2nd School on Multiwavelength Astronomy
ITN 215212: Black Hole Universe

Amsterdam, 28 June to 9 July 2010

VLBI

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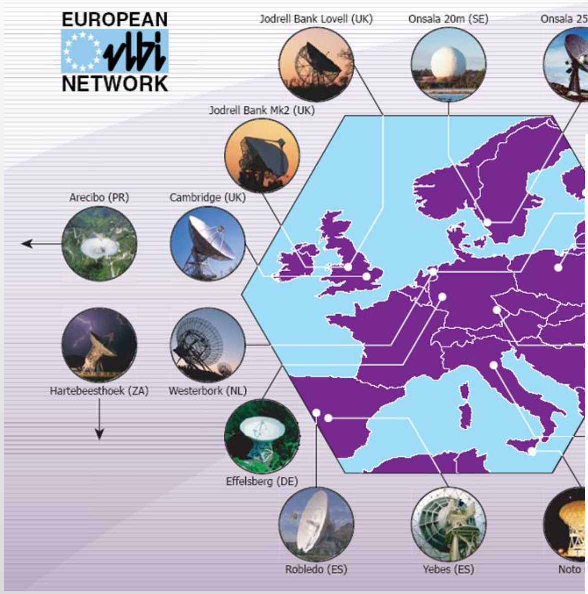
(based on material from the ERIS2009 school by T. Venturi)

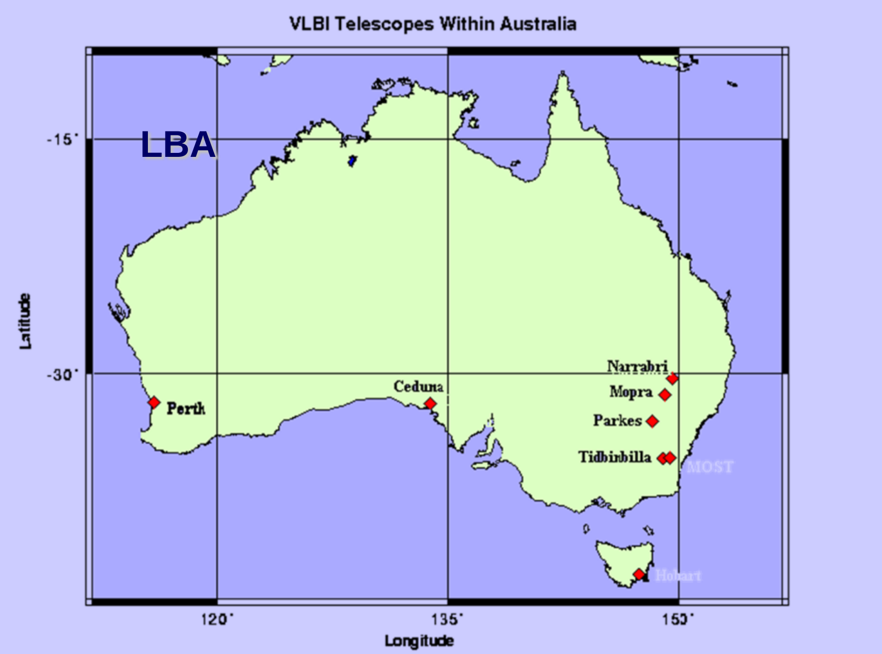
Outline of the presentation

- Introduction to VLBI
- A taste of VLBI science
- Similarities and differences compared to connected element arrays
- Special issues in the amplitude & phase calibration
- EVN & e-VLBI
- Space VLBI

Very Long Baseline Interferometry

Arrays of local autonomous telescopes, distant hundreds to thousands of km one another. A number of ground VLBI arrays exist to date:





… and many others:

KVLBI, VERA, …

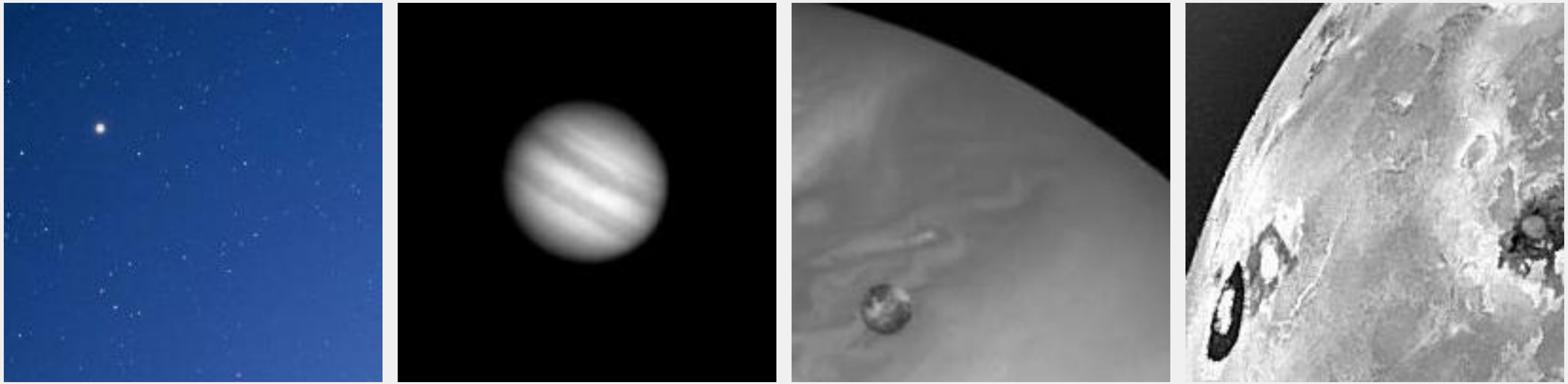
VLBI opens the access to milliarcsecond resolution

Resolution = Observing wavelength / Telescope diameter

Angular Resolution	Optical (5000A)		Radio (4cm)	
	Diameter	**Instrument**	**Diameter**	**Instrument**
1′	**2mm**	**Eye**	**140m**	**GBT+**
1″	**10cm**	**Amateur Telescope**	**8km**	**VLA-B**
0.″05	**2m**	**HST**	**160km**	**MERLIN**
0.″001	**100m**	**Interferometer**	**8200km**	**VLBI**

Atmosphere gives 1" limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth



1 arcmin

1 arcsec

0.05 arcsec

0.001 arcsec

Simulated with Galileo photo

Adapted from C. Walker

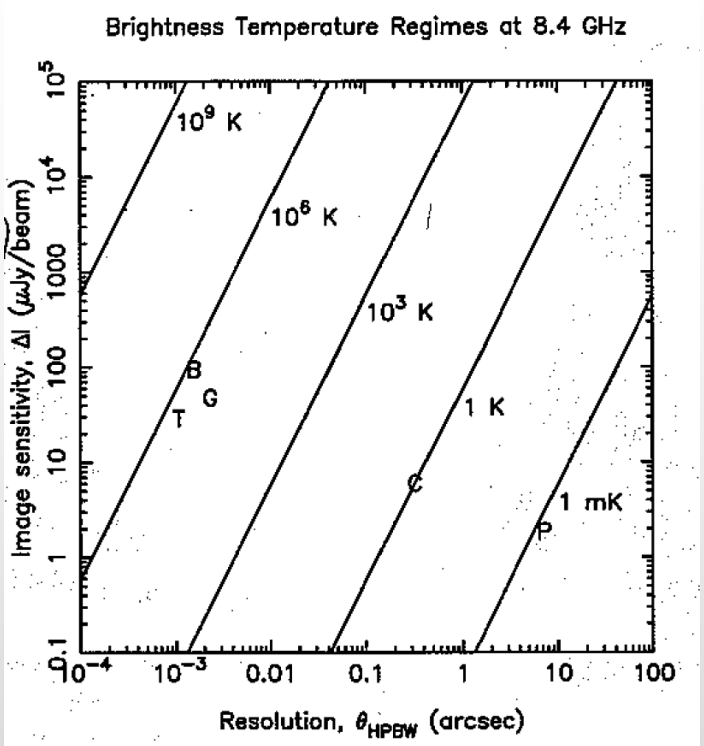
The high resolution and sparse distribution of telescopes have some straightforward implications on the science

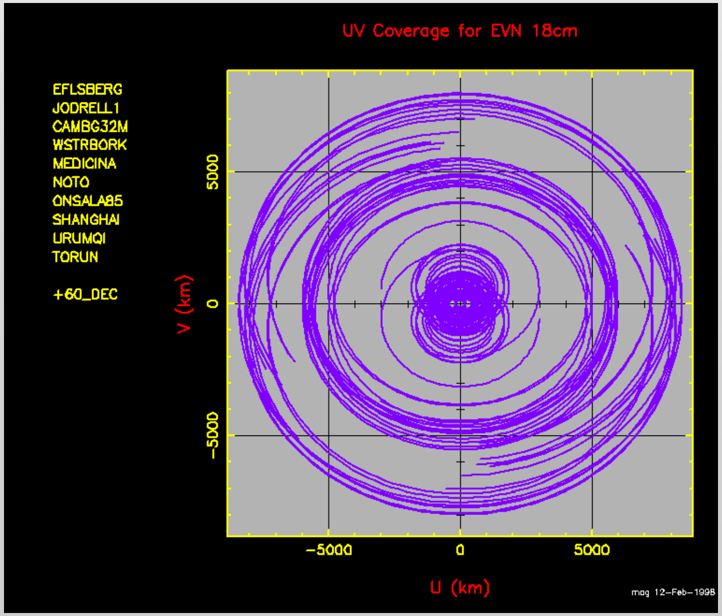
- **Only sensitive to non-thermal emission processes ($T_{b,min} \propto \theta^{-2}_{HPBW}$)**
  - **- 10^6 K brightness temperature limit**
  - **- Tailored science cases**

To improve sensitivity:

Need bigger telescopes

For continuum, need a higher data rate

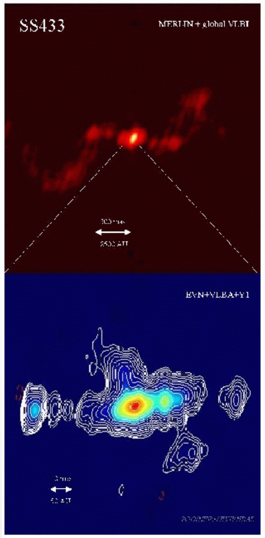




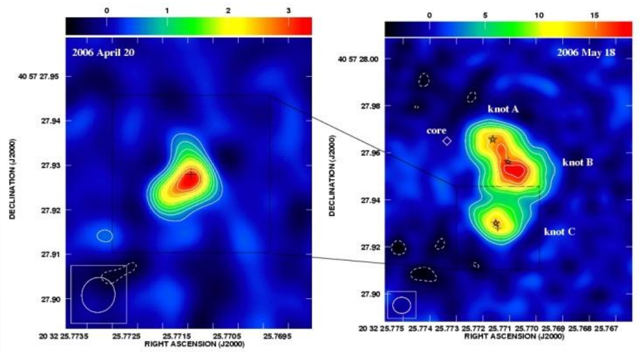
To improve the uv coverage:

Larger number of telescopes

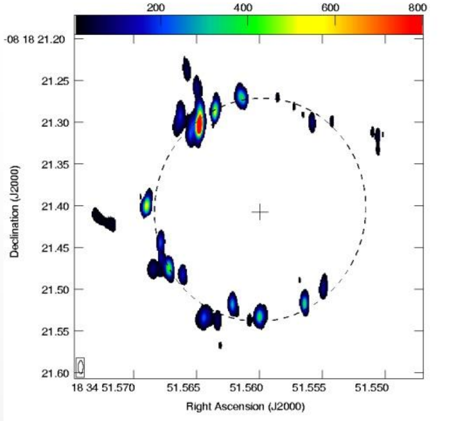
Wider bandwidth



SS433
10 mas = 50AU



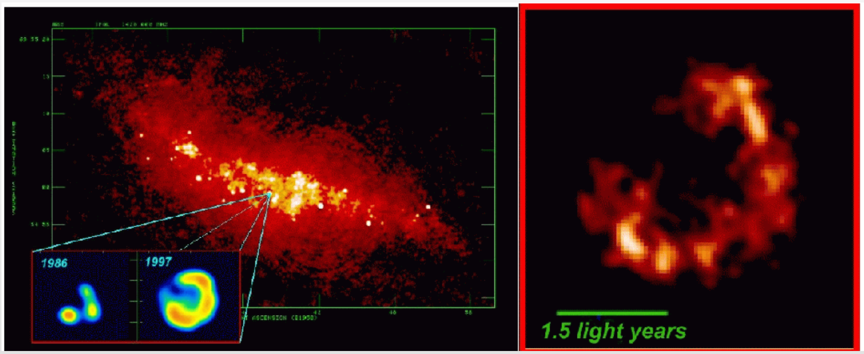
Cygnus X-3



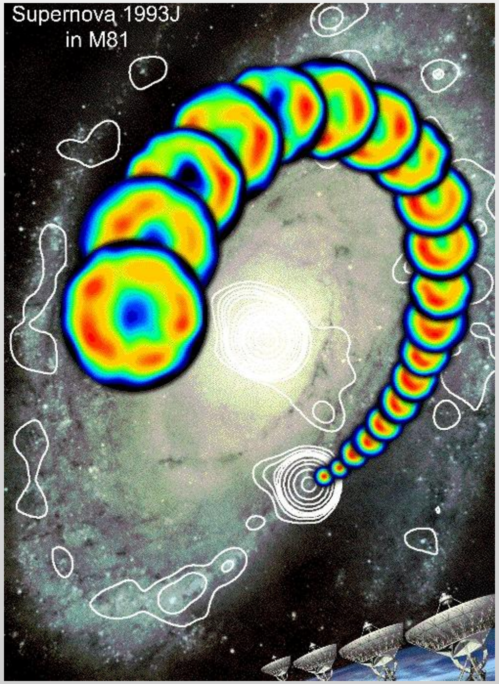
Total intensity (zero moment map) of G23.657–0.127.

Galactic methanol maser

Total extent 650 AU

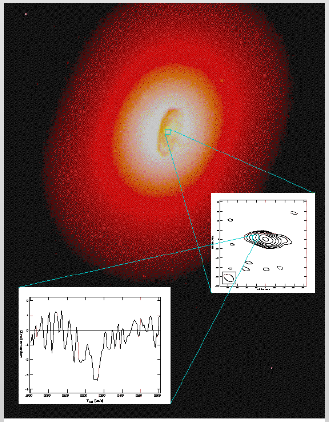


Starburst in M82



1993J in M81(z=0.00013)

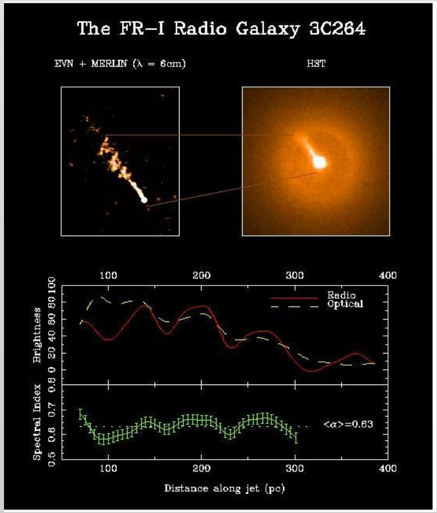
Fraction of light year res.



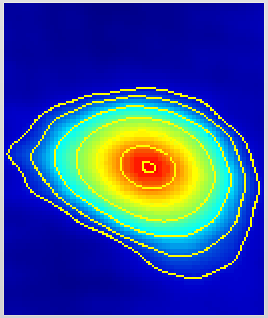
The first scientific result of the EVN data processor at JIVE is locating atomic Hydrogen close to the nucleus of NGC4261. The background is the Hubble telescope image showing a neutral accretion disk in the inner part of this active galaxy. Insets are the VLBI image of the nucleus at 21 cm (right) and the HI absorption spectrum, observed slightly offset from the nucleus (left).

van Langevelde, Pihlstroem, Conway, Jaffe, Schilizzi, 2000, A&A 354, L45

HST and VLBI in NGC4261 (z0.0074)



