Millimeter interferometry for the next decade : The ALMA project

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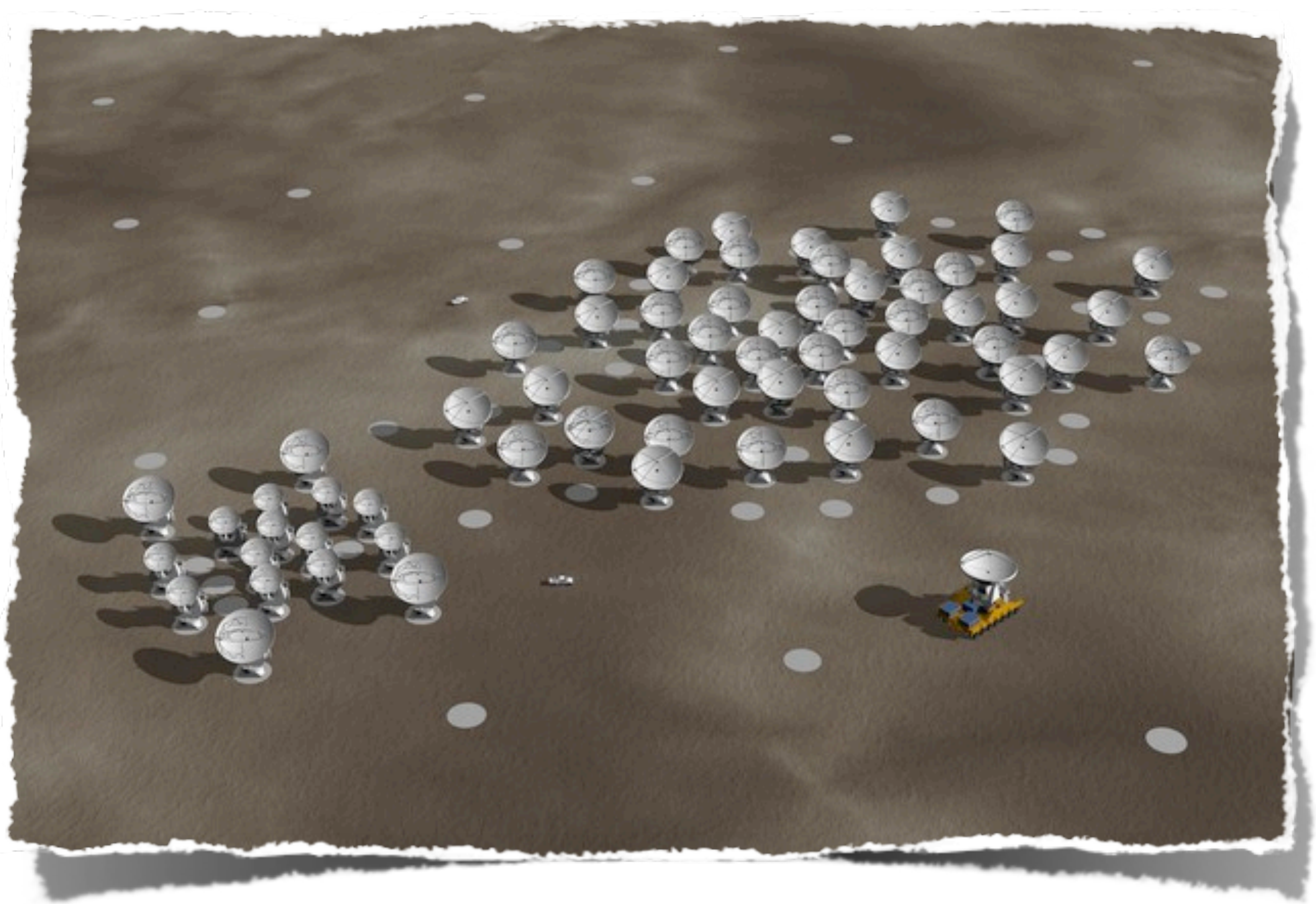


Overview

History of radio-astronomy in a single slide !

- From Maxwell's equations to the discovery of the Cosmic Microwave Background

The issue of angular resolution

- Observing with a single antenna
- The need for higher angular resolution

Principles of radio interferometry

- The example of Young's experiment
- Radio versus optical interferometry
- Super-synthesis
- Short spacings
- Atmospheric turbulences
- Mosaicing
- Deconvolution

The ALMA project

- Technical specifications
- Science goals and pretty pictures...

Early days of radio-astronomy

1873 Maxwell's equations unify electricity and magnetism. Electromagnetic waves such as visible light can propagate.

1888 Heinrich Hertz builds a system for emitting and receiving EM waves at a wavelength of 5 meters.

1890 Thomas Edison proposes an experiment to detect radio emission from the Sun. Several other experiments are proposed in the later years of the century, but none is successful.

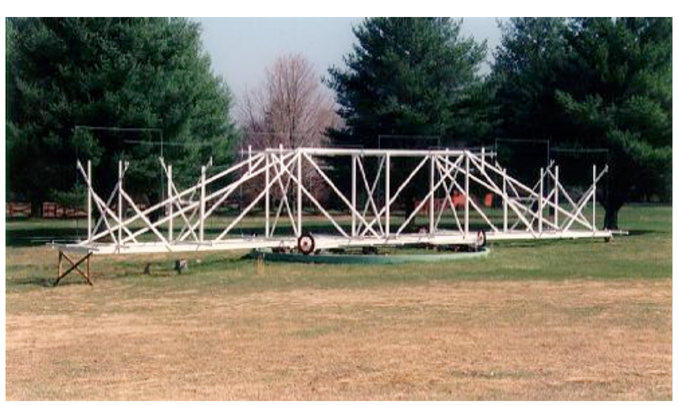
1902 Max Planck discovers the blackbody emission law, and Oliver Heaviside predicts the existence of an ionized layer of the atmosphere acting as a mirror for radio waves. Both findings render detection of cosmic radio emission difficult...

1932 Karl Jansky, a physicist working for Bell Laboratories, discovers continuum radio emission from the Galaxy at 20.5 MHz.

1938 Grote Reber detects Galactic emission at 160 MHz using a parabolic reflector he built, at his own expense, in his backyard. He will single-handedly map the emission over the following years.

1951 Edward Purcell and Harold Ewen detect Galactic neutral hydrogen line emission at 21 cm.

1965 Arno Penzias and Robert Wilson detect a uniform radiation field at 4 GHz, the Cosmic Microwave Background, which is a remnant of the Big Bang, predicted by Robert Dicke and George Gamow in 1946.



Jansky's antenna

Reber's antenna

Ewen and Purcell's antenna

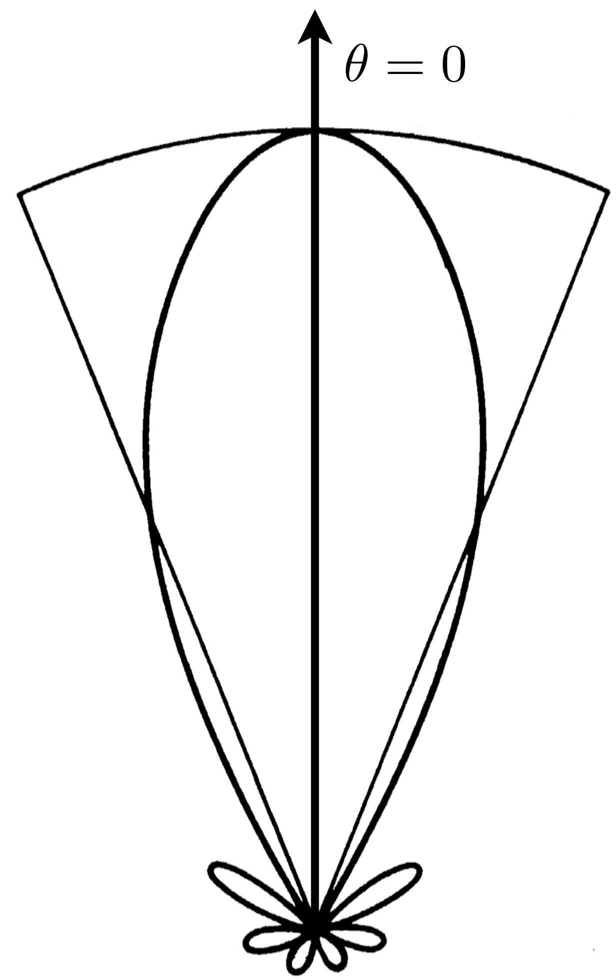
The “single dish” radiotelescope

Direction-dependent sensitivity

Scans towards and around a point source → ***Point Spread Function (PSF) = Diffraction pattern = Beam pattern***

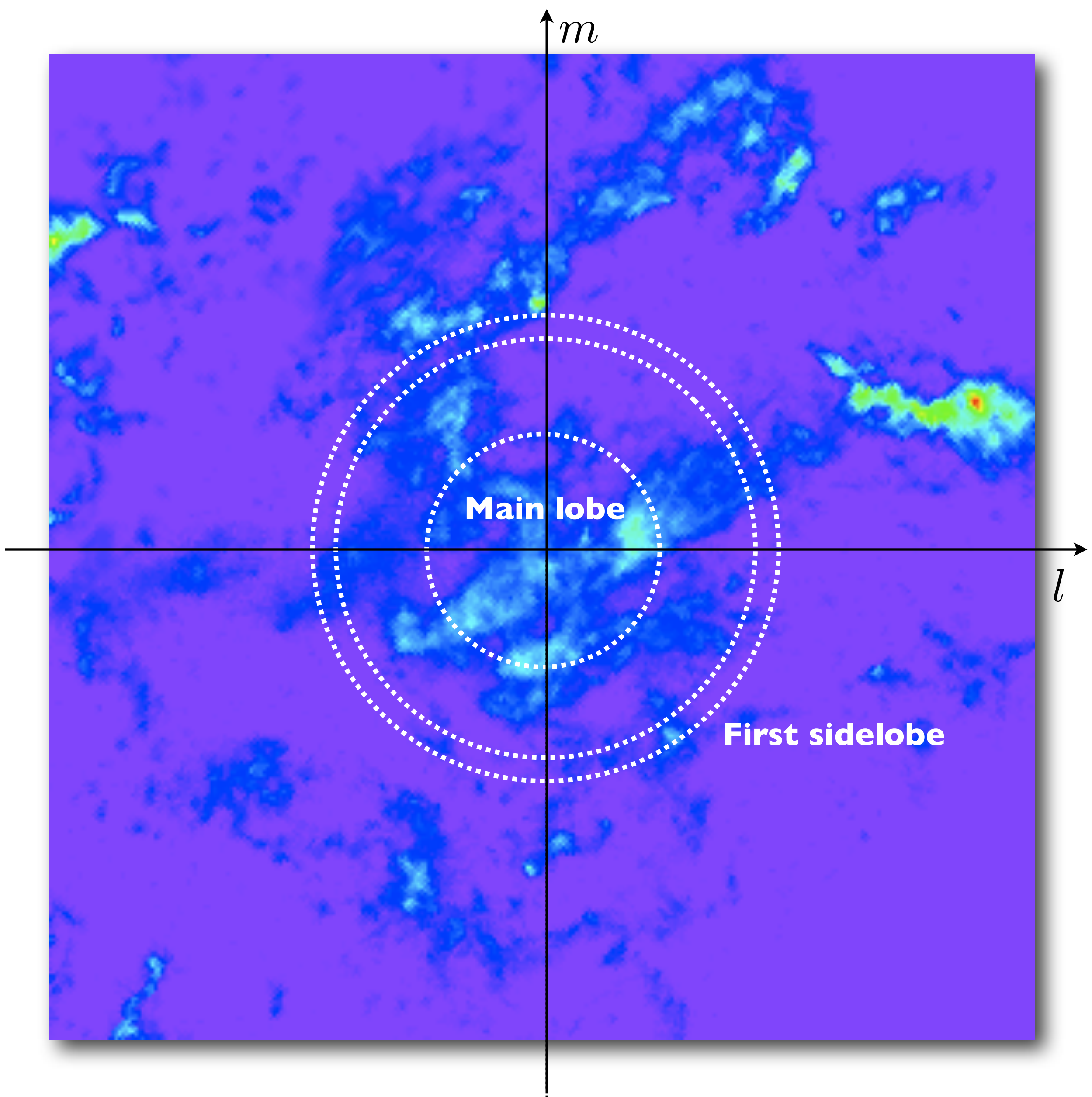
Optical : Airy function

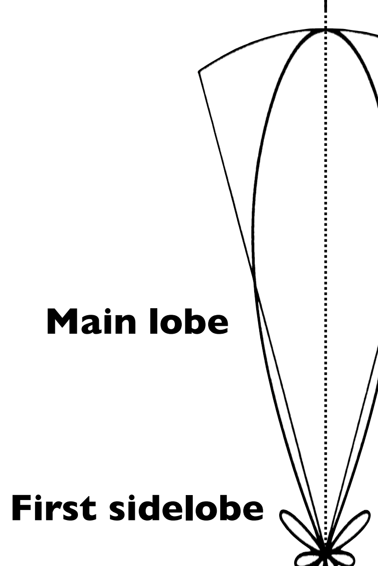
Radio : Gaussian

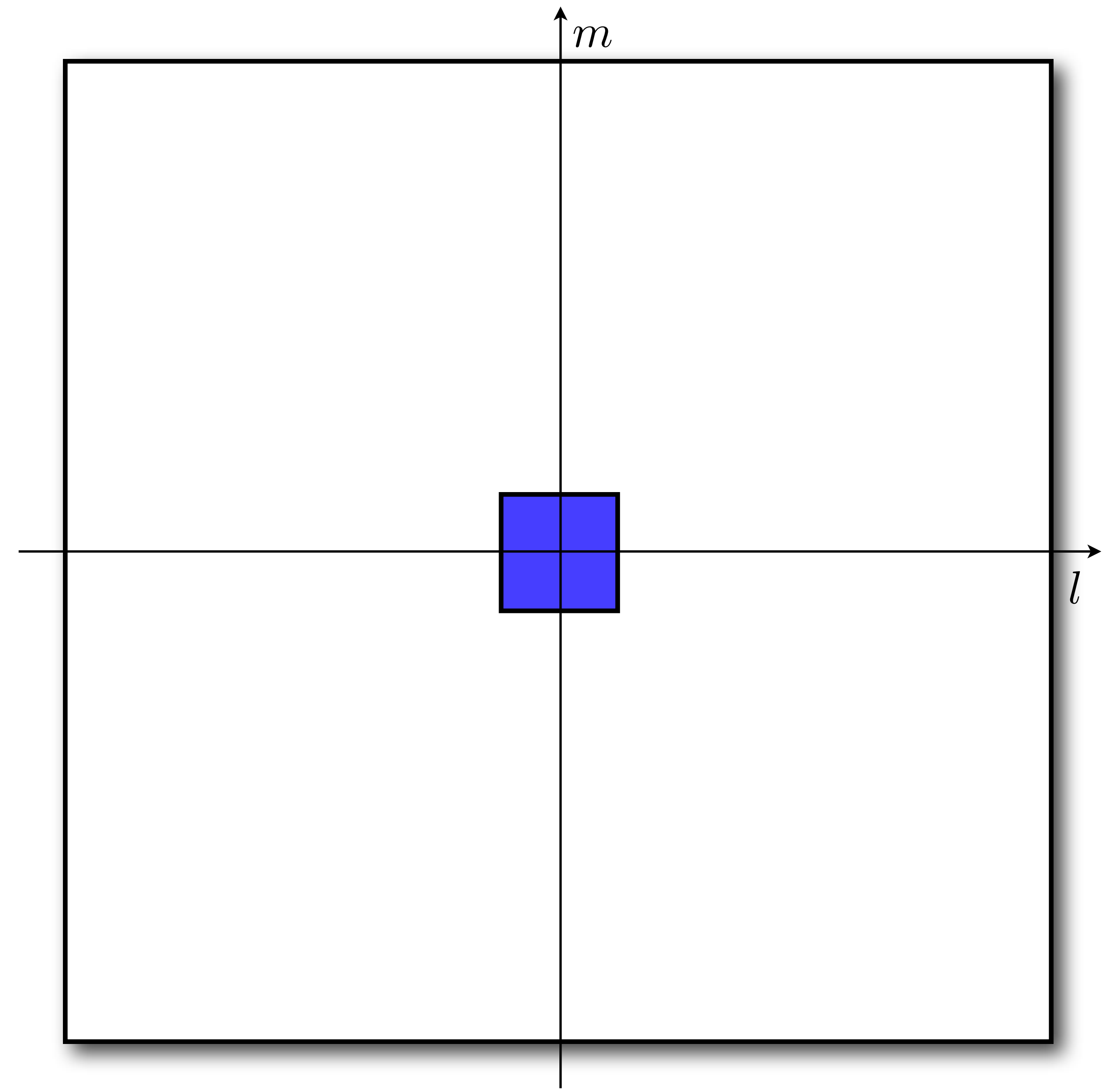


Single dish sensitivity in polar coordinates

Mapping radiation with a single dish antenna



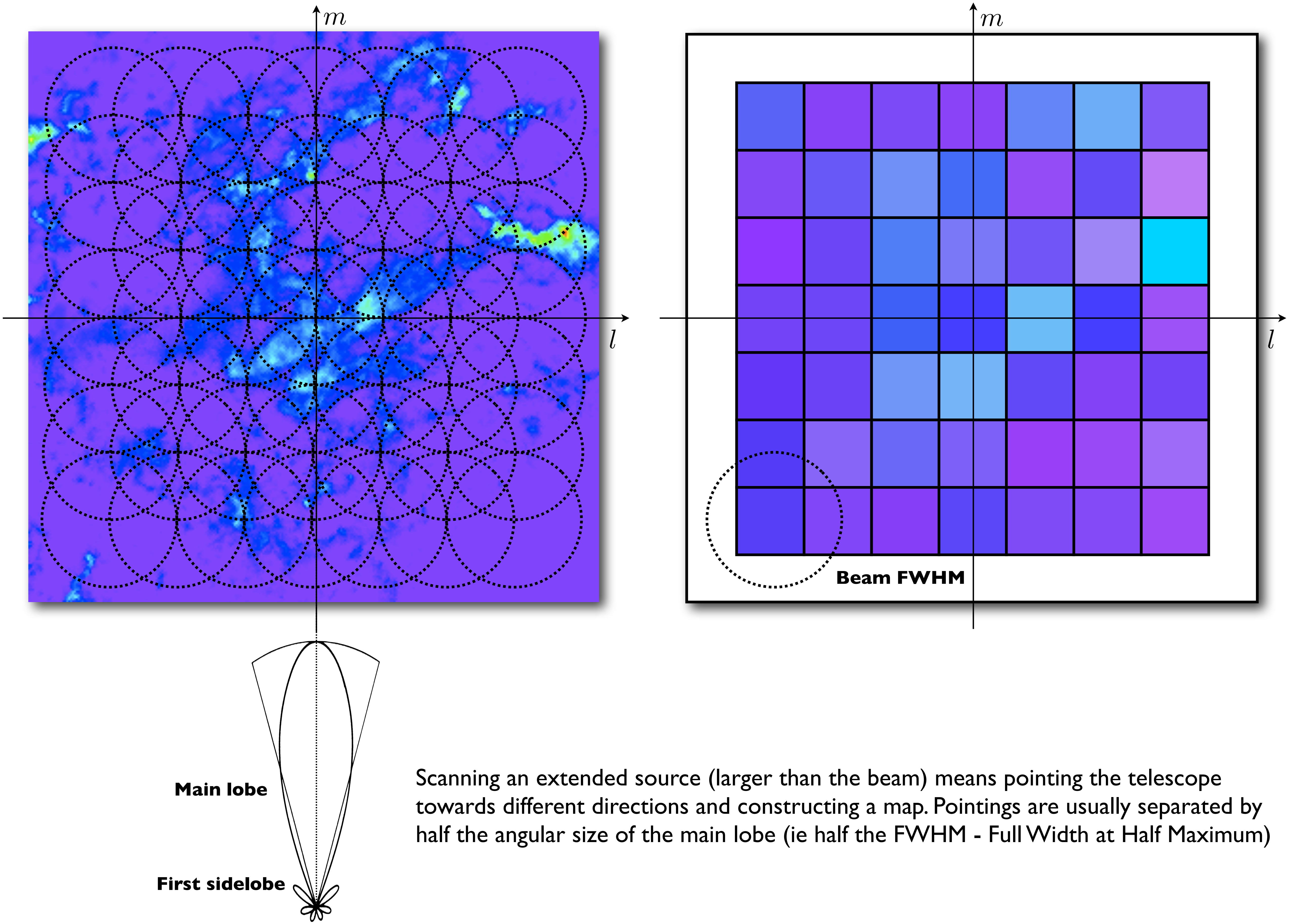




All the emission within the beam is collected by the receiver, weighted by the antenna's sensitivity in each direction, which amounts to a convolution of the brightness distribution by the antenna beam :

$$I(l,m) = \iint P(l-l', m-m') \times I_0(l', m')$$

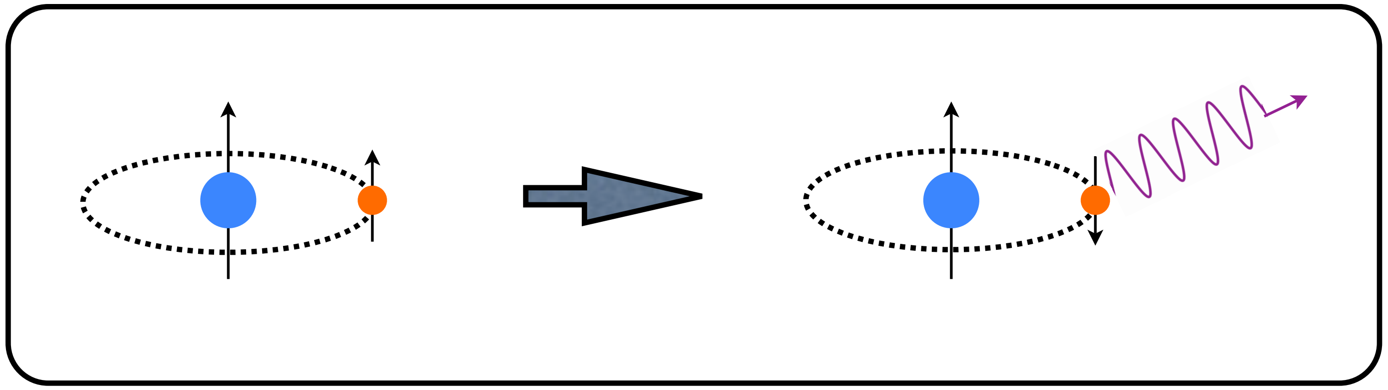
Mapping radiation with a single dish antenna



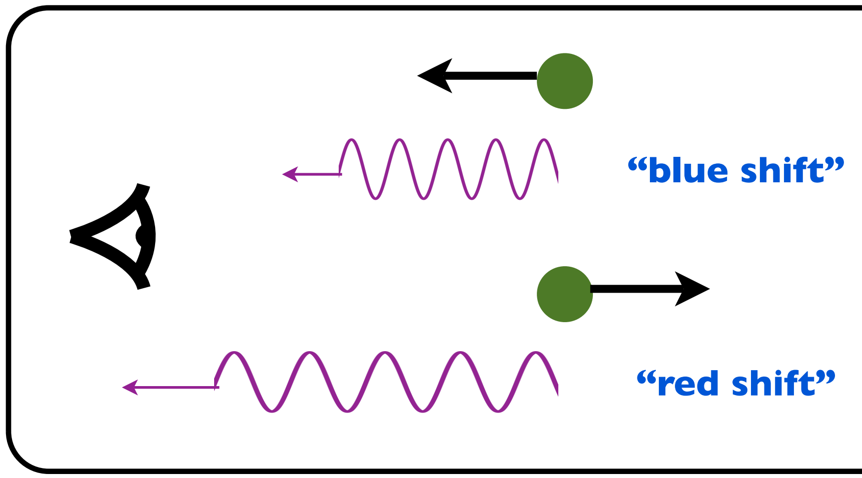
Scanning an extended source (larger than the beam) means pointing the telescope towards different directions and constructing a map. Pointings are usually separated by half the angular size of the main lobe (ie half the FWHM - Full Width at Half Maximum)

Getting to the gas kinematics : spectral lines

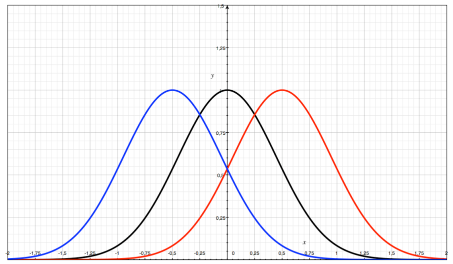
For instance : hyperfine transition of neutral hydrogen (HI) at 21 cm



