

Introduction to ALMA and Radio Interferometry



Ben Tofflemire – UT Austin
ALMA Ambassador

Authors: Alison Peck, Jim Braatz, Ashley Bemis, Sabrina Stierwalt, Lisa Young, Neal Jackson, Dave Wilner

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Very Long Baseline Array



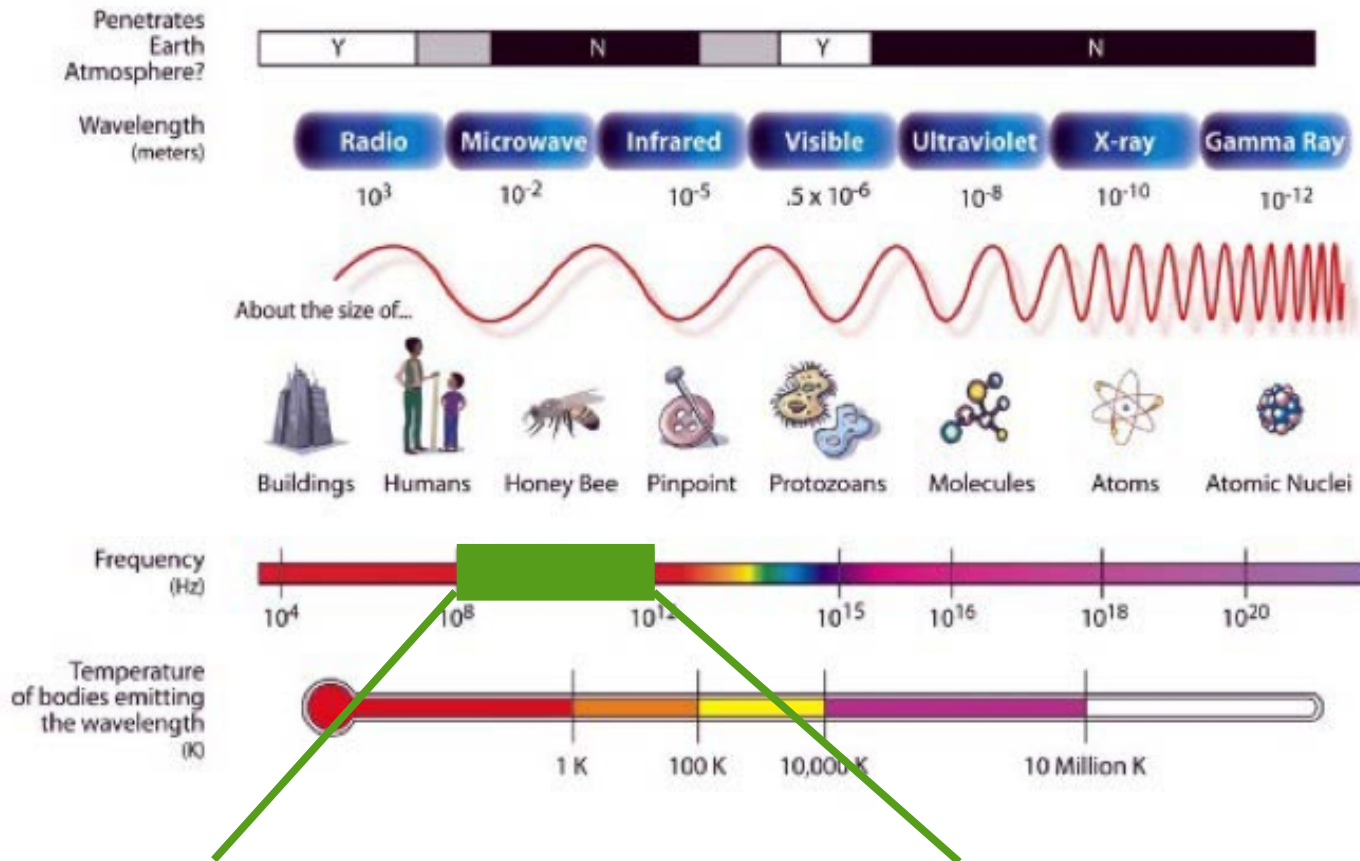
ALMA in a Nutshell...

ALMA is a sensitive mm and sub-mm interferometer

So why the mm/sub-mm?
And why interferometry?



Why mm/sub-mm?

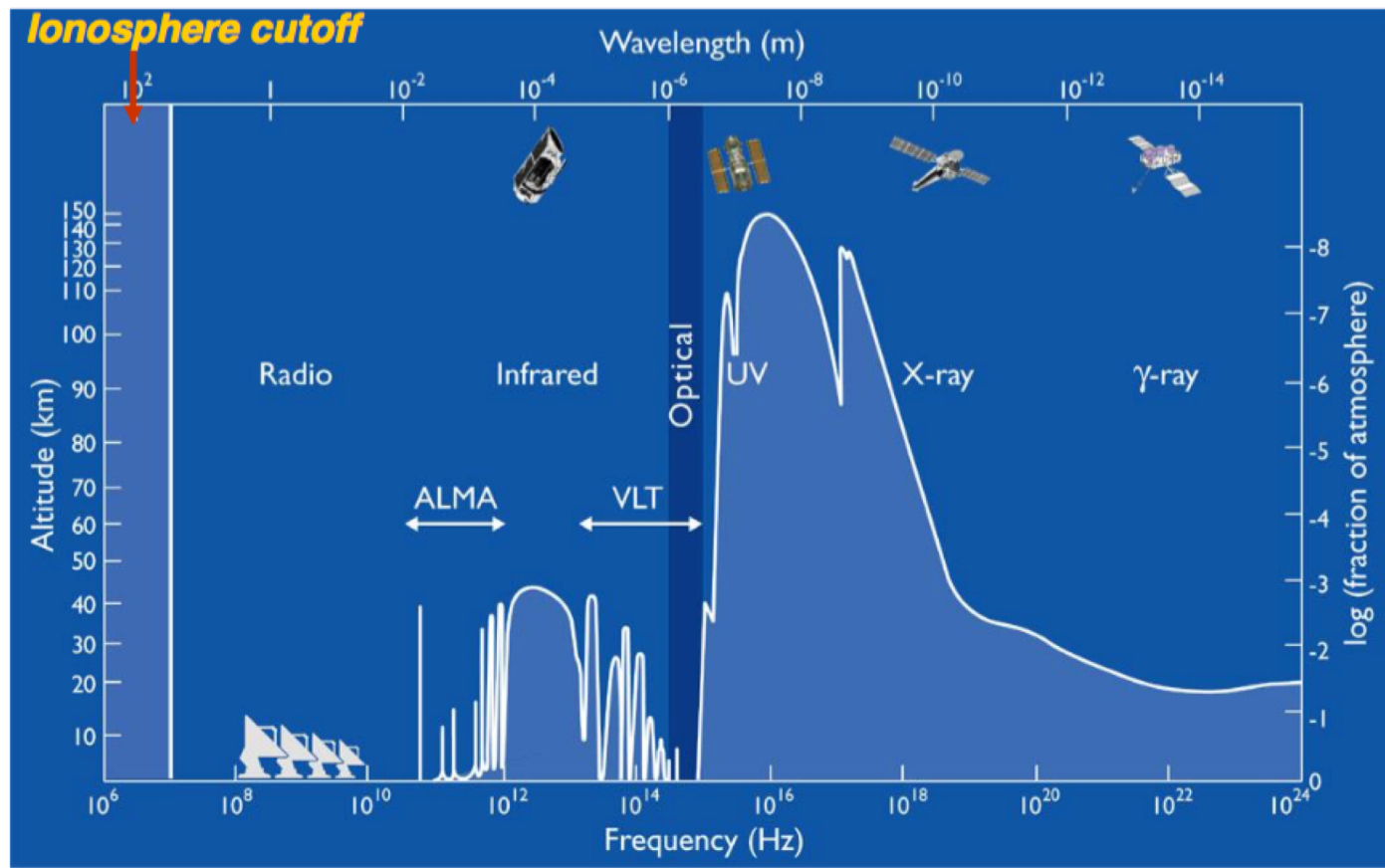


VLA
~1 - 50 GHz
~300 - 6 mm

ALMA
~84 - 950
GHz
~3 - 0.3 mm

Why mm/sub-mm?

