High spatial resolution AGN imaging with Global Millimeter VLBI

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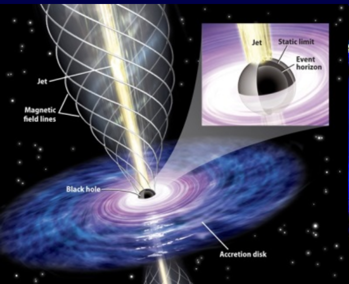
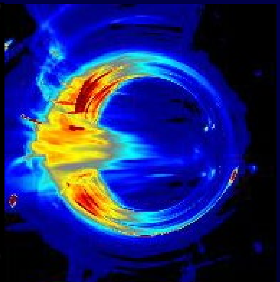
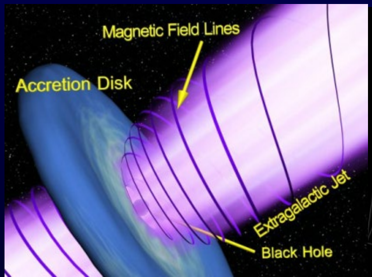
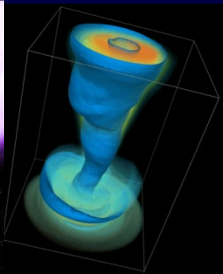
& Boston Group (A. Marscher, S. Jorstad)
& GMVA observatories
& EHT collaboration



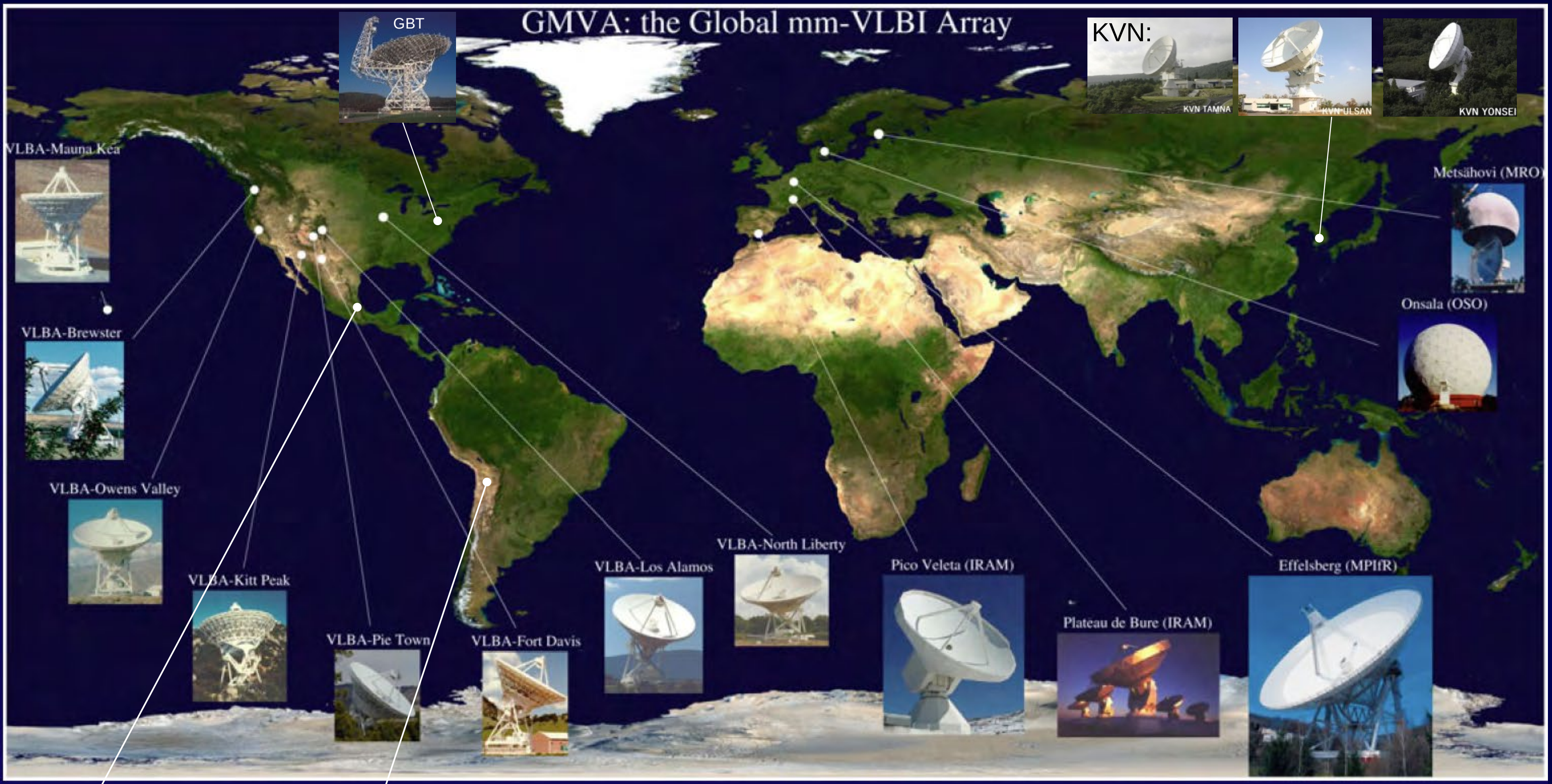






Global 3mm VLBI with the GMVA

2015/2016: fringes (first light) to KVN, LMT, ALMA now established



telescopes to be added 2017 - 2020:

ALMA, LMT, SRT, NOEMA, ...

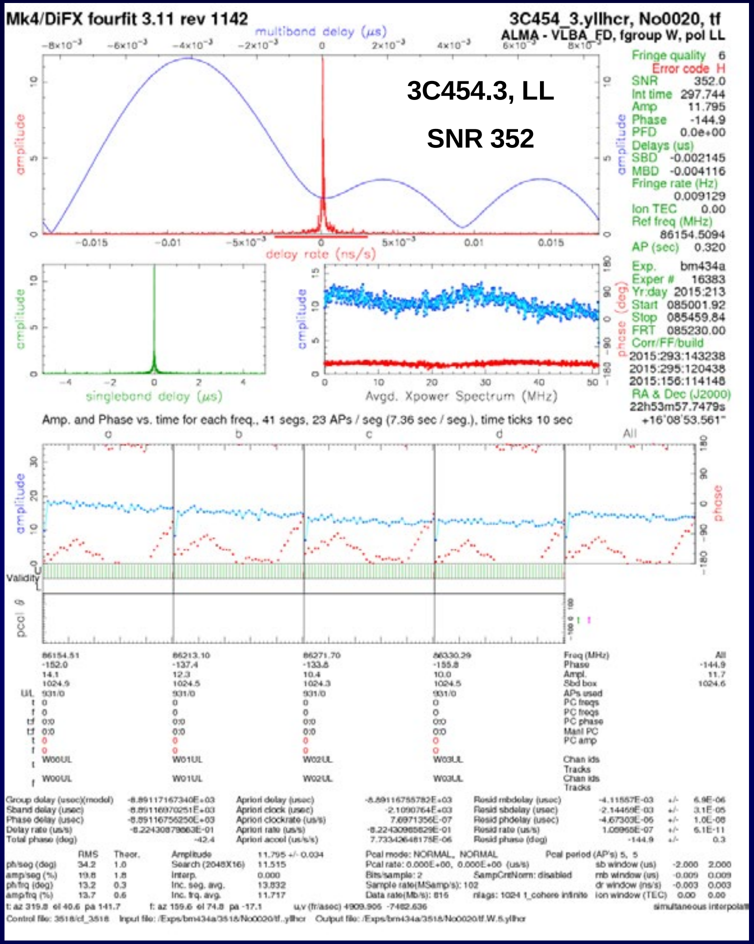
Global 3mm VLBI with the GMVA

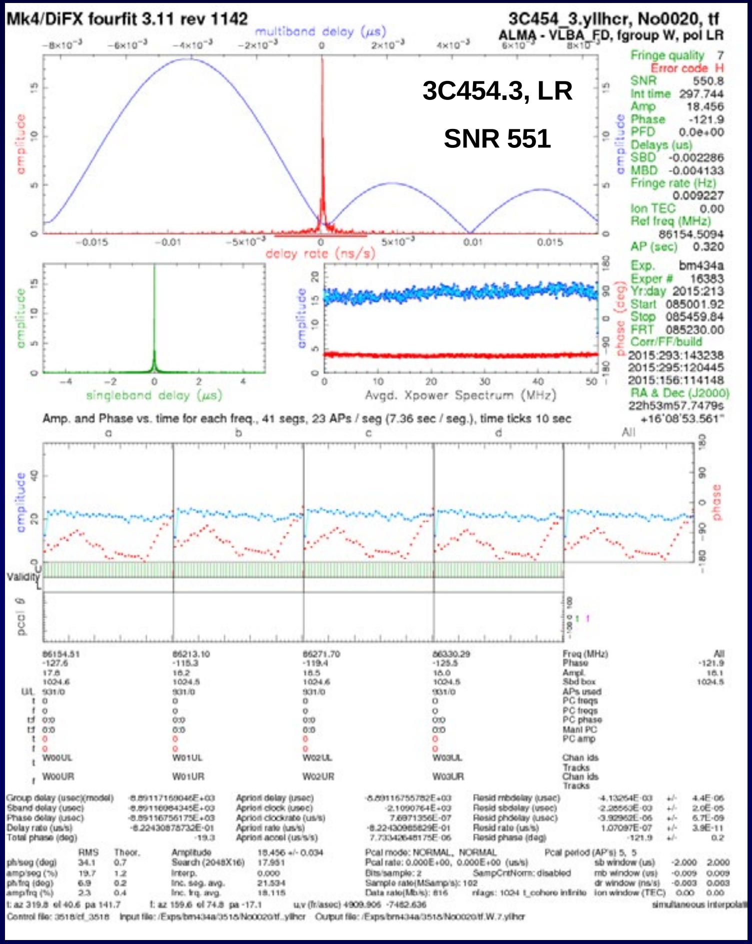
2015/2016: fringes (first light) to … LMT, ALMA now established

telescopes to be added 2017 - 2020:

ALMA, LMT, SRT, NOEMA, ...

86 GHz Fringes between ALMA and VLBA (Aug. 2015)





comparable SNR in parallel and cross hands owing to linear ALMA feeds

Note: VLBA 2 x 128 MHz
ALMA 4 x 52 MHz

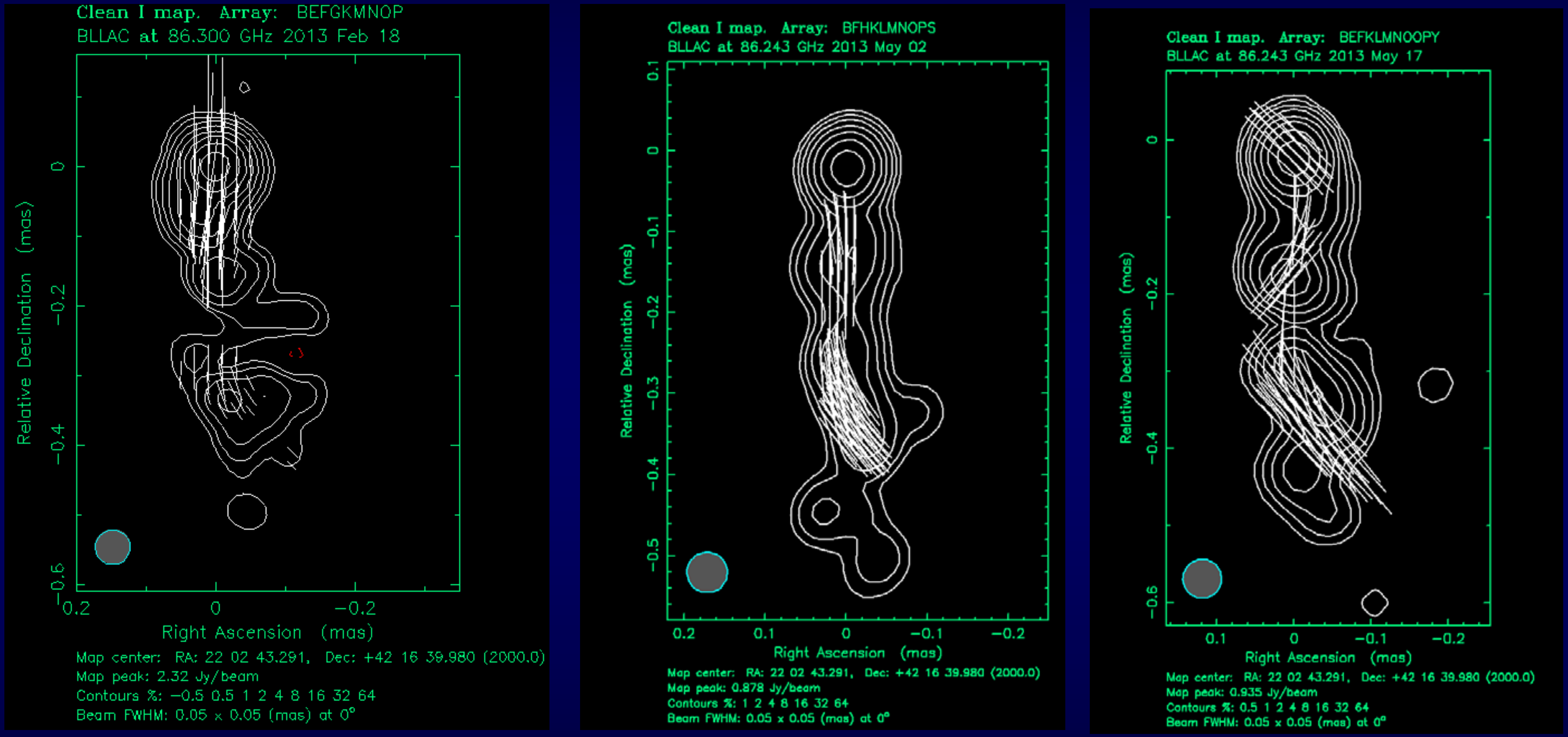
POLCONVERT:
Marti-Vidal+ ...