HST and EVN*MERLIN in 3C264



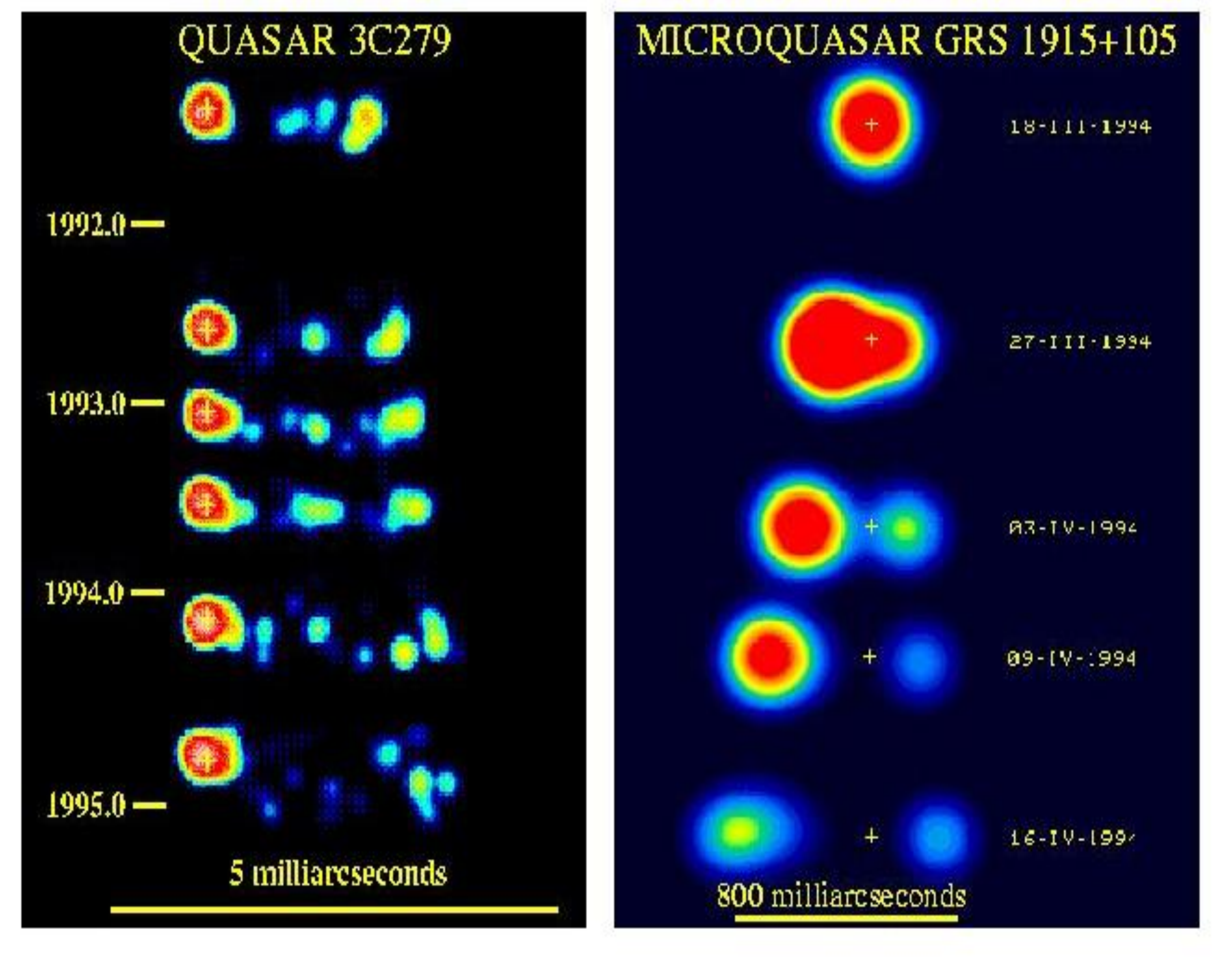
0836+0054 z=5.82

1 mas ~ 6 pc

SUPERLUMINAL MOTION IN QUASARS

VLBI at
22 GHz
~ 1,3 cm

~ milliarcsec.
scale

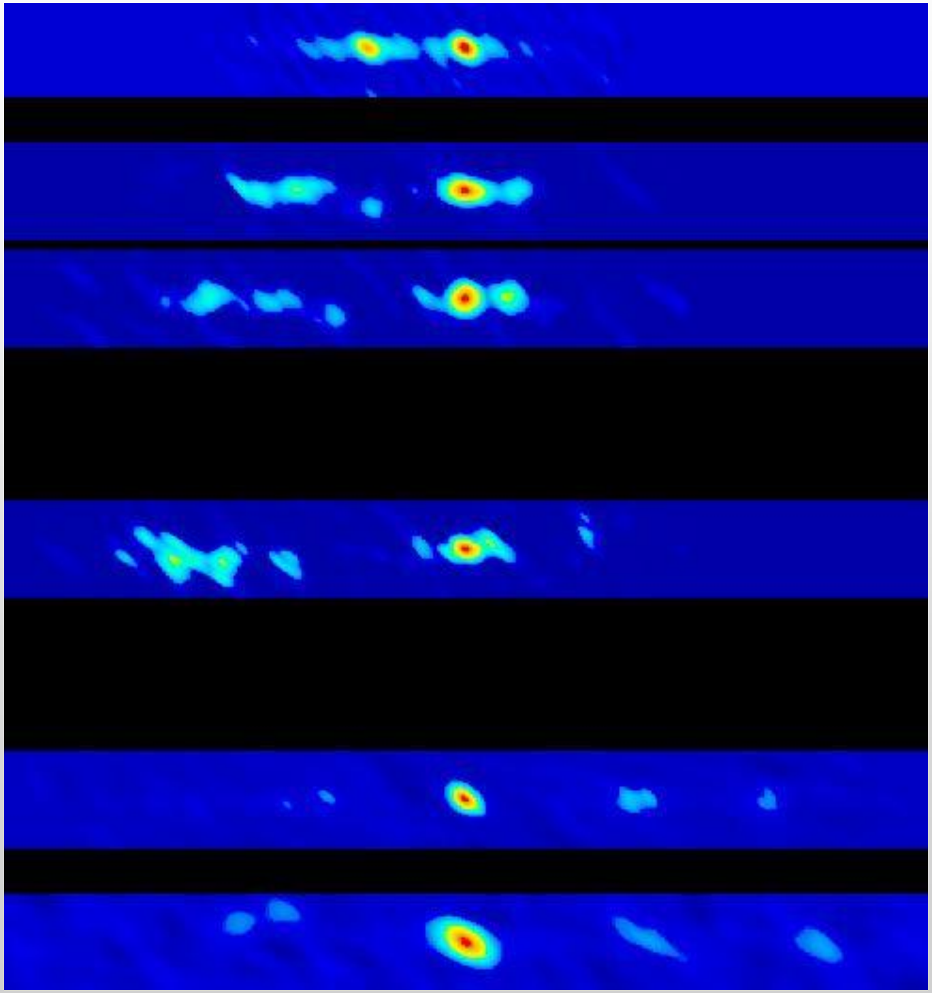


VLA at
3,5 cm

~ arcsec.
scale

EPISODIC (SUPERLUMINAL) EJECTIONS IN MICROQUASARS

GRO J1655-40 (VLBA at 1.6 GHz)



18-19 Aug. 1994

22-23 Aug. 1994

25-26 Aug. 1994

1-2 Sep. 1994

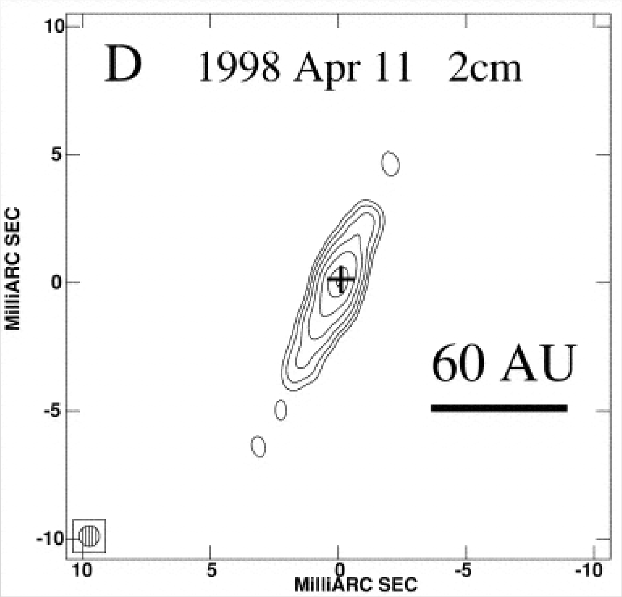
8-9 Sep. 1994

12-13 Sep. 1994

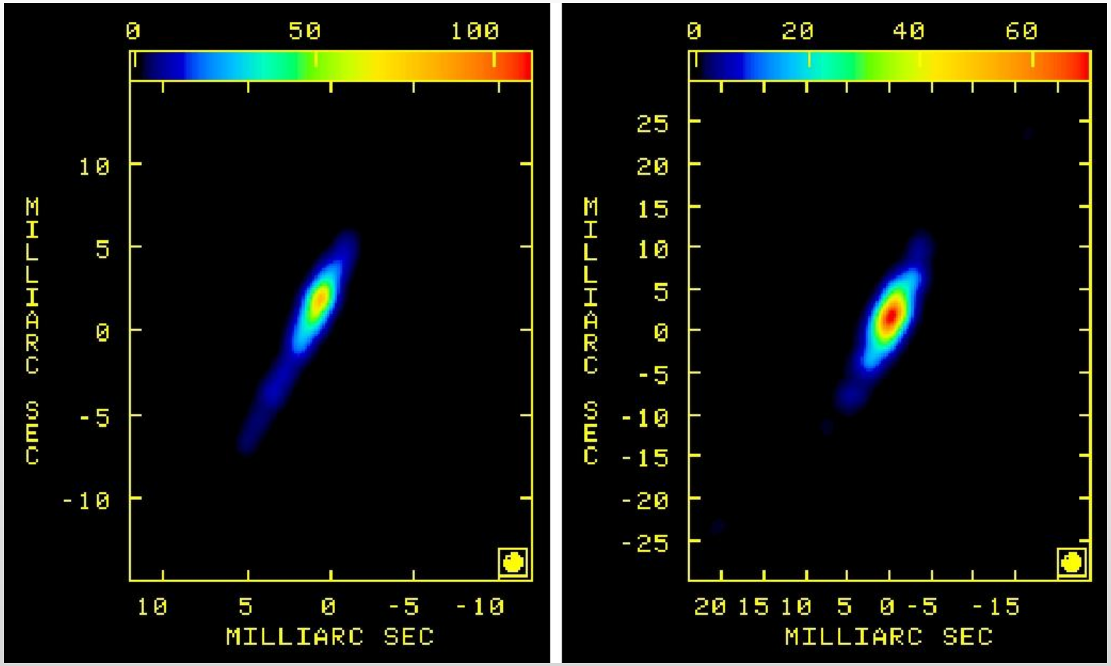
$\beta = 0.92$, $\theta = 85^\circ$

(Hjellming & Rupen 1995, Tingay et al. 1995)

VLBA images of **GRS 1915+105** reveal a **compact jet which is slightly asymmetric**. The Lorentz factor of the jet is not very high, or we would not see the counter-jet.

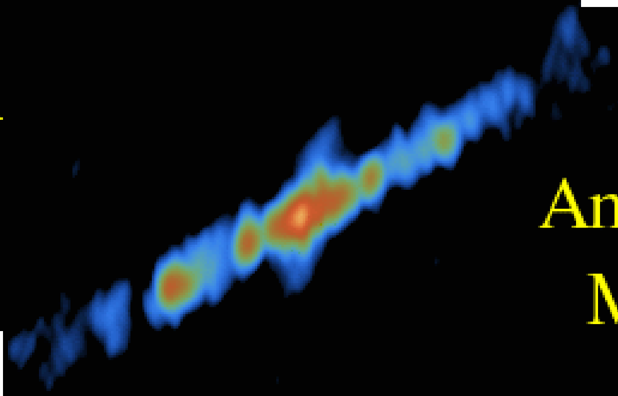


(Dhawan et al. 2000)



(Ribó et al. 2004).

SS433
VLBA



Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor

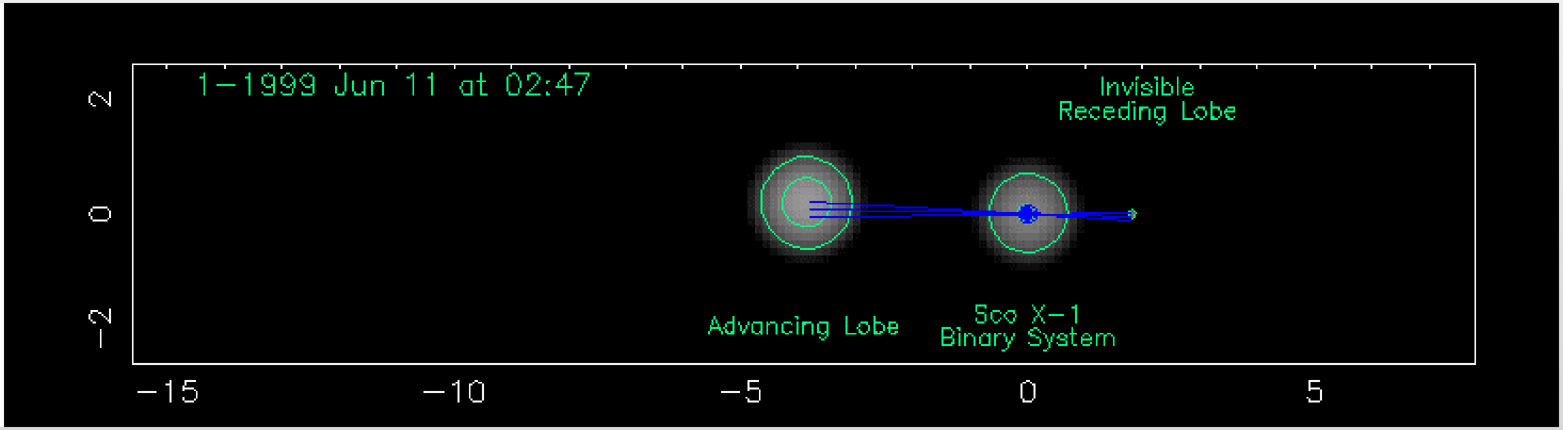
ENERGY TRANSFER
FROM THE CORE TO THE RADIO JETS

Sco X-1 (Global VLBI at 5 GHz)

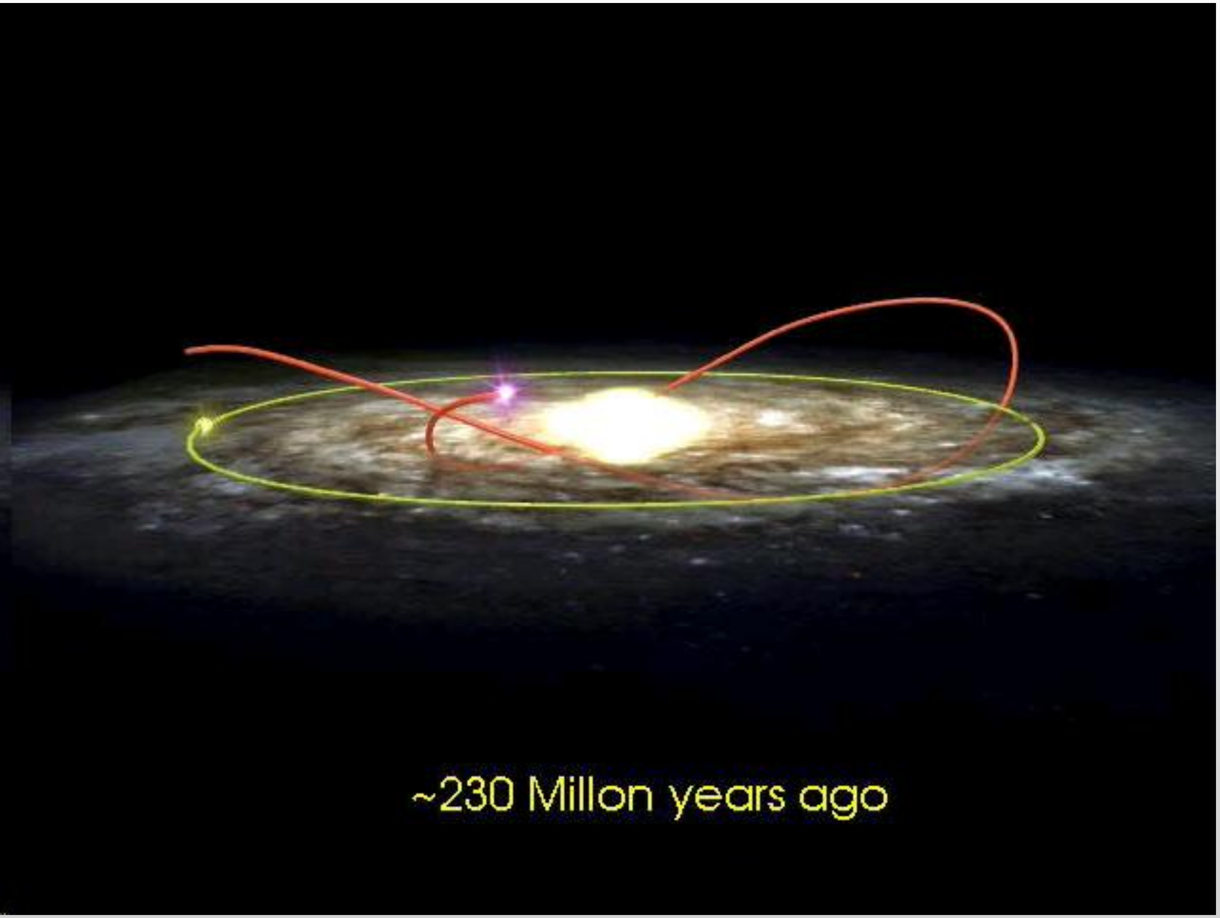
Fomalont et al. (2001)

$\beta = 0.45$, $\theta = 44°$

Energy transfer at $\beta > 0.95$



A BLACK HOLE FORMED ~7 BILLONS YEARS AGO



(Nature, 413, 139, 2001)

XTE J1118+480

GALACTOCENTRIC ORBIT

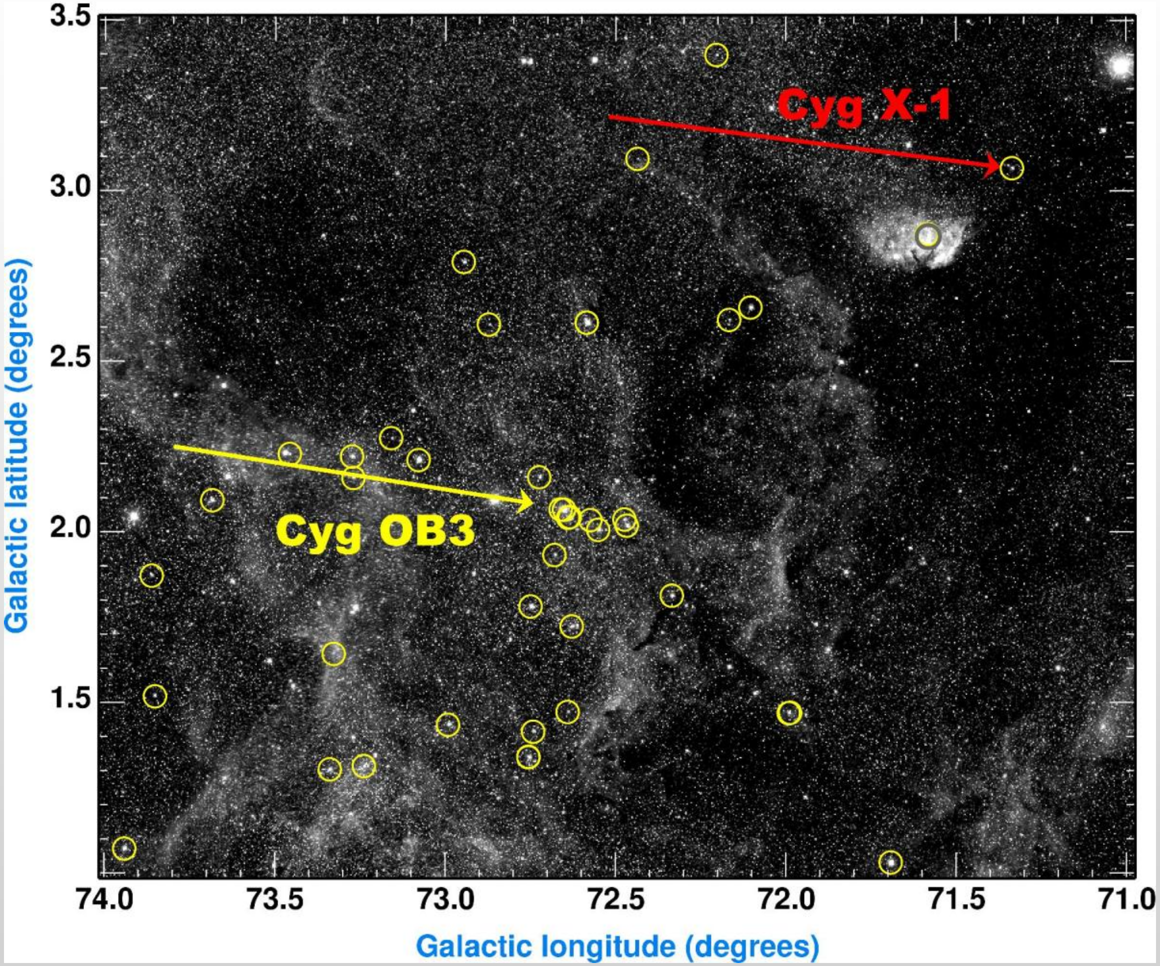
FOR THE LAST 230 Myrs

GALACTIC ARCHEOLOGY

OF MASSIVE STARS

IN A GLOBULAR CLUSTER OF THE GALACTIC HALO

FORMATION OF A BLACK HOLE IN THE DARK



Cygnus X-1

M. & Irapuan Rodrigues

(Science, May 16, 2003)

