Progress on 1mm-VLBI with Apex

Micro-arcsecond scale imaging of black holes and jet nozzles

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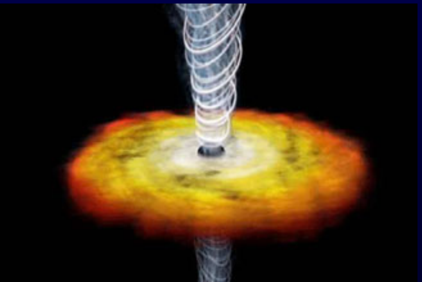


people involved:

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.

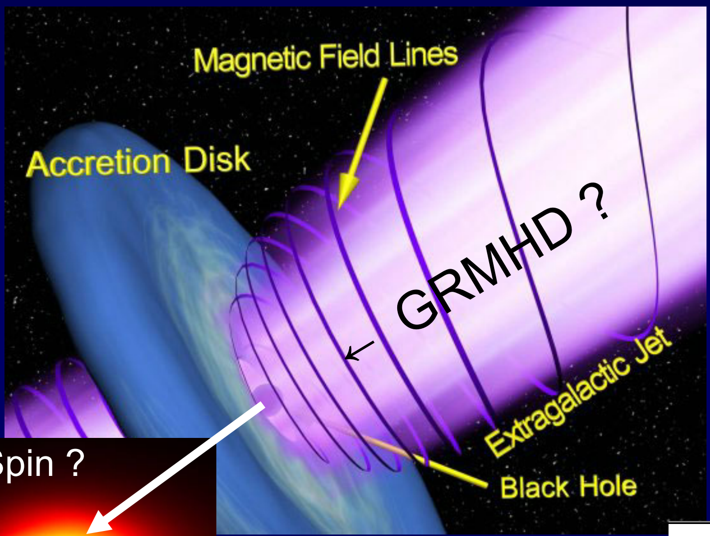
JCMT: P. Friberg, R. Tilanus, et al.

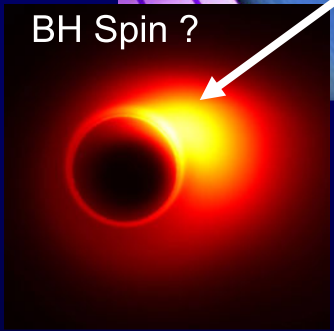
SMA: R. Blundell, J. Weintroub, K. Young, et al.

SMTO: R. Freund, D. Marrone, P. Strittmatter, L. Ziurys et al.

Scientific Motivation:

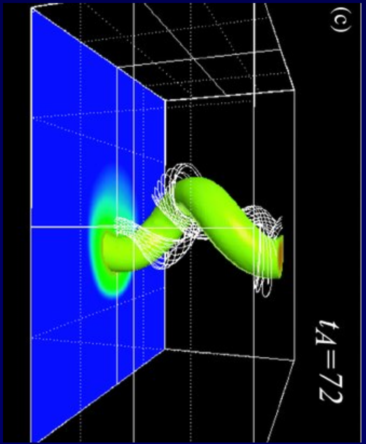
Detailed understanding of initial jet formation, acceleration and collimation. Image region around SMBHs, test GR near event horizon and test jet launching models.



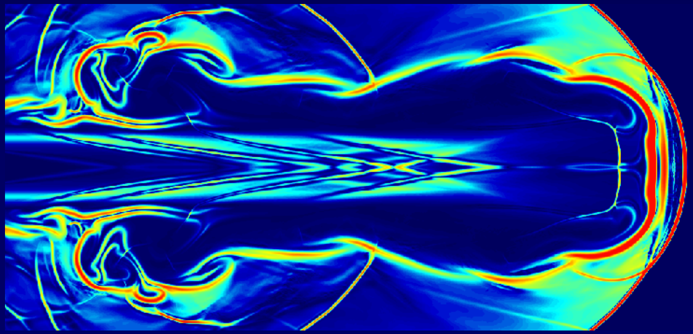


BH converts magnetic into kinetic energy

Spin determines photon ring shape and jet width



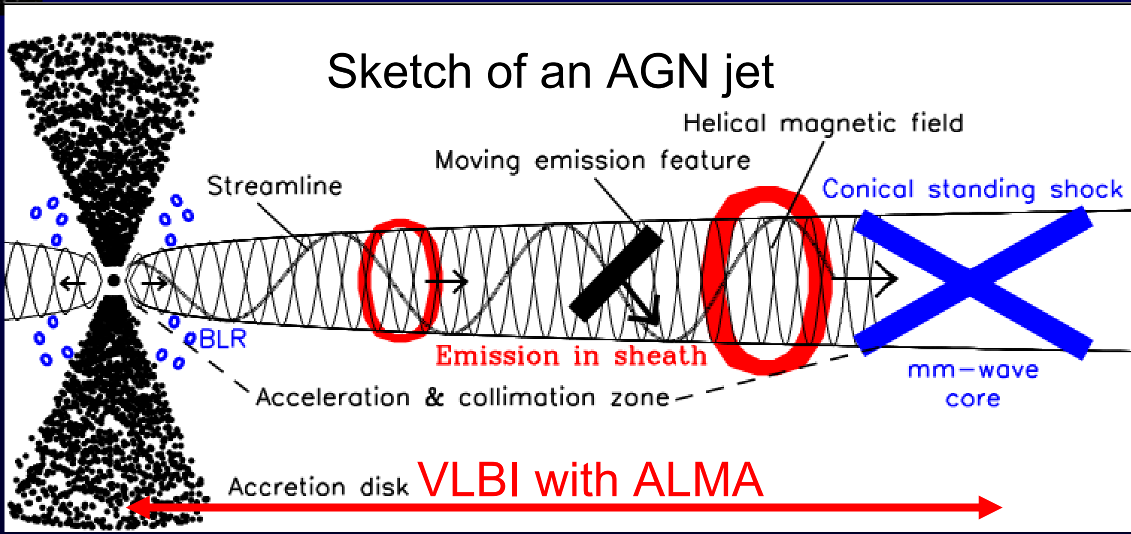
Rotation & instabilities cause helical jets



instabilities and shocks propagating through jet

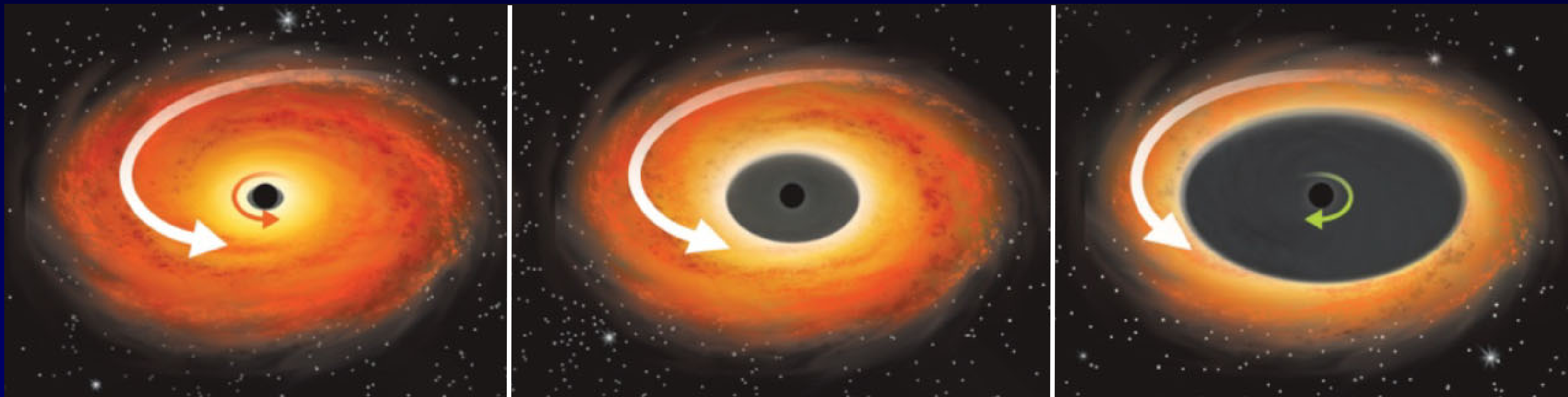
fundamental tests of BH physics

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

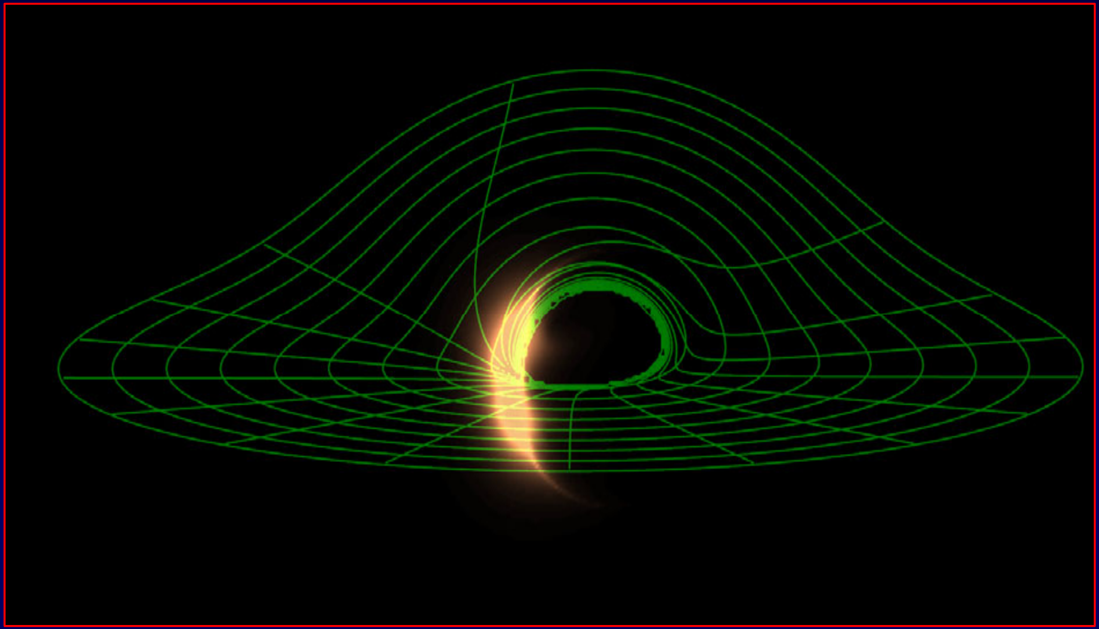
from talk by Laura Brenneman (CfA)

