The Global Millimeter VLBI Array:

The central regions of Active Galactic Nuclei and the Origin of Jets

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(on behalf of the GMVA team)

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MPIfR: W. Alef, U. Bach, D. Graham, T. Krichbaum, R. Porcas, A. Zensus, et al.

Onsala: J. Conway, M. Lindquist, H. Olofsson, et al.

Metsähovi: A. Mujunen, M. Tornikoski, E. Valtaoja, et al.

NRAO-VLBA: V. Dhawan, C. Walker, et al.

Scientific Contributions/Collaborations:

Boston: A.Marscher, S. Jorstad, I. Agudo, et al.

KVN: S.S. Lee, B.W. Sohn, et al.

MIT-Haystack: S. Doeleman, V. Fish, et al.

FGAMMA program: L. Fuhrmann, M. Angelakis, I. Nestoras, et al. (MPIfR)

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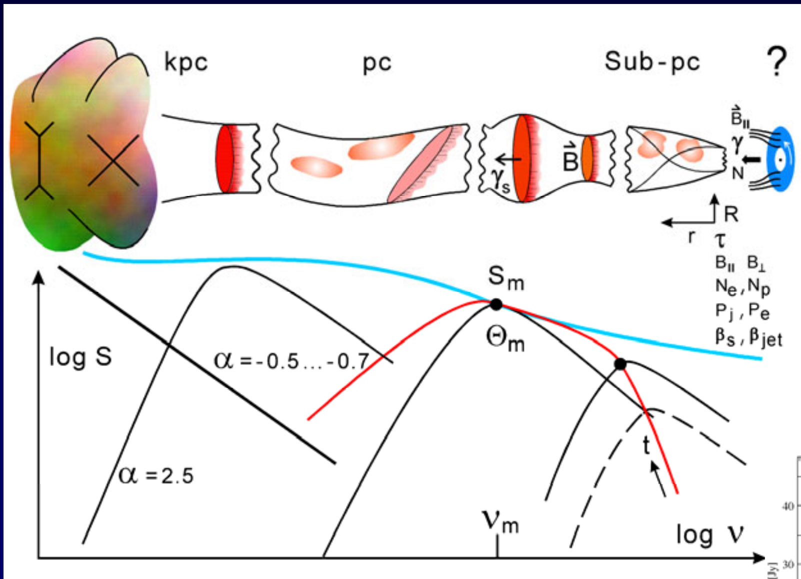
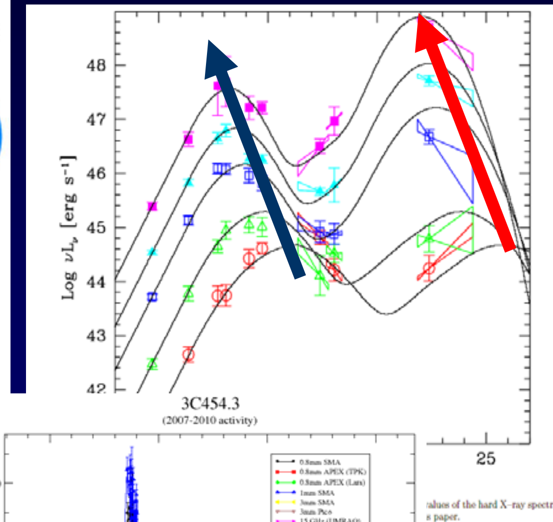
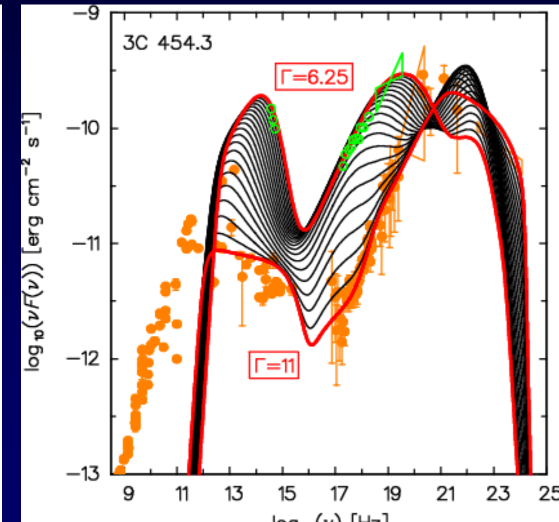
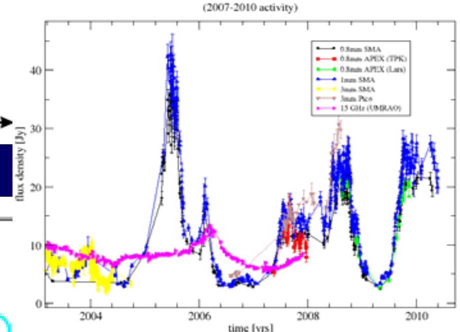
Motivation for mm-VLBI: The Physical Origin of Jets

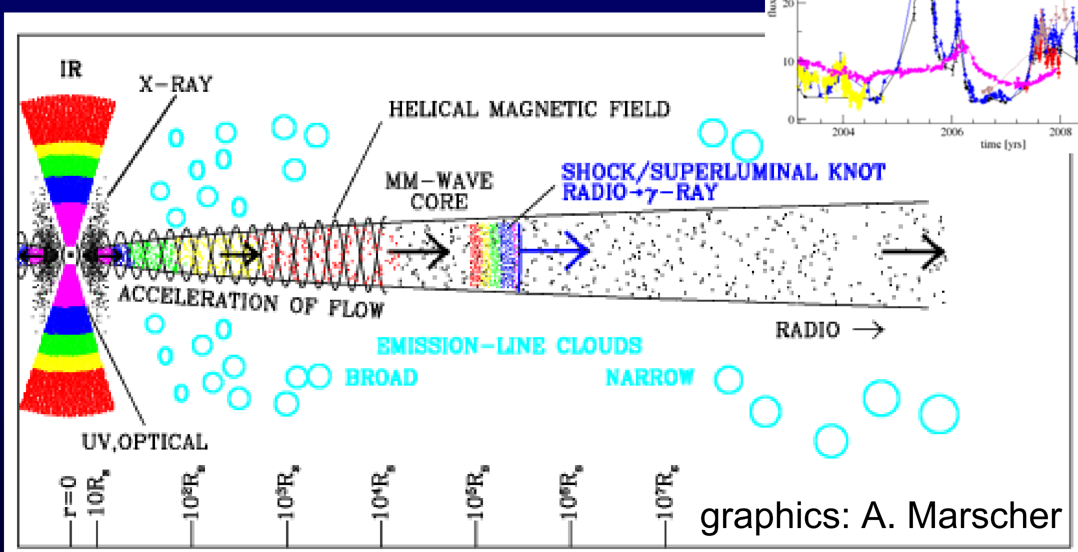


Broad-band Spectral Energy Distribution – Relation to source structure

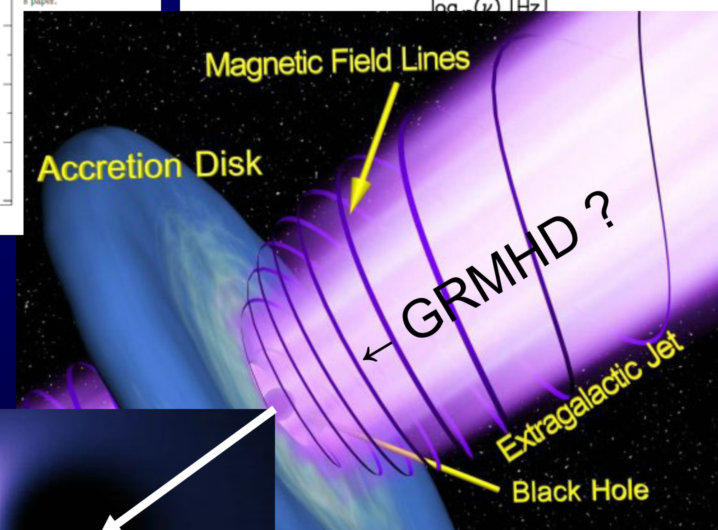






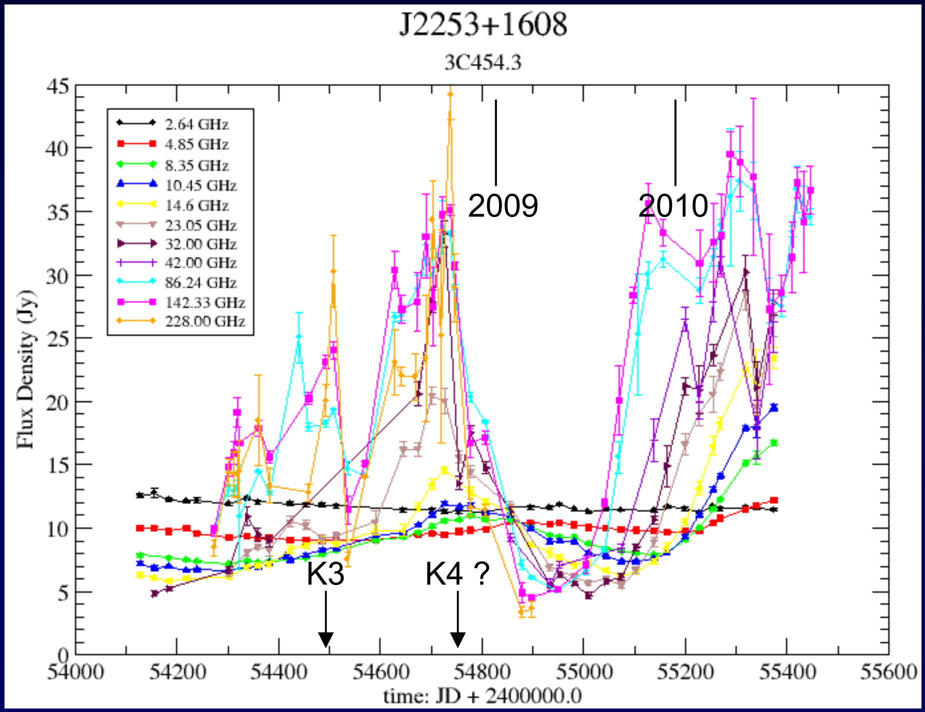


graphics: A. Marscher



Jet-disk coupling and imaging of Event Horizons near SMBHs

3C454.3 – Spectral Variability in Radio-Bands



complex spectral evolution

time-lags vary between flares

mm-variability: high $T_B > 10^{11...12}$ K

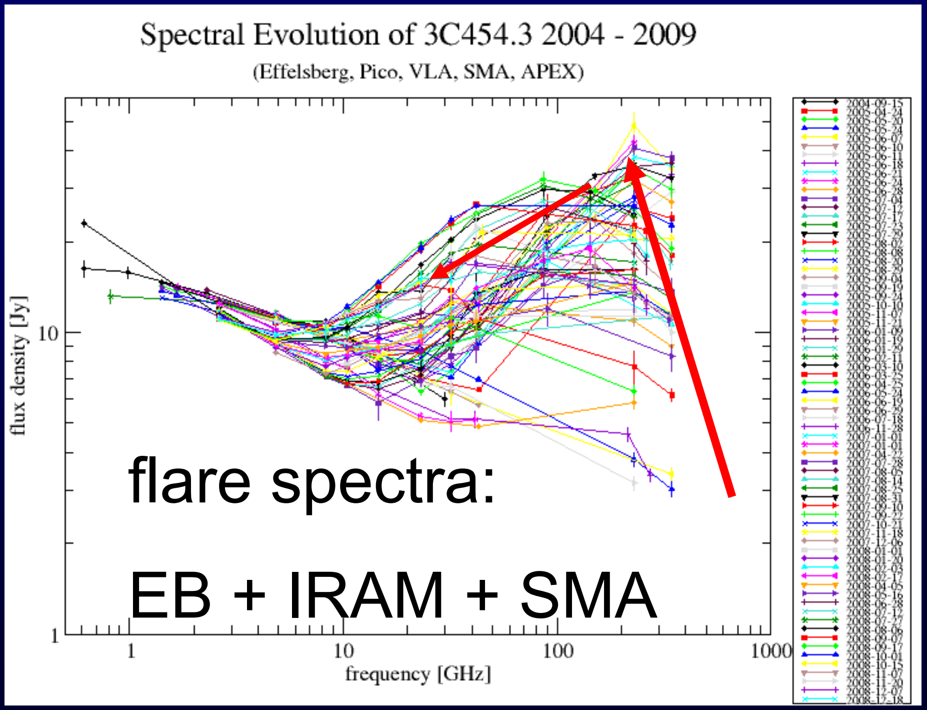
I. Pauliny-Toth's: "superluminal brightening"

data: FGAMMA collaboration (Fuhrmann et al.)

spectral variability most pronounced and fastest at mm-/submm λ (turnover ν_{max} ~ 40-230 GHz)

variability timescales of days to months lead to sizes of ~1-100 μas (or < 5-50 milli-pc)

→ need mm-VLBI to monitor these regions !



What does VLBI at short millimeter wavelengths offer ?

- Study compact galactic and extragalactic radio sources and their jets with an angular resolution of a few ten micro-arcseconds in early stages of their kinematic evolution.

- Image regions which are (self-) absorbed and therefore not observable at longer cm-wavelength (spectrum, radiation/energy transport, outburst – ejection relations from radio to γ – rays, counter-jets + torus).

- Study of the region of jet formation with highest achievable resolution (size & shape of jet at its base, 3D curvature + transverse jet structure, kinematics, spectrum, polarization & B-field).

- For nearby SMBHs (SgrA*, M87) reach scales of ≤ ~10 gravitational radii, image Event Horizon and regions where GR-effects become important (orbital motion in accretion disk, light-bending, relativistic precession, frame dragging + BH rotation, jet-disk coupling (GRMHD), jet nozzle).

For all of this we need a high as possible observing frequency and a small as possible observing beam. Global VLBI at ≥ 86 GHz provides this.