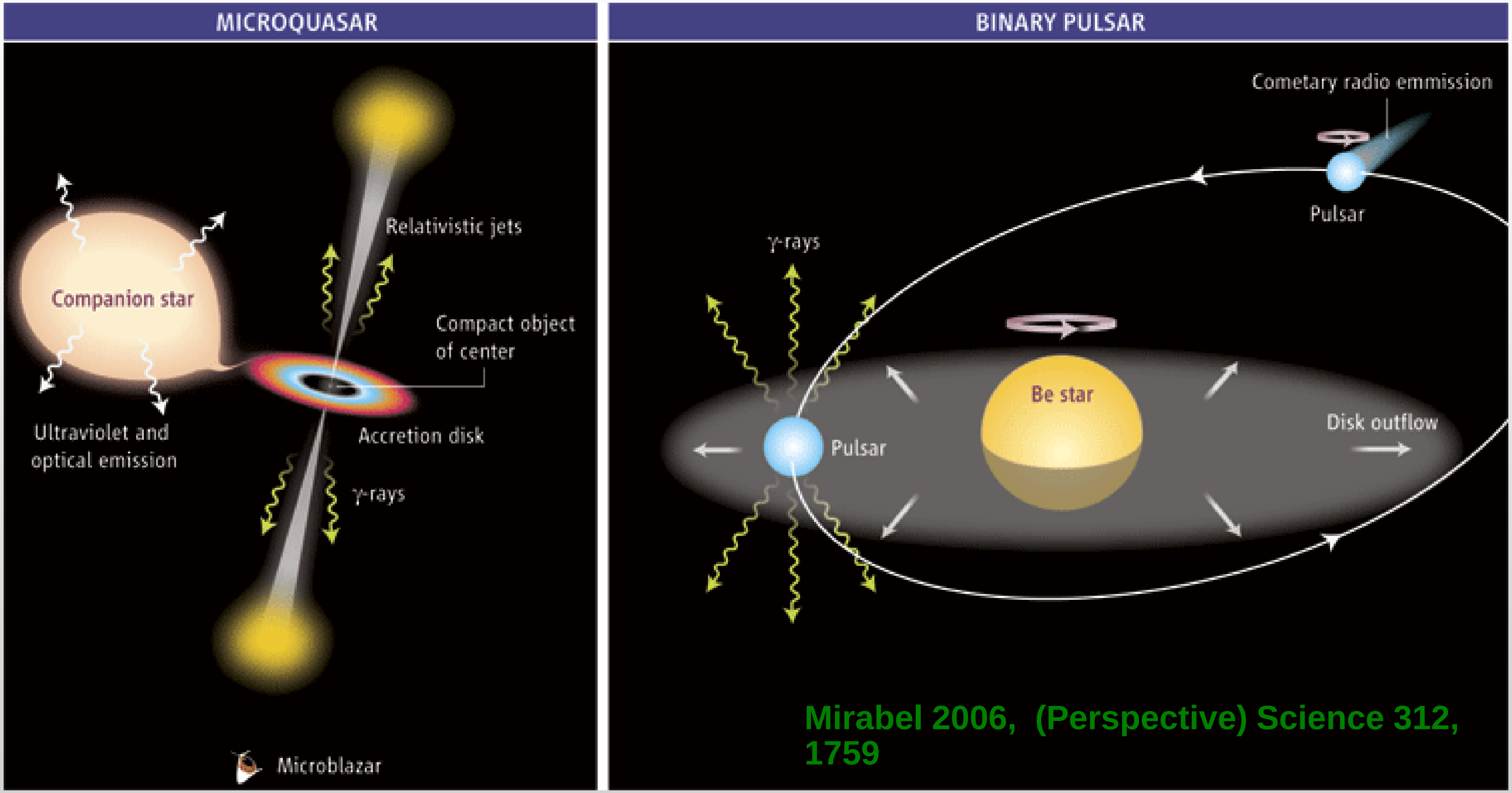
FROM KINEMATICS:

THE PROGENITOR OF THE $M_{BH} \sim 10\ M_\odot$ BLACK HOLE IN Cyg X-1 HAD AN INITIAL MASS $> 40\ M_\odot$ AND DID NOT EXPLODE AS A TYPICAL SN

THE DEATH OF MASSIVE STARS MAY NOT BE IN TYPICAL SNe

& HIGH-MASS STELLAR BLACK HOLES MAY FORM SILENTLY

A FEW WORDS ON GAMMA-RAY BINARIES



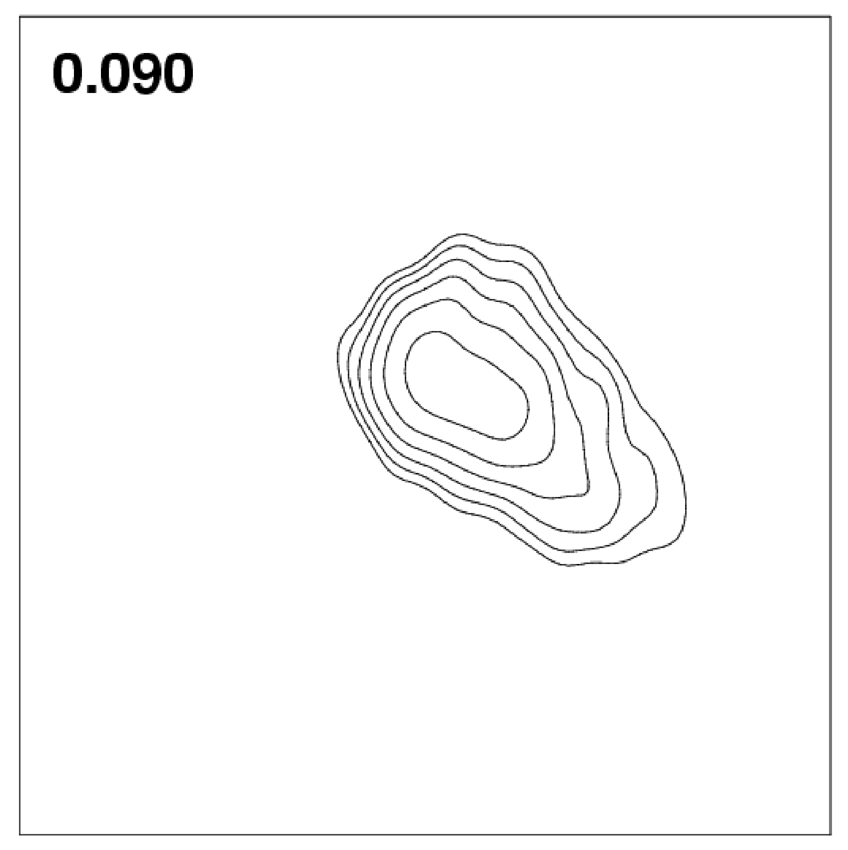
Mirabel 2006, (Perspective) Science 312, 1759

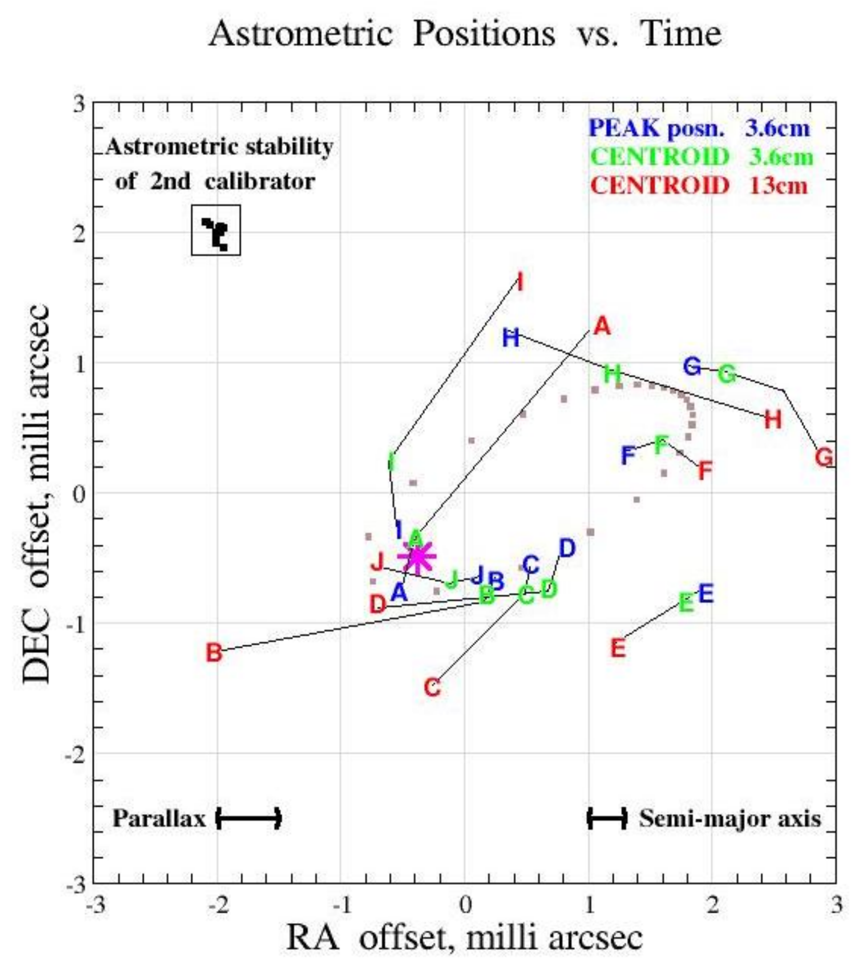
Cygnus X-1

LS 5039 ? LS I +61 303 ? PSR B1259-63
HESS J0632+057 ?

LS I +61 303. Jet-like features have been reported several times, but show a puzzling behavior **(Massi et al. 2001, 2004)**. **Later VLBI observations show a rotating jet-like structure (Dhawan et al. 2006)**.

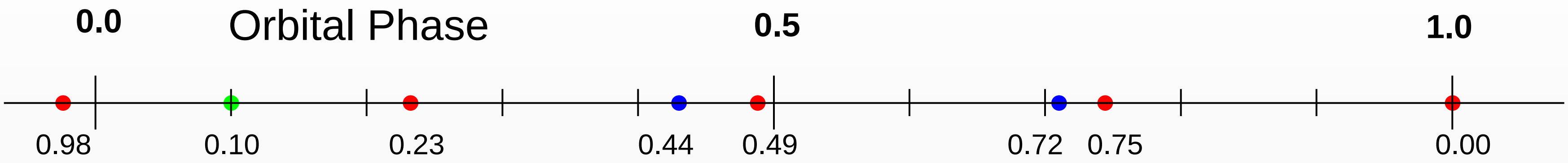
Orbital phase:



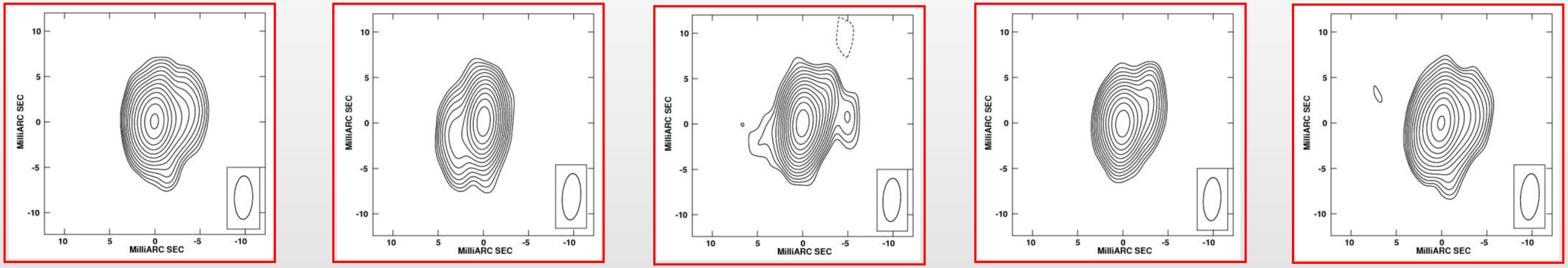


3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU. Contours 0.2mJy, increment sqrt(2).

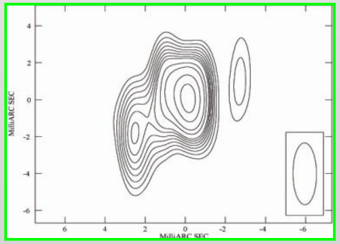
Orbital morphological variability of LS 5039 at 5 GHz.

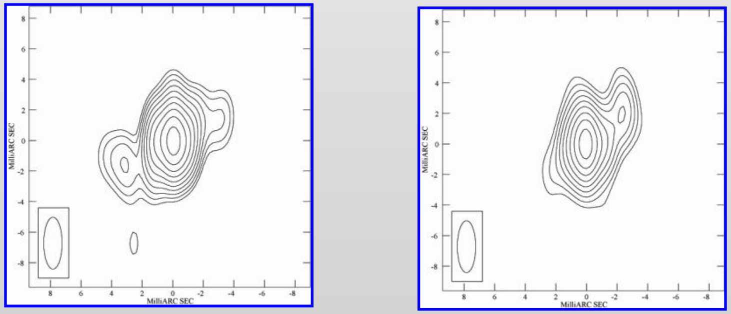


(2007)



(1999)

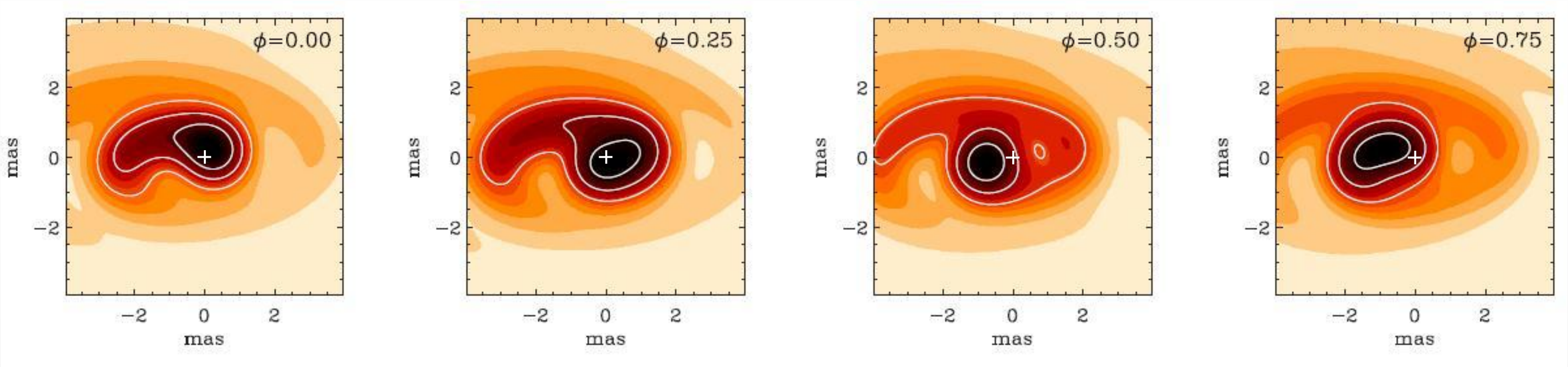


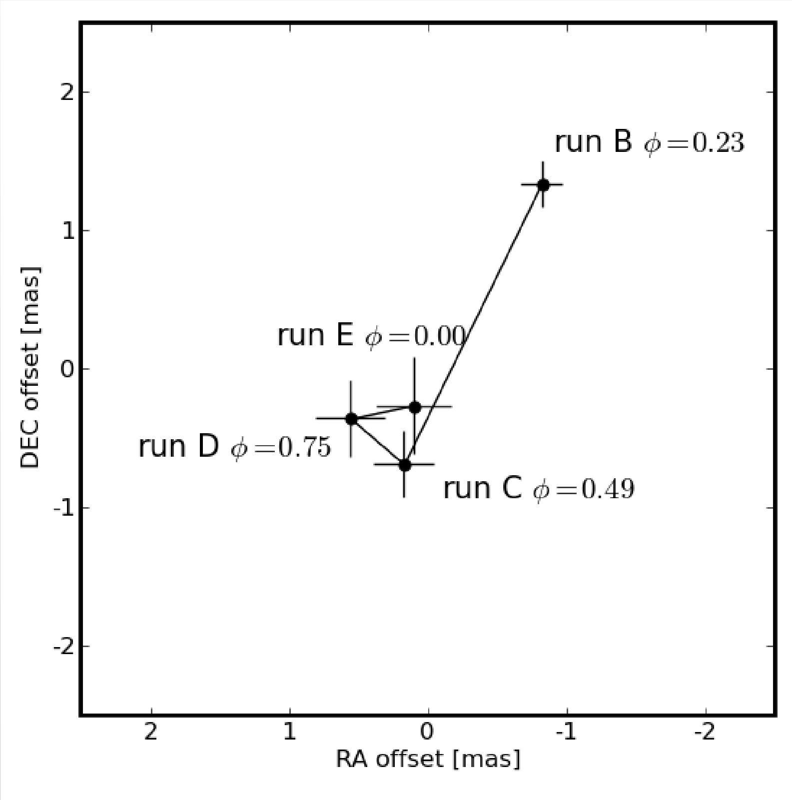


(2000)

Images at the same phase have similar morphology.
Images between adjacent runs show a hybrid morphology of the two runs.
(Moldón et al., in prep).

Orbital astrometric variability.

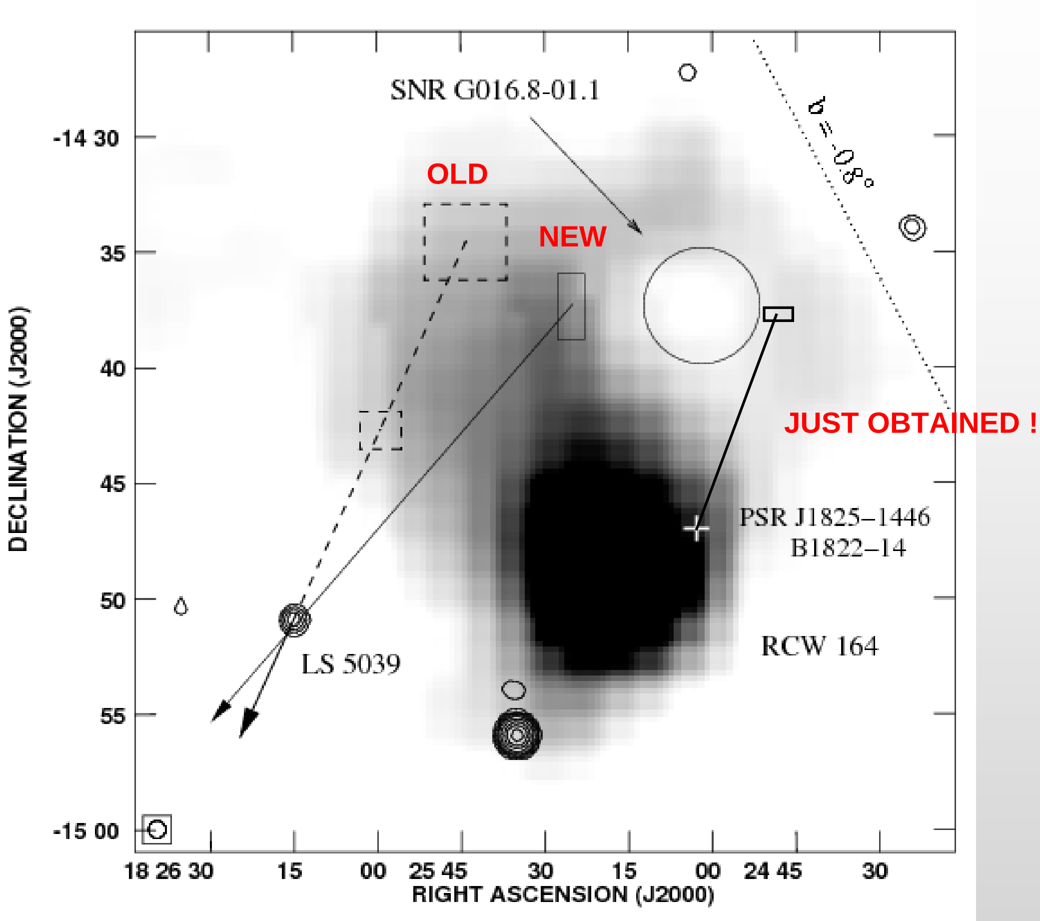




The **modeling** by **Dubus (2006)** **predicts orbital astrometric variability** at mas scales in the non-accreting pulsar scenario.

