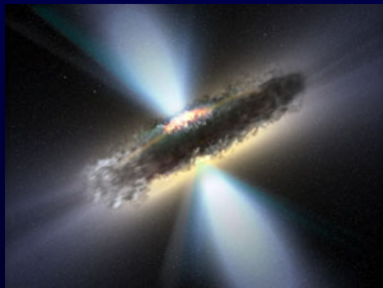
Studying black holes and jet formation using global millimeter VLBI with ALMA

T.P.Krichbaum

(on behalf of the team)

Max-Planck-Institut für Radioastronomie
Bonn, Germany

tkrichbaum@mpifr.de



people involved:

<u>MPIfR:</u> W. Alef, U. Bach, A. Bertarini, T. Krichbaum,
H. Rottmann, A. Roy, J. Wagner, J.A. Zensus, et al.

<u>APEX:</u> R. Güsten, D. Muders, K. Menten, et al.

<u>IRAM:</u> M. Bremer, S. Sanchez, P. Cox, et al.

<u>OSO:</u> M. Lindqvist, I. Marti-Vidal, M. Pantaleev, R. Haas, H. Olofsson, et al.

<u>INAF:</u> G. Tuccari et al.

<u>ESO:</u> G. Wieching et al.

in collaboration with:

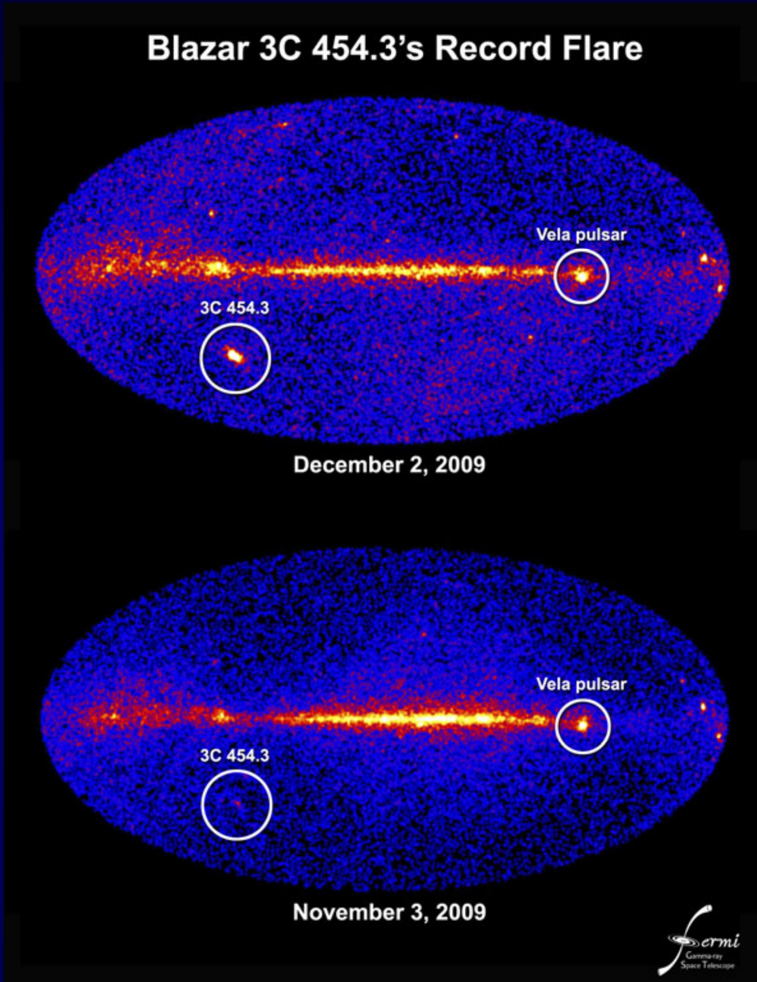
<u>Haystack Obs.:</u> S. Doeleman, V. Fish, R. Capallo, M. Titus, et al.

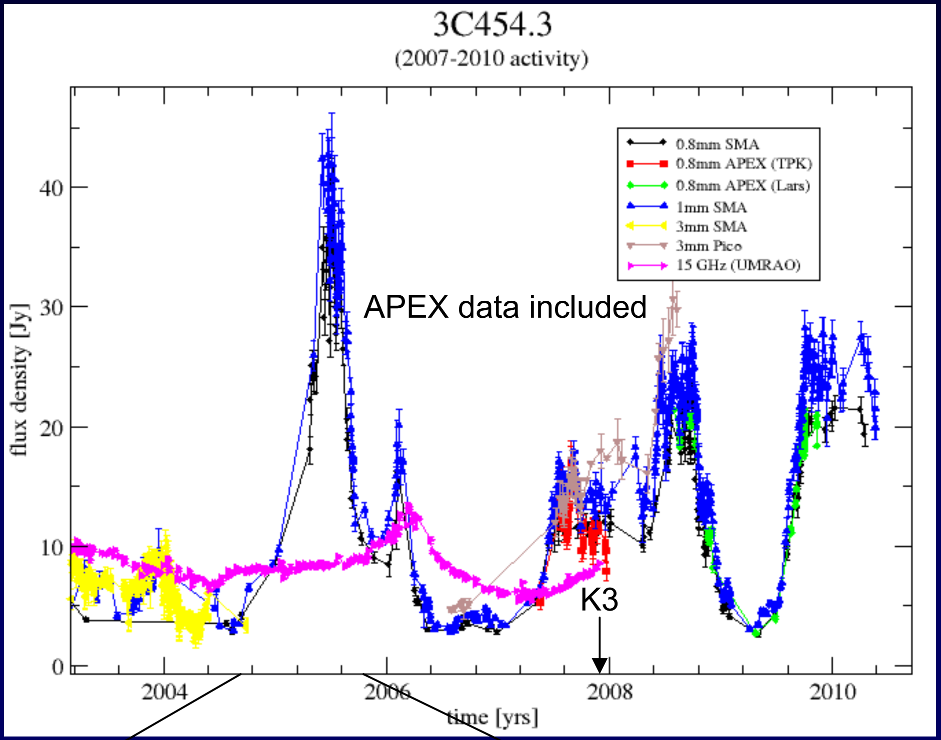
<u>SMTO:</u> R. Freund, L. Ziurys, P. Strittmatter, et al.

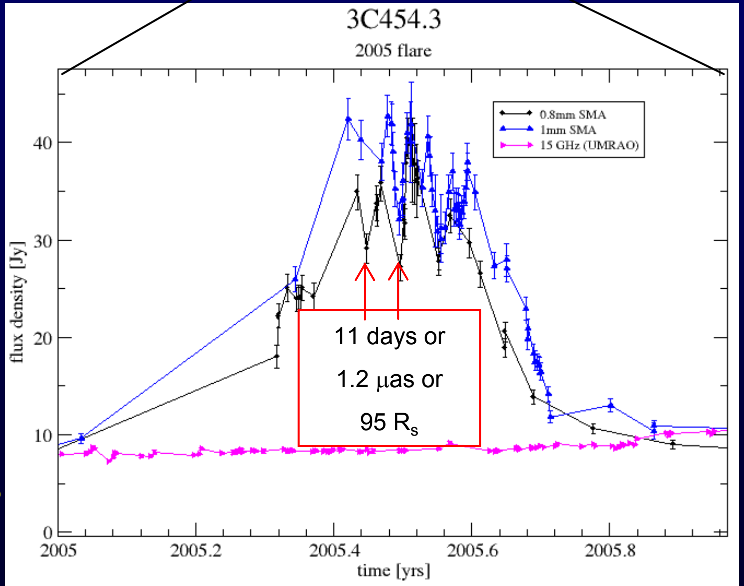
<u>SMA:</u> J. Weintroub, K. Young, R. Blundell

FGAMMA: Fuhrmann et al.; Boston: Marscher et al., Würzburg: Kadler et al.

3C454.3 – The brightest gamma-ray AGN in the sky







data:

M. Gurwell et al.

H. + M. Aller et al.

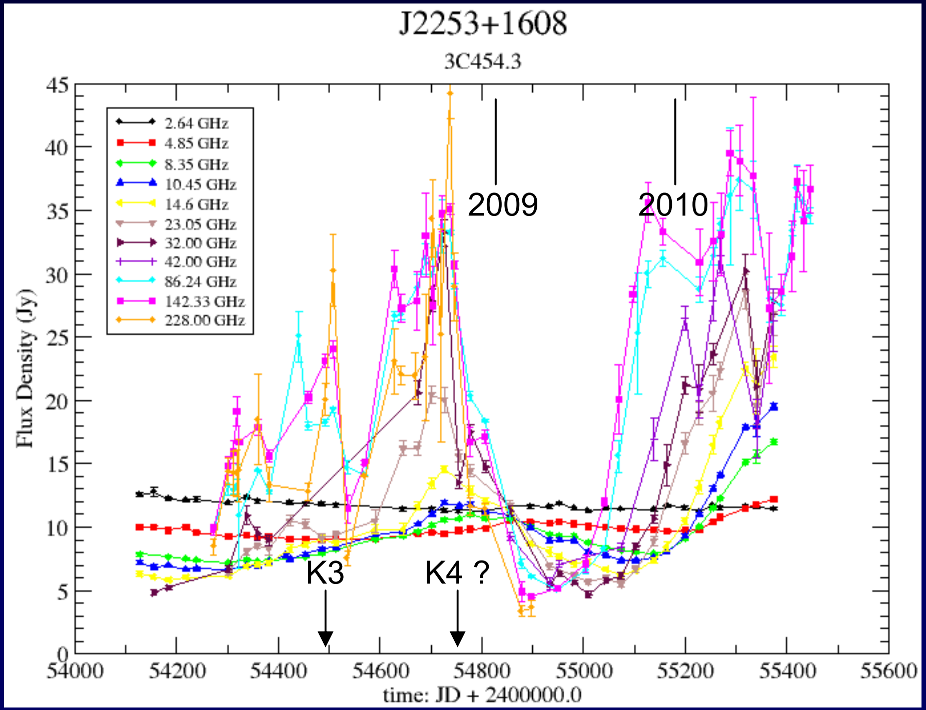
FGAMMA collab.:

L. Fuhrmann et al.

mm-/sub-mm flaring correlates with optical and γ-ray activity

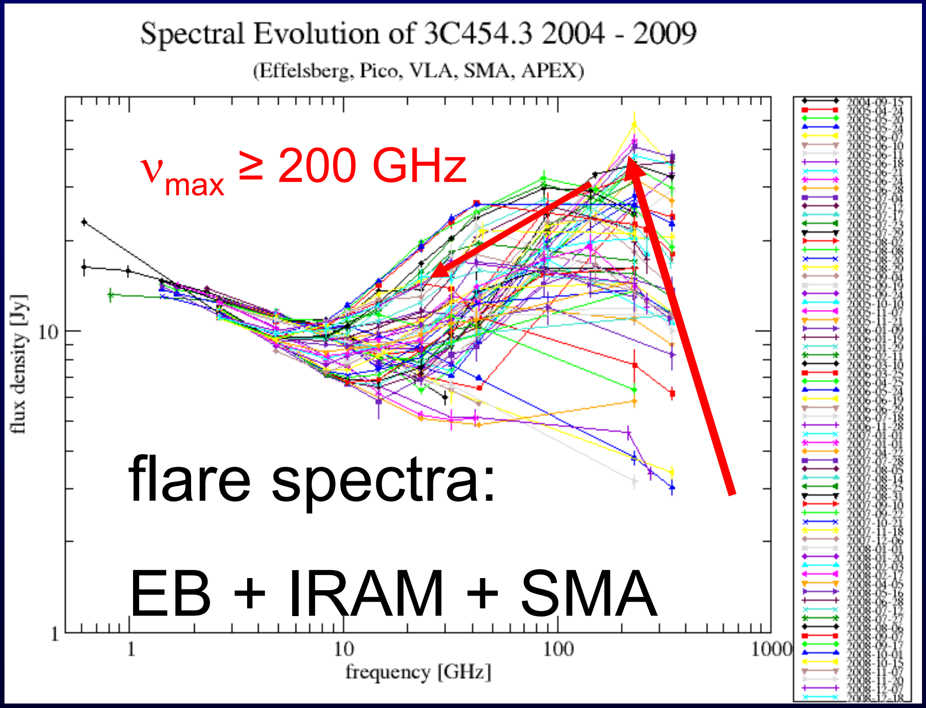
peak: t_{var} ~ 10-20 days→ jet or BLR?

Rapid broad band flux density variability of AGN



data: FGAMMA collaboration (Fuhrmann et al.)

- activity cylces repeat every few years
- complex spectral evolution
- time-lags vary between flares
- mm-variability: high $T_B > 10^{11...12}$ K , $\delta > 1$
- peak frequency varies from flare to flare
- correlation with optical, X-ray, gamma-ray



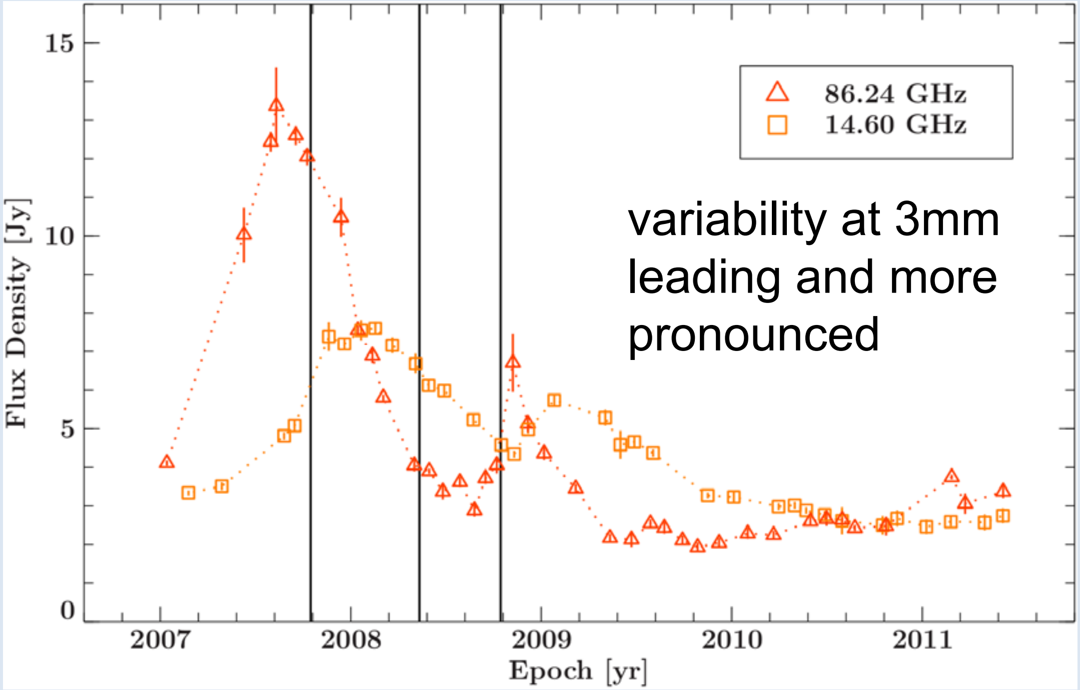
spectral variability more pronounced and faster at mm-/submm λ (turnover ν_{max} > 100-200 GHz)

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

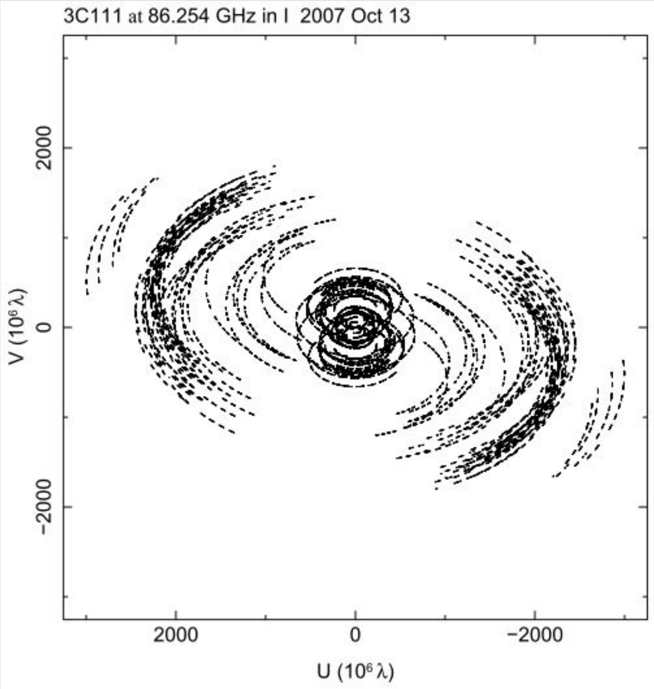
→ need high resolution mm-VLBI imaging !