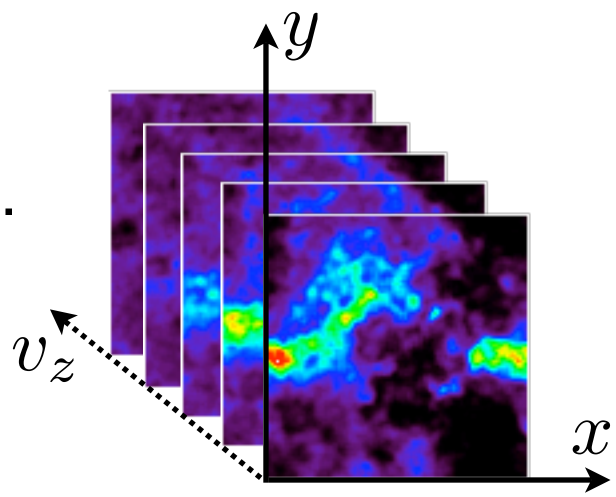
Doppler-Fizeau shift

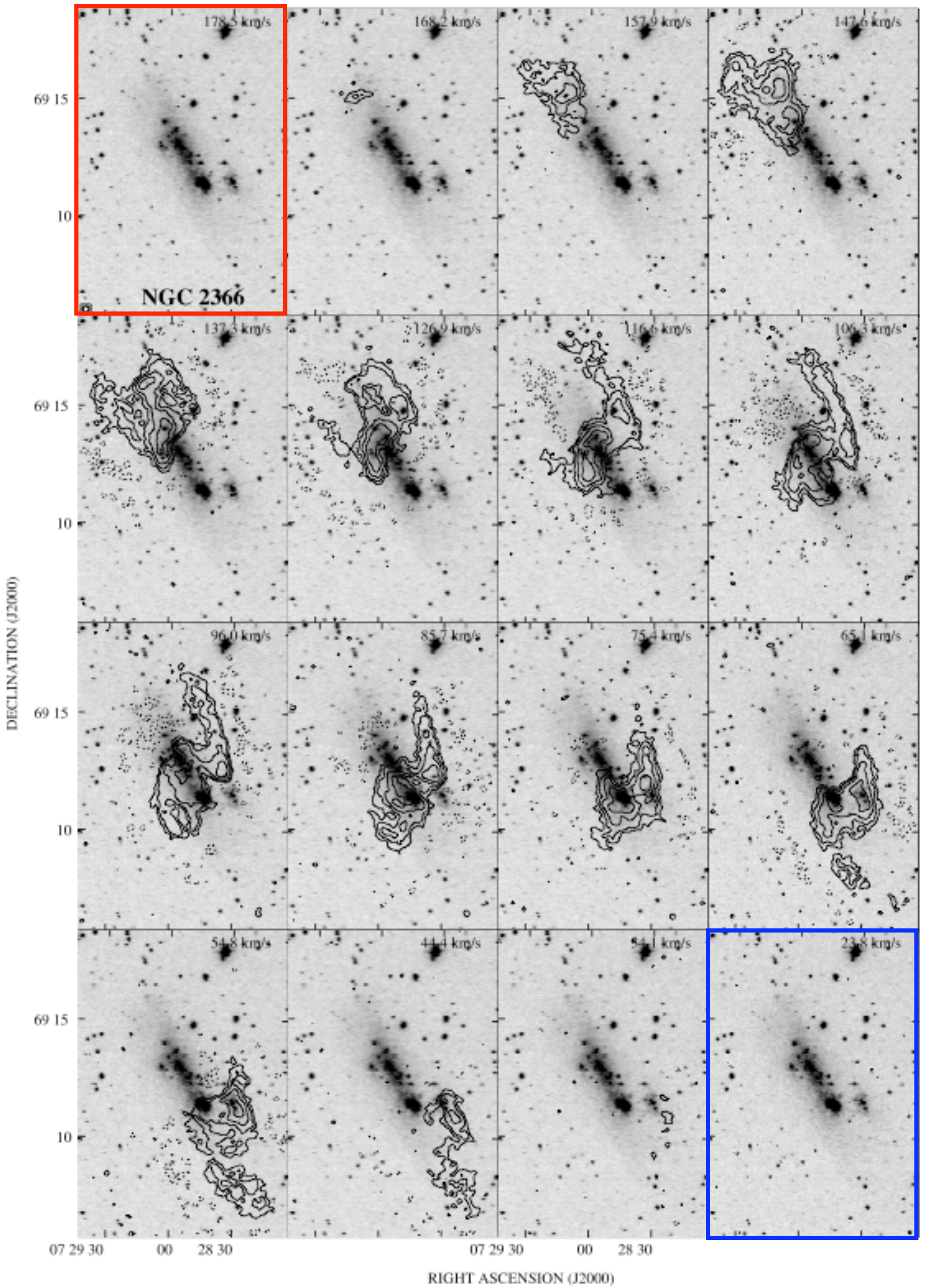


Shift of the emission line



- One spectrum per line of sight.
- Channel maps of the emission at a given velocity.

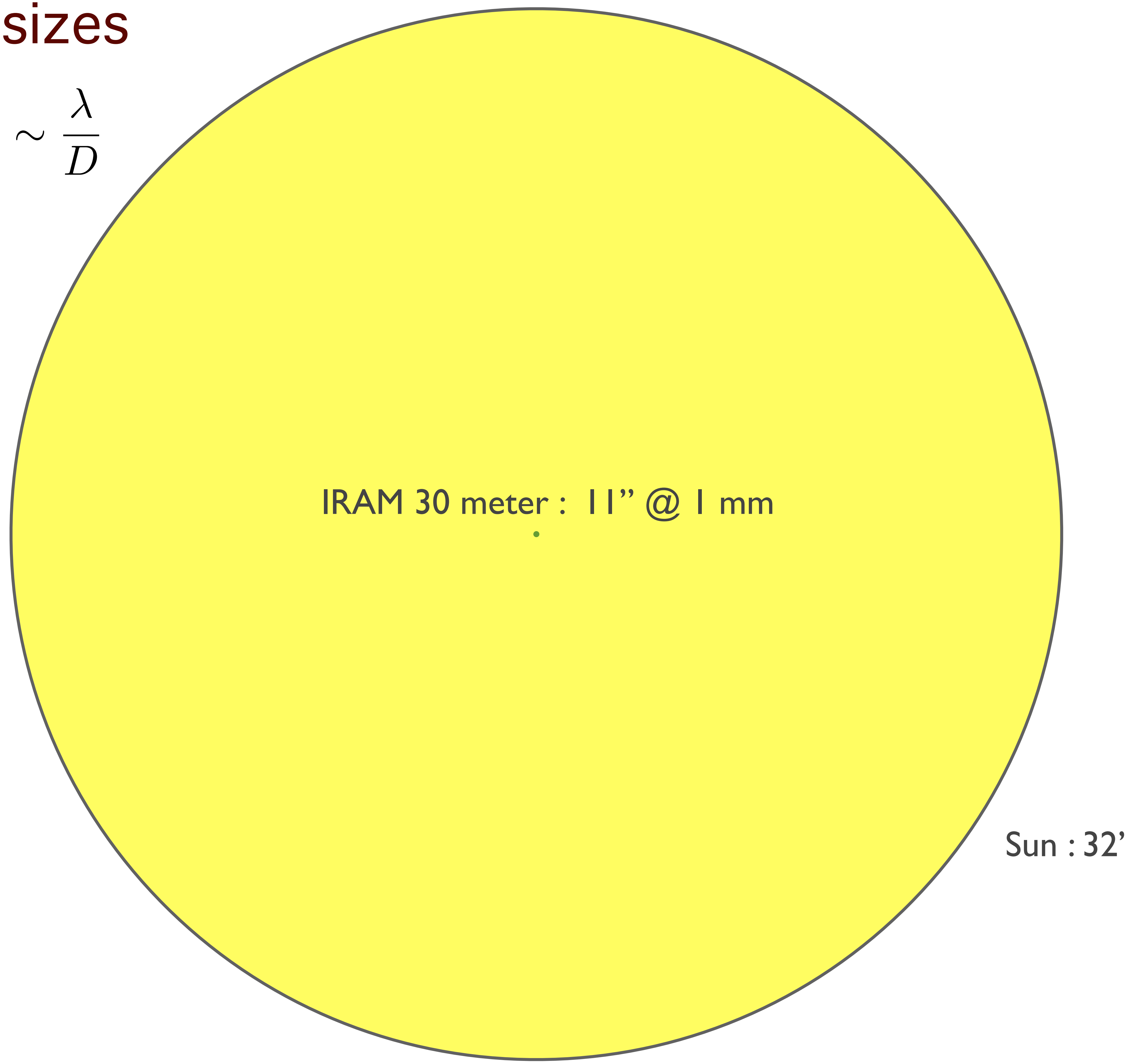




Channel maps of HI in NGC 2366 (Thuan, Hibbard & Levrier, 2004

Beam sizes

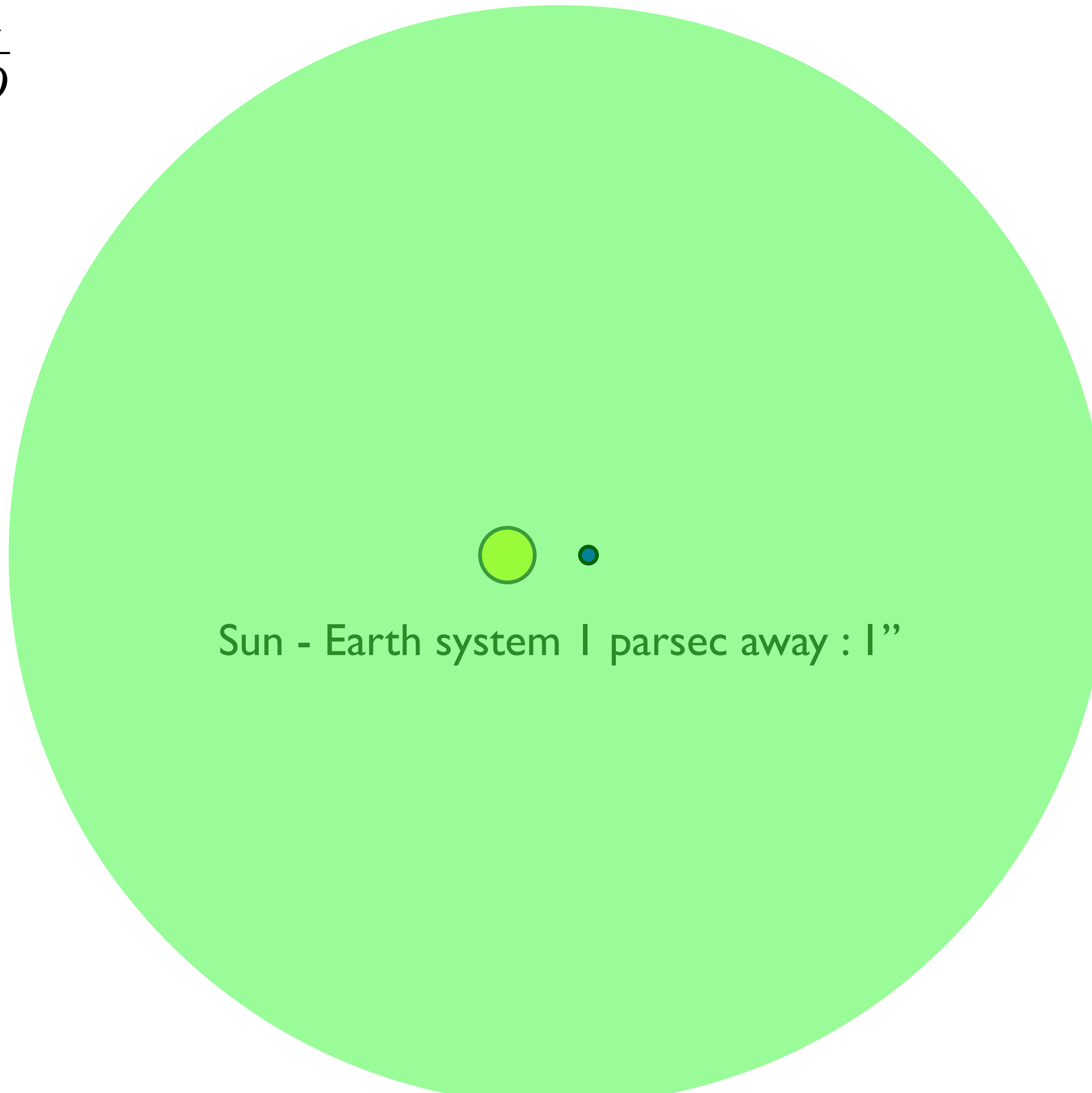
$$\theta_{\mathrm{FWHM}} \sim \frac{\lambda}{D}$$



Beam sizes

$$\theta_{\mathrm{FWHM}} \sim \frac{\lambda}{D}$$

IRAM 30 meter : 11” @ 1 mm



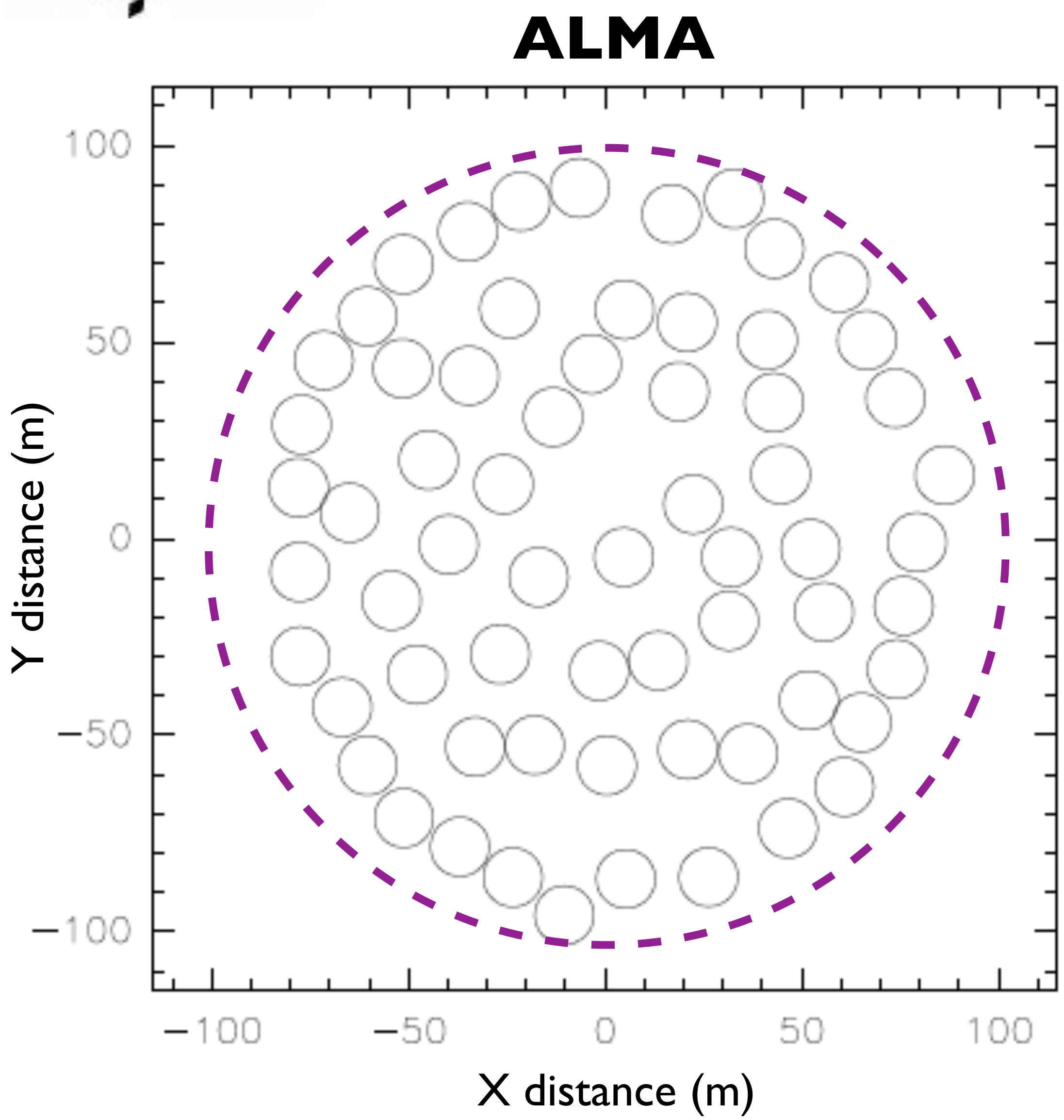
How can we improve resolution ?

$$\theta_{\mathrm{FWHM}} \sim \frac{\lambda}{D}$$

Need to increase the telescope diameter while keeping surface and pointing accuracy

Effelsberg 100 meter telescope is about the largest you can get

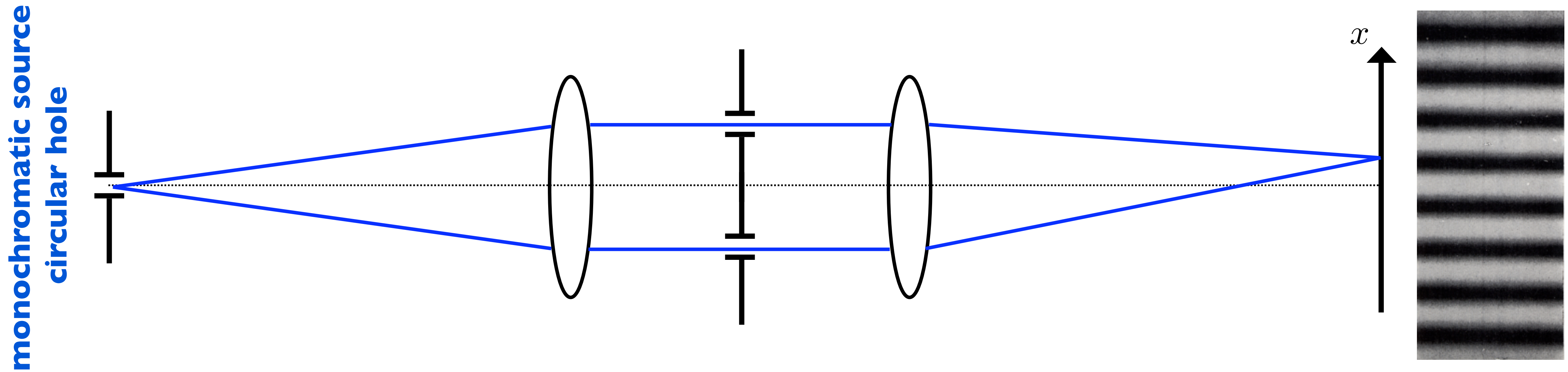
Aperture synthesis : Let's replace that hypothetical single large telescope by a collection of smaller ones filling the aperture of the large one ...



Baseline Line segment between two antennas
Configuration Antenna layout
Primary beam Single antenna beam pattern

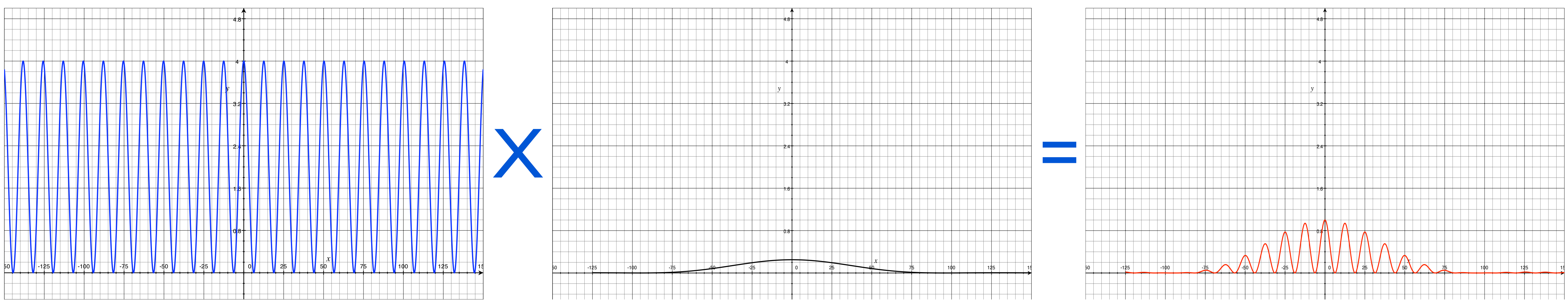
How do we make a smaller beam out of this ?

Back to basics : Young's experiment



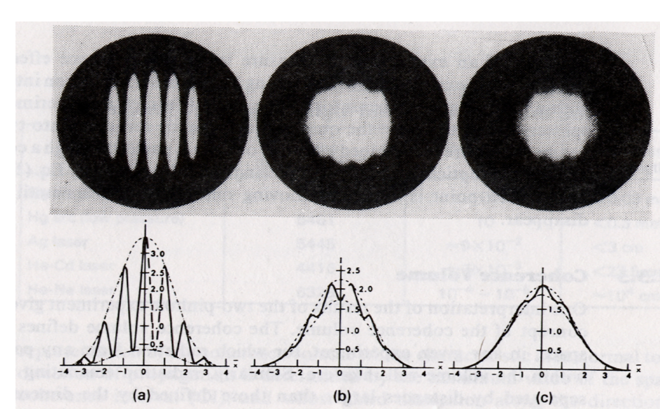
$$I(x) = 2I_0\left[1+\cos\left(\frac{bx}{\lambda}\right)\right]$$

Taking into account the diffraction pattern of each hole :



But if the primary source is incoherent, minimum intensity is not zero, contrast is less than one, and fringes can disappear if the primary source size is increased :

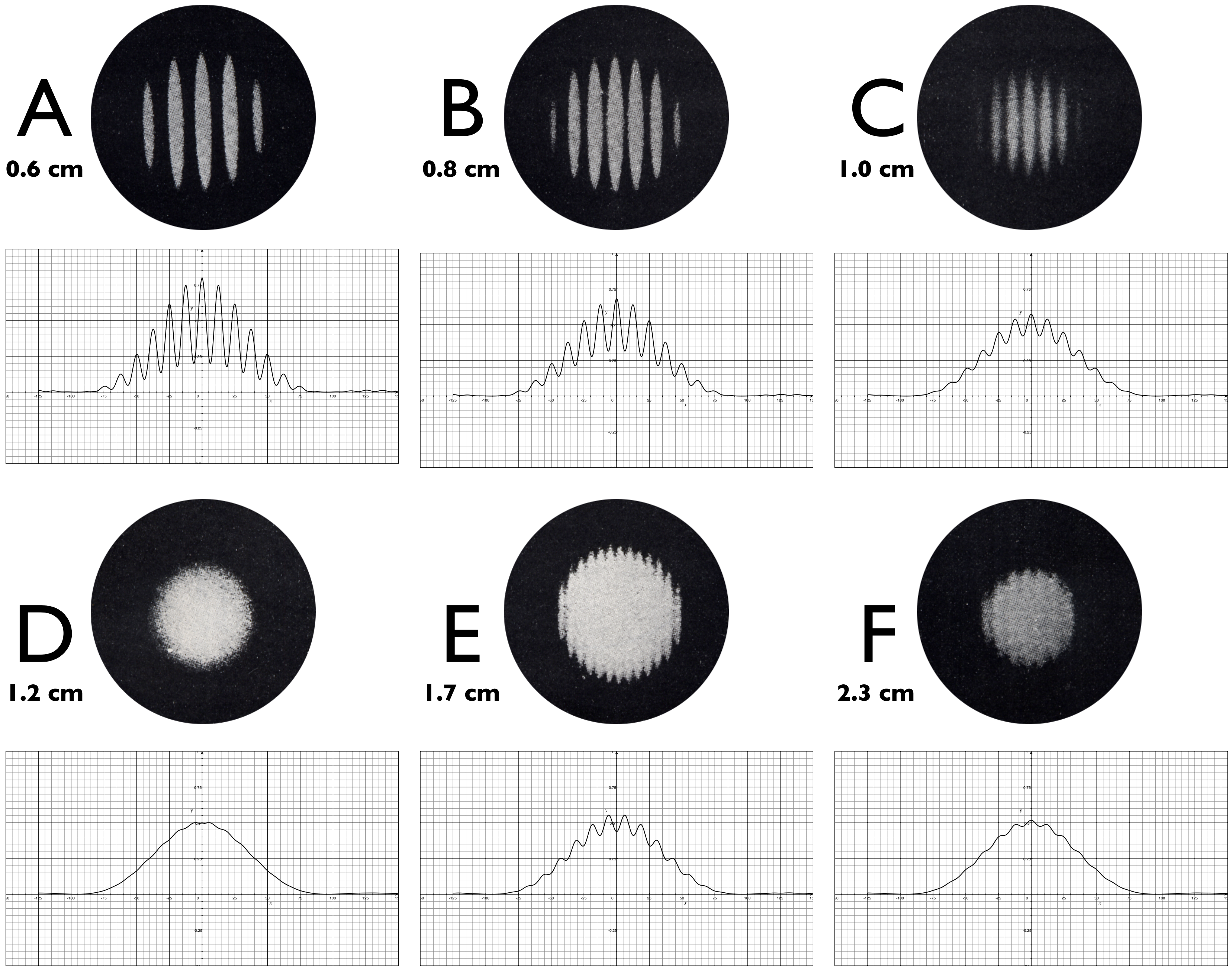
$$I(x) = 2I_0\left[1+|C|\cos\left(\frac{bx}{\lambda}+\phi_C\right)\right]$$