Opacity of the Atmosphere (solid line is altitude at which transmission is reduced by factor of 2)



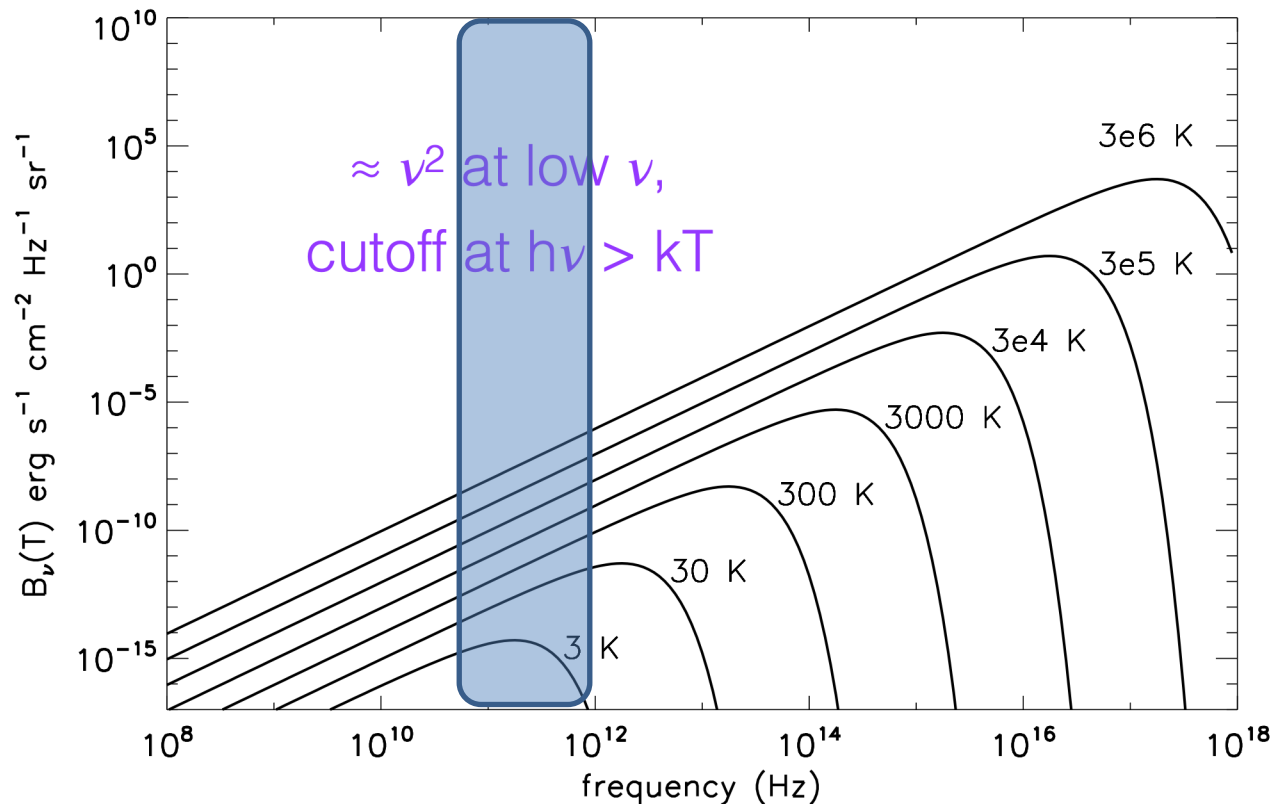
mm and sub-mm range

NRAO Synthesis Workshop 2014

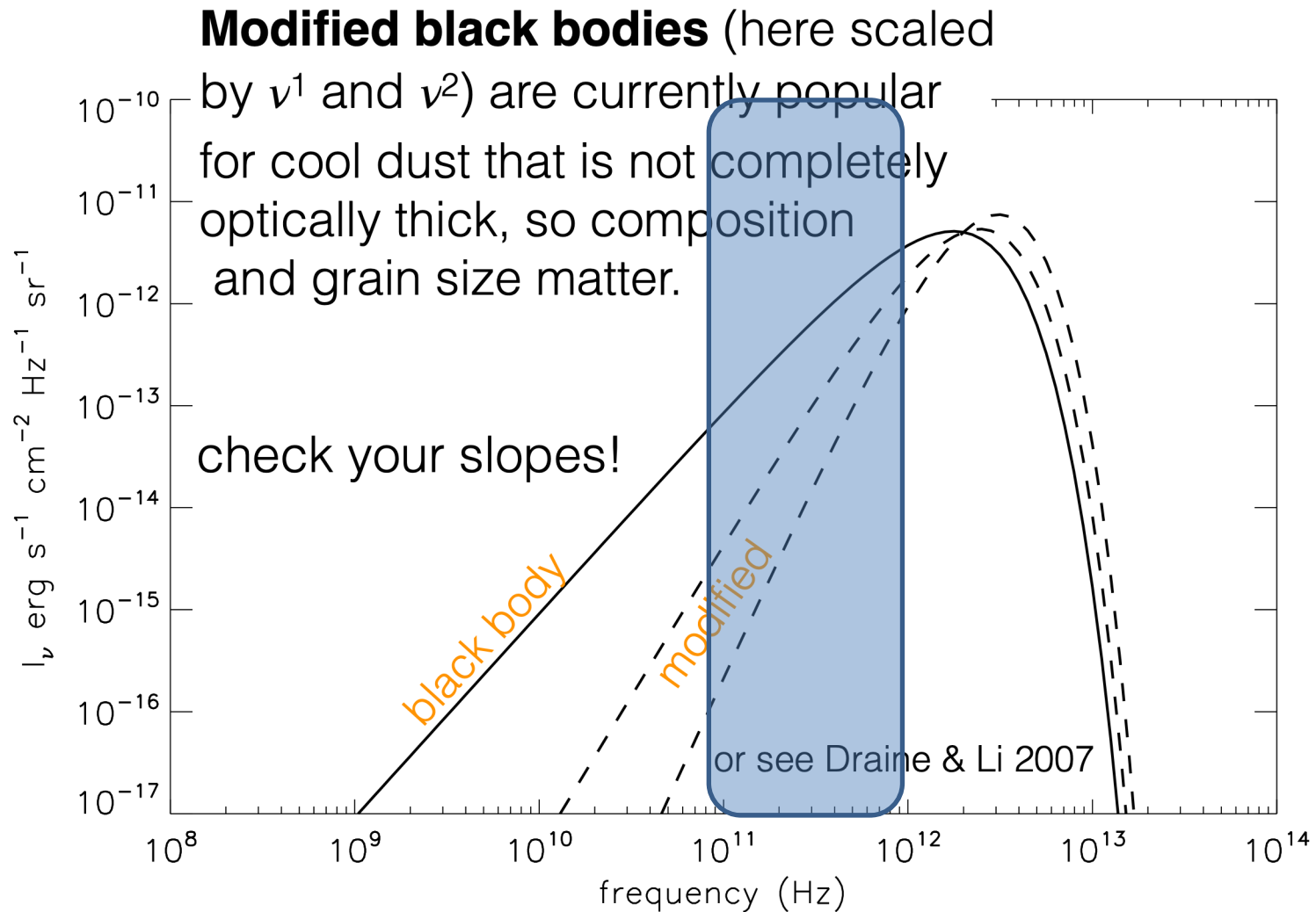
Why mm/sub-mm?

Black body emission has a characteristic shape.

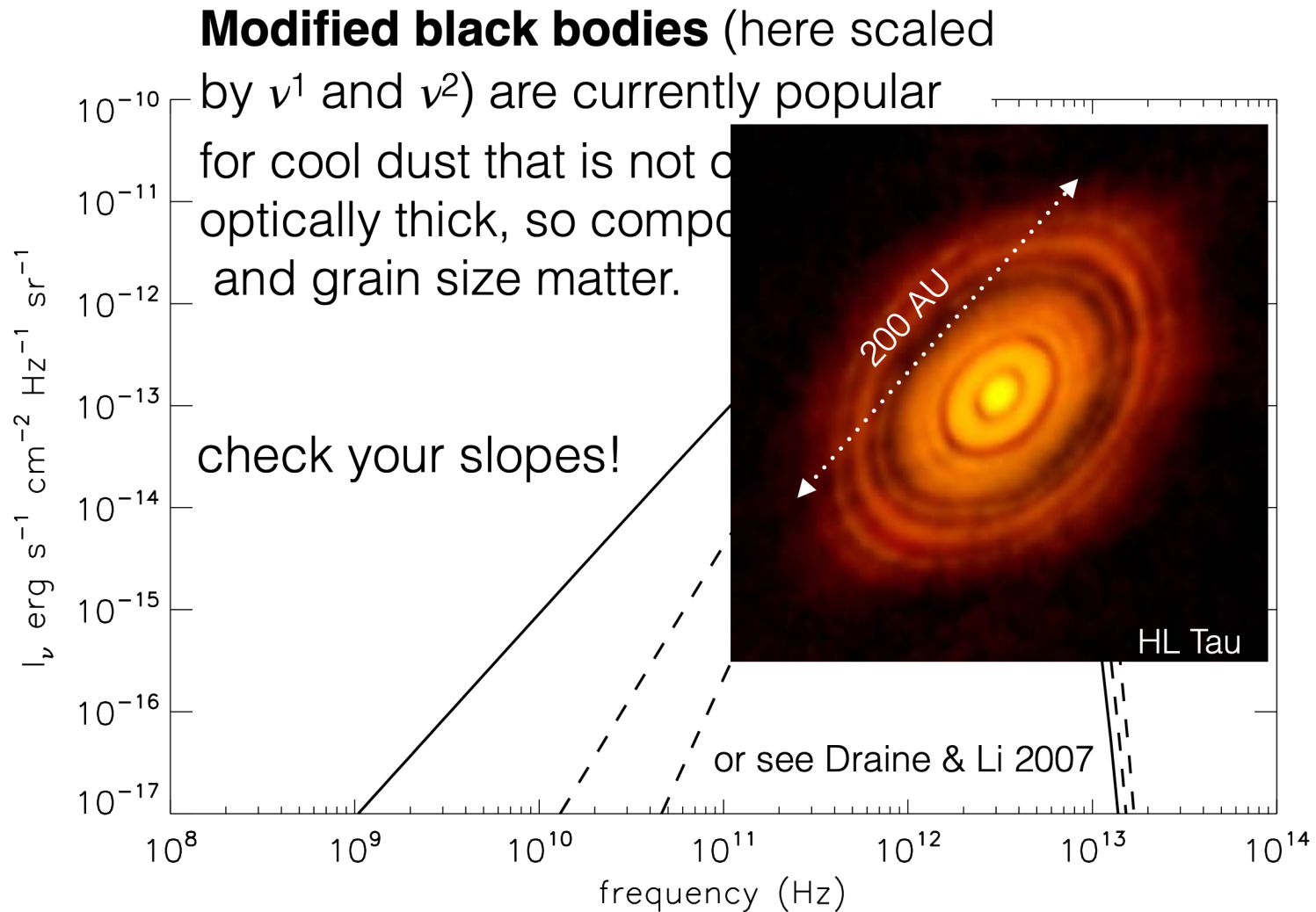
$$B(\nu, T) = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}$$