GMVA Observations of 3C111 in Outburst

- Thesis Projects (R. Schulz, Grossberger) @ Würzburg Univ. (M. Kadler)
- In collaboration with MPIfR & BU (T. Krichbaum, A. Marscher)
- and Univ. of Valencia (E. Ros)



Lightcurve obtained by F-Gamma program, vertical lines indicate the three GMVA epochs



uv-coverage (1st epoch)

The Global Millimeter VLBI Array (GMVA)

Imaging with ~40 μas resolution at 86 GHz

Baseline Sensitivity

in Europe:

30 – 300 mJy

in US:

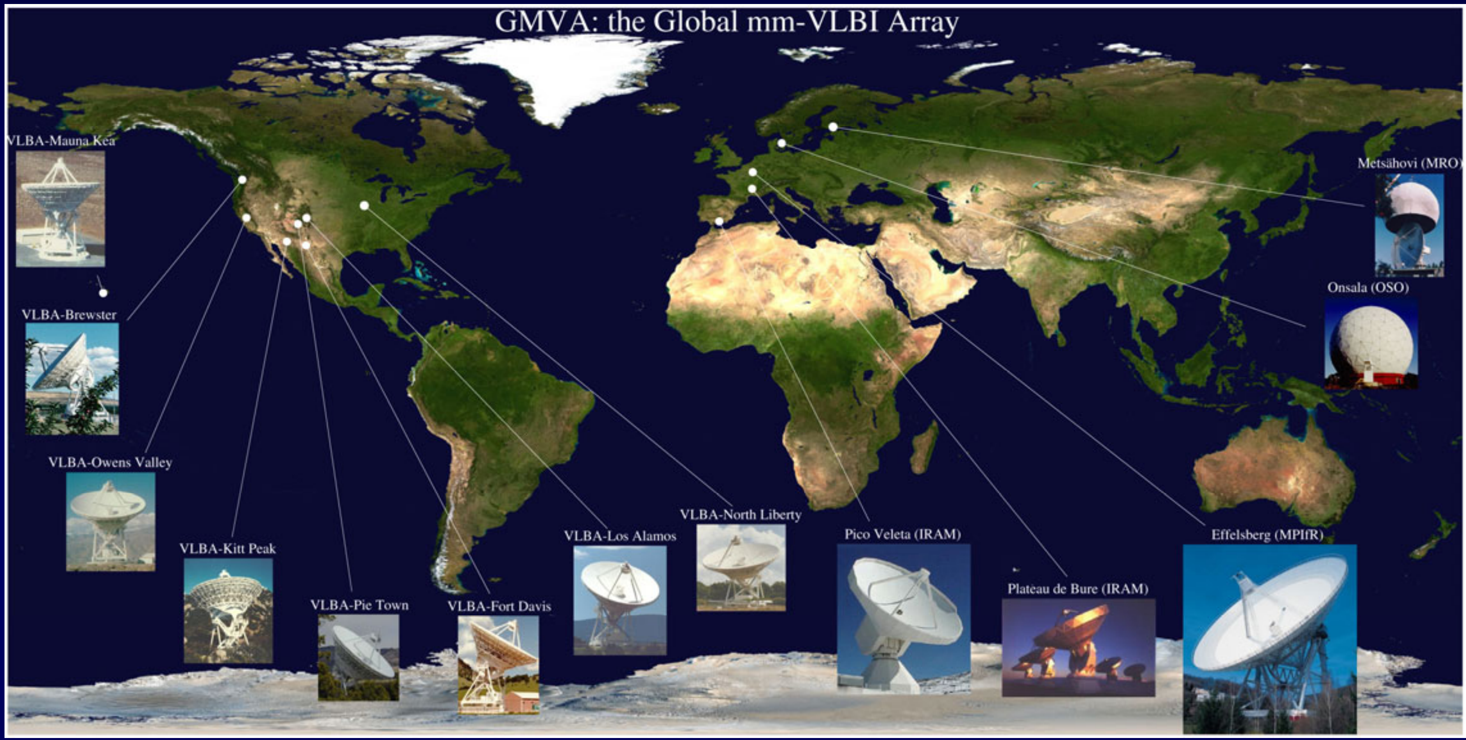
100 – 300 mJy

transatlantic:

50 – 300 mJy

Array:

1 – 3 mJy / hr



(assume 7σ, 100sec, 512 Mbps)

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

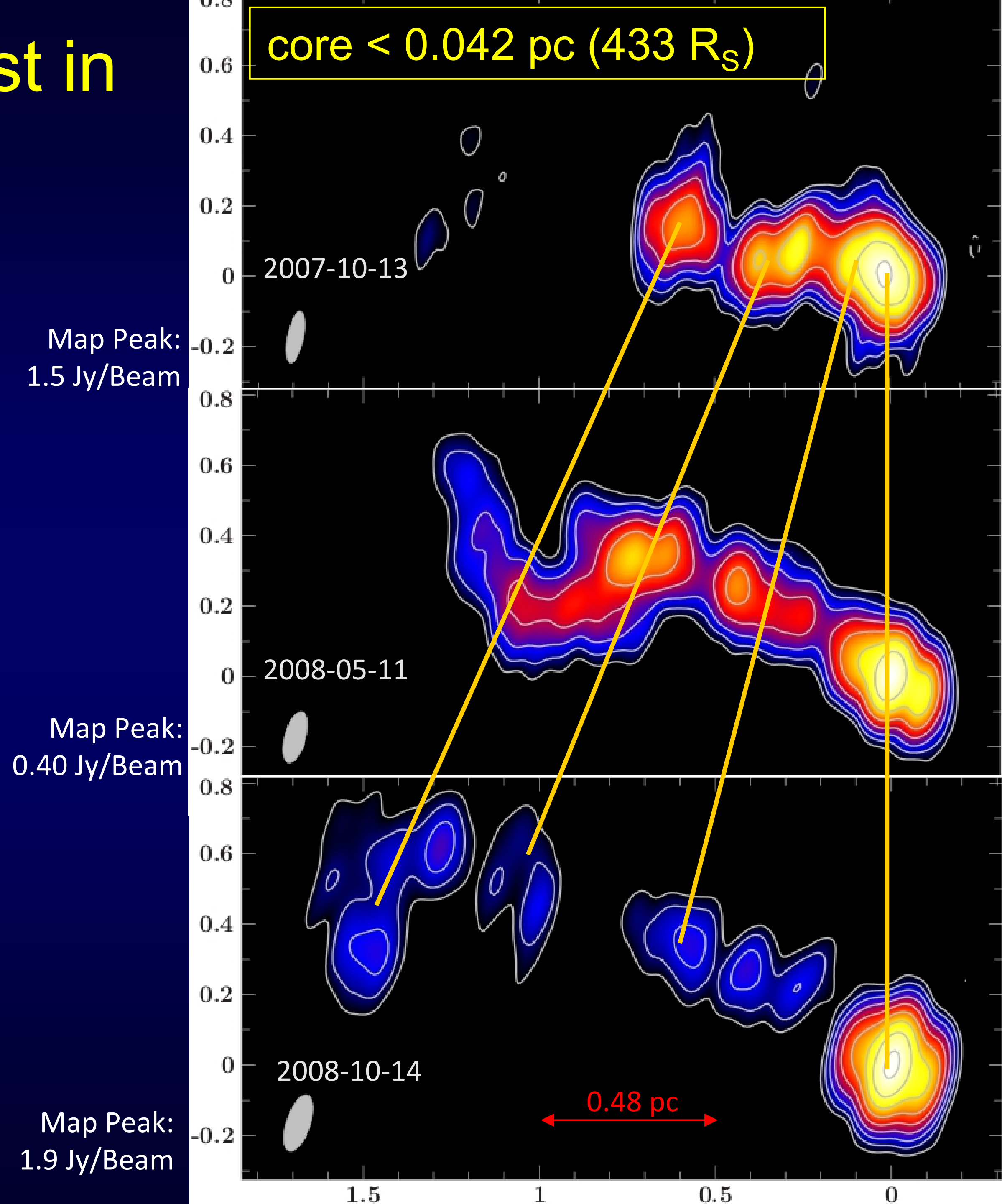
- Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (35m), Onsala (20m), Metsähovi (14m), Yebes (40m), planned: GBT (100m), Future: phased ALMA
- USA: 8 x VLBA (25m)

Proposal deadlines: February 1st, August 1st

Tracing an Outburst in 3C111

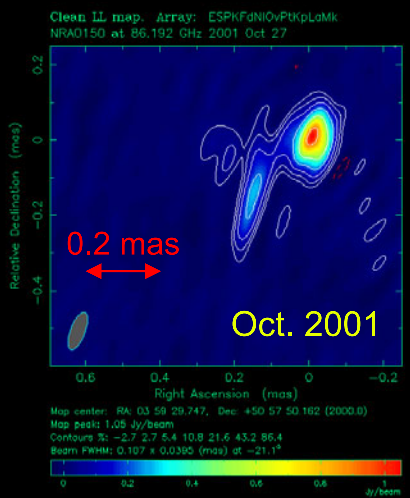
- Major Outburst ≠ Single Blob
- v= 1.6 c at r=0.5 mas
  v= 2.9 c at r=1-1.5 mas
  v~ 6 c at r>2 mas (Mojave)
  → acceleration ?
- possible counter jet ?
- moving kinks or jet-rotation ?
- Bent Structure
  - non-ballistic motion
  - precession of jet-base?
- Kinematics analysis ongoing

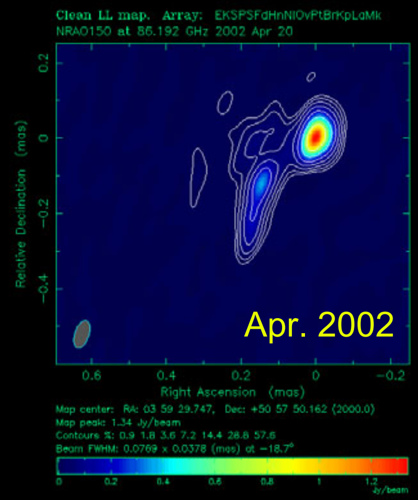
Schulz, Kadler et al. (2012)

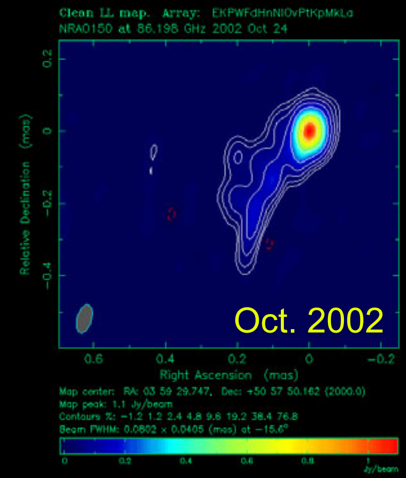


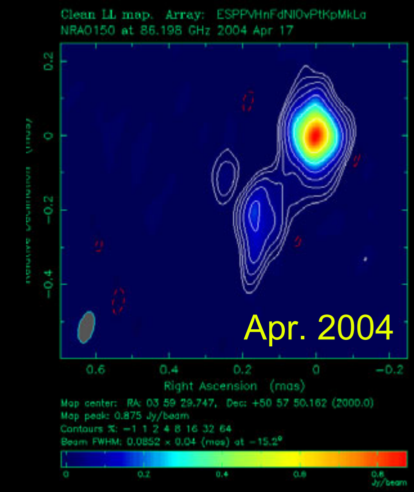
The swinging jet of NRAO150: sub-mas scales

3 mm-VLBI images using the GMVA

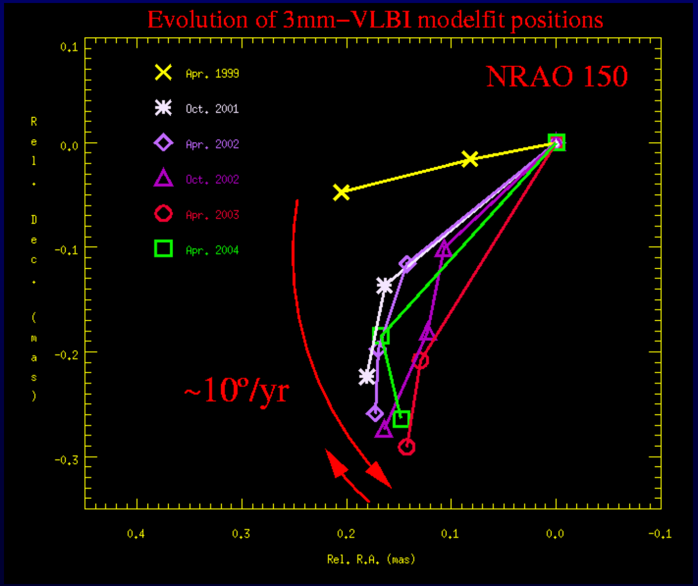


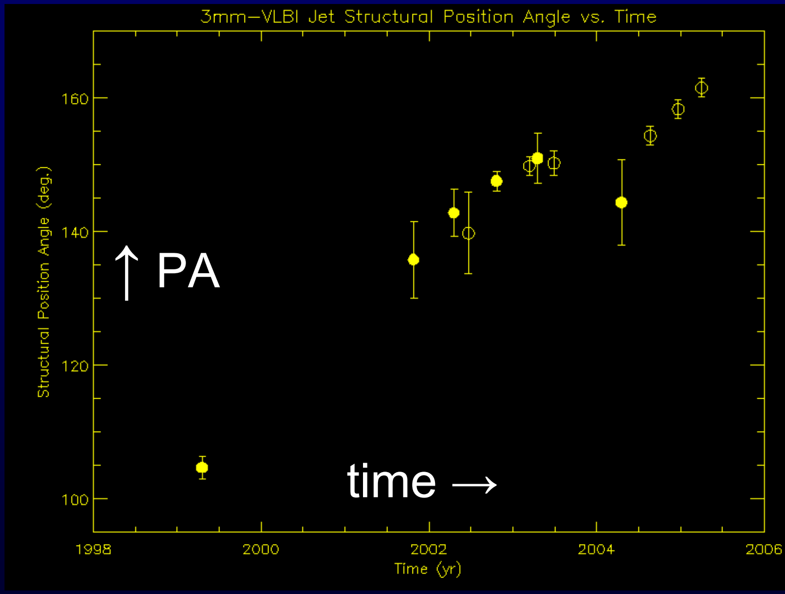






3 mm-VLBI shows jet rotation with an angular speed of ~10º/yr and an extrapolated rotation period of 20 – 30 yrs