We have **just measured a displacement after the periastron passage** in the VLBA images obtained in 2007. This displacement is not compatible with the predicted one **(Moldón et al., in prep.)**.

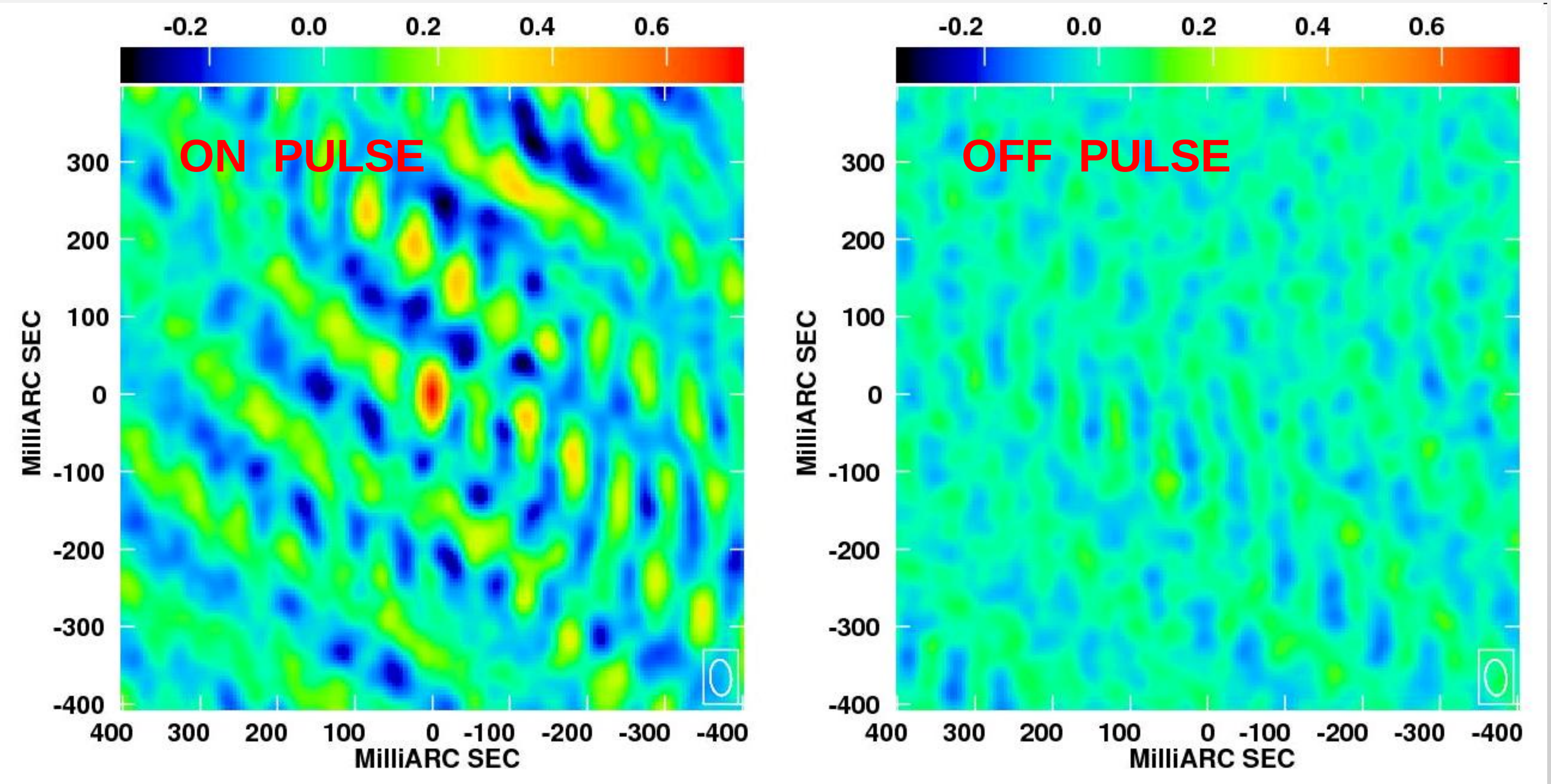
The origin of LS 5039.



Updated **proper motion of LS 5039 suggests an origin in SNR G016.8-0.1.** about 10^5 yr ago **(Moldón et al., in preparation)**. However, **PSR J1825-1446 appears to come from the same SNR** about $2{\cdot}10^5$ yr ago, although the characteristic age is one order of magnitude bigger.

- A GeV (*Fermi*) and radio (GBT) **pulsar** has been found in the region of **TeV J2032+4130** **(Camilo et al. 2009)**, which is also coincident with an X-ray source previously reported **(Paredes et al. 2007)**. This **suggests that a pulsar wind nebula is behind the first (and still) unidentified TeV source**.

- We have just **detected the 0.2 mJy pulsar with the EVN** and will follow its proper motion during the following years **(Moldón et al., EVN Newsletter)**. We are **searching for a radio PWN** with the EVLA **(Paredes et al., just observed)**.

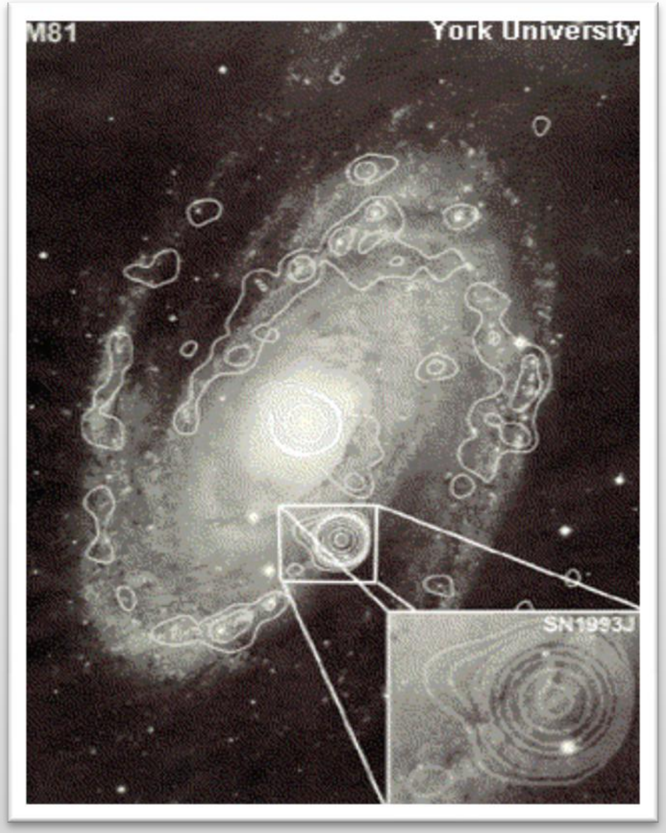


DiFX software correlators are now available at VLBA, LBA and EVN Bonn correlator. The EVN JIVE correlator will soon become a software correlator as well.

Software correlators have **several advantages**. Among them:

Use **binning instead of gating to correlate pulsars**. This allows you to significantly improve the final S/N ratio of your images, and hence **improve astrometric measurements**.

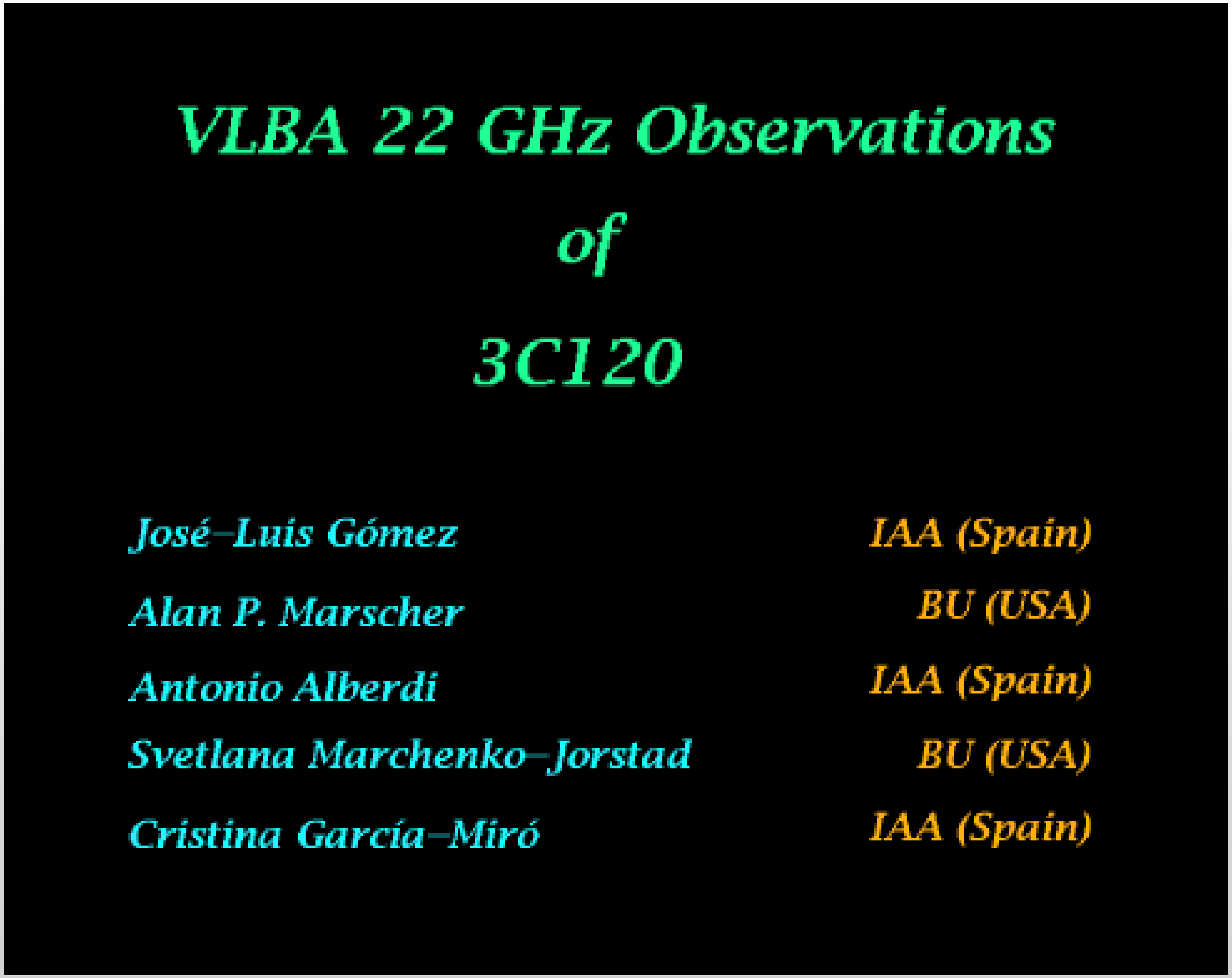
Correlate up to 500 (!) phase centers using a factor 2.5 the time needed to correlate a single phase center. For hardware correlators a new correlation is needed for each phase center. This allows us to map the whole primary beam in a much faster way, look for calibrators around the target, etc.



(Bartel and Bitenholtz)

A Decade of Expansion of SN1993J

J.M. Marcaide, I. Martí-Vidal,
A. Alberdi, E. Ros, et al.

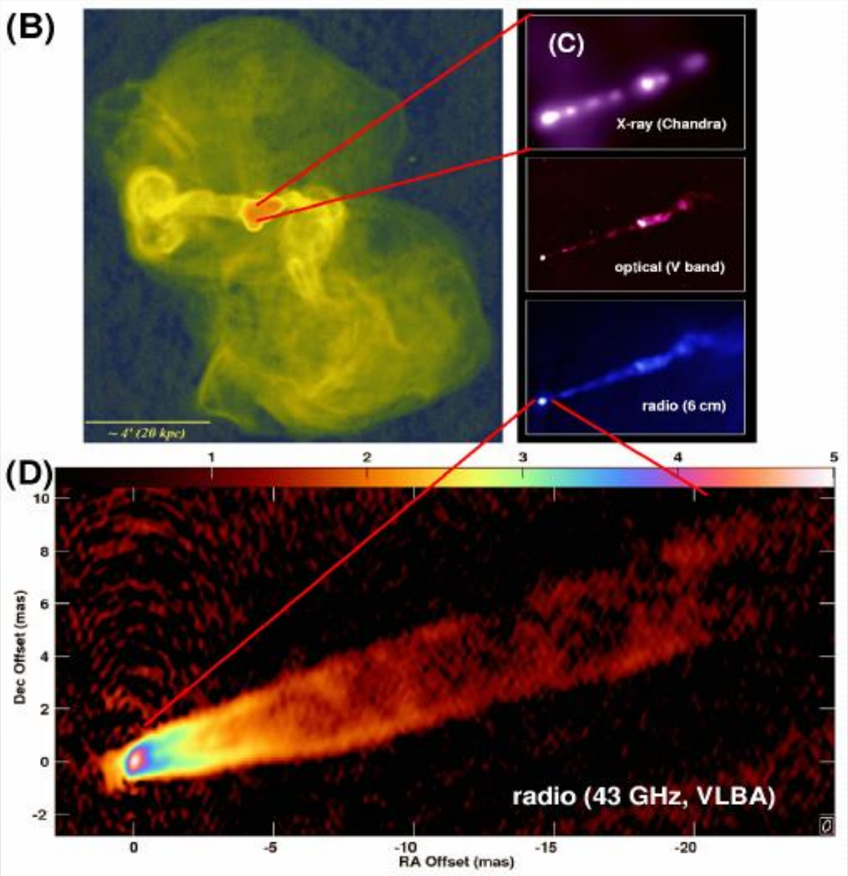


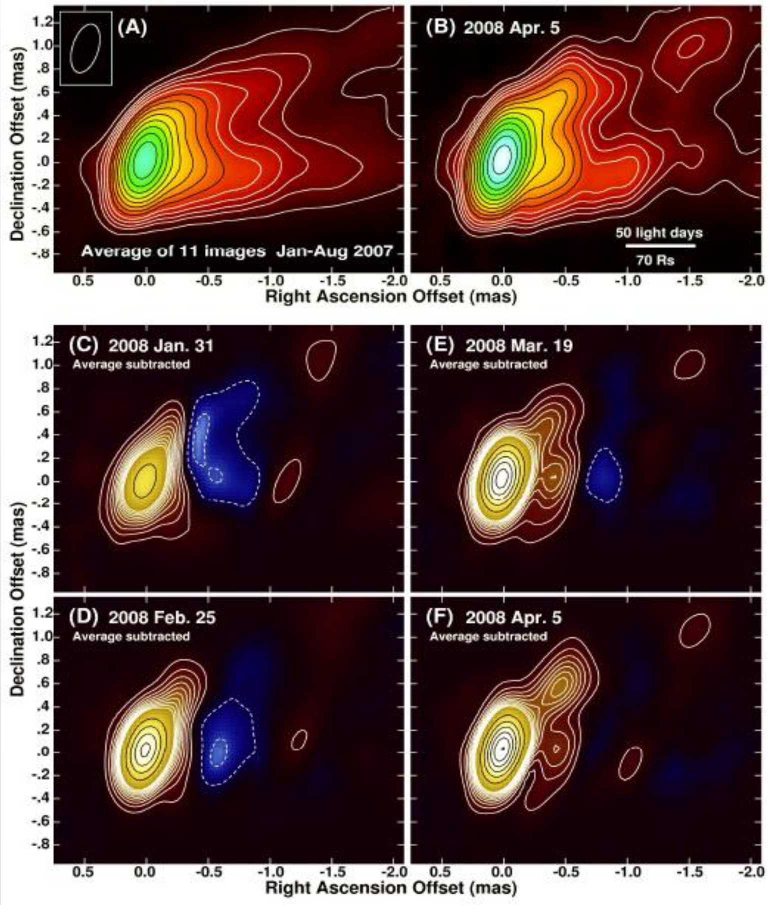
VLBA 22 GHz Observations
of
3C120

José–Luis Gómez IAA (Spain)
Alan P. Marscher BU (USA)
Antonio Alberdi IAA (Spain)
Svetlana Marchenko–Jorstad BU (USA)
Cristina García–Miró IAA (Spain)

Radio galaxies.

The FR I radio galaxy M87. Recent **VLBA** and **MAGIC/VERITAS/HESS** coordinated observations show a period of extremely strong **VHE γ-ray flares accompanied by a strong increase of the radio flux from its nucleus**. This implies that **charged particles are accelerated to very high energies in the immediate vicinity of the black hole (Acciari et al. 2009)**.



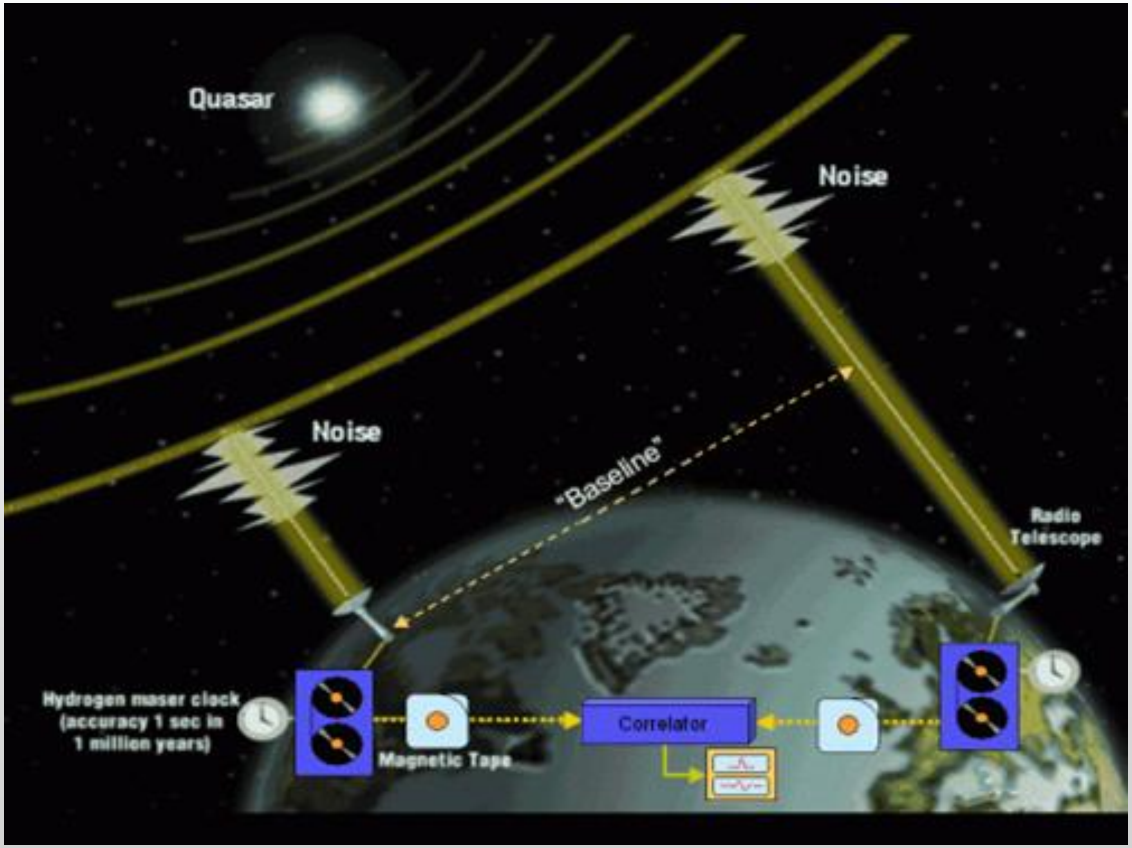


Differences and similarities from connected element interferometry

Same principles as connected element interferometry: bring coherent signal together for correlation and get fringes from each interferometer

BUT

No wired connections between antennas, so accurate time standards and recording systems are used to preserve the phase of the wave. The signal is correlated at a later stage, when disks have been sent to the correlator



Phase solutions

→

The separate clocks, independent atmosphere at each antenna, differences in phase stability at each telescope, inaccurate source & station positions, Earth orientation cause rapid phase variations

→

Fringe fitting

Amplitude solutions

→

The calibrators are usually a little resolved and often variable:
No standard flux calibrators and
No point source amplitude calibrators

→

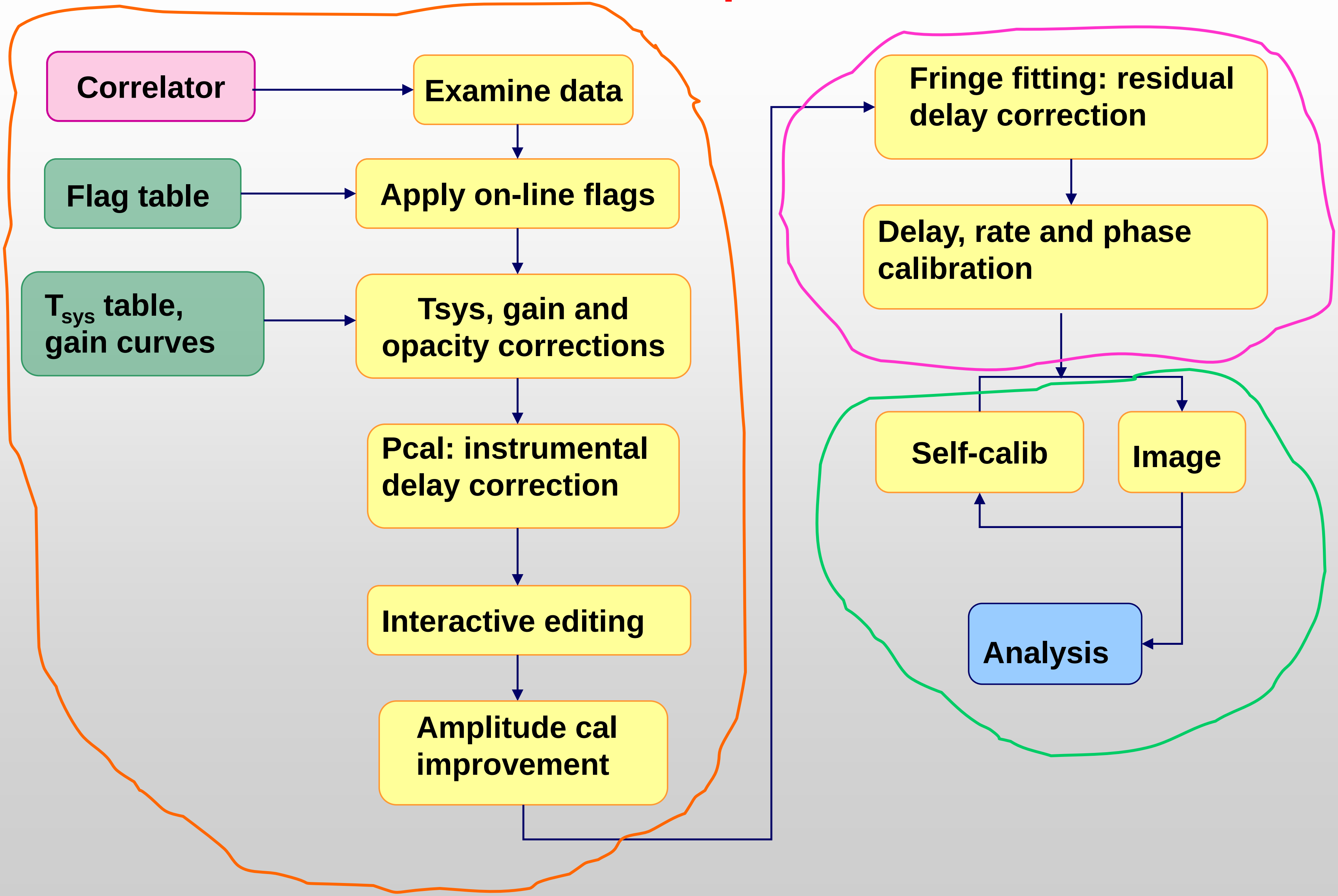
Use T_{sys} and antenna gains to calibrate the amplitudes

Only sensitive to limited scales
Structure easily resolved out

→

Include shorter baselines
(MERLIN, VLA)

VLBI data reduction path - continuum



Correlator

Flag table

T_{sys} table, gain curves

Examine data

Apply on-line flags

Tsys, gain and opacity corrections

Pcal: instrumental delay correction

Interactive editing

Amplitude cal improvement

Fringe fitting: residual delay correction

Delay, rate and phase calibration

Self-calib

Image

Analysis

The task of the correlator

- Cross multiply signals from the same wavefront
  - Antennas at different distances => delay
  - Antennas move at different speed => rate
- Offset estimates removed using a geometric model
- Remaining phase errors normally dominated by the atmosphere
- Write out data

Apriori editing

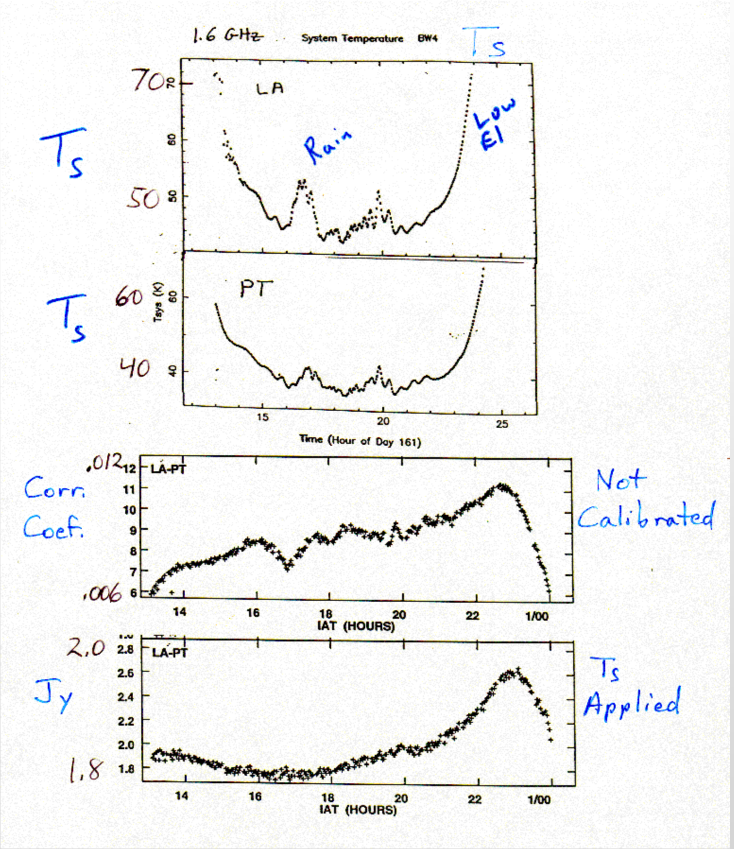
- Flags from the on-line system will remove bad data from
  - Antenna not yet on source
  - Subreflector not in position
  - LO synthesizers not locked

VLBI amplitude calibration

$$S_{cij} = \rho \frac{A}{\eta_s} \sqrt{\frac{T_{si} T_{sj}}{K_i K_j e^{-\tau_i} e^{-\tau_j}}}$$

- S_{cij} = Correlated flux density on baseline i - j
- ρ = Measured correlation coefficient
- A = Correlator specific scaling factor
- η_s = System efficiency including digitization losses
- T_s = System temperature
    - Includes receiver, spillover, atmosphere, blockage
- K = Gain in degrees K per Jansky (includes gain curve)
- $e^{-\tau}$ = Absorption in atmosphere plus blockage

Calibration with system temperatures

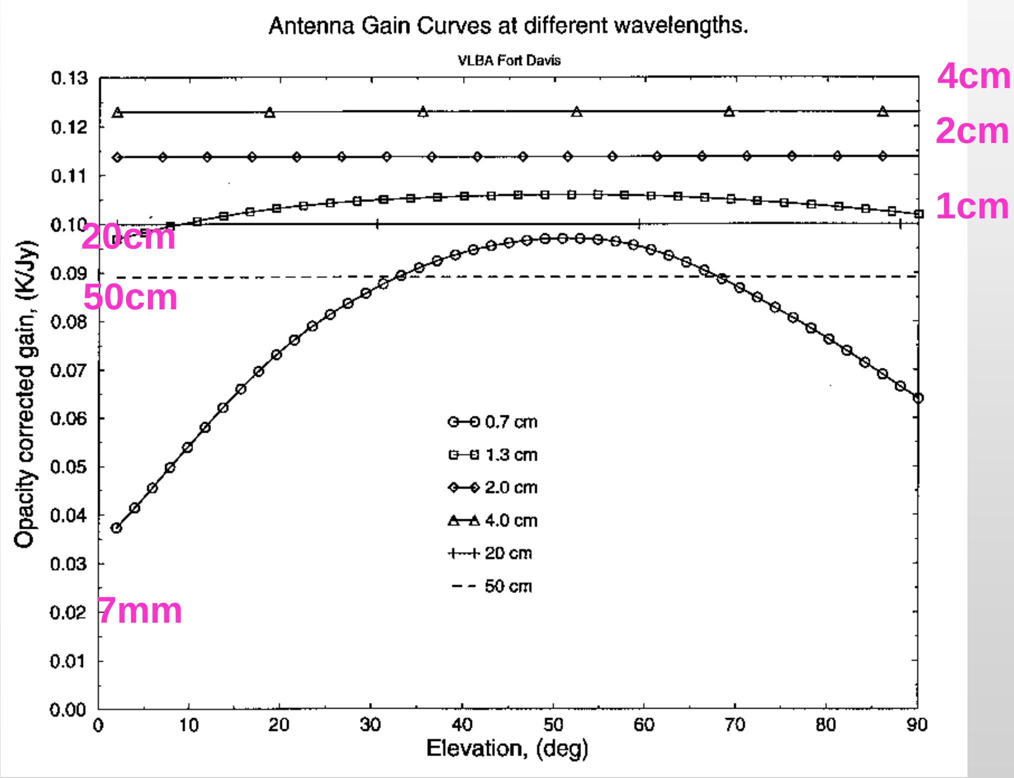


Upper plot: increased T_{sys} due to rain and low elevation.

Lower plot: removal of the effect.

Gain Curves

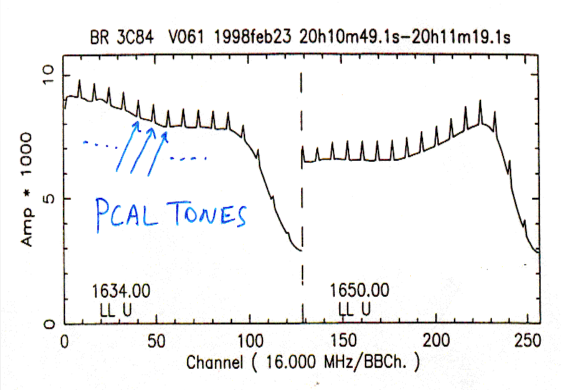
- **Caused by gravitationally induced distortions of antenna**
- **Function of elevation, depends on frequency**



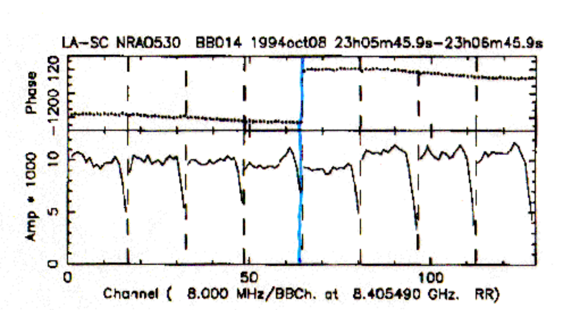
Adapted from C. Walker

Pulse cal system

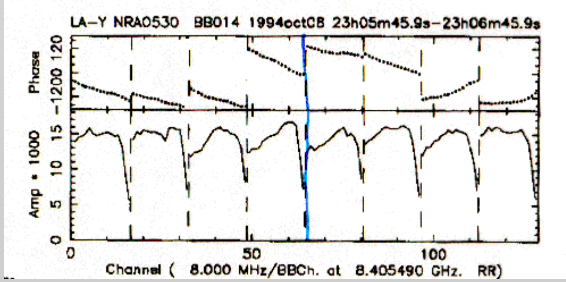
- Tones generated by injecting pulse once per microsecond
- Use to correct for instrumental phase shifts



Pcal tones

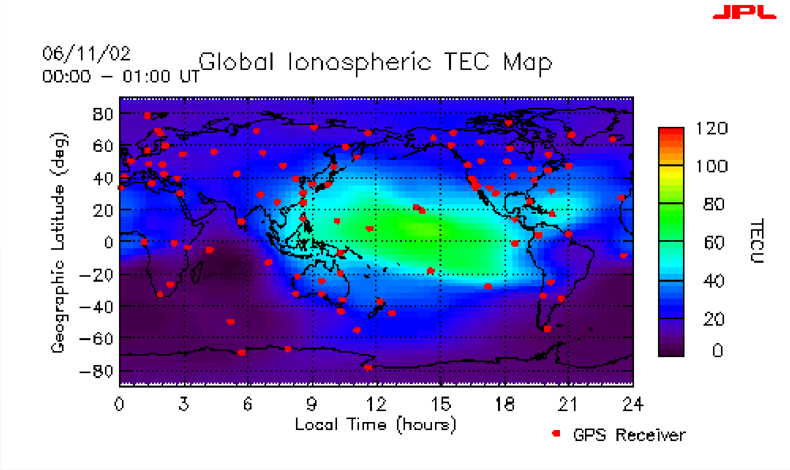


Pulse Cal applied

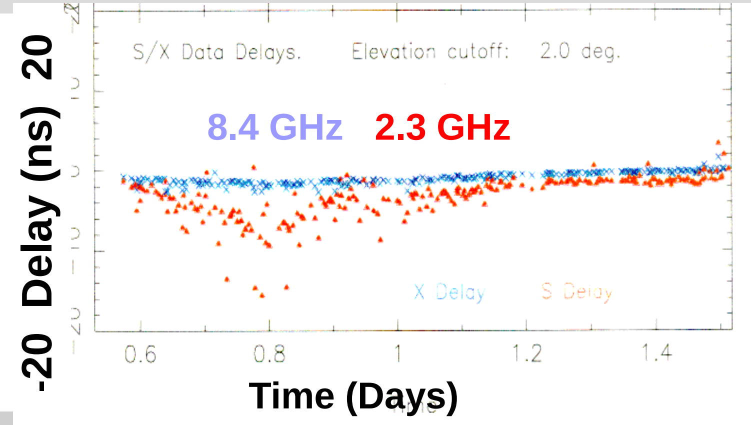


No PCAL applied

Ionospheric Delay

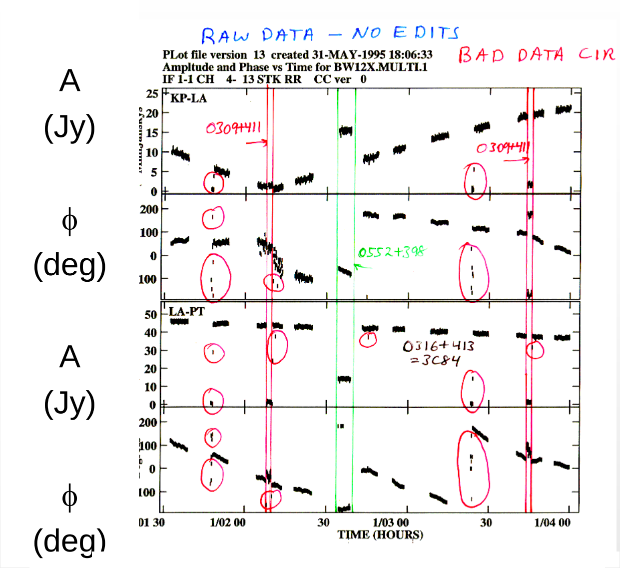


Delay scales with 1/ν2
Ionosphere dominates errors at low frequencies- Can correct with dual band observations (S/X) -GPS based ionosphere models help (AIPS task TECOR)