- **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

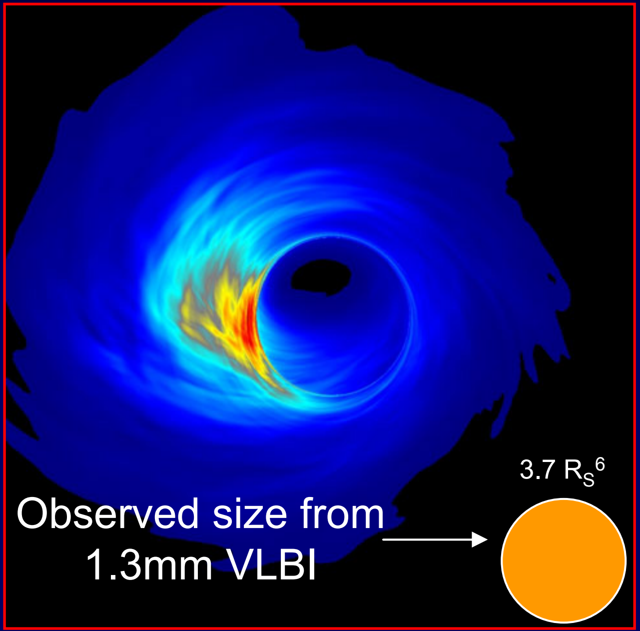


image credit: Noble & Gammie

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

observed size: 43 (+14/-8) µas

deconvolved : 37 µas

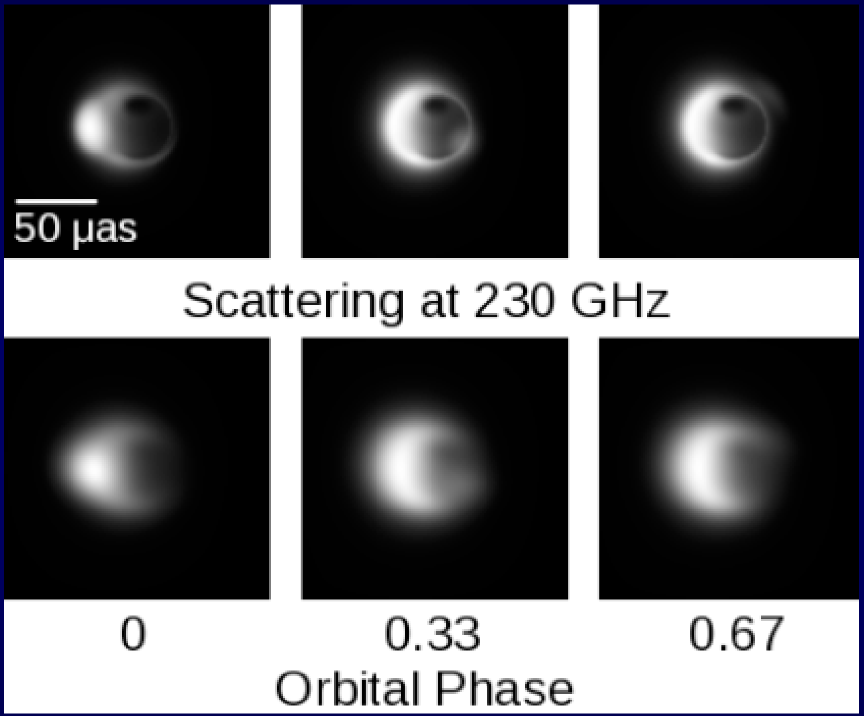
intrinsic : 3.7 R_S

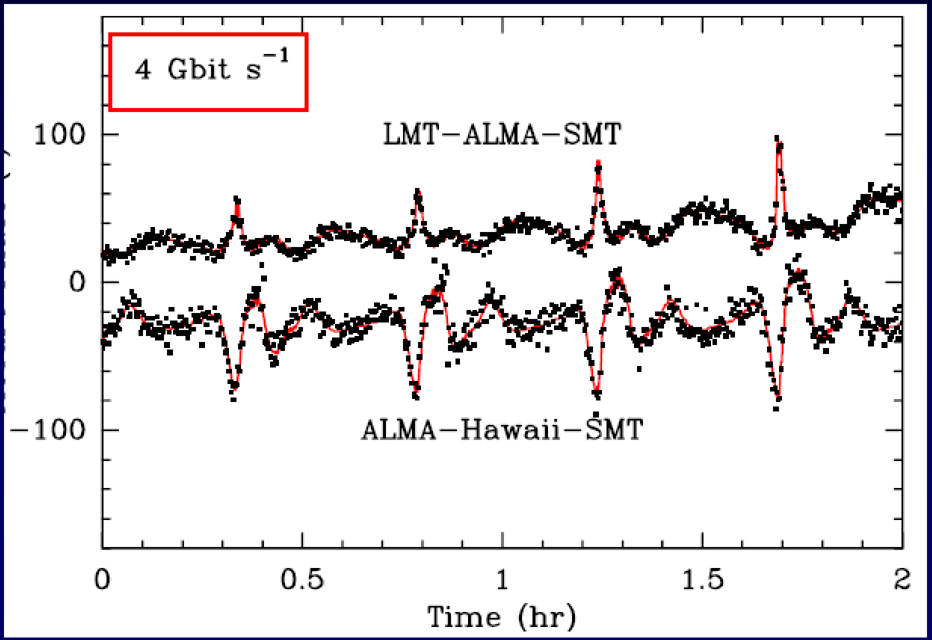
Observed size is smaller than expected size of accretion disk

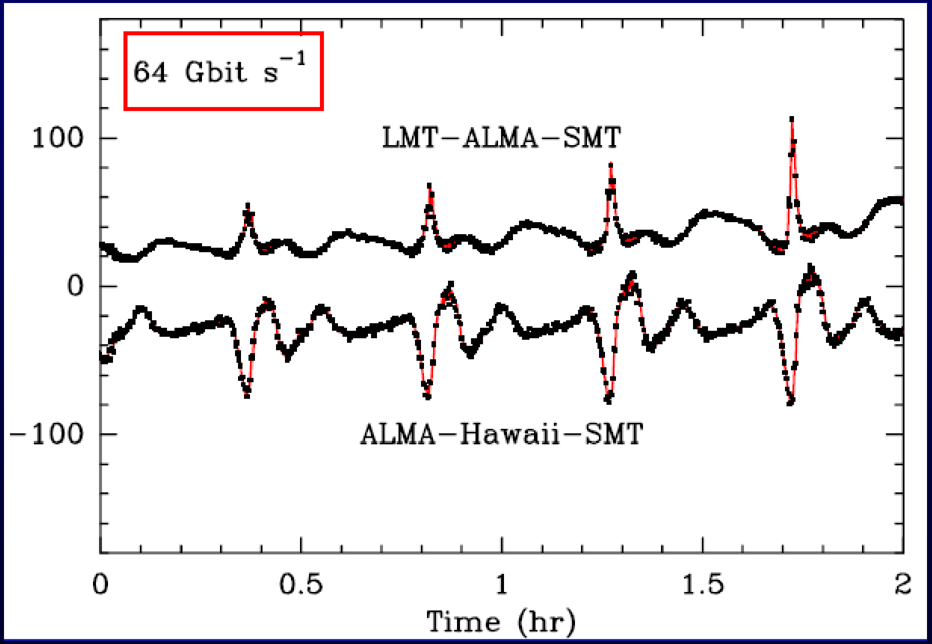
→ emission from hot spot or width of crescent shaped photon ring ?

Time resolving BH orbits and determination of ISCO

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



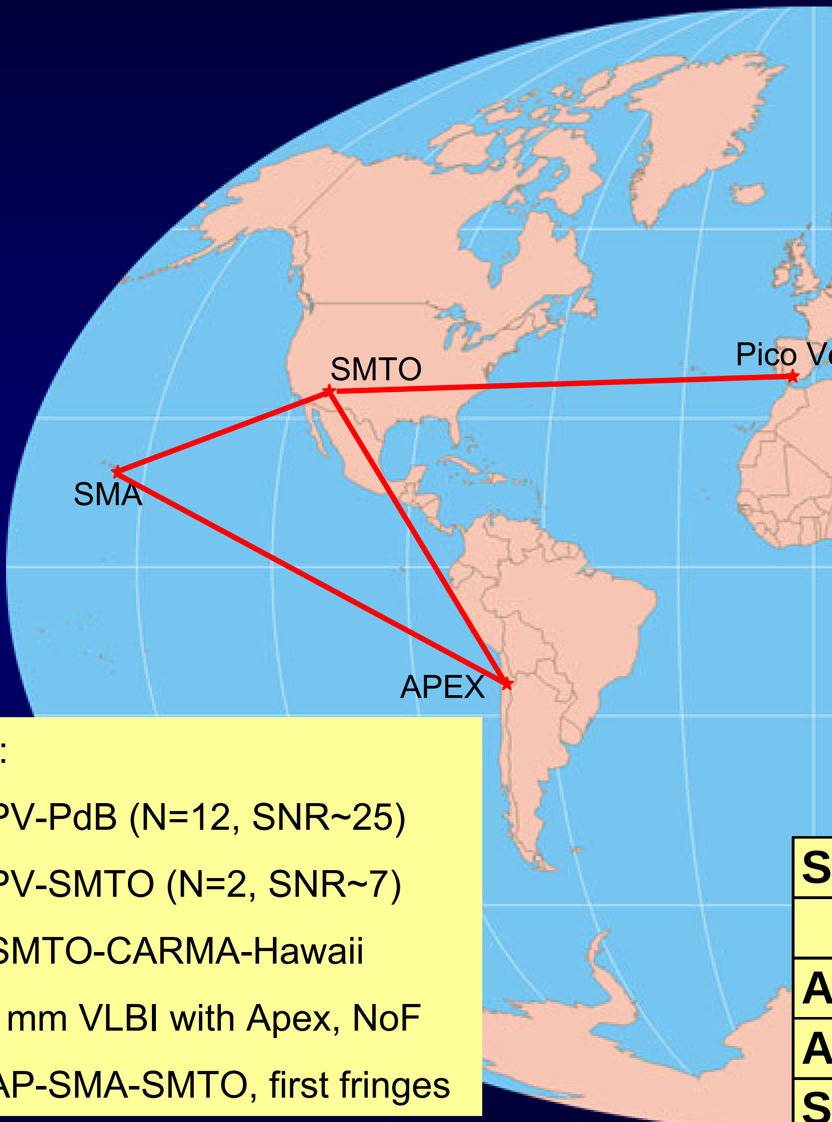


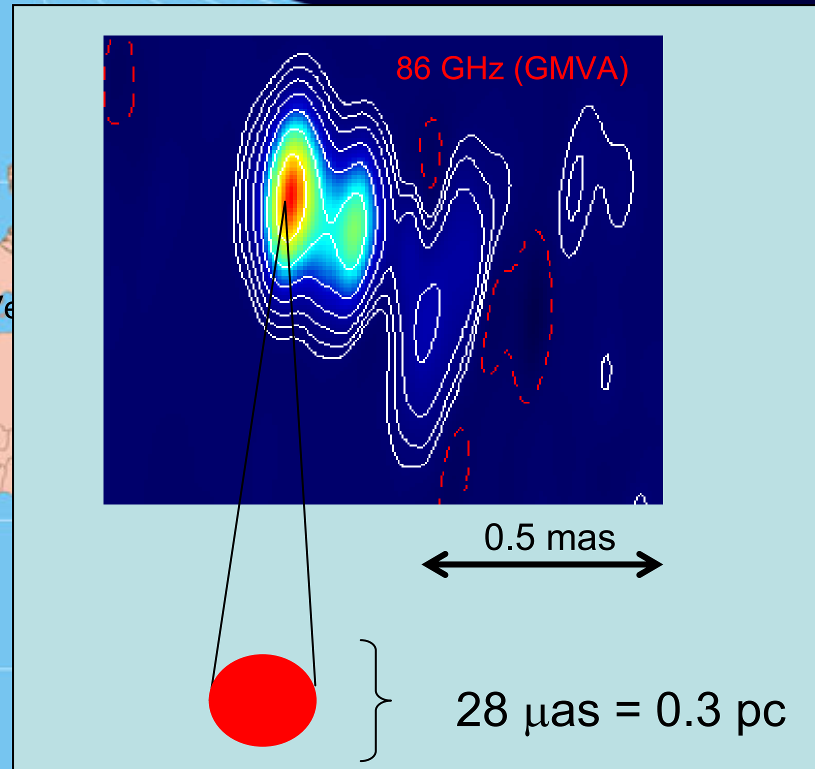


Sensitivity depends on observing bandwidth: will increase data rates from 4 Gbps to 64 Gbps

Fish et al. 2013, Doeleman et al. 2009

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

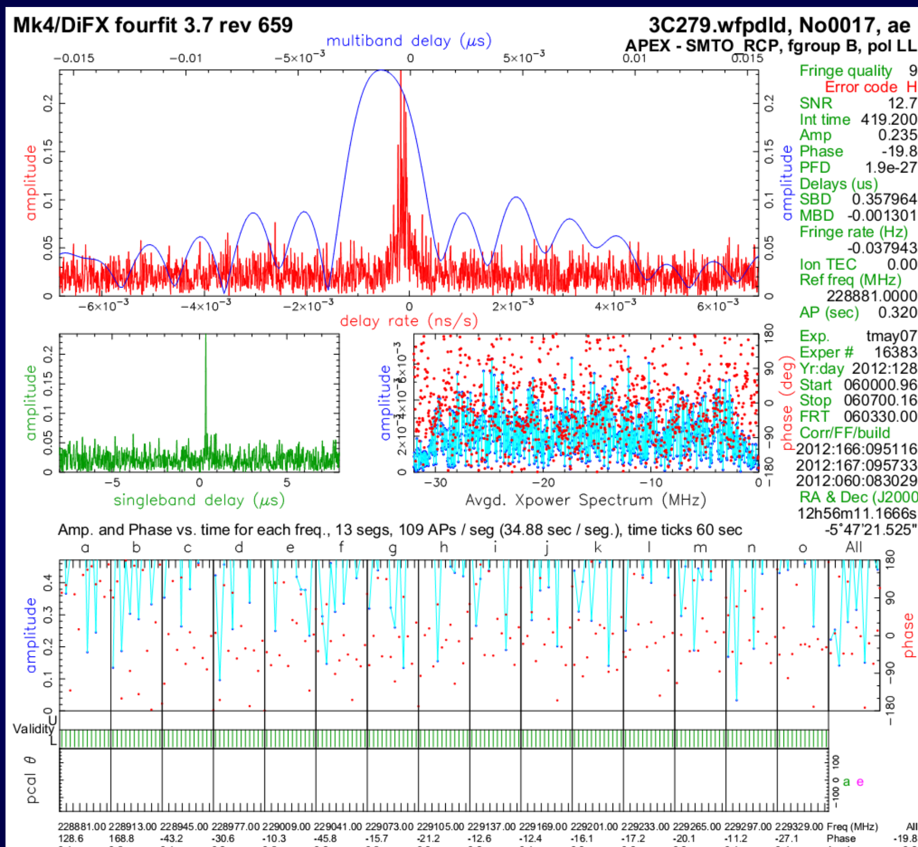
2012: AP-SMA-SMTO, first fringes

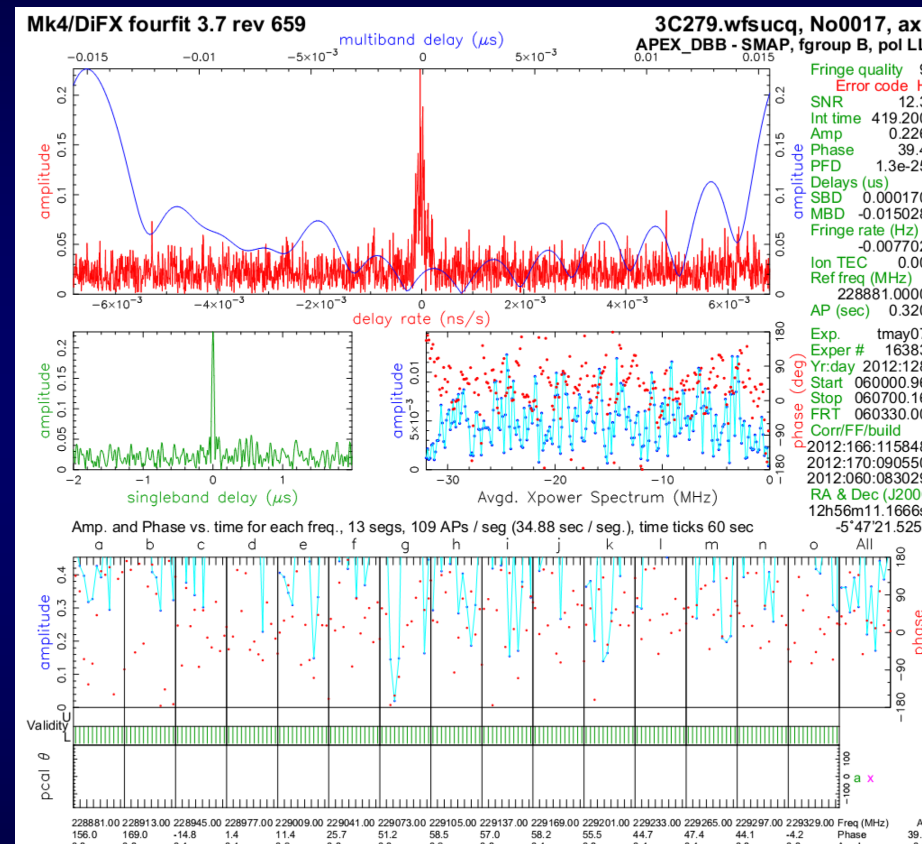
Station	**Station**	**Length (km)**	**Resolution (μas)**
APEX	**SMA**	**9447**	**28,4**
APEX	**SMTO**	**7174**	**37,4**
SMTO	**SMA**	**4627**	**58,0**

