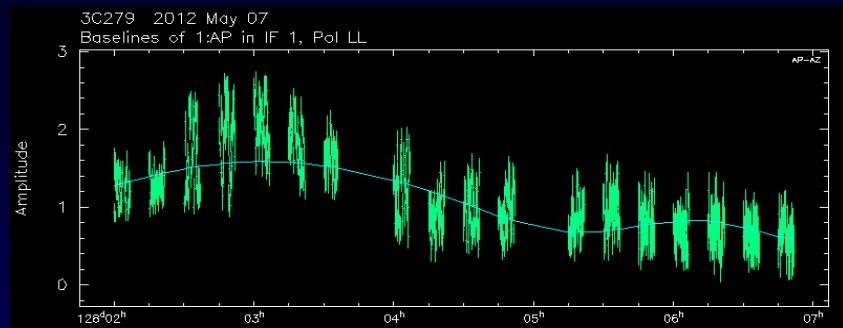
D=7170 km



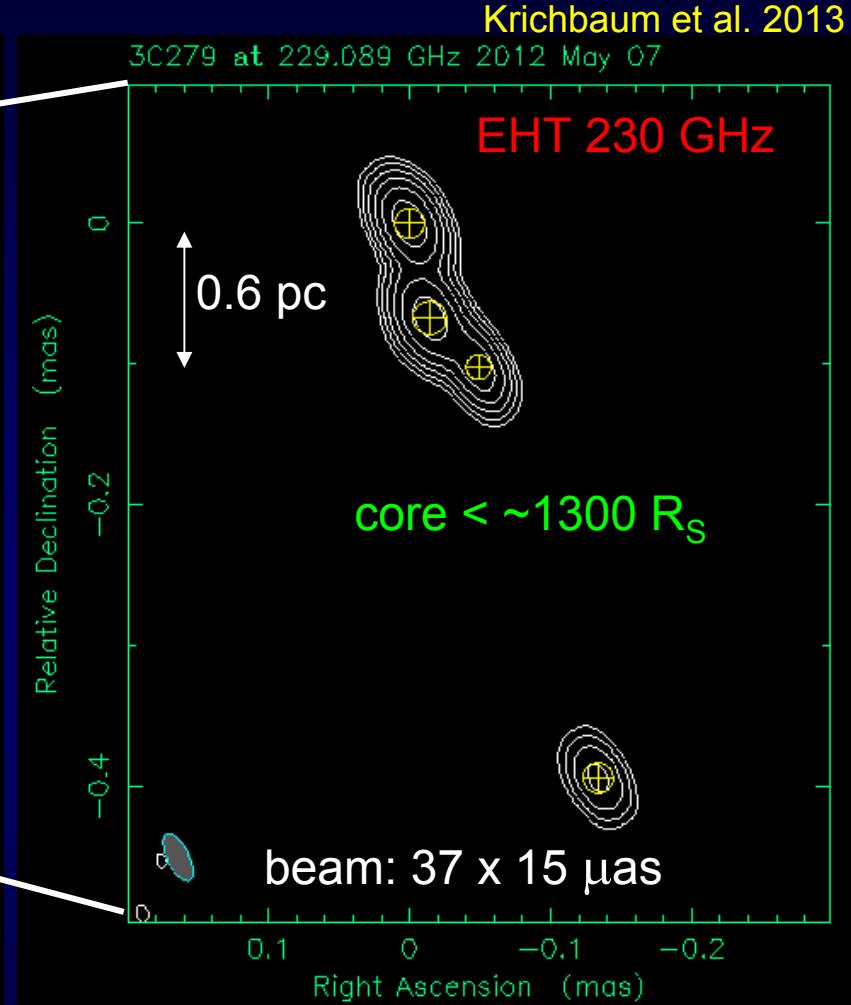
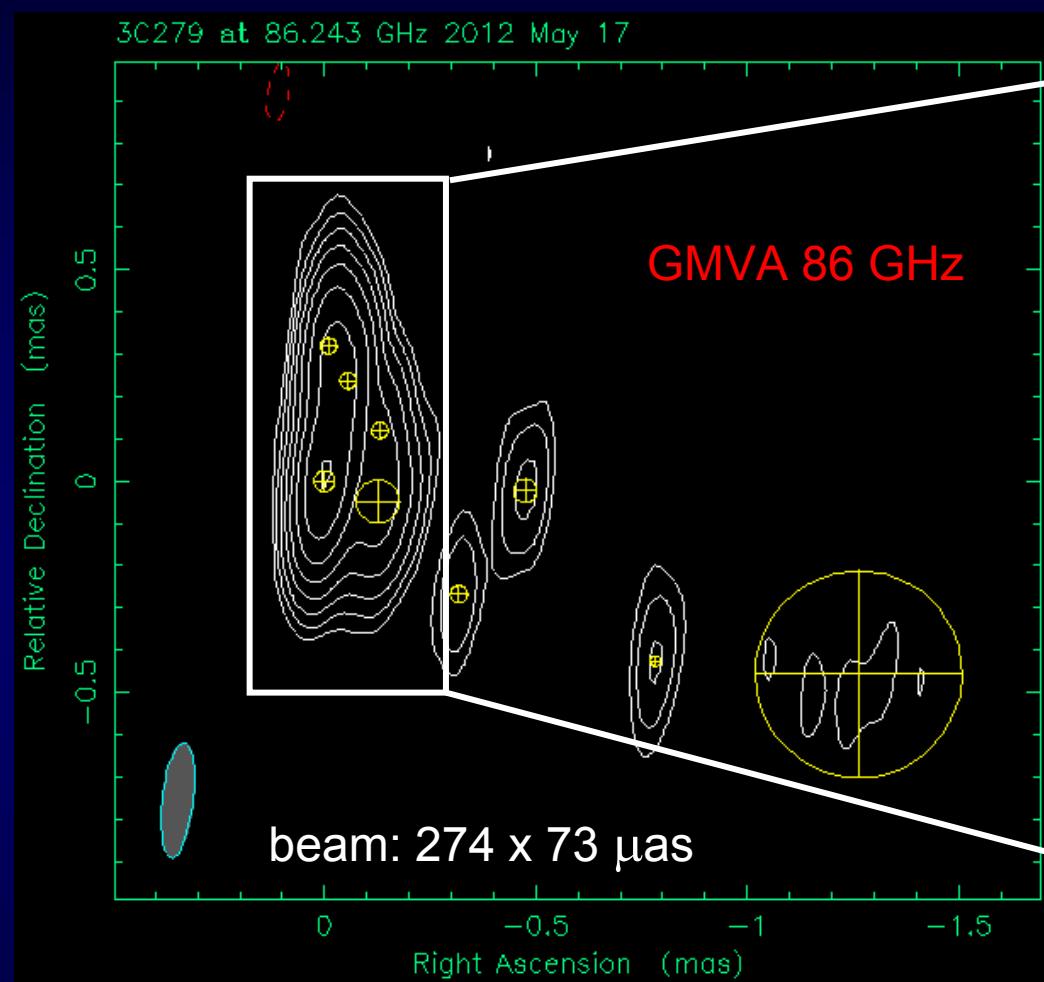
APEX – SMA (Hawaii): SNR 12.3

D=9450 km

credit: A. Roy and Apex team



North-South extension seen at 1mm confirmed by 3mm VLBI



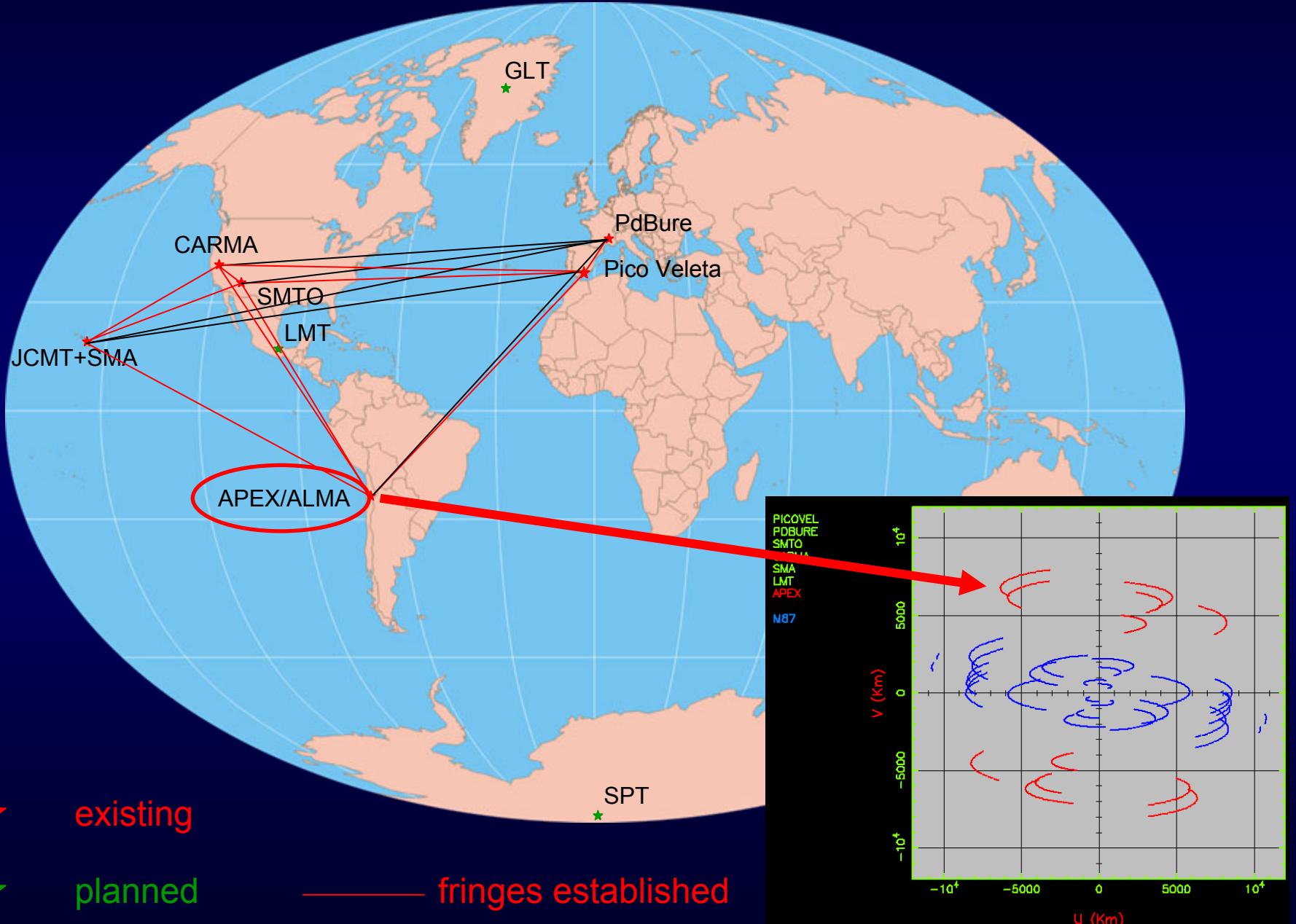
Map center: RA: 12 56 11.167, Dec: -05 47 21.525 (2000.0)
Map peak: 3.66 Jy/beam
Contours %: -0.75 0.75 1.5 3 6 12 24 48 96
Beam FWHM: 0.274×0.0731 (mas) at -6.32°

