Title: New Results from Global Millimeter VLBI observations - How small an AGN can be ?

Date: Nov 11, 2014 02:30 PM

URL: http://pirsa.org/14110083

Abstract: VLBI observations at the highest possible frequency penetrate the opacity barrier in the nuclear regions of radio-galaxies and blazars, which are synchrotron self-absorbed at longer wavelength. This facilitates a direct and sharper than ever view into the 'heart' of Active Galactic Nuclei (AGN), into region in which BH physics and general relativity effects become important and where radio jets are launched. Here we report on new results from global 3mm and 1.3mm VLBI observations adding the APEX and IRAM to the Event Horizon Telescope. New images and core size estimates for a number of AGN jets and for Sgr A* are presented and discussed.

New results from Global Millimeter VLBI – How small an AGN can be ?

T.P.Krichbaum et al, with:

(+EHT team, +GMVA team

+A. Marscher's group)

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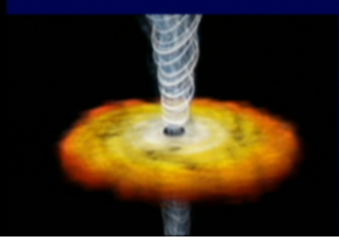
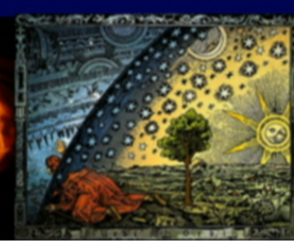
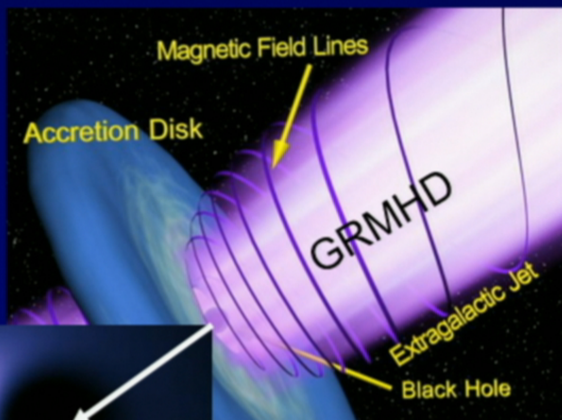




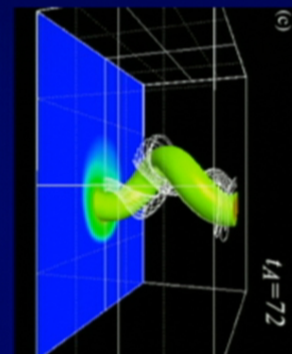
Scientific Motivation:

What is the physical origin of an AGN? How do BHs launch jets, how are jets accelerated and collimated. Measure fundamental physical processes near BHs, test GR and the metric, discriminate between various jet launching models.

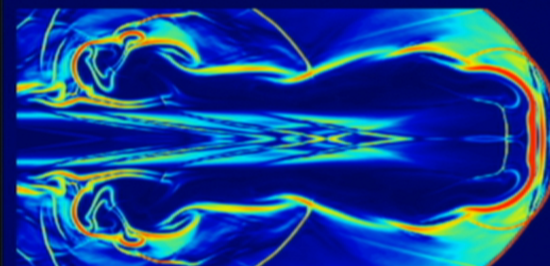


Jet energy extraction from accretion disk and/or spin of Black Hole, role of B-field?

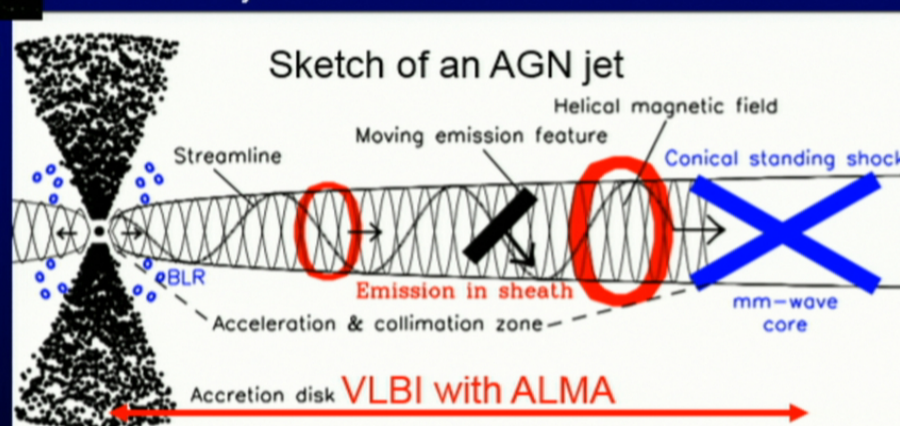
Relativistic aberration around rotating BH



Rotation & instabilities cause helical jets



instabilities and shocks propagating along jet (mpc → Kpc)



study BH physics and GRMHD

via combined mm- and submm-VLBI

The size of a synchrotron self-absorbed emission region

size:

$$\theta_{\min} \geq \sqrt{\frac{1.22 \cdot S}{\nu^2} \cdot \frac{1}{T_B^{\max}}}$$

T_B = brightness temperature

IC limit:

$$\text{for } \mathrm{T}_B^{\max} \leq 10^{12}\,\mathrm{K} \cdot \delta$$

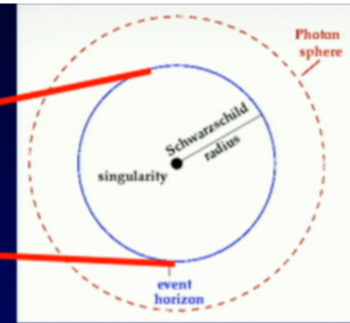
$$\rightarrow \theta_{\min} \geq 10 - 20\,\mu as \cdot \delta^{-0.5}$$

The size of the emission region is one of the primary physical parameters in radiation transport. Accurate size measurements are therefore important for the determination of energy budget (between particles & fields), for the particle composition, and in the relativistic jet model for jet geometry, speed, etc...

The apparent size of a BH

Observable size:

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

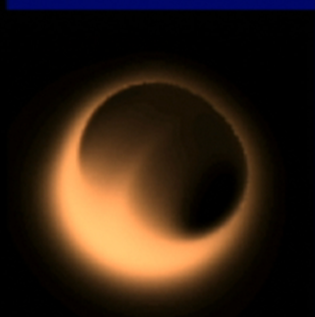


BH radius:

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

in convenient units:

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



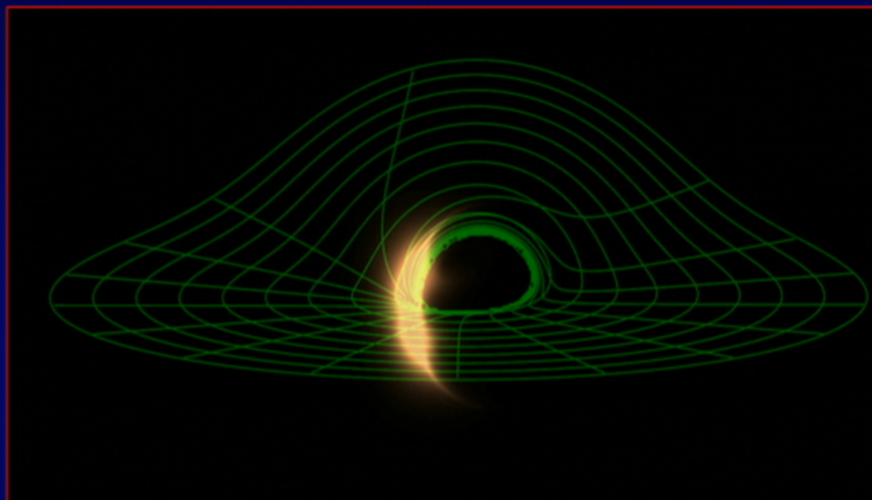
	Spin	R/R_s	R/R_g	α	$\theta_0[\mu as]$
Last stable orbit	a=0	3.0	6	6	59
Last stable orbit	a=1	0.5	1	1	10
Photon ring	a=0	1.5	3	3	30
Photon ring	$a > 0$	5.2	10.4	10.4	103

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 ~4-5 µas for SgrA* and M87.

Interpretation of the 1mm VLBI size measurement

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



Broderick & Loeb 2008

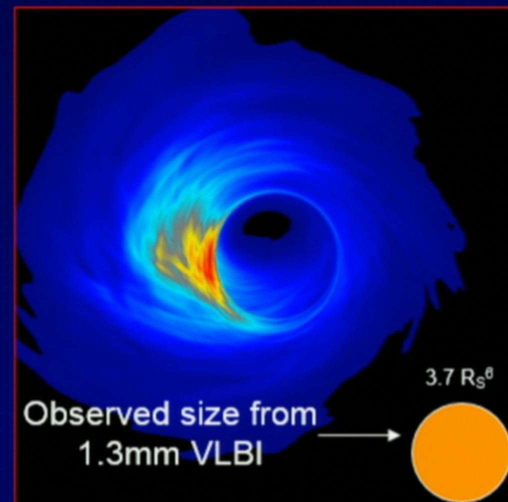


image credit: Noble & Gammie

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

observed size: 43 (+14/-8) μas

deconvolved : 37 μas

intrinsic : 3.7 R_S

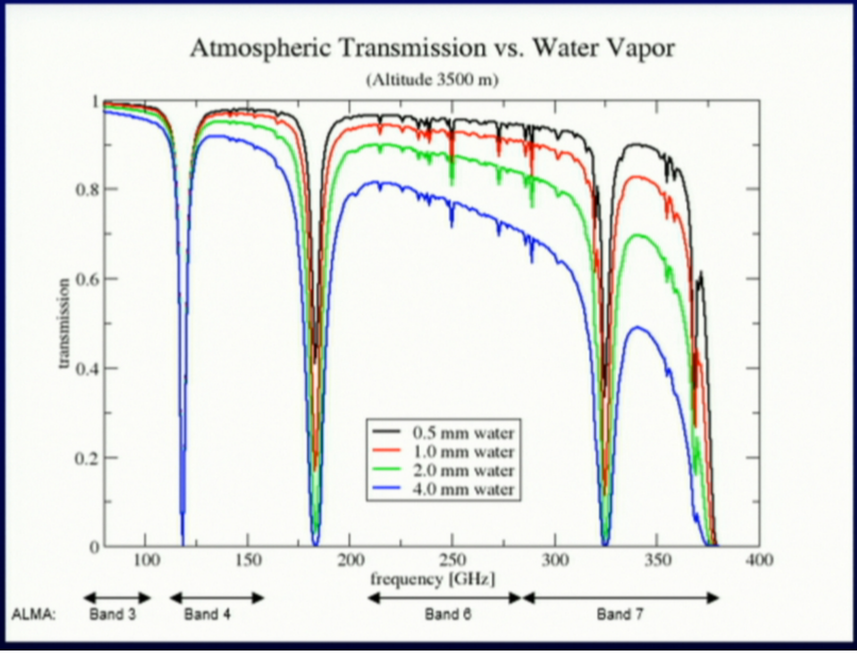
$$M_6 = \frac{0.1}{\alpha}\,\theta_{\mu\mathrm{as}}\,D_{\mathrm{Kpc}}$$

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

→ emission from hot spot/MRI or abberation crescent → physics or geometry ?

