Imaging AGN at highest frequencies and resolutions

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(on behalf of the global 1mm VLBI/EHT team)

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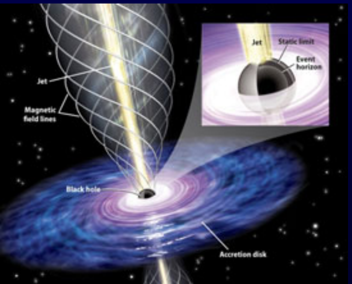


people involved in Global Millimeter VLBI (GMVA):

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 (in 2013) :

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

Haystack: S. Doeleman, V. Fish, R. Lu, M. Titus, R. Capallo, 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 Origin of Jets: Understanding BH – Disk – Jet coupling

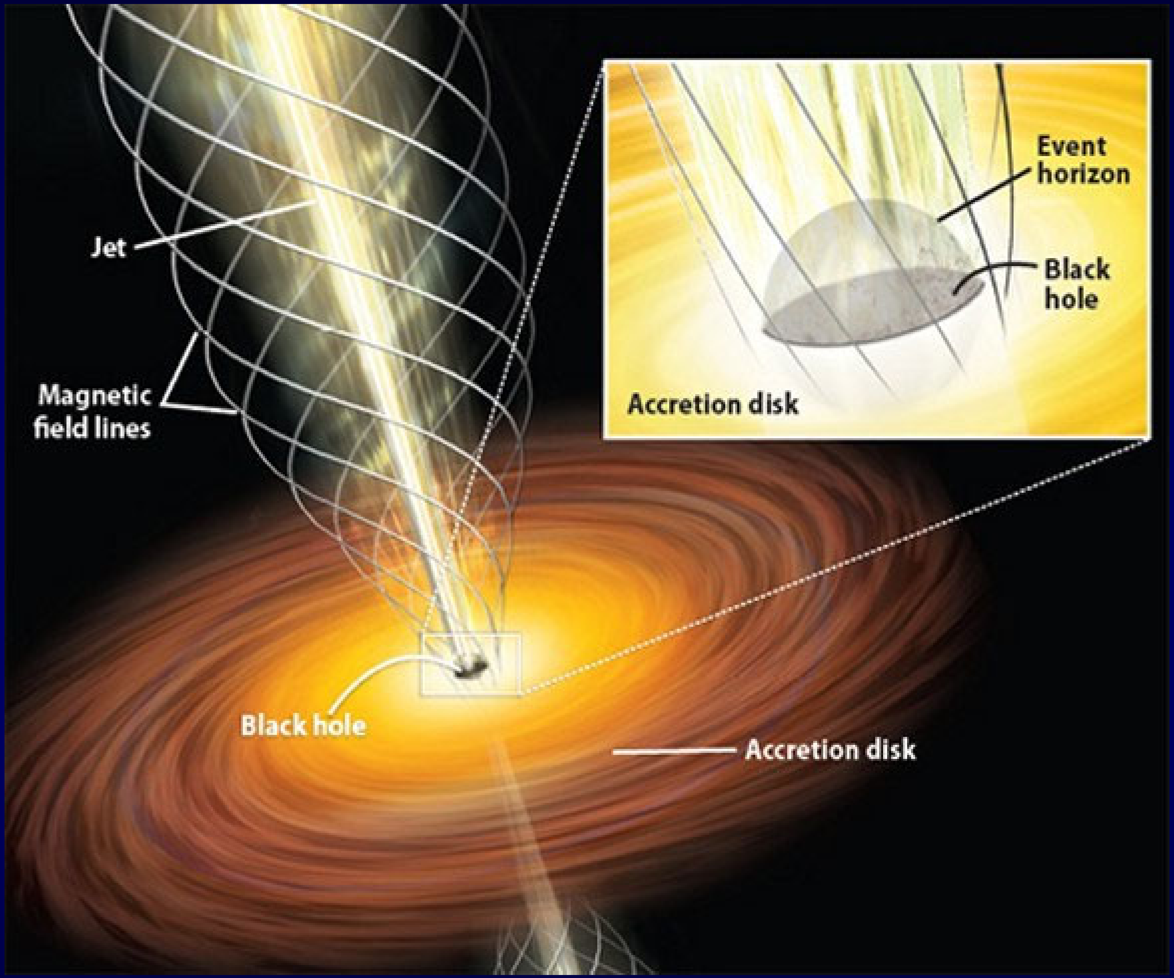


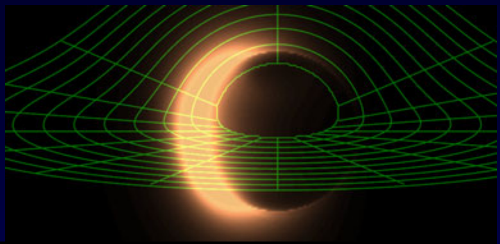
Image Credit: Astronomy/Roen Kelly

- VLBI at mm- and sub-mm λ overcomes opacity barrier
- sub-mm and space VLBI reach Event Horizon scales

Specific Science goals

- main aim: high dynamic range imaging with VLBI at $\lambda \leq 1.3$mm
  - map fine structure of BH-disk-jet systems (origin of jets)
  - map event horizon scale structures (light bending, photon ring, BH spin, etc.)
- study nearby objects with highest possible spatial resolution (SgrA*, M87, ...)
  - testing GR & alternative theories
- test energy budget via size measurements
  - kinetic or magnetic dominance, equipartition ?
- brightness temperature as function of frequency and jet distance
  - test jet launching models and jet particle composition (leptonic vs. hadronic)
- determine component spectra (global VLBI@ 7, 3, 1, 0.8 mm, + space VLBI)
  - turnover frequency and compactness, spectral evolution, shocks, SSA-models
- polarisation of AGN cores (plus RM)
  - test GR-MHD models, plasma-physics near BH and at jet base
- AGN survey (cosmological evolution of BHs, QSO/BL/RG statistics)
- absorption line VLBI (physics of circum-nuclear gas)

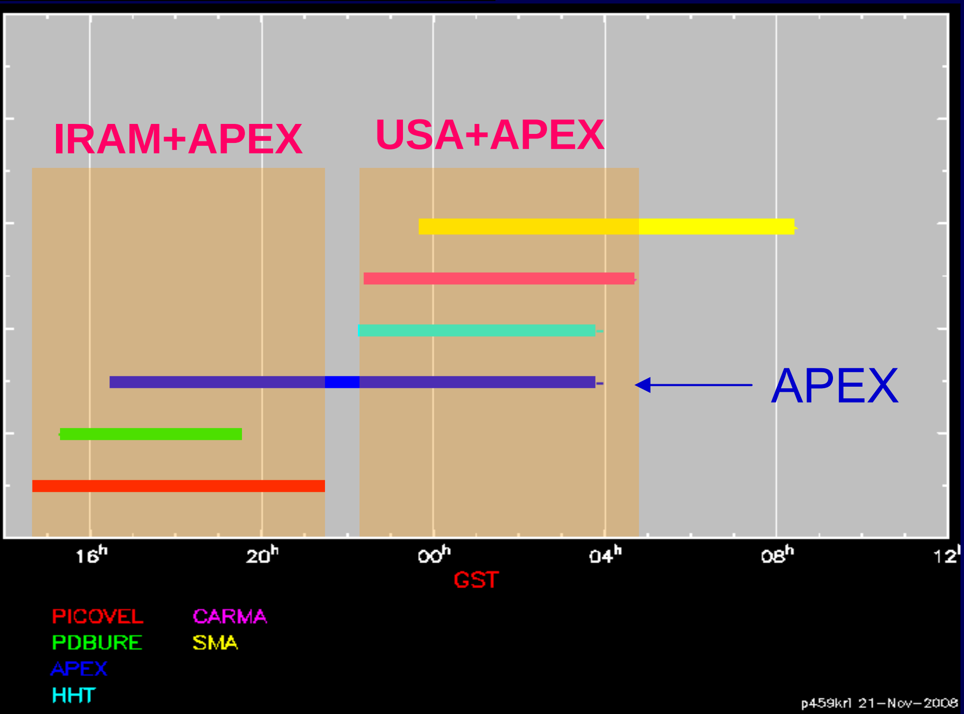
Millimeter VLBI with APEX/ALMA



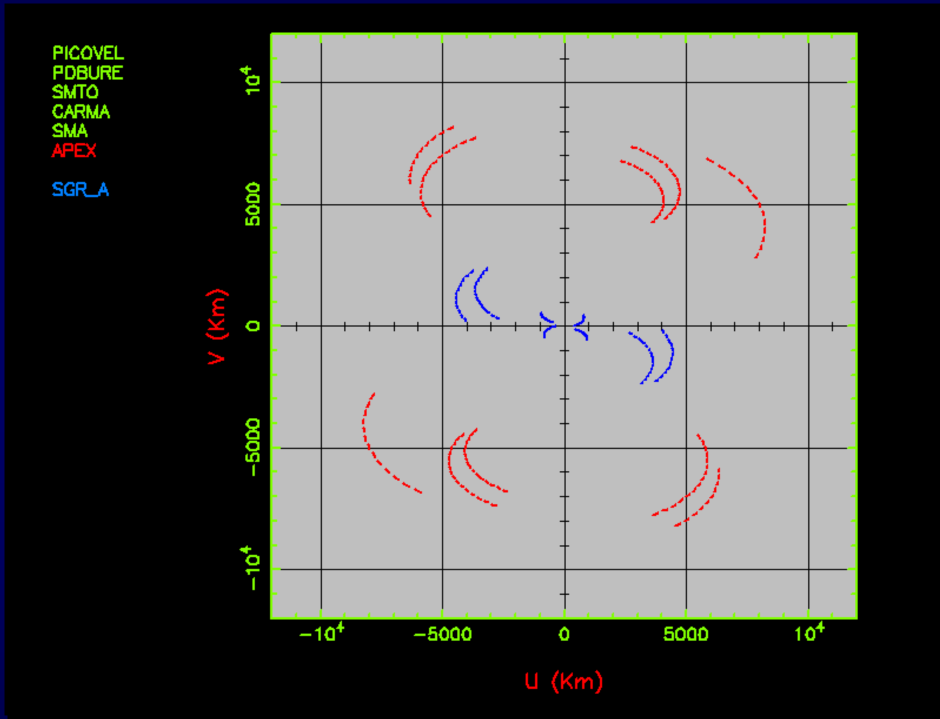
Determine the shape of the event horizon

Observations of Sgr A*

ν = 230, 345 GHz



Mutual Visibility



uv coverage (Apex high-lighted)