Map center: RA: 12 56 11.167, Dec: -05 47 21.525 (0.0)
Map peak: 2.46 Jy/beam
Contours %: 2 4 8 16 32 64
Beam FWHM: 0.0369×0.015 (mas) at 26.2°

base of jet is transversely resolved and has a width of ~ 1 pc ($\sim 10^4 R_s$)
size of individual components (emission regions) < 0.1 pc ($1000 R_s$)

The next step towards truly global 1.3 mm VLBI array (EHT)

Status March 2013 with APEX added



Antenna Properties 1.3mm VLBI March 2013

Ant.	Code	D_eff	Tsys_eff	Gain	App.Eff	SEFD	Pol.	Comment	
		[m]	[K]	[K/Jy]		[Jy]			
PICO	V	30	250	0,110	0,43	2273	dual		
APEX	A	12	360	0,026	0,63	13846	LCP	Coherence loss 1,5	
SMTO	S	10	250	0,018	0,64	13889	LCP		
CARMA	F	21,6	300	0,0759	0,57	3953	dual	4x10,4m+4x6,1m, phasing=0,9	
SMA	P	15,1	300	0,045	0,69	6667	LCP	7x6m, phasing=0,9	
JCMT	J	15	200	0,040	0,63	5000	RCP		

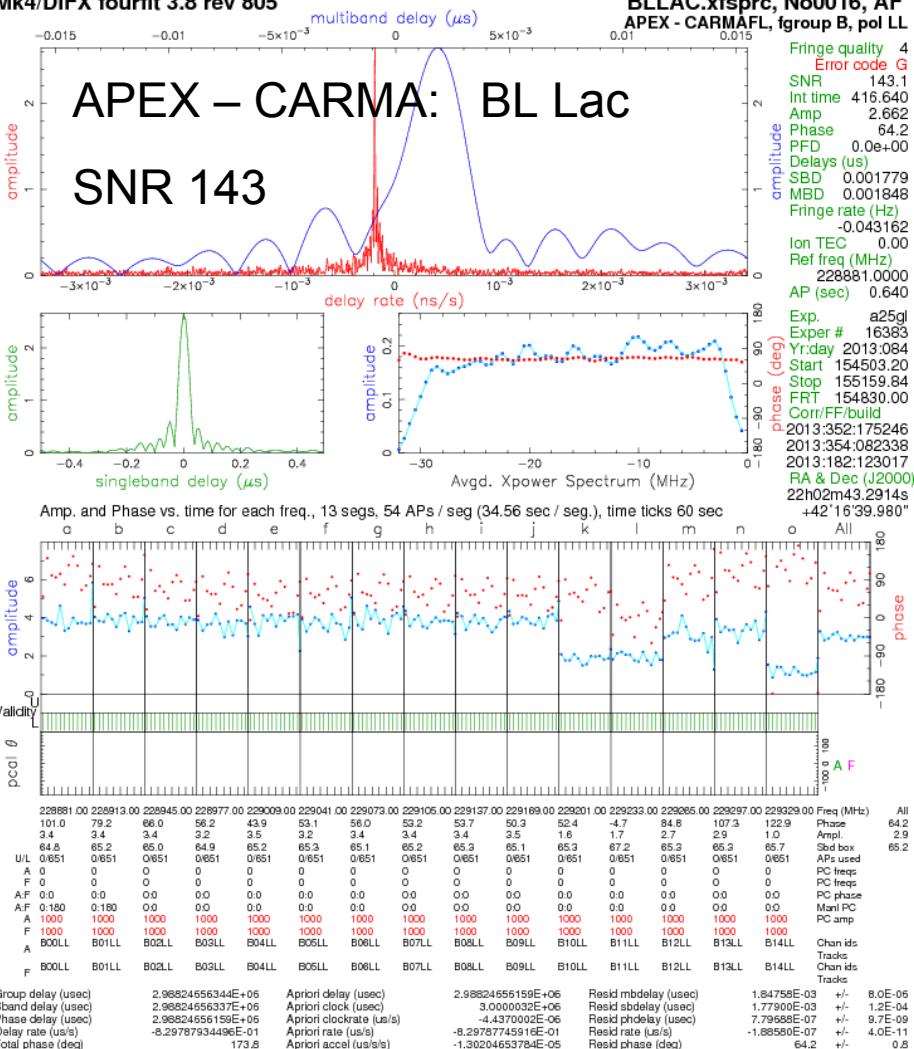
Baseline Sensitivity (7sigma, 10sec, 500 MHz, 2 Gbps):

APEX-PICO	0,45	Jy
APEX-CARMA	0,59	Jy
APEX-SMA	0,76	Jy
APEX-JCMT	0,66	Jy
APEX-SMTO	1,10	Jy

2 Gbps → 32 Gbps:

Factor 4 improvement possible

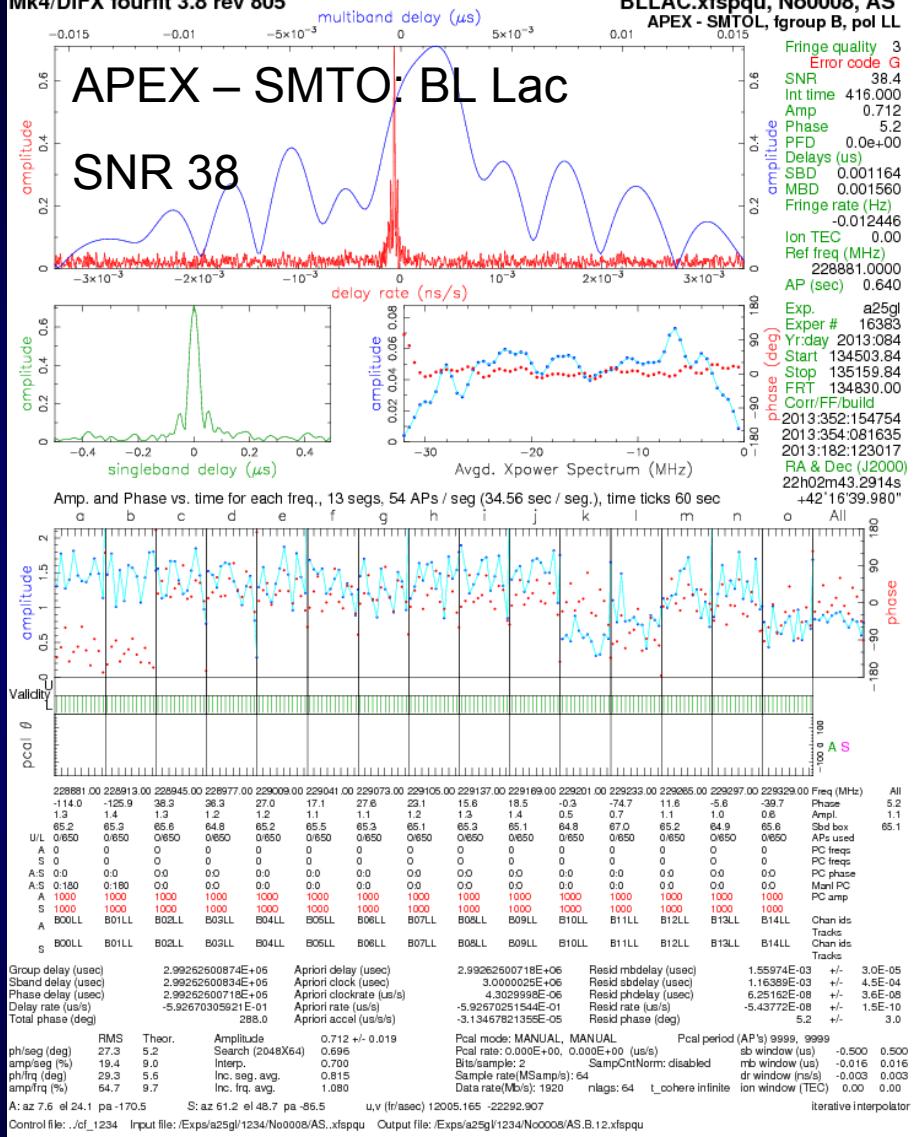
Mk4/DiFX fourfit 3.8 rev 805



A: az 343.6 el 21.9 pa 159.4 F: az 68.1 el 66.8 pa -92.3 u.v (fr/asec) 16089.10A -20014.965 iterative interpolator

