Very Long Baseline Interferometry (VLBI) - Techniques and Applications

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ATNF Radio Astronomy School

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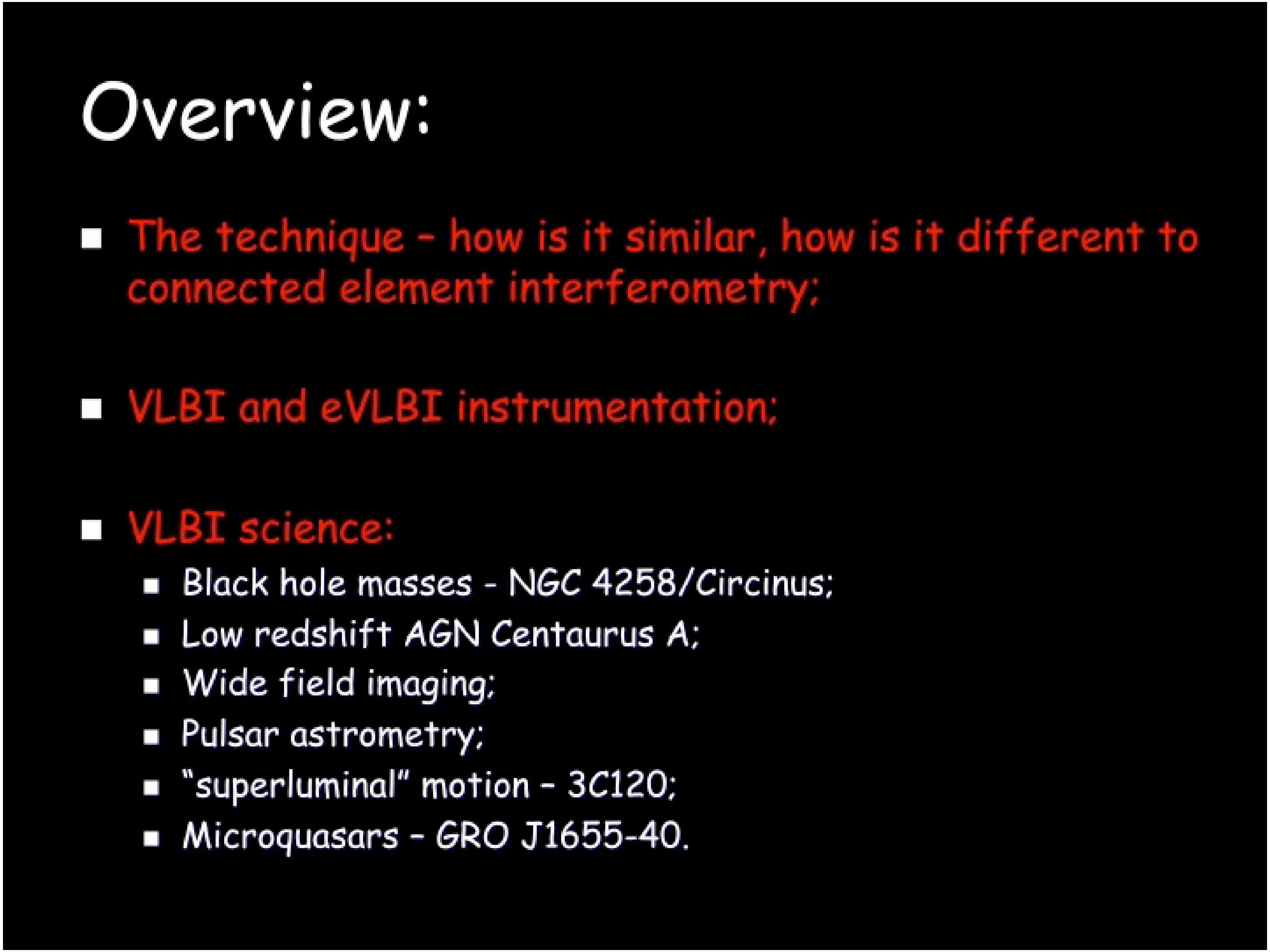
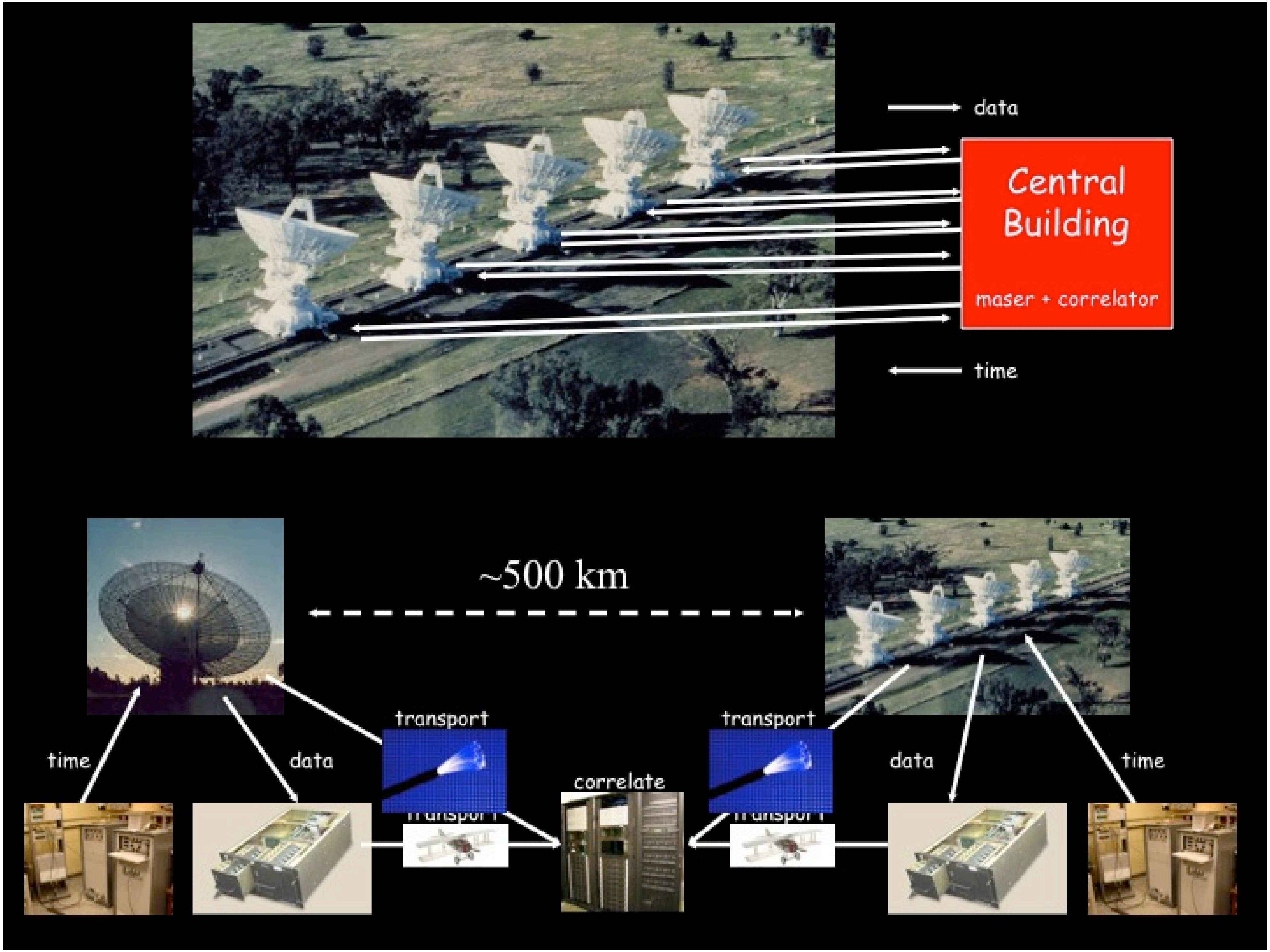

Overview:
The technique – how is it similar, how is it different to connected element interferometry;
VLBI and eVLBI instrumentation;
VLBI science:
Black hole masses - NGC 4258/Circinus;
Low redshift AGN Centaurus A;
Wide field imaging;
Pulsar astrometry;
"superluminal" motion – 3C120;
Microquasars – GRO J1655-40.

The Technique:

- Elements are not connected
  - Electronics are locked using station clocks;
  - Data are recorded on tape for post-observation processing
- Elements can therefore be placed, in principle, anywhere, including in space;
- Resolution between an Earth-based antenna and a space antenna in a 20,000 km orbit at 5 GHz is approximately 0.25 mas - Earth baseline, 15 GHz;
- VLBI is thus very sensitive to errors in the geometric model used by the correlator
  - Source and station positions (these change with time);
  - Vastly different weather conditions possible at each element



data
Central Building
maser + correlator
time
~500 km
transport
time
data
correlate
transport
data
time

Table 22–1. Terms of a VLBI Geometric Model [a]

Item	Approx max Magnitude [b]	Time scale
Zero order geometry.	6000 km	1 day
Nutation	$\sim 20''$	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration	$20''$	1 year
Retarded baseline	20 m	1 day
Gravitational delay	4 mas @ 90° from sun	1 year
Tectonic motion	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	$\sim$1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	$0.5''$	~ 1.2 years
UT1 (Earth rotation)	Random at several mas	Various
Ionosphere	~ 2 m at 2 GHz	seconds to years
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	seconds to seasonal
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

[a] Adapted from Sovers, Fanselow, & Jacobs 1998

[b] For an 8000 km baseline, 1 mas ↔ 3.9 cm. ↔ 130ps

The Technique (cont):

- A time-variable delay error in the geometry+timing model used by the correlator causes slopes of phase with frequency and time;
- Several schemes (some closely related to self-calibration) have been developed to determine these errors directly from the data;
- Modern (last ten years) correlators have access to geometric models that are good to a few cm at worst at all stations and GPS for long timescale time-keeping - the atmosphere becomes the limiting factor for determination of the astronomical phase - similar to connected element arrays like the ATCA.

VLBI Instrumentation:

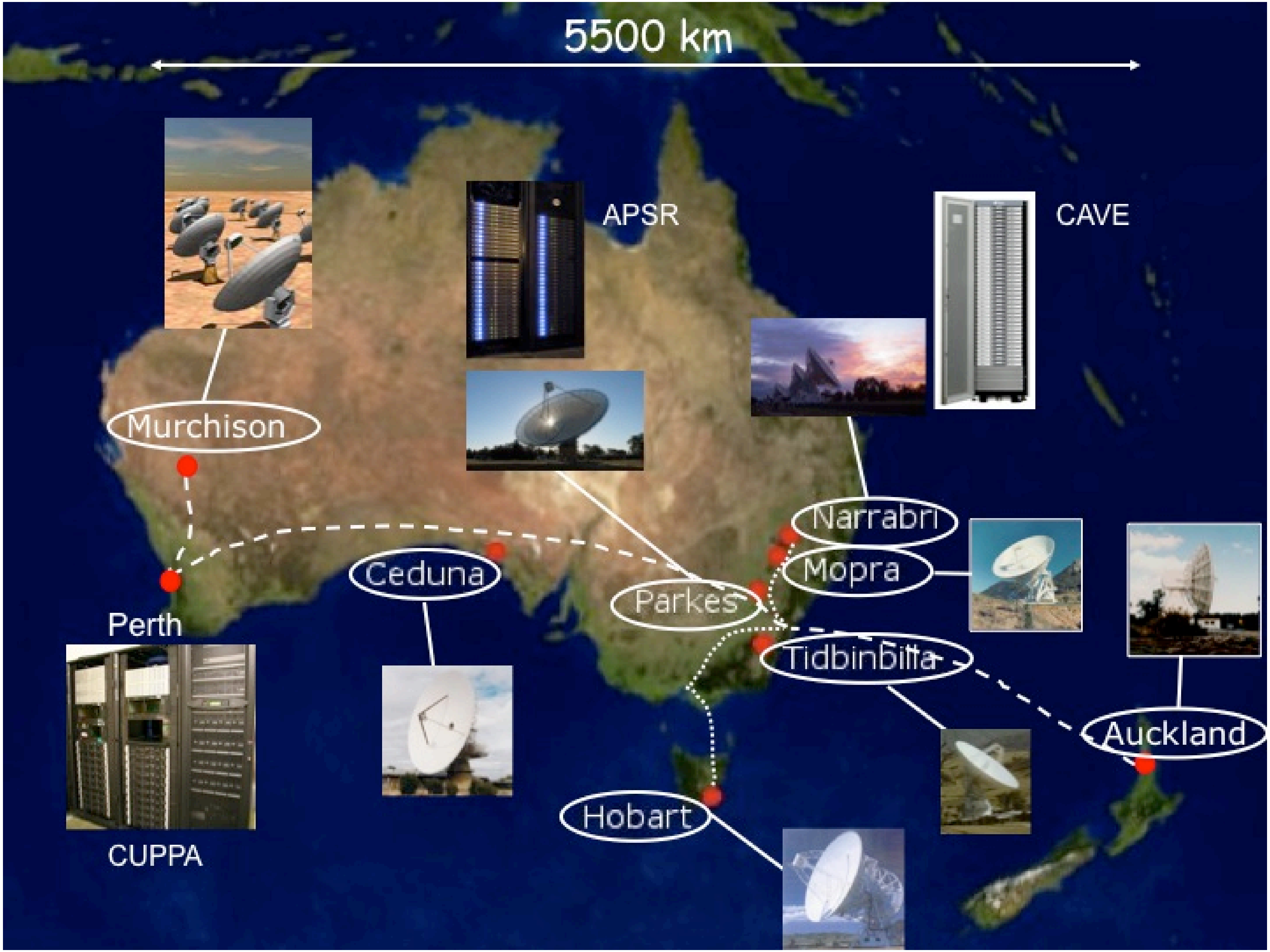
- Very Long Baseline Array (VLBA), a dedicated 10 station array within US territory, operated by NRAO;
- Correlator in Socorro, NM;
- Open proposal system;
- 10 x 25 m antennas;
- 8,600 km maximum baseline;
- 330 MHz to 43 GHz;

Instrumentation (Cont):

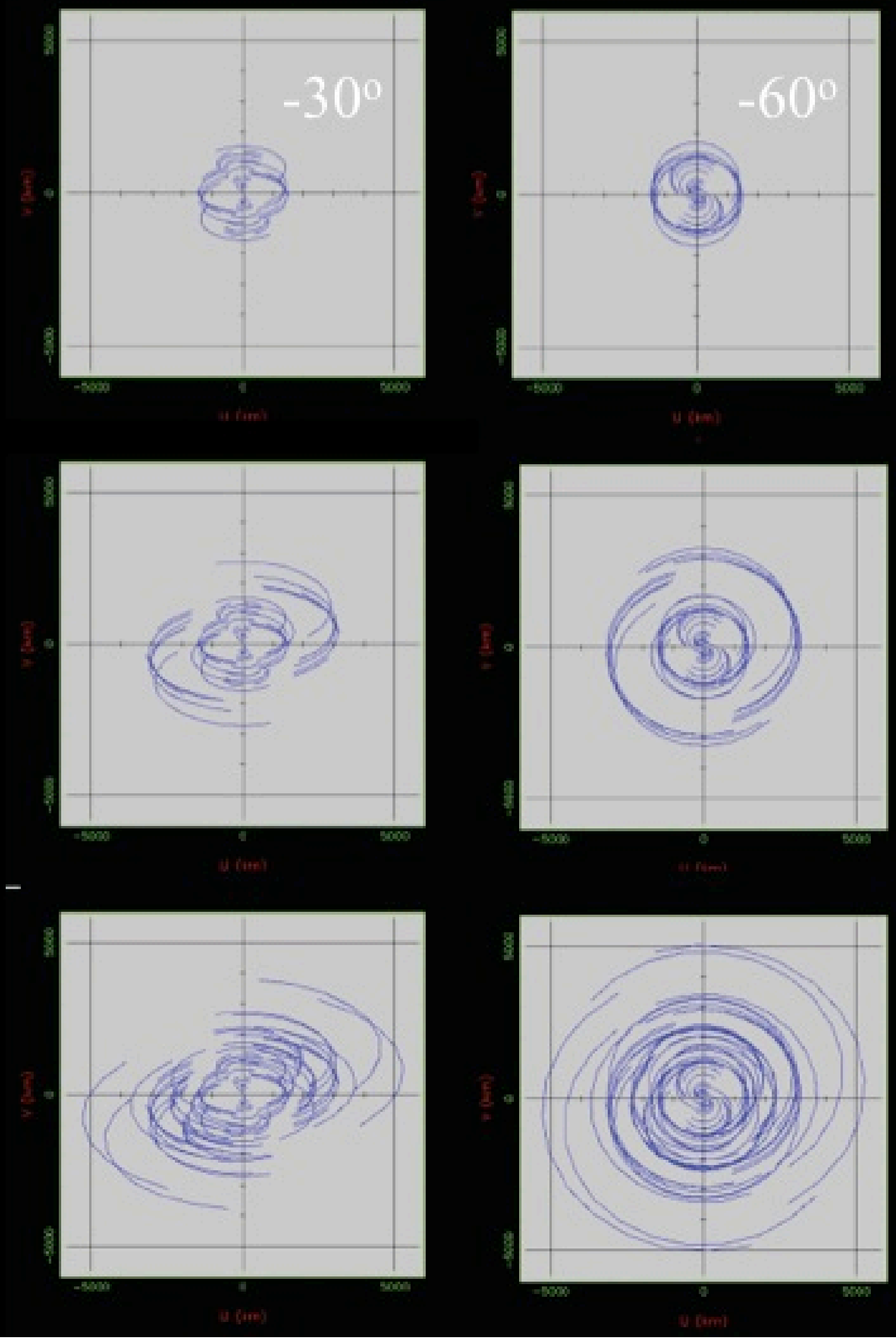
- European VLBI Network (EVN), a consortium of observatories and institutes in Eurasia – 18 stations;
- JIVE, VLBA, Bonn correlators;
- Open proposals;
- 9,169 km baseline;
- Various antennas;
- 3 week blocks 3 times per year;
- 330 MHz – 43 GHz.

Instrumentation (cont):

- Australian VLBI National Facility, 6 stations in Australia;
- Curtin University software correlator + eVLBI capability;
- Open proposals;
- 1,700 km baseline;
- 843 MHz – 22 GHz;
- ~3 weeks per year;



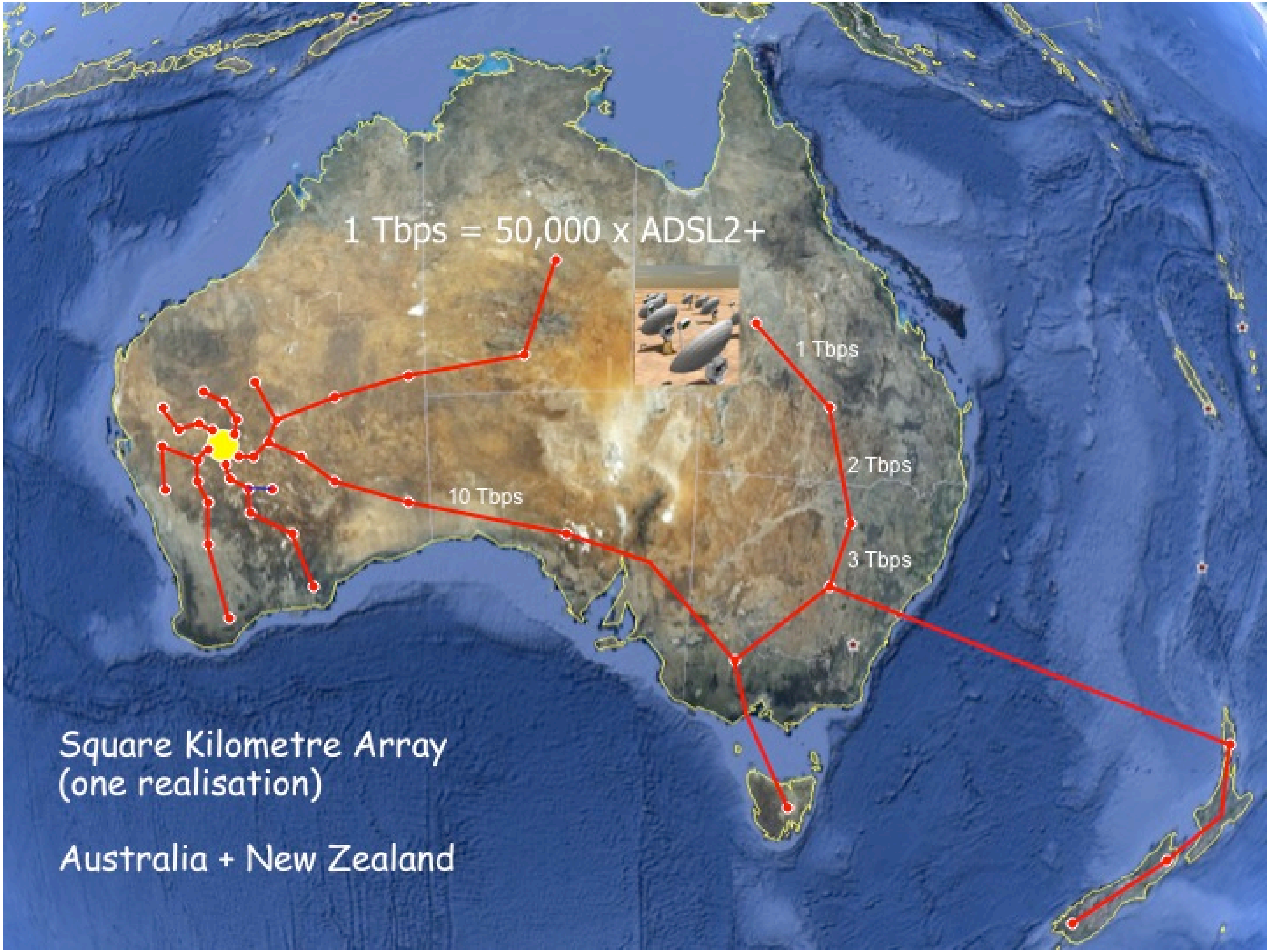
5500 km
APSR
CAVE
Murchison
Narrabri
Mopra
Ceduna
Parkes
Perth
Tidbinbilla
Auckland
Hobart
CUPPA



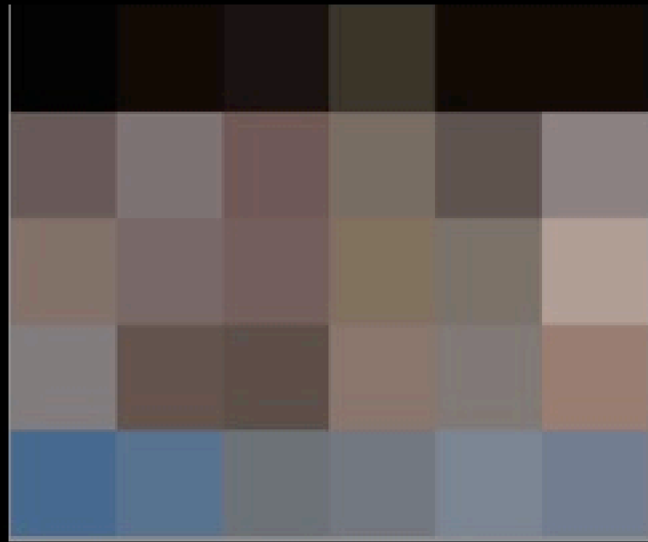
ATCA, Parkes, Ceduna, Tidbinbilla, Mopra, Hobart

+ ASKAP

+ New Zealand


1 Tbps = 50,000 x ADSL2+
1 Tbps
2 Tbps
10 Tbps
3 Tbps
Square Kilometre Array
(one realisation)
Australia + New Zealand

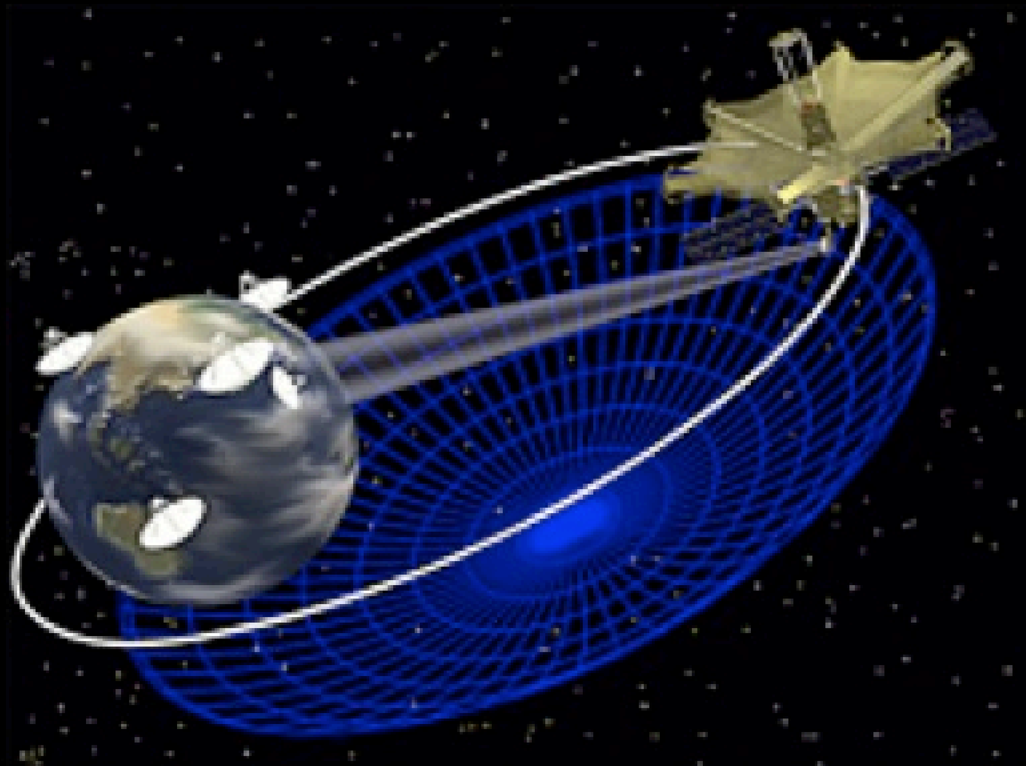
1 arcsec



10 mas

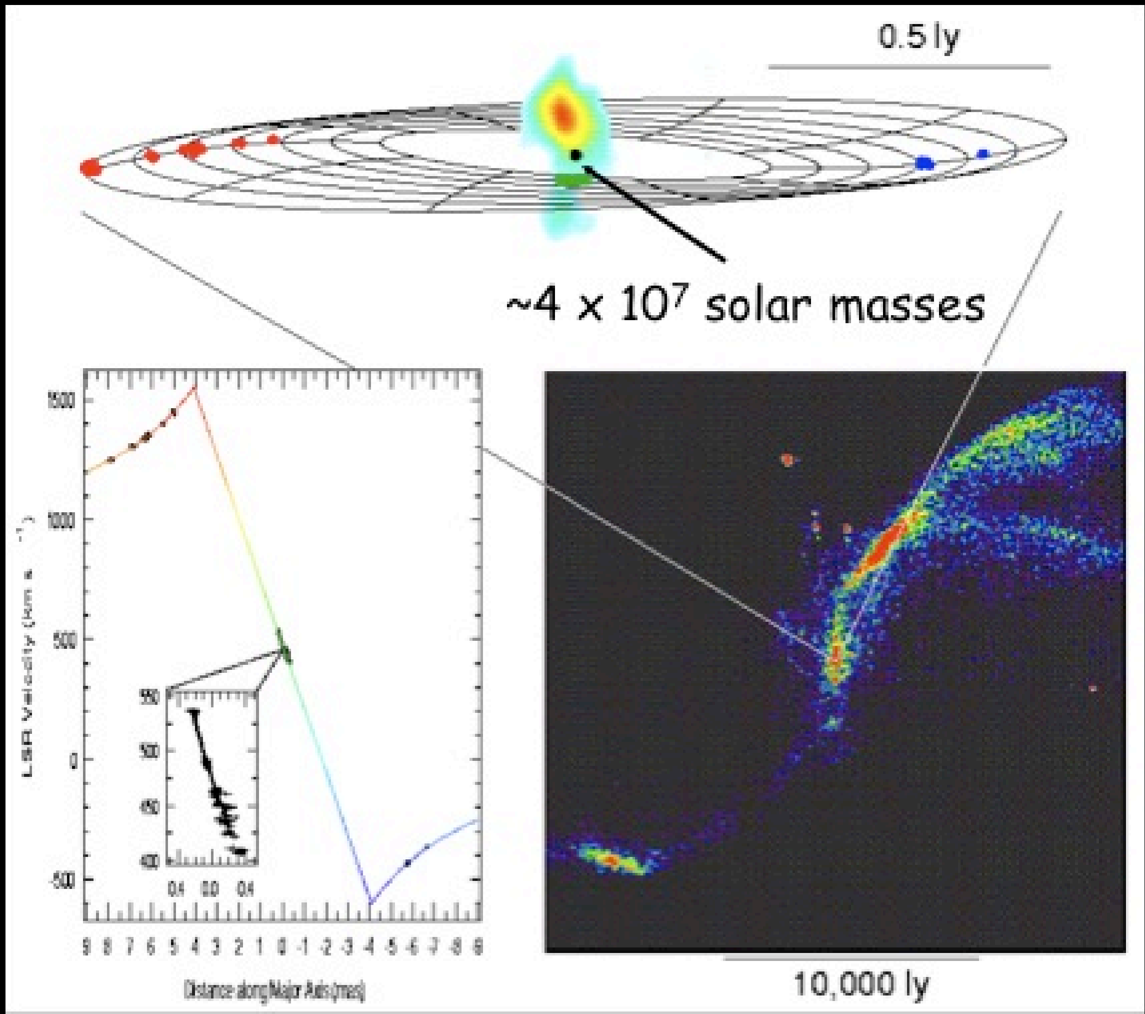
Instrumentation (cont):

- VLBI Space Observatory Programme (VSOP) - was operated between 1997 and 2003, supported by ground networks;

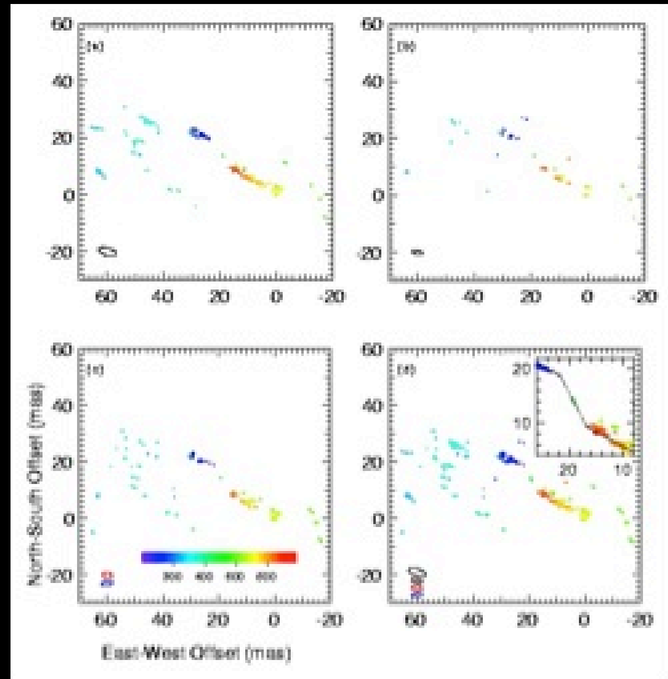


- ~20,000 km apogee;
- ~30,000 km baseline;
- 1.6 and 5 GHz;
- VSOP2.

Black Hole Masses – NGC 4258 and Circinus

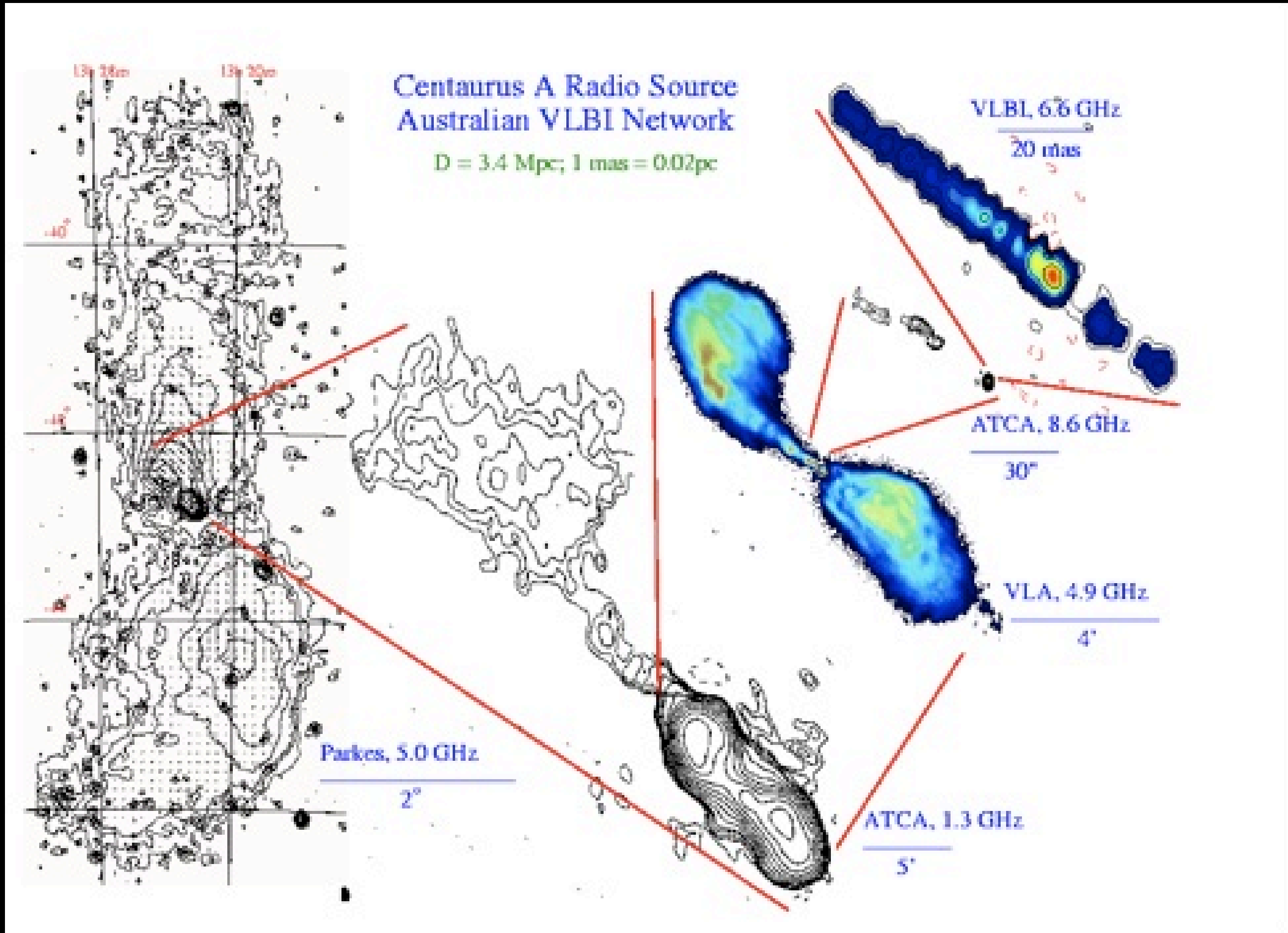


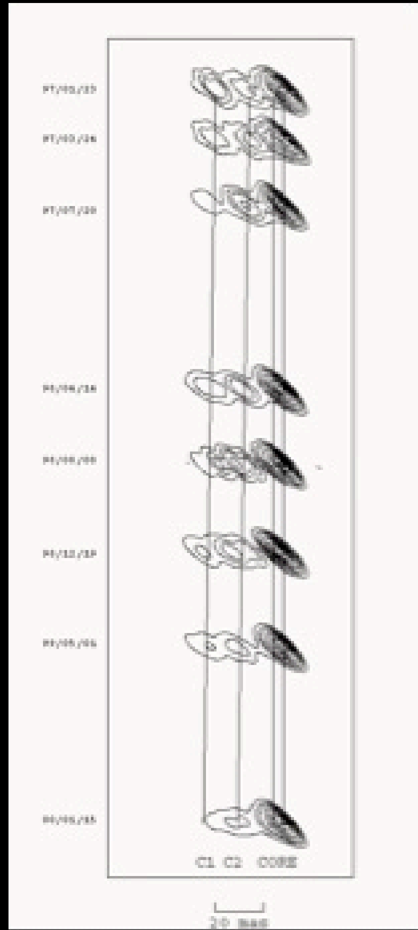
Greenhill et al. (2001)



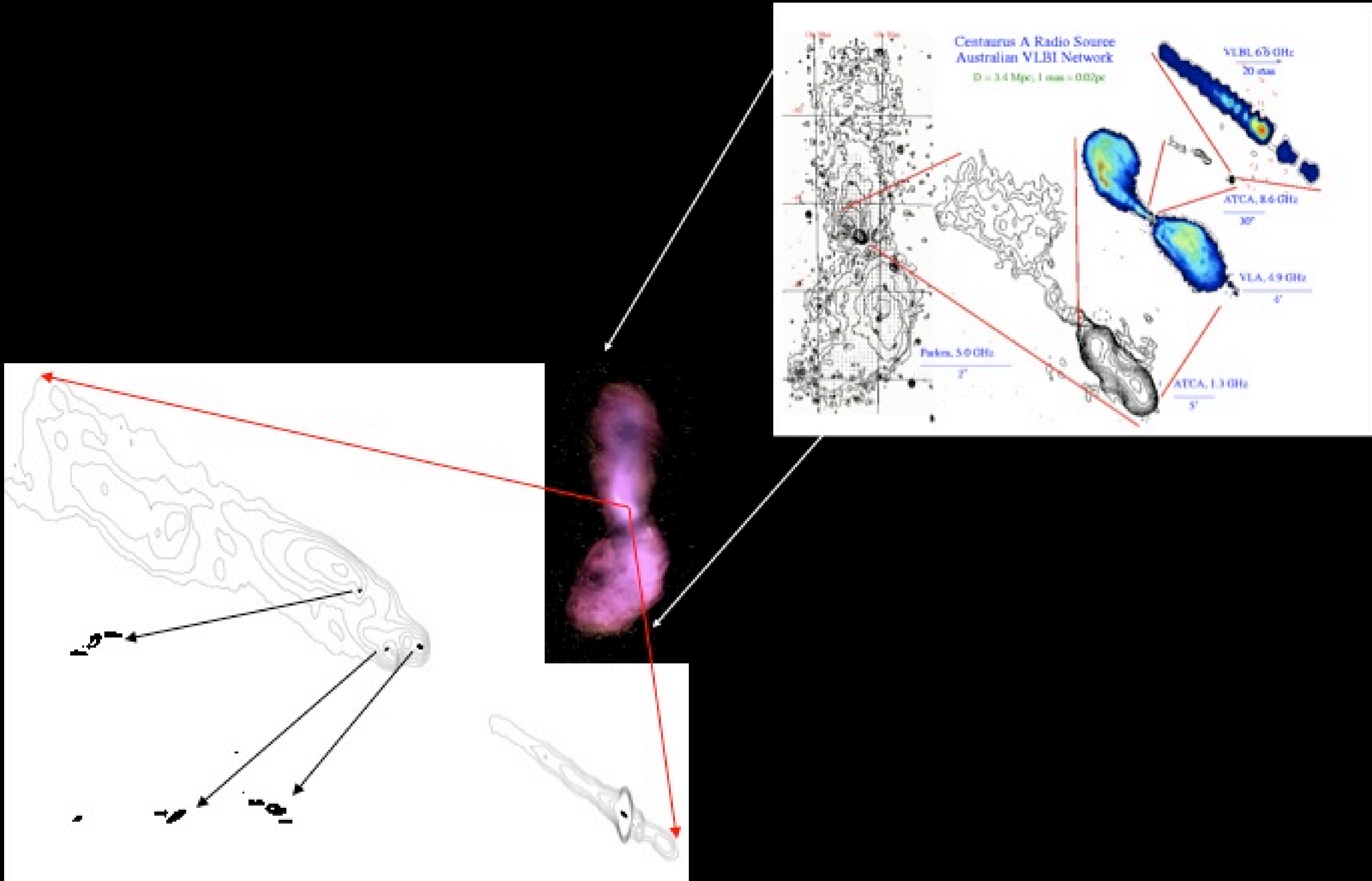
Miyoshi et al. (1995)
Herrnstein et al. (1997)

Low redshift Active Galactic Nucleus Centaurus A





Tingay, Preston, and Jauncey (2001)

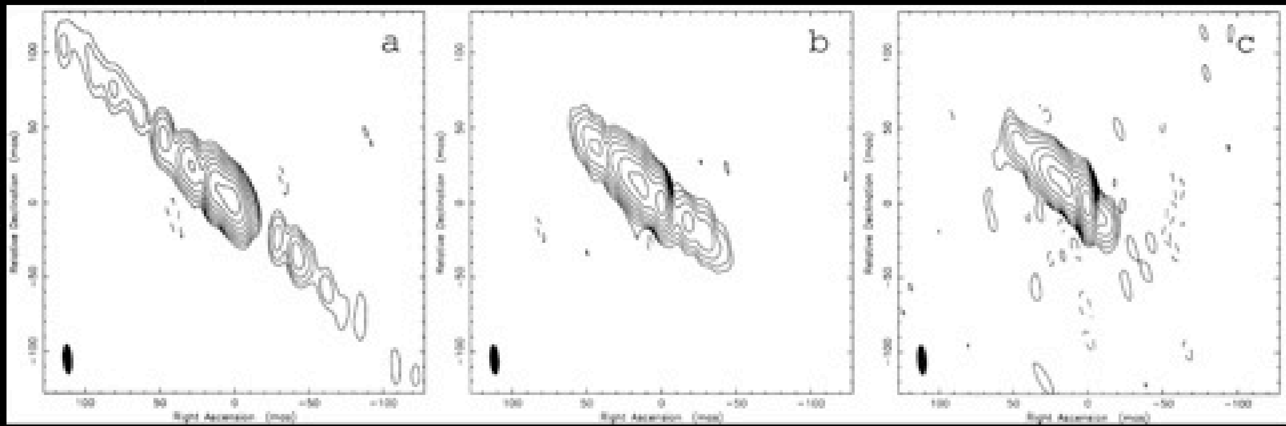


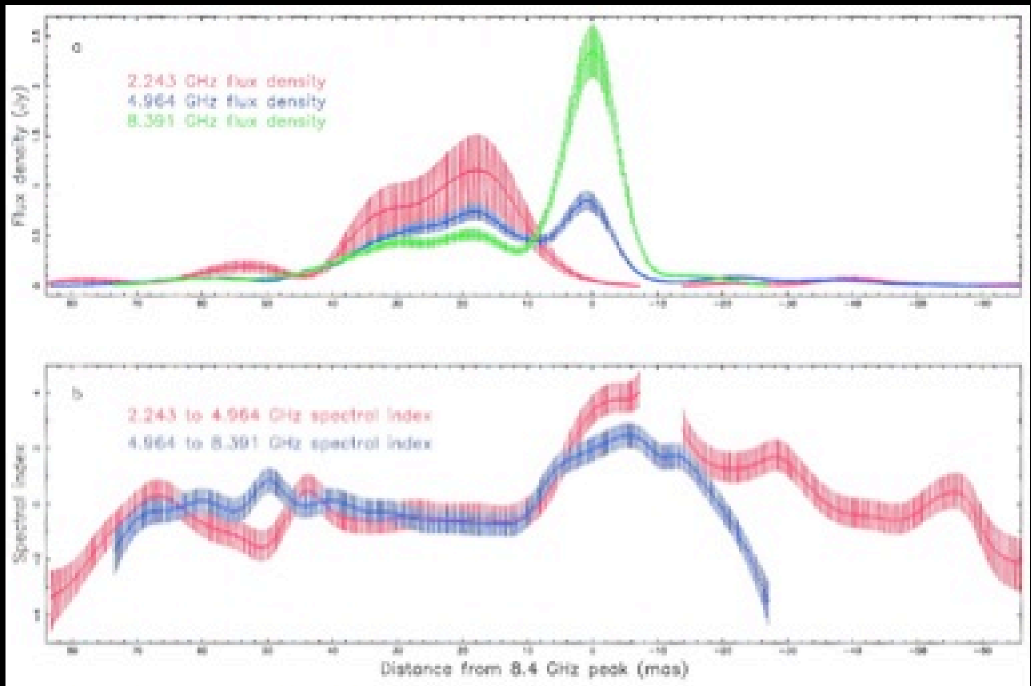
Stars caught in the powerful jet, cause massive disruption.

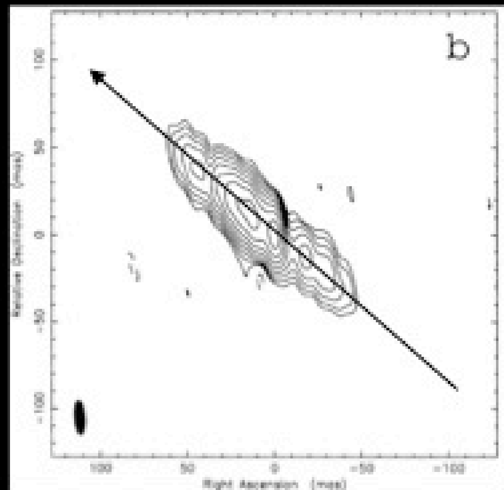
Massive black hole lives here, generates powerful jet

Multi-frequency, simultaneous VLBA observations at:

2.3 GHz　　4.8 GHz　　8.4 GHz







4.8 GHz

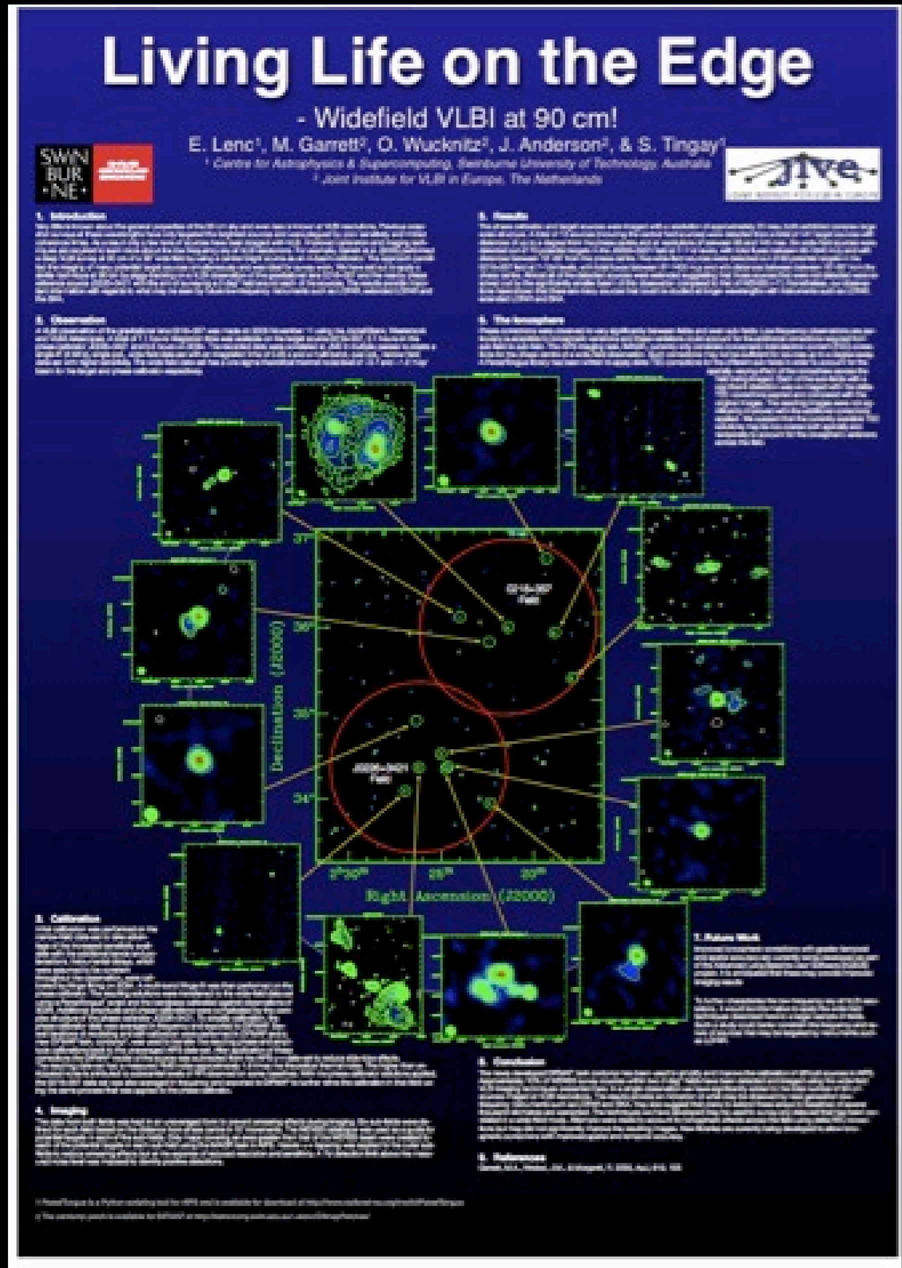
Tingay & Murphy (2001)

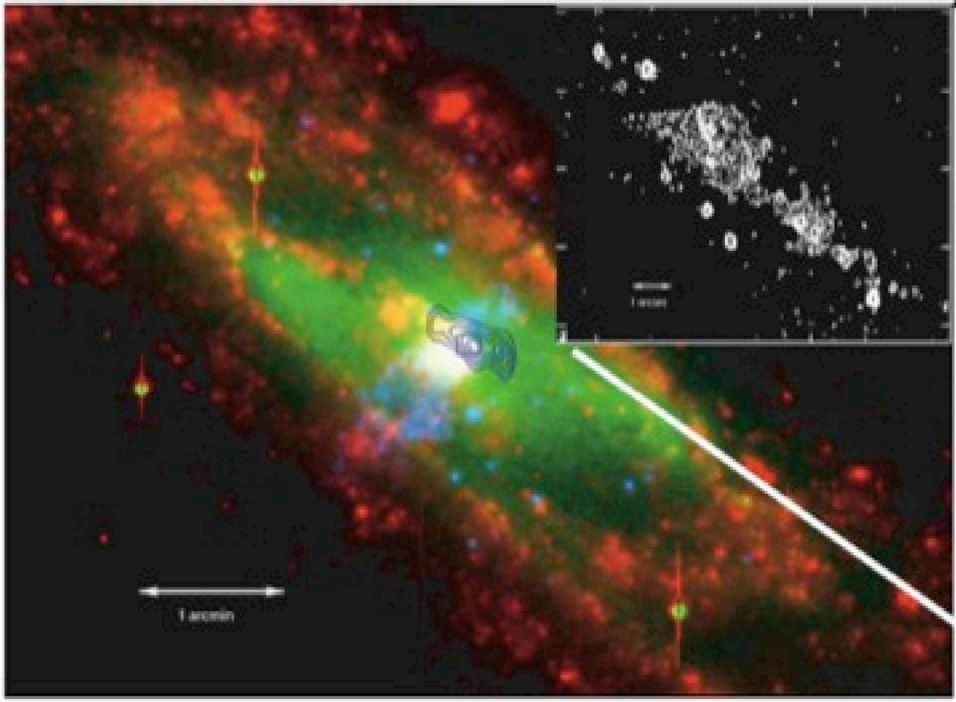
Widefield imaging - surveys of AGN and starburst galaxies

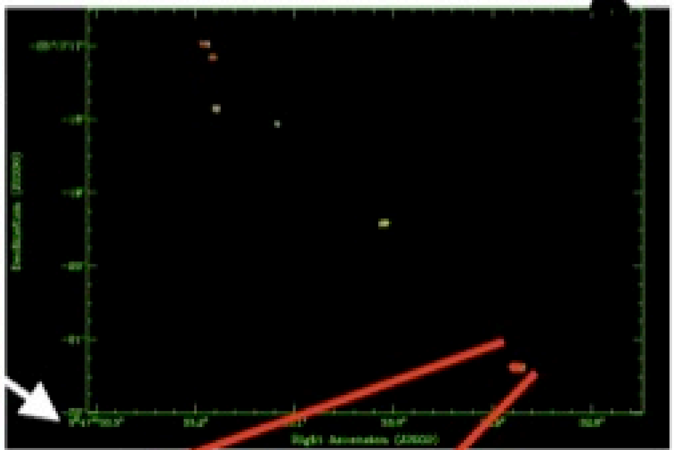
Separating starburst galaxies and AGN.

Pathfinder observations, science and data processing techniques for the SKA.

- 327 MHz VLBA observations
- 2 x 28 sq. deg. Fields
- 620 objects surveyed
- 27 detected
- Including one transient



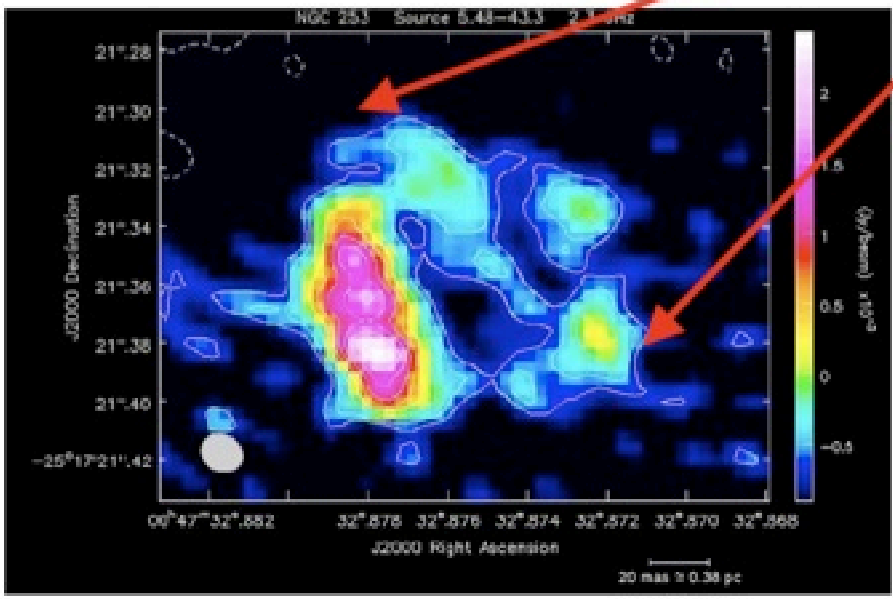




Lenc & Tingay (2006)

NGC 253

~4 Mpc distant

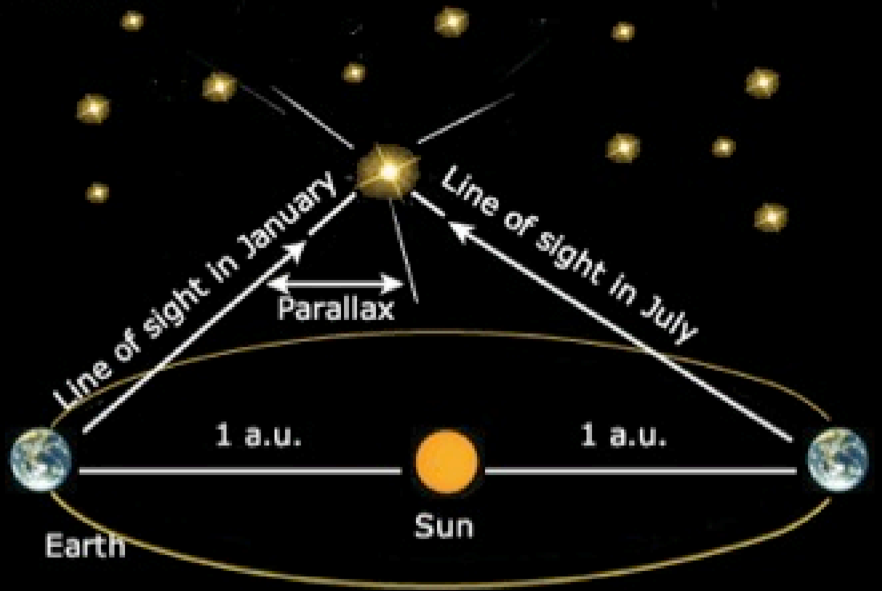


Pulsar astrometry

Distance determination in astronomy is hard, but vitally important.

- Linear sizes scale as distance
- Areas scale as distance squared
- Volumes scale as distance cubed

The most direct method of distance determination is via measurement of the parallax:



If an object is close enough, and/or your observational techniques have high enough angular resolution, you can measure the parallax.

Defines the parsec:

An object at 1 pc has a parallax of 1″

⇒ An object at 1 kpc has a parallax of 1 milliarcsecond

VLBI can be used to measure parallax for objects < ~1 kpc and therefore determine accurate distances to them.

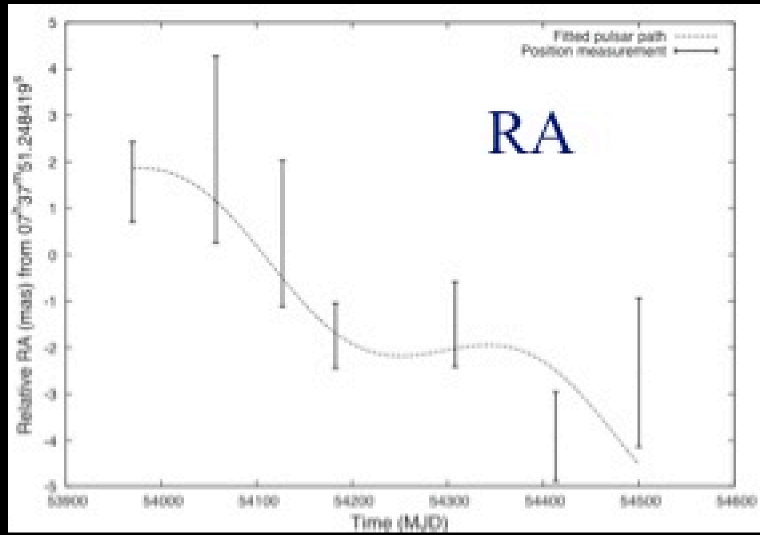
Double pulsar (mentioned by Dick Manchester) discovered at Parkes.

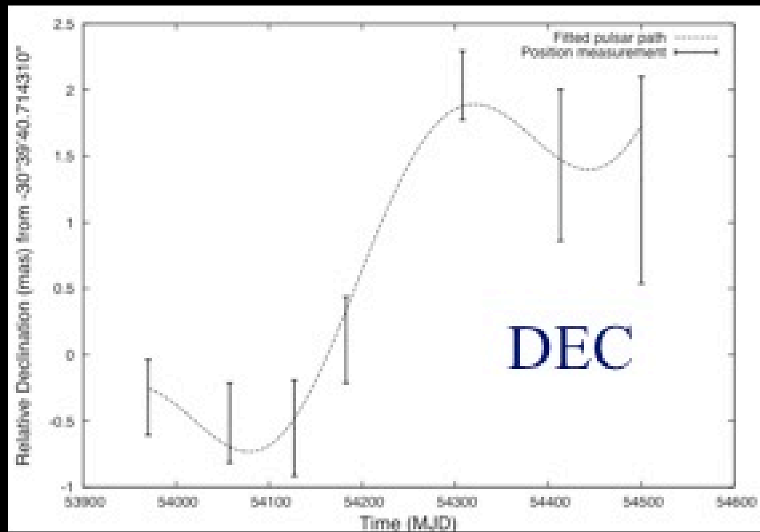
Can use to test theories of gravity in the strong field regime I.e. gravitational radiation emission from the system.

But only if you know the distance:

1150 +/- 190 pc

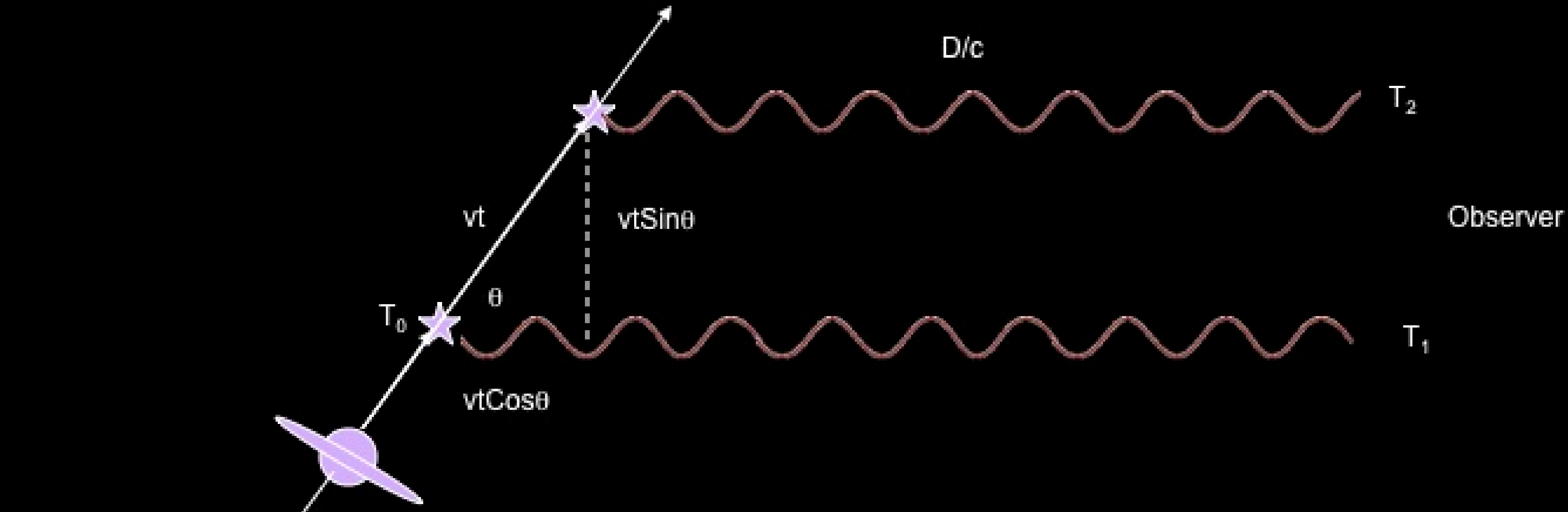
Distance plus a decade of pulsar timing can test gravitational radiation theories at 0.01% level.





