The Black Hole – Jet Connection

Study of Active Galactic Nuclei using global mm-/submm-VLBI

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(on behalf of the European mm-VLBI team)

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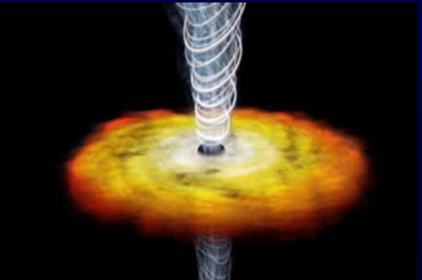

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people involved in the European 1mm VLBI effort:

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

IRAM: M. Bremer, P. Cox, C. Kramer, S. Sanchez, K. Schuster, M. Torres, et al.

OSO: M. Lindqvist, I. Marti-Vidal, H. Olofsson, et al.

INAF: G. Tuccari

APEX: R. Güsten, K. Menten, D. Muders, G. Wieching, et al.

in collaboration with:

US-EHT: S. Doeleman et al. (Haystack + SMA/JCMT + Carma)

SMTO: L. Ziurys, P. Strittmatter, et al.

science:

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

1mm-VLBI: Sources detected in early days with PV-PdB

1994-1995:

early detection of ~ 10 mm-bright sources at 215 GHz on the PV-PdB baseline

1mm VLBI looks promising and is doable or many AGN!

		3MM				1MM		correl. flux	
Date	Source	$S_t(86)$	SNR_{max}			$S_t(215)$	SNR_{max}	$S_c(86)$	$S_c(215)$
	Baseline	[Jy]	XP	BX	BP	[Jy]	XP	XP [Jy]	XP [Jy]
Oct.94	0528+134	5.0	81				NOF	3.2	
	4C39.25	6.5	28					1.6	
	1749+096	5.2	52					3.2	
	SGR A	7.1	19					1.1	
	1823+568	2.3	49					1.6	
	1921-293	12.7	105					6.0	
	2145+067	7.1	184				NOF	4.0-5.0	
	3C454.3	7.1	107				NOF	4.5	
Dec.94	3C273B	23.5				13.5	10		1.6
	3C279	16.0				10.5	10		2.4
	1823+568	2.6				1.5	<5		<0.9
	2145+067	6.9	136			5.6	7	3.2-4.2	1.0
Mar.95	0528+134	6.0	350	156	128	3.3		4-5	
	4C39.25	6.6				3.5	<5		<0.4
	3C273B	17.1	342	138	251	9.2	7	3.5-5	0.8
	3C279	19.9	988	438	266	11.0	35	13-14.5	3-4.5
	1334-127	6.0				3.2	12		1.0
	3C345	6.2				3.0	6(?)		<0.4
	1749+096	6.2				3.9	11		1.0
	NRAO530	11.2	140	191	36	6.2	11	8	1.2
	SGR A	7.8	30	16	6	4.2	6(?)	1.5	0.8
	1921-293	13.0				6.4	7		1.0

Greve et al.

Krichbaum et al.

First transatlantic detections with VLBI at 230 GHz in 2003:

(PV –PdB – HHT baselines):

short baselines: SNR : ≤ 25

long baseline: SNR : 6 – 7

Two Blazars detected at 6.4 Gλ:

3C454.3 and 0716+714

for 3C454.3 (z = 0.859)

ν′ = 428 GHz (in source rest frame)

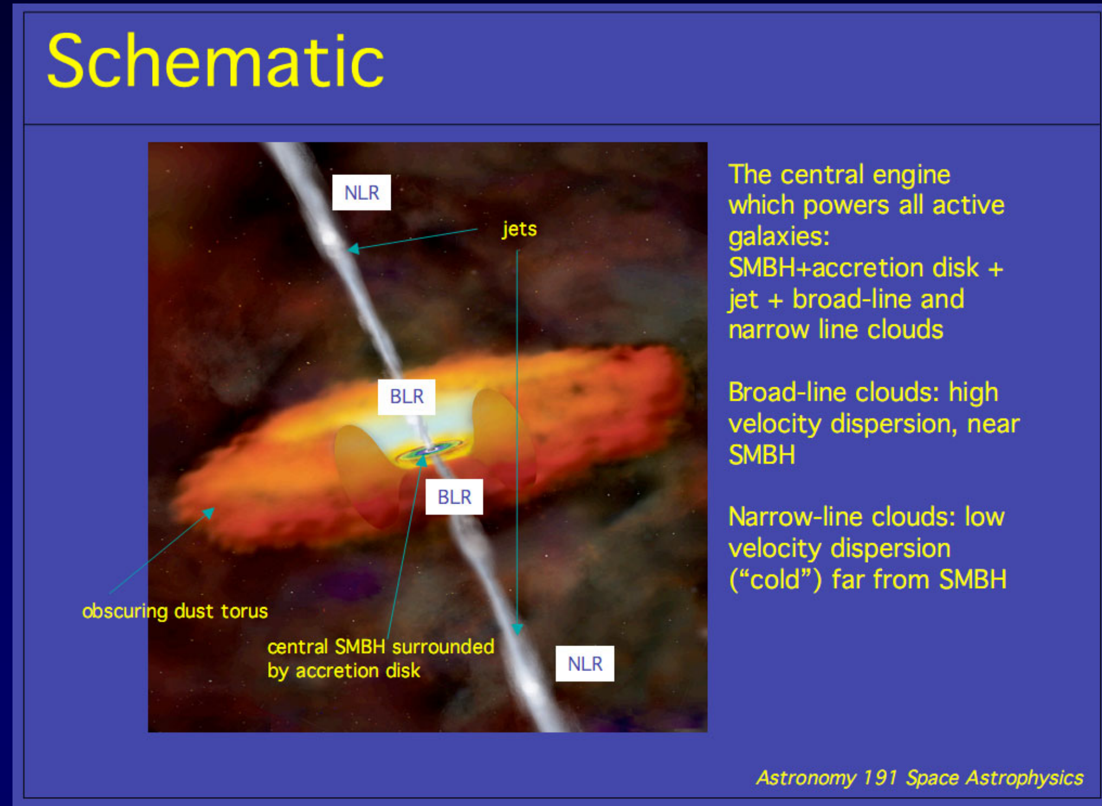
$\theta \leq 16\ \mu as = 0.1\ pc = 1050\ R_S{}^9$

SSA: $B \leq 1\ G \rightarrow \gamma > 600$

Source	PdBI - PV	HHT - PV
NRAO150	10.7	
3C120	8.2	
0420-014	24.9	
0736+017	7.1	
0716+714	6.8	6.4
OJ287	10.4	
1055+018		
3C273	8.2	
3C279	9.6	
NRAO530		
SgrA*		
3C345		
1633+382		
1749+096		
2013+370		
BL Lac	9.0	
2145+067		
CTA102		
3C454.3		7.3

Krichbaum et al. 2004

The AGN paradigm



Unified Scheme:

depending on viewing angle: jet brightness and jet-to-counter jet ratio changes

polarisation properties vary

spectral lines (absorption/emission) become visible

depending on BH mass, spin and luminosity:

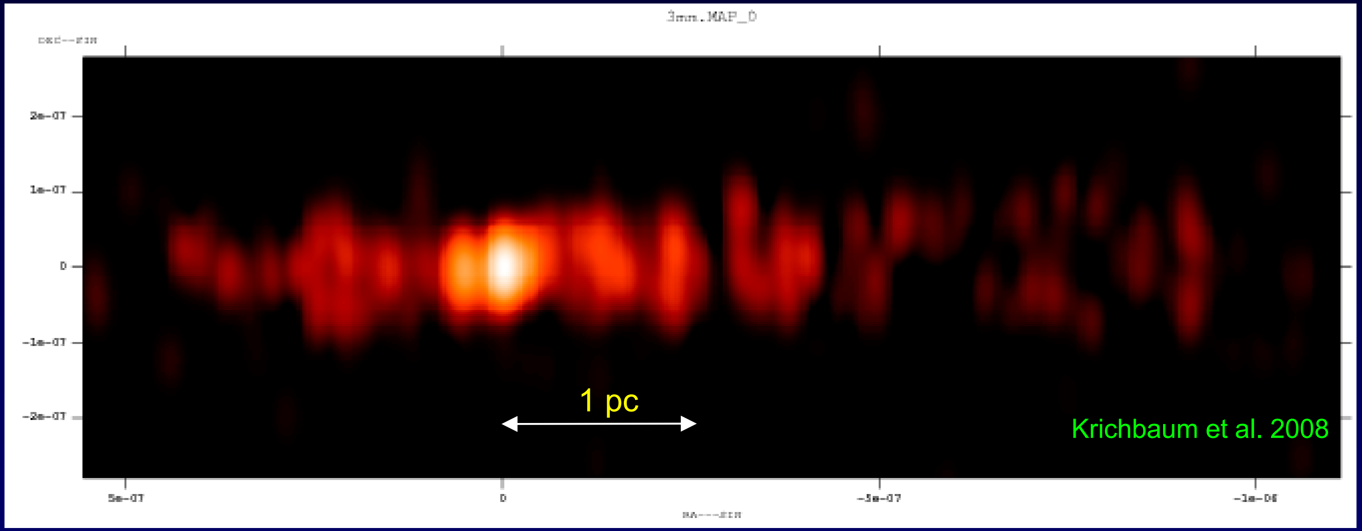
different AGN classes such as FRI/FRII RGs, QSOs, BLLACs

magnetic field, accretion rate and angular momentum distribution:

radio loud / radio quiet (jet/no-jet) ??

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

86 GHz   2005.791   GMVA

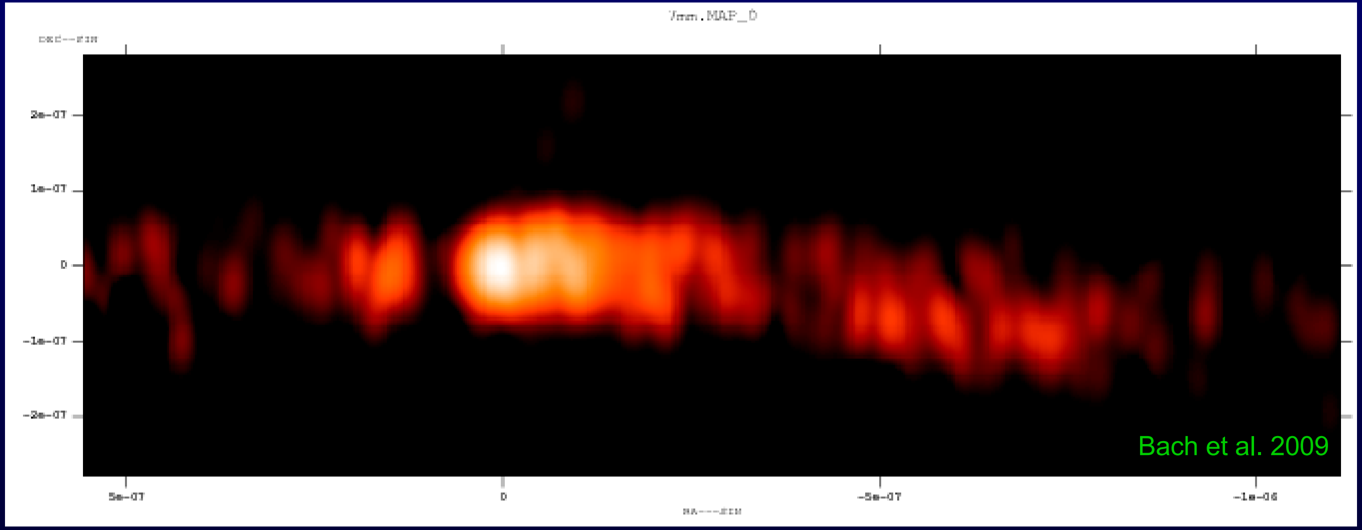


beam:

140 x 56 μas

0.15 x 0.06 pc

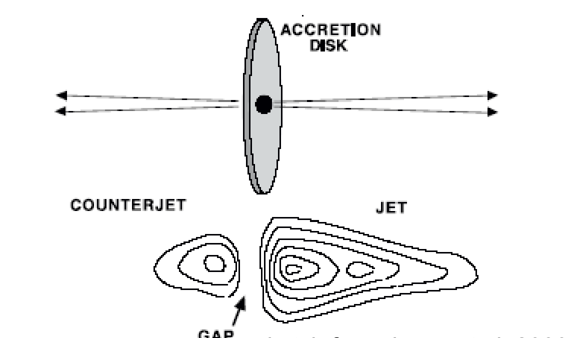
43 GHz   2007.807   Global VLBI



gap between jet and counter jet at 43 GHz: ≈ 0.5 mas ~ 2200 R_s

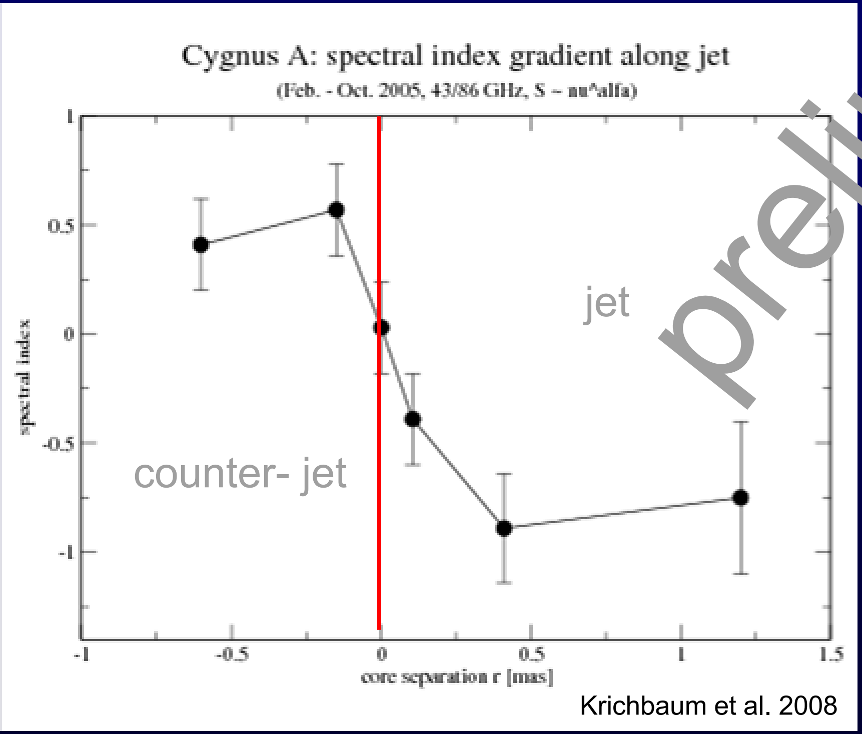
at 86 GHz: ≤ 0.2 mas ≤ 880 R_s

The spectral index distribution on sub-mas scales

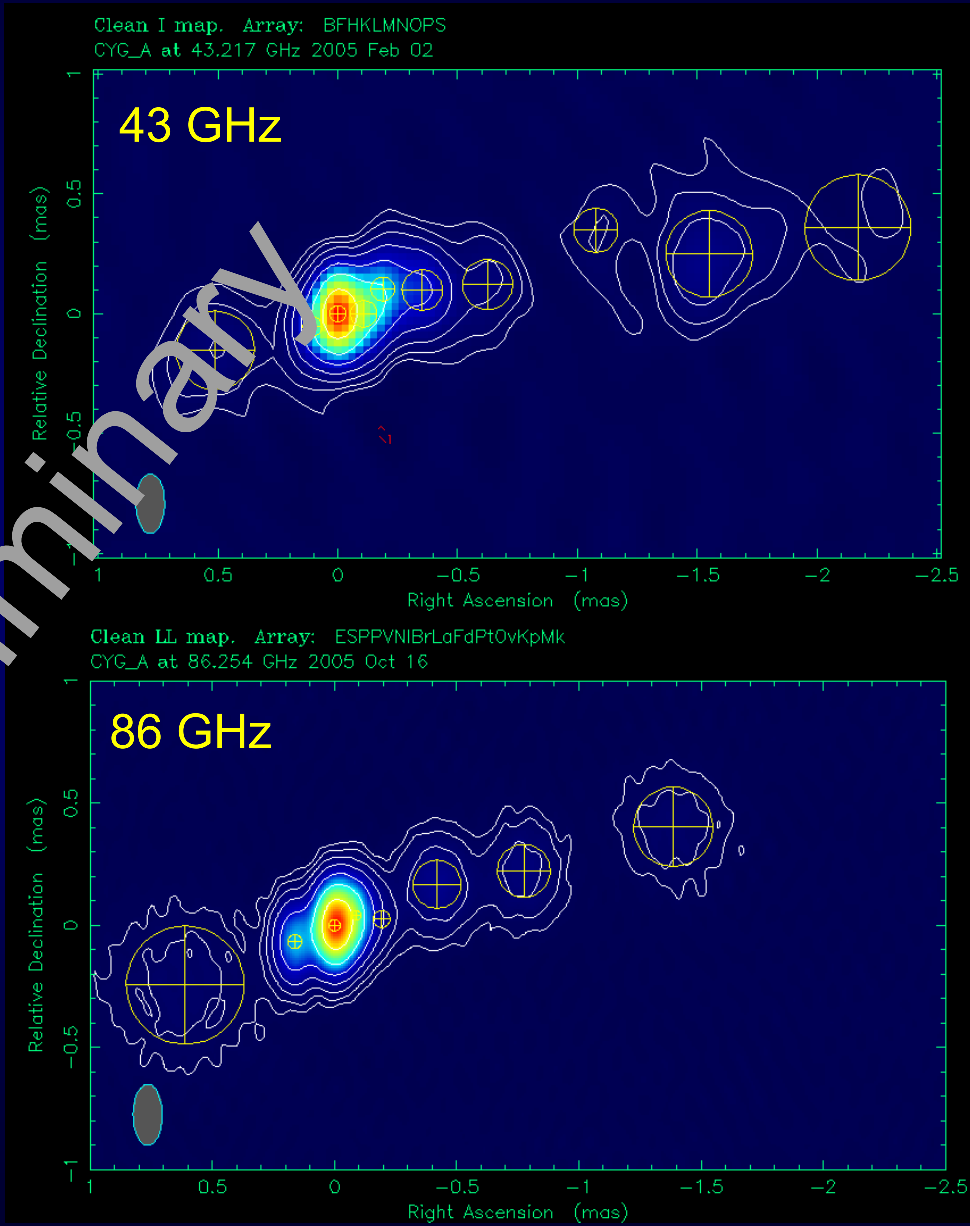


sketch from Jones et al. 2000

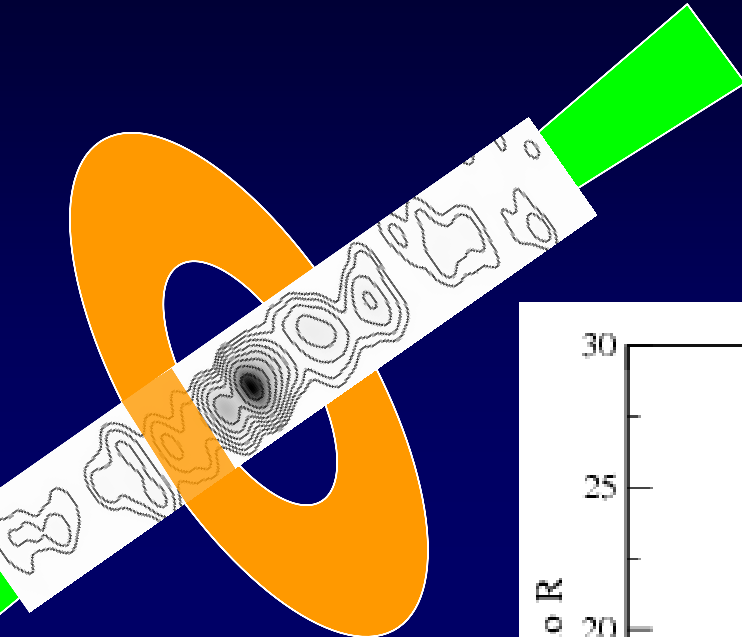
inverted spectrum on counter-jet side

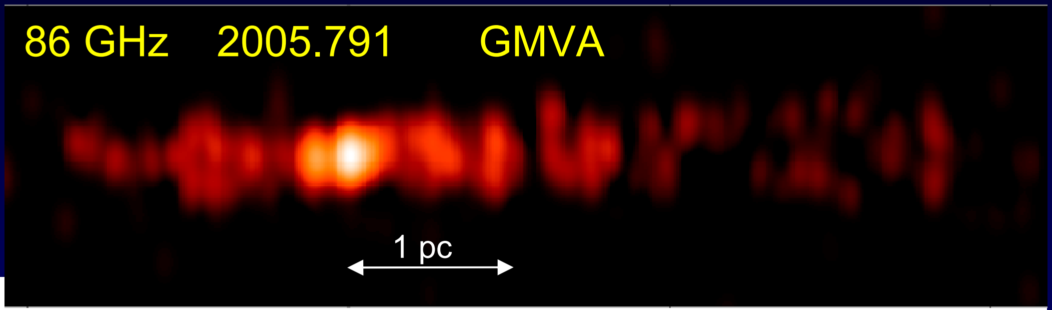


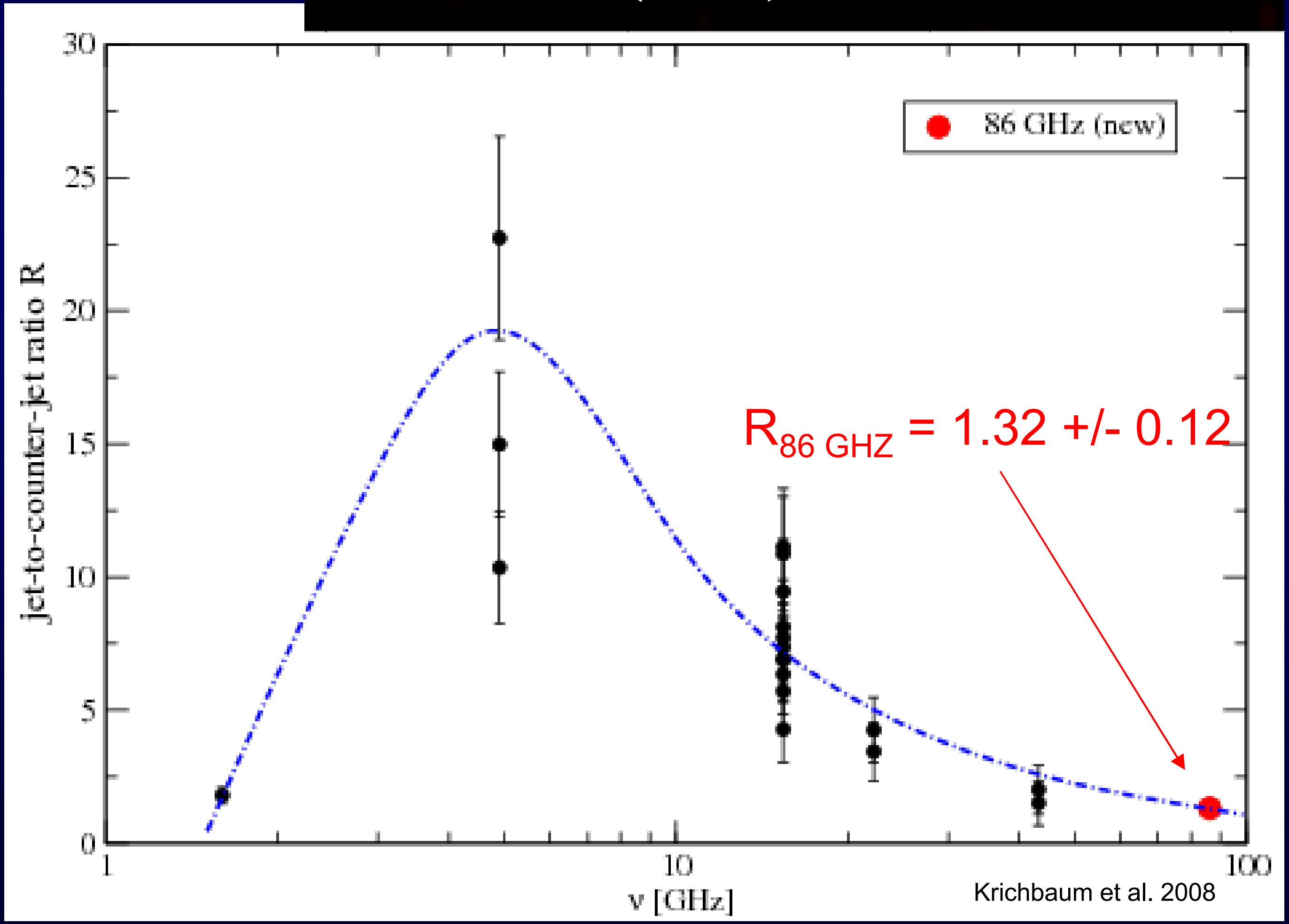
Krichbaum et al. 2008



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







Parameters of torus:

inner edge: 0.3 mas

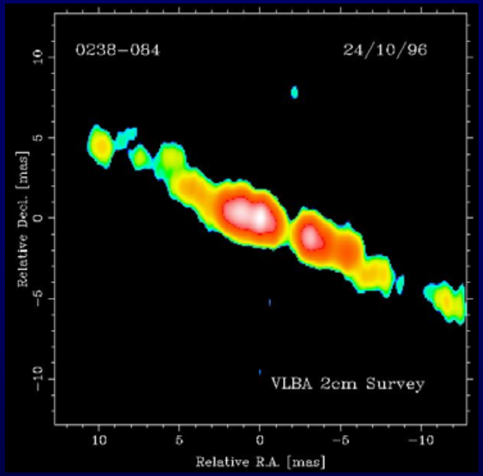
(0.3 pc)

outer edge: 4-5 mas

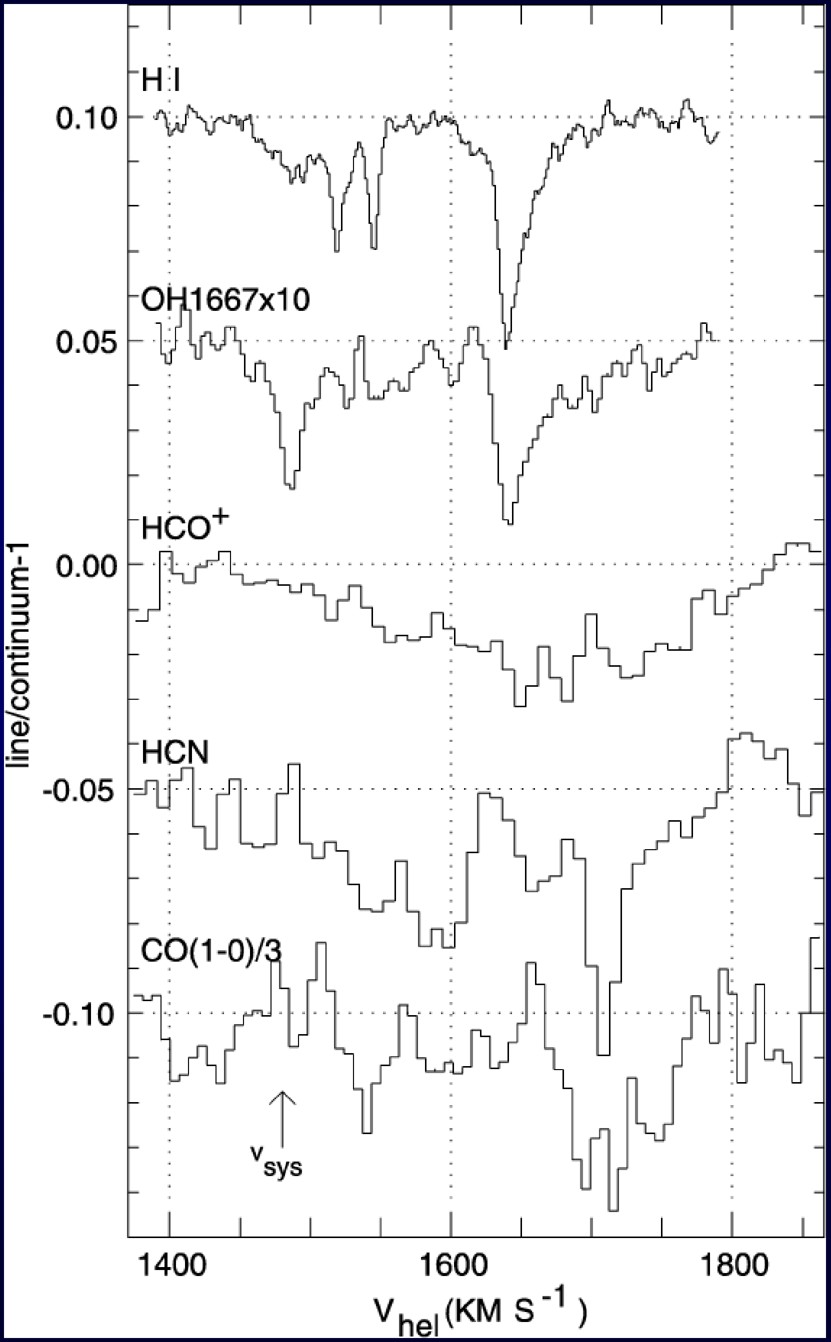
(4-5 pc)

cm- and mm- absorption line spectra of NGC 1052

2MASS, IR



VLBA, 2cm



broad absorption profiles at mm-wavelenght (Δ v= 300–400 km/s)

Liszt & Lucas 2004

The size of a synchrotron self-absorbed emission region

SSA:

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

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

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

accurate size measurements allow to test the relativistic jet model and the physical details of the (non-thermal) radiation mechanism (eg. equipartition conditions, jet speed, viewing angle, etc ...)

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

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

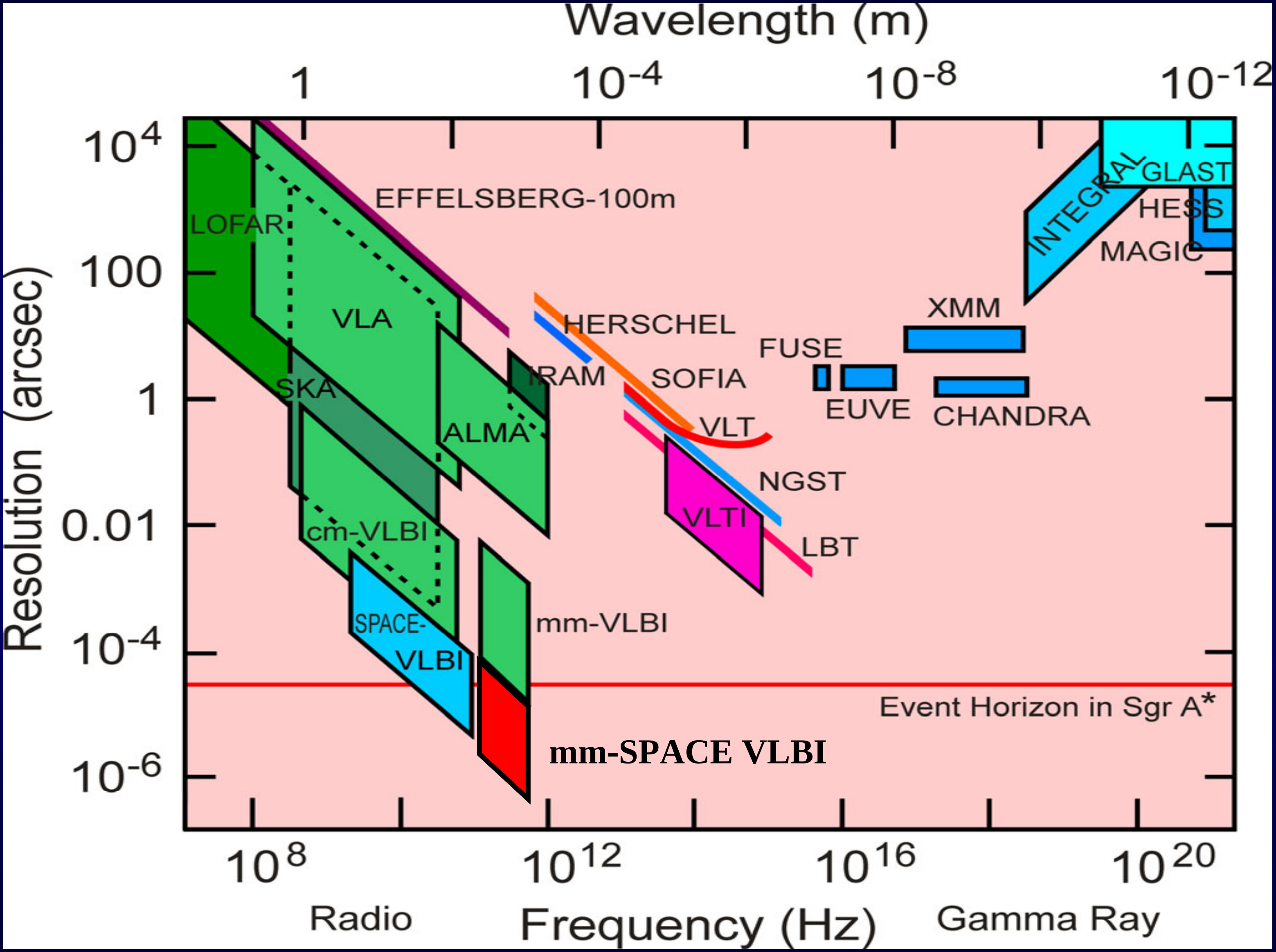
→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory) !

→ 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 (i.e. ALMA) to image the emission around Black Holes in AGN

→ need a full global VLBI array for sensitivity and resolution .

Angular Resolution



Millimetre VLBI provides the highest angular resolution in Astronomy !