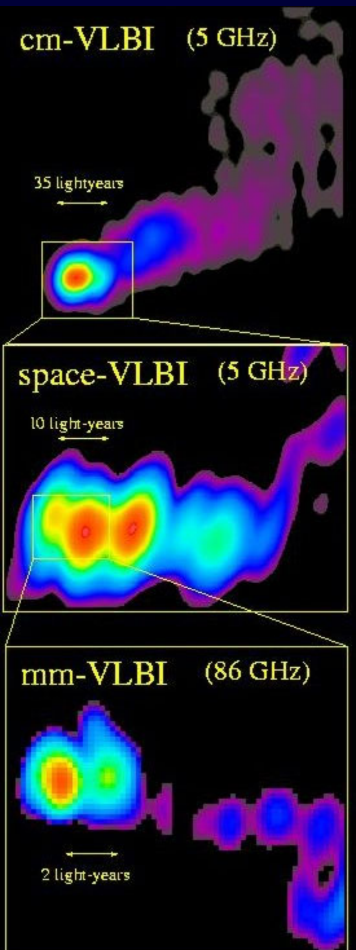


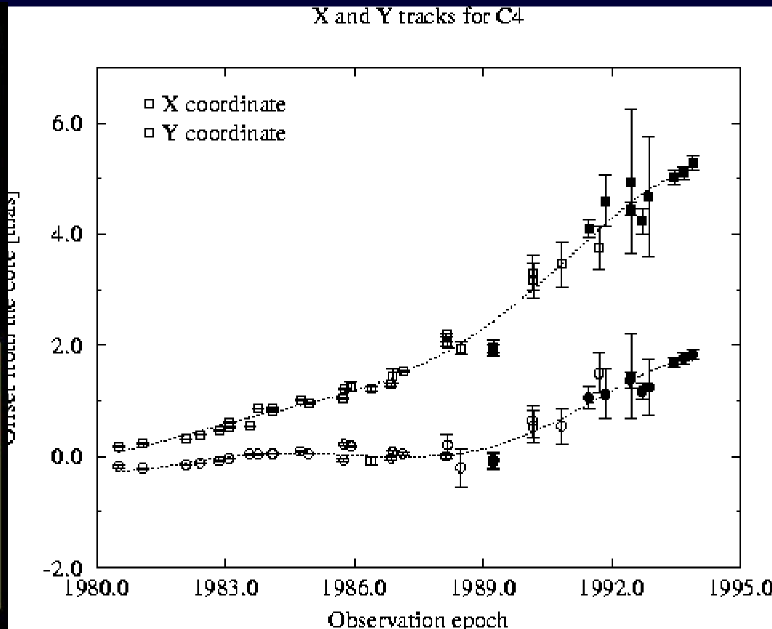


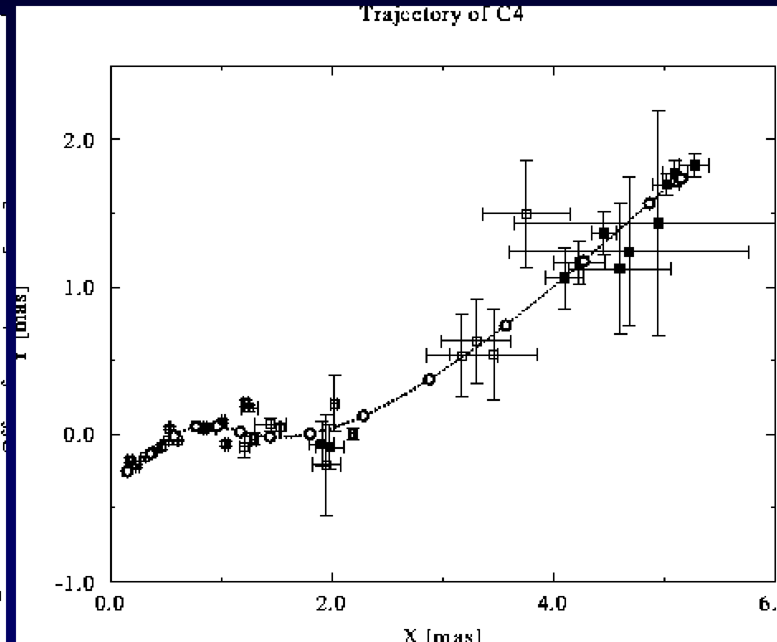
Agudo et al. 2007 (AA)

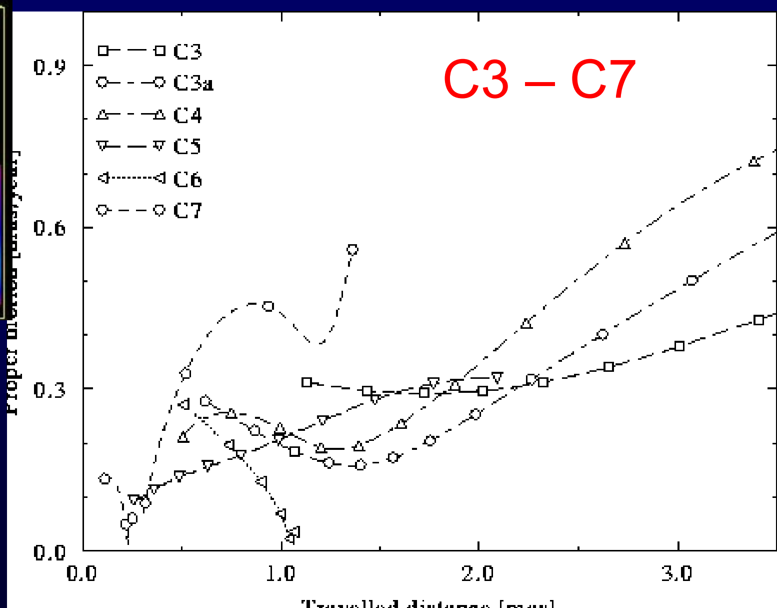
Non-ballistic (helical) motion in the jet of quasar 3C345

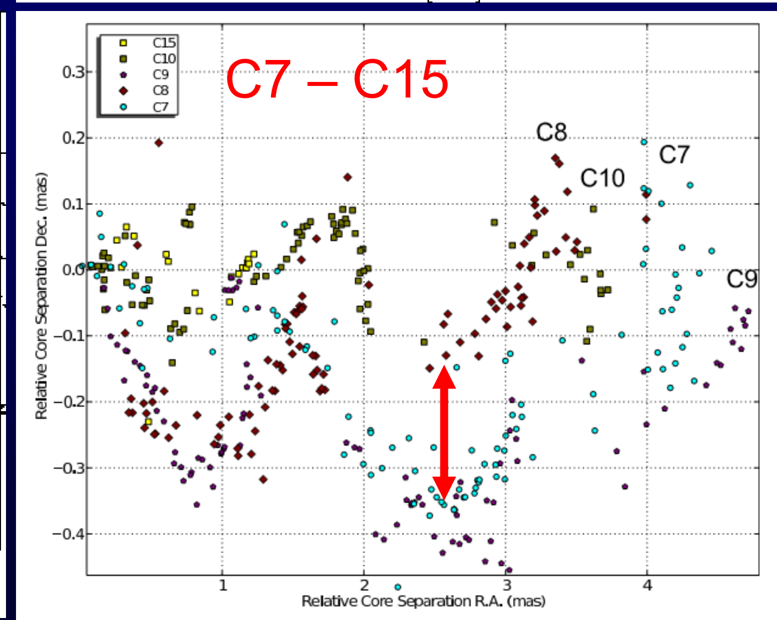
results from F. Schinzel, PhD Thesis 2011





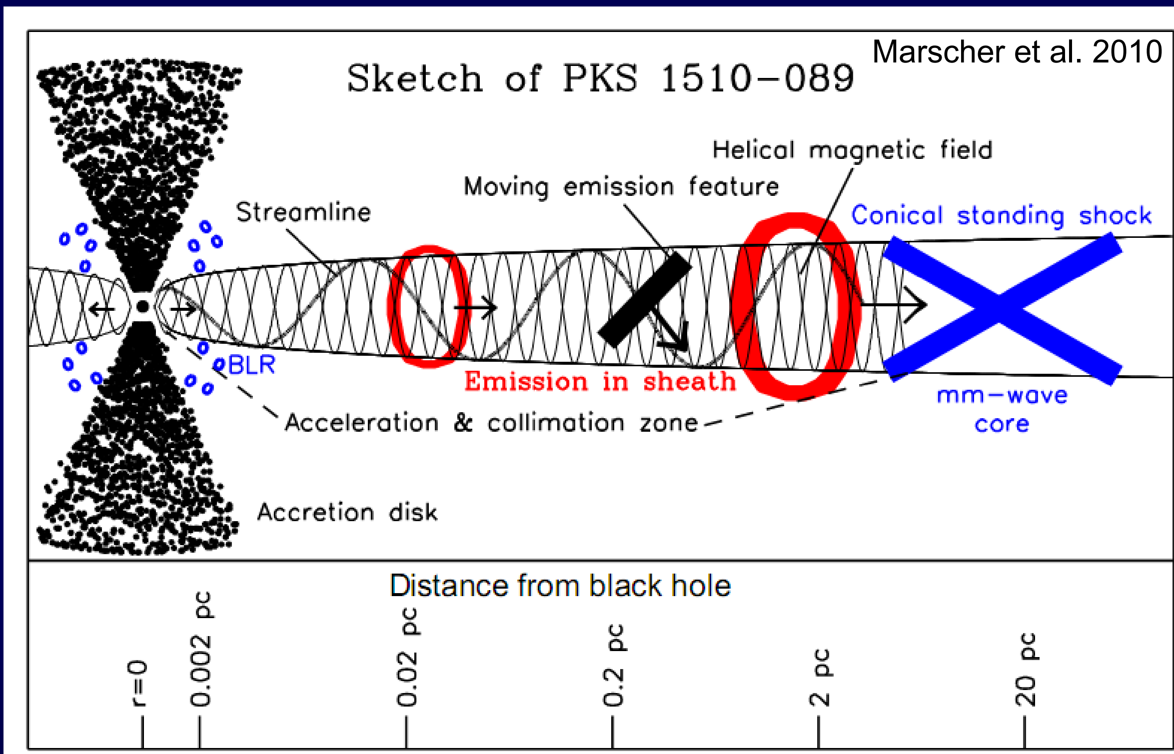






Optical Polarization angle swings during mm-optical-gamma-ray flare

VLBI at 3, 1, 0.8 mm with ALMA VLBA 7mm



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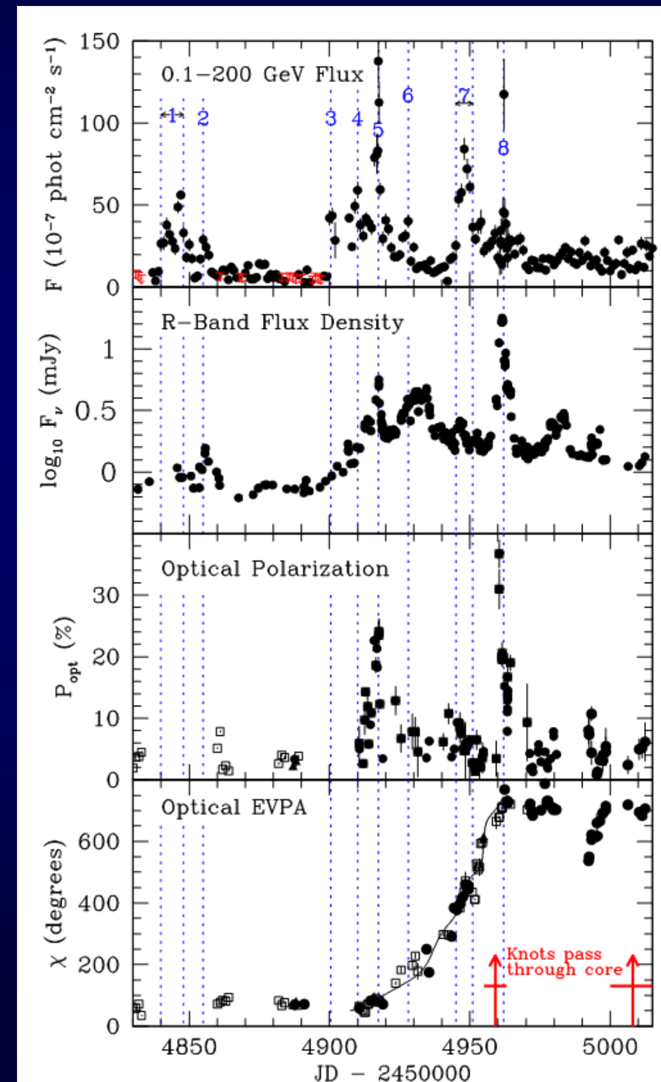


Marscher et al. 2010

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

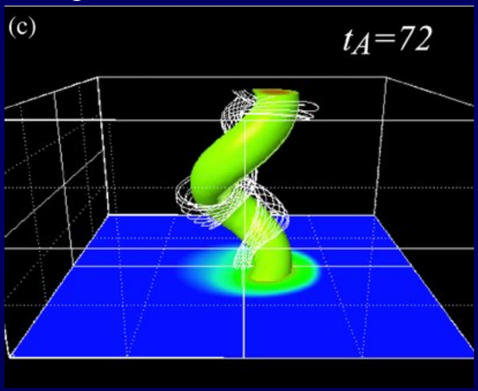
3C279: similar behaviour (Abdo et al. 2010 , Nat 463, 919)

Scientific Motivation:

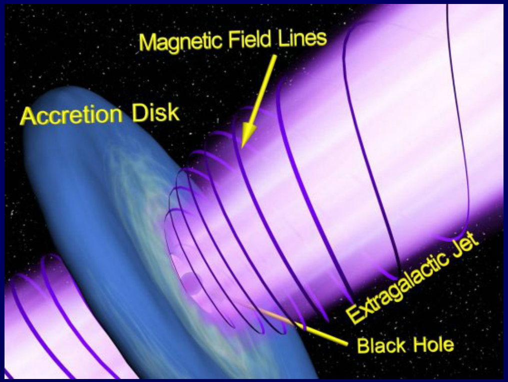
What is the physical origin of jets ? How does the region around a super-massiv black hole look like ?

The micro-arcsecond scale resolution of global mm- and sub-mm VLBI is needed to answer fundamental questions in BH-physics and about jet launching (test GR and GRMHD)!

Helical jet rotation caused by magnetic kink instabilities ?

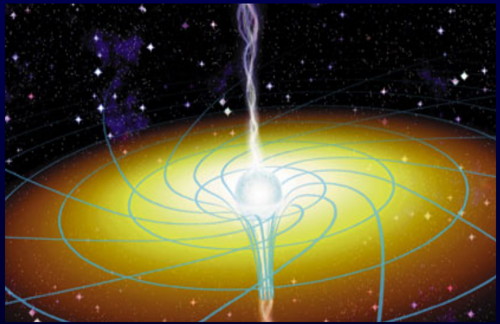


Magnetically driven jet launching ?