credit: APP team

correlation: Haystack

BL Lac: Polarimetry with the GMVA at 86 GHz

beam: 50 μas = 0.07 pc = ~ 830 R_S



data: B. Rani et al., in prep

see B. Rani's talk

EVPA variations along jet on 0.1 mas scales

The Origin of Jets: Understanding BH – Disk – Jet coupling

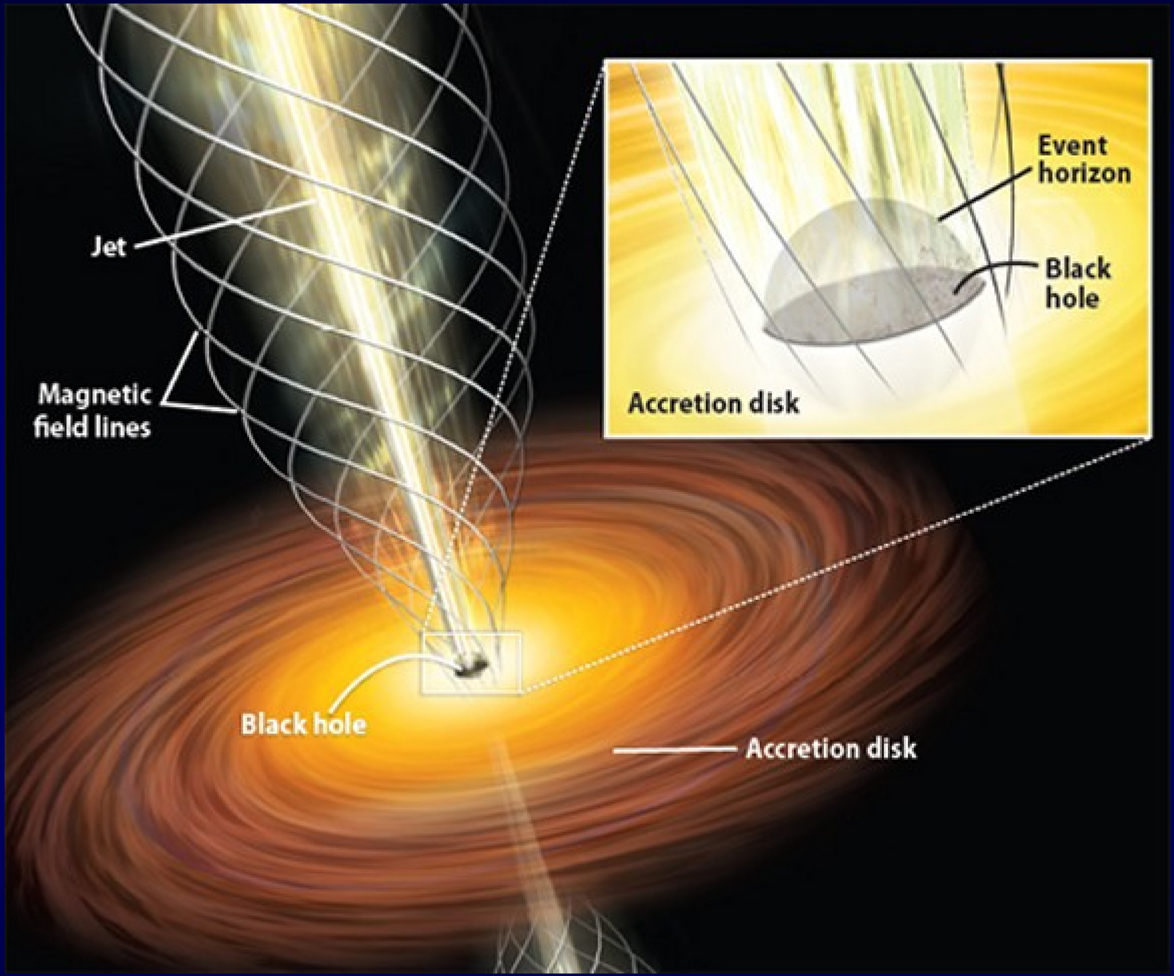
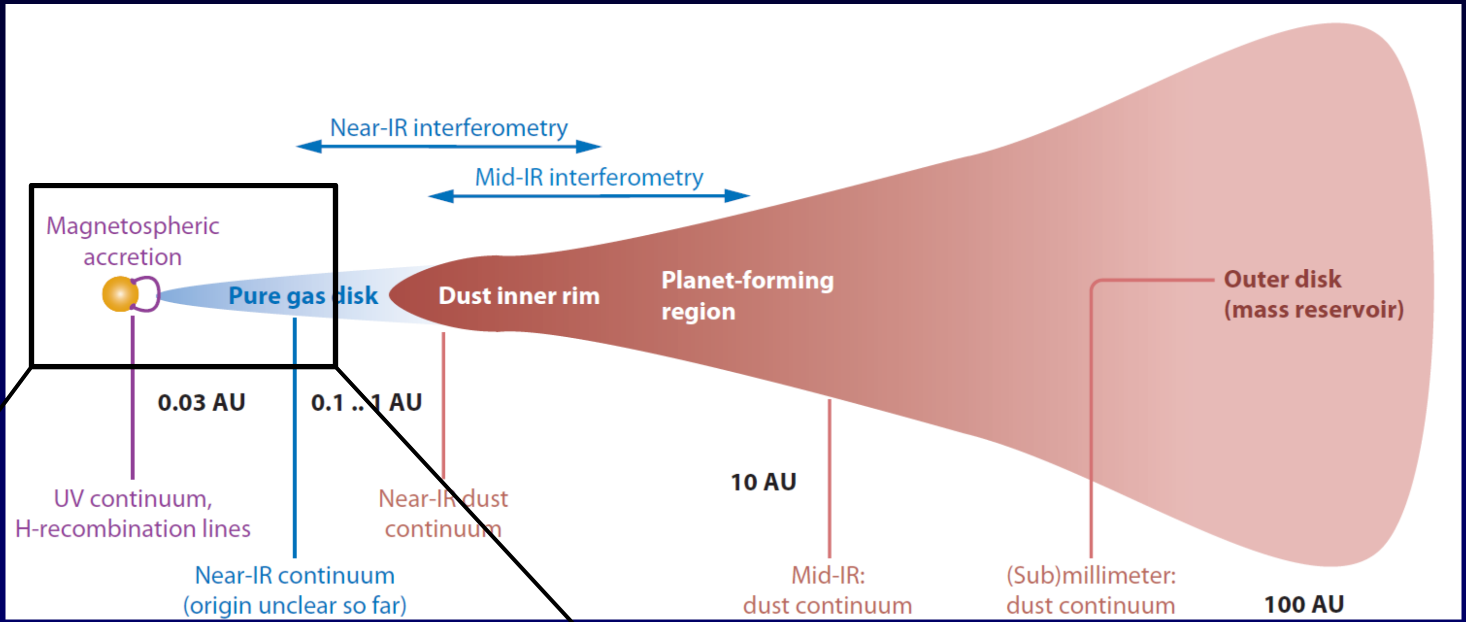


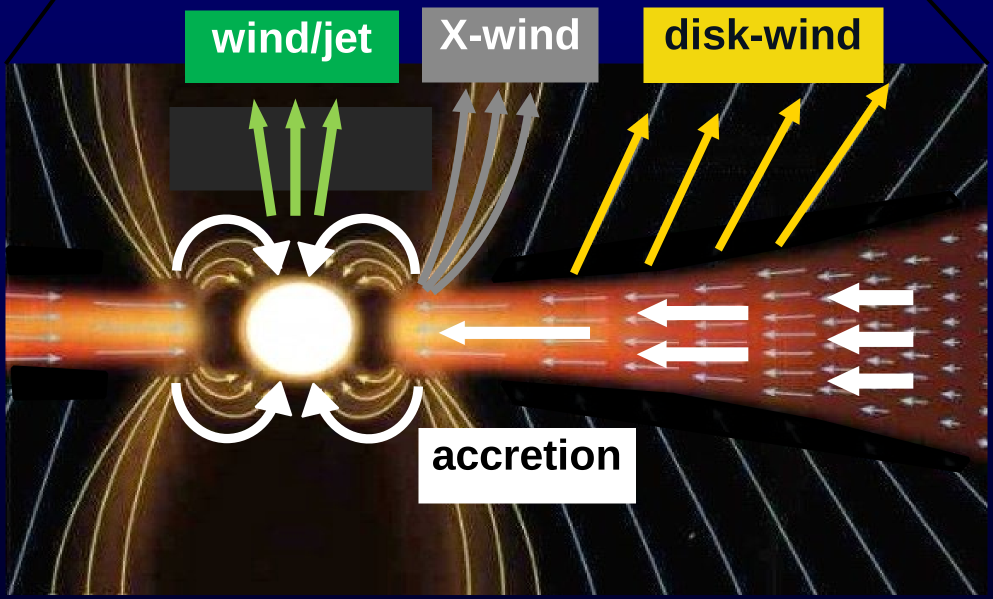
Image Credit: Astronomy/Roen Kelly

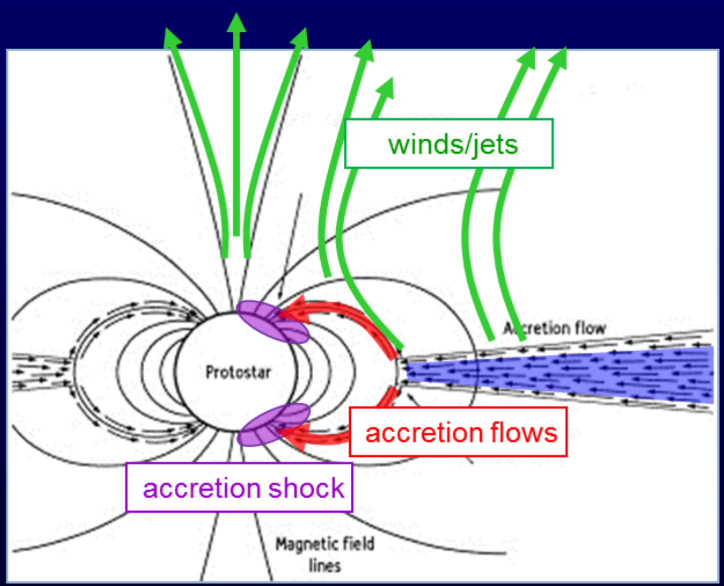
- VLBI at mm- and sub-mm λ overcomes opacity barrier
- sub-mm and space VLBI reach Event Horizon scales

Sketch of jet formation in stellar systems

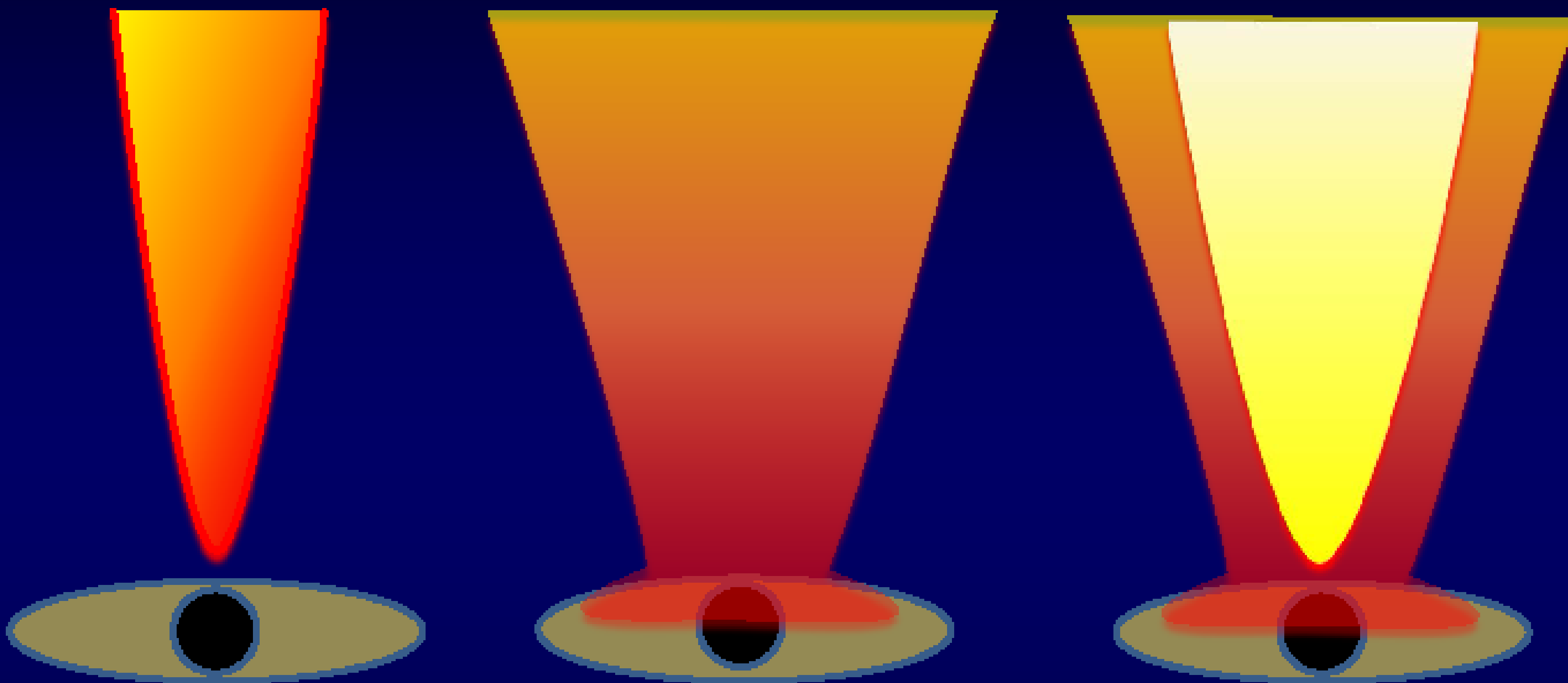
adopted from:
S. Antoniucci+2015, and
Dullemond & Monnier 2015