APEX/ALMA connects 2 IRAM telescopes with the US stations

IRAM + APEX: ~5 hrs

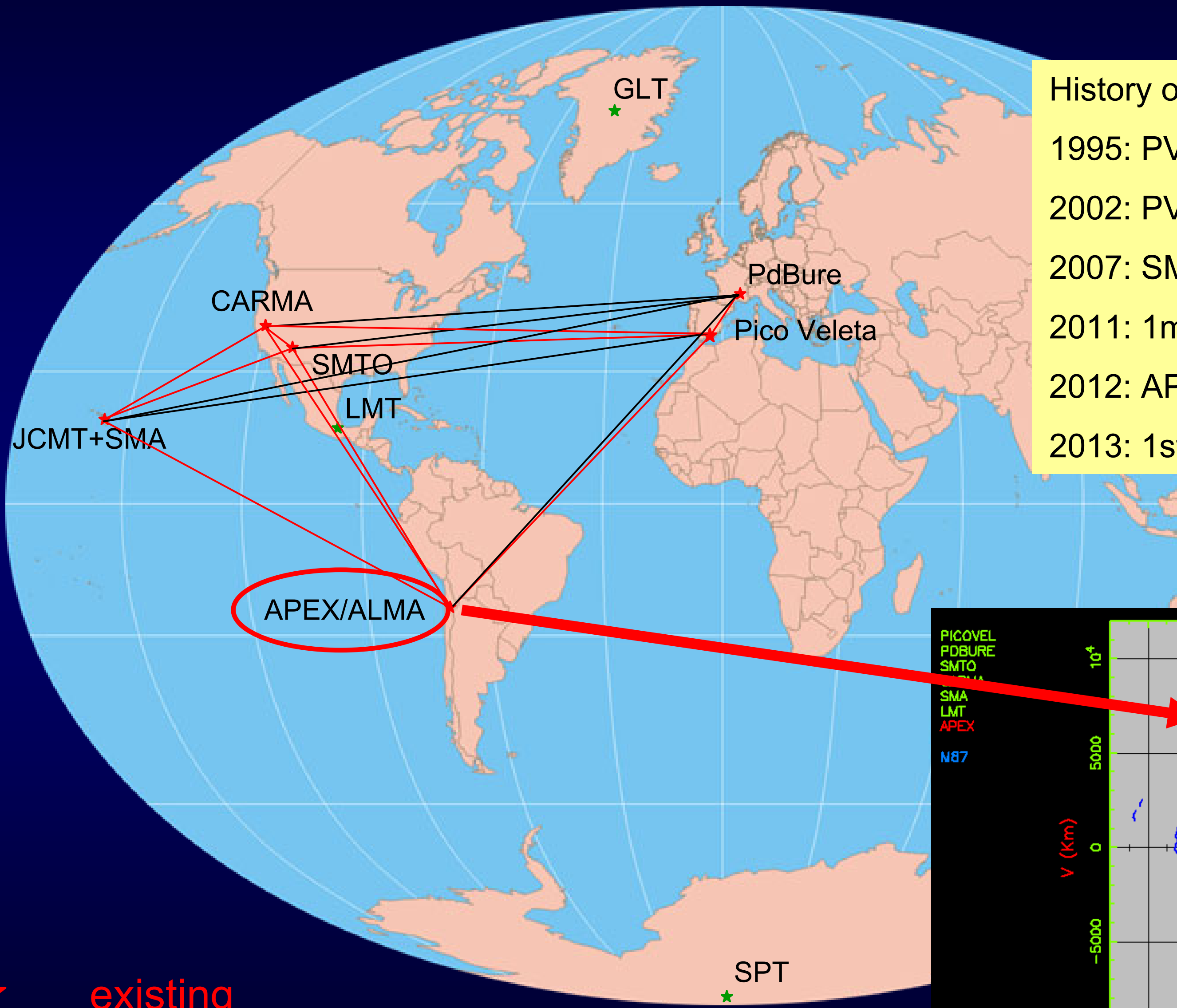
USA + APEX: ~6 hrs

Angular Resolution: 20-30 µas @230 GHz

10-20 µas @345 GHz

Building a truly global 1.3 mm VLBI array

Status March 2013 with APEX added



History of 1mm VLBI:

1995: PV-PdB (N=12, SNR~25)

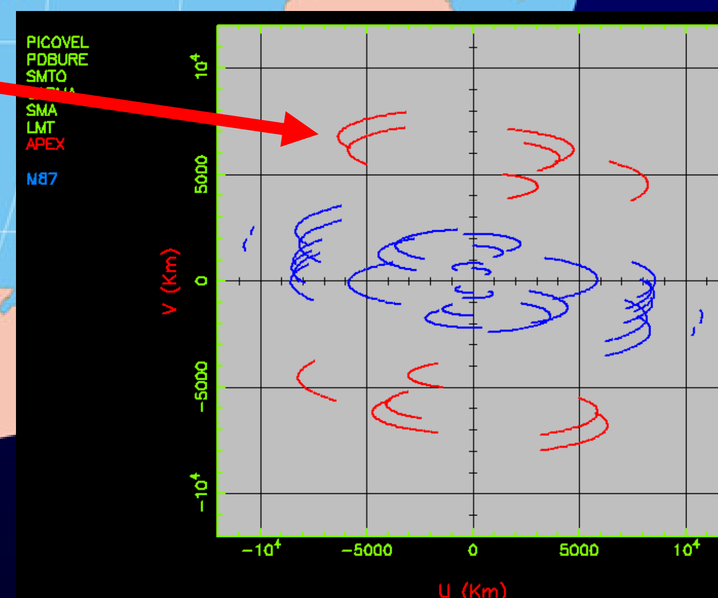
2002: PV-SMTO (N=2, SNR~7)

2007: SMTO-CARMA-JCMT/SMA

2011: 1mm VLBI with Apex, NoF

2012: AP-SMA-SMTO, first fringes

2013: 1st global 1mm VLBI run



★ existing

★ planned

—— fringes established

SNR of detection (LCP, low + high band)

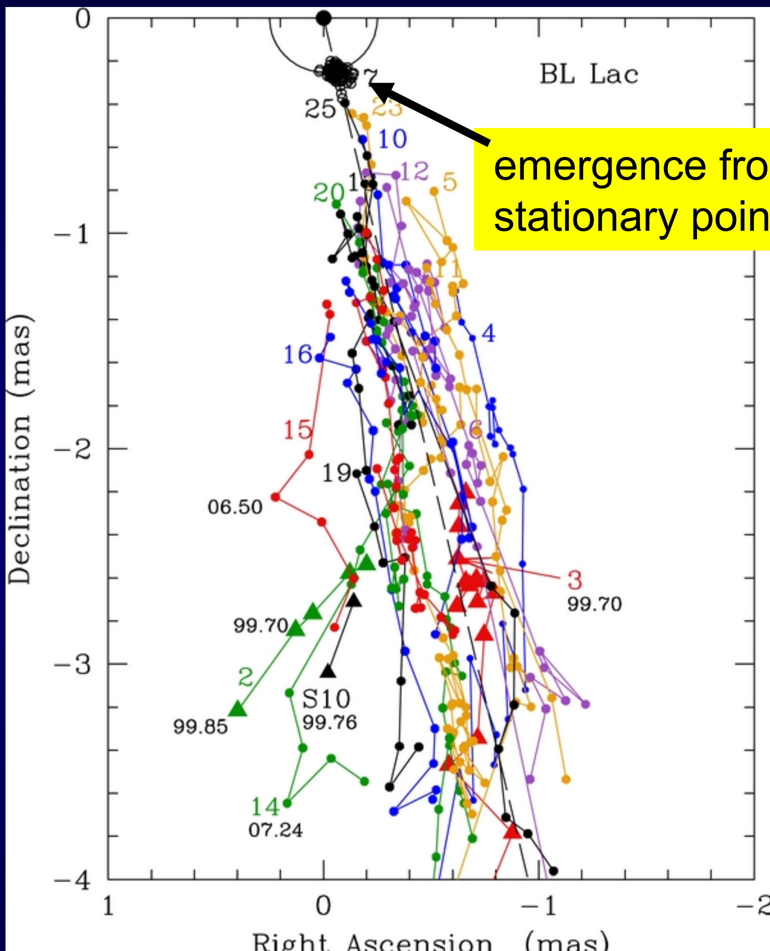
230 GHz, March 21-27, 2013

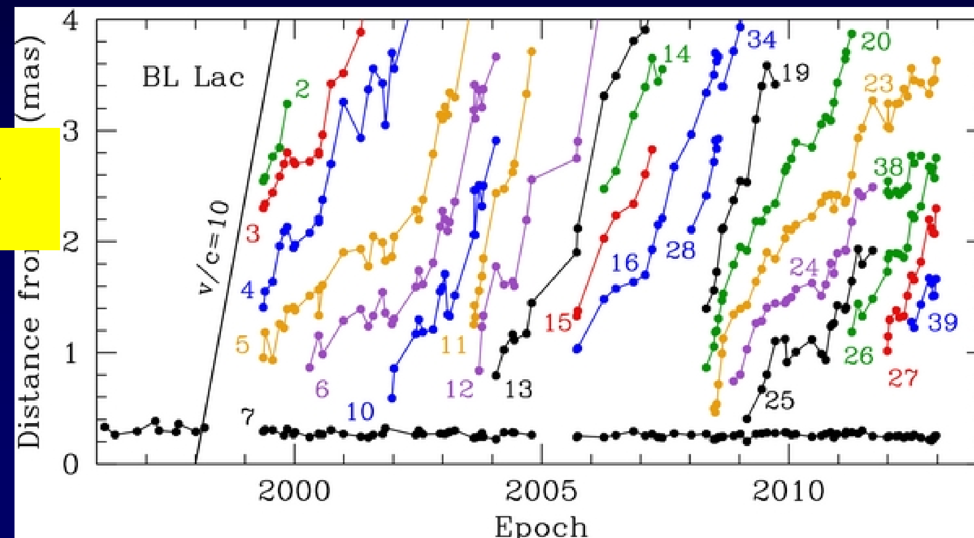
		AP-CA	AP-SMA	AP-SMT	CA-SMA	CA-SMT	SMT-SMA	CA-PV	AP-PV	PV-SMT	PV-SMA
Source	**Flux**	**AF**	**AP**	**AS**	**FP**	**FS**	**SP**	**FV**	**AV**	**VS**	**VP**
	[Jy]										
OJ287	3,8				84	30	62				
3C84	10,0					36					
3C111	2,2					26					
3C273	4,1	23	13	12	39	74	15				
M87	1,5	11	6	6	13	32	8				
3C279	10,8	16	6	7	49	172	29				
1337-129	3,4				30	67	39				
1749+096	1,9	31	9	13	22	48	7				
NRAO530	1,4					10					
SGRA	3,1	11	6	6	22	59	16				
1633+382	4,1	30	12	13	48	41	17				
3C345	2,4				9						
1921-293	2,5	10	10	7	36	31	8				
2013+370	3,3	20	17	17	66	26	24				
BLLAC	8,0	115	67	75	248	156	225	13	15	9	7

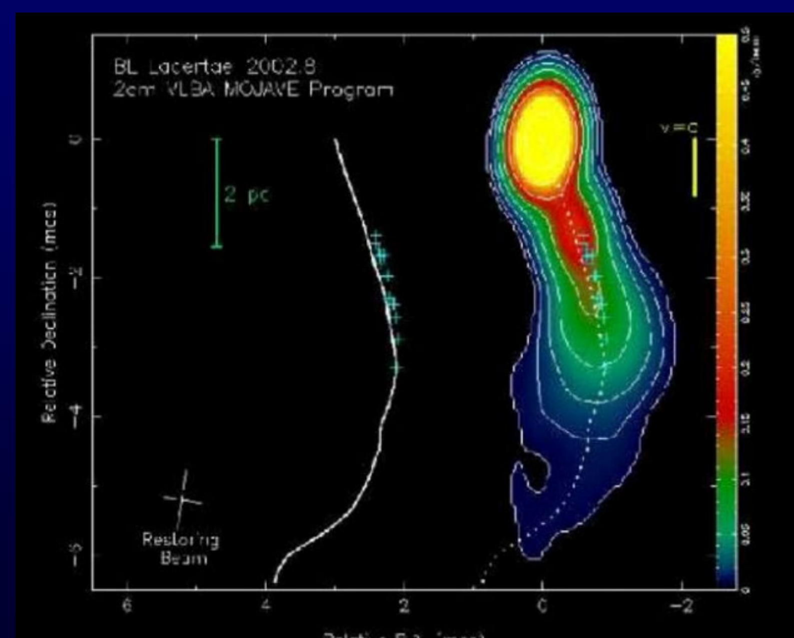
14 sources on inter-US baselines, 9 sources on APEX baselines detected !