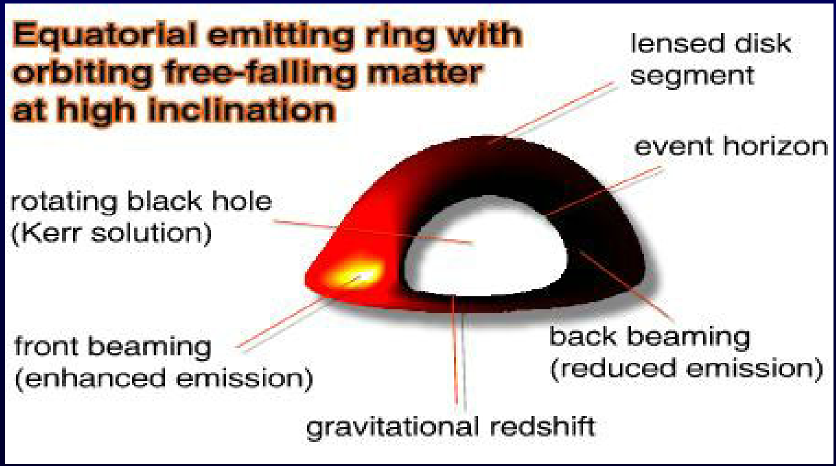


Relativistic aberration & asymmetric emission around a rotating BH ?

Jet rotation/precession due to frame dragging or binary BH?



The Black Hole:
A GR-MHD dynamo ?



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: ~$10^3\ R_s^{\ 9}$ 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 !

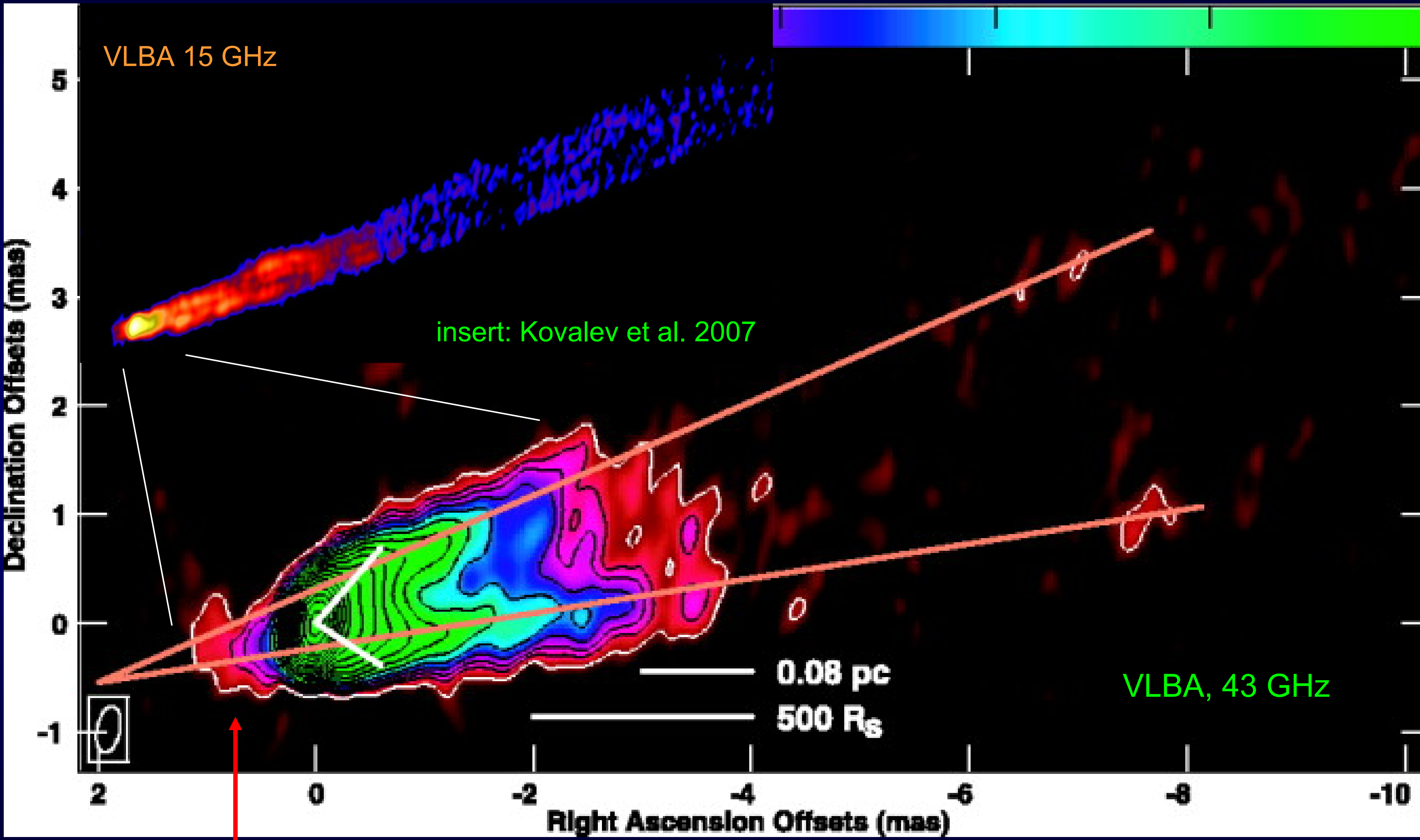
→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, test GR) !

→ 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 (sub-)mm VLBI array for sensitivity and resolution .

mm-VLBI imaging of the jet of M87



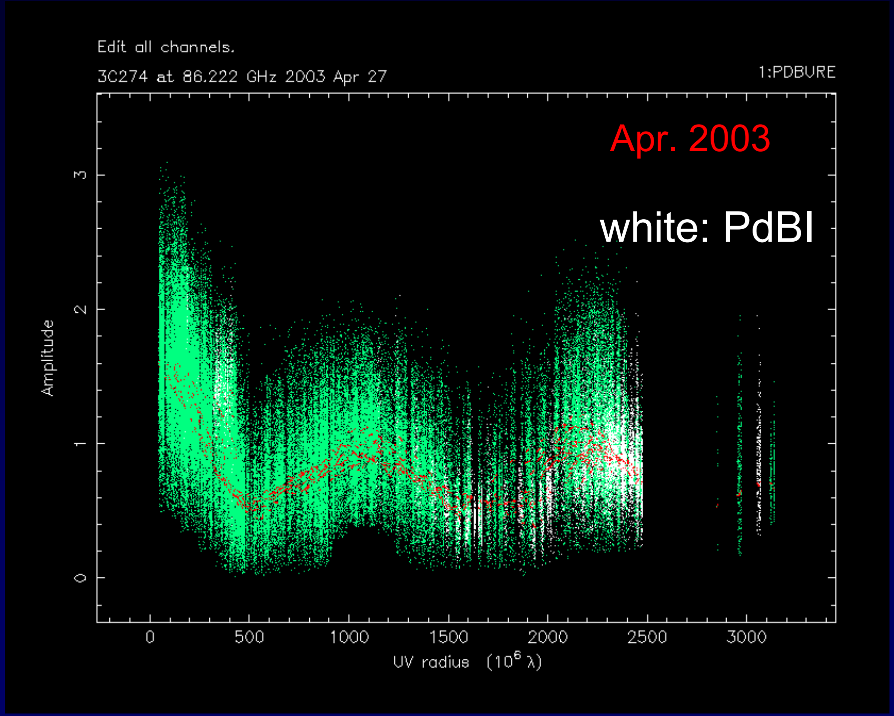
counter-jet or self-absorbed jet base ?

Ly, Walker et al. 2004, & 2007

Global 3mm VLBI of M87 with the GMVA

Structural variability in M87 on < 50 µas scales ($< 8\ R_s$) in 1-year

Peak: approx. 1.5 Jy



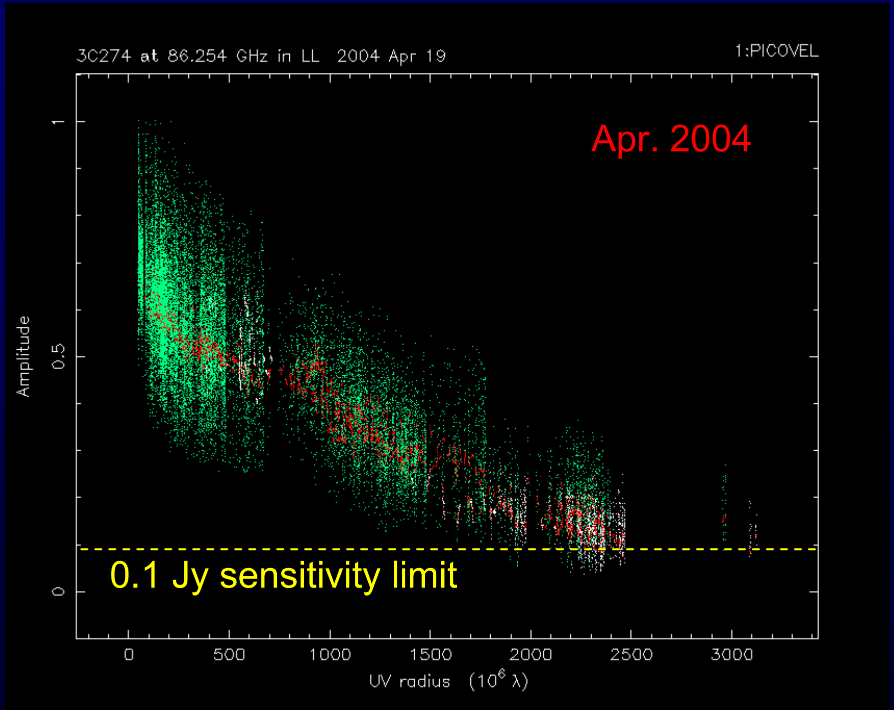
note:

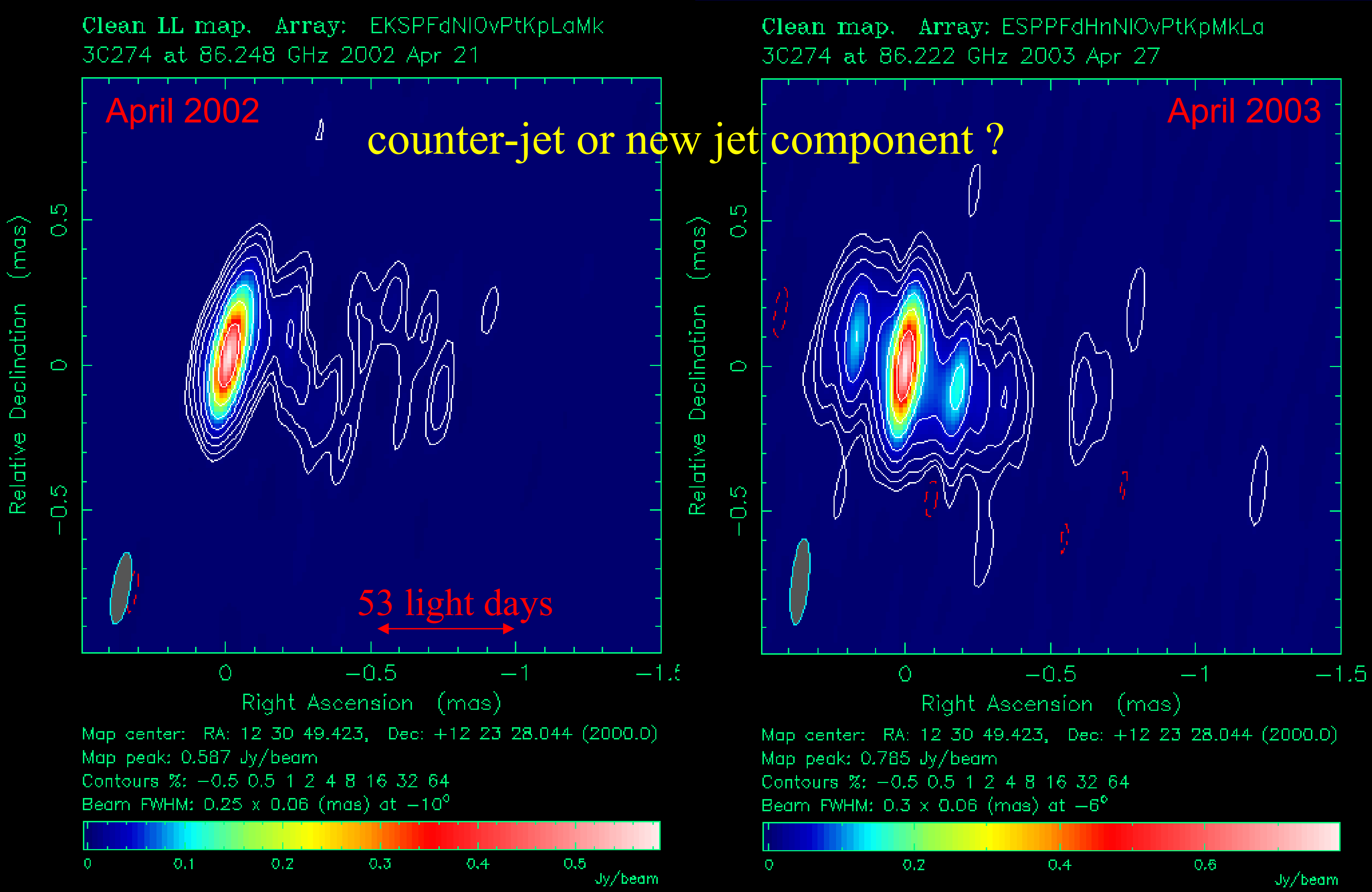
at mm/sub-mm wavelength AGN generally become weaker and jets become partially resolved

→ need good sensitivity (≤ 0.1 Jy)

→ large bandwidth / collecting area

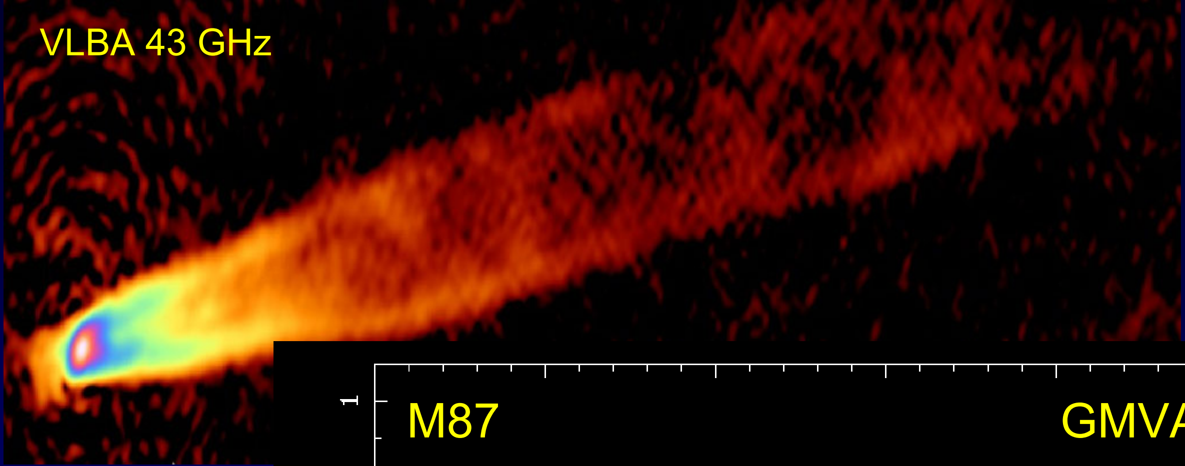
Peak: approx 0.7 Jy





Variability in the inner jet of M87 detected : ≥ 0.2 mas/yr ↔ ≈ 18000 km/s (0.06c)