The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

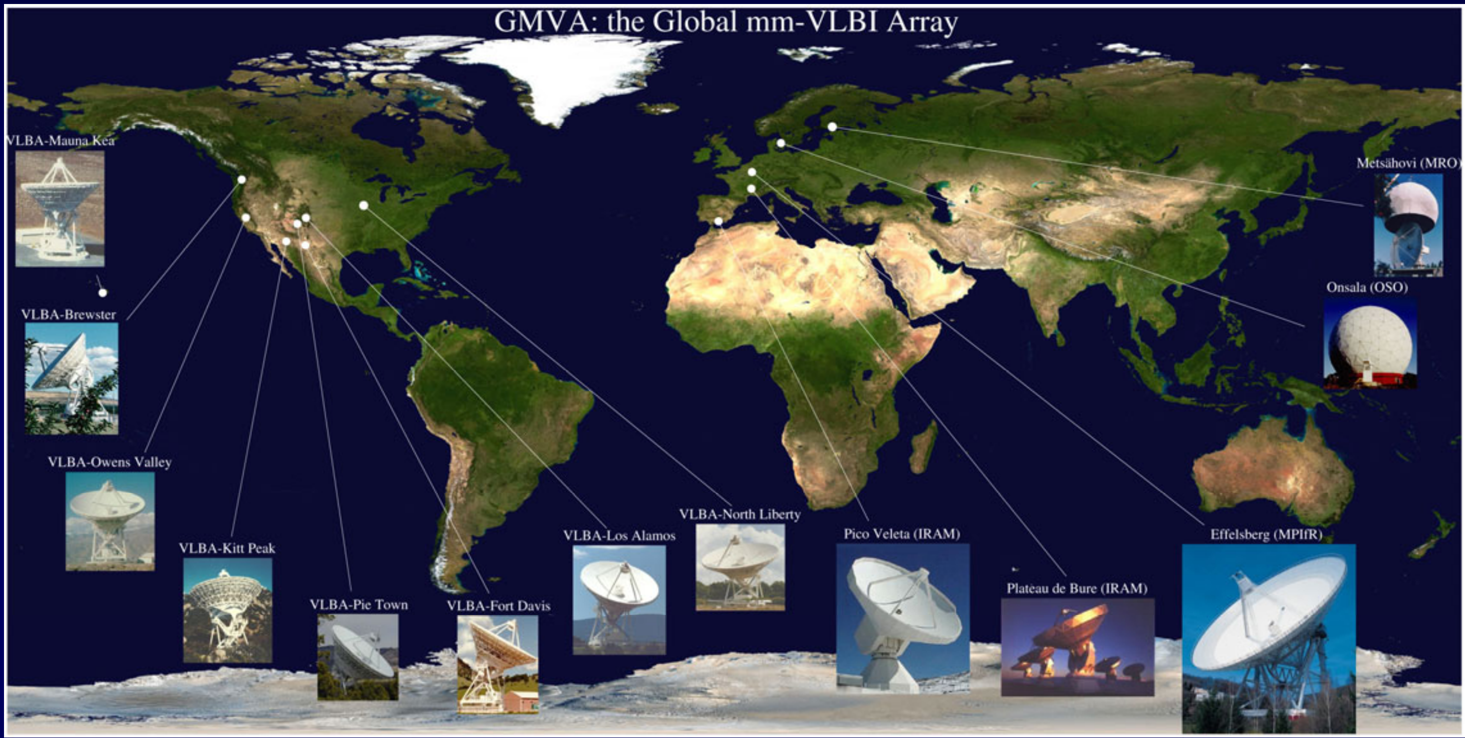
100 – 300 mJy

transatlantic:

50 – 300 mJy

Array:

1 – 3 mJy / hr



(assume 7σ, 100sec, 512 Mbps)

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

- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), planned: Yebes (40m)
- USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, October 1st

Global 3mm VLBI: History and Overview

- History of 3mm-VLBI
  - 1981: first mm-VLBI experiments successful
  - early 1990's: formation of the Coordinated Millimeter VLBI Array (CMVA) by Haystack observatory in conjunction with a number of mm-capabale observatories
  - throughout the 1990's: efforts to enhance and expand this collaboration e.g. provision of VLBI recorders and masers to IRAM by MPIfR, outfitting VLBA antennas with 3mm receivers
  - 2002: disengagement of Haystack obs. and last CMVA session in Autumn 2002
  - early 2003: MPIfR initiative to continue the facility, MoU between MPIfR, NRAO, IRAM, OSO and MRO for future, global VLBI at 3mm

→ new organisation: the Global mm VLBI Array (GMVA)

  - September 2003: first GMVA Call for proposals, include phased PdB
  - April 2004: first GMVA observations
  - 2005: switch to MK5A disk recording, add dual polarisation
  - 2007/2008: PdB upgrade (better phasing stability, new H-maser)
  - 2009: new EMIR receiver at PV, better sensitivity

Current Operation of the GMVA

- Observing sessions
  - 2 sessions per year (spring/autumn) , each up to 5 days duration (dates fixed 6-12 months in advance)
- Proposing for observations
  - proposal deadlines 1st February, 1st October), ‘Call for proposals’ 6 months in advance
  - information for astronomers wishing to use the GMVA is provided by a web page: http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/index.html
  - proposal review by participating GMVA observatories following their own internal procedures. Results collated by the European GMVA Scheduler, a joint decision is made together with the VLBA scheduler regarding scheduling
- Observations
  - European and VLBA schedulers jointly agree a block schedule for each session
  - PI of proposals provide scheduling details of their observations in collab. with the Schedule Coordinator at MPIfR
  - Schedule Coordinator provides a final, integrated session schedule to the GMVA observatories (taking into account e.g. need for pointing checks, antenna calibration, etc.)
  - individual GMVA observatories perform the observations on behalf of the investigators with often MPIfR logistical and observing support and expertise at the IRAM sites
  - disk-based MK5 recording systems: recording rate of 512 Mb/s as default for all GMVA continuum observations
  - correlation at Bonn MK4 correlator; data conversion to UV-fits AIPS standard

Enhance 3mm global VLBI by including the 3 largest European high frequency-telescopes:


Effelsberg 100 m (MPIfR)


Plateau de Bure, 6 x 15 m (IRAM, France)


Pico Veleta 30 m (IRAM, Spain)

Baseline lengths (km):

	PdB	PV
EB	658	1700
Pdb		1146

fringe spacing: 0.4 – 1.1 mas,

sensitivity > 50 -90 mJy (7σ, 512 Mbps)

GMVA Proposal and Observation Statistics 2003 – 2010

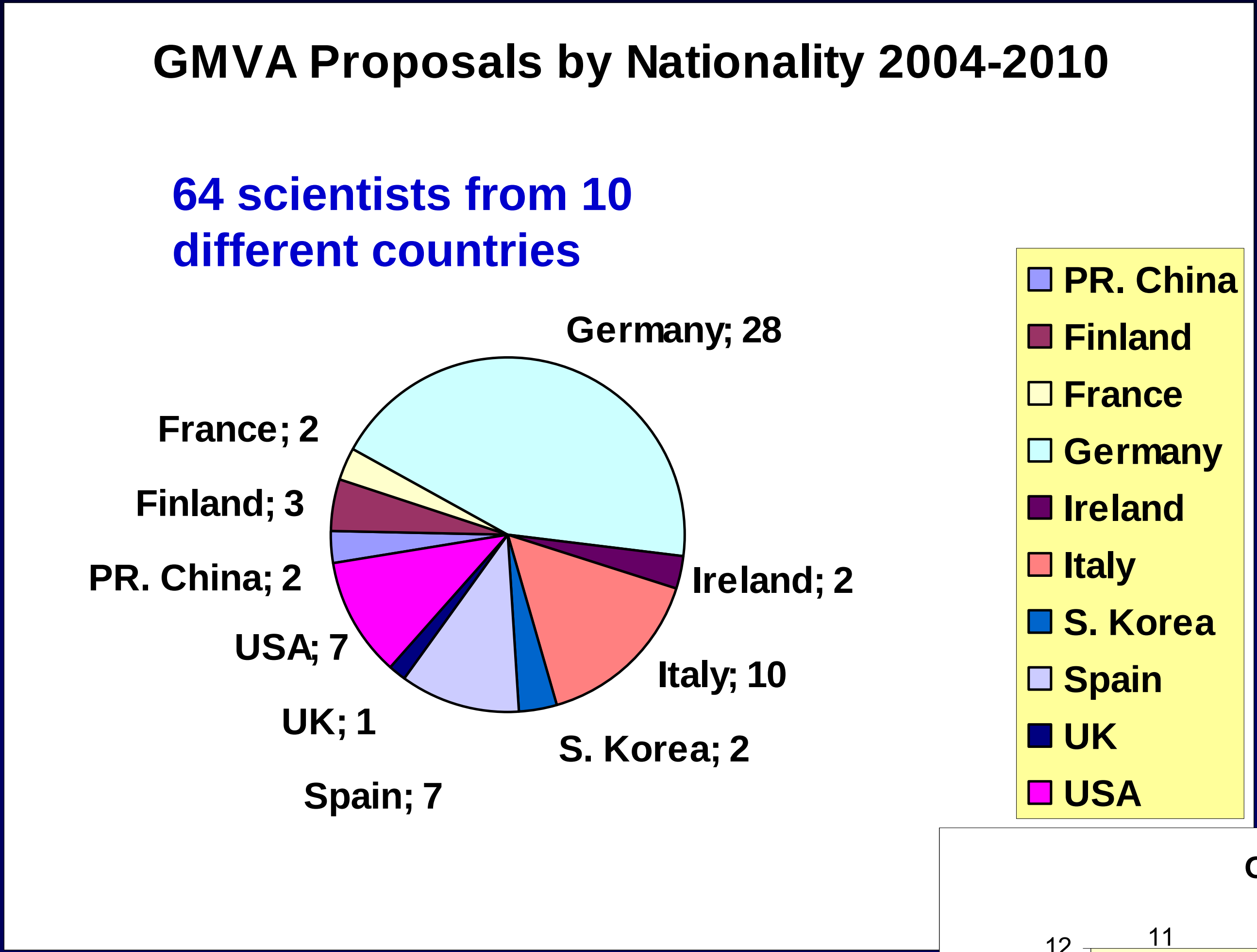
- Proposals
  - 15 proposal deadlines since October 2003 with a total of 61 submitted proposals (including Oct. 2010), many for multi-epoch monitoring covering several sessions
  - dual polarisation requested now in most proposals, spectral line (SiO masers) in 1 proposal, often strong and compact (famous) AGNs for up to 6 epochs (e.g. 3C84, 3C454.3, BL Lac, OJ287, NRAO150), γ-ray sources (Fermi, Boston, Bologna)
  - 20 out of the 61 so far reviewed proposals rejected, 5 approved for partial observation
  - 4 MPIfR-IRAM add hoc observations, ToOs

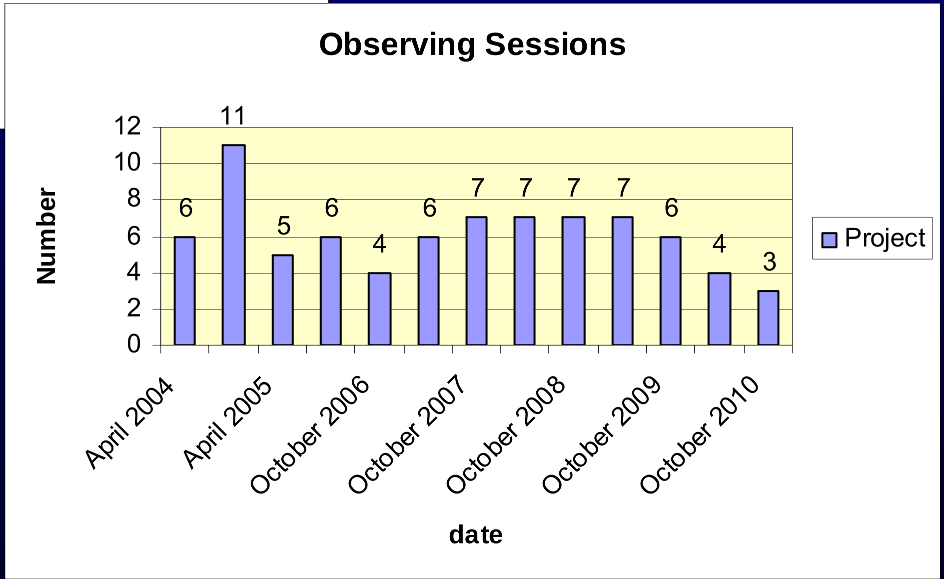
Detailed Proposal and Observation statistics:

about 70% of the proposals make it on the sky

Deadine Year	Proposals	rejected	Observations	rejected
October 2003	6	0	11	0
February 2004	8	3,5	15	7
October 2004	4	1	10	1
February 2005	3	1	9	3
October 2005	3	2,7	7	6
February 2006	5	0	18	0
October 2006	2	1	3	1
February 2007	3	1	8	2
October 2007	6	3,3	12	7
February 2008	2	1,75	5	4
October 2008	4	2	9	4
February 2009	3	1	4	1
October 2009	3	1	5	1
February 2010	3	1,3	8	4
October 2010	6		12	
Sum	61	20,55	136	41

GMVA – Proposal statistics





Observed experiments: 87

about 50% multi-epoch

Why is mm-VLBI still non-standard and requires special care ?

- variable weather, non optimum observing conditions, limited scheduling flexibility
- phase fluctuations and short atmospheric coherence time (< 20s)
- limitations at telescopes (pointing, focusing, gain curves, low η_A, etc .)
- limited bandwidth, low SNR in 8-16 MHz wide IFs (frequency synthesis)
- alignment of IFs (man. phasecal problem)

Solution:

better control of telescope gain, larger bandwidth+DBEs, more mm-telescopes

phase correction (WVR), improved analysis software (eg. fringe fitting),

AND more accurate:

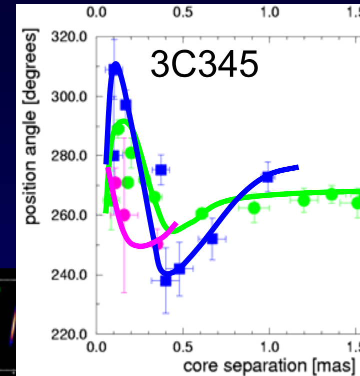
calibration, calibration, calibration, ...