Note: due to weather, station performance and GST range, the SNR of the detected sources varies by a factor of 2-3

BL Lac: Modeling component trajectories through superluminal Alfvén – waves

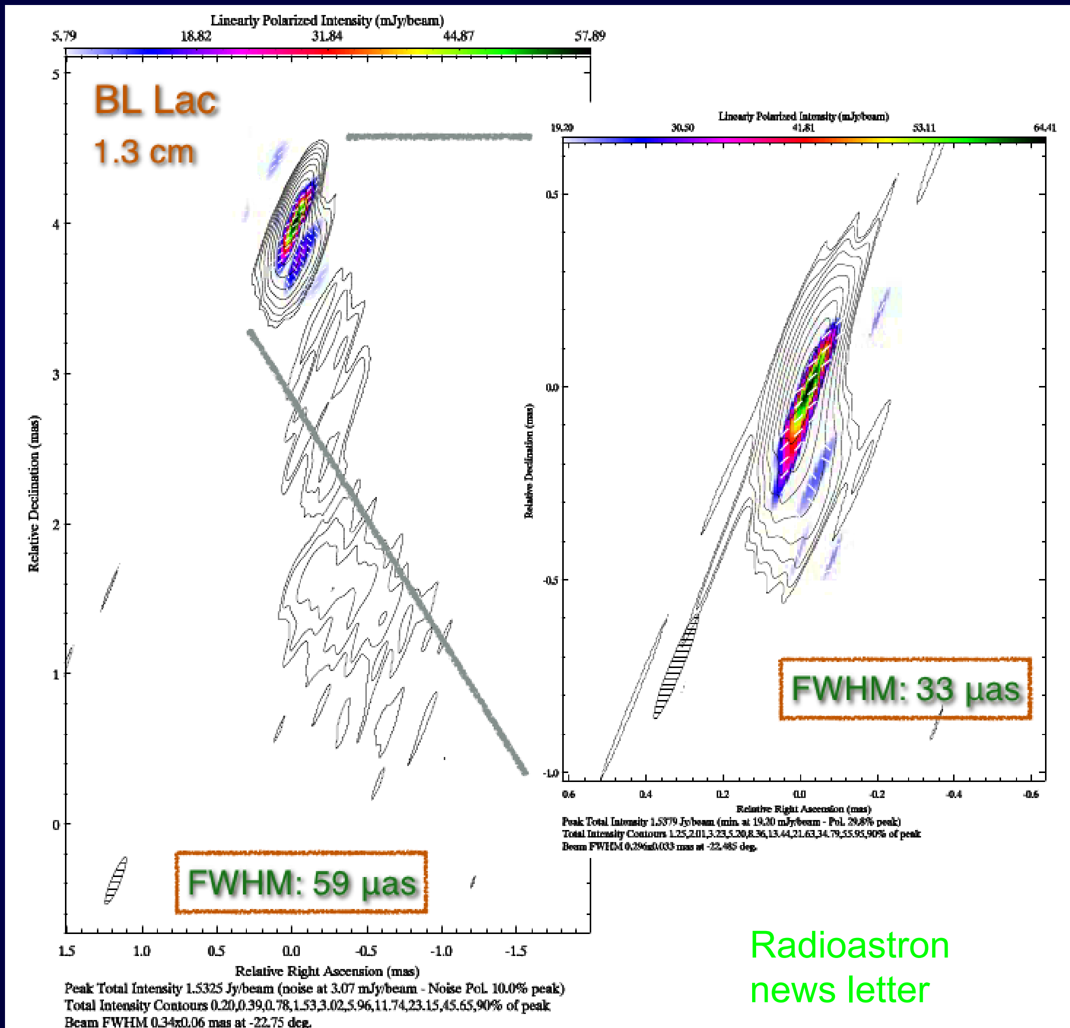




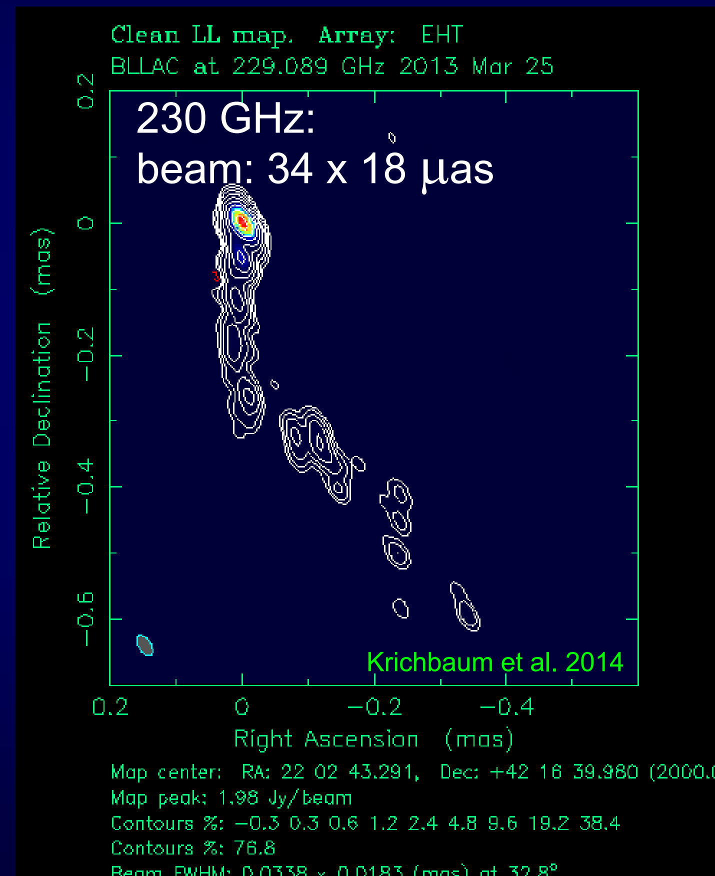


Cohen et al. 2014, 15 GHz VLBI (Mojave)

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

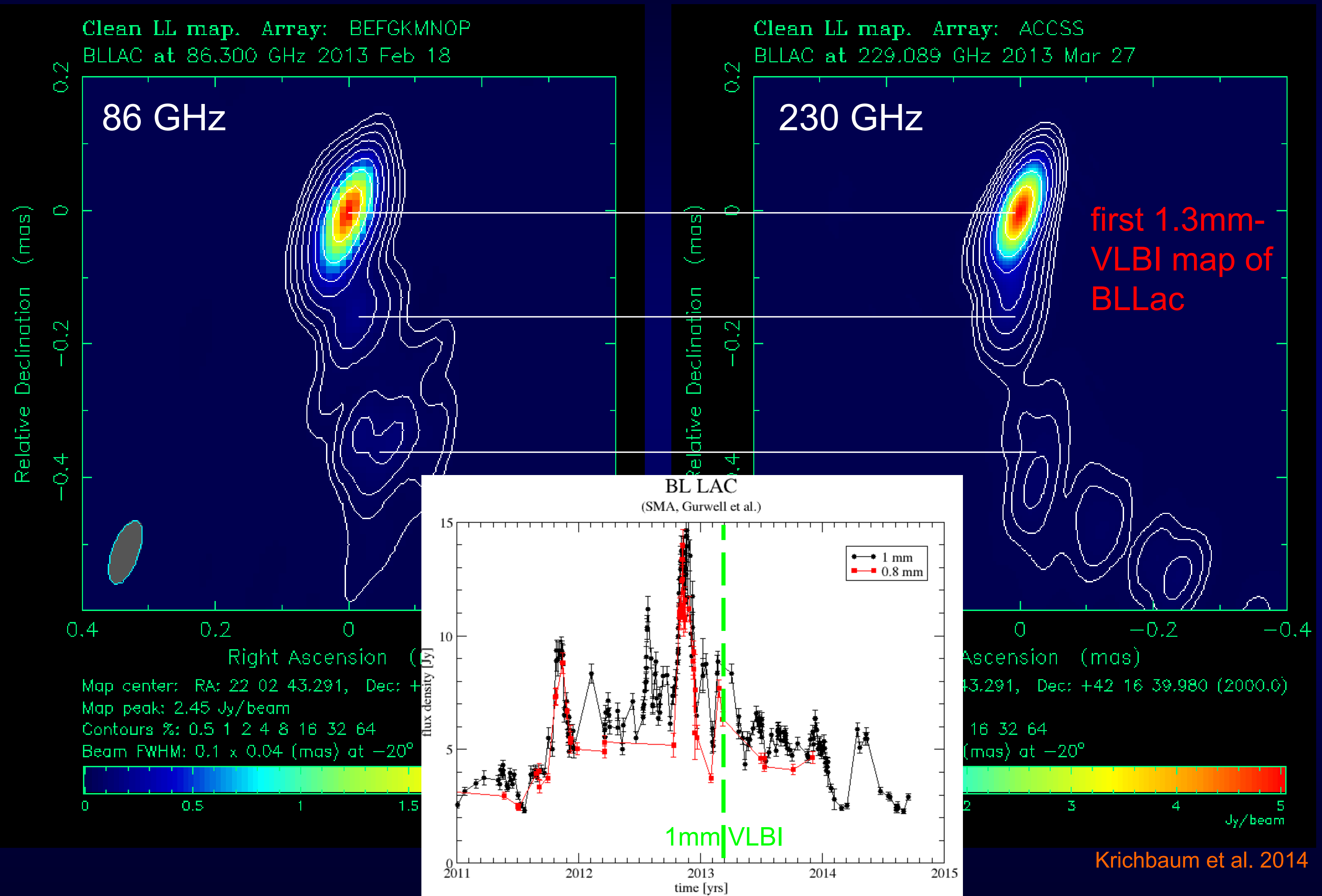


EHT – 5 telescopes, incl. Pico



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

Comparison of BLLAc data 3mm GMVA & 1mm EHT



Krichbaum et al. 2014

Energy Budget

core parameters from model fit : S_m=5.3 Jy, θ_m=13μas

turnover frequency: spectrum inverted up to 1.3mm → $\nu_m \approx$ 230 GHz

equipartition Doppler-factor: δ_{eq} = 3 – 4

magnetic field strength: B_{core} = 2 – 8 Gauss

energy dominance: $u_{mag}/u_{particle} > 1$, when $\delta \geq \delta_{eq}$

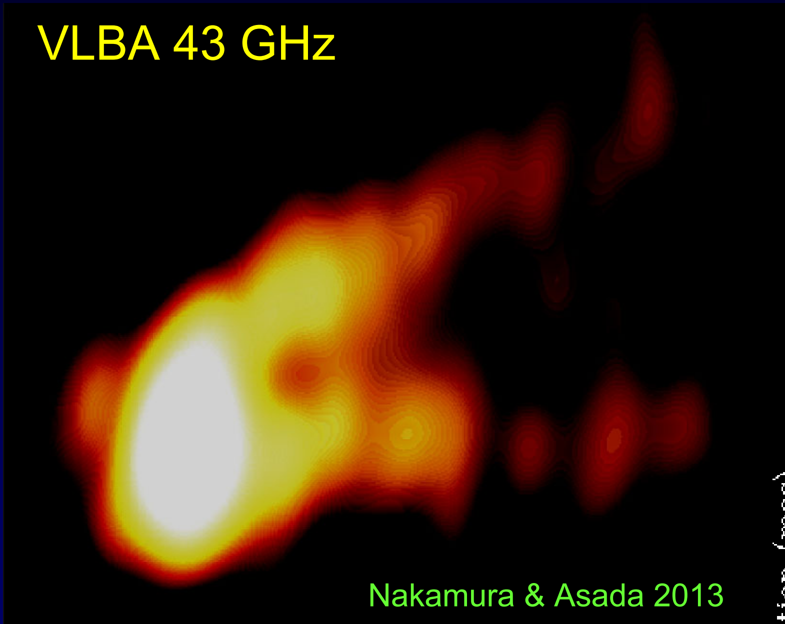
with $\delta \sim \beta_{app} \sim 10$ (observed at 15 GHz on pc)

→ $u_{mag} / u_{part} = 5 \cdot 10^3$

but: we don't know δ on < 0.2 mas scales !!