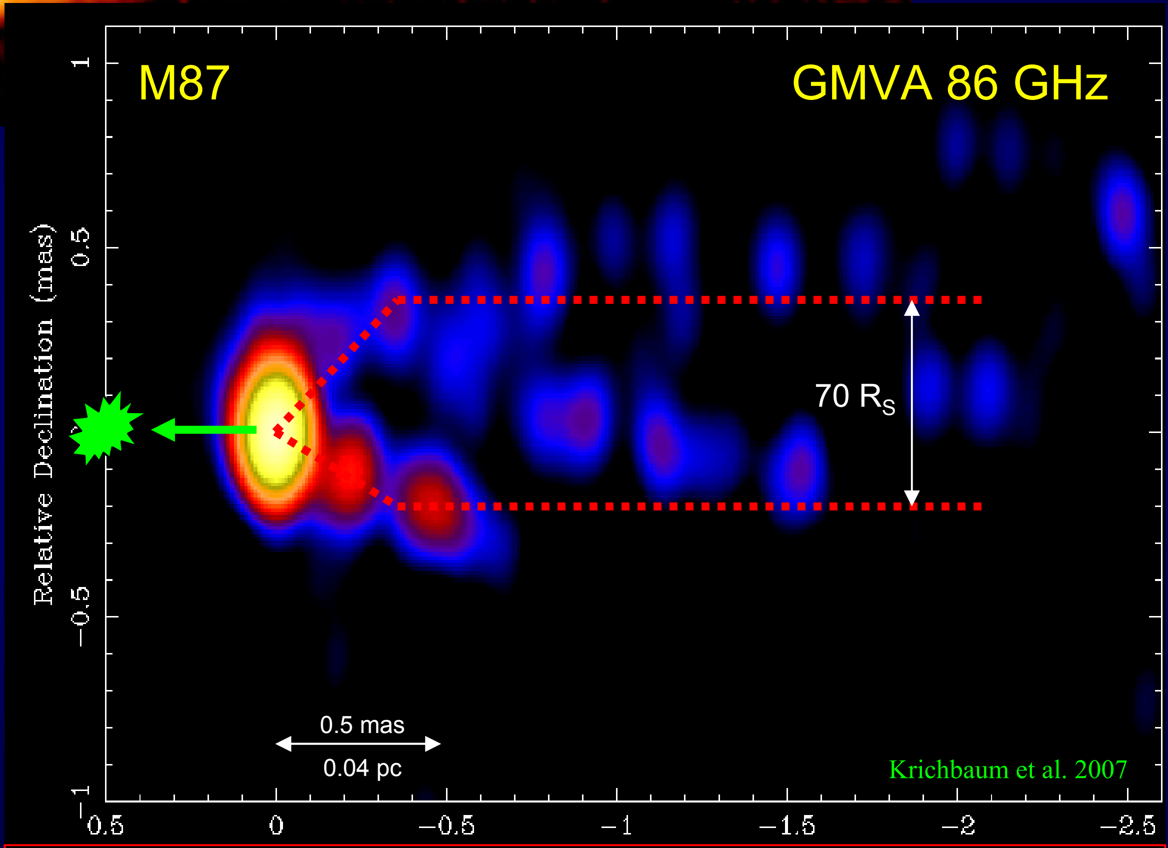
(but: 3 – 6 c seen further downstream)



Walker et al. 2008

Size of jet base may be too small for magnetic sling-shot acceleration. Evidence for direct coupling to BH spin ? → a GR-MHD Dynamo ?

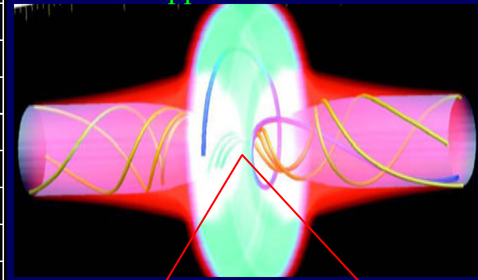
unknown separation from BH

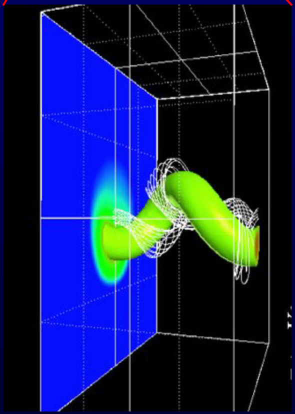


Krichbaum et al. 2007

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>27 x 8</u> R_s[9]

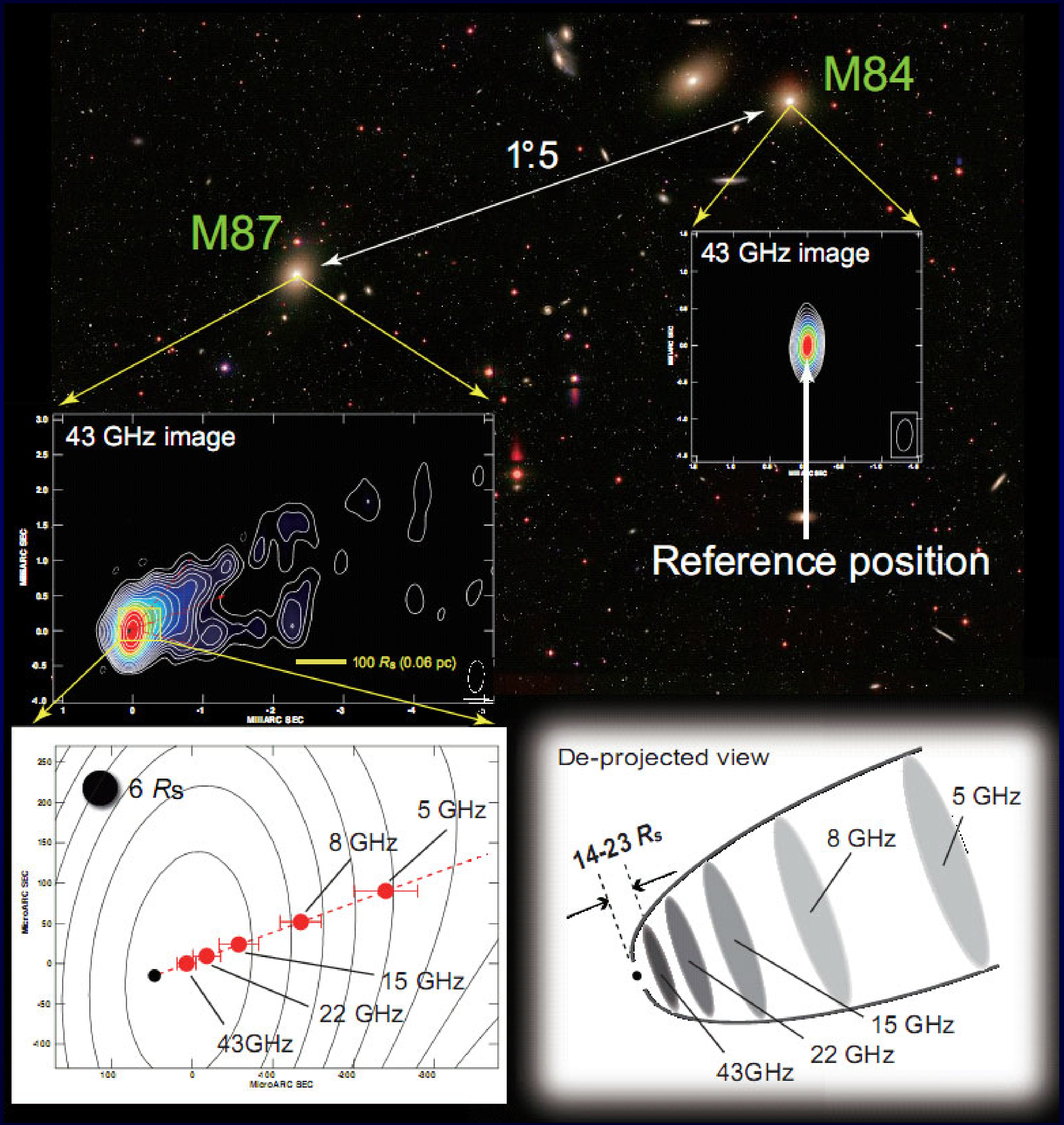
transverse width of jet at 0.5 mas: ~70 R_s[9]

Astrometric phase-referencing VLBI on M87:

$D_{jetbase}$= 14-23 R_s

distance between jet base and black hole.

The higher the observing frequency the closer one approaches the 'central engine' – the SMBH

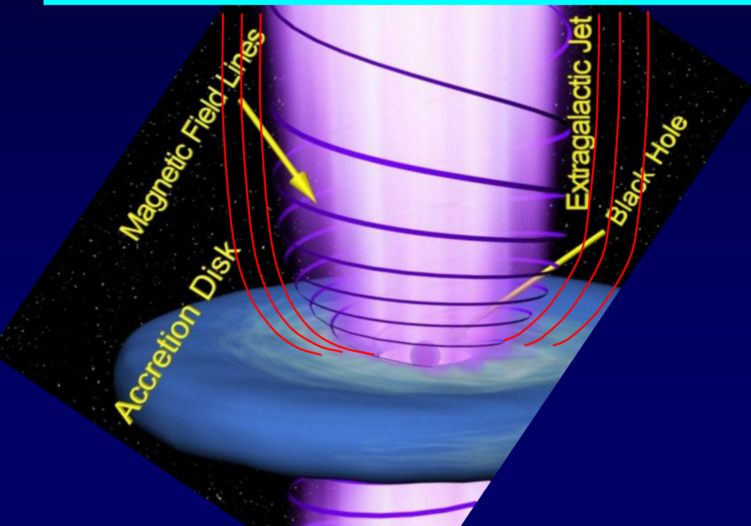


Hada et al. 2011

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

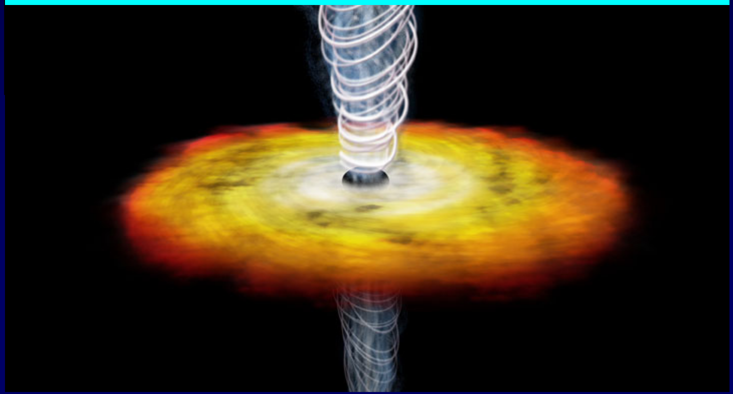
BH Spin

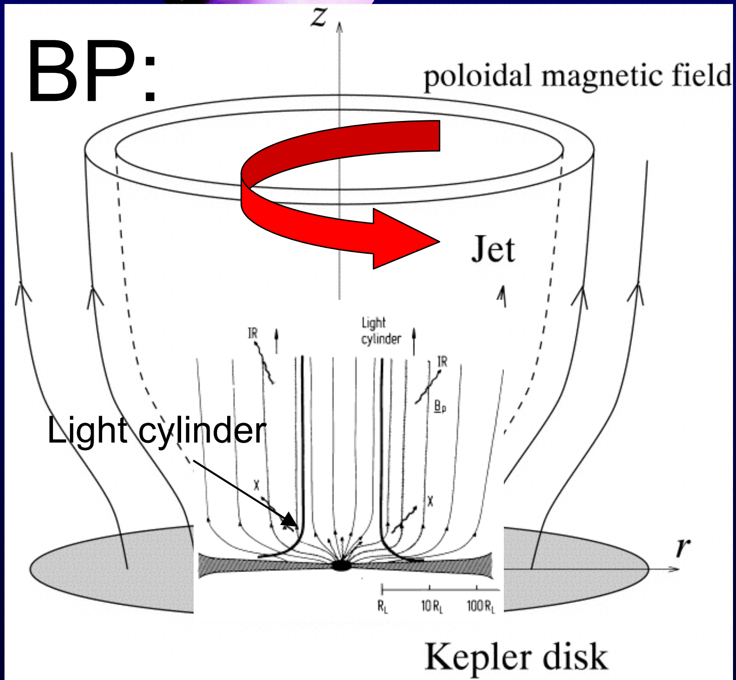
etc.

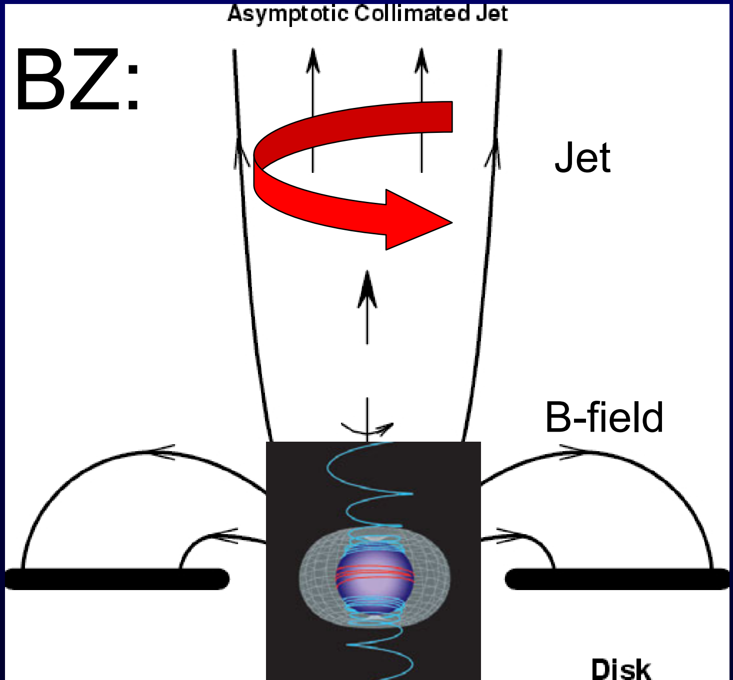
need to reach scale of a few R_G

Blandford – Znajek mechanism:

electromagnetic extraction of rotational energy from Kerr BH





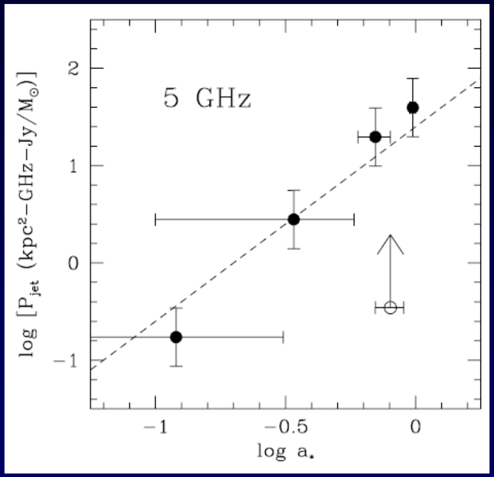


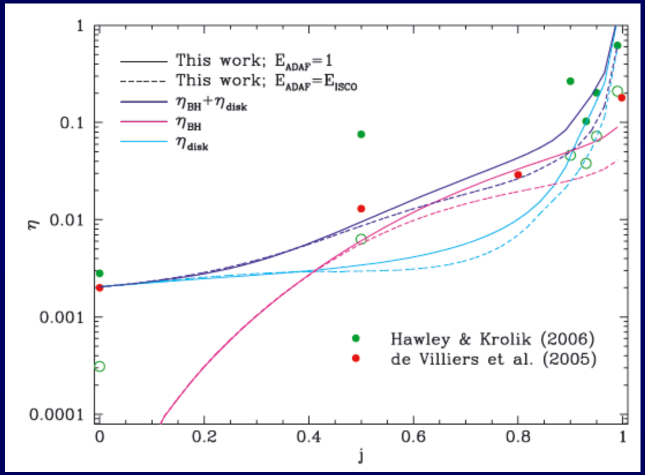
Jet Power and BH Spin

Narayan & McClintoc 2012:

BH spin correlates with jet power

(in 4 stellar BBHs with ballistic jets)

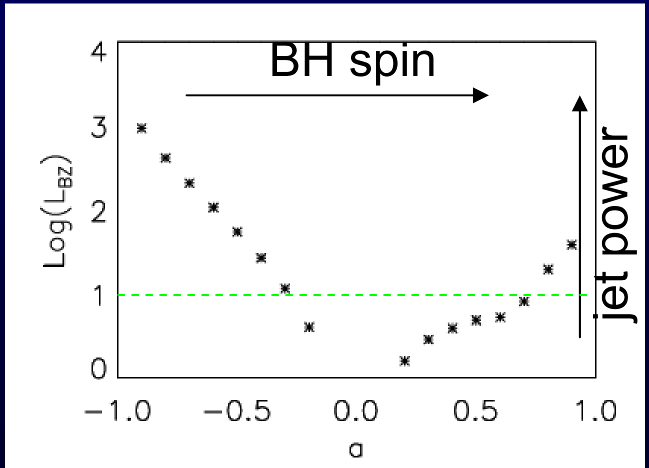




jet power increases with BH spin

equilibrium spin ~0.93 in ADAF models

(Benson & Babul 2009, Hawley & Krolik 2006)



BZ works!, spin energy from BH, η > 100%

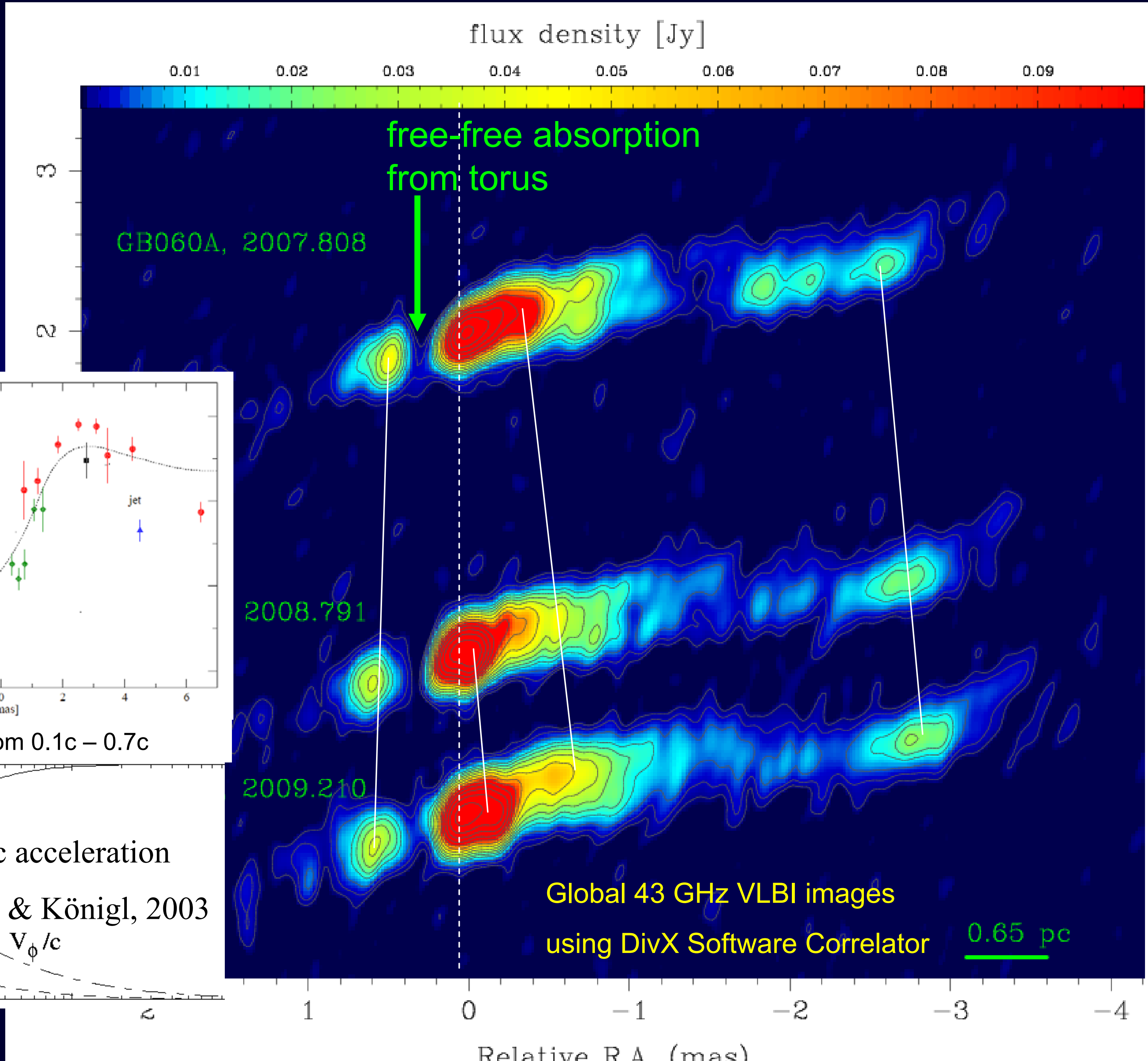
jet power maximized for large retrograde BH spins

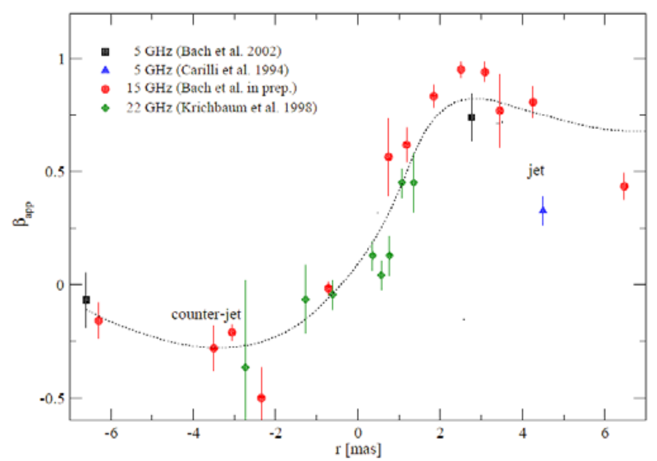
(Garafalo 2009, McKinney+ 2012, Tchekhovskoy+ 2012)

→ use jets to study cosmological evolution of SMBHs (spin, radio-loud/quite)

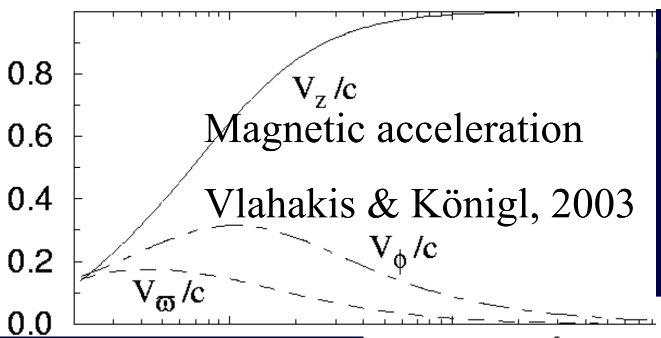
Global 7mm VLBI maps of Cyg A

(EVN, VLA, VLBA, GBT)





jet acceleration from 0.1c – 0.7c



U. Bach et al. 2008

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 increasing frequency ?

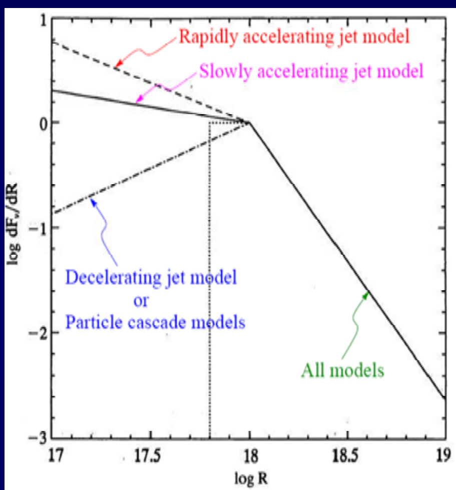
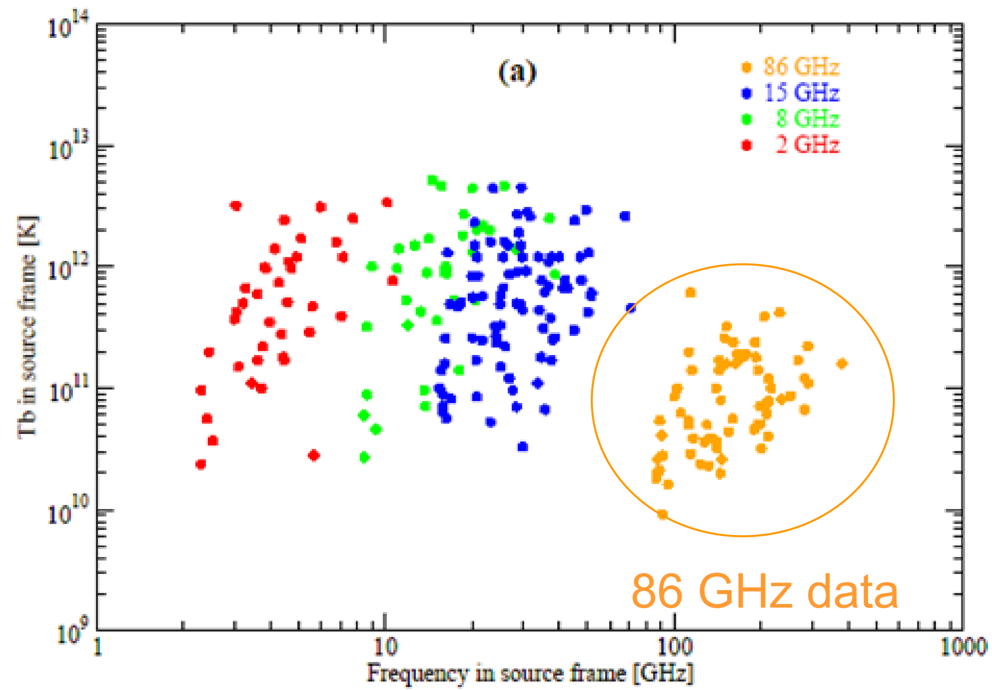
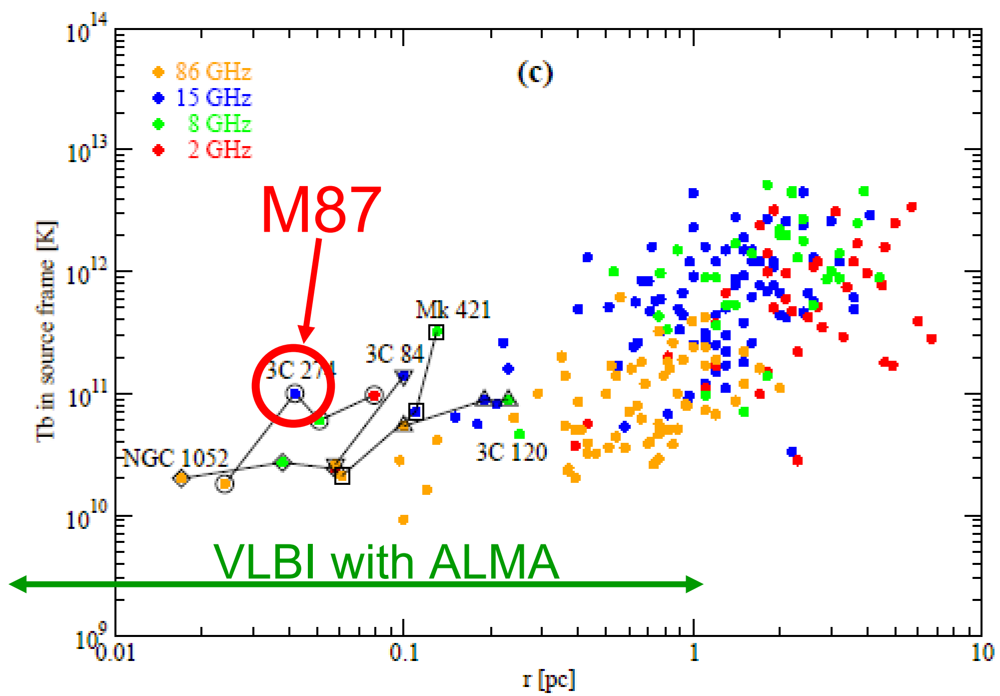


Figure adopted from A. Marscher (1995)

