Radio Interferometry

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AST 542 Observational Seminar

May 4, 2011

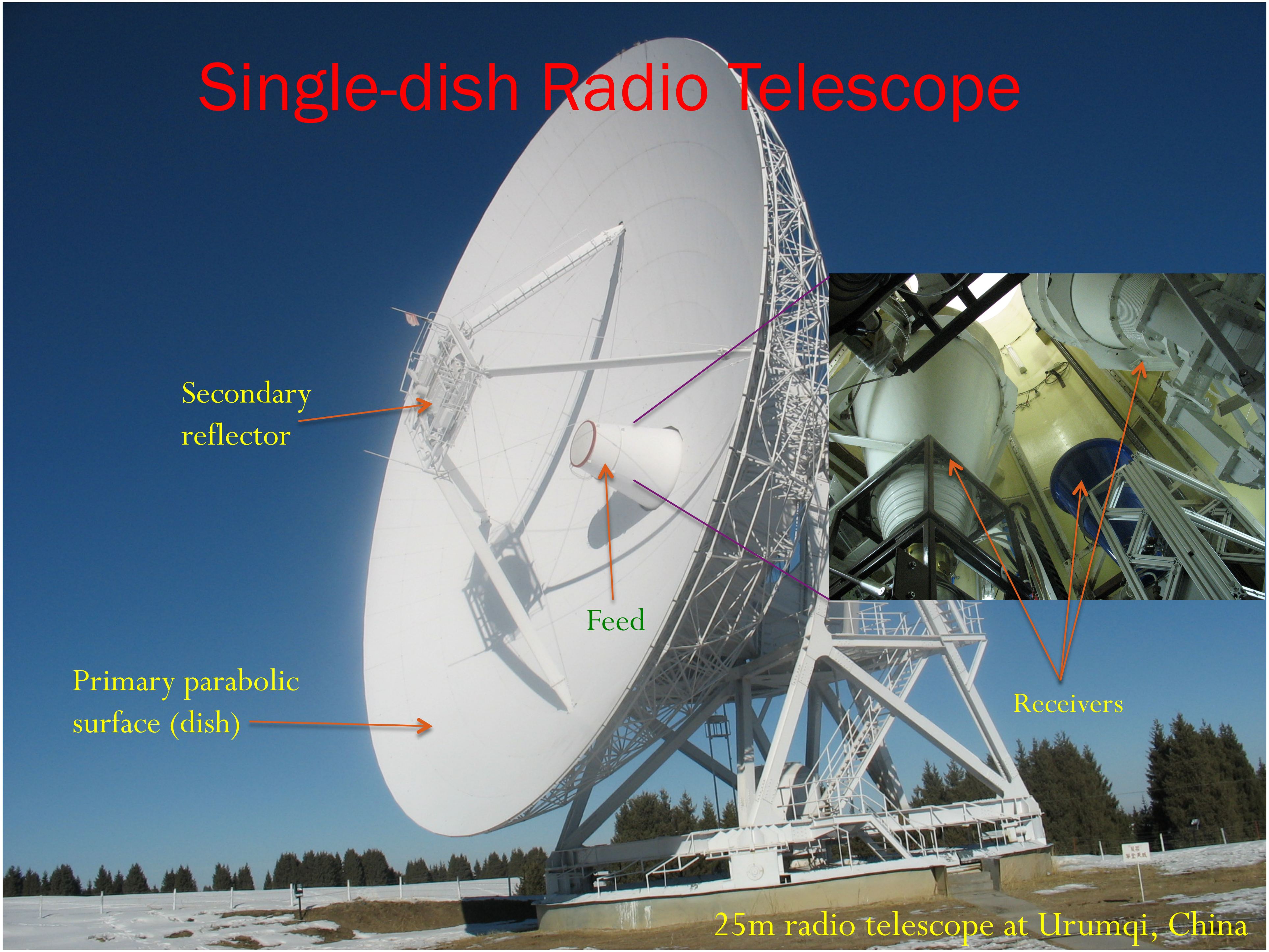
Outline

- Single-dish radio telescope
- Two-element interferometer
- Interferometer arrays and aperture synthesis
- Very-long base line interferometry
- Interferometry at millimeter wavelength

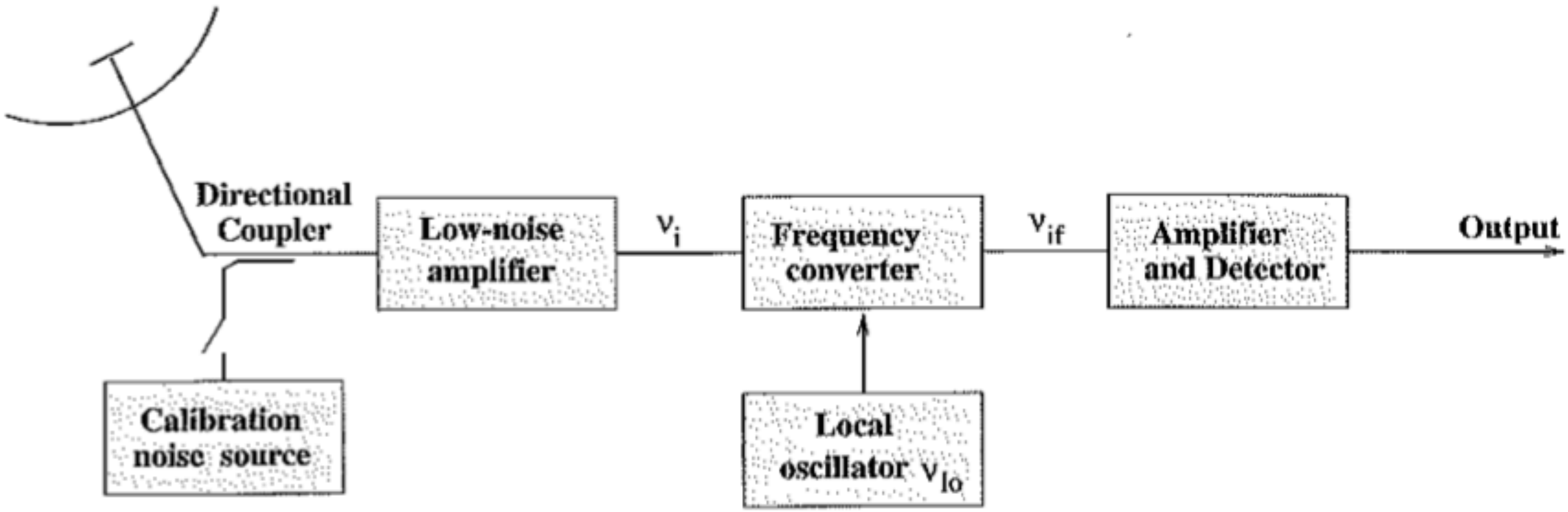
Brief history of astronomical interferometry

- 1920: Michelson stellar interferometer
- 1946: First astronomical observations with a two-element radio interferometer
- 1962: Earth-rotation synthesis
- 1967: Very-long baseline interferometry
- 1974: Nobel prize to Martin Ryle and Antony Hewish
- 1980-1990s: mm/sub-mm wavelength instruments

Single-dish Radio Telescope



Heterodyne Receiver



- Incoming signal is generally very weak: pre-amplify.
- Convert high-frequency signal to intermediate-frequency.
- Receiver cooled to reduce noise.
- Spectrum: multi-channel / autocorrelation spectrometer.

Measurement: noise and sensitivity

- Spatial resolution:

$$\theta = \frac{1.22\lambda}{D} \approx 4.2' \frac{\lambda/\mathrm{cm}}{D/10\mathrm{m}}$$

- Calibration:

  resistive load at fixed T

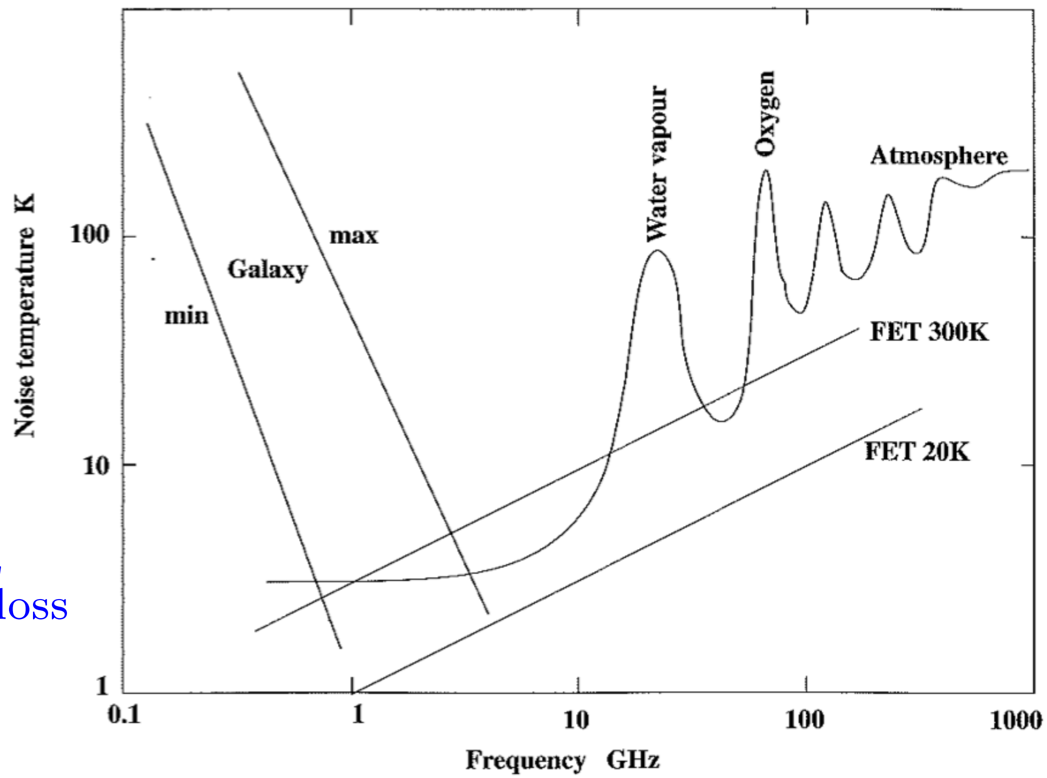
- System noise:

$$T_{\rm sys} = T_{\rm atm} + T_{\rm bg} + T_{\rm sl} + T_{\rm loss}$$

- Sensitivity:

$$\Delta S = \frac{2kT_{\rm sys}}{A_{\rm eff}\sqrt{\mathcal{BT}}}$$

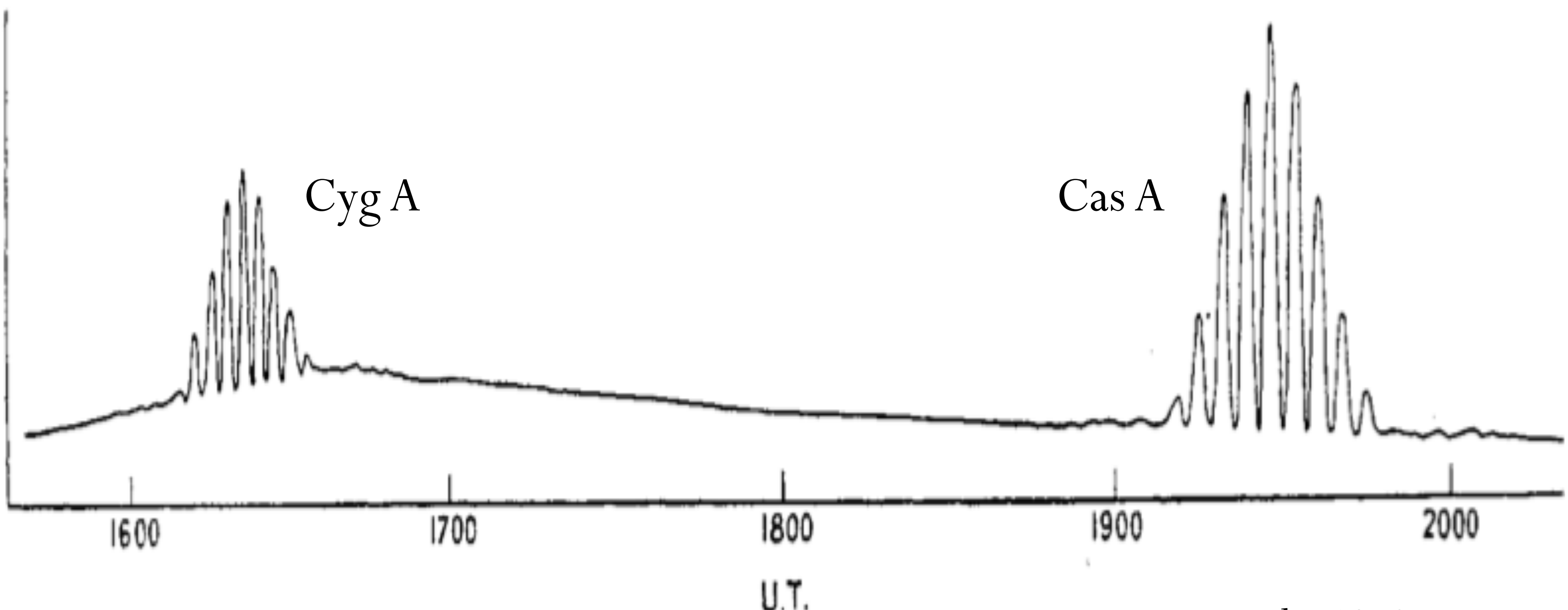
Sources of noise



In general, $T_{\rm sys} \gg T_a$

Need for better resolution: interferometry

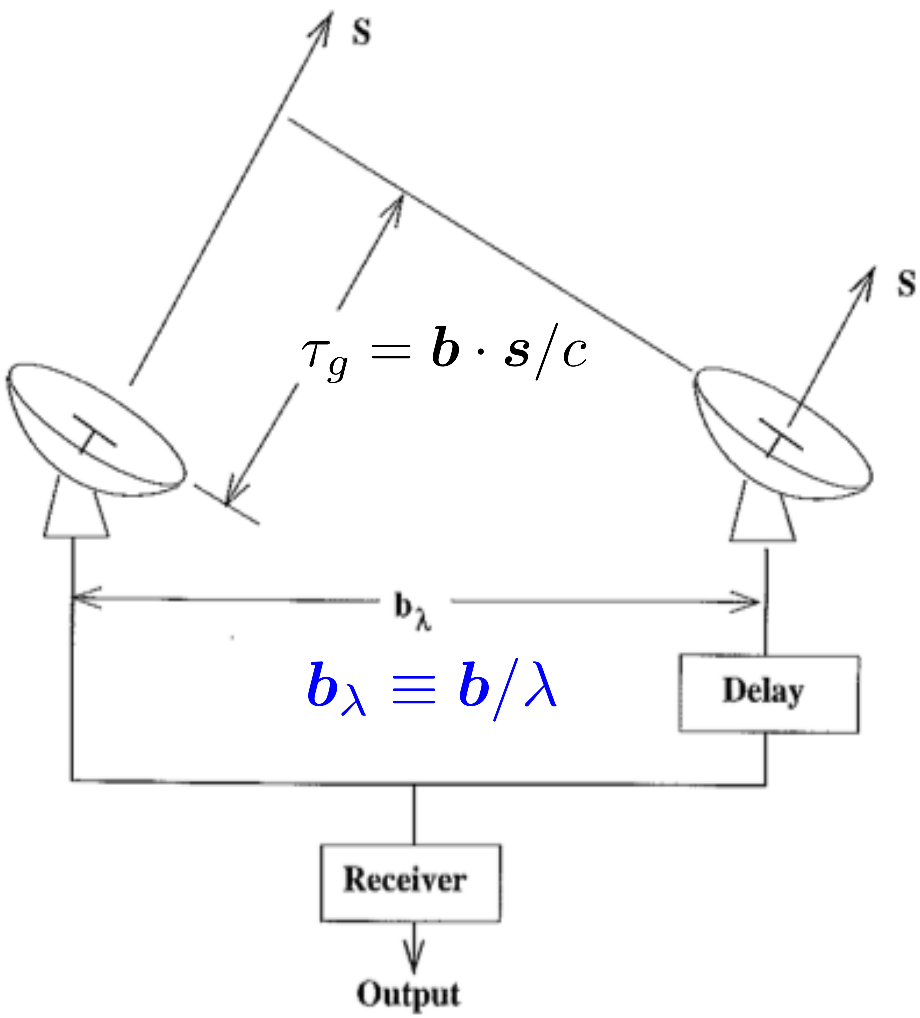
- Filled-aperture telescope limited to ~100m
- With interferometers, resolution $\sim \lambda/B$, with B (baseline) up to $R_\oplus$, improvements by factors of thousands.



(Ryle, 1950)

Primary beam + interference

Two-element interferometer



Fringe pattern changes as the Earth rotates

Assumptions:

Monochromatic point source with two identical antennas.

Cross-correlation:

$$R_{xy}(\tau) = \langle x(t) y(t-\tau) \rangle$$

$$R_{xy}(\boldsymbol{s}) = A(\boldsymbol{s}) F \cos(2\pi \boldsymbol{b}_\lambda \cdot \boldsymbol{s})$$

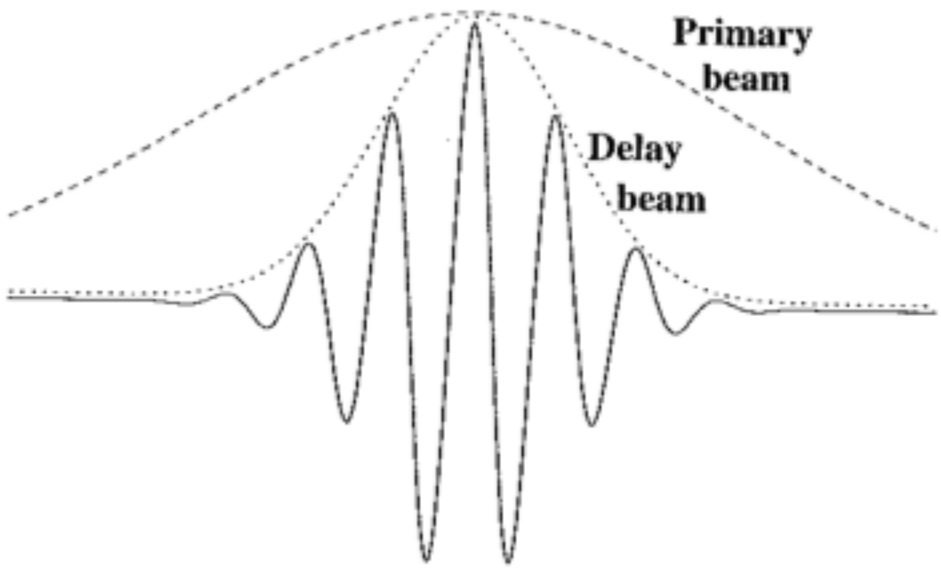
Cross-spectrum power density:

$$S_{xy}(\nu) = X(\nu) Y^*(\nu)$$

$$\boxed{S_{xy}(\boldsymbol{s}) = A(\boldsymbol{s}) F_\nu \exp\left(\mathrm{i}2\pi \boldsymbol{b}_\lambda \cdot \boldsymbol{s}\right)}$$

S gives the fringe amplitude and phase.

Effect of finite bandwidth



Solution: add time delay to compensate for phase difference

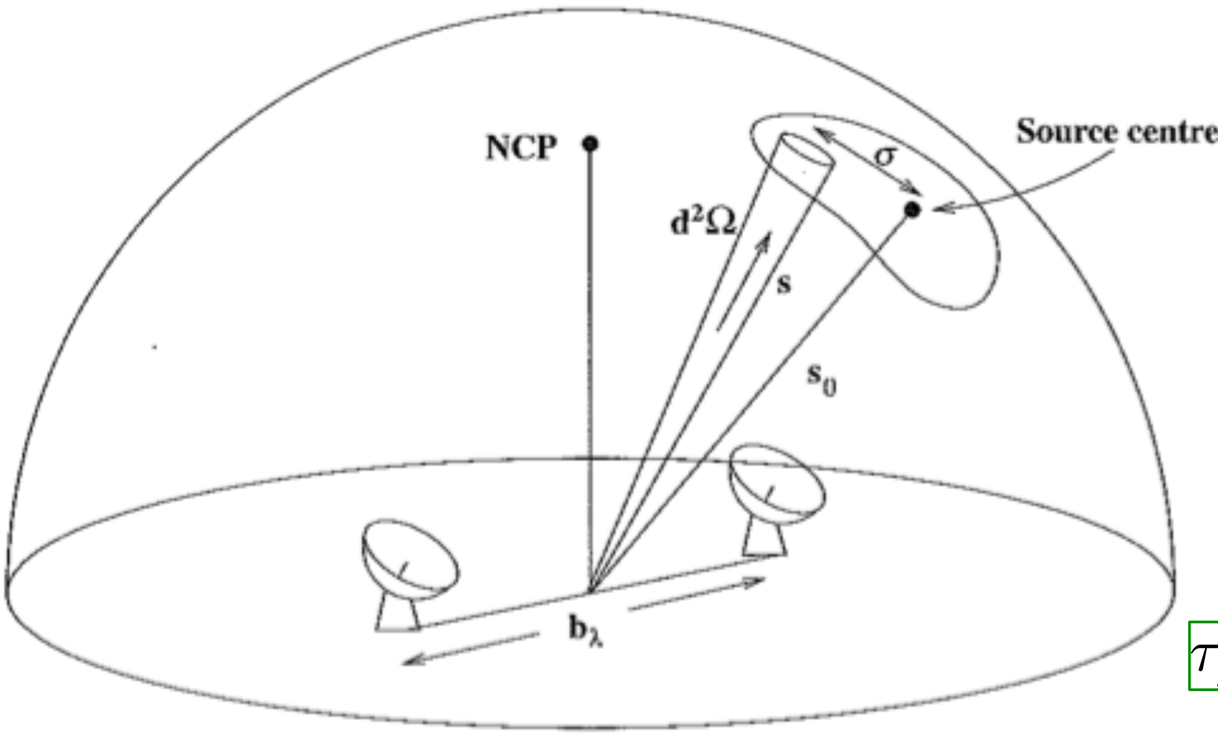
$$\tau_i = \tau_g = \boldsymbol{b} \cdot \boldsymbol{s}/c$$

$$S_{xy}(\nu_0, \boldsymbol{s}) = \int_{\nu_0 - \mathcal{B}/2}^{\nu_0 + \mathcal{B}/2} A(\nu, \boldsymbol{s}) F_\nu \exp(\quad i2\pi\nu\tau_g) d\nu$$

$$\approx A(\nu_0, \boldsymbol{s}) F_{\nu_0} \exp(\quad i2\pi\nu_0\tau_g) \mathrm{sinc}(\mathcal{B}\tau_g)$$

interferometer response attenuated

Effect of finite source size



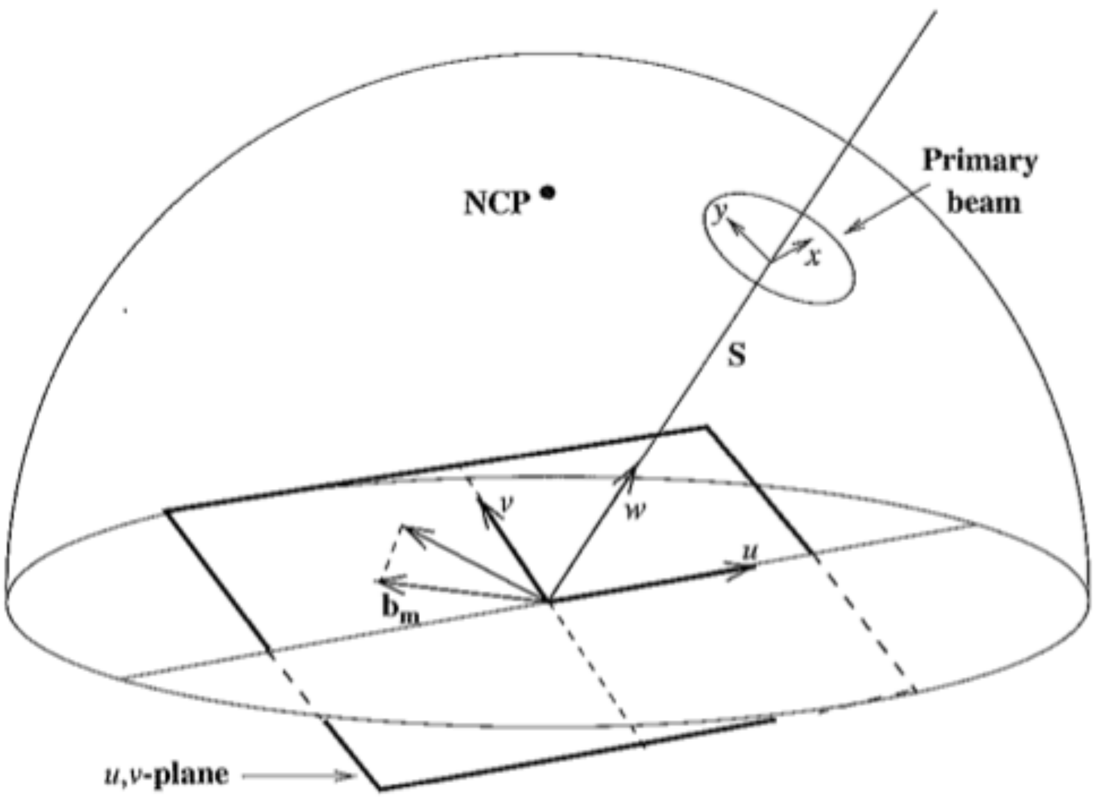
$$\boxed{\tau_g - \tau_i = \boldsymbol{b}_{ij} \cdot \sigma / c}$$

$$S_{xy}(\nu_0, \boldsymbol{s}_0) \approx \int_{4\pi} A(\boldsymbol{s}_0 + \sigma) B_{\nu_0}(\boldsymbol{s}_0 + \sigma) \exp[\mathrm{i}2\pi\nu_0(\tau_g - \tau_i)] \mathrm{sinc}[\underline{\mathcal{B}(\tau_g - \tau_i)}] d\Omega$$

small

Fringe visibility: $V_{ij} \equiv \int \mathcal{A}(\sigma) B_\nu(\sigma) \exp\left(2\pi i \boldsymbol{b}_{ij,\lambda} \cdot \sigma\right) d\Omega$

u-v plane



$$\boldsymbol{b}_{ij,\lambda} = u\boldsymbol{e}_u + v\boldsymbol{e}_v + w\boldsymbol{e}_w$$

$$\sigma = x\boldsymbol{e}_u + y\boldsymbol{e}_v$$

$$V_{ij} \equiv \int \mathcal{A}(\sigma) B_\nu(\sigma) \exp\left(2\pi i \boldsymbol{b}_{ij,\lambda} \cdot \sigma\right) d\Omega$$

$$\Rightarrow \quad V(u,v) = \int \mathcal{A}(x,y) B_\nu(x,y) \exp\left[\mathrm{i}2\pi(ux+vy)\right] dx\,dy$$

General properties

$$\boxed{\tau_g - \tau_i = \boldsymbol{b}_{ij} \cdot \sigma / c}$$

Recall:

$$S_{xy}(\nu_0, \boldsymbol{s}_0) \approx \int_{4\pi} A(\boldsymbol{s}_0 + \sigma) B_{\nu_0}(\boldsymbol{s}_0 + \sigma) \exp[\mathrm{i}2\pi\nu_0(\tau_g - \tau_i)] \mathrm{sinc}[\underbrace{\mathcal{B}(\tau_g - \tau_i)}_{\text{small}}] d\Omega$$

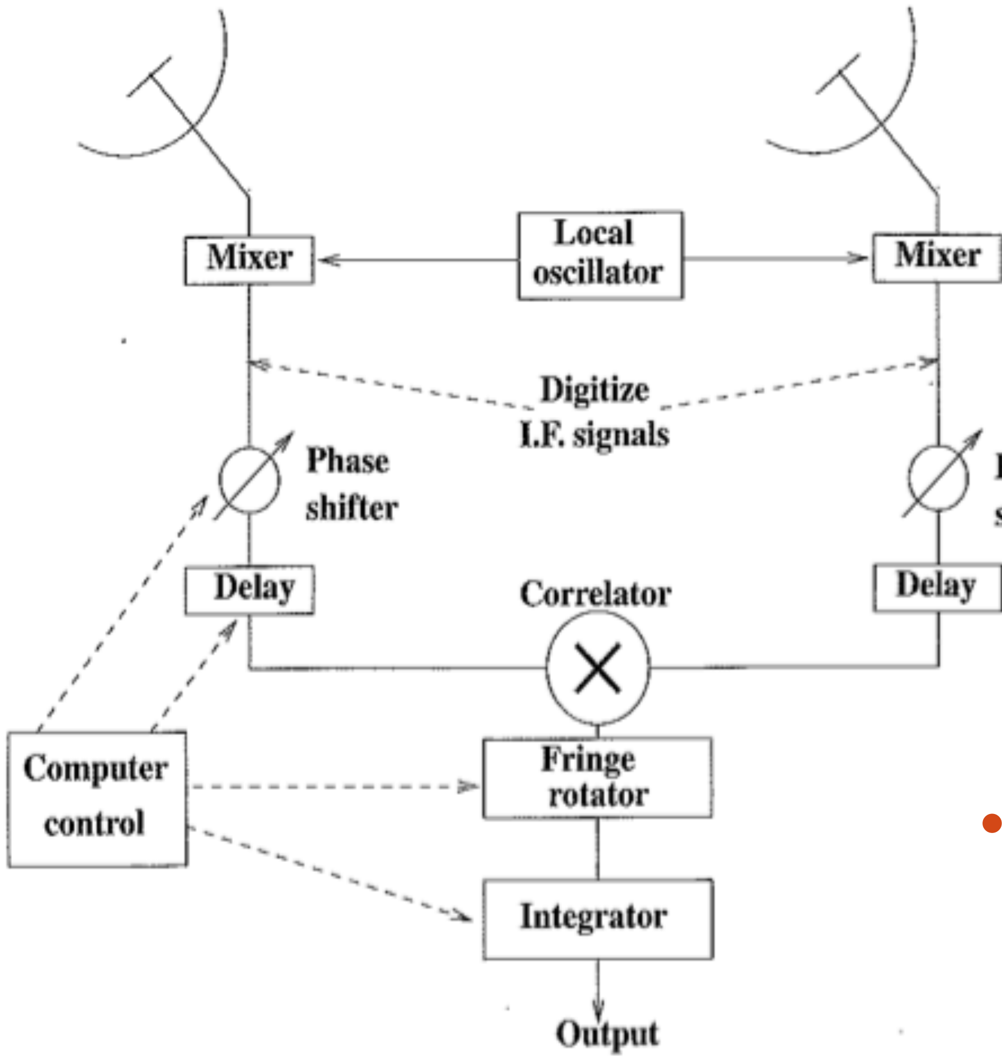
$$V_{ij} \equiv \int \mathcal{A}(\sigma) B_\nu(\sigma) \exp\left(2\pi i \boldsymbol{b}_{ij,\lambda} \cdot \sigma\right) d\Omega$$

- Interferometers have the same field of view as individual antennas.
- Bandwidth has to be narrow in high-resolution observations.

$$\frac{\Delta\nu}{\nu_0} \ll \frac{\theta_{\mathrm{res}}}{\theta_{\mathrm{fov}}}$$

- Visibility is zero if surface brightness is constant.

Practical interferometers



Local oscillators must be coherent

Extra phase difference raised from individual receivers

Geometric time delay

- Different antennas have different effective areas, etc.

$$A(\sigma) \rightarrow A_{\text{eff}}(\sigma) \equiv \sqrt{A_1(\sigma)A_2(\sigma)}$$

Interferometer arrays

- N antennas => $N(N\text{-}1)/2$ pairs of baselines
- Each interferometer pair makes a curve on the u-v plane, as the Earth rotates
- Resolution: $\sim \lambda$ / longest baseline
- Field of view: same as individual antennas
- Sensitivity: lowered by the beam dilution factor $\sim(L/D)^2$
- Capability relies on receivers and electronics

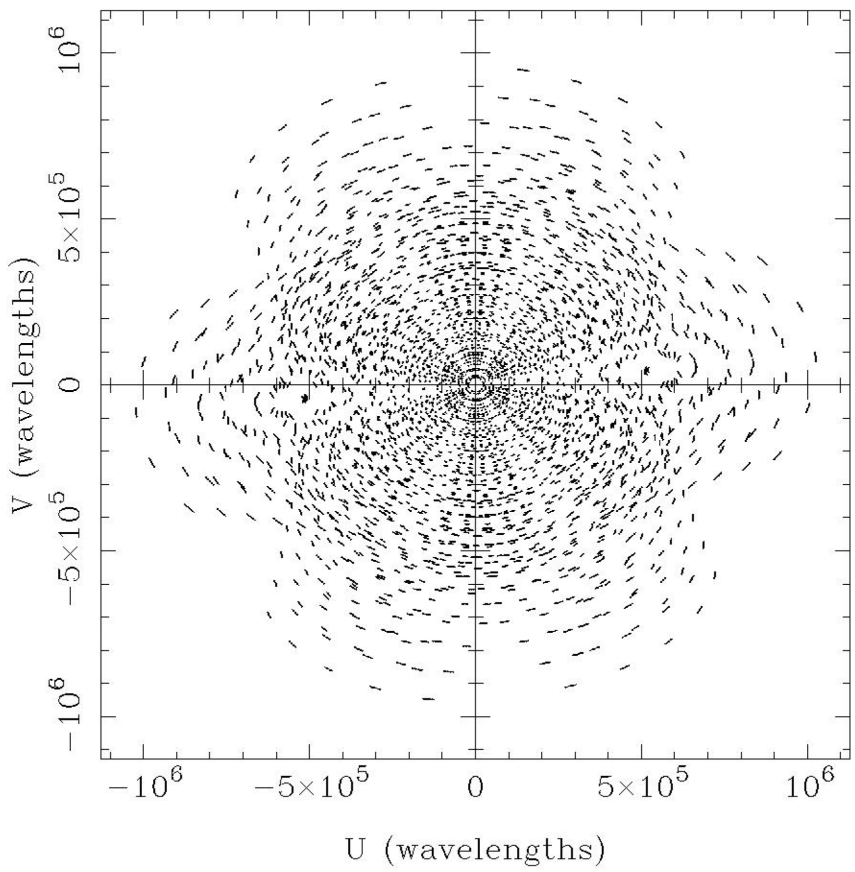
Very Large Array

Located on the plains of San Agustin in West-Central New Mexico

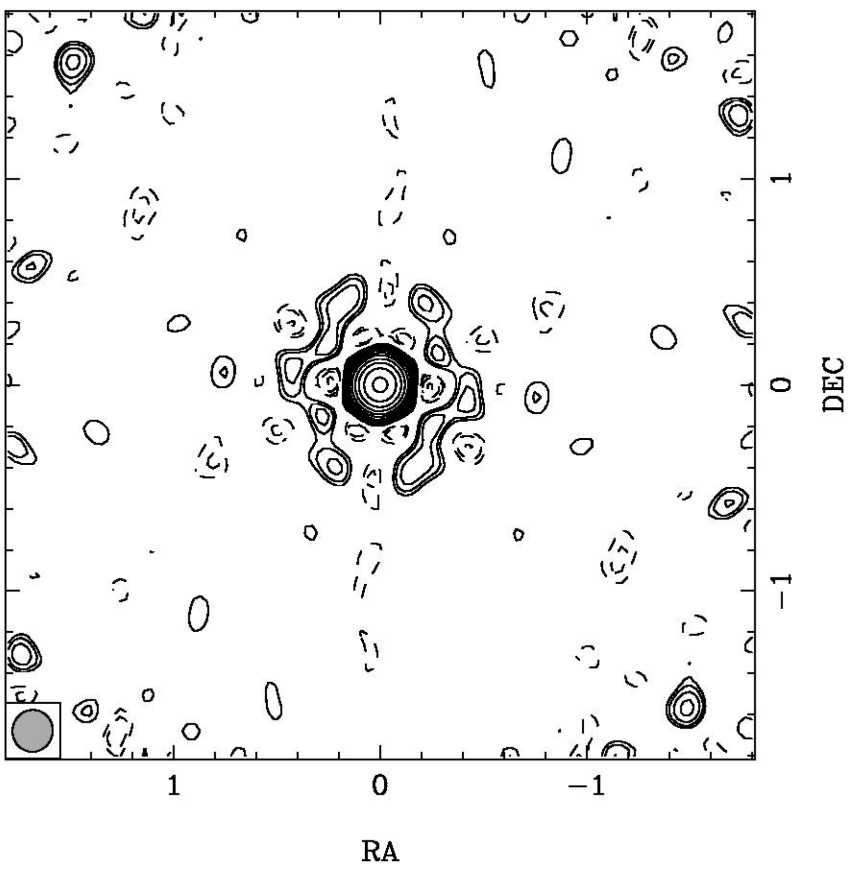
EVLA: basic facts

- 27 independent antennas of 25m each
- Distributed in Y-shape along railroad tracks
- Configurations A-D, with baseline of 36 km – 1 km
- Upgraded with state of the art receivers and electronics recently
- Frequency accessibility: 1.0-50 GHz, 8 GHz bandwidth (maximum)
- Spectral resolution up to 1 Hz
- Angular resolution up to 20 mas at 10 GHz
- Point-source sensitivity better than 1 micro-Jy at 2-40 GHz

u-v plane coverage by the VLA

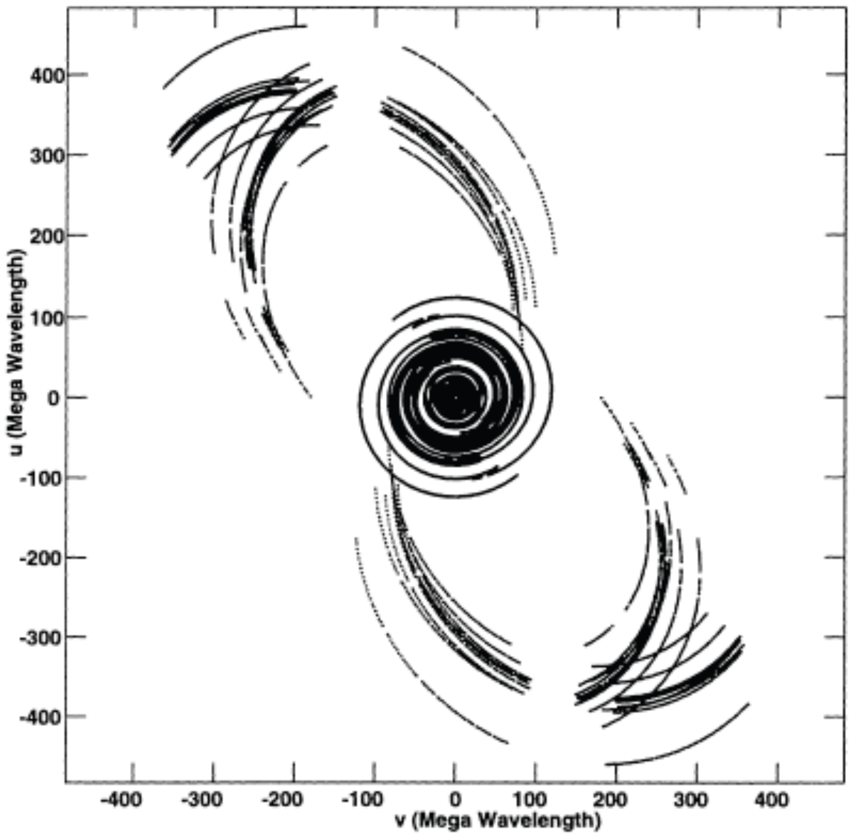


uv-plane coverage



PSF

Aperture synthesis



Goal: construct images from partial coverage in the u-v plane

- Lots of Fourier components are missing
- Synchronization of clocks
- Phase error from the atmosphere and individual receivers
- Voltage gains from the antennas are different

Calibration

- Flagging: check for "bad baselines" for removal.
- Phase and flux calibrators: nearby strong point radio sources
- Closure relation for phase calibration

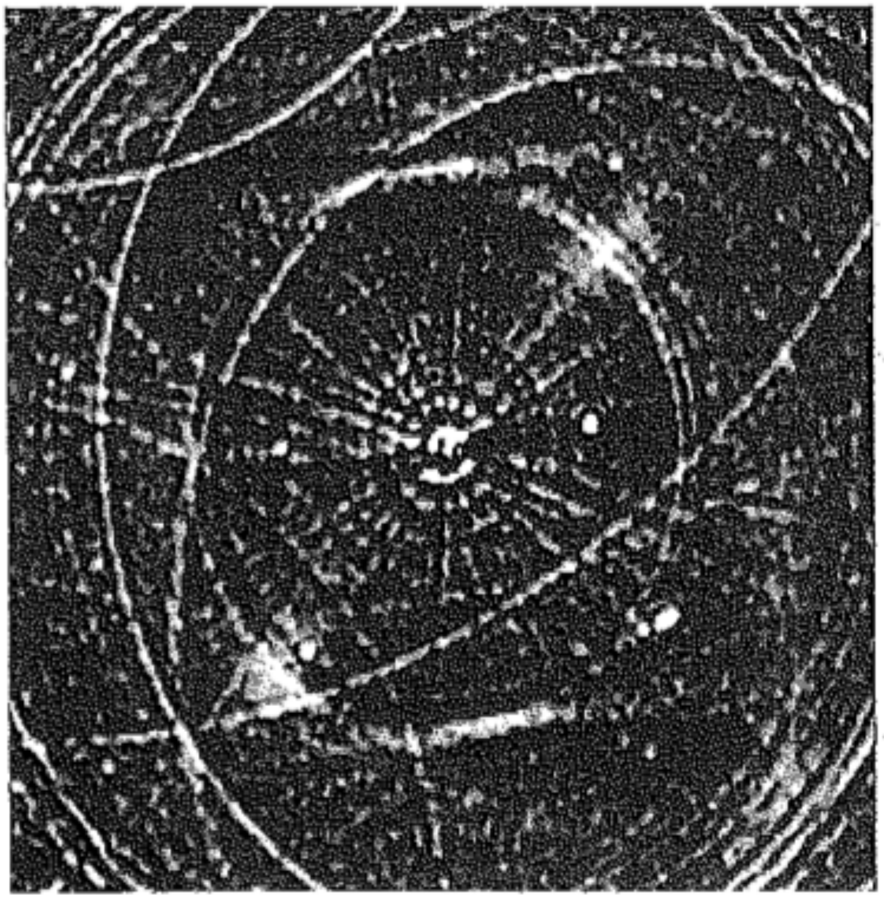
$$\phi_{ijk} \equiv \phi_{ij} + \phi_{jk} + \phi_{ki}$$

- Closure relation of fringe amplitude (for gain calibration)

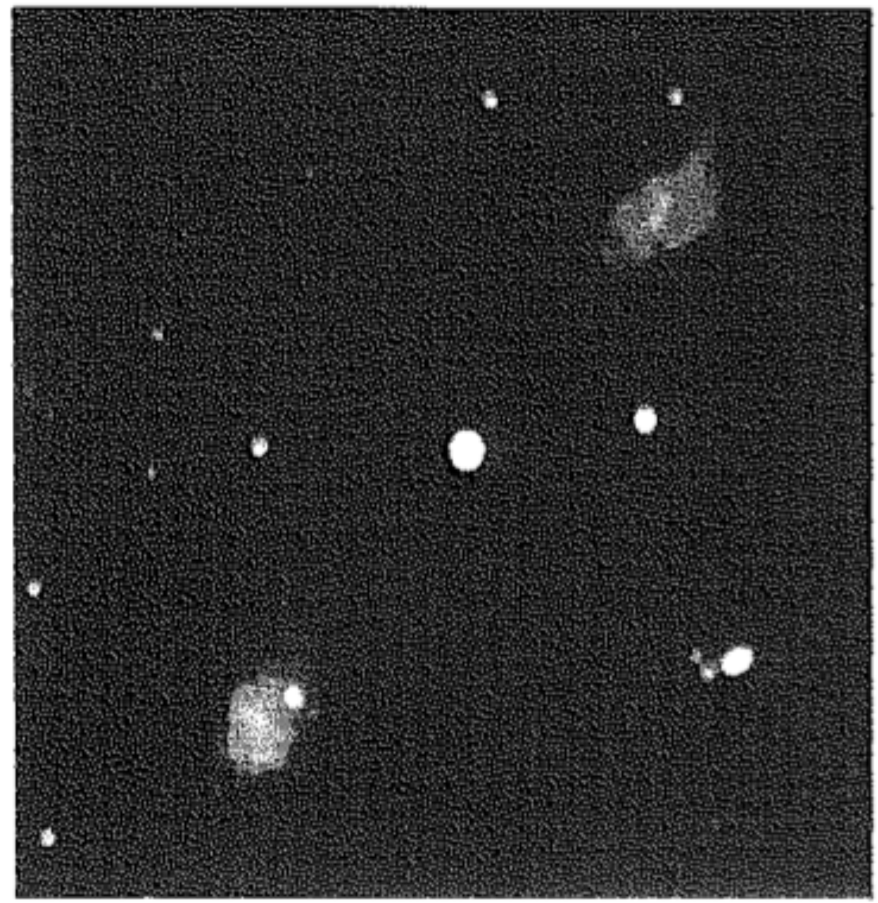
$$A_{ijkl} \equiv \frac{|V_{ij}||V_{kl}|}{|V_{ik}||V_{jl}|}$$

- More antennas => Better calibration
- Intense computation is involved.

