The large ground-based instruments for 21st century radio-interferometry

The SKA project

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LRA-ENS

FIP seminar, 24.11.2015

The ALMA observatory

Talk outline

An introduction to radio-interferometry in astronomy

The Atacama Large Millimeter Array (ALMA)

The Square Kilometer Array (SKA)

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

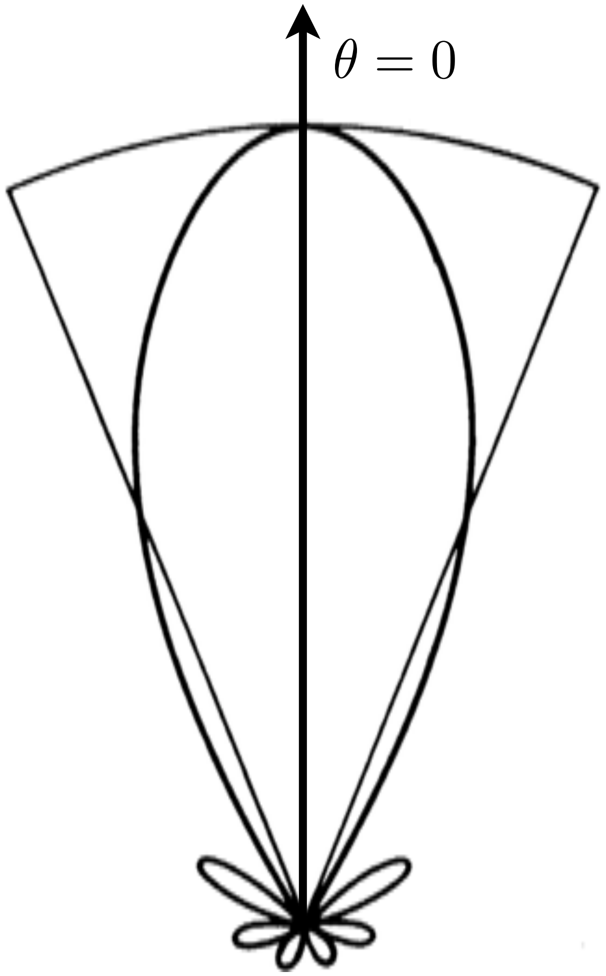
The “single dish” radiotelescope

<u>*Direction-dependent sensitivity*</u>

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

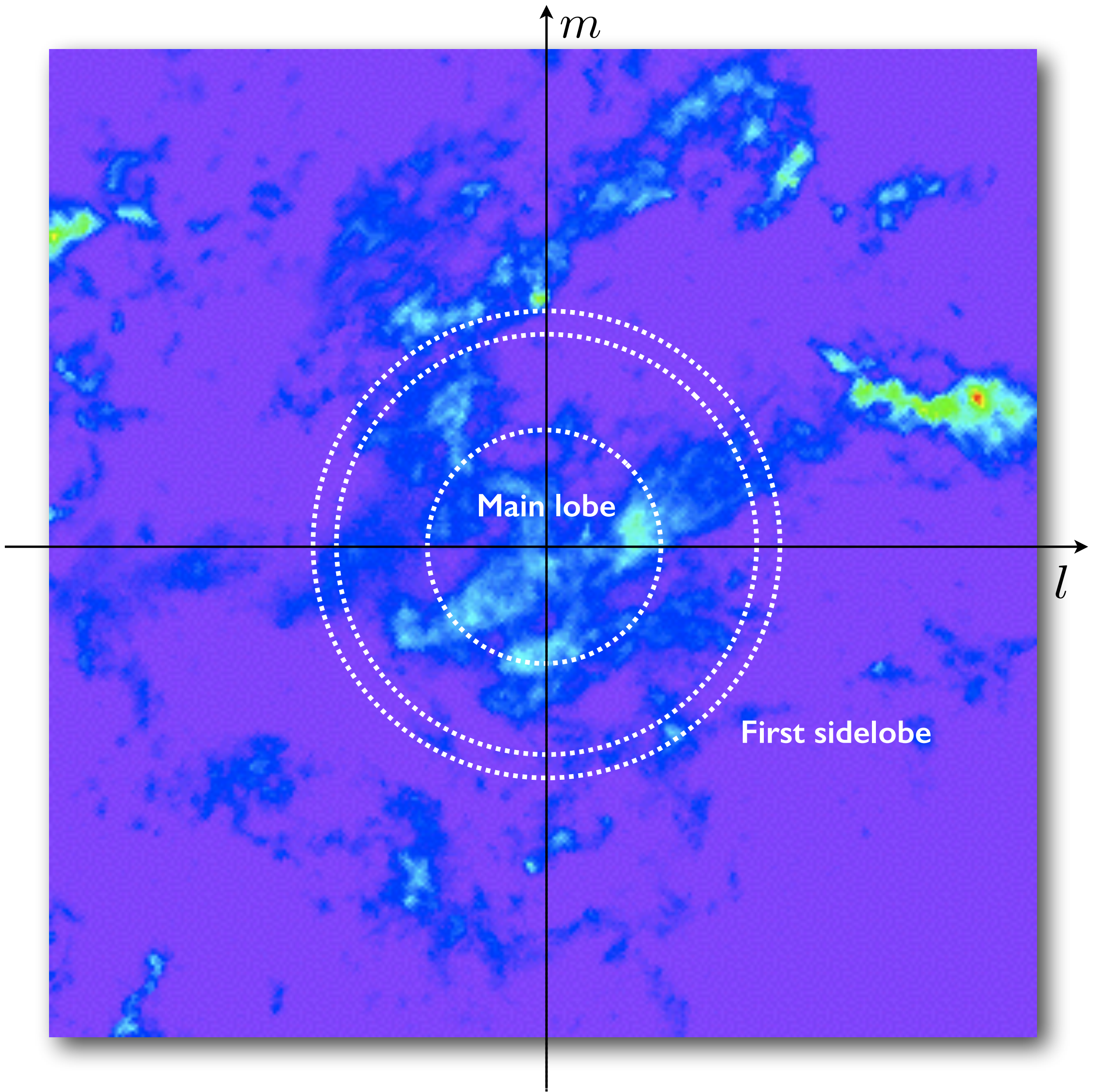
Optical : Airy function

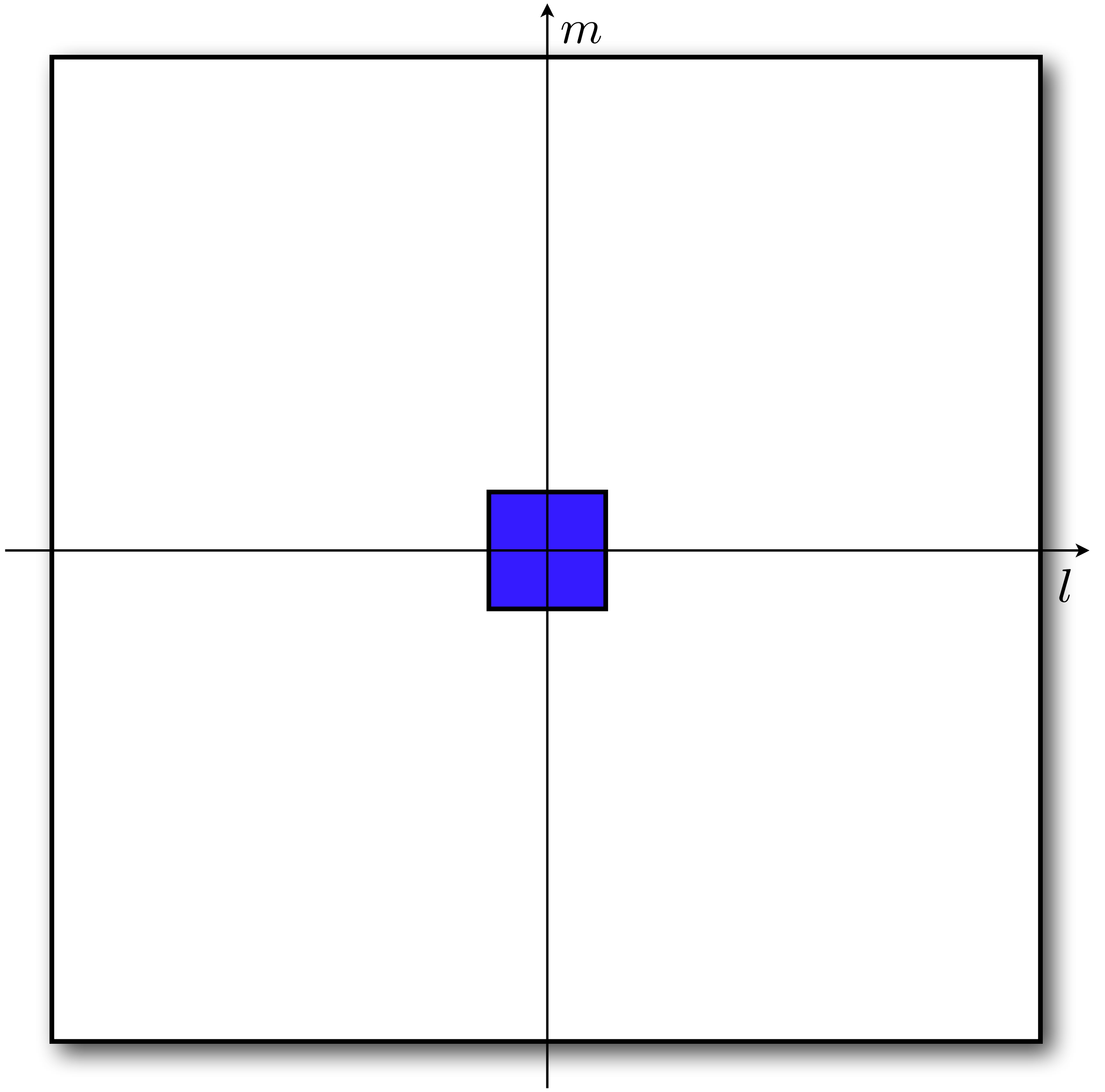
Radio : Gaussian

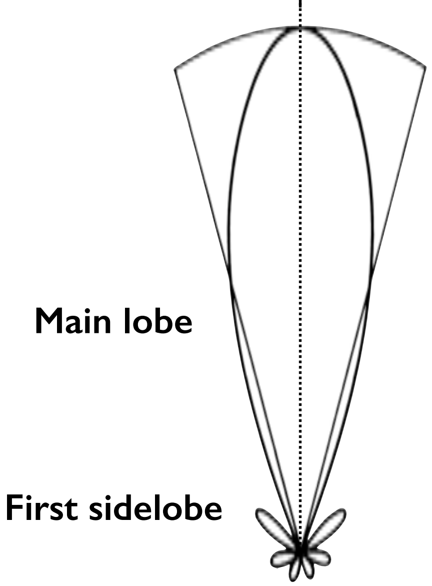


Single dish sensitivity in polar coordinates

Mapping radiation with a single dish antenna



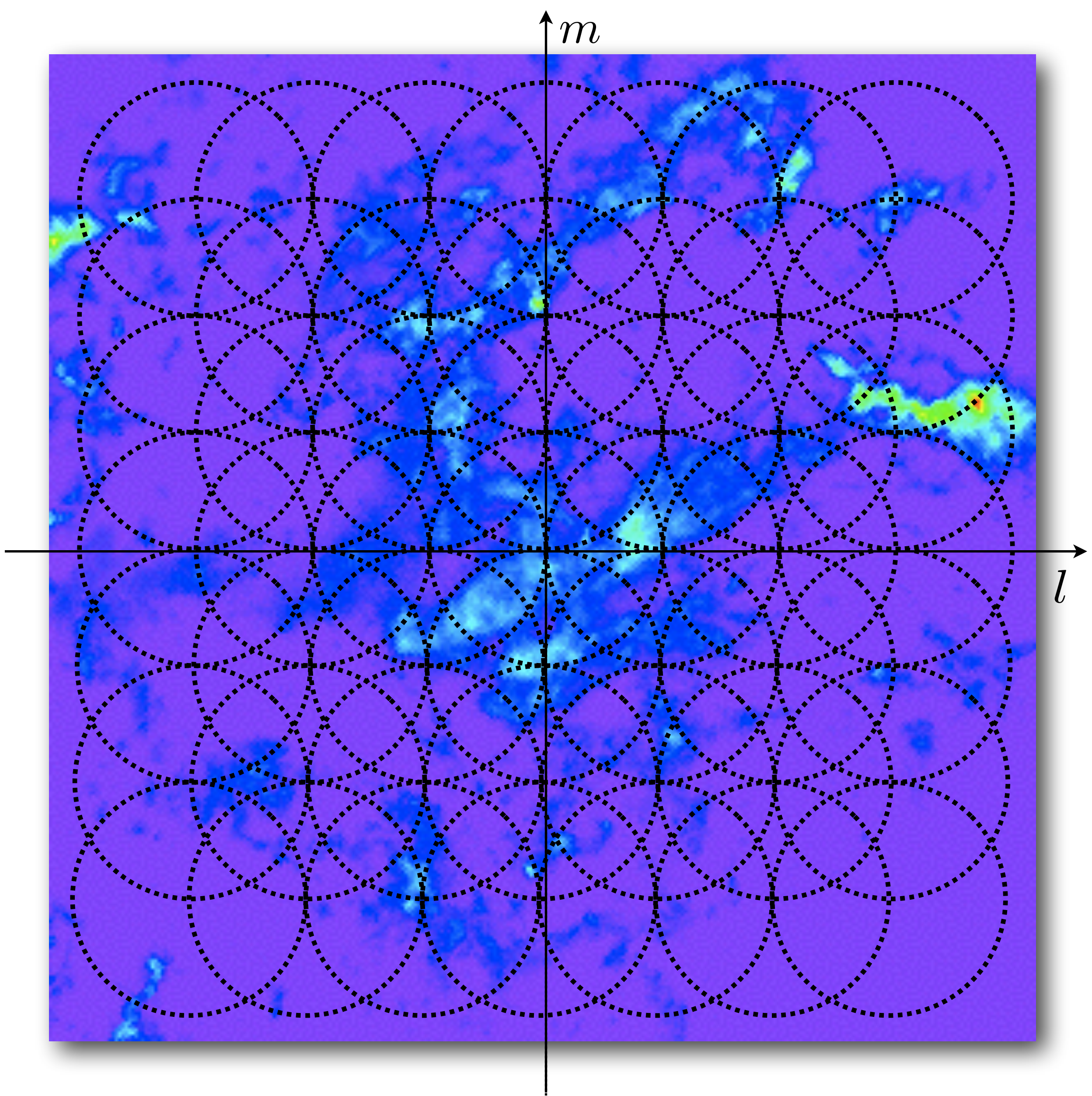


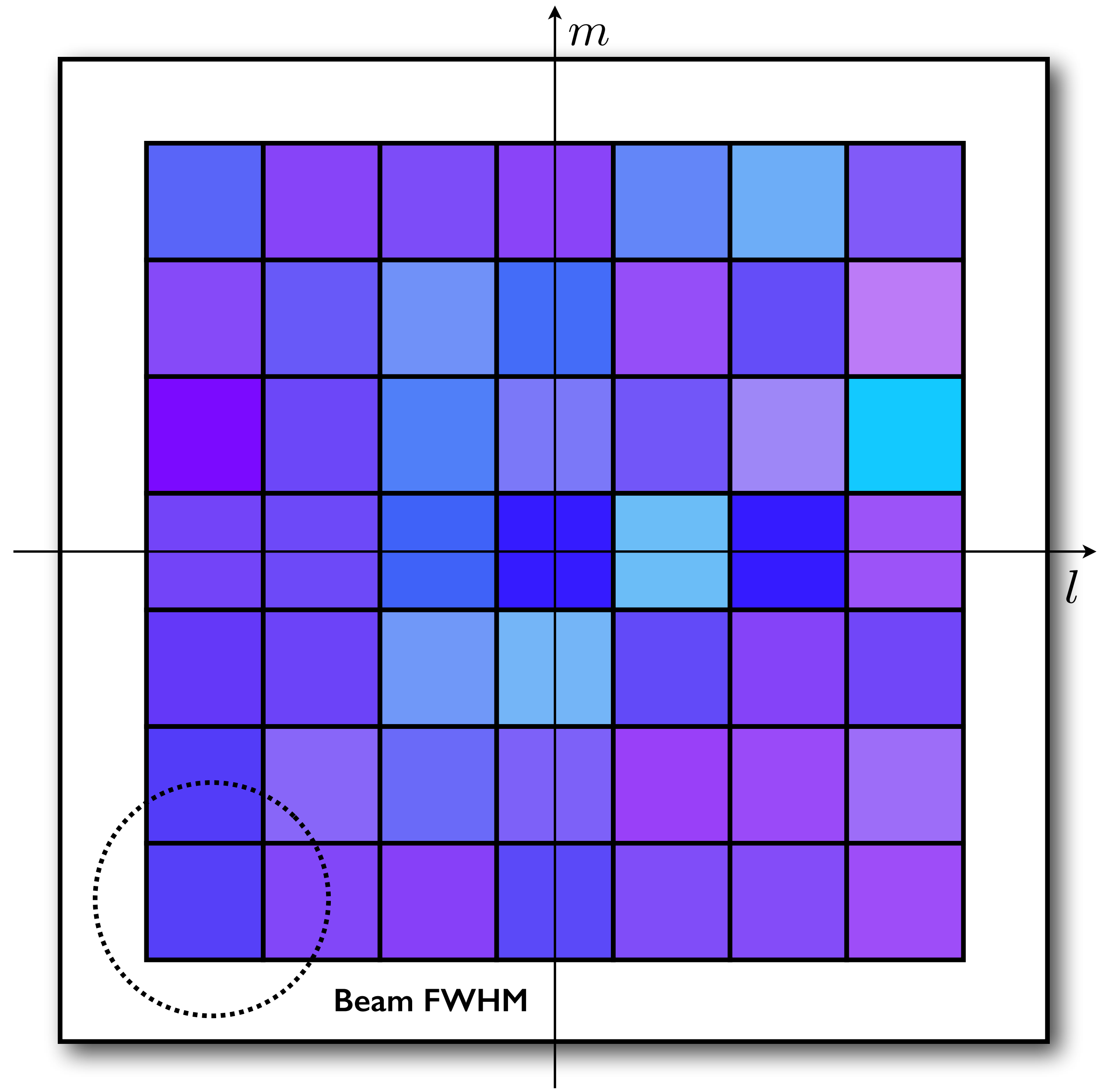


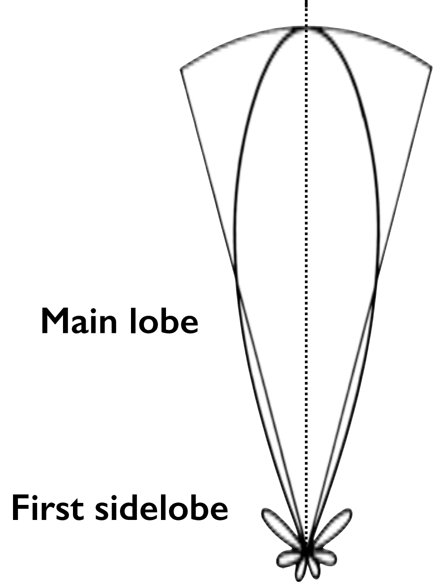
All the emission within the beam is collected by the receiver, weighted by the antenna's sensitivity in each direction, which amounts to a convolution of the brightness distribution by the antenna beam :