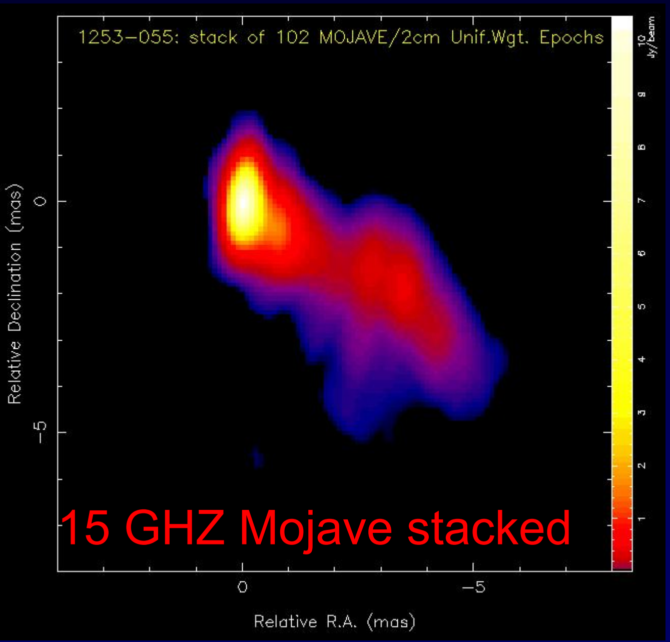


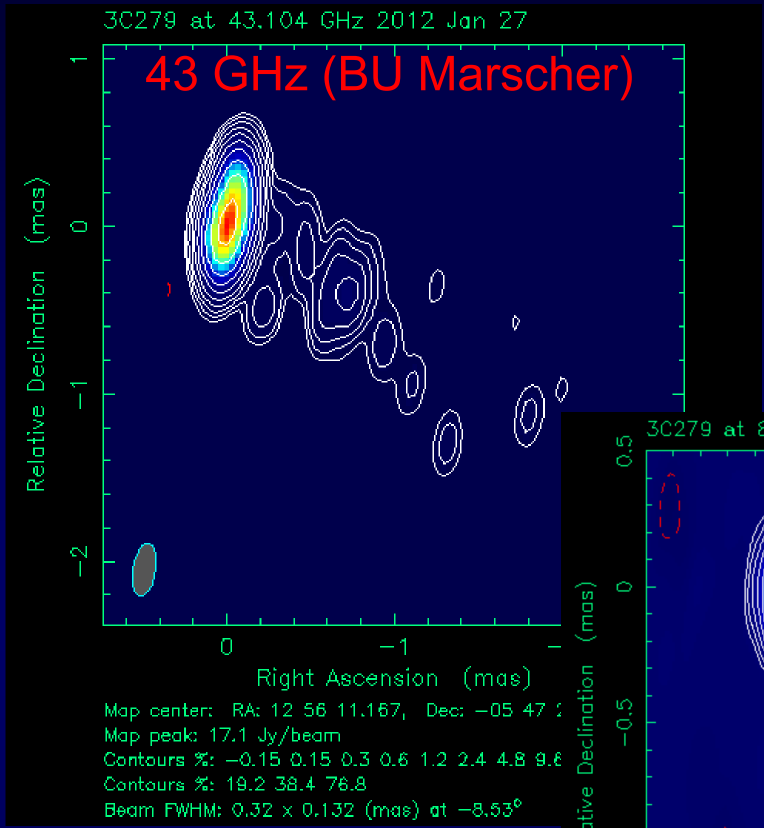


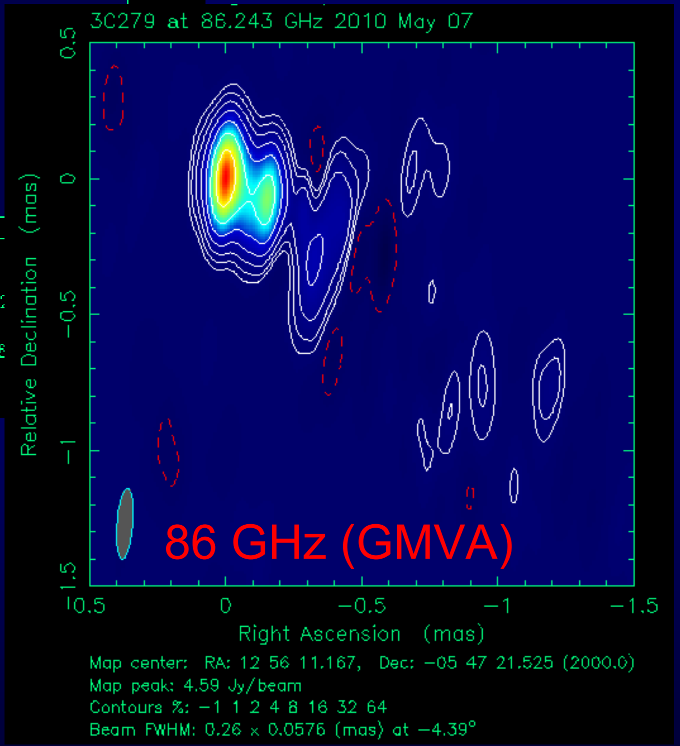
Brightness temperature increasing along jet; evidence for intrinsic acceleration ?

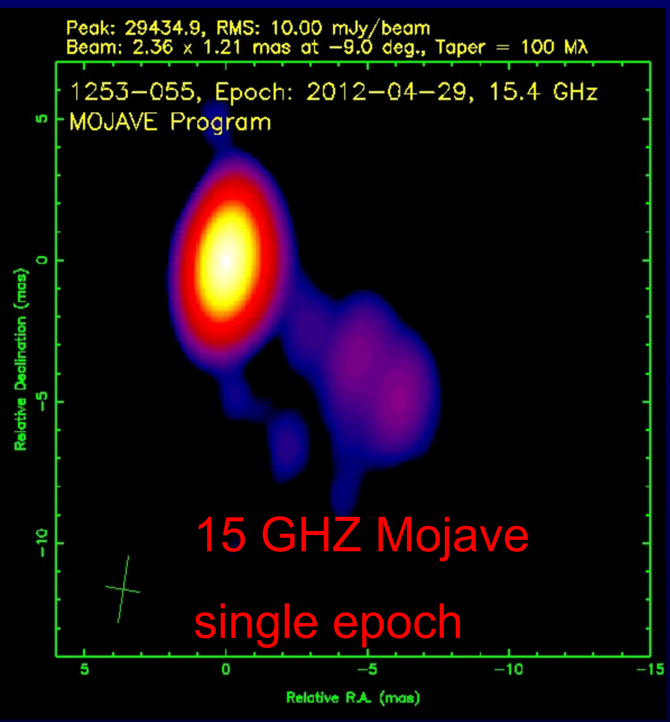
mm-VLBI surveys of AGN can discriminate between fundamental models of jet formation

The VLBI Jet of 3C279









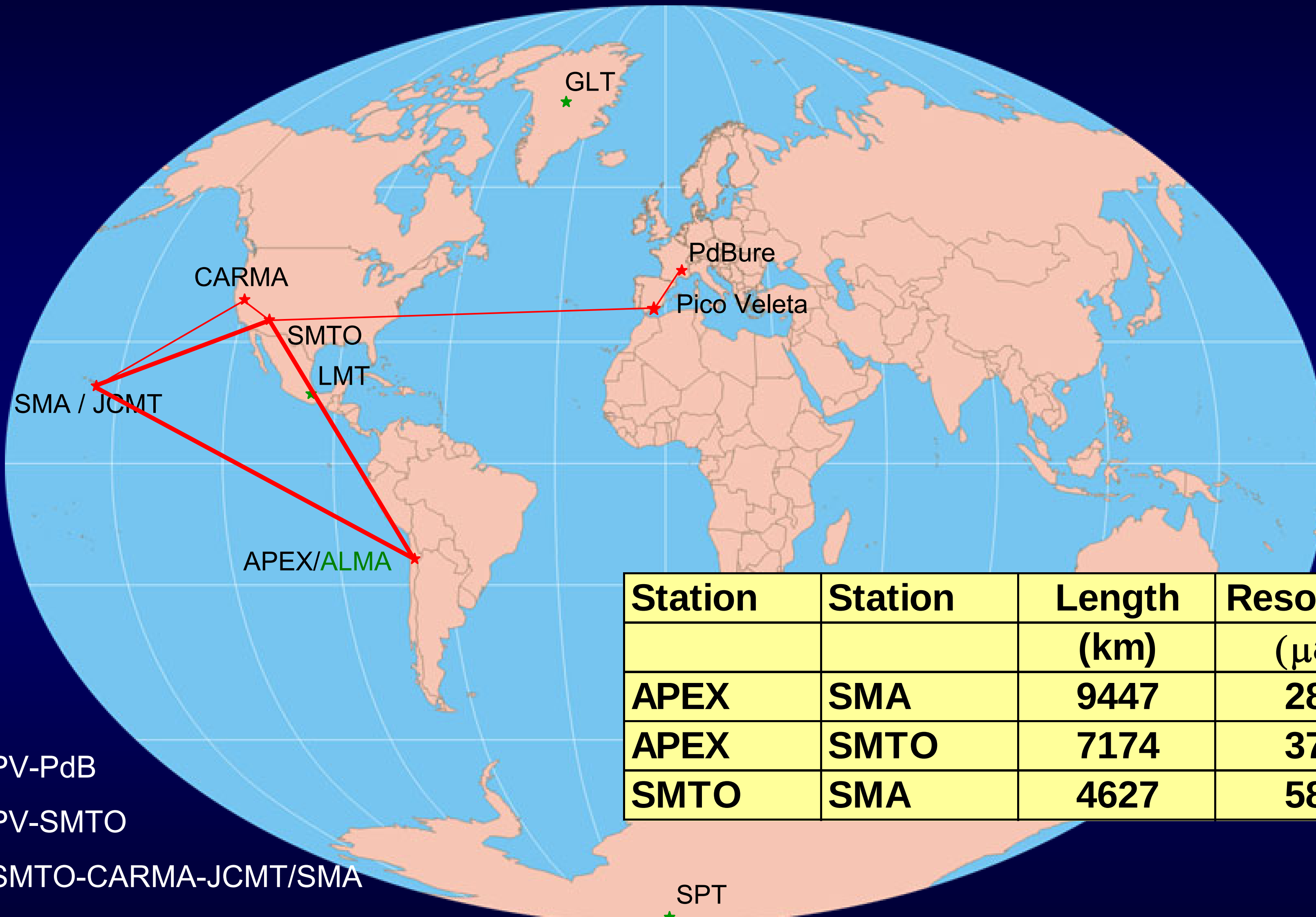
$z = 0.536$

$D_L = 3.0$ Gpc

1 mas = 10.7 pc

57 µas beam = 0.6 pc

Fringe detection with APEX at 230 GHz (May 7, 2012)



Station	Station	Length (km)	Resolution (μas)
APEX	SMA	9447	28,4
APEX	SMTO	7174	37,4
SMTO	SMA	4627	58,0

1995: PV-PdB

2002: PV-SMTO

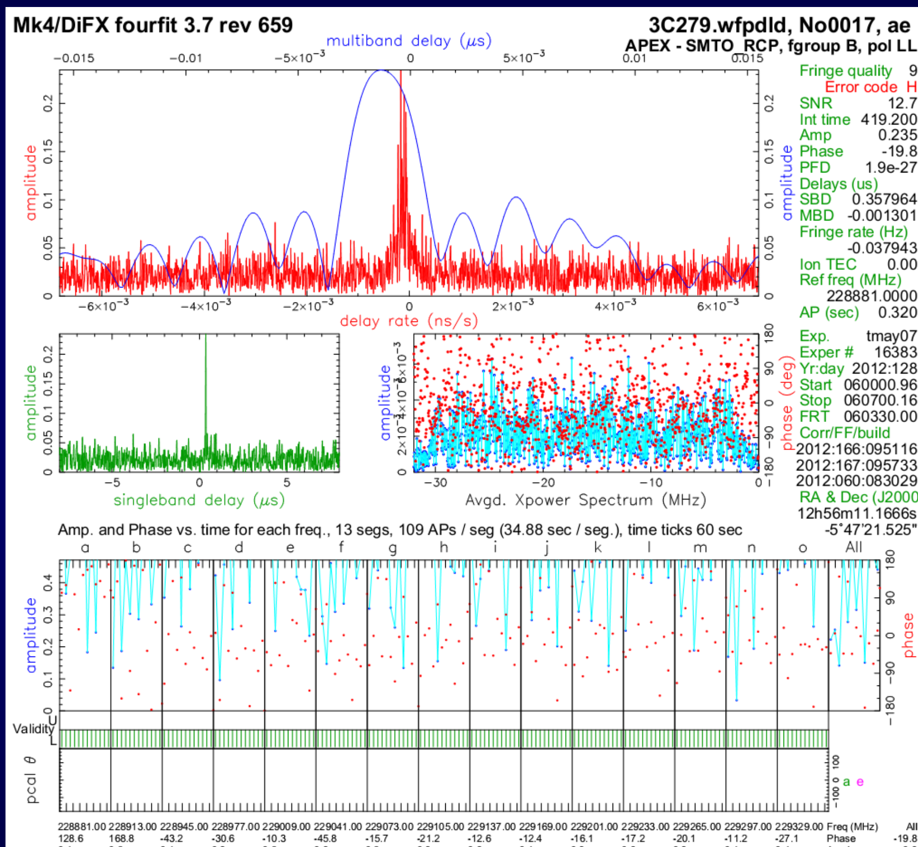
2007: SMTO-CARMA-JCMT/SMA

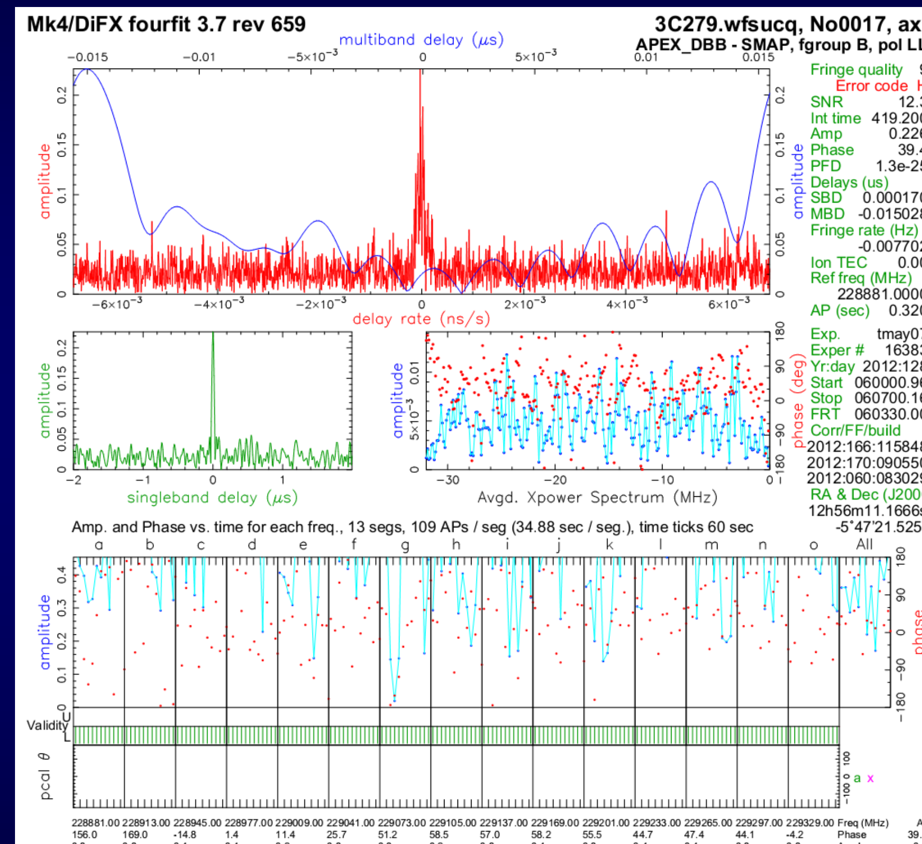
2012: AP-SMA-SMTO

★ existing station — 1mm fringes established ★ planned station

First VLBI fringes with APEX at 230 GHz
(May 7, 2012)