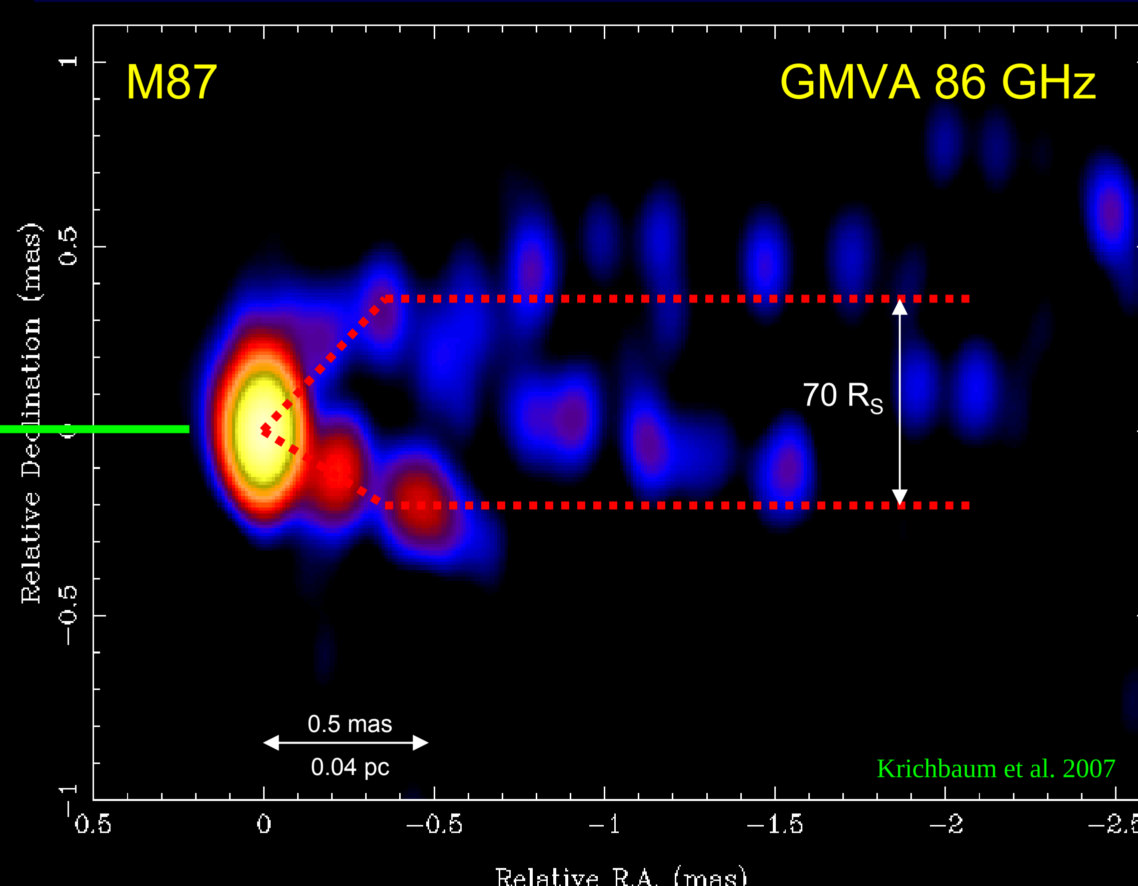
future: need kinematics also at 1mm, → regular VLBI monitoring

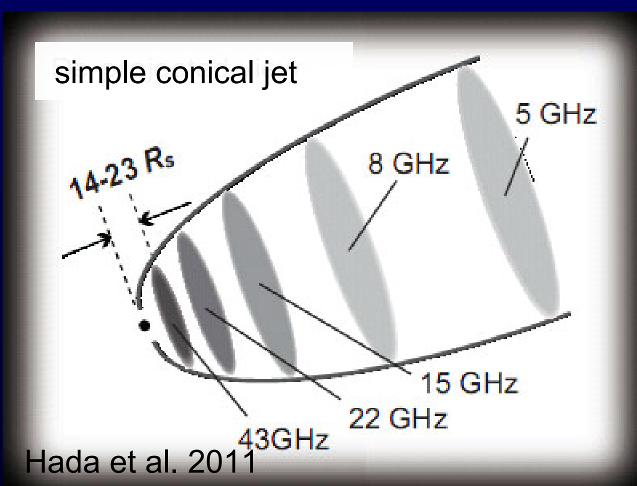
The jet base in M87



separation to BH:

~14-23 R_s



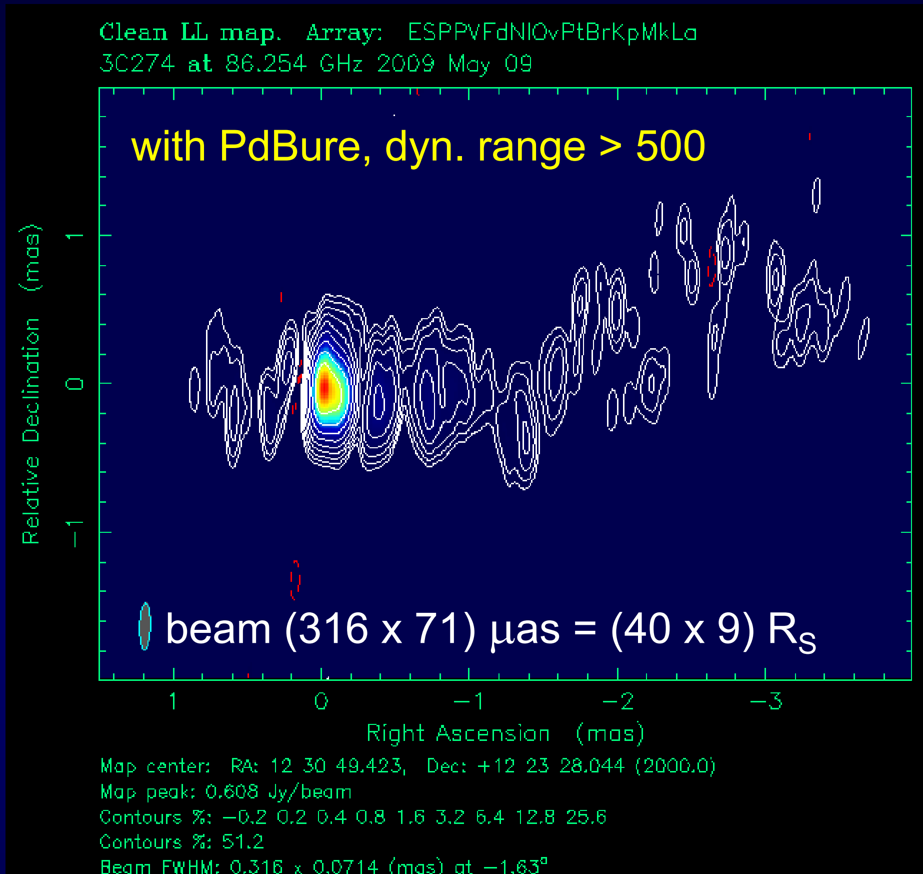


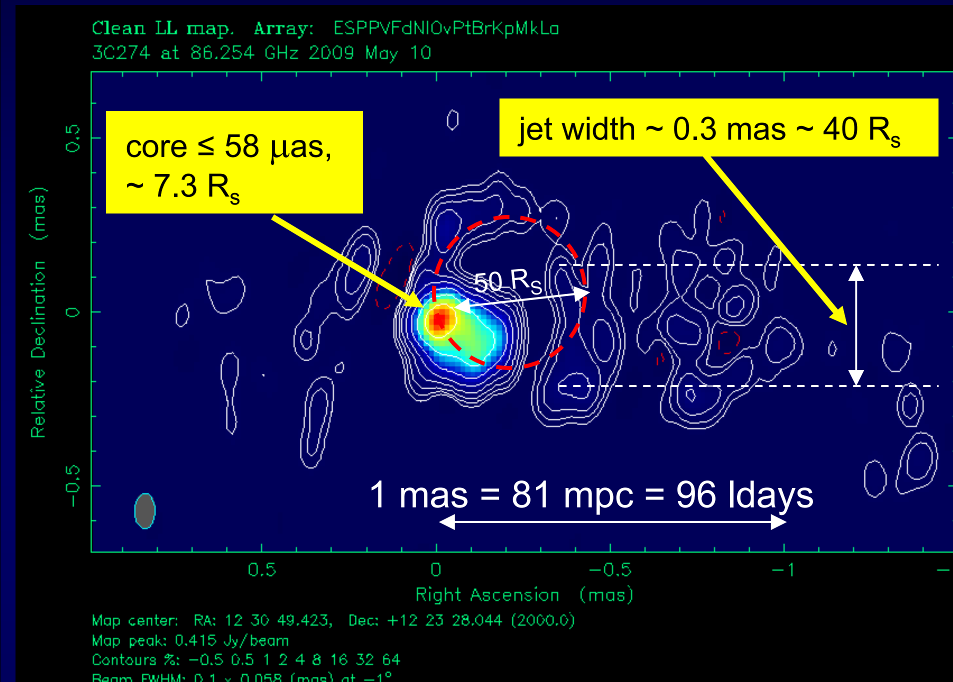
Limit to the size of the jet base (uniform weighting):

197 x 54 µas = 21 x 6 light days = <u>27 x 8</u> R_s[9]

transverse width of jet at 0.5 mas: ~70 R_s[9]

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

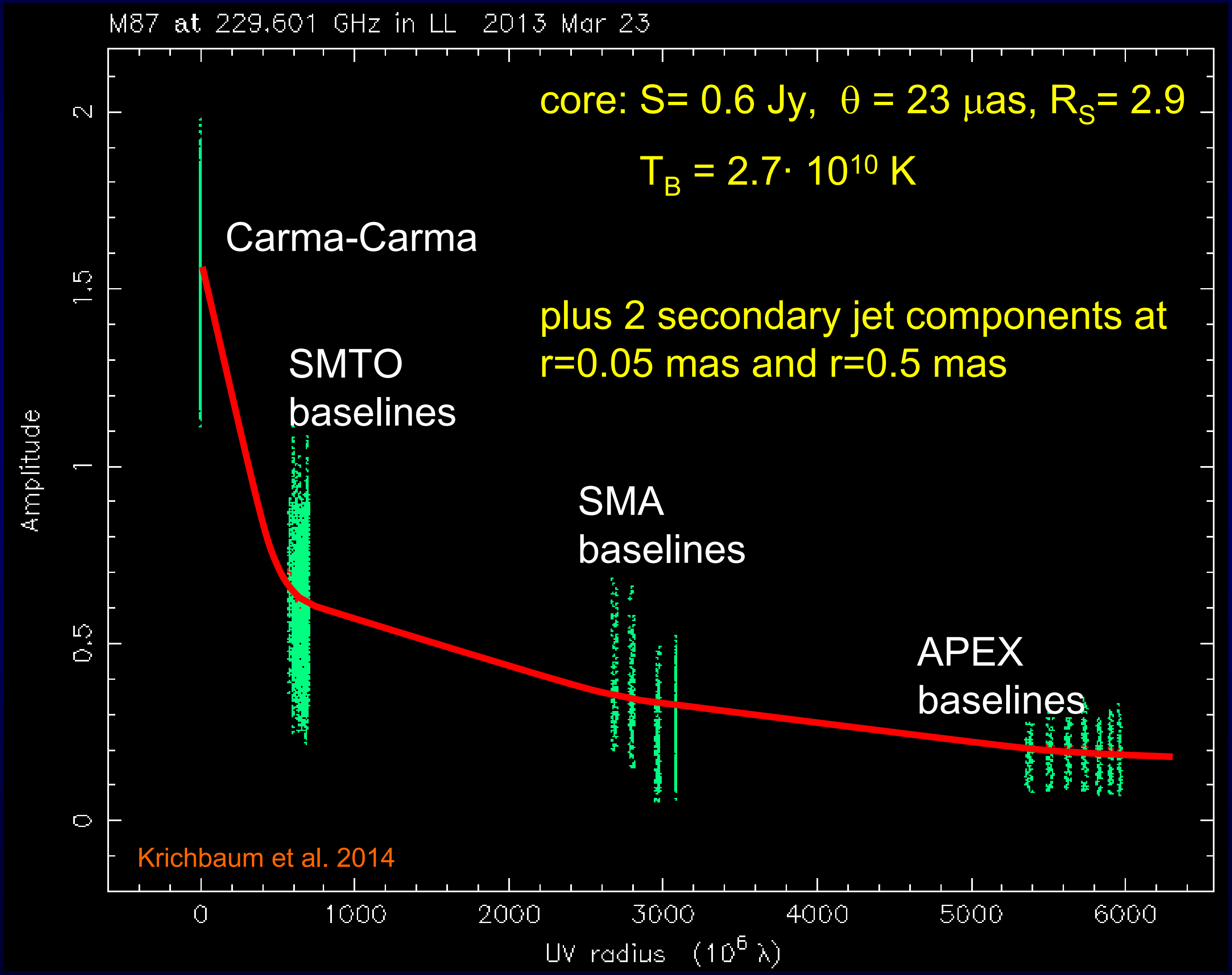




Krichbaum et al. 2014

- first time that counter-jet is seen at 3mm
- peak $T_B \sim 2 \cdot 10^{10}$ K at core
- core size ≤ 7.3 R_S, expected size of photon ring 41.3 µas (5.2 R_S)
- jet width ~ 40 R_S at r = 0.5 - 1 mas (at ~ 30 - 65 R_S)