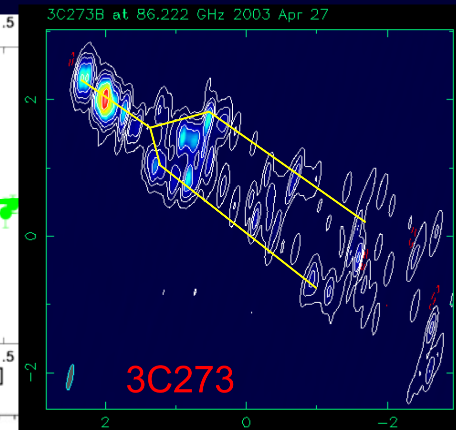
Important: mm-VLBI relies on ampl. self-cal, works well only for N > 10 antennas !

Highlights from recent 3mm-VLBI with the GMVA

- stratified + helical jets (3C345, 3C273)

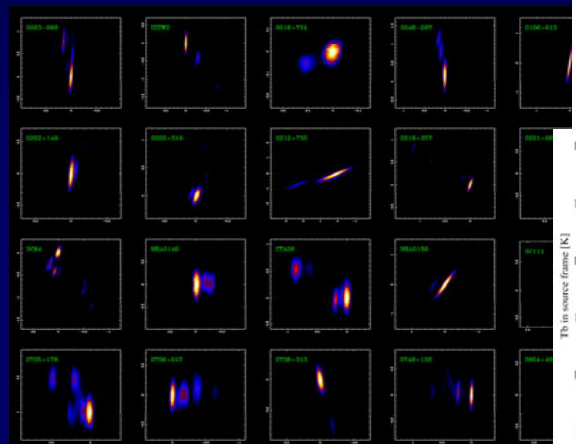
e.g. Qian et al. 2009 (RAA)

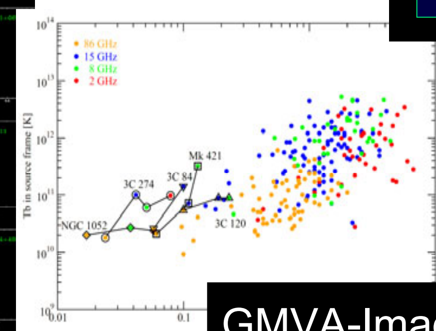




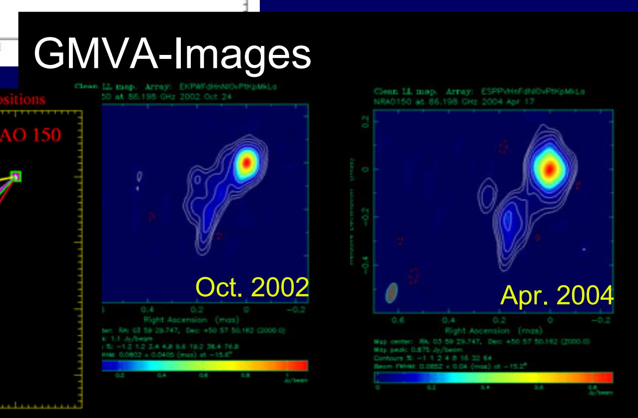
- 3mm AGN survey

(127 sources)

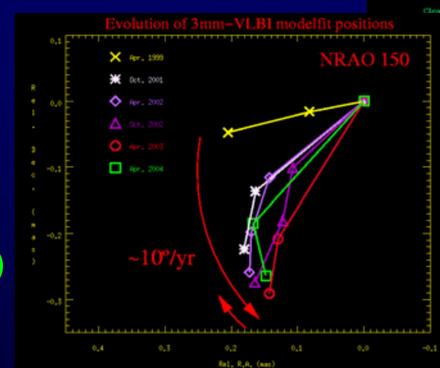




Lee et al. 2008 (AJ)

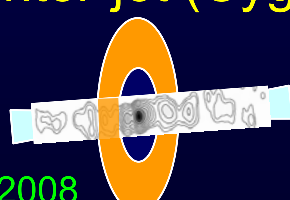


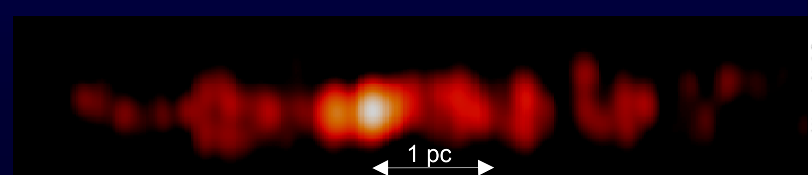
- precessing jet nozzle (NRAO150)

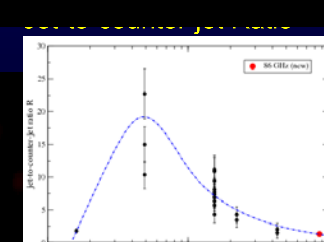


Agudo et al. 2007 (A&A)

- obscured counter-jet (Cygnus A)







Krichbaum et al. 2008

Results from the new 3mm VLBI survey (127 sources):

$$T_{\mathrm{b,s}} = \frac{2\ln 2}{\pi k_{\mathrm{B}}} \frac{S_{\mathrm{tot}}\lambda^2}{d^2}(1+z)$$

Brightness temperature decreasing with frequency ?

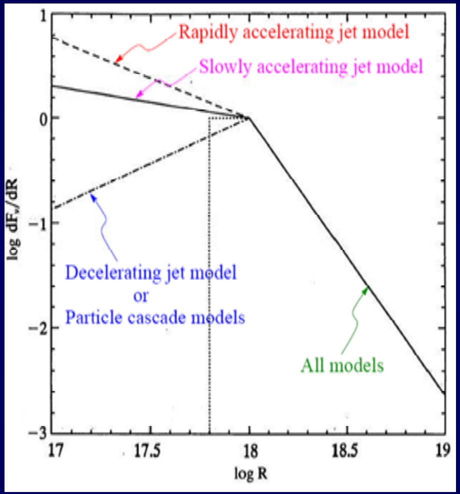
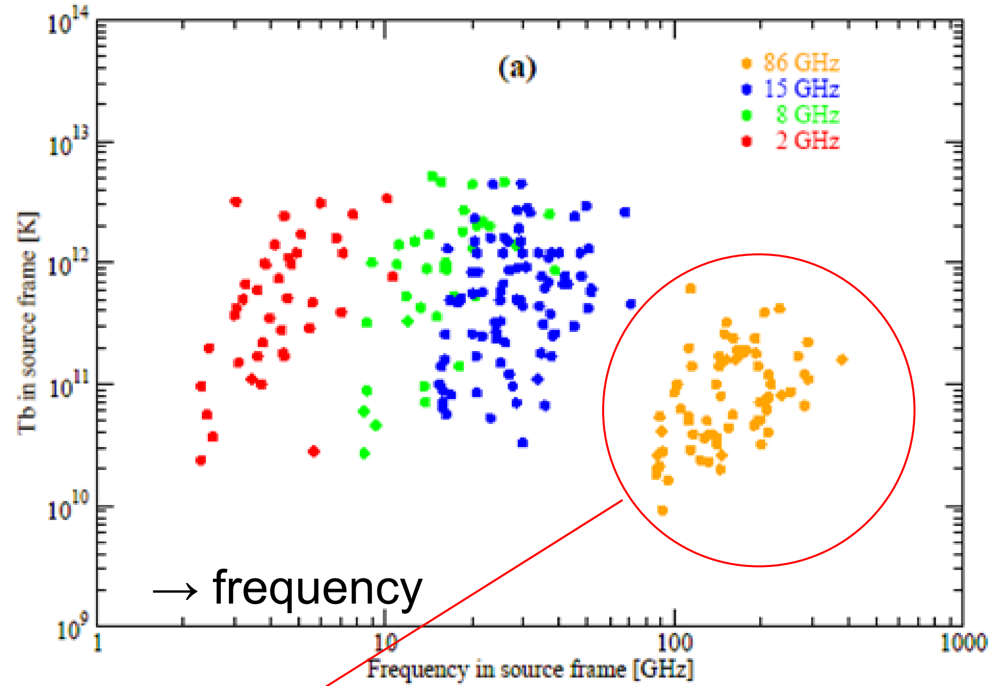
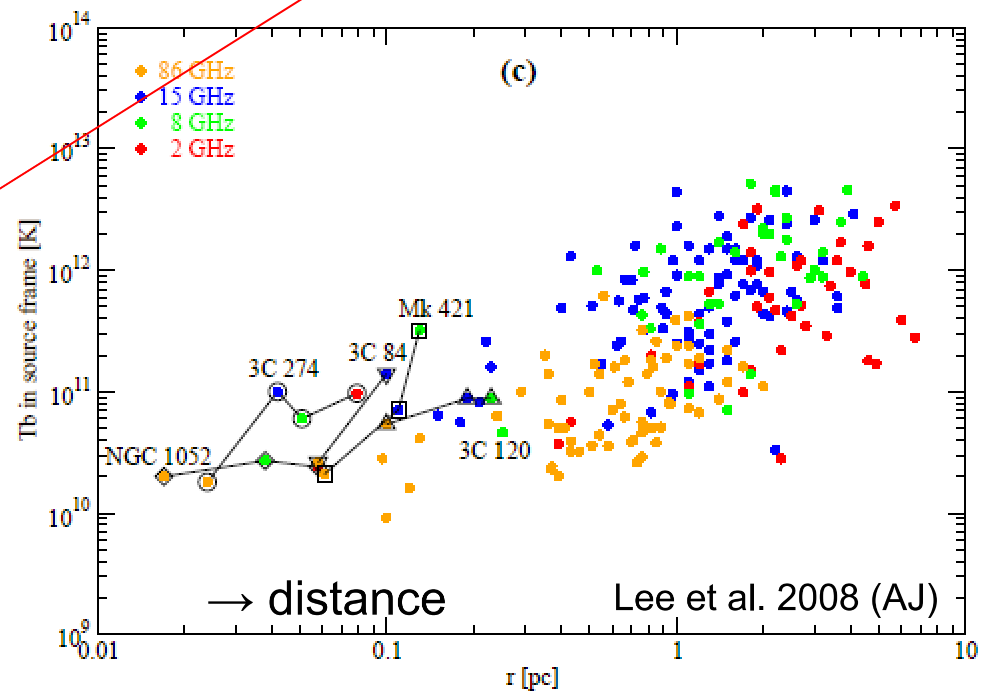


Figure from

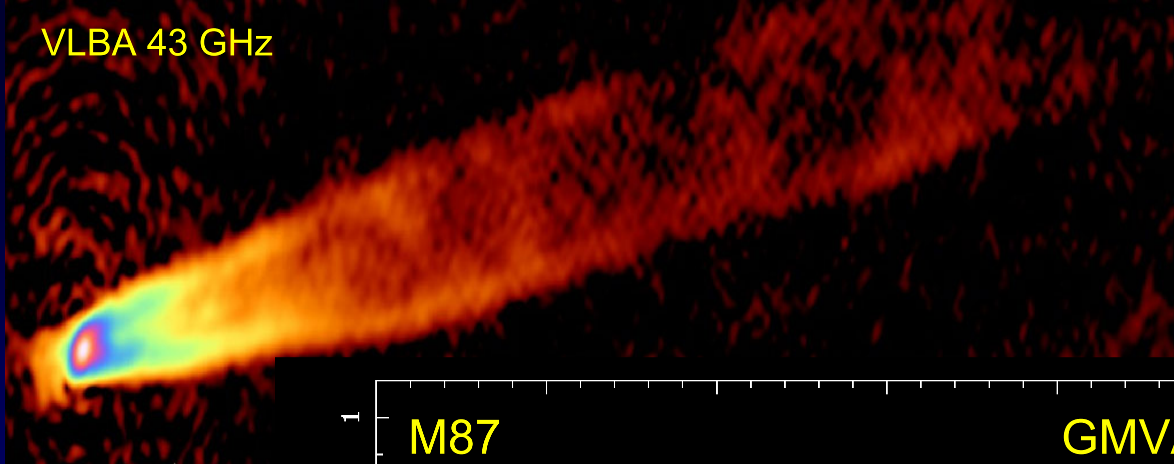
A. Marscher (1995)





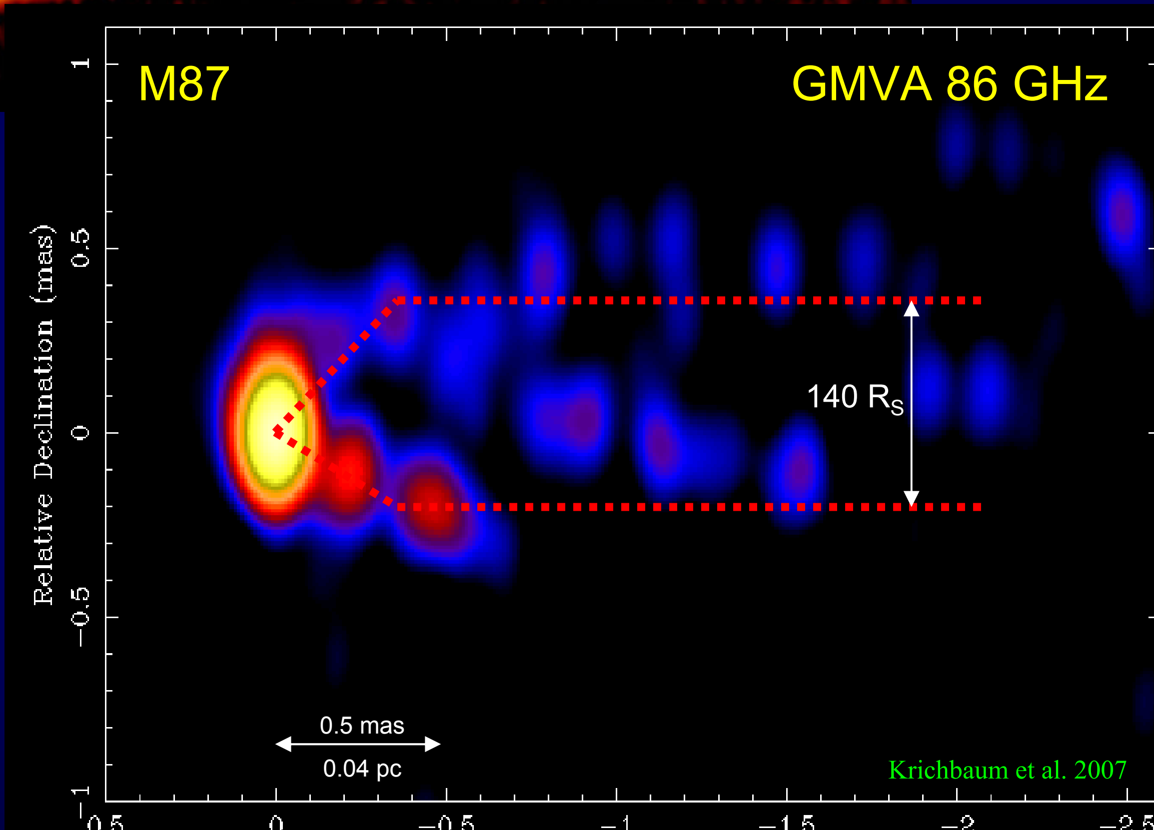
Brightness temperature increasing along jet; accelerating jets ?

a larger mm-VLBI AGN survey is needed !