Why mm/sub-mm?

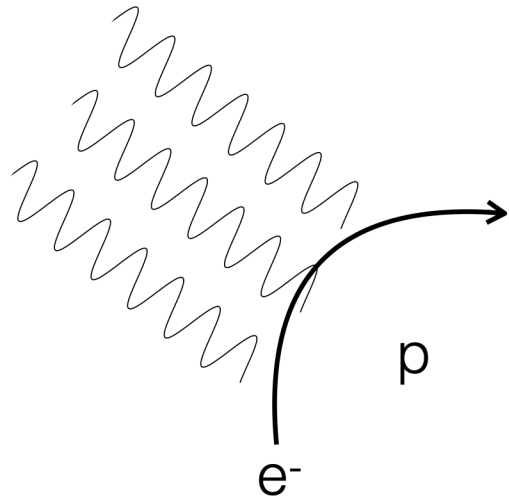


Why mm/sub-mm?



Why mm/sub-mm?

Bremsstrahlung (a.k.a. free-free) emission



optically thin, thermal emission
from ionized gas : HII regions etc.

good for estimating density &
temperature of ionized gas

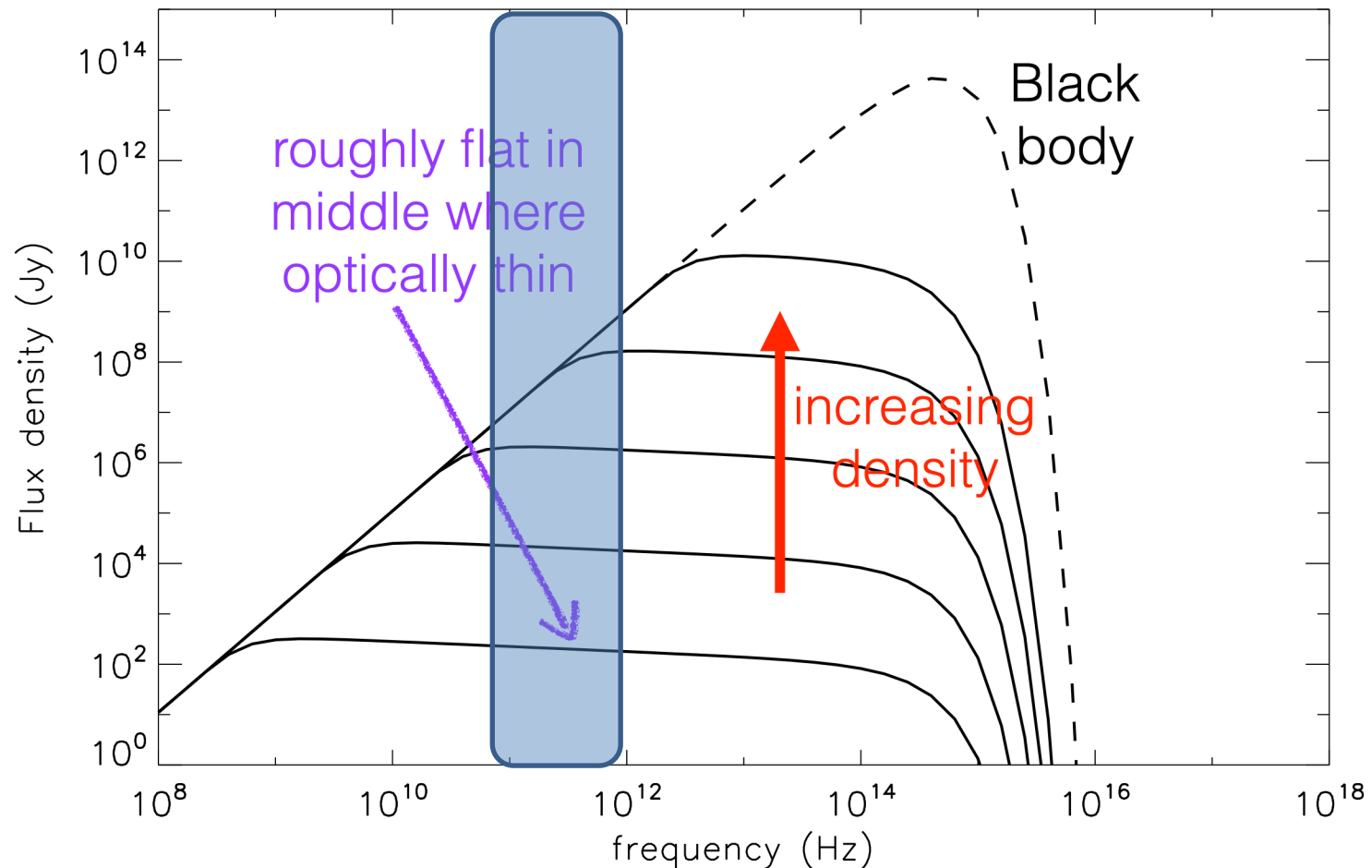
- counting ionizing photons
- inferring star formation rate

$$j_{\text{ff}}(\nu) = \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{\text{ff}}(\nu, T) e^{-h\nu/k_B T}$$

emission coefficient (e.g. $\text{erg s}^{-1} \text{cm}^{-3} \text{Hz}^{-1} \text{ster}^{-1}$)

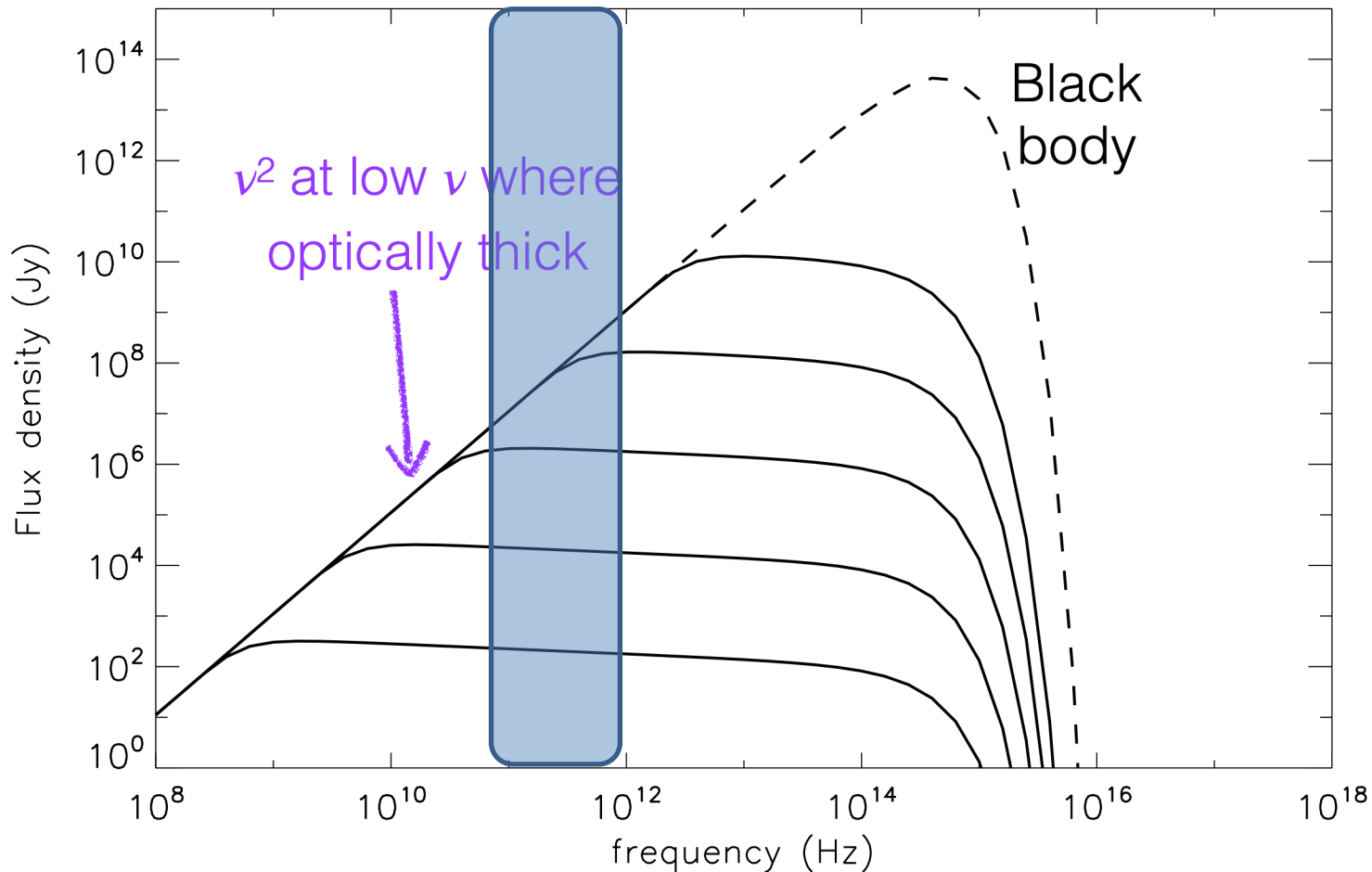
Why mm/sub-mm?