The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

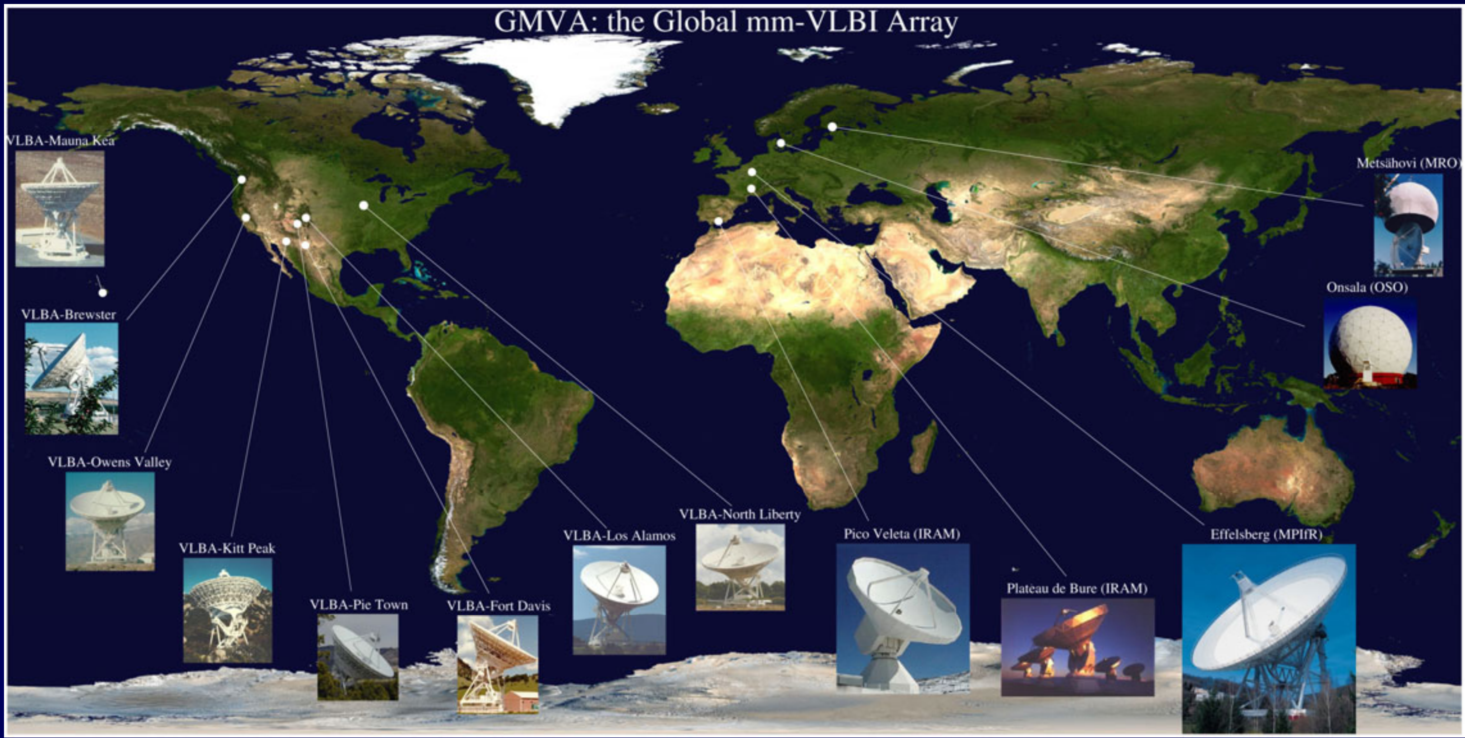
100 – 300 mJy

transatlantic:

50 – 300 mJy

Array:

1 – 3 mJy / hr



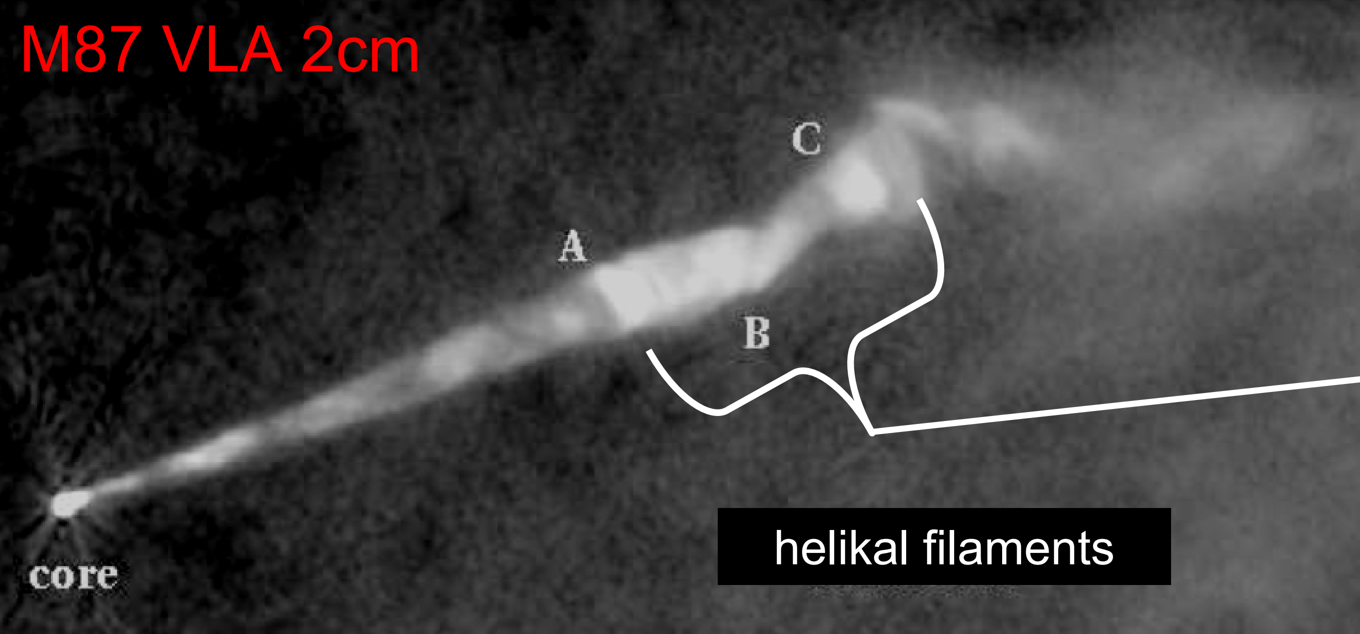
(assume 7σ, 100sec, 512 Mbps)

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

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

Proposal deadlines: February 1st, August 1st

M87 VLA 2cm

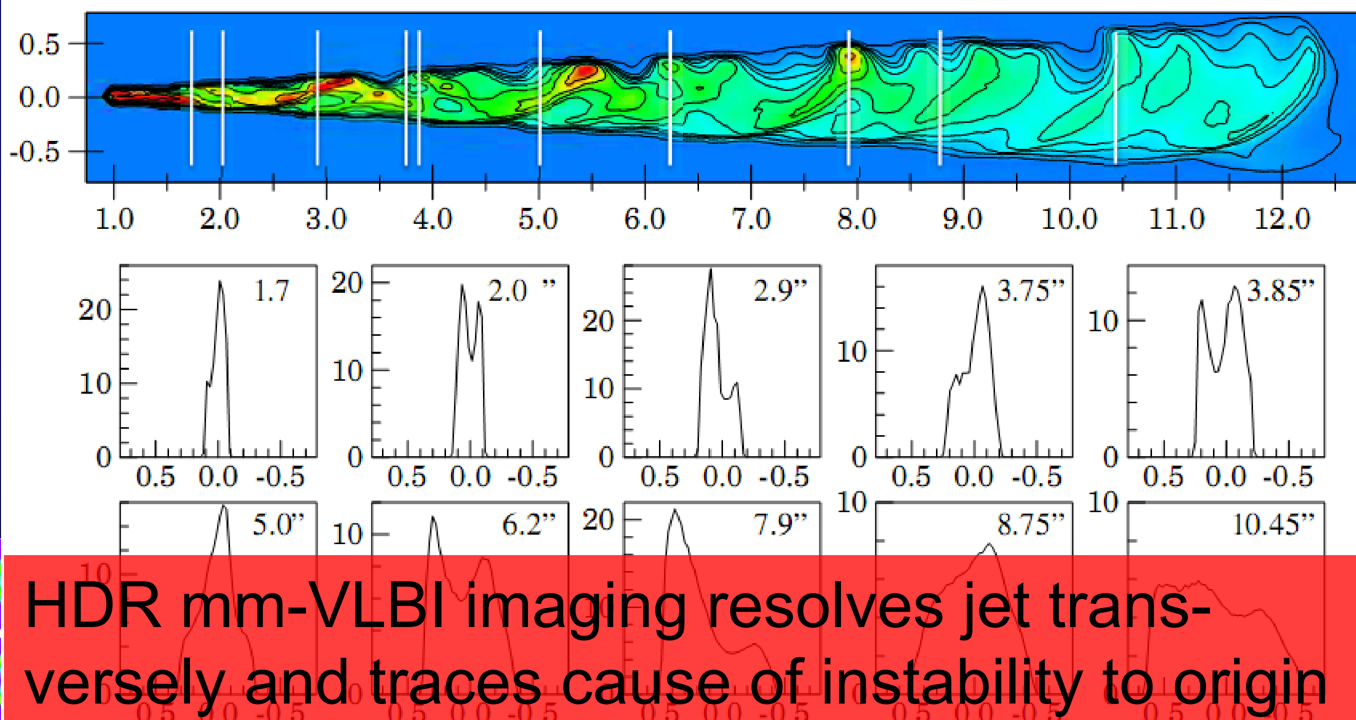


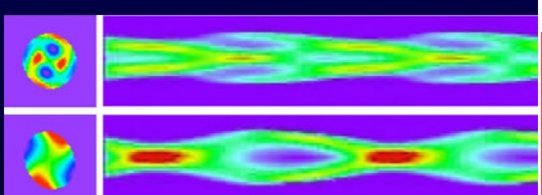
Owen et al. 1989

FIG. 3.—Gray scale image of the jet from feature A through C

Kelvin-Helmholtz Instabilities

Elliptical body mode and double peaked transverse jet-profiles



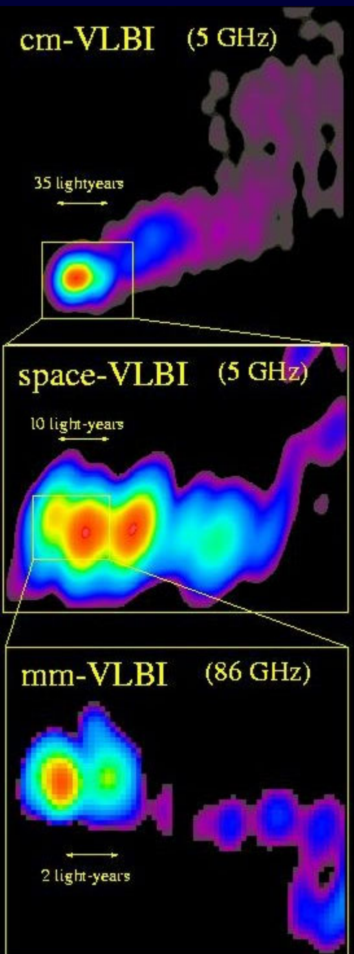


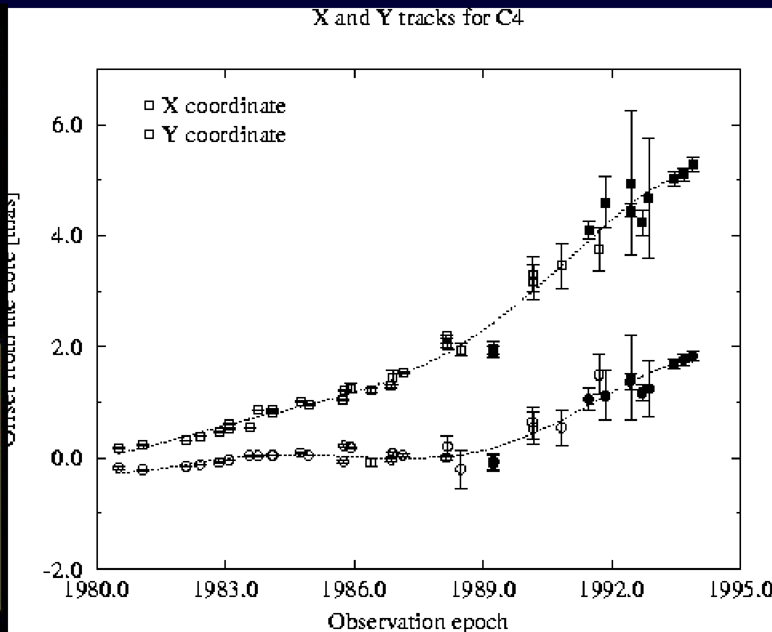
HDR mm-VLBI imaging resolves jet trans-versely and traces cause of instability to origin

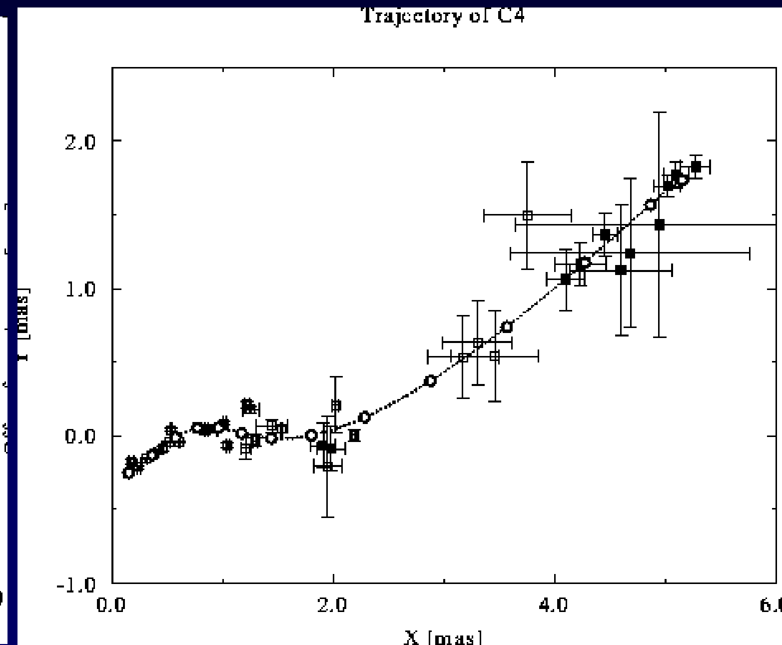
Hardee & Eilek 2011

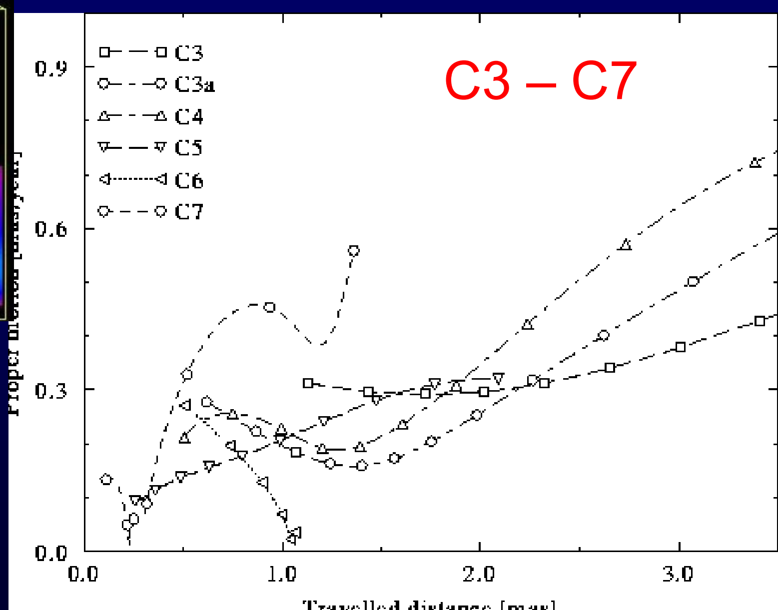
Non-ballistic (helical) motion in the jet of quasar 3C345

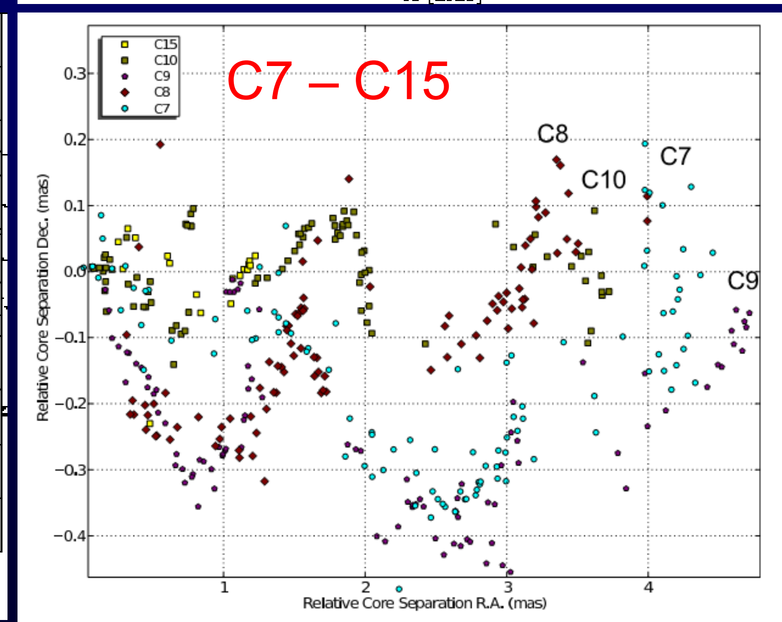
results from F. Schinzel, PhD Thesis 2011