Walker et al. 2008

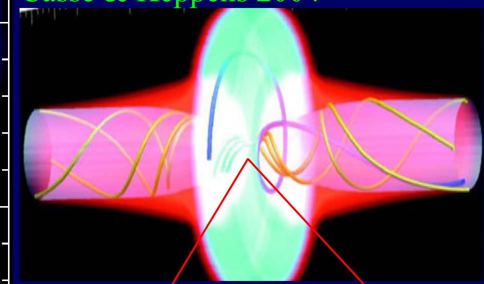
Size of jet base appears too small for magnetic sling-shot acceleration. Direct relation to BH more likely $\rightarrow$ a GR-MHD Dynamo ?

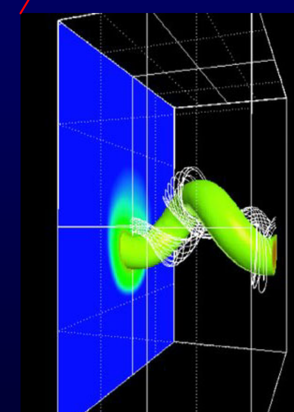


Krichbaum et al. 2007

MHD Jet Simmulation:

Casse & Keppens 2004





Mizuno et al. 2009

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

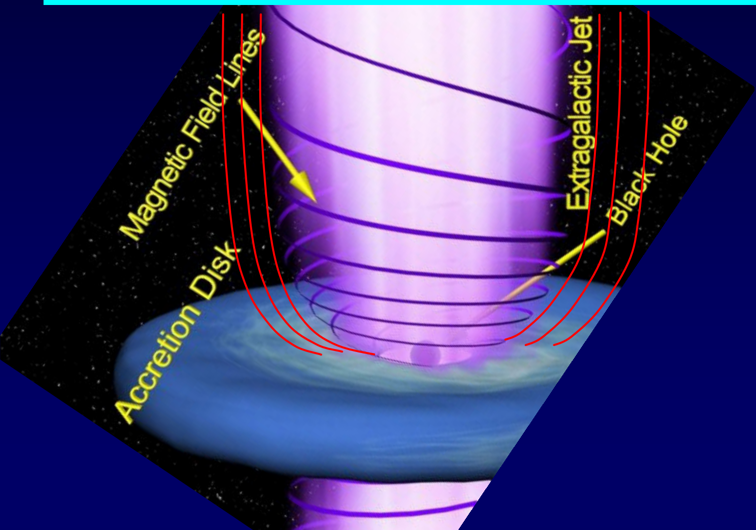
197 x 54 µas = 21 x 6 light days = <u>54 x 15</u> R_s

transverse width of jet at 0.5 mas: ~140 R_s

BP versus BZ mechanism

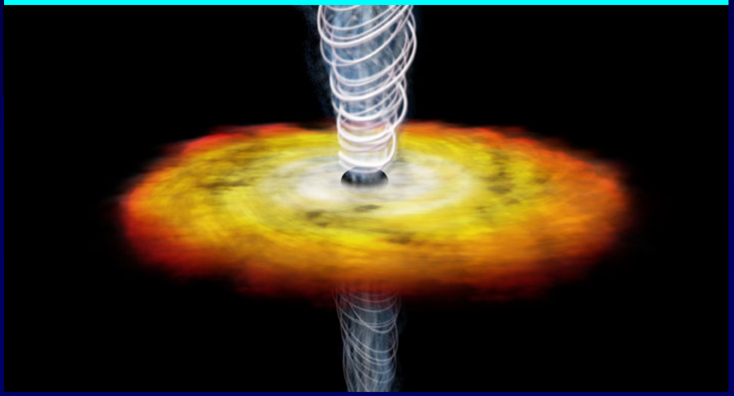
Blandford – Payne mechanism:

centrifugal acceleration in magnetized accretion disk wind



Blandford – Znajek mechanism:

electromagnetic extraction of rotational energy from Kerr BH



discriminate via

Jet speed

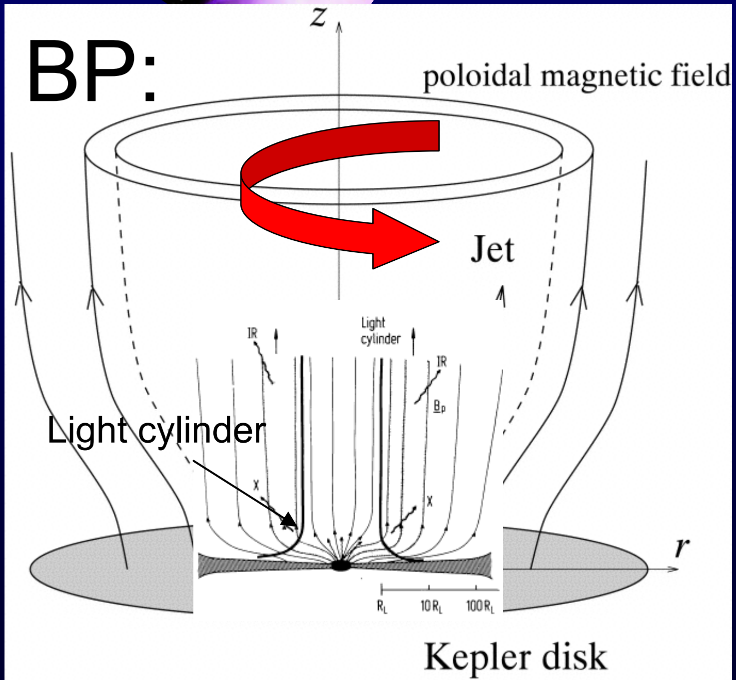
Jet width

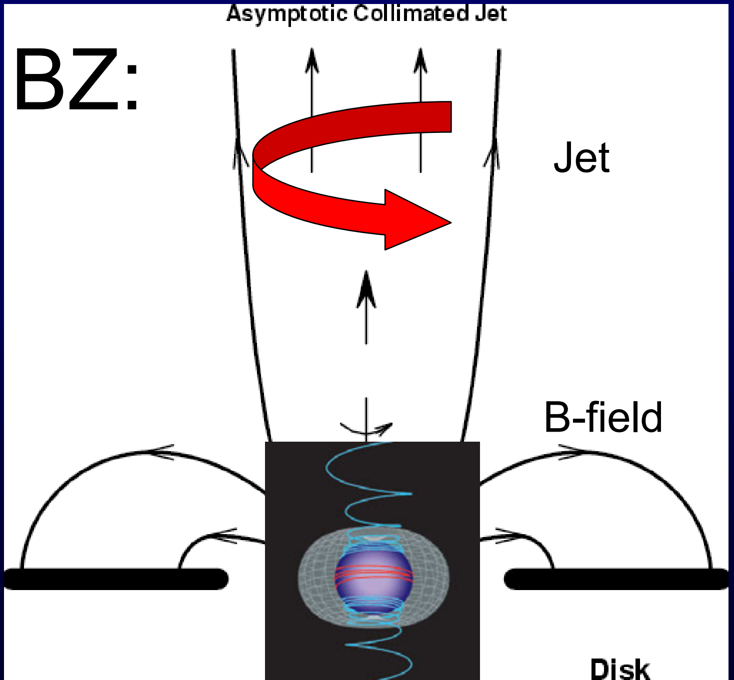
Shape of Nozzle

Jet structure

etc.

need to reach scale of ~1-10^3 R_G

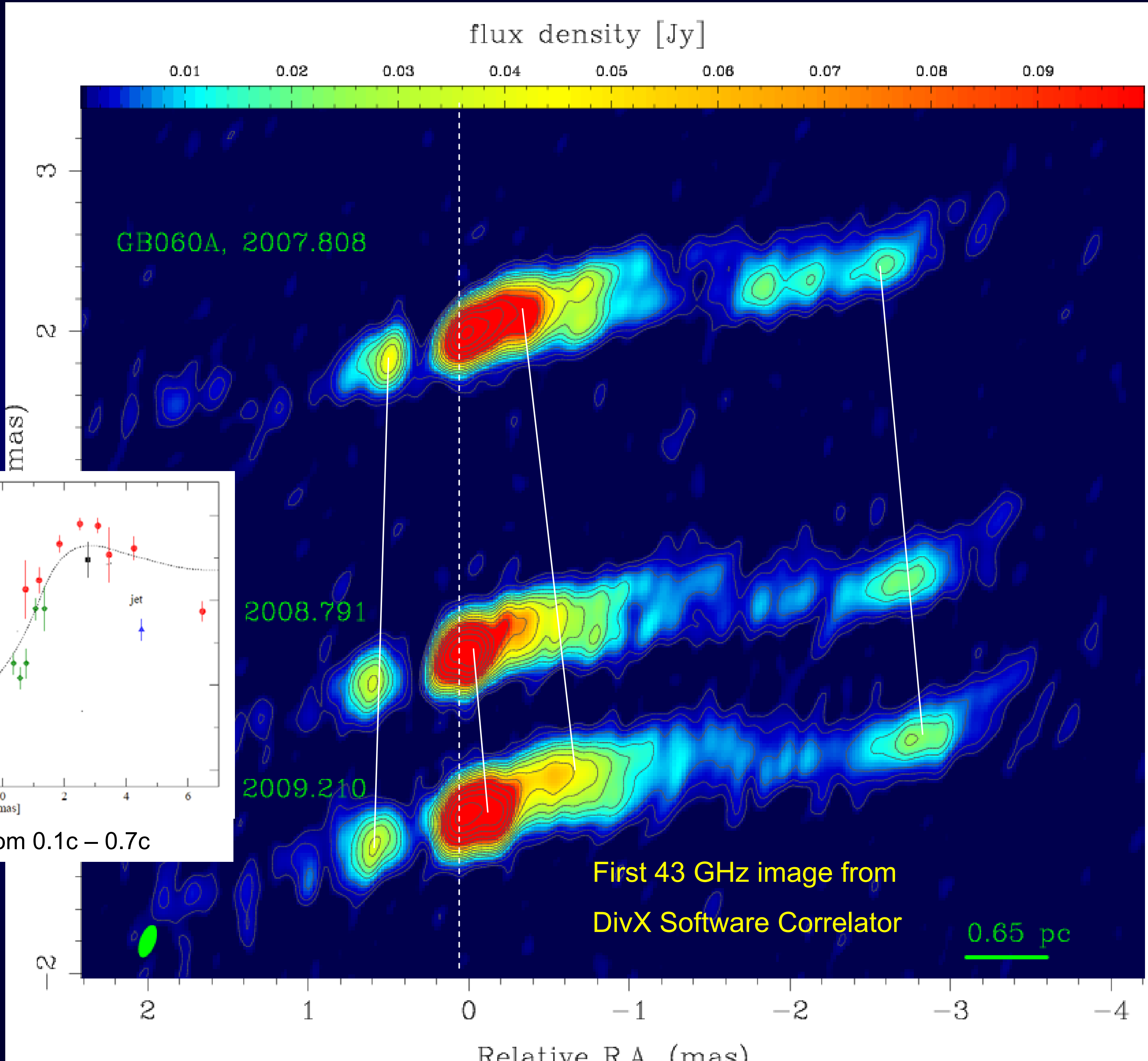


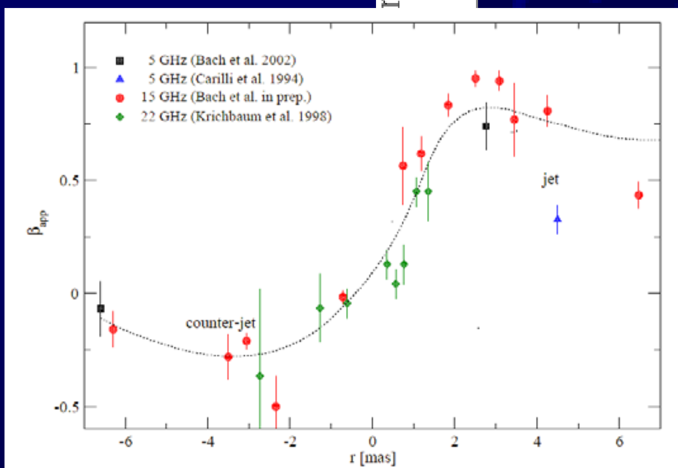


New:

Global 7mm VLBI maps of Cyg A

(EVN, VLA, VLBA, GBT)