3C279 and MK5C, DBE & DBBC, 1.92 Gbit/s, 480 MHz bandwidth





APEX – SMTO (Arizona): SNR 12.7

D=7170 km

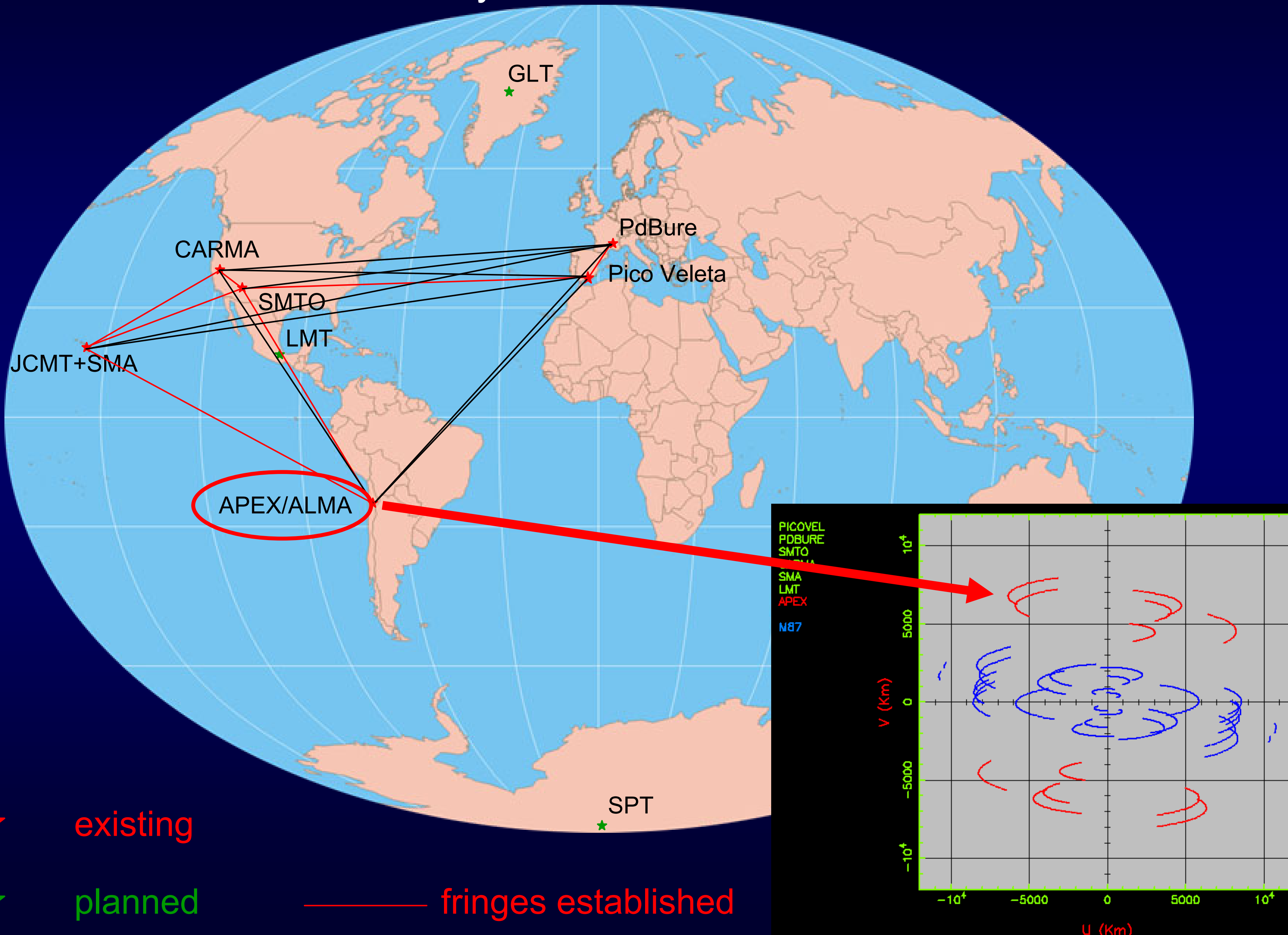
APEX – SMA (Hawaii): SNR 12.3

D=9450 km

credit: A. Roy and Apex team

Toward a global 1.3 mm-/sub mm VLBI array (EHT)

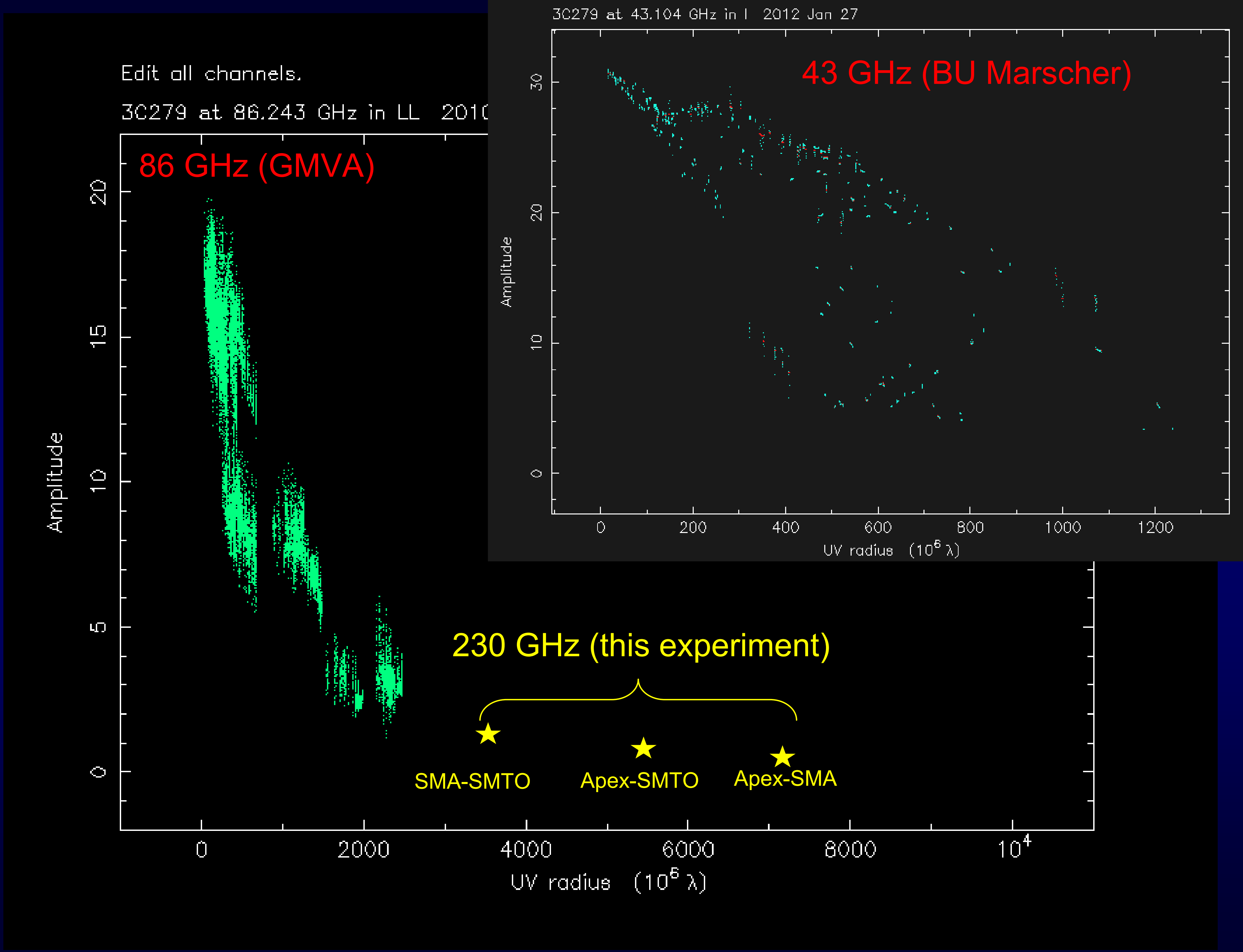
Status May 2012 with APEX added



★ existing

★ planned

——— fringes established



Edit all channels.
3C279 at 86.243 GHz in LL 2010
86 GHz (GMVA)
Amplitude
UV radius (10^6 λ)
230 GHz (this experiment)
SMA-SMTO
Apex-SMTO
Apex-SMA
3C279 at 43.104 GHz in I 2012 Jan 27
43 GHz (BU Marscher)
Amplitude
UV radius (10^6 λ)

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

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

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 AGN jet visibilities

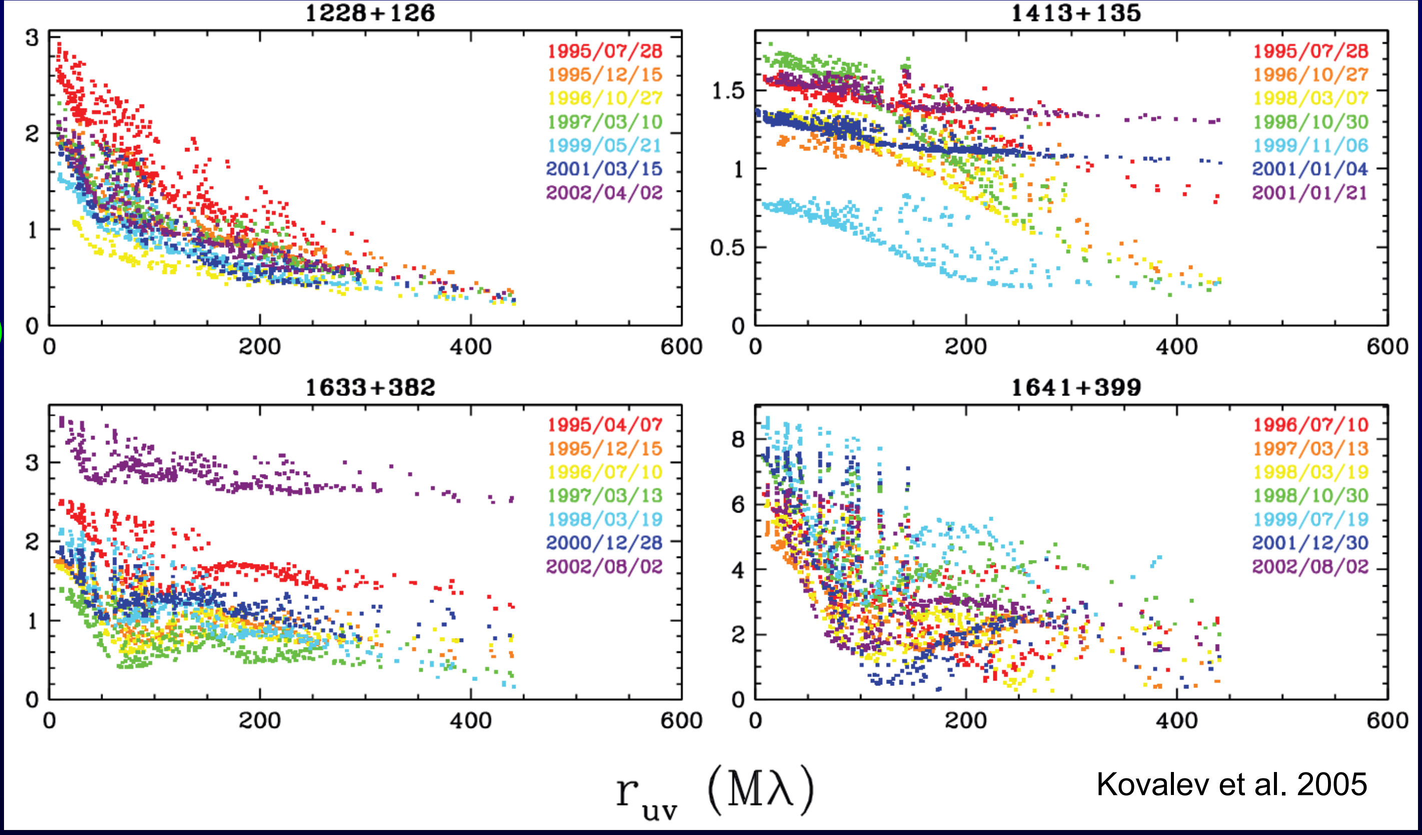
at 15 GHz

(Mojave AGN sample)

dramatic variations

of compactness on

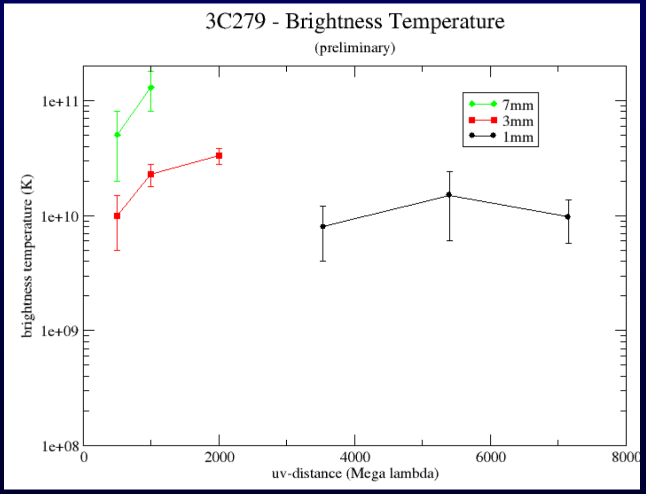
≤ 1 year timescale !



Kovalev et al. 2005

Preliminary results – further analysis pending

- 3C279 detected on 3 baselines covering 5400-7200 Mλ.
- calibration still uncertain, but data suggest relatively low correlated flux of ~(0.3 – 1.5) Jy (S_{tot} ~18 Jy)
- emission comes from an ultra-compact region of ~28 μas in size (0.3 pc, ~3000 R_s), embedded in emission of considerably larger extend
- this implies brightness temperatures ≥ 10^{10} K (consistent with lower freqs)
- possible decrease of T_B towards smaller r needs confirmation (calibration uncertainties still large)
- ratio long/short baseline flux is barely consistent with point source model, more complicated structure is likely (this also effects T_B estimate)
- need better uv-coverage and sensitivity

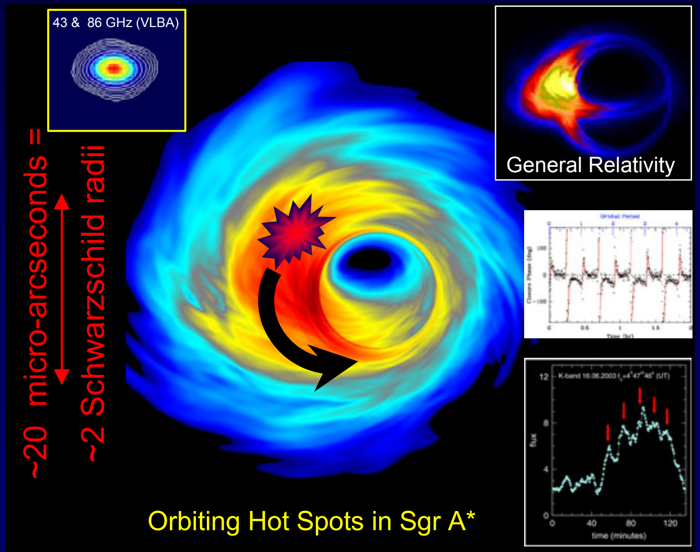


- need VLBI with ALMA at 7mm, 3mm, 1mm to image faint and partially resolved structures !!

Image Black Holes and the region of jet formation with sub-millimeter VLBI

- achieve 10-25 micro-arcsecond resolution at sub-mm wavelengths
- image Sgr A* and M87 with a few R_G resolution (BH imaging and GR-effects)
- study jet formation in nearby Radio-Galaxies (jet-disk connection, outburst ejection relations, etc.)
- AGN studies at mm-λ, study SMBHs at high redshifts (cosmological evolution of SMBHs)
- build a global sub-mm VLBI array: PV, PdBI SMTO, Hawai, Carma, LMT, SPT, APEX/ ALMA (Event Horizon Telescope).
- the large collectiong area of ALMA is needed to reach milli-Jansky sensitivity

Sgr A*:



M87+Jets: