mm-VLBI observations: Black hole physics and the origin of jets

T.P.Krichbaum et al, with:

(+GMVA team, +EHT team

+A. Marscher's group)

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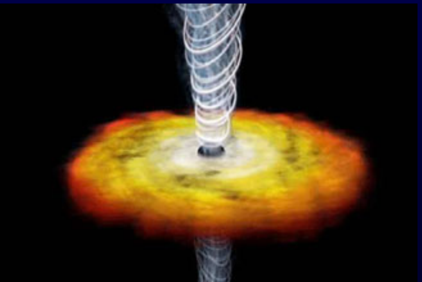

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people involved in GMVA:

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

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

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

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

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

NRAO: W. Brisken, V. Dhawan, C. Walker, et al.

plus:

A. Marscher, S. Jorstad, et al.

1mm VLBI, EHT collaboration with (in 2013) :

APEX: R. Güsten, K. Menten, D. Muders, A. Roy, J. Wagner, et al.

Haystack: R. Capallo, 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.

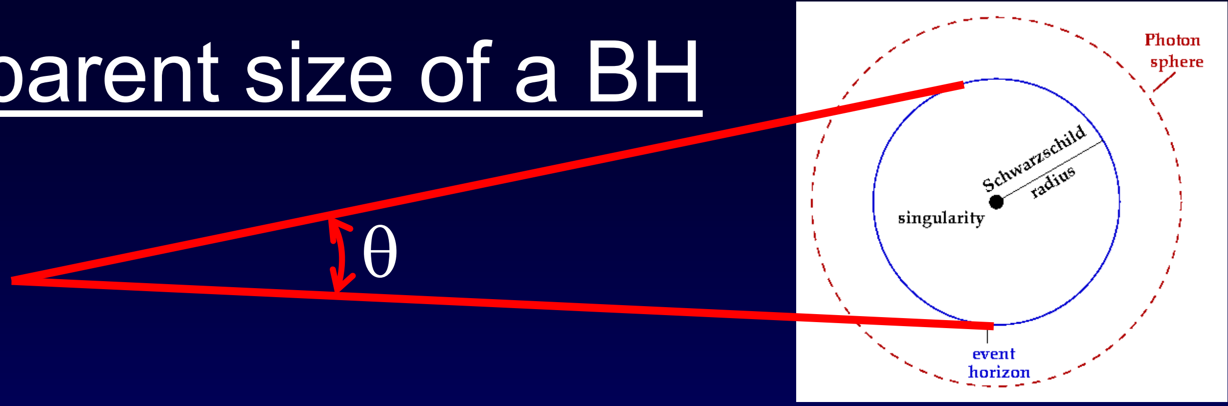
SMA: R. Blundell, J. Weintroub, K. Young, et al.

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

The apparent size of a BH

Observable size:

$$\theta = \frac{2R}{D}$$

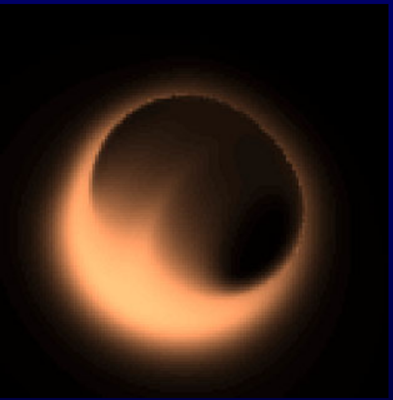


BH radius:

$$R_{BH} = \alpha\, R_G = \alpha\, \frac{GM}{c^2}, \text{ Schwarzschild: } \alpha = 2$$

in convenient units:

$$\theta_{BH} = 9.9\, \alpha\, \frac{M_6}{D_{\mathrm{Kpc}}}\, \mu\mathrm{as}$$



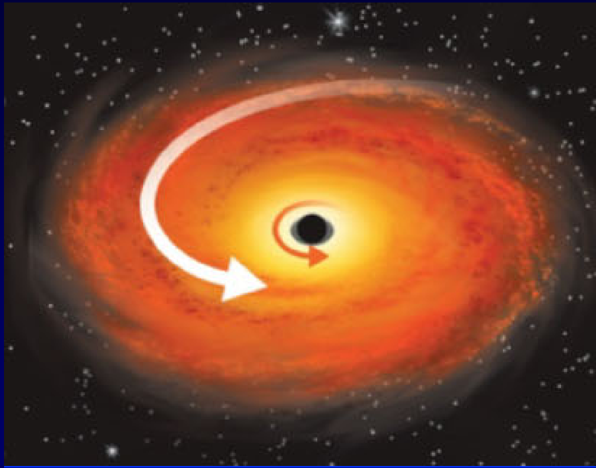
	Spin	R/R_s	R/R_g	α	$\theta_0[\mu as]$
Last stable orbit	a=0	3.0	6	6	59
Last stable orbit	a=1	0.5	1	1	10
Photon ring	a=0	1.5	3	3	30
Photon ring	$a > 0$	5.2	10.4	10.4	103

For Sgr A* the photon ring has a size of 52 μas, for M87 ~41 μas.

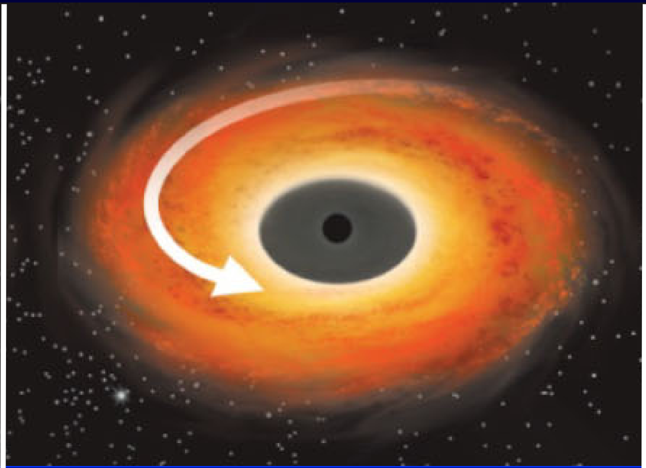
For a maximal spinning BH, the ISCO size is at 4-5 μas for SgrA* and M87.

The Innermost Stable Circular Orbit

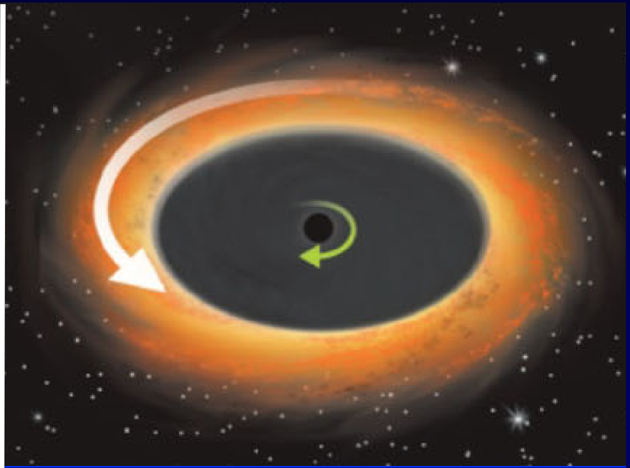
graphics: Sky & Telescope



- 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

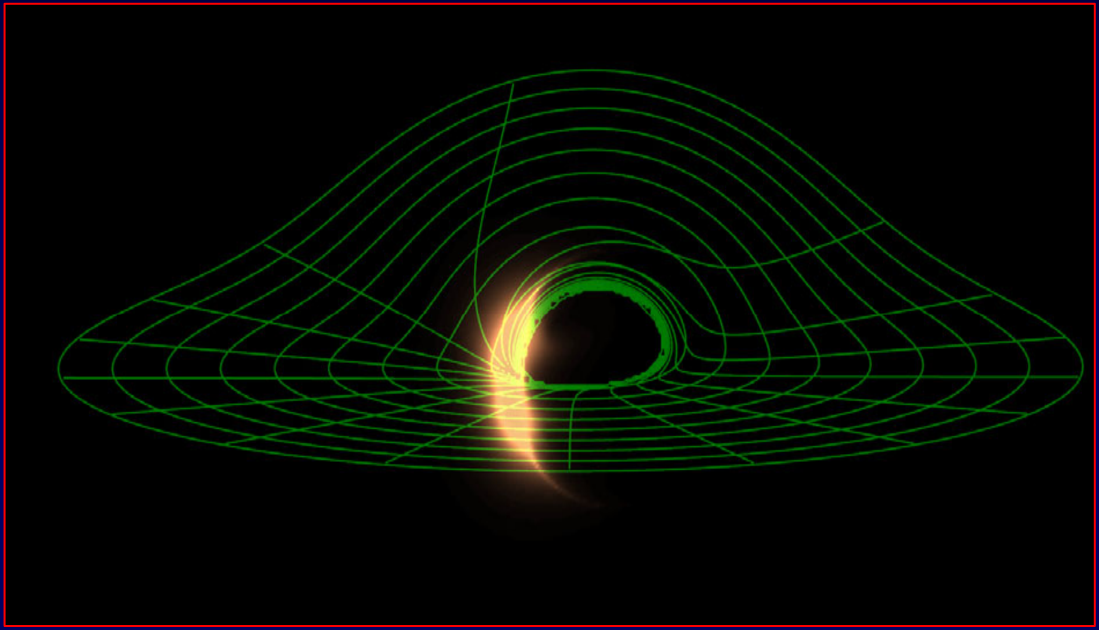


- Maximally-spinning ***retrograde* BH** (spinning in opposite direction as disk)
- ISCO at $R = 9\ GM/c^2$
- Frame-dragging acts in opposition to disk angular momentum, causing orbits to plunge farther out

see: Laura Brenneman (CfA)

Interpretation of the 1mm VLBI size measurement

gravitationally lensed image of accretion disk or orbiting hot spot / instability