Deller, Bailes & Tingay (2009)

Apparent superluminal motion



Time of arrival of photon 1: $T_1 = T_0 + (D + vt\mathrm{Cos}\theta)/c$

Time of arrival of photon 2: $T_2 = T_0 + t + D/c$

Difference in time of arrival: $T_2 - T_1 = t - vt\mathrm{Cos}\theta/c$

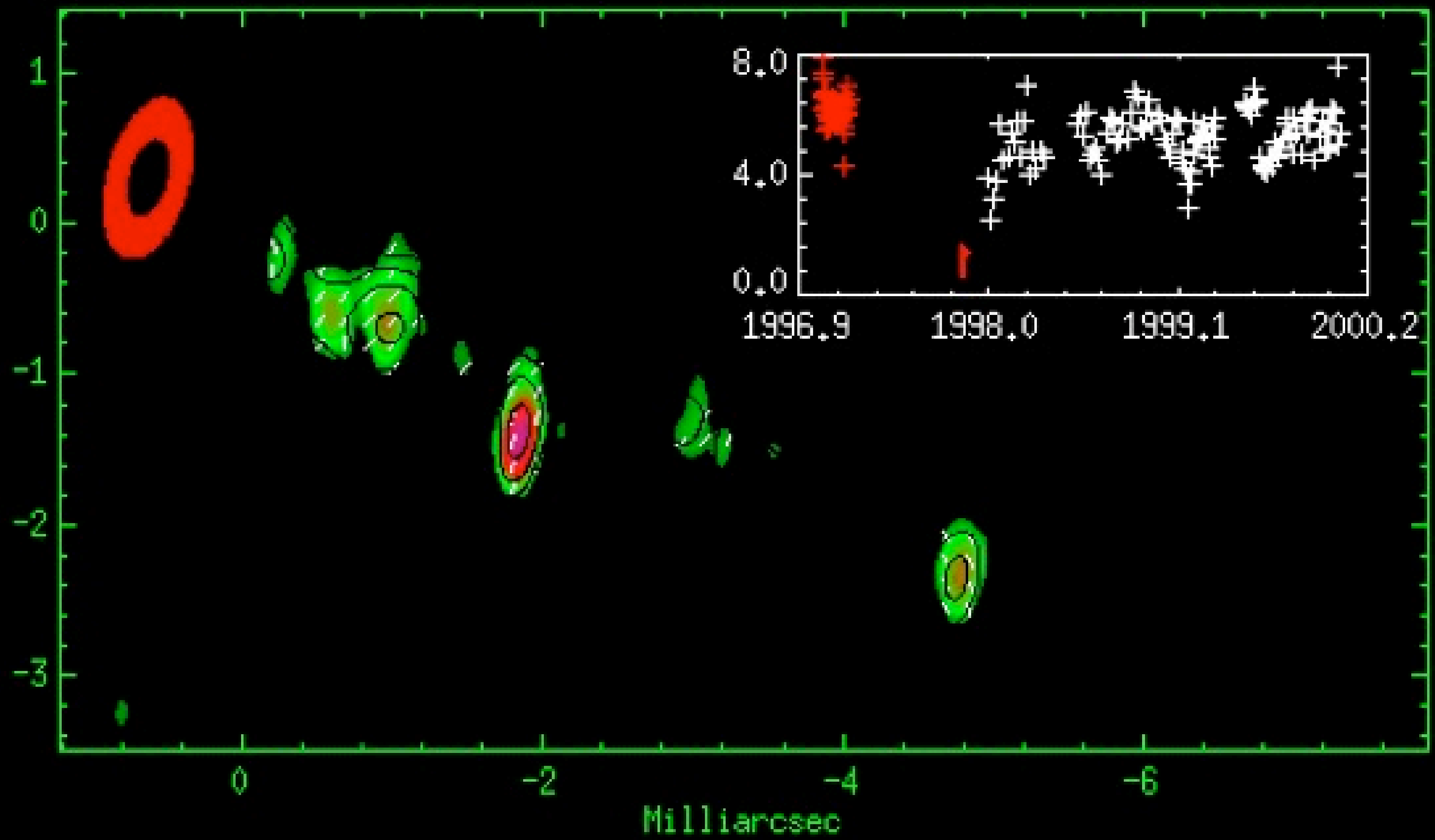
Apparent distance travelled, as seen by observer: $r_{app} = vt\mathrm{Sin}\theta$

Apparent speed:

$$v_{app} = vt\mathrm{Sin}\theta/(t - vt\mathrm{Cos}\theta/c)$$
$$= v\mathrm{Sin}\theta/(1 - v\mathrm{Cos}\theta/c)$$

$$\beta_{app} = \beta\mathrm{Sin}\theta/(1 - \beta\mathrm{Cos}\theta)$$

3C 120 (Marscher et al. 2002)



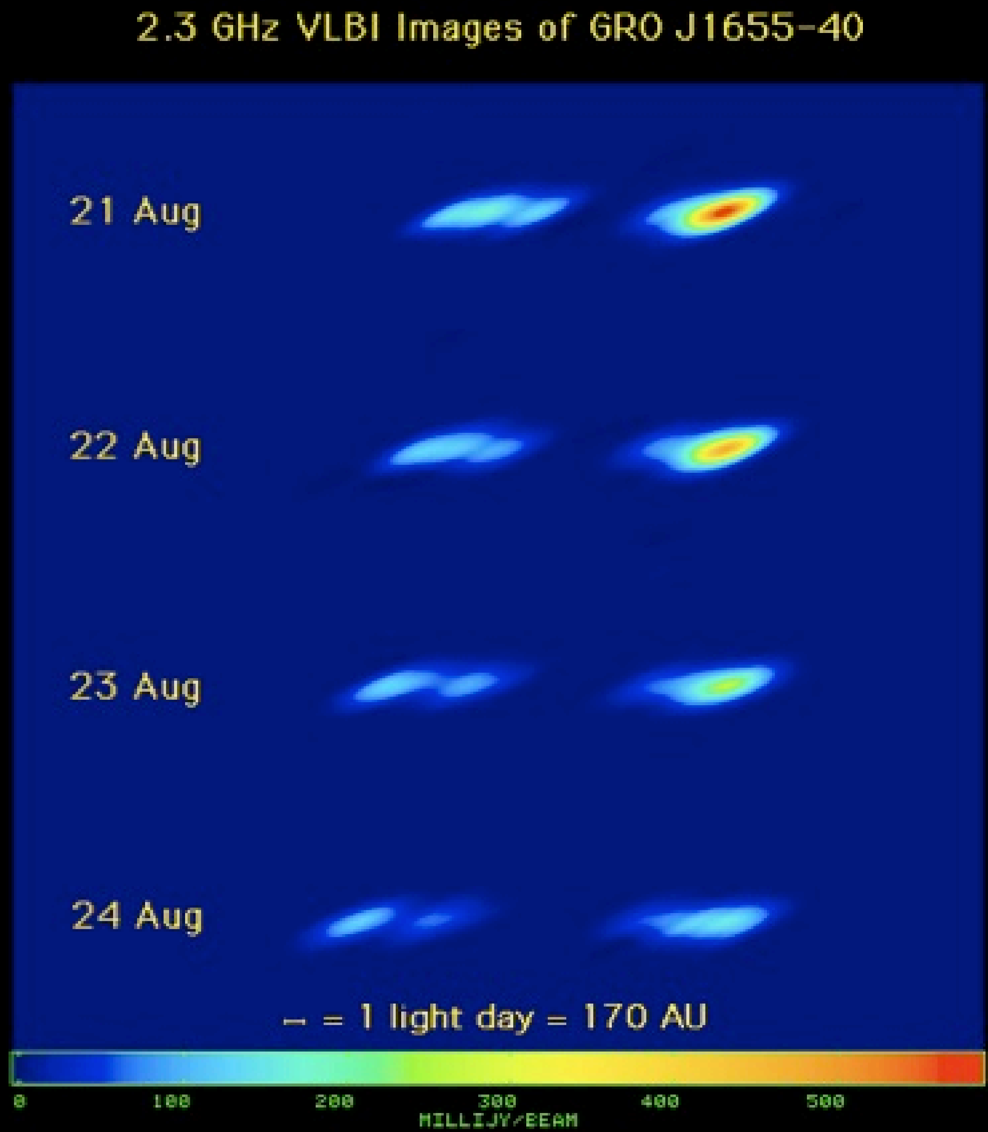
Microquasars

• 3.2 kpc distant;

• Binary system of star (1.7 – 3.3 solar masses) and black hole (4 – 7 solar masses);

• VLBI shows 65 mas/day – largest transverse apparent motion for an extra-solar system object, 1.1c - 1.9c;

• True speed 0.92c and inclined 85 degrees to our line of sight.



Tingay et al. (1995)

Summary:

- VLBI is just interferometry;
- VLBI is the highest angular resolution direct imaging technique in astronomy;
- VLBI enables the study of a wide range of astrophysical problems because of this characteristic;
- Long baseline capabilities have a place as a part of next generation instruments like the SKA.