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

Mapping radiation with a single dish antenna



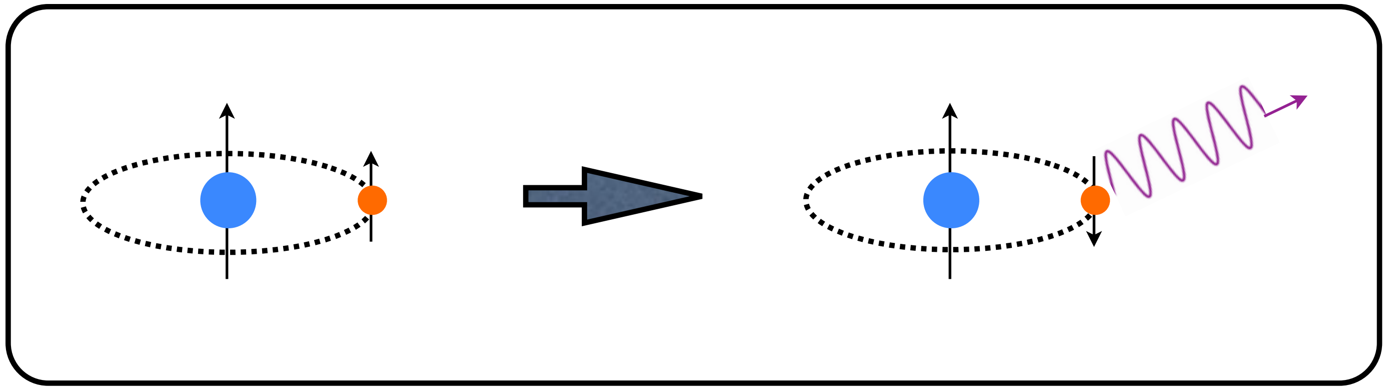




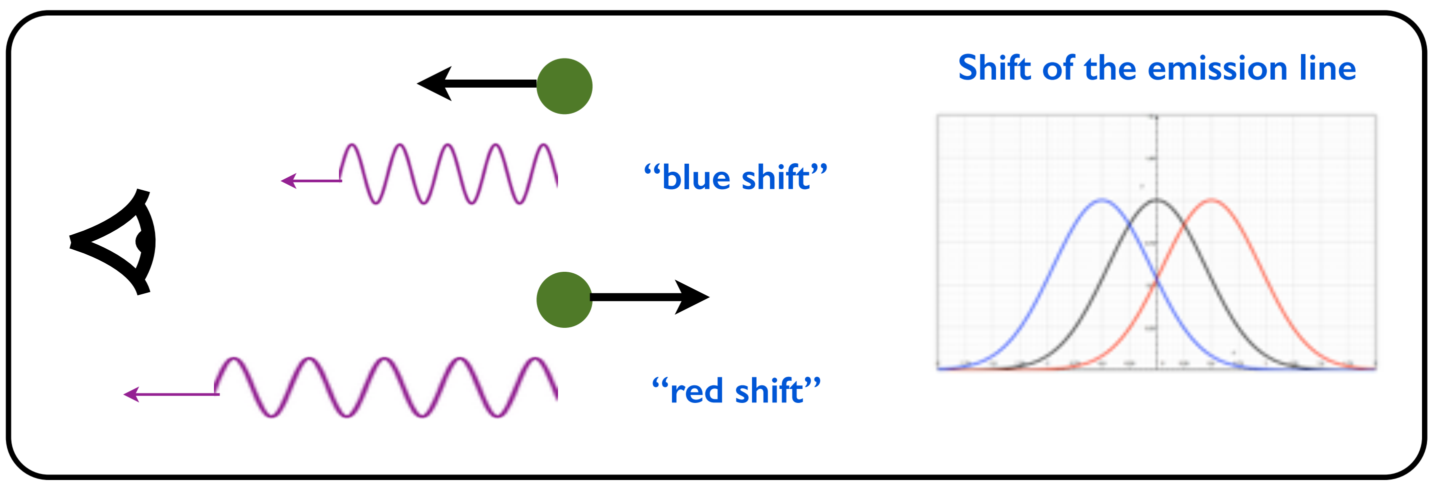
Scanning an extended source (larger than the beam) means pointing the telescope towards different directions and constructing a map. Pointings are usually separated by half the angular size of the main lobe (ie half the FWHM - Full Width at Half Maximum)

Getting to the gas kinematics : spectral lines

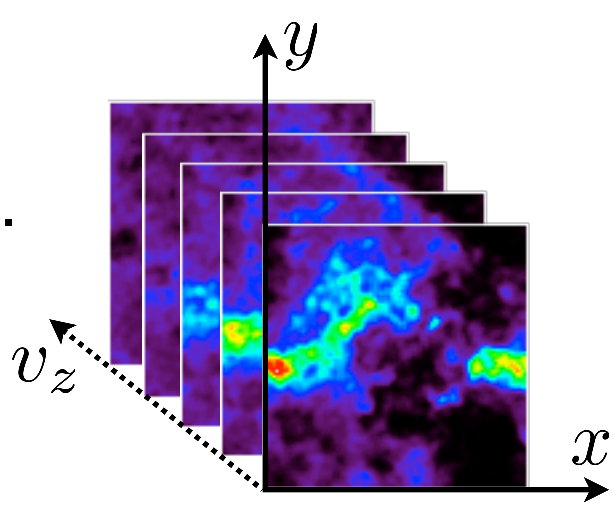
For instance : hyperfine transition of neutral hydrogen (HI) at 21 cm

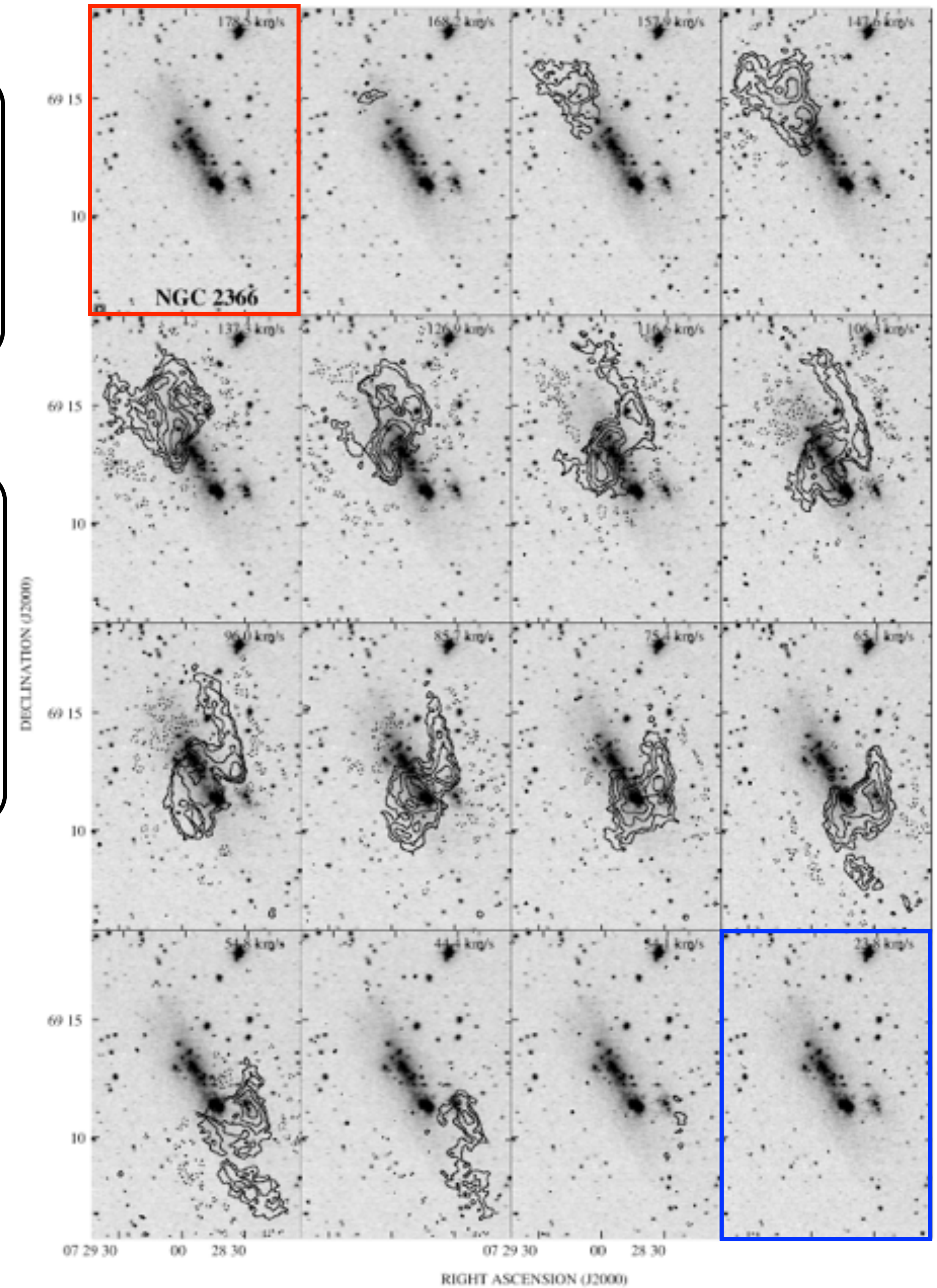


Doppler-Fizeau shift



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

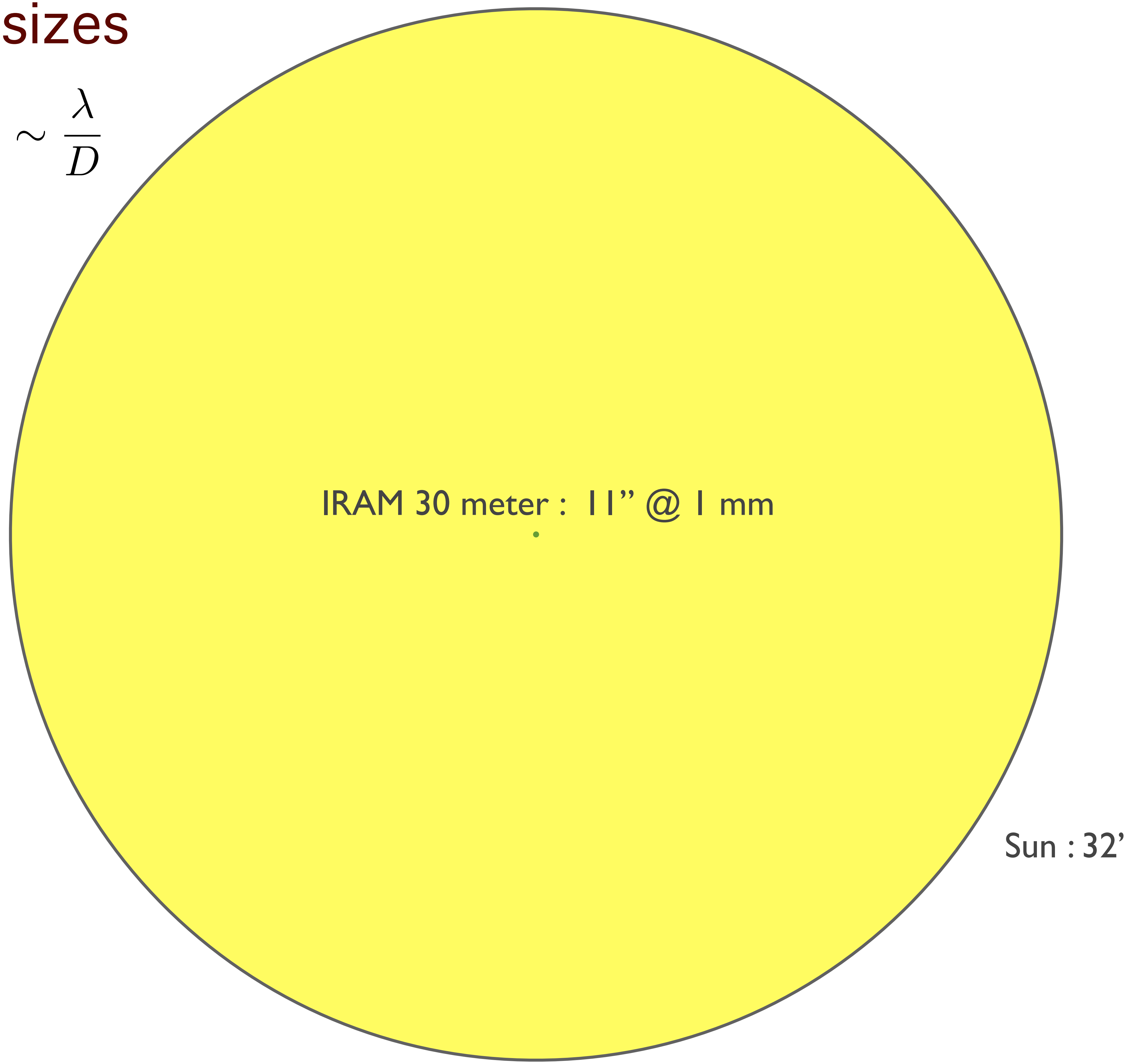




Channel maps of HI in NGC 2366 (Thuan, Hibbard & Levrier, 2004)

Beam sizes

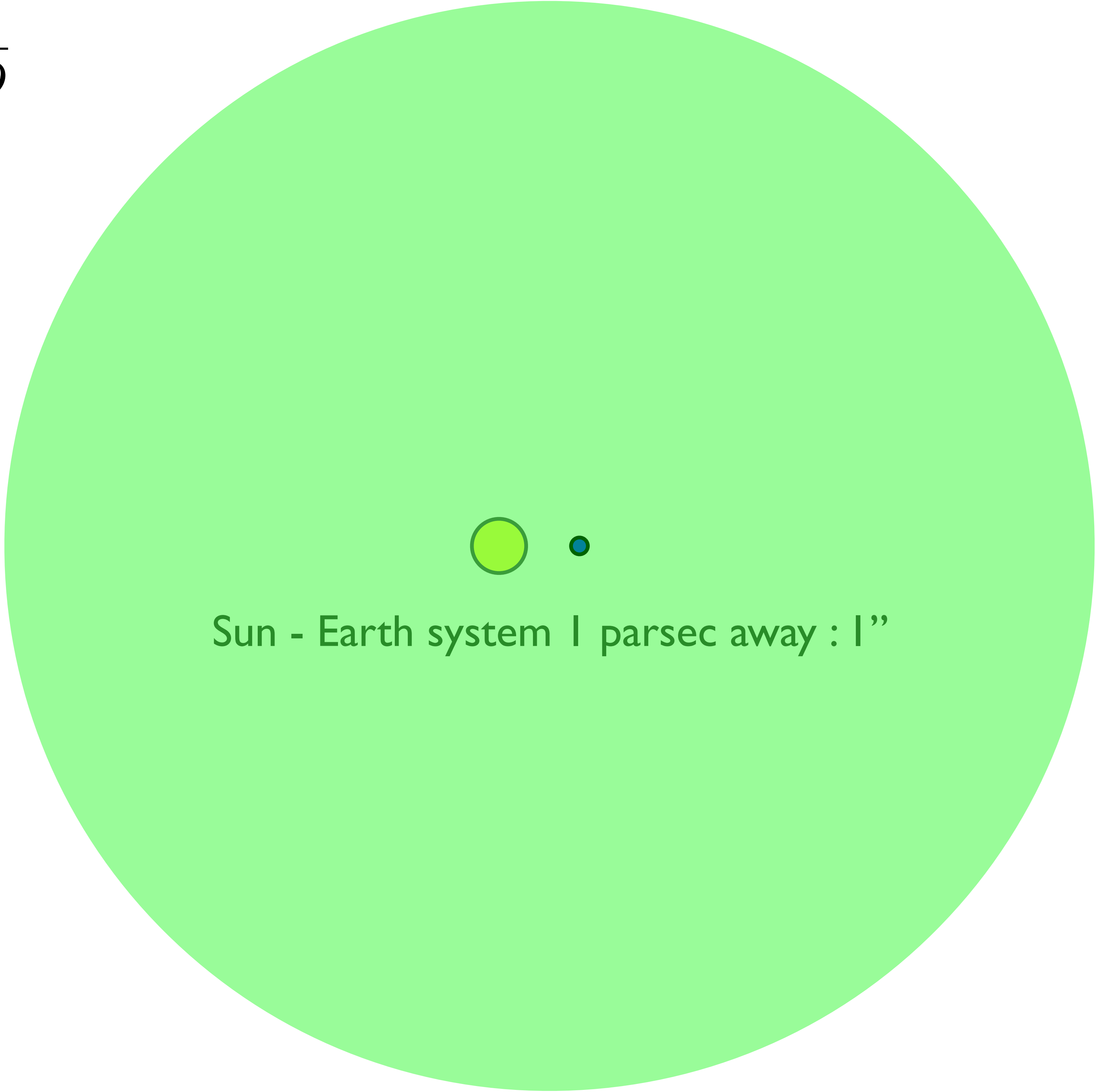
$$\theta_{\mathrm{FWHM}} \sim \frac{\lambda}{D}$$