Existing VLBI arrays observing at mm-wavelength

• 9mm (32 GHz): DSN+EB+Geo-VLBI telescopes	adhoc
• 7mm (43 GHz): HSA, VLBA, EVN, KVN+VERA	regular
• 3mm (86 GHz): GMVA, VLBA	regular
• 2mm (129/150 GHz): IRAM+SMTO+Metsahovi	fringes in early 2000
• 1mm (230 GHz): IRAM+APEX+SMTO+CARMA+SMA/JCMT	once per 1-2 years



The Global Millimeter VLBI Array (GMVA)

HDR imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

10 – 75 mJy

in US:

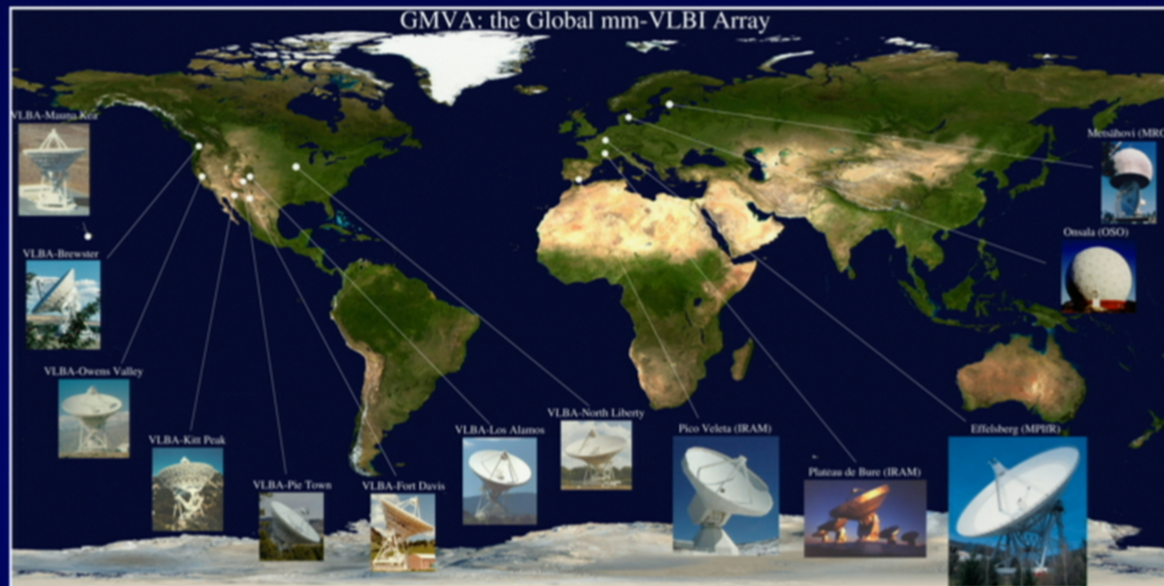
25 – 75 mJy

transatlantic:

10 – 75 mJy

Array:

0.3 – 1 mJy / hr



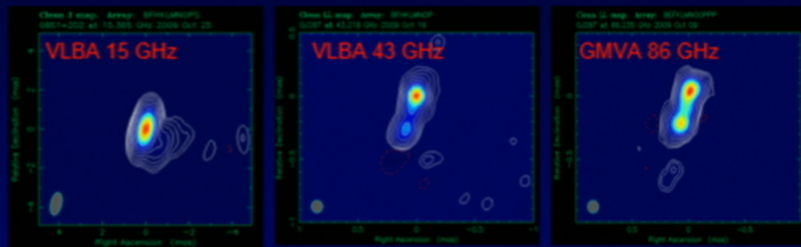
(assume 7σ, 100sec, 2 Gbps)

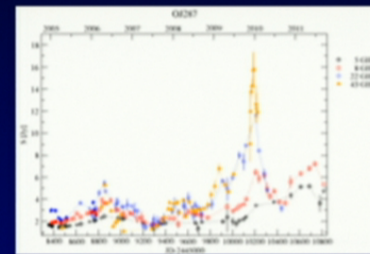
http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm

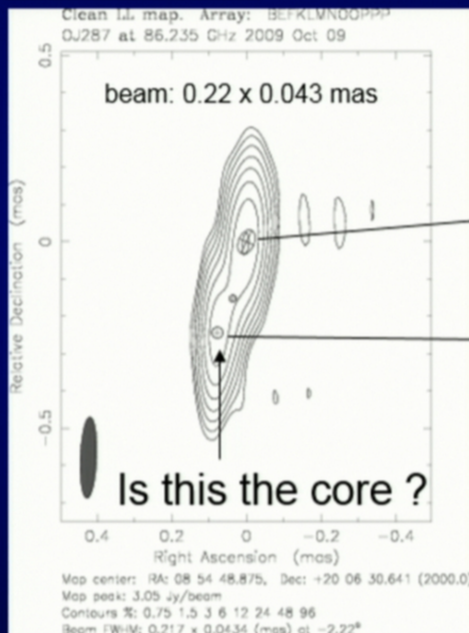
up to 18 stations:

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), Yebes (40m), 3x KVN, planned: SRT, ALMA, ...
- USA: 8 x VLBA (25m), GBT (100m), planned: LMT (50m)

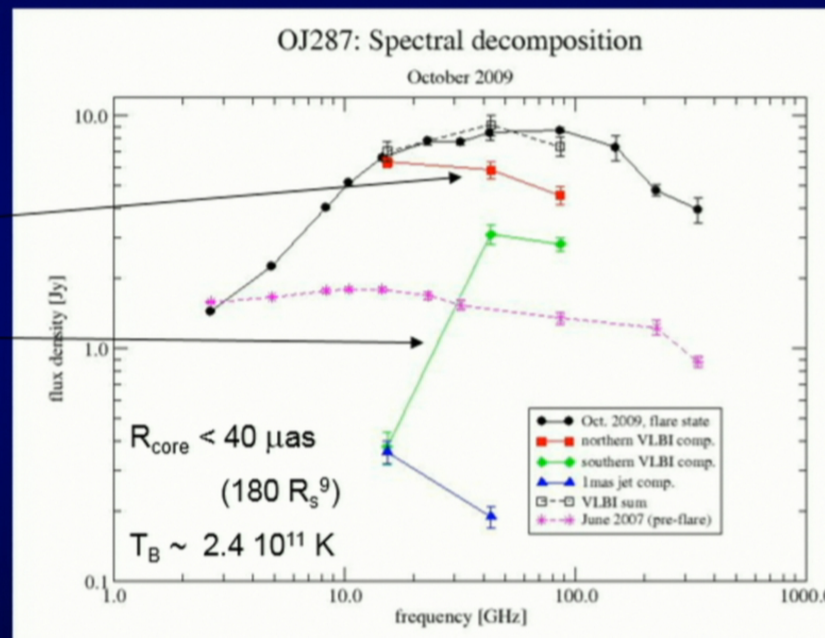
OJ 287: Spectral decomposition using multi-λ mm-VLBI







modelfit: 0.21 x 0.043 mas beam

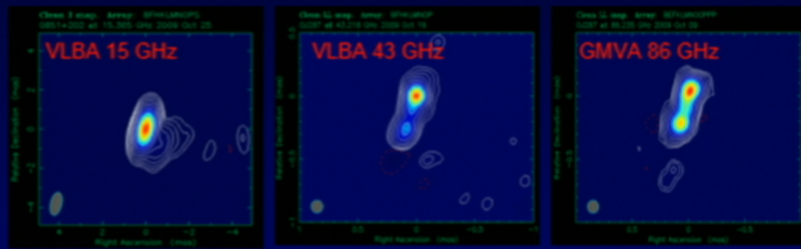


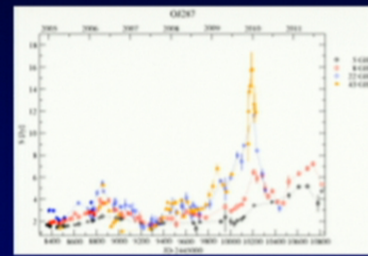
total spectrum from FGAMMA monitoring program (radio to gamma-rays)

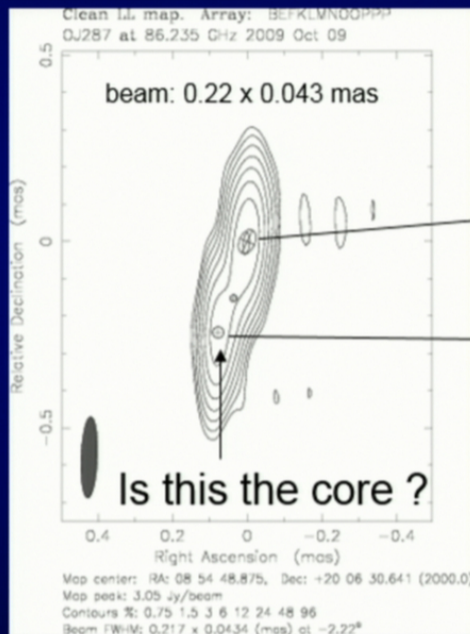
VLBI component spectra from VLBI at 15 + 43 + 86 GHz, need to add 230 GHz

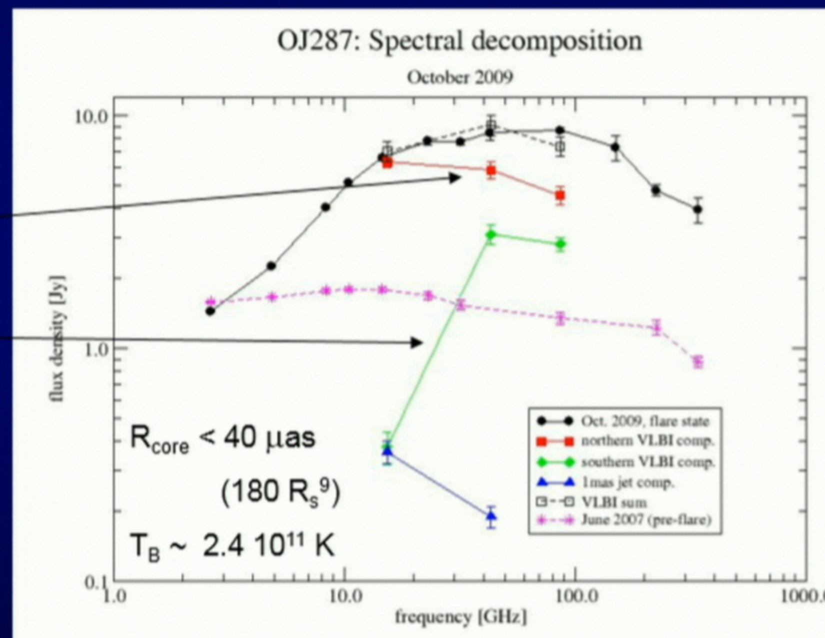
OJ 287: Spectral decomposition using multi-λ mm-VLBI

F-GAMMA
G
M
V
A









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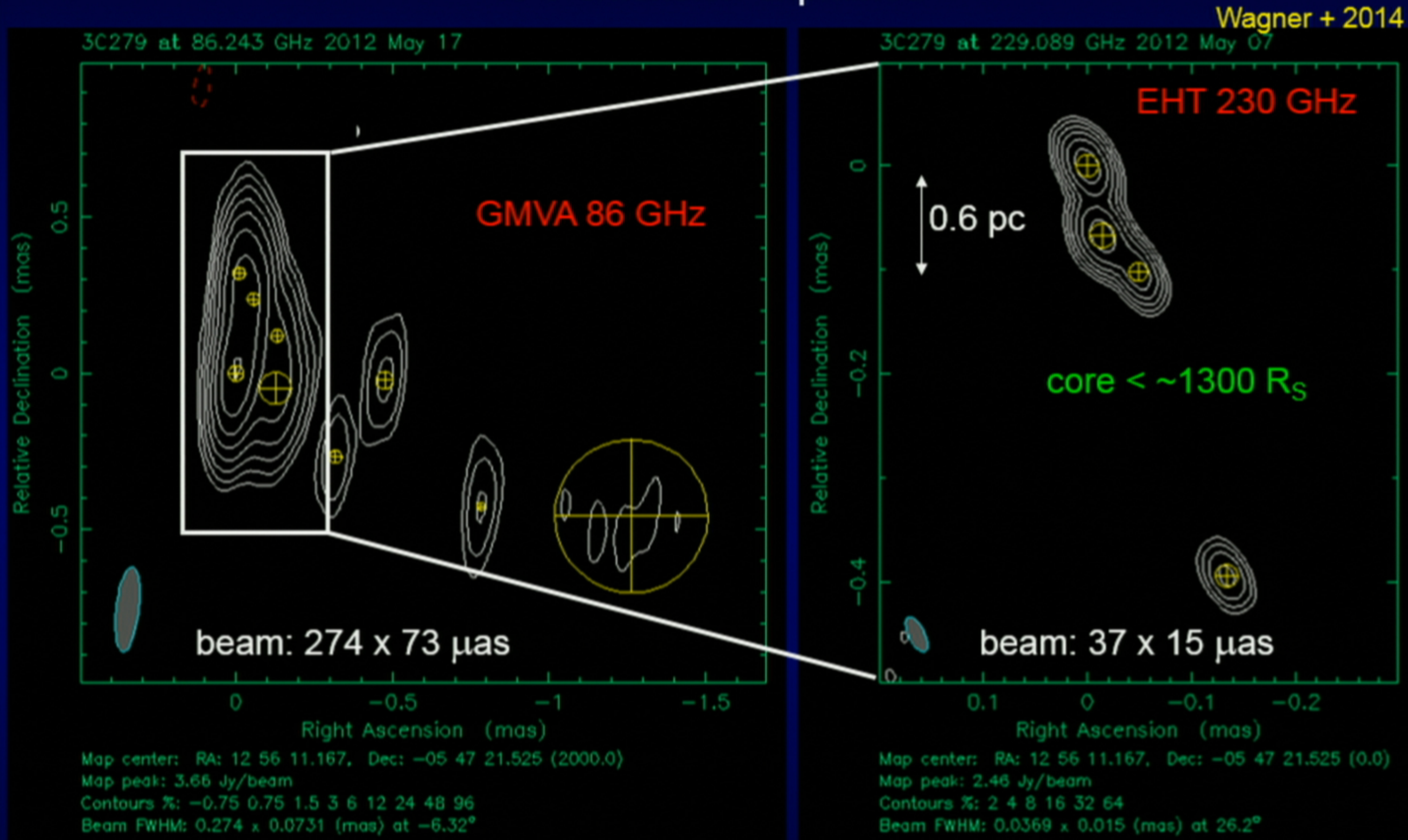
total spectrum from FGAMMA monitoring program (radio to gamma-rays)