Broderick & Loeb 2008

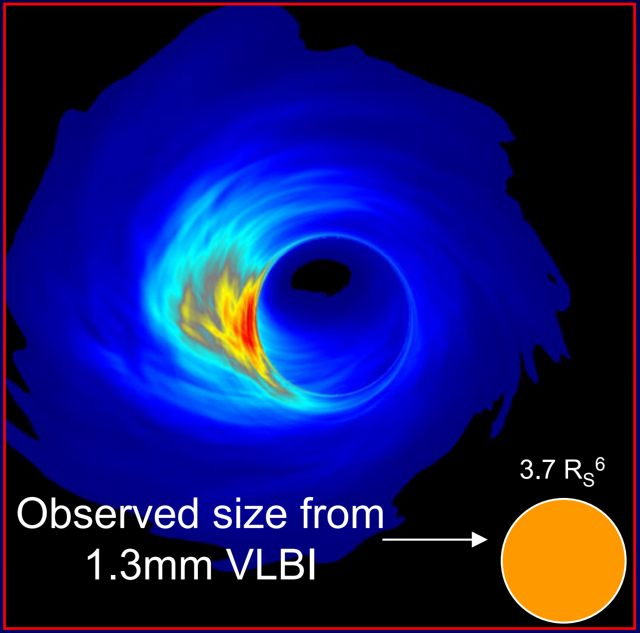


image credit: Noble & Gammie

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

observed size: 43 (+14/-8) µas

deconvolved : 37 µas

intrinsic : 3.7 R_S

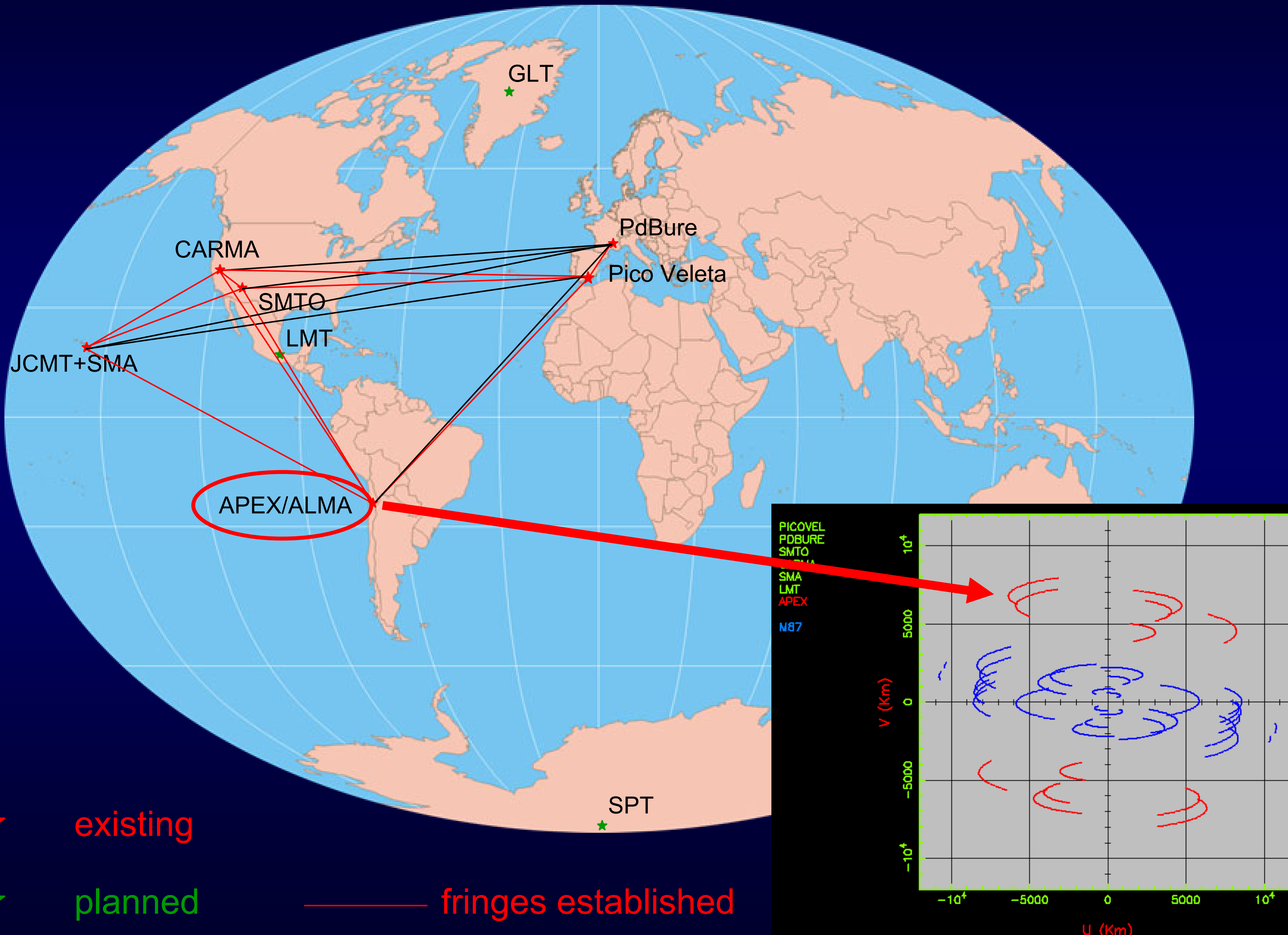
$$M_6 = \frac{0.1}{\alpha} \theta_{\mu as} D_{Kpc}$$