Beam sizes

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

IRAM 30 meter : 11" @ 1 mm



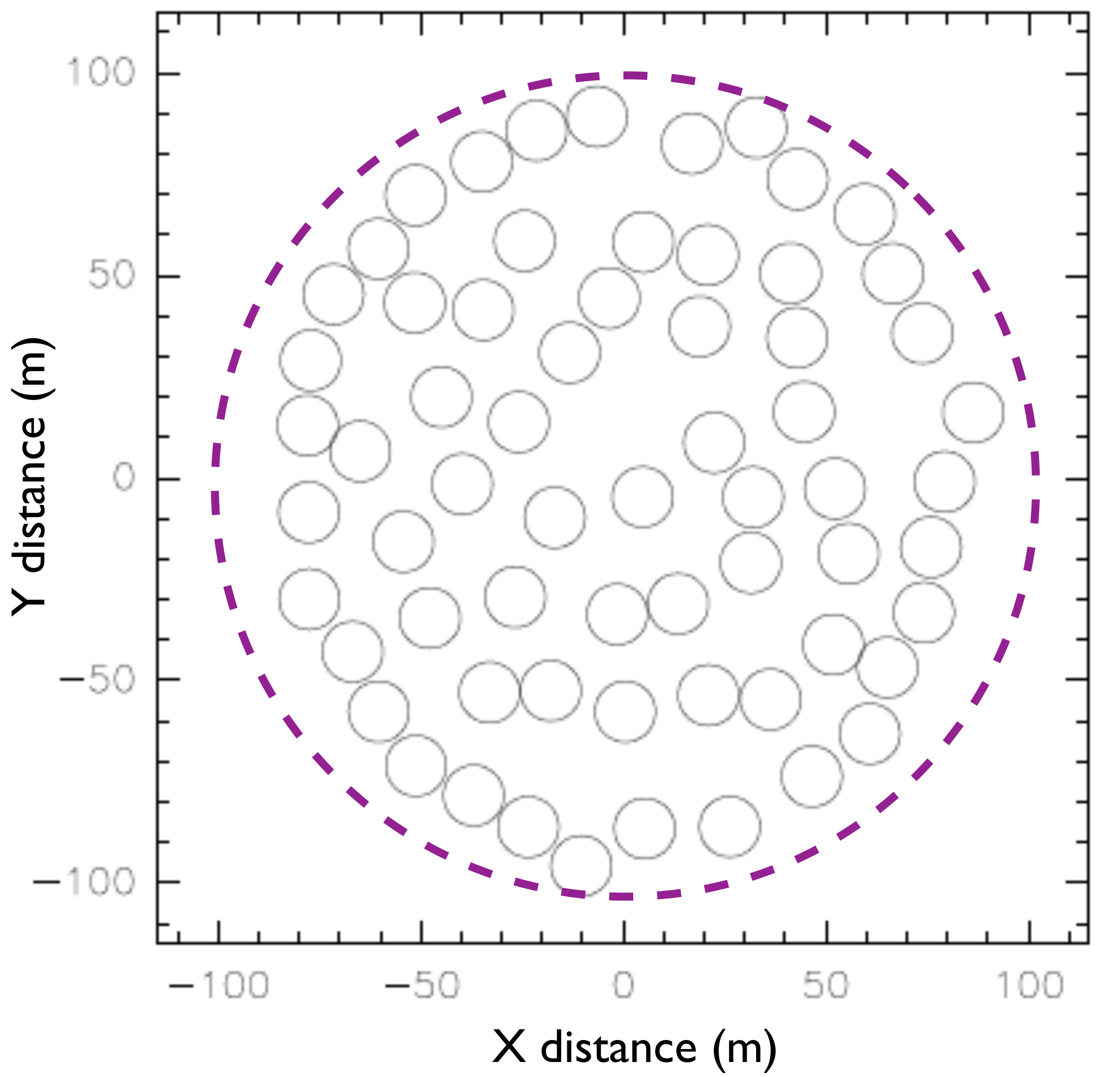
How can we improve resolution ?

$$\theta_{\rm FWHM} \sim \frac{\lambda}{D}$$ → 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 ...

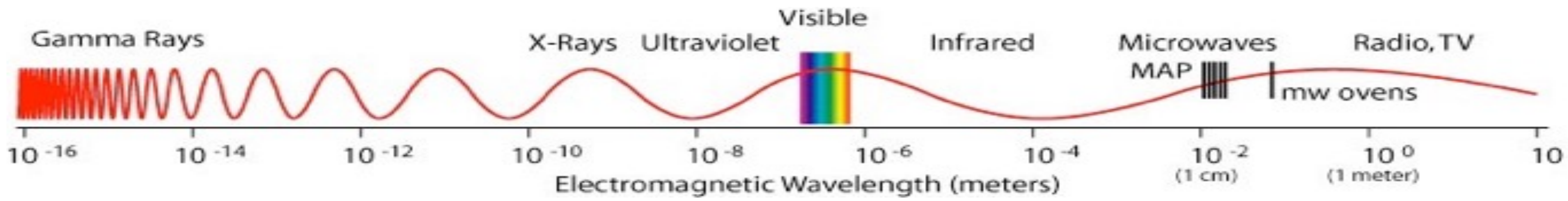
ALMA



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 ?

Optical vs. radio interferometry



Much lower frequencies → HETERODYNE DETECTION

Direct detection of the electric field

Optical

Quadratic detection

$$I = |E|^2$$

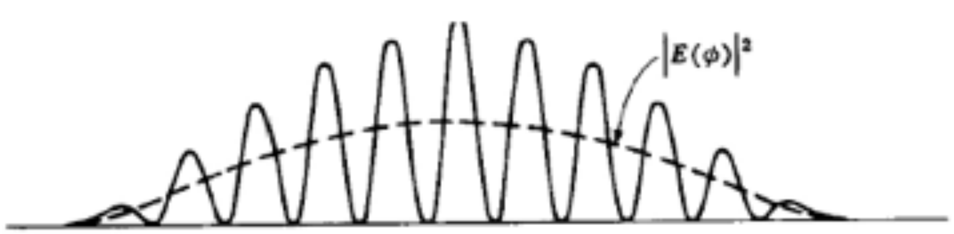
Optical fringes

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

"Contrast function"

Additive interferometry

$$I_1 + I_2 + 2\sqrt{I_1 I_2}|C| \cos\left(\frac{bx}{\lambda} + \phi_C\right)$$



Radio

Linear detection

$$|E| \exp(i\phi)$$

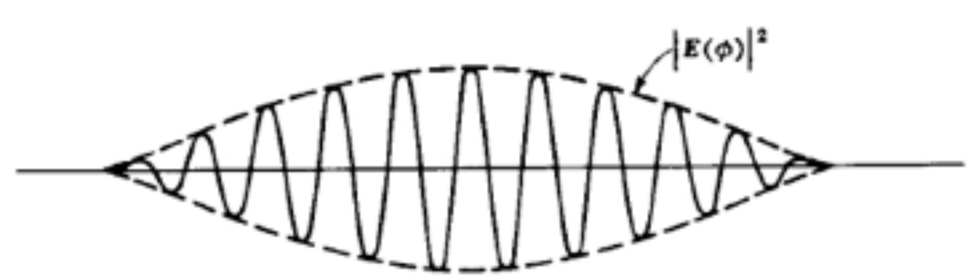
Electronic correlation

$$|V| \exp(i\phi_V) = \langle E_1 E_2^* \rangle$$

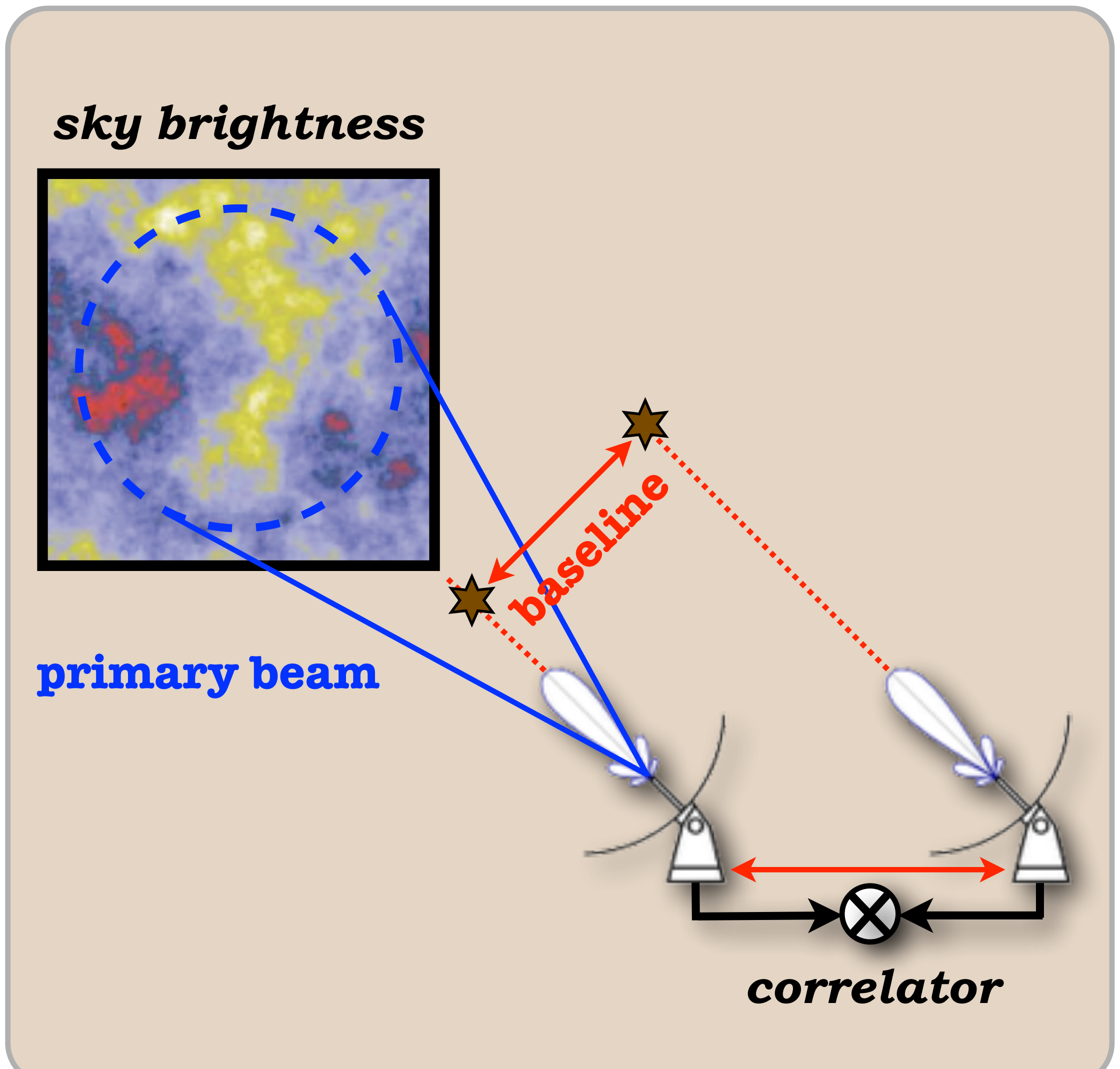
"Visibility function"

Multiplicative interferometry

$$|E_1||E_2||C| \cos\left(\frac{bx}{\lambda} + \phi_C\right) = |V| \cos\left(\frac{bx}{\lambda} + \phi_V\right)$$



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.

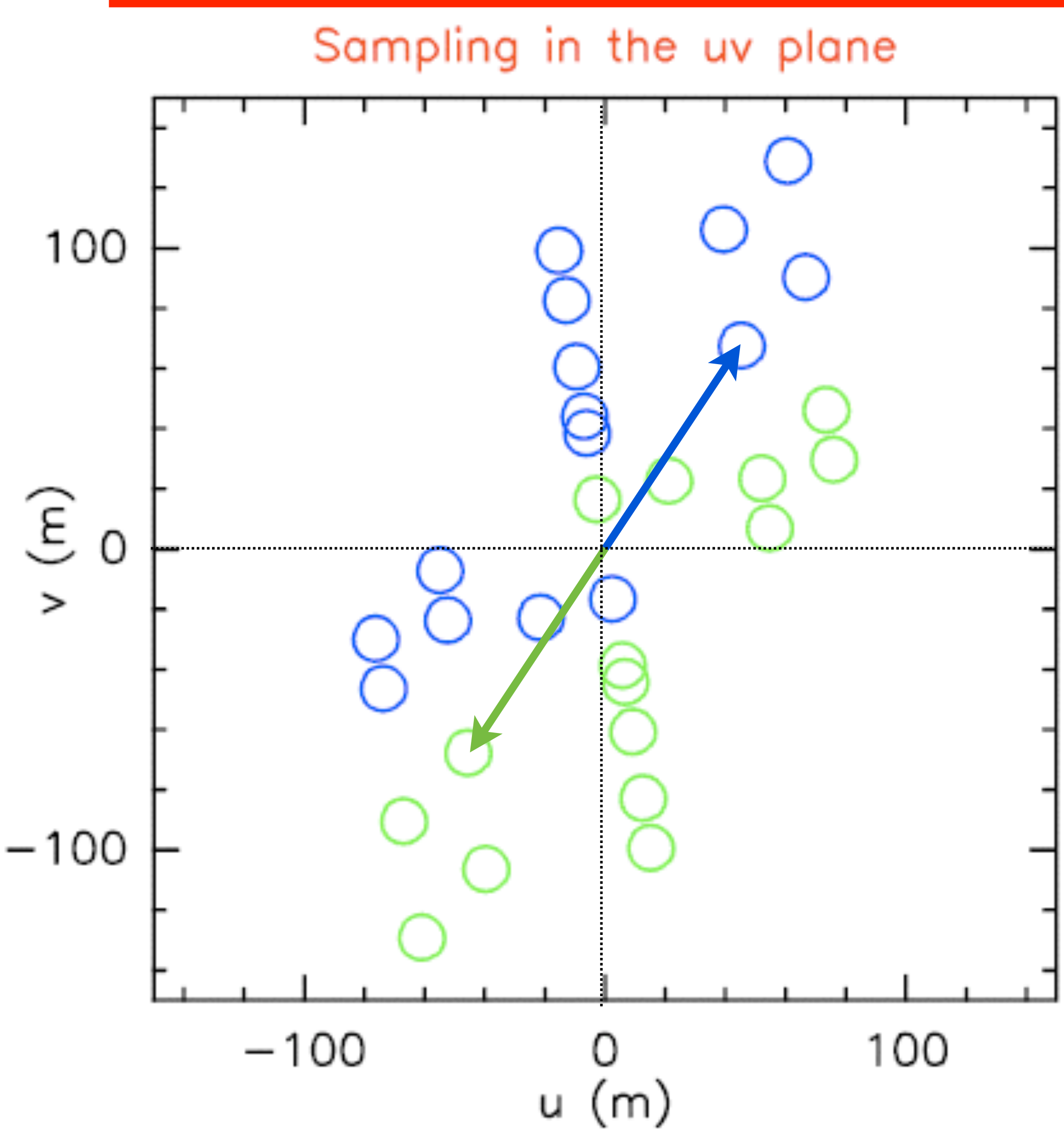
Fringe visibilities are measured : one Fourier component measured by antenna pair at a spatial frequency determined by the baseline - projection of the antenna separation perpendicular to the line of sight.

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

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)

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

Image is real !