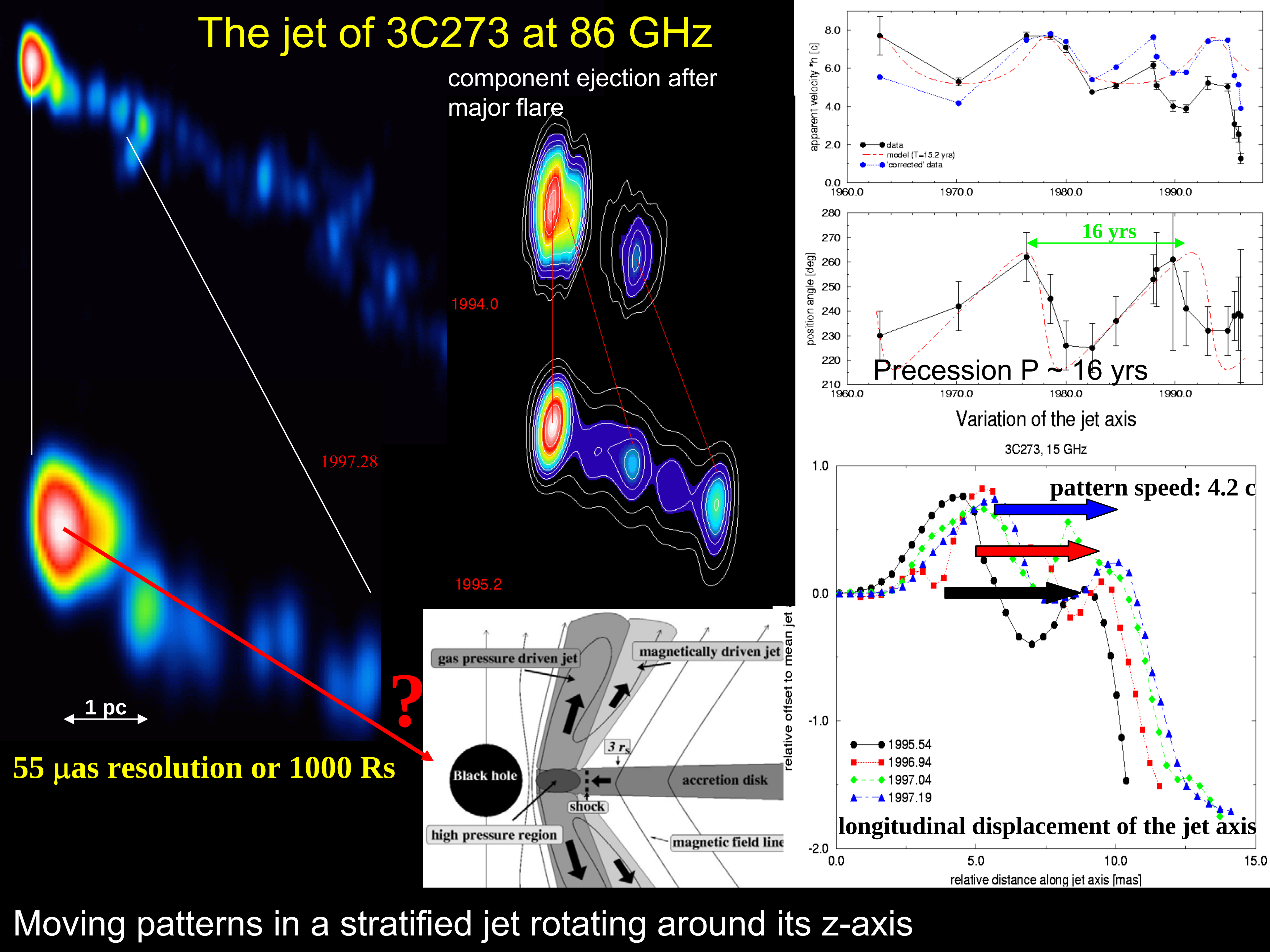








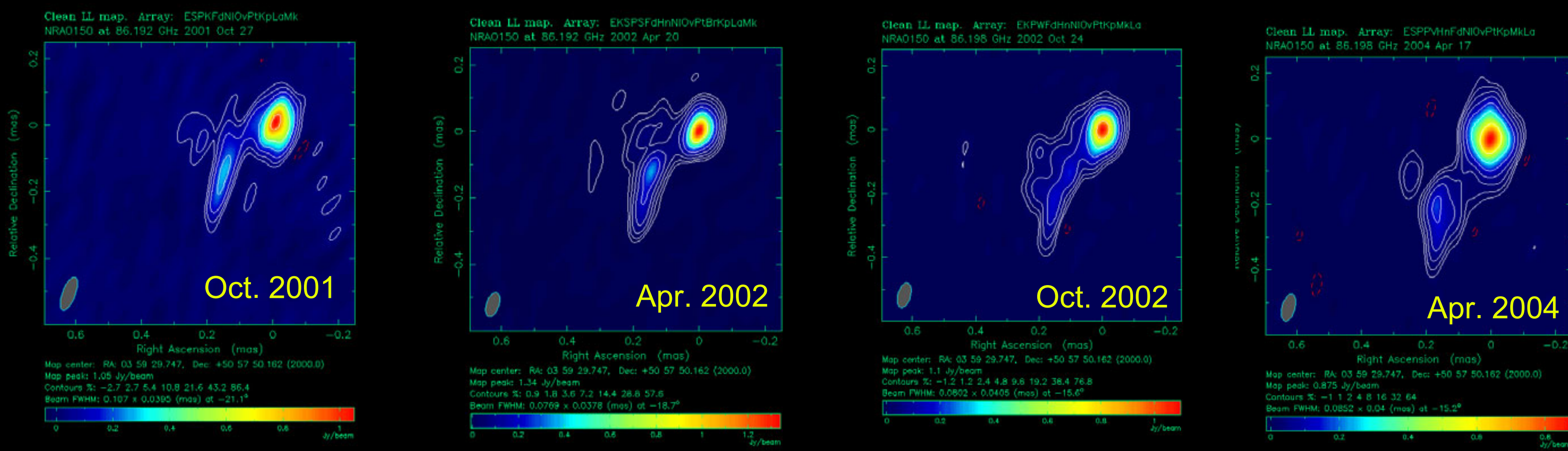




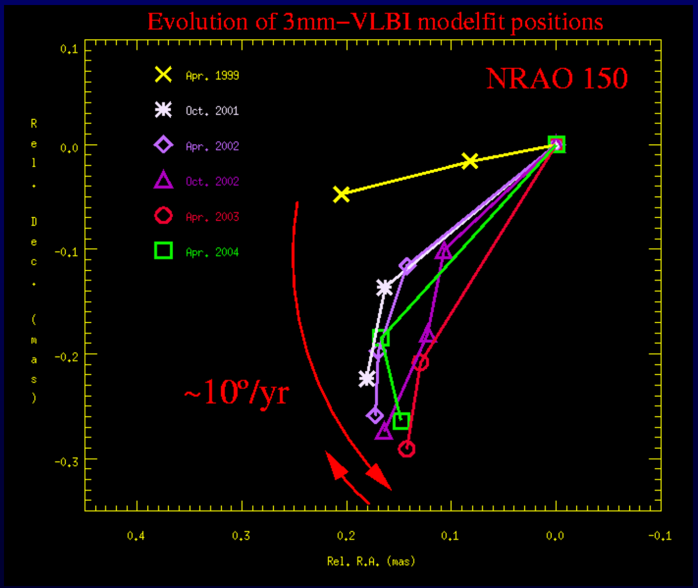
The jet of 3C273 at 86 GHz
component ejection after major flare
1994.0
1997.28
1995.2
1 pc
55 µas resolution or 1000 Rs
?
gas pressure driven jet
magnetically driven jet
3 rs
Black hole
accretion disk
shock
high pressure region
magnetic field line
data
model (T=15.2 yrs)
'corrected' data
position angle [deg]
16 yrs
Precession P ~ 16 yrs
Variation of the jet axis
3C273, 15 GHz
pattern speed: 4.2 c
relative offset to mean jet
1995.54
1996.94
1997.04
1997.19
longitudinal displacement of the jet axis
relative distance along jet axis [mas]
Moving patterns in a stratified jet rotating around its z-axis

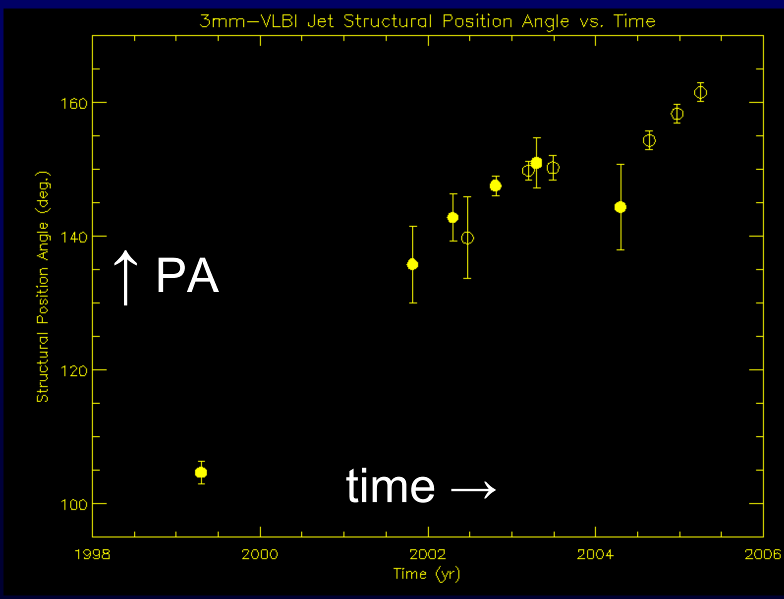
The swinging jet of NRAO150: sub-mas scales

3 mm-VLBI images with the GMVA

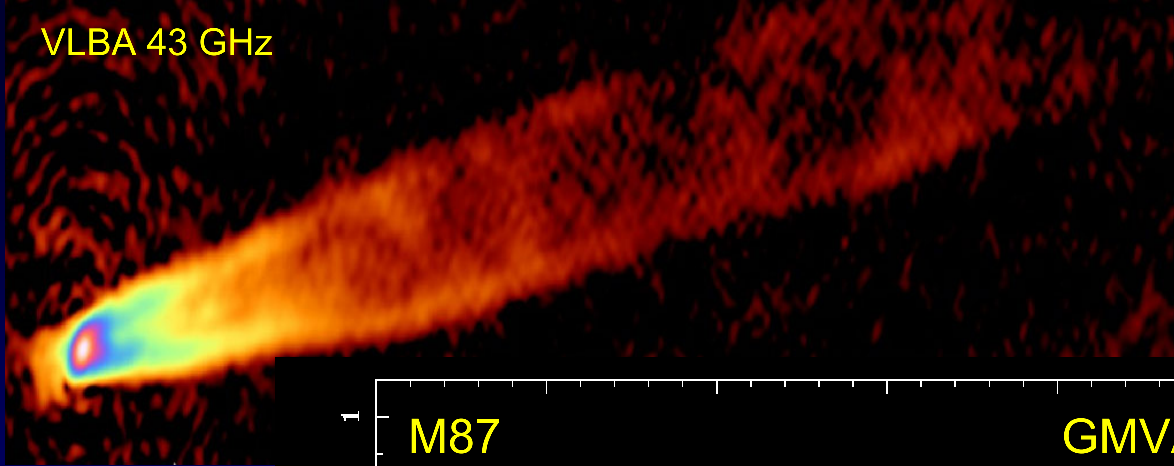


3 mm-VLBI shows jet rotation with an angular speed of ~10º/yr and an extrapolated rotation period of 20 – 30 yrs



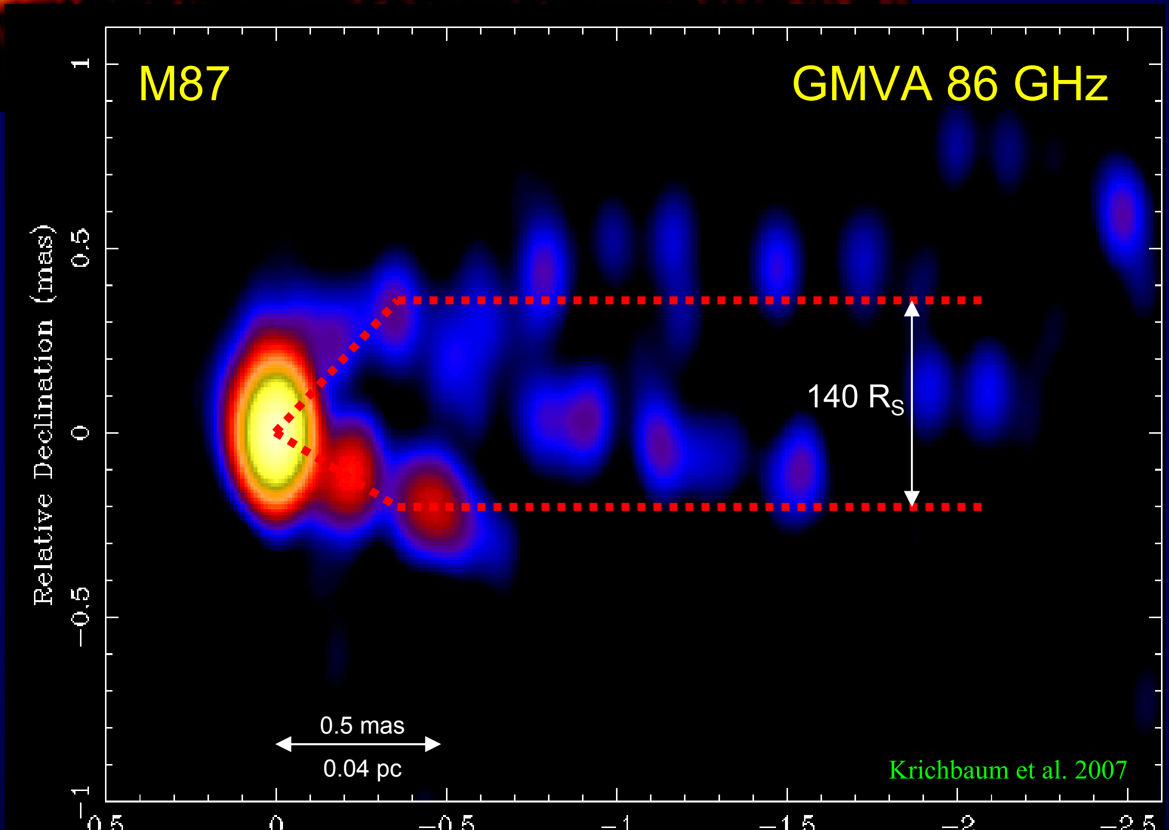


Agudo et al. 2007 (AA)



Walker et al. 2008

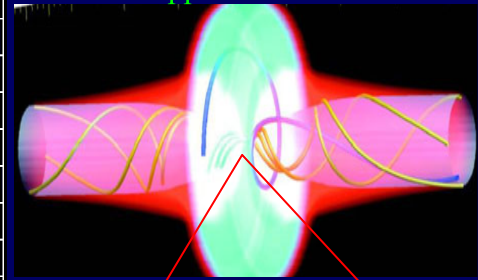
Size of jet base appears too small for magnetic sling-shot acceleration. Direct relation to BH more likely → a GR-MHD Dynamo ?

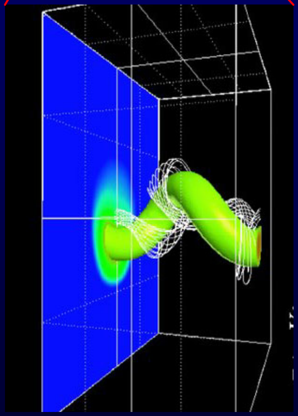


Krichbaum et al. 2007

MHD Jet Simmulation:

Casse & Keppens 2004





Mizuno et al. 2009

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

A 3mm VLBI survey of 127 AGN:

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

Brightness temperature decreasing with frequency ?

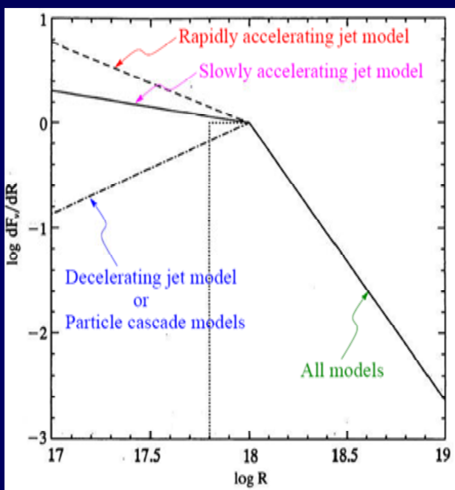
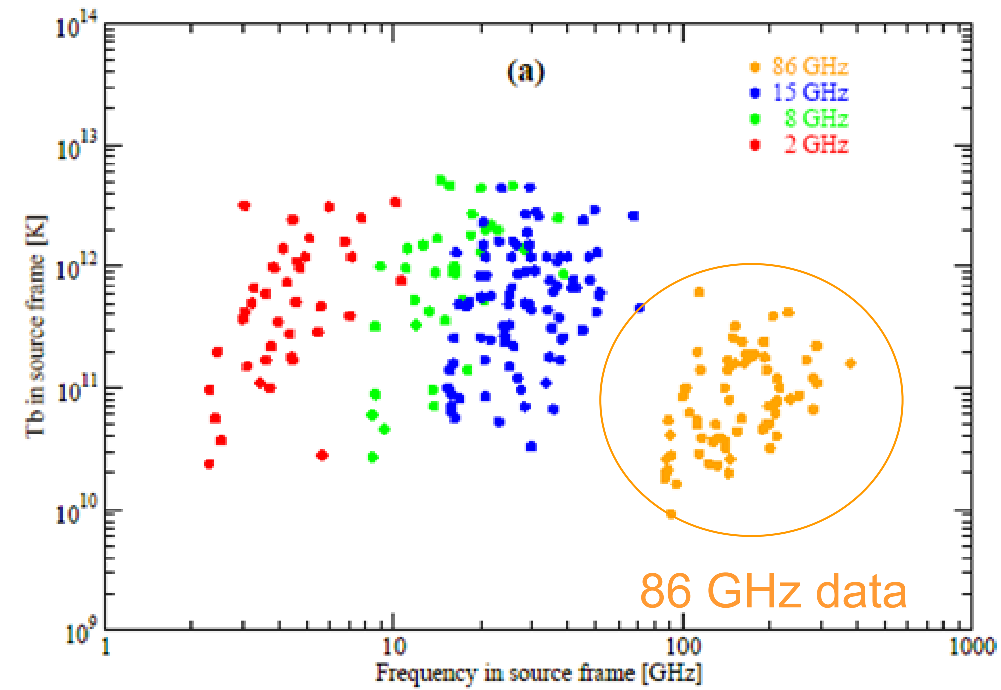
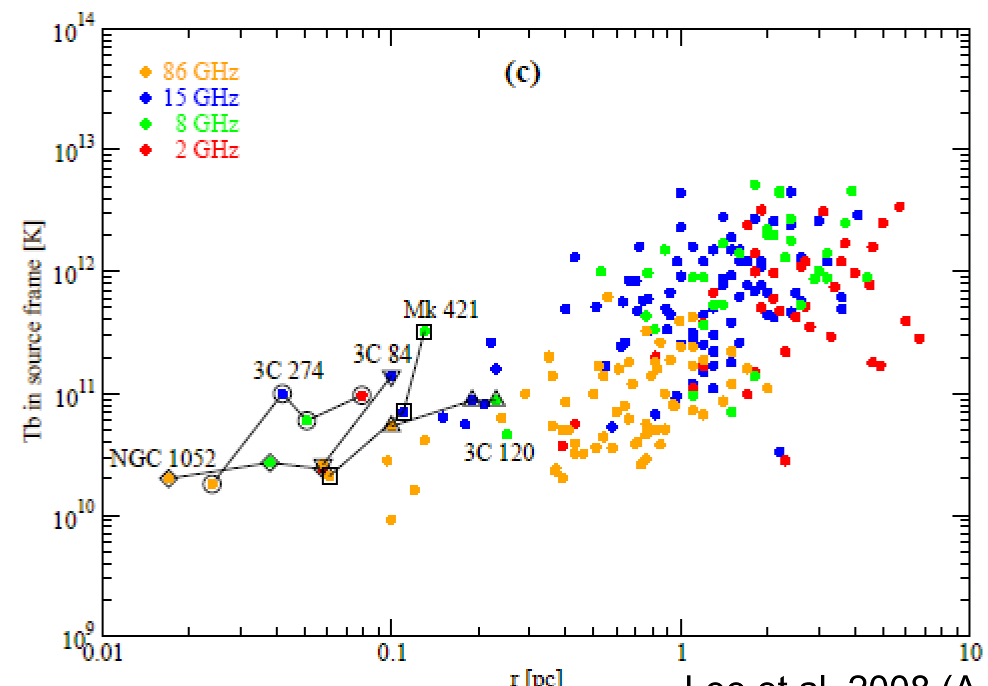