Observed size is smaller than expected size of ISCO or photon ring

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

Another step towards truly global 1.3 mm VLBI

Status March 2013 with APEX added

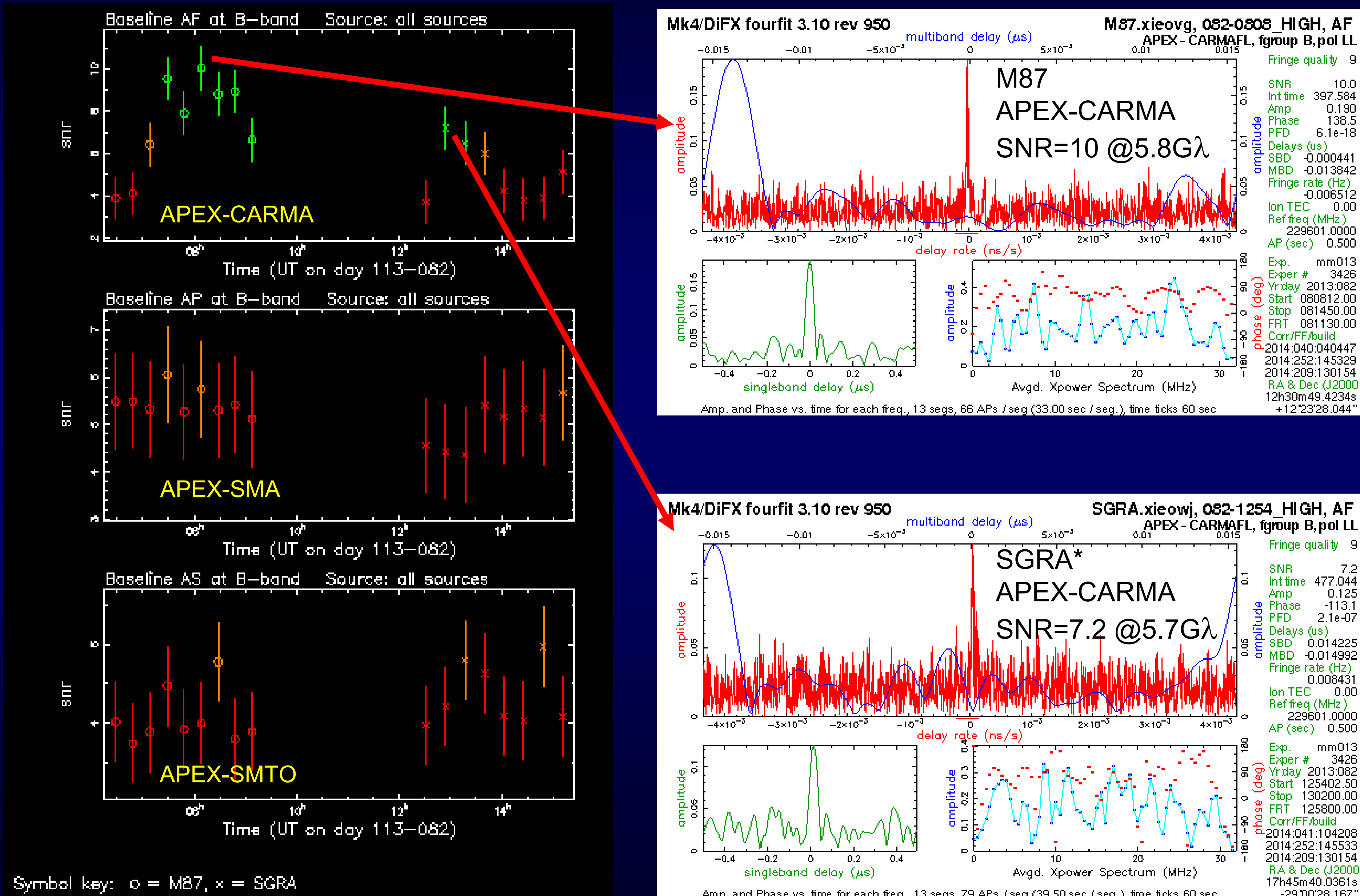


existing

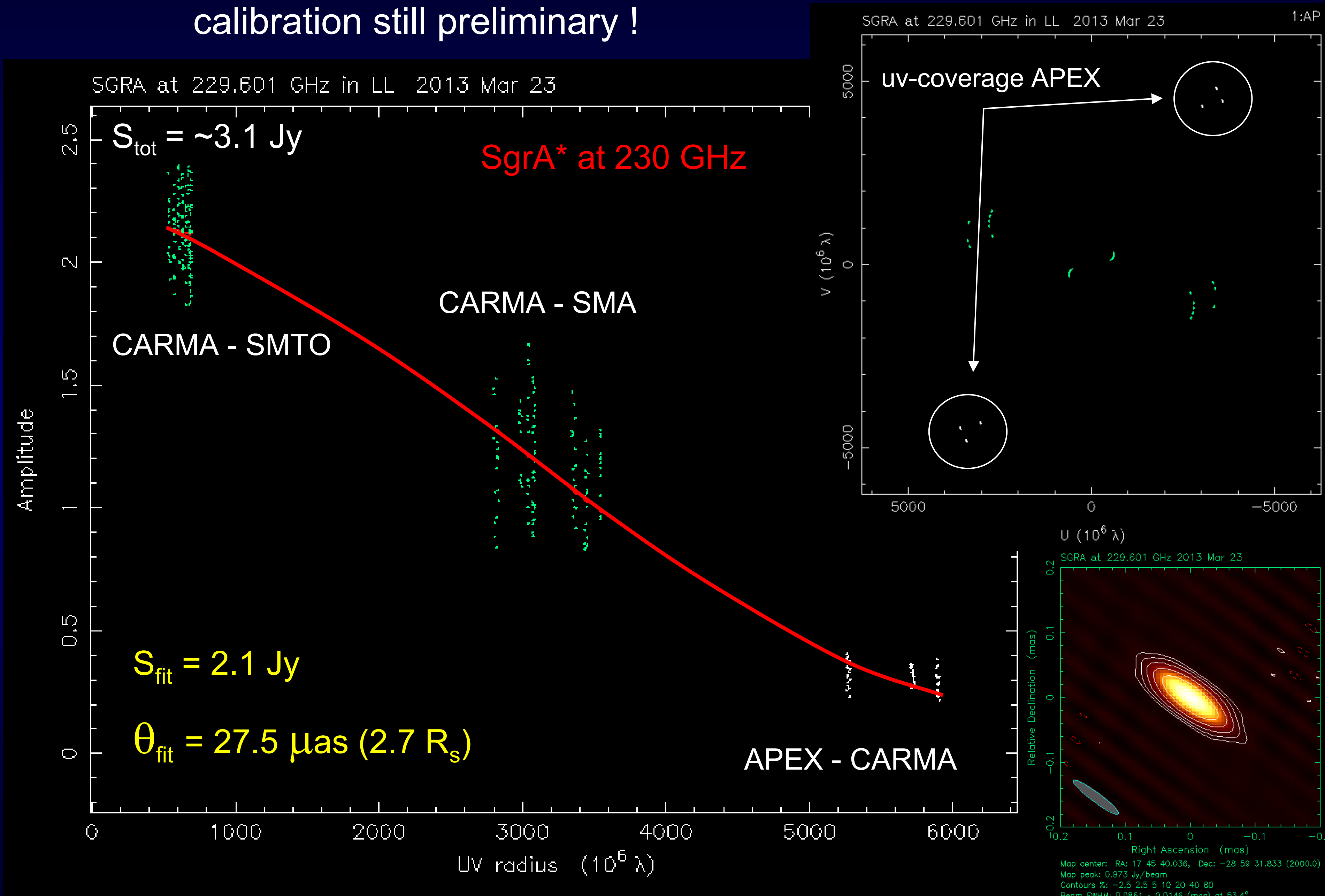
planned

fringes established

230 GHz detection of Sgr A* and M87 on APEX baselines at 35 micro-arcsecond fringe spacing



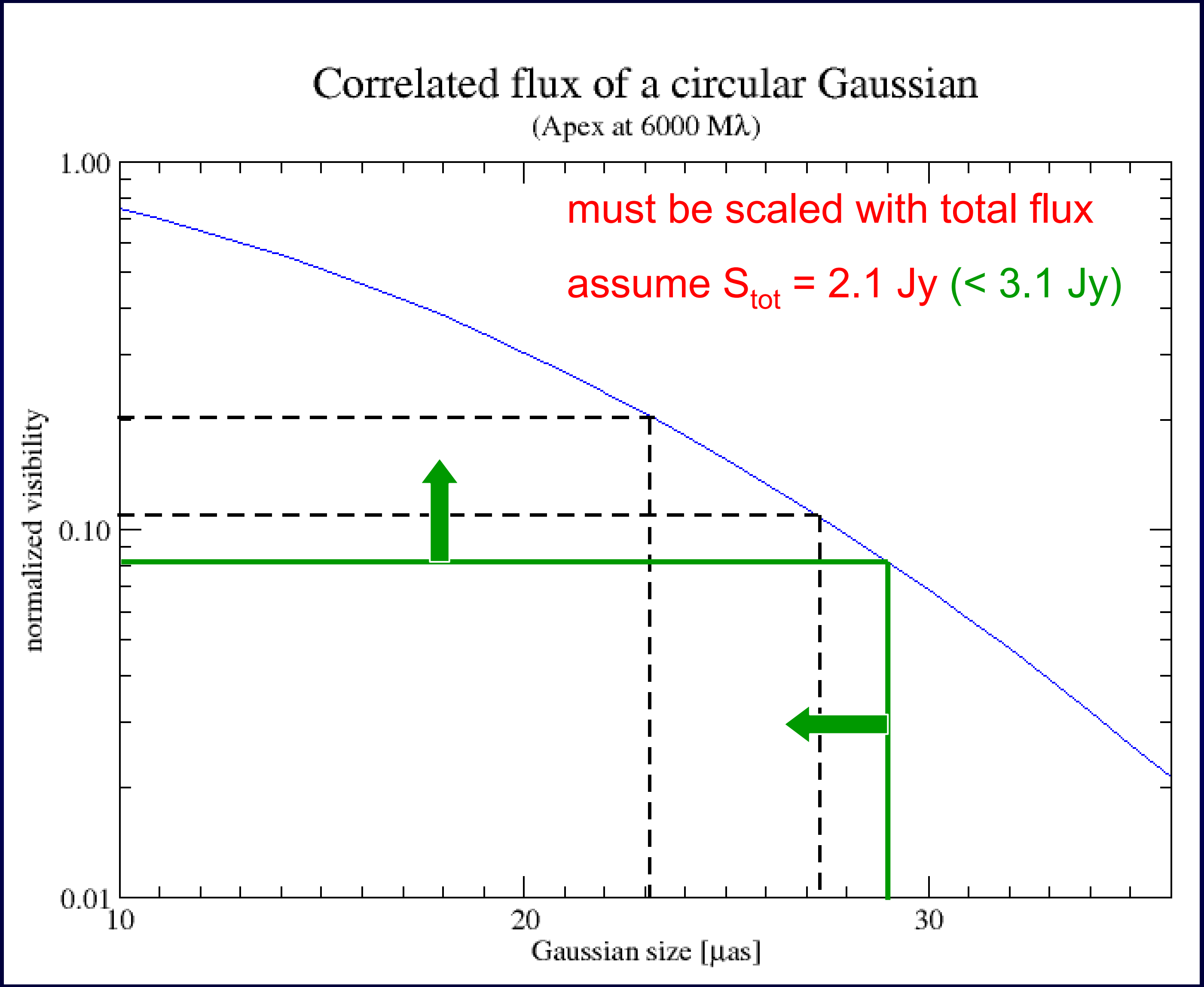
New size estimate of SgrA* at 230 GHz (March 23, 2013), calibration still preliminary !



Dependence of size measurement from total flux

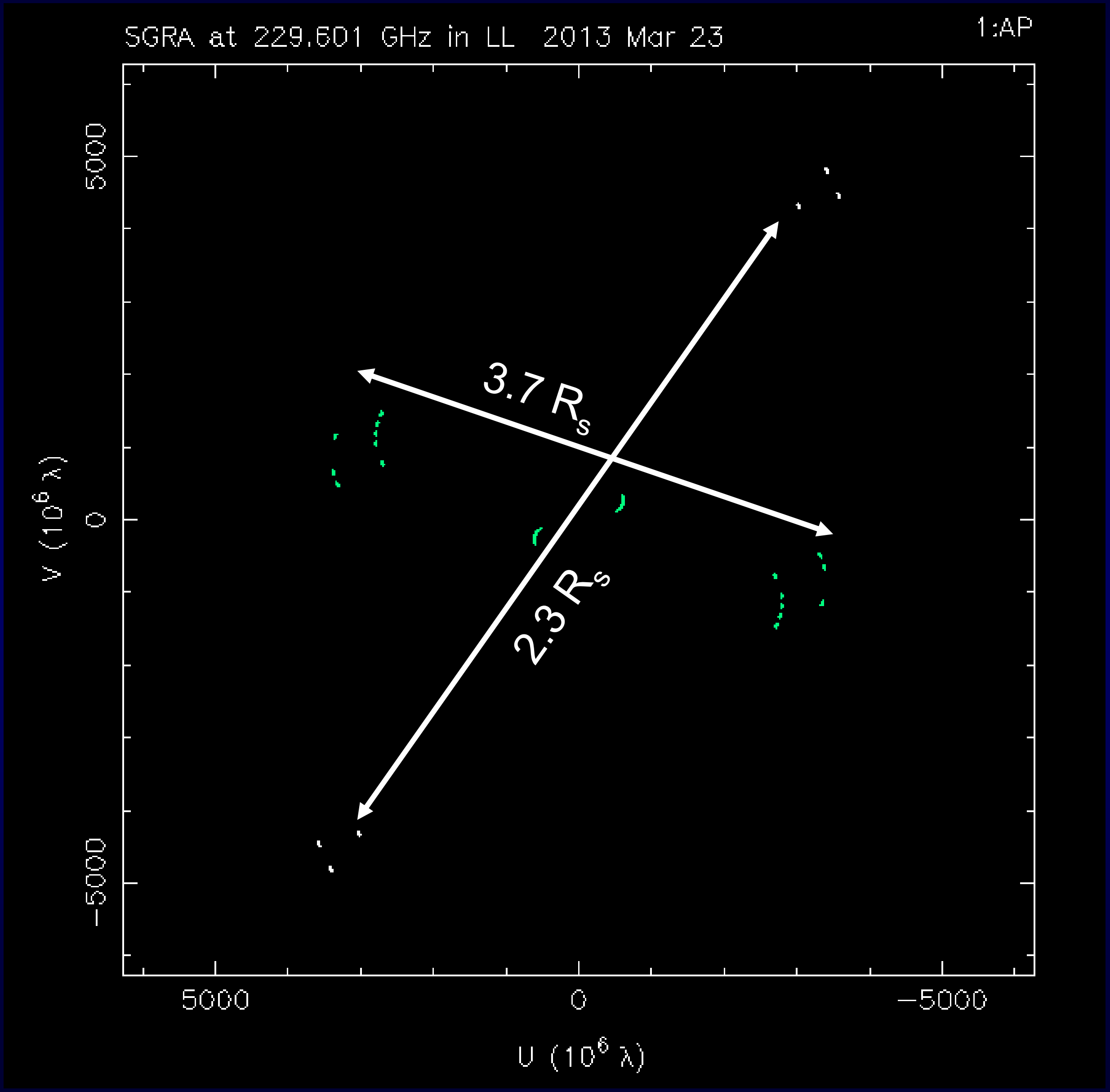
Visibility:

$V = S_{corr} / S_{tot}$



size definitively < 29 μas, and most likely between 23 - 27.5 μas

The compact emission region in SgrA* is not circular, but at least elliptical



and:

some closure phases are non-zero !