N antennas

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

$N(N-1)$ baselines

Duality

Longest baseline ⟷ Image resolution

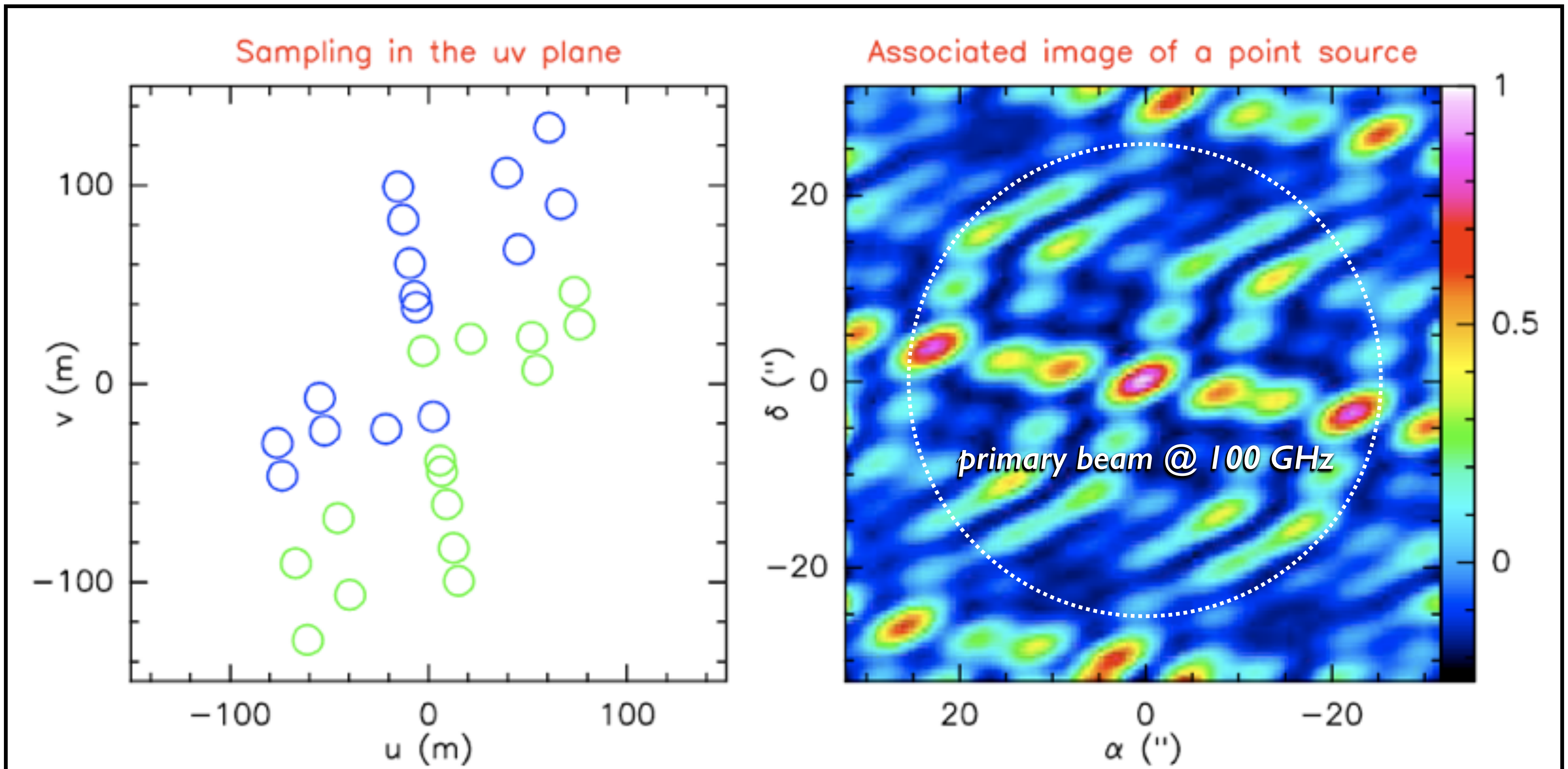
Smallest baseline ⟷ Largest scale accessible

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.

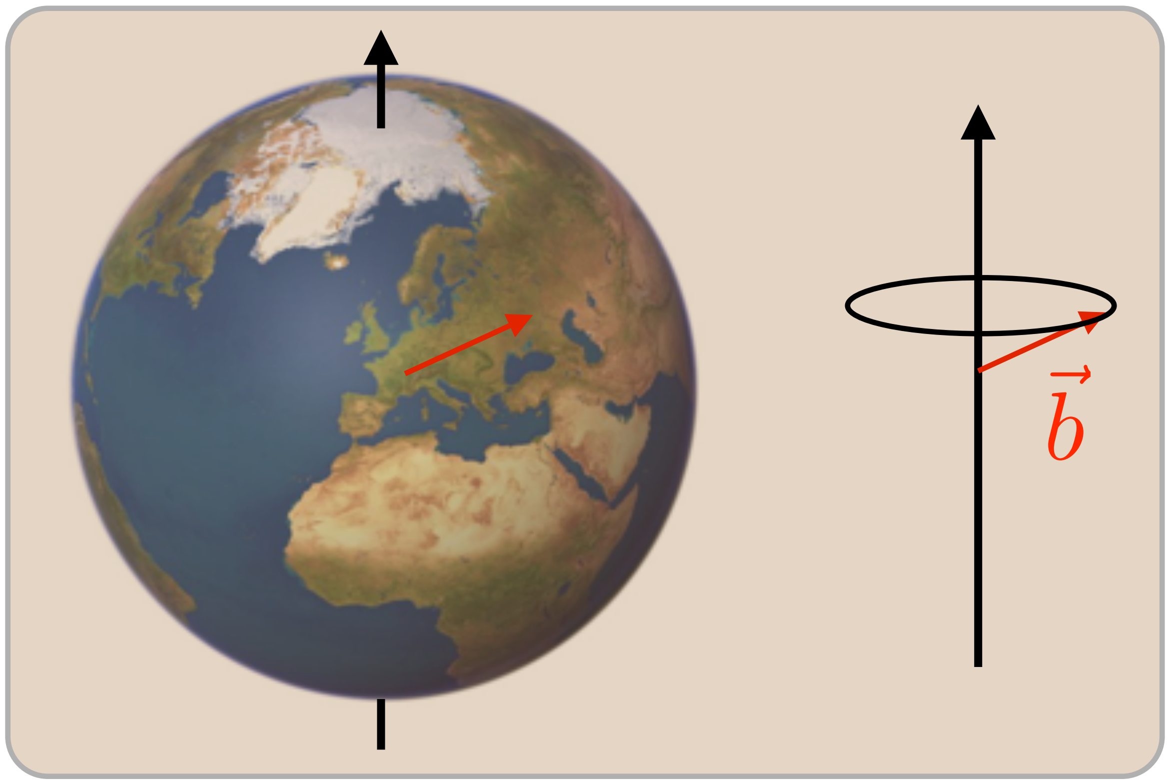
2D Fourier transform of the sampled visibility function yields the instrument's PSF

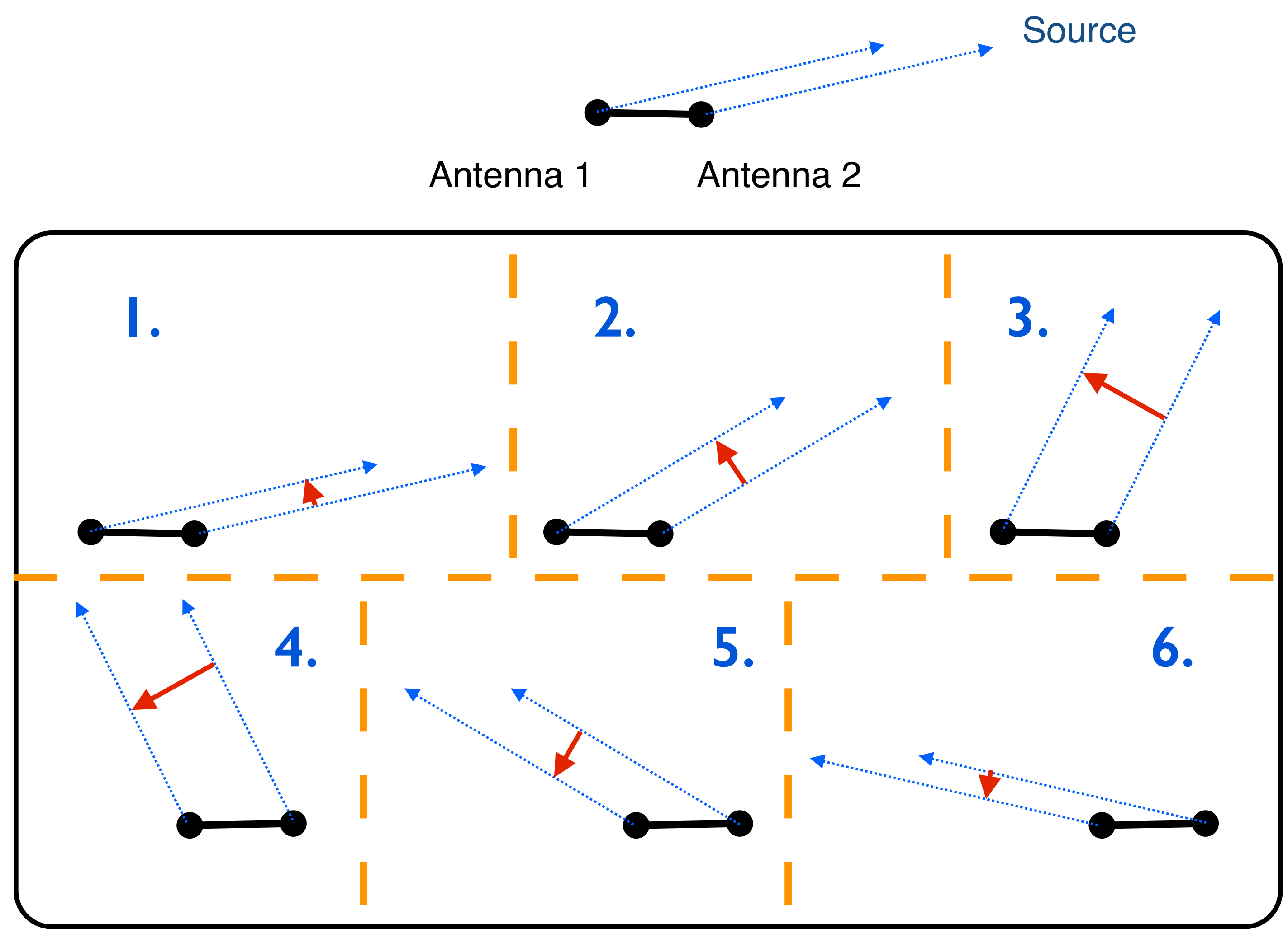


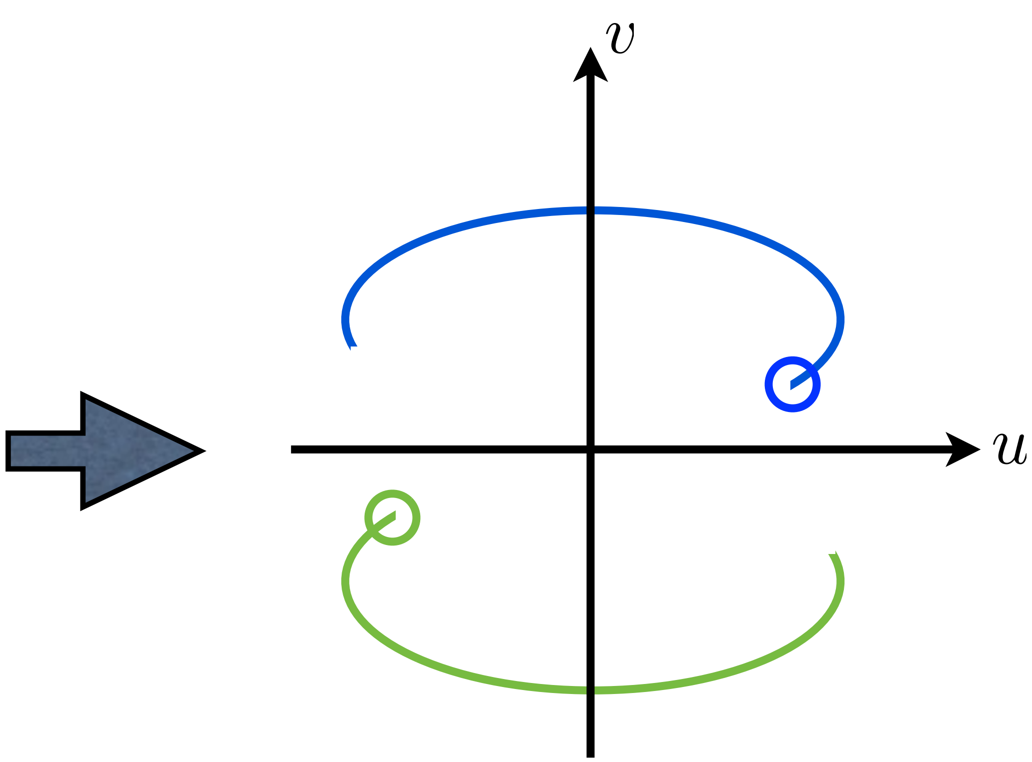
Figures by J. Pety (IRAM Grenoble)

Earth rotation and super-synthesis

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

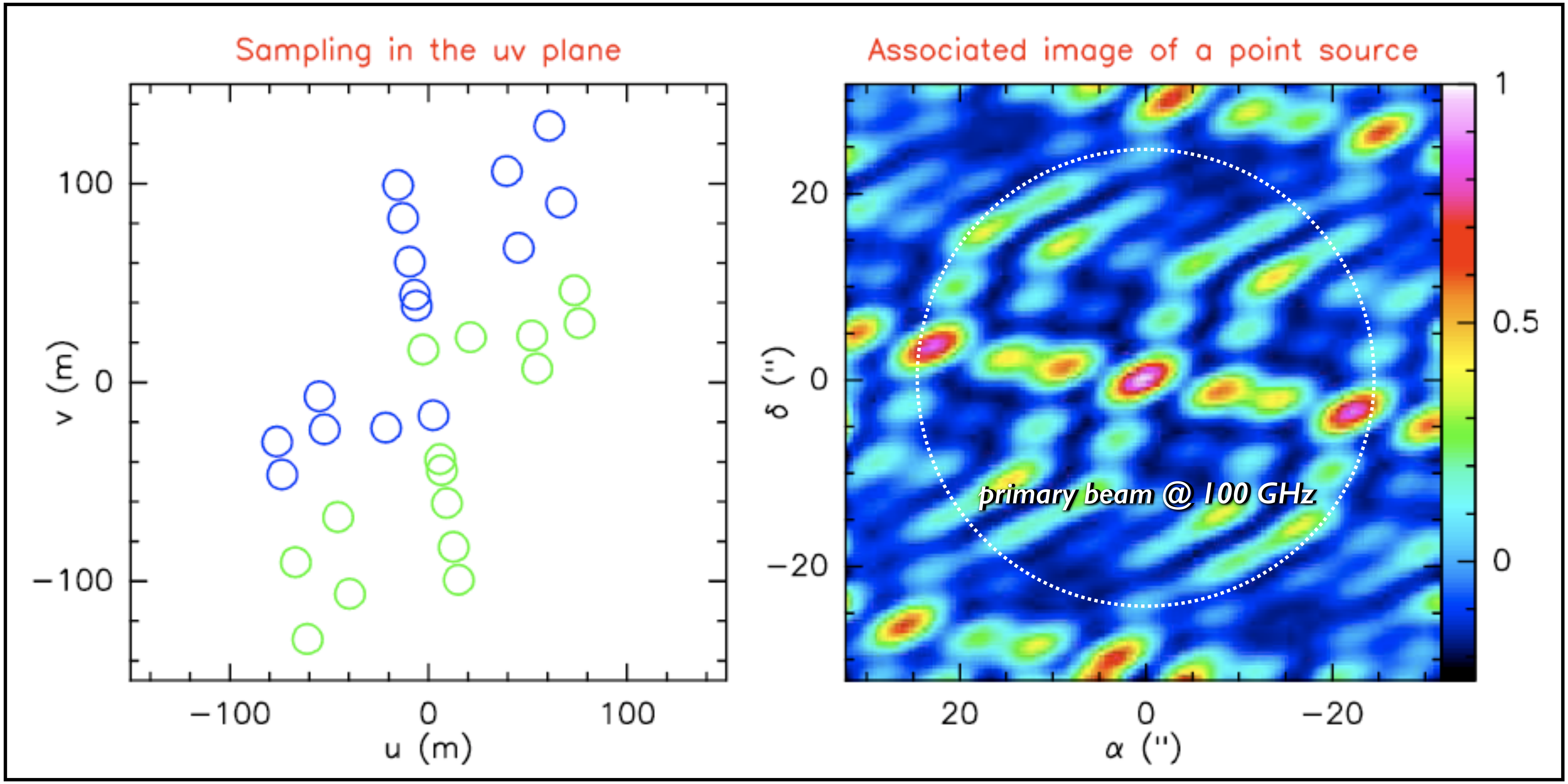






Baselines follow elliptical tracks in the uv plane

Earth rotation and super-synthesis



Figures by J. Pety (IRAM Grenoble)

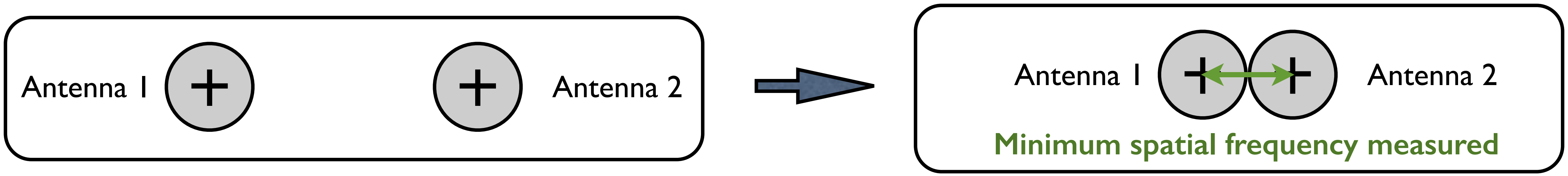
PSF = Interferometer beam = dirty beam = synthesized beam

Artifacts !

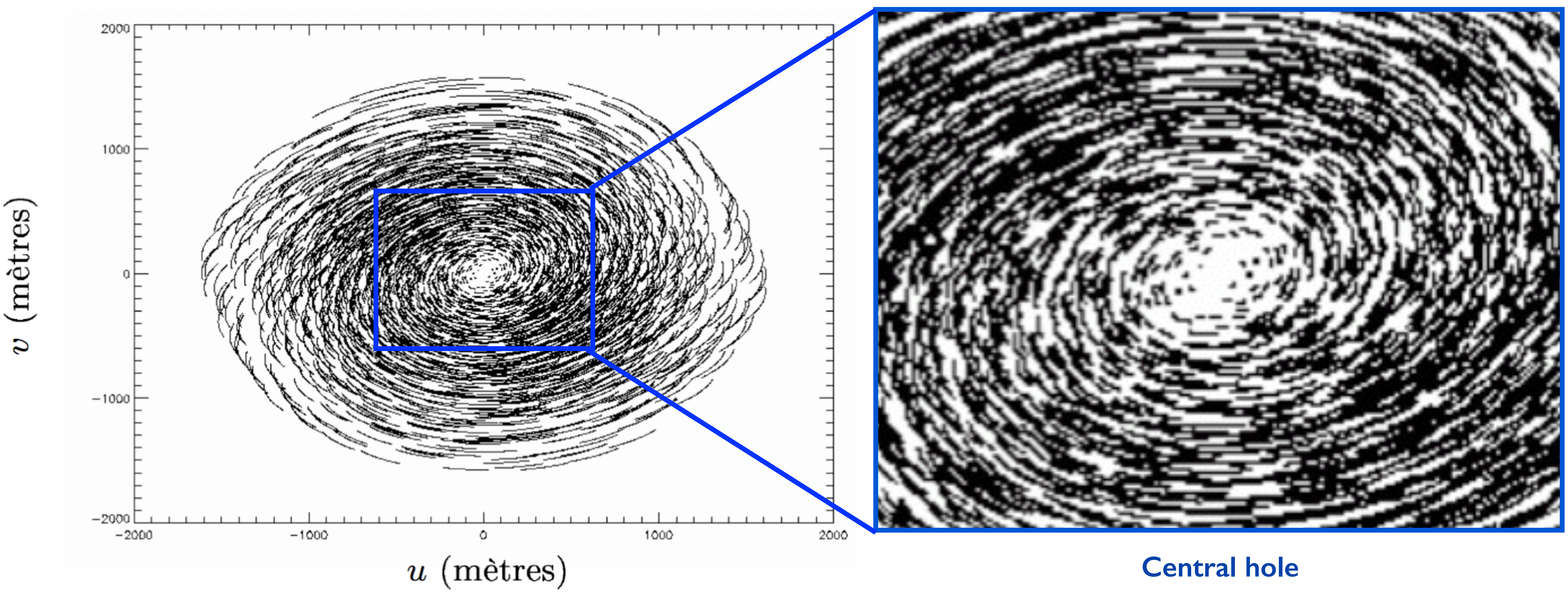
The missing short spacings

Zero frequency component gives total flux

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



Example ALMA cover



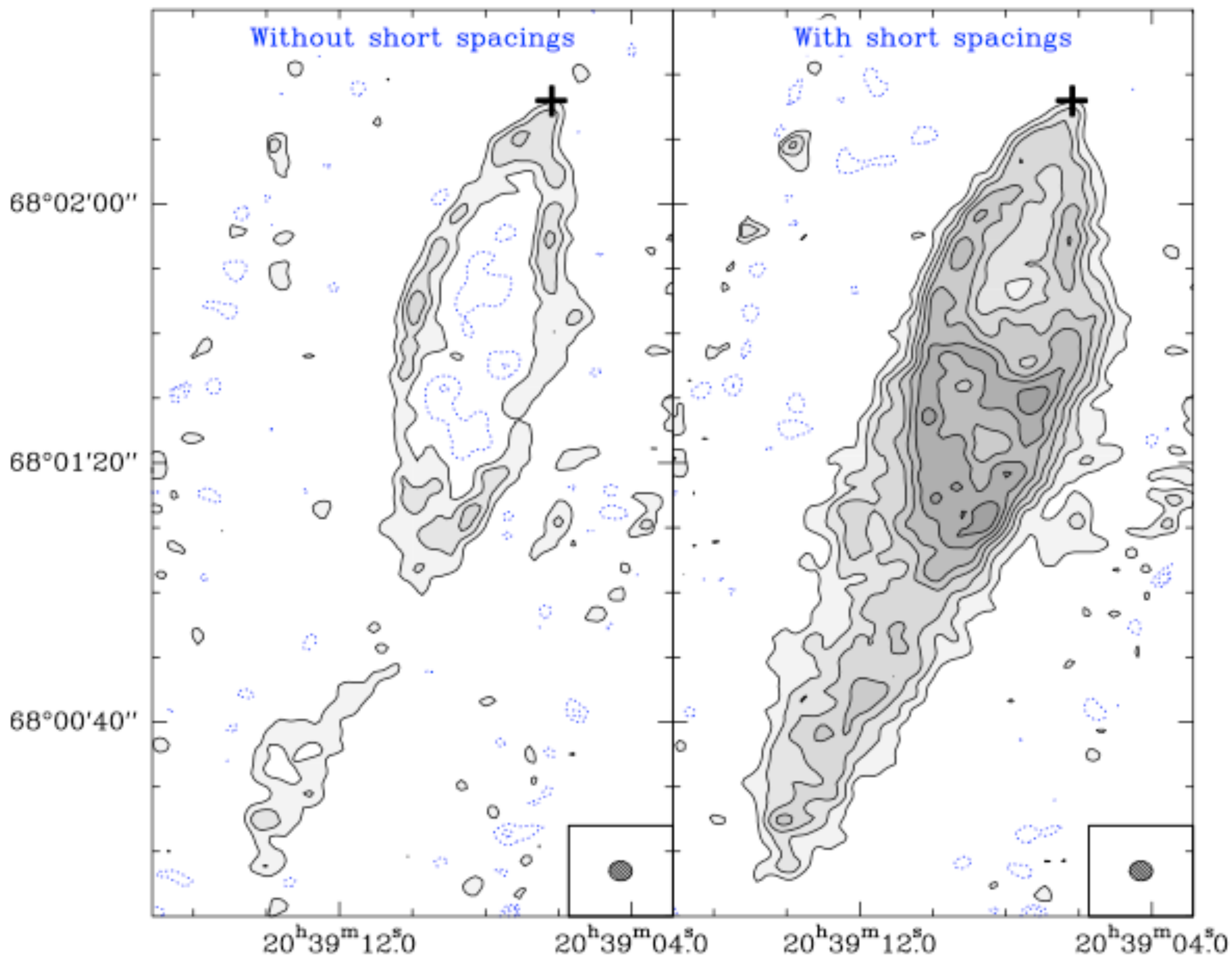
Central hole

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*



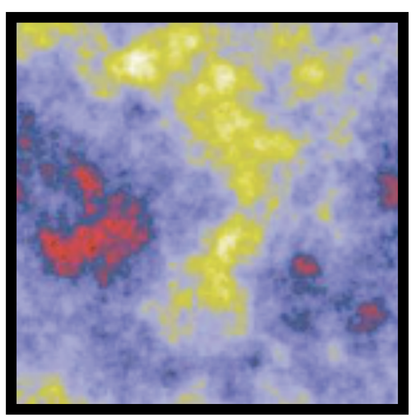
The issue of deconvolution

Measurement equation

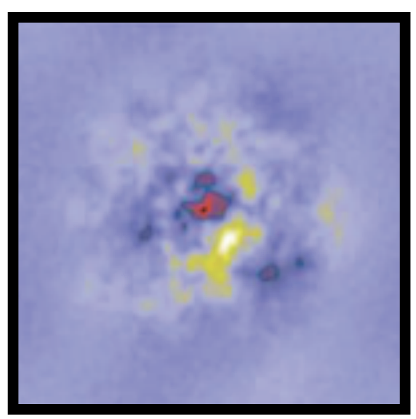
$$J = T_F^{-1}[C \times T_F[B \times I]] = T_F^{-1}[V] = S \ast (B \times I)$$

Convolution plaguing the image with the dirty beam's artifacts

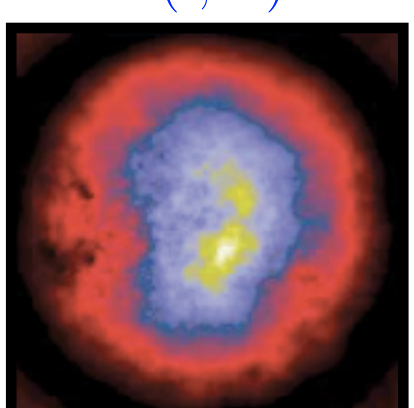
- $C(u,v)$ uv cover (sampling function)
- $B(l,m)$ Primary beam
- $I(l,m)$ True sky brightness
- $J(l,m)$ "Dirty map"
- $V(u,v)$ Visibility function
- $S(l,m)$ Synthesized beam



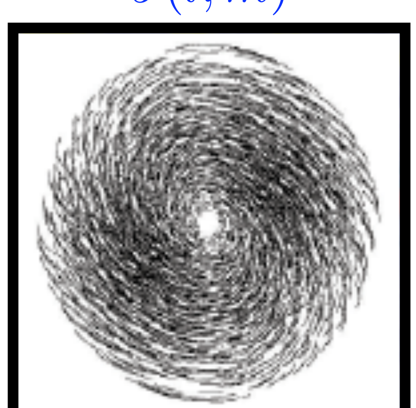
$I(l,m)$



$J(l,m)$

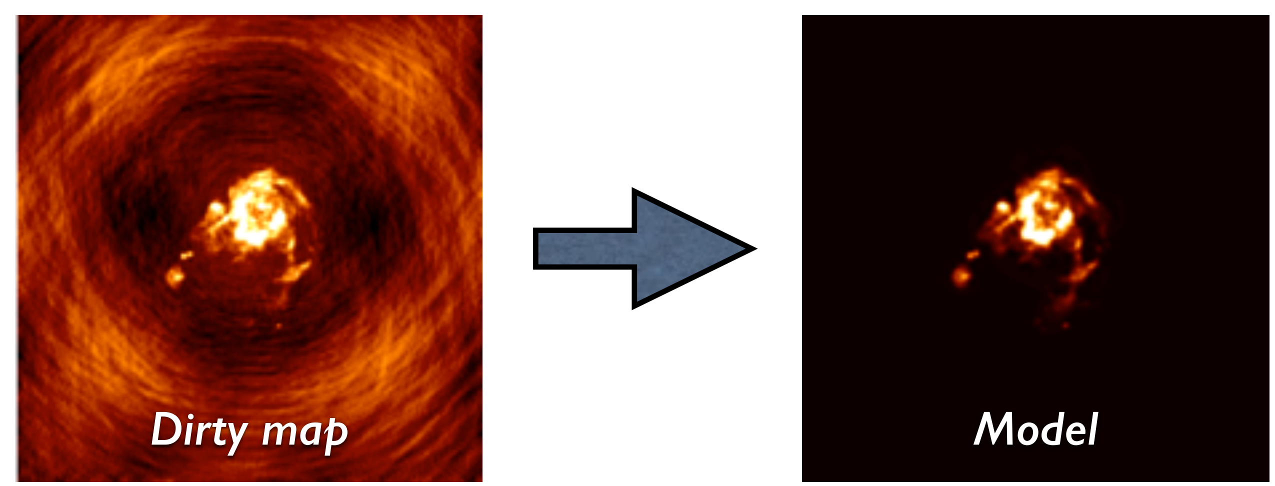


$B(l,m) \times I(l,m)$



$C(u,v)$

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



Figures by S. Bhatnagar (NRAO)

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

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**

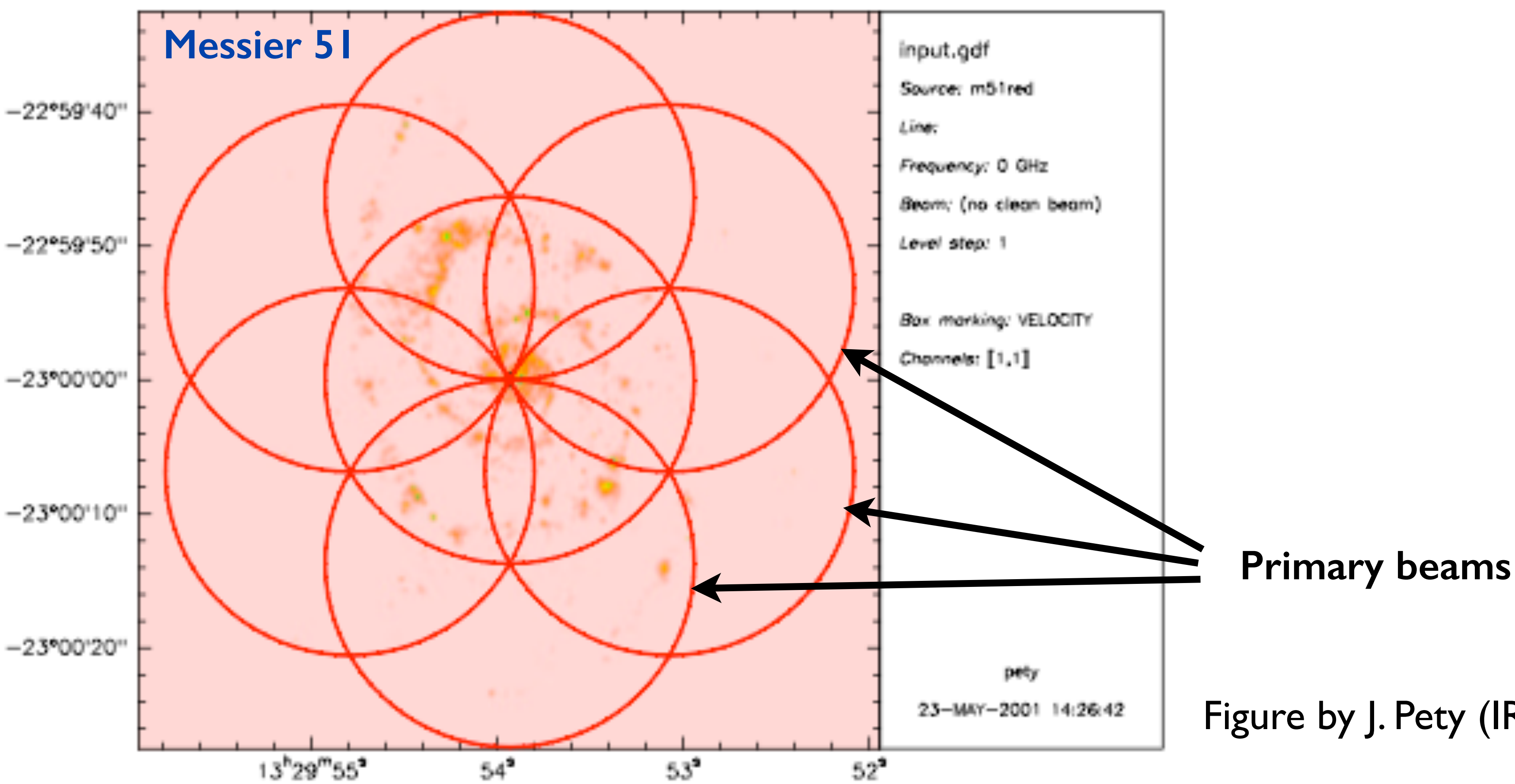


Figure by J. Pety (IRAM Grenoble)

Some radio-interferometers around the globe... in 2009

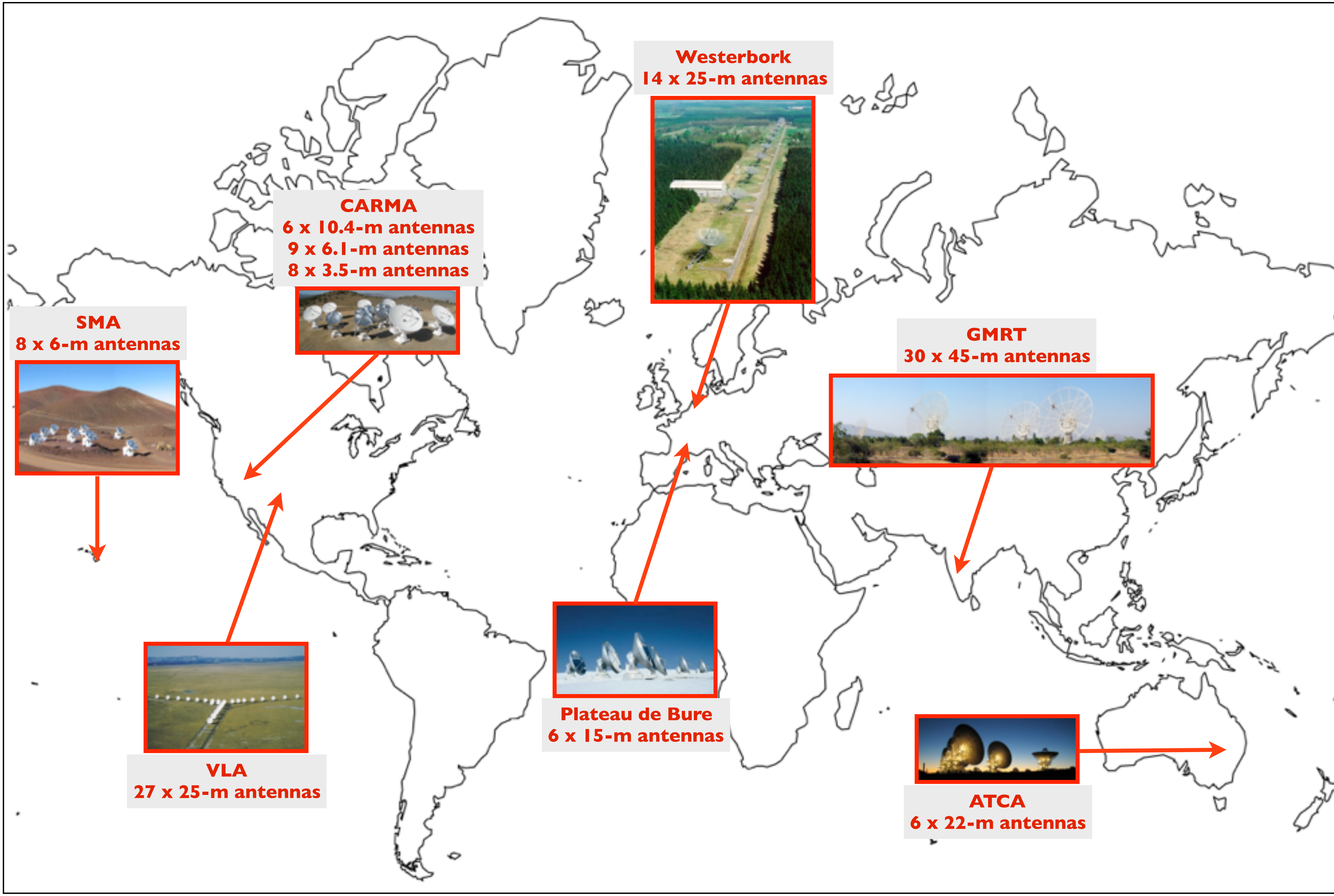


Image credits : NRAO/AUI - IRAM - ATNF - P. Lah - CARMA - SMA - NWO

Talk outline

An introduction to radio-interferometry in astronomy

The Atacama Large Millimeter Array (ALMA)

The Square Kilometer Array (SKA)

The ALMA observatory

Global partnership (shared cost ~1.3 billion 2006$):

- North America (37.5%: US, Canada, Taiwan)
- Europe (37.5%: ESO)
- East Asia (25%: Japan,Taiwan, Korea)
- In collaboration with Chile as host nation

Unique high, dry site:

- 5000 m in Chilean Atacama desert
- Submm sky access through the atmosphere

66 submillimeter/millimeter telescopes

- 50 12-m antennas in the ALMA array proper
- 12 7-m and 4 12-m antennas for the ALMA Compact array (ACA)

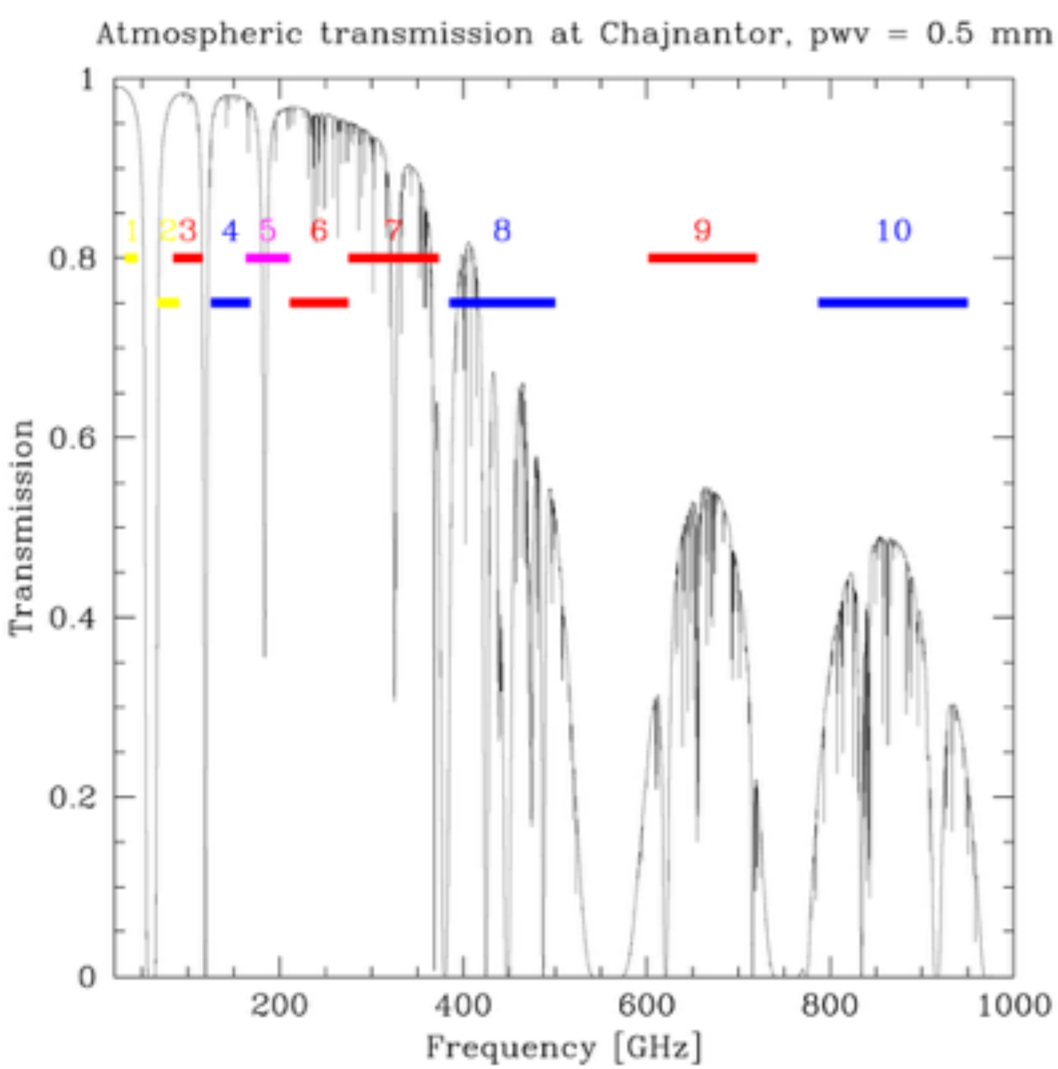
Slide : A.Wootten

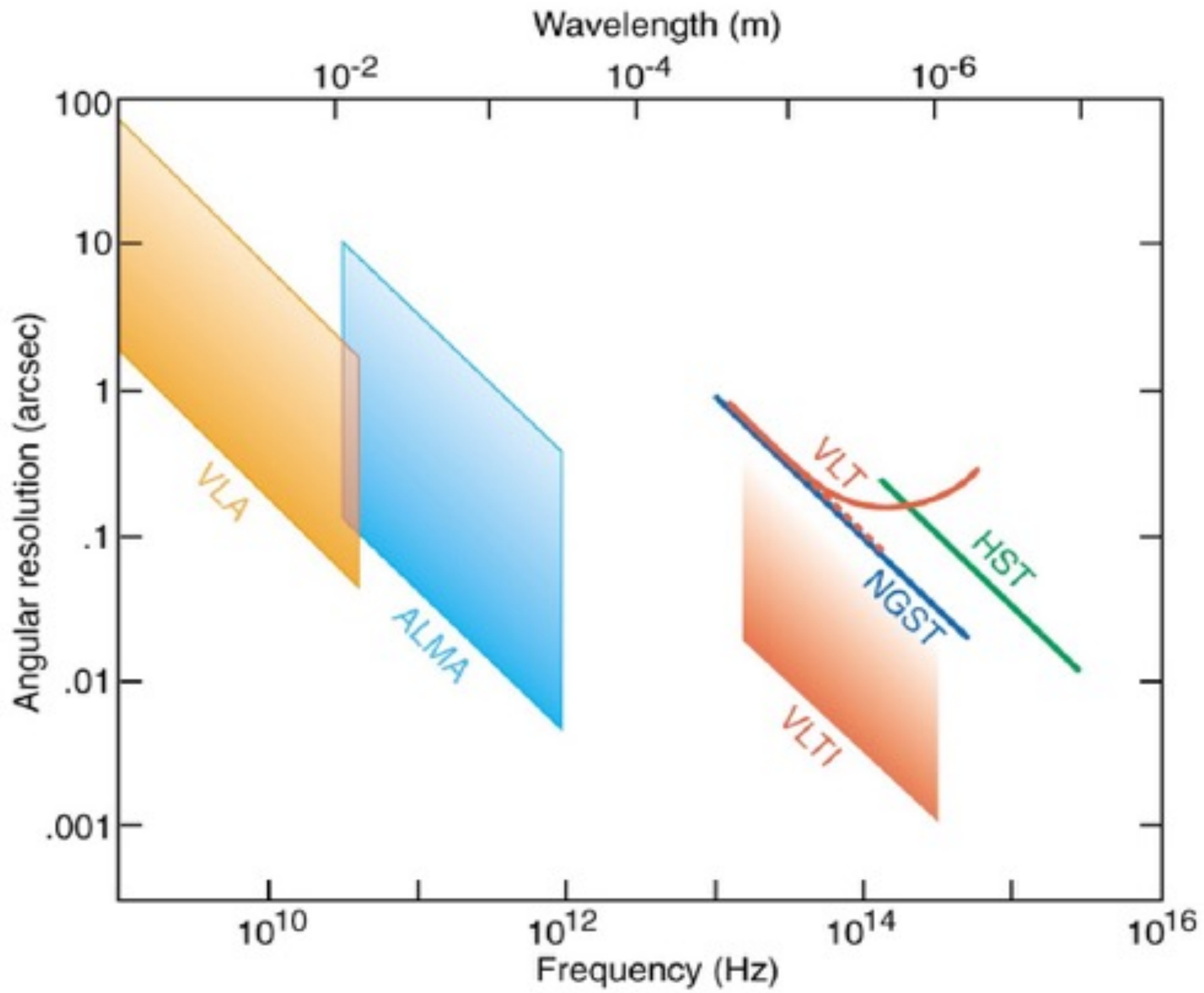
Completed 2014

ALMA
ATACAMA LARGE MILLIMETER ARRAY

ALMA technical specifications

Antennas	54 x 12-m and 12 x 7-m
Collecting area	> 6600 m^2
Resolution	0".02 λ_{mm}
Receivers	10 bands: 0.3 – 7 mm (35 - 950 GHz)
Correlator	2016 baselines
Bandwidth	16 GHz/baseline
Spectral channels	4096 per IF (8 x 2 GHz)
Baselines	150 m - 15 km





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 (150pc)."

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*

The first science cycles from ALMA

Cycle 0 Early Science (2011-2012) :
113 projects
All data delivered, available in archive, 178 papers

Cycle 1 Early Science (2012-2013) :
198 projects
Data becoming available in archive, 25 papers

Cycle 2 Early Science (2013-2014):
354 projects
5 papers.

Cycle 3 Early Science (2014-2015):
401 projects
Observing started Oct. 2015

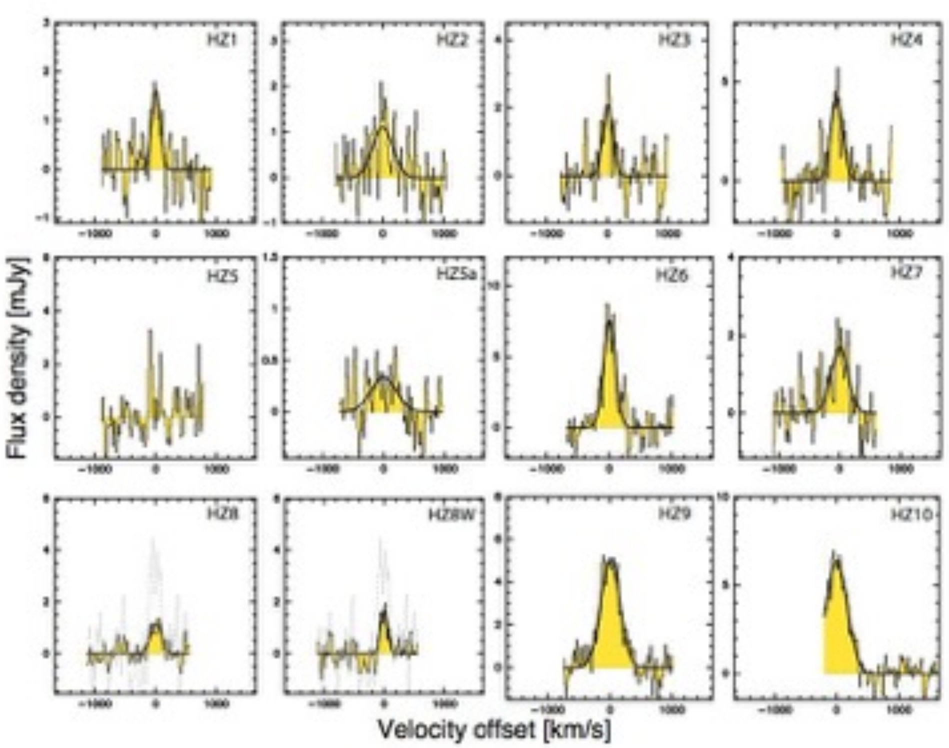
Some highlights of the first science results with ALMA

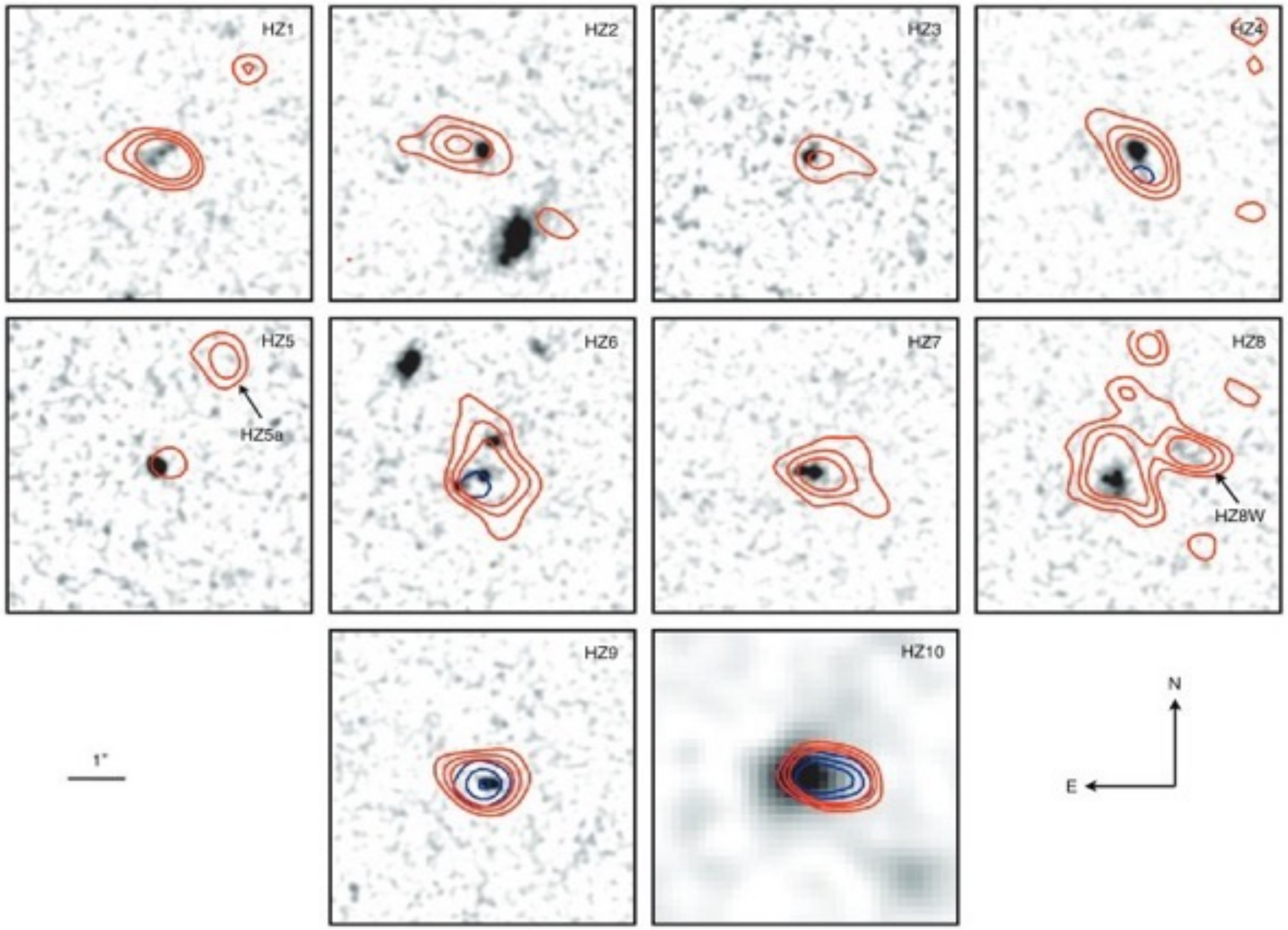
The Interstellar medium of galaxies at high redshift