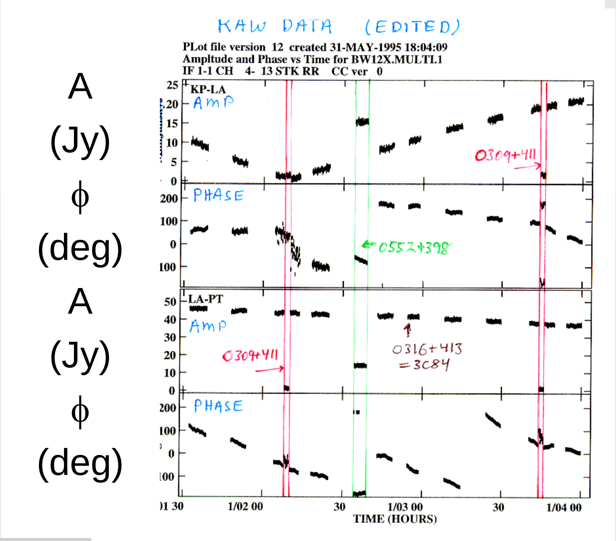


Editing

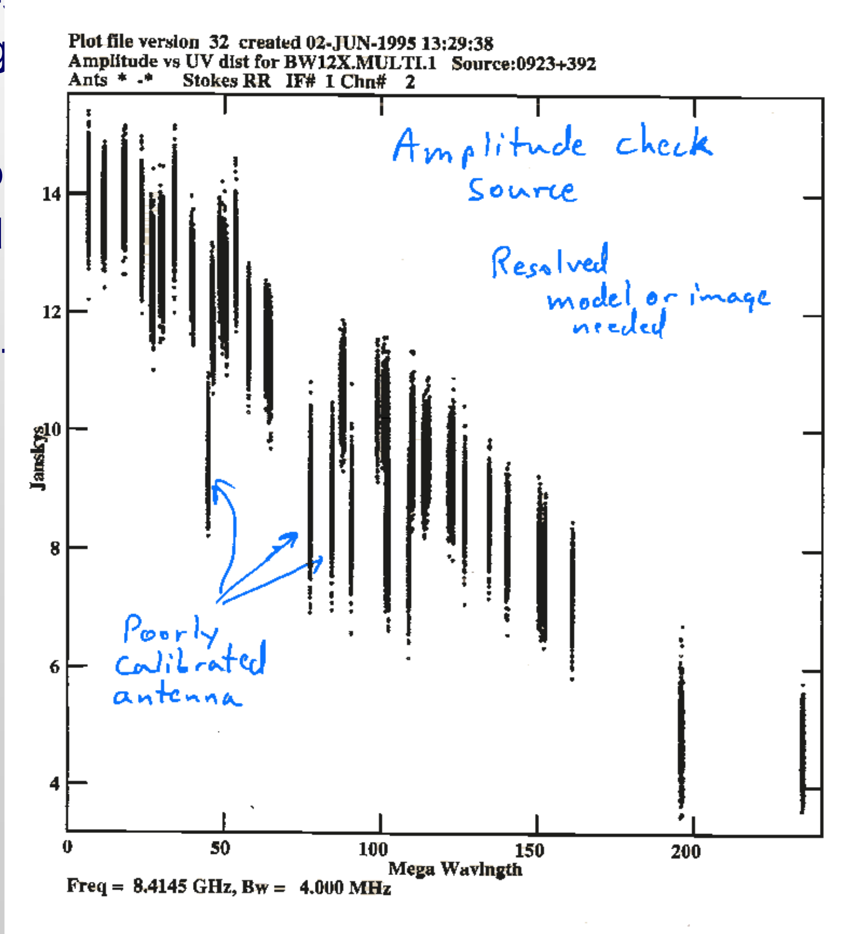
Raw Data - No Edits



Raw Data - Edited

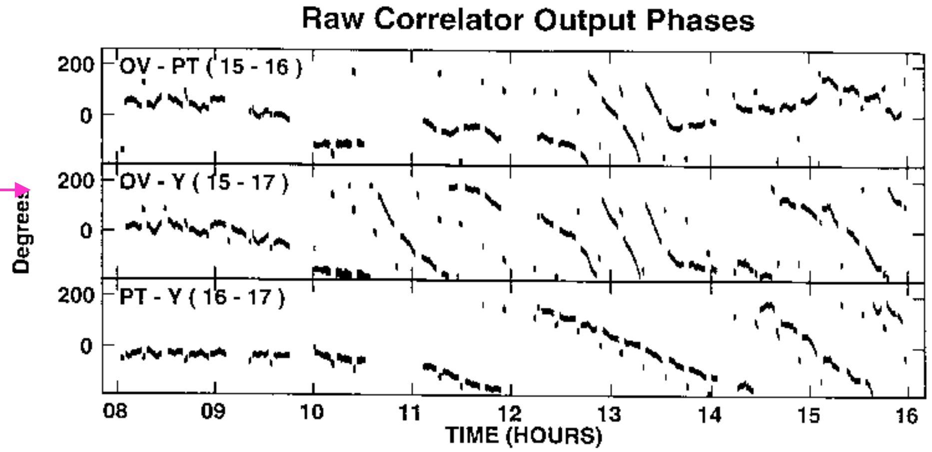


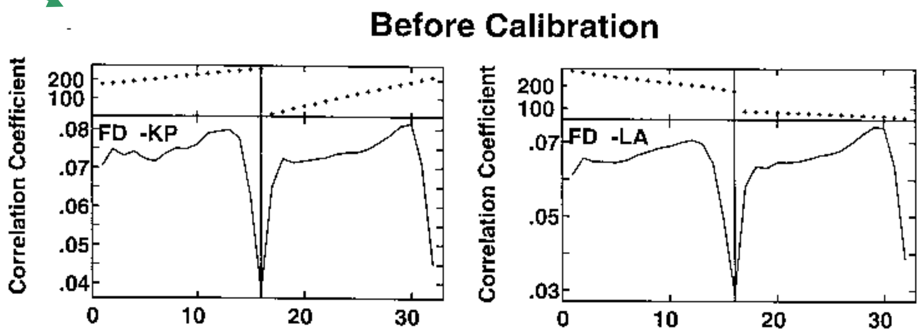
- Flags from on-line system will remove most bad data. Examples:
  - Antenna off source
  - Subreflector out of position
  - Synthesizers not locked
- Final flagging done by examining data
  - Flag
    -
  - Poo
  - Bad
  - RFI
  - Firs



Residual phase slopes

- Raw correlator output has residual phase slopes in time and frequency
  - Slope in time is "fringe rate"
    - Usually from imperfect troposphere or ionosphere model
- Slope in frequency is "delay"
  - A phase slope because $\phi=\upsilon\tau$
  - Fluctuations worse at low frequency because of ionosphere
  - Troposphere affects all frequencies equally ("nondispersive")
- Fringe fit is self calibration with first derivatives in time and frequency


Raw Correlator Output Phases

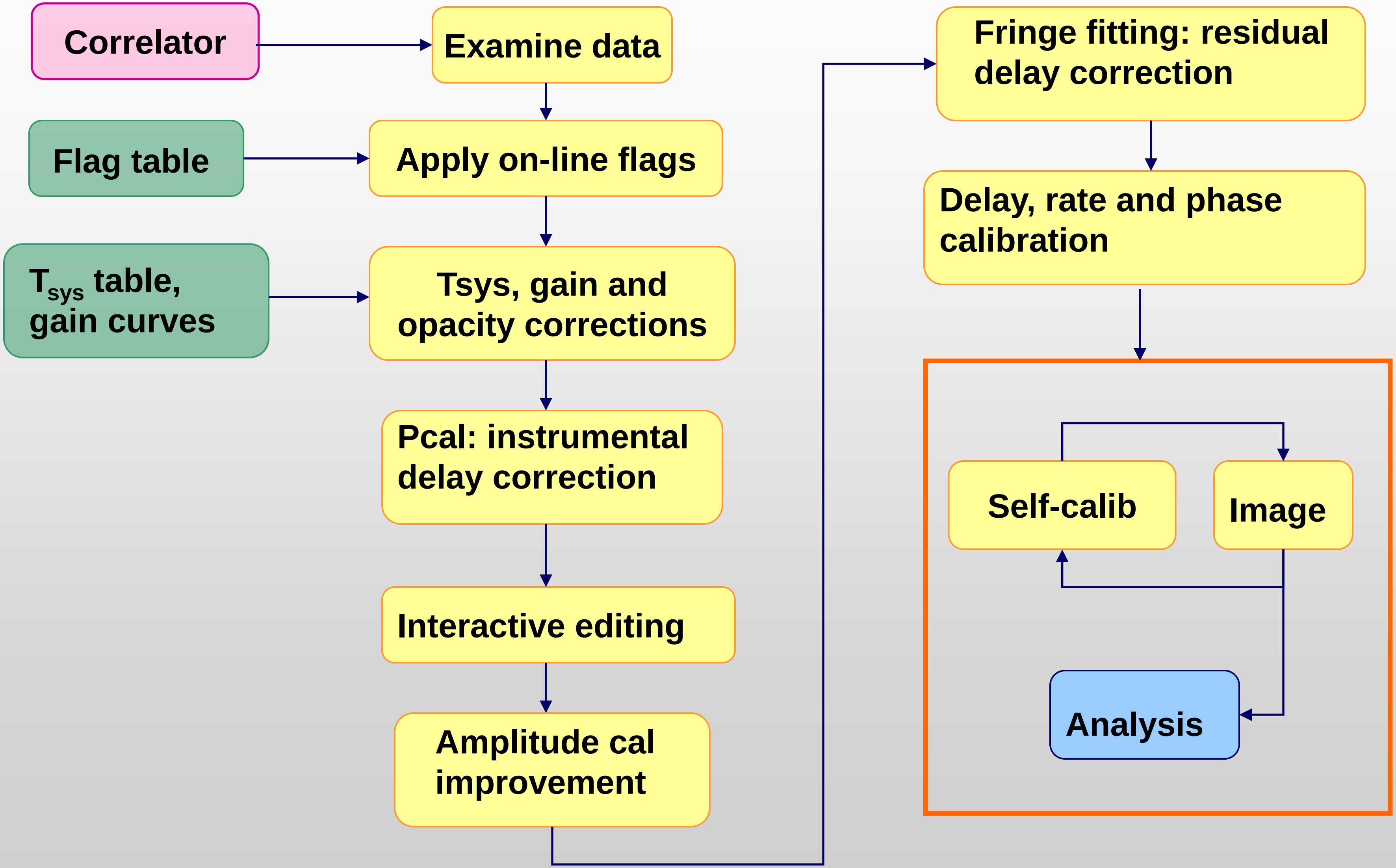

Before Calibration

Fringe fitting

Fringe fitting is the procedure used to determine the residual fringe rate and delay: it forms averages of the data in time and frequency with a range of trial fringe rates and delays, and determines which values maximise the signal

- **Usually a two step process**
  1. **2D FFT to get estimated rates and delays to reference antenna**
     - **Use these for start model for least squares**
     - **Can restrict window to avoid high sigma noise points**
  2. **Least squares fit to phases starting at FFT estimate**
- **Baseline fringe fit**
  - **Fit each baseline independently**
  - **Must detect source on all baselines**
  - **Used for geodesy.**
- **Global fringe fit (like self-cal)**
  - **One phase, rate, and delay per antenna (with respect to a reference antenna)**
  - **Best SNR because all data used**
  - **Improved by good source model**
  - **Best for imaging and phase referencing**

VLBI data reduction path - continuum



Correlator

Flag table

T_{sys} table,
gain curves

Examine data

Apply on-line flags

Tsys, gain and
opacity corrections

Pcal: instrumental
delay correction

Interactive editing

Amplitude cal
improvement

Fringe fitting: residual
delay correction

Delay, rate and phase
calibration

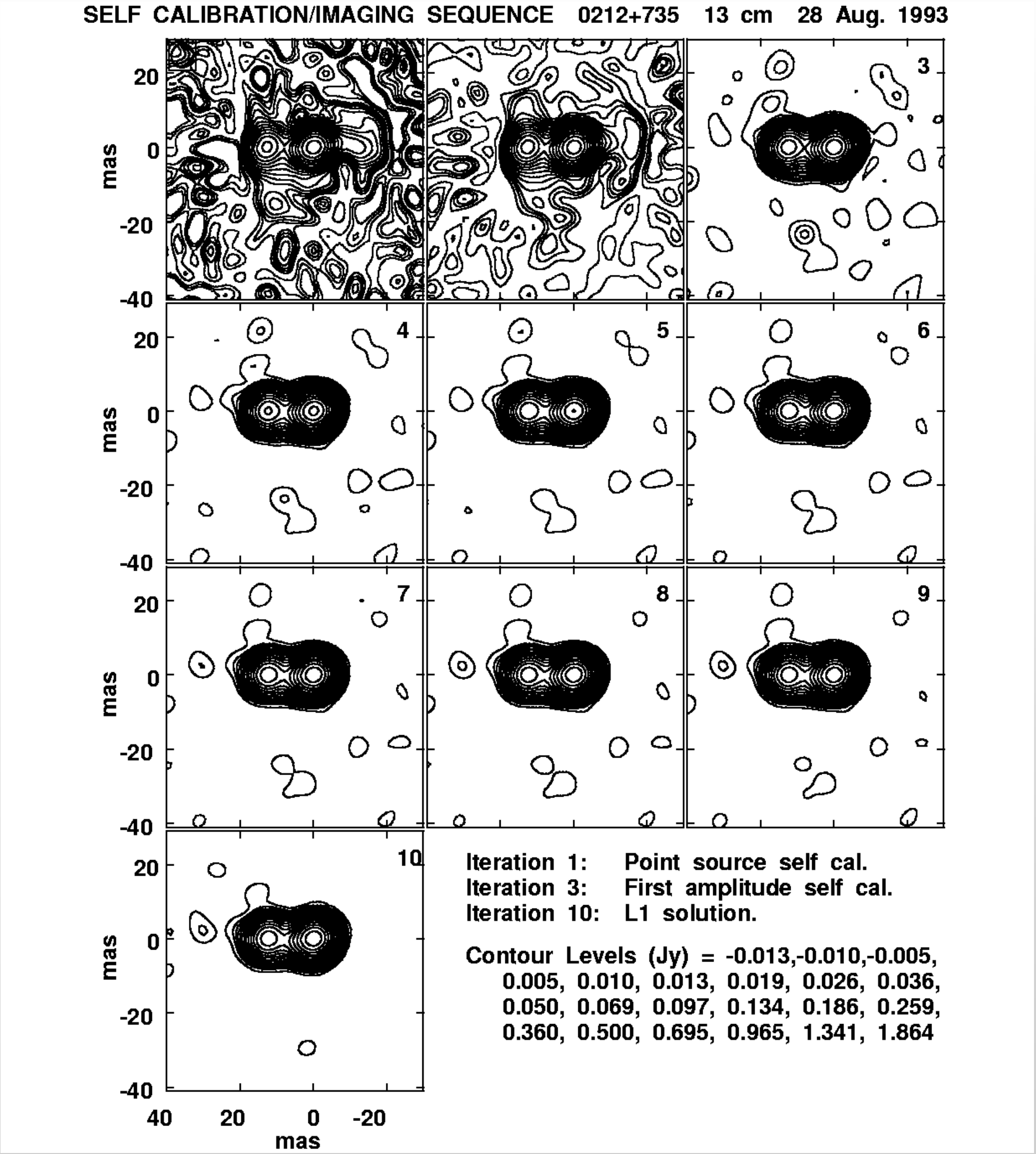
Self-calib

Image

Analysis

Self calibration & imaging sequence

  - – Iterative procedure to solve for both image and gains:
    - Use best available image to solve for gains (start with point)
    - Use gains to derive improved image
    - Should converge quickly for simple sources
- Does not preserve absolute position



SELF CALIBRATION/IMAGING SEQUENCE 0212+735 13 cm 28 Aug. 1993

Iteration 1: Point source self cal.
Iteration 3: First amplitude self cal.
Iteration 10: L1 solution.

Contour Levels (Jy) = -0.013,-0.010,-0.005, 0.005, 0.010, 0.013, 0.019, 0.026, 0.036, 0.050, 0.069, 0.097, 0.134, 0.186, 0.259, 0.360, 0.500, 0.695, 0.965, 1.341, 1.864

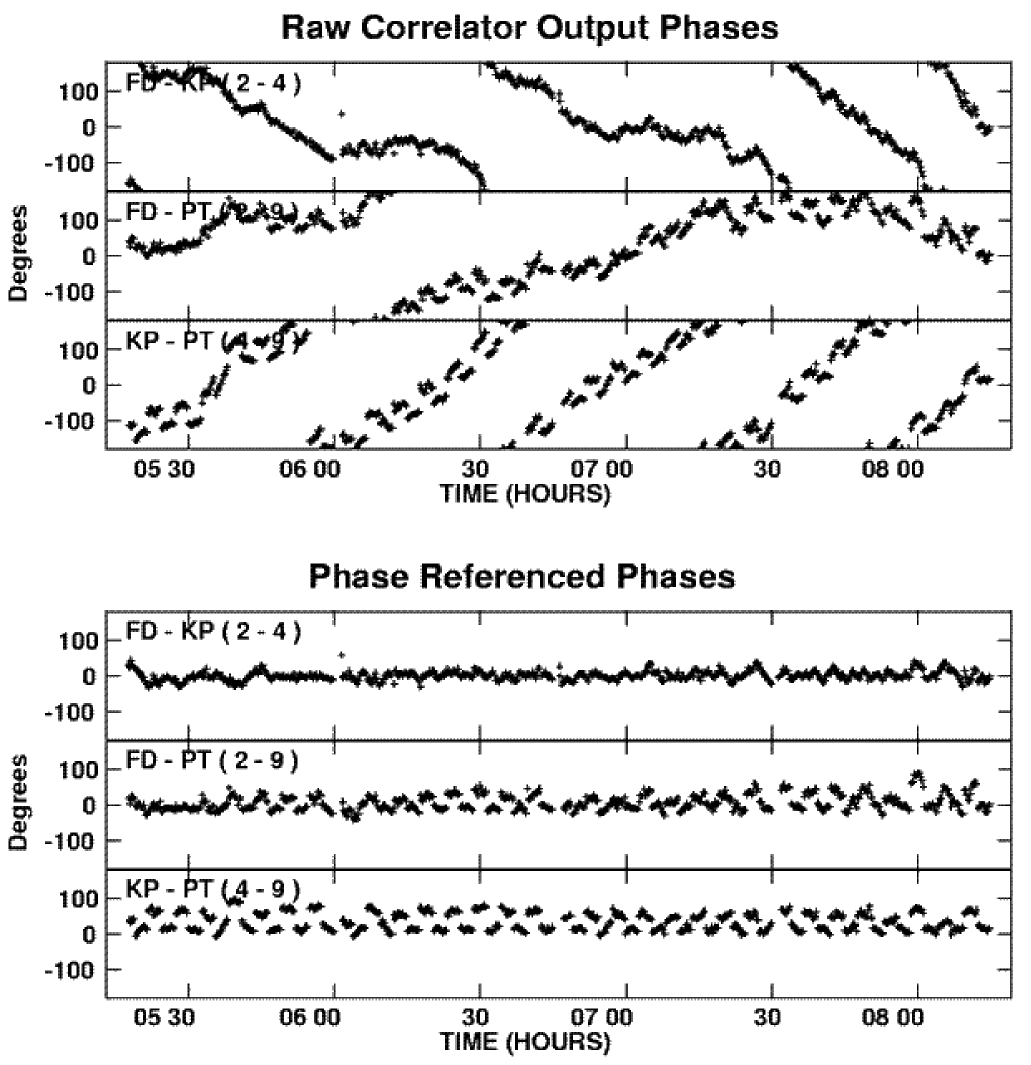
Faint sources - Phase referencing

- Calibration using phase calibrator outside target source field
  - Nodding calibrator (move antennas)
  - In-beam calibrator (separate correlation pass)
  - Multiple calibrators for most accurate results – get gradients