How are jets made – a sketch of present knowledge

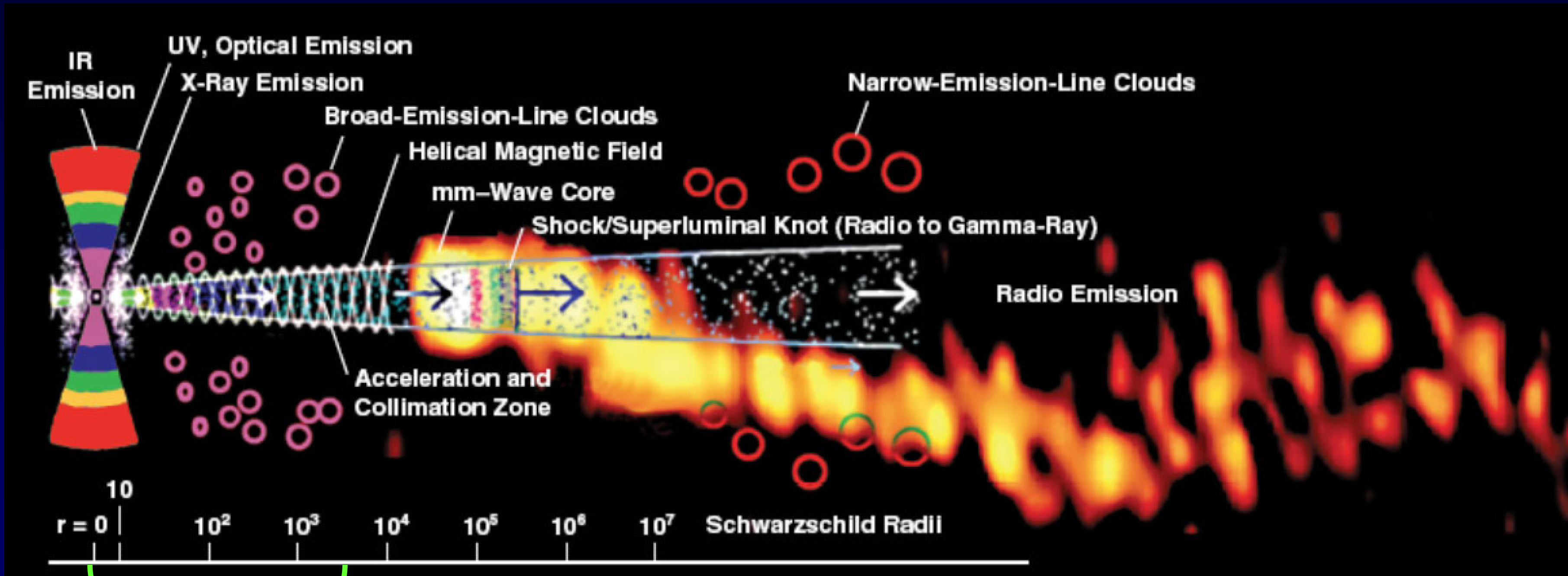


image: Rani@MPIfR

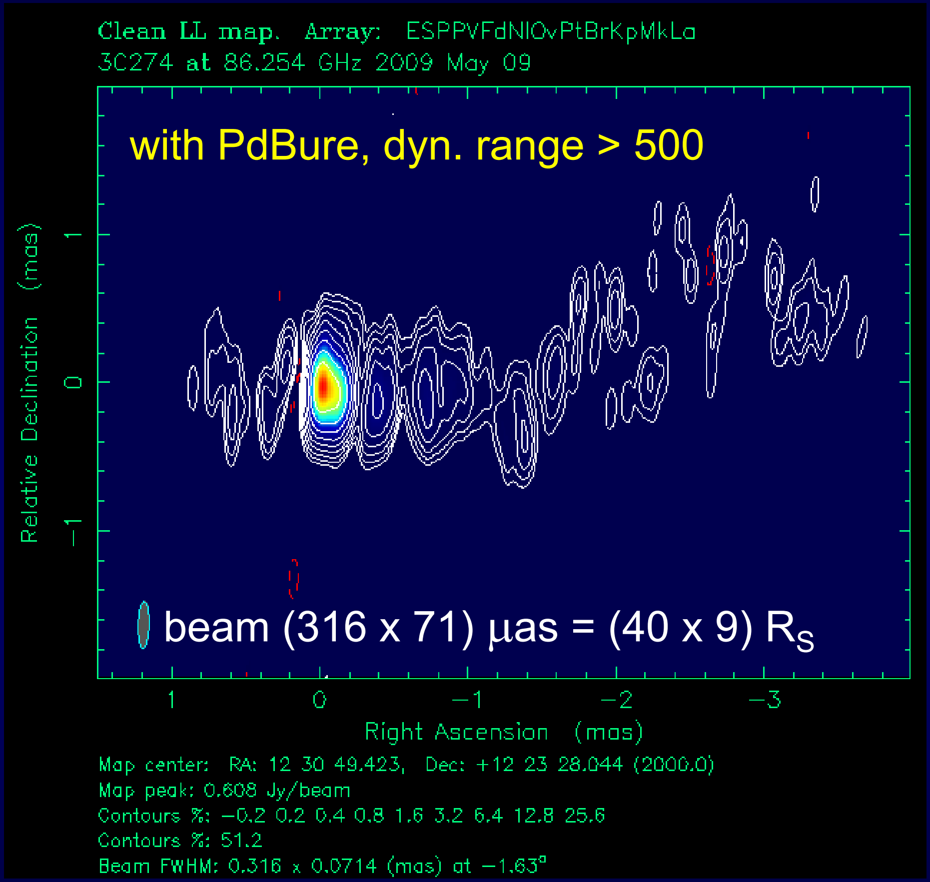
this region can be probed by mm-VLBI and by variability (at high energies)

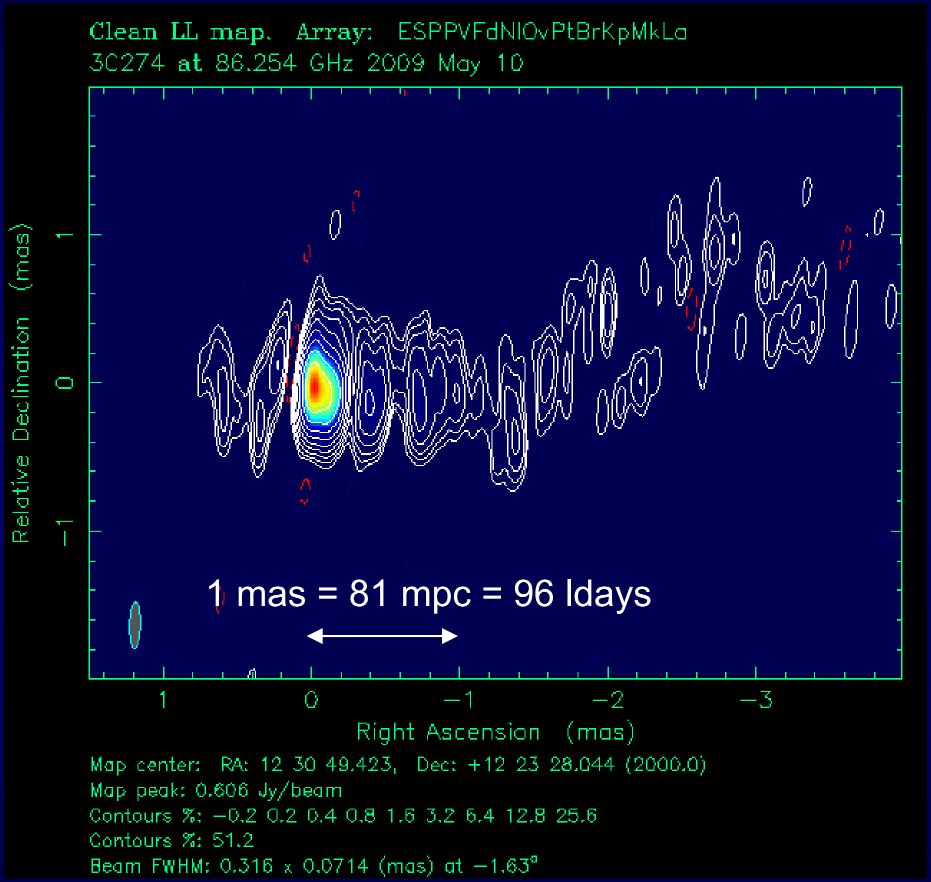
mm VLBI can measure:

- jet brightness temperature as function separation r from BH at $r < 10^{(2\text{-}3)} R_g$
- opacity and radial dependence of $\tau=1$ surface (core shift)
- polarization / magnetic field vs. r
- BH mass and spin, respectively observational limits to these

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

(uvtaper = 0.3)