$$j_{\text{ff}}(\nu) = \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^{3/2} c^3} \frac{n_e n_i}{(k_B T)^{1/2}} g_{\text{ff}}(\nu, T) e^{-h\nu/k_B T} + \text{radiative transfer}$$

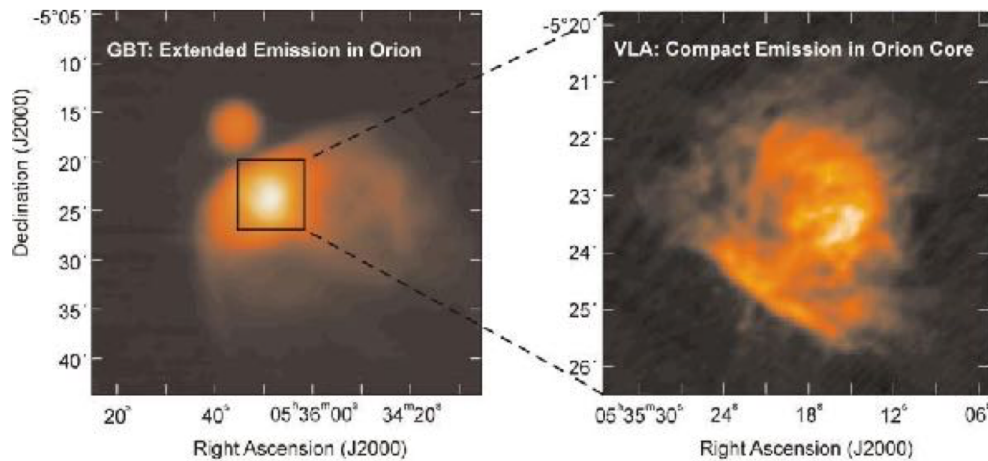


Why mm/sub-mm?

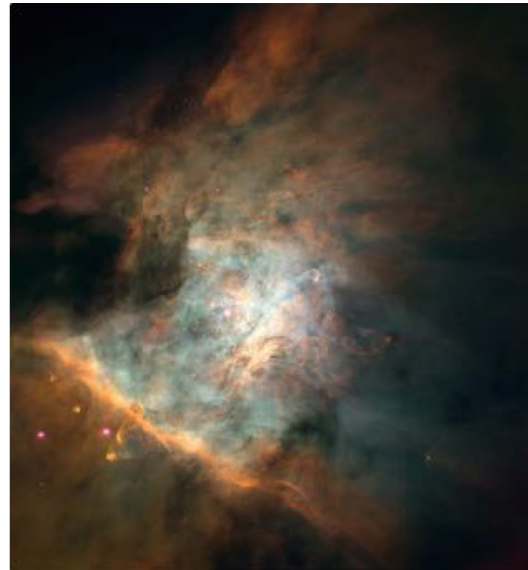
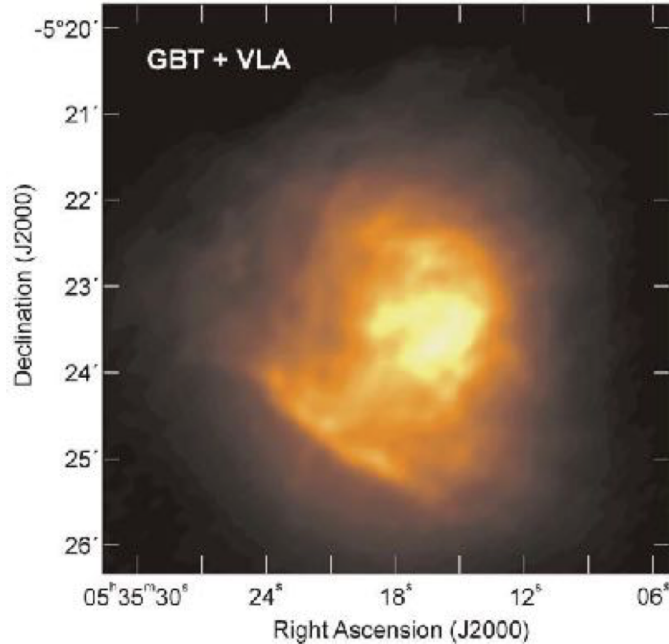
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Why mm/sub-mm?



Orion Nebula
8.4 GHz
Dicker et al 2009

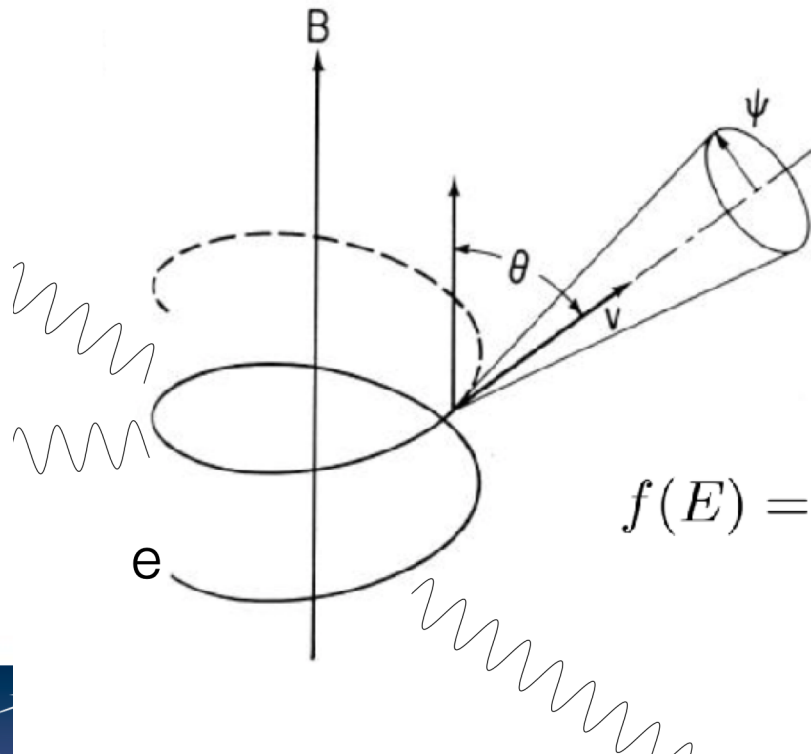


HST
optical

Why mm/sub-mm?