Figure adopted from A. Marscher (1995)

Brightness temperature increasing along jet; evidence for intrinsic acceleration ?

mm-VLBI surveys of AGN can discriminate between fundamental models of jet formation

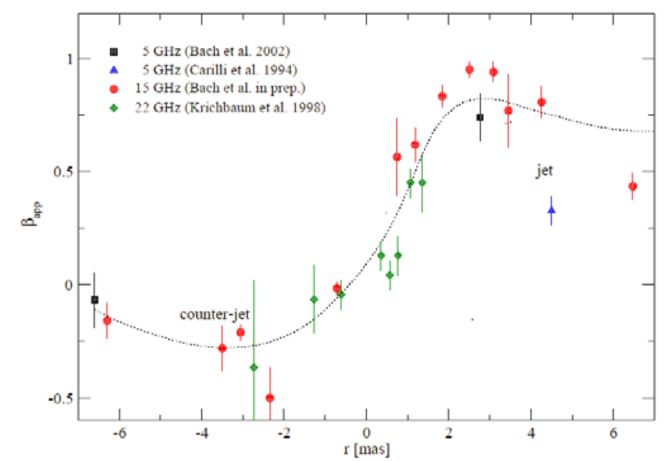




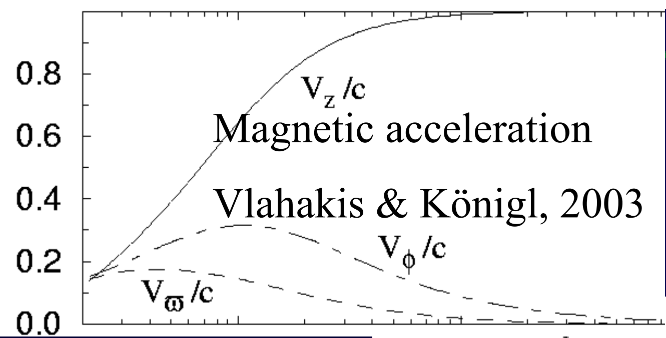
Lee et al. 2008 (AJ)

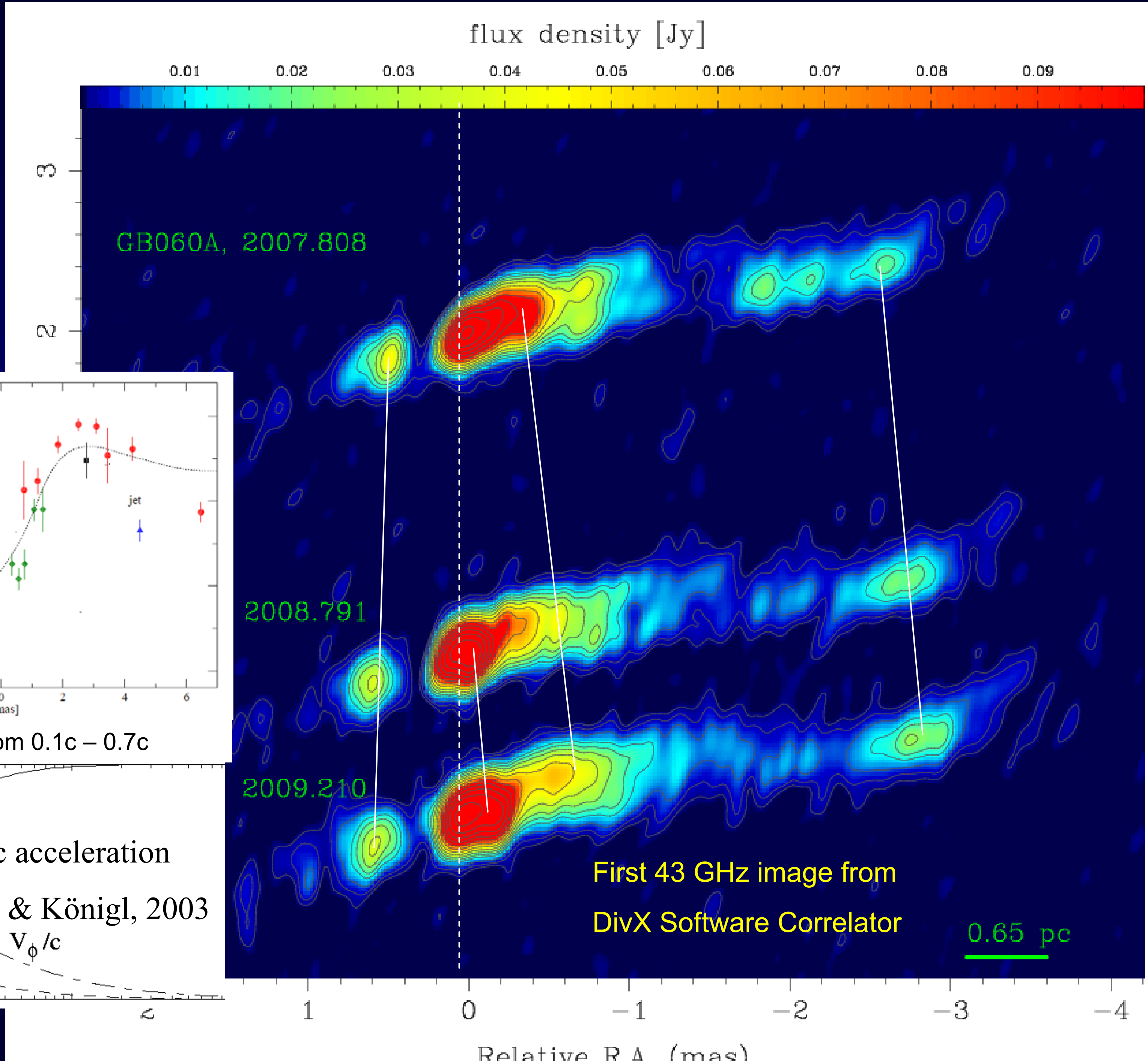
Global 7mm VLBI maps of Cyg A

(EVN, VLA, VLBA, GBT)



jet acceleration from 0.1c – 0.7c





U. Bach et al. 2008

overwhelming evidence for :

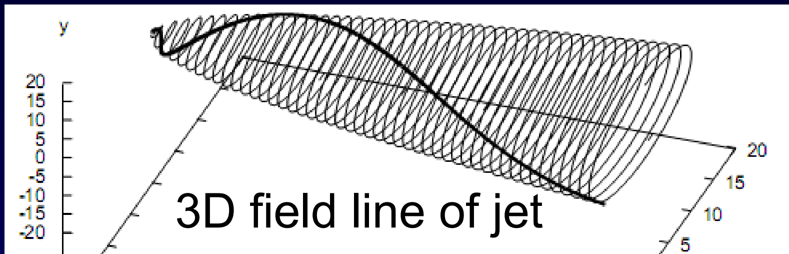
- jet acceleration from sub-pc to pc distances
- core-sheath structure at jet base (hollow jet)
- rotation of jet base / whole jet around z-axis
- small gap between base of jet and counter-jet
- high brightness temperature within < few 10 R_s

but:

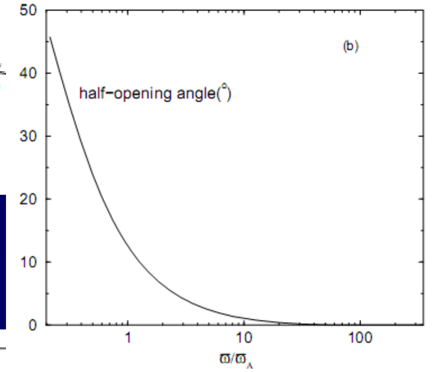
more good quality images with high spatial resolution (< 0.1 pc) needed

(multi-frequency, multi-epoch, preferably with polarization)

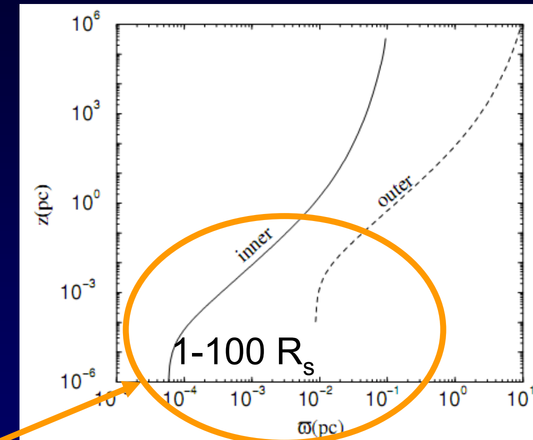
Magnetically driven relativistic Jets



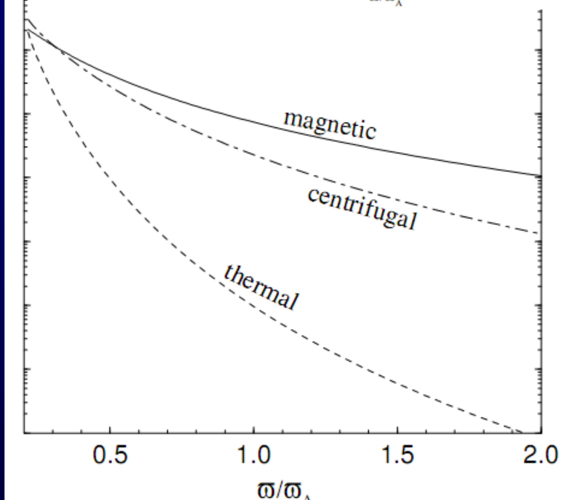
3D field line of jet



inner and outer field lines guide plasma flow above the disk



Check this using mm-VLBI !



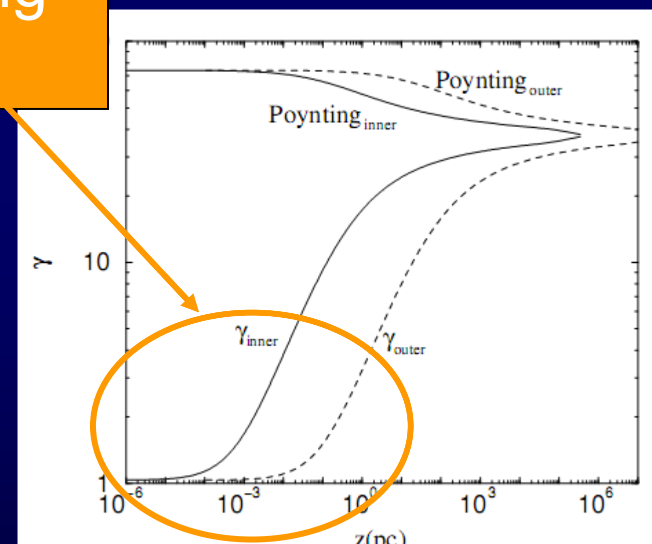
model explains observed:

conical jet opening

helical motion

jet speeds up to $\gamma \sim 50$

acceleration f(z)



Accelerating forces: Magnetic driving is most efficient

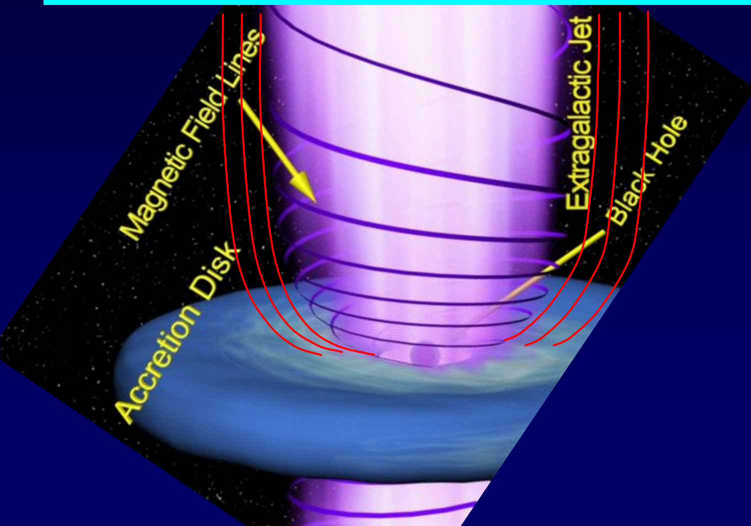
Lorentz-factor and Poynting-to-mass flux ratio for inner and outer field lines

Vlahakis & Königl 2003, 2004; Vlahakis 2006

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.

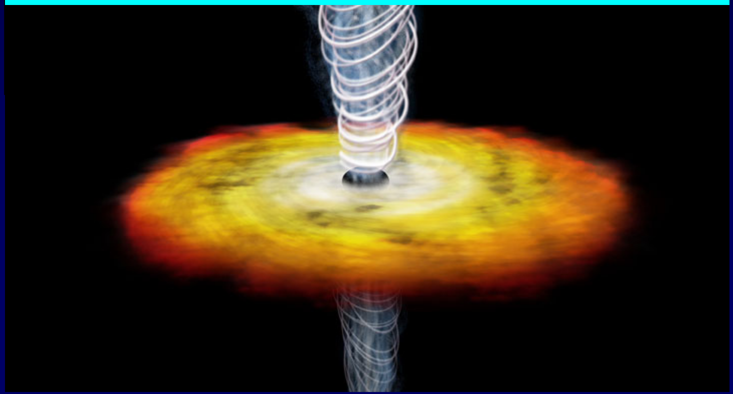
need to reach

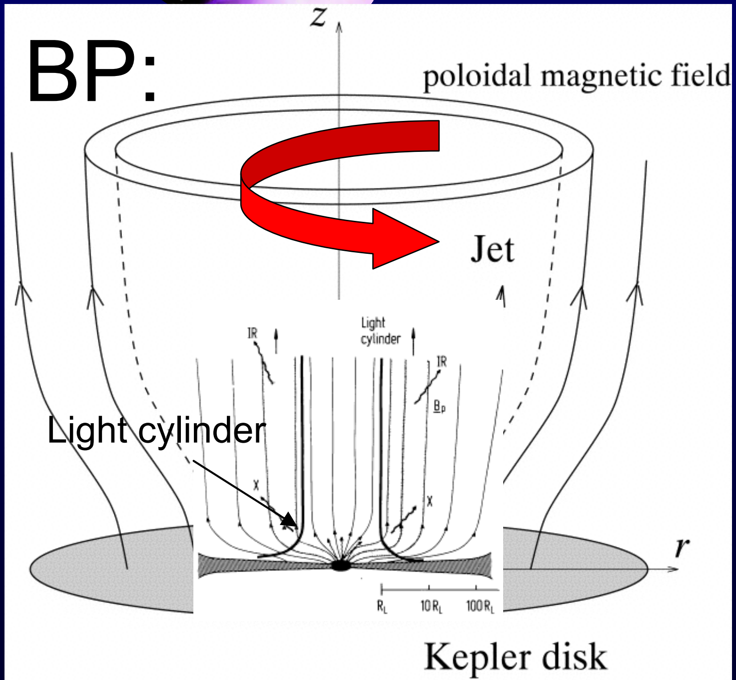
scale of

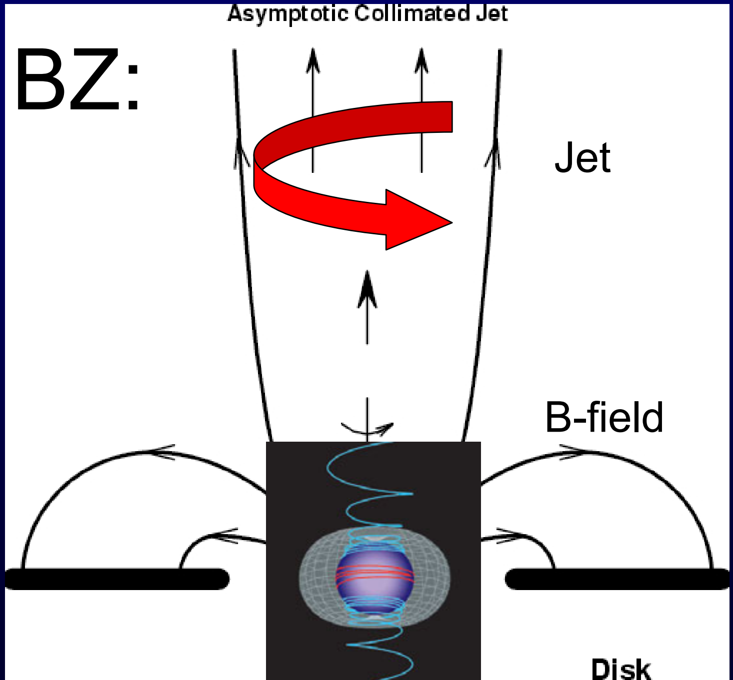
a few R_G

Blandford – Znajek mechanism:

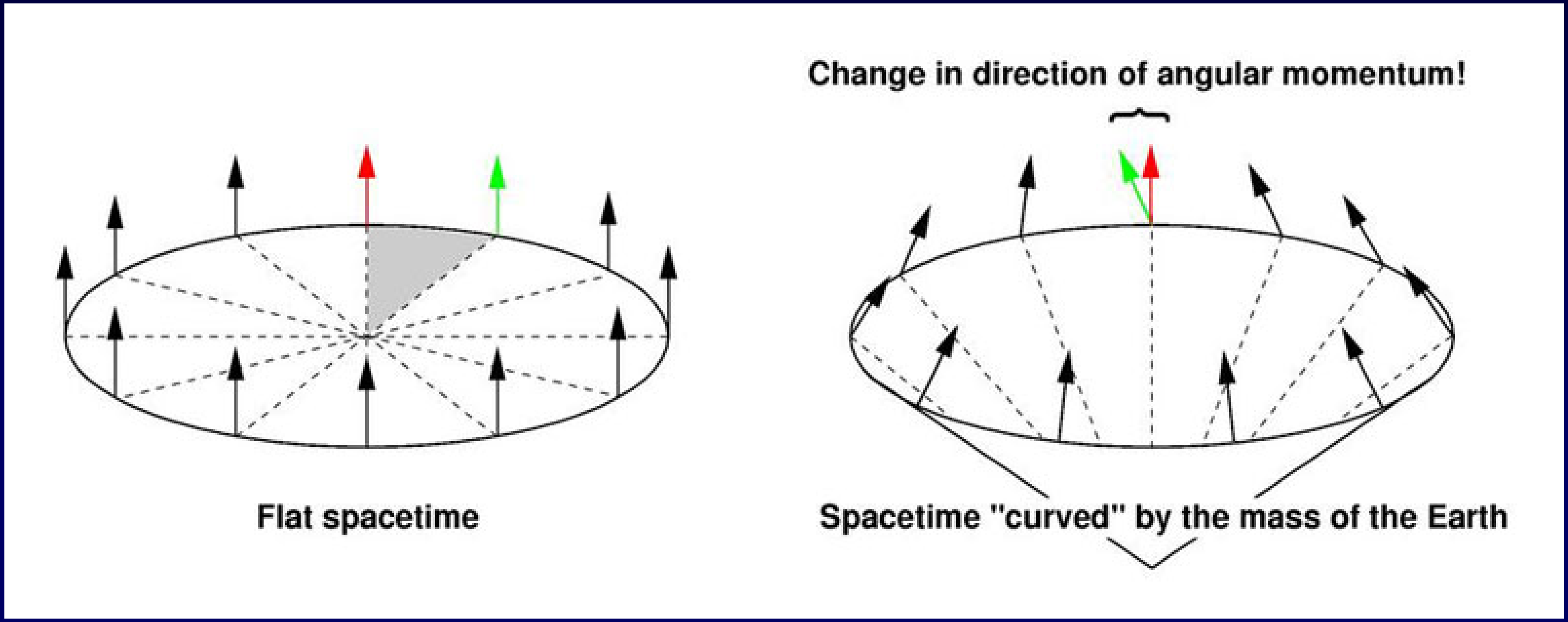
electromagnetic extraction of rotational energy from Kerr BH







Geodetic Precession in curved space-time

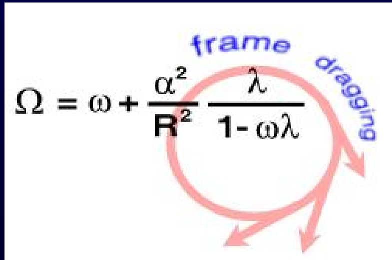


central mass is not rotating:

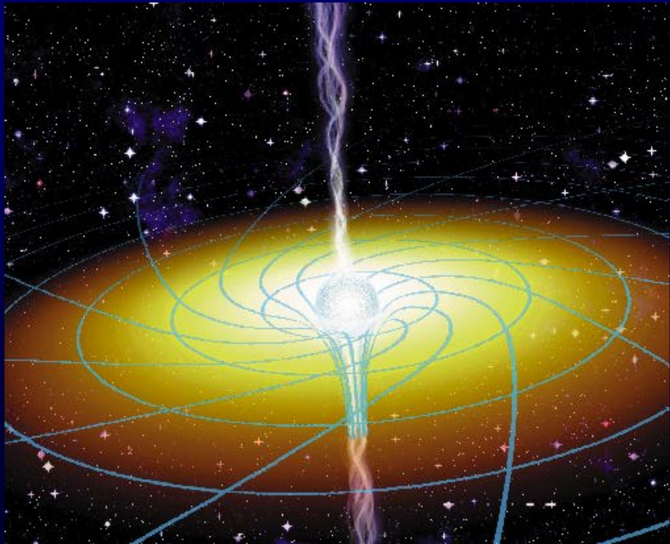
geodetic precession, de Sitter precession

central mass is rotating:

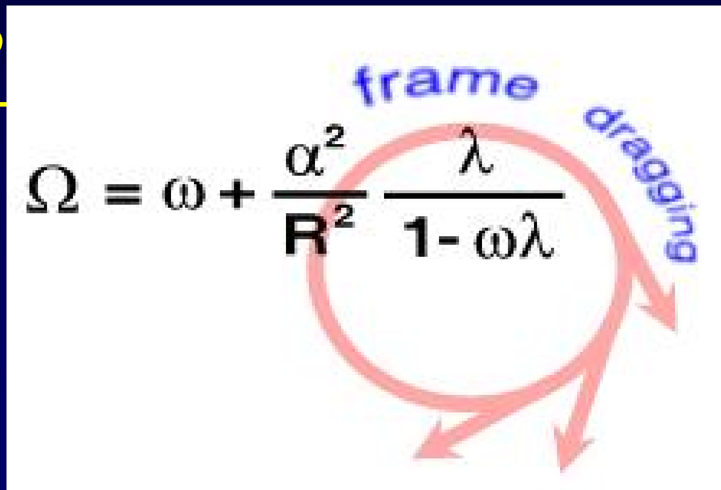
frame dragging, Lense-Thirring effect

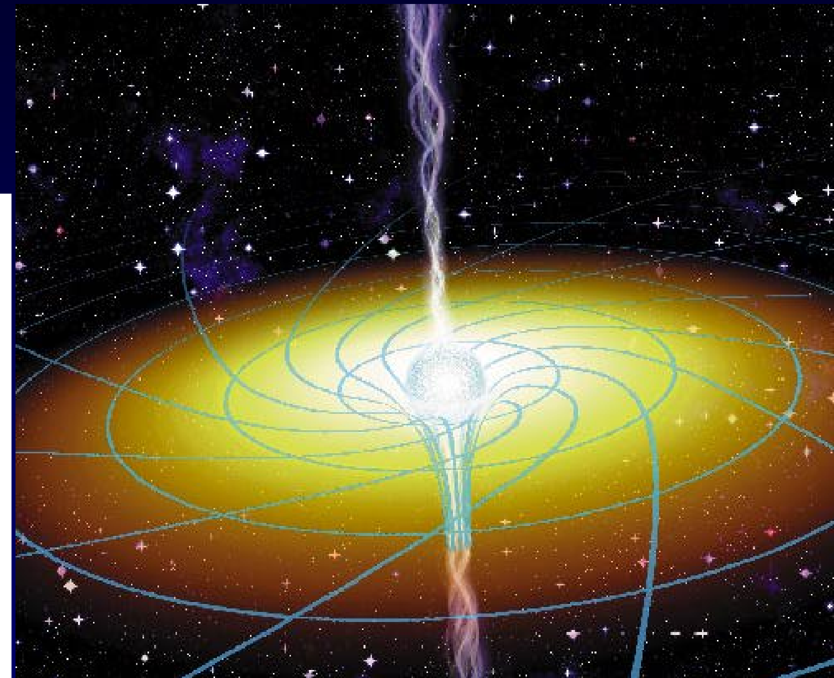


$$\Omega = \omega + \frac{\alpha^2}{R^2}\frac{\lambda}{1-\omega\lambda}$$



Are GR-MHD effects near the BH the main jet driver ?





matter and fields are forced to co-rotate with the horizon

torque due to misalignement of $\vec{L}$ from accr. disk and Kerr BH

→ P =0.3 - 20 yrs appear possible

(e.g. Caproni et al., 2004)

known „precessing" sources:

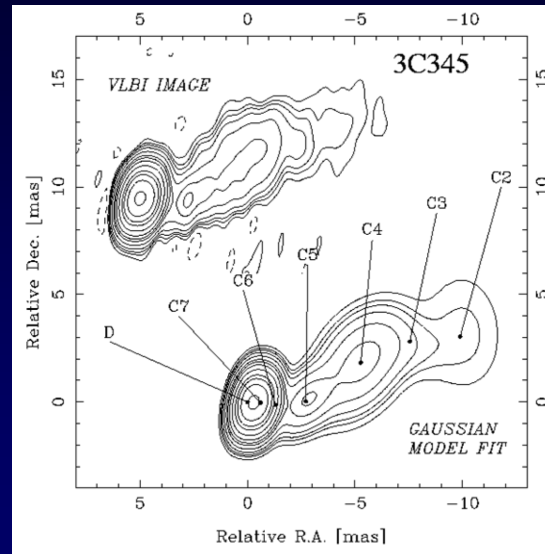
3C84	Gal
NRAO150	QSO
0716+714	BL
3C120	Gal
3C273	QSO
3C279	QSO
3C345	QSO
BLLac	BL

3C345: A Binary Black Hole ?

The assumption of a supermassive binary Black Hole in 3C345 explains:

1. observed helical trajectories of the jet components
2. flux density changes of the jet components
3. optical variability
4. morphology and evolution of the jet

Combination of flux density evolution and kinematic data allow determination of mass and orbit of BBHs.

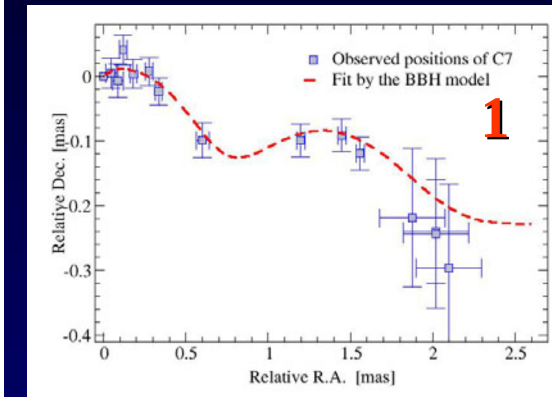


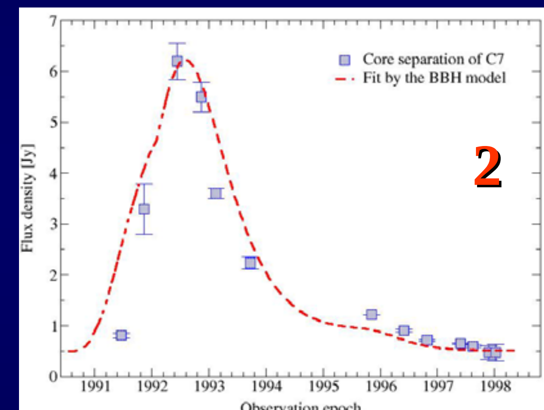
Parameters of BBH in 3C345

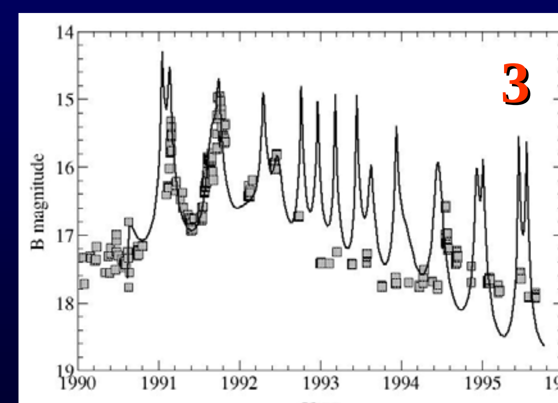
$M_1 = 1 \cdot 10^9 \mathrm{M_{sol}}, \quad M_2 = 5 \cdot 10^8 \mathrm{M_{sol}}$

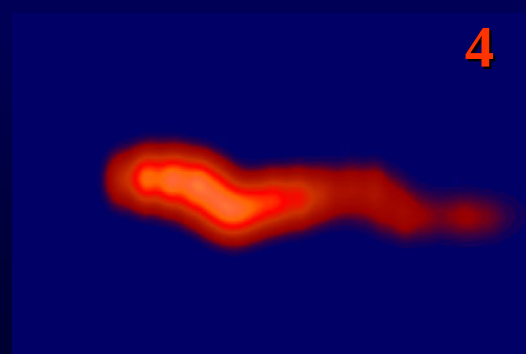
$a_{\mathrm{maj}} = 0.63\mathrm{pc}\,(0.13\,\mathrm{mas}), \quad e = 0.1$

$P_{\mathrm{orb}} \approx 170\mathrm{years}, \; P_{\mathrm{prec}} \approx 2500\,\mathrm{years}$



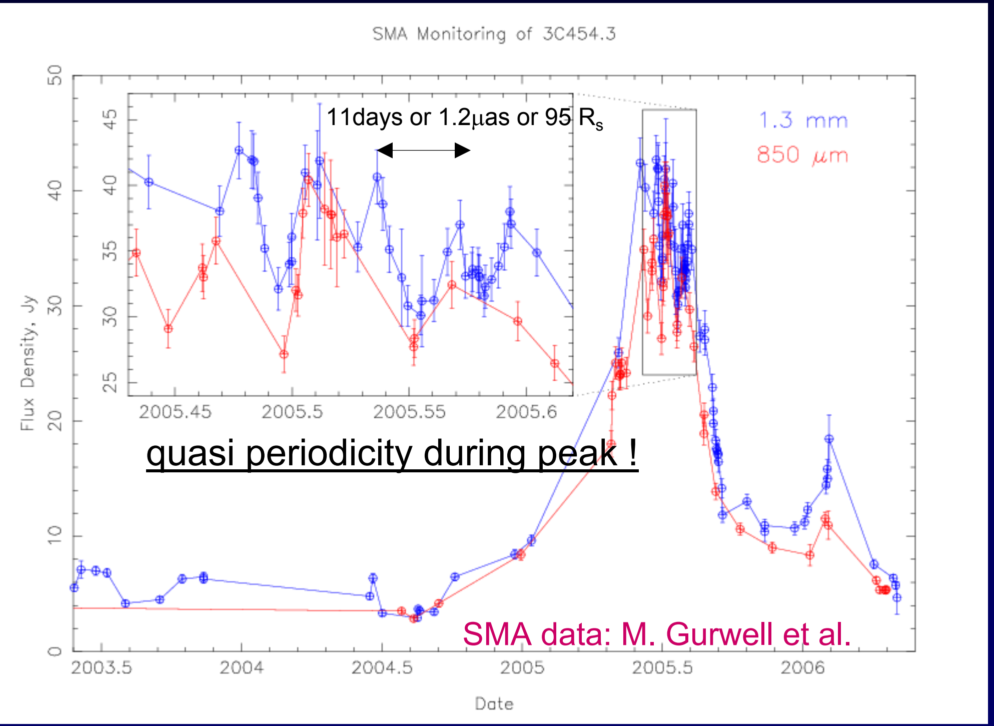






Lobanov & Roland 2002

Spectral variability of 3C454.3 after gamma-ray flare (May 2005):



Effelsberg:

1.4 – 32 GHz

Pico Veleta:

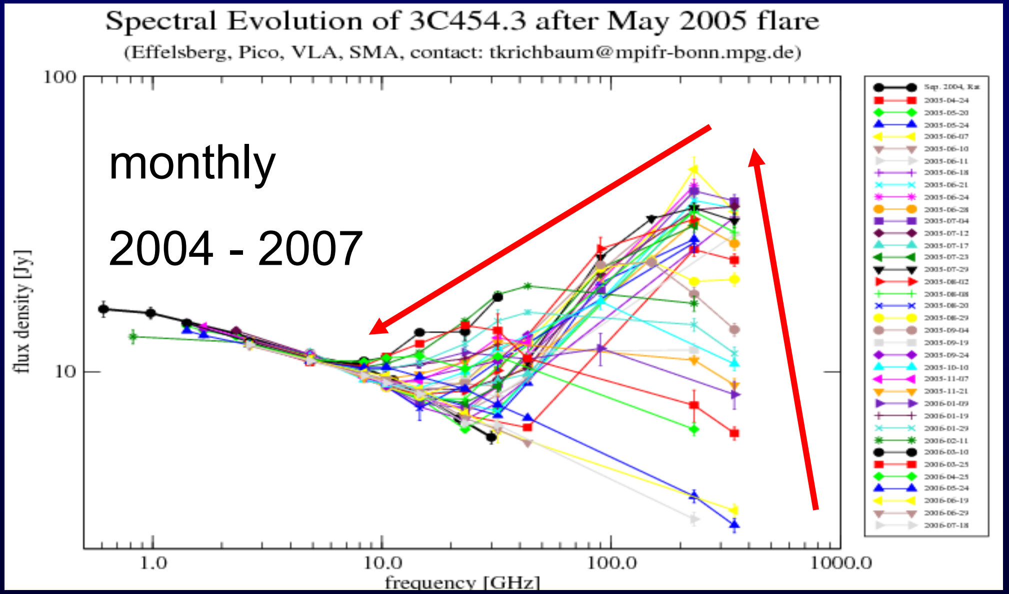
90 – 230 GHz

SMA:

230, 350 GHz

variability amplitudes peak in mm/sub- mm band

ν_m ~ 100-300 GHz

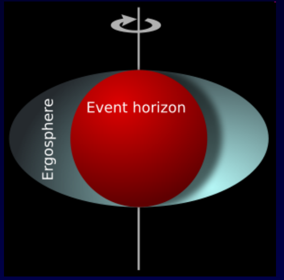


T. Krichbaum, et al. 2007

combined data:

Krichbaum, Fuhrmann, Ungerechts, Wiesemeyer, Gurwell et al.