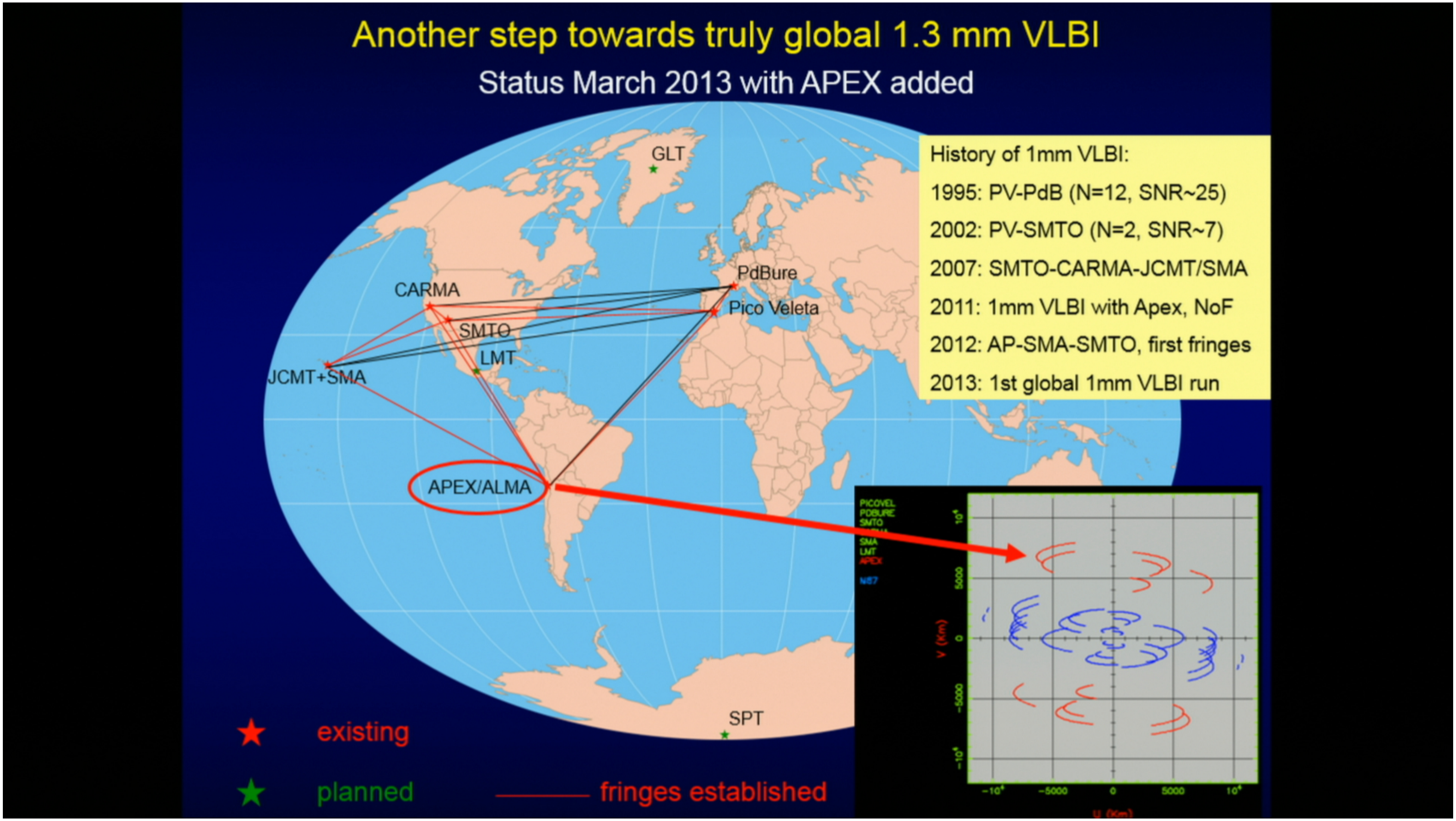
VLBI component spectra from VLBI at 15 + 43 + 86 GHz, need to add 230 GHz

Synergy: 3C279 1mm APEX detections interpreted using 3mm GMVA map – N-S extension explained

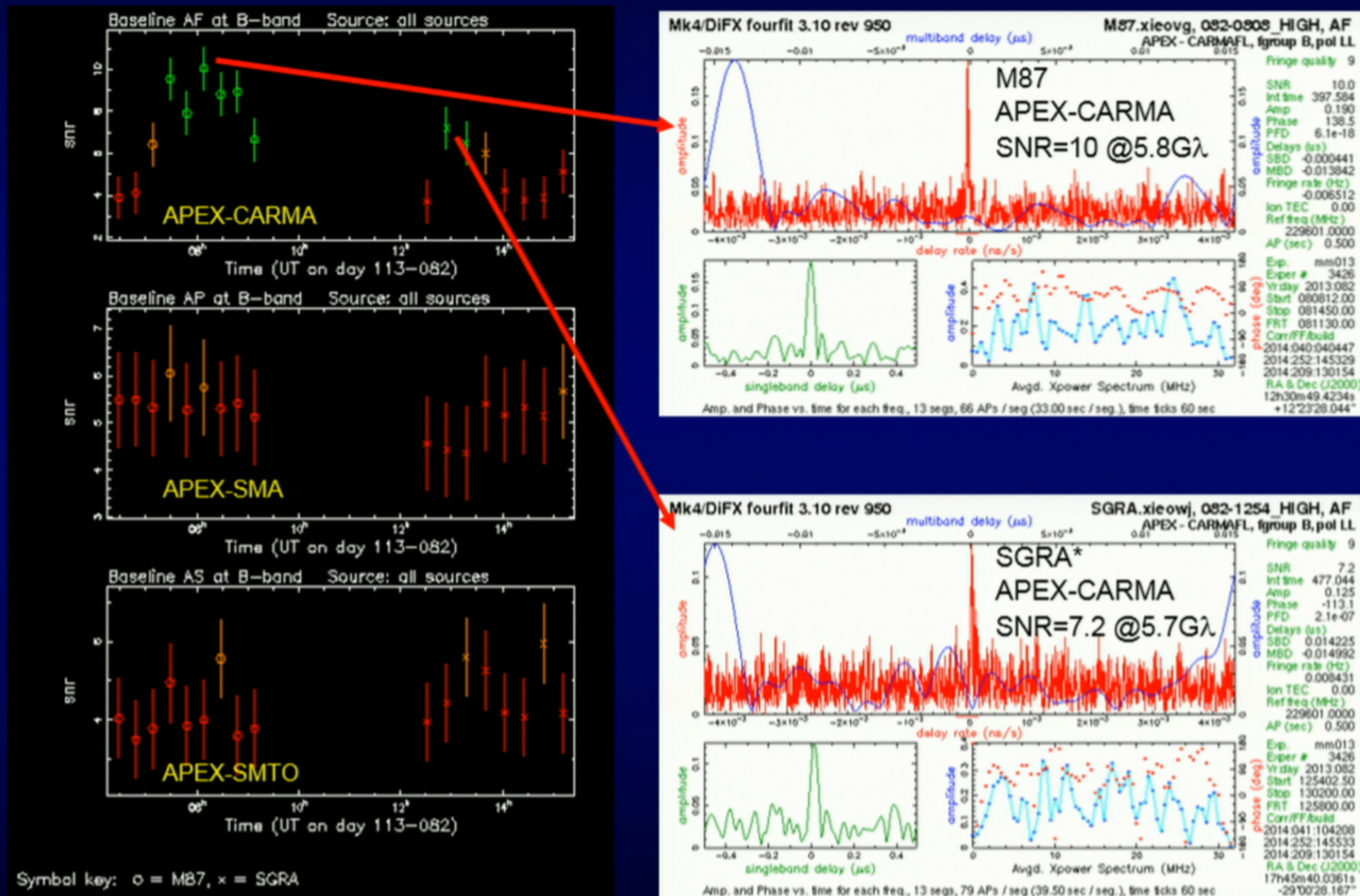


base of jet is transversely resolved and has a width of ~1 pc (~10^4 R_S)

size of individual components (emission regions) < 0.1 pc (1000 R_S)


Another step towards truly global 1.3 mm VLBI
Status March 2013 with APEX added
GLT
PdBure
Pico Veleta
CARMA
SMTO
LMT
JCMT+SMA
APEX/ALMA
SPT
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

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



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

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230 GHz, March 21-27, 2013

Source	Flux [Jy]	AP-CA AF	AP-SMA AP	AP-SMT AS	CA-SMA FP	CA-SMT FS	SMT-SMA SP	CA-PV FV	AP-PV AV	PV-SMT VS	PV-SMA VP
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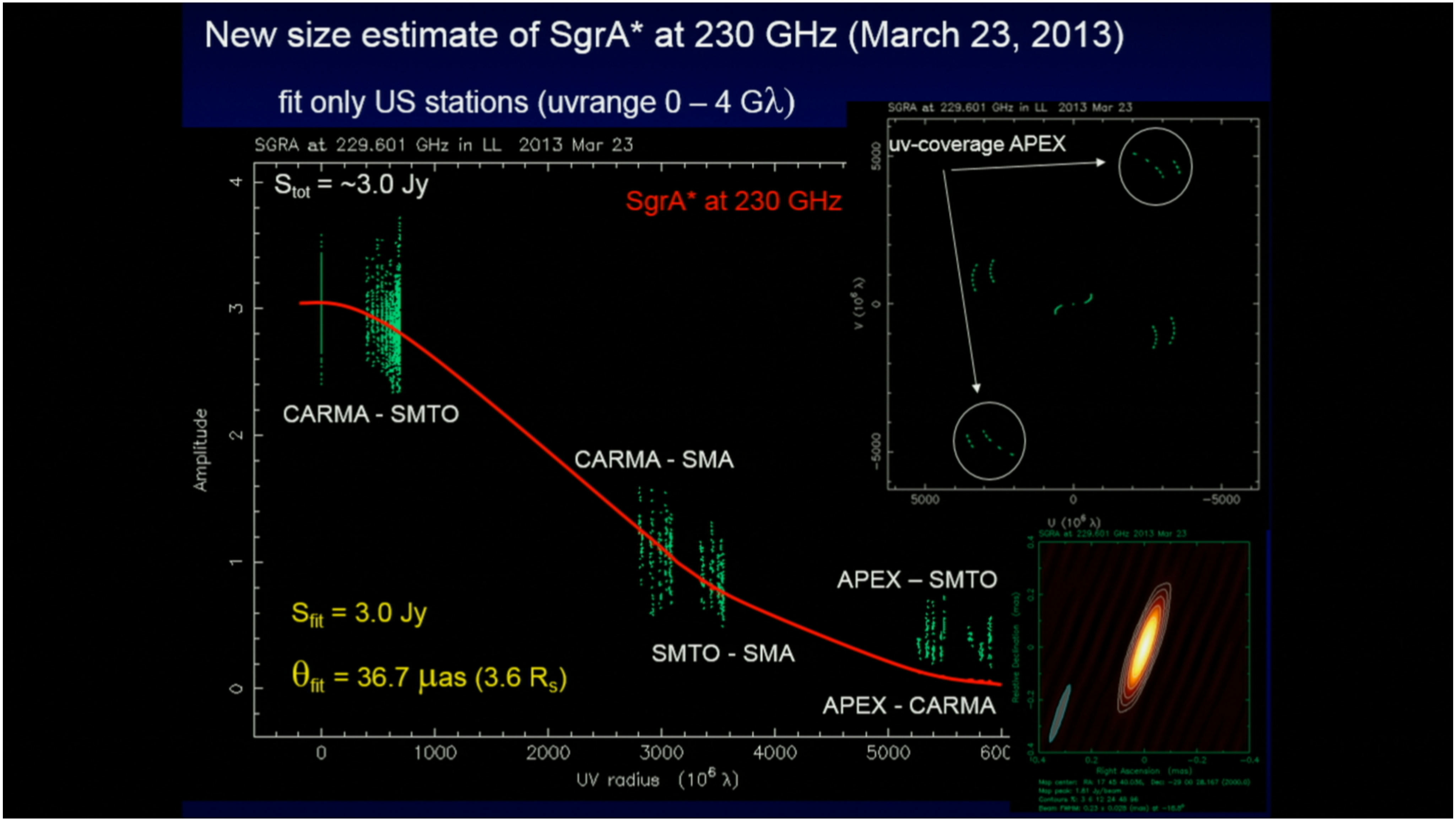
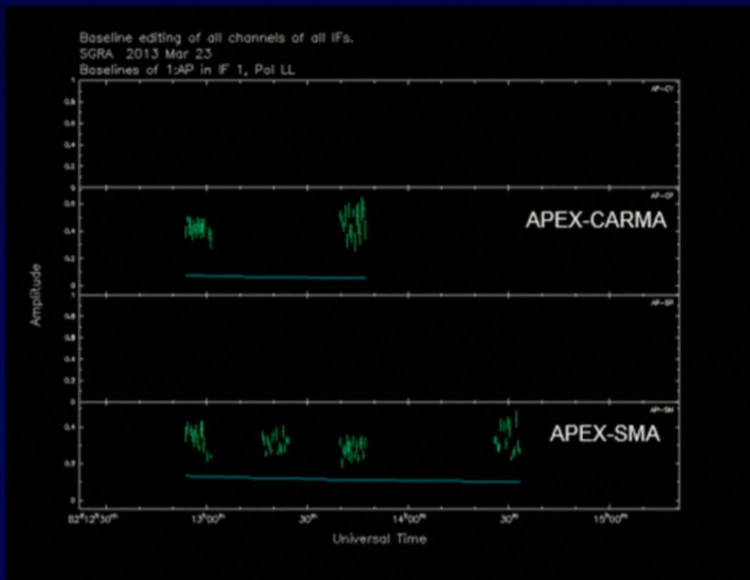
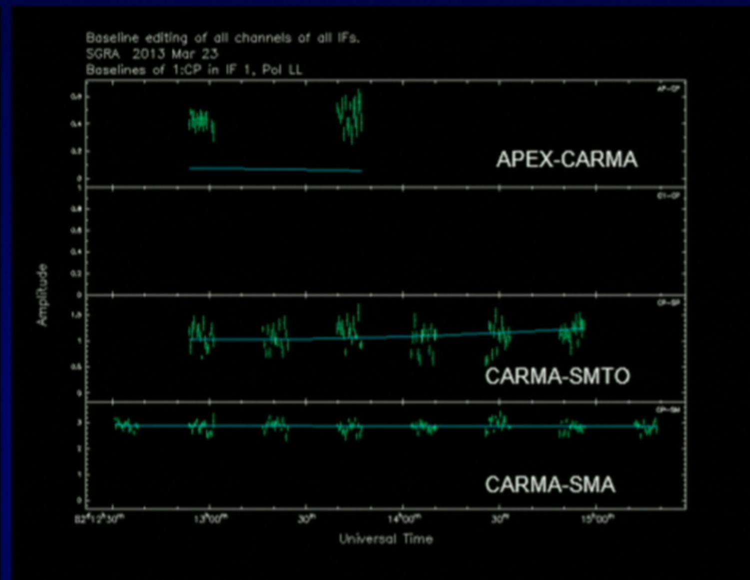