Synchrotron emission

nonthermal (usu: relativistic) electrons in a B field
can get particle energies, n and B



$$\nu_c = \frac{3}{4\pi} \gamma^2 \frac{eB}{mc} \sin \theta$$

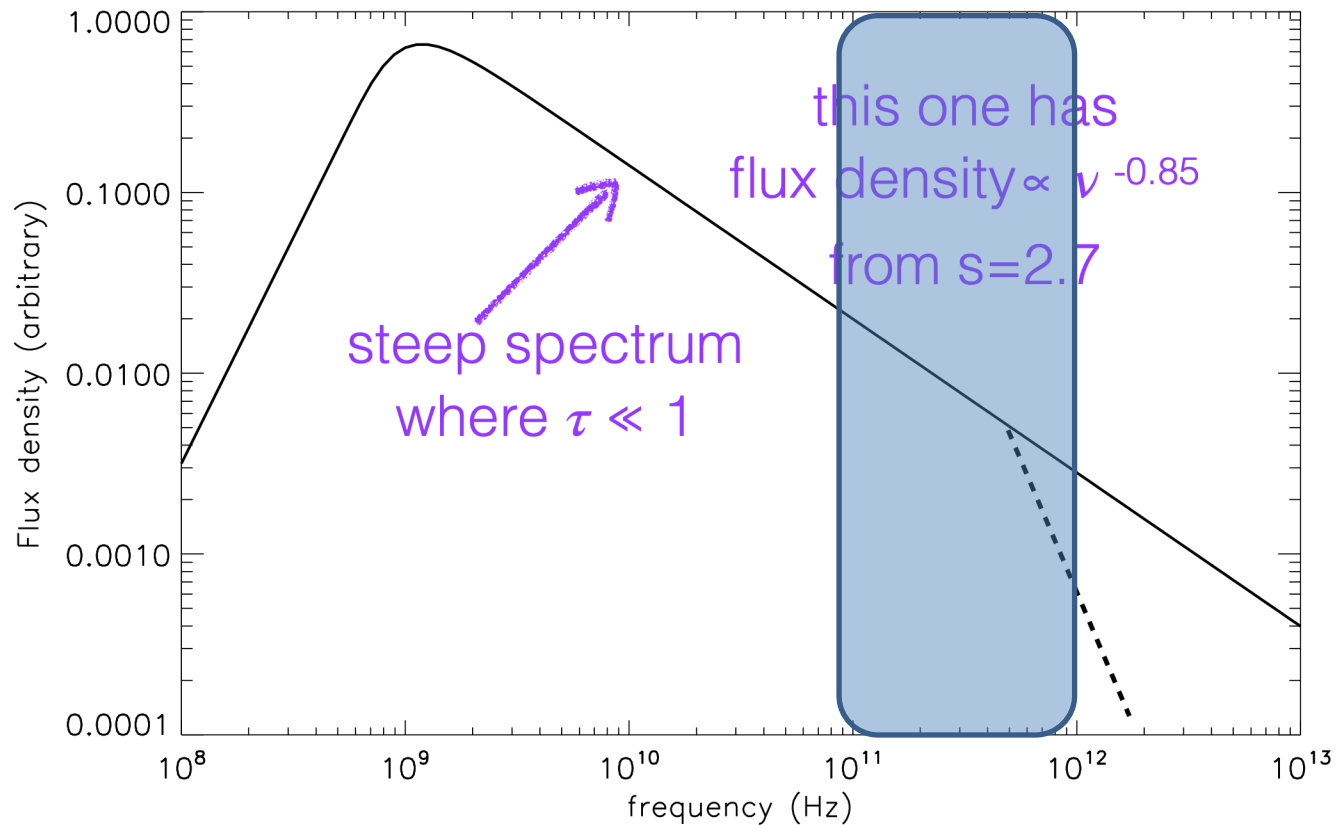
An electron of energy γ
($E = \gamma mc^2$) radiates at
this frequency.

$$f(E) = f_o E^{-s}$$

power law distribution of
electron energies

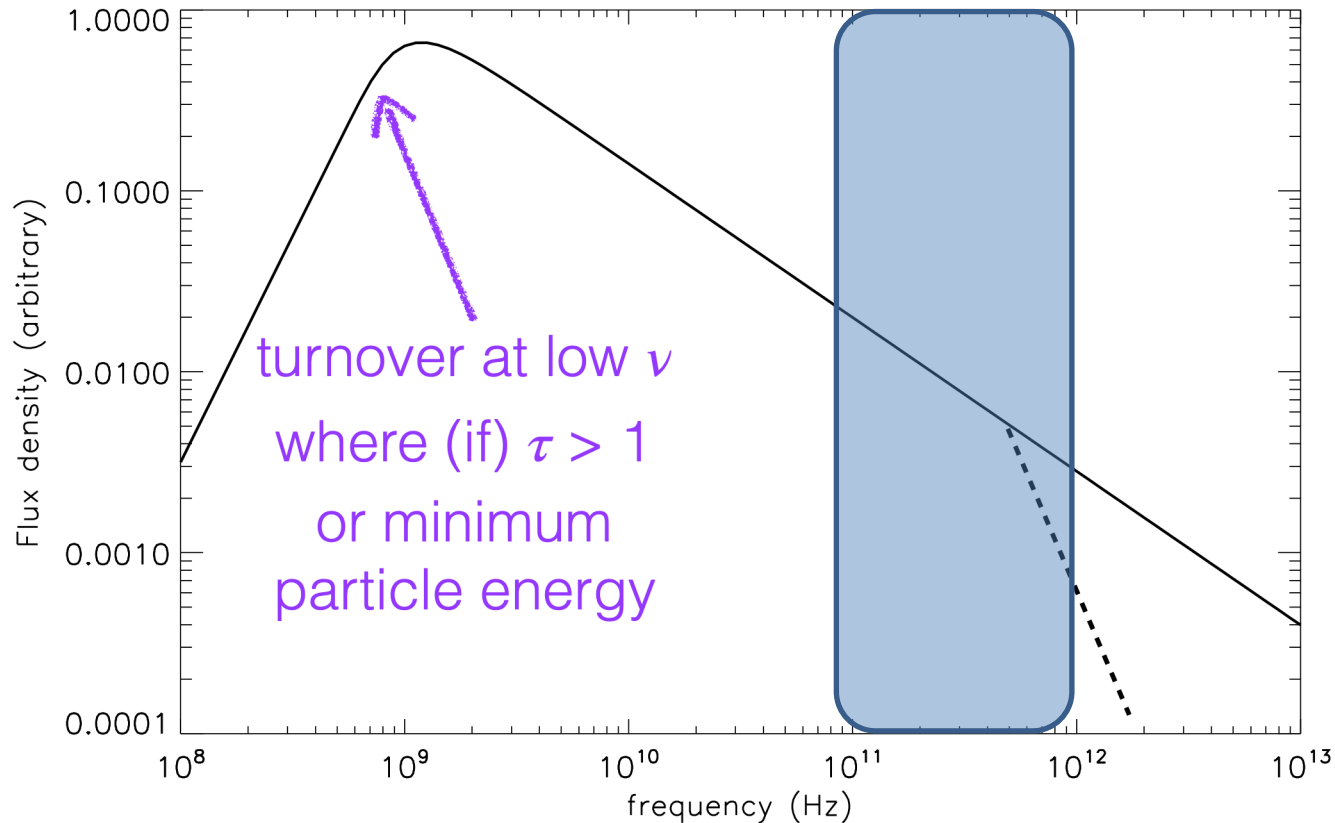
Why mm/sub-mm?

$$j_{sy}(\nu) \propto P_o B^{(s+1)/2} f_o \nu^{-(s-1)/2} + \text{radiative transfer}$$



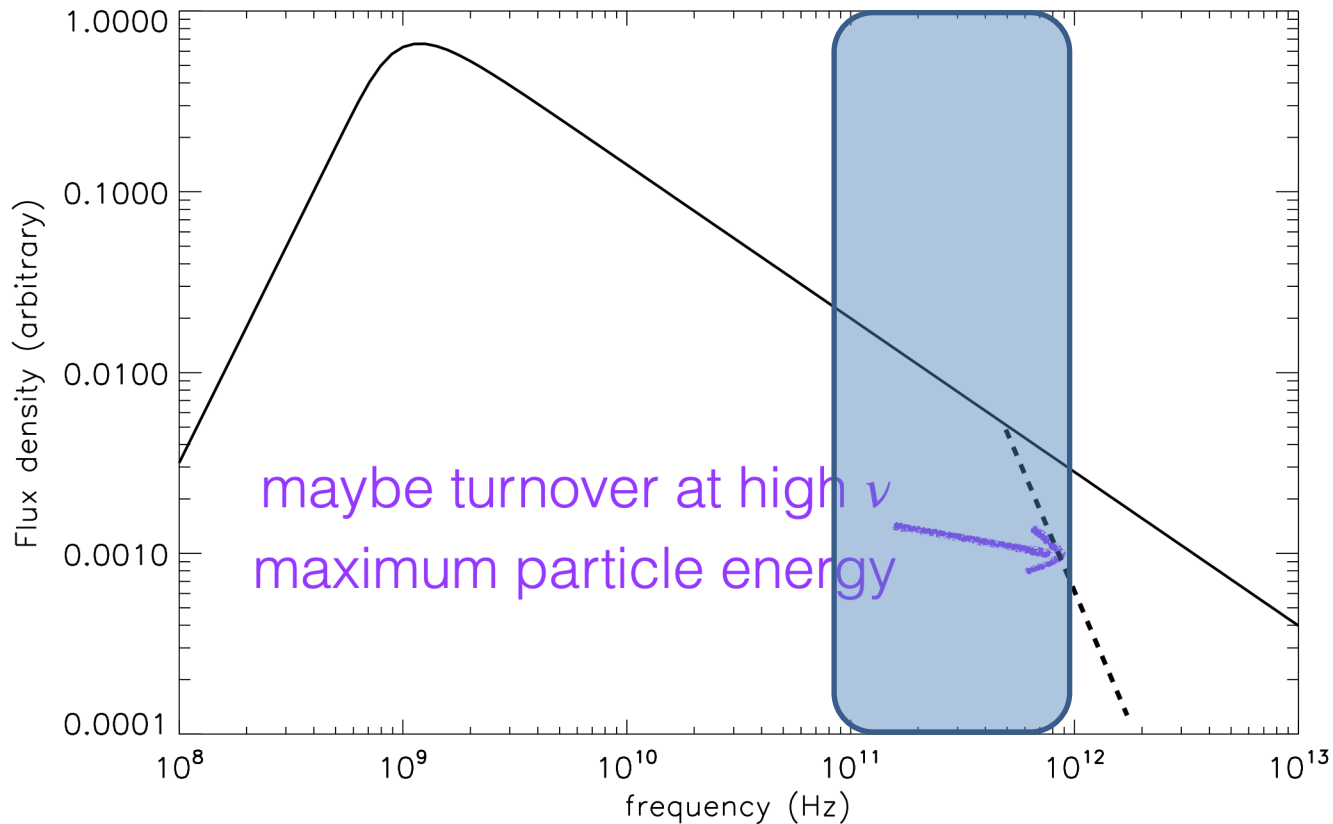
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Why mm/sub-mm?