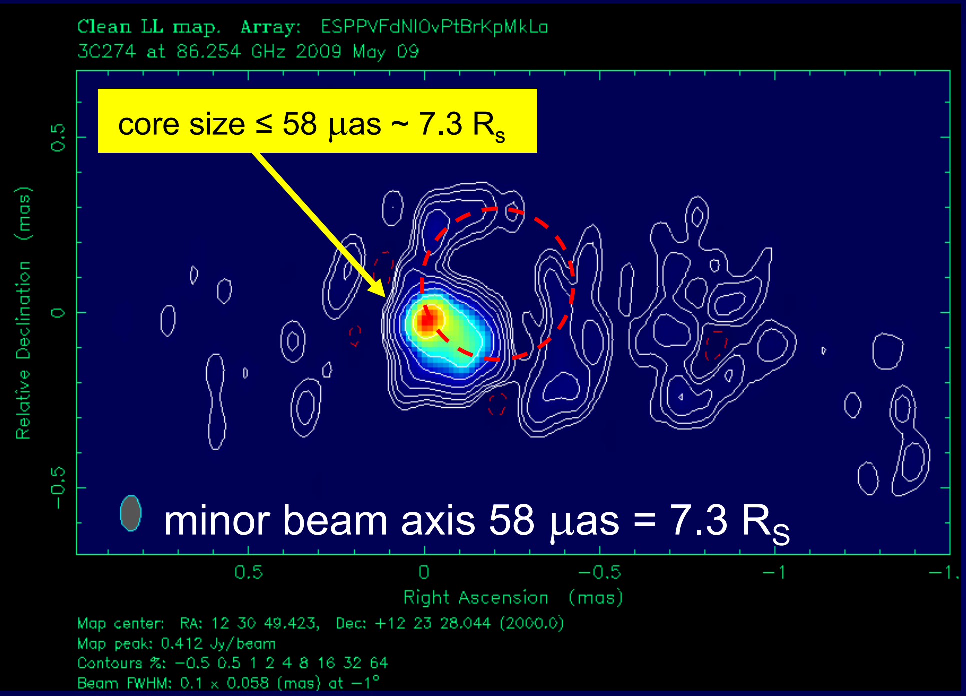


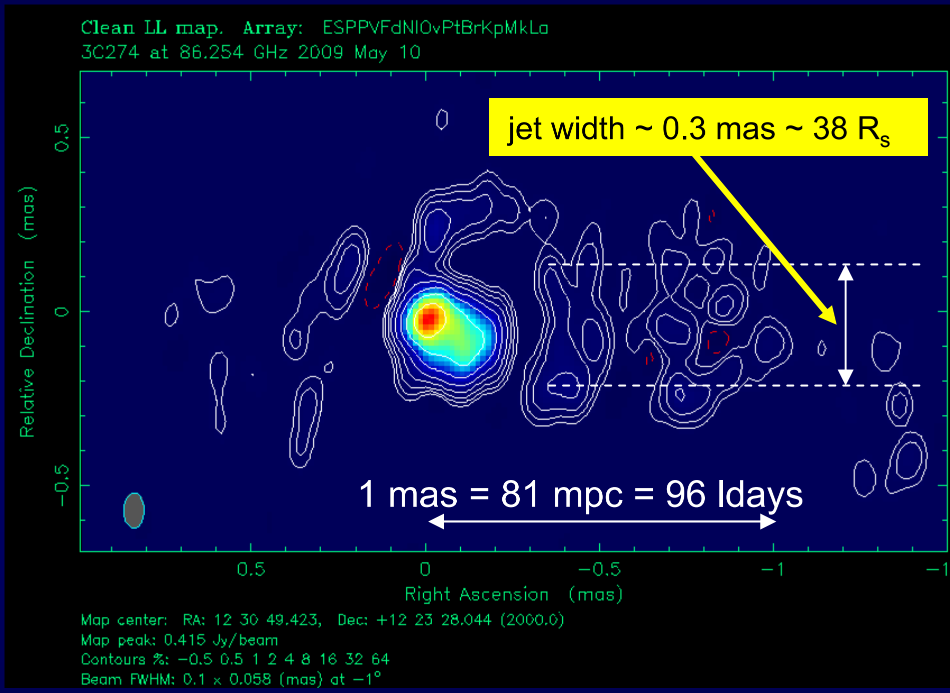


- striking similarities on both days, no significant variations in flux
- counter-jet cannot be calibrated 'away'
- conical Y-shape structure (bi-furcation) with this beam not so evident

86 GHz GMVA images of the jet of M87 on two consecutive days

(no uv-taper, N-S beam axis compressed by fac. 3, E-W axis unchanged)

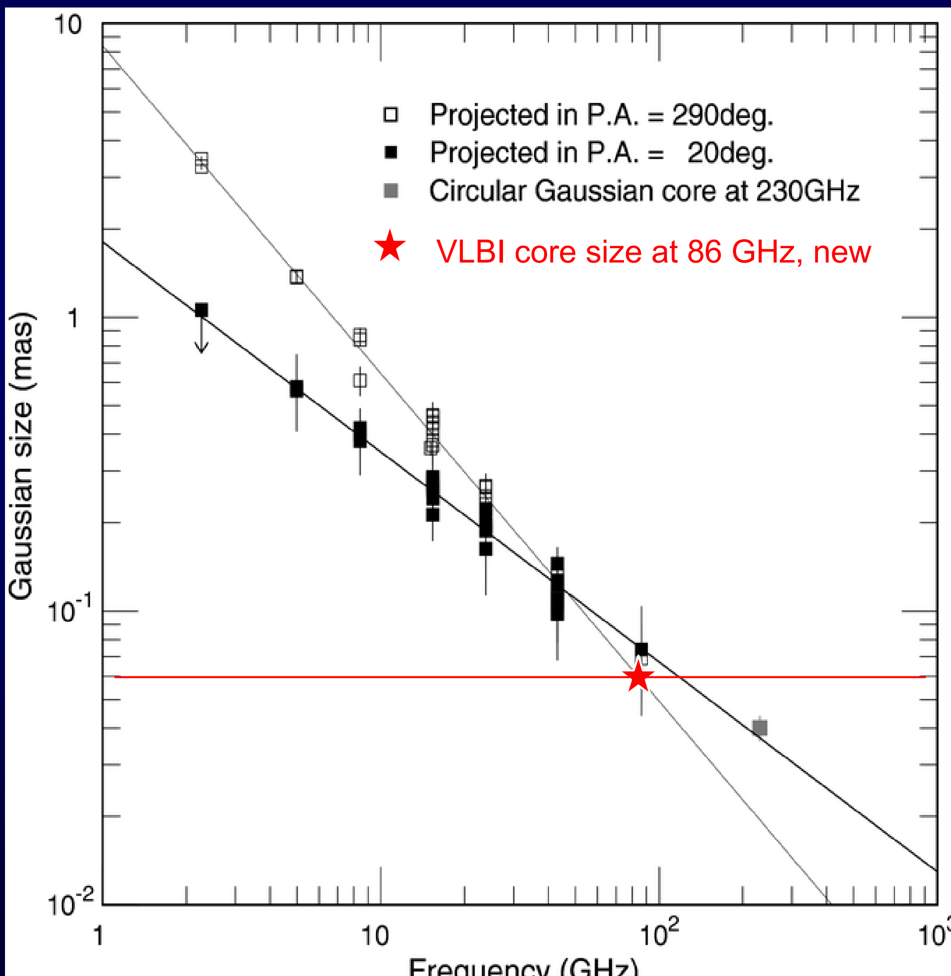


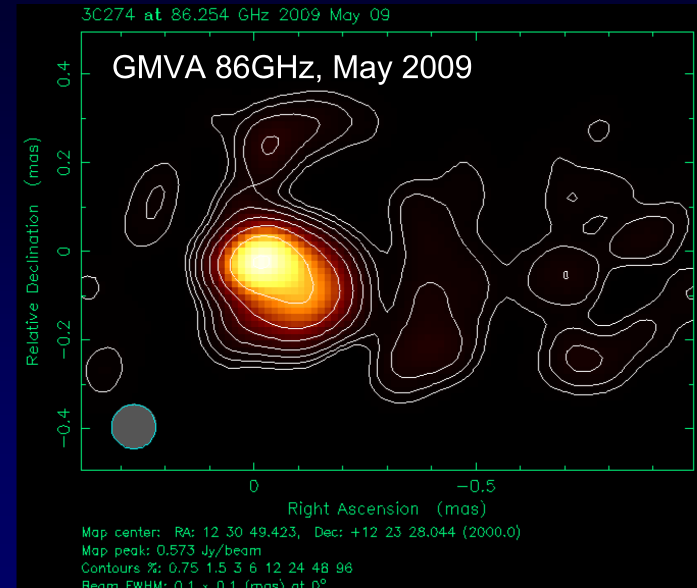


- striking similarities on both days, core is inclined south-west
- ring-like feature present in both images (similarity to 3C454.3)
- peak $T_B \sim 2 \cdot 10^{10}$ K