M87: Gaussian Modelfit to combined data set of March 23, 2013



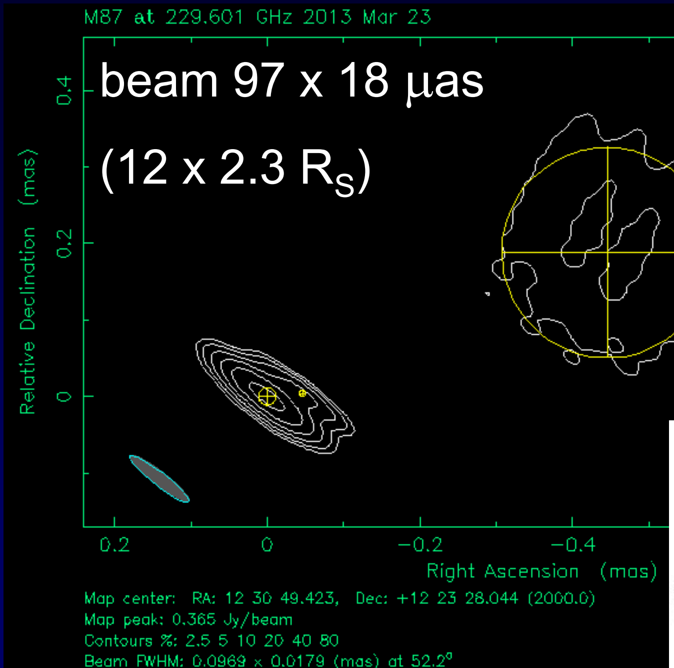
- visibilities can't be fitted by a single Gaussian
- strong resolution effects already at 600 Mλ
- unfortunately no non-trival closure phases in this dataset
- T_B at 86 & 230 GHz comparable

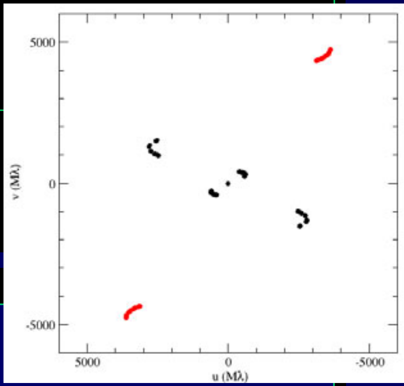
M87 at 230 GHz

Gaussian modelfit

no uvtaper

uniform weight, uvw 2,-2

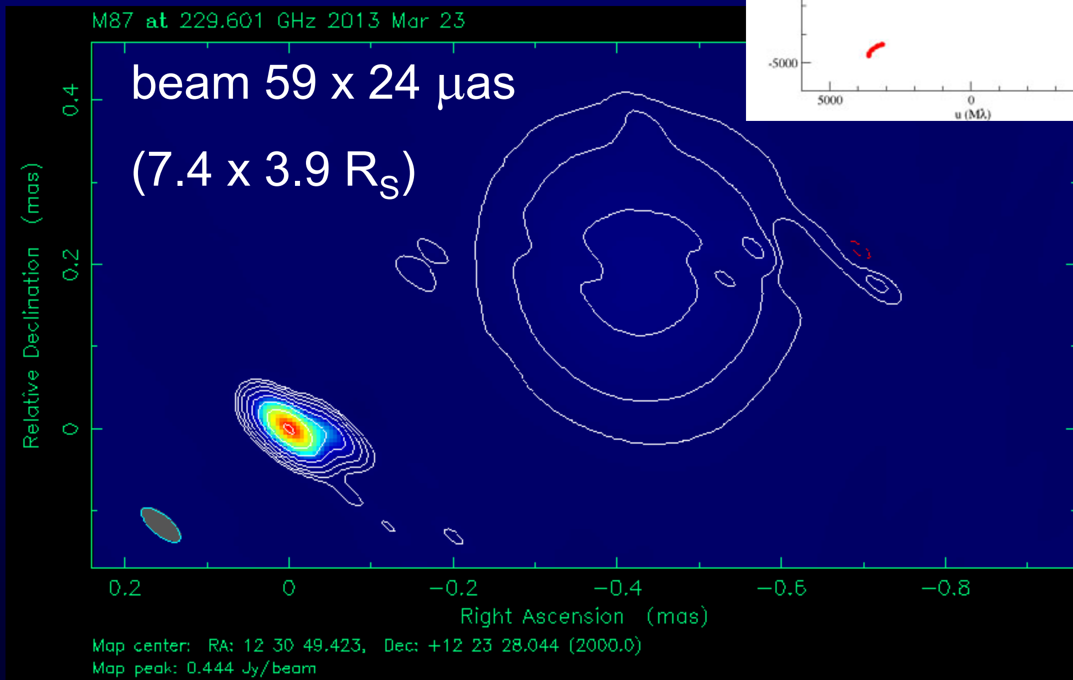




Modelfit + Clean Map

uvtaper 0.3@6Gλ

uniform weight, uvw 2,-1



East west orientation of jet consistent with known 3mm VLBI structure

Krichbaum et al. 2014

M87's core size falls below parabolic streamline estimate

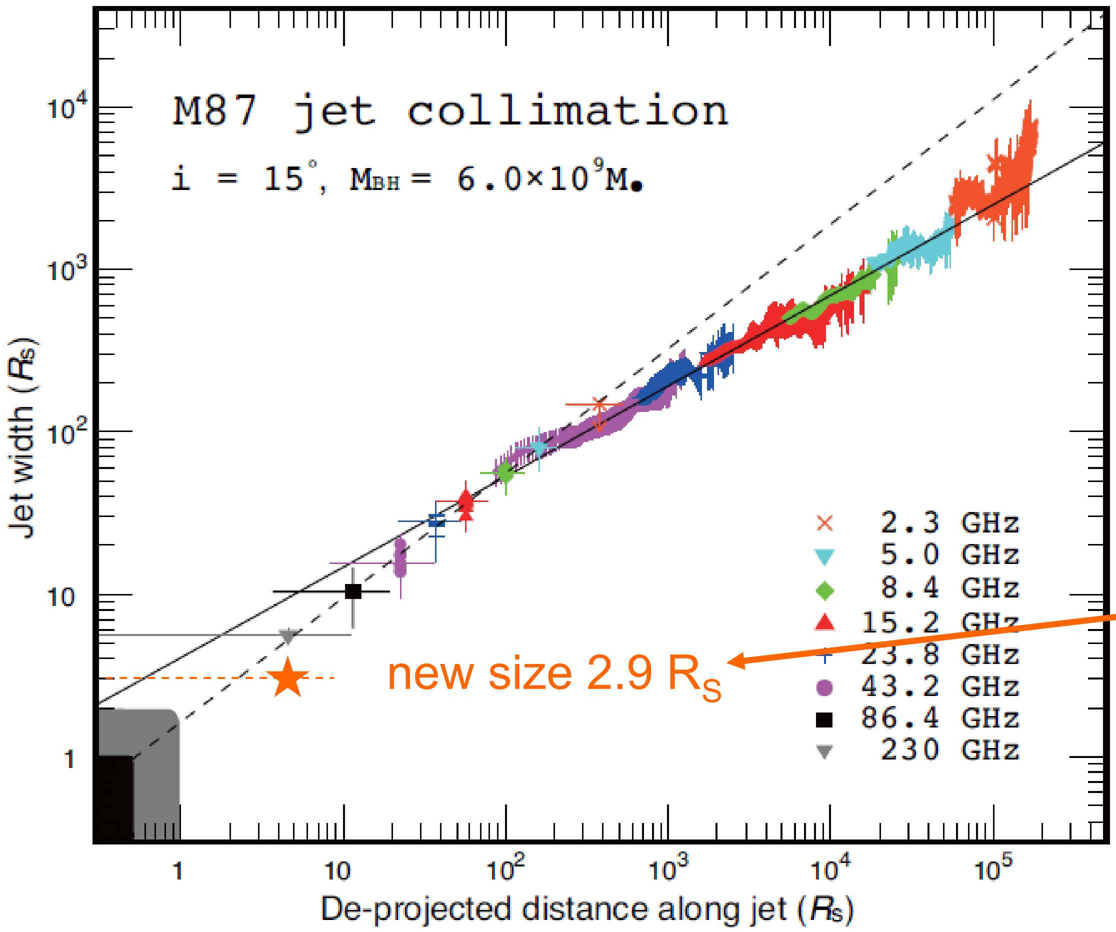


Figure 4. Jet width profile of M87 as a function of distance (taken from [41]). A jet viewing angle of $i = 15°$ and a black hole mass of $M_{BH} = 6.0 \times 10^9 M_\odot$ are adopted. Densely-sampled part indicates the width profile of the edge-brightened jet measured at multiple frequency with errors. Discretely-sampled part indicates the FWHM size profile for the core region projected in P.A=20° (W_c). The core positions and the errors are estimated based on the previous astrometry result [40]. A solid line indicates the best fit solution for the edge-brightened jet width $W_j \propto r^{0.56}$, while a dashed line indicates $r^{0.76}$. The grey/black rectangles at the bottom left corner of the figure represent surfaces (event horizons) for non-spinning/maximally-spinning black holes, respectively.

new data point

core size:

23 μas or

2.9 R_s

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

plot from Hada 2013

Competing Jet Models

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

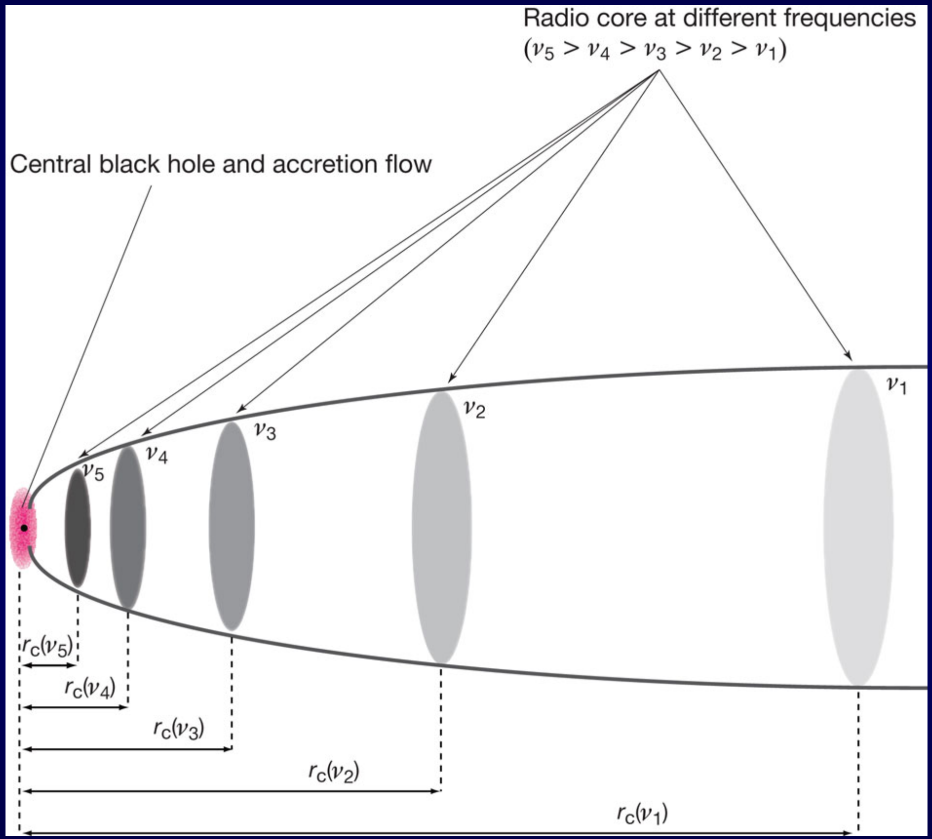
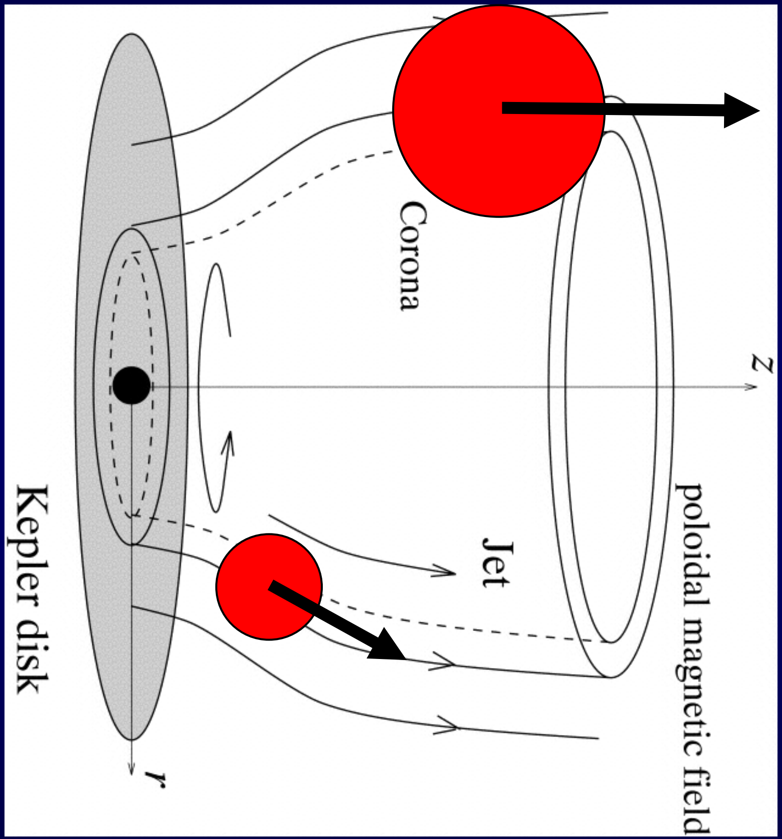


Figure from Hada et al. 2011, Nature

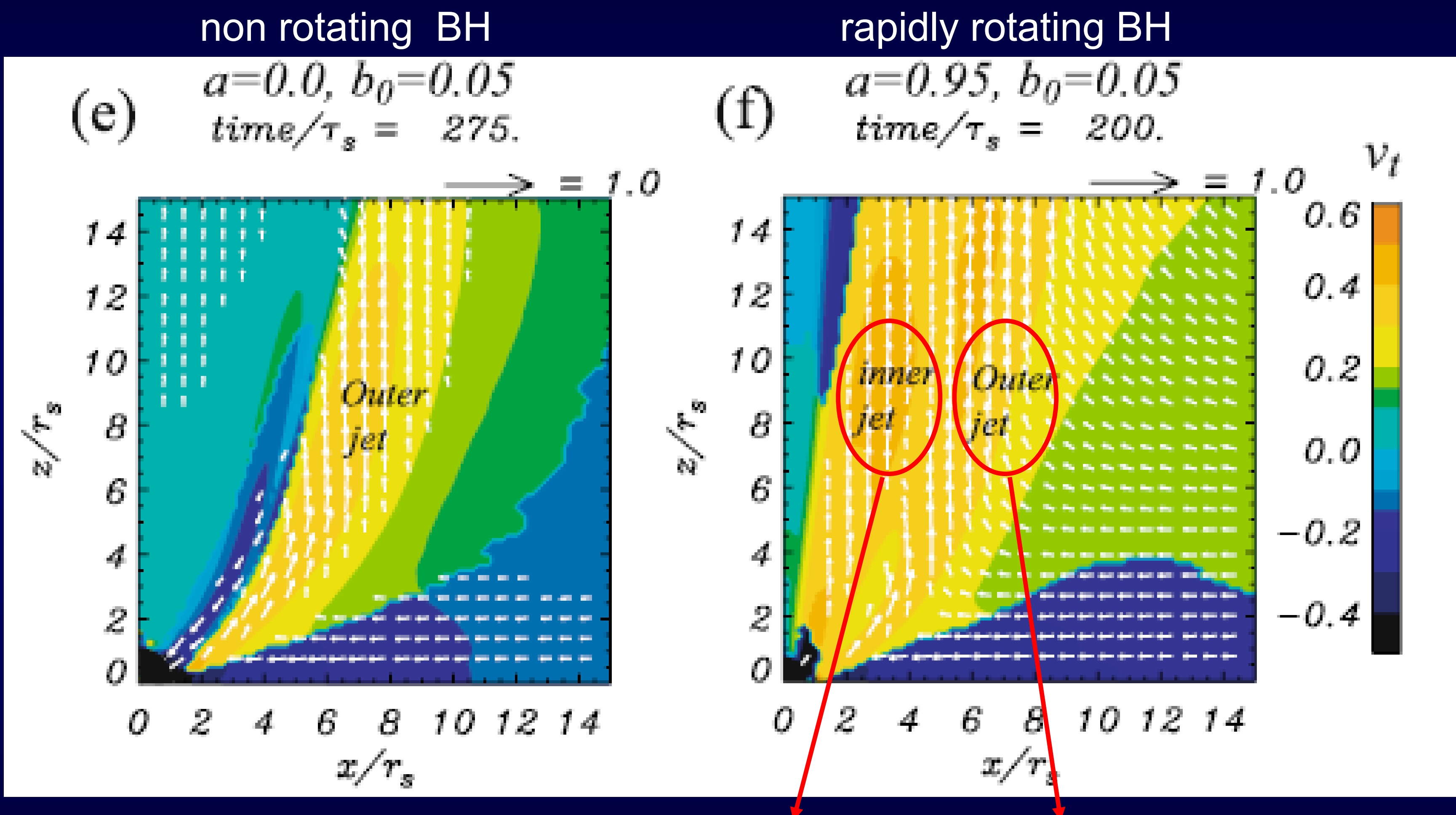
stratified (MHD) jet with moving hot spots/shocks or filamentary patterns



still unclear of what is seen at 1mm, need high quality images

Spine-sheath structure in relativistic jet simulations

total velocity plots

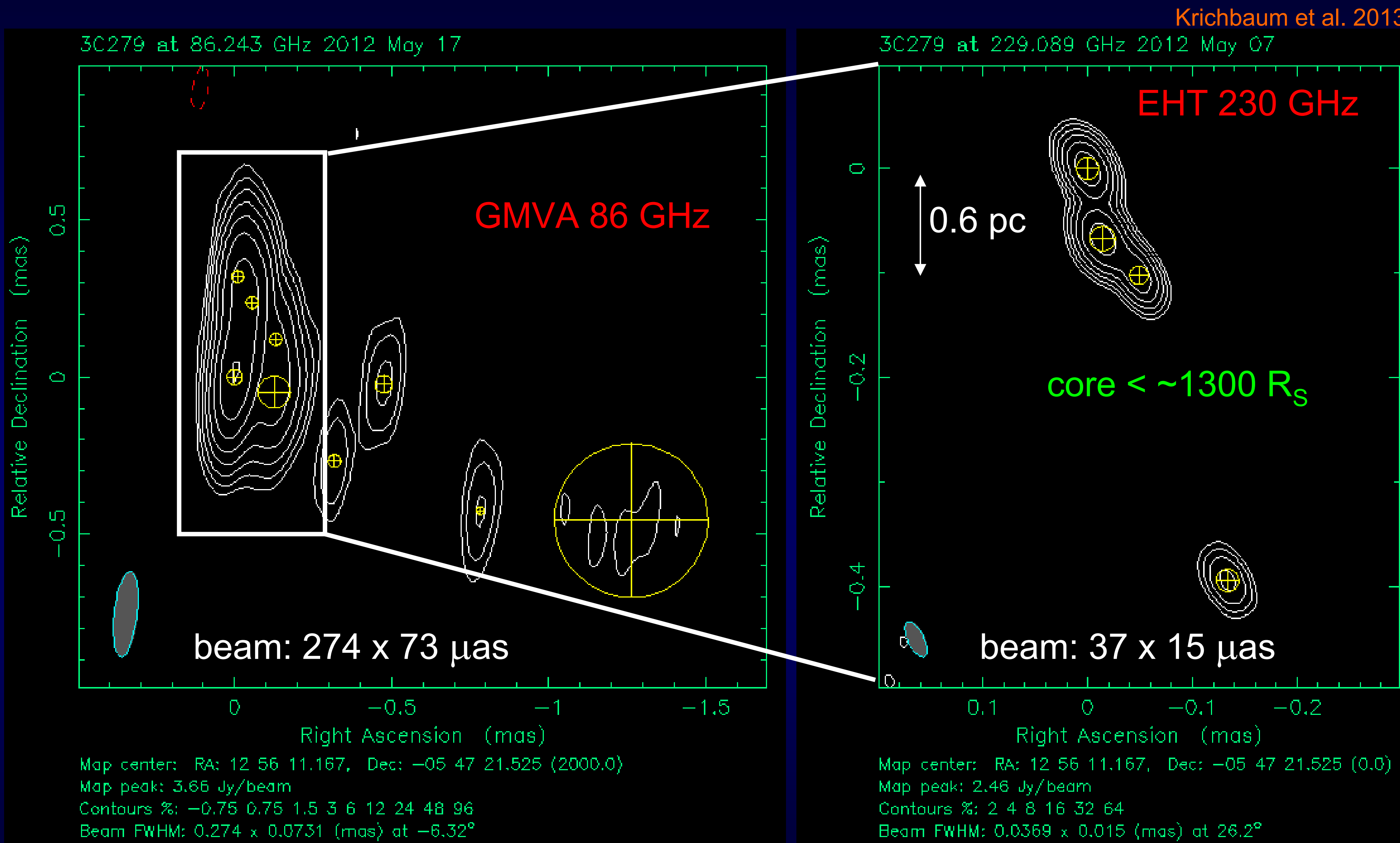


Jets from fast spinning BHs develop a slower inner and faster outer jet sheath

at v= 0.2 - 0.6 c → jet edge-brightening and stratification on ≤ ~10 R_S scales

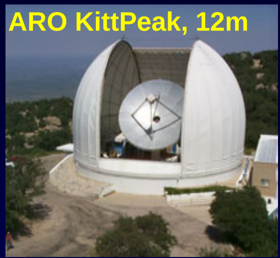
Hardee, Mizuno, Nishikawa, Ap&SS, 2007

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



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)