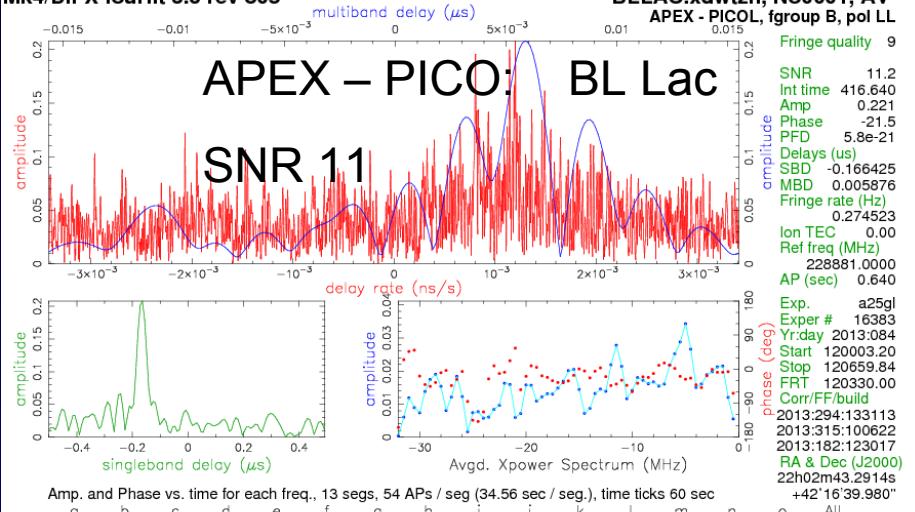
Control file: ./cf_1234 Input file: /Exp/a25gl/1234/No0016/AF.xfsprc Output file: /Exp/a25gl/1234/No0016/AF.B.11.xfsprc

Mk4/DiFX fourfit 3.8 rev 805

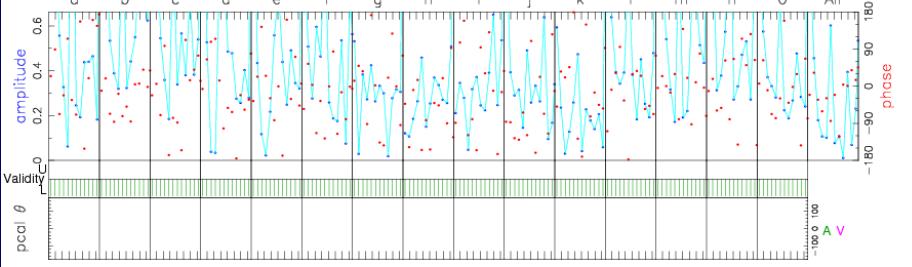


strong fringes to APEX on several bright mm-sources

Mk4/DiFX fourfit 3.8 rev 805



Amp. and Phase vs. time for each freq., 13 segs, 54 APs / seg (34.56 sec / seg.), time ticks 60 sec



228881.00	228913.00	228945.00	228977.00	229009.00	229041.00	229073.00	22915.00	22917.00	22919.00	229201.00	229233.00	229265.00	229297.00	229329.00
Freq (MHz)	All													
6.0	-16.2	-14.4	25.1	-27.5	-45.7	-27.4	21.4	-100.1	-71.4	-40.4	-7.3	4.3	-4.5	Phase
0.3	0.6	0.3	0.3	0.2	0.3	0.0	0.1	0.0	0.2	0.1	0.2	0.4	0.3	0.2
42.7	43.7	42.8	43.8	42.7	29.6	71.8	69.6	111.5	72.0	45.3	44.2	43.2	42.2	Sbd box
UL	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	0.651	43.7
A	0	0	0	0	0	0	0	0	0	0	0	0	0	
V	0	0	0	0	0	0	0	0	0	0	0	0	0	
A/V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
A/V:0.13	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	
A	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	PC amp
V	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	
A	B00LL	B01LL	B02LL	B03LL	B04LL	B05LL	B06LL	B07LL	B08LL	B09LL	B10LL	B11LL	B12LL	B13LL
V	B14LL													

Group delay (usec) 2.9865610585E+06 Apriori delay (usec) 2.98656107996E+06 Resid mbdelay (usec) 5.57604E-03 +/- 1.0E-04

Sband delay (usec) 2.9865609135E+06 Apriori clock (usec) 3.0000010E+06 Resid sbdelay (usec) -1.66425E-01 +/- 1.5E-03

Phase delay (usec) 2.98656107996E+06 Apriori clockrate (usec) -9.070001E-07 Resid phdelay (usec) -2.60509E-07 +/- 1.2E-07

Delay rate (usec) 1.05518552575E+06 Apriori rate (usec) 1.0551843263E+00 Resid rate (usec) 1.19941E-05 +/- 5.1E-10

Total phase (deg) 110.6 Apriori accel (us/s) -5.44393443398E-05 Resid phase (deg) -21.5 +/- 10.2

RMS Theor. Amplitude 0.221 +/- 0.020 Pcal mode: MANUAL, MANUAL Pcal period (AP's) 9999, 9999 sb window (us) -0.500 0.500

ph/seg (deg) 34.4 RMS 0.221 +/- 0.020 Pcal rate: 0.000E+00, 0.000E+00 (us/s) SampCrnNorm: disabled mb window (us) -0.016 0.016

amp/seg (%) 131.5 30.8 Interp. 0.202 Bits/sample: 2 SampCrnNorm: disabled dr window (ms) -0.003 0.003

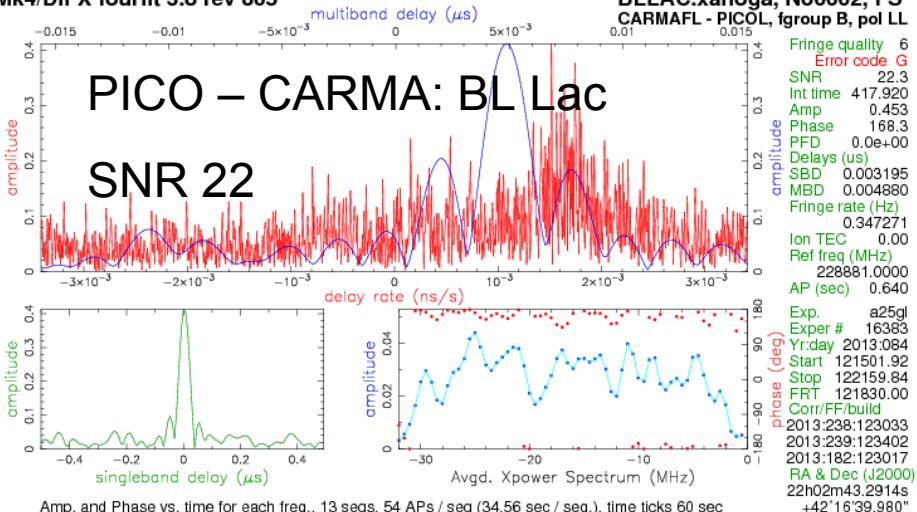
ph/freq (deg) 26.7 19.1 Inc. seg. avg. 0.277 Data rate(MB/s): 1920 nlags: 64 t_cohere infinite ion window (TEC) 0.00 0.00

amp/freq (%) 69.1 33.3 Inc. frq. avg. 0.232 Data rate(MB/s): 1920 nlags: 64 t_cohere infinite ion window (TEC) 0.00 0.00

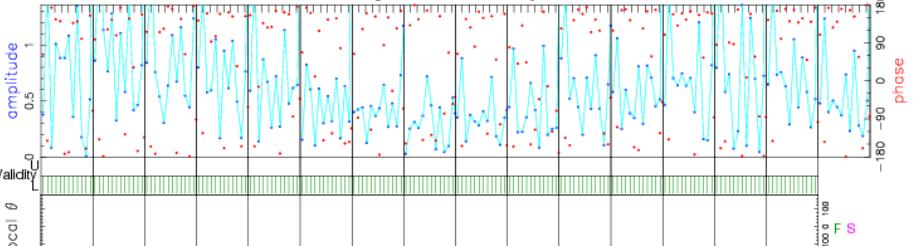
A: az 26.6 el 16.9 pa -146.0 V: az 292.4 el 67.3 pa 94.3 u.v (fr/asec) -21760.158 -18038.321 iterative interpolator

Control file: ./cl_1234 Input file: /Exp/a25gl/1234/No0001/AV.xdwtzh Output file: /Exp/a25gl/1234/No0001/AV.B12.xdwtzh

Mk4/DiFX fourfit 3.8 rev 805



Amp. and Phase vs. time for each freq., 13 segs, 54 APs / seg (34.56 sec / seg.), time ticks 60 sec



228881.00	228913.00	228945.00	228977.00	229009.00	229041.00	229073.00	22915.00	22917.00	22919.00	229201.00	229233.00	229265.00	229297.00	229329.00
Freq (MHz)	All													
168.1	167.0	168.6	161.1	172.5	170.8	150.0	-170.2	157.1	-169.2	170.2	179.5	165.1	167.7	161.3
0.3	0.4	0.3	0.7	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
66.0	66.0	65.3	65.5	65.8	65.3	65.3	65.3	42.7	63.8	70.6	61.0	64.5	56.5	64.6
UL	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653	0.653
F	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F_S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
S	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
F	B00LL	B01LL	B02LL	B03LL	B04LL	B05LL	B06LL	B07LL	B08LL	B09LL	B10LL	B11LL	B12LL	B13LL
S	B14LL													

Group delay (usec) -8.5211331706E+03 Apriori delay (usec) -8.52113805088E+03 Resid mbdelay (usec) 4.88024E-03 +/- 5.2E-05

Sband delay (usec) -8.52113485567E+03 Apriori clock (usec) -2.4810455E+00 Resid sbdelay (usec) 3.19521E-03 +/- 7.7E-04

Phase delay (usec) -8.52113804884E+03 Apriori clockrate (usec) 3.530001E-06 Resid phdelay (usec) 2.04215E-06 +/- 6.2E-08