Image cleaning



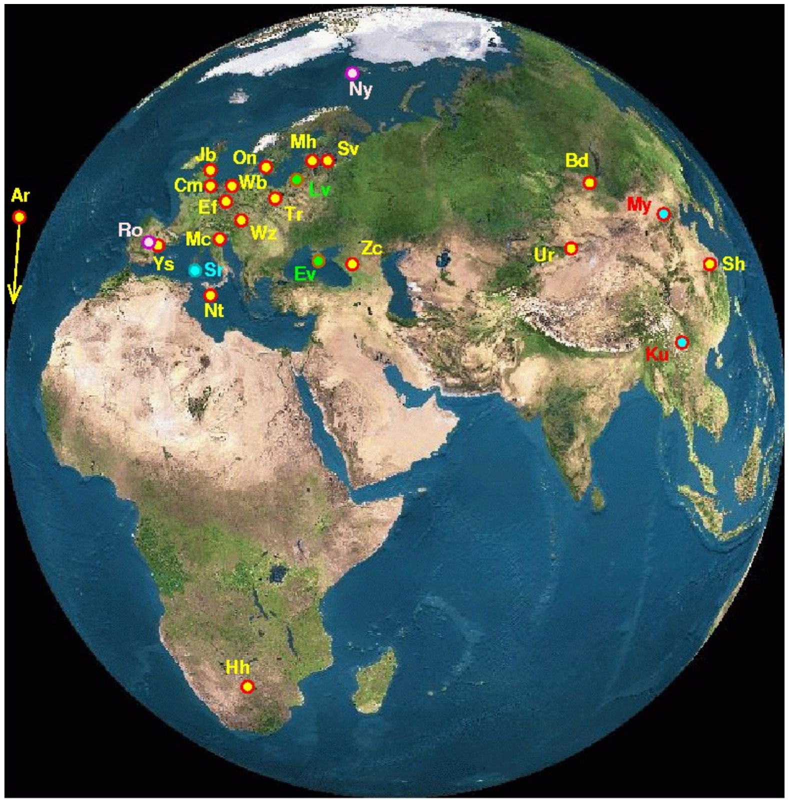
dirty beam



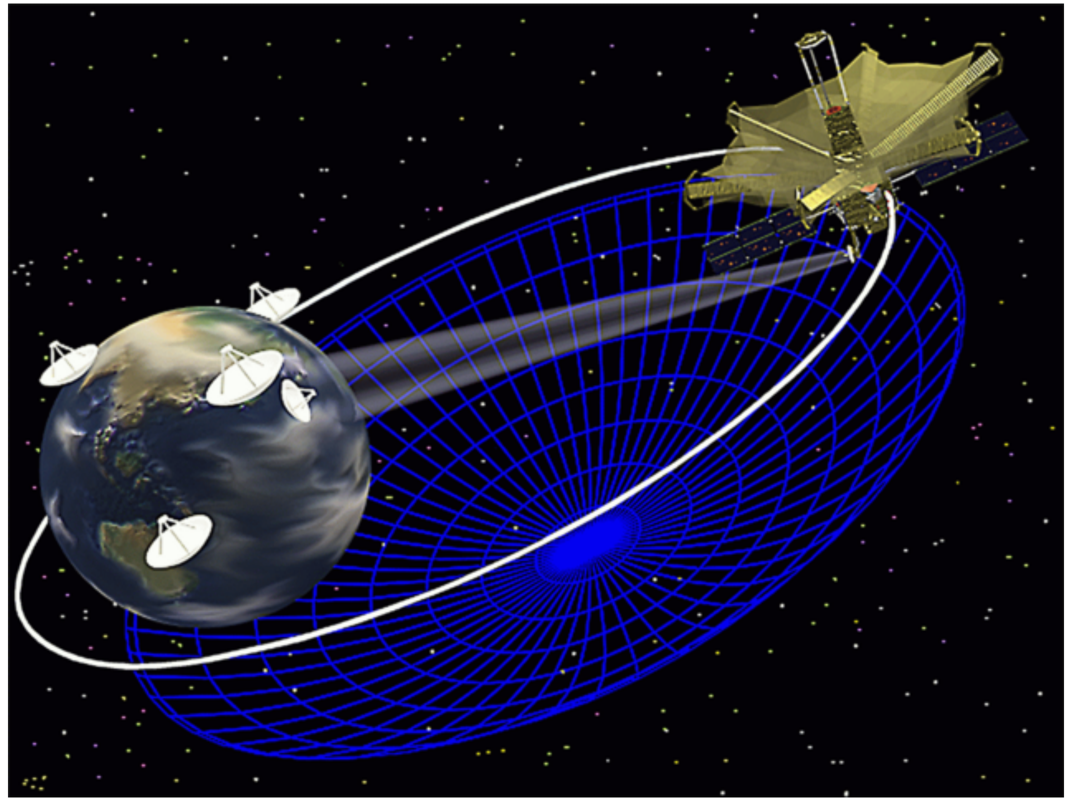
after being CLEANed

Involves CLEAN, hybrid-mapping, and self-calibration, computationally intensive.

Very-long baseline interferometry



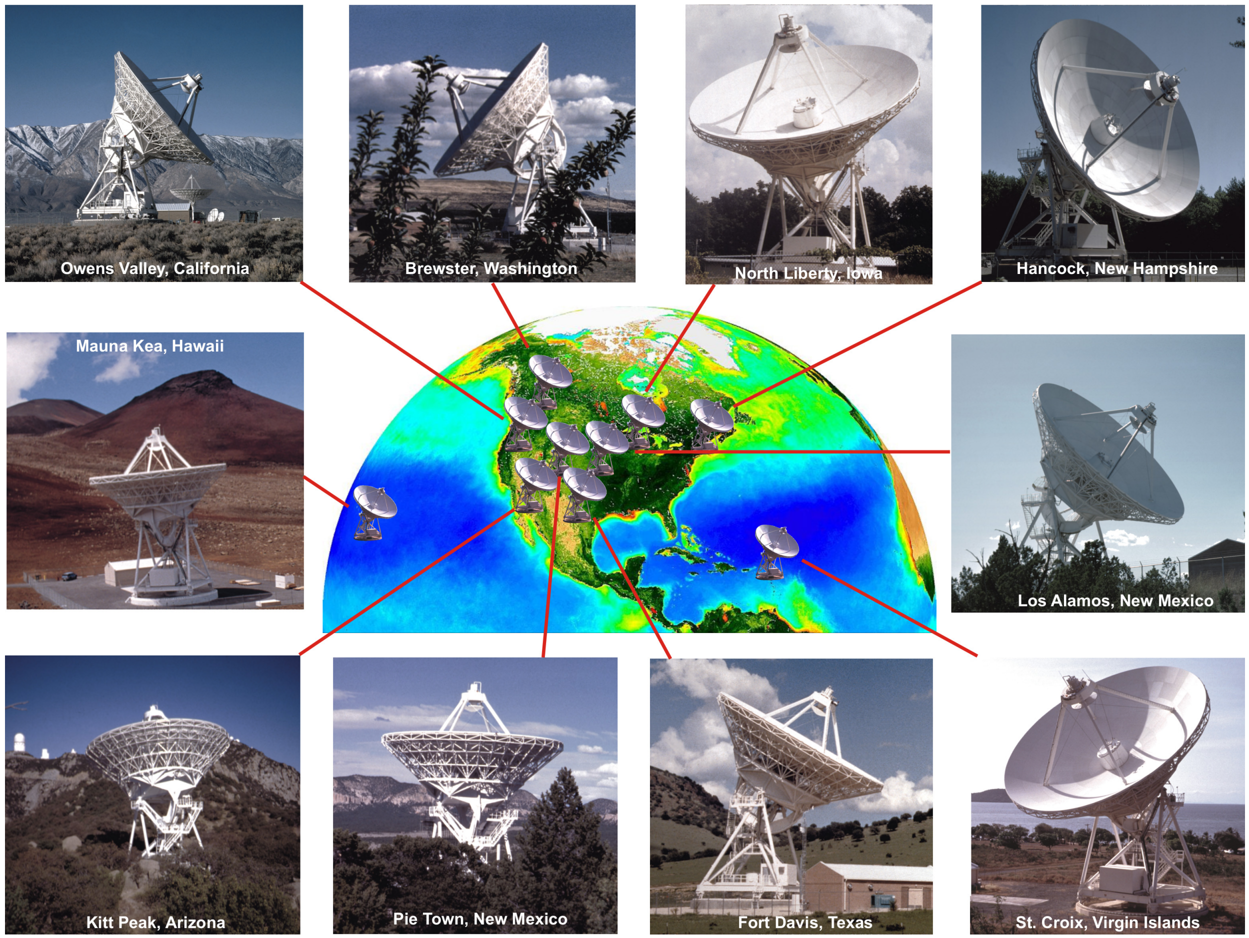
European VLBI Network



space VLBI

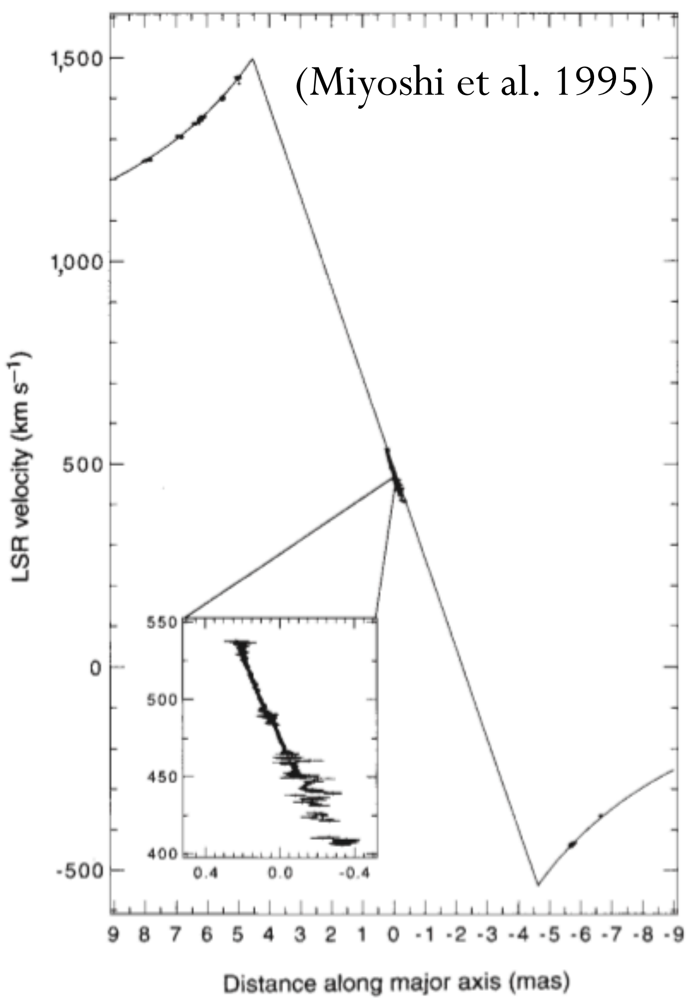
- Signal recorded by tapes/disks and brought together for correlation

Very-long baseline array (VLBA)

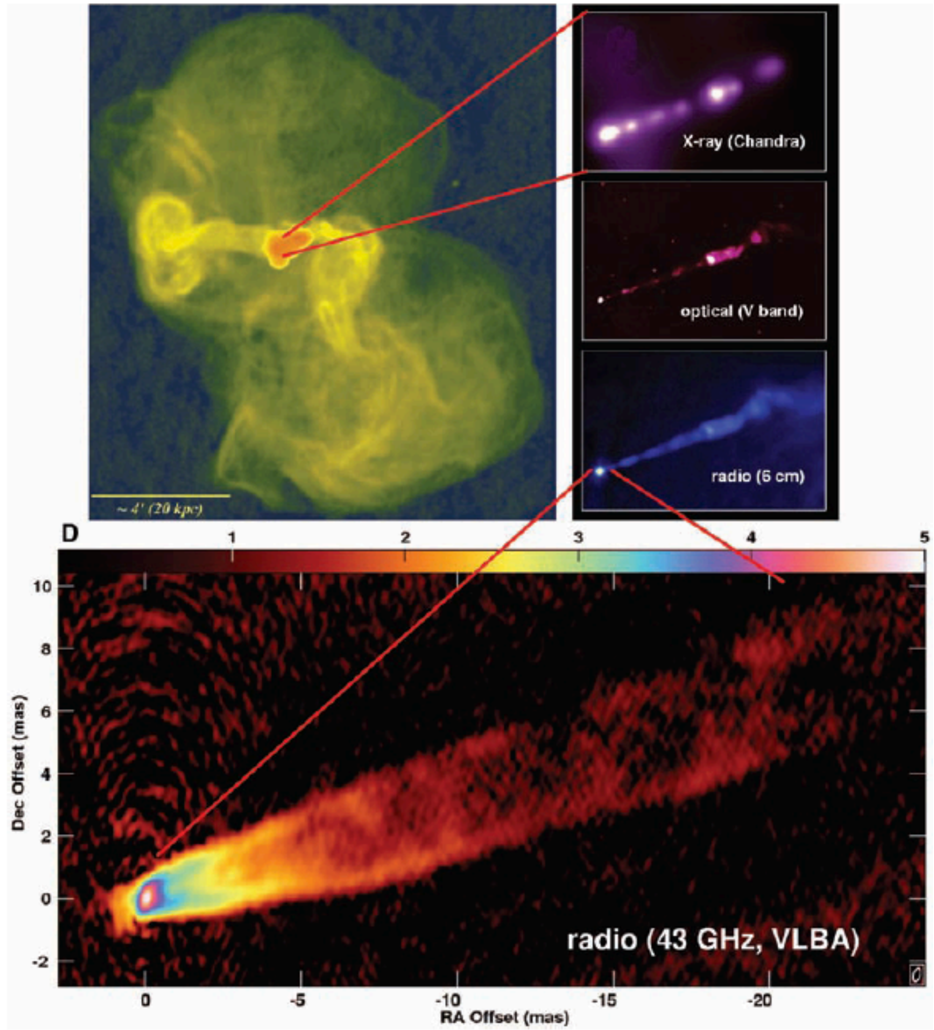


- NRAO facility of 10 radio-telescopes, 25m each.
- Located from Hawaii to Virgin Islands, baseline >5000 miles

Famous results from VLBA



water maser surrounding the SMBH of NGC 4258
=> SMBH mass $\sim 3.6 \times 10^7 M_\odot$



resolving the jet-launching region of M87

Millimeter interferometory

- Frequency is high: signal processing is more demanding
- Small dishes are used: reduced sensitivity
- Strong emission from water vapor and oxygen: reduced sensitivity

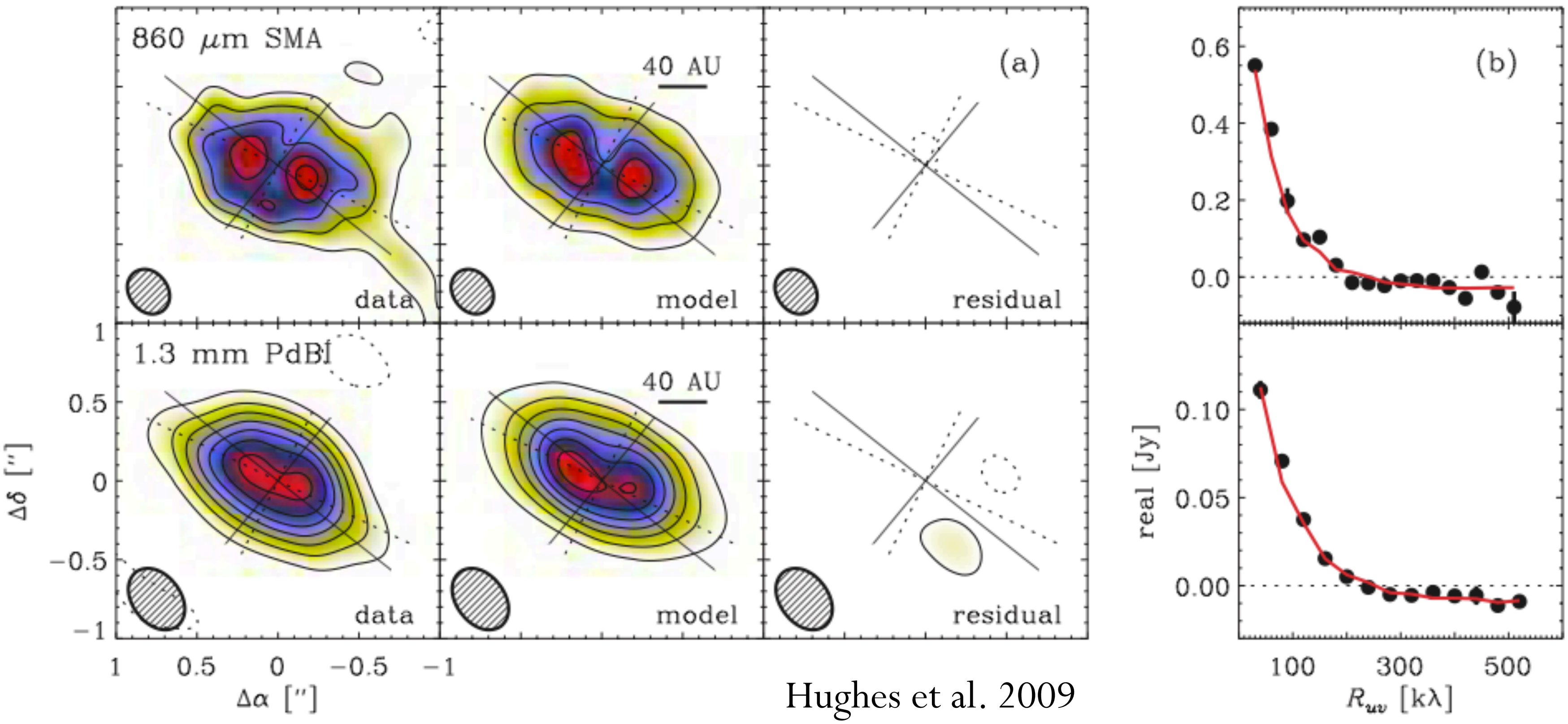
Submillimeter array at Mauna Kea

- Atmospheric effect: phase correction is difficult
- Water vapor content rapidly varying: phase stability issues