New size estimate of SgrA* at 230 GHz (March 23, 2013)
fit only US stations (uvrange 0 – 4 Gλ)
SGRA at 229.601 GHz in LL 2013 Mar 23
S_tot = ~3.0 Jy
SgrA* at 230 GHz
CARMA - SMTO
CARMA - SMA
SMTO - SMA
APEX – SMTO
APEX - CARMA
S_fit = 3.0 Jy
θ_fit = 36.7 μas (3.6 R_S)
Amplitude
UV radius (10^6 λ)
uv-coverage APEX
V (10^6 λ)
U (10^6 λ)

The correlated flux of SgrA* on APEX baselines

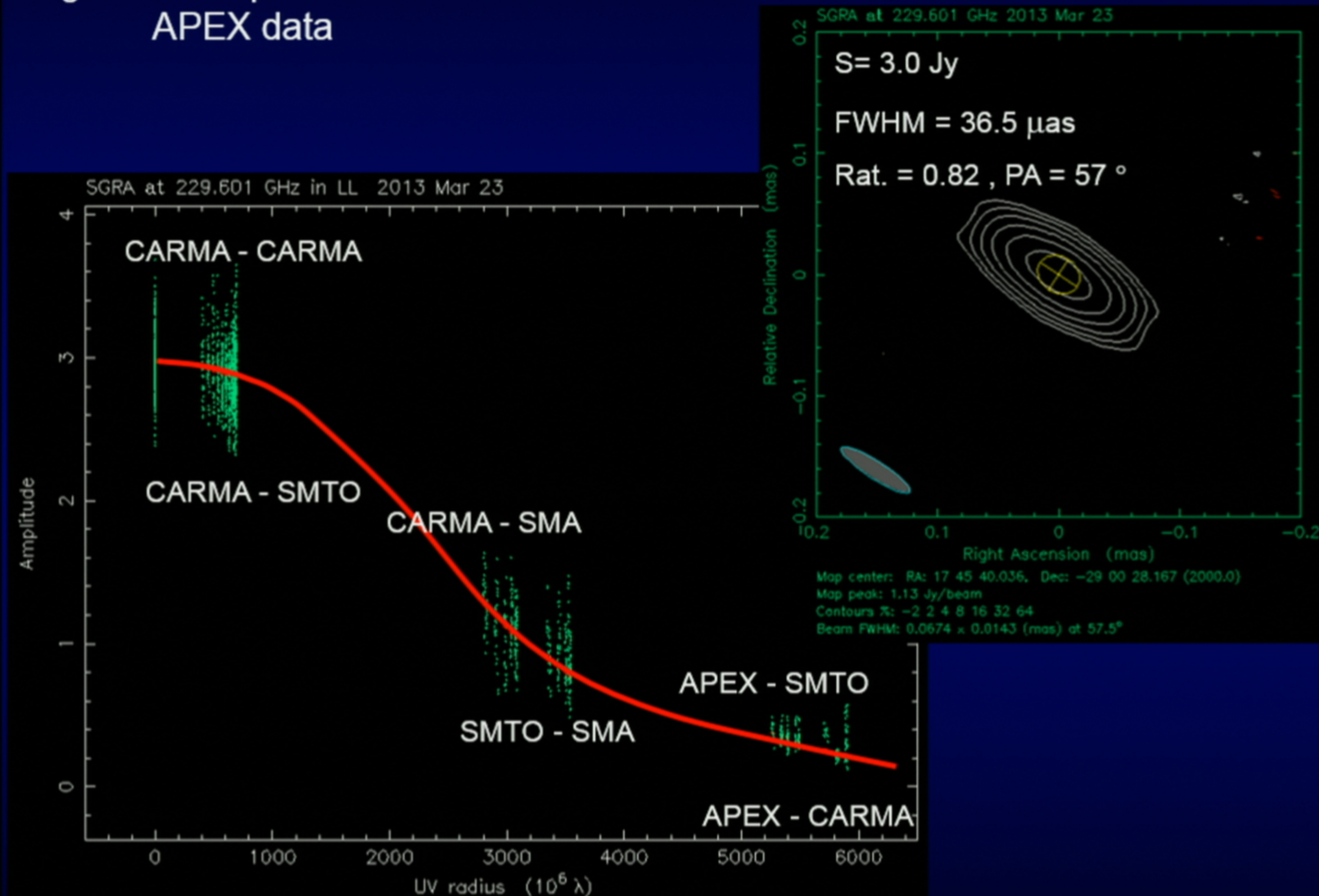




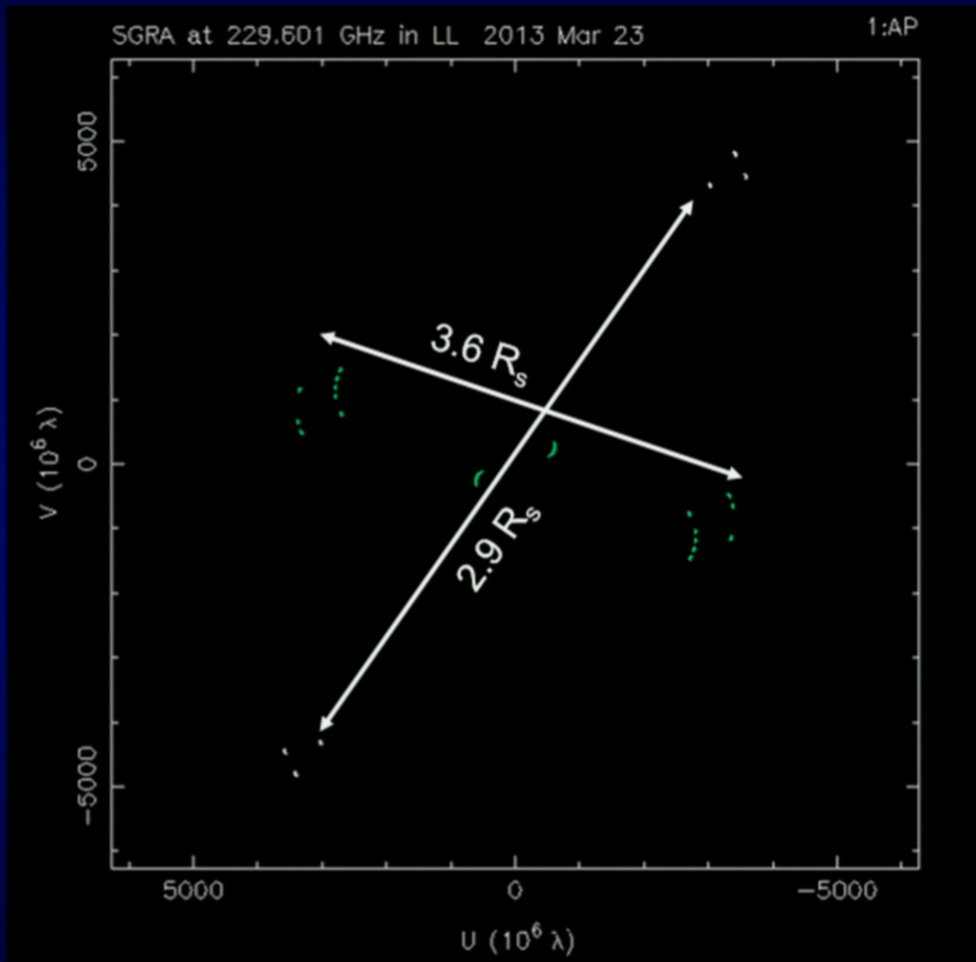
The correlated flux measured on APEX baselines is about a factor of 2-4 higher than expected for a circular Gaussian source of 37 μas FWHM.