Delay rate (usec) 1.40958077355E+00 Apriori rate (usec) 1.40958077355E+00 Resid rate (usec) 1.51725E-06 +/- 2.8E-10

Total phase (deg) 67.7 Apriori accel (us/s) 4.551893598E-05 Resid phase (deg) 168.3 +/- 5.1

RMS Theor. Amplitude 0.453 +/- 0.020 Pcal mode: MANUAL, MANUAL Pcal period (AP's) 9999, 9999 sb window (us) -0.500 0.500

ph/seg (deg) 30.1 RMS 0.453 +/- 0.020 Pcal rate: 0.000E+00, 0.000E+00 (us/s) SampCrnNorm: disabled mb window (us) -0.016 0.016

amp/seg (%) 82.8 15.5 Interp. 0.404 Bits/sample: 2 SampCrnNorm: disabled dr window (ms) -0.003 0.003

ph/freq (deg) 10.4 9.6 Inc. seg. avg. 0.584 Data rate(MB/s): 1920 nlags: 64 t_cohere infinite ion window (TEC) 0.00 0.00

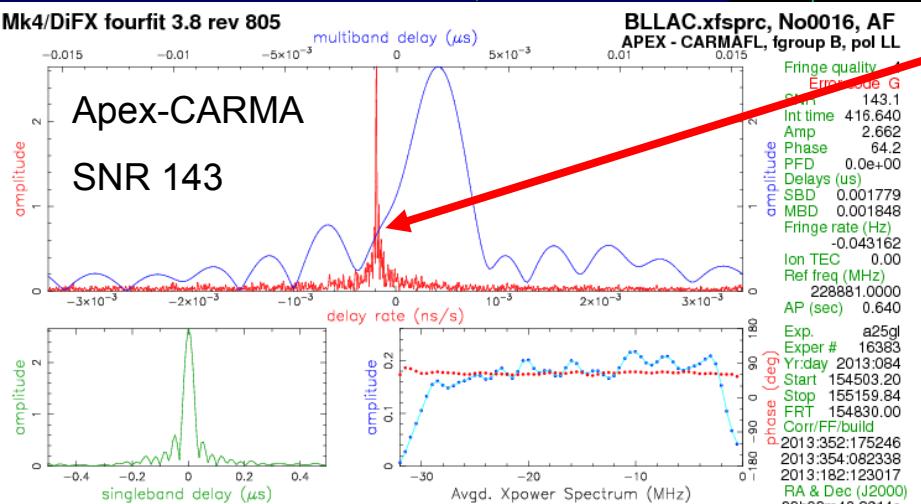
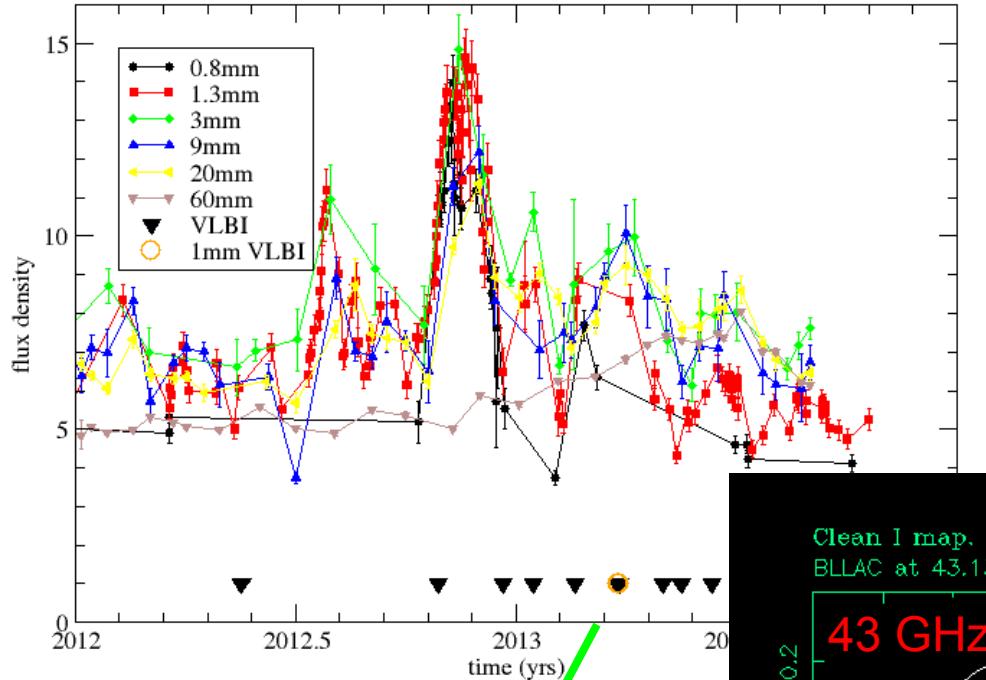
amp/freq (%) 69.1 16.8 Inc. frq. avg. 0.450 Data rate(MB/s): 1920 nlags: 64 t_cohere infinite ion window (TEC) 0.00 0.00

F: az 57.0 el 29.1 pa -64.5 S: az 292.2 el 64.7 pa 91.6 u.v (fr/asec) -28752.798 9115.656 iterative interpolator

Control file: ./cl_1234 Input file: /Exp/a25gl/1234/No0002/FS.xahoga Output file: Suppressed by test mode

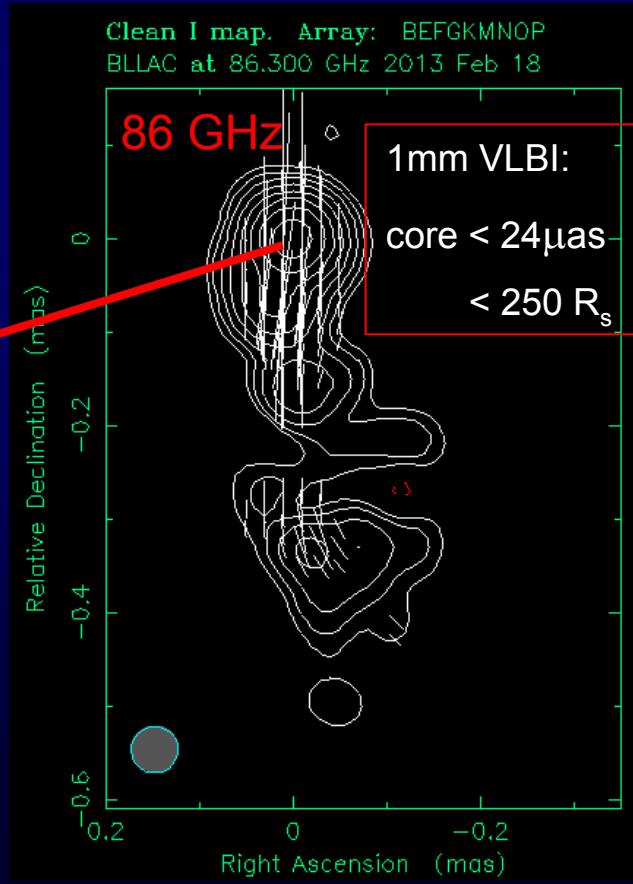
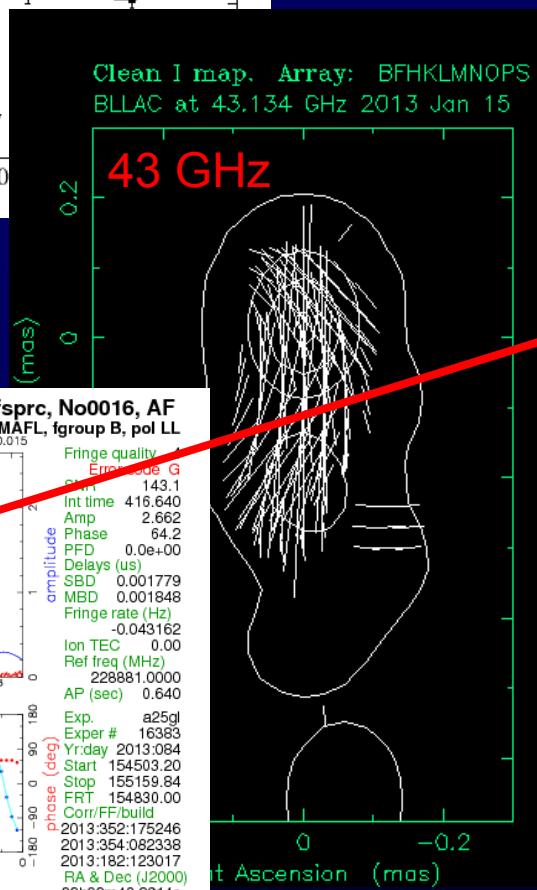
low SNR at Pico Veleta due to very bad weather and a DBBC configuration problem

BL Lac
(FGAMMA monitoring)



Monitoring BLLac after Dec. 2012 outburst:

Fringe detection of BLLac on APEX baselines at 230 GHz (SNR < 143)



Preliminary Summary of APEX VLBI Source detections

(Jan. 2014)

Source	z	DOY	UT	Baseline	SNR	B	size	lin. size	R_s
			[hrs]			[Mlambda]	[muas]	[pc]	
3C273	0,158	82	7h40	AP-SMTO	11	5422	26	0,083	853
3C279	0,5362	82	8h00	AP-CARMA	12	6041	21	0,220	2262
3C84	0,0176	82	20h30	AP-CARMA	8	5626	22,4	0,008	82
1749+096	0,322	82	14h40	AP-SMTO	12	4830	26	0,170	1748
BLLAC	0,0686	84	12-17	AP-CARMA	50-145	5400	21	0,029	298
BLLAC		84	12-17	AP-SMA	20-44	7200	17,5	0,024	247
BLLAC		84	12-17	AP-SMTO	20-43	5380	23,4	0,032	329
2013+370	0,859	84	12-15	AP-CARMA	16-25	5900	21,4	0,160	1645
2013+370		84	12-15	AP-SMA	7-13	7200	17,5	0,140	1439
2013+370		84	12-15	AP-SMTO	8	5300	23,9	0,180	1850