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Why mm/sub-mm?

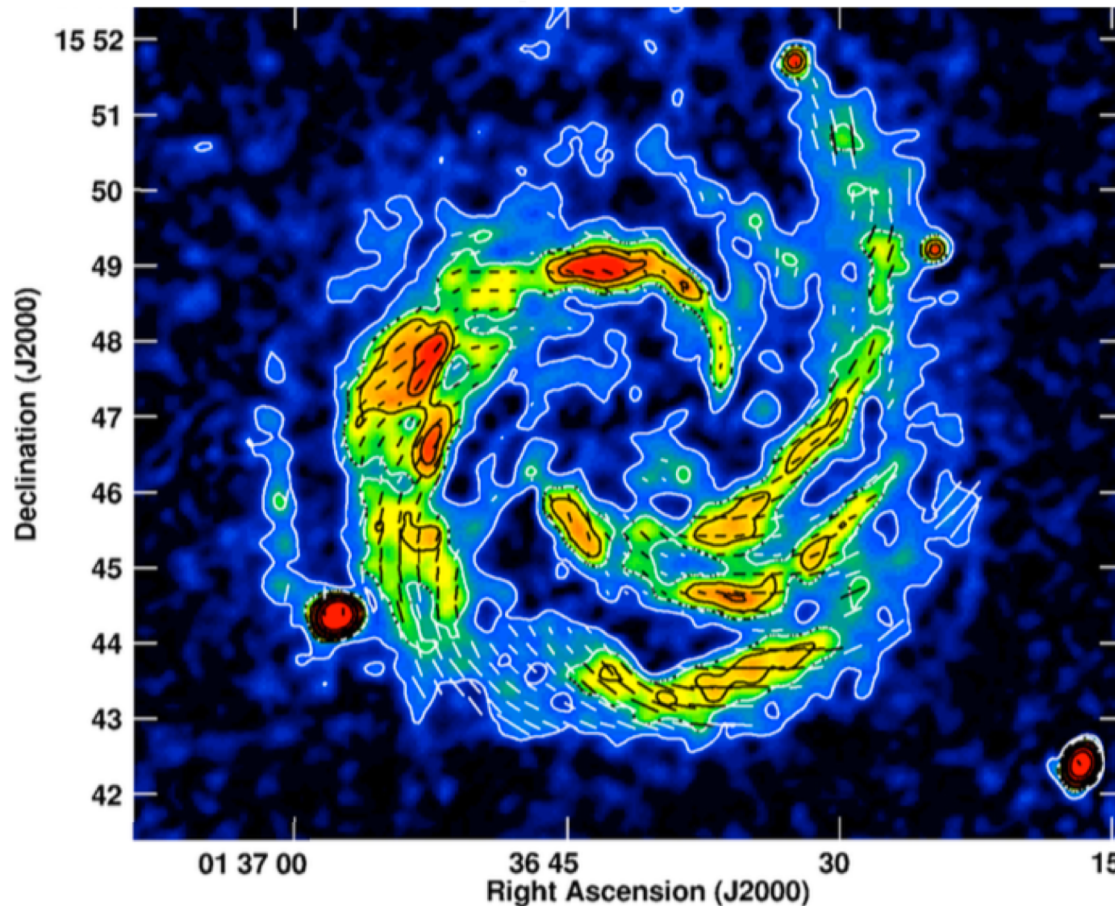
synchrotron from active galaxy Her A, $\nu \sim 6.5$ GHz



B. Saxton, W. Cotton and R. Perley (NRAO/AUI/NSF)

Why mm/sub-mm?

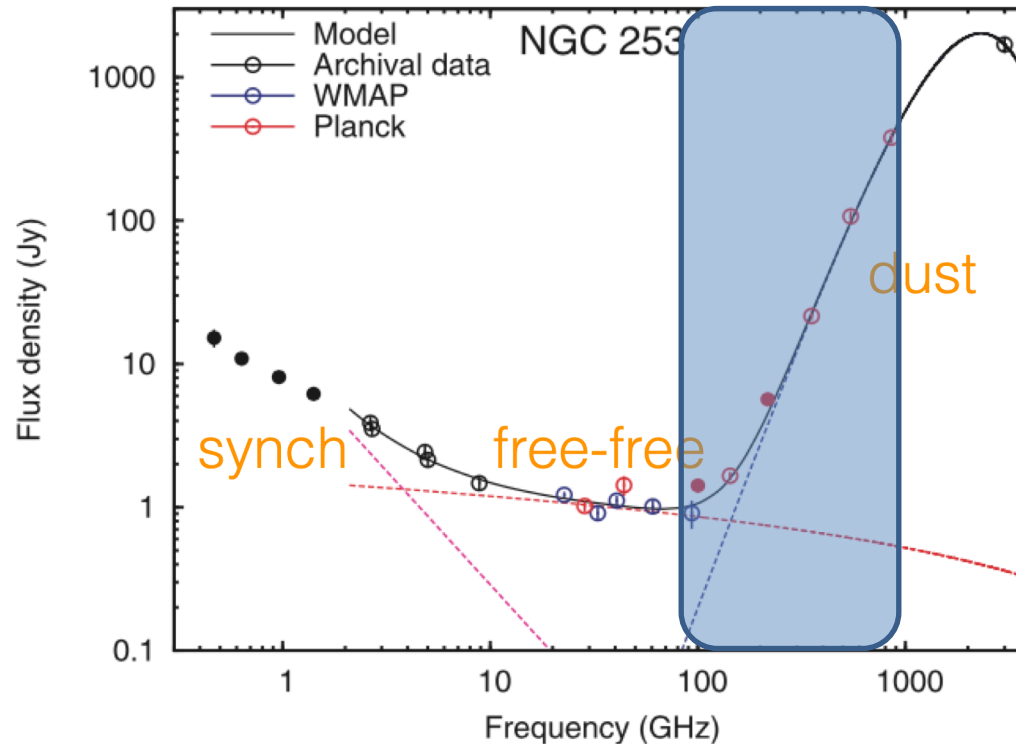
Synchrotron emission is polarized! Gives info on B field.