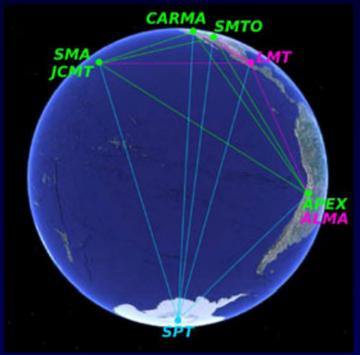
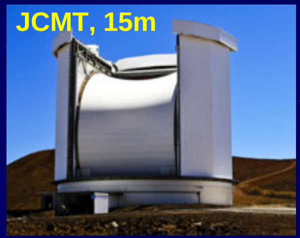
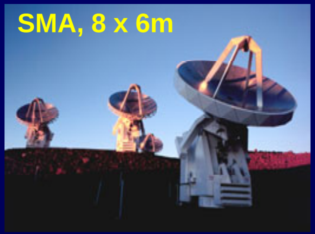
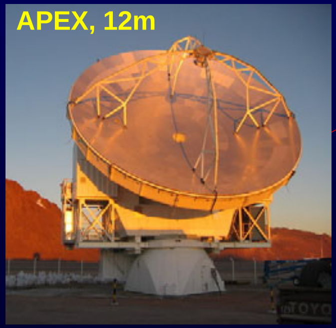
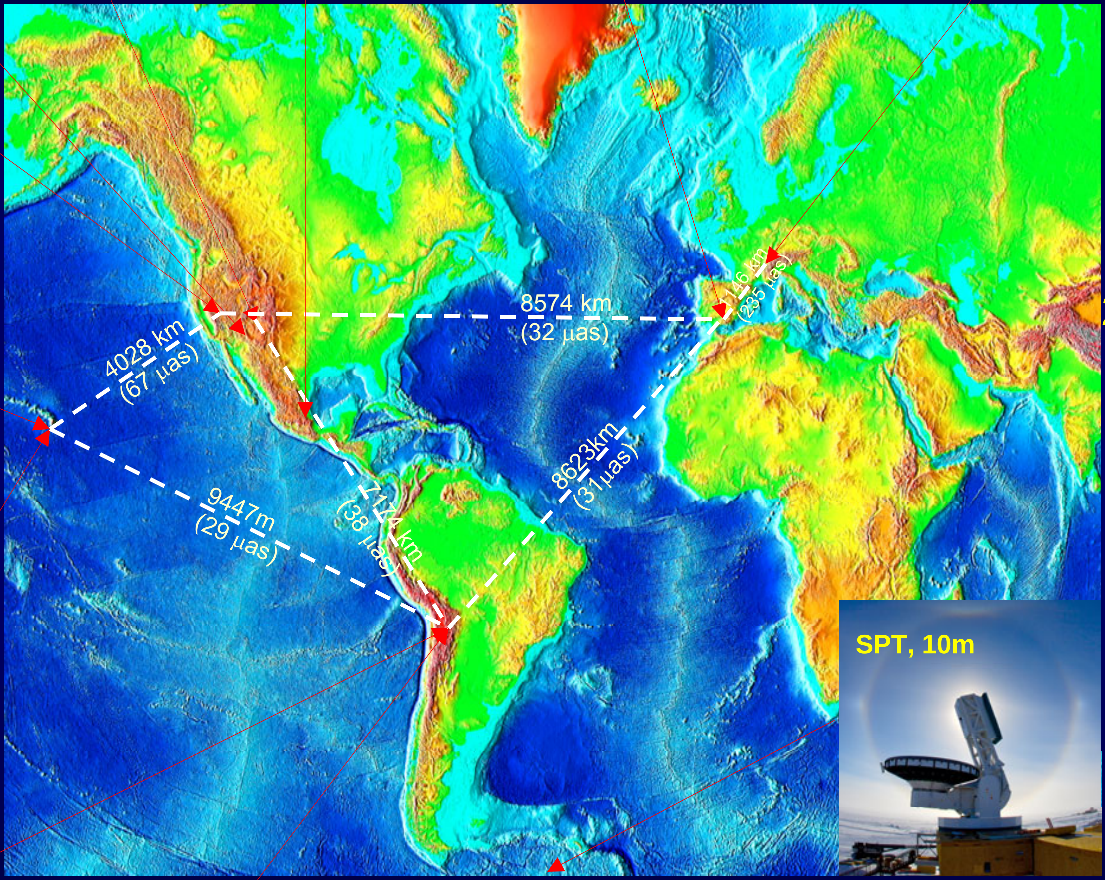


image: EHT collaboration







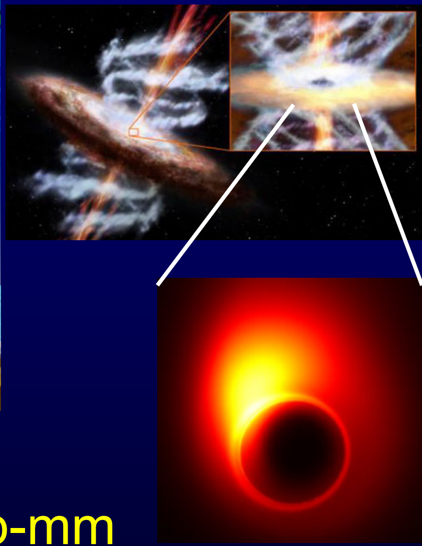


(angular resolutions calculated for 230 GHz)

<u>Angular Resolution:</u>

25-30 µas @230 GHz

15-20 µas @345 GHz



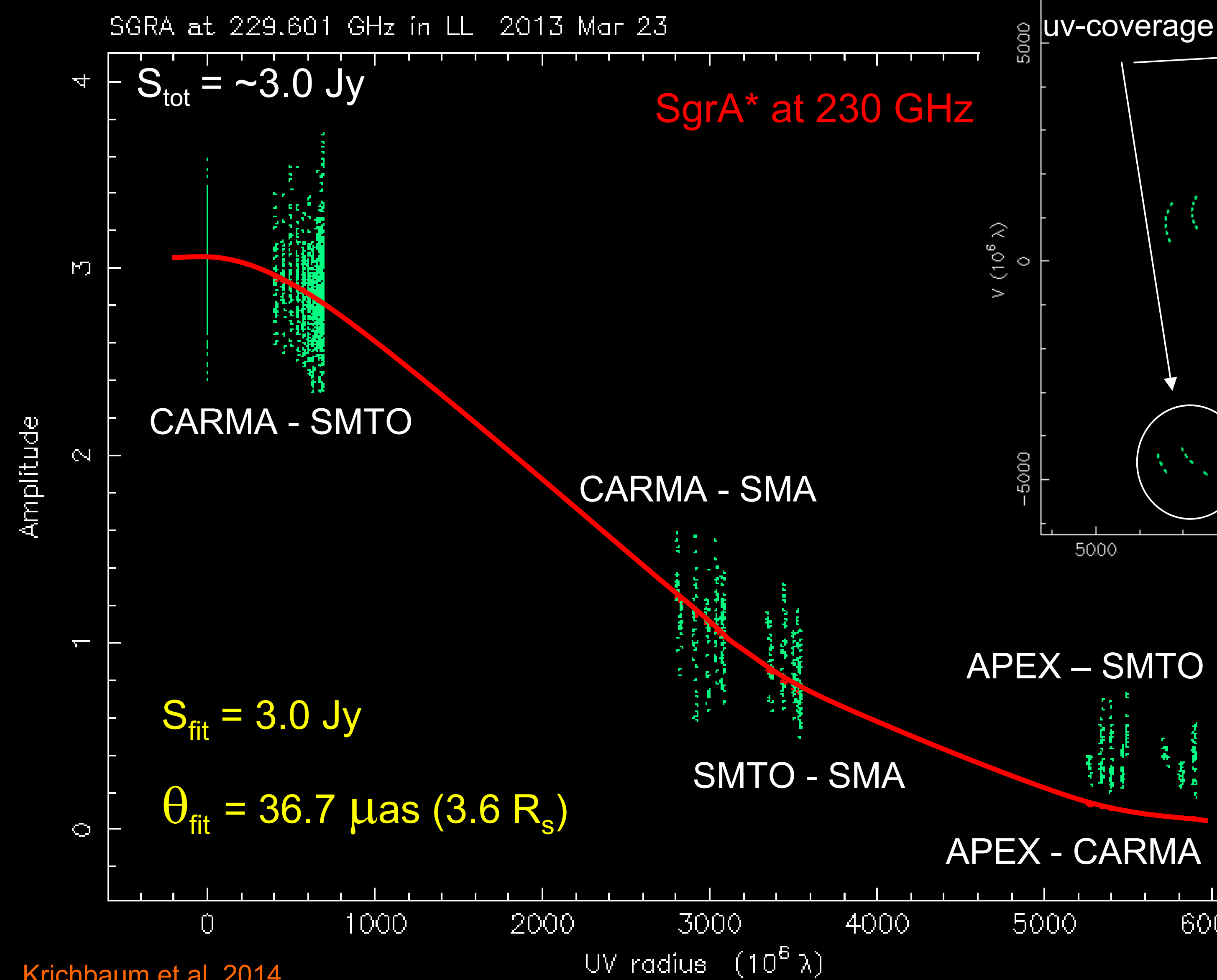
<u>Towards a global mm-/sub-mm VLBI array for BH imaging</u>

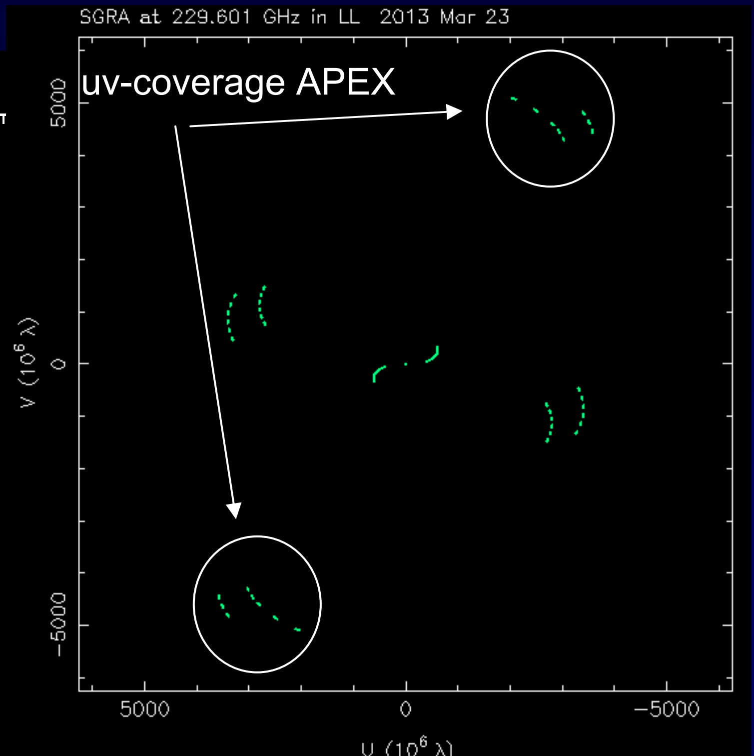
(Event Horizon Telescope)

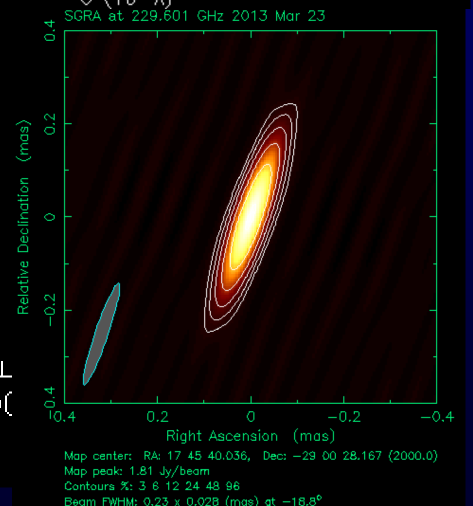
composition: tkrichbaum@mpifr

New size estimate of SgrA* at 230 GHz (March 23, 2013)

fit only US stations (uvrange 0 – 4 Gλ)