Different types of jet launching models

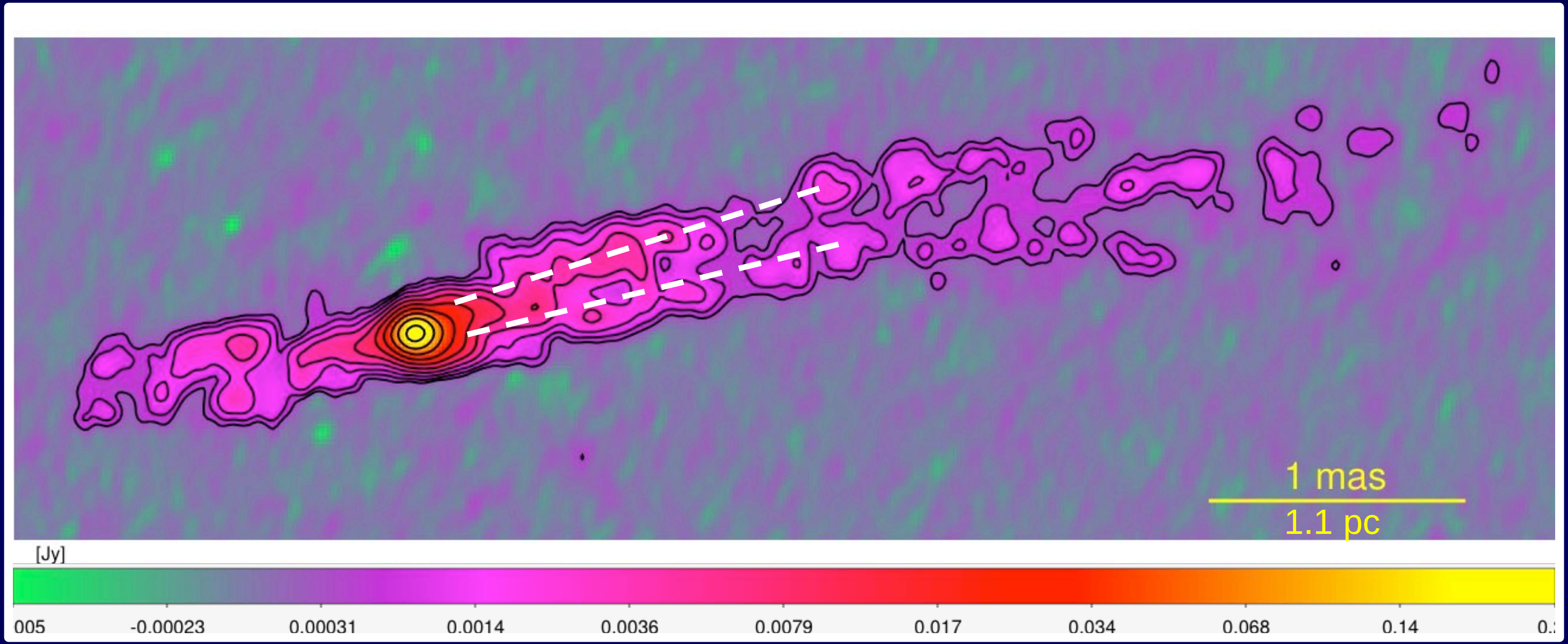


BH launched	disk launched	BH + disk launched
narrow jet	wider jet	stratified jet
BZ-type	BP-type	combined BP+BZ

Cygnus A: stacked VLBI image at 86 GHz

(GMVA, 3 epochs, 2009 – 2010)

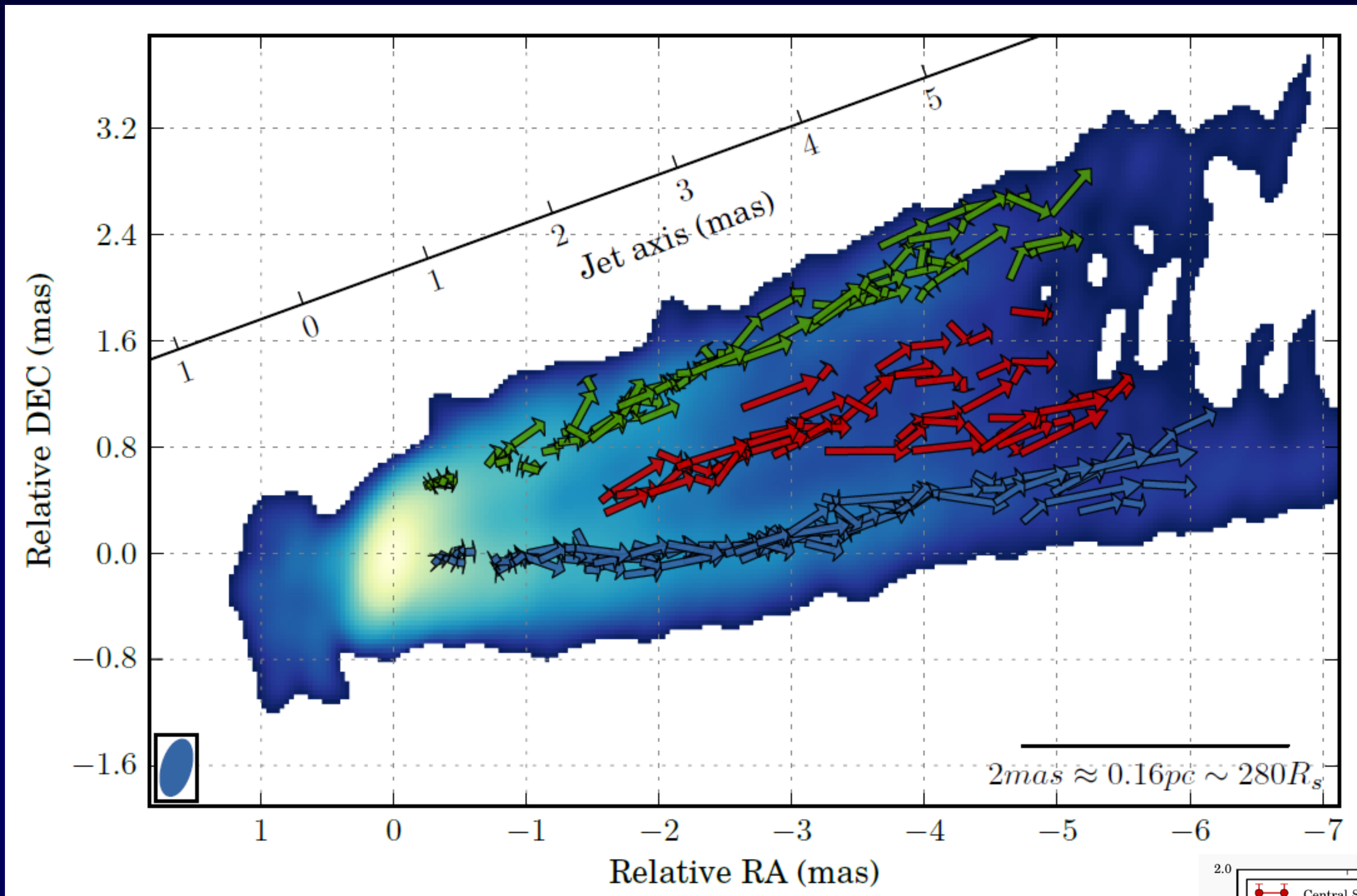
see Bia Boccardi's talk



- jet transversely resolved on pc-scales, width > ~230 R_S
- conical expansion of jet and counter-jet (at r < 1pc)
- stacking helps to transversely resolve counter-jet

Boccardi et al. 2016

M87 – Strong evidence for a stratified jet flow from VLBA 43 GHz monitoring



wavelet based image analysis

data:

43 GHz VLBA

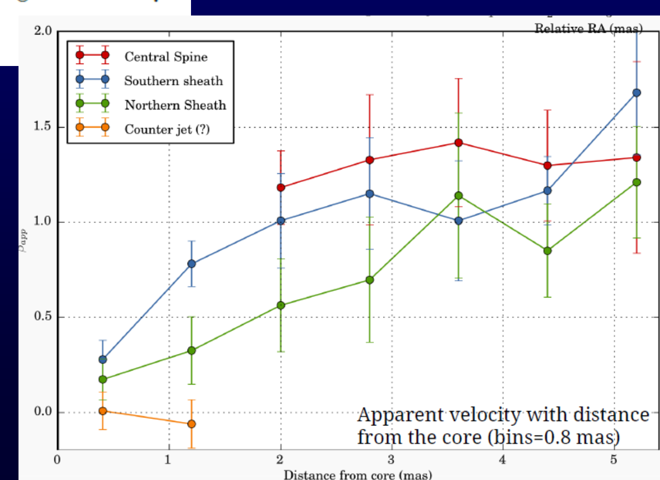
(C. Walker et al.)

Mertens & Lobanov 2014 &
Mertens+ 2016

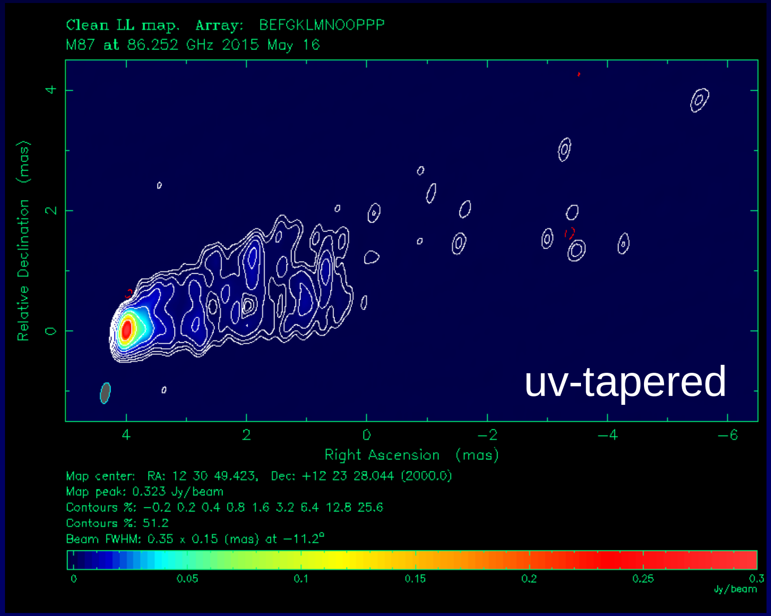
apparent acceleration on sub-pc scales

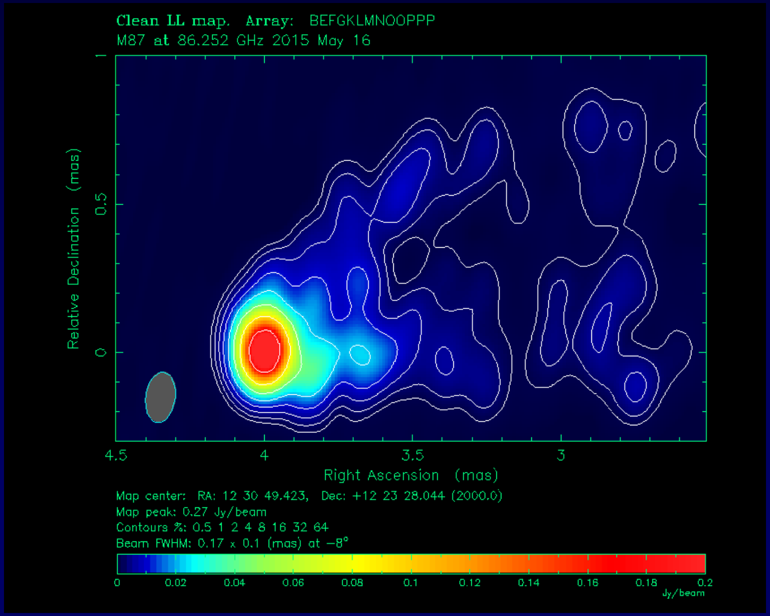
velocity difference spine/sheath

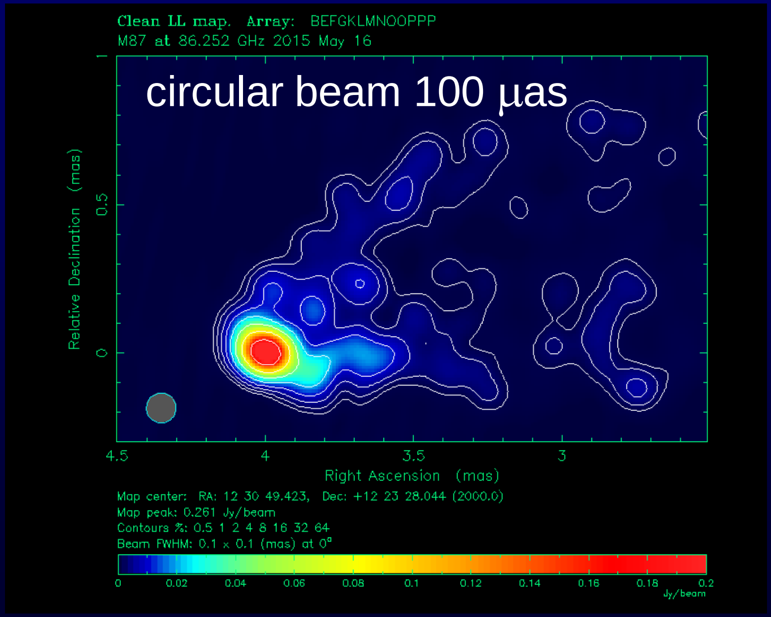
differential Doppler-boosting !!

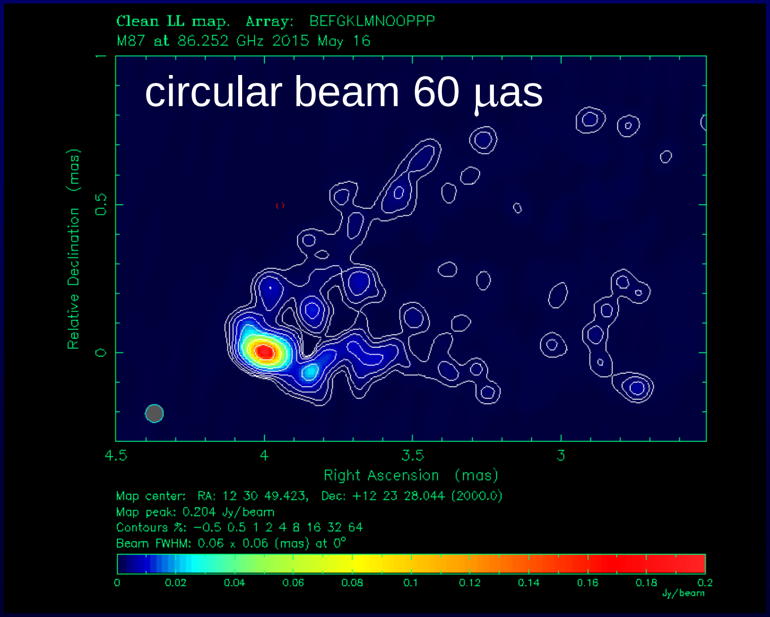


M87: new GMVA map of May 2015



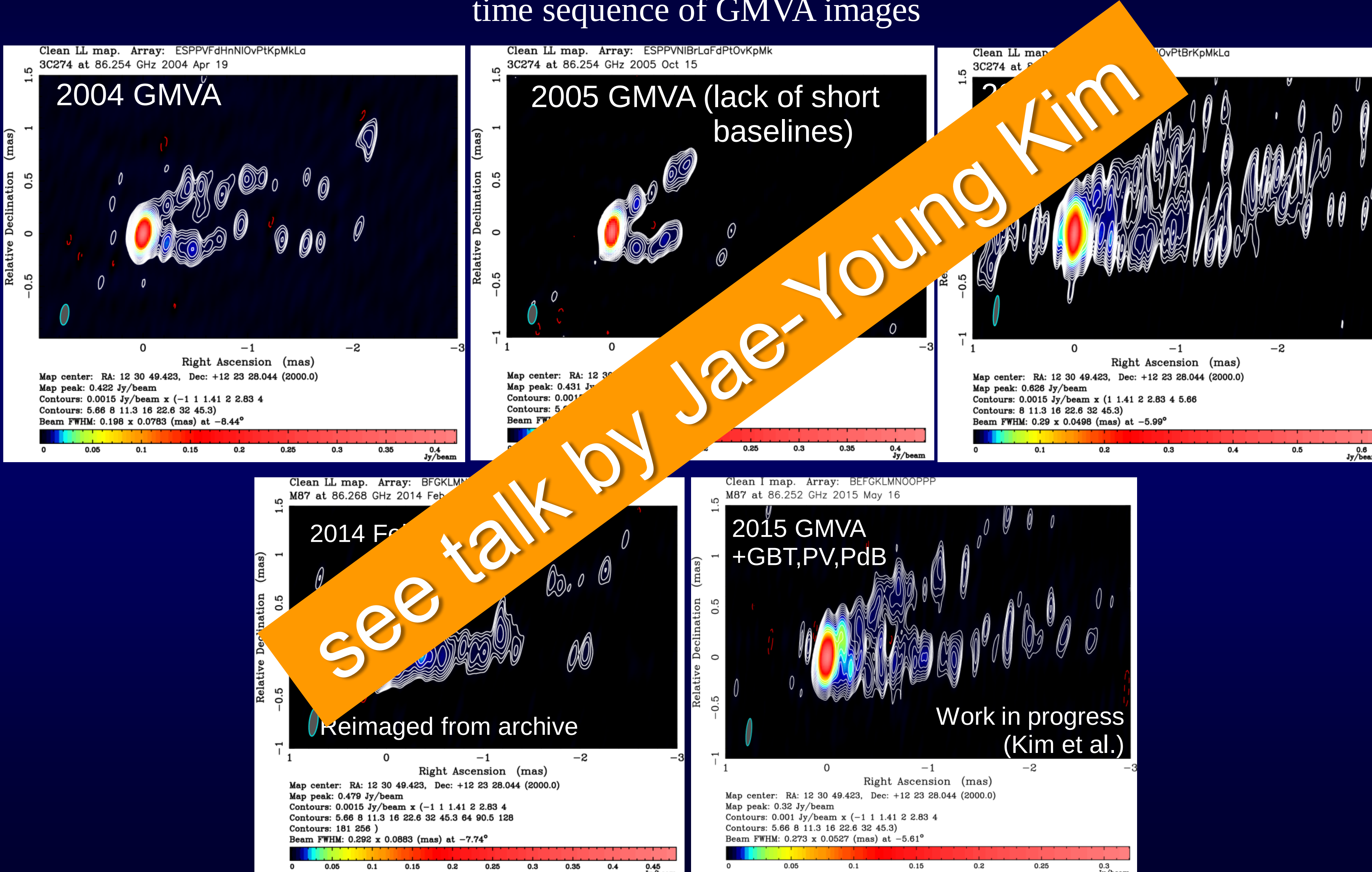




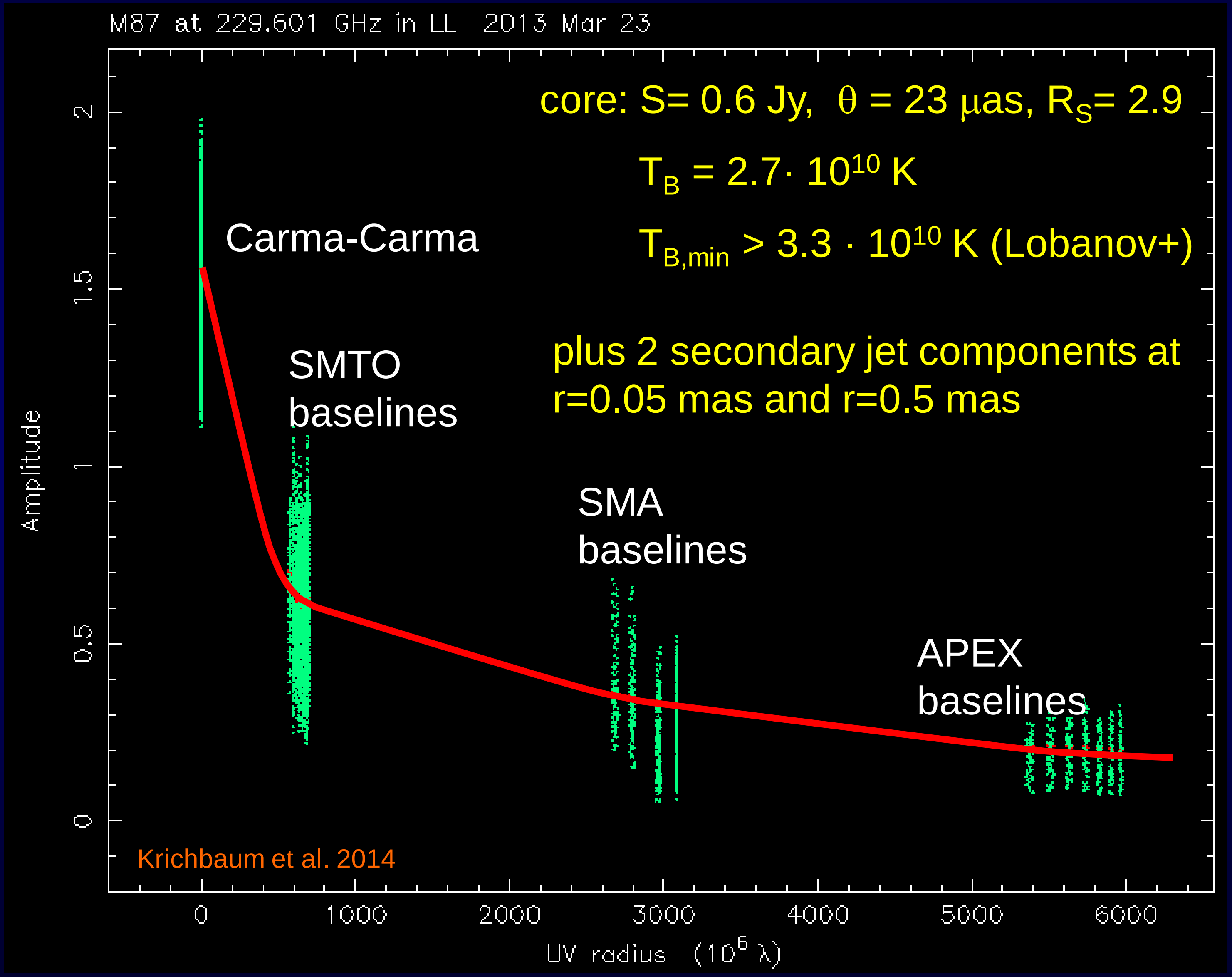


3mm GMVA maps of M87

time sequence of GMVA images



M87: Gaussian Modelfit to 230 GH data (March 2013)



- visibilities can't be fitted by a single Gaussian compo.
- strong resolution effects already at 600 Mλ
- T_B at 86 & 230 GHz comparable
- T_B may be close to equipartition limit

M87 at 86 and 230 GHz

GMVA @ 86 GHz

(11 stations)

EHT @ 230 GHz:

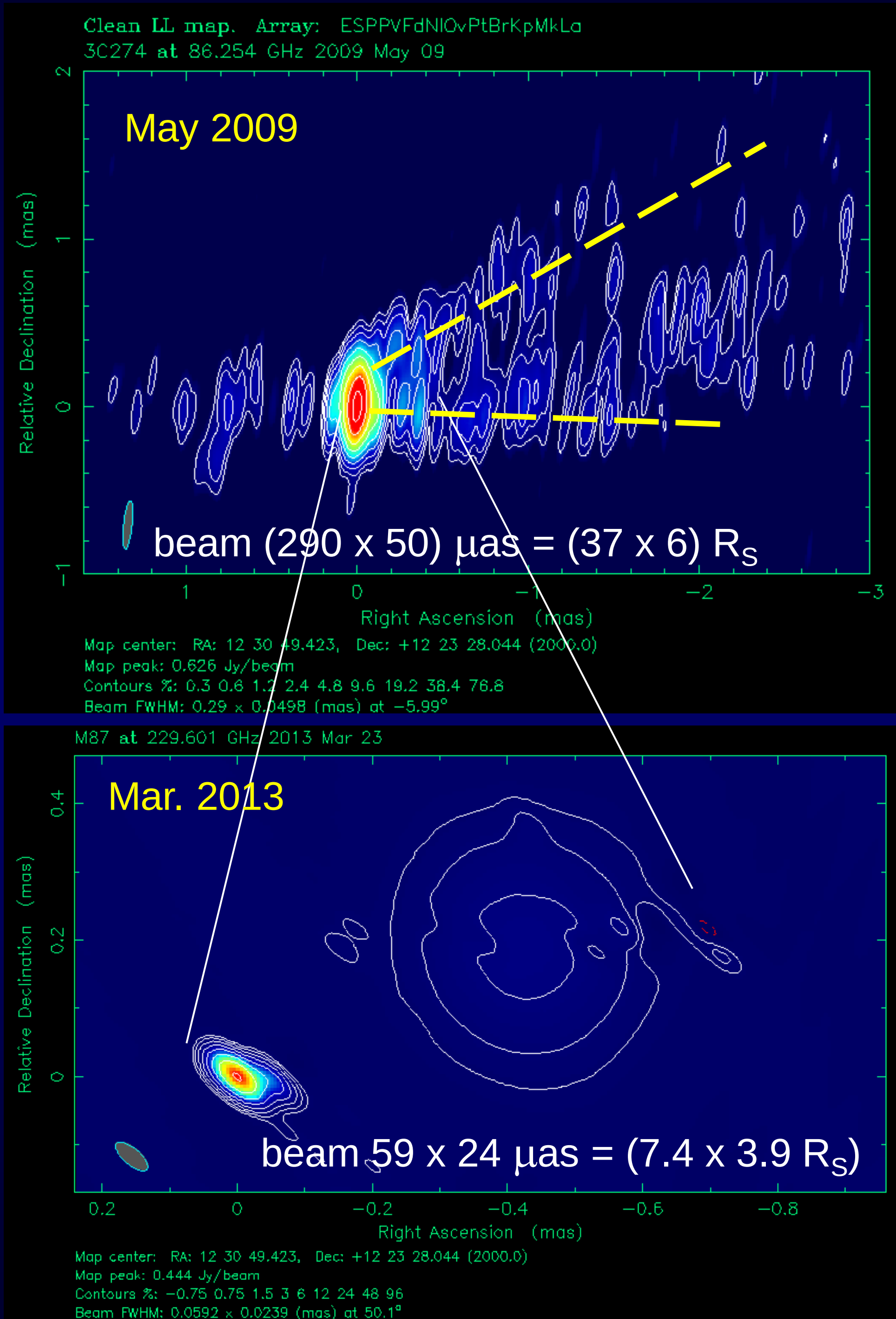
(4 stations)

Modelfit + Clean Map

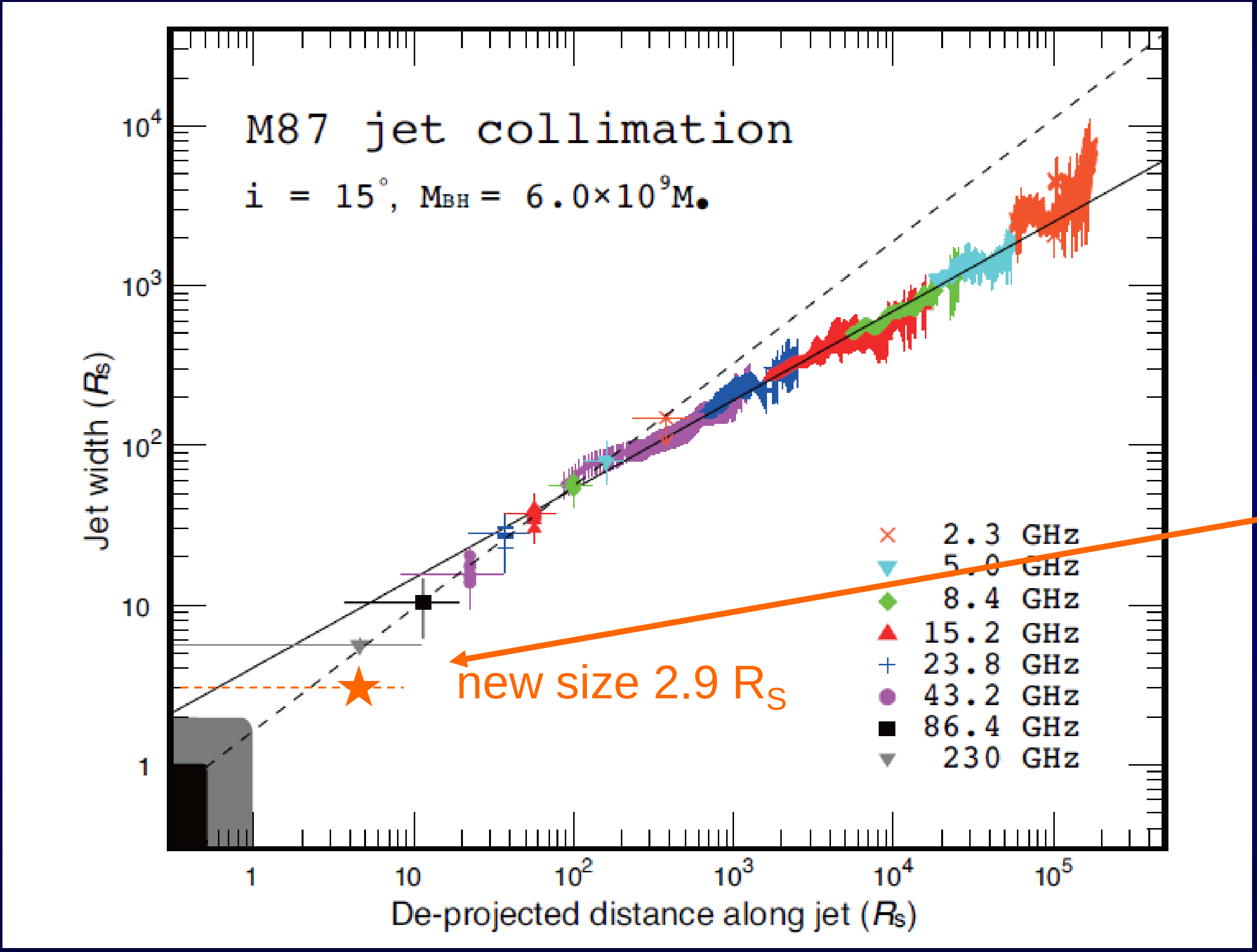
uvtaper 0.3@6Gλ

Core jet structure traced down to ~25 μas scale

small size may indicate BH spin a > 0



M87's core size falls below extrapolated jet width



new M87 core size:

23 μas or

2.9 R_s

This is smaller than the size of the photon ring for a non-spinning BH !

plot adopted from Hada+ 2013

see also Asada & Nakamura

Alternative Jet Models

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

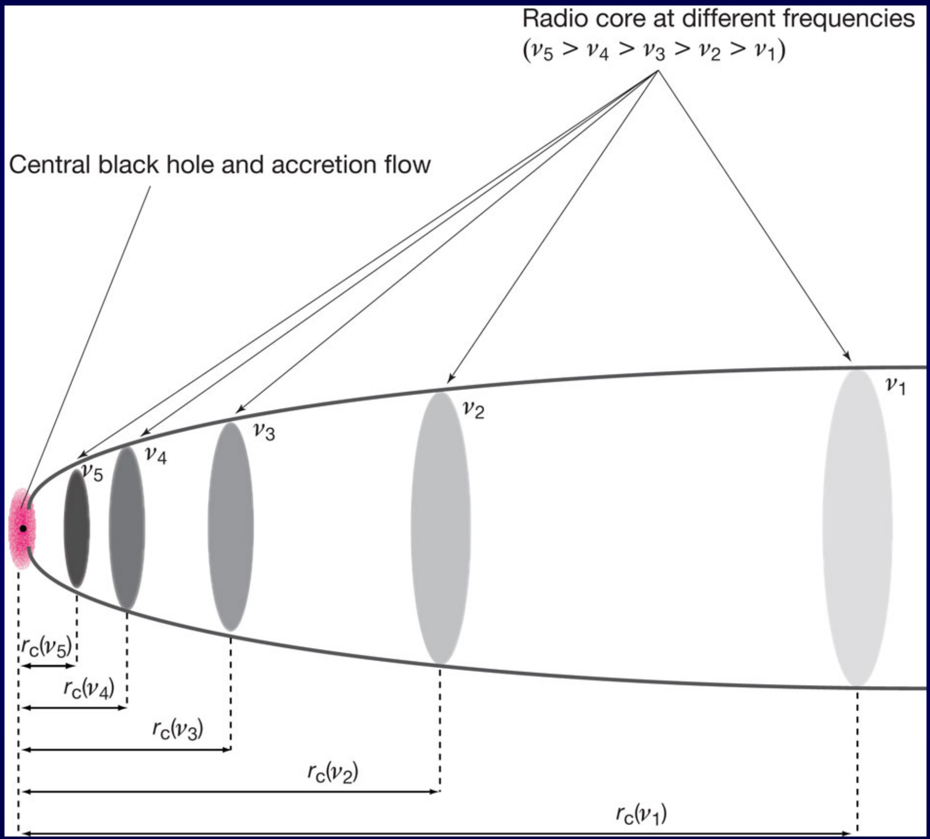
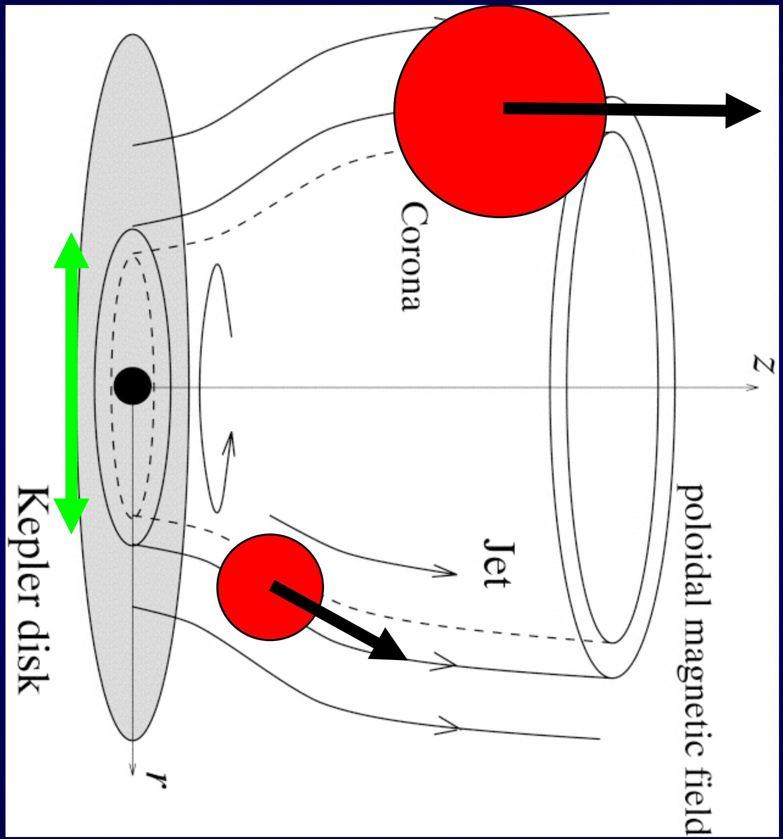


Figure from Hada et al. 2011.

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

$2\ R_0 \geq 10\ R_S$ (a=0)



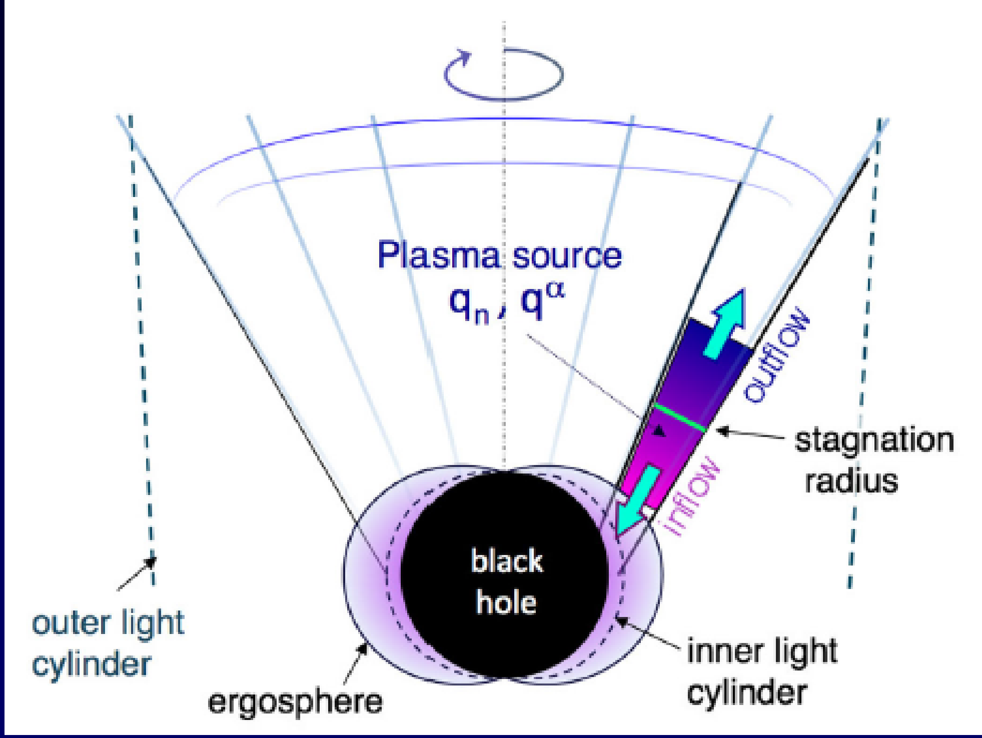
last stable orbit radius: $1 \rightarrow 6\ R_s$ for BH spin $a = 1 \rightarrow 0$

uv-coverage at 1mm is limited, GMVA provides uv-coverage and sensitivity

Magneto-hydrodynamic plasma flows in Kerr space time

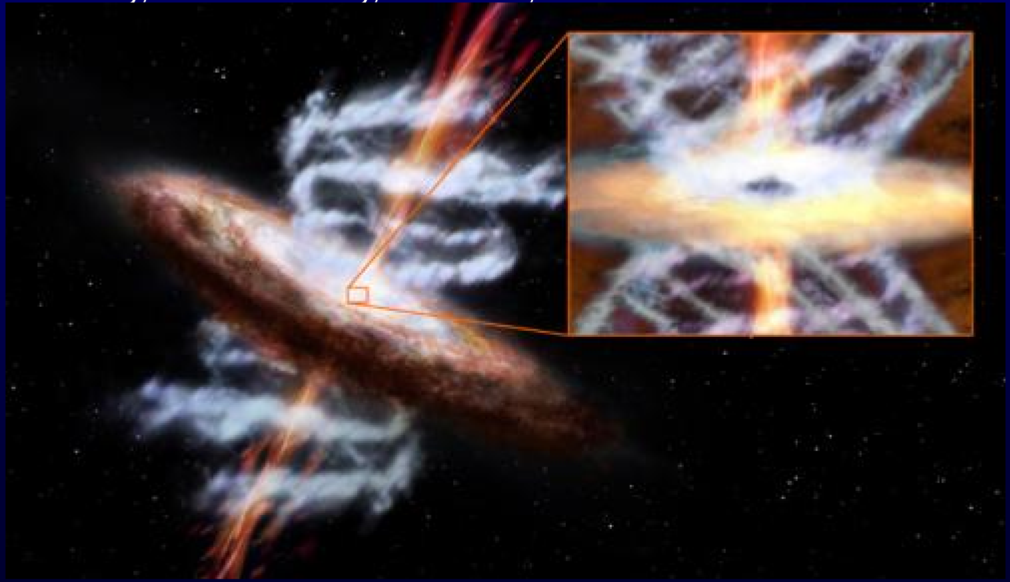
complex stratified and filamentary structures expected near BH
variable on 1-1000 ISCO timescales

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

→ expect:

- stratified (multi-velocity) structures at jet base
- helical and rotating jet filaments

The intrinsic brightness temperature

$$T_B = 1.22 \frac{S}{(\nu \cdot \theta)^2} \cdot \frac{\delta}{(1+z)} 10^{12} K$$

$$T_{B,int} = T_{B,measure} \frac{(1+z)}{\delta}$$

→ T_B becomes smaller for larger emission region size

→ T_B becomes smaller at higher frequencies

→ T_B becomes smaller for highly boosted sources

→ T_B becomes smaller for nearby sources

Equipartition brightness temperature

$$T_B = t_\alpha \left[\eta \, s_{pc} \, \nu_m^{\,(1.5-\alpha)}\right]^{1/8} 10^{11} \, K$$

$$\eta = \frac{U_K}{U_B}$$

kinetic to magnetic energy ratio

A. Singal , 2009 (ApJ)

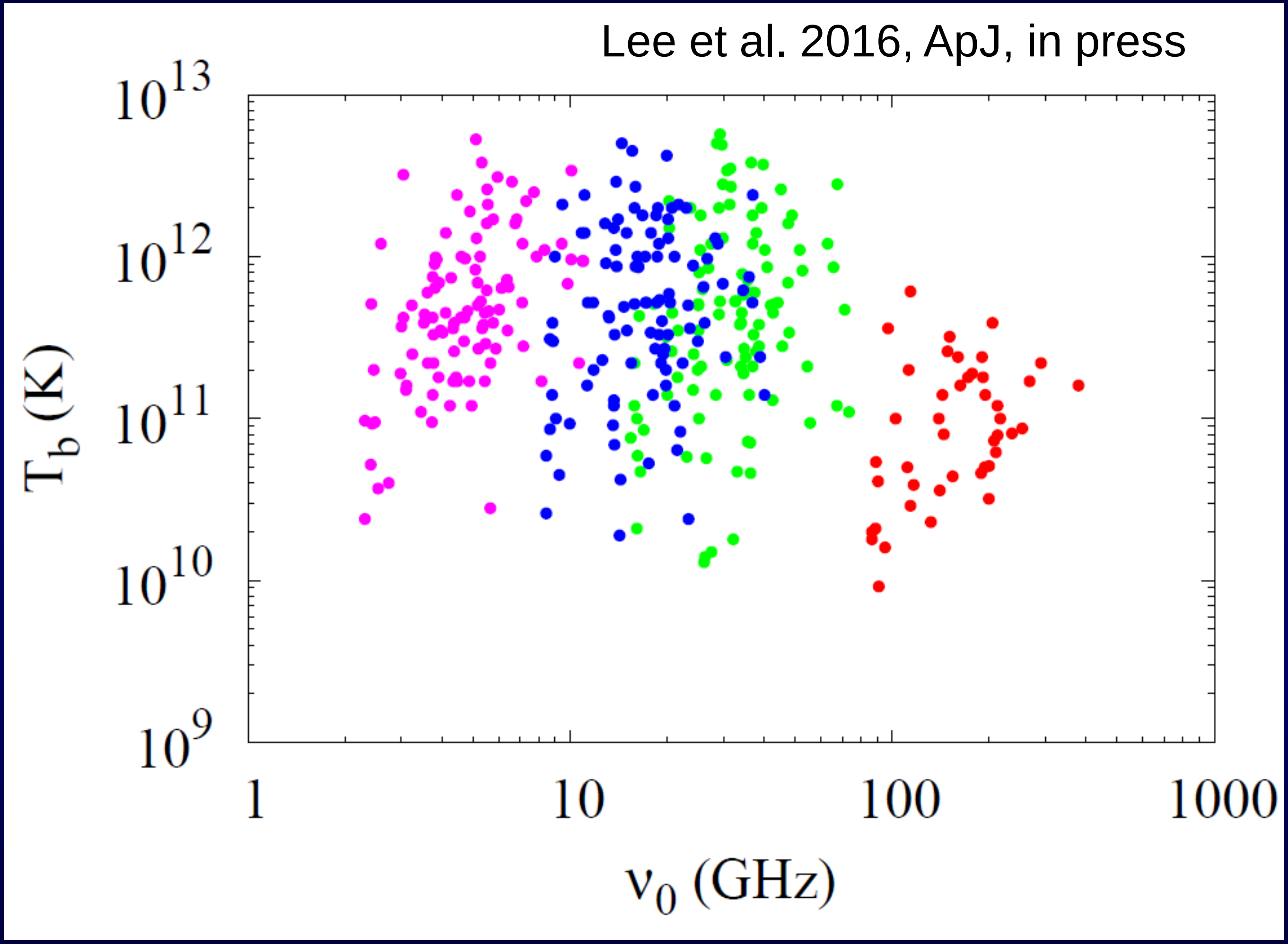
for energy equipartition:

$\eta = 1 : T_B = T_{B,eq} = \sim 5 \cdot 10^{10}$ K

magnetic: $U_B > U_K$: eg. $\eta = 0.01 \quad T_B = 0.5 \, T_{B,eq}$

kinetic: $U_K > U_B$: eg. $\eta = 100 \quad T_B = 1.8 \, T_{B,eq}$

Brightness temperatures versus frequency from 2 to 86 GHz



- 2 GHz
- 8 GHz
- 15 GHz
- 86 GHz

The brightness temperature may decrease beyond ~ 22 GHz.

Is this already evidence for magnetic jet launching, which requires $T_B < T_{B,eq}$?

Building up the global 1.3 mm VLBI array

Status March 2015 with APEX+LMT added

History of 1mm VLBI:

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

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

2007: SMTO-CARMA-JCMT/SMA

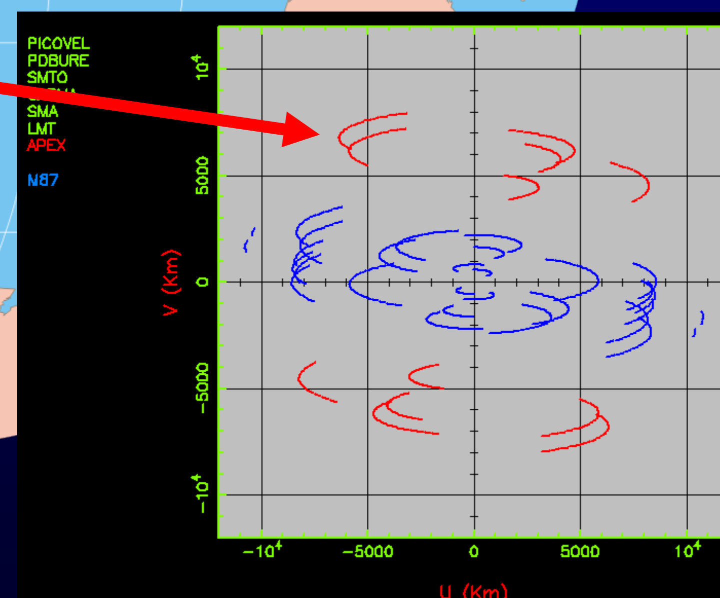
2011: 1mm VLBI with Apex, NoF

2012: AP-SMA-SMTO, first fringes

2013: 1st global 1mm VLBI run

2015: fringes AP-ALMA, PV-ALMA

2015: fringes to LMT



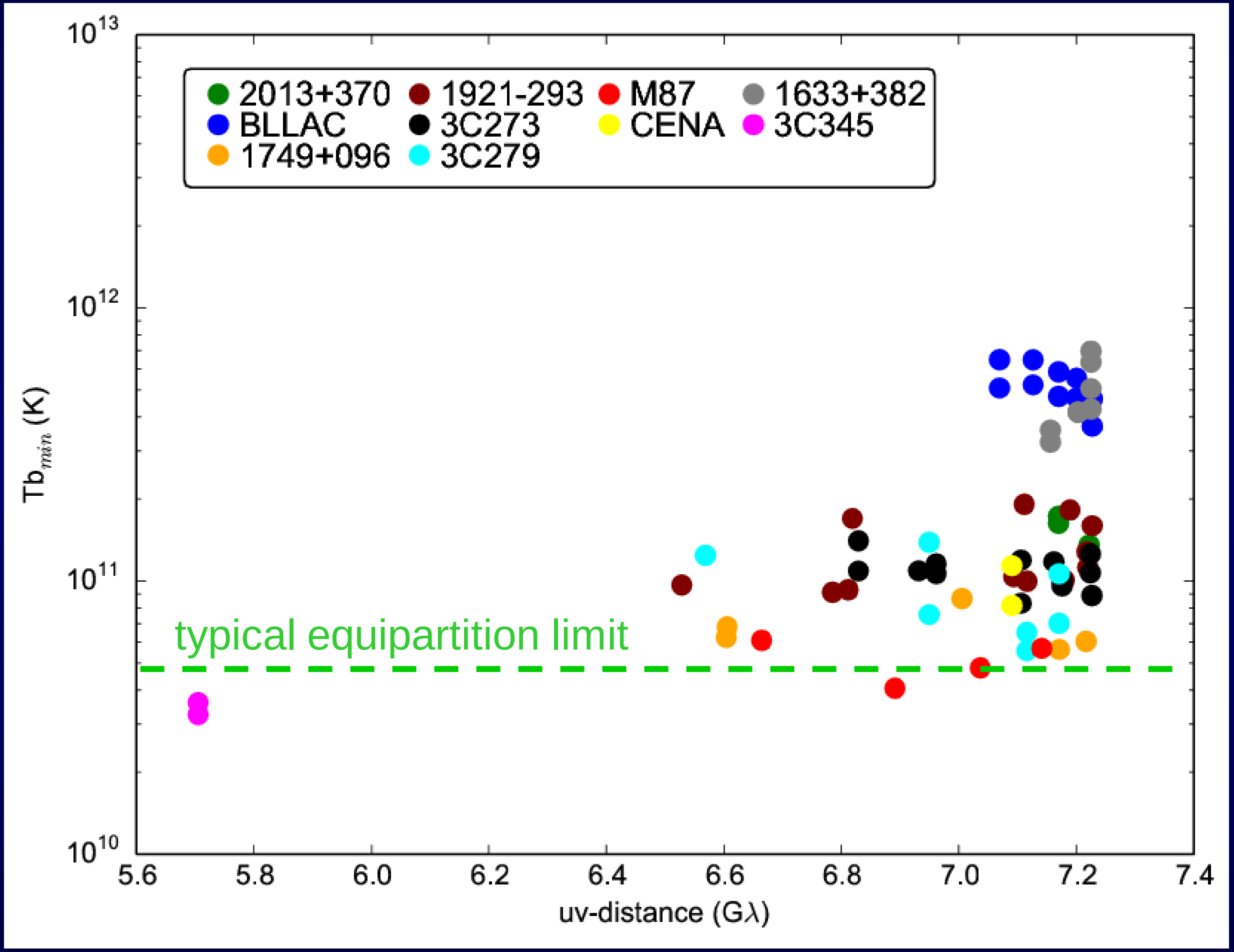
★ existing

★ planned

—— fringes established

Brightness temperatures of AGN detected @ 230 GHz

(March 2013, long baselines to APEX)



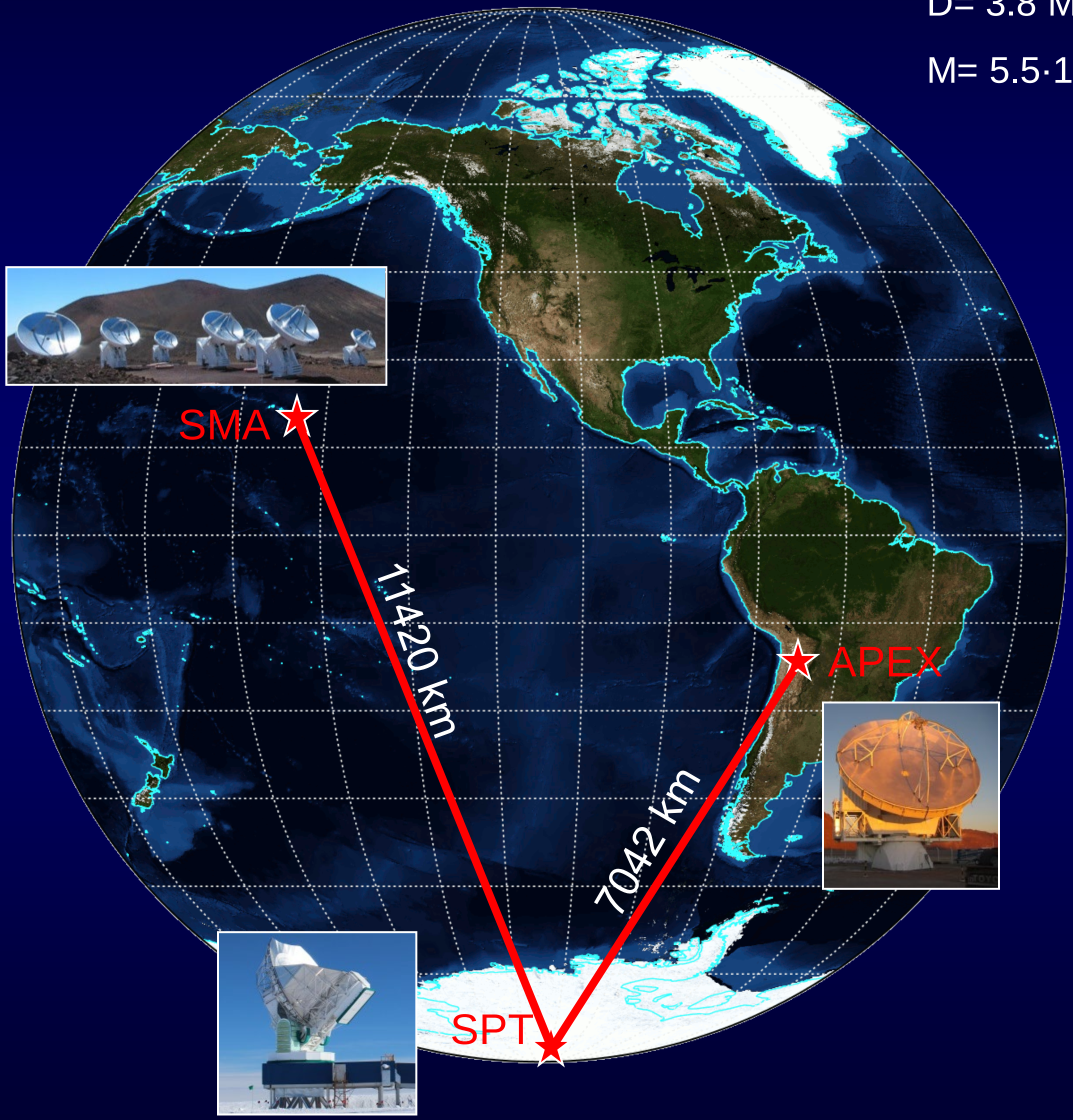
$$T_{B,int} = T_{B,meas} \frac{(1+z)}{\delta}$$

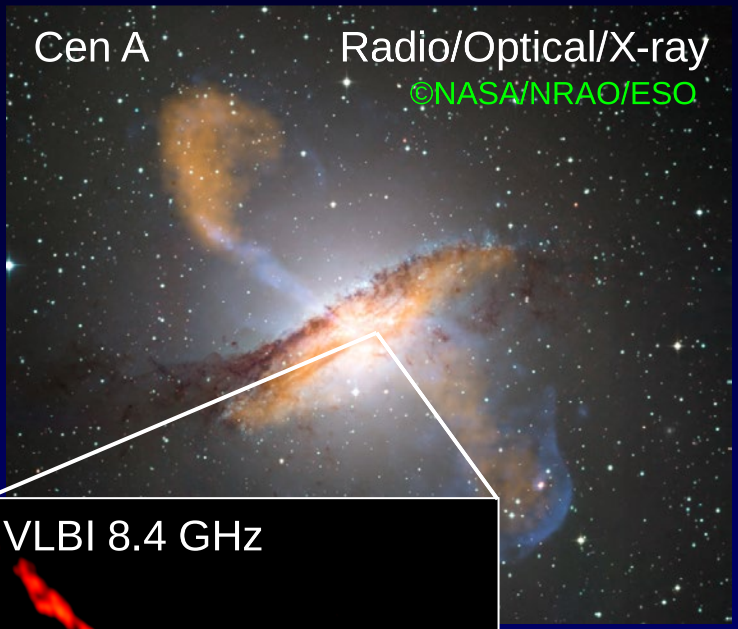
here: Doppler correction not yet applied

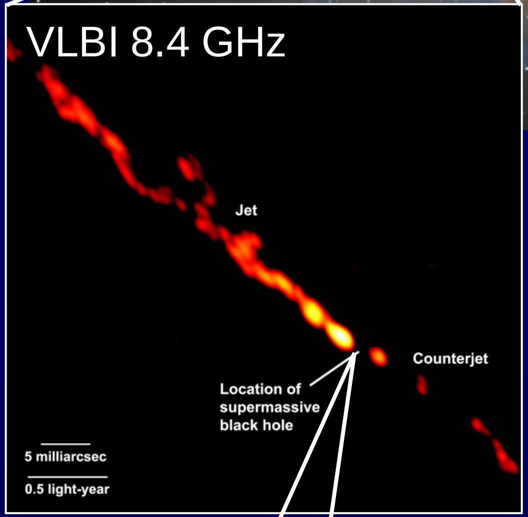
1.3 mm VLBI pilot observations of Centaurus A

D= 3.8 Mpc

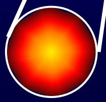
M= $5.5 \cdot 10^7\ M_\odot$







Müller+ 2014



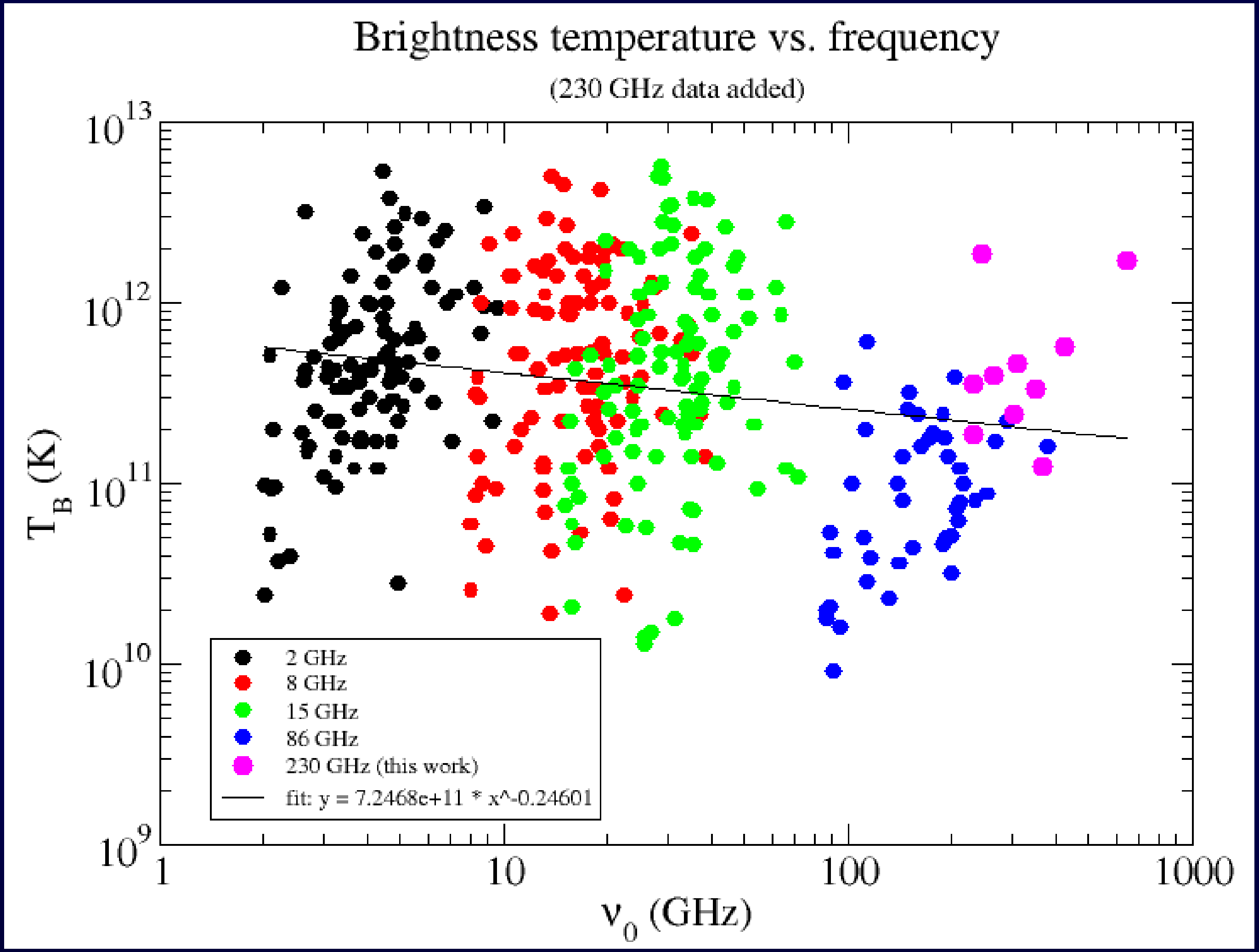
$T_B \geq 8 \cdot 10^{10} K / \delta$

compact VLBI core

$\leq 29\ \mu as\ (\sim 100\ R_S)$

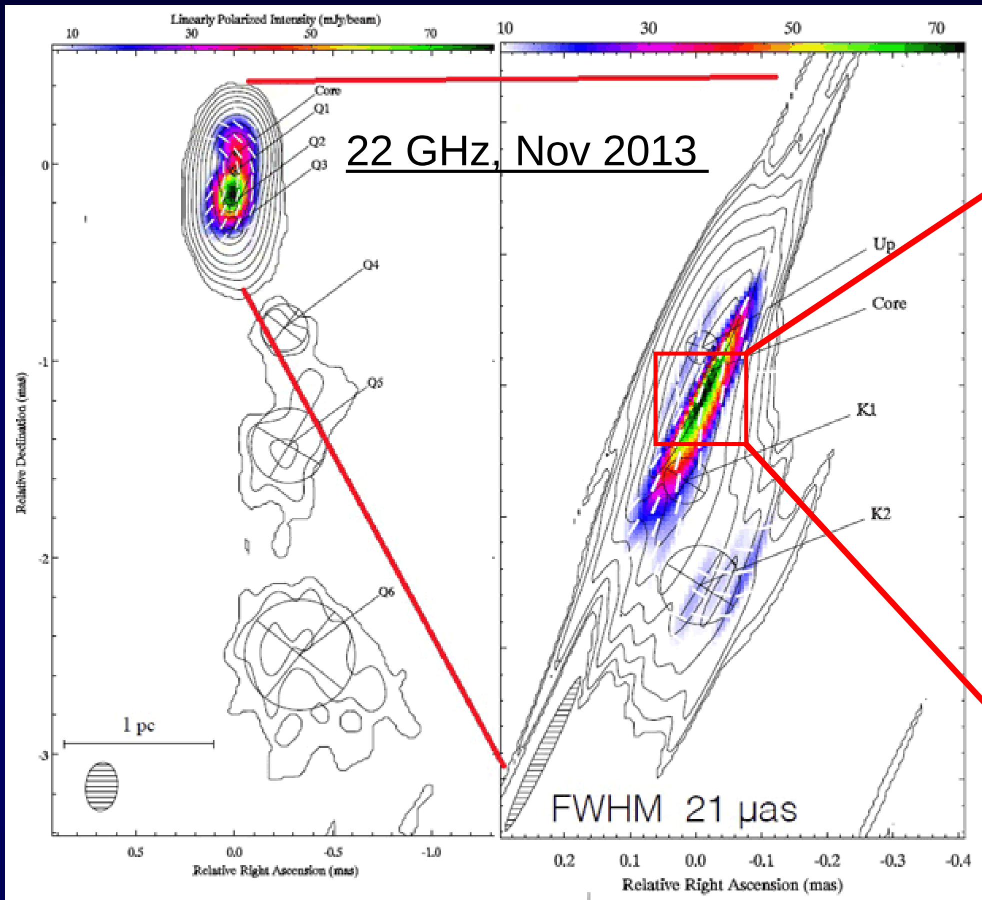
data: Marrone, Roy + EHT team

1.3mm T_B measurements added to lower frequency data of Lee et al. 2016

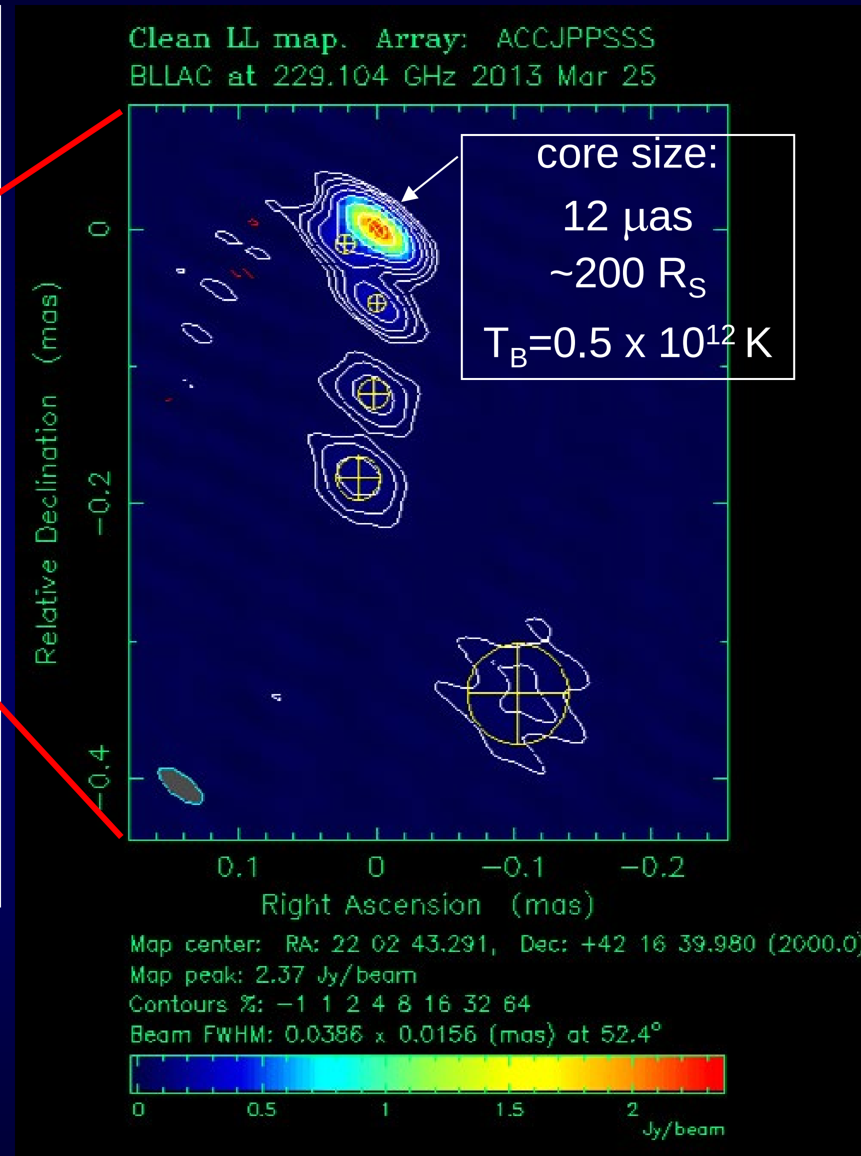


T_B decreases with frequency but perhaps not so strong as indicated previously

BLLac: Comparison 22 GHz Radioastron vs. 230 GHz EHT



Gomez et al. 2016

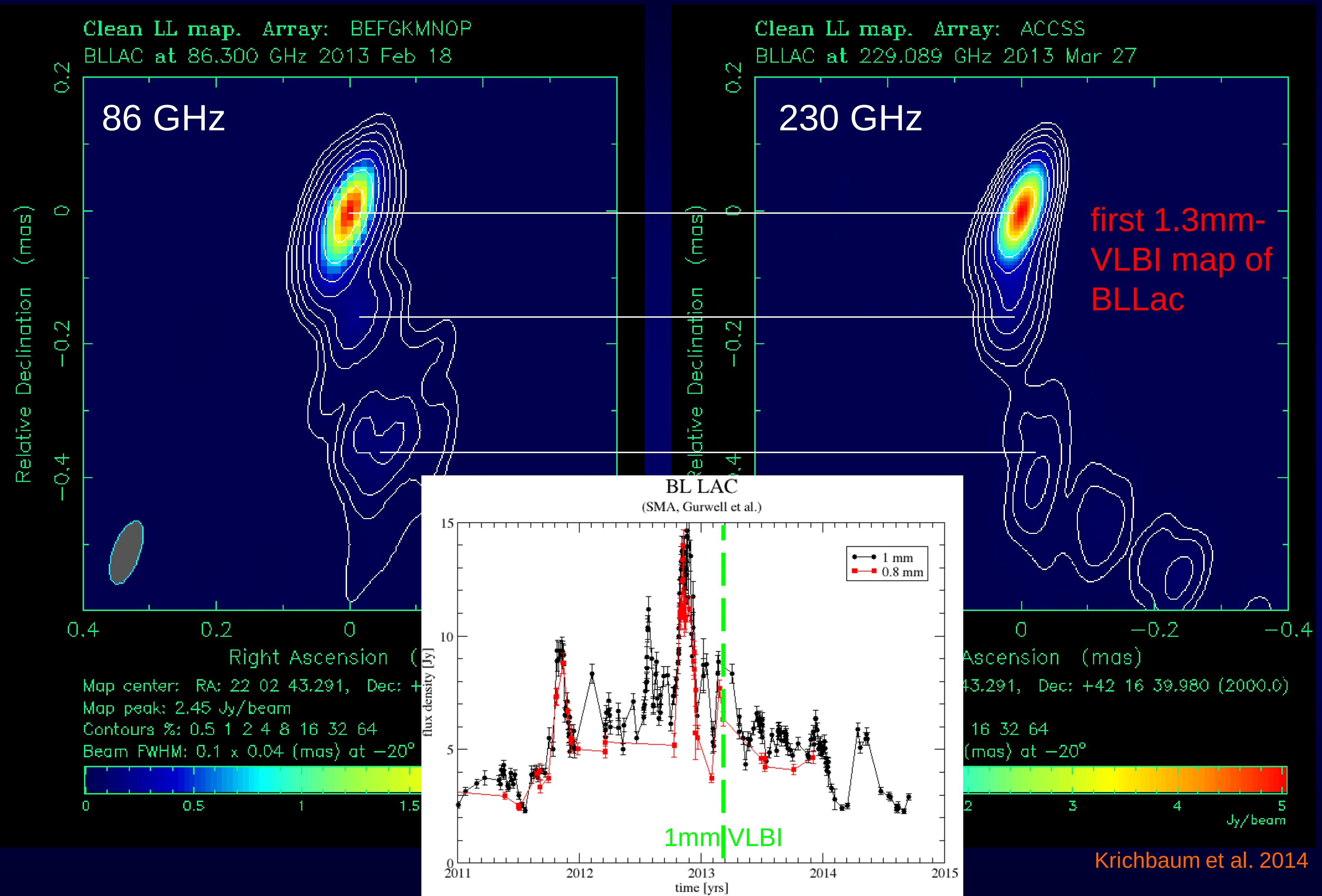


new 1.3mm modelfit map →

1mm VLBI beam: 39 x 16 µas

651 x 267 R_S

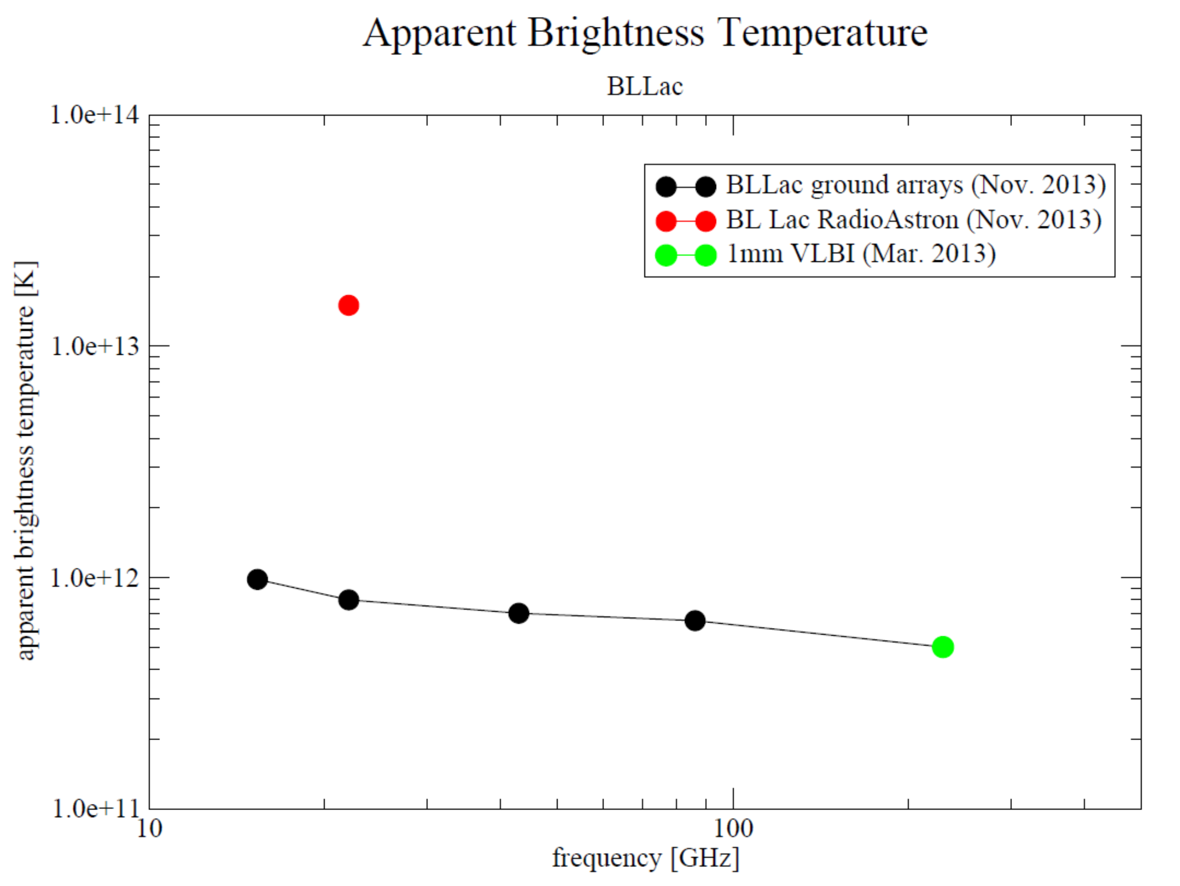
Comparison of BLLac images from 3mm GMVA & 1.3mm EHT



Krichbaum et al. 2014

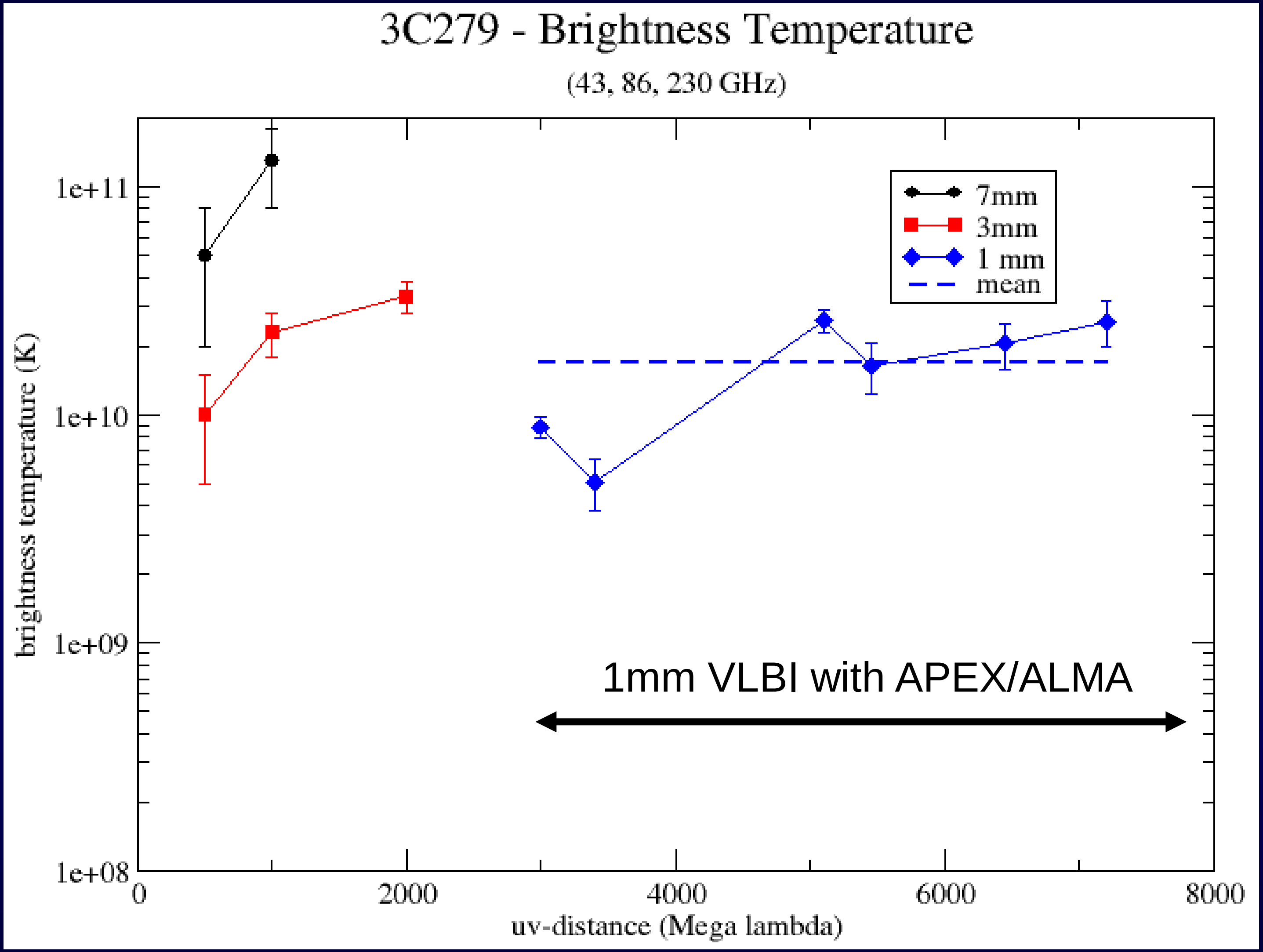
BL Lac: frequency dependence of brightness temperature up to 230 GHz

- T_B from space VLBI a factor of ~10 higher than from ground
- very shallow decrease of T_B with frequency
- $T_{B,min}$ just below IC limit
- since intrinsic $T_B \sim \delta^{-1}$,would need $\delta > 15$ to enforce magnetic energy dominance on < sub-pc scales
- unless the Doppler-boosting would be very large, the jet is dominated by particle energy



data: Lister+ (15 GHz), Gomez+ (22 GHz), Jorstad+ (43 GHz), Rani+ (86 GHz), Krichbaum+ (230 GHz)

Brightness temperature of 3C279 in May 2012



brightness temperature at 1mm : (1.7± 0.9) 10^{10} K * (1+z) = (2.6 ± 1.4) 10^{10} K

accuracy of size measurement
determined by SNR visibilities at
a given uv-spacing:

$$\theta_{\lim} = b_{\psi} \sqrt{\underbrace{\frac{4 \ln 2}{\pi}}_{0.88} \ln\left(\frac{\mathrm{SNR}}{\mathrm{SNR}-1}\right)}$$

at 1mm with APEX: SNR=13 → 0.26 * beam ~ 7 μas

at 1mm with ALMA: SNR=500 → 0.04 * beam ~ 1 μas ← need this !

time variability

of jet visibilities

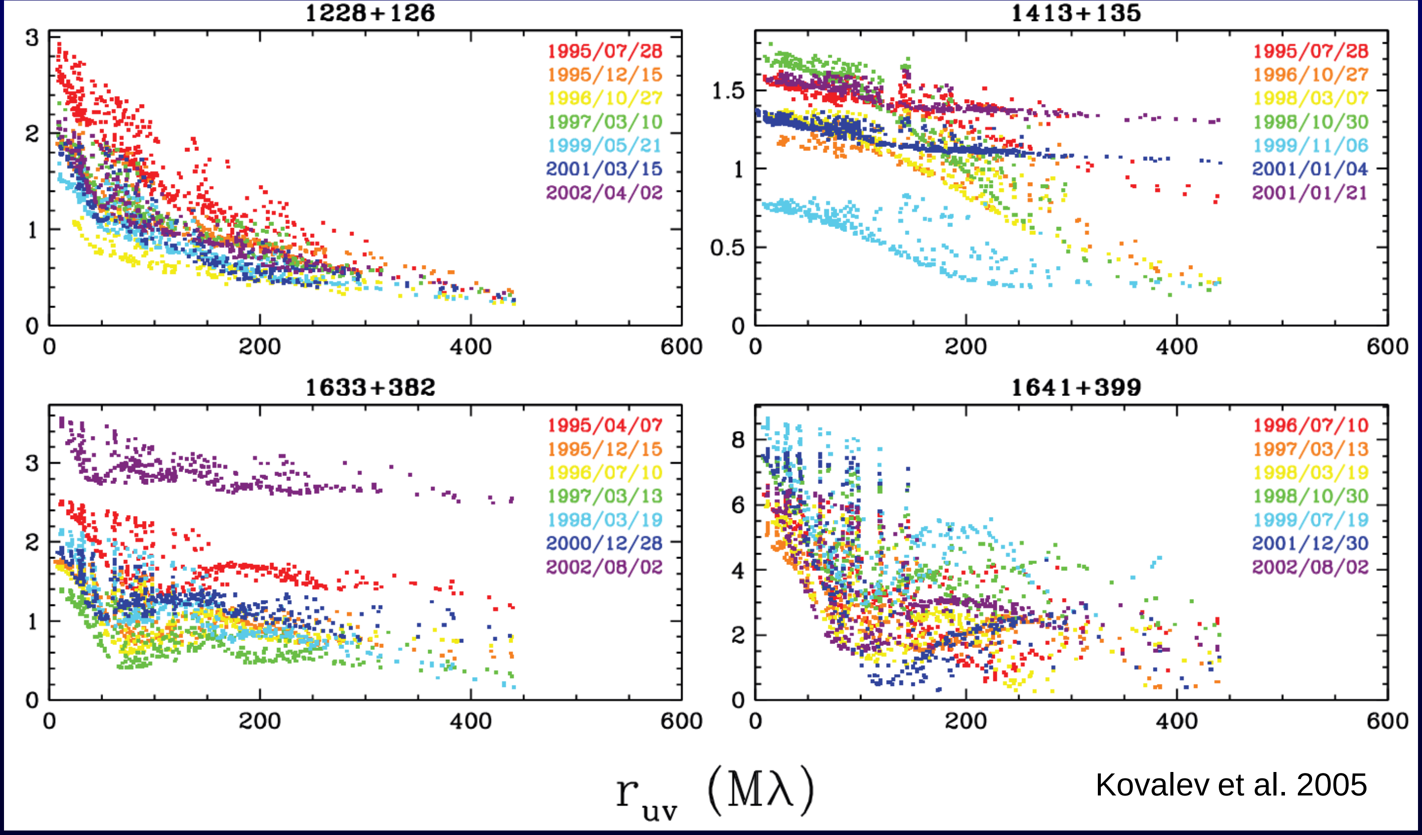
at 15 GHz

(Mojave AGN sample)

dramatic variations

of compactness on

≤ 1 year timescale !



Kovalev et al. 2005

Participation of ALMA in global 3mm VLBI

Credit P. Carillo - ALMA (ESO/NAOJ/NRAO)

sensitivity on ALMA baselines:

(10s, 2 Gbps)

ALMA – GBT	:	6 mJy
ALMA – IRAM	:	15 mJy
ALMA – Eb/Yb	:	20 mJy
ALMA – VLBA	:	30-40 mJy

dynamic range from imaging simulations:

GMVA with ALMA	:	1623
GMVA with GBT	:	1007
GMVA w/o GBT	:	864
VLBA stand alone	:	674

ALMA 3mm fringes to USA and Europe established

Summary and Outlook

- the brightness temperatures of AGN jets stays high at 3mm and 1mm wavelength
- jets are stratified on sub-pc scales and accelerate
- small cores size in M87 could be explained by stratification,
- expect differential boosting between northern and southern arm
- measured T_B of AGN sample, does not show strong evidence for magnetic jet launching (unless Dopper-factors on 10-100 R_G scale would be > 10)

- calibration limitations are overcome by large array size
- the addition of large telescopes is needed to further increase the sensitivity (ALMA, LMT, NOEMA, SRT, ...)
- the increase of the observing bandwidth beyond 2 Gbps is developped actively (ALMA: up to 64 Gbps)
- need a much denser time sampling to trace rapidly evolving sources at mm-λ
- 3mm VLBI (uv, rms) and 1.3mm VLBI (beam) complement each other very nicely