Variability Timescale for Keplerian Motion around a BH



Angular velocity of co-rotating matter in BH orbit

$$\Omega = \frac{M^{1/2}}{r^{3/2} + aM^{1/2}}$$

$$r = R/R_g$$

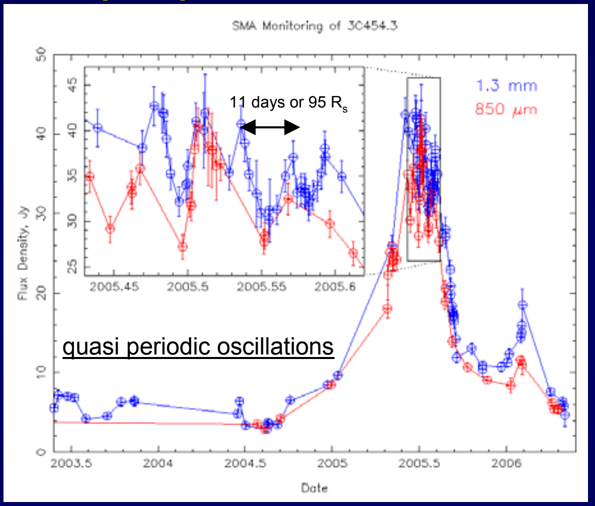
a = spin parameter

Black hole mass and Period

$$\frac{M}{M_\odot} = \frac{3.23 \times 10^4 \; P_{\text{sec}}}{(r^{3/2} + a)(1 + z)}$$

non rotating BH: a= 0, r > R_{LSO} = 6 R_g

rotating Kerr BH: a> 0, r > R_{LSO} = 1 R_g (a=0.9982, r= 1.2 R_g)



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example: SgrA*, M= 4 x 10^6 $M_\odot$, P=30 min for a=0, P=5 min for a=0.9982

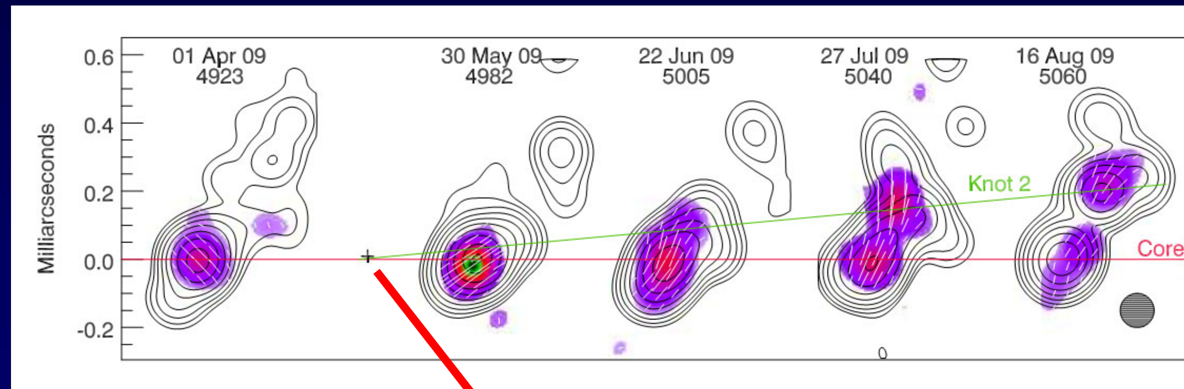
M87 , M= 3 x 10^9 $M_\odot$, P=16 days for a=0, P=60 hrs for a=0.9982

Need to search for rapid and quasi-periodic flux density variations and do quasi-simultaneous mm-VLBI monitoring to determine the mass and spin of the SMBH.

Superluminal ejection during Gamma-ray outburst

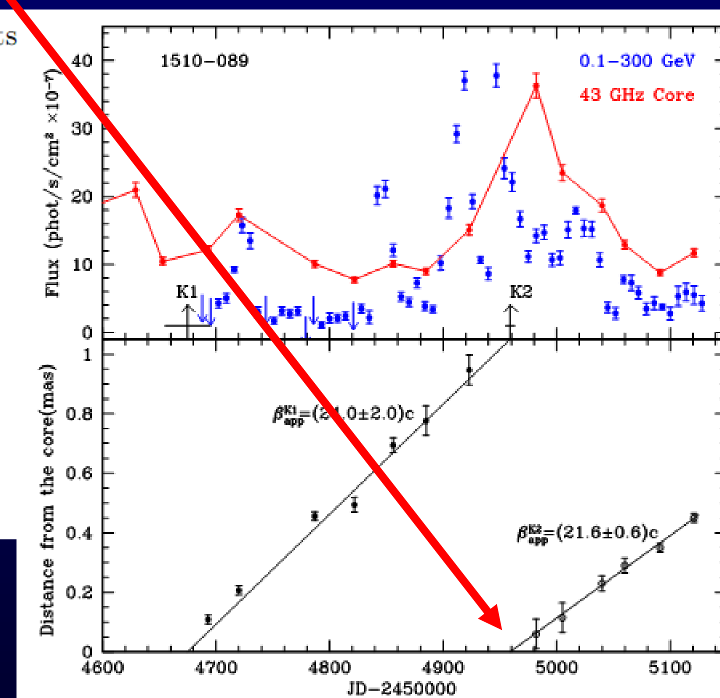
mm-VLBI relates gamma-ray production with variability in VLBI core. Need high angular resolution and dense time sampling !

1510-089   43 GHz VLBA



Correspondence between Gamma-Ray Flares and Time of Ejections of Superluminal Knots

Source	τ	Knot	$T_\circ$ RJD	T_γ RJD	ΔT days	β_{app} c	S_γ^{max} 10^{-6}ph cm^{-2}s^{-1}
0235+164	0.79	K1	4728±30	4730±4	-2±34	56±10	0.91±0.07
3C 273	0.21	K2	4747±45	4744±4	+3±49	8.3±1.4	1.40±0.13
		K3	4901±33	4947±4	-46±37	8.9±0.7	1.03±0.10
		K4	∼5029	5100±4	∼-71	∼23	5.13±0.27
3C 279	0.32	K2	4779±24	4800±4	-21±29	14.5±2.0	1.48±0.10
1510−089	0.56	K1	4675±23	4723±4	-48±27	24.0±2	0.91±0.07
		K2	4959±4	4962±4	-3±8	21.6±0.6	3.78±0.17
3C 345	0.28	K1	4677±21	4737±4	-60±25	7.1±0.6	0.15±0.07
		K2	4904±50	4982±4	-78±54	10.2±2.2	0.28±0.09

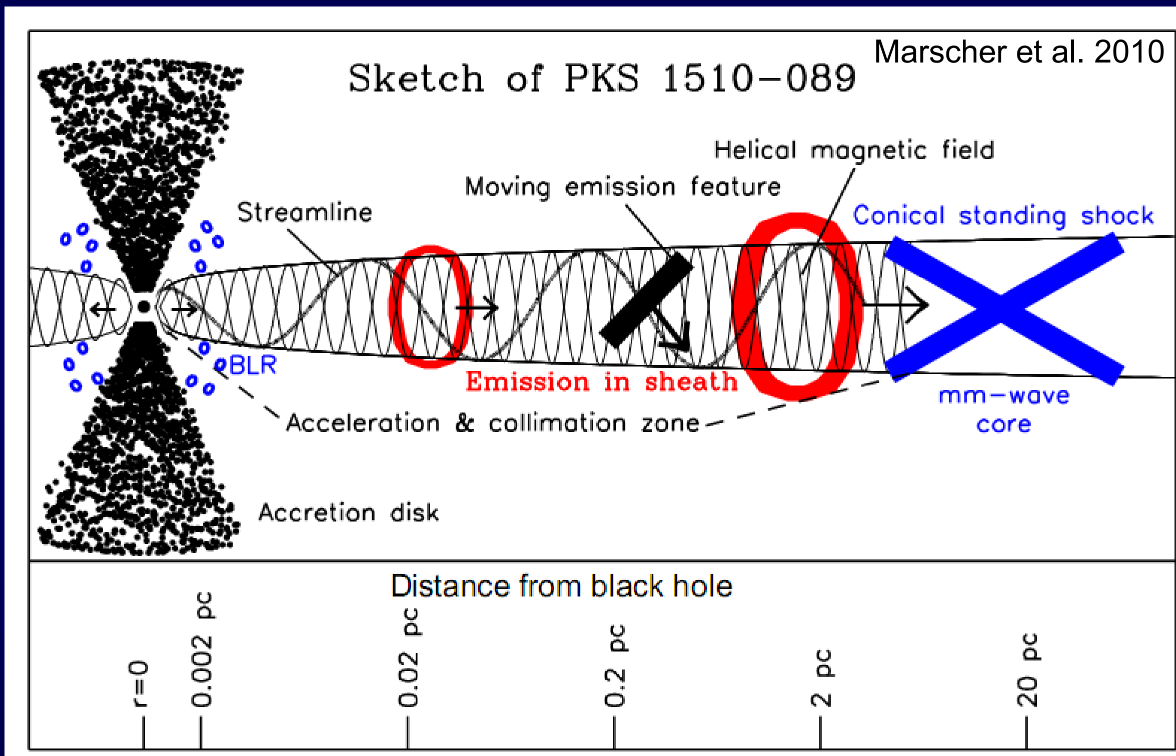


new jet components appear within < ~60 days

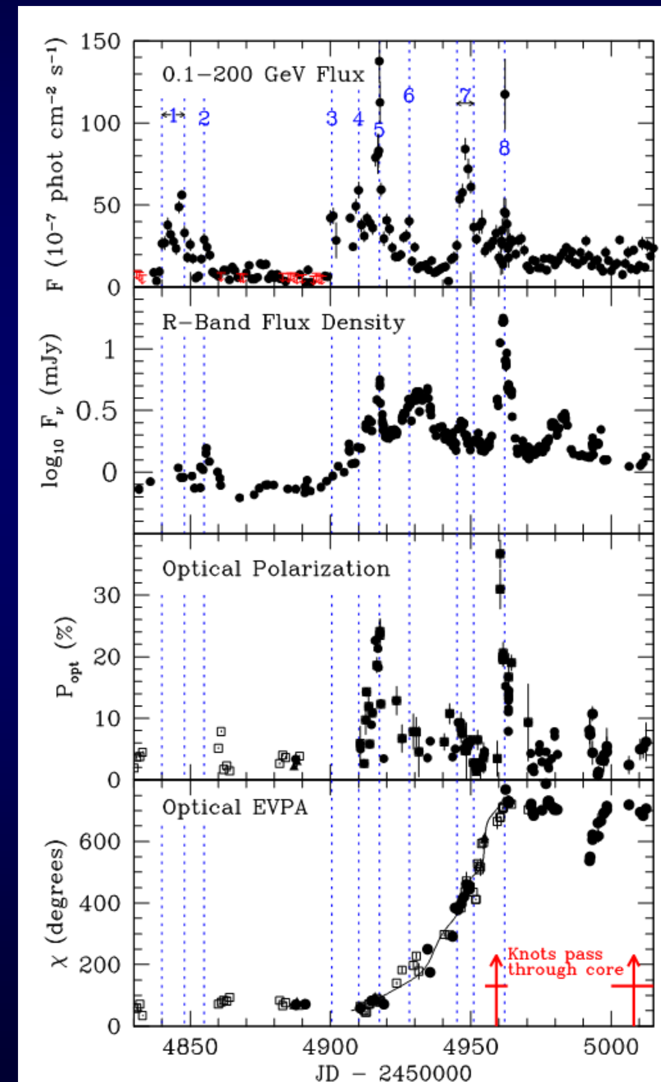
Jorstad et al. 2009, Marscher et al. 2010

Optical Polarization angle swings during mm-optical-gamma-ray flare

future VLBI at 0.8, 1, & 3mm — VLBA 7mm



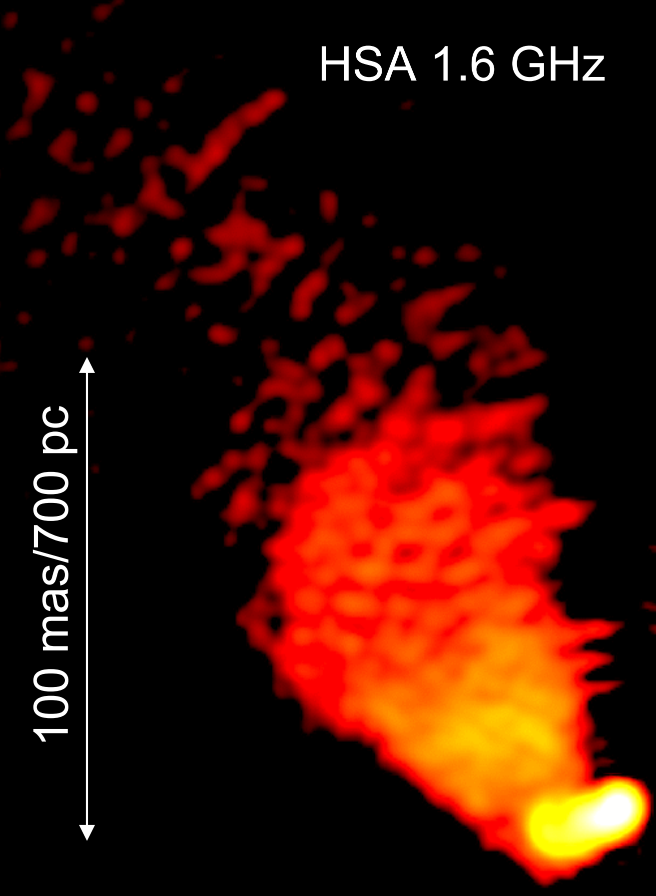
1510-089



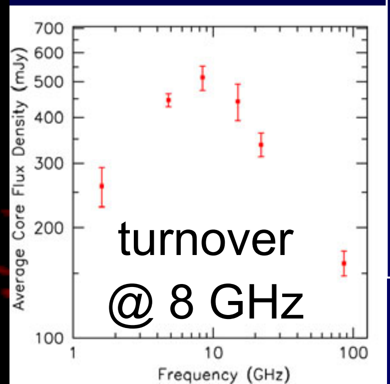
Marscher et al. 2010

Sketch: polarization angle swing due to motion of shock in a magnetized helical jet

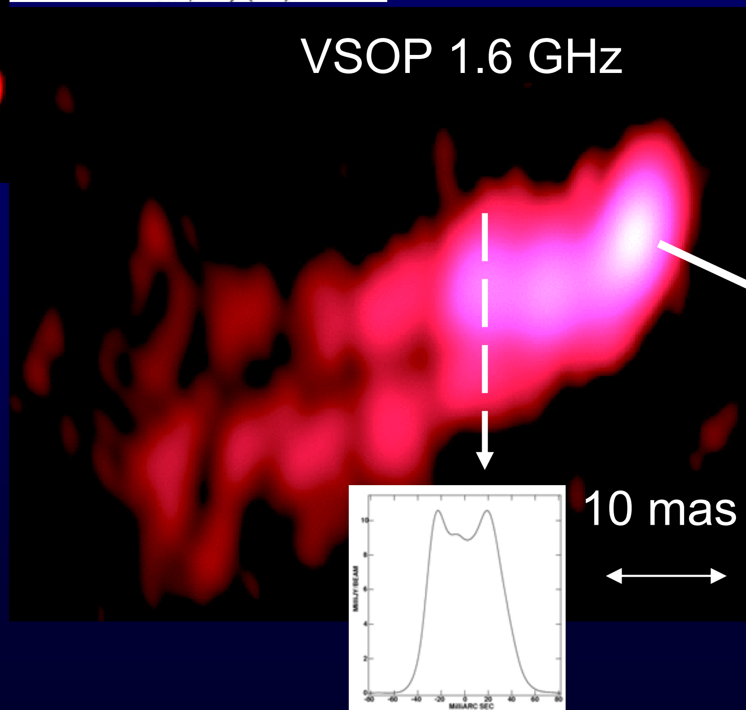
3C279: similar behaviour (Abdo et al. 2010 , Nat 463, 919)

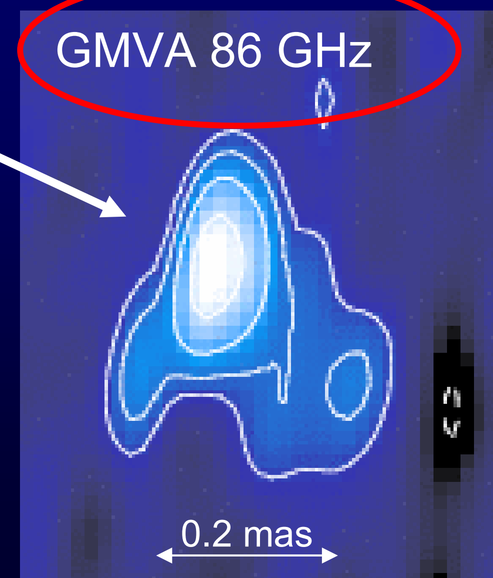


spectrum
VLBI core



- resolution ~110 x 40 μas
- core unresolved at 86 GHz
  - size smaller than 0.03 pc (gaussian fit)
  - $M_{BH}=10^9$ M_{sun}, 1 $R_S=10^{-4}$ pc
  - size ~ 320 x 210 R_S
  - $T_B > 4 \times 10^9$ K
- S_t=150 mJy, S_c=45 mJy





Mrk 501

z=0.0337

TeV & γ-ray source

Giroletti et al. 2004, 2008

Main questions addressed by mm-/sub-mm VLBI

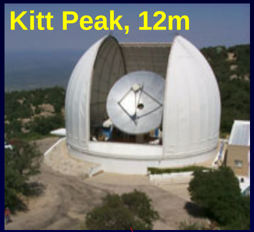
- What are the physical conditions in regions of strong gravitational field near SMBHs ?
- How are the powerfull jets created and launched ? Test of GR-MHD dynamo model.

in detail:

- for nearby sources image silhouette around BH, determine its mass, spin, polarization
- measure shape & morphology of jet at its origin
- determine properties of jet nozzle, size, orientation, opening angle & time variability
- measure linear and transverse jet profile (ridgeline, hollow jet, stratification)
- measure jet speed, acceleration, compare to max. possible Lorentz-factor of dynamo
- find reason for helical jet structure (geodetic precession, MRI or KH instabilities)
- measure brightness temperature profile, leptonic or hadronic jet composition
- study outburst /ejection relation (broad-band variability, gamma-ray/TeV production)
- polarization of the jet nozzle, topology of B-field, overcome Faraday rotation at mm-λ

For all this one needs a high as possible observing frequency and a small as possible observing beam in combination with good (mJy) sensitivity.