The APEX SEFD can be larger, but not smaller → smaller size unavoidable

SgrA*: an elliptical Gaussian better fits the APEX data

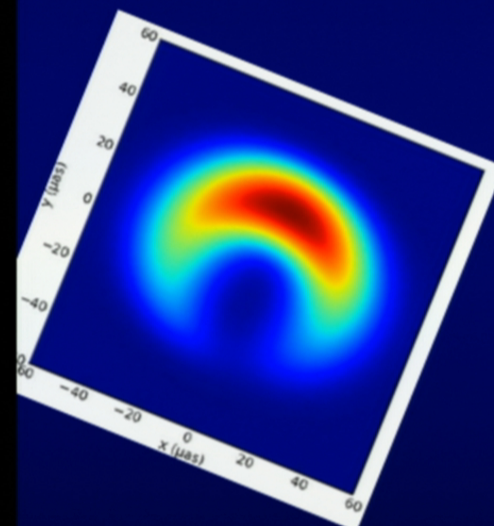


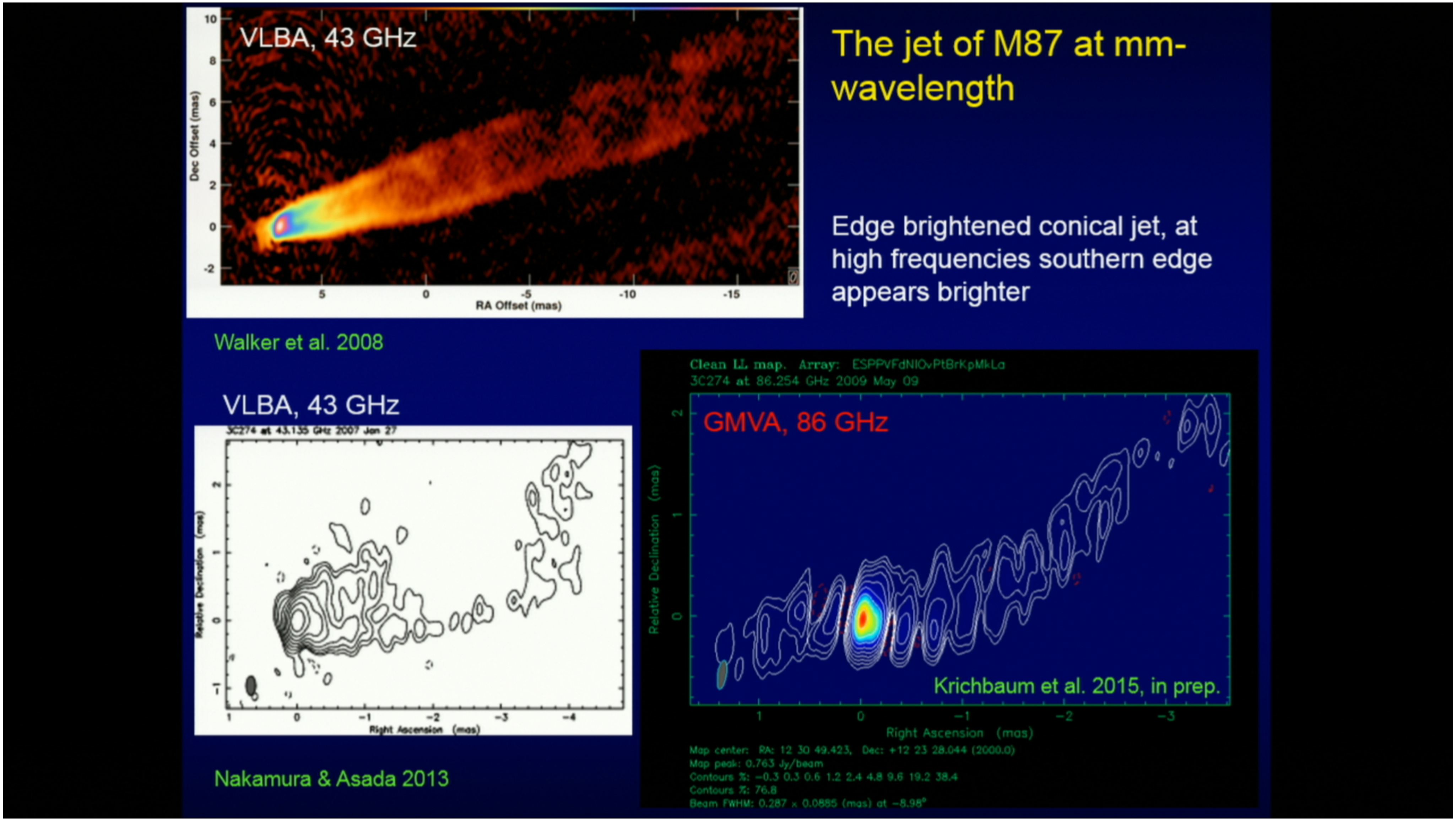
The compact emission region in SgrA* is not circular, but at least elliptical

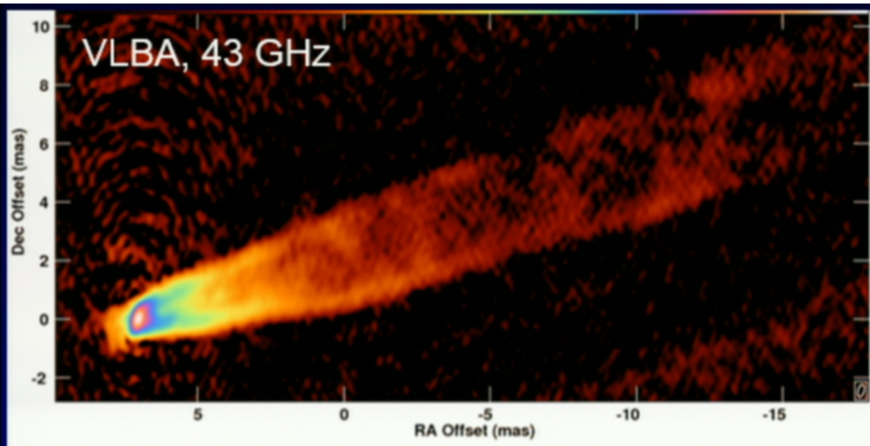


consistent with e.g.

blurred crescent model of Kamruddin & Dexter (2013)




The jet of M87 at mm-wavelength
Edge brightened conical jet, at high frequencies southern edge appears brighter
VLBA, 43 GHz
Dec Offset (mas)
RA Offset (mas)
Walker et al. 2008
VLBA, 43 GHz
3C274 at 43.135 GHz 2007 Jan 27
Relative Declination (mas)
Right Ascension (mas)
Nakamura & Asada 2013
Clean LL map. Array: ESPPVFdNlOvPtBrKpMkLa
3C274 at 86.254 GHz 2009 May 09
GMVA, 86 GHz
Relative Declination (mas)
Right Ascension (mas)
Krichbaum et al. 2015, in prep.
Map center: RA: 12 30 49.423, Dec: +12 23 28.044 (2000.0)
Map peak: 0.763 Jy/beam
Contours %: -0.3 0.3 0.6 1.2 2.4 4.8 9.6 19.2 38.4
Contours %: 76.8
Beam FWHM: 0.287 x 0.0885 (mas) at -8.98°

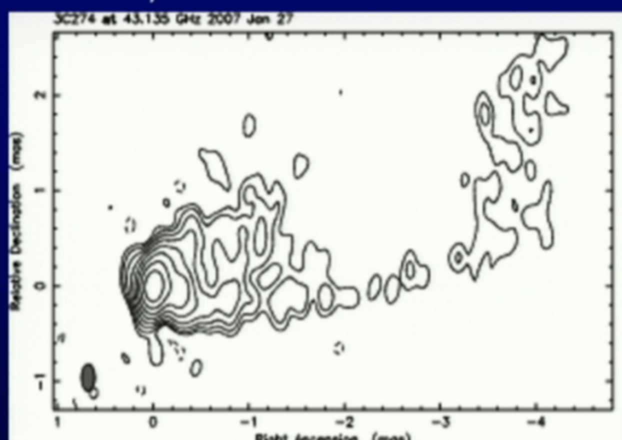


Walker et al. 2008

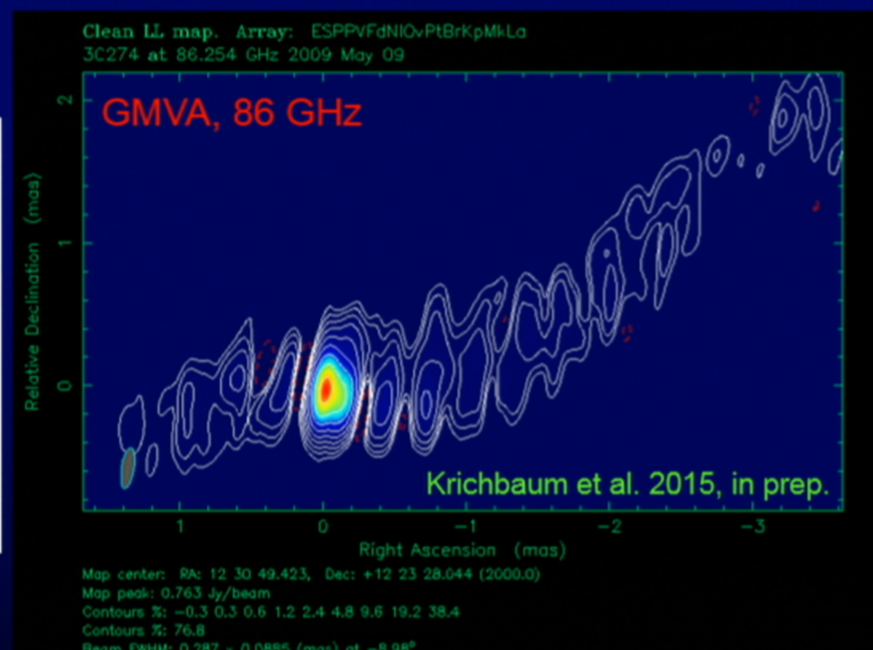
The jet of M87 at mm-wavelength

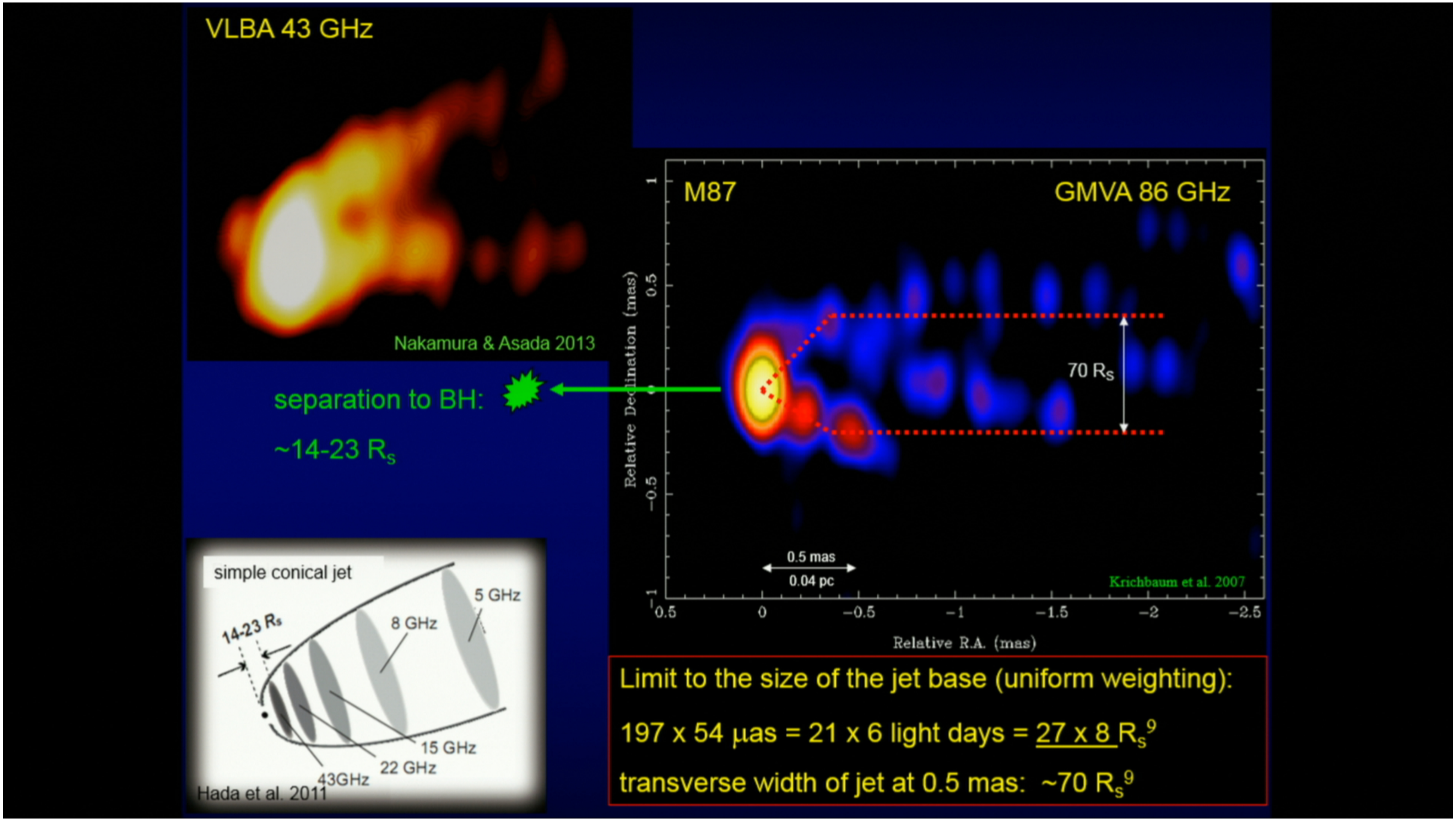
Edge brightened conical jet, at high frequencies southern edge appears brighter

