ROLE OF LARGE SINGLE DISHES IN VERY LONG BASELINE INTERFEROMETRY

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NEED FOR AN INTERFEROMETER

- Angular Resolution

$$\theta \propto \lambda / D$$

where D is the diameter of the telescope

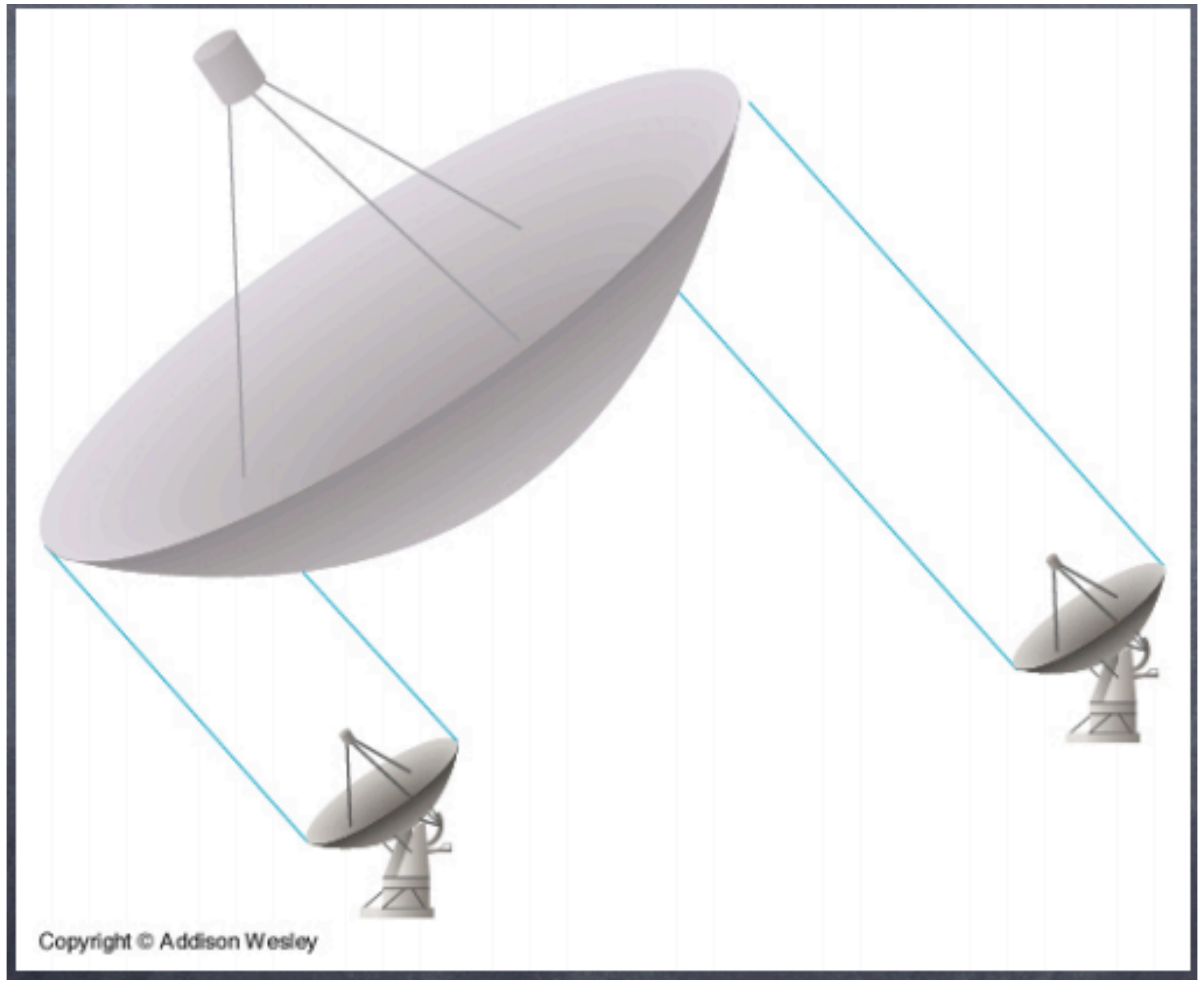
Hubble space telescope with D=2.4 m, wavelength=500 nm,

Resolution ~ 0.05 arcsec.

For cm observations, one would need ~800 km diameter antenna (Not practical!)

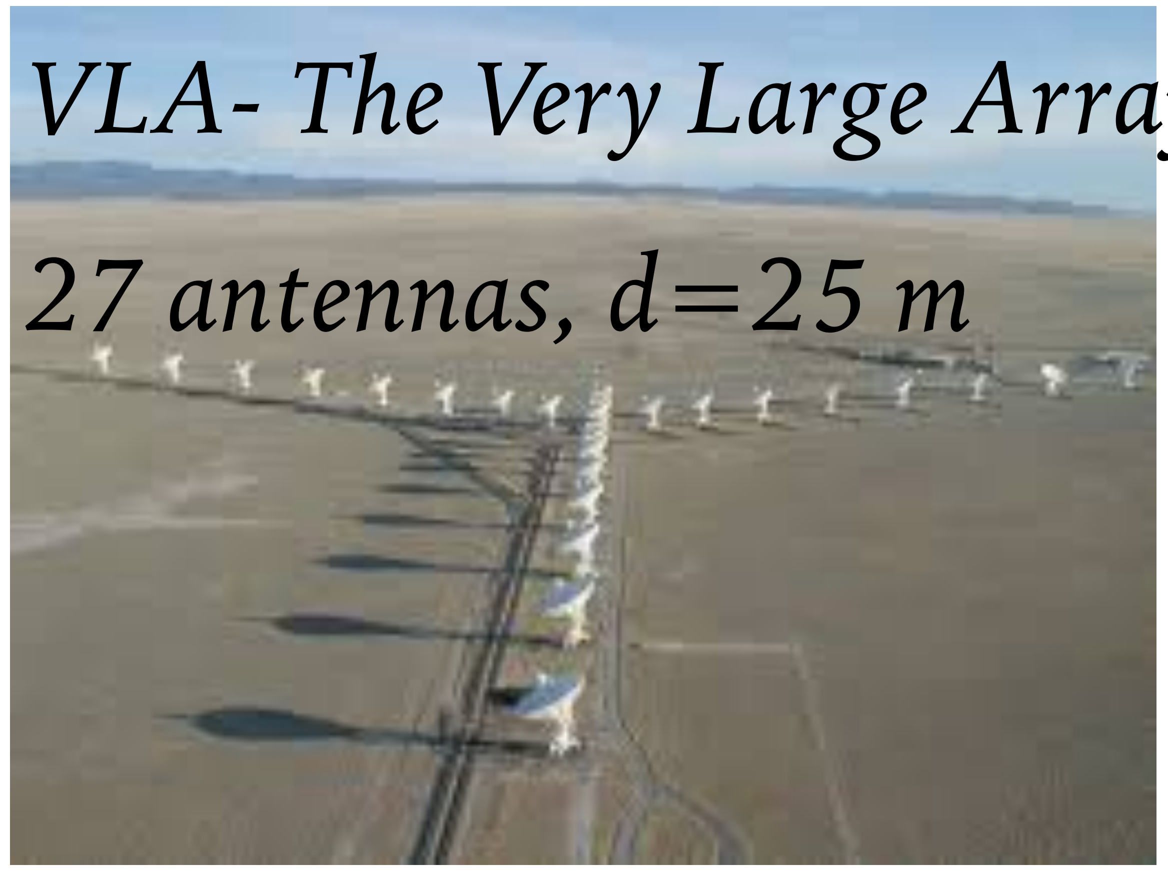
Instead we use arrays of small telescopes and measure the interference pattern from the telescopes (like a double-slit experiment) → This is **interferometry**.

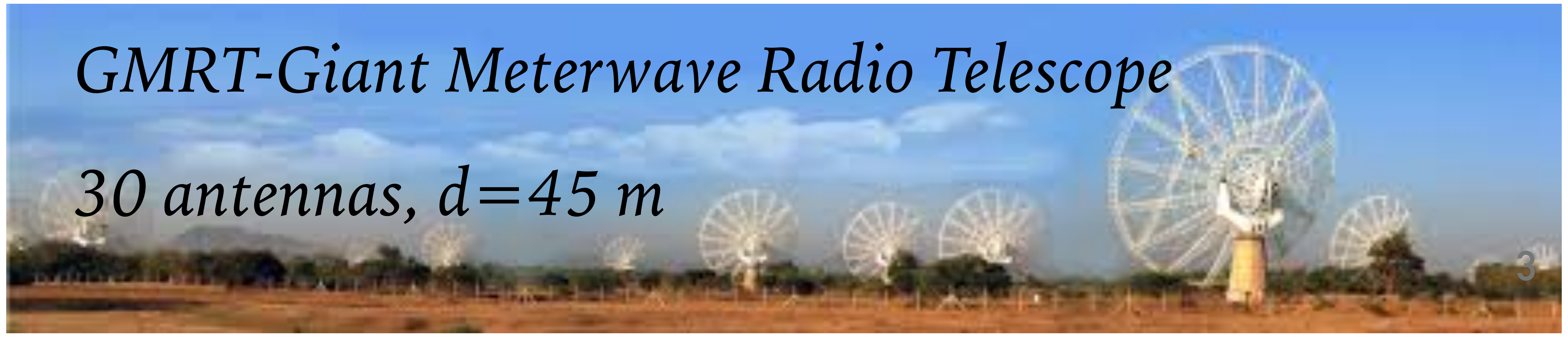
Synthesize a single telescope of large aperture from a number of small telescopes.



LINKED INTERFEROMETERS

- Radio interferometry consists of two or more radio telescopes that are separated by a distance, known as **baseline**.
- Examples:
  - VLA has 27 antennas with baseline of 1-36 km; operating frequency: 1-40 GHz
  - ALMA has 66 antennas; 35-950 GHz.
  - GMRT has 30 antennas with baseline of 100 m-26 km; operates from 100-1200 MHz.
  - LOFAR has ~20,000 dipoles; operates from 10-240 MHz

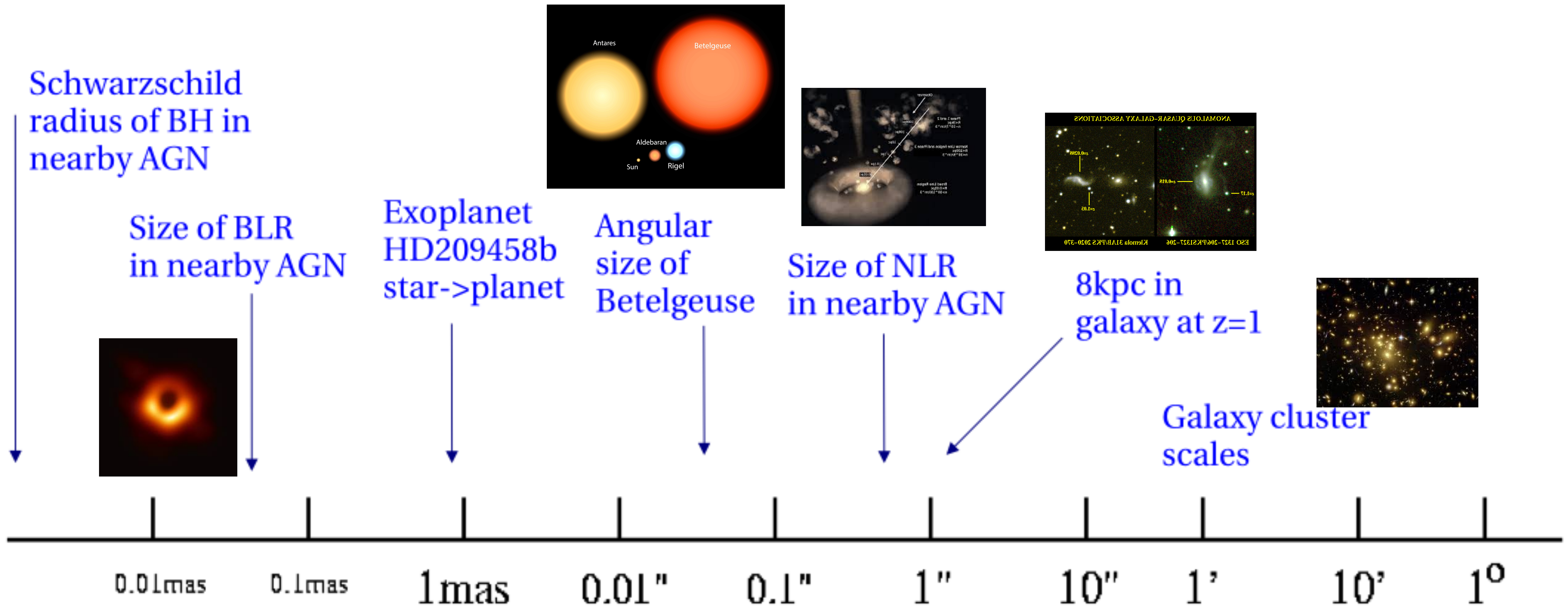




NEED FOR VLBI

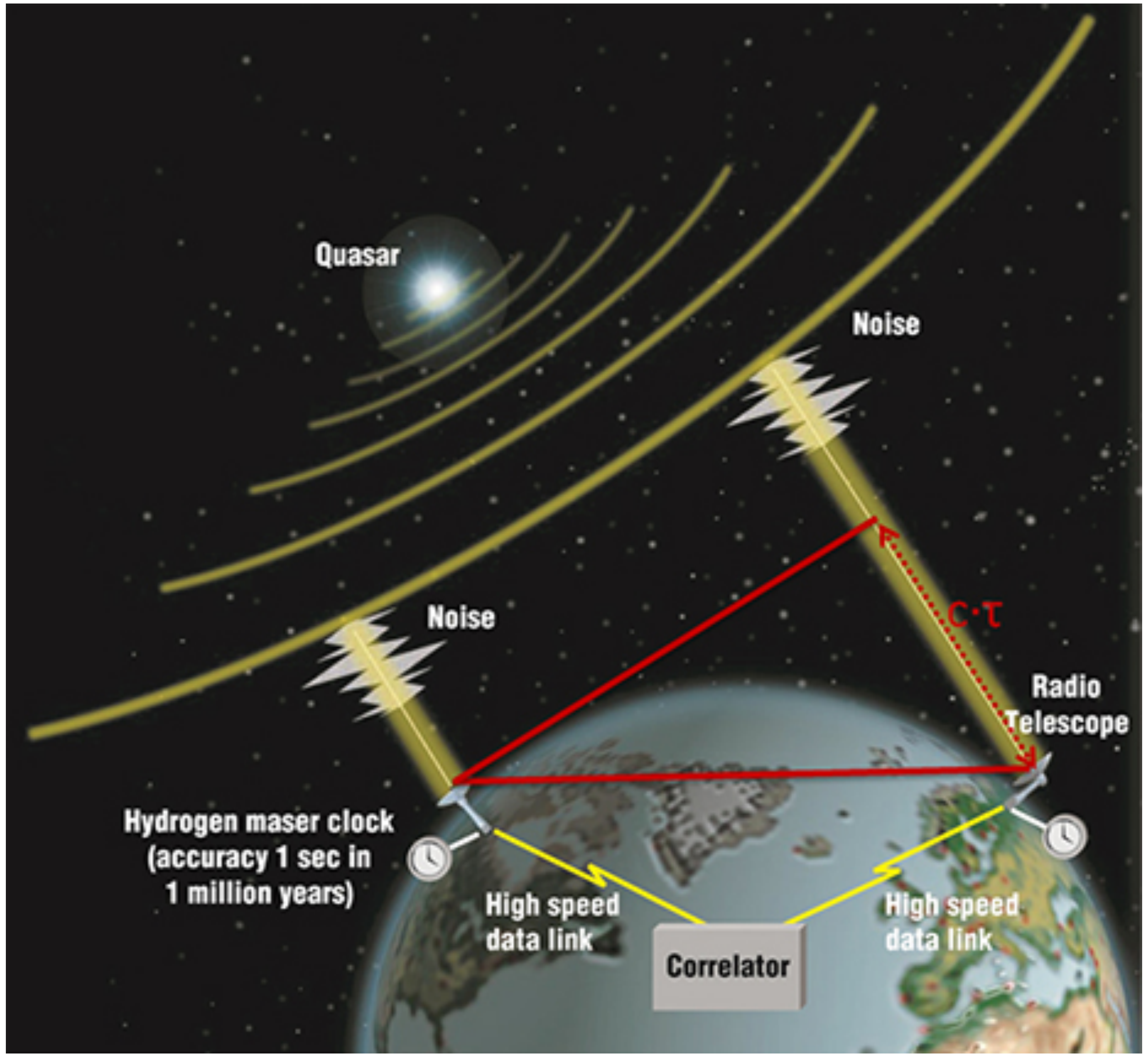
HIGH RESOLUTION

- An array of max baseline of 6000 km gives a resolution of
  - 7 milli arcsec at 1.4 GHz (21 cm)
  - 30 micro arcsec at 230 GHz (1 mm)



WHAT IS VLBI?

- Radio interferometry with distant, ***physically unconnected*** antennas
  - Baselines up to an Earth diameter for ground-based VLBI
  - High resolution – mas to μas
  - Can extend to space (HALCA, RadioAstron)
- Traditionally uses no IF/LO link between antennas
  - Disc-based recorders for temporary data storage & transport
  - Real time over the internet (eVLBI) option
  - Delayed correlation after shipment of disc packs
  - Atomic clocks for time and frequency – usually H-masers
- Can use available single-dish antennas
- No fundamental difference between linked interferometers & VLBI arrays



VLBI data acquisition
Picture Credit: NASA

CURRENT VLBI NETWORKS

These fall into three main categories:

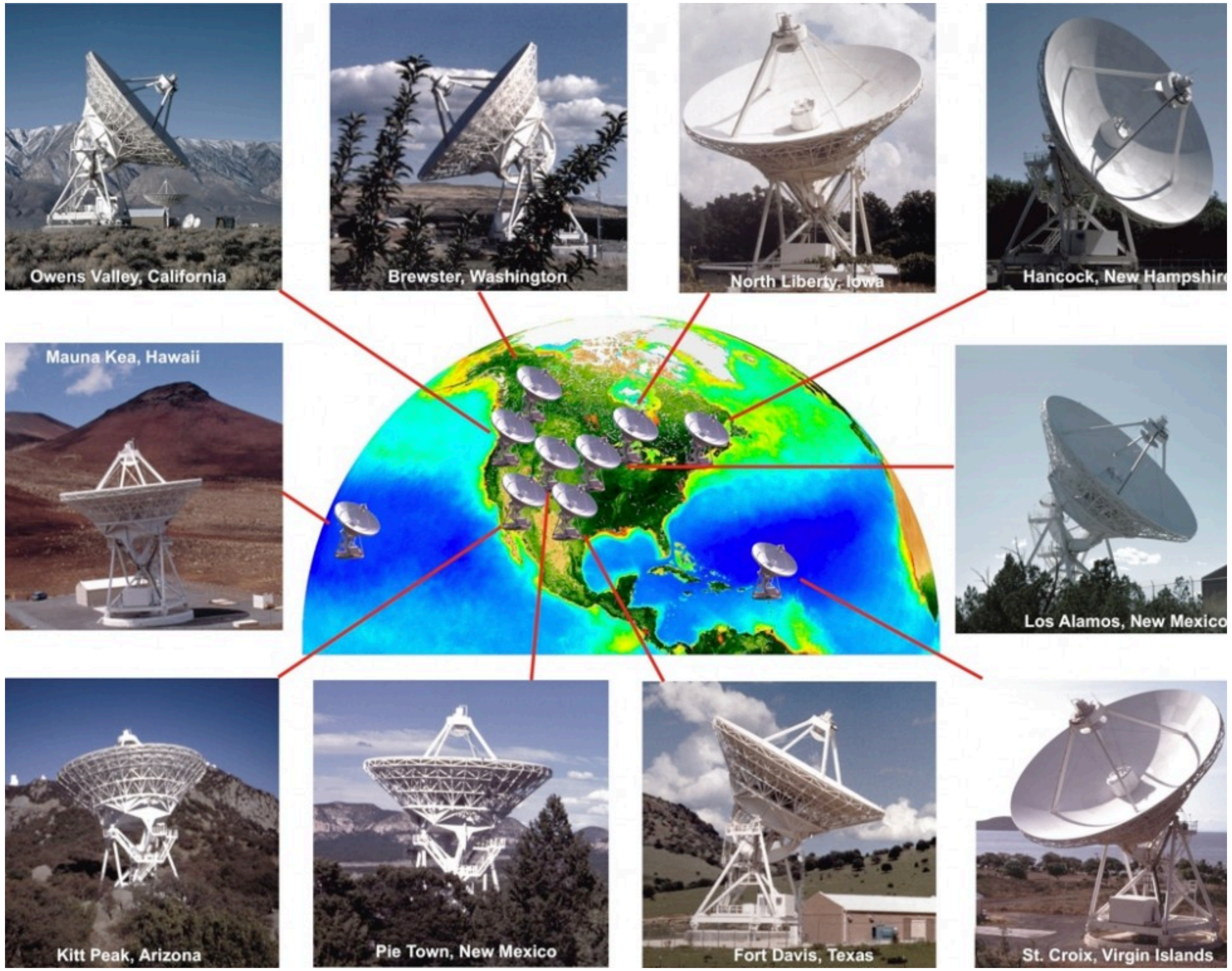
Continental – Baselines of 100s to 1000s of km

- VLBA
- EVN+Ar (12m)
- HSA - VLBA+ (~~Ar~~, Ef, GBT, VLA)

- Global – Baselines of tens of 1000s of km
  - Global mm-VLBI (EVN+VLBA)
- Space VLBI – involves the use radio dish on board satellite
  - VSOP using 8 m dish,
  - Radioastron using 10m dish.

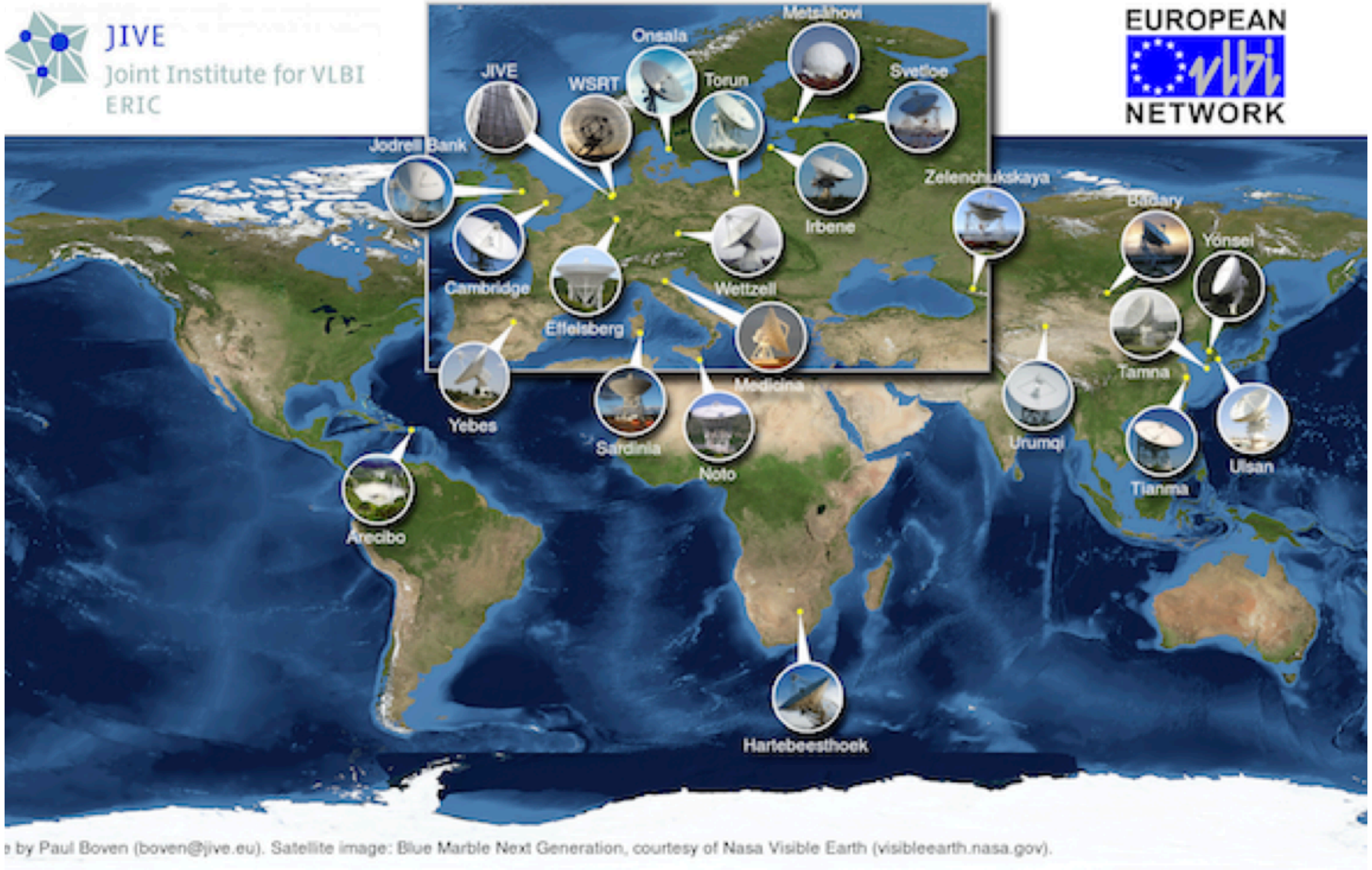
CURRENT VLBI NETWORKS - VERY LONG BASELINE ARRAY (VLBA)

- 10 x 25m antennas distributed across the US
- 0.3 - 86 GHz
- maximum baseline ~8,000 km
- Resolution of ~ 0.1 mas at 86 GHz.



CURRENT VLBI NETWORKS – EUROPEAN VLBI NETWORK (EVN)

- ~23 stations, 10m -> 100m diameter
- 0.3 - 43 GHz
- maximum baseline ~ 9000 km
- EVN+Ar gives a baseline of ~ 11,000 km



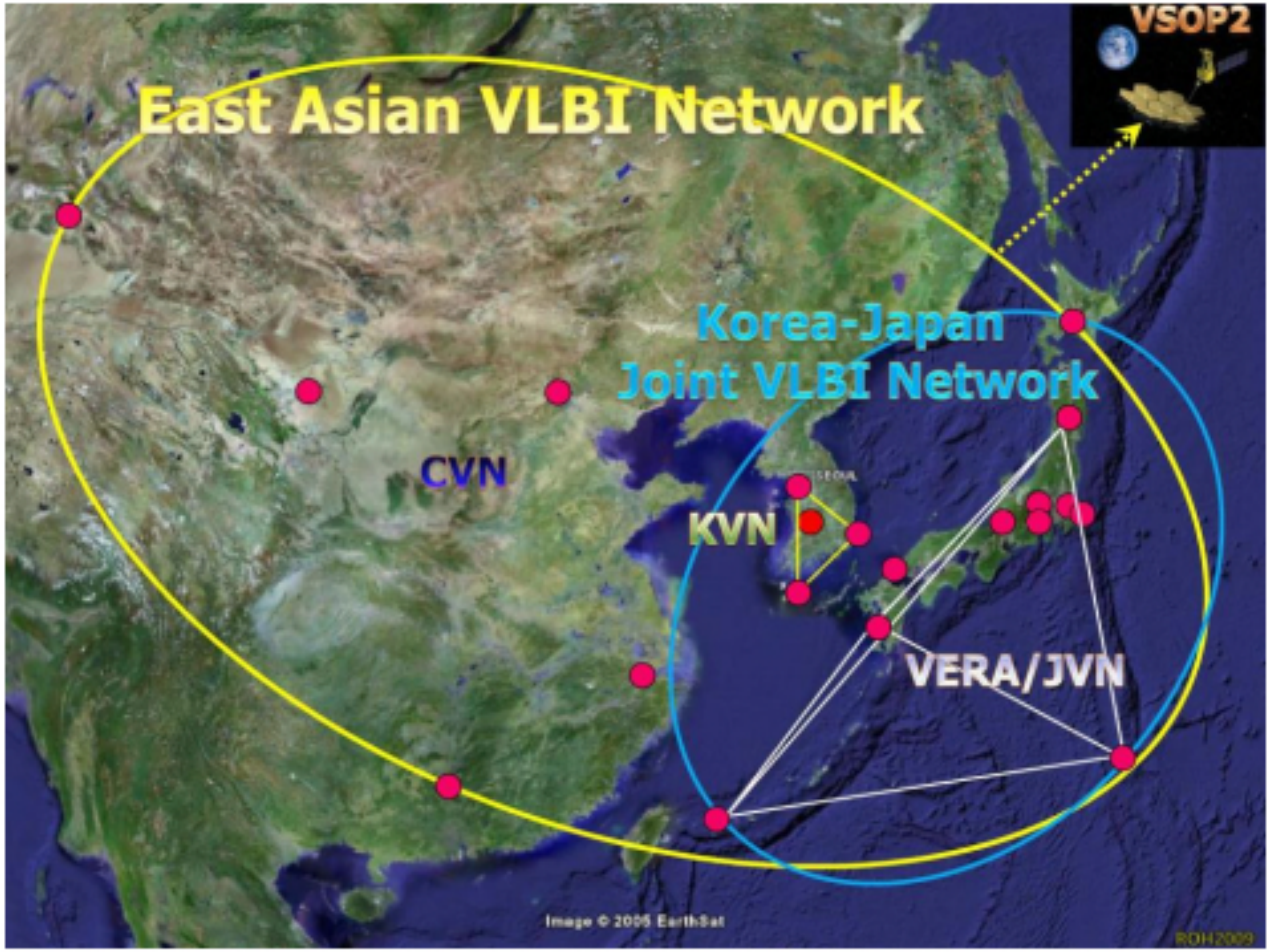
CURRENT VLBI NETWORKS – HIGH SENSITIVE ARRAY (HSA)

EAST ASIAN VLBI NETWORK

Chinese (CVN): 4 ants

Korean (KVN): 3 ants., simultaneous 22, 43, 86, 129 GHz

VERA: 4 dual-beam ants., maser astrometry 22-49 GHz

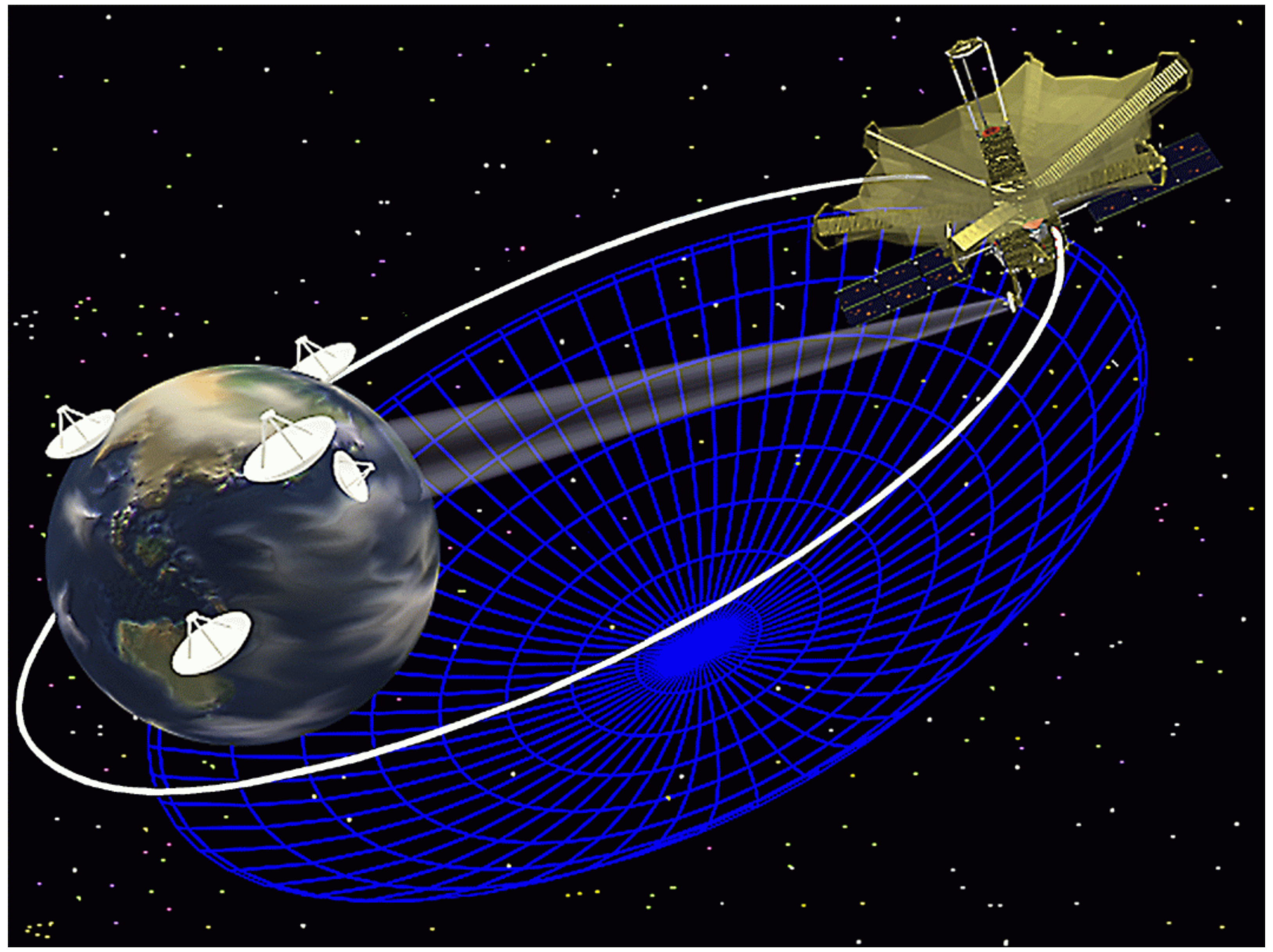


SPACE VLBI

VSOP/HALCA had an orbit with apogee ~2 Earth diameters.

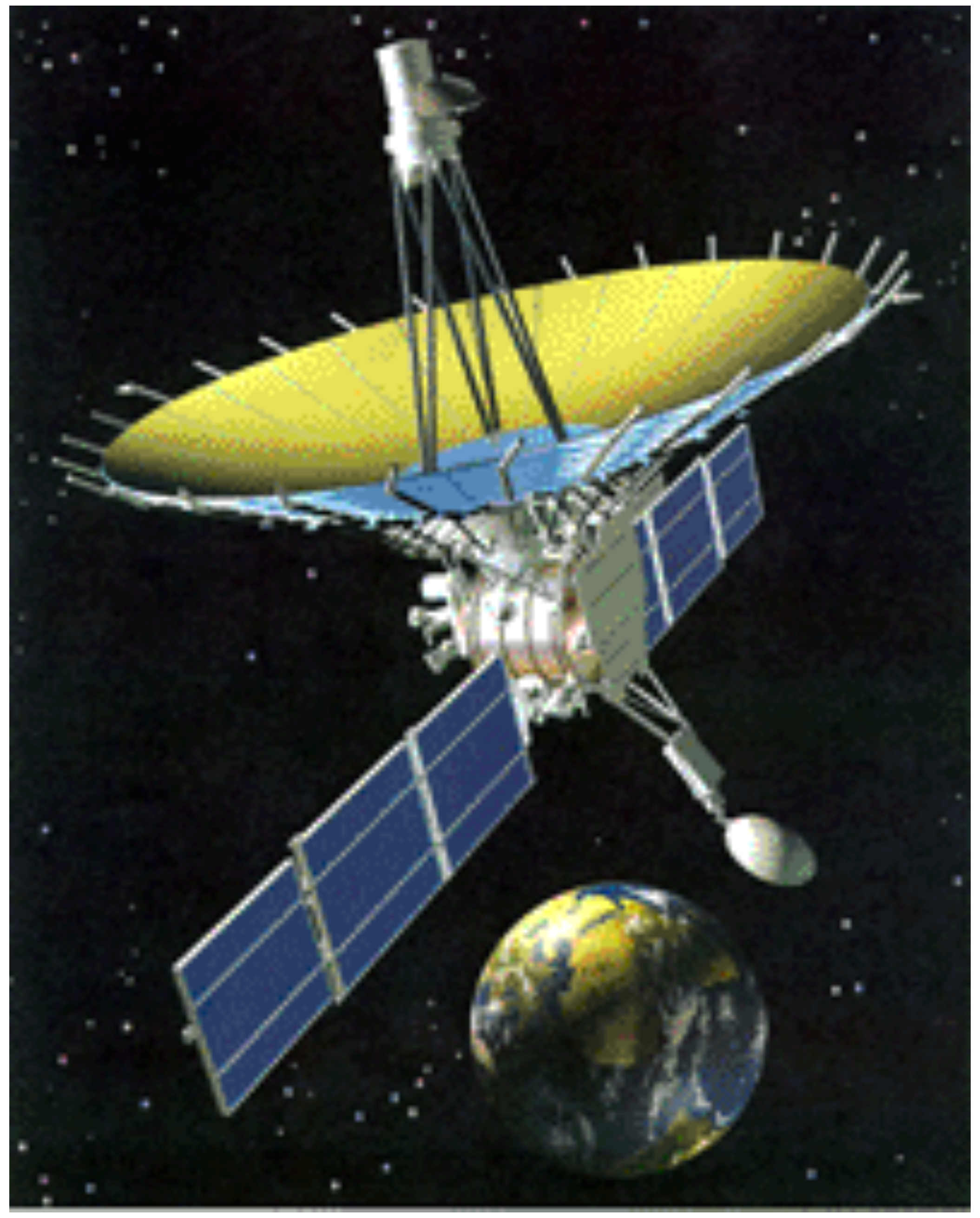
8m radio telescope

Operating freq: 1.6, 5 GHz



From 1999 to 2001, VLBA & Ar co-observed with this antenna.

RadioAstron has an orbit with apogee ~30 Earth diameter



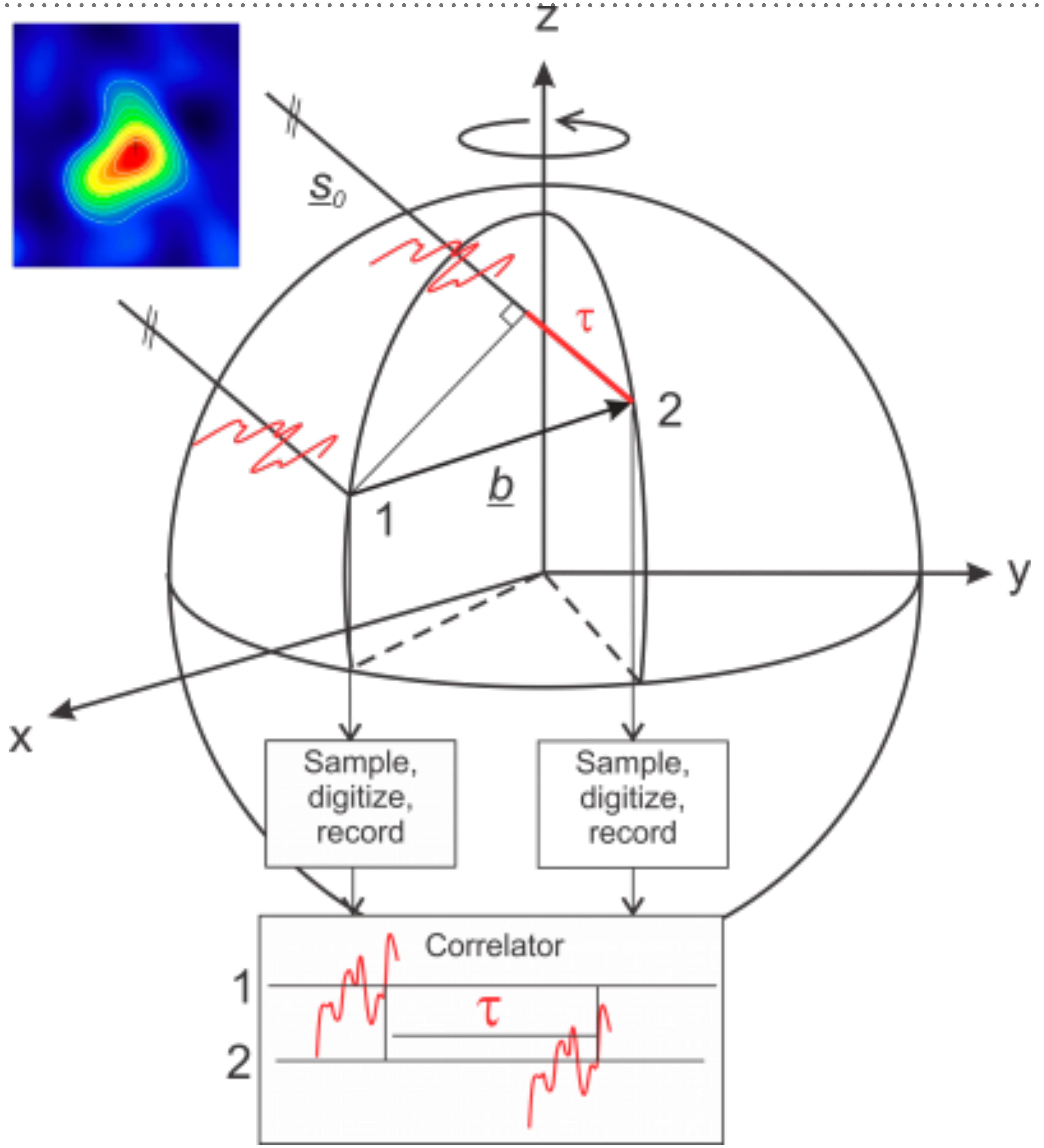
From 2012, GBT & Arecibo have co-observed with this Russian 10-m antenna, finding a new component of our ISM, unexpected phenomena in quasars, probing innermost regions of AGN jets and B fields.

BASIC ELEMENTS OF VLBI

- Antennas
- Receivers
- Analog stages

VLBI stage

- Recorders and data transport
- Correlation, post-processing



Picture Credit: Vienna VLBI satellite software

VLBI RECORDING SYSTEM AT AO

Consists of

- Roach Digital BackEnd (RDBE), digital processing unit
- Mark 6 recorder, records the data from the RDBE
- Field System, software unit communicates with RDBE and Mark6

The system was upgraded in 2019.

Offers :

- 512 MHz BW in PFB and DDC mode --> total of 2 GHz
- 4 Gbps recording speed
- 32 TB disk capacity
- E-shipping to JIVE

RECORDER MARK6 AT AO

Mark6 extension

Mark6

CORRELATOR

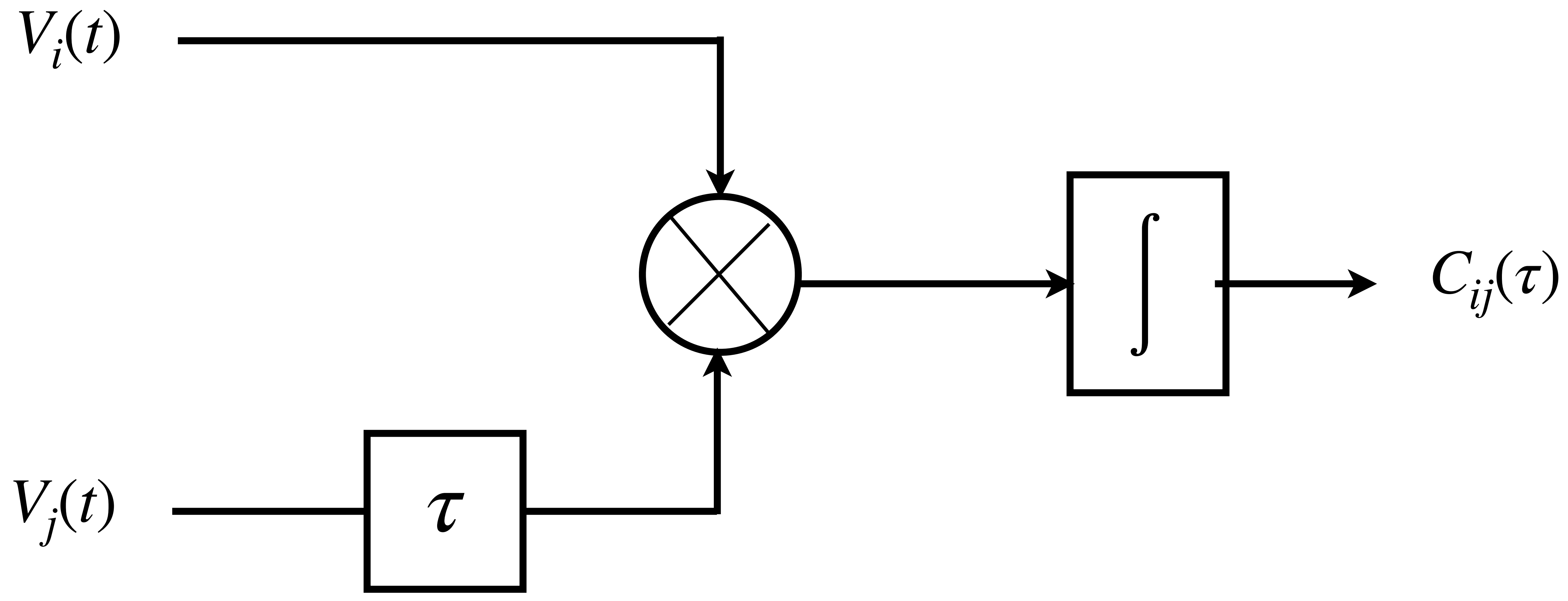
- Performs cross-correlation of two signals

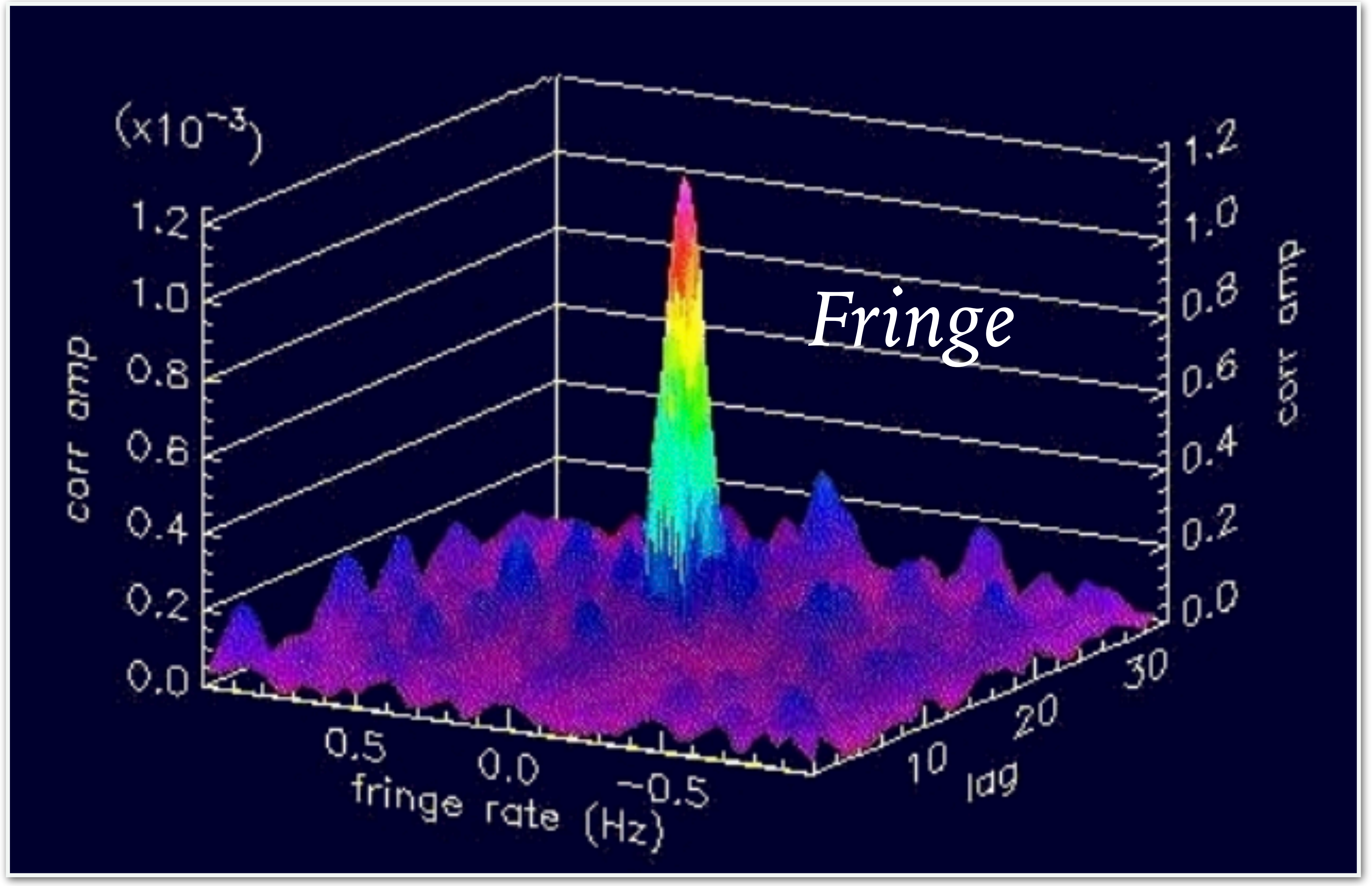
$$C_{ij}(\tau) = \int V_i(t)V_j(t+\tau)dt$$

where i,j are the stations.

The output of the correlator is called a 'fringe'.

DiFX software correlators





Credit: IVSSC NASA GSFC Kingham lectures

ROLE OF LARGE SINGLE DISHES IN VLBI

IMPROVEMENT IN SENSITIVITY

VLBI Sensitivity of an array:

For identical antennas:

$$\Delta I\ (Jy/beam) \approx \frac{T_{sys}/G}{\sqrt{(N(N-1)\Delta\nu\tau)}}$$

For non-identical antennas, $T_{sys}/G = \sqrt{((T_{sys}/G)_1\ .\ (T_{sys}/G)_2\ .\ \ldots}$

Bigger antenna —> larger gain —> low noise & high sensitivity

For example, for continuum observations at L-18cm, data rate=1024 Mbps, 2 hours of observing time,

EVN - 13 μJy/beam	Global (VLBA+EVN) - 9 μJy/beam
EVN+GBT - 6.5 μJy/beam	VLBA+EVN+GBT - 5.3 μJy/beam

SPECIAL CONSIDERATIONS

Slew rate

Field of View

LONGER SLEW TIME & POINTING CALIBRATION

- Larger dishes have longer slew times and can lead to loss of time in phase-referencing VLBI.

Telescope	Azimuth (deg/min)	Elevation (deg/min)
GBT	36	18
Arecibo305m	24	2.4
20-m	120	120

- use a small antenna to track the calibrator continuously while the large dish tracks only the target with occasional visits to the calibrator.

- Sufficient setup time and breaks in schedule are required for better pointing and focus.

Frequency	Telescope	Break time
4-10 GHz	GBT	6min every 4-5 hr
	Effelsberg	8 min every 4 hr
40 - 90 GHz	GBT	8 min every 30-60 min
	Effelsberg	8 min every 2 hr

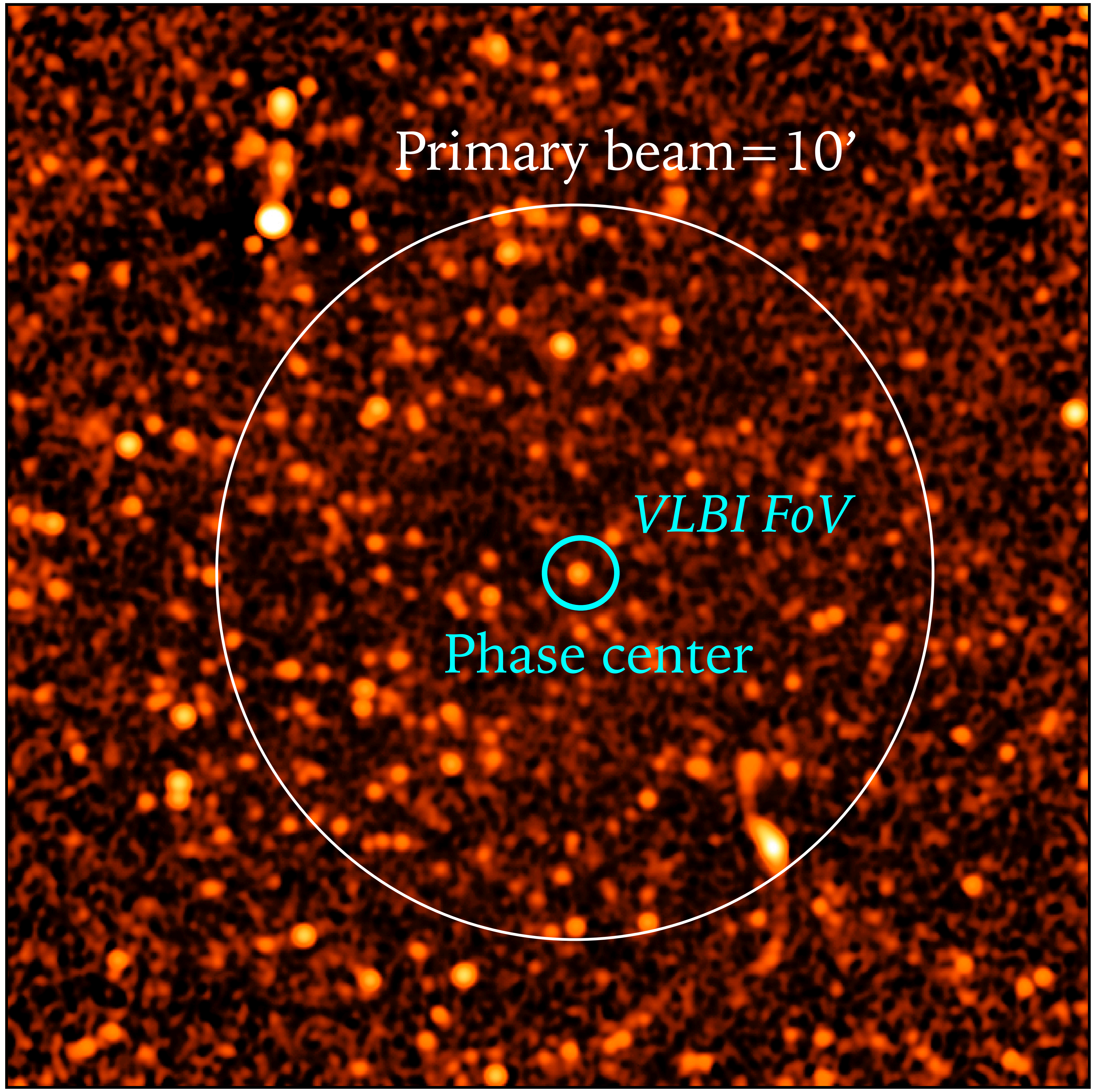
FIELD OF VIEW

FoV in an interferometry is determined by the primary beam of the largest antenna —> Bigger dishes have smaller FoV

VLBI FoV is limited by bandwidth and time smearing —> FoV ~ 10^{-4} x primary beam

VLBI field is usually empty, full beam imaging not useful —> target small fields

Multiple phase center technique



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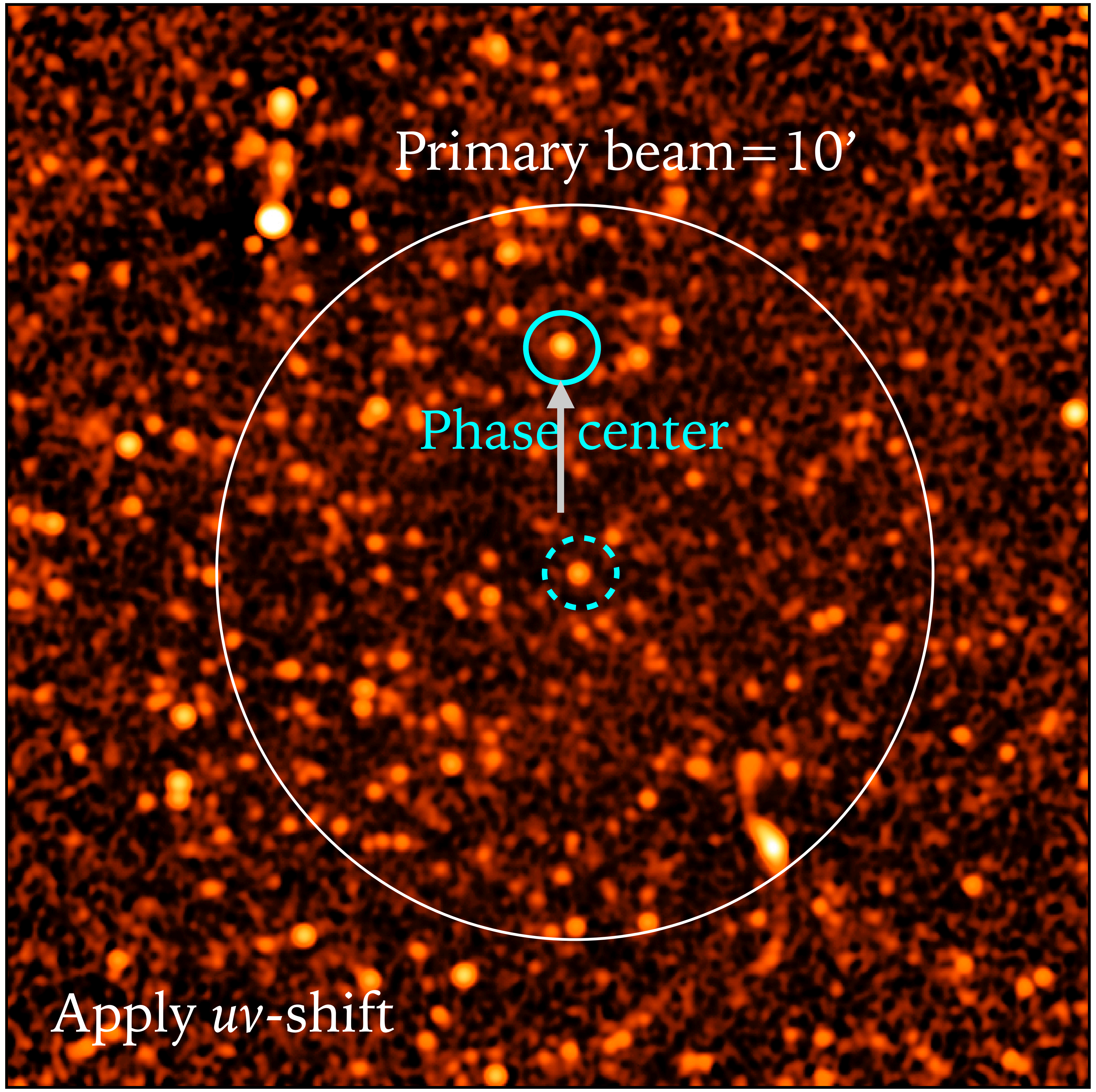

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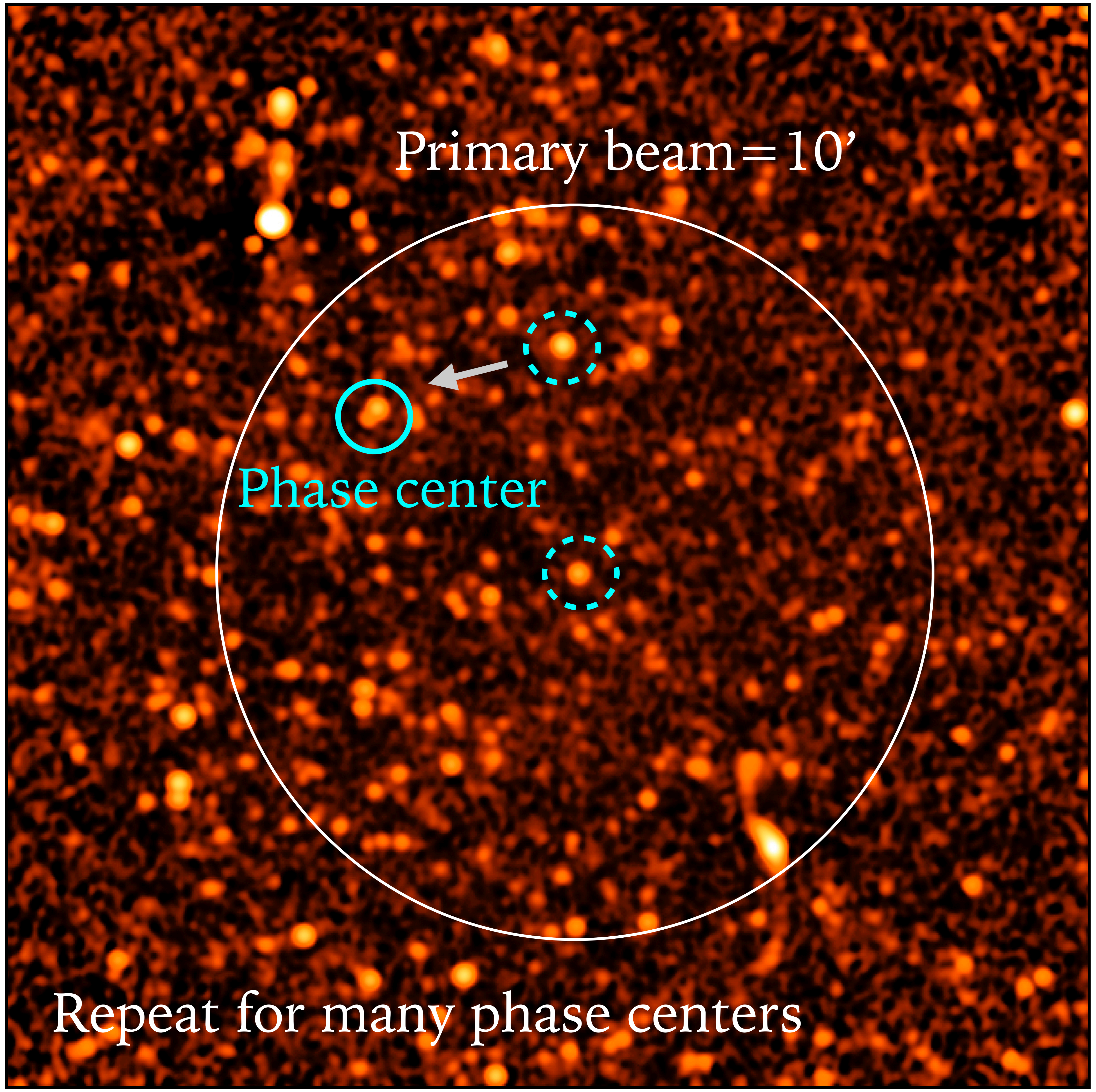

SCIENCE WITH VLBI – ESPECIALLY WITH BIG DISHES

A VLBI resolution of the Pleiades distance controversy

Carl Melis[1,*], Mark J. Reid[2], Amy J. Mioduszewski[3], John R. Stauffer[4], Geoffrey C. Bower[5]
+ See all authors and affiliations

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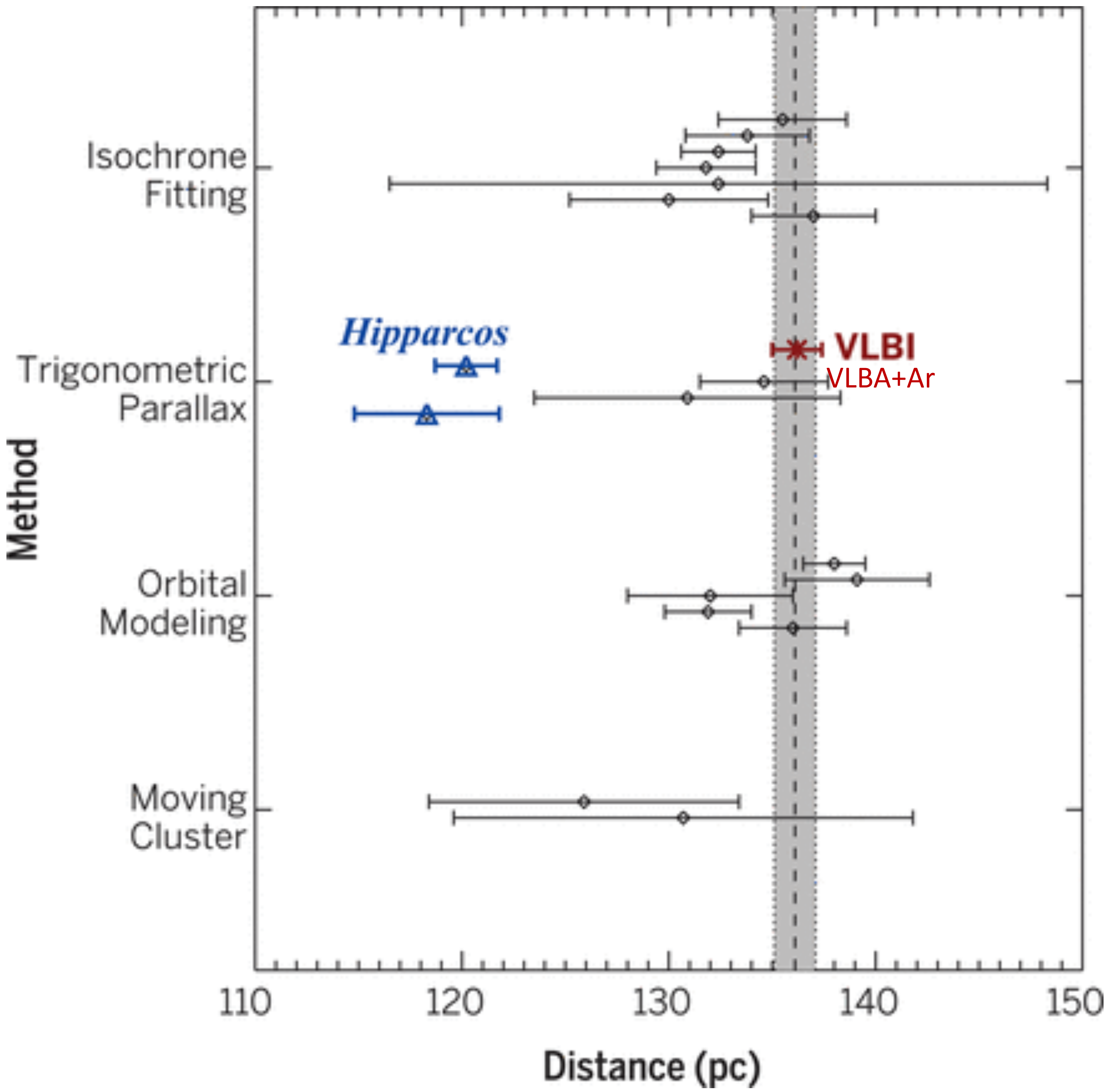
DOI: 10.1126/science.1256101



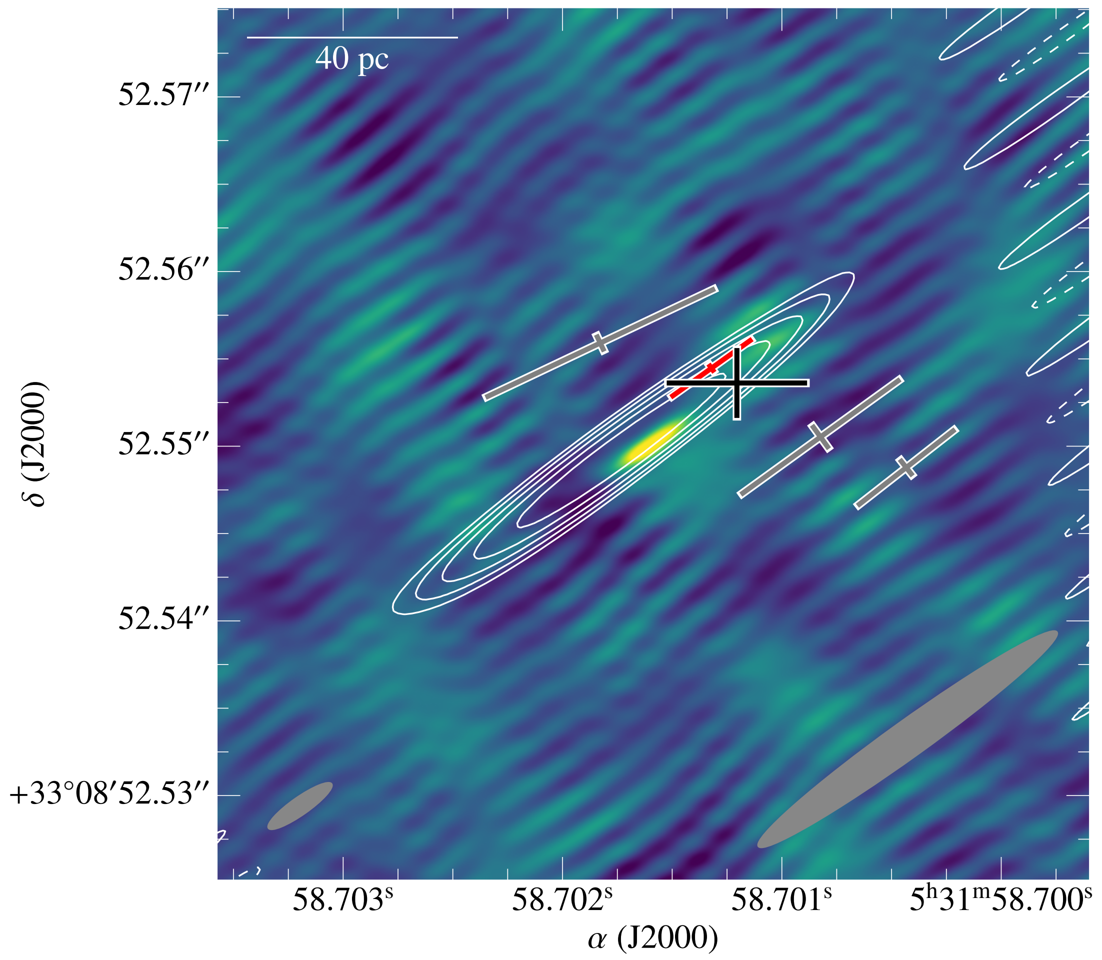
RadioAstron Observations of the Quasar 3C273: A Challenge to the Brightness Temperature Limit

Kovalev, Y. Y.; Kardashev, N. S.; Kellermann, K. I.; Lobanov, A. P.; Johnson, M. D.; Gurvits, L. I.; Voitsik, P. A.; Zensus, J. A.; Anderson, J. M.; Bach, U.; Jauncey, D. L.; Ghigo, F.; Ghosh, T.; Kraus, A.; Kovalev, Yu. A.; Lisakov, M. M.; Petrov, L. Yu.; Romney, J. D.; Salter, C. J.; Sokolovsky, K. V.

Inverse Compton cooling limits the brightness temperature of the radiating plasma to a maximum of $10^{11.5}$ K. Relativistic boosting can increase its observed value, but apparent brightness temperatures much in excess of 10^{13} K are inaccessible using ground-based very long baseline interferometry (VLBI) at any wavelength. We present observations of the quasar 3C 273, made with the space VLBI mission RadioAstron on baselines up to 171,000 km, which directly reveal the presence of angular structure as small as 26 μas (2.7 light months) and brightness temperature in excess of 10^{13} K. These measurements challenge our understanding of the non-thermal continuum emission in the vicinity of supermassive black holes and require a much higher Doppler factor than what is determined from jet apparent kinematics.

Publication: The Astrophysical Journal

Pub Date: March 2016



Localization of repeating FRB

For FRB121102, three out of the four e-EVN detected pulses could not have been found without Arecibo.

Marcote+2017

SUMMARY

- VLBI offers high resolutions

- Addition of large single dishes (e.g. GBT, Effelsberg, FAST) to VLBI arrays
  - provide significant boost in sensitivity.
  - Are invaluable for spectral line and transient source studies where bandwidth and integration times have natural limits.

- Specials considerations such as slew rate and FoV