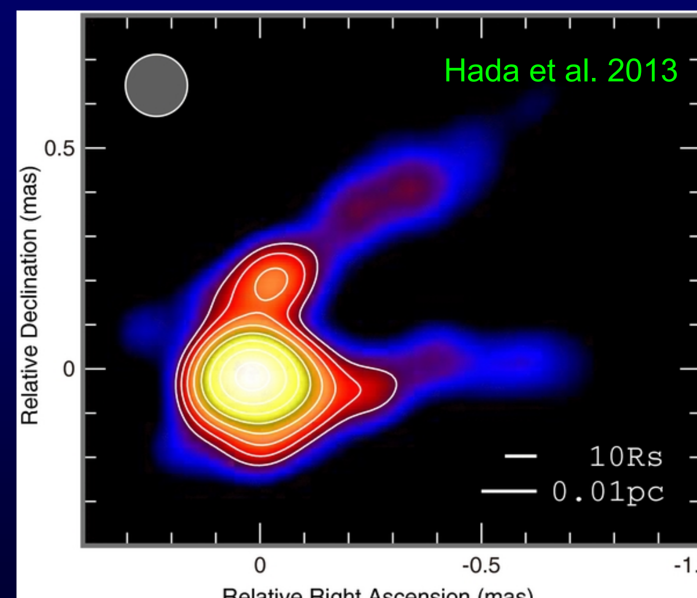
M87: Comparison 86 GHz vs. 43 GHz

overplot new results on Hada et al.'s size plot



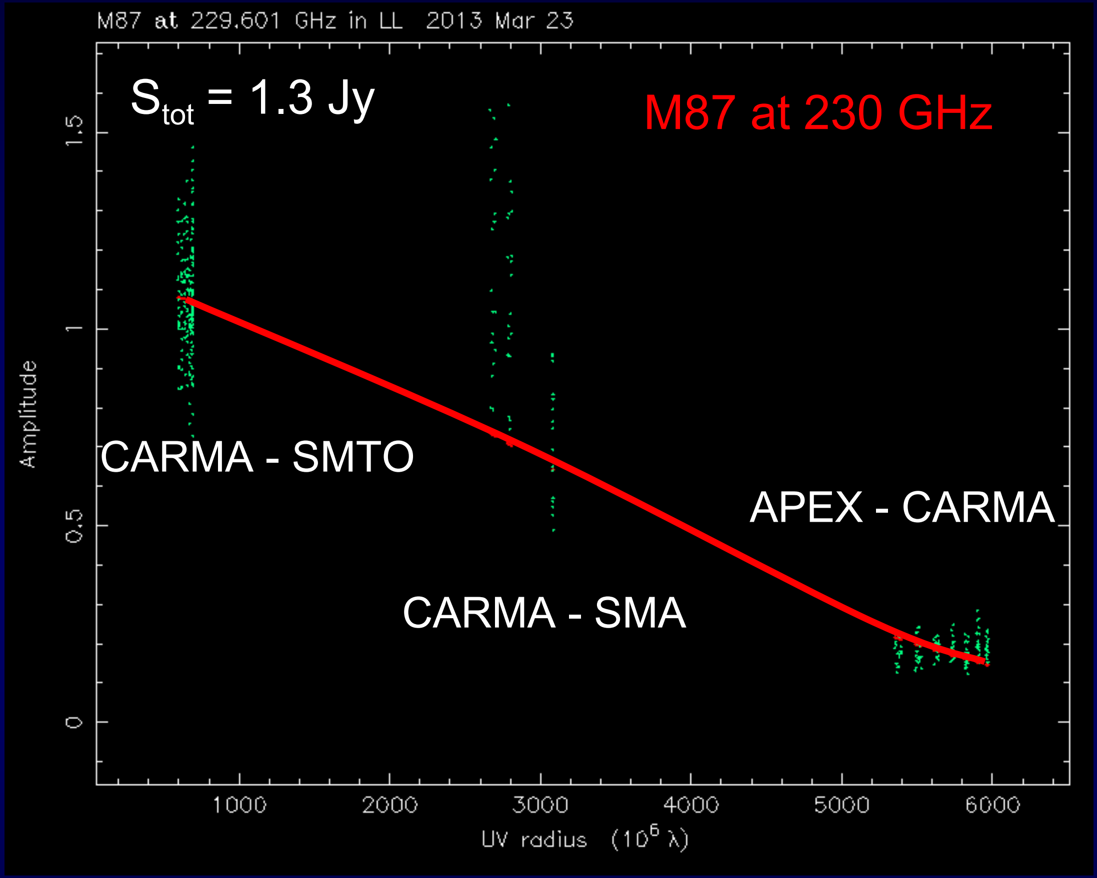


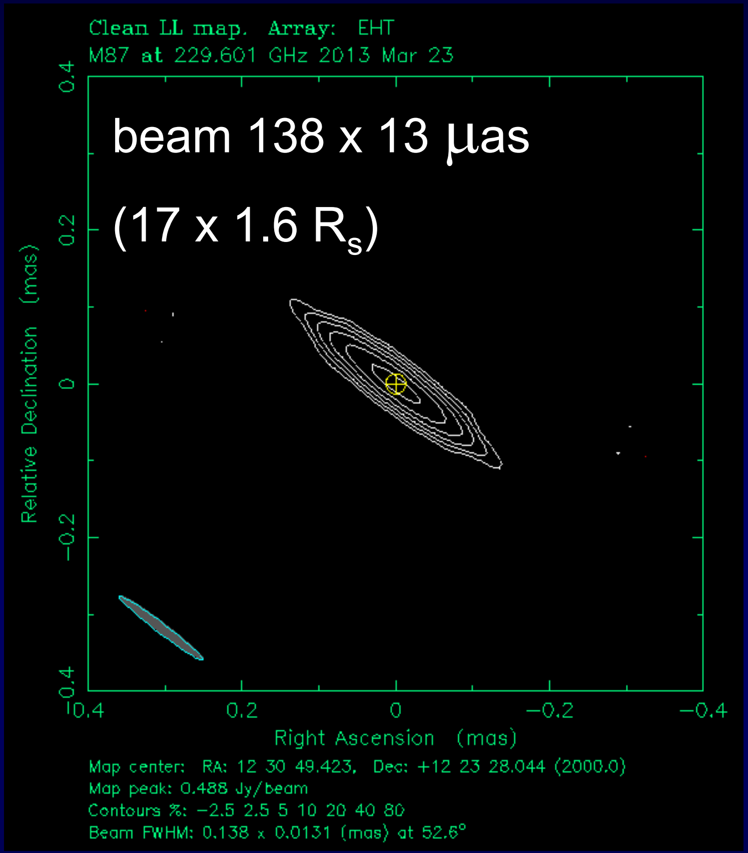
May 2009, 86 GHz, beam 0.10 mas



April 2010, 43 GHz, beam 0.14 mas

M87: New size estimate from 1mm VLBI with APEX



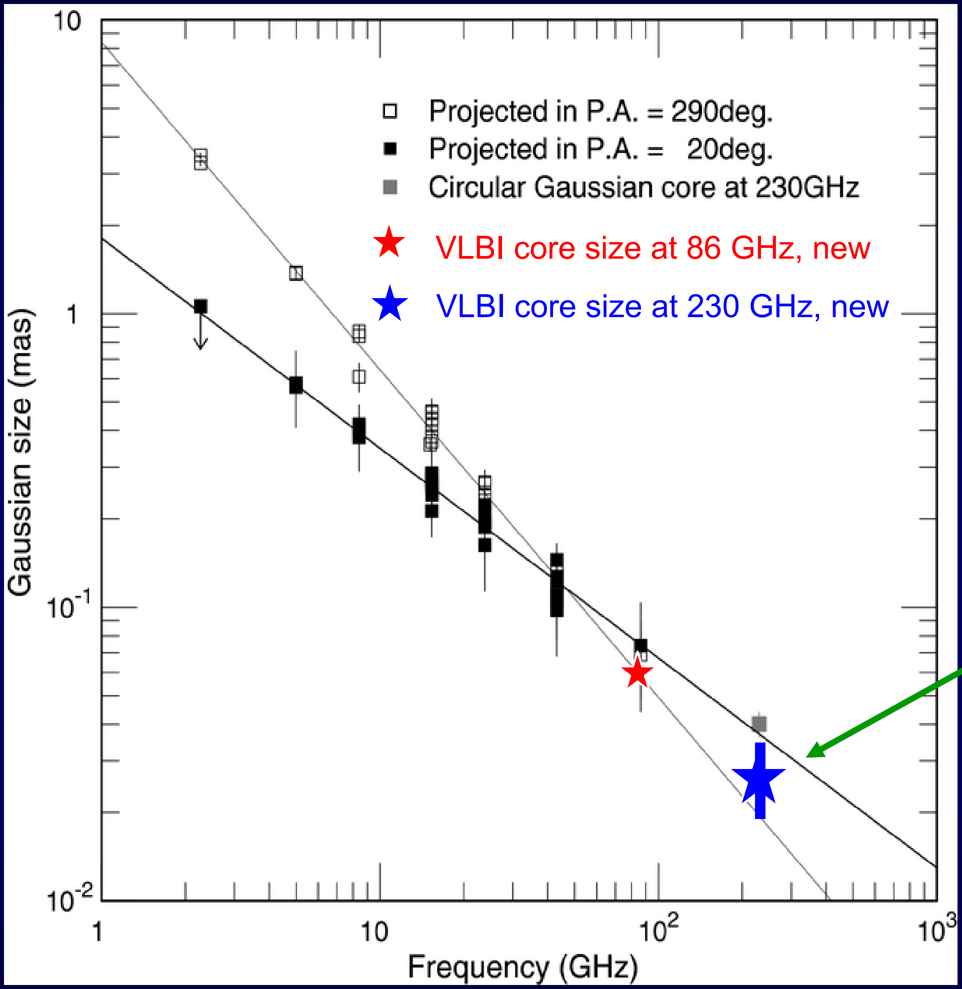


Circular Gaussian: S= 1.1 Jy, θ= 26 μas → R= 3.3 R_s

S = 0.2 Jy at 6 Gλ → θ= 34 μas → jet nozzle R= 4.3 R_s , $T_B \geq 4 \cdot 10^9$ K

but calibration still uncertain, correlated flux may be somewhat higher

M87's core size is smaller than previously thought



new data point

(13 ... 34) μas

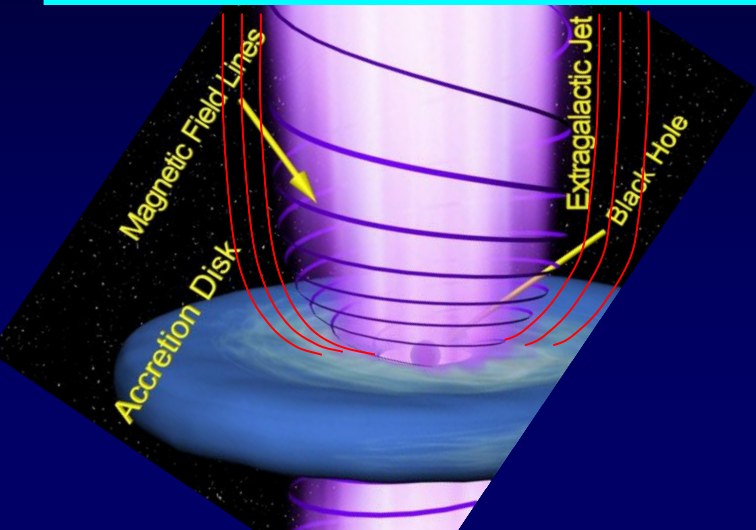
(1.6 – 4.3) R_s

APEX baselines are N-S oriented: the above numbers may measure the N-S jet width !

BP versus BZ mechanism

Blandford – Payne mechanism:

centrifugal acceleration in magnetized accretion disk wind



measure

Jet speed f(r,z)

Jet width f(z)

T_B f(z)

→

Shape of Nozzle

Magnetic Field

BH Spin

etc.