VLBA, 43 GHz



Nakamura & Asada 2013



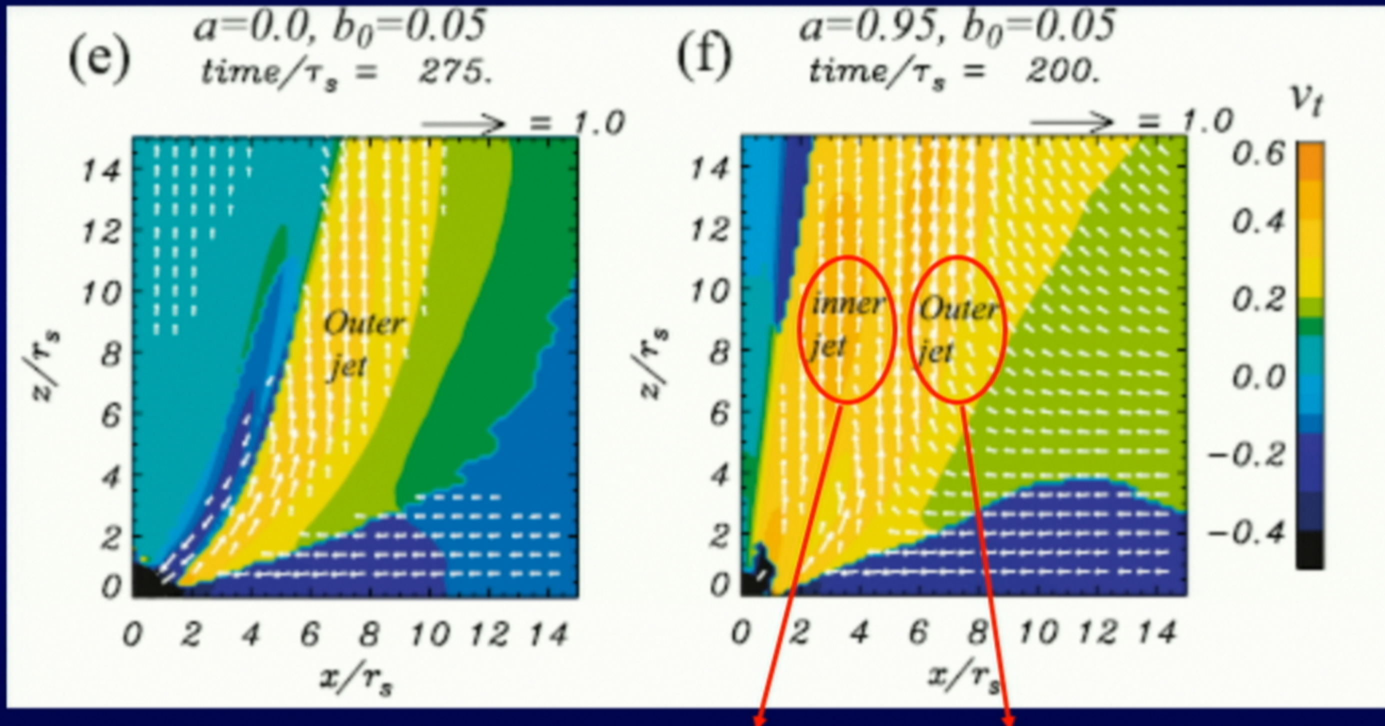

VLBA 43 GHz
Nakamura & Asada 2013
separation to BH:
~14-23 R_S
simple conical jet
14-23 R_s
5 GHz
8 GHz
15 GHz
22 GHz
43GHz
Hada et al. 2011
M87
GMVA 86 GHz
70 R_S
0.5 mas
0.04 pc
Krichbaum et al. 2007
Relative Declination (mas)
Relative R.A. (mas)
Limit to the size of the jet base (uniform weighting):
197 x 54 μas = 21 x 6 light days = 27 x 8 R_S[9]
transverse width of jet at 0.5 mas: ~70 R_S[9]

Spine-sheath structure in relativistic jet simulations

total velocity plots

non rotating BH

rapidly rotating BH

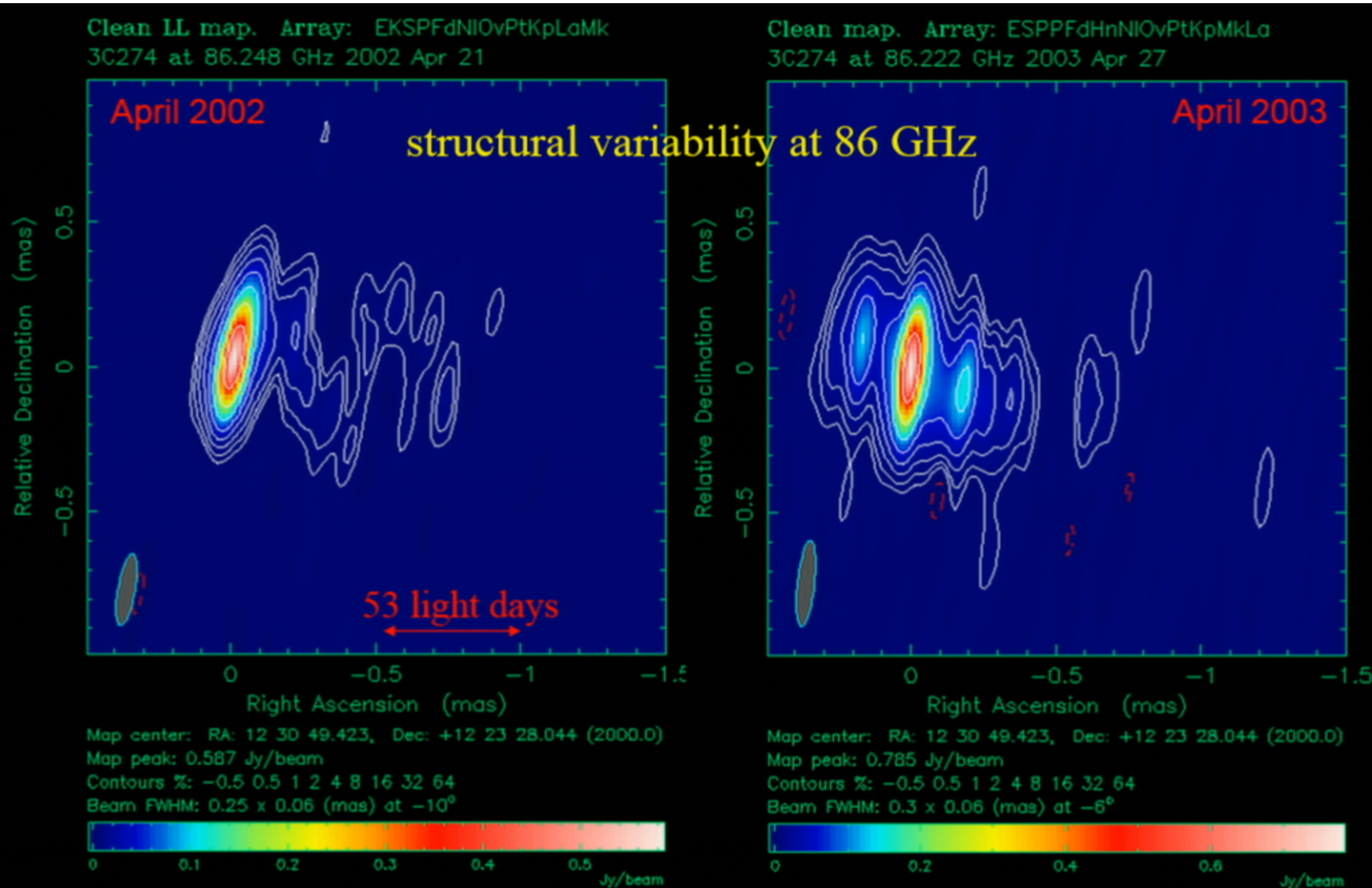


Jets from fast spinning BHs develop a slower inner and faster outer jet sheath

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

Hardee, Mizuno, Nishikawa, Ap&SS, 2007

structural variability at 86 GHz

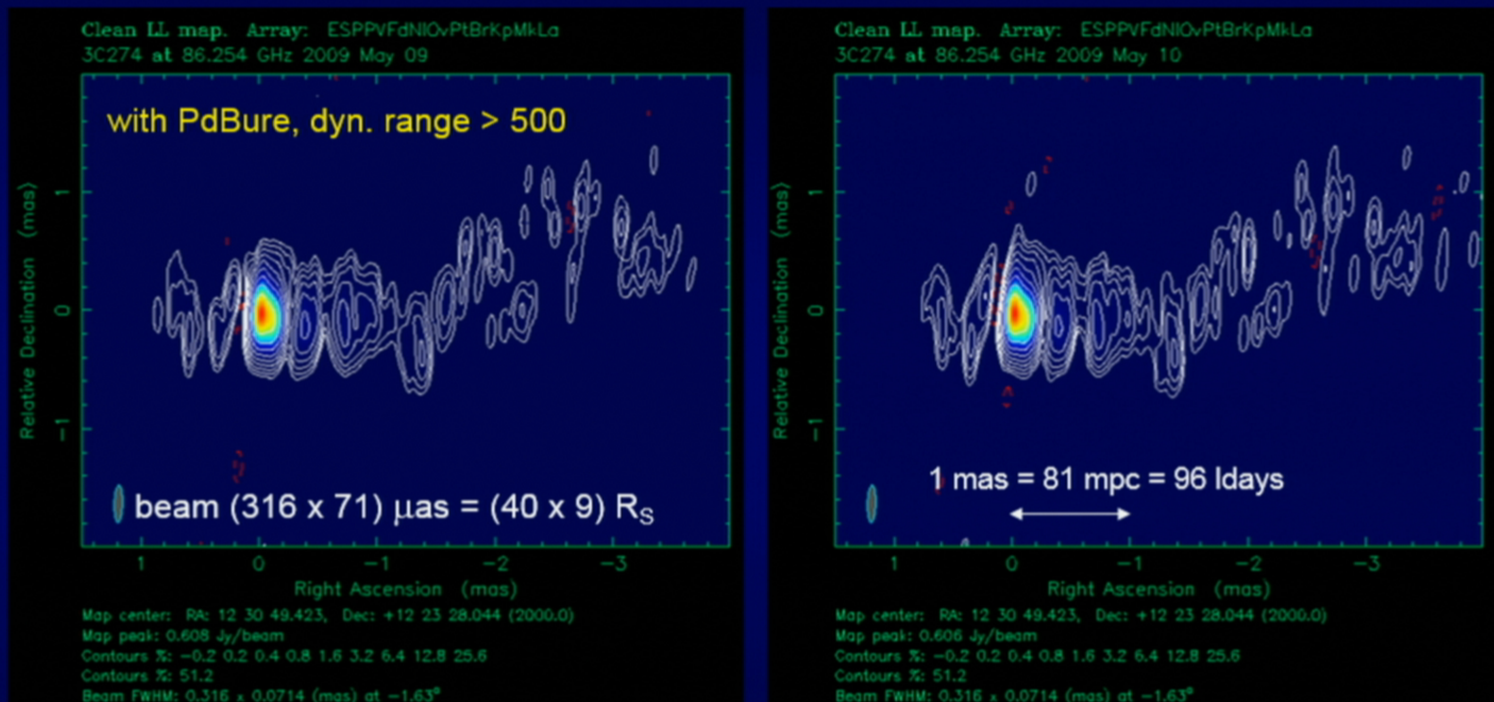


Motion in the inner jet of M87 detected : $\geq$ 0.2 mas/yr $\leftrightarrow$ $\approx$ 18000 km/s (0.06c)

(but: 3 – 6 c seen further downstream)

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

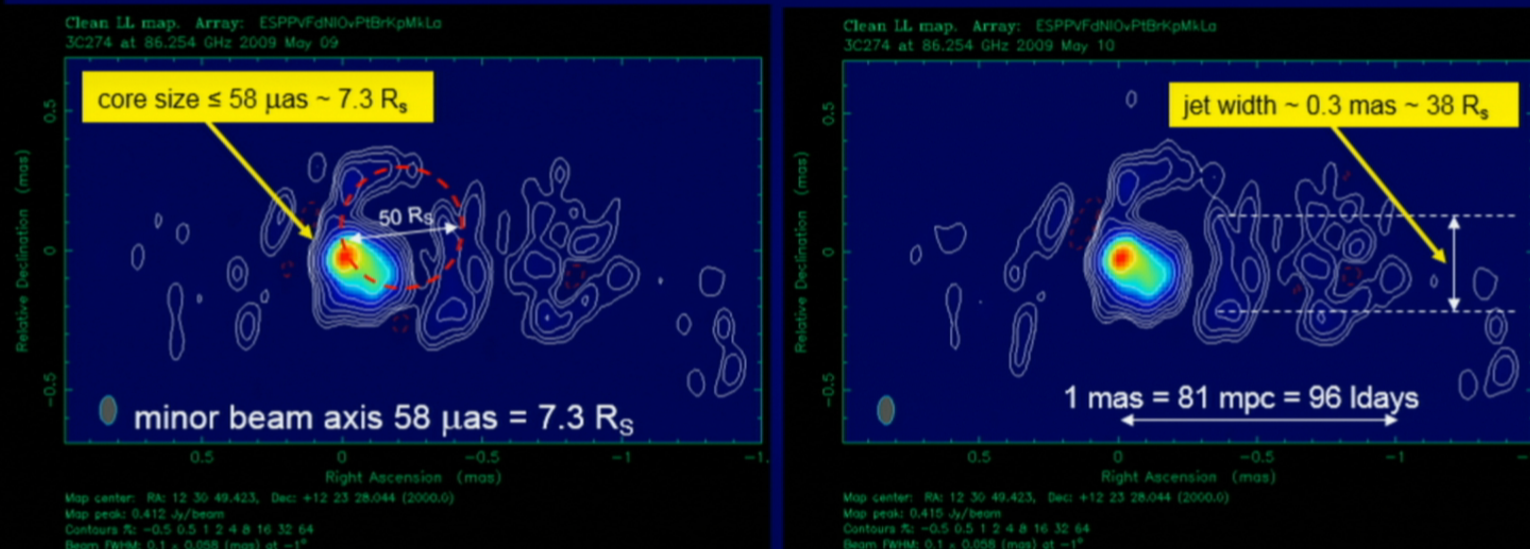
(uvtaper = 0.3)