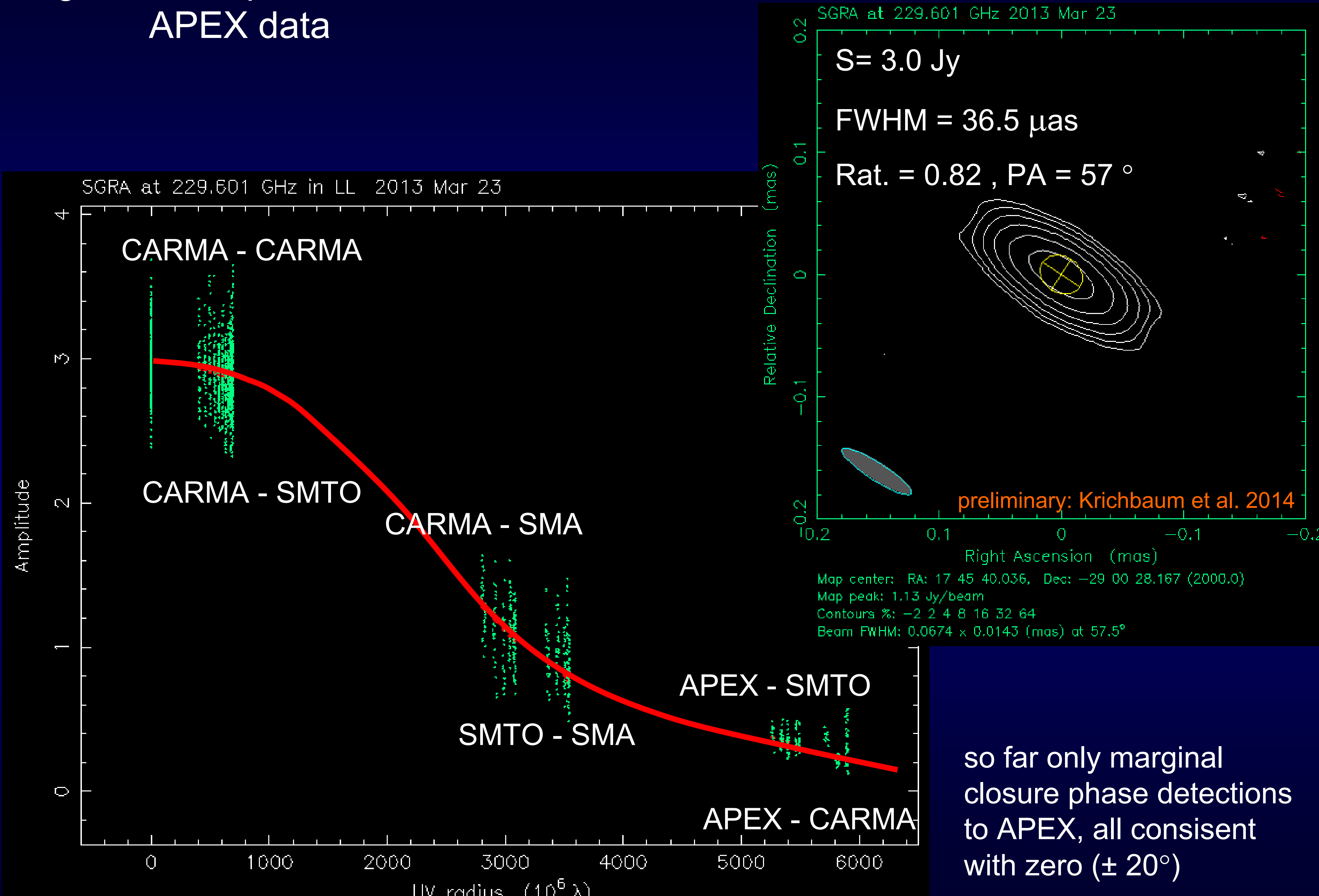






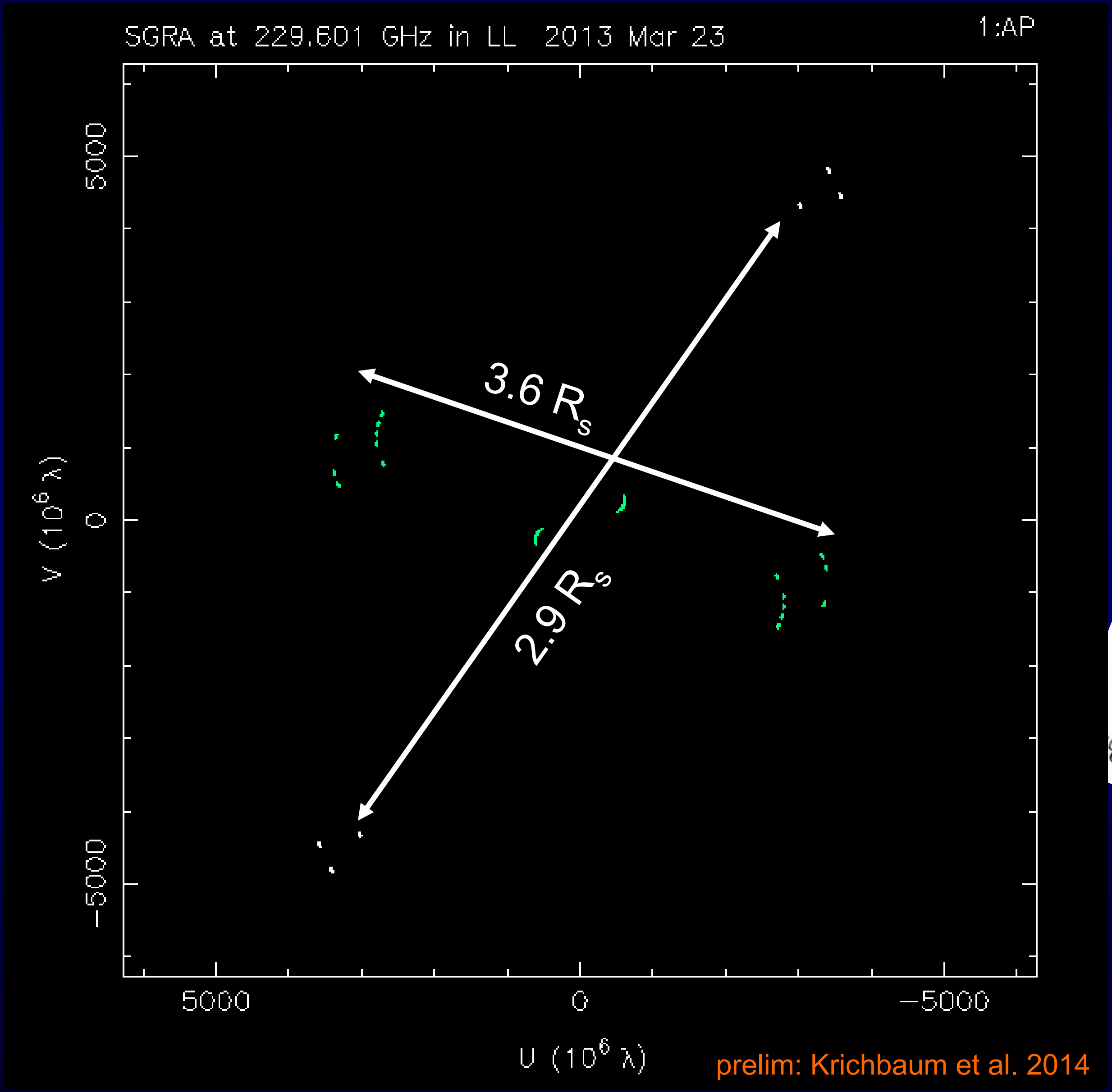
Krichbaum et al. 2014

SgrA*: an elliptical Gaussian better fits the APEX data



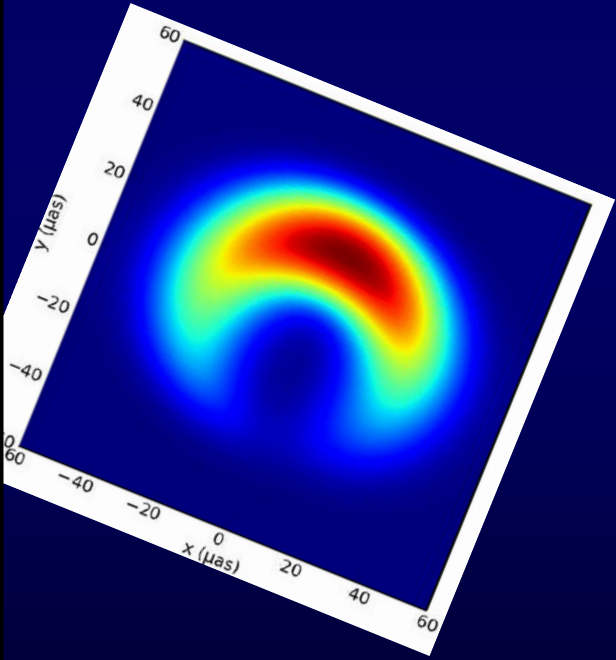
so far only marginal closure phase detections to APEX, all consisent with zero (± 20°)

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



consistent with e.g.

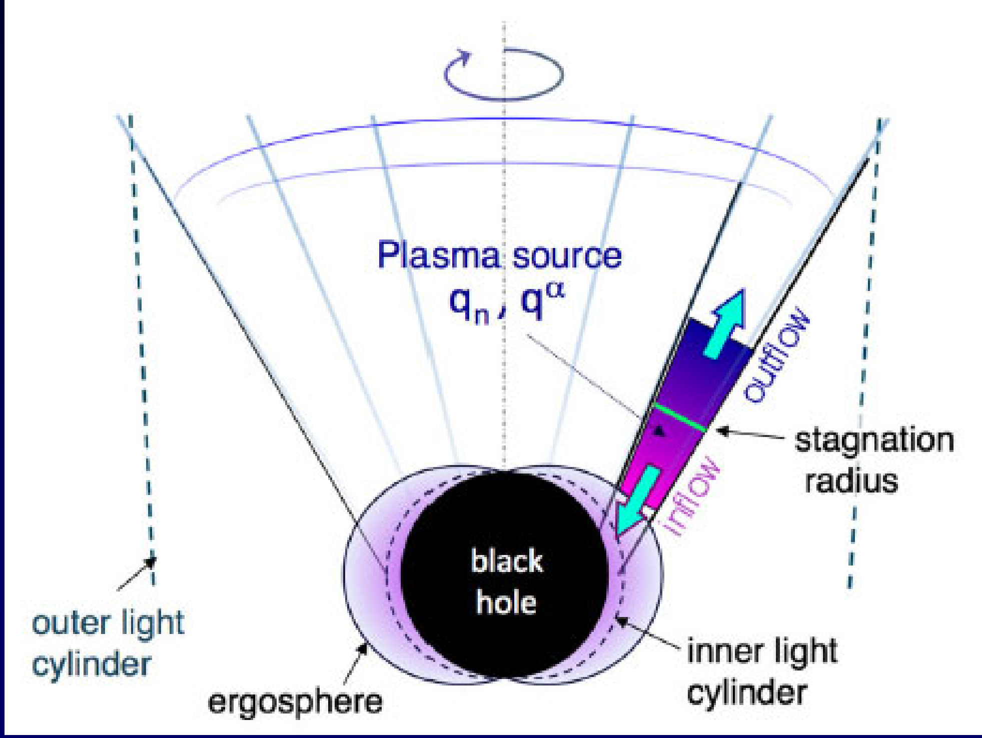
blurred crescent model of Kamruddin & Dexter (2013)



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

Concluding Technical Remarks

- 1.3 mm long baseline fringes detected (≤9500 km) for APEX+IRAM+US
- compact (15-30 μas) emission regions exist in most sources, many future VLBI targets
- APEX yields highest SNR to CARMA, the latter being the most sensitive northern station of the present 1mm VLB-array
- most sources are largely resolved, correlated flux decreases rapidly with uv-distance, compactness on longest baselines often is < 20%
- short and intermediate length uv-spacings are critical to recover all of the emission
- need < 10% calibration accuracy to discriminate between ambiguous models
- the combination of APEX/LLAMA with ALMA will provide the important very short uv-spacings, but only for southern sources