Capak et al. (2015)

9 dusty normal galaxies at z=5-6

Detected [CII] in all nine at 290 GHz in all nine objects





Slide : A.Wootten

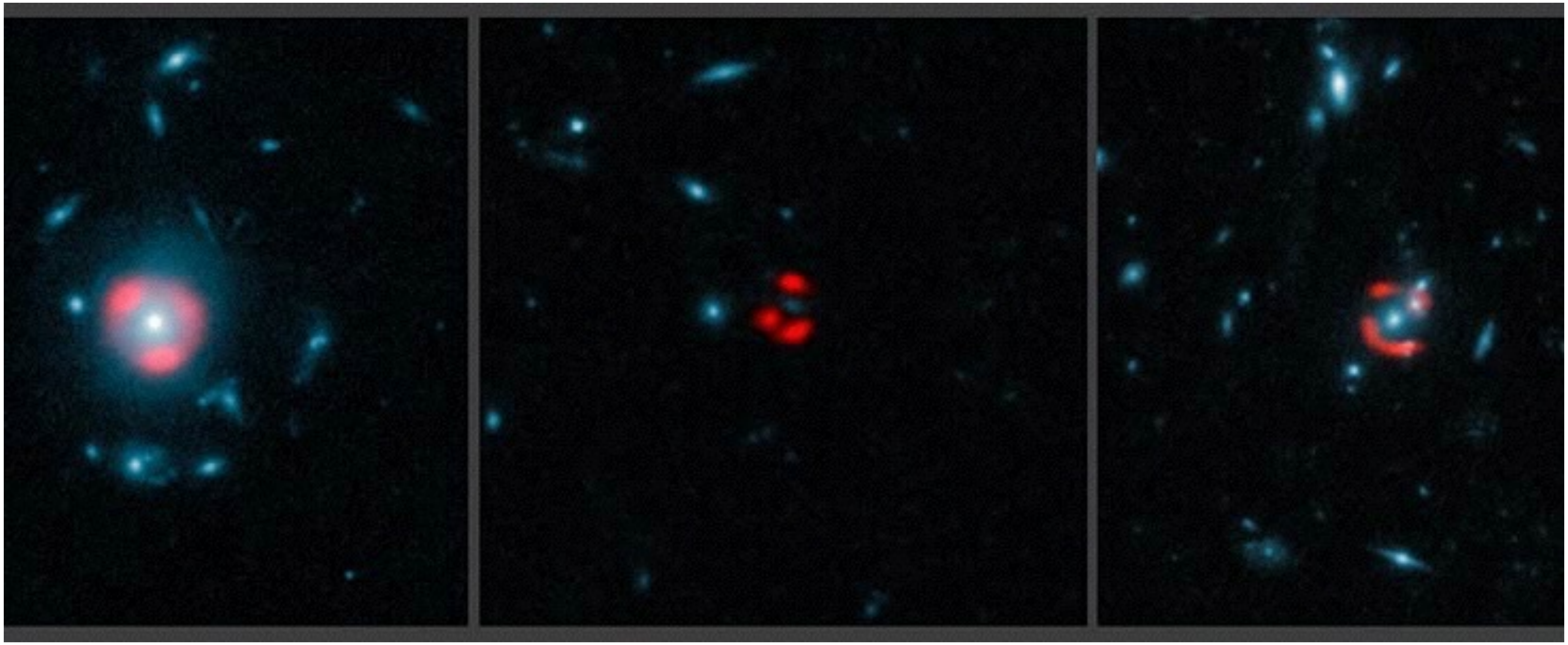
Some highlights of the first science results with ALMA

The Interstellar medium of galaxies at high redshift

47 1.4mm-bright SPT sources not coincident with IRAS/radio galaxies Imaged ~1 min with ALMA at 3 and 0.8 mm : Many are lensed Einstein rings

Blind spectroscopic observations of 26 sources followed : 23 showed high redshift CO; ten with z>4; doubling the number of such objects known

Fraction of high-z dusty starbursts higher than previously thought.



Vieira et al. (2013); Weiss et al. (2013); Hezaveh et al. (2013)

Slide : A.Wootten

Some highlights of the first science results with ALMA

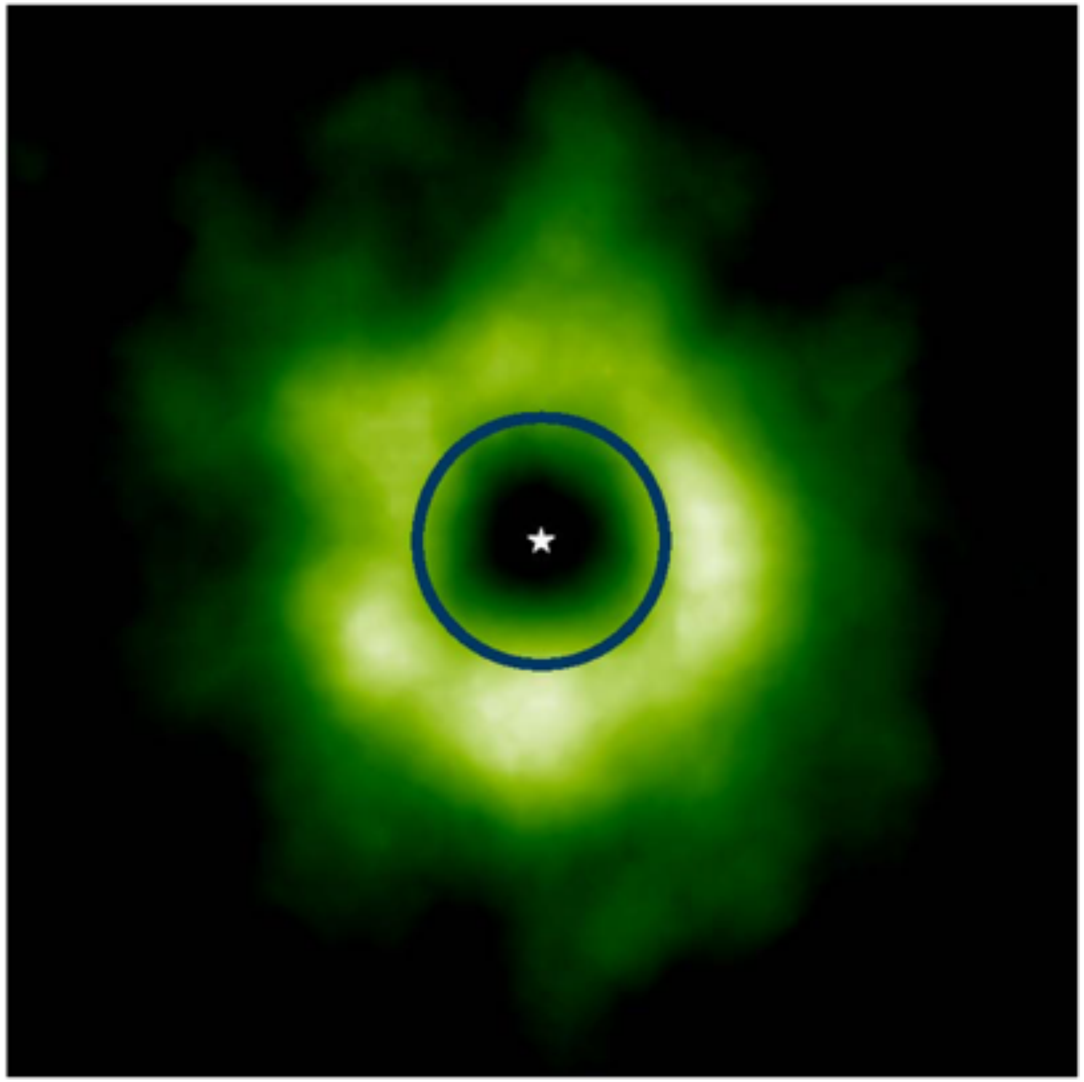
Observation of snow lines in protoplanetary disks

Qi et al. (2013)

Observation of the TW Hya protoplanetary disk

CO in the gas phase near the star, destroys N_2H^+

N_2H^+ emission seen where CO is frozen of dust grains in the outer system



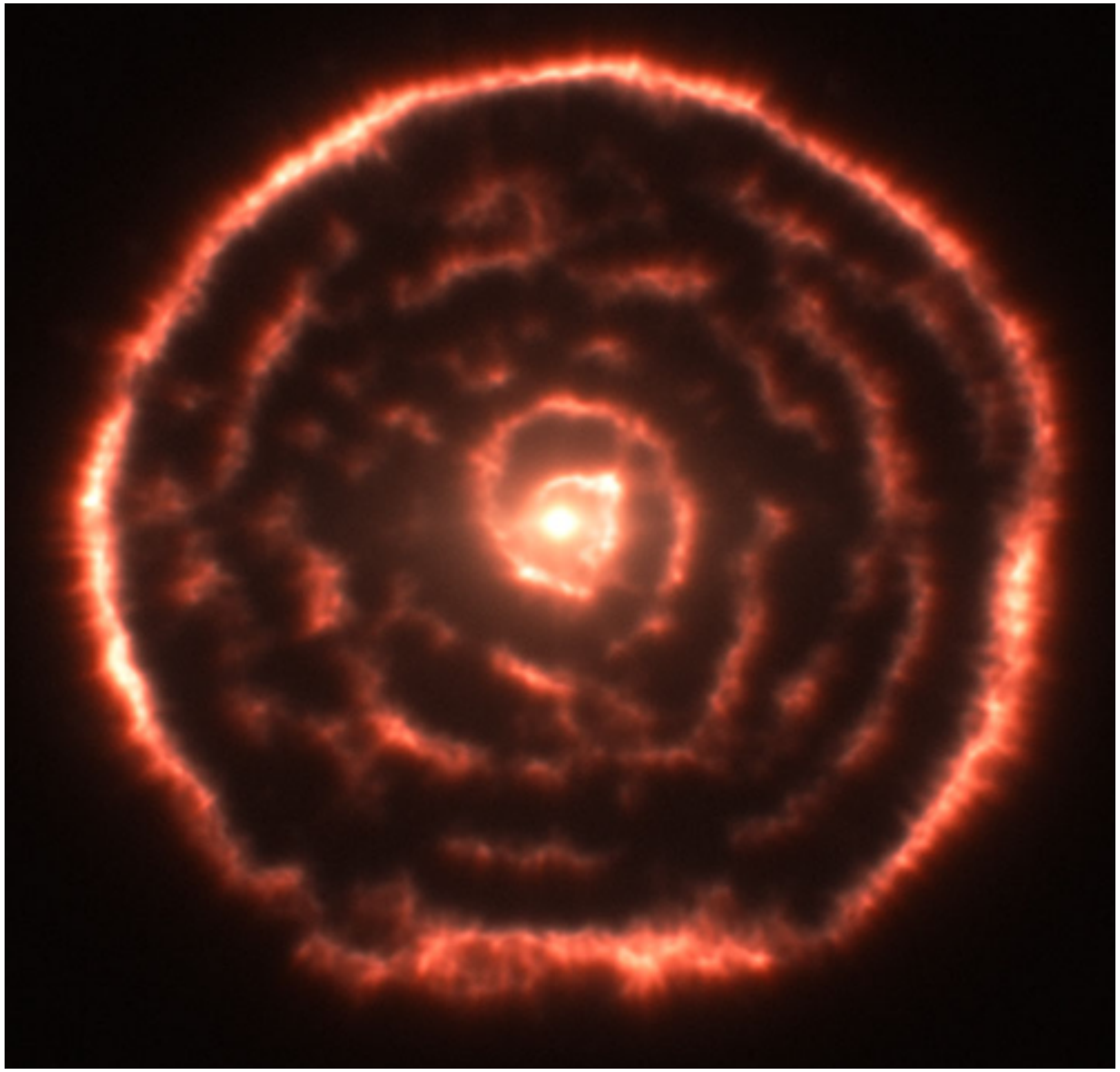
Some highlights of the first science results with ALMA

Structures in the envelope of a dying star

Maercker et al. (2012)

Observation of the R Sculptoris AGB star

CO emission shows a spiral structure interpreted as the intermittent mass loss of the star being channelled by an unseen companion



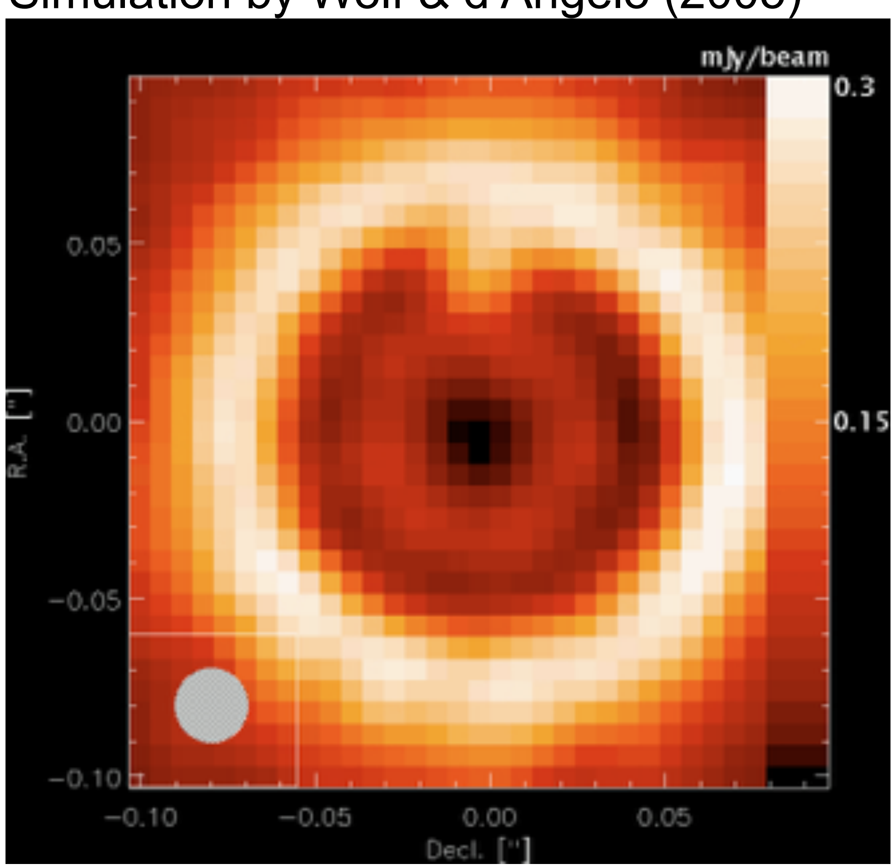
Some highlights of the first science results with ALMA

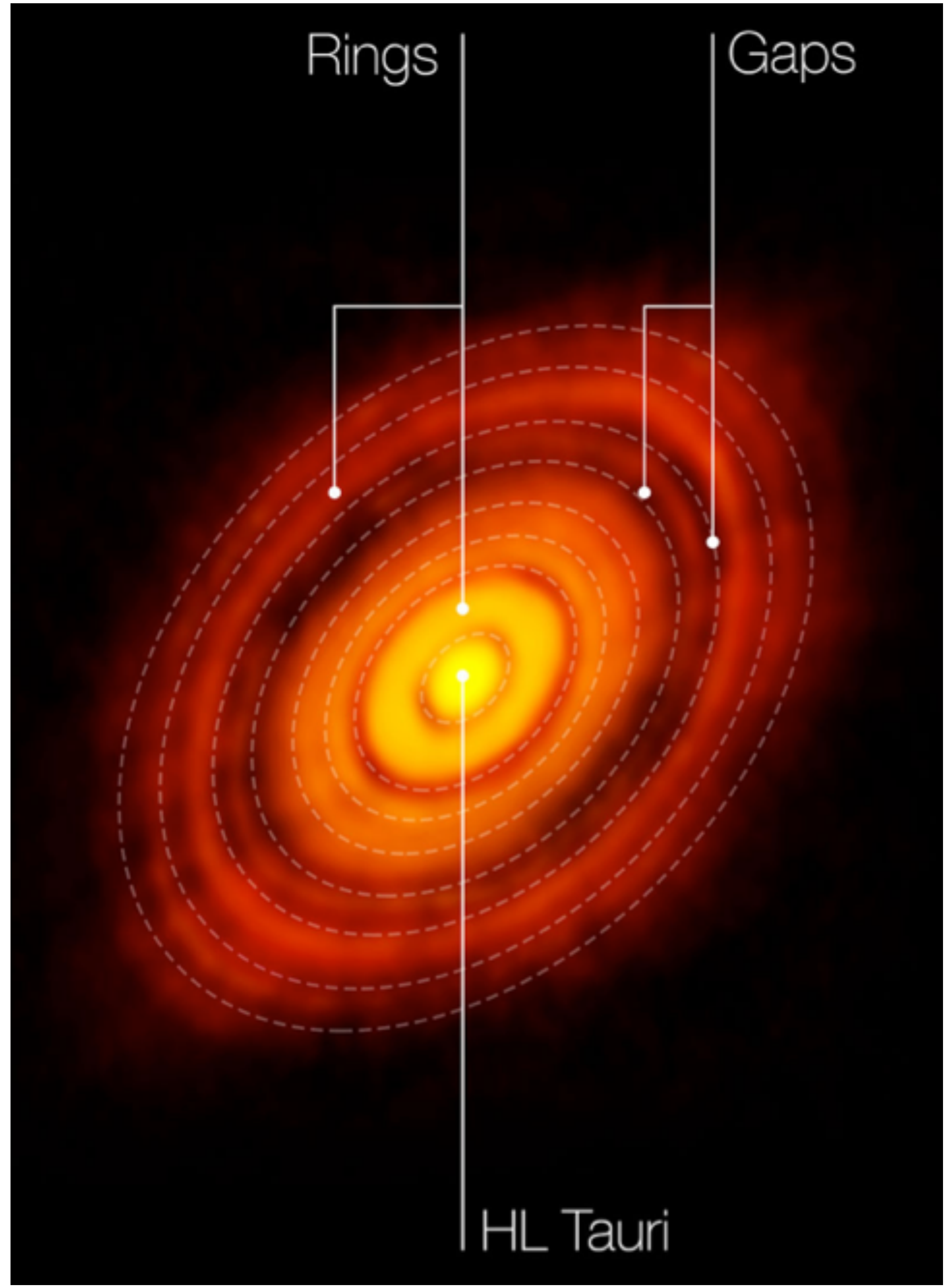
Gaps in a protoplanetary disk

Observation of the young star HL Tau and its protoplanetary disk

Gaps may be due to forming planets

Simulation by Wolf & d'Angelo (2005)