- 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

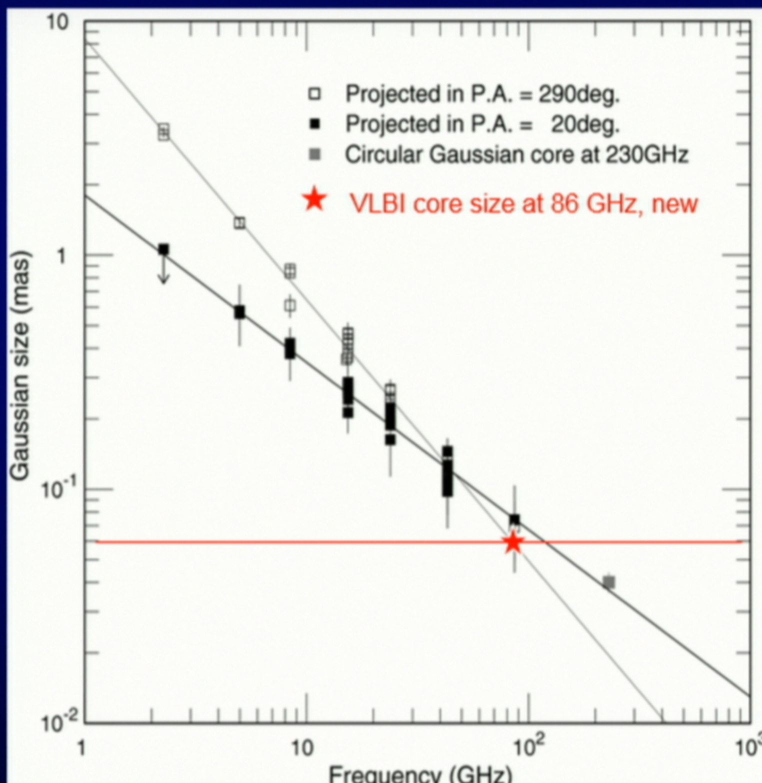
(no uv-taper, N-S beam axis compressed by fac. 3, E-W axis unchanged)

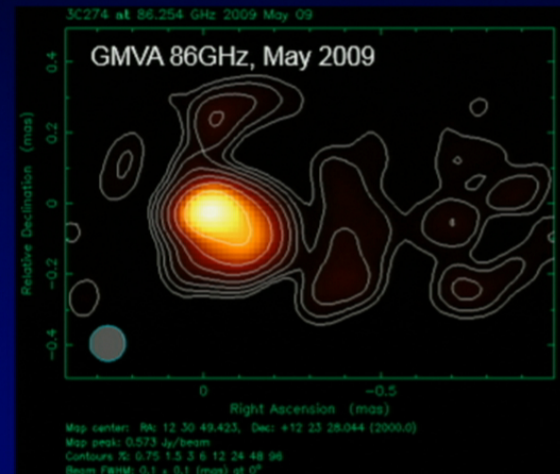


- striking similarities on both days, core is oriented south-west
- ring-like feature present in both images (similarity to 3C454.3)
- peak $T_B \sim 2 \cdot 10^{10}$ K at core
- core size ≤7.3 R_S, expected size of photon ring 41.3 μas (5.2 R_S)

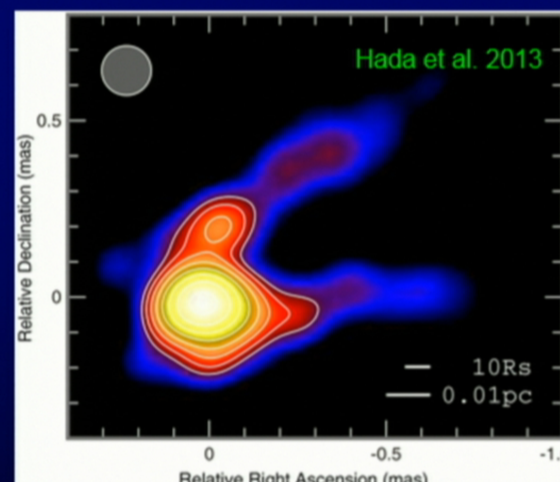
M87: Comparison 86 GHz vs. 43 GHz

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

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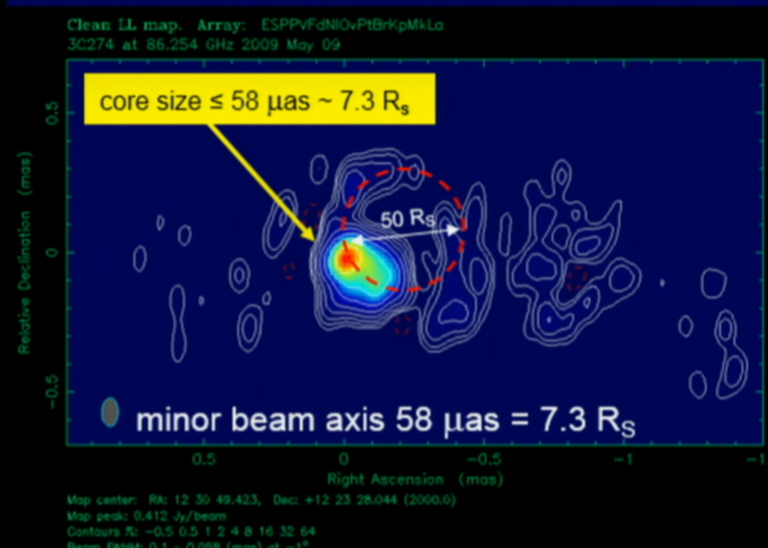

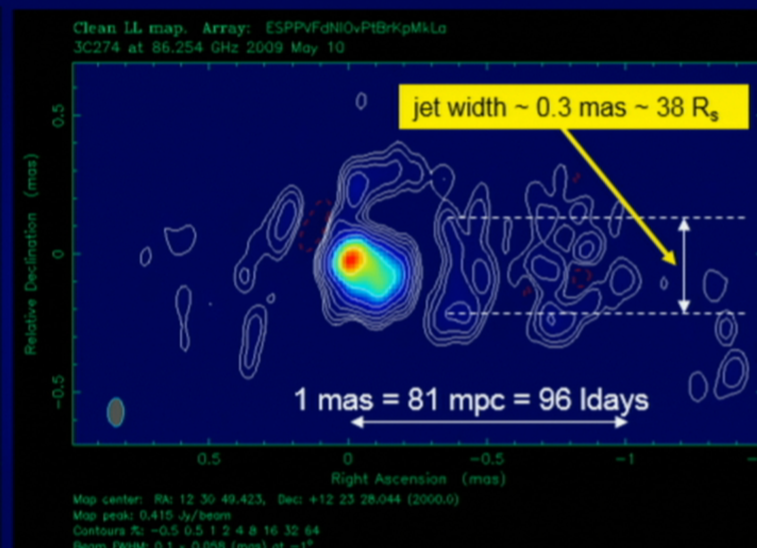

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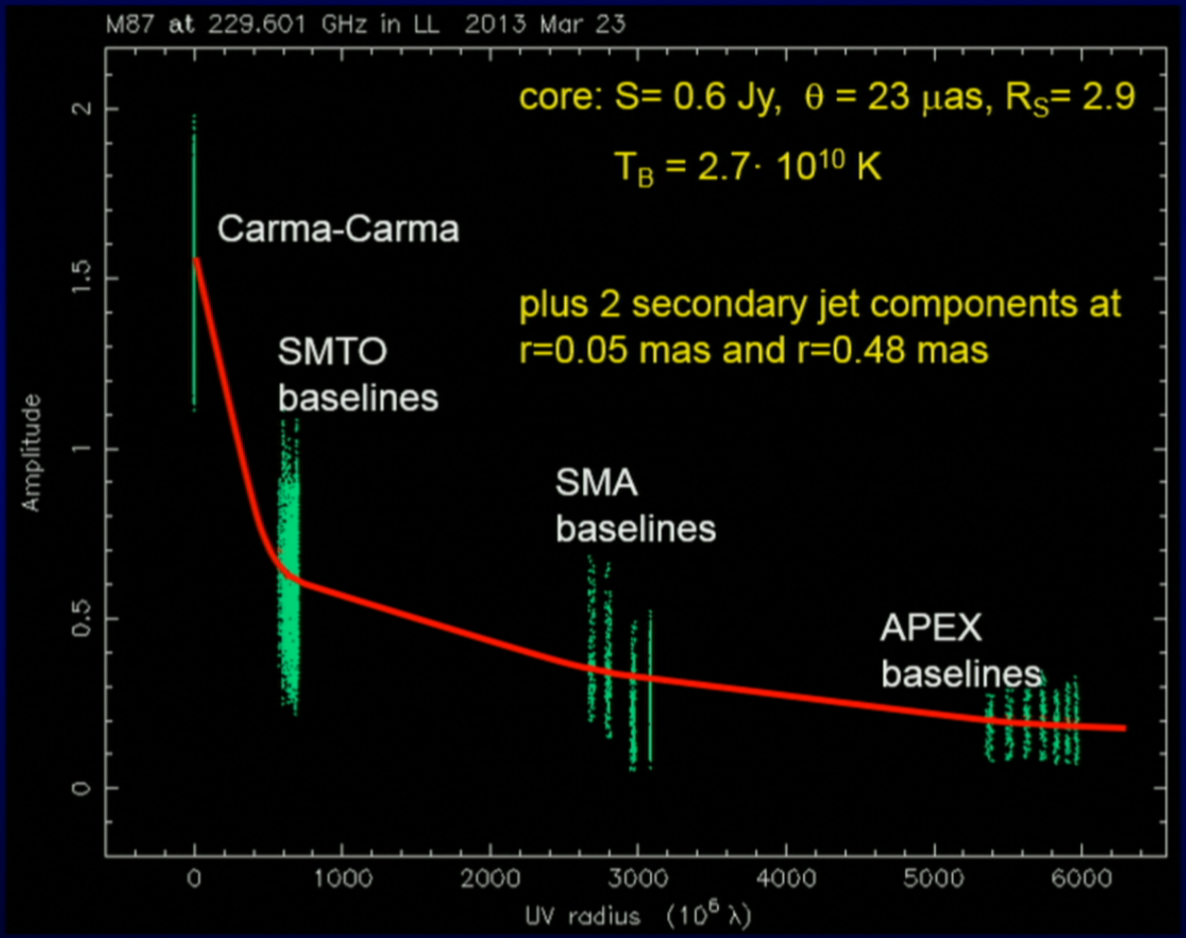
M87: Gaussian Modelfit to combined data set of March 23, 2013



- 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

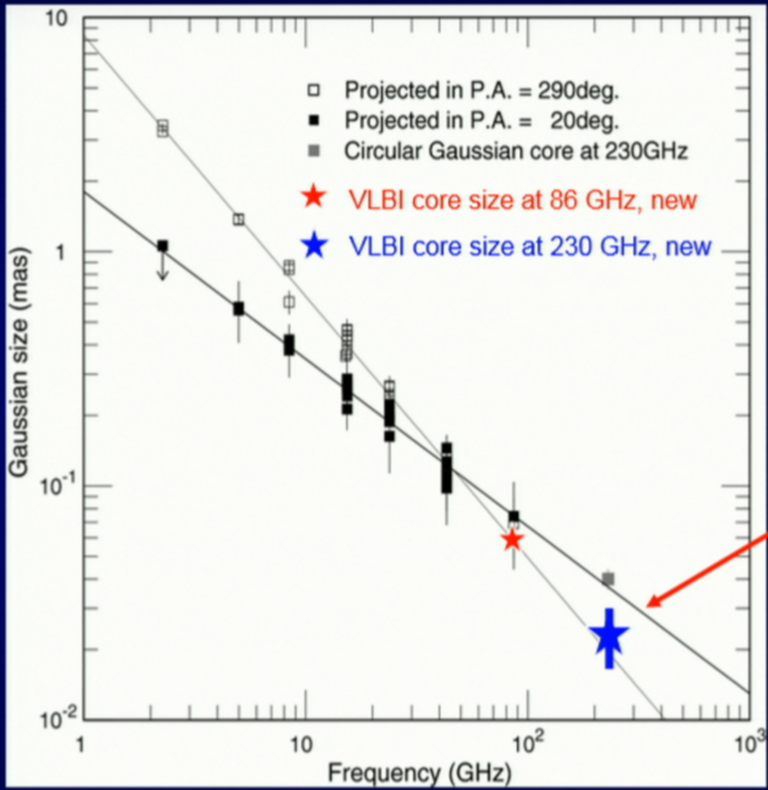
Modelfit + Clean Map

uvtaper 0.3@6Gλ

uniform weight, uvw 2,-1

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

M87's core size is smaller than previously thought



new data point

core size:

23 μas or

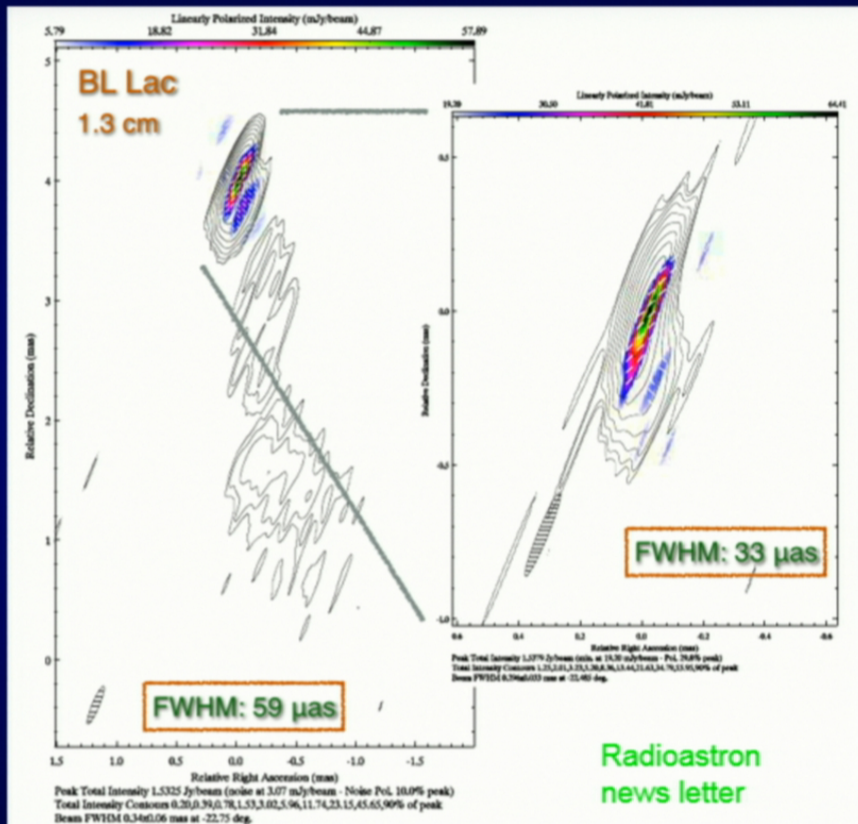
2.9 R_s

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

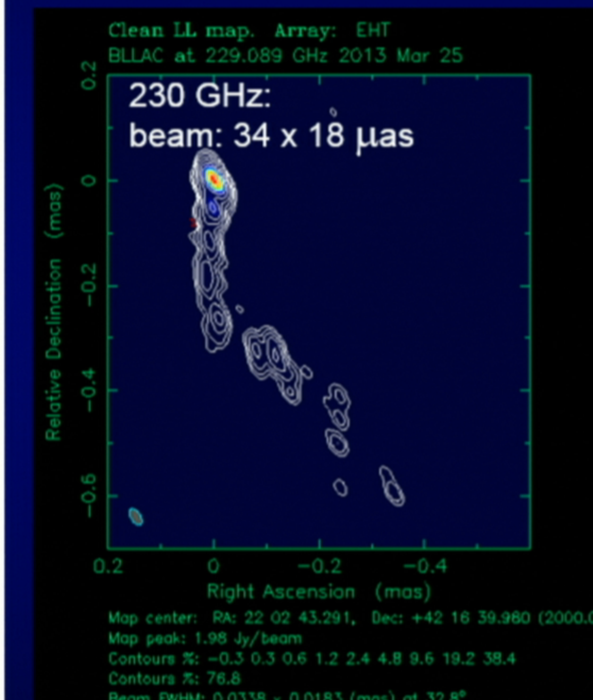
APEX baselines are more N-S oriented, than the E-W orientation of the US-array:

the above numbers may measure the N-S jet width or sheath rather than the core !

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

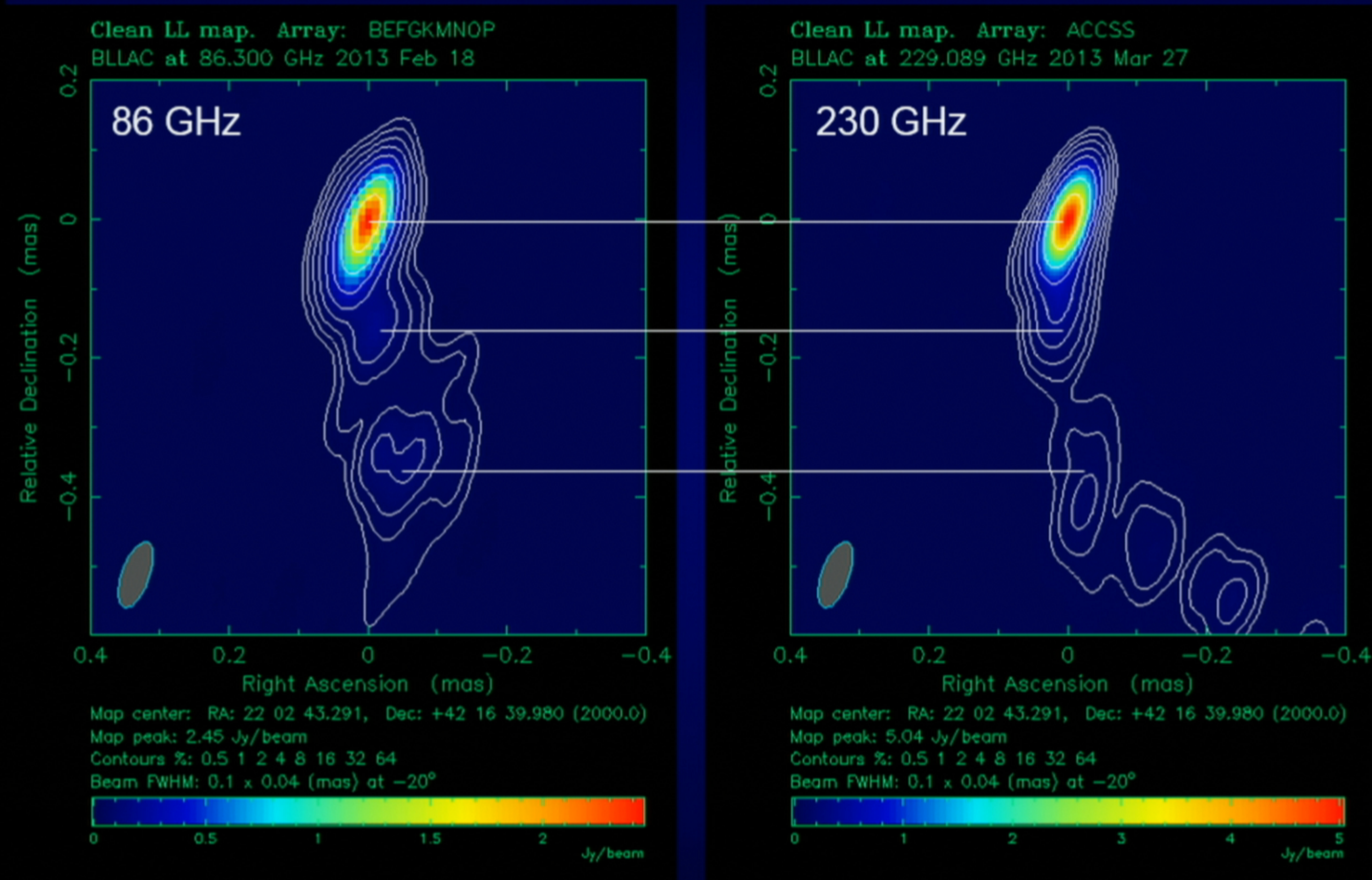


EHT – 5 telescopes, incl. Pico



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



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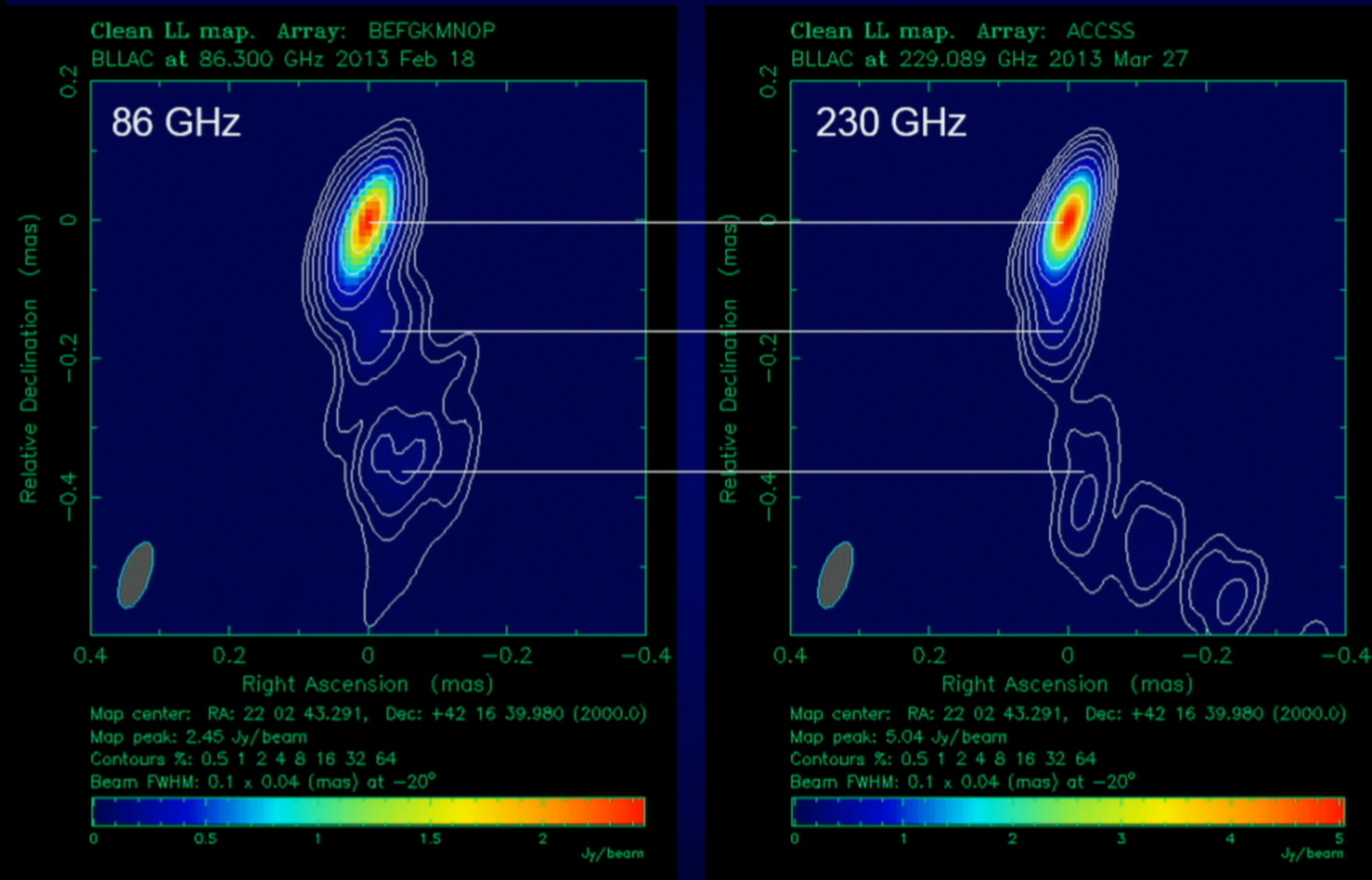

Energy Calculations

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

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Concluding Technical Remarks

- 1mm long baseline fringes detected, sources are compact on on 15-30 muas scales (PV, AP), many future targets
- APEX yields highest SNR to CARMA, the latter being the most sensitive northern station of the present 1mm VLB-array
- fringes between Pico Veleta, Apex and the US stations despite bad weather
- most sources are largely resolved, correlated flux decrease 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
- calibration strategy should be improved, need <10% accuracy to distingusih between ambiguous models
- the addition of ALMA and LMT may not fully compensate for the loss of CARMA
- the combination of APEX with ALMA will provide the important very short uv-spacings, but only for southern sources