Example from the sub-millimeter array

Image

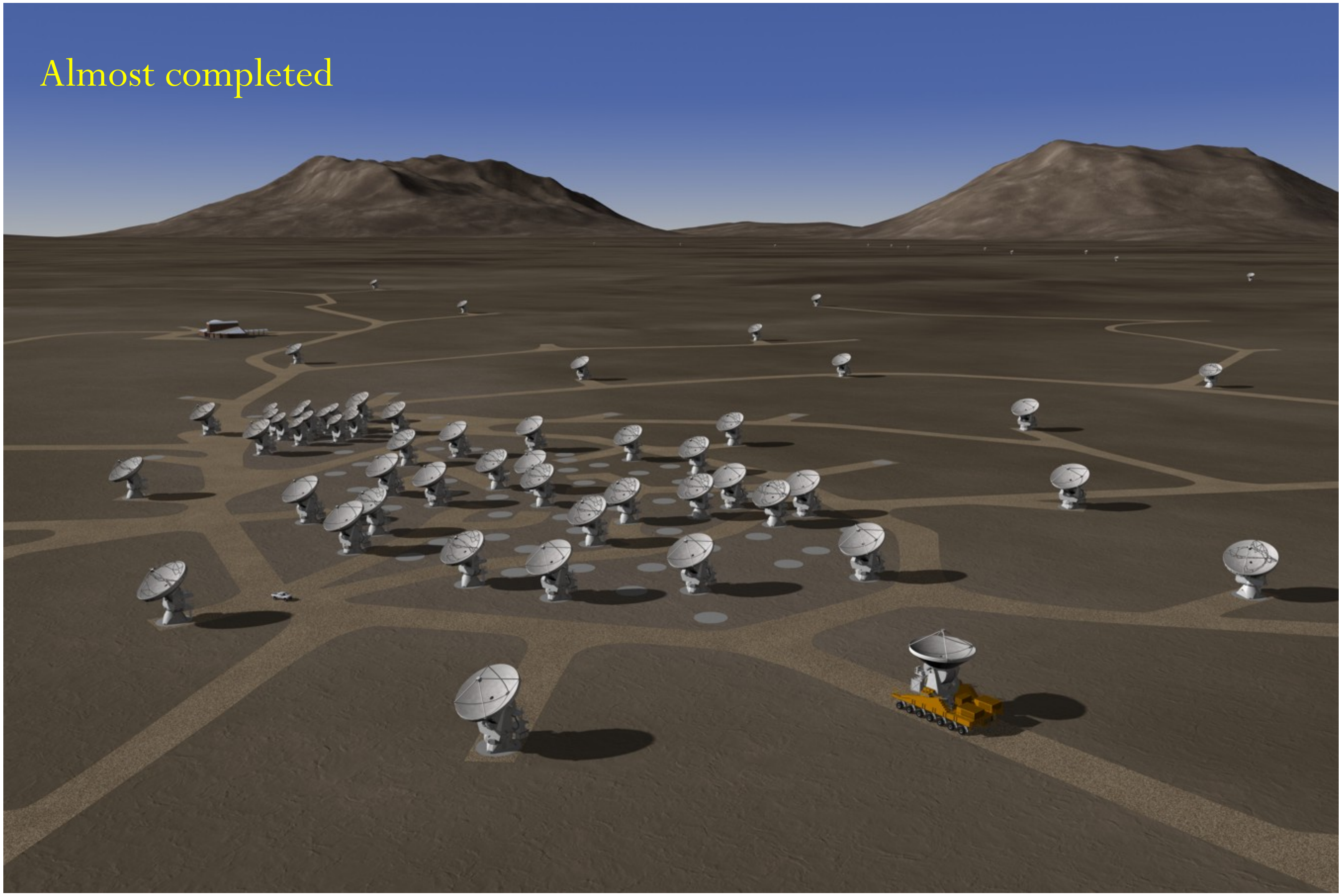
Visibility



Hughes et al. 2009

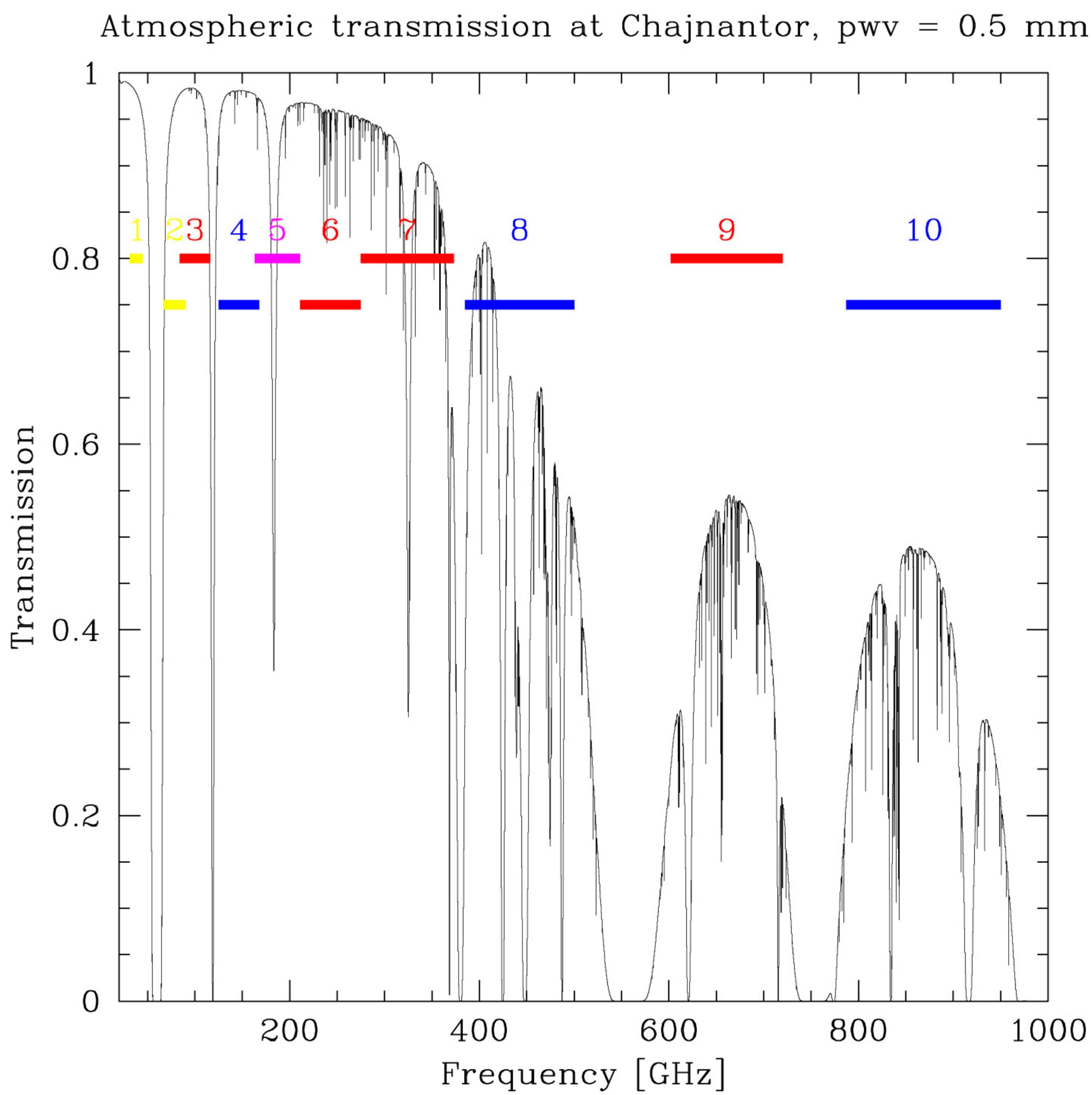
A spatially resolved inner hole in the disk around GM Aurigae

Atacama Large Millimeter/sub-mm Array



Location: Chajnantor plain, Chile (altitude ~5000m)

ALMA: bands and atmospheric transmission



ALMA: Basic Facts

- Arrays: 50 Antennas of 12m each
- Wavelength: 0.4-3mm (84-720 GHz)
- FWHM of the primary beam: 21" (at 300 GHz)
- Baseline: 125m – 16 km
- Spatial resolution: 4.8"-37 mas (at 110 GHz)
- Spectral resolution: 3.8 kHz – 2GHz (0.01 km/s at best!)
- Sensitivity: ~mJy for 60s integration
- Science: high-*z* universe, star/planet formation, …

Summary

- Radio telescopes use heterodyne receivers
- Observable from two-element interferometer: fringe visibility
- u-v plane: Fourier counterpart of the sky
- Interferometers make use of the Earth rotation to achieve large coverage in the u-v plane
- Aperture synthesis: image reconstruction from the u-v plane

Tri-State ALMA Community Day 2011

When:

May 27, 2011, from 9am to 5pm.

Where:

Columbia University, Department of Astronomy (directions forthcoming).

Why:

The Atacama Large Millimeter/submillimeter Array (ALMA) has now released its "Cycle 0" Early Science call for proposals. To ensure that the North American community is prepared to participate fully during ALMA's ES phase, the North American ALMA Science Center (NAASC) at the National Radio Astronomy Observatory in Charlottesville, Virginia is supporting a number of "Community Days" across the country, which will introduce ES capabilities and the software tools required to develop and submit ALMA ES proposals. We have agreed to host one such Community Day for astronomers in the tri-state (Connecticut, New Jersey, and New York) area.

Who:

This event is being organized by Andrew Baker (Rutgers, ajbaker[at]physics.rutgers.edu), Héctor Arce (Yale), Jill Knapp (Princeton), Jin Koda (Stony Brook), Mary Putman (Columbia), and Jacqueline van Gorkom (Columbia). All graduate students, postdocs, and faculty in the tri-state area are welcome to attend.

How:

Please register for the May 27th event at the main NRAO website, making sure to provide information about your laptop's operating system if you plan to stay for one or both of the afternoon "hands-on" tutorial sessions. Important: registration for the "hands-on" sessions will close on May 6th.