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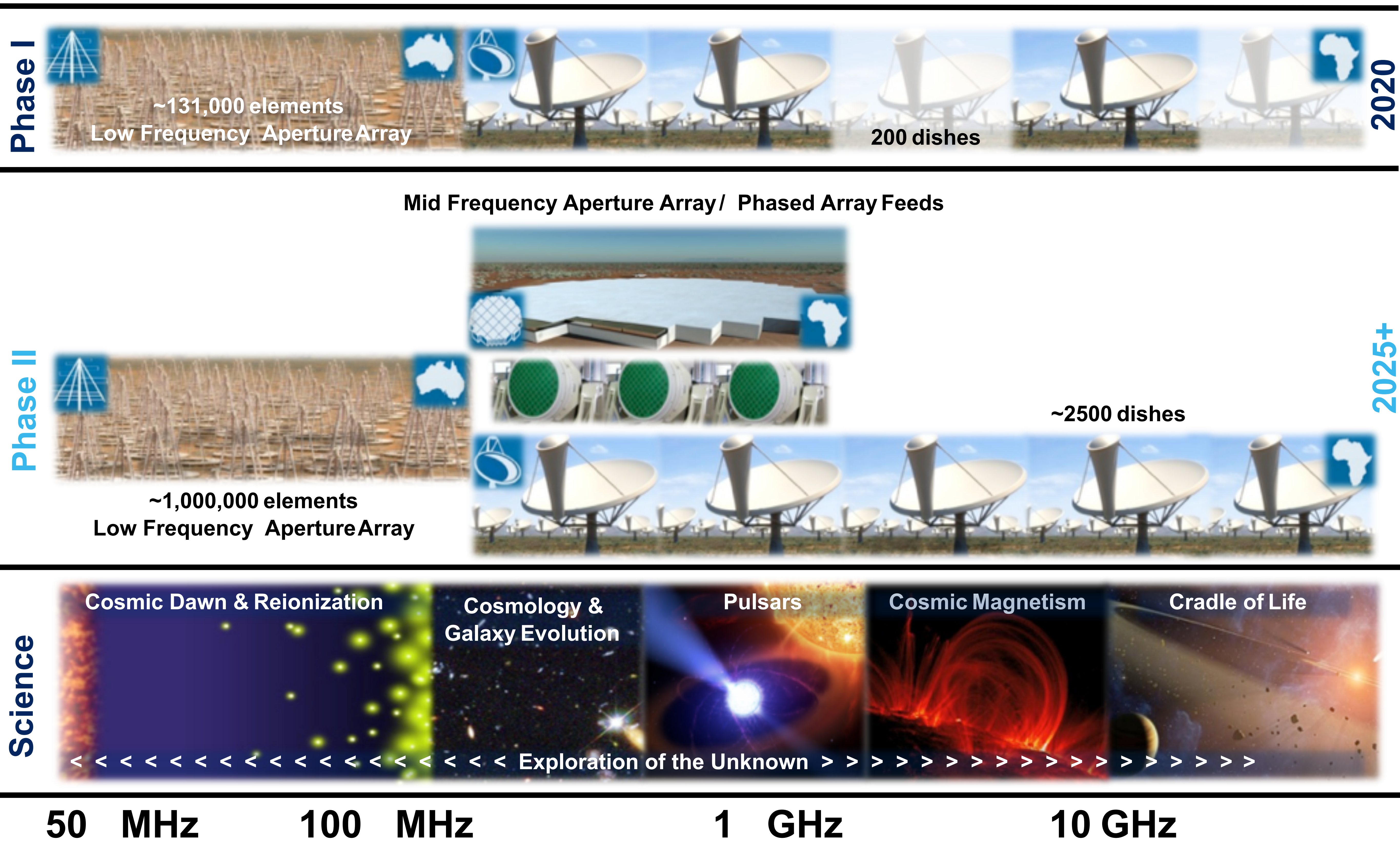
The SKA project



Slide : T. Bourke

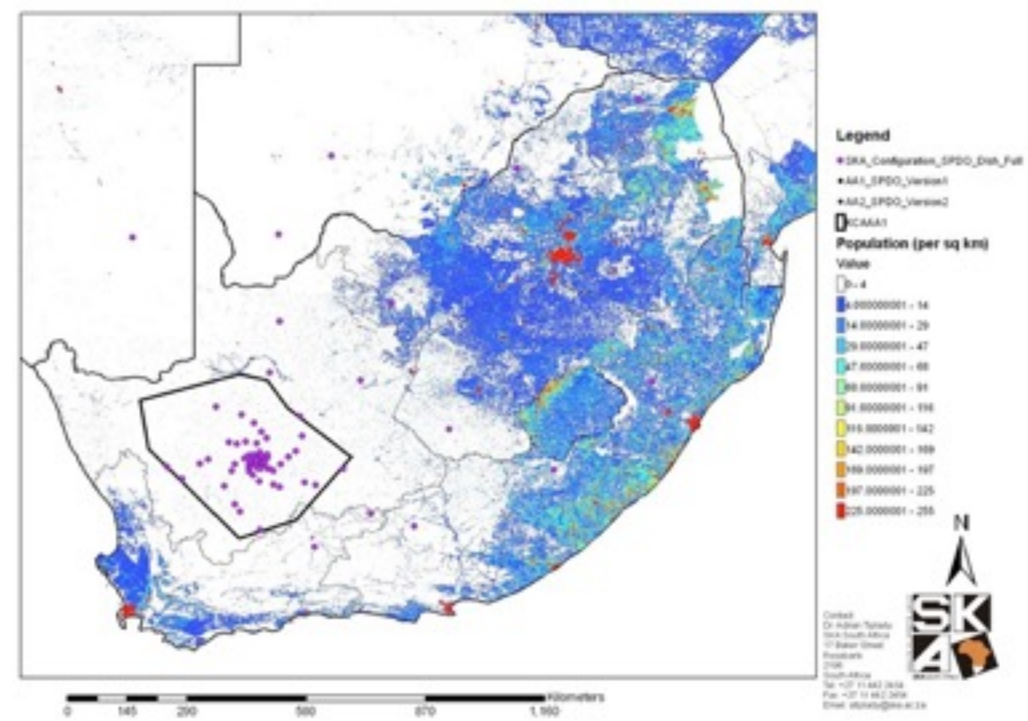
Slide : T. Bourke

SKA Phase 1

SKA1--Low: ~131,000 low--freq dipoles, AUS

SKA1--Mid: ~133 x 15m dishes + MeerKAT, RSA

2 sites; 2 telescopes; **one Observatory**
Frequency range: 50 MHz – 13.8 GHz
Construction Cost--cap: €650M
Construction: 2018 – 2023
Early science: 2020+



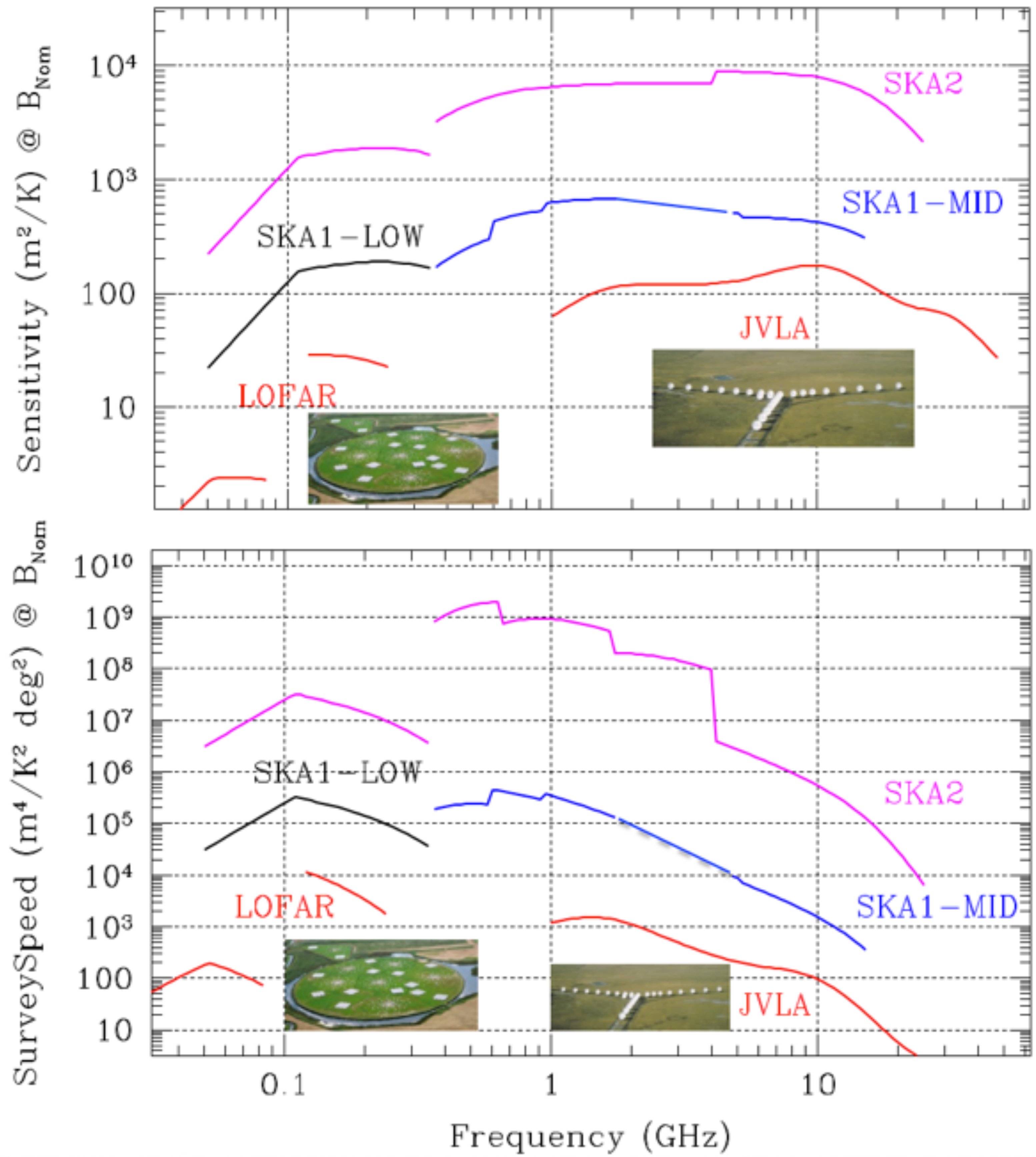
Western Australia
131,000 Log-periodic dipoles
50 - 350 MHz (11” @ 110 MHz)
300 MHz BW; 65k Channels. 1 kHz resolution

South Africa
133 15-m dishes plus 64 Meerkat 12-m dishes
0.35 – 13.8 GHz (0.22” @ 1.7 GHz; 40 mas @ 13 GHz)
15.3-38.1 kHz over 65k channels

Sensitivity and survey speed improvements

SKA-1 is at least an order of magnitude improvement over existing facilities

SKA-2 is at least another…



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Data challenges for SKA

Raw Data Rates (Transport)
- ➢LOW ~150 Tb/s, ~5 Zb/yr
- ➢MID ~ 2 Tb/s, 62 Eb/yr

Tera	10^{12}
Peta	10^{15}
Exa	10^{18}
Zetta	10^{21}

Processing Power (HPC)
- ◈LOW ~21 PFlops
- ◈MID ~60 PFlops

Power (300 PFlops) = Power to run San Fran.
Remote, power limited, future = renewables

Archive(s)
- Exa-byte capacity
- Where (Regional Data Centres?)
- What (… should be in it)
- ➢Growth rates are 10s Pb/year
- ➢SKA2 ~10^6 times worse!

AWS, IBM, Google, Nvidia
SGI, Intel, …

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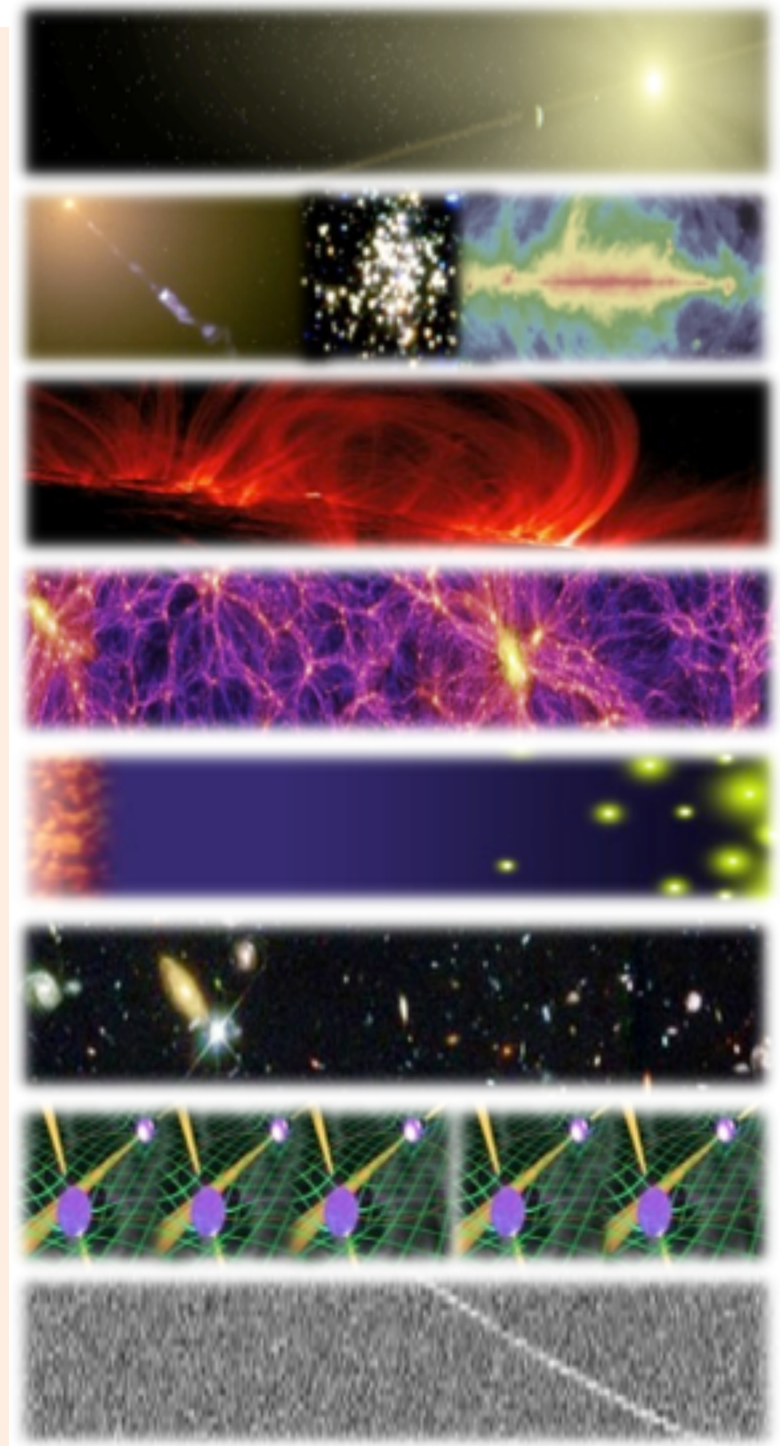
SKA-1 Headline science

From Near to Far …

- **The Cradle of Life & Astrobiology**
  - *Proto--planetary disks*
- **Strong--field Tests of Gravity with Pulsars and Black Holes**
  - *Gravitational waves and fundamental physics*
- **The Origin and Evolution of Cosmic Magnetism**
  - *The role of magnetism in galaxy evolution*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *Resolved gaseous disks and angular momentum growth*
- **The Transient Radio Sky**
  - *Fast Radio Bursts as cosmological probes*
- **Galaxy Evolution probed in the Radio Continuum**
  - *Star formation rates and resolved disks*
- **Cosmology & Dark Energy**
  - *Primordial non--Gaussianity, super--horizon scales and the maJer dipole*
- **Cosmic Dawn and the Epoch of Reionization**
  - *Direct imaging of the earliest structures*



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I WANT YOU
FOR RADIOASTRONOMY