- highest SNR: BL Lac on APEX-CARMA, SNR = 145
- smallest angular scale, BLLac, 2013+37, 17.5 μ as ($\sim 250 R_s$)
- smallest linear scale, 3C84, ~ 82 Schwarzschild radii
- typical resolution for AGN < 0.1-0.2 pc (< 2000 R_s)

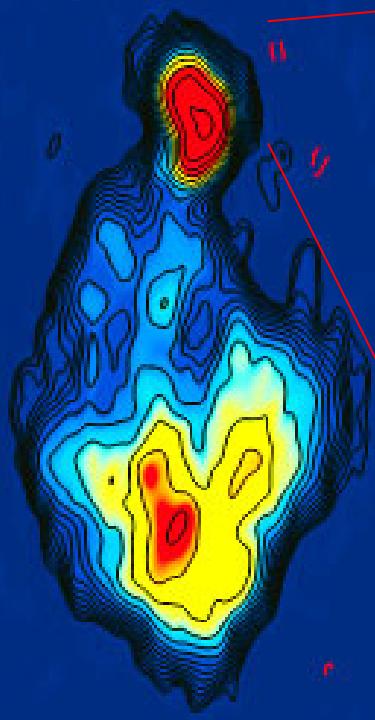
Central Engine of 3C84 (NGC1275) detected with VLBI at 230 GHz

VSOP 5 GHz

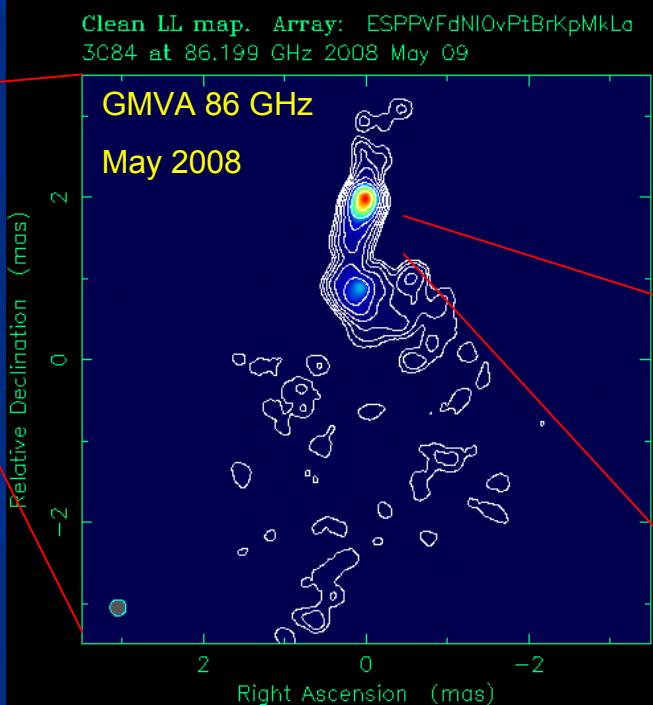
Aug 2001



10 mas / 3.3 pc

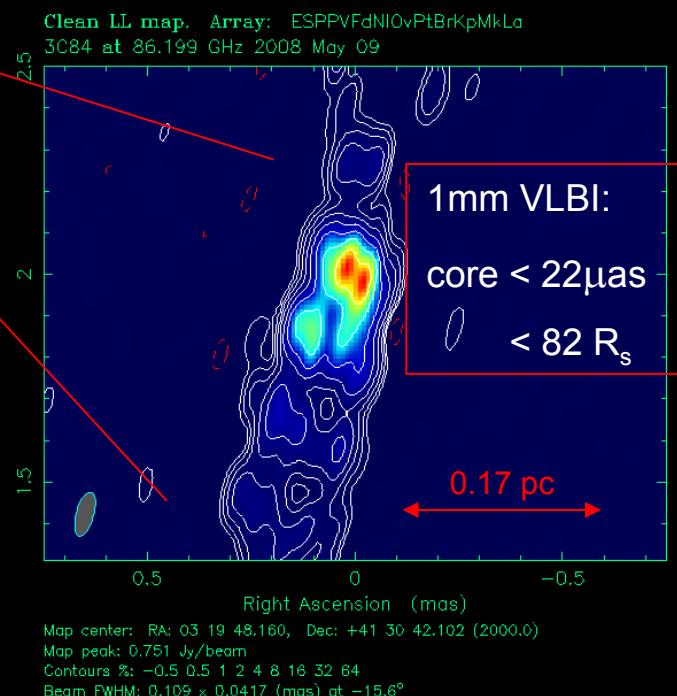


Asada et al. 2006

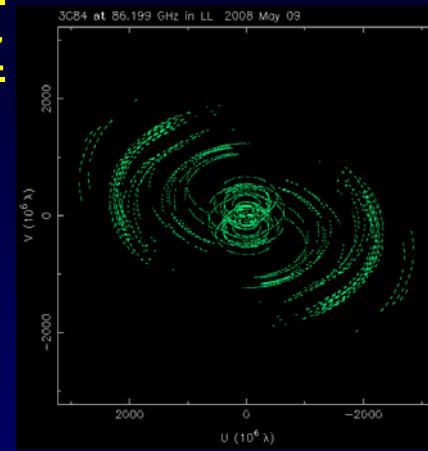


data:

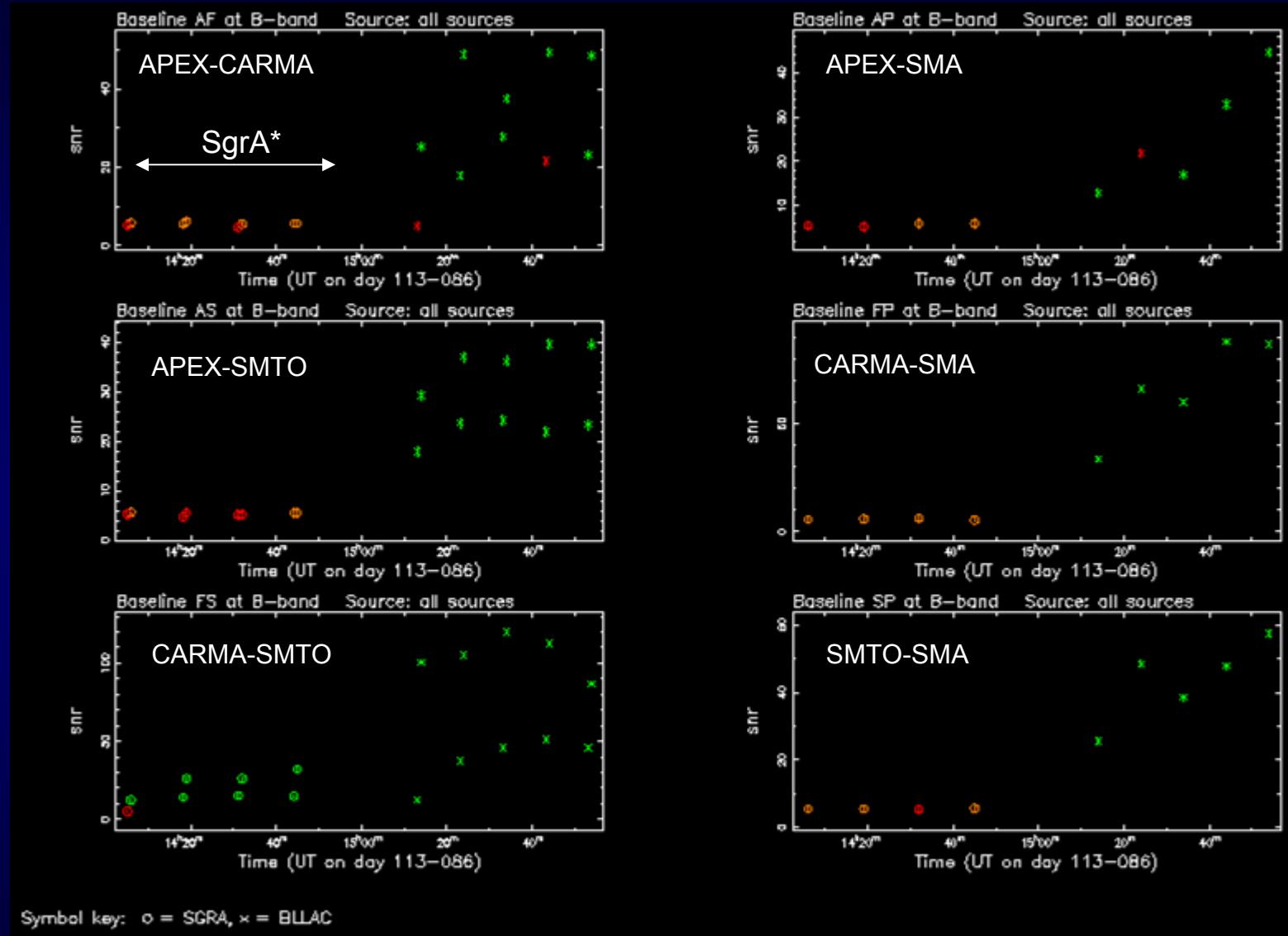
M.J. Kim, S.S. Lee et al. 2010



Size of nuclear region and jet base: 22 μas corresponding to a linear scale of 9 light-days or $82 R_s^9$ in units of the central SMBH → great potential for future studies !