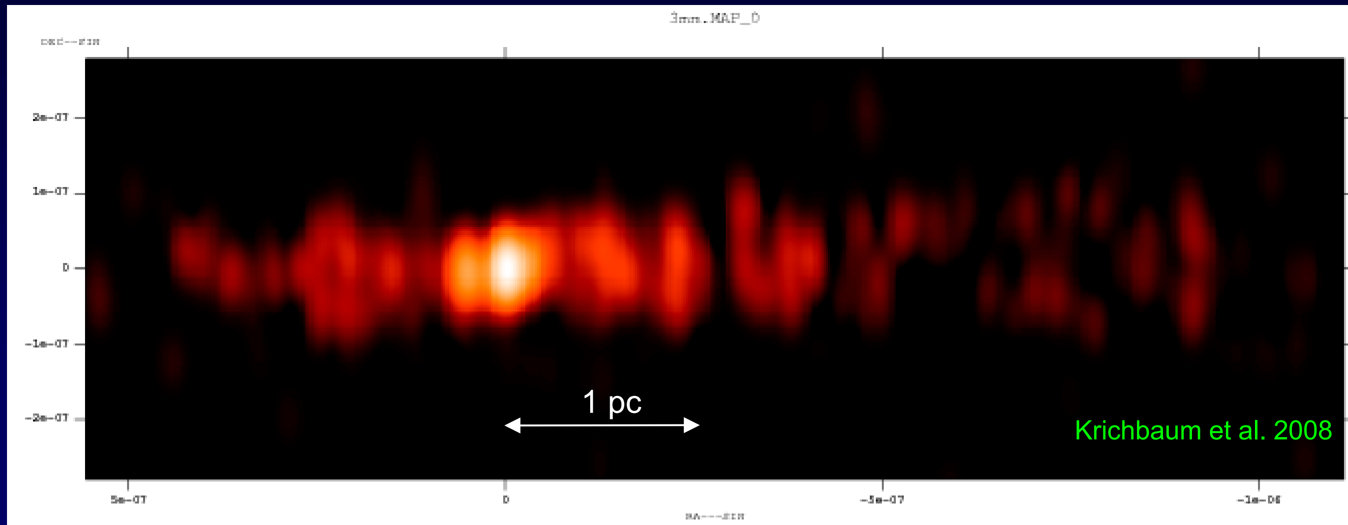


jet acceleration from 0.1c – 0.7c

U. Bach et al. 2008

Detection of the counter-jet of Cygnus A at 43 and 86 GHz

86 GHz 2005.791 GMVA

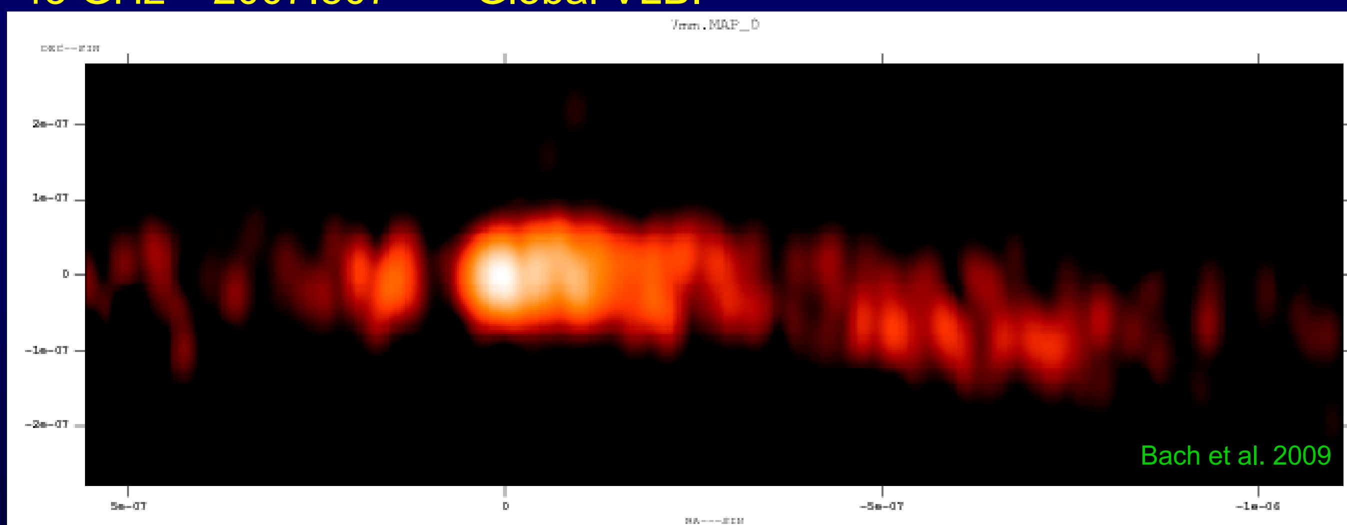


beam:

140 x 56 μas

0.15 x 0.06 pc

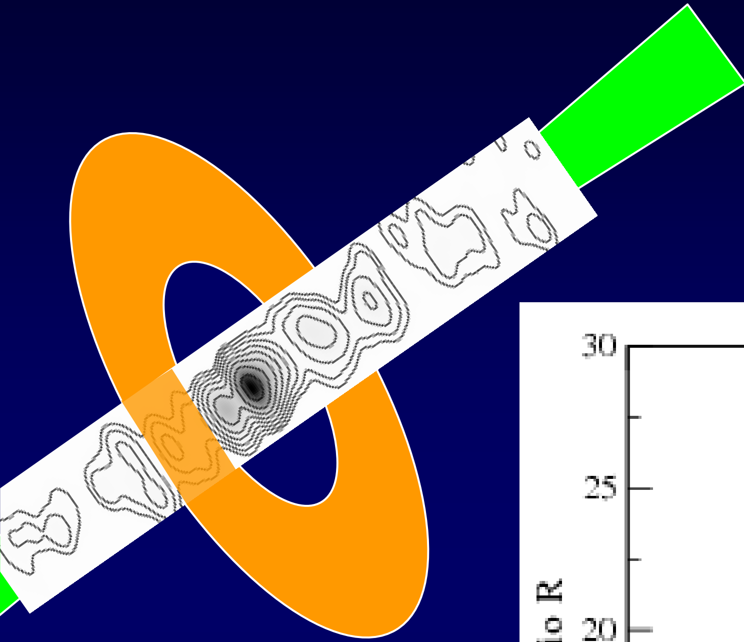
43 GHz 2007.807 Global VLBI



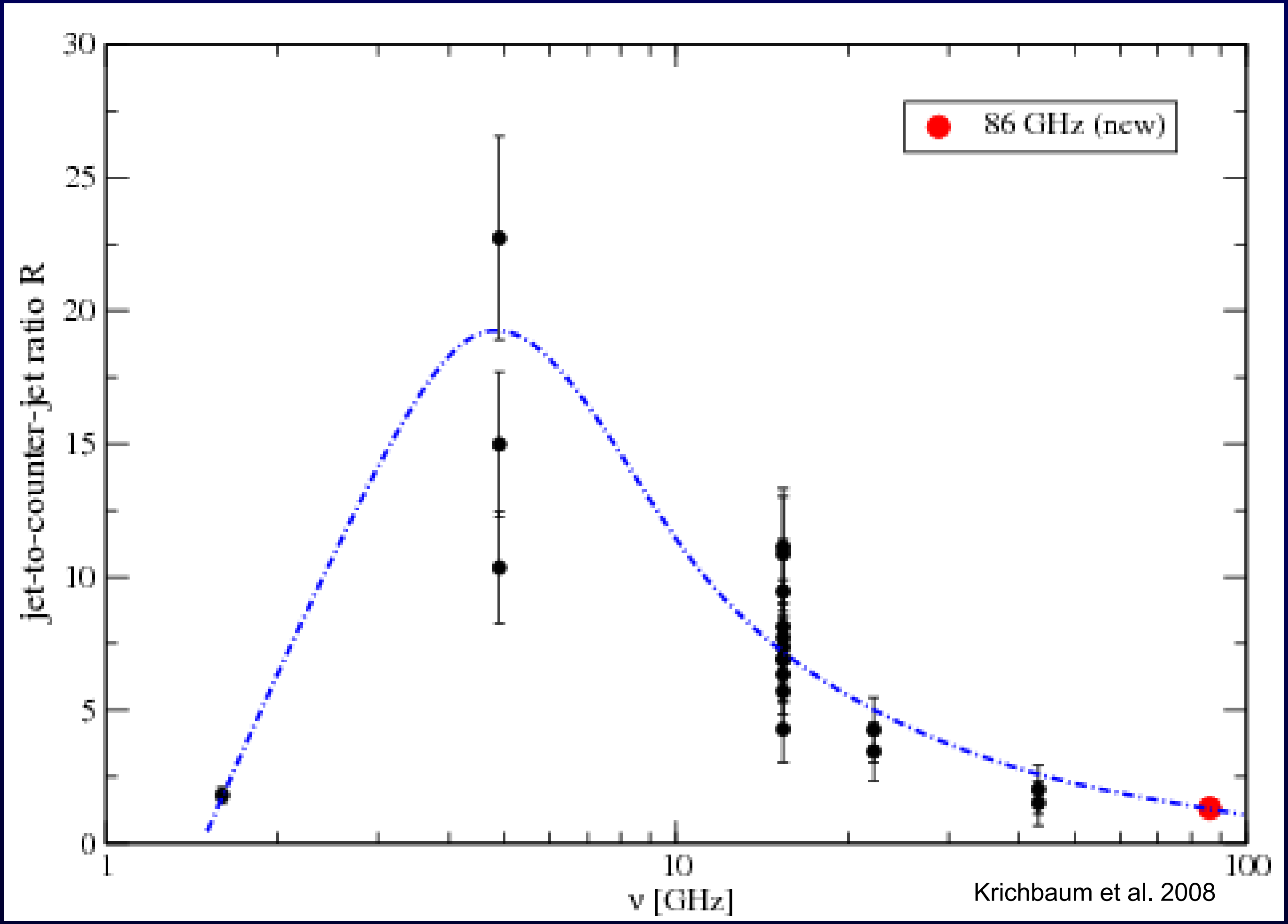
gap between jet and counter jet at 43 GHz: $\approx$ 0.5 mas ~ 2200 R_s

at 86 GHz: $\leq$ 0.2 mas $\leq$ 880 R_s

New: Intrinsic Jet-to-Counterjet Ratio determined from 3mm-VLBI



$R_{86\ GHZ} = 1.32 +/- 0.12$



Krichbaum et al. 2008

Parameters of torus:

inner edge: 0.3 mas

(0.3 pc)

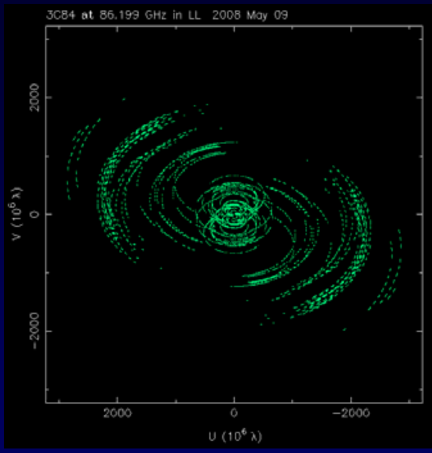
outer edge: 4-5 mas

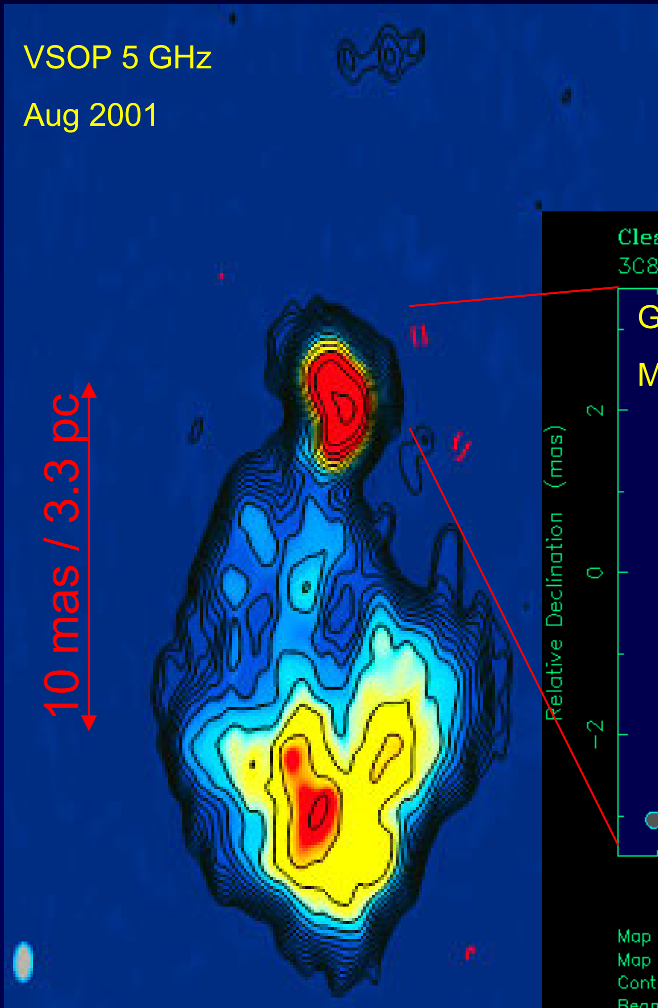
(4-5 pc)

86 GHz GMVA images of 3C84: jet base resolved !

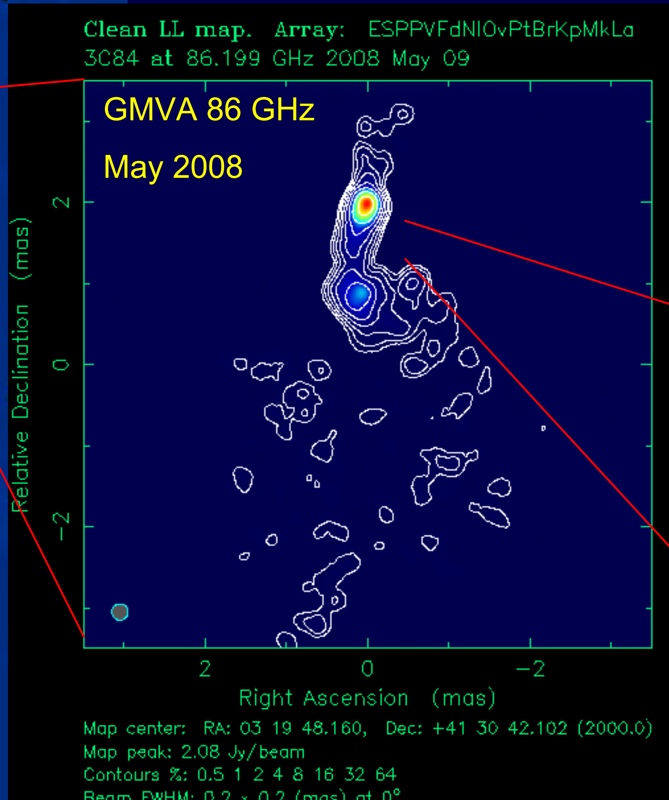
data:

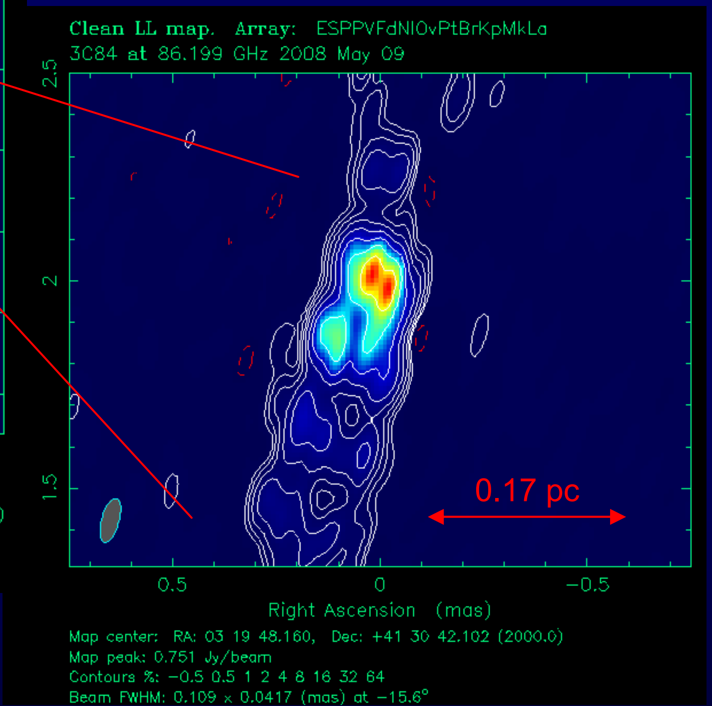
M.J. Kim, S.S. Lee et al. 2010
and in prep.