★ 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





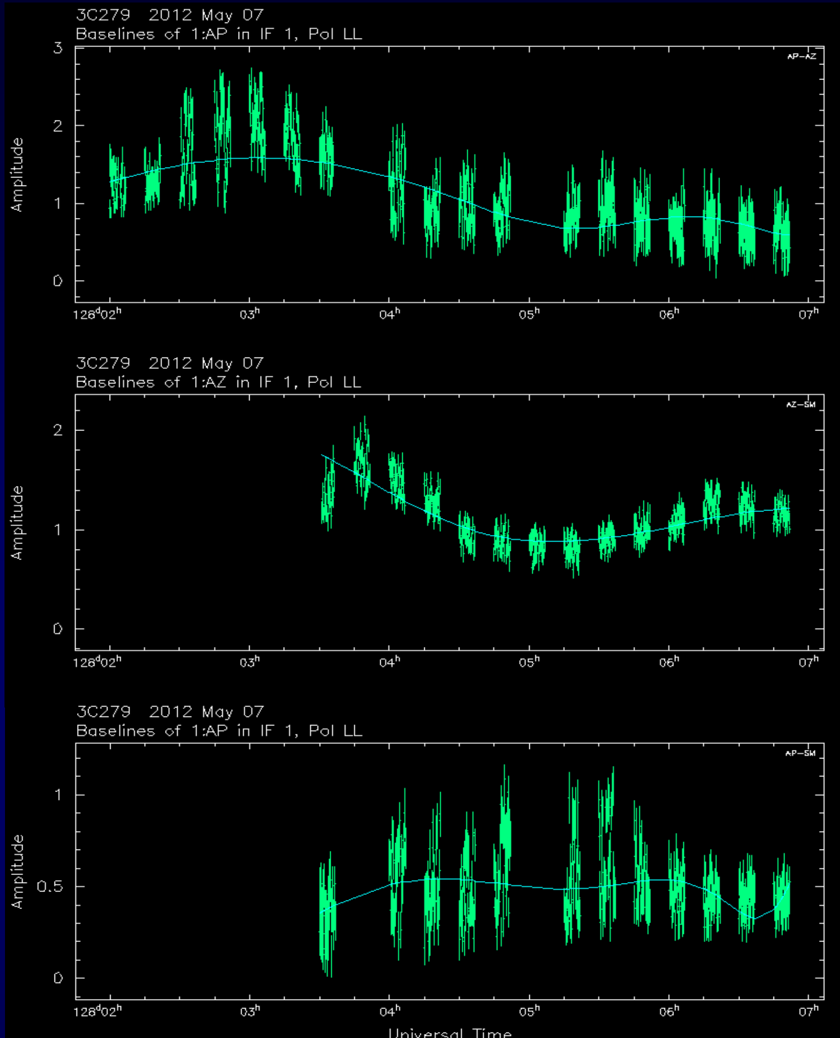
APEX – SMTO (Arizona): SNR 12.7

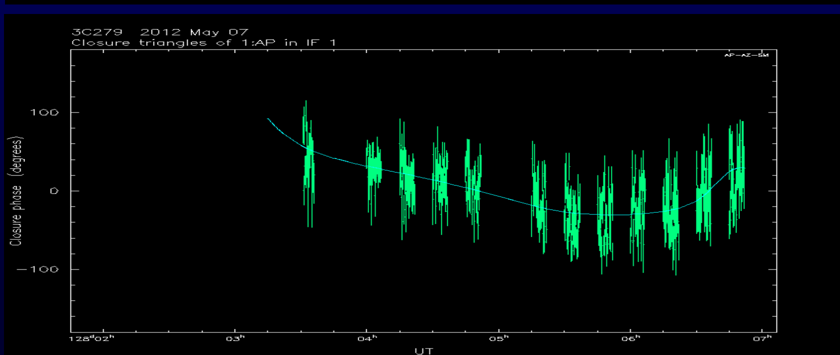
D=7170 km

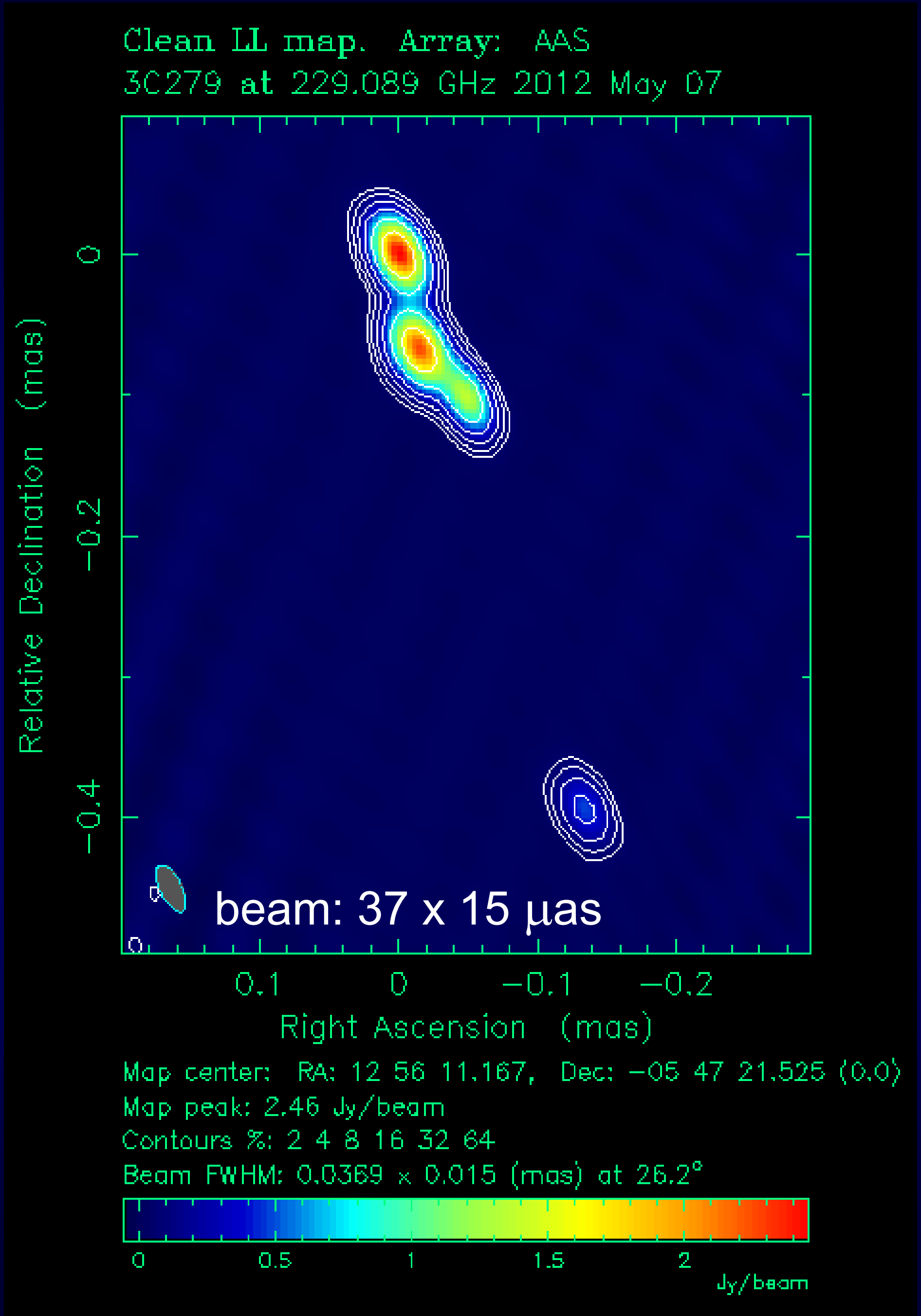
APEX – SMA (Hawaii): SNR 12.3

D=9450 km

credit: A. Roy and Apex team

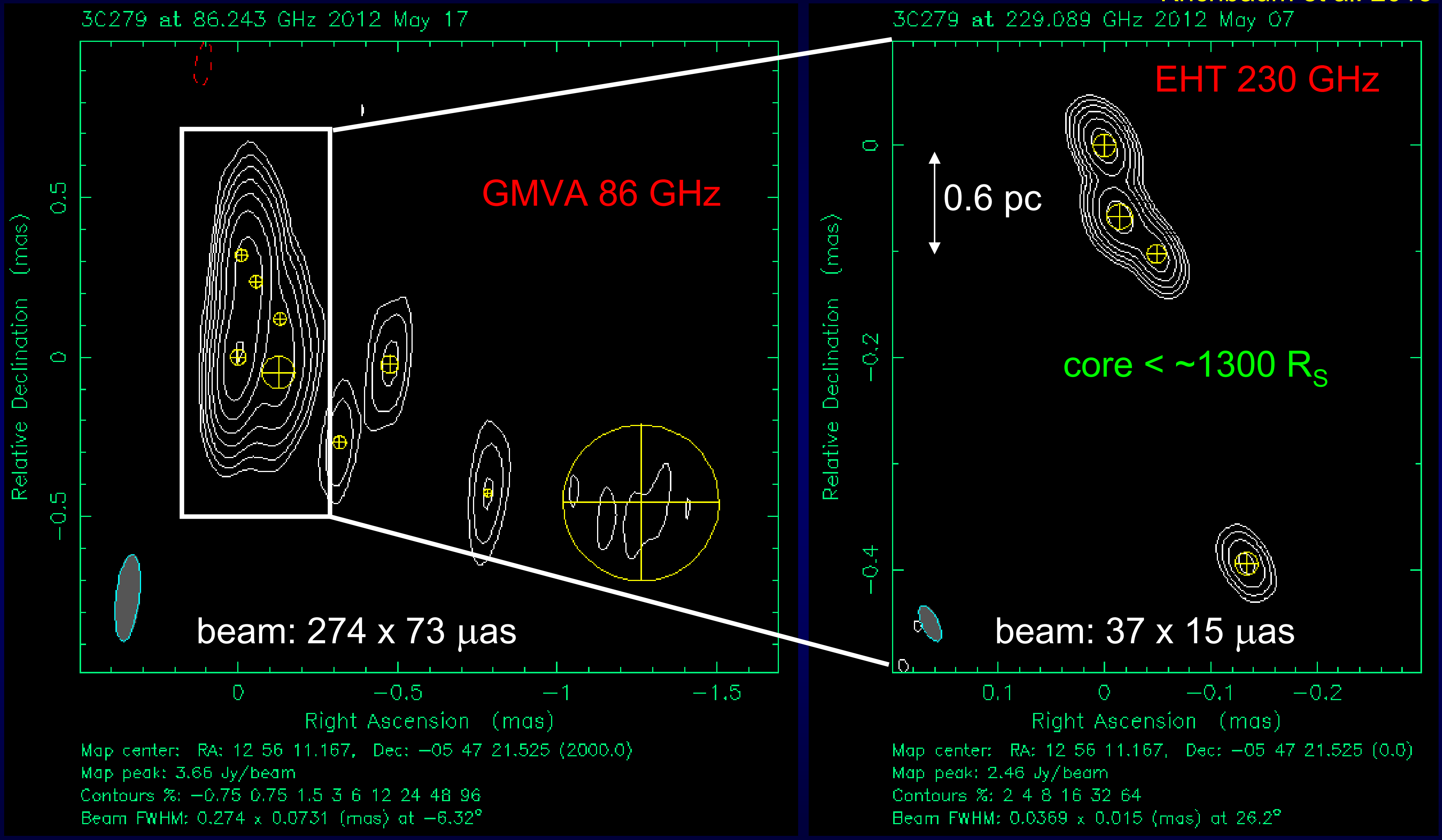

3C279 2012 May 07
Baselines of 1:AP in IF 1, Pol LL
Amplitude
3C279 2012 May 07
Baselines of 1:AZ in IF 1, Pol LL
Amplitude
3C279 2012 May 07
Baselines of 1:AP in IF 1, Pol LL
Amplitude
Universal Time