Sgr A* not yet seen on APEX baselines, but lower size limit:



$S_{\text{corr}} < \sim 0.5 \text{ Jy} @ 5400 - 7200 \text{ M}\lambda$

A: APEX

P: SMA

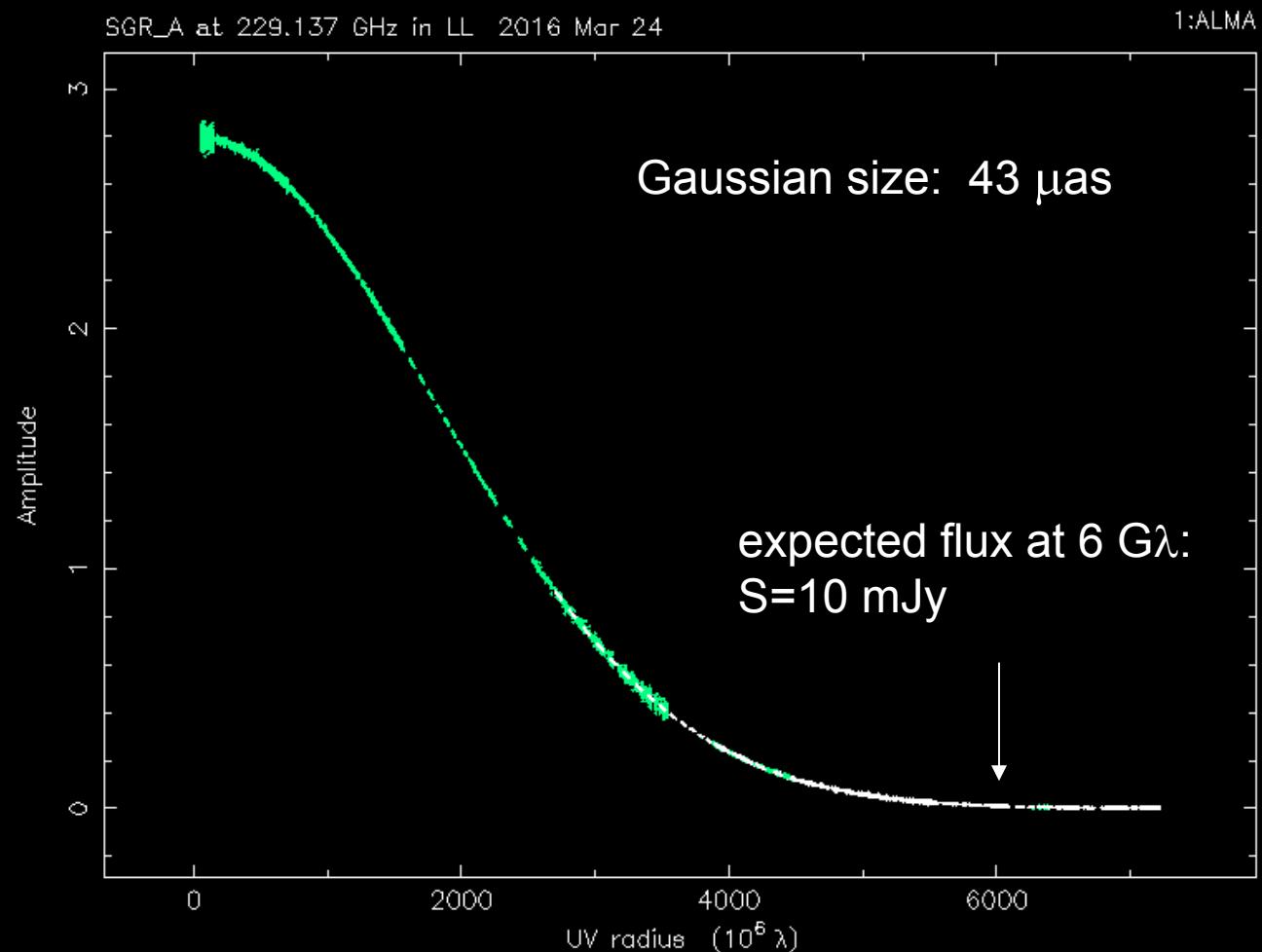
S: SMTO

F: CARMA

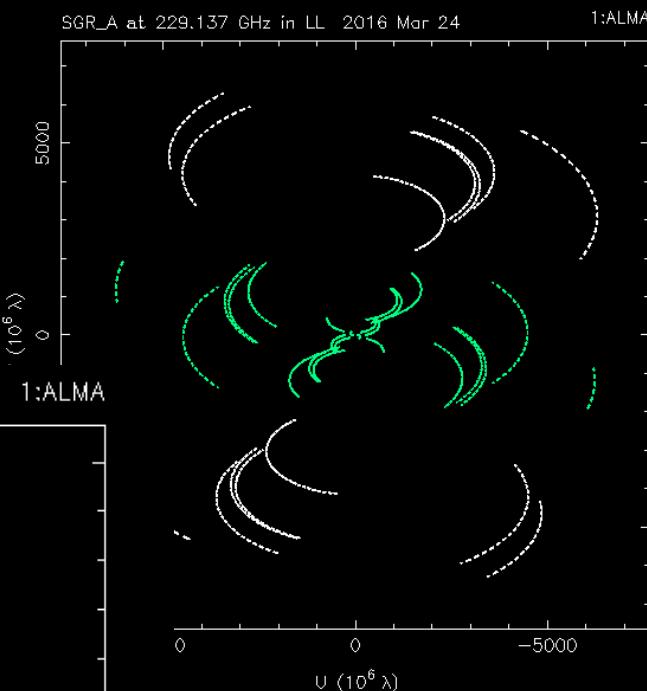
$\Theta \geq 21-27 \mu\text{as} (2.1 - 2.7 R_S)$ in N-S direction

Detection of SgrA* with APEX ?

$$S_{\text{VLBI}} = 2800 \exp(-(2975 \Theta^2) [\text{mJy}]$$

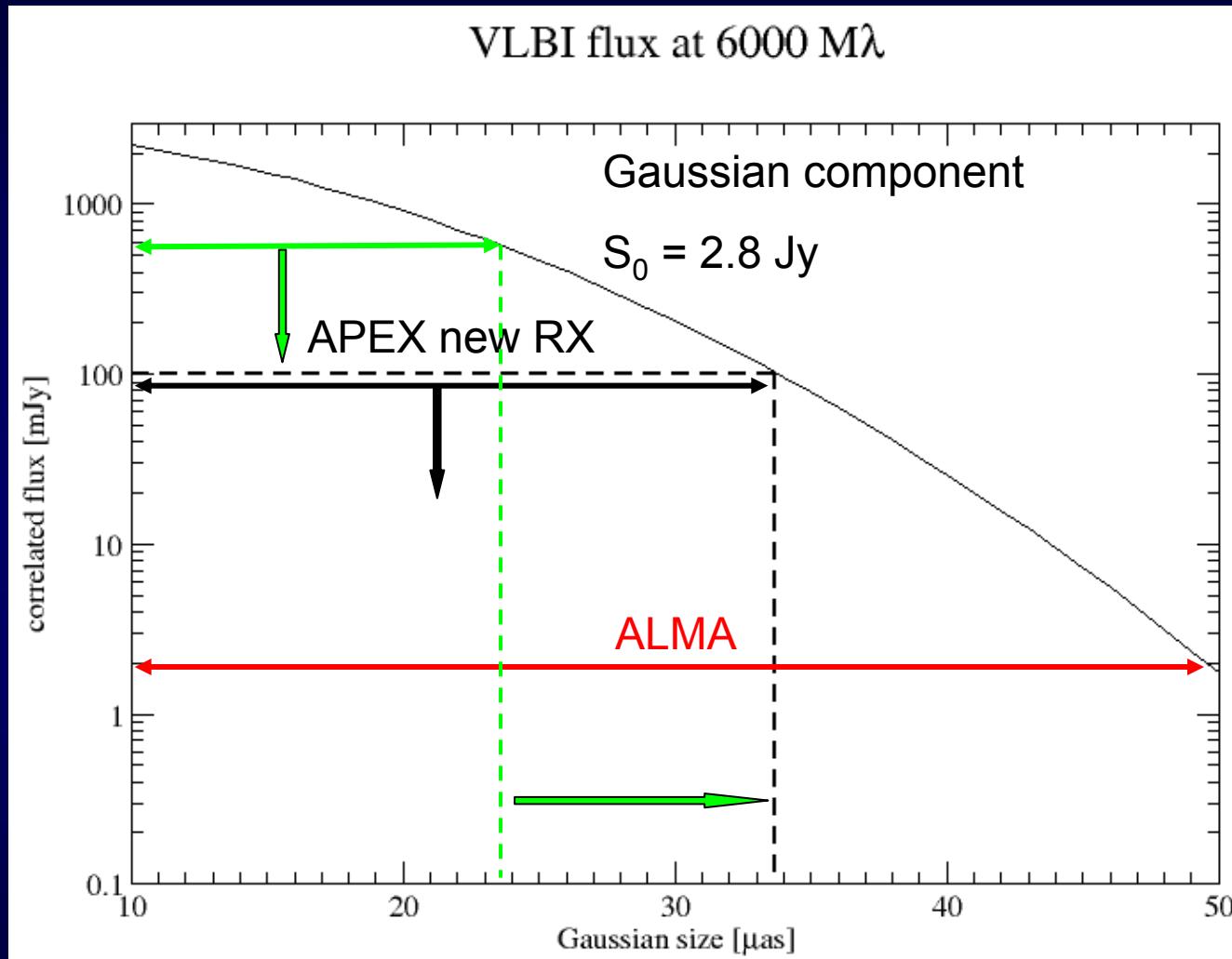


stations: Pico, PdBI, SMTO, KPMM, CARMA, SMA, LMT, ALMA/APEX



but for a size of
 $\Theta = 33 \mu\text{as}$
 $S_{\text{VLBI}} = 100 \text{ mJy} \rightarrow$
detectable w. APEX

Size of SgrA* and APEX detection limit



for $S_{\text{limit}} \geq 100 \text{ mJy} \rightarrow \text{size } \Theta \leq 33.5 \mu\text{as} (3.3 R_s)$

note: non Gaussian brightness distributions may increase correlated flux

Testing the "no-hair theorem" using mm-VLBI with APEX/ALMA

"No-hair" theorem of General Relativity:

A Black Hole is uniquely defined by its mass (monopole moment) and spin (dipole moment).