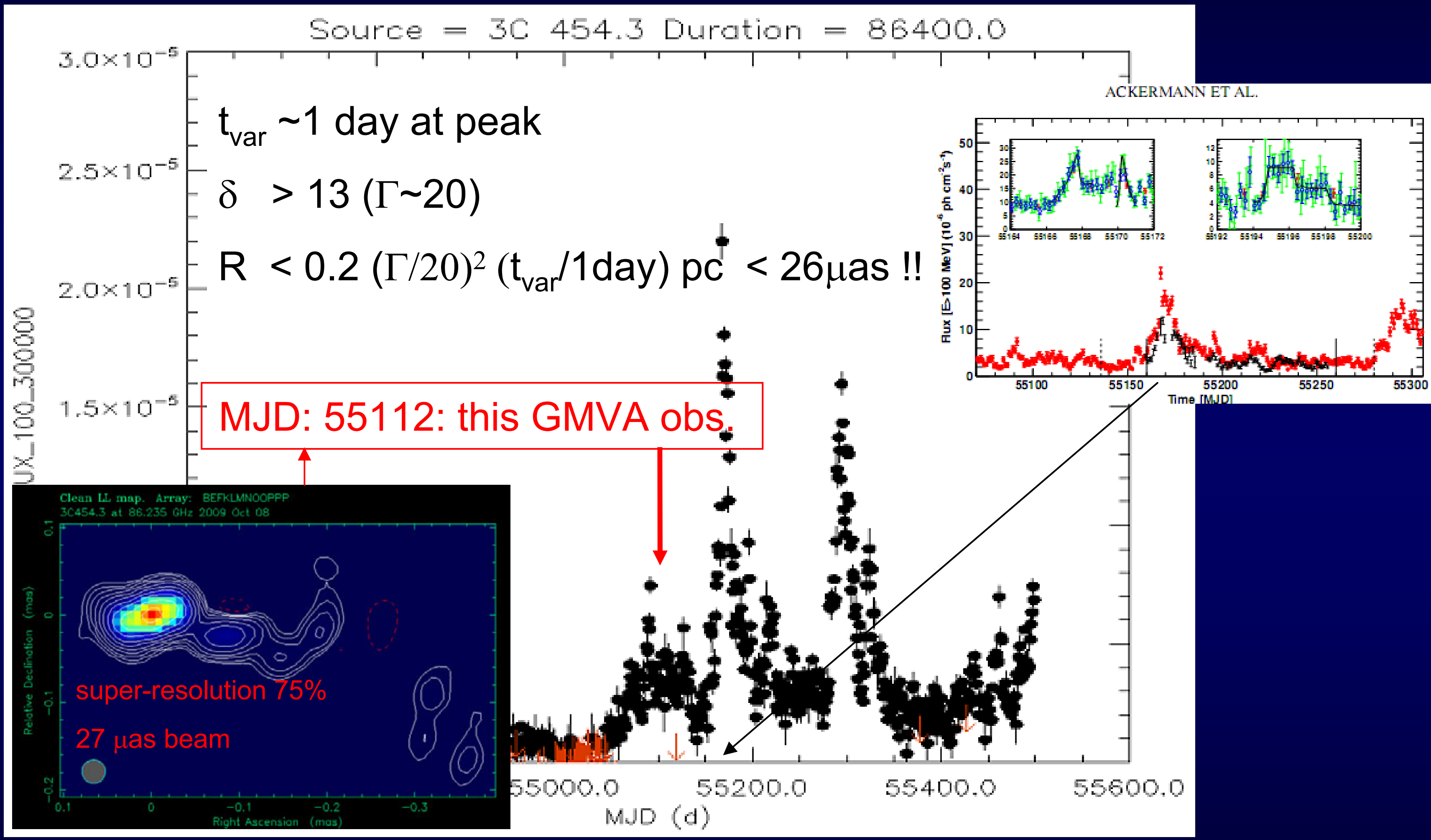
Asada et al. 2006





Nuclear region and sub-mas jet base resolved: 42 μas corresponding to a linear scale of 16 lightdays or 142 R_S[9] in units of the central SMBH → huge potential for future studies !

FERMI-LAT: Gamma-ray lightcurve of 3C454.3



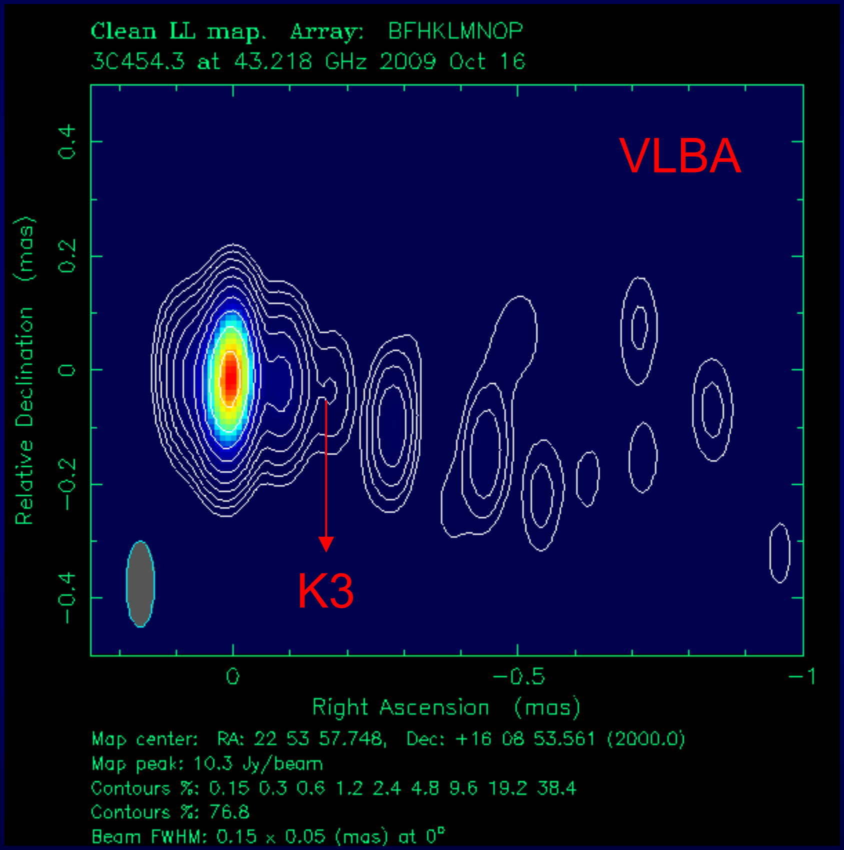
data: gamma-ray variability from public Fermi web site
+ Dermer et al. 2010, Ackermann et al. 2010

Origin of inter-day γ-ray variability within unresolved mm-VLBI core ?

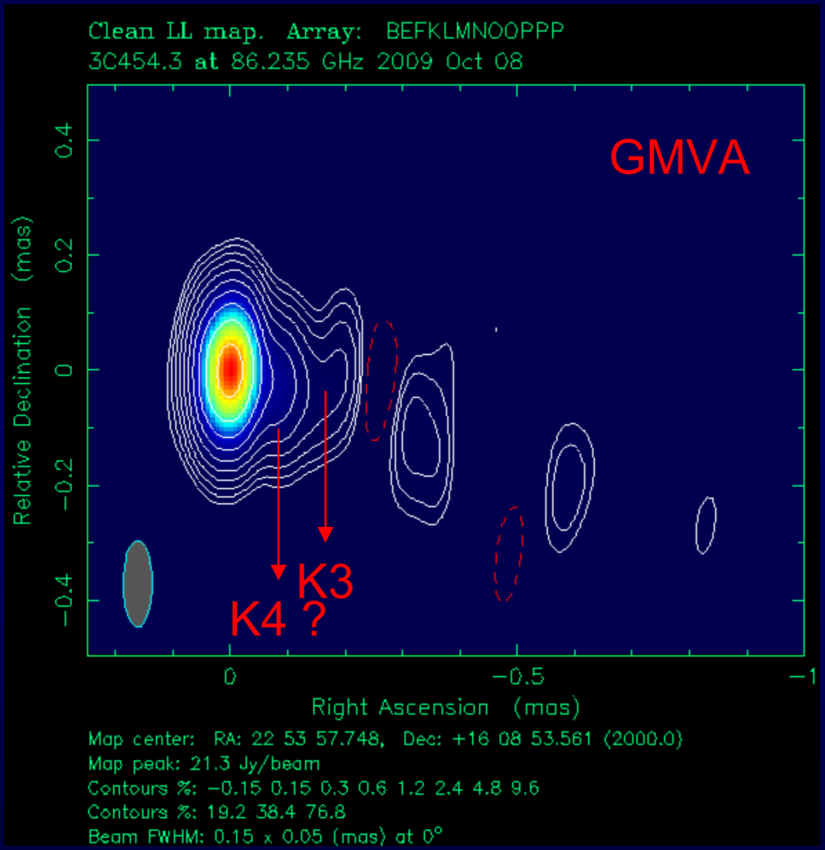
3C454.3 – Quasi-simultaneous VLBI images at 7mm and 3mm

identical beam: 0.15 x 0.05 mas

43 GHz: Oct. 16 2009



86 GHz: Oct. 08 2009

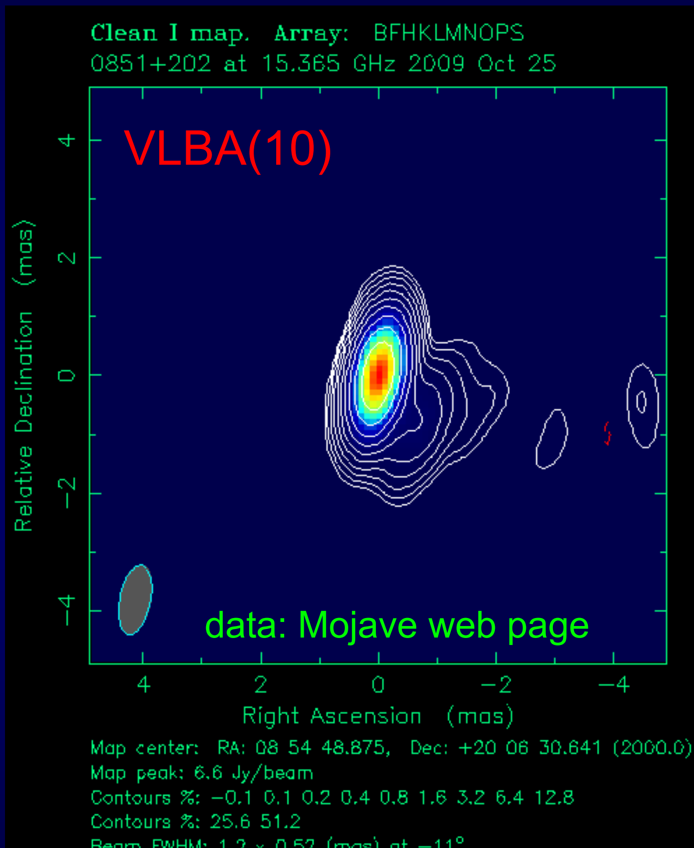


two inner jet components at r ~ 0.08 and 0.15 mas (0.6 / 1.2 pc)

Jorstad 2010: expected position K3 (T_0=2007.93, μ=0.09 mas/yr) → r= 0.17±0.05 mas

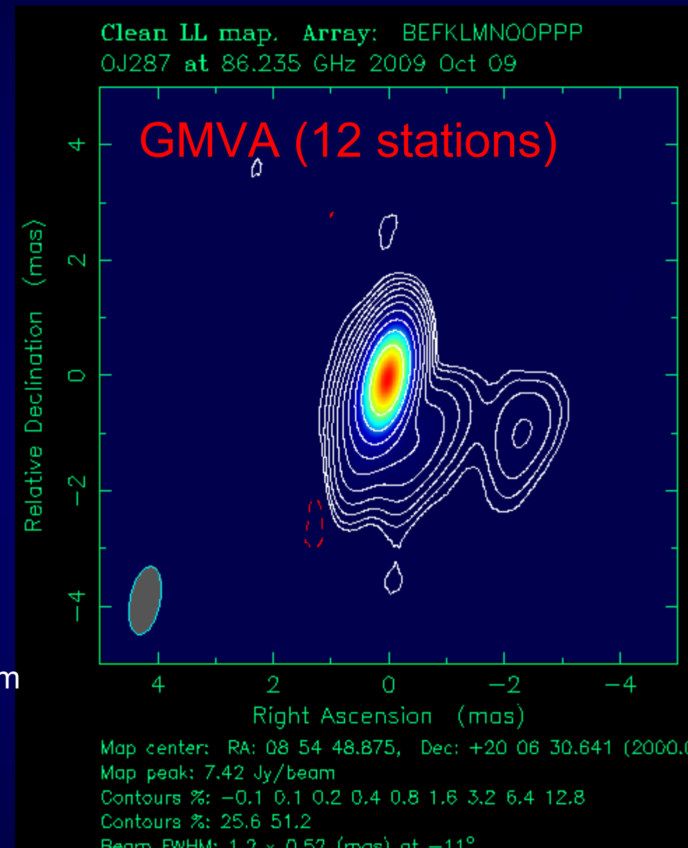
OJ 287 in October 2009: comparison of outer structure