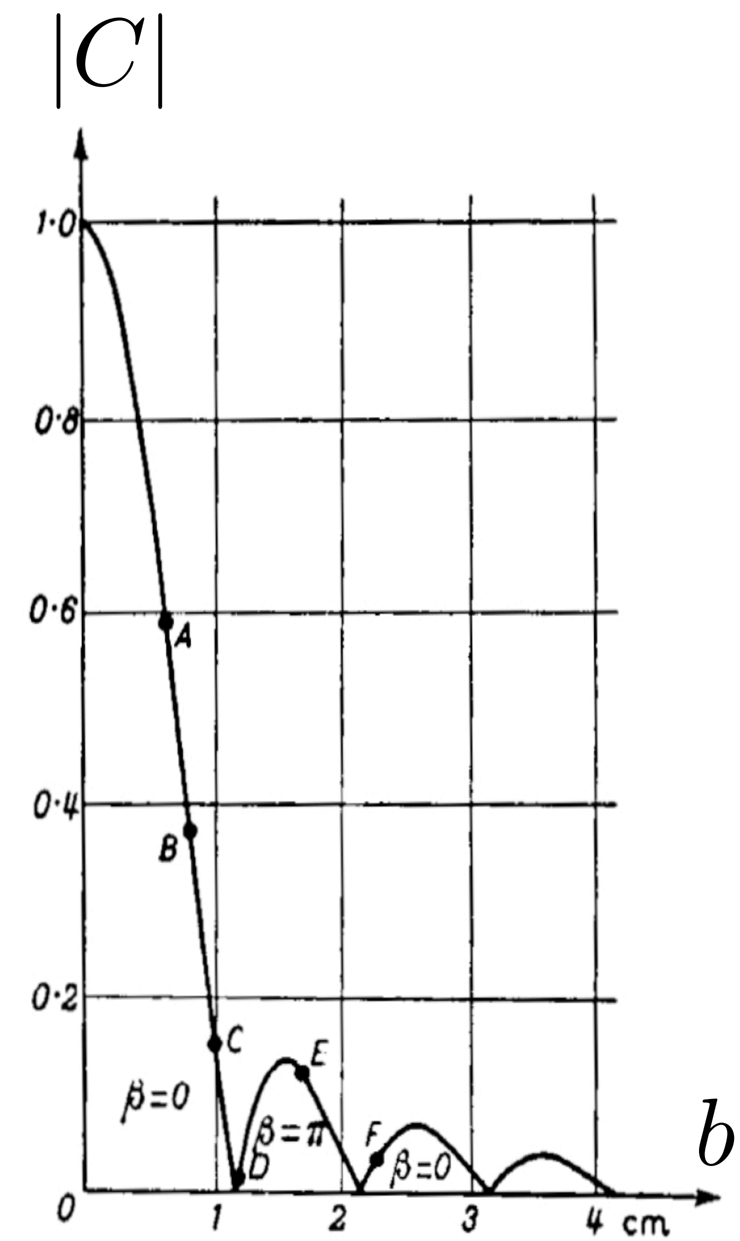


$$|C| = \frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}$$

Effect of secondary source separation

Double hole separation increases from left to right and top to bottom

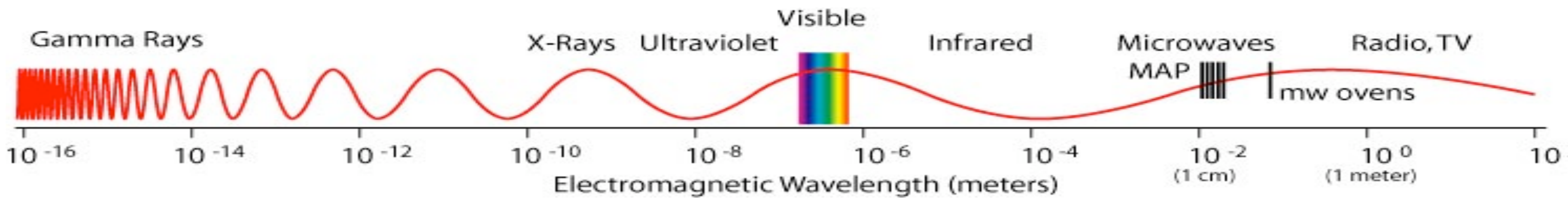




$$\frac{J_1(b)}{b} = \mathrm{TF}\left[H(\theta)\right]$$

The "contrast function" is the 2D Fourier transform of the primary source illumination

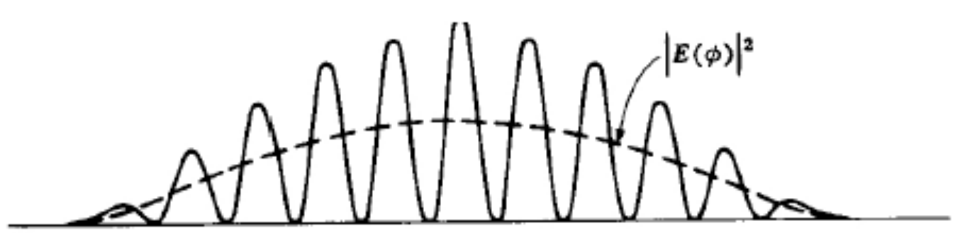
What of <u>radio</u> interferometry ?

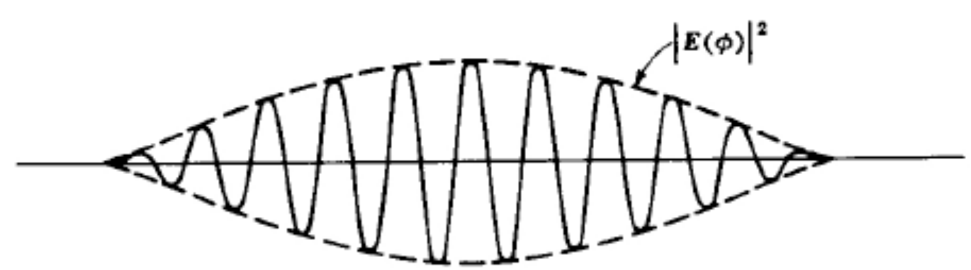


Much lower frequencies → **HETERODYNE DETECTION**

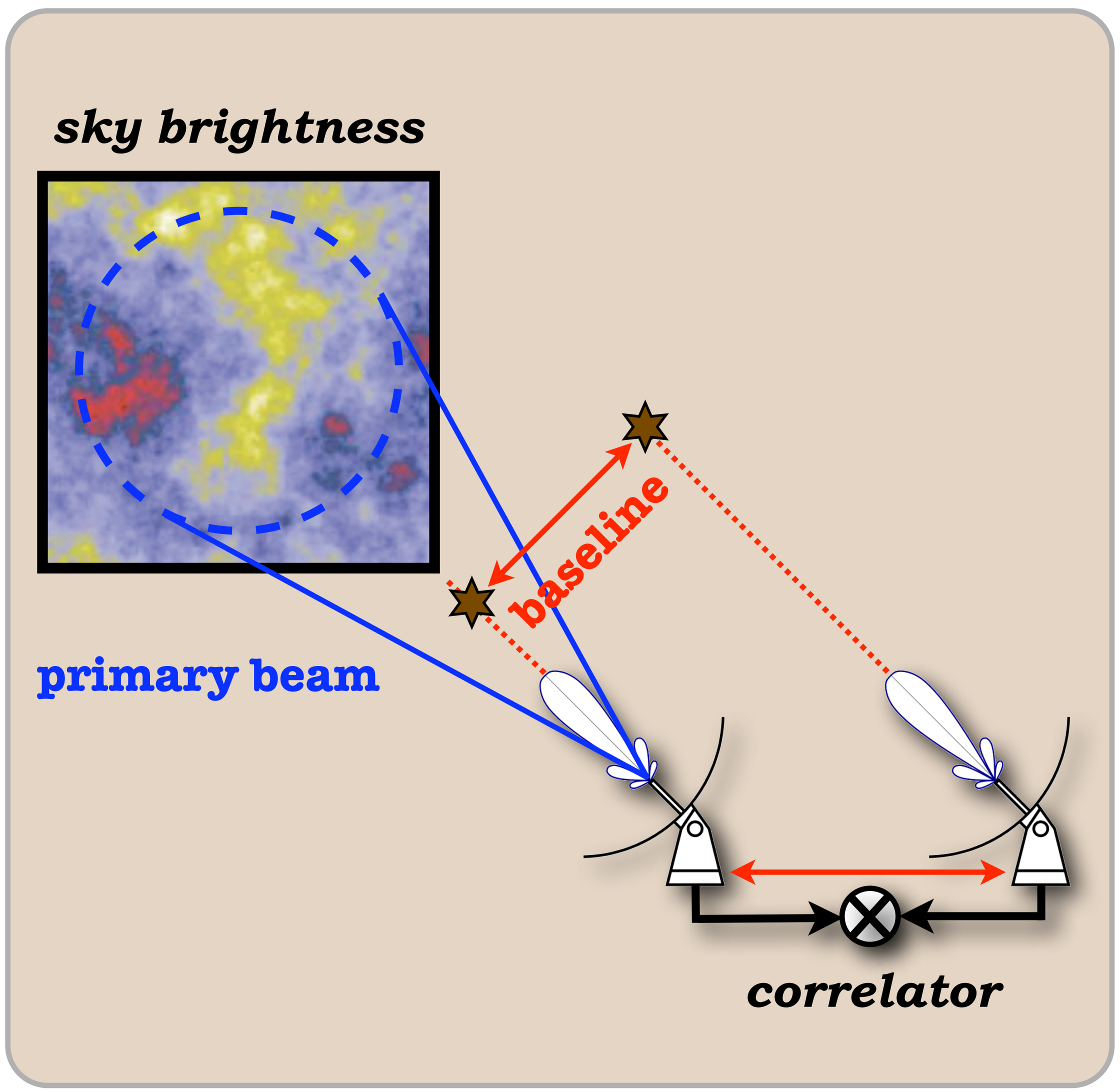
Direct detection of the electric field

Optical	*Radio*
Quadratic detection	Linear detection
$I = \|E\|^2$	$\|E\| \exp(i\phi)$
Optical fringes	Electronic correlation
$\|C\| = \dfrac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$	$\|V\| \exp(i\phi_V) = \langle E_1 E_2^* \rangle$
"Contrast function"	**"Visibility function"**
Additive interferometry	Multiplicative interferometry
$I_1 + I_2 + 2\sqrt{I_1 I_2}\|C\| \cos\left(\dfrac{bx}{\lambda} + \phi_C\right)$	$\|E_1\|\|E_2\|\|C\| \cos\left(\dfrac{bx}{\lambda} + \phi_C\right) = \|V\| \cos\left(\dfrac{bx}{\lambda} + \phi_V\right)$





So, radio interferometry in a nutshell...



Incoming EM field from the direction (l, m) is $\propto B(l, m) \times I(l, m)$

primary beam ***sky brightness***

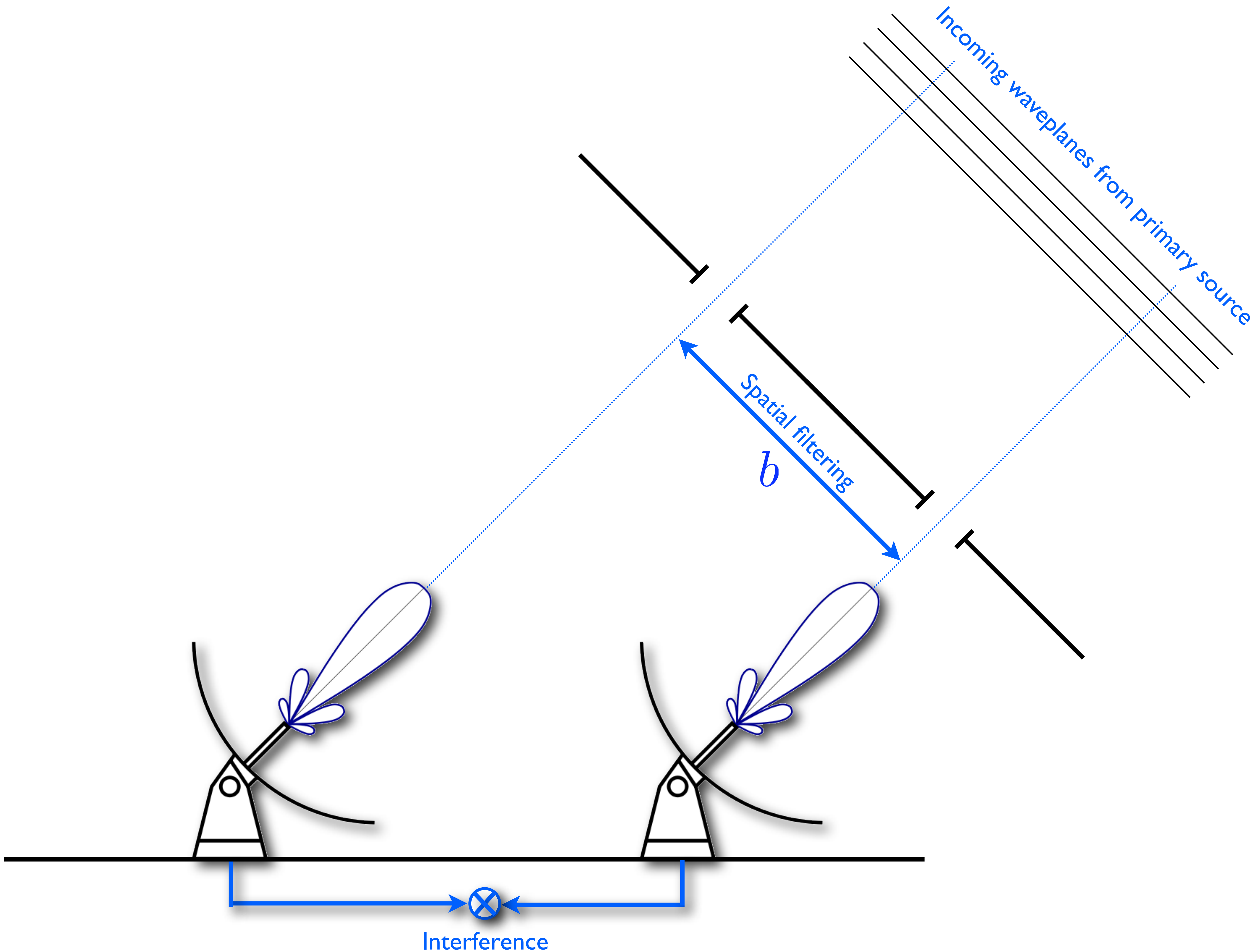
At each antenna, receivers convert the EM field to a voltage.

Correlators perform the electronic multiplication and averaging of voltages coming from two antennas.

Fringe visibilities are measured : one Fourier component measured by antenna pair at a spatial frequency determined by the baseline - projection of the antenna separation perpendicular to the line of sight.

The visibility function is the 2D Fourier Transform of $B(l, m)I(l, m)$

Telescopes act like Young's holes



Some properties of Fourier transforms

Convolution theorem

$$\mathrm{TF}\left[F_1 \times F_2\right] = \mathrm{TF}\left[F_1\right] * \mathrm{TF}\left[F_2\right]$$

Zero frequency component

$$\mathrm{TF}[F](0) = \int F$$

Duality

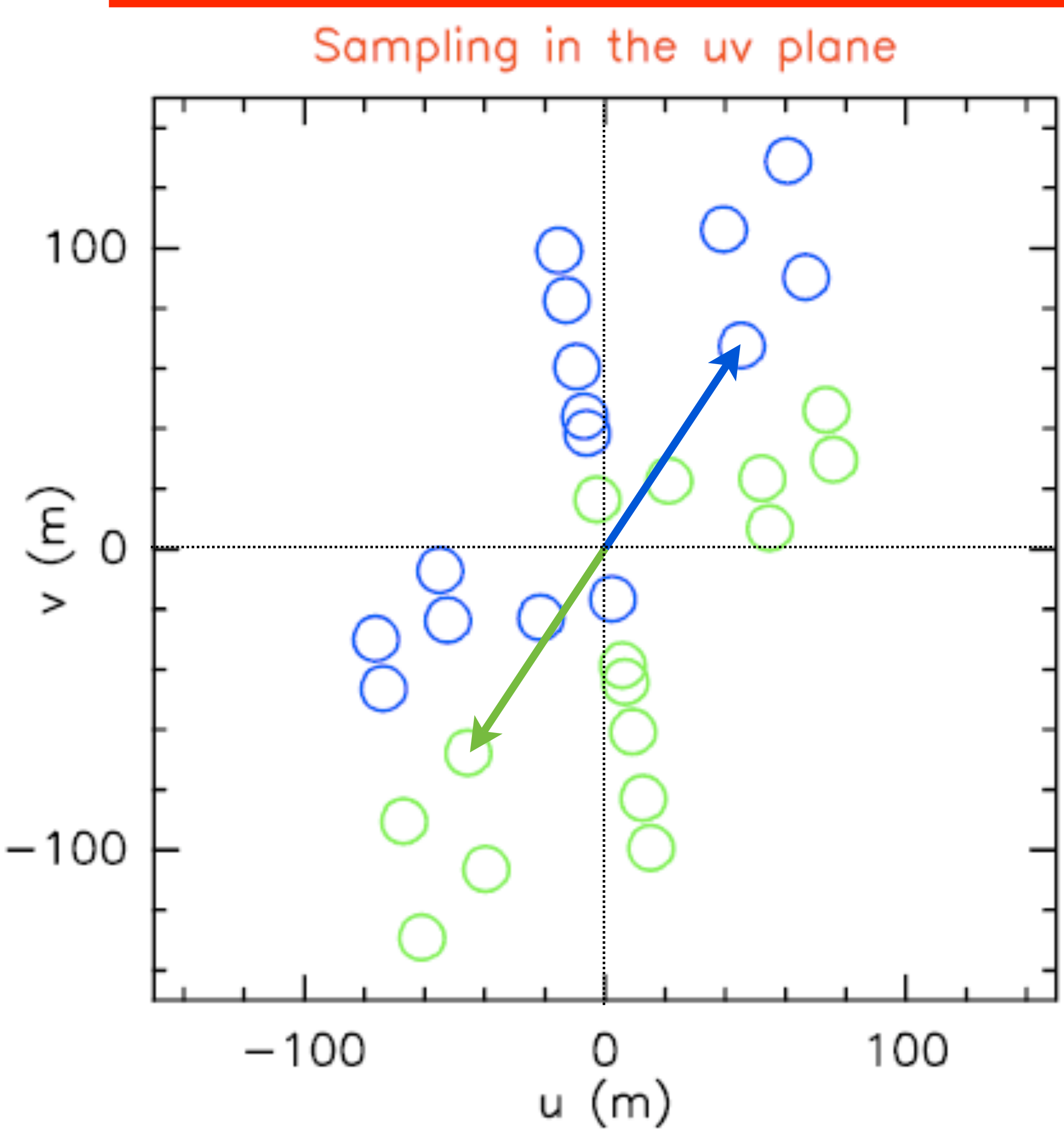
Longest baseline $\longleftrightarrow$ Image resolution

Smallest baseline $\longleftrightarrow$ Largest scale accessible

Coverage of the uv plane

uv plane Fourier plane
Visibilities Fourier components of the source, measured by antenna pairs
Baseline Line-of-sight projected distance between two antennas

Example : IRAM's Plateau de Bure - 6 antennas



baseline i-j

baseline j-i

Figure by J. Pety (IRAM Grenoble)

$$\boxed{V_{ij} = V_{ji}^*}$$

Image is real !

N antennas

$\dfrac{N(N-1)}{2}$ antenna pairs

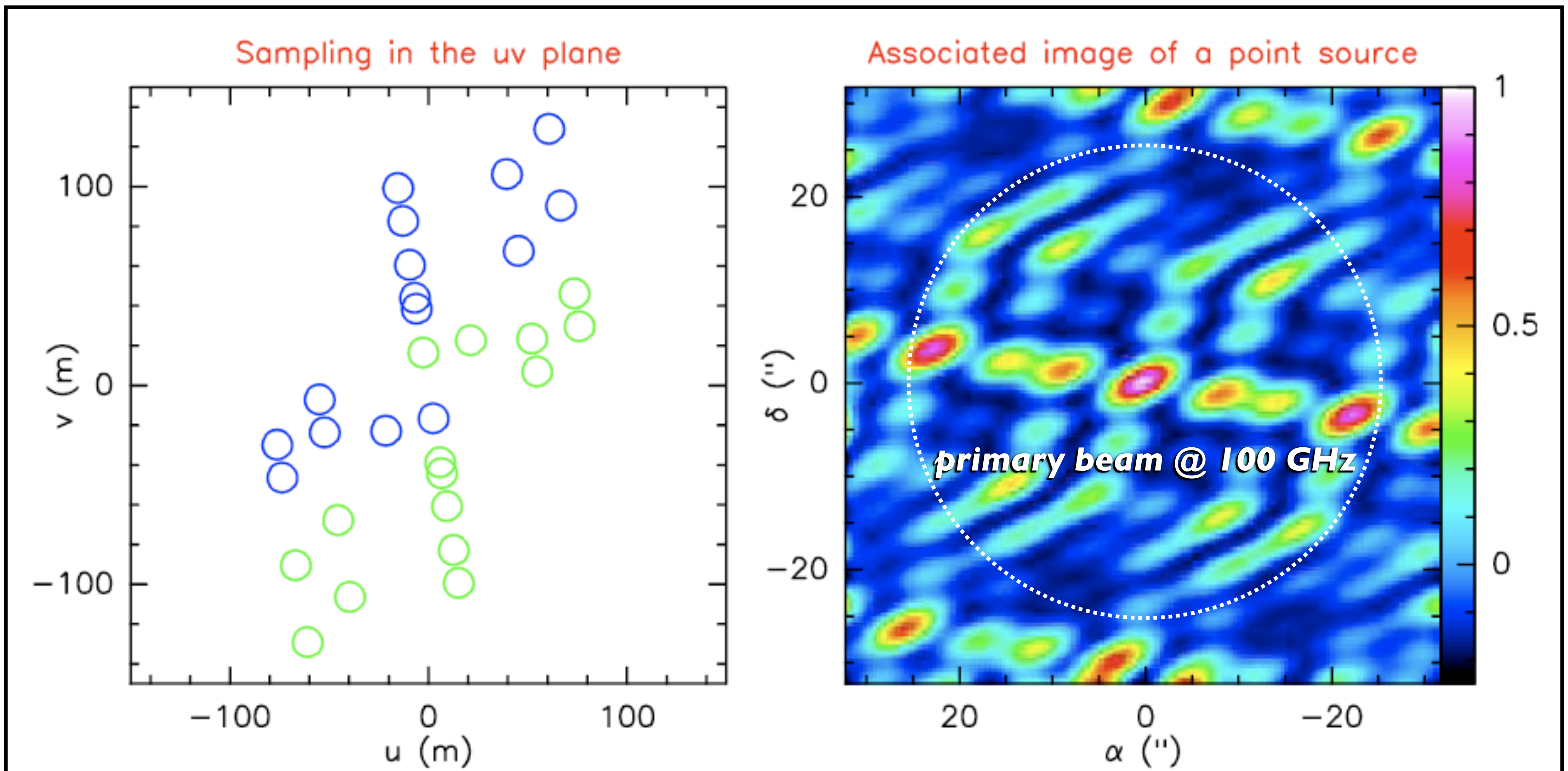
$N(N-1)$ baselines

Point-spread function

2D Fourier transform of a point source : uniform visibility function

Sampled at each point corresponding to a measured baseline. Non-measured points set to zero.

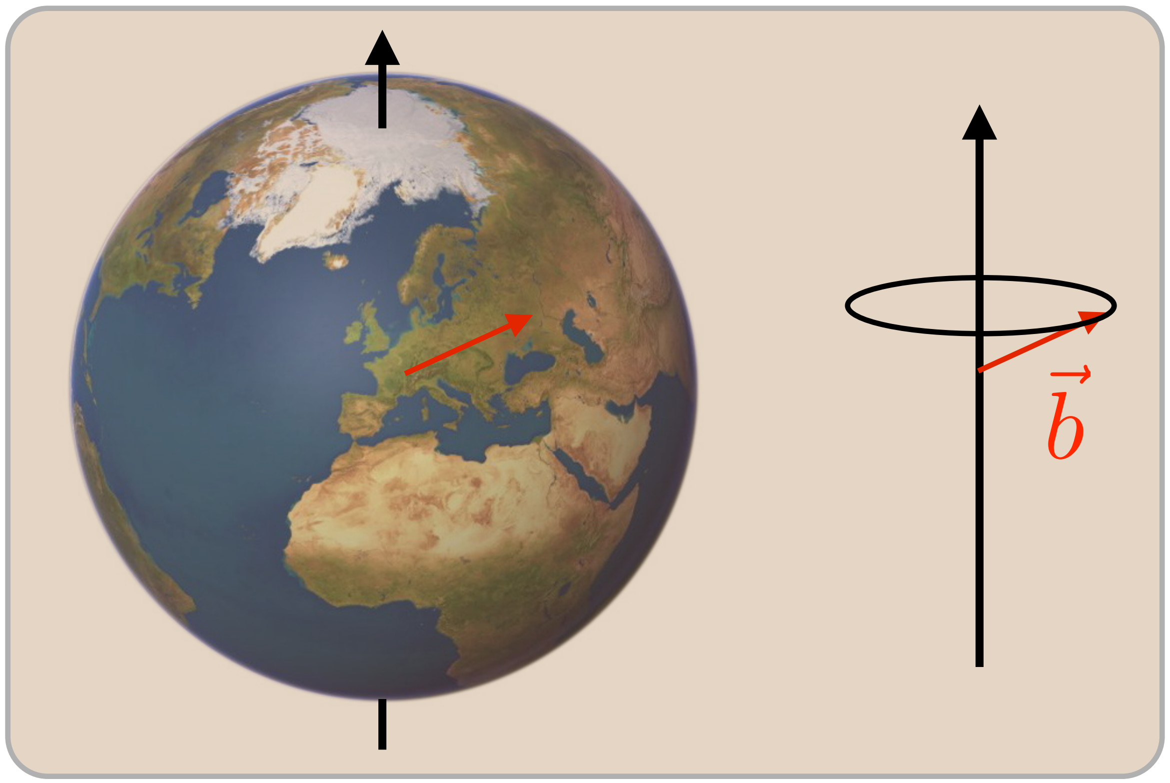
2D Fourier transform of the sampled visibility function yields the instrument's PSF

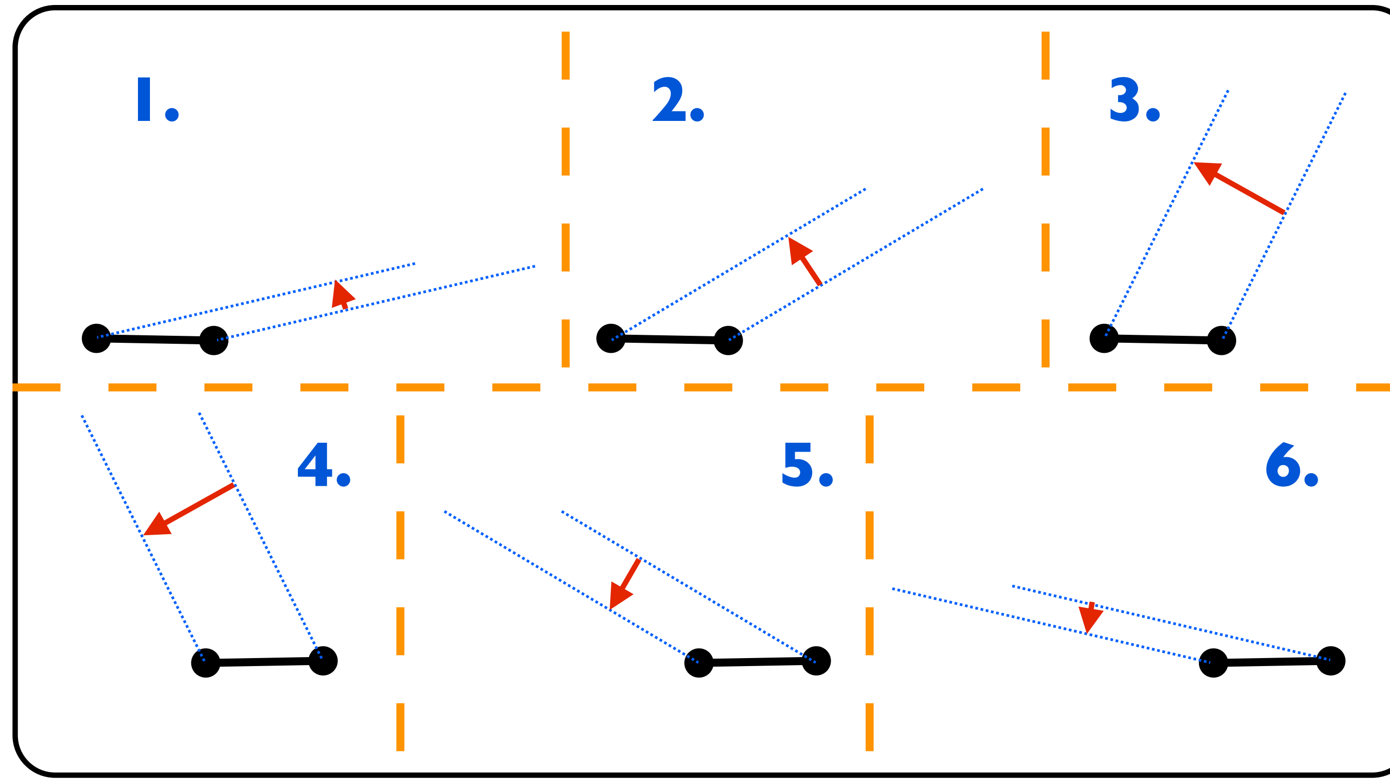


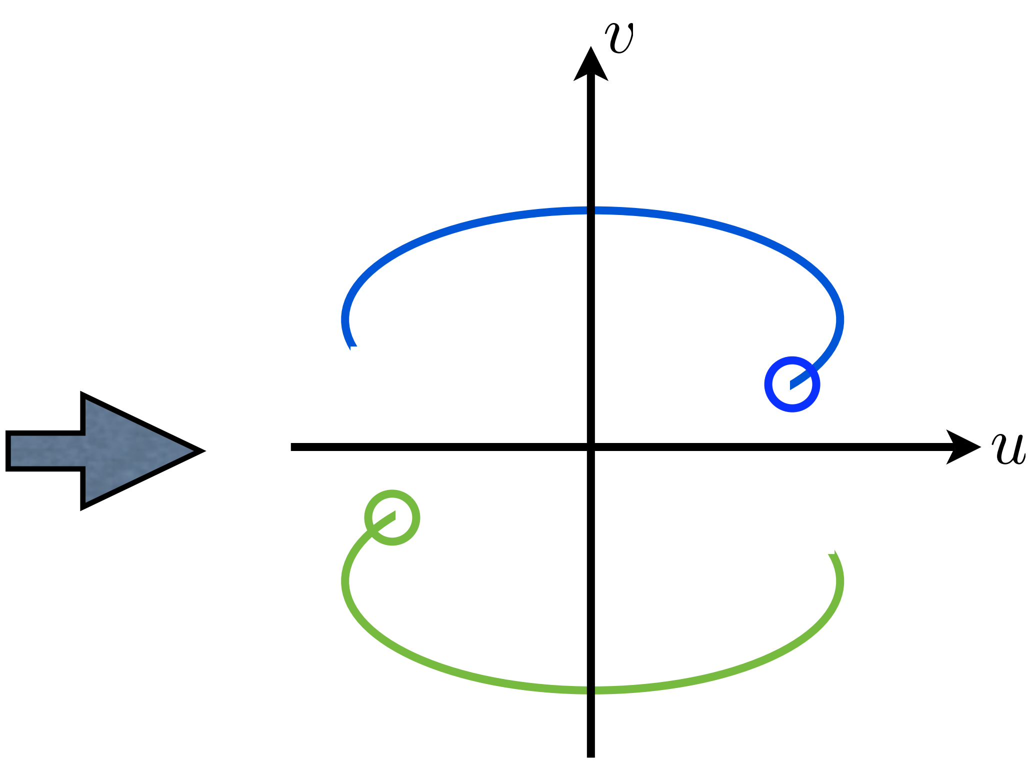
Figures by J. Pety (IRAM Grenoble)

Earth rotation and super-synthesis

As the Earth rotates, the baseline for a given pair of antennas changes...

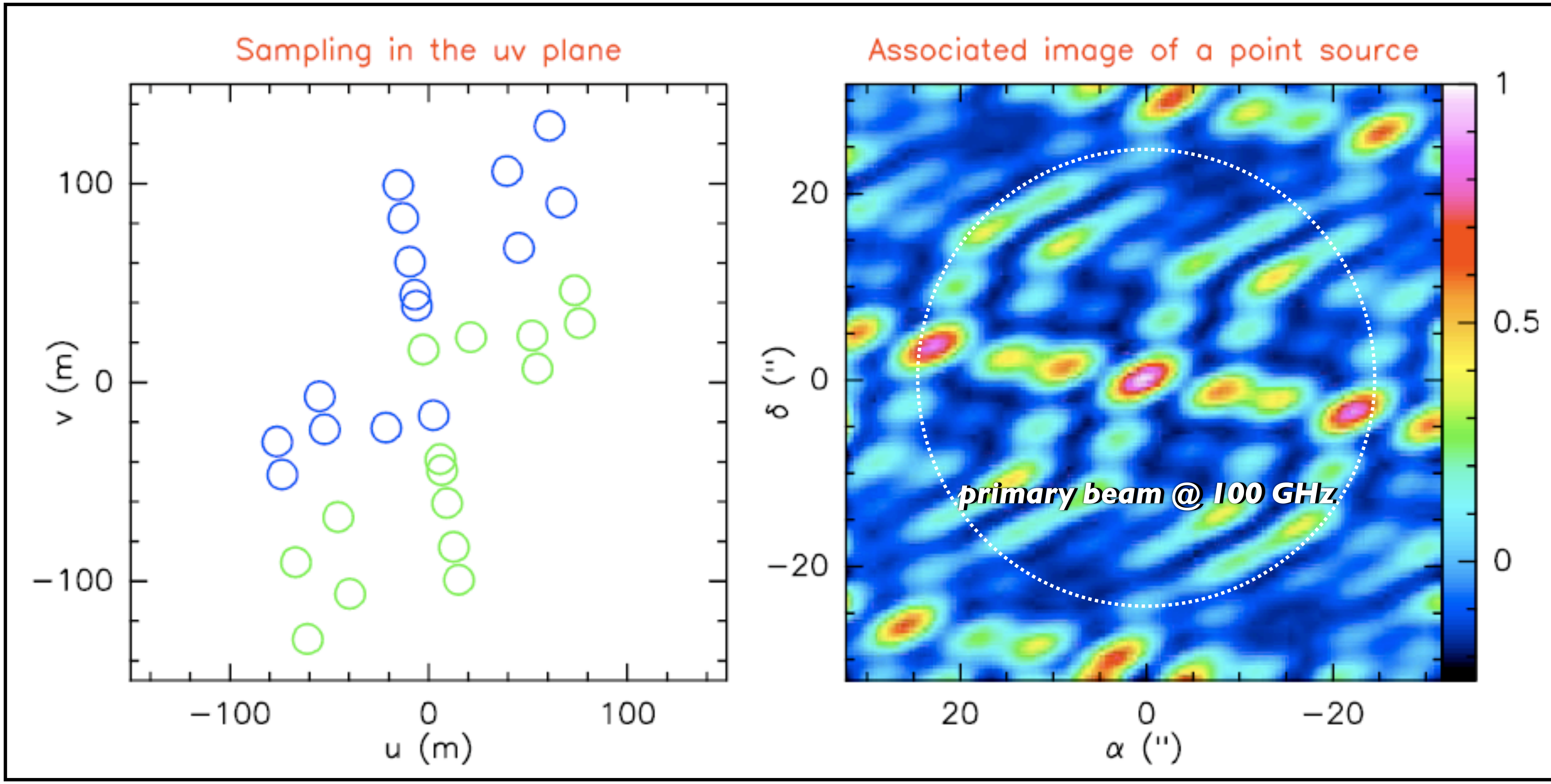






Baselines follow elliptical tracks in the uv plane

Earth rotation and super-synthesis



Figures by J. Pety (IRAM Grenoble)

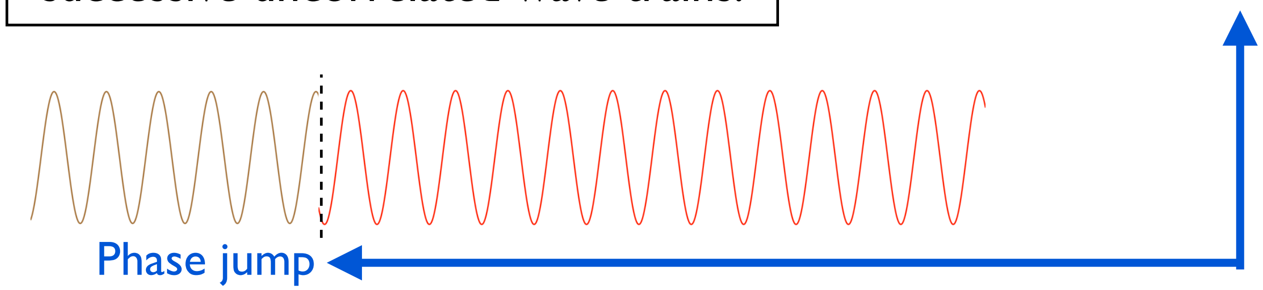
PSF = Interferometer beam = dirty beam = synthesized beam

Artifacts !

Correcting for the geometric delay

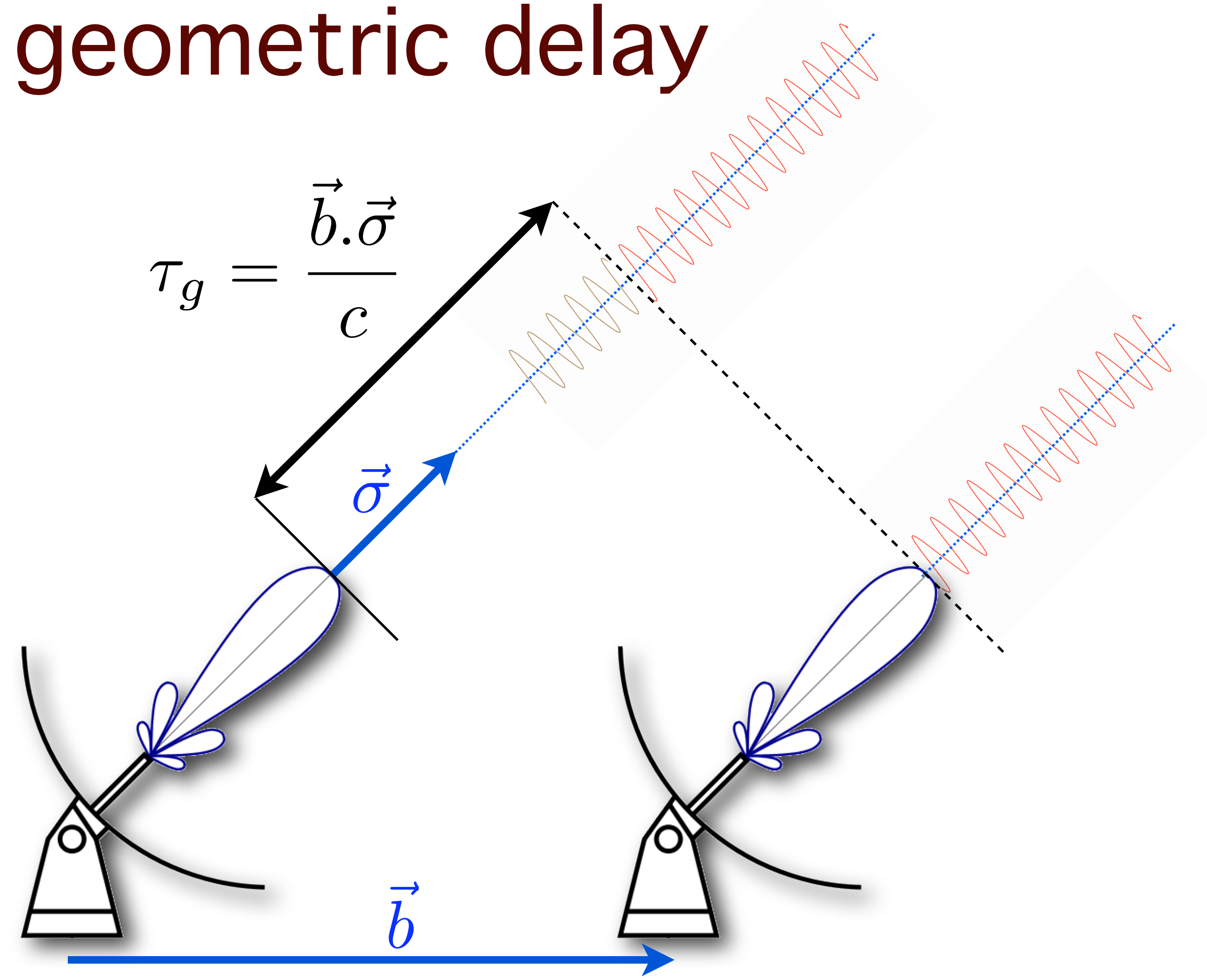
Temporally incoherent source means successive uncorrelated wave trains.

$$E = E_0 \cos(\omega t + \phi)$$



Coherence time τ_c
Time over which phase is constant

$$\tau_g = \frac{\vec{b}.\vec{\sigma}}{c}$$



The geometrical delay is an issue as we need to correlate the same wave trains

$\tau_c < \tau_g \longrightarrow$ Fringes disappear !

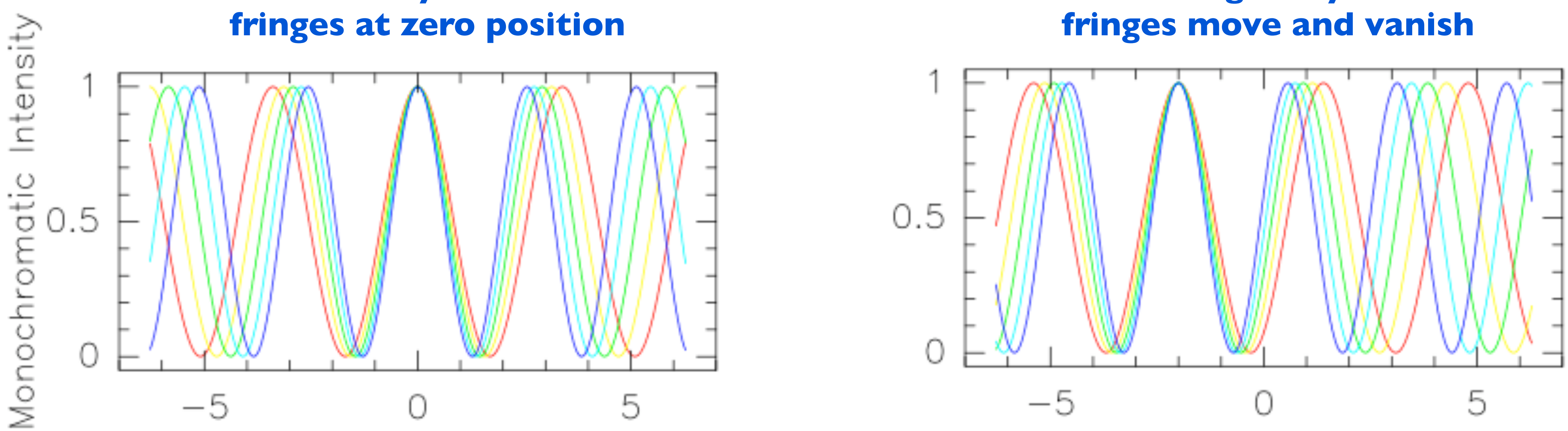
Need time-dependent electronic correction for the delay

Geometric delay with a finite bandwidth

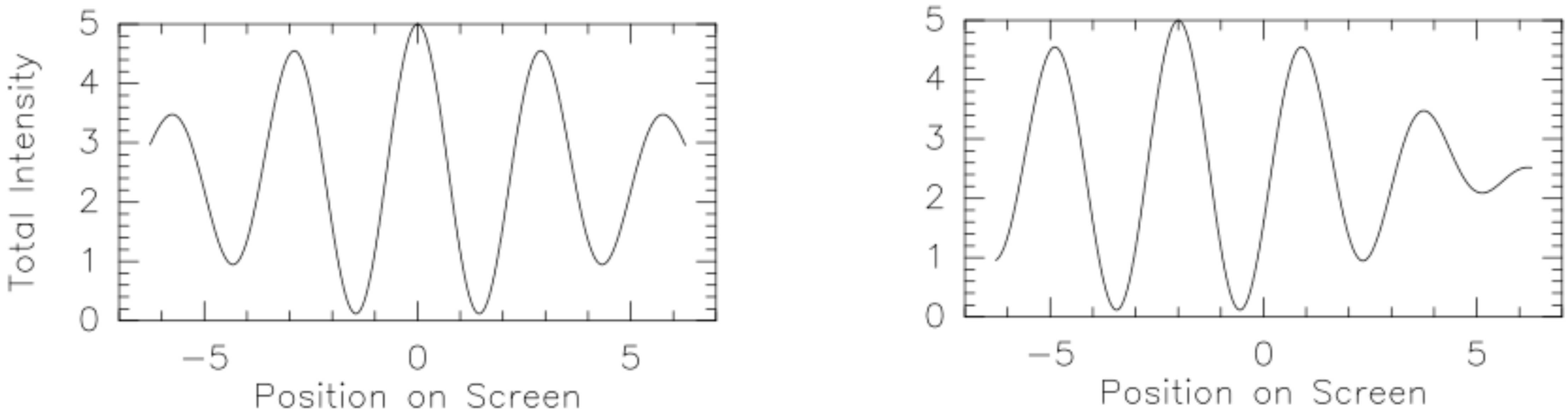
Back to Young's experiment, in polychromatic light

Perfect delay correction : fringes at zero position

Increasing delay error : fringes move and vanish

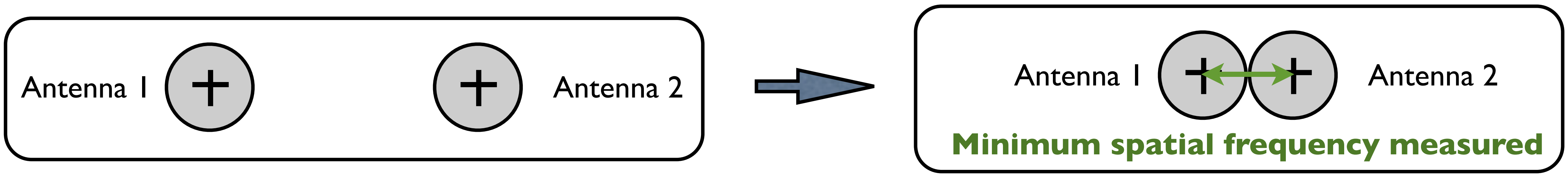


Figures by J. Pety (IRAM Grenoble)

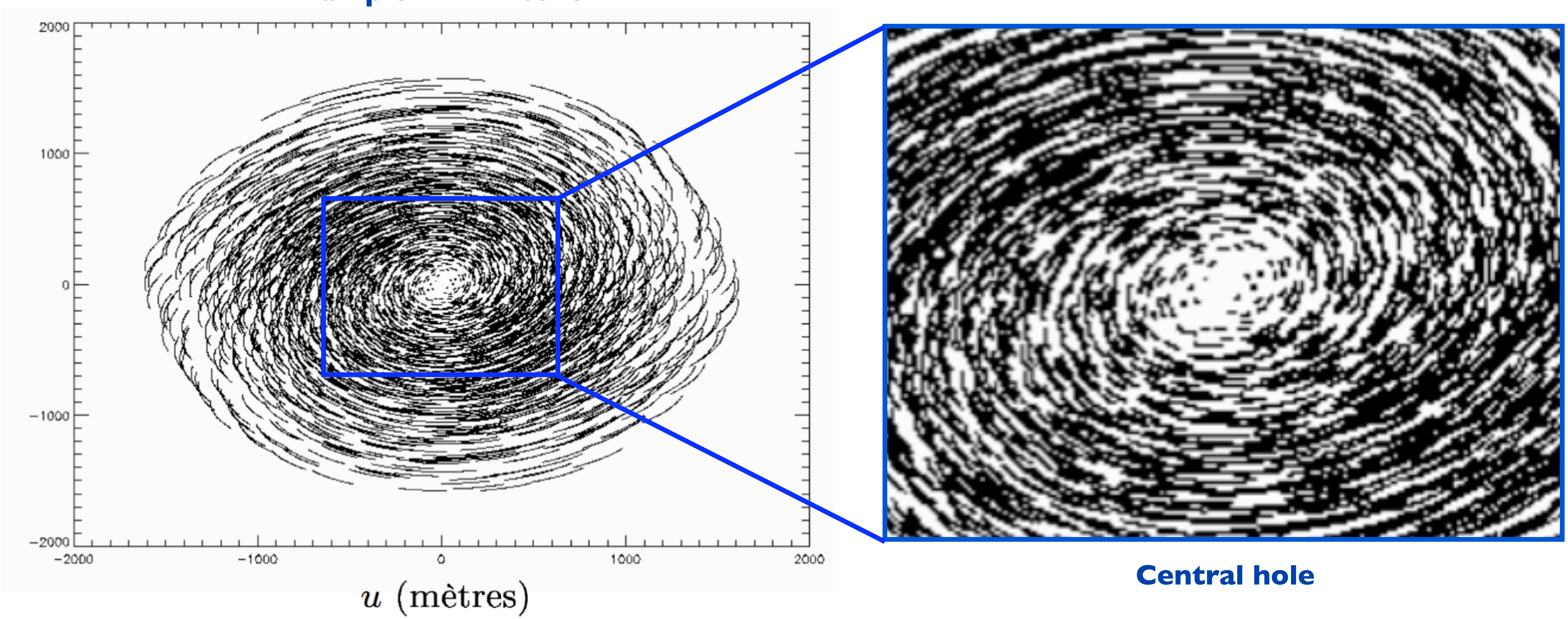


Hence delay correction is also called "fringe stopping"

The missing short spacings



Example ALMA cover



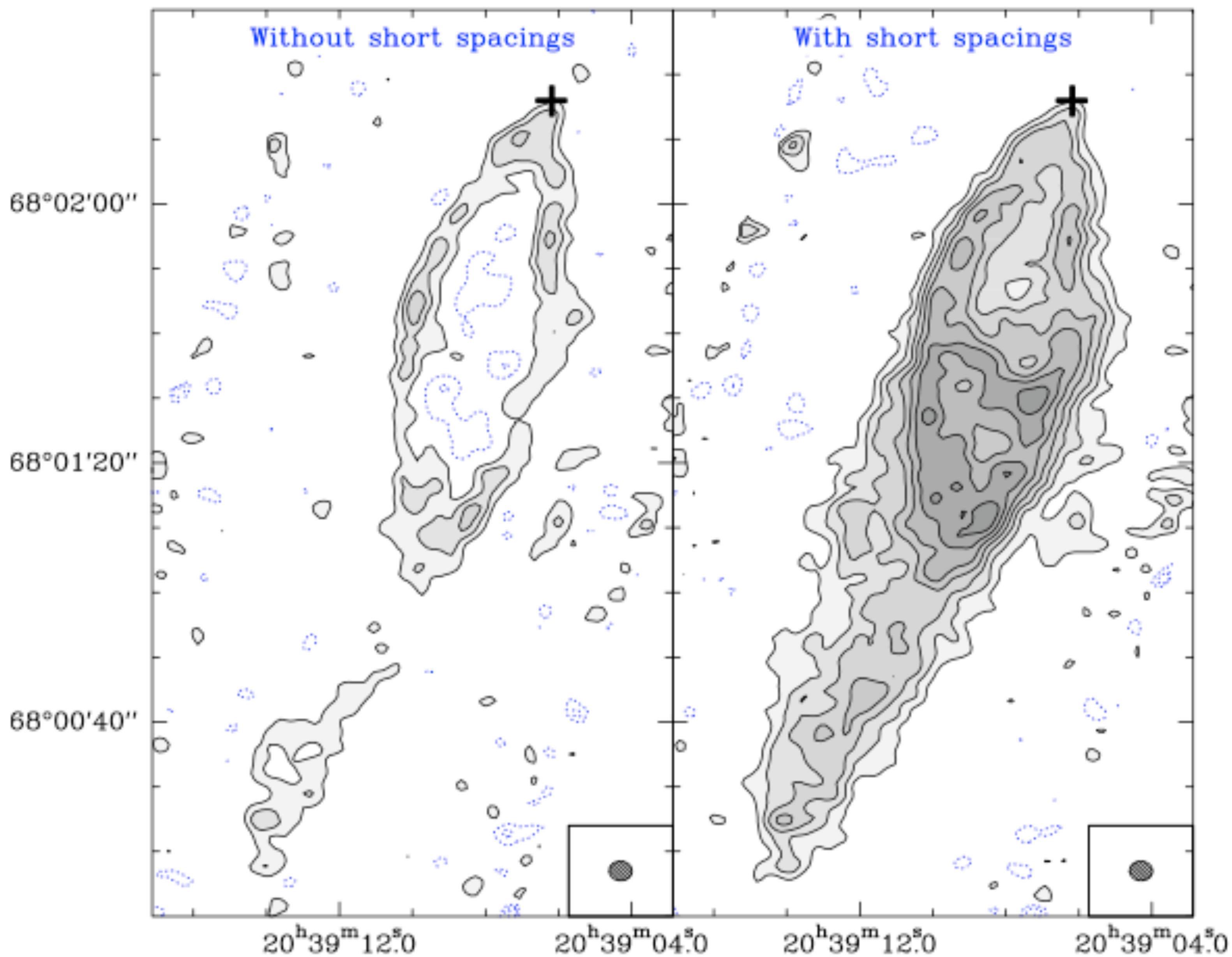
Central hole

The missing short spacings

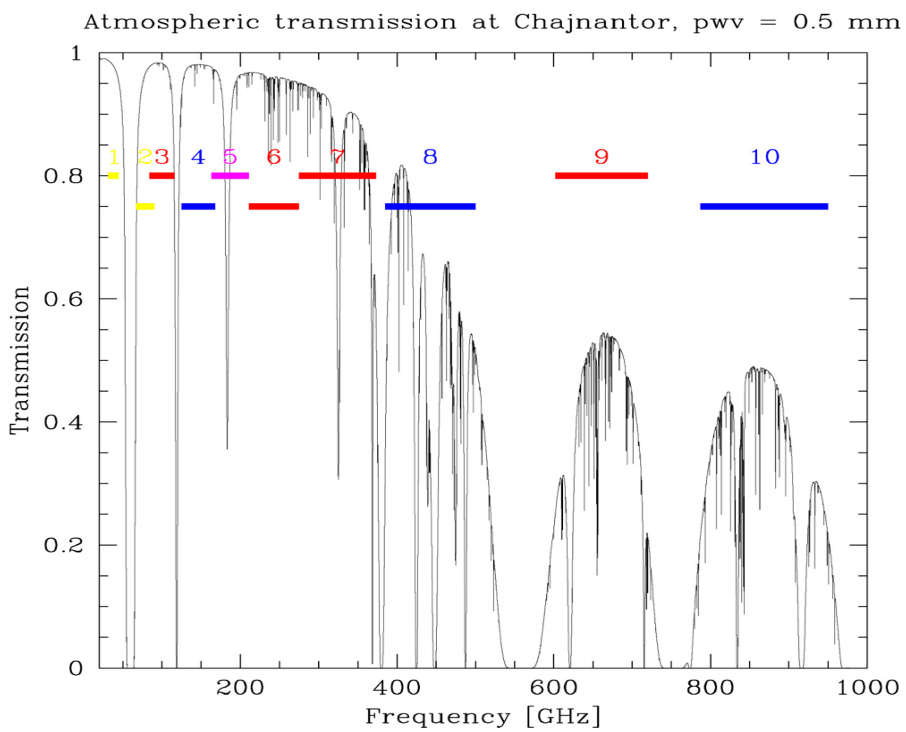
Low spatial frequencies are filtered out : Large scale structures are invisible to the instrument ! → ***Additional array with smaller antennas***

ALMA Compact Array (ACA)

The zero frequency component is not measured either, so total intensity is zero ! → ***Single-dish measurement***

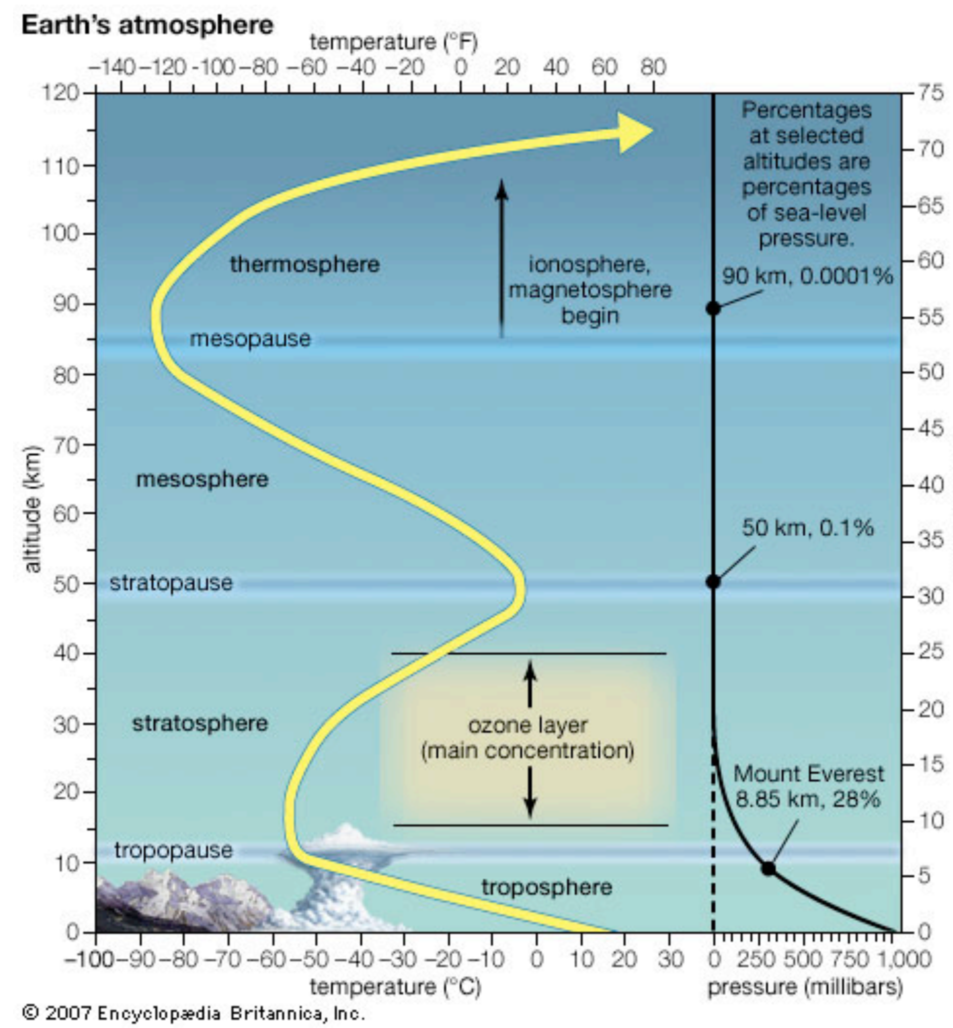


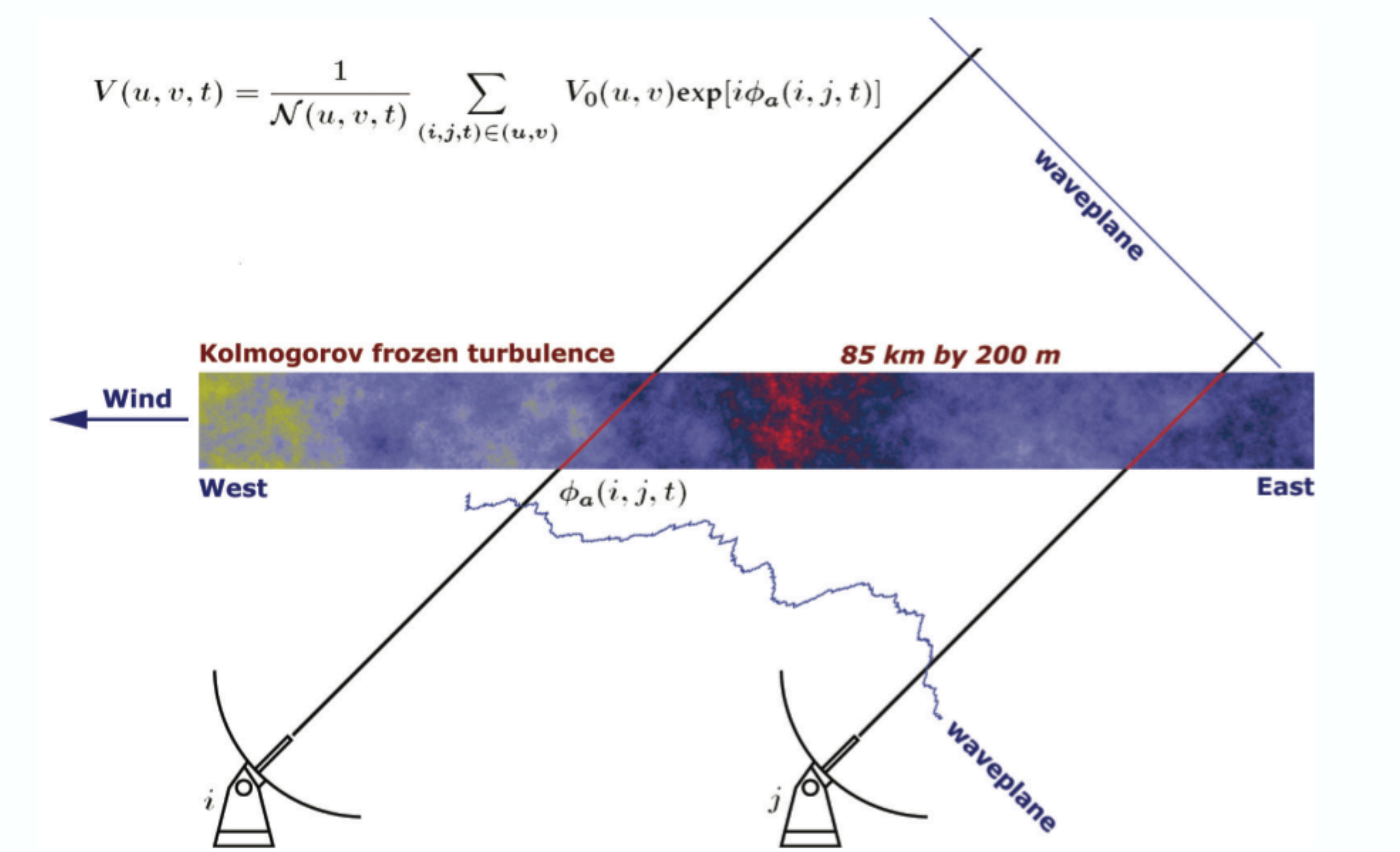
Atmospheric absorption and turbulences



Water vapor in the troposphere absorbs radiation

Need to measure water vapor content above the telescope





Turbulent motions imply gradients of the refraction index and deform waveplanes

Need to correct "in real time" (a few minutes timescale) above each antenna

The issue of deconvolution

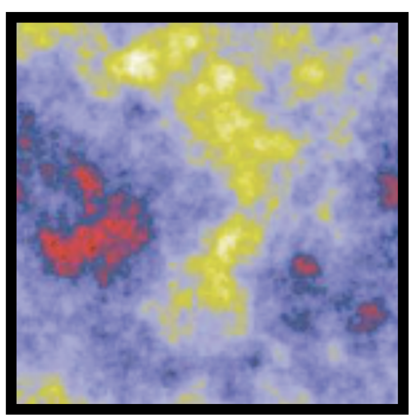
Measurement equation

$$J = T_F^{-1}[C \times T_F[B \times I]] = T_F^{-1}[V] = S * (B \times I)$$

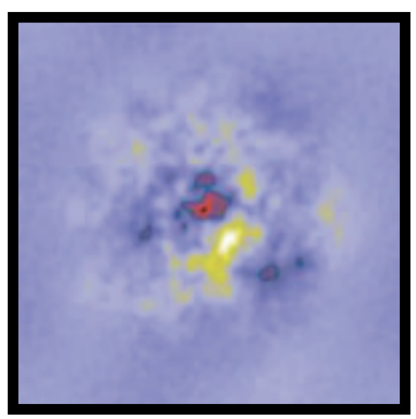
Convolution plaguing the image with the dirty beam's artifacts

- $C(u,v)$ uv cover (sampling function)
- $B(l,m)$ Primary beam
- $I(l,m)$ True sky brightness
- $J(l,m)$ "Dirty map"
- $V(u,v)$ Visibility function
- $S(l,m)$ Synthesized beam

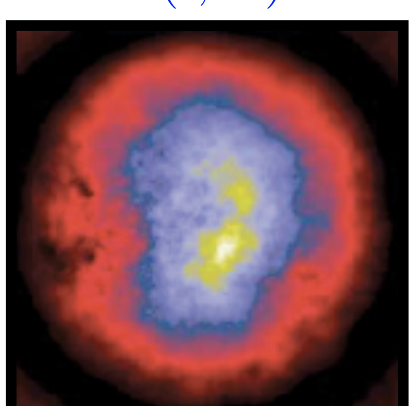
Deconvolution means building a model of the true sky brightness that fits the data and is "reasonable"



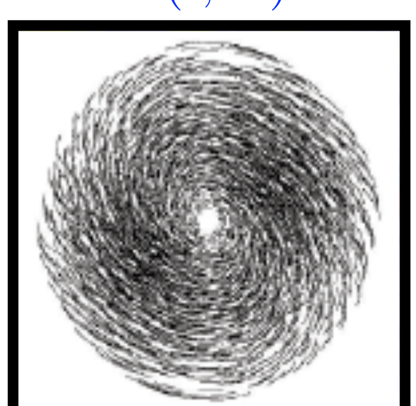
$I(l,m)$



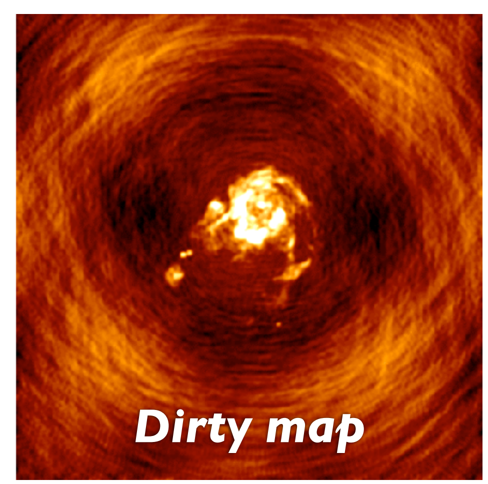
$J(l,m)$

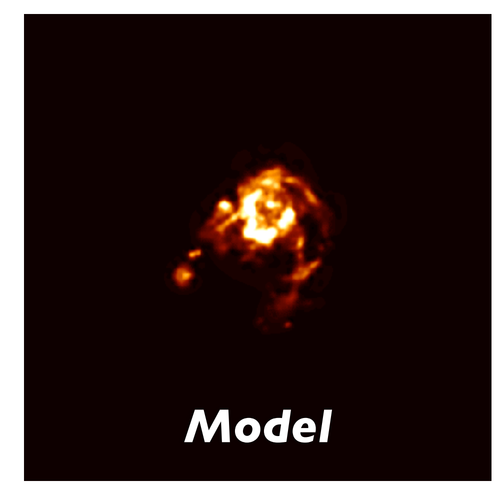


$B(l,m) \times I(l,m)$



$C(u,v)$





Figures by S. Bhatnagar (NRAO)

Deconvolution also means "inventing" the visibilities that were not measured by the instrument, using a priori hypotheses...

Two deconvolution algorithms

CLEAN

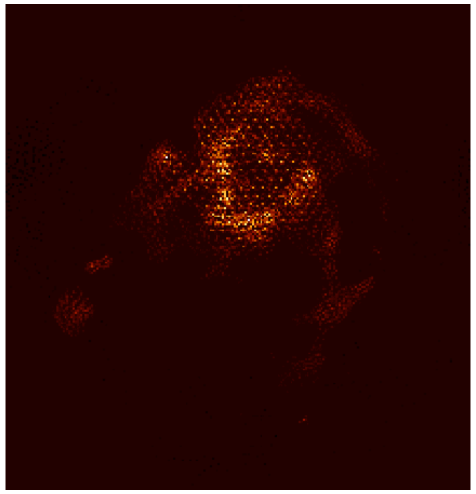
Hypotheses

- Sky is made up of point sources
- Sky is mostly blank

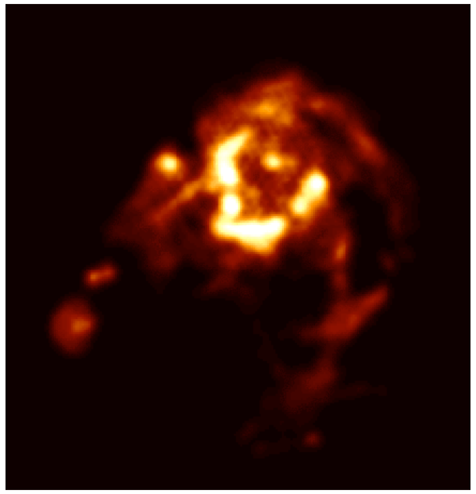
Principle

1. Start with an empty model sky.
2. Search for the peak in the dirty image.
3. Add a fraction of the peak value to the model sky.
4. Subtract a scaled version of the dirty beam from the dirty image at the position of the peak.
5. If residuals are not noise, return to step 2.
6. If residuals are noise, smooth the model with a Gaussian clean beam of the same FWHM as the dirty beam, and add the residuals. End result is the restored image.

CLEAN components



Restored image



Does well on point sources, not so on extended sources.

Maximum Entropy Method

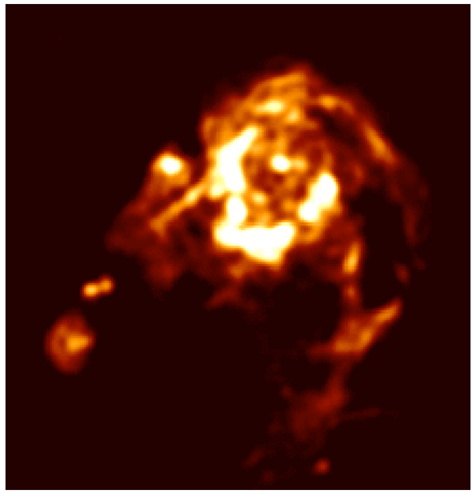
Hypotheses

- Sky is positive
- Sky should be the least unlikely given the data

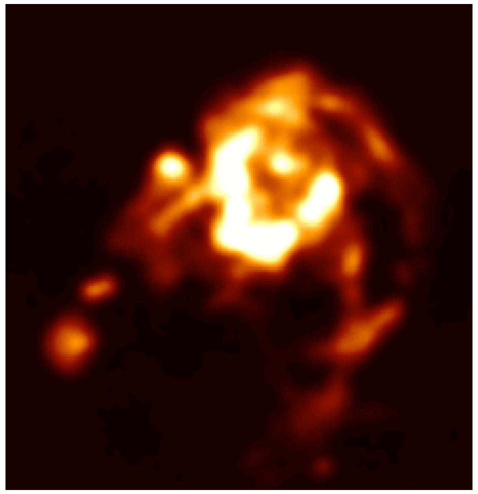
Principle

- Constrained optimization algorithm.
- Solve the convolution equation by an iterative process, with a constraint of smoothness based on an information entropy of the image (maximum for least unlikely image).
- Can use a default image as a template.

MEM Model



Restored image



Does well on extended sources, but is in trouble when many scales are present in the image.