Broderick et al. 2010

see also: Johannsen & Psaltis 2010

Doeleman et al. 2009, Astro2010

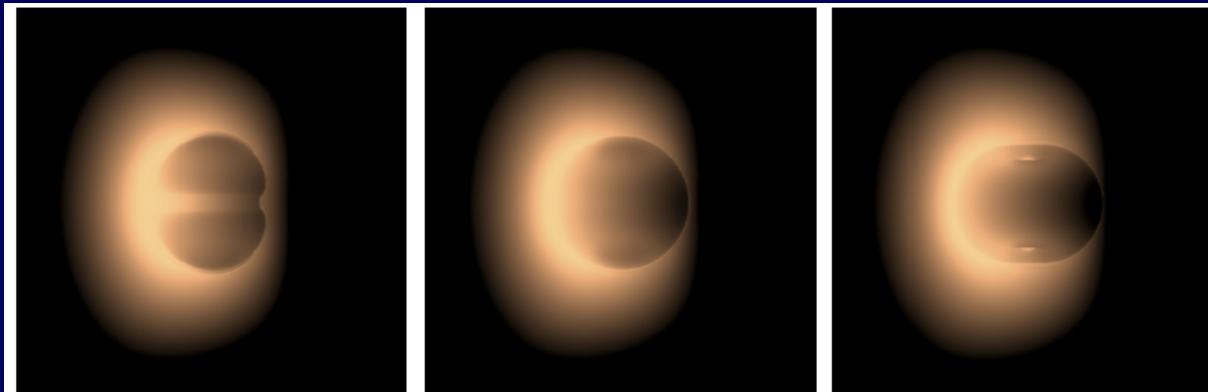
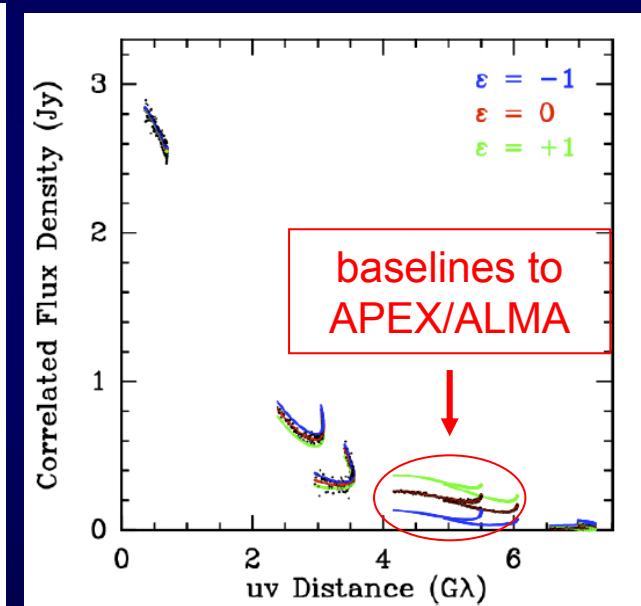


Figure 4: Testing GR. The left three images show the best fit RIAF model for SgrA* ray-traced through space times with $\epsilon = -1$, $\epsilon = 0$, and $\epsilon = +1$. If $\epsilon \neq 0$, then SgrA* is either not a GR black hole, or GR does not describe the space time of black holes.



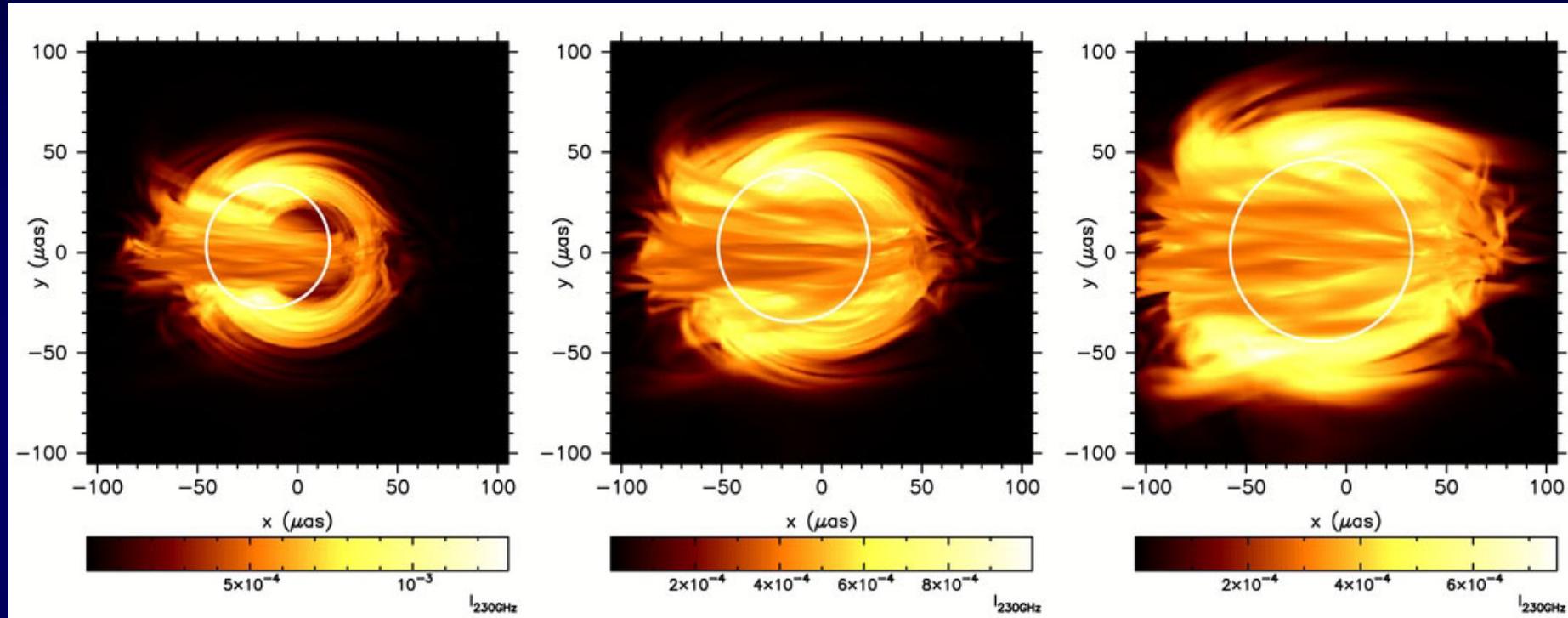
quadrupole moment: $Q = -M(a^2 + \epsilon M^2)$

$\epsilon \neq 0$, GR is violated

mm/ sub-mm VLBI can test the validity of General Relativity near a SMBH (but: excellent image fidelity required) !

Enhanced Accretion can hide Photon Ring

GRMHD simulation: BH und accretion flow



accretion rate increases

critical rate: $> 8 M_0$ @230 GHz shadow disappears
 $> 16 M_0$ @345 GHz

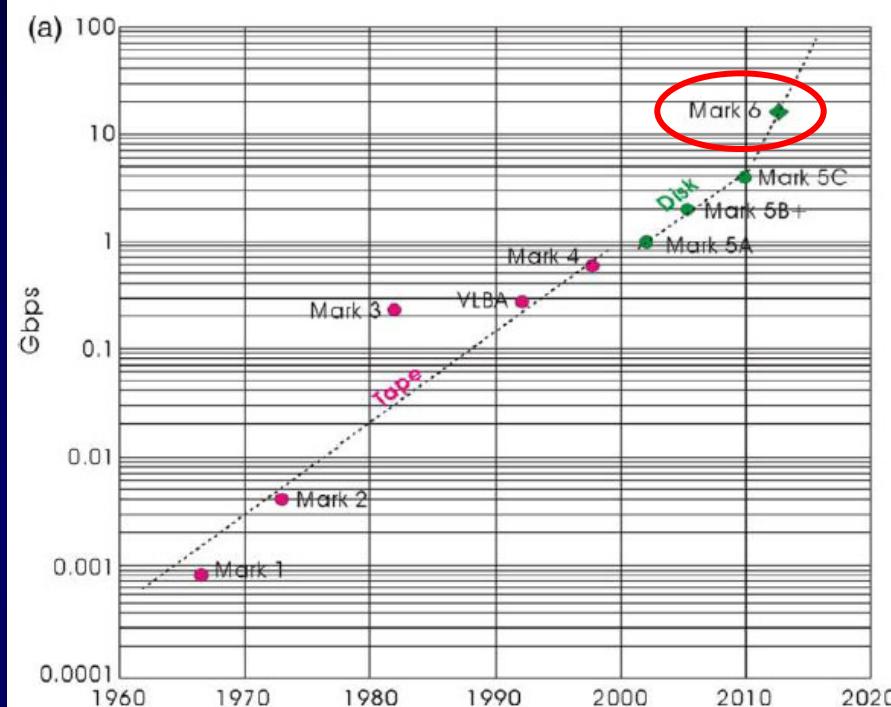
Moscibrodzka et al. 2012

Do we need APEX when ALMA is there ?