→ Global mm/submm-VLBI monitoring using the most sensitive mm-antennas



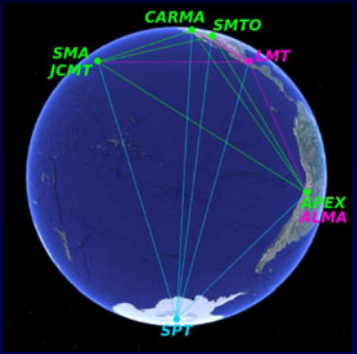
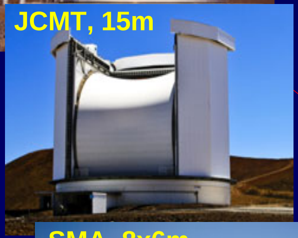
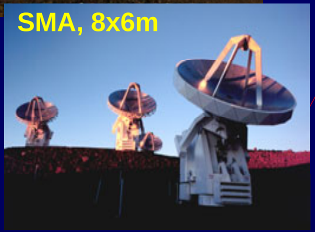
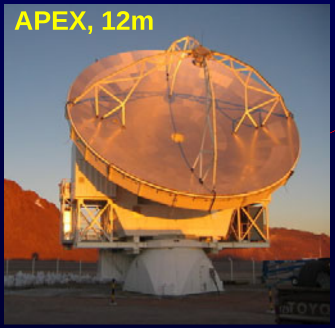
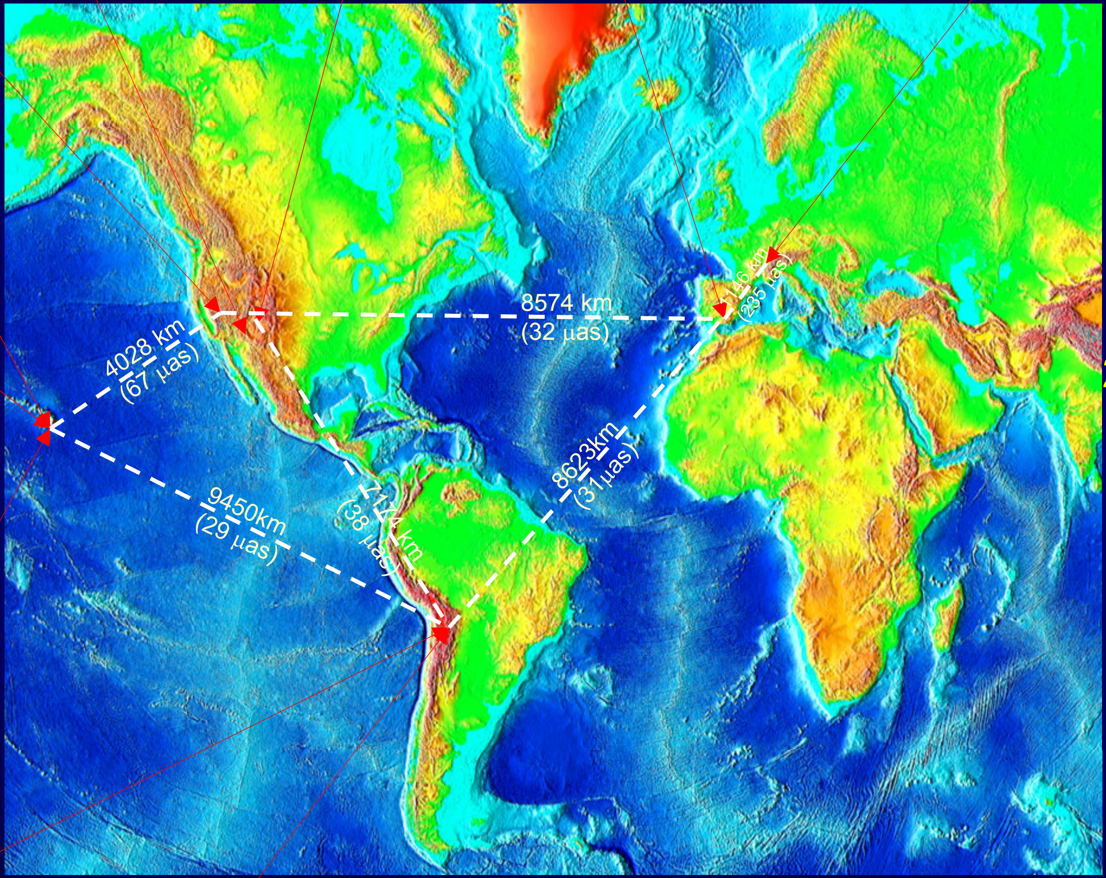


image: S. Doeleman







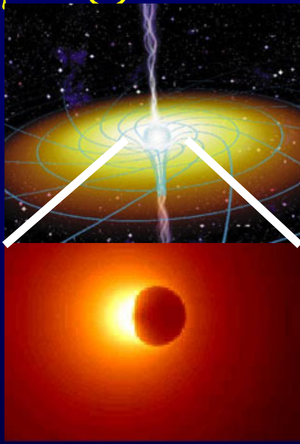


(angular resolutions calculated for 230 GHz)

Angular Resolution:

25-30 µas @230 GHz

16-20 µas @345 GHz



Imaging Black Holes and the Central Engine with mm-/sub-mm VLBI

(now called Event Horizon Telescope)

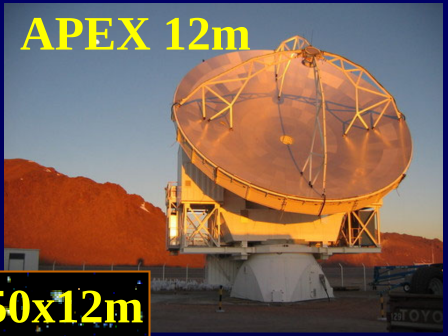
composition: tkrichbaum@mpifr

Future 1mm-VLBI – Sensitivities

(7σ in [mJy])

	PdBure	CARMA	Hawaii	SMTO	APEX	ALMA
Pico	40	50	56	124	100	14
PdBure		40	45	100	81	12
CARMA			56	124	100	15
Hawaii				139	113	17
SMTO					254	39
APEX						31

assume: 4 GHz (16 Gbit/s) bandwidth , 20 s integration time, 2 bit sampling

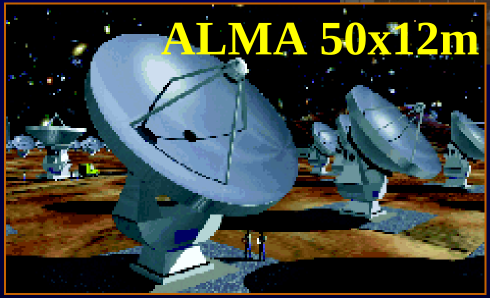


expected (7σ) detection limits:

Pico-SMTO/APEX : ~ 110 mJy

plus PdBure /CARMA : ≥ 40 mJy

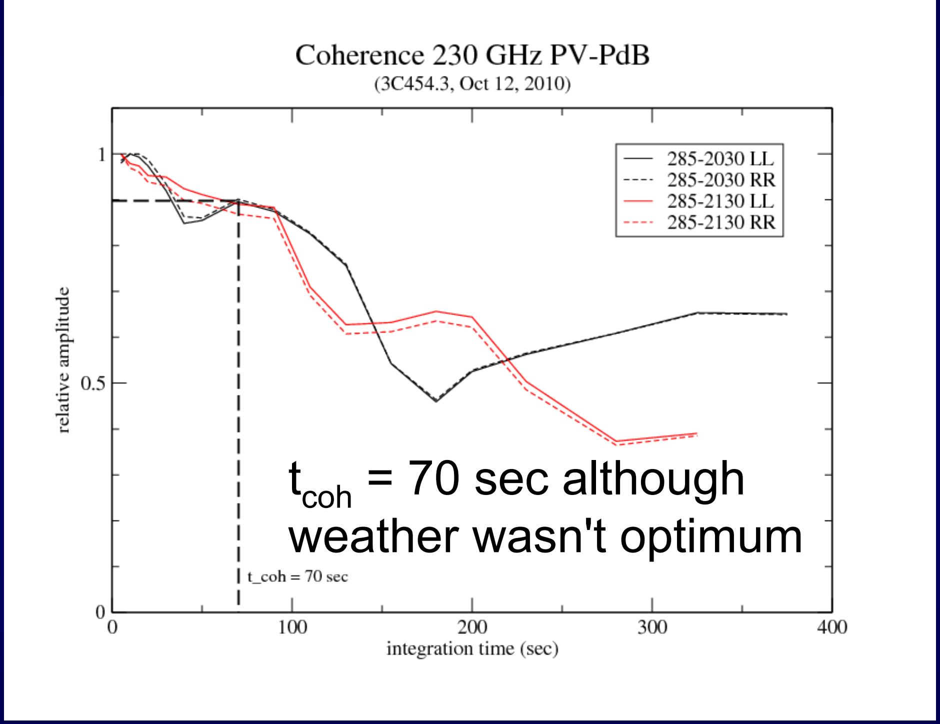
plus ALMA : ≥ 12 mJy

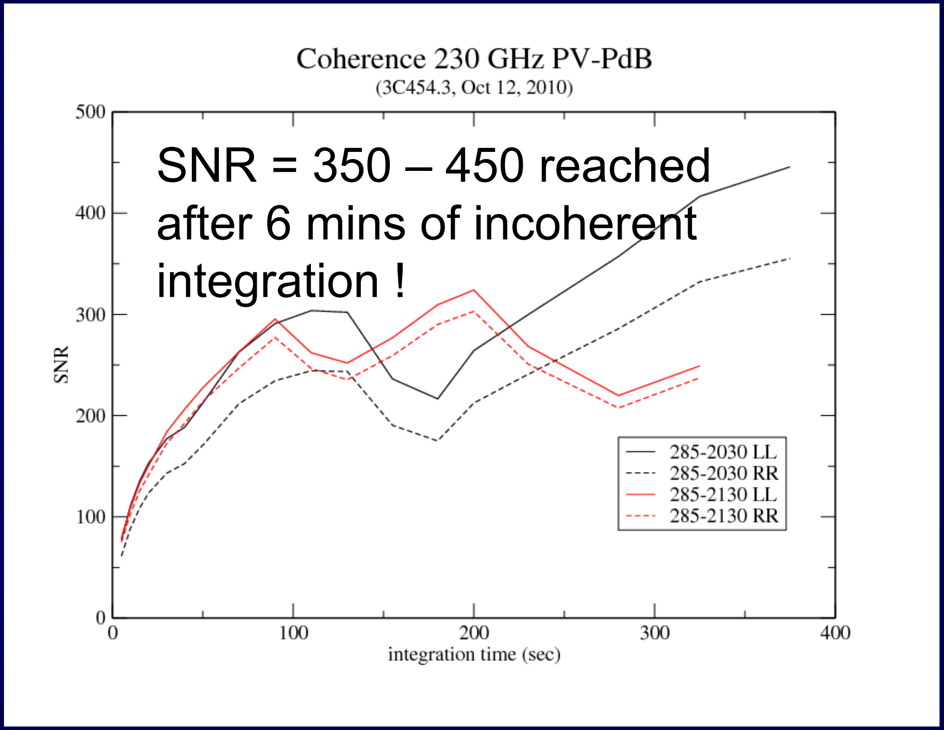


numbers will improve if phase corrections are used to prolongue coherence

Phase coherence at 230 GHz in October 2010

PV - PdB (phased)





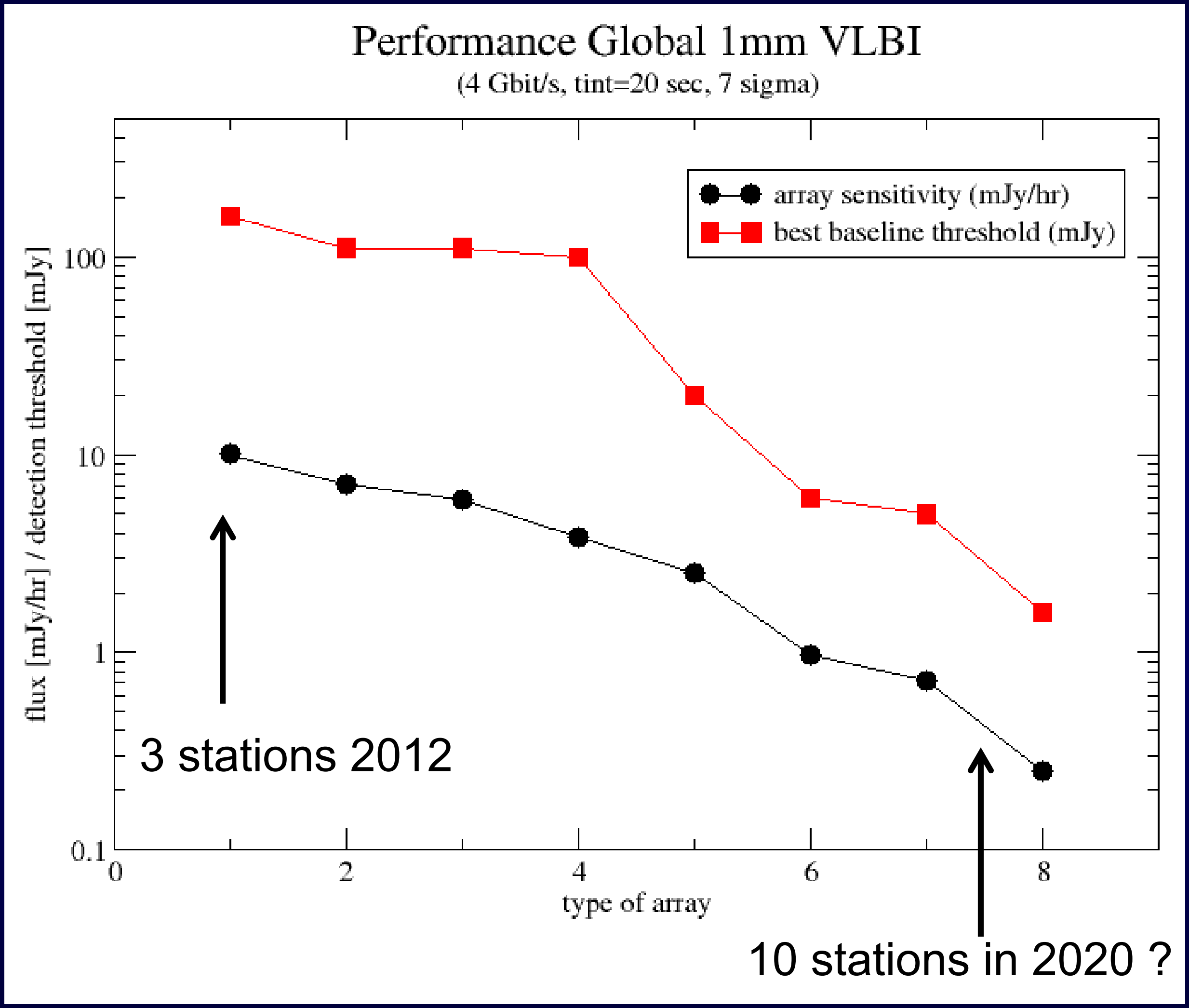
good VLBI-phasing efficiency of the 6 elements of the PdB interferometer

old correlator supports only 1 GBit/s (16 MHz, MK5A), correlation with DiFX

new correlator will allows phasing and processing of 32 MHz bands.

Performance of a global 1mm VLBI array

1. SMTO-CARMA-JCMT
2. SMTO-CARMA-Hawaii
3. + Apex
4. + Pico Veleta
5. + PdBure
6. + ALMA
7. +LMT+SPT+GL
8. +2x4GHz (32 Gb/s)



With the participation of ALMA the baseline sensitivity will be lowered to 1-5 mJy (depending a bit on BW). With 10 VLBI stations 1.5 mJy / hr can be reached.

Global VLBI at 1mm and shorter

- image SMBH in Sgr A*
- image SMBH / central engine of M87
- BH – jet connection on <~ 100 R_s in nearby AGN (another 5-10 targets)
- jets on scales of 100-1000 R_s (dozens of AGN)

- need time resolution (several epochs per year)
- need spectral information (complementary VLBI at 3mm, 7mm, ...)
- need monitoring of total flux densities and SED

- need ahead planning, roadmap, MoU
- need proposal and schedule coordination

Near future planning for mm-/sub-mm VLBI

- VLBI fringe test with Pico - APEX at 230 GHz at 4 Gbit/s in 2012.

  Mk5C and DBBC at Pico updated and tested in 2011.
- in 2012/13 use PdBI at 1 Gbit/s and DiFX. Buy Mk5C & DBBC

  The combination of Pico-PdB-APEX plus rest of the world gives good sensitivity and uv-coverage. Baseline sensitivity of Pico-PdB-APEX ~ 0.1-0.2 Jy.
- global VLBI with both IRAM instruments, APEX, ASTE, HHT, SMA, CARMA, etc.,

  (regular VLBI imaging of AGN, jets, etc. → global VLBI array)
- go to 345 GHz as soon as possible. For this, the next 2 logical steps are:

  1. short baseline Pico-PdBI VLBI using 1 Gbit/s and old Mk5A

  2. long baseline Pico/PdB(1)-APEX VLBI using 4 Gbit/s (Mk5C), 7σ =0.4 Jy
- phasing of PdB (IRAM internal development ~ 4-5 yrs ?, participate in phased array processor development for ALMA)
- more sensitive global sub-mm VLBI with ALMA (> 2016/17, at this time APEX may run out of funding)

End