Imaging wide fields

Largest structures filtered out due to the lack of the short spacings

→ **Add the short spacing information**

Field of view limited by the antenna primary beam width

→ **Observe a mosaic [several adjacent overlapping fields]**

Deconvolution algorithms not very good at recovering small- and large-scale structures

→ **Multi-Scale CLEAN, Multi-Resolution CLEAN, ...**

The largest structures that can be mapped are ~ 2/3 of the primary beam (field of view)
Structures larger than ~ 1/3 of the primary beam may already be affected

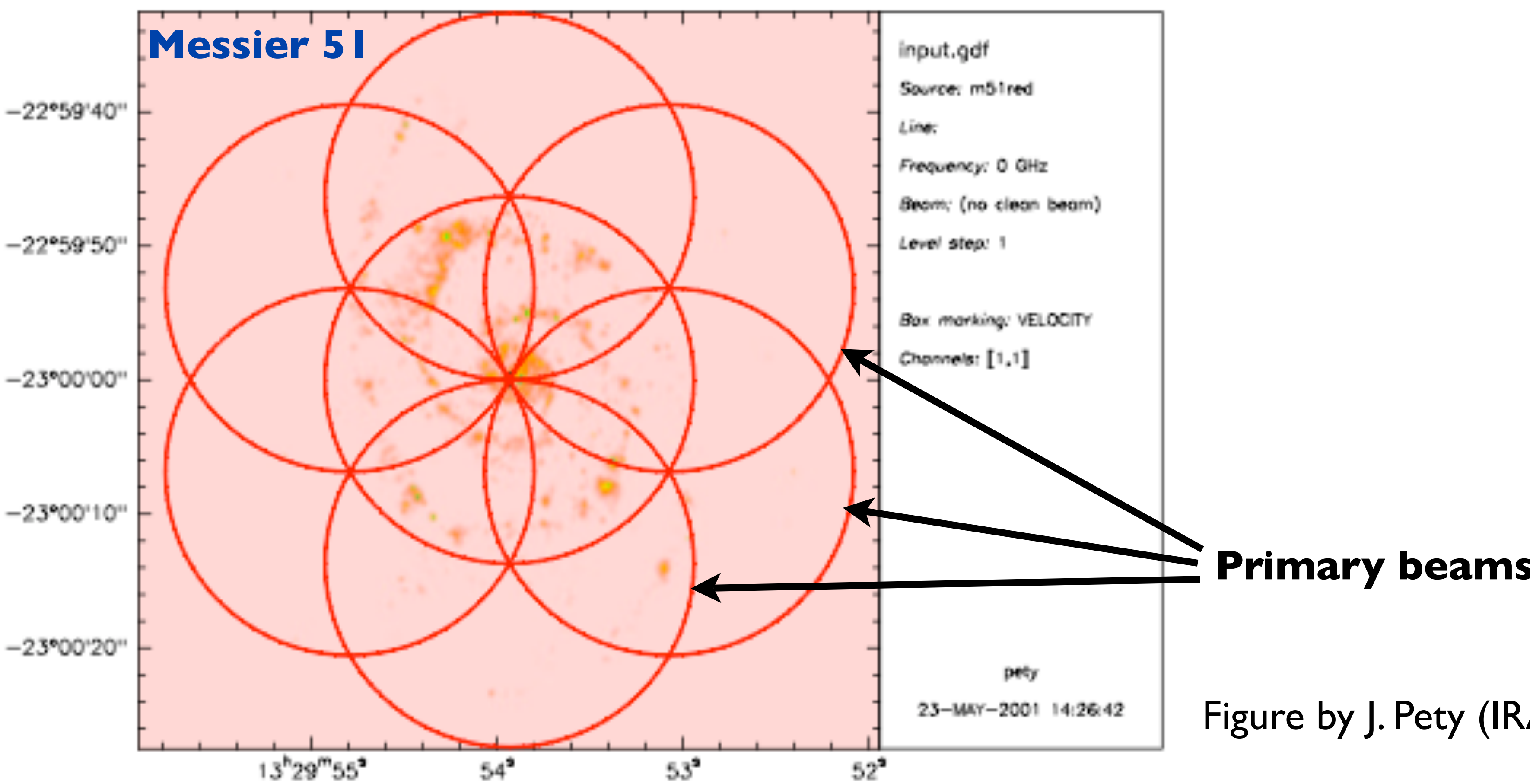


Figure by J. Pety (IRAM Grenoble)

Some radio-interferometers around the globe

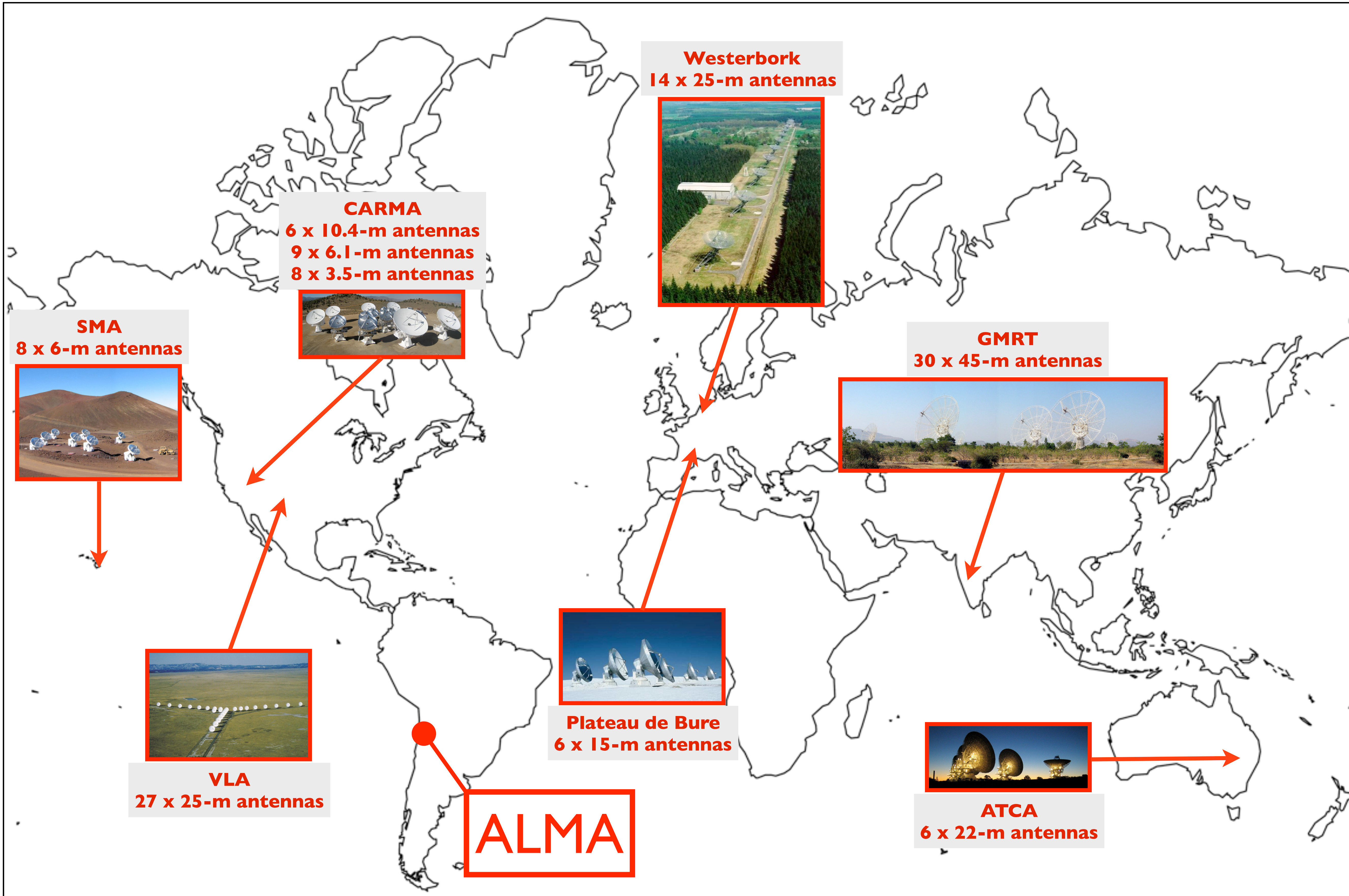
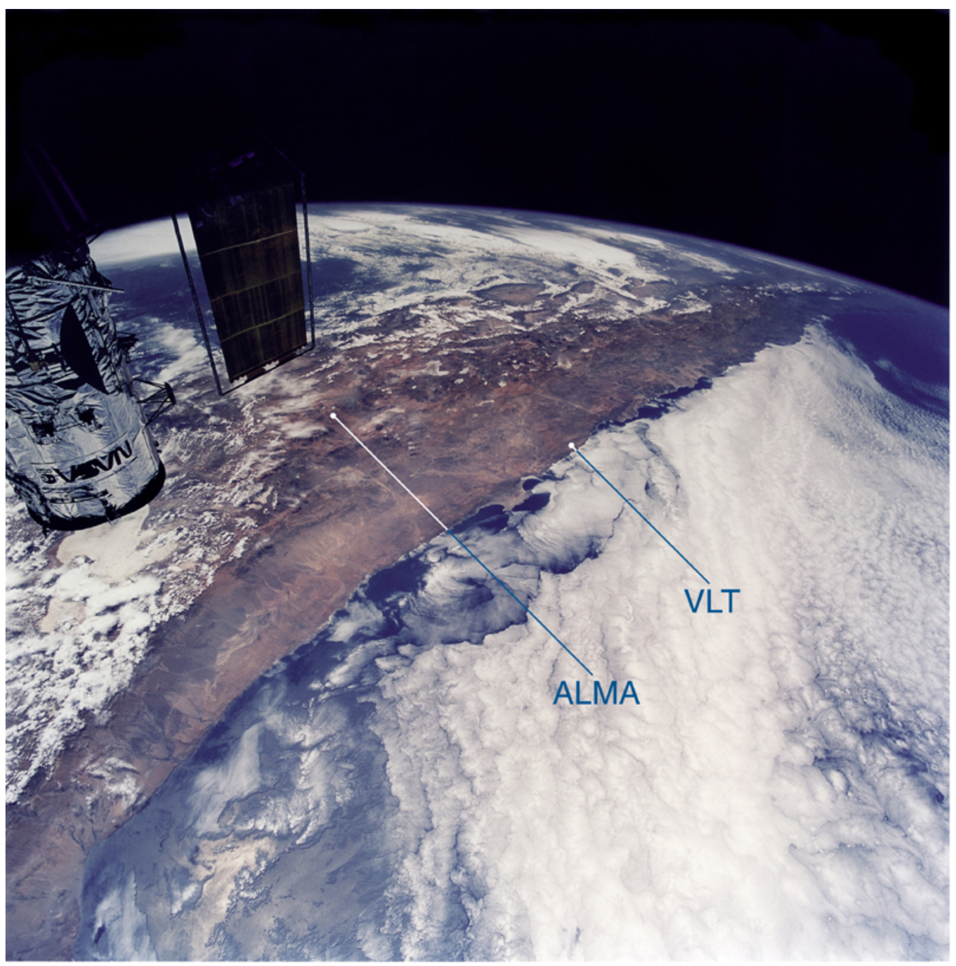


Image credits : NRAO/AUI - IRAM - ATNF - P. Lah - CARMA - SMA - NWO

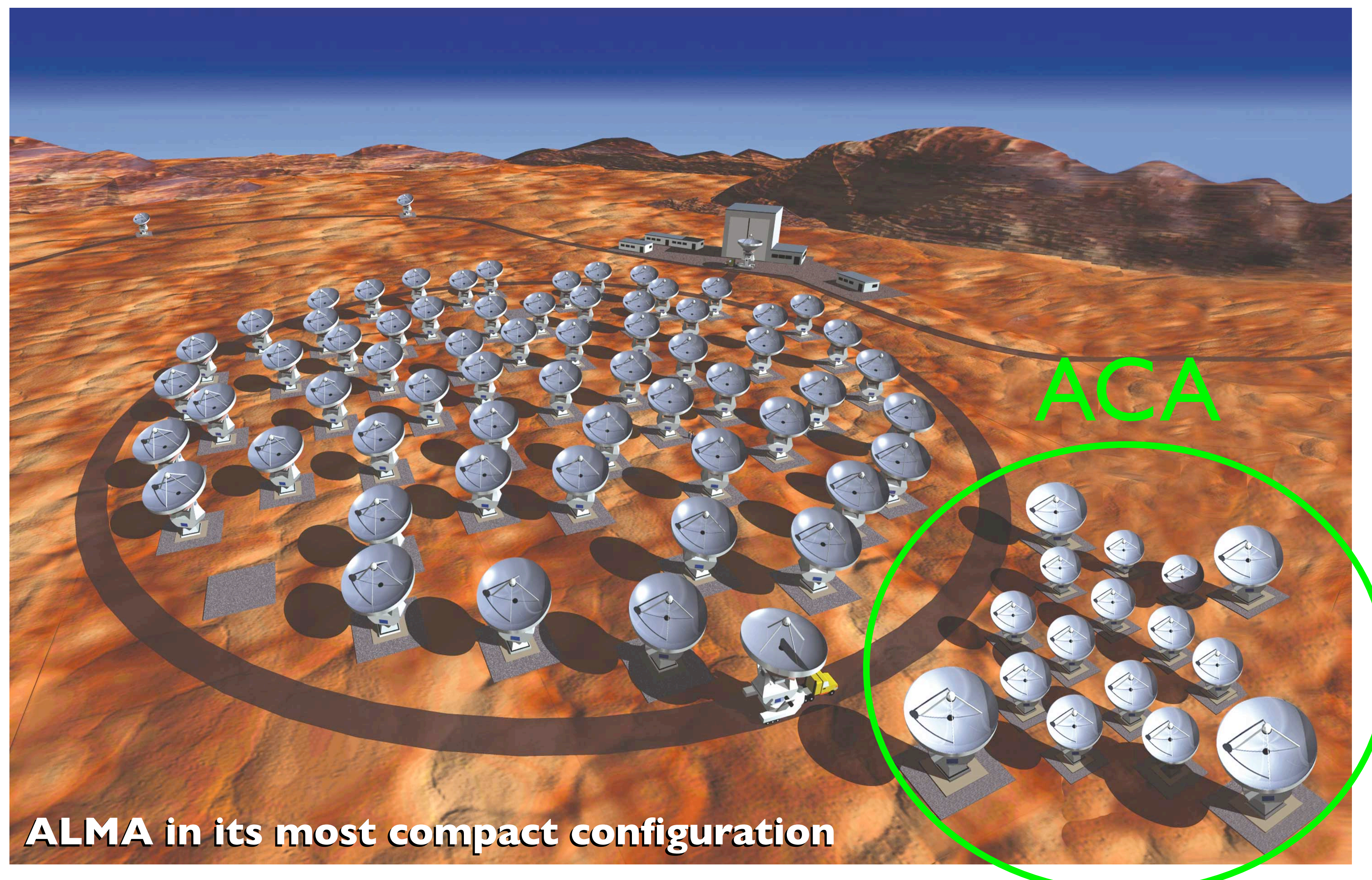
The ALMA project

ALMA
ATACAMA LARGE MILLIMETER ARRAY



View of Northern Chile (NASA Space Shuttle)

ESO PR Photo 24b/99 (8 June 1999)

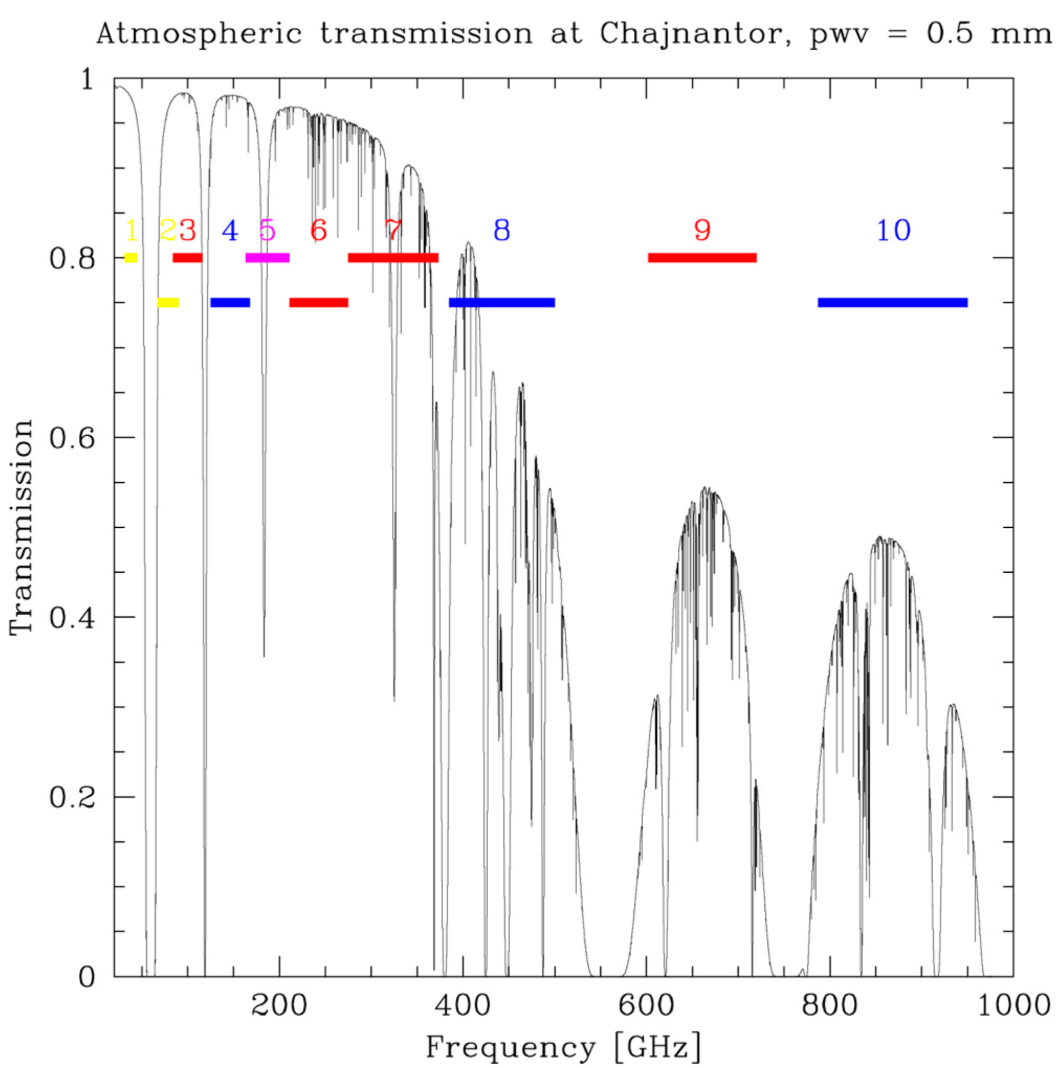


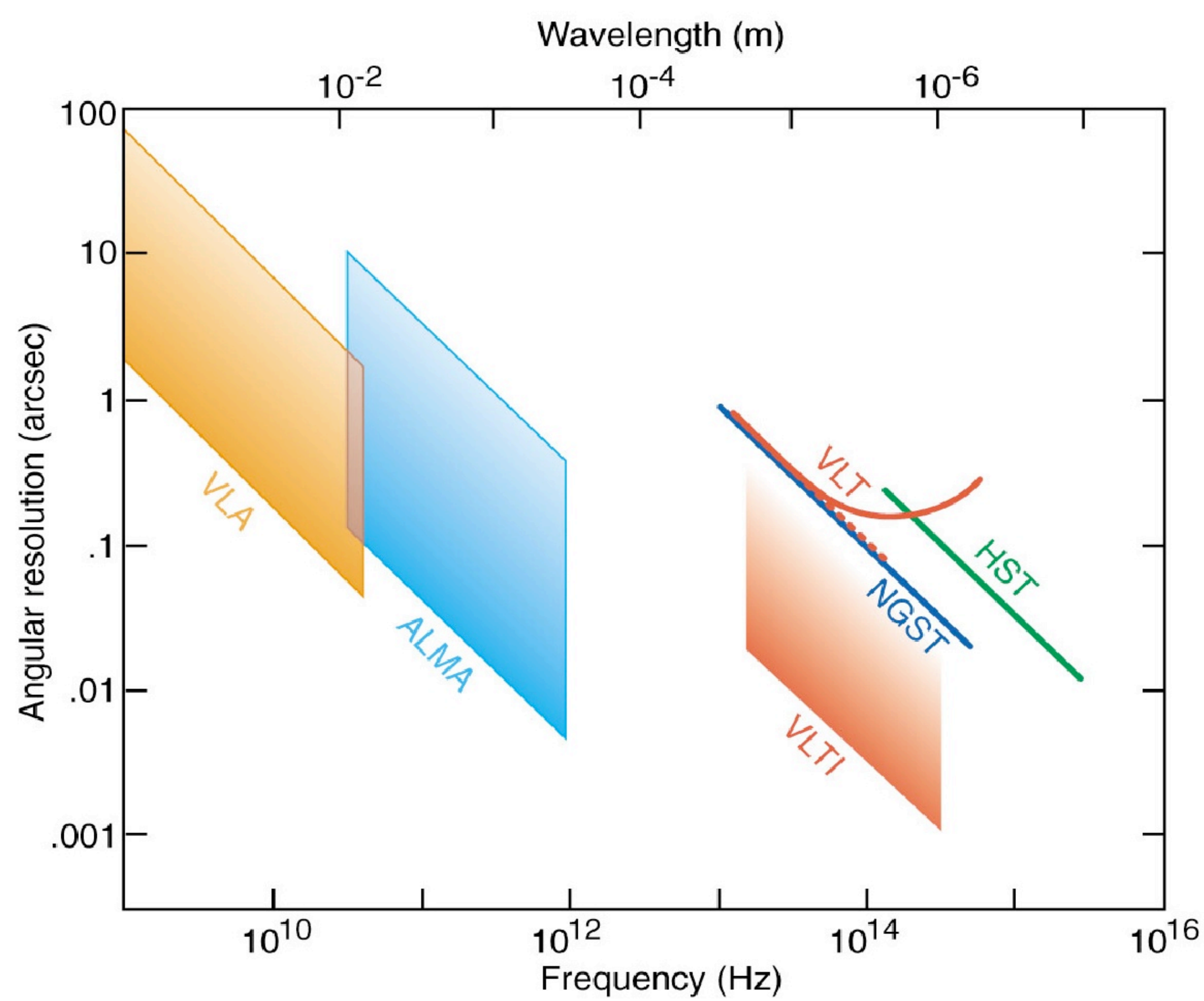
NRAO ESO NAOJ

Technical specifications

Antennas	64 x 12 m
Collecting area	>7000 m^2
Resolution	0”.02 λ_{mm}
Receivers	10 bands: 0.3 – 7 mm (36 - 850 GHz)
Correlator	2016 baselines
Bandwidth	16 GHz/baseline
Spectral channels	4096 per IF (8 x 2 GHz)
Baselines	150 m - 14 km

Not necessarily met...





Science goals

Design driven by primary science goals

- "Detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of 3, in less than 24 hours of observation."
- "Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distane of the nearest star-forming clouds."

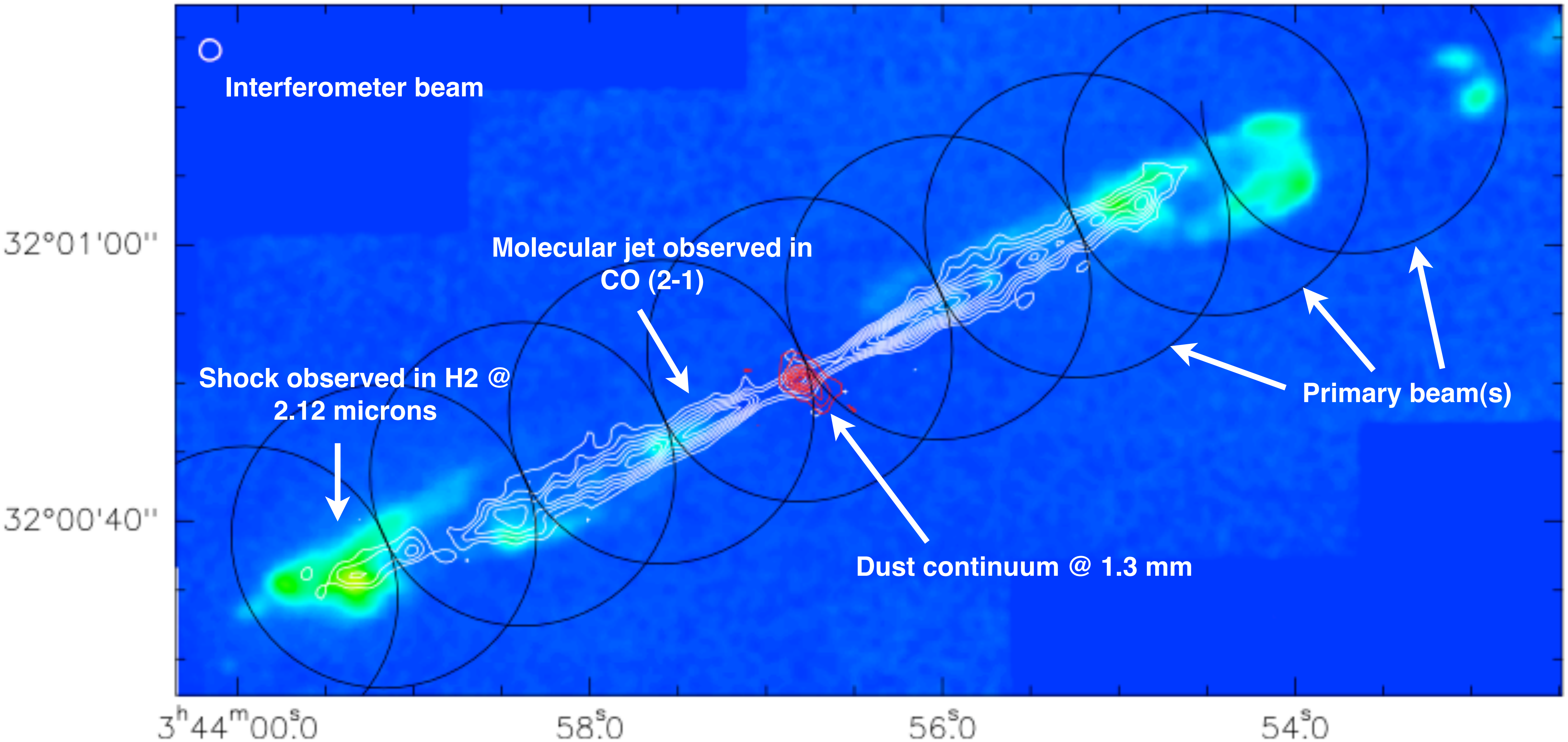
Secondary science goals as a bonus...