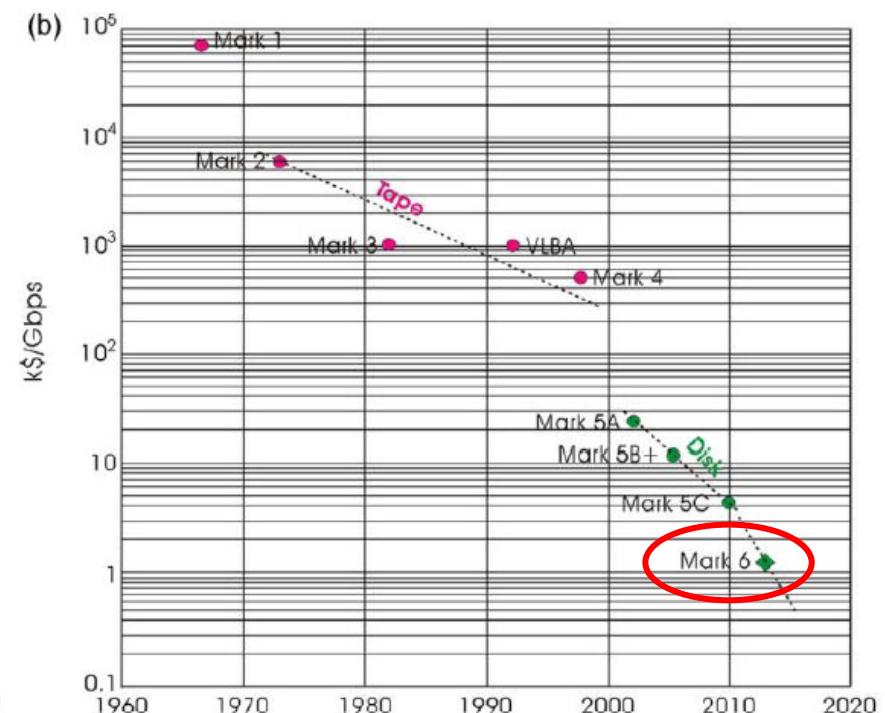
- phasing capability of ALMA for VLBI is now beeing developed
- 1st VLBI test experiments with ALMA sub-array expected in 2015/2016 (APP)
- sensitivity of phased ALMA array will be $\text{sqrt}(N)$ better than APEX, but:
 - APEX required for initial VLBI tests with ALMA during APP transition period
 - VLBI time at ALMA will be very limited due to heavy oversubscription
 - ALMA not needed for every AGN study
 - better scheduling flexibility of APEX than ALMA
 - a VLBI telescope in Chile always improves the angular resolution by ~2
 - need many stations for image fidelity (self calibration needs > 10 stations)
 - combination of APEX with other telescopes in the South (LLAMA, LMT, SPT)
 - VLBI at 345 GHz soon

Future: Continuous increase of recording bandwidth

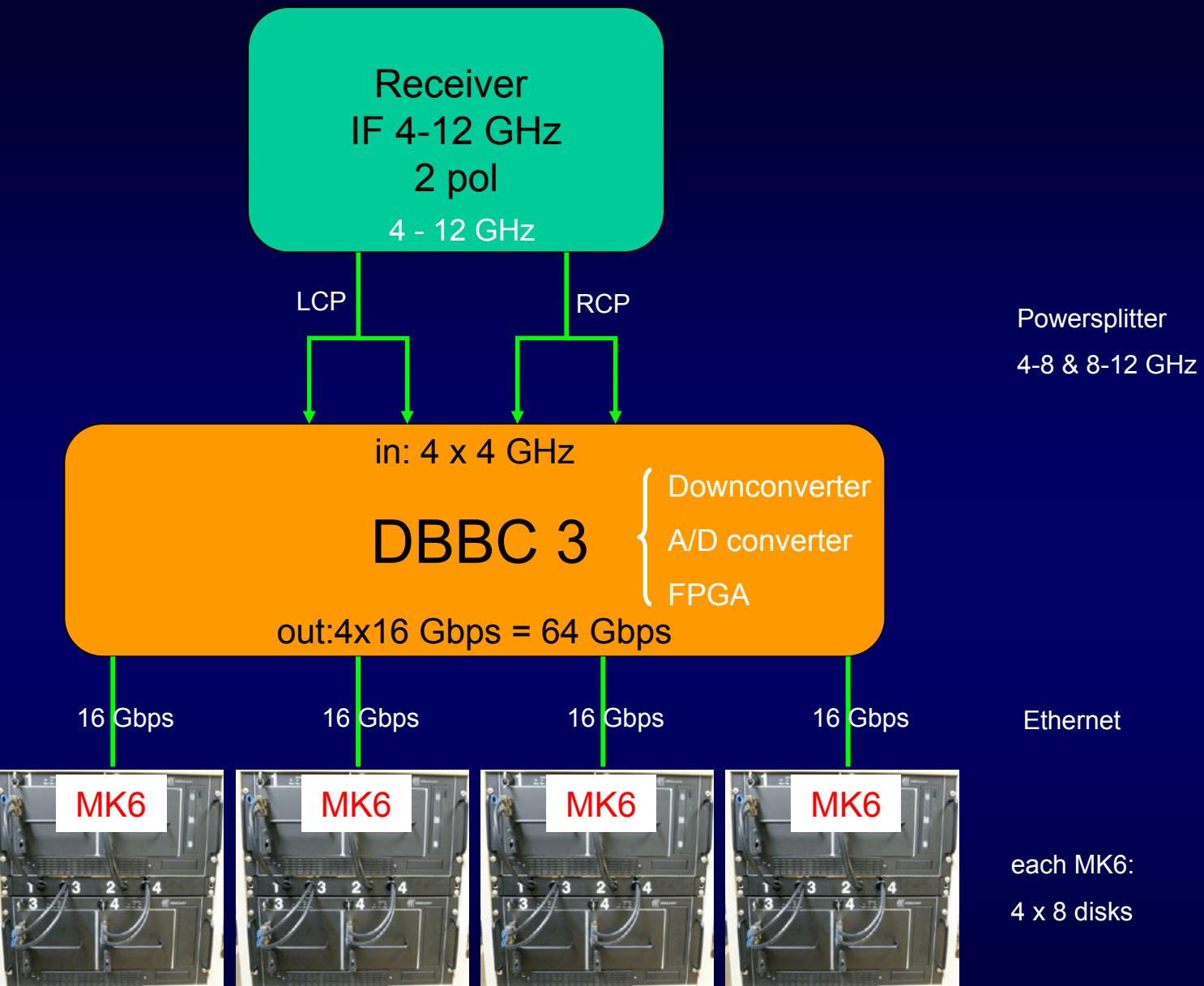
Recording Data rate vs. time



Cost vs. time



Mark 6: 16 Gbps (4 GHz bandwidth)
4 modules (each 8 disks)
helium filled disks for high altitude



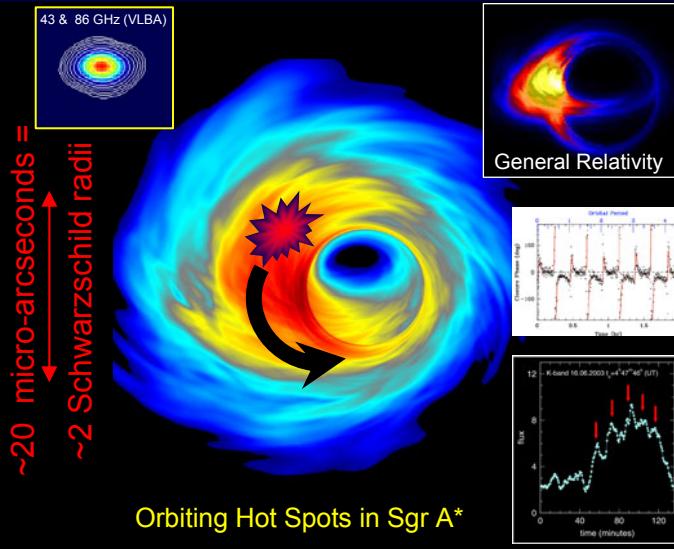
Final stage: 2 x 8 GHz BW (64 Gbps, factor $\sqrt{64/2} = 8$ sensitivity increase !

Testing GR near Black Holes and study the origin of jets with global 1.3 mm VLBI

see EHT Whitepaper (Fish et al. 2013)

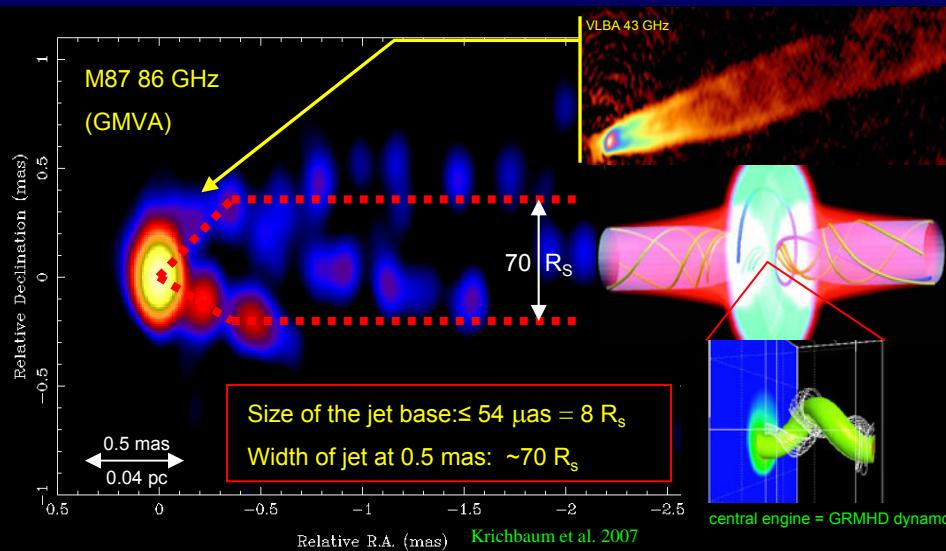
- achieve 10-20 micro-arcsecond resolution at sub-mm wavelengths
- image Sgr A* and M87 with a few R_G resolution (BH imaging and GR-effects)
- study jet formation and acceleration in nearby Radio-Galaxies (jet-disk connection, outburst ejection relations, etc.)
- study AGN and their SMBHs at high redshifts (cosmological evolution of SMBHs)
- establish a global 1mm VLBI array: PV, PdBI, SMT0, SMA, CARMA, LMT, SPT, APEX/ ALMA (Event Horizon Telescope).
- add ALMA through ALMA phasing project (APP)

Sgr A*:



Orbiting Hot Spots in Sgr A*

M87+ AGN Jets:



Krichbaum et al. 2007

Thats it for today.

Have a nice dinner
and thank you !