- Similar to phased array calibration except:
  - Geometric and atmospheric models worse
    - Model errors usually dominate over fluctuations
    - Errors scale with total error times source-target separation in radians
  - Need to calibrate often (5 minute or faster cycle)
  - Need calibrator close to target (< 5 deg)
  - Used by about 30-50% of VLBI observations

Example of referenced phases

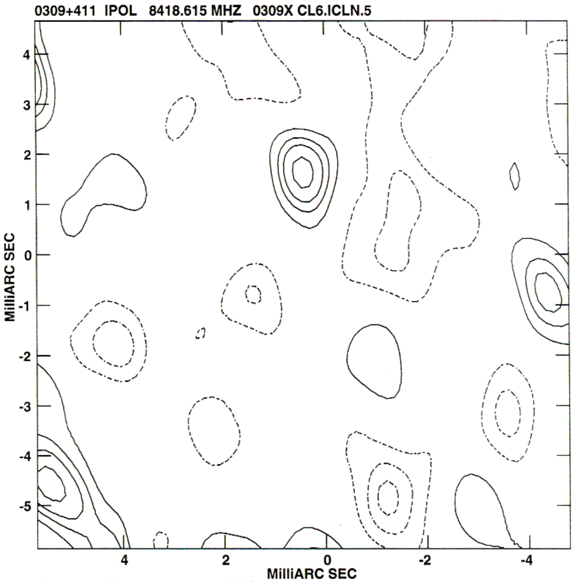
- **6 min cycle - 3 on each source**
- **Phases of one source self-calibrated (near zero)**
- **Other source shifted by same amount**



Phase referencing/self cal example

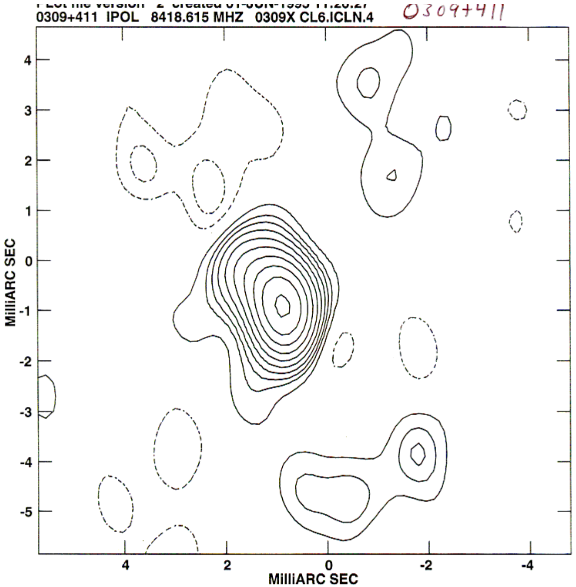
- No phase calibration: source not detected
- Phase referencing: detected, but distorted structure (target-calibrator separation probably large)
- Self-calibration on this source shows real structure

No Phase Calibration



Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 9.4978E-02 JY/BEAM
Levs = 1.0000E-02 * (-2.83, -2.00, -1.00,
1.000, 2.000, 2.828, 4.000, 5.657, 8.000,
11.31, 16.00, 22.63, 32.00, 45.25, 64.00,
90.51, 128.0, 181.0, 256.0, 362.0, 512.0,
724.1, 1024., 1448., 2048., 2896., 4096.,
5793., 8192.,11585.)

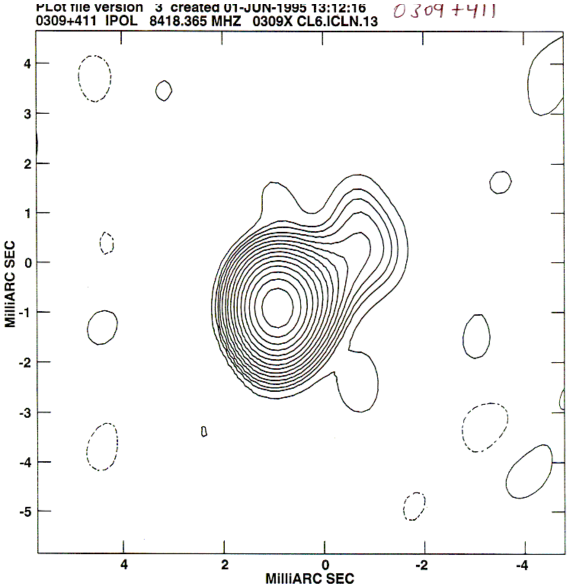
Reference Calibration



Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.4321E-01 JY/BEAM
Levs = 1.0000E-02 * (-2.83, -2.00, -1.00,
1.000, 2.000, 2.828, 4.000, 5.657, 8.000,
11.31, 16.00, 22.63, 32.00, 45.25, 64.00,
90.51, 128.0, 181.0, 256.0, 362.0, 512.0,
724.1, 1024., 1448., 2048., 2896., 4096.,
5793., 8192.,11585.)

VLBA
9 SCANS
12 MINUTES DATA

Self-calibration



Center at RA 03 13 1.96210 DEC 41 20 1.1840
Peak flux = 3.7156E-01 JY/BEAM
Levs = 2.0000E-03 * (-2.68, -1.93, -1.00,
1.000, 1.931, 2.683, 3.728, 5.179, 7.197,
10.00, 13.89, 19.31, 26.83, 37.28, 51.79,
71.97, 100.0, 138.9, 193.1, 268.3, 372.8,
517.9, 719.7, 1000., 1389., 1931., 2683.,
3728., 5179., 7197.)

Issues about scheduling

- PI provides the detailed observation sequence
- The schedule should include:
  - Fringe finders (strong sources - at least 2 scans – helps operations)
  - Amplitude check source (strong, compact source)
  - If target is weak, include a delay/rate calibrator
  - If target very weak, fast switch to a phase calibrator
  - For spectral line observations, include bandpass calibrator
  - For polarization observations, calibrate instrumental terms
    - Get good Parallactic angle coverage on polarized source or
    - Observe an unpolarized source
  - Absolute polarization position angle calibrator (Get angle from VLA)
- Leave occasional gaps for readback tests and Tsys measurements (2 min)
- Check the total data volume

… Just a few words on the European VLBI Network

Puerto Rico

China

South Africa

… Just a few words on the European VLBI Network

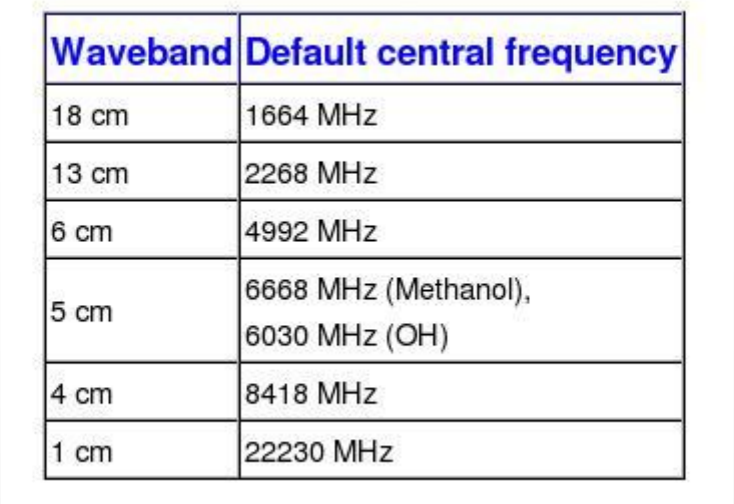
QUASAR Network: 3 x 32m dishes

Russia

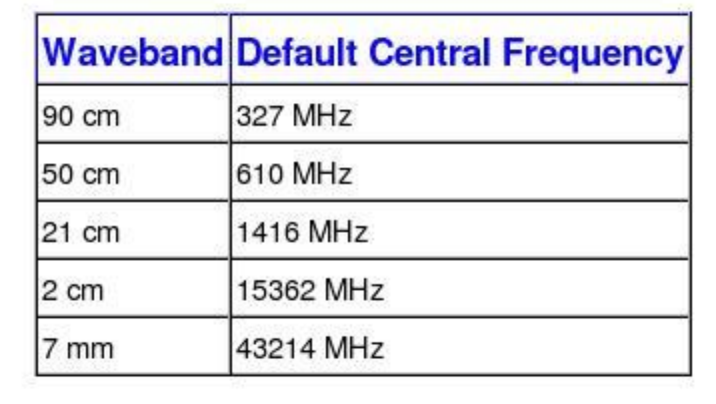
Puerto Rico

China

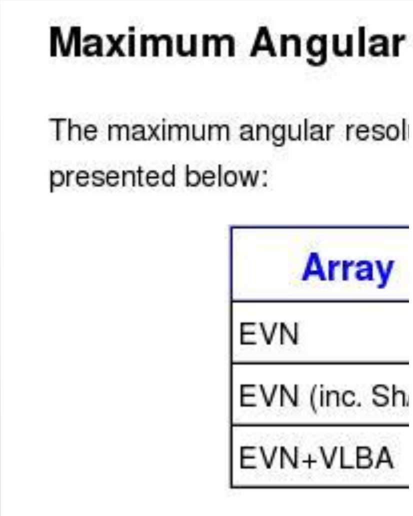
South Africa



Waveband	Default central frequency
18 cm	1664 MHz
13 cm	2268 MHz
6 cm	4992 MHz
5 cm	6668 MHz (Methanol), 6030 MHz (OH)
4 cm	8418 MHz
1 cm	22230 MHz



Waveband	Default Central Frequency
90 cm	327 MHz
50 cm	610 MHz
21 cm	1416 MHz
2 cm	15362 MHz
7 mm	43214 MHz

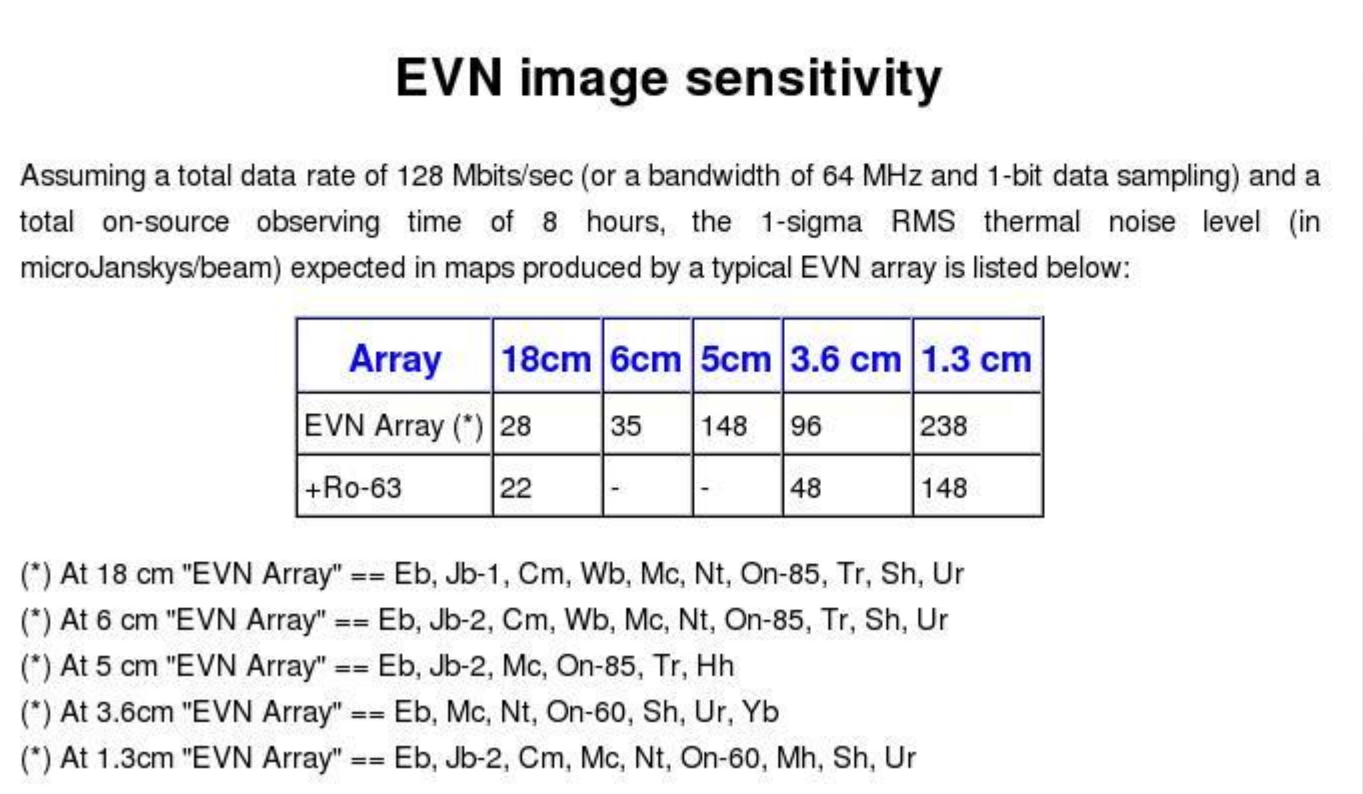


Maximum Angular Resolution

The maximum angular resol

presented below:

Array
EVN
EVN (inc. Sh
EVN+VLBA



EVN image sensitivity

Assuming a total data rate of 128 Mbits/sec (or a bandwidth of 64 MHz and 1-bit data sampling) and a total on-source observing time of 8 hours, the 1-sigma RMS thermal noise level (in microJanskys/beam) expected in maps produced by a typical EVN array is listed below:

Array	18cm	6cm	5cm	3.6 cm	1.3 cm
EVN Array (*)	28	35	148	96	238
+Ro-63	22	-	-	48	148

(*) At 18 cm "EVN Array" == Eb, Jb-1, Cm, Wb, Mc, Nt, On-85, Tr, Sh, Ur

(*) At 6 cm "EVN Array" == Eb, Jb-2, Cm, Wb, Mc, Nt, On-85, Tr, Sh, Ur

(*) At 5 cm "EVN Array" == Eb, Jb-2, Mc, On-85, Tr, Hh

(*) At 3.6cm "EVN Array" == Eb, Mc, Nt, On-60, Sh, Ur, Yb

(*) At 1.3cm "EVN Array" == Eb, Jb-2, Cm, Mc, Nt, On-60, Mh, Sh, Ur

Staff at JIVE is available for help/consultation at any stage:

Proposal writing

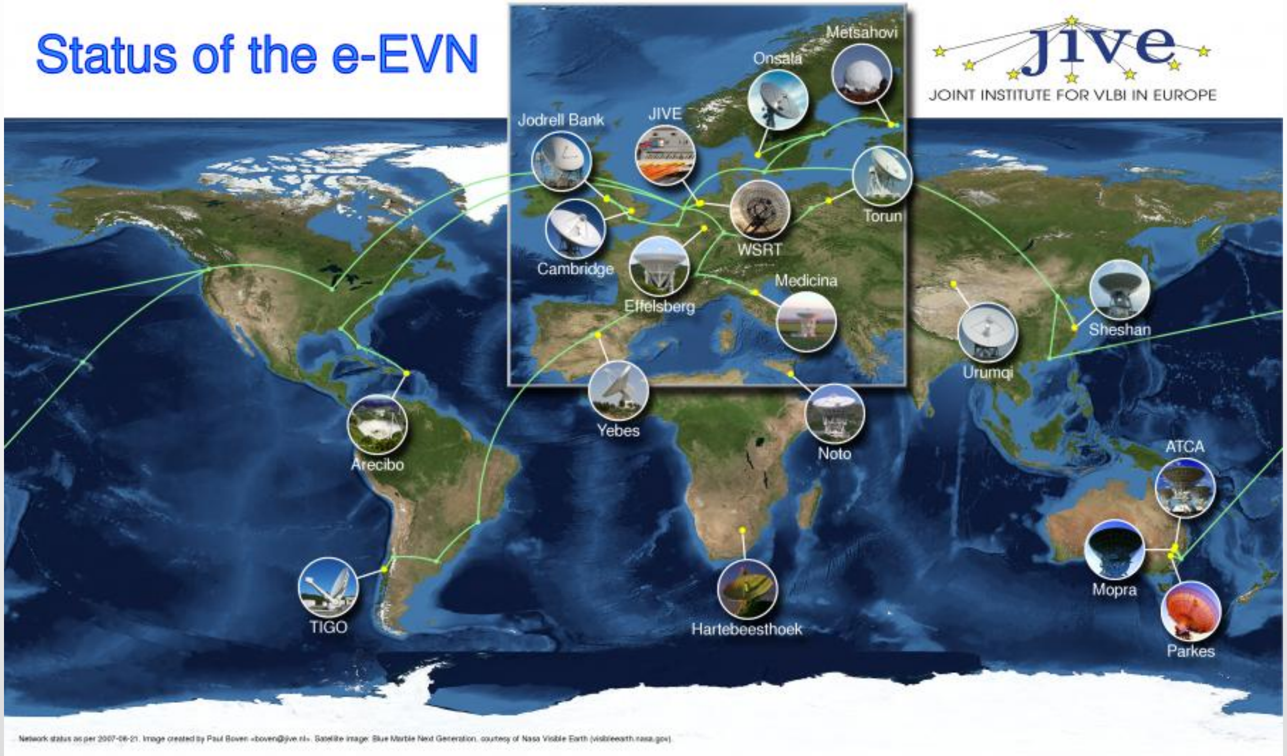
Preparation of observing file

Post processing

EU fundings available for (co)-PIs of observed proposals to visit JIVE during the data reduction and analysis

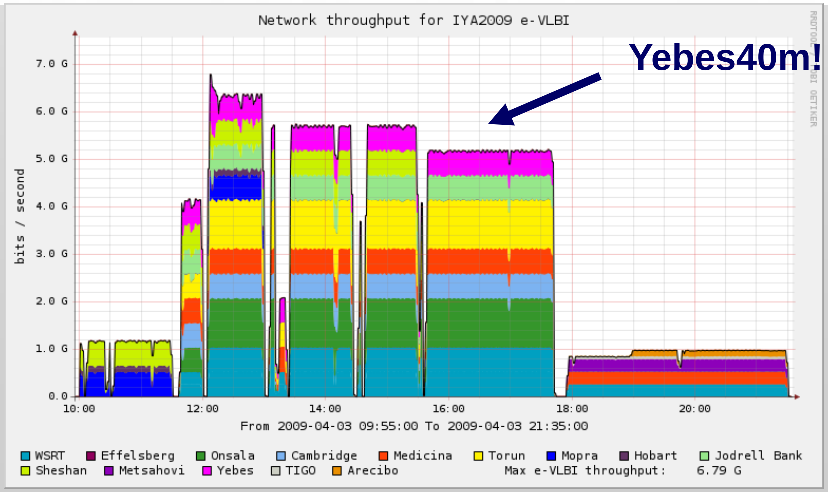
e-VLBI: Real Time VLBI

High-speed communication networks operating in real-time and connecting some of the largest and most sensitive radio telescopes on the planet