- "Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z = 10."
- "Probe the cold dust and molecular gas in nearby galaxies, allowing detailed studies of the interstellar medium in different galactic environments."
- "Image the complex dynamics of the molecular gas at the center of our own Galaxy with unprecedented spatial resolution."
- "Use the emission from CO to measure the redshift of star-forming galaxies throughout the universe."
- "Image the formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae"
- "Refine dynamical and chemical models of the atmospheres of planets in our own Solar System, and provide unobscured images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects."

- *Formation of galaxies and clusters*
- *Formation of stars*
- *Formation of planets*
- *Old stellar atmospheres*
- *Supernova ejecta*
- *Planetary composition and weather*
- *Structure of interstellar gas and dust*
- *Astrochemistry and the origins of life*

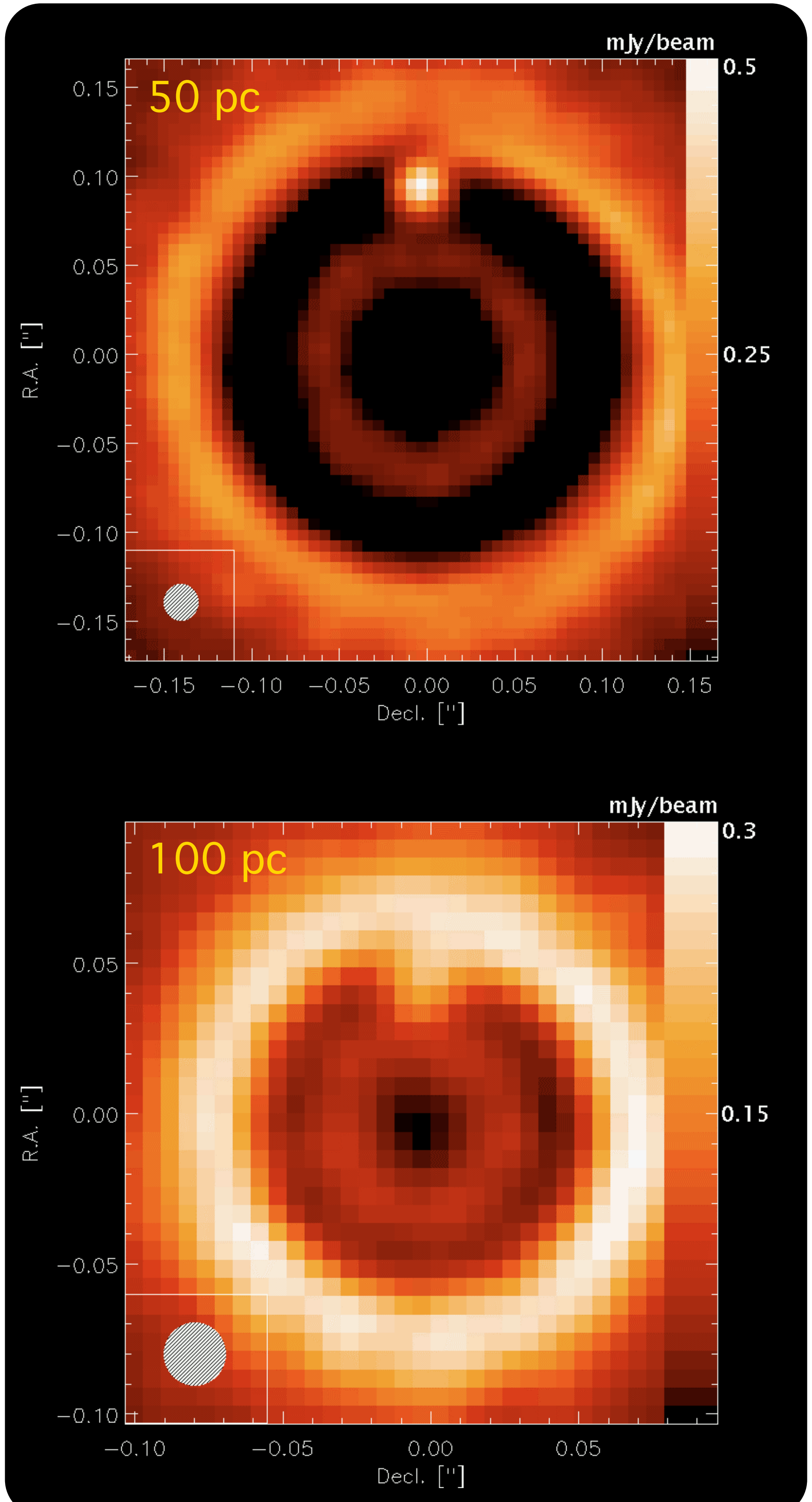
Jets from protostars

“The spatial resolution of ALMA will allow the accretion of cloud material onto an accretion disk to be imaged, and will trace the formation and evolution of disks and jets in young protostellar systems.”



(Gueth & Guilloteau 1999)

Proto-planetary disks around young stars



"For older protostars and pre-main sequence stars ALMA will show how planets form, sweeping gaps in circumstellar and debris disks."

Wolf & D'Angelo (2005)

$$M_{\rm planet} = M_{\rm Jupiter}$$

$$M_{\rm star} = 0.5 \times M_{\rm Sun}$$

Orbital radius : 5 AU

Maximum baseline: 10km

λ=333μm

t_{int}=8h

30deg phase noise

Astrochemistry in circumstellar environments

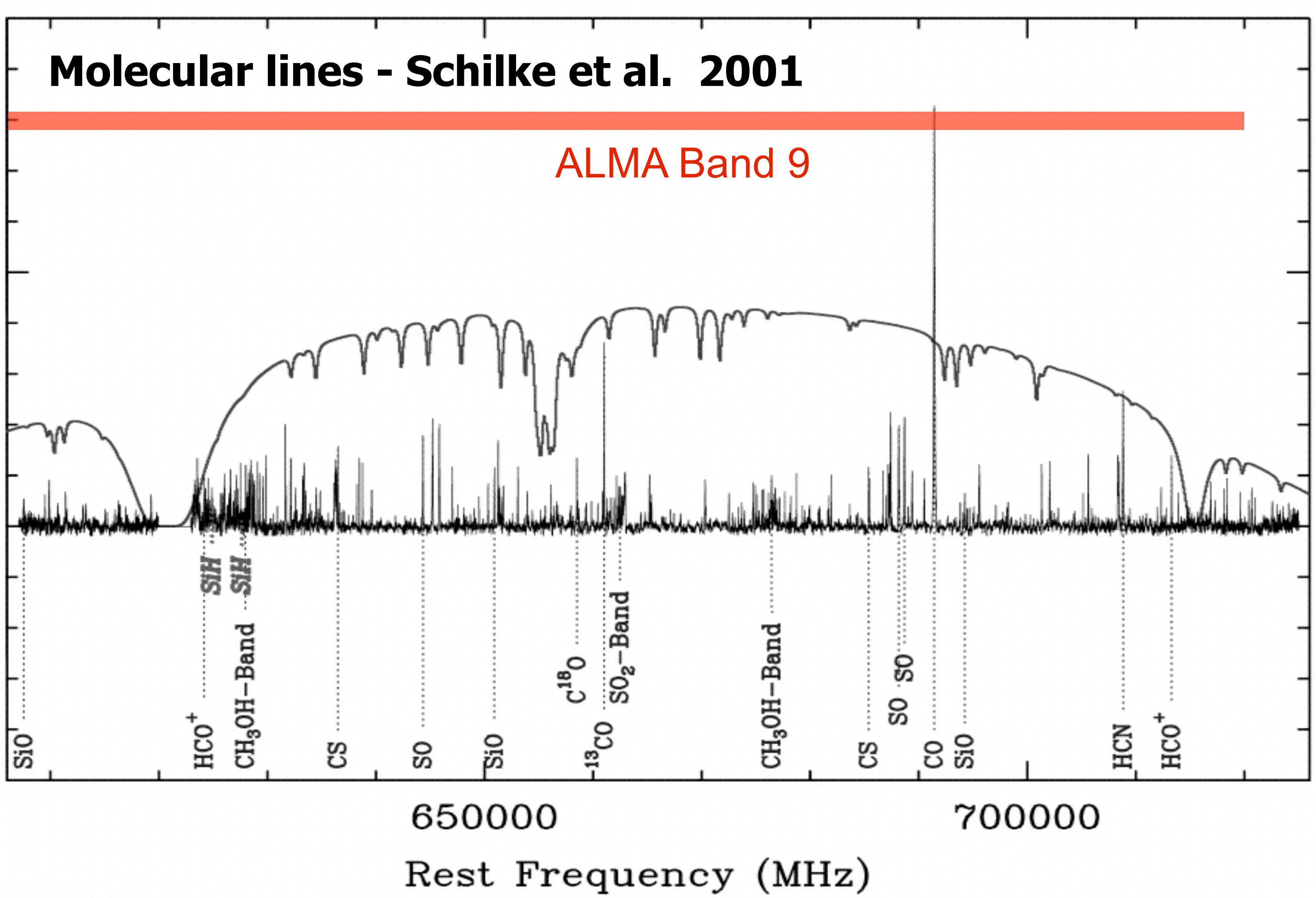
"Uncover the chemical composition of the molecular gas surrounding young stars, including establishing the role of the freeze-out of gas-phase species onto grains, the re-release of these species back into the gas phase in the warm inner regions of circumstellar disks, and the subsequent formation of complex organic molecules. ALMA will have the large total bandwidth, high spectral resolution, and sensitivity needed to detect the myriad of lines associated with heavy, pre-biotic molecules such as those which may have been present in the young Solar System."

Rotational and vibrational modes of many molecules in the millimeter and sub-millimeter bands

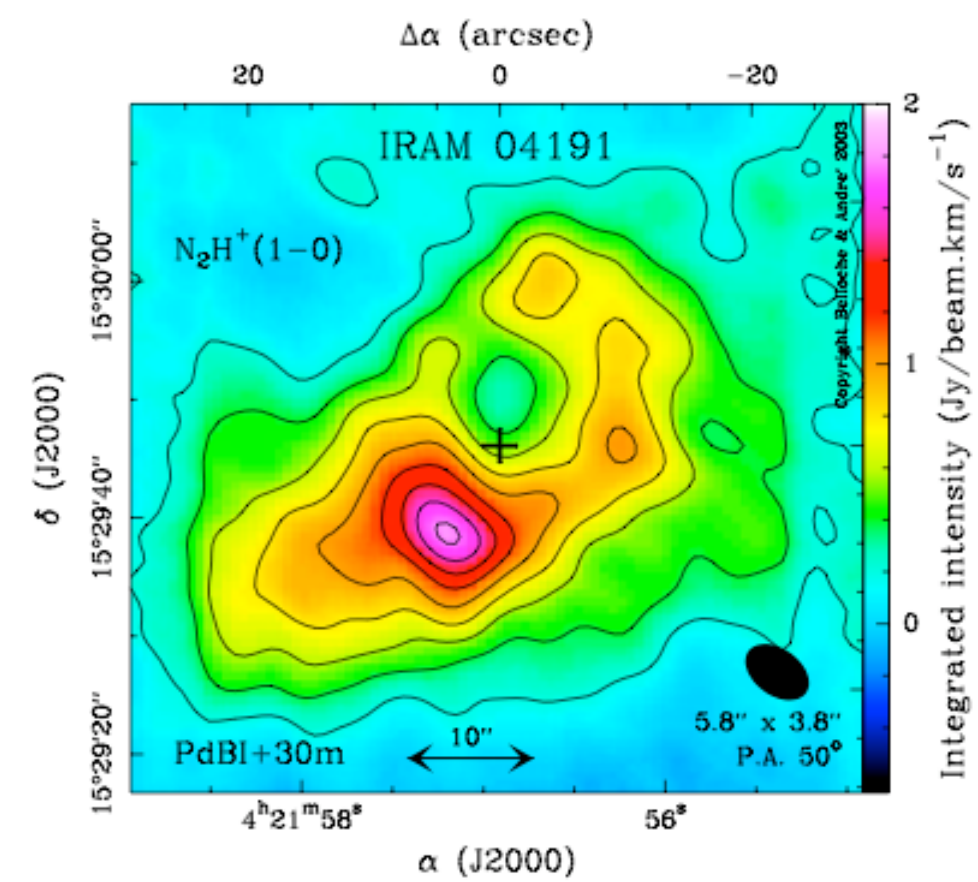
~150 different molecules detected in the interstellar medium or circumstellar shells

~35 in extragalactic sources

CO, H_2O, OH, HCN, HCO^+, CS, NH_3, H_2CO

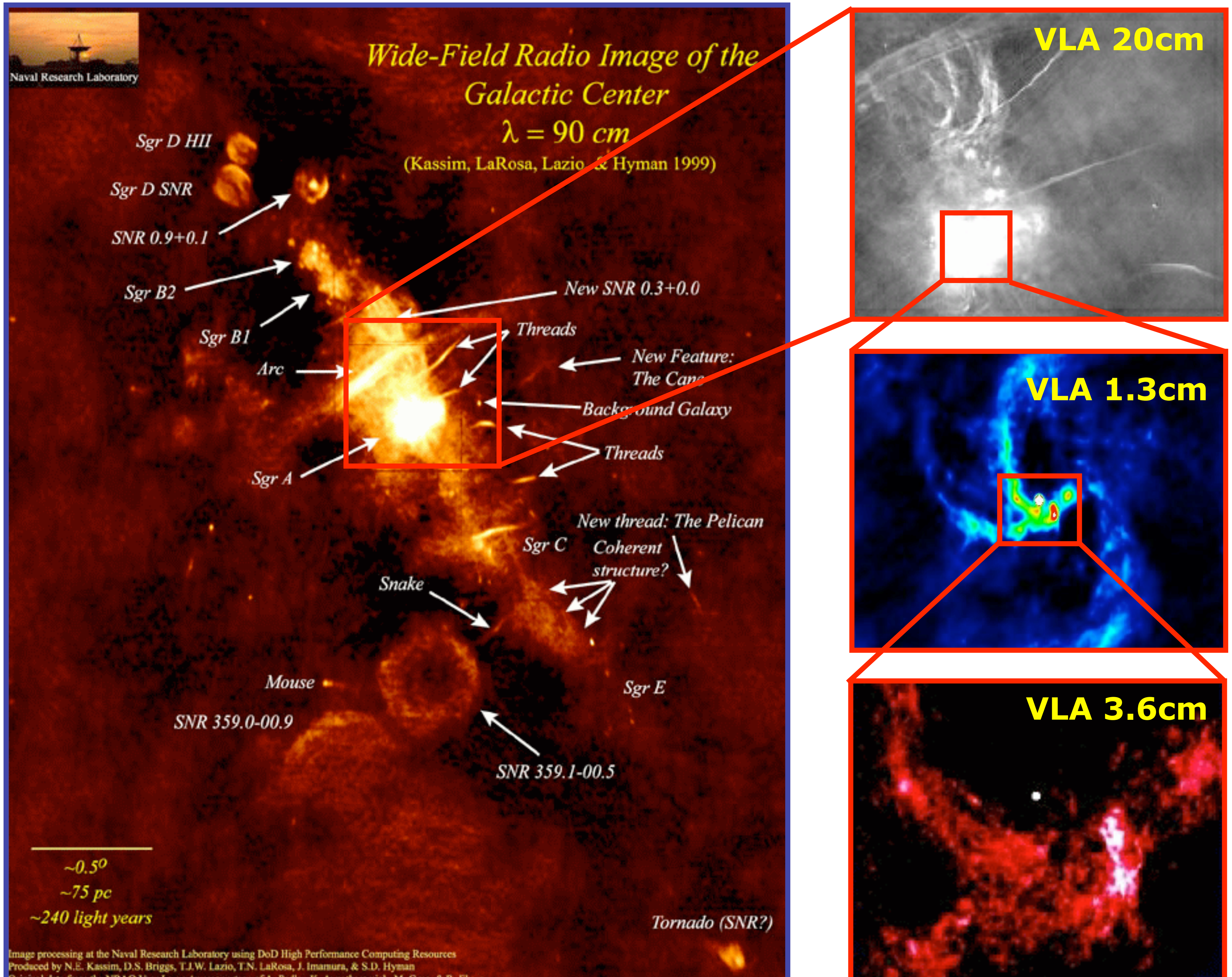


N_2H^+ in the IRAM 04191 protostar (Belloche et al. 2004)



Galactic Center

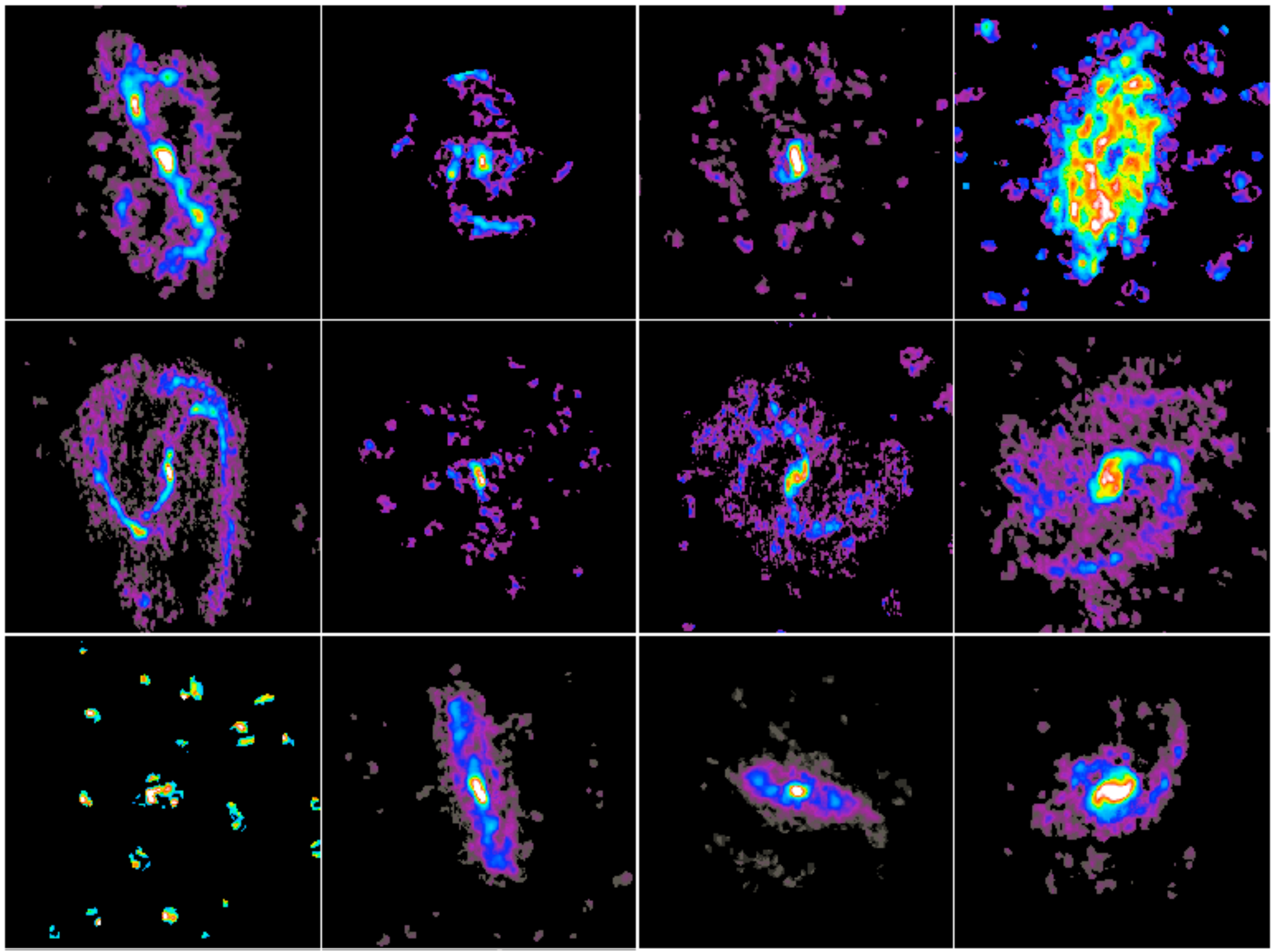
"Image the complex dynamics of the molecular gas at the center of our own Galaxy with unprecedented spatial resolution, thereby revealing the tidal, magnetic, and turbulent processes that make stellar birth and death at the Galactic Center more extreme than in the local Solar neighborhood."



Credits: Lang, Morris, Roberts, Yusef-Zadef, Goss, Zhao

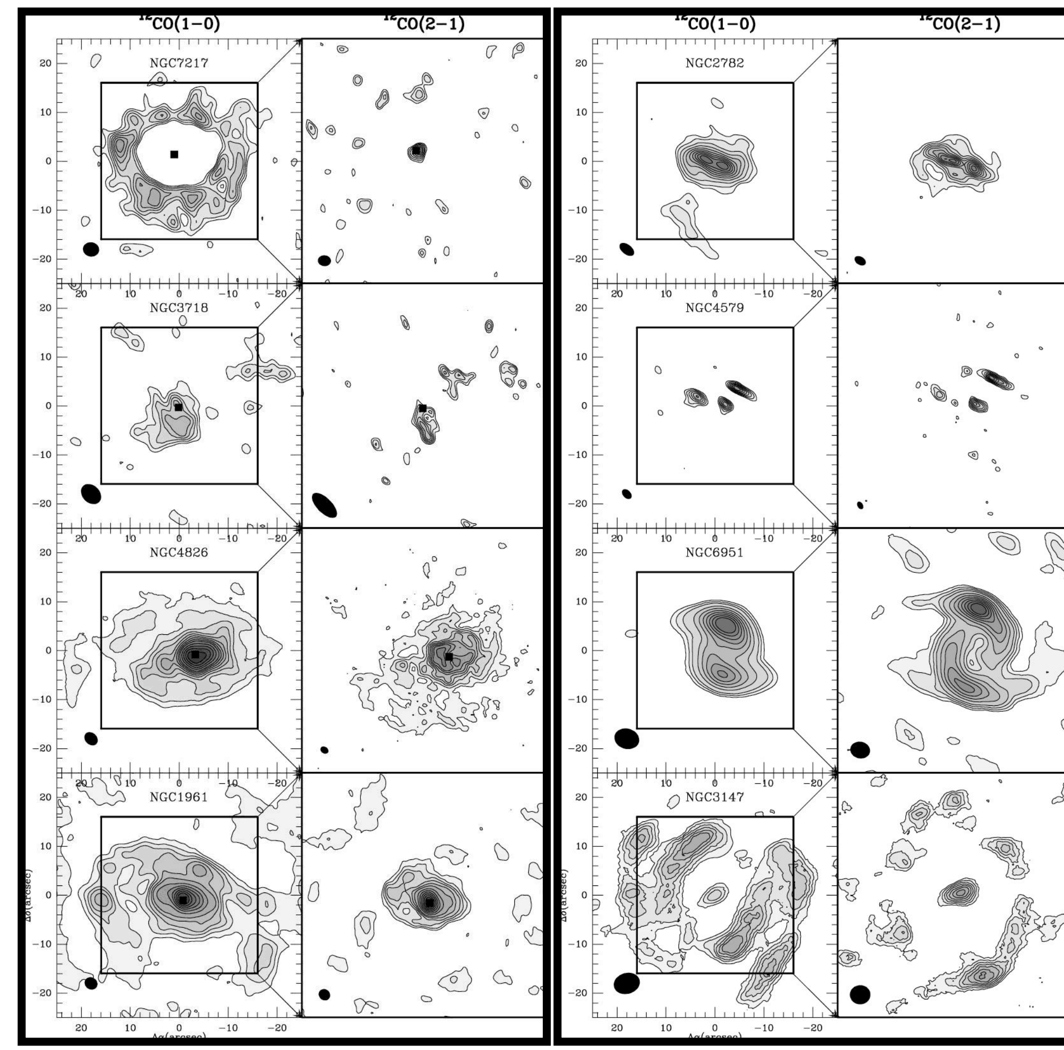
Molecular gas in nearby galaxies

“Probe the cold dust and molecular gas in nearby galaxies, allowing detailed studies of the interstellar medium in different galactic environments, the effect of the physical conditions on the local star formation history, and galactic structure. The resolution of ALMA will reveal the kinematics of obscured active galactic nuclei and quasars on spatial scales of 10-100 pc, and will be able to test unification models of Seyfert galaxies.”