3C279 2012 May 07
Closure triangles of 1:AP in IF 1
Closure phase (degrees)
UT


Clean LL map. Array: AAS
3C279 at 229.089 GHz 2012 May 07
Relative Declination (mas)
Right Ascension (mas)
beam: 37 x 15 μas
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 x 0.015 (mas) at 26.2°
Jy/beam

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

Krichbaum et al. 2013

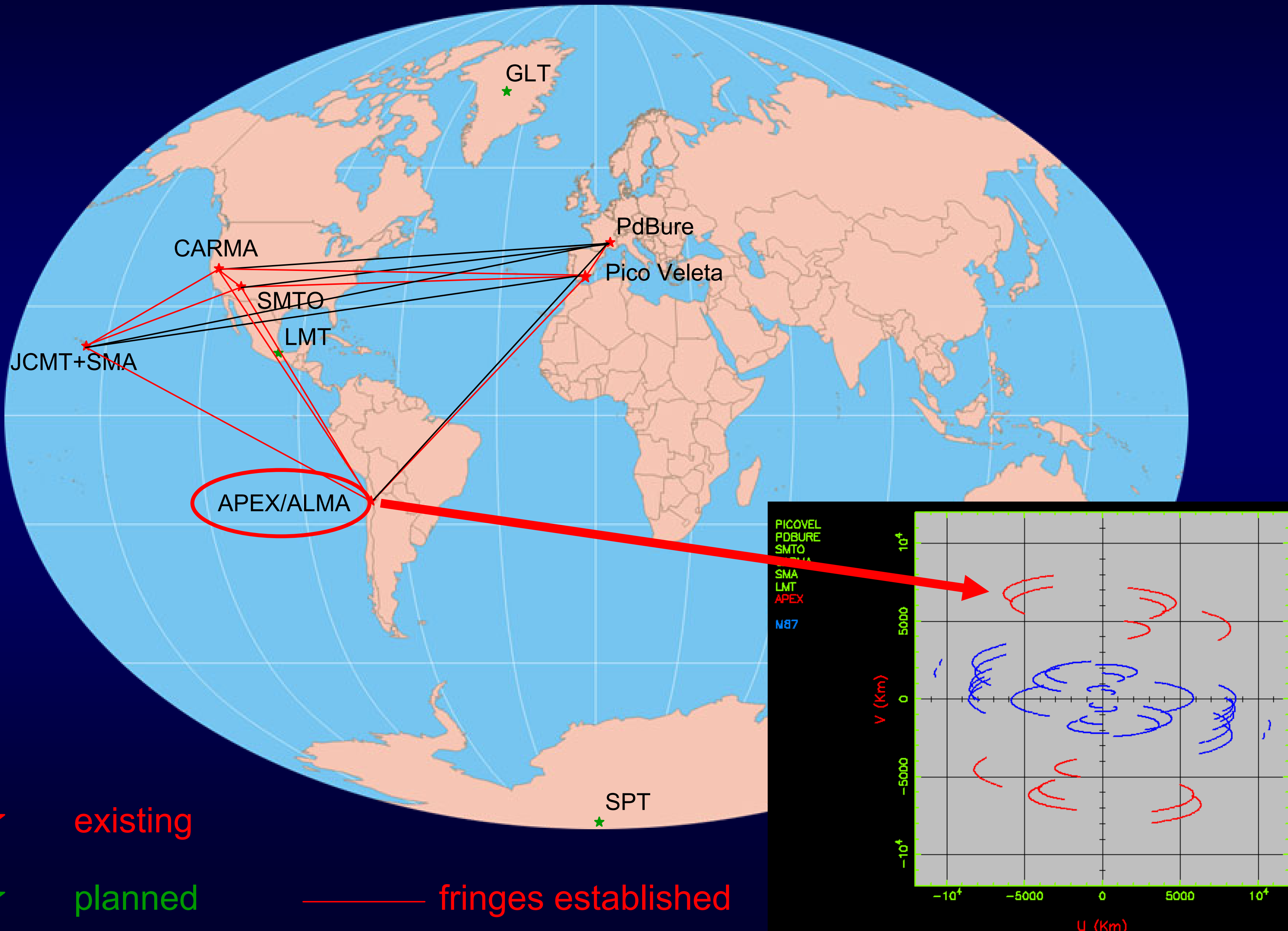


base of jet is transversely resolved and has a width of ~1 pc (~10^4 R_S)

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



existing

planned

fringes established

Antenna Properties 1.3mm VLBI March 2013

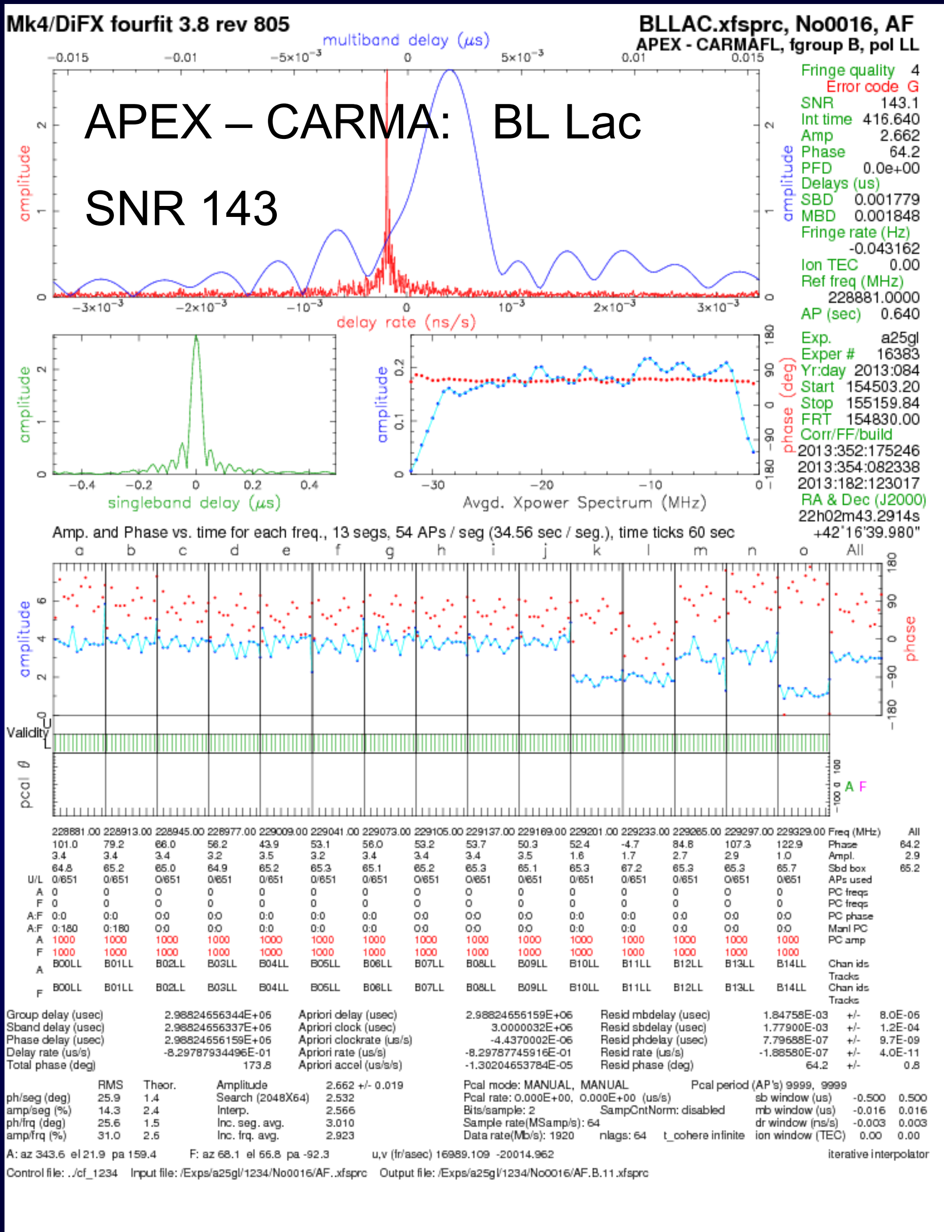
Ant.	Code	D_eff	Tsys_eff	Gain	App.Eff	SEFD	Pol.	Comment
		[m]	[K]	[K/Jy]		[Jy]		
PICO	V	30	250	0,110	0,43	2273	dual	
APEX	A	12	360	0,026	0,63	13846	LCP	Coherence loss 1,5
SMTO	S	10	250	0,018	0,64	13889	LCP	
CARMA	F	21,6	300	0,0759	0,57	3953	dual	4x10,4m+4x6,1m, phasing=0,9
SMA	P	15,1	300	0,045	0,69	6667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

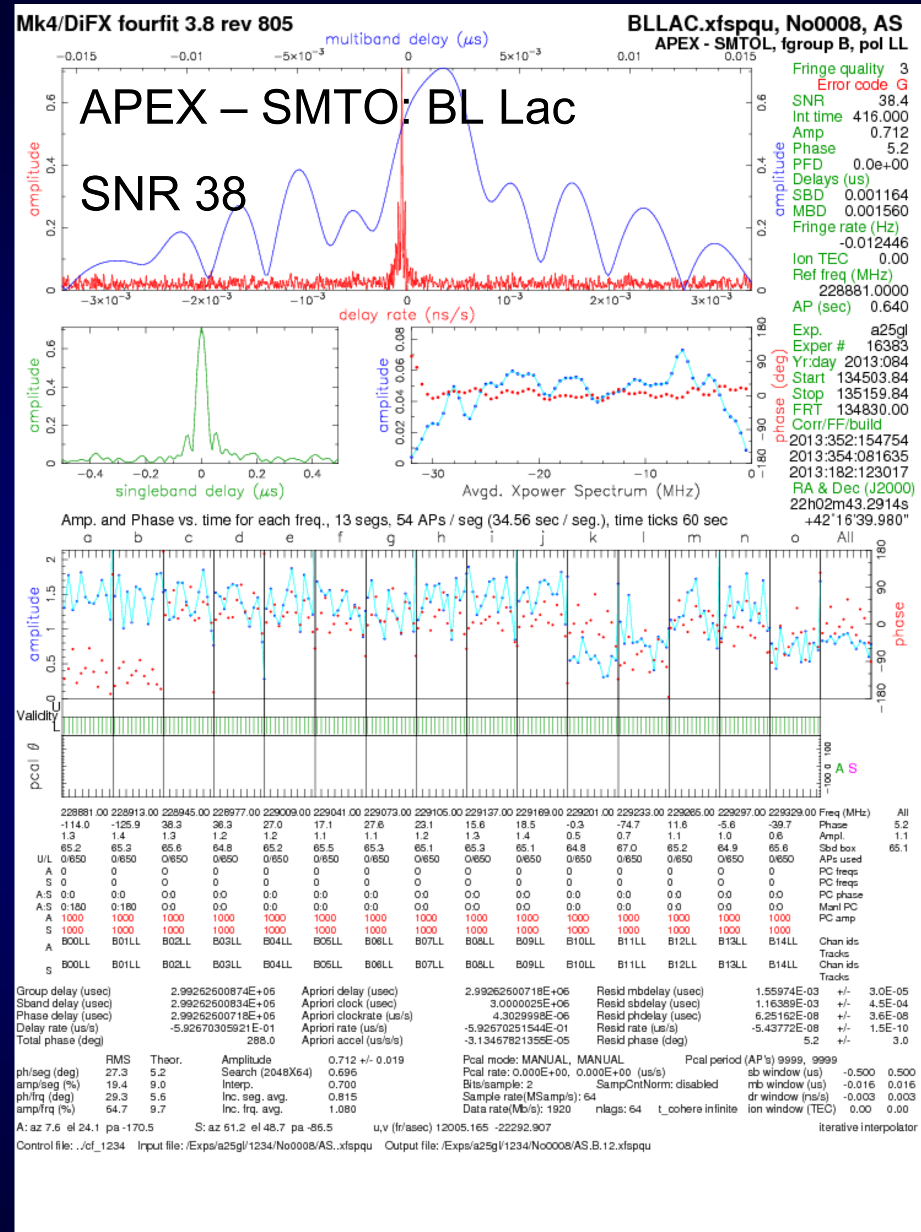
Baseline Sensitivity (7sigma, 10sec, 500 MHz, 2 Gbps):