15 GHz 2009 Oct 25



rms ~ 7 mJy/beam

86 GHz 2009 Oct 09

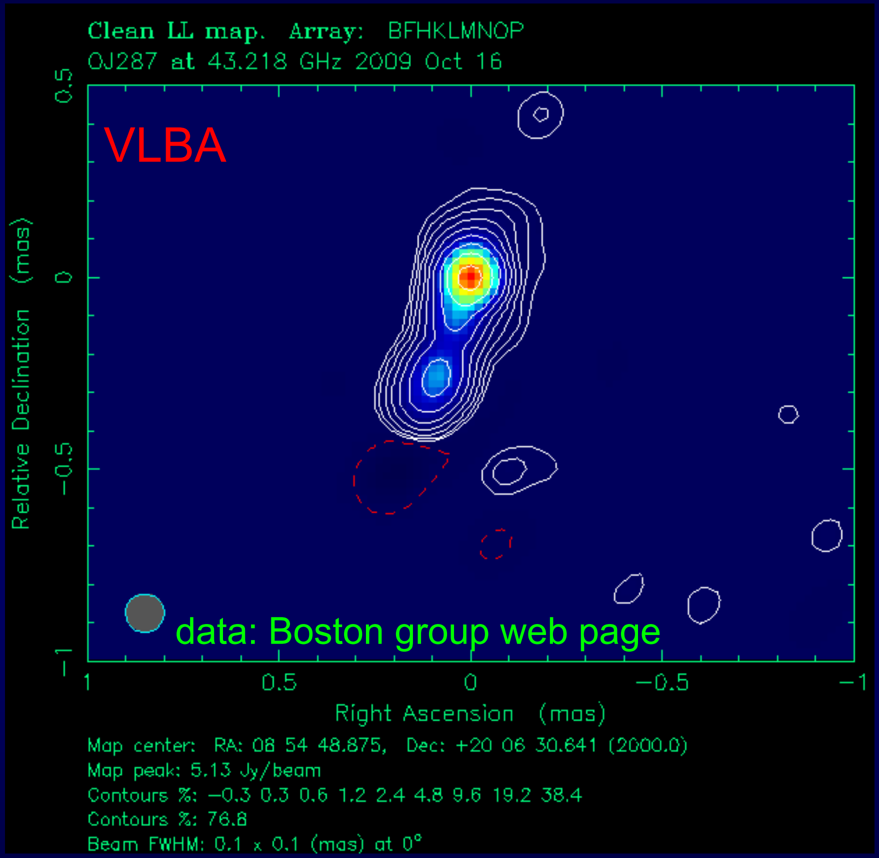


both maps convolved with tapered 1.2 x 0.52 mas beam

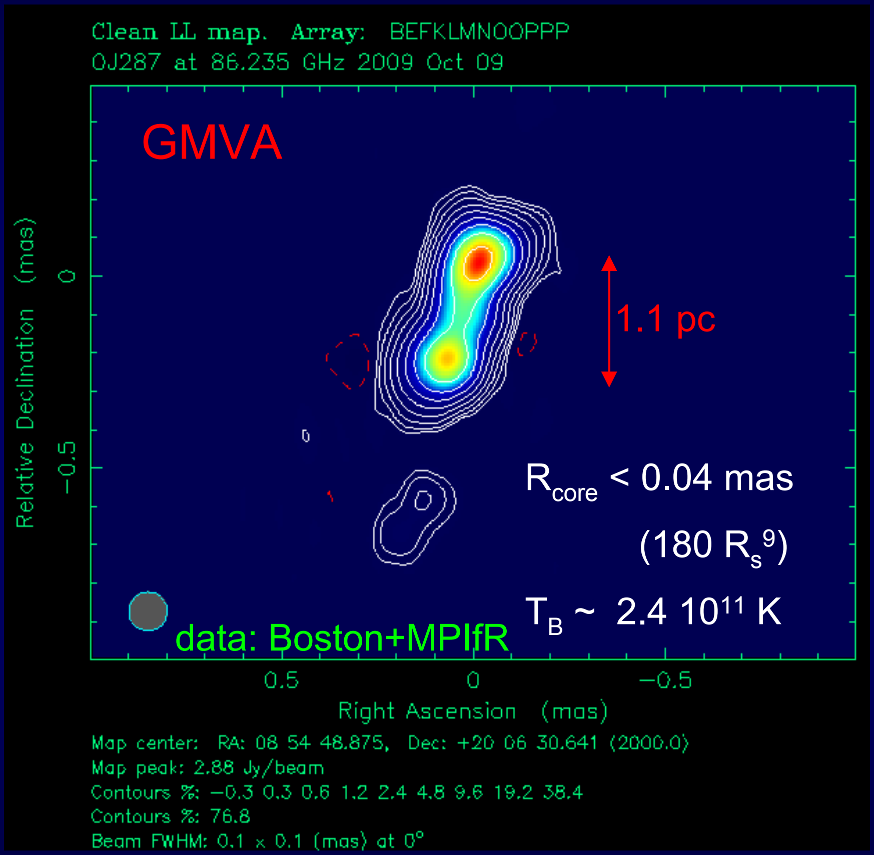
Faint jet seen at 15 GHz (VLBA) is also detected at 86 GHz in a strongly uv-tapered GMVA image! The imaging sensitivity of the GMVA will further improve with MK5C.

OJ 287 in October 2009: comparison of inner structure

43 GHz 2009 Oct 16



86 GHz 2009 Oct 09

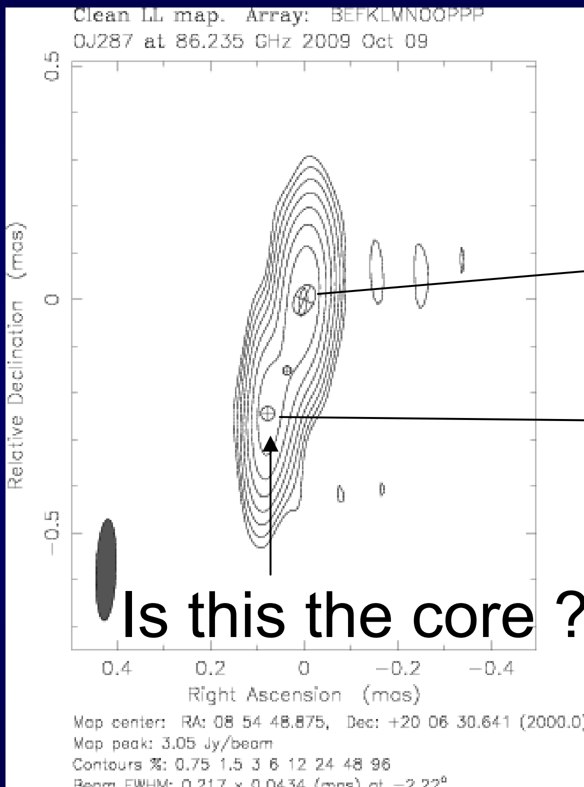


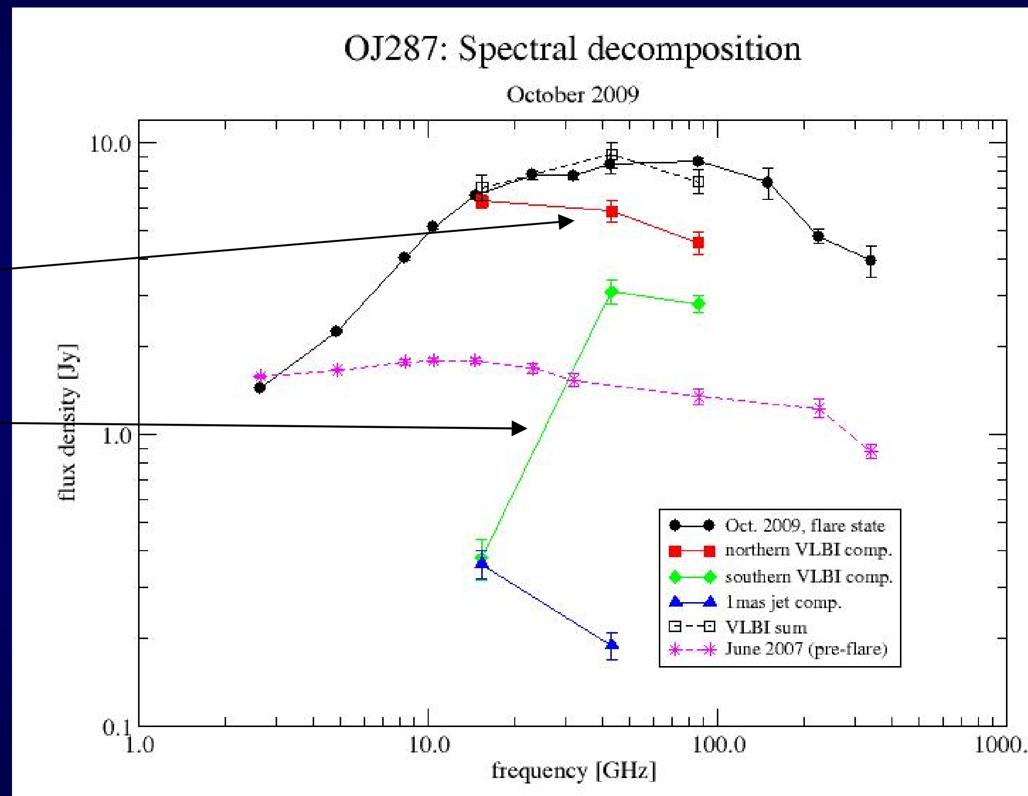
both maps convolved with 0.1 mas circular beam

43 GHz VLBA & 86 GHz GMVA image both show a jet extending 0.4 mas (1.8 pc) south. It is misaligned by about 90 deg relative to the mas-scale jet !

OJ 287 in October 2009: Spectrum of inner jet

86 GHz 2009 Oct 09





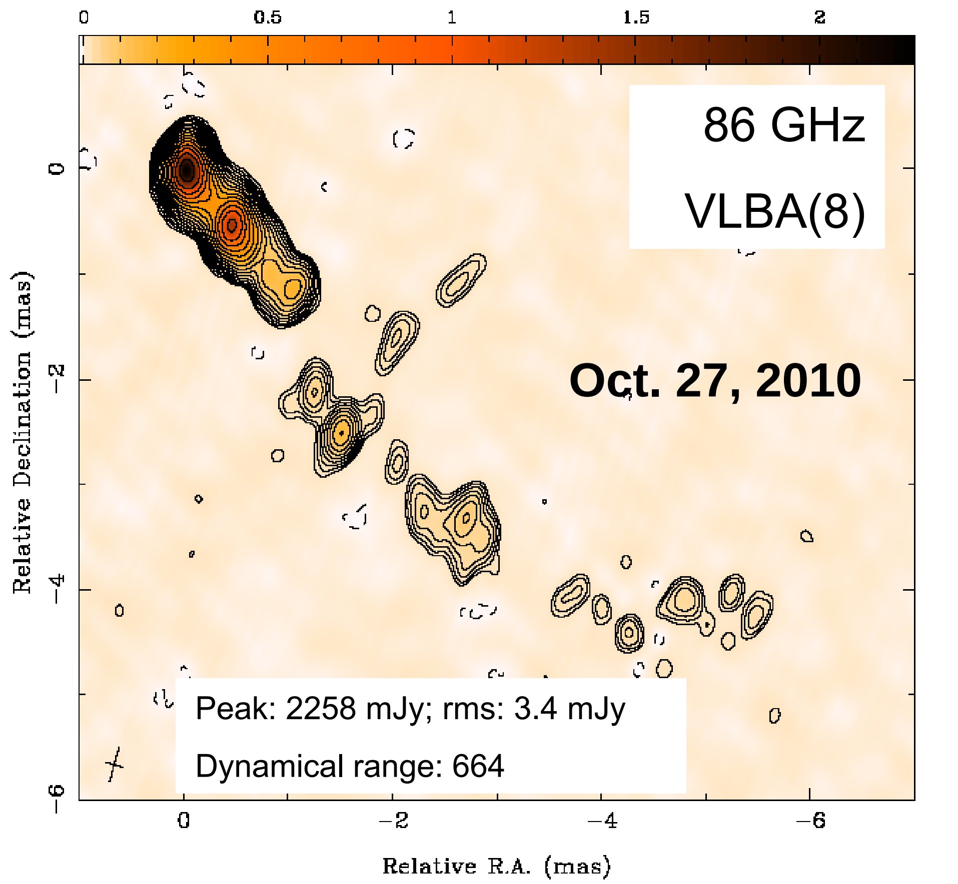
modelfit: 0.21 x 0.043 mas beam

quasi simultaneous radio spectrum from FGAMMA program

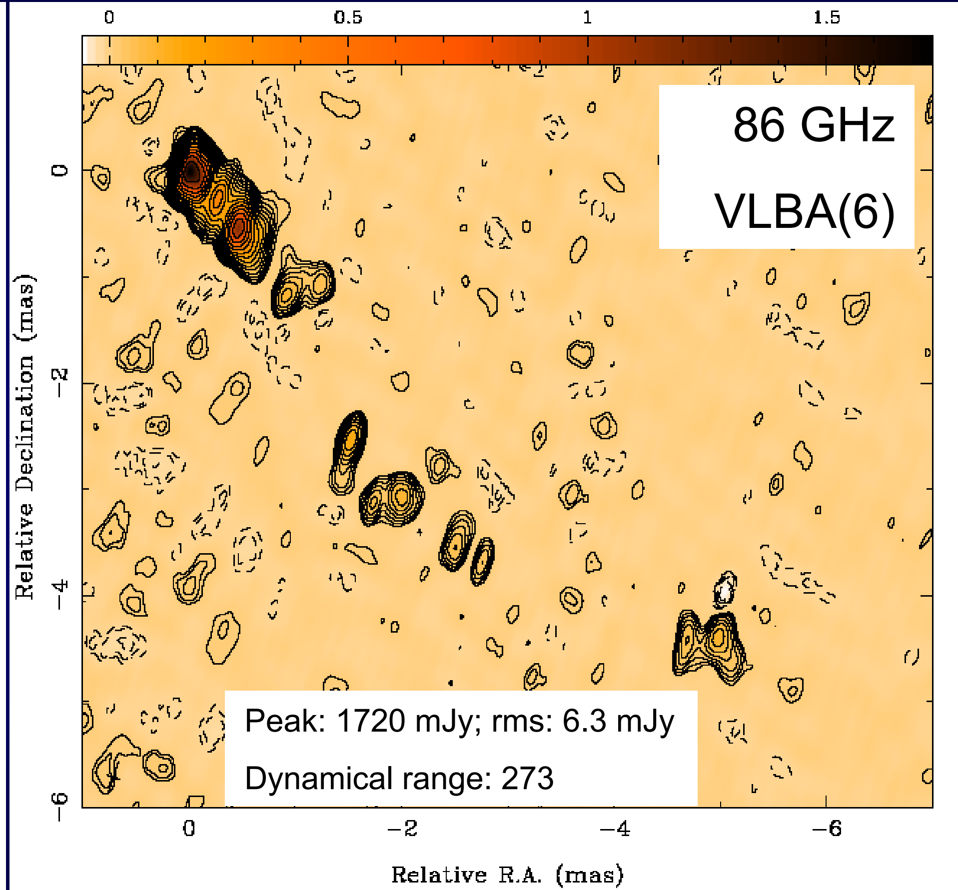
VLBI component spectra from 15 + 43 + 86 GHz

Quality of VLBA images – The jet of 3C273

8 VLBA stations (no 3mm at SC and HN)



6 VLBA stations (KP and LA removed)



Dramatic loss (2.5) in image fidelity and sensitivity if the "wrong" VLBA stations would be removed !

data:T. Savolainen et al.