BIMA Survey of Nearby Galaxies - SONG: (Helfer et al. 2002)

Imaging survey of the CO J=(1–0) emission in 44 nearby spiral galaxies



NUGA (Combes et al. 2003)

Imaging survey of the CO emission in 12 nearby active galactic nuclei (AGN) with Plateau de Bure

Star-forming galaxies in the early Universe

“Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z = 10. The inverse K-correction on the Rayleigh-Jeans side of the spectral energy distribution of a dusty galaxy compensates for dimming at high redshift, making ALMA the ideal instrument for investigating the origins of galaxies in the early universe, with confusion minimized by the high spatial resolution.”

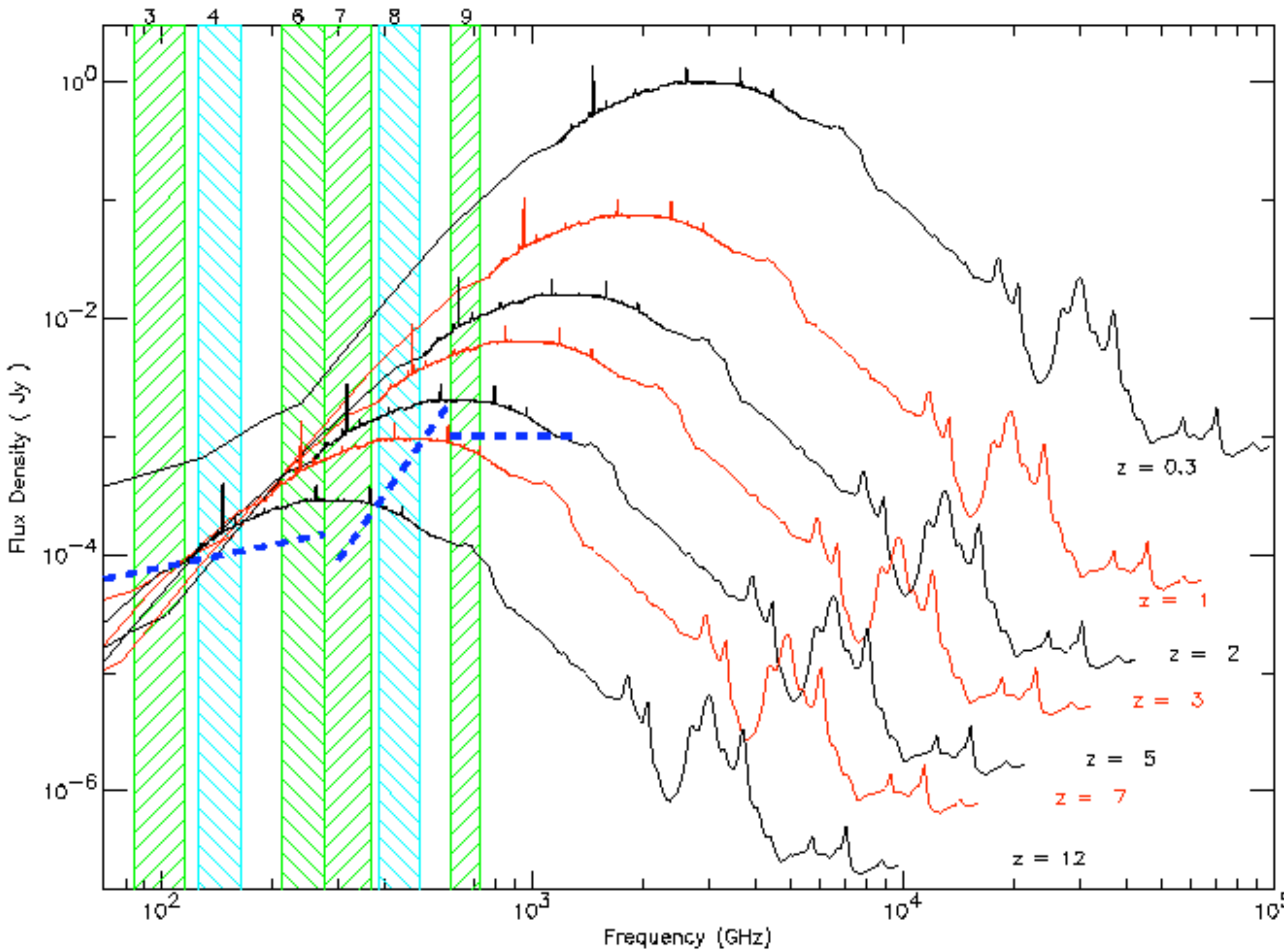
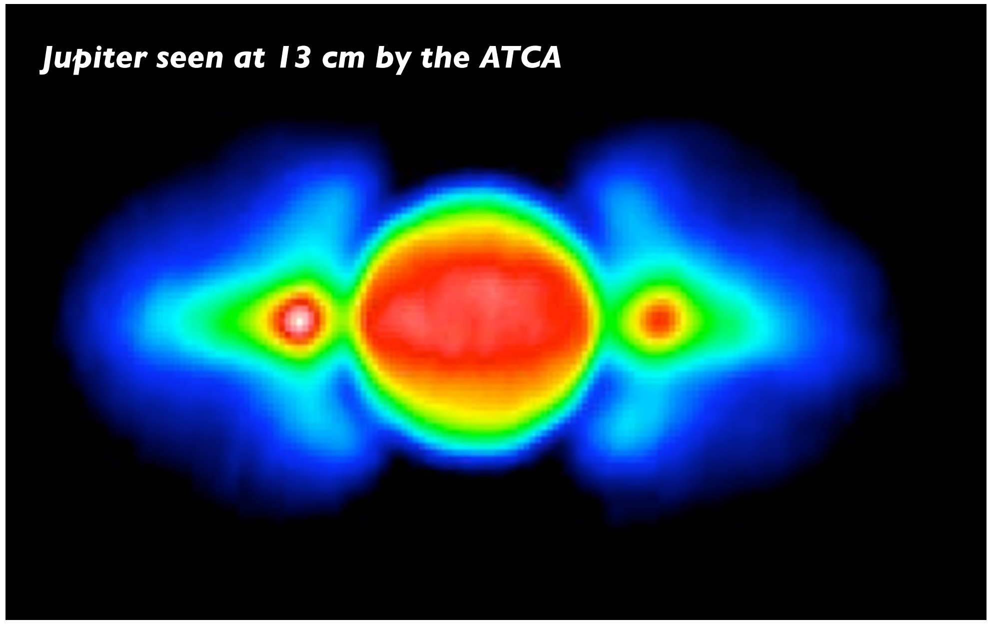
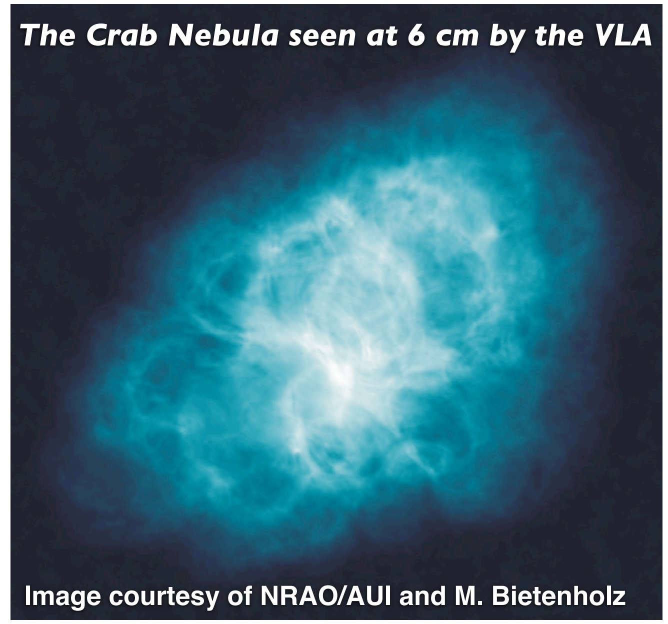
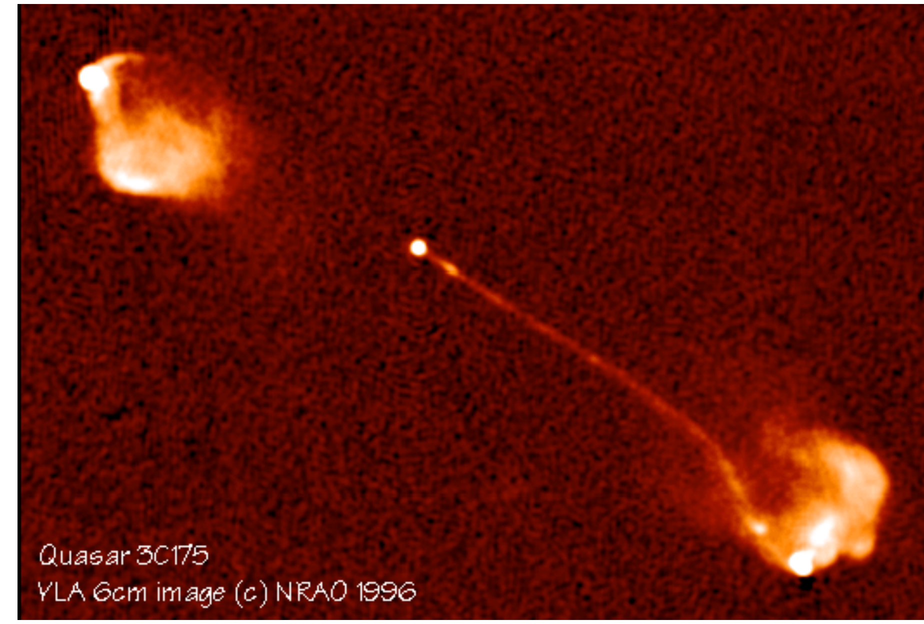


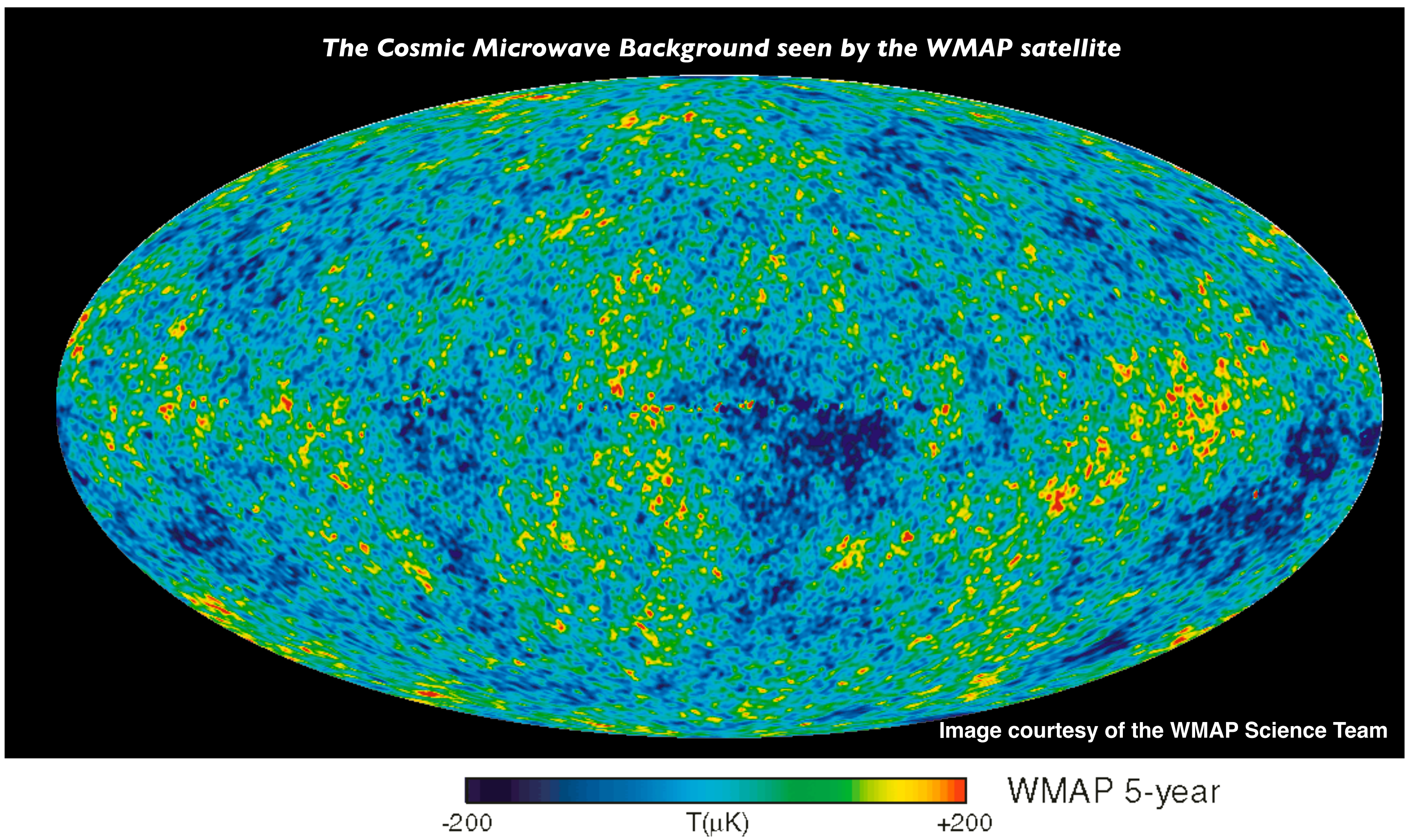
Figure by A. Wootten (NRAO)

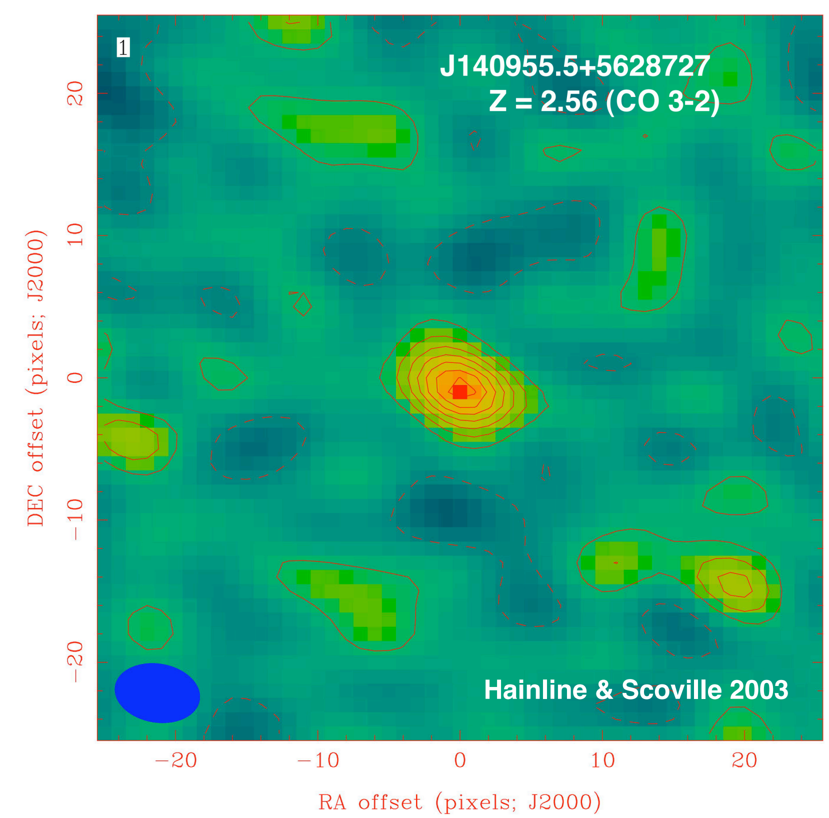
Some more pretty pictures of the radio Universe



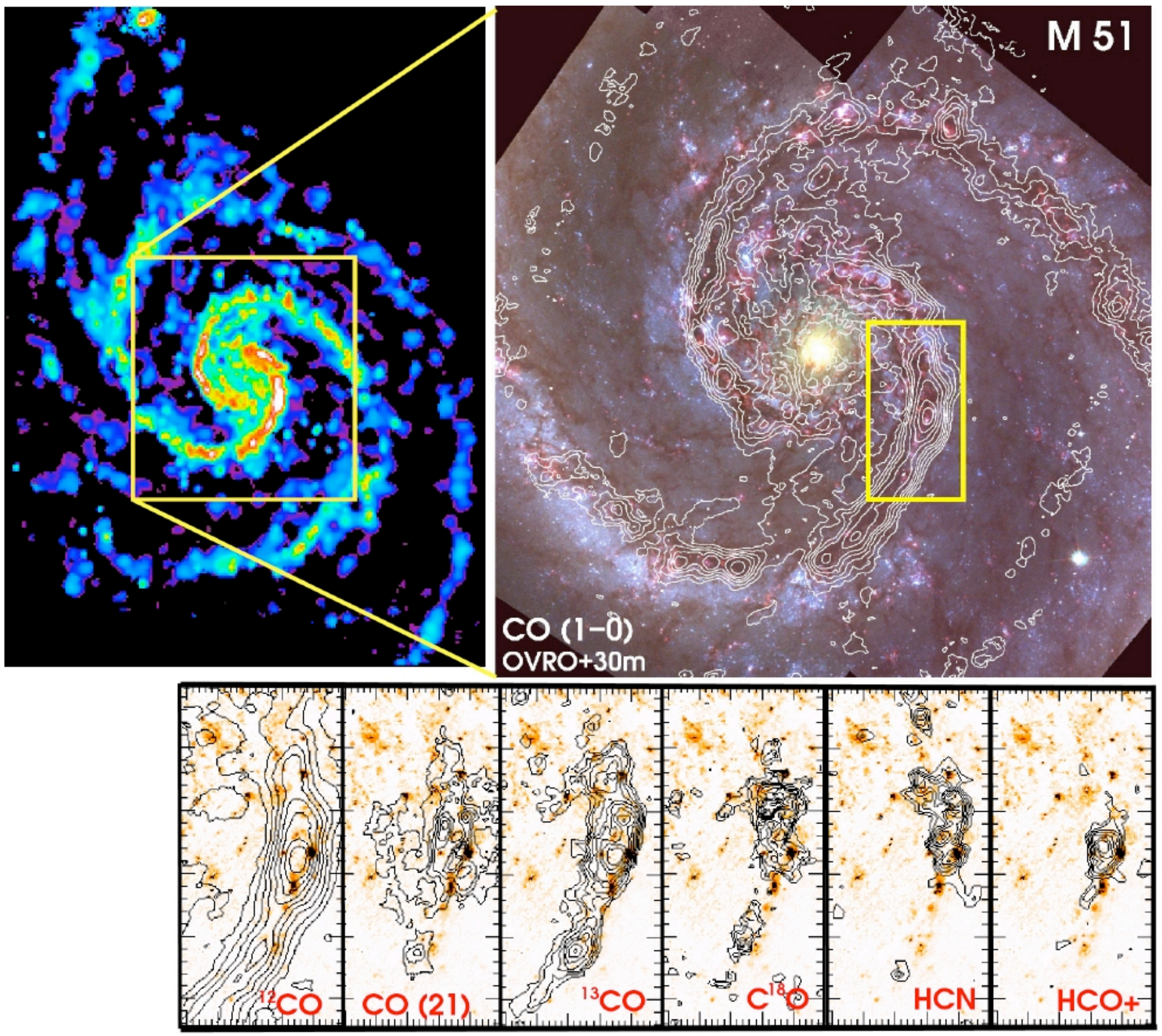


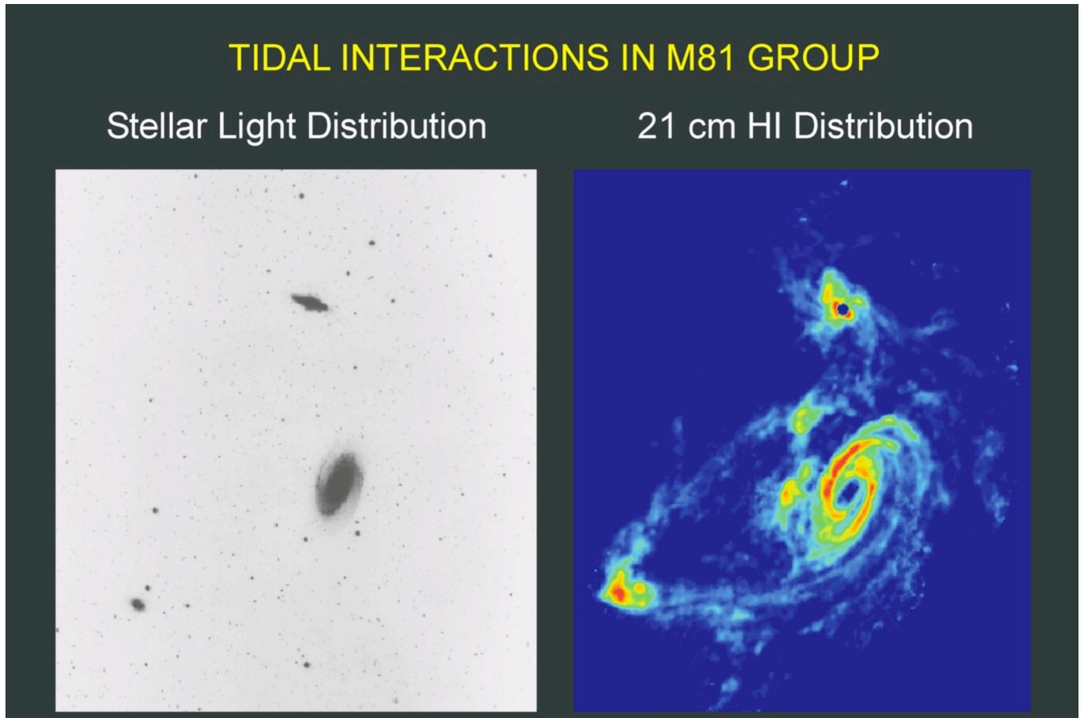




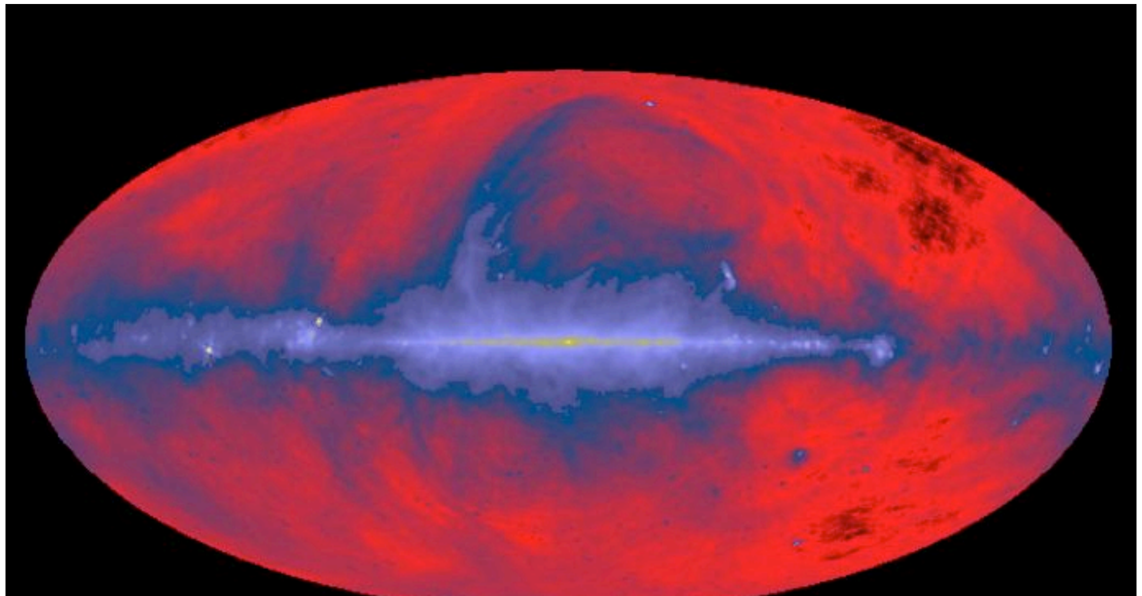


Some more pretty pictures of the radio Universe





VLA 12-pointing mosaic, Yun et al. 1994


Full sky @ 408 MHz (Haslam et al. 1982)

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FOR RADIOASTRONOMY