Mulcahy et al 2017; NGC 628, VLA @ 3 GHz

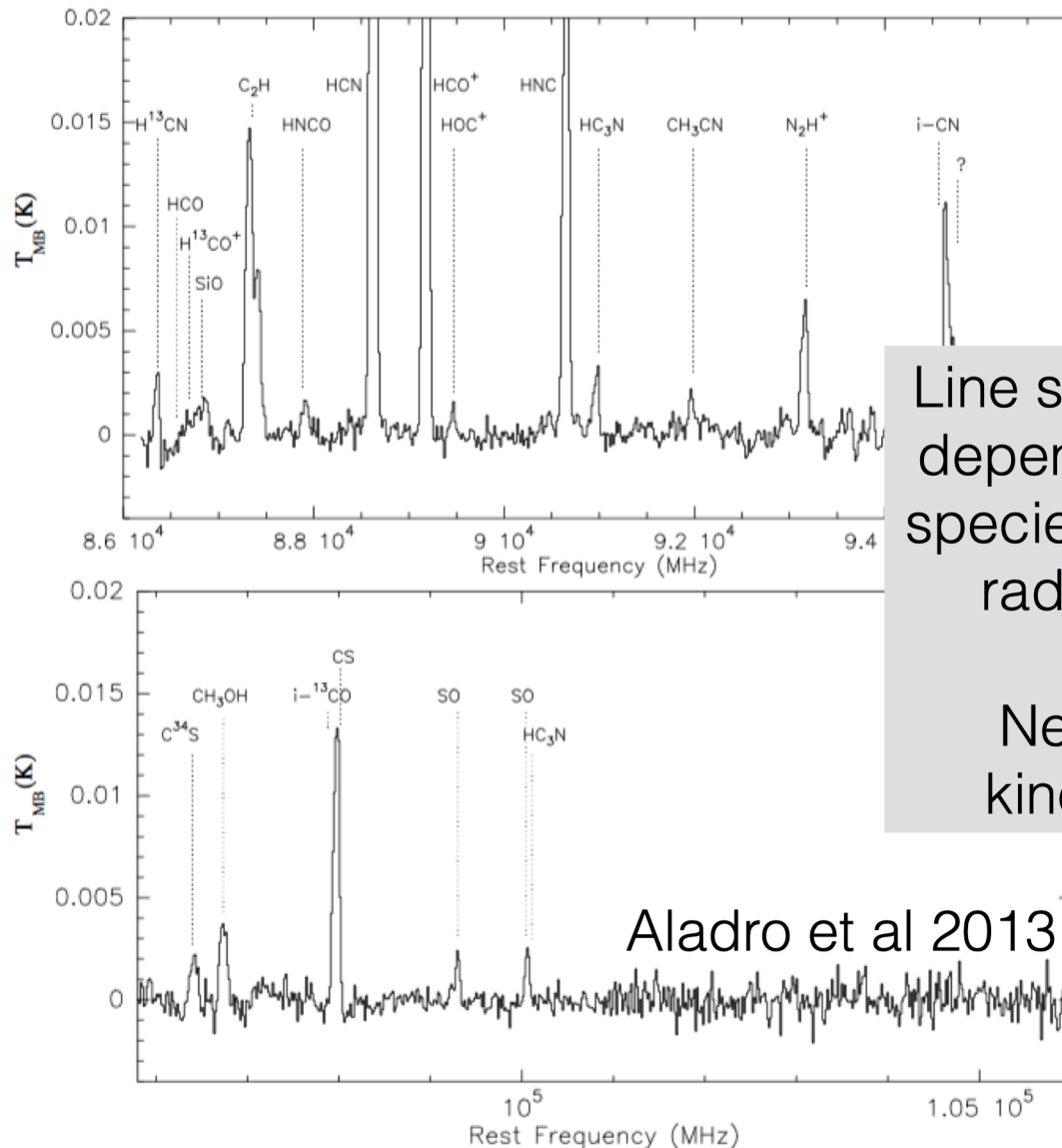
Why mm/sub-mm?

Real objects often have a combination of many kinds of emission.



Peel et al 2011

Why mm/sub-mm?



Line strengths generally depend on gas density, species abundance, T_{ex} , radiation field, etc.

Need lines to get kinematics of gas.

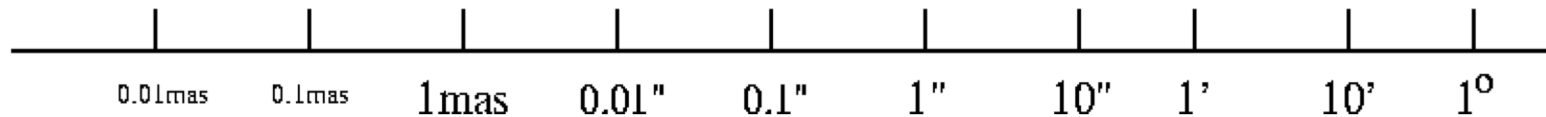
Aladro et al 2013

Why Interferometry?

Why Interferometry?

$$\theta \sim \lambda/D$$

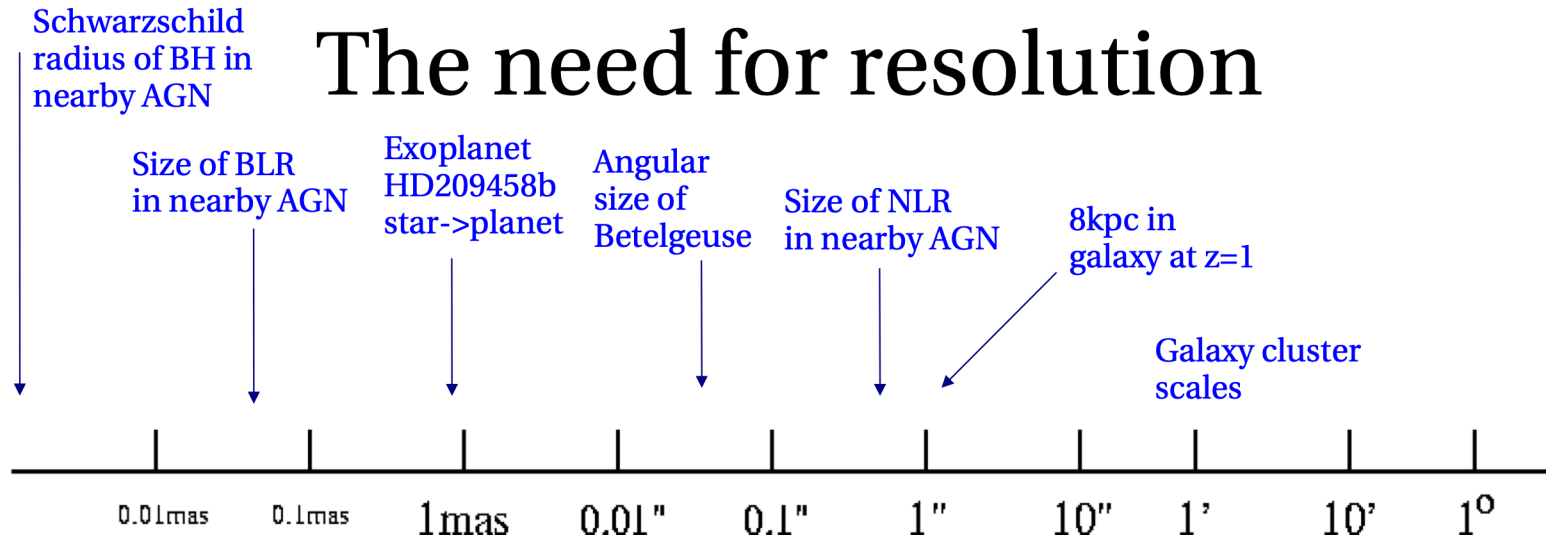
The need for resolution



Why Interferometry?

$$\theta \sim \lambda/D$$

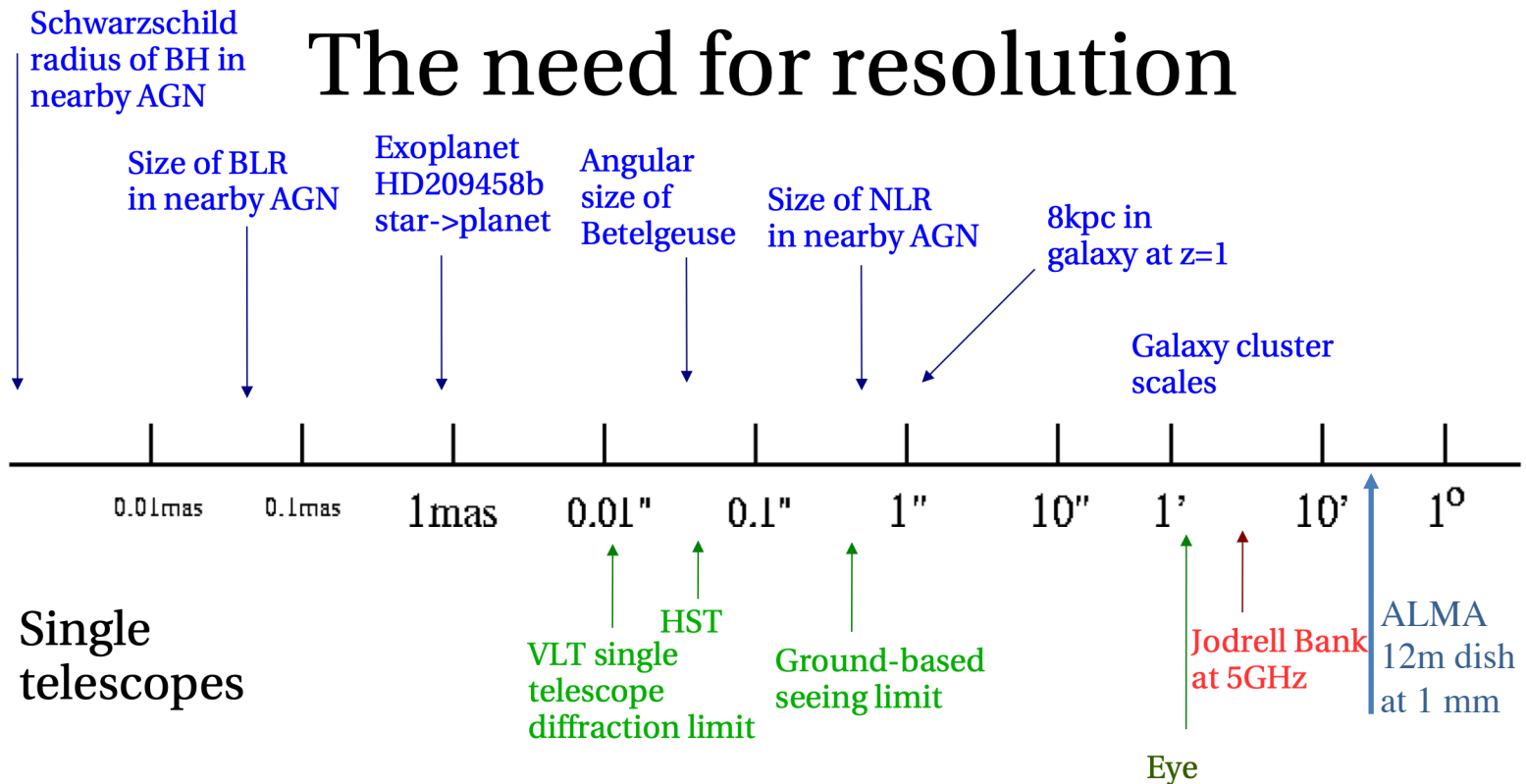
The need for resolution



Why Interferometry?