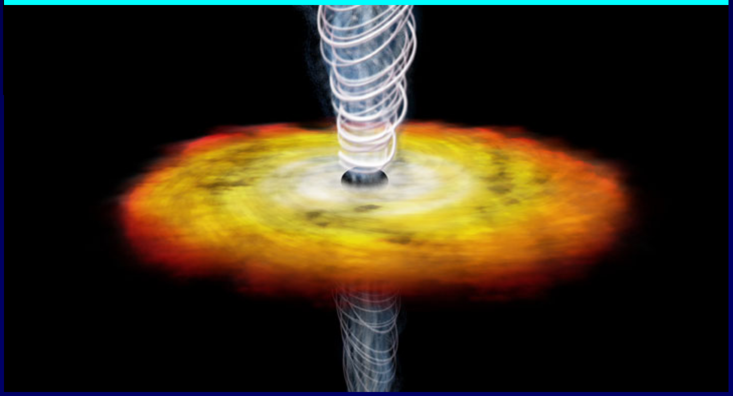
need to reach

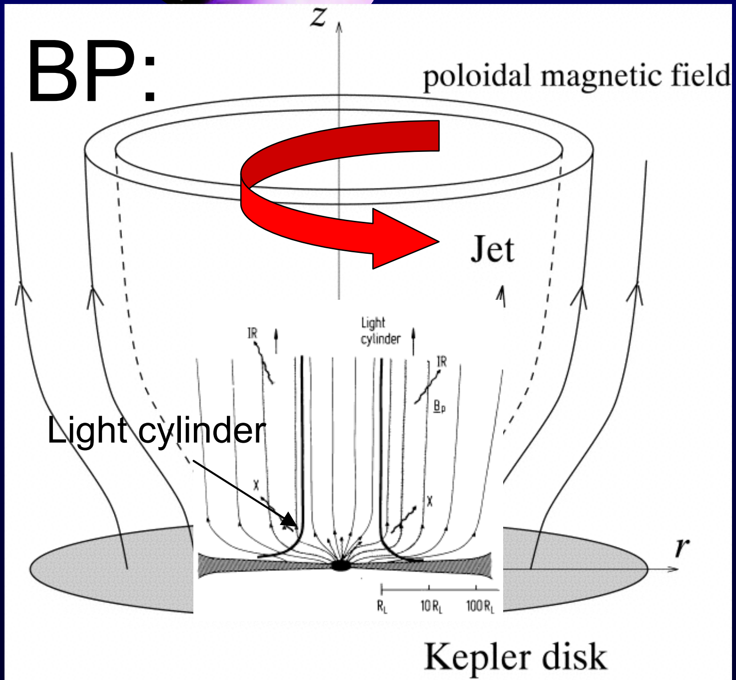
scale of

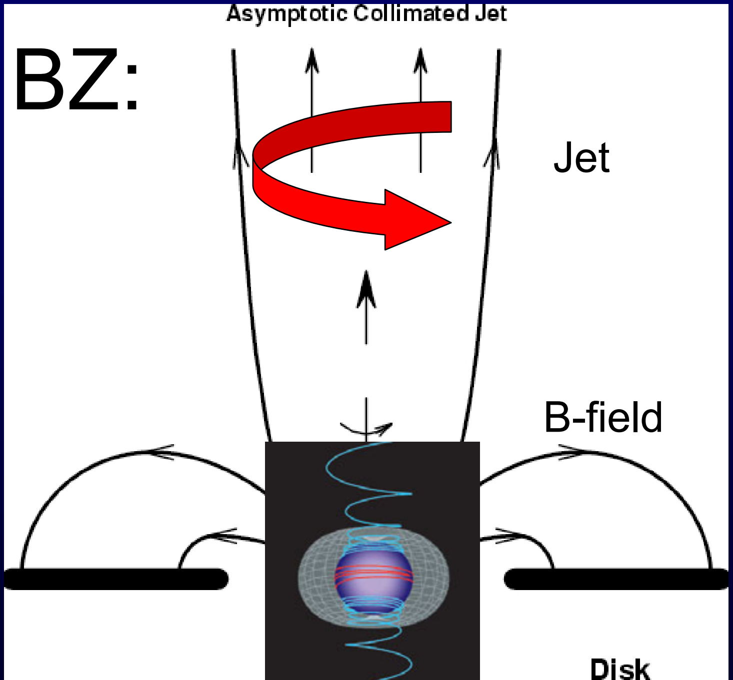
a few R_G

Blandford – Znajek mechanism:

electromagnetic extraction of rotational energy from Kerr BH

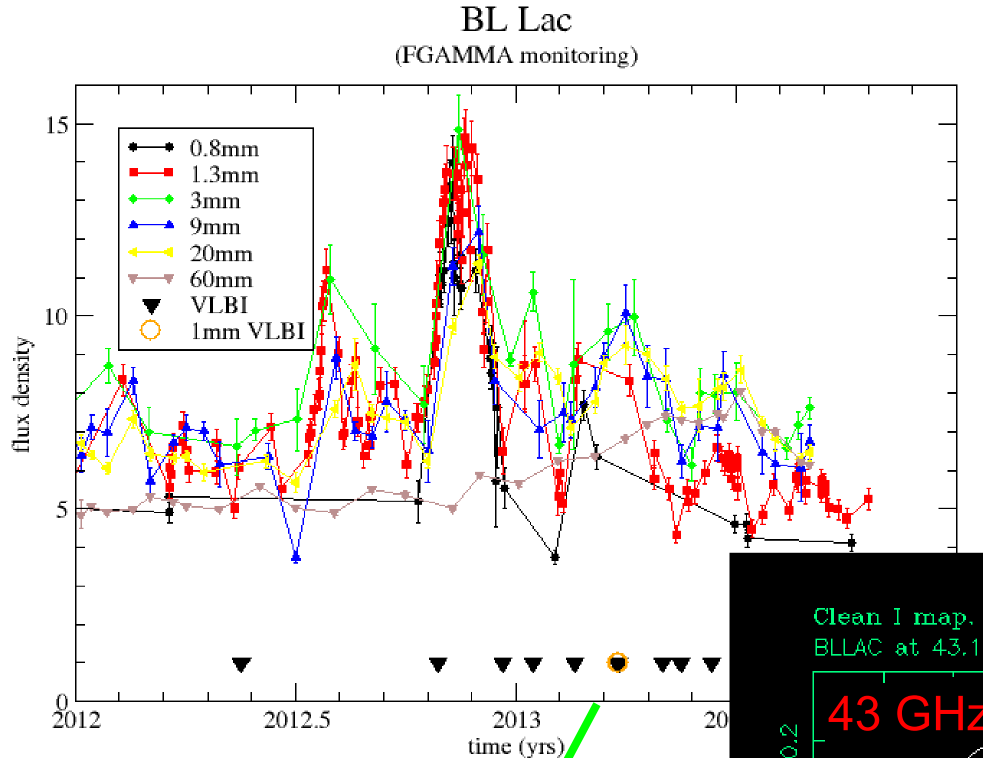


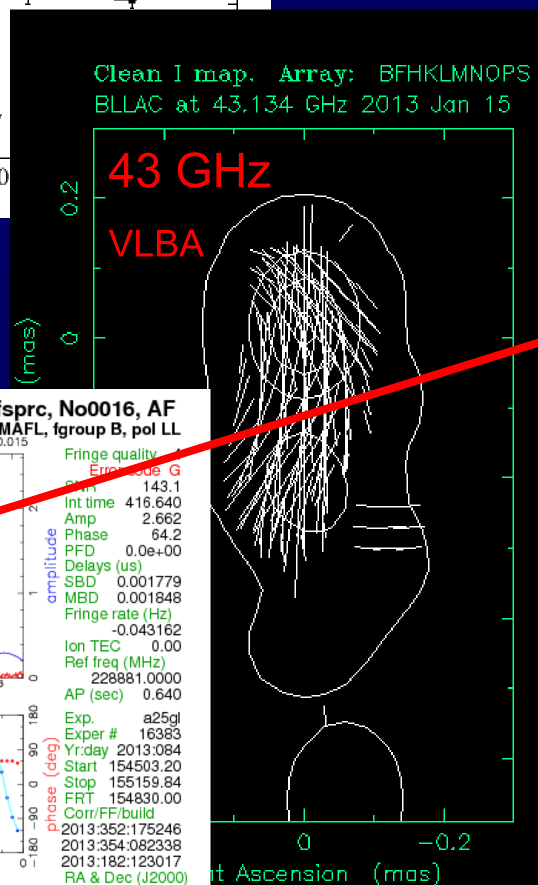


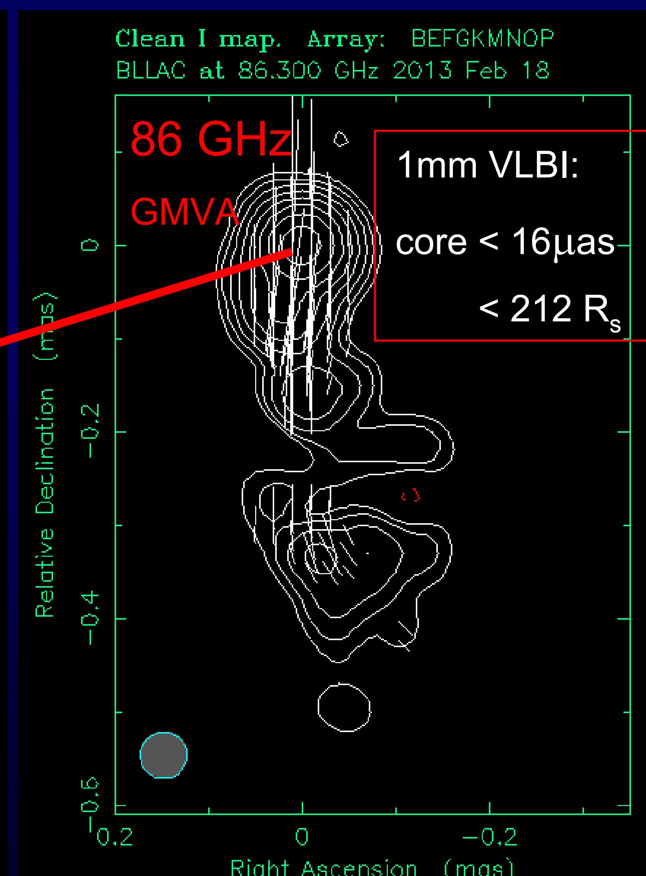


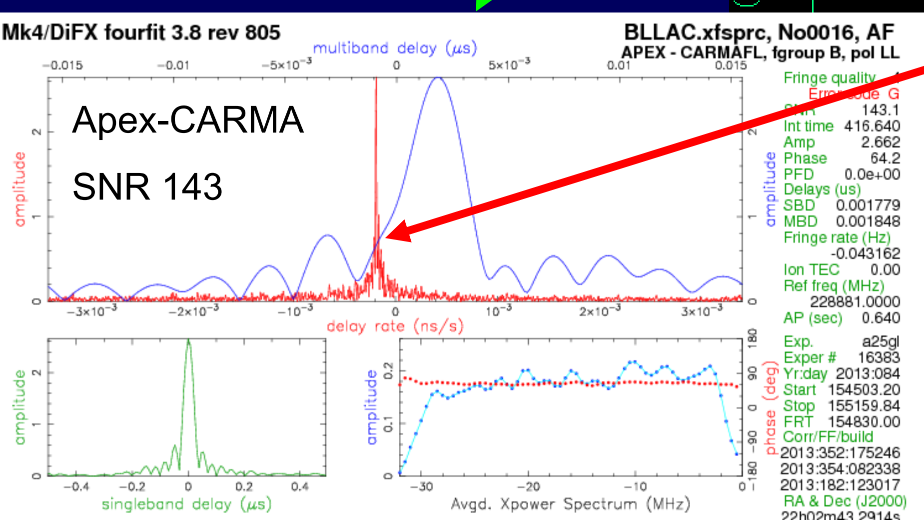
Monitoring BLLac after Dec. 2012 outburst:

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

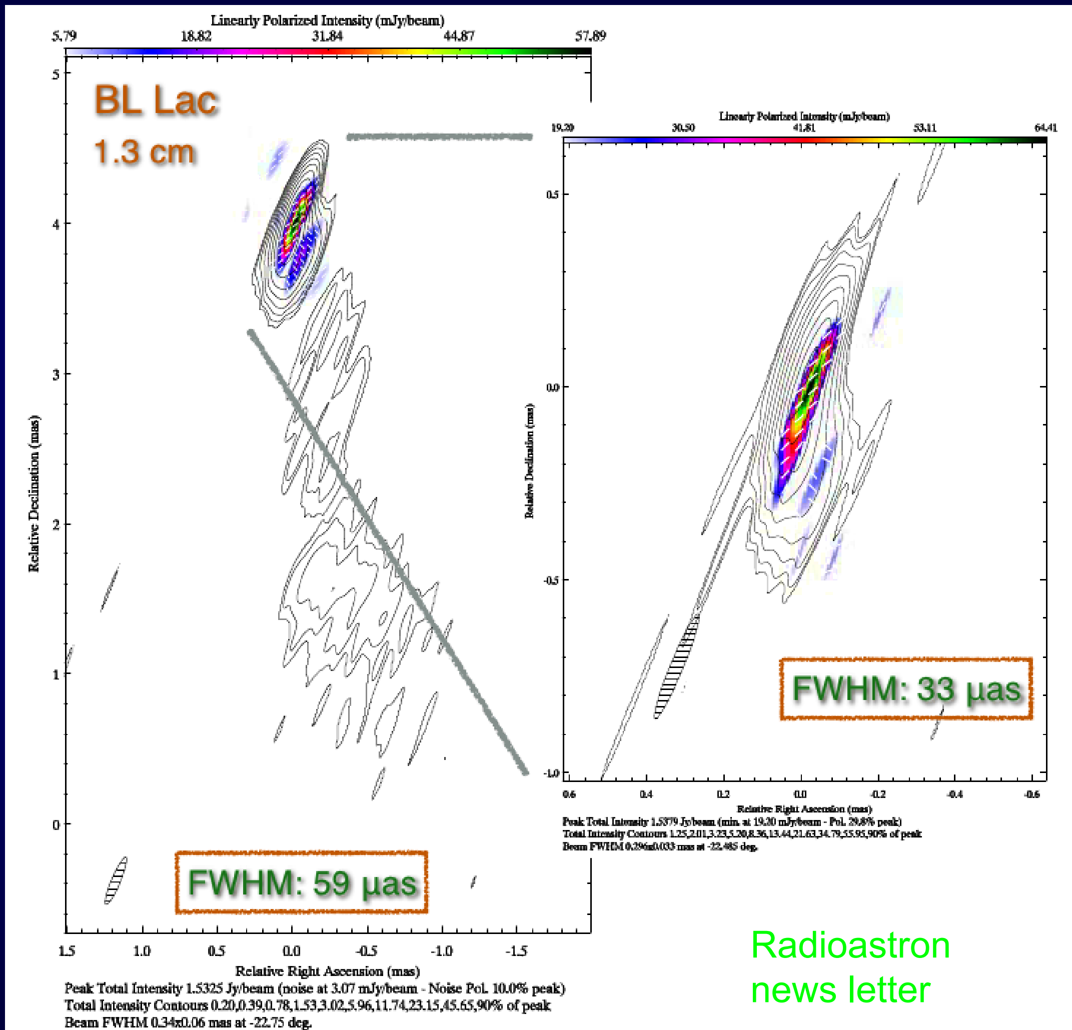




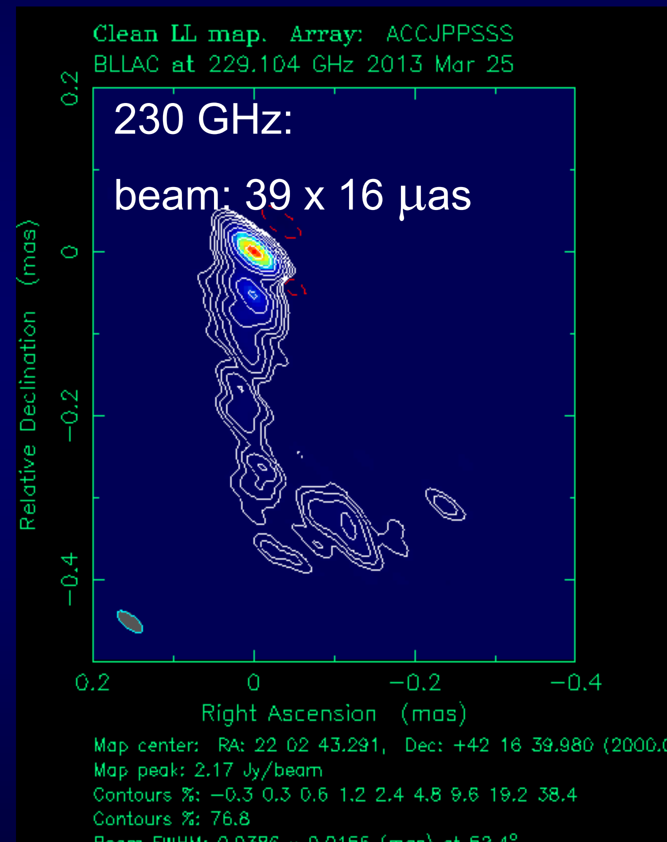




BL Lac observed with Radioastron (1.3cm) and the Event Horizon Telescope (EHT, 1.3mm)



EHT – 5 telescopes, incl. APEX



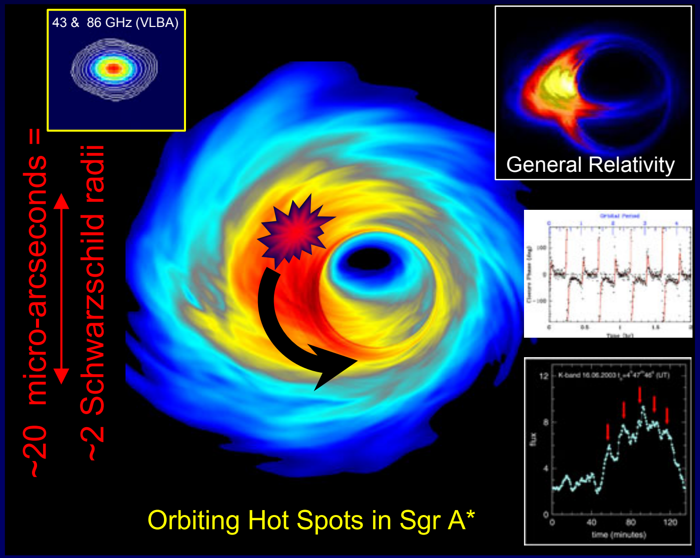
combination of cm-space VLBI and mm-ground VLBI – great potential for multi-frequency studies with matched beam size

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

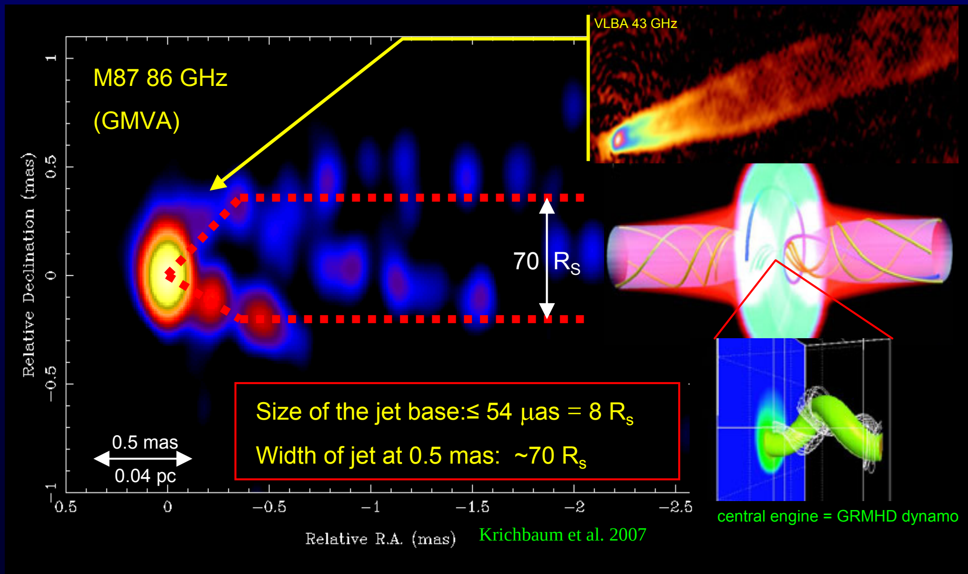
see EHT Whitepaper (Fish et al. 2013)

- 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, γ-ray emission region, etc.)
- study AGN and their SMBHs at high redshifts (cosmological evolution of SMBHs)
- further improve global 1mm VLBI: PV, PdBI, SMTO, SMA, CARMA, LMT, SPT, APEX/ ALMA (Event Horizon Telescope).
- add phased ALMA (Alma phasing project)

Sgr A*:



M87+ AGN Jets:



now lets stop here,

Thank you !