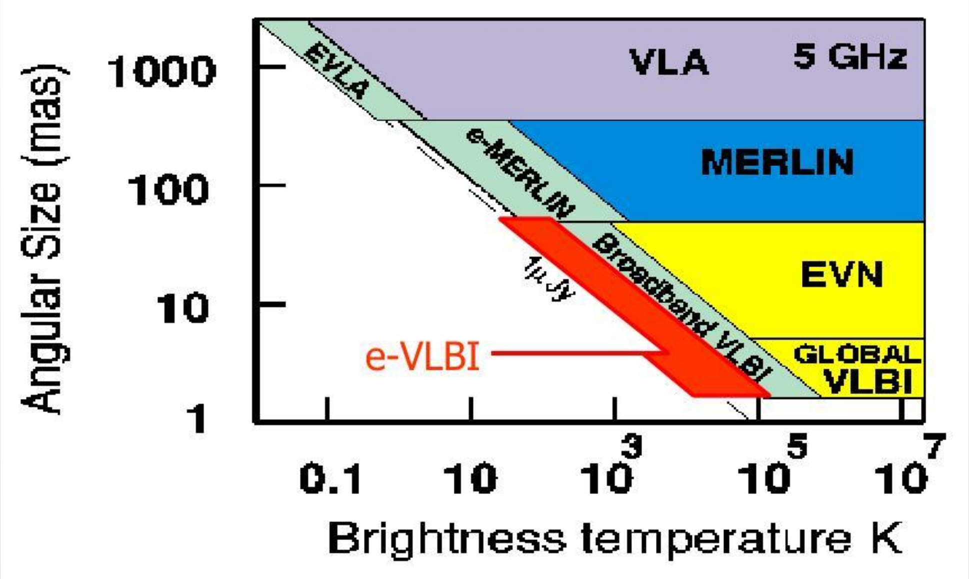
Network status as per 2007-08-21. Image created by Paul Boven <boven@jive.nl>. Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov)

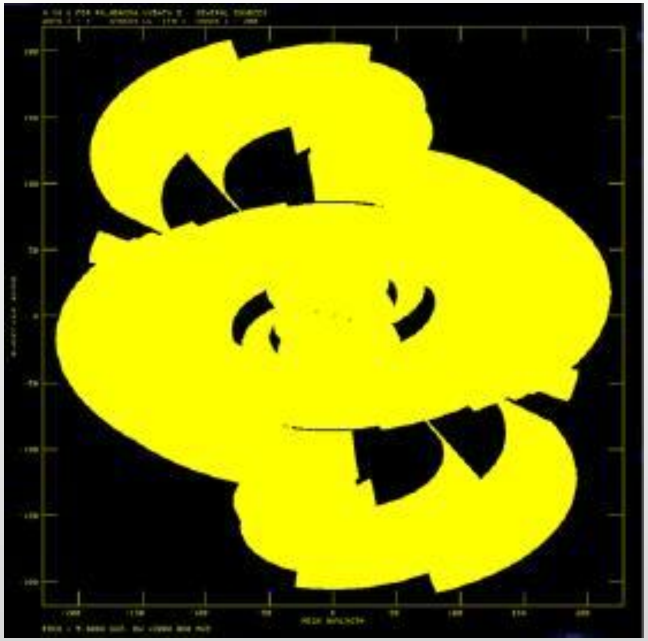
Gbps recording at most stations in the array and data transfer to the EVN correlator at JIVE



Data throughput during the IYA2009 demo

Major improvement in sensitivity & u-v coverage!





eVLBI considerations

- The e-EVN routinely operates with data transfer (from some telescopes) exceeding 1 Gbps [1000 Mbps] over thousands of kilometers, and is going towards multi-Gbps data rates that will be required for the SKA.

- There is a new community forming that will take advantage of a flexible, real-time VLBI instrument, pioneering scientific applications of a large resolution SKA. Before SKA, exciting opportunities to explore new areas jointly with e-Merlin, LOFAR, WSRT/Apertif.

- The EXPReS e-VLBI array has demonstrated the feasibility of operating a global real-time instrument over the Internet.

e-EVN vs “standard” VLBI today:

Comparable sensitivity and resolution to the EVN
…but…

Rapid response for rapid variability

- Fast response to requests
- Immediate analysis of data, flexible observing
- Coordination with current and future observatories

Immediate feedback

- Increased robustness

Fewer consumables, logistics

- Constantly available VLBI network
  - Monitoring: for example astrometry
  - Spacecraft tracking (landing of the Huygens probe on Titan)

Growth path for more bandwidth

- Increased sensitivity

Current e-EVN Table

Frequency Band	e-VLBI Array
1.4-1.6 GHz (18-21cm)	Ar,Cm,Ef,Jb,Mc,On85,Sh,Tr,Wb14
5 GHz (6 cm)	Ar,Cm,Ef,Jb,Mc,On85,Sh,Tr,Ys,Wb14
6 GHz (5cm)	Ar,Cm,Ef,Jb,Mc,On85,Tr,Ys,Wb14
22 GHz (1.3cm)	Cm,Ef,Jb,McMh,On60,Sh,Ys

1 e-VLBI run every month or so

Each run lasts 24 hours at one single frequency

Call for Proposals

Three deadlines each year: **Feb 1st, Jun 1st, Oct st**

Same deadlines apply for standard VLBI (EVN and Global), VLBA and e-EVN (although these might change soon to Feb 1st and Aug 1st for the NRAO, i.e., VLBA, EVLA, GBT)

Some useful links

http://www.evlbi.org

http://www.jive.nl

http://www.evlbi.org/evlbi/evlbi.htm

http://www.nrao.edu

http://www.ira.inaf.it/evn_doc/guidelines.html

Future Space VLBI Missions

There is in principle no limit to the application of Very Long Baseline Interferometry, and the Earth itself may not be large enough.

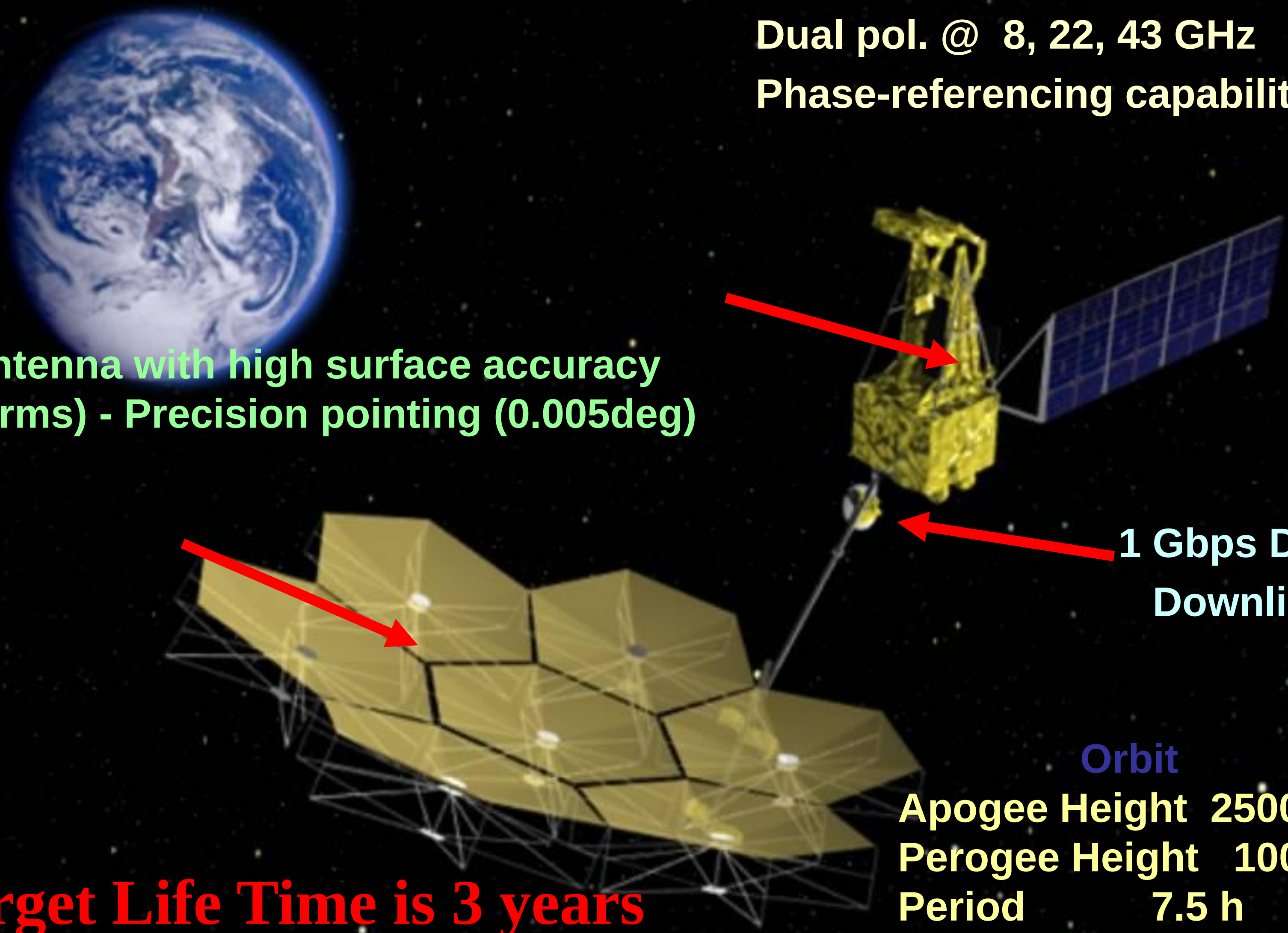
VSOP/Halca has been the first very successful Space VLBI mission, and started in 1997.

Two new missions are now in progress, and are expected to be completed in the near future:

VSOP-2/ASTRO-G (Japan)

RadioAstron Space Radio Telescope (Russia)

ASTRO-G Mission in 2015 ?



Dual pol. @ 8, 22, 43 GHz

Phase-referencing capability

9.3 m Antenna with high surface accuracy (0.4mm rms) - Precision pointing (0.005deg)

1 Gbps Data Downlink

Orbit

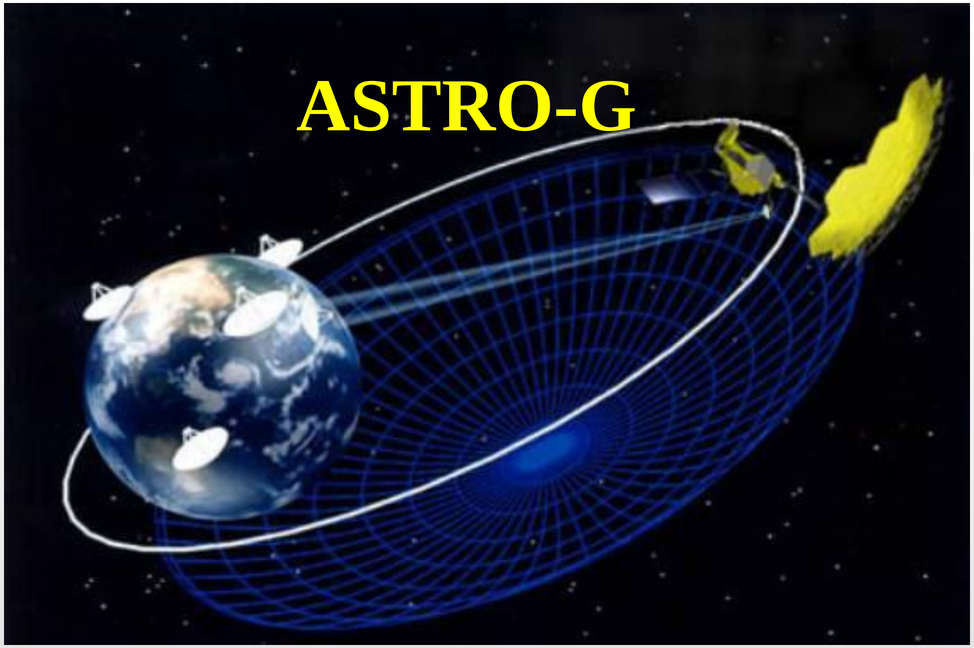
Apogee Height	25000 km
Perogee Height	1000 km
Period	7.5 h

Target Life Time is 3 years

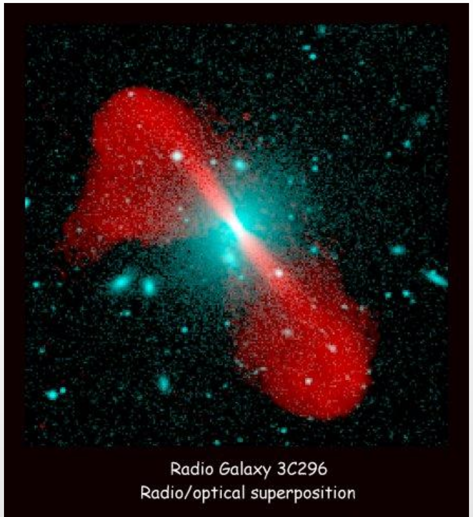
More at www.vsop.iasa.ac.jp/vsop2

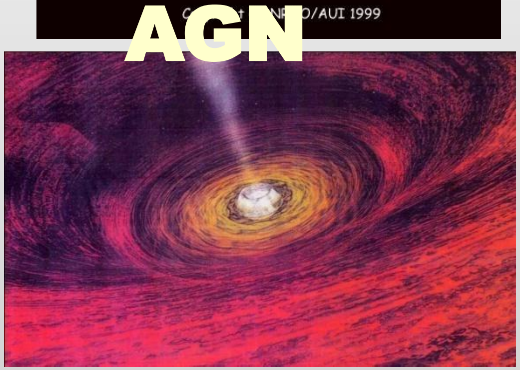
ASTRO-G project purpose

Generate VLBI Array with Ground Radio Telescopes.

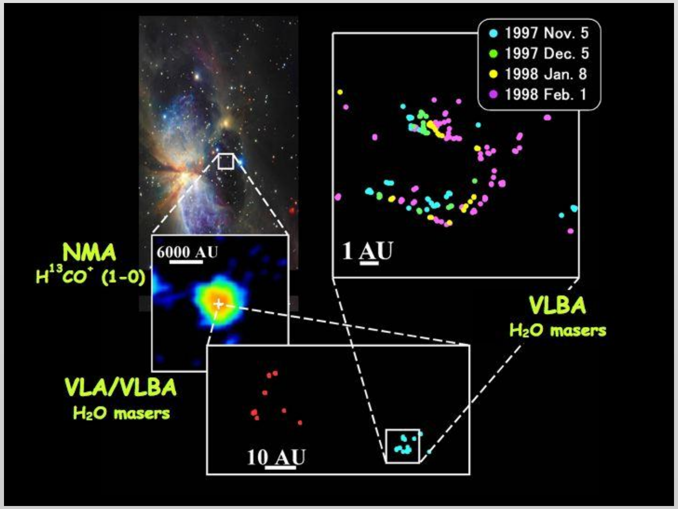


Imaging of Jets from the accretion disks

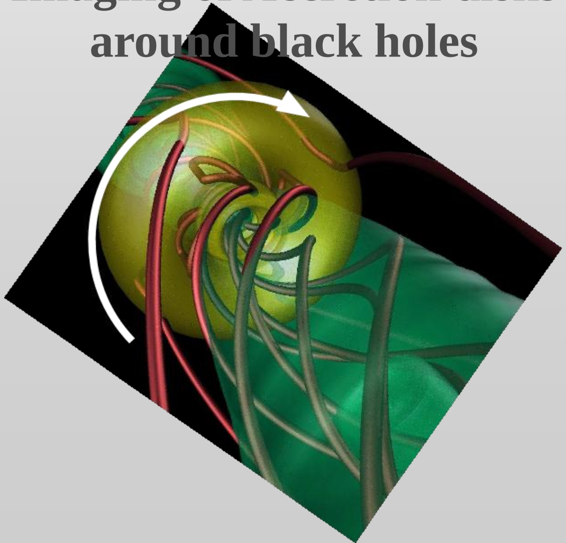

Radio Galaxy 3C296
Radio/optical superposition
[illegible] O/AUI 1999



Imaging of YSOs & Masers



Imaging of Accretion disks around black holes



Imaging of

Magnetic fields of Jets

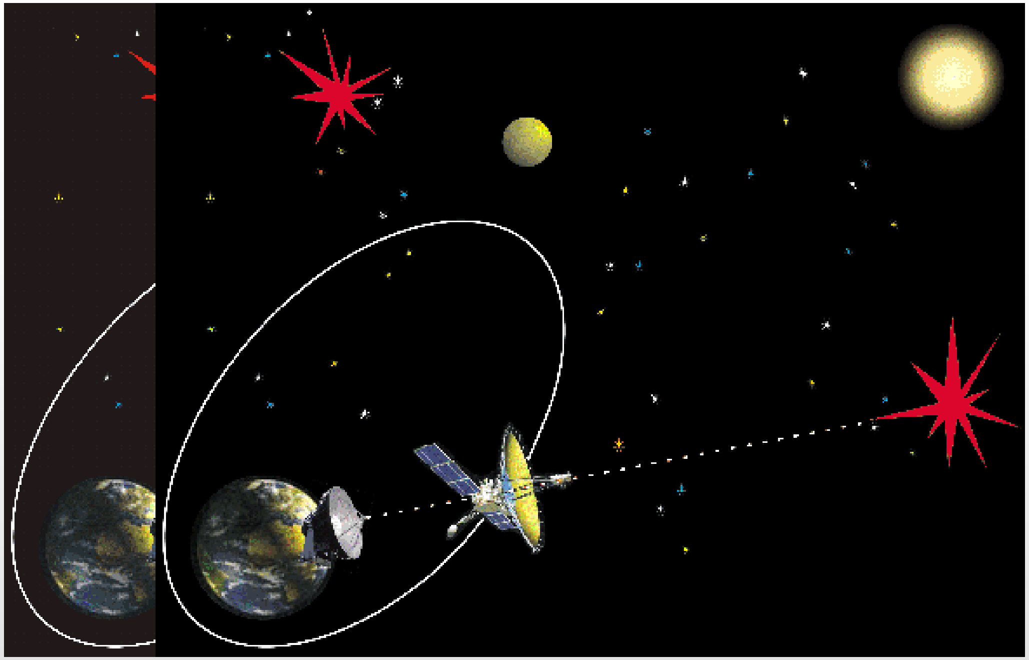
Space Radio Telescope

10 metre antenna

Perigee: 10-70 thousand km

Apogee: 310-390 thousand km

Mean period: 9.5 days



Band	P	L	C	K
Obs. Freq.	327 MHz	1665 MHz	4830 MHz	18-25 GHz
BandWidth	4	32	32	32
T_{sys}	70	50	50	60
Ant. Eff.	0.3	0.5	0.5	0.3
Sensitivity	8200	3500	3500	7000

More at : www.asc.rssi.ru/radioastron/news/news.html

… to conclude…

- VLBI is not fundamentally different from connected element interferometry
- A few additional issues to address when observing and reducing data
- VLBI provides very high angular resolution and position accuracy (ph. ref)
- It is a continuously evolving technique, where major steps in the achieved sensitivity have been recently done and more are in the queue

e-VLBI is now reality

Space VLBI missions to be completed in the near future will allow to reach μas resolution from 327 MHz to 43 GHz, thus expanding the scientific potentials of VLBI