$$\theta \sim \lambda/D$$

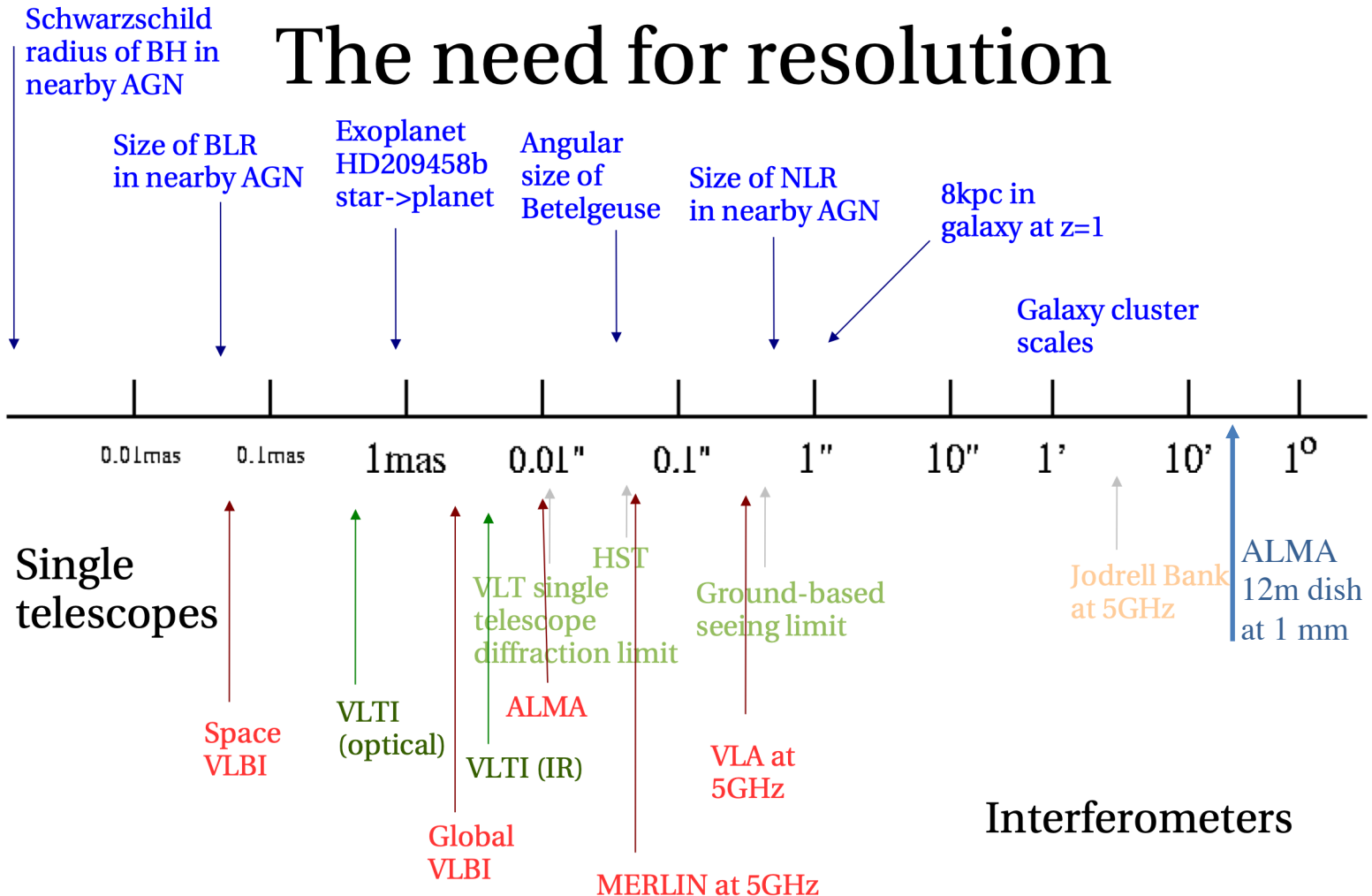
The need for resolution



Why Interferometry?

$$\theta \sim \lambda/D$$

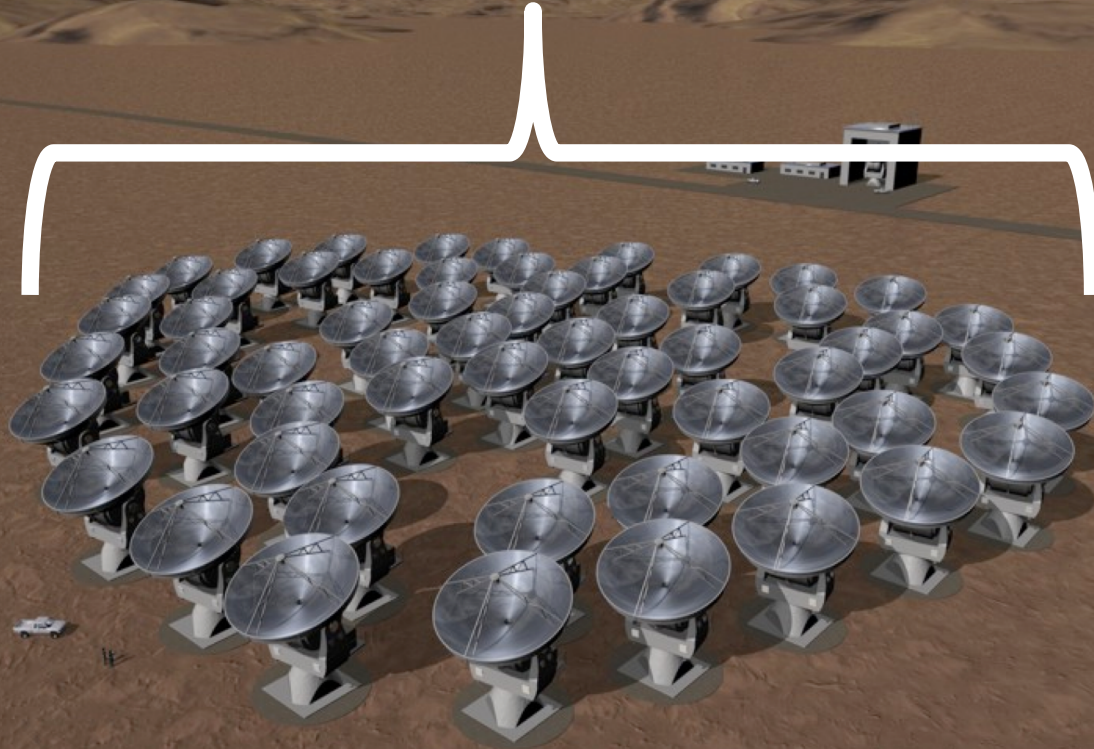
The need for resolution



Why Interferometry?

$$\theta \sim \lambda/D$$

D



ALMA in a Nutshell...

- ◆ Angular resolution down to $0.015''$ (at 300 GHz)
- ◆ Sensitive, precision imaging 84 to 950 GHz (3 mm to 320 μm)
- ◆ State-of-the-art low-noise, wide-band receivers* (8 GHz bandwidth)
- ◆ Flexible correlator with high spectral resolution at wide bandwidth
- ◆ Full polarization capabilities including circular.
- ◆ Estimated 1 TB/day data rate
- ◆ All science data archived
- ◆ Pipeline processing

ALMA is 10-100 times more sensitive and has 10-100 times better angular resolution than current mm interferometers*

*With 90 Degree Walsh Switching in Bands 9 and 10, this gives 16 GHz of instantaneous bandwidth.

In either case, this is using the Time Division Mode (TDM) modes.



What is ALMA?

- A global partnership to deliver a revolutionary millimeter/submillimeter telescope array (in collaboration with Chile)
 - ◆ North America
 - ◆ Europe
 - ◆ East Asia
- 66 reconfigurable, high precision antennas
- $\lambda \sim 0.32 - 8.5\text{mm}$. Array configurations
- between 150 meters and >16 kilometers: 192 possible antenna locations:
 - ◆ Main Array: 50 x 12m