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

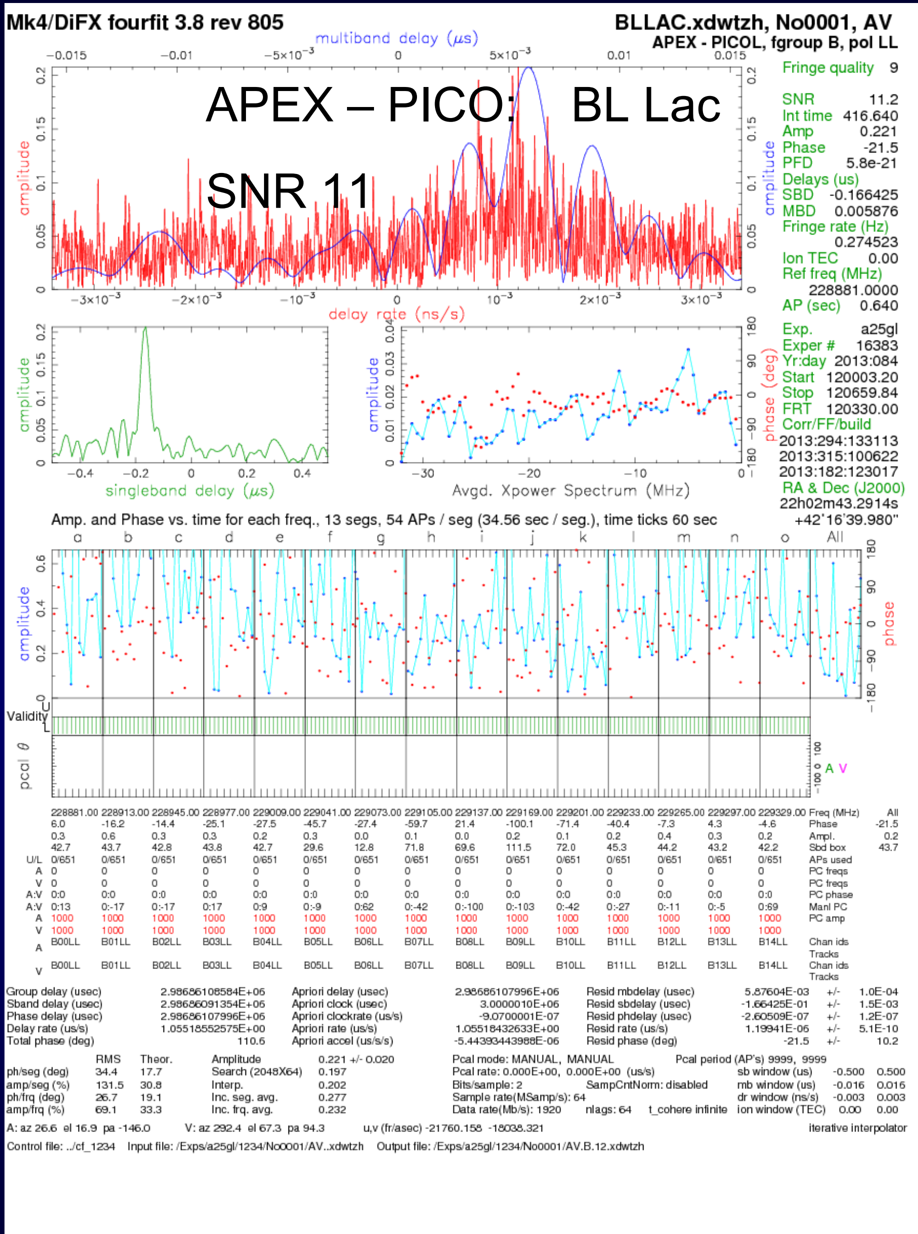
2 Gbps → 32 Gbps:

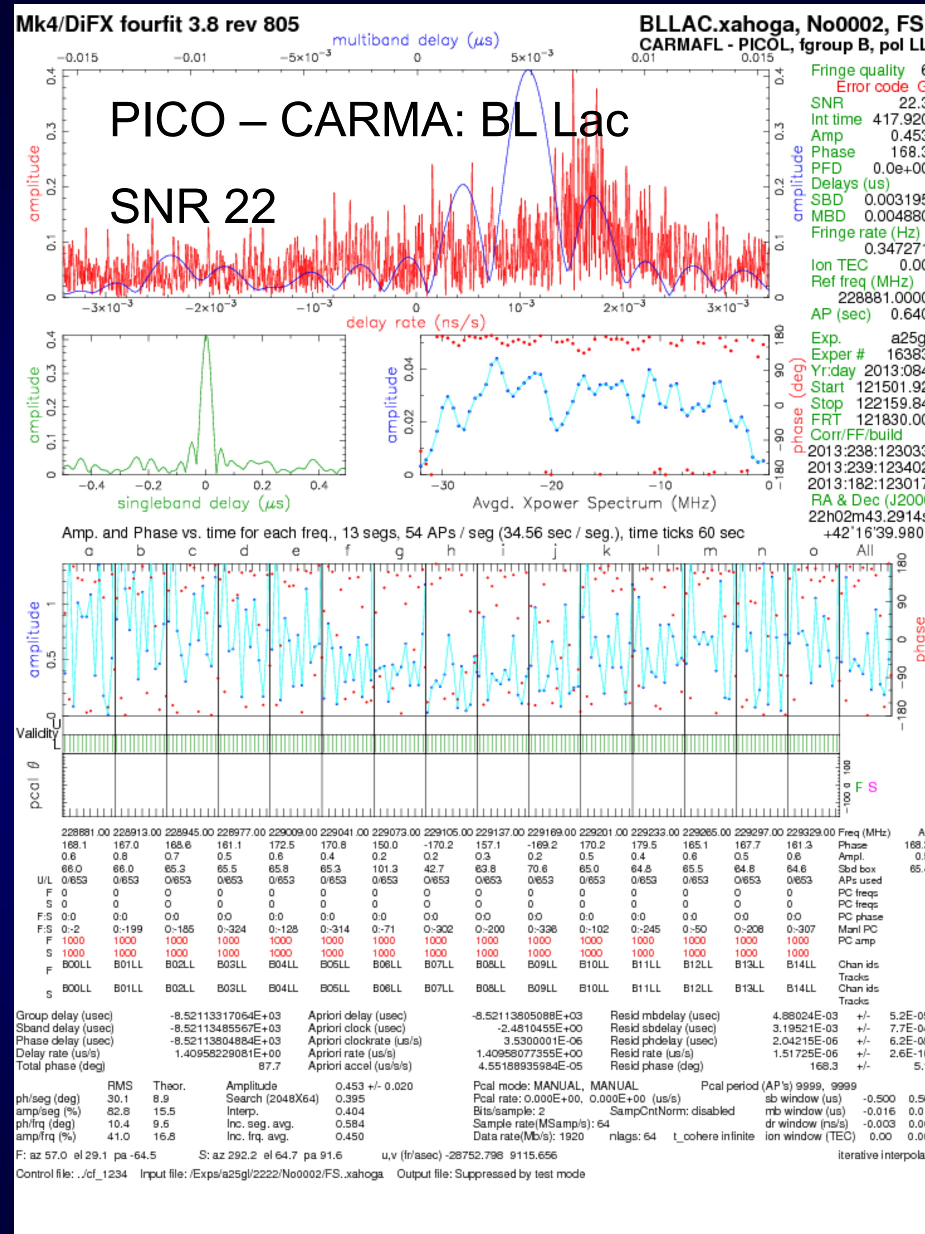
Factor 4 improvement possible





strong fringes to APEX on several bright mm-sources

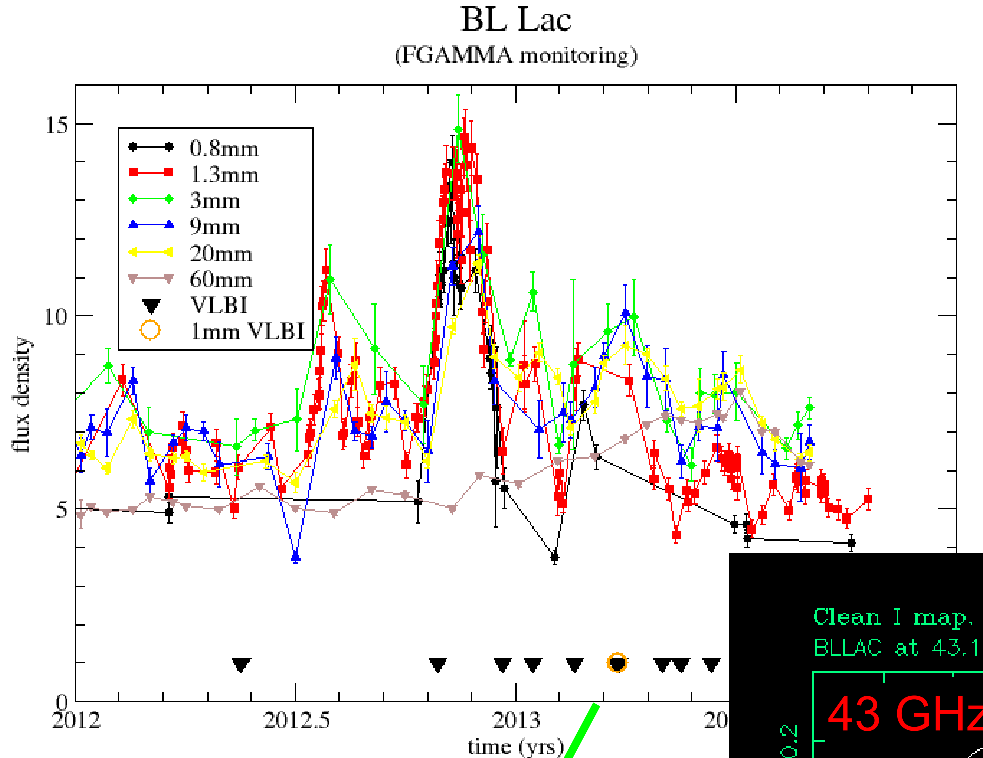


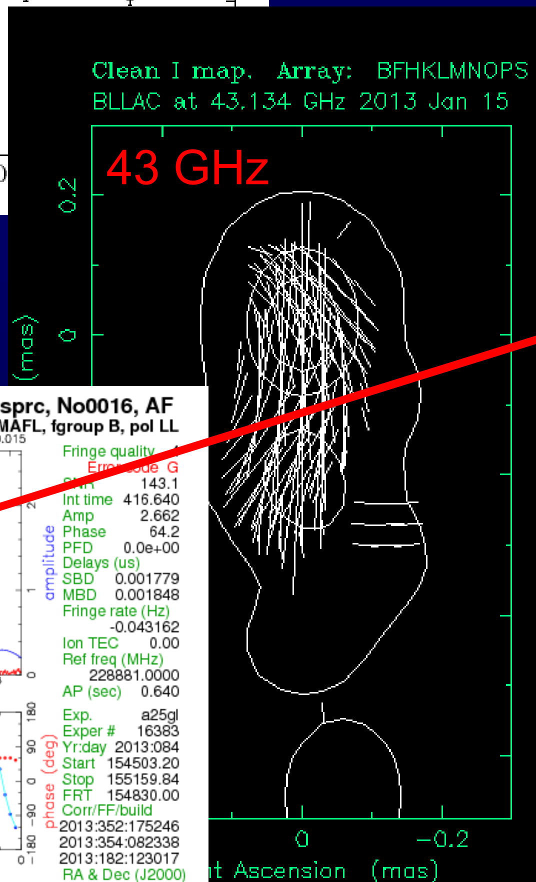


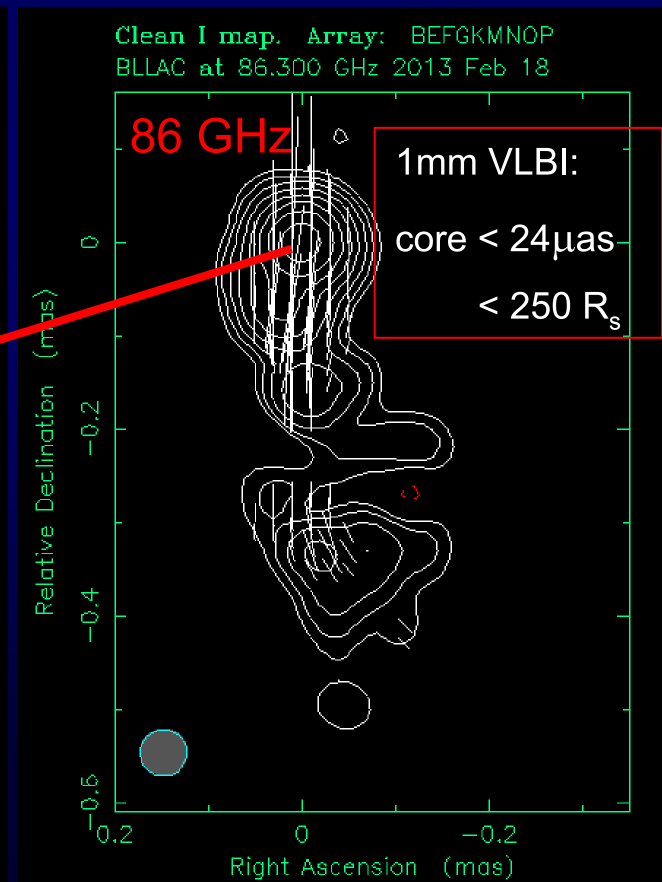
low SNR at Pico Veleta due to very bad weather and a DBBC configuration problem

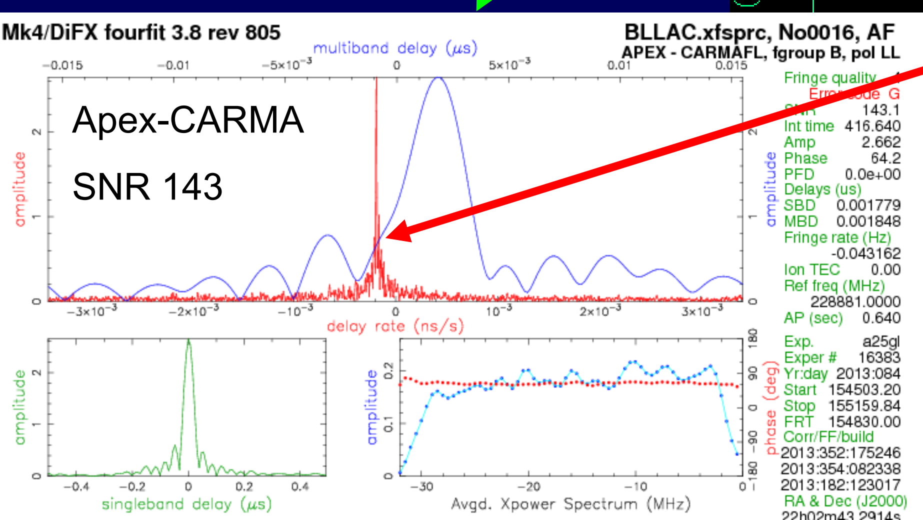
Monitoring BLLac after Dec. 2012 outburst:

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









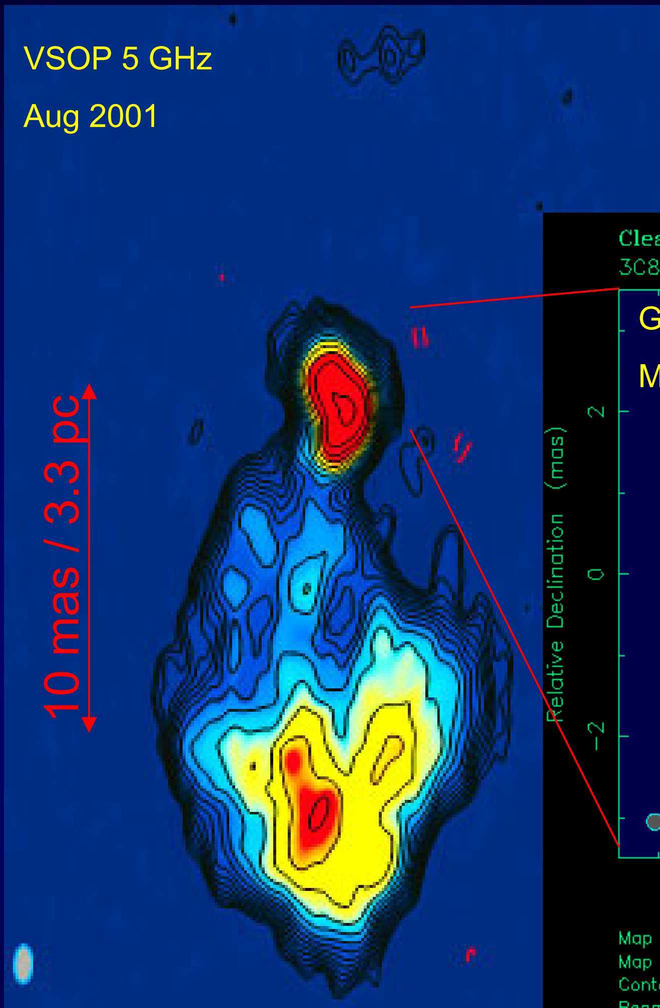
Preliminary Summary of APEX VLBI Source detections

(Jan. 2014)

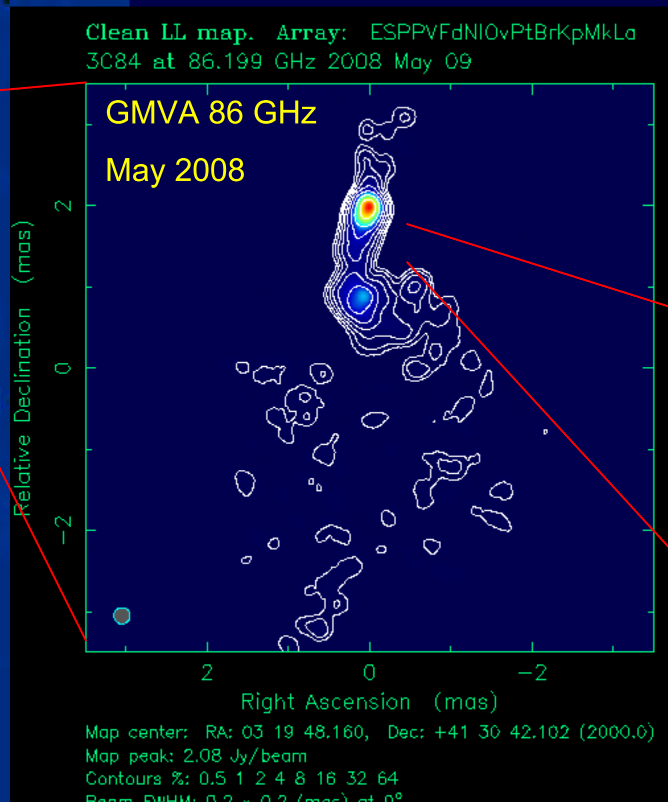
Source	z	DOY	UT	Baseline	SNR	B	size	lin. size	R_s
			[hrs]			[Mlambda]	[muas]	[pc]	
3C273	0,158	82	7h40	AP-SMTO	11	5422	26	0,083	853
3C279	0,5362	82	8h00	AP-CARMA	12	6041	21	0,220	2262
3C84	0,0176	82	20h30	AP-CARMA	8	5626	22,4	0,008	82
1749+096	0,322	82	14h40	AP-SMTO	12	4830	26	0,170	1748
BLLAC	0,0686	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

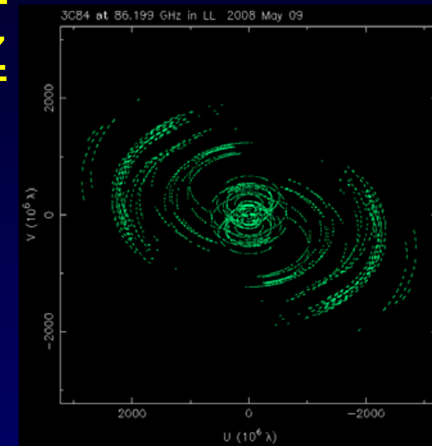
- highest SNR: BL Lac on APEX-CARMA, SNR = 145
- smallest angular scale, BLLac, 2013+37, 17.5 μas (~ 250 R_s)
- smallest linear scale, 3C84, ~ 82 Schwarzschild radii
- typical resolution for AGN < 0.1-0.2 pc (< 2000 R_s)

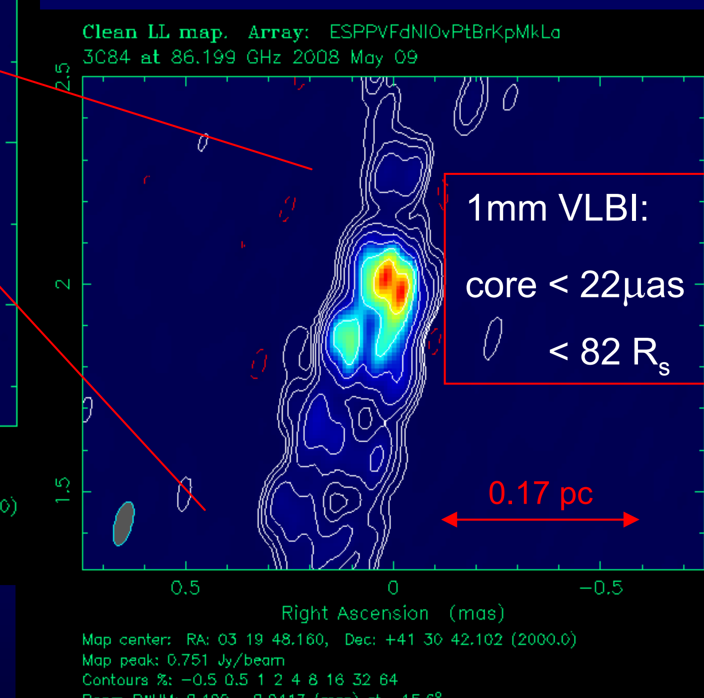
Central Engine of 3C84 (NGC1275) detected with VLBI at 230 GHz



Asada et al. 2006





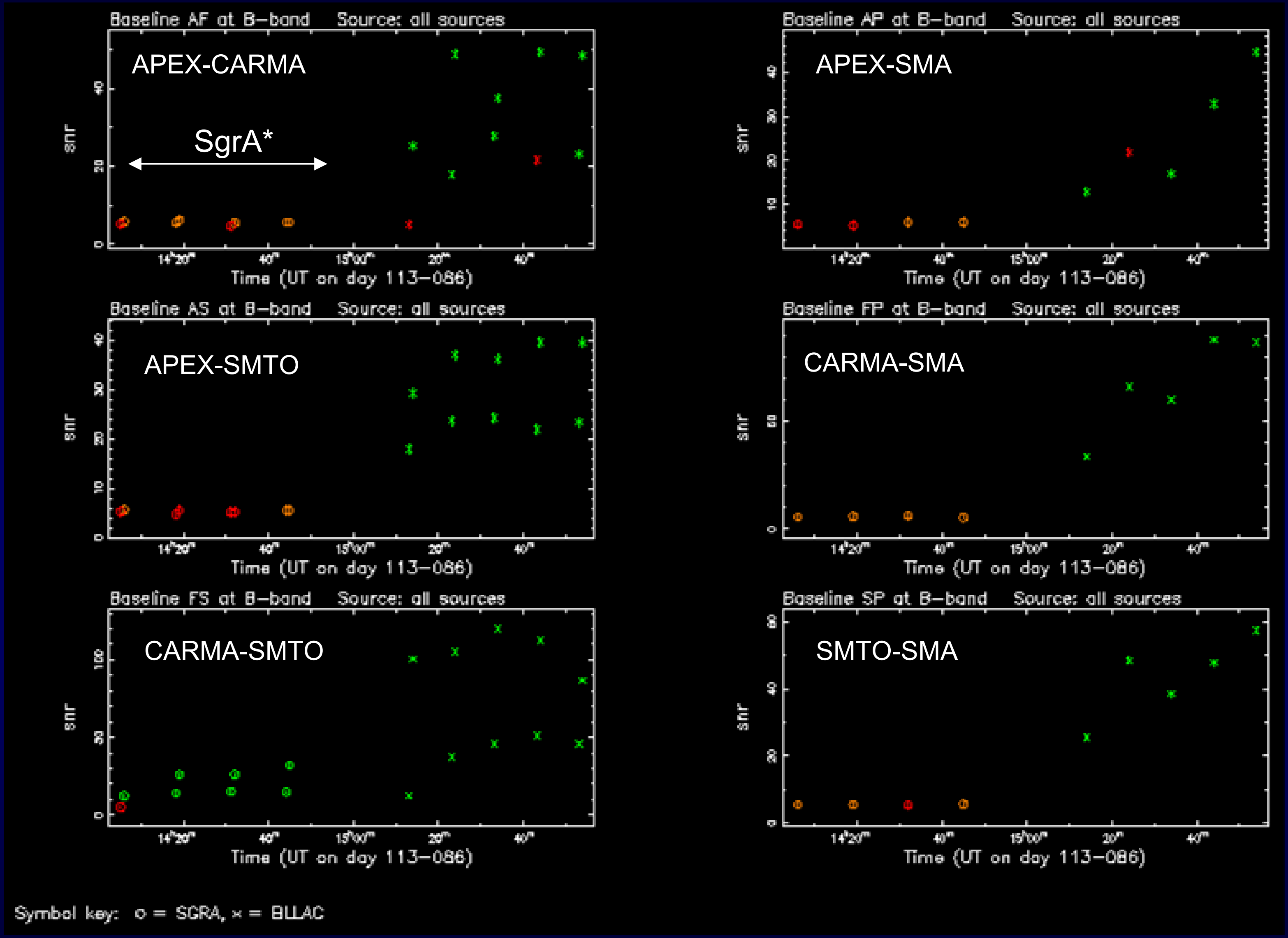


data:

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_{corr} < ~0.5 Jy @ 5400 – 7200 Mλ

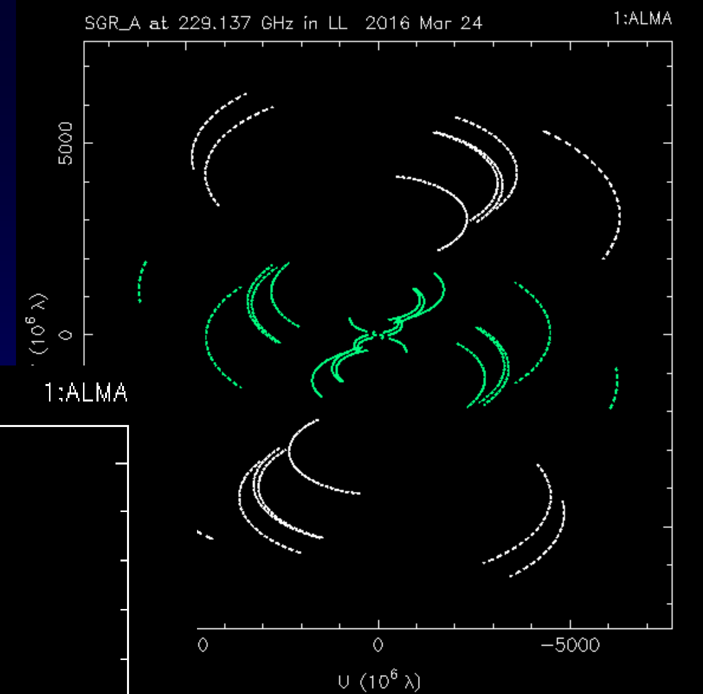
A: APEX P: SMA

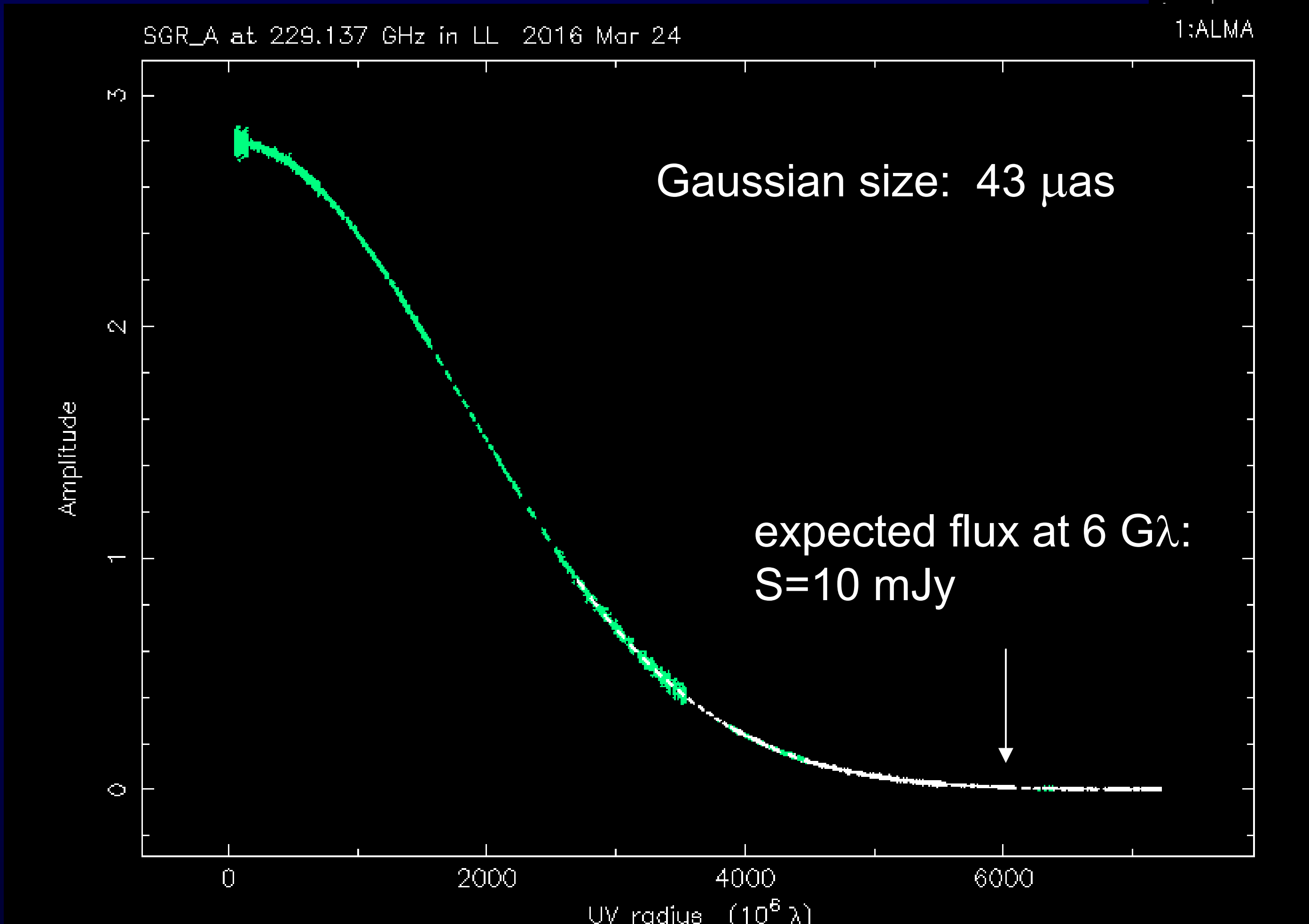
S: SMTO F: CARMA

Θ ≥ 21-27 μas (2.1 – 2.7 R_S) in N-S direction

Detection of SgrA* with APEX ?

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





but for a size of

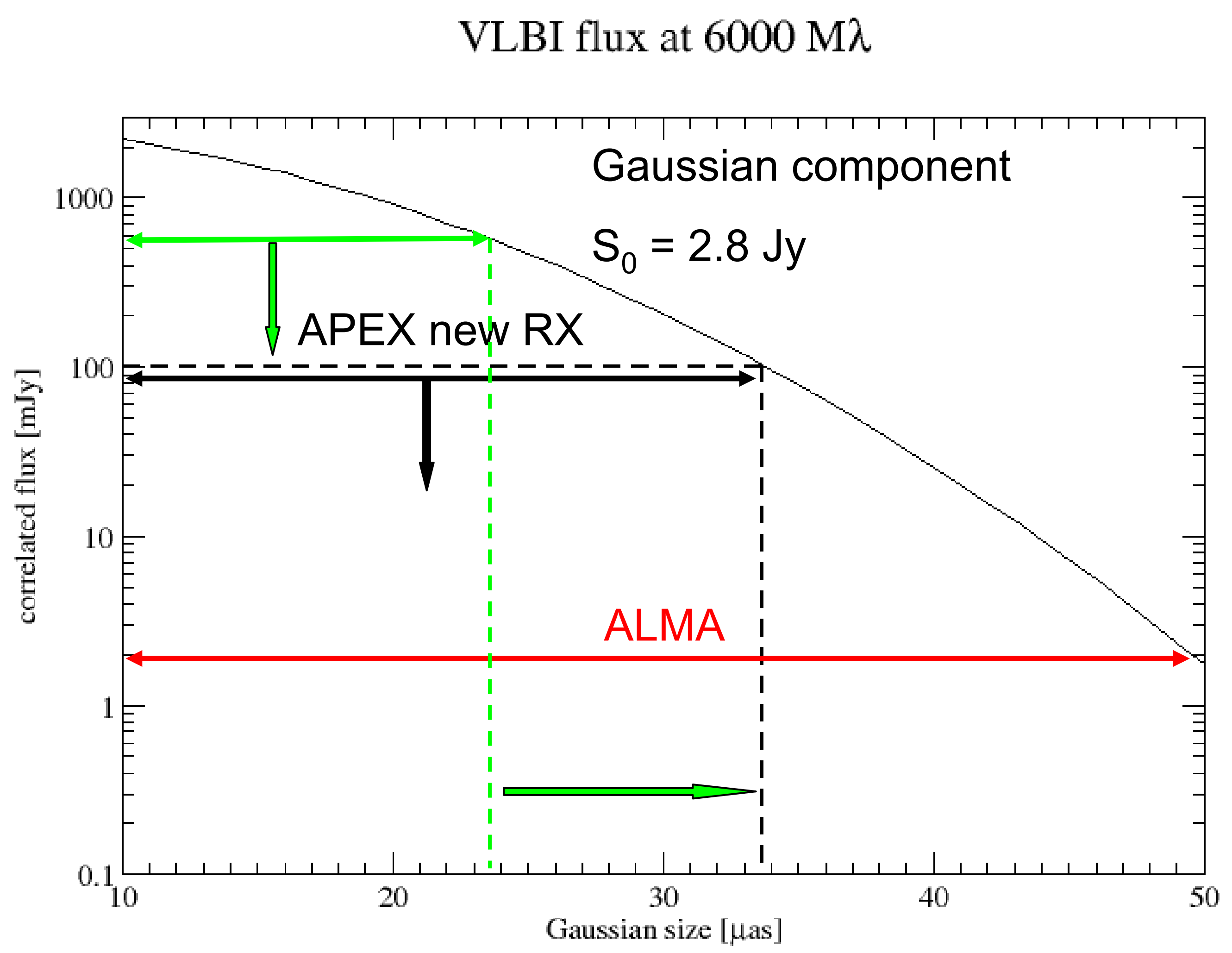
$\Theta = 33$ μas

S_{VLBI}= 100 mJy →

detectable w. APEX

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

Size of SgrA* and APEX detection limit



for $S_{limit} \geq 100$ mJy → size $\Theta \leq 33.5$ μas (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 (monopol moment) and spin (dipole moment).

Broderick et al. 2010 see also: Johannsen & Psaltis 2010

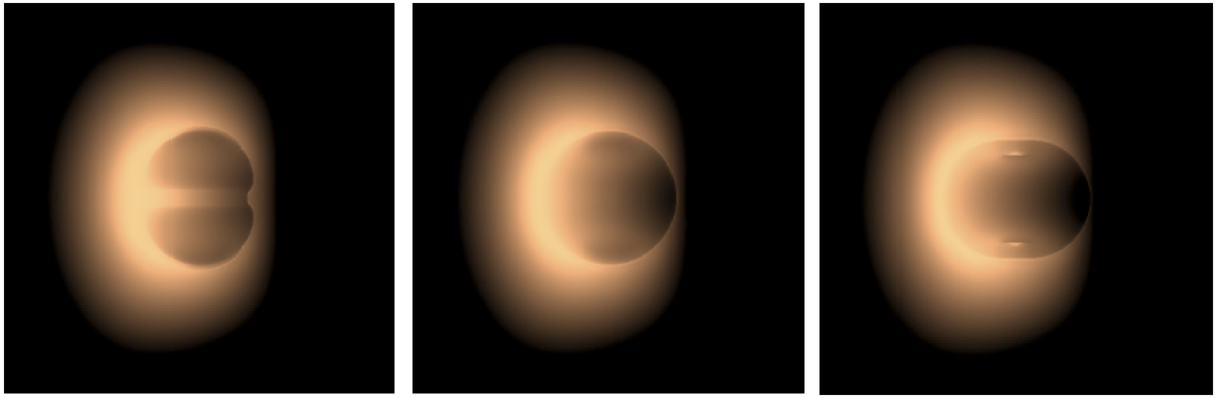
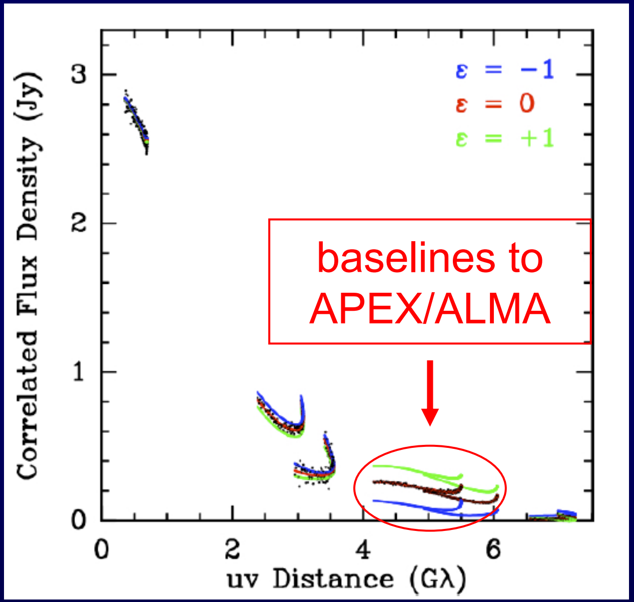


Figure 4: Testing GR. The left three images show the best fit RIAF model for SgrA* ray-traced through space times with ε=−1, ε=0, and ε=+1. If ε≠0, then SgrA* is either not a GR black hole, or GR does not describe the space time of black holes.

Doeleman et al. 2009, Astro2010



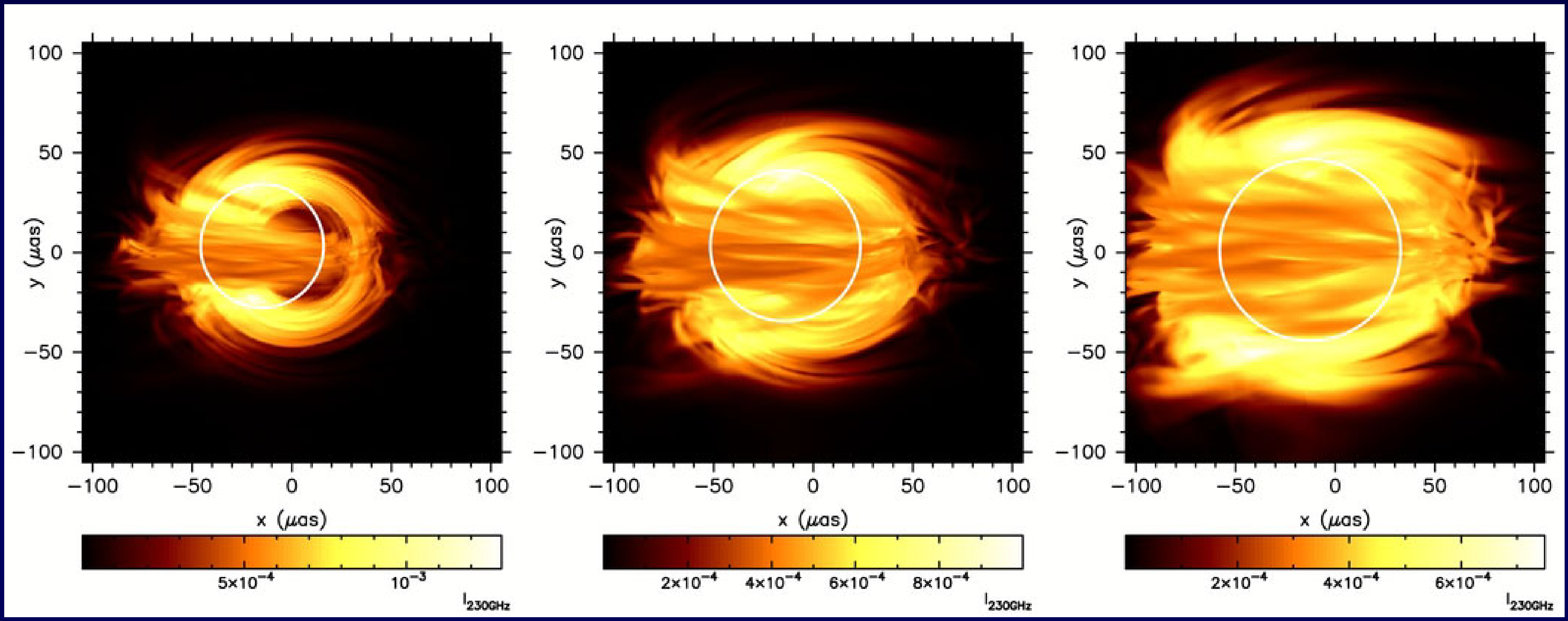
$$\text{quadrupole moment: } Q = -M(a^2 + \varepsilon M^2)$$

$\varepsilon \neq 0$, 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 $\dot{M}_0$ @230 GHz shadow disappears

> 16 $\dot{M}_0$ @345 GHz

Moscibrodzka et al. 2012

Do we need APEX when ALMA is there ?

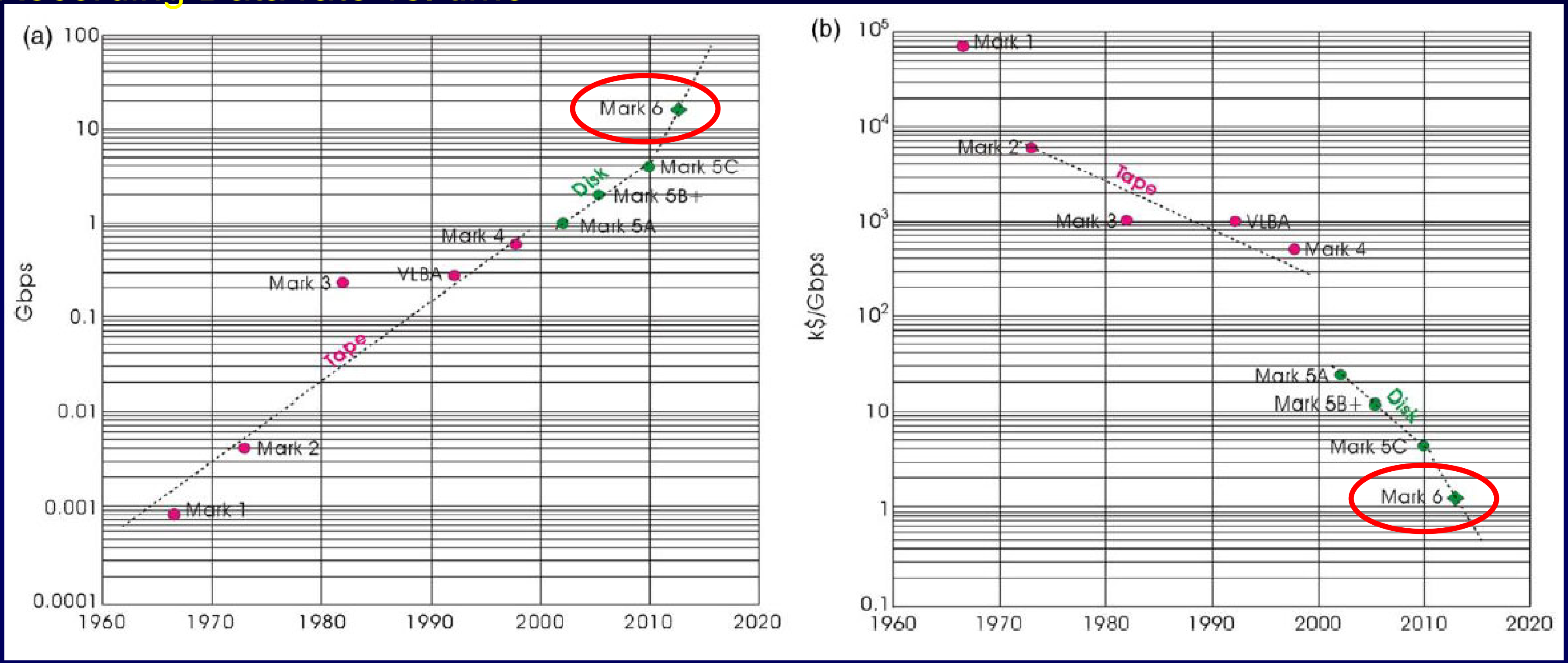
- phasing capability of ALMA for VLBI is now beeing developed
- 1st VLBI test experiments with ALMA sub-array expected in 2015/2016 (APP)
- sensitivity of phased ALMA array will be sqrt(N) better than APEX, but:

  - 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

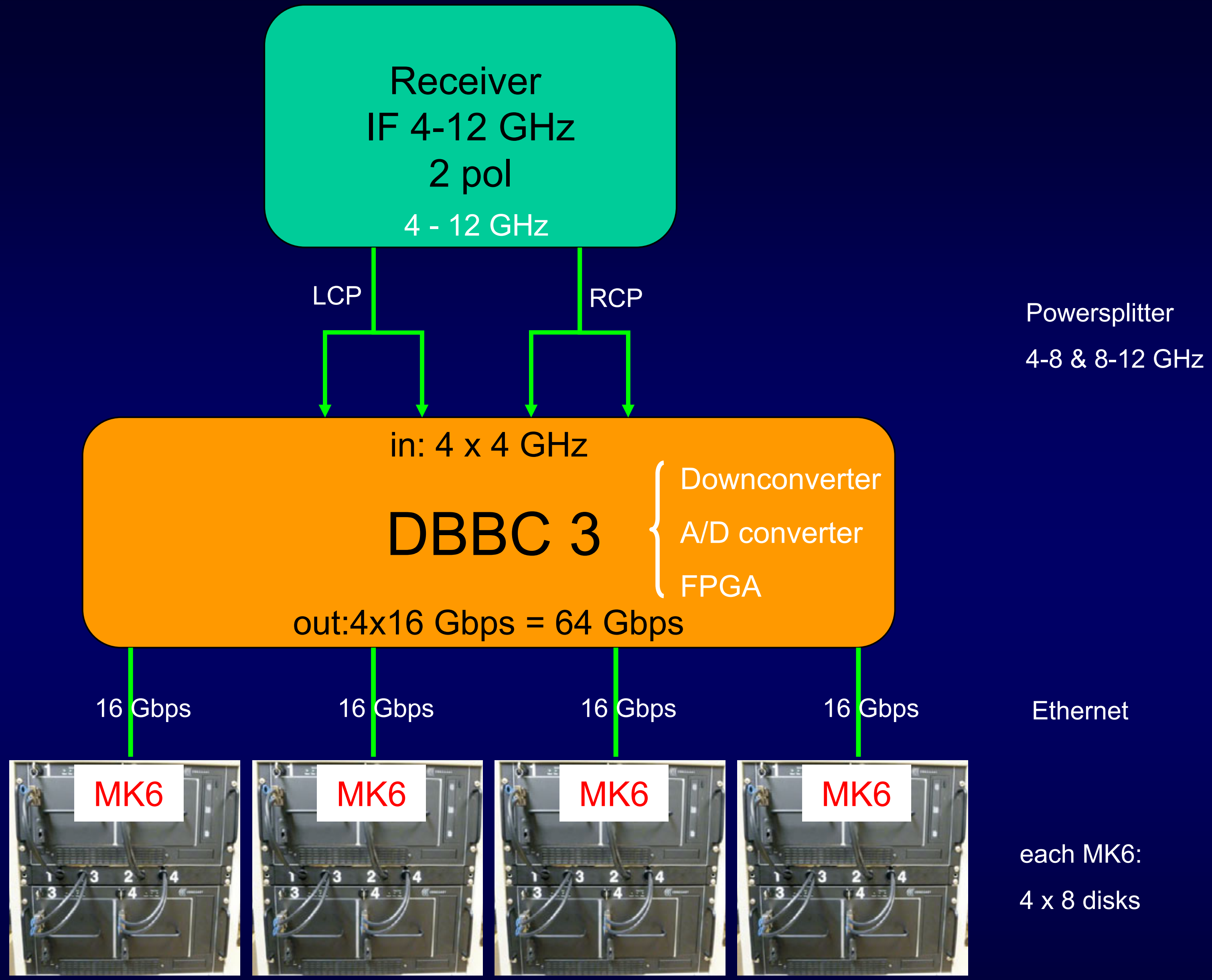


Mark 6: 16 Gbps (4 GHz bandwidth)

4 modules (each 8 disks)

helium filled disks for high altitude

Whitney et al. 2013



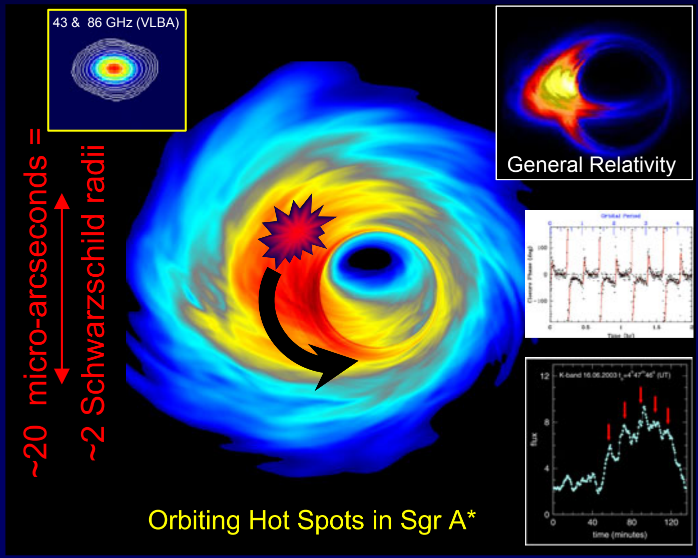
Final stage: 2 x 8 GHz BW (64 Gbps, factor sqrt (64/2) = 8 sensitivity increase !

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

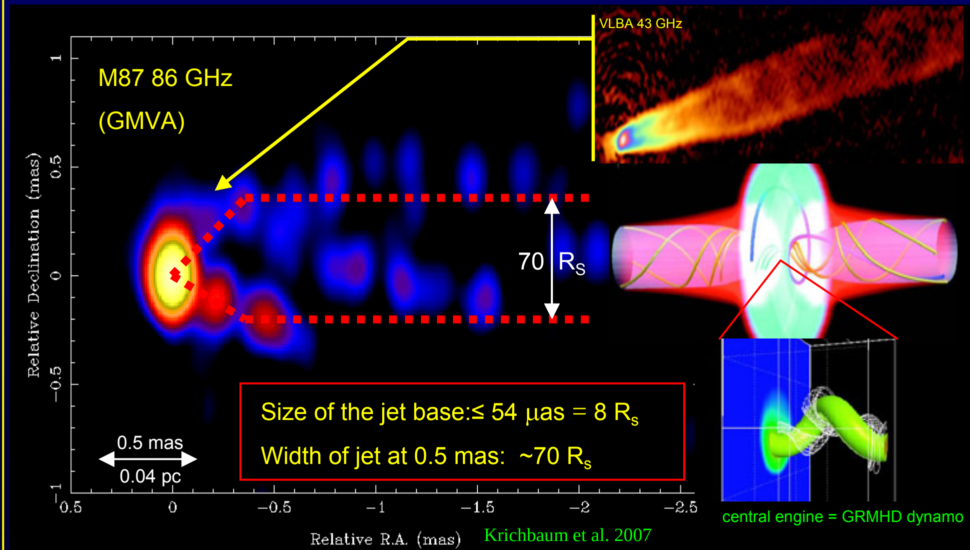
see EHT Whitepaper (Fish et al. 2013)

- 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, SMTO, SMA, CARMA, LMT, SPT, APEX/ ALMA (Event Horizon Telescope).
- add ALMA through ALMA phasing project (APP)

Sgr A*:



M87+ AGN Jets:



Thats it for today.

Have a nice dinner
and thank you !