Angular and Spatial Resolution of mm-VLBI

λ	ν	θ	z=1	z=0.01	d= 8 kpc
3 mm	86 GHz	45 μas	0.36 pc	9.1 mpc	1.75 μpc
2 mm	150 GHz	26 μas	0.21 pc	5.3 mpc	1.01 μpc
1.3 mm	230 GHz	17 μas	0.14 pc	3.4 mpc	0.66 μpc
0.87mm	345 GHz	11 μas	0.09 pc	2.2 mpc	0.43 μpc

linear size: $\sim 10^3\ R_s{}^9$ 20-100 $R_s{}^9$ 1-5 $R_s{}^6$

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass !

→ mm-VLBI can directly <u>image (!)</u> the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory) !

→ best candidates: Sgr A* (10 μas = 1 $R_s{}^6$) and M 87 (Cen A is far south, M81 & NGC4258 are weak)

→ need sensitive mm-telescopes (ALMA) to image the emission around Black Holes in AGN

→ need both, European + US-telescopes to obtain optimum sensitivity and resolution.

Observing Black Holes with mm-VLBI using the phased ALMA

High speed jets ejected by Black Hole.

Disk of material spiraling into Black Hole.

The Black Hole:

measure curved space time, mass and spin

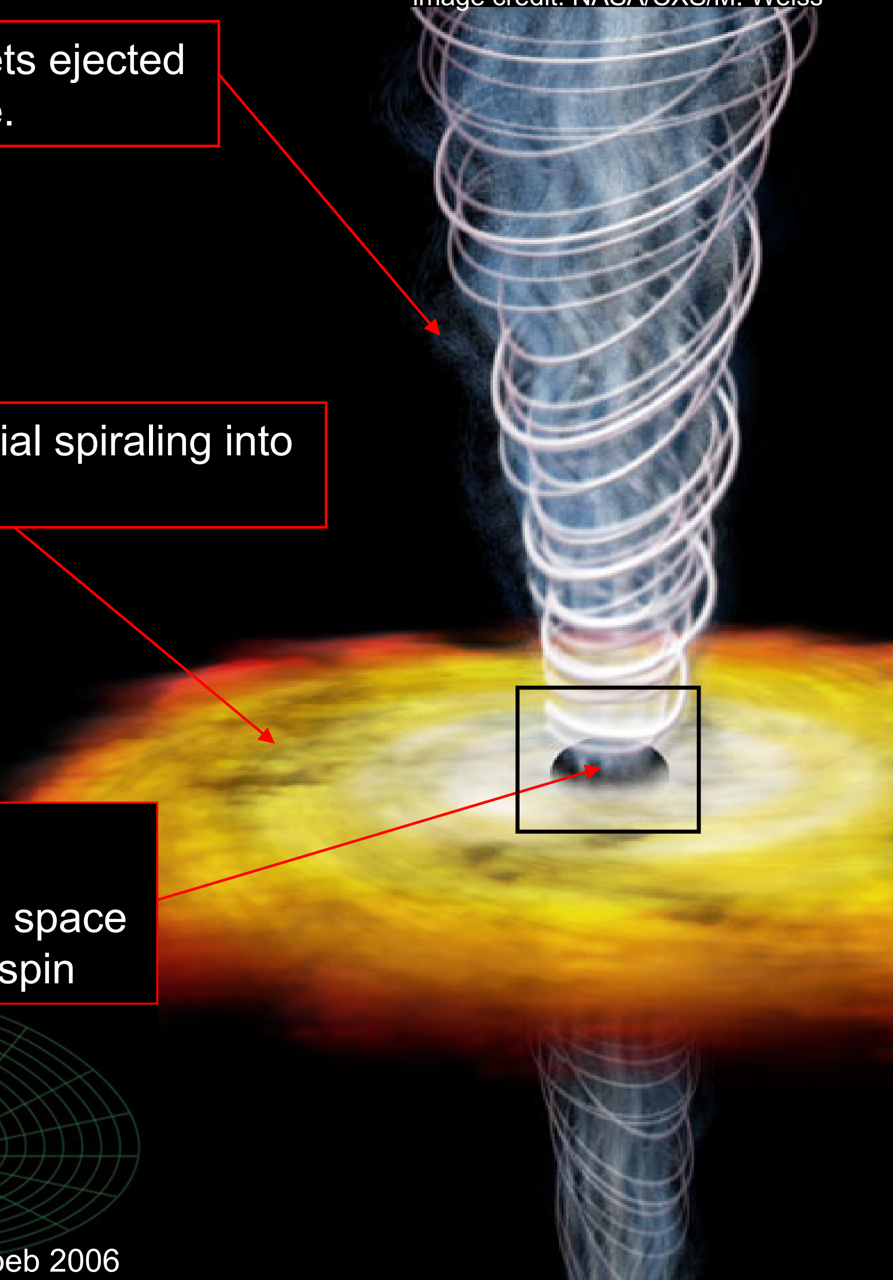
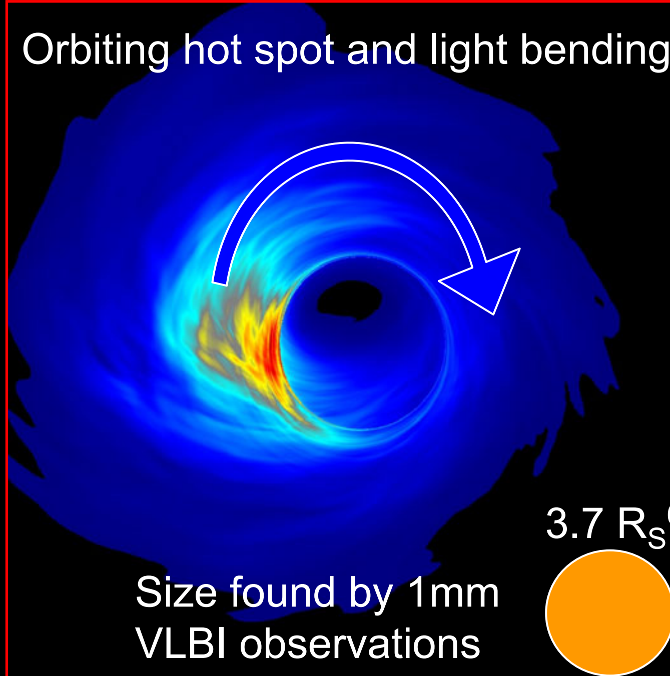


image credit: NASA/CXS/M. Weiss

Orbiting hot spot and light bending



Size found by 1mm VLBI observations

3.7 R_S[6]

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

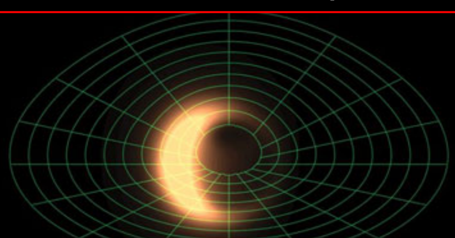
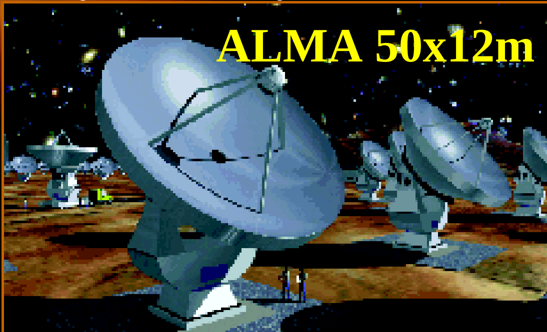


Image: Broderick & Loeb 2006

mJy sensitivity with ALMA



Global 3mm VLBI: Future Sensitivities

Array	Stations	Baseline [mJy]	Array [mJy/hr]	12hr Map [SNR]	Comment
VLBA, 2 Gb/s	VLBA(8)	> 164	2,33	1.0e03	no HN, no SC
GMVA, 2 Gb/s	VLBA+EB+PV+PB+ON+MH	> 33	0,86	2.8e03	68 mJy VLBA-IRAM
+ Yb	present GMVA+Yebes	> 27	0,67	3.7e03	68 mJy VLBA-Yb
+ LMT + GBT	present GMVA+Yebes+LMT+GBT	> 10	0,30	8.2e03	31 mJy VLBA-GBT
+ ALMA	present GMVA+Yebes+LMT+GBT+ALMA	> 5	0,19	12.9e03	5 mJy ALMA-GBT

assuming: 500 MHz bandwidth (2 Gbit/s), t=20 sec, 7sigma fringe detection, 2 bit sampling

- Adding European mm-telescopes to the VLBA improves the angular resolution by factor ~ 2 and imaging sensitivity by a factor of ~3.
- The addition of telescopes with large collecting area (GBT, LMT, CARMA, SRT, ...) will give another factor of 2-3.
- Addition of ALMA leads to mJy sensitivities and improves the overall sensitivity by a factor of 10, over present day values.
- Another factor of sqrt(rate/ 2Gbit/s) in sensitivty will be obtained via a further increase of observing bandwidth.

Summary

- 3mm VLBI imaging complements broad-band variability studies (SEDs) and is absolutely essential for the interpretation of results from satellite missions (e.g. PLANCK, FERMI, etc.).
- 3mm VLBI is needed to bridge the gap between cm-VLBI (up to 43 GHz) and planned submm-VLBI at 230/345 GHz (Event Horizon Telescope).
- Future addition of large apertures (ALMA, GBT, CARMA) will boost 3mm-VLBI to mJy sensitivities. (Note: 3mm VLBI helps to justify ALMA phasing effort.)
- Since the atmosphere limits the accuracy of the a-priori calibration, one needs a sufficiently large number of VLBI telescopes (> 10) to obtain reliable results from amplitude self-calibration.
- Because of the small observing beam and rapid structural variability of the sources, a much denser time sampling would be very desirable (>> 2 times per year).

$\Rightarrow$ The VLBA can and "should" play a major role in this.

END

EVN/Global VLBI: Image Sensitivities

(numbers in μJy/beam)

Array	90cm	18/21cm	6cm	3.6cm	1.3cm	7mm	3mm
EVN	248	28	29	65	254	917	-
VLBA	691	91	97	95	156	321	895
Global	170	20	21	35	121	278	-
HSA	34	7	8	9	45	84	-
GMVA	-	-	-	-	-	-	290

assumptions: 512 Mbit/s, single polarisation, 2 bit sampling, 60 min. on source

1 sigma thermal noise, natural weighting

Future aim: mm-VLBI should reach similar sensitivity/performance as global VLBI at cm-wavelengths !

→ add stations + increase observing bandwidth to Gbit/s rates

→ expect to reach < 100 μJy/beam @ 86 GHz in 2011/12

(for 2 Gbit/s with MK5C)

EVN/Global VLBI: Angular Resolution

(numbers in milli-arcseconds)

Array	90cm	18cm	6cm	3.6cm	1.3cm	0.7cm	0.3cm
EVN	-	15	5,0	3,0	1,00	0,55	-
EVN+Ur/Sh	30	5	1,5	1,0	0,30	-	-
EVN+VLBA	19	3	1,0	0,7	0,25	0,13	-
VLBA	21	4	1,4	0,9	0,30	0,17	0,10
GMVA	-	-	-	-	-	-	0,04

spatial scale: for z =1 (ΛCDM cosmology), 1 mas = 8 pc

sub-pc scale resolution only for global VLBI at $\lambda \leq$ 3mm !

large IRAM telescopes important for sensitivity across Atlantic !

ALMA will revolutionize mm-VLBI

Global VLBI at 3mm: Existing and possible future antennas

now

Station	Country	Diameter	Eff.Diameter	Zenith Tsys	Gain	App.Eff.	SEFD
		[m]	[m]	[K]	[K/Jy]	[%]	[K]
Effelsberg	Germany	100	80	125	0,137	8	915
Plateau de Bure	France	6x15	34,8	90	0,208	67	433
Pico Veleta	Spain	30	30	90	0,141	55	639
Onsala	Sweden	20	20	250	0,051	45	4882
Metsähovi	Finland	14	14	250	0,017	30	14944
VLBA(8)	USA	25	25	100	0,034	19	2960
future Europe							
Yebes	Spain	40	40	100	0,205	45	488
Noto	Italy	32	32	100	0,087	30	1144
Sardinia (SRT)	Italy	64	64	100	0,350	30	286
future America							
GBT	VA,USA	100	100	100	0,996	35	100
CARMA	Ca,USA	6x10m+9x6m	31,4	100	0,140	50	713
LMT	Mexico	50	50	100	0,356	50	281
ALMA	Chile	50x12	85	100	1,233	60	81
ALMA, single	Chile	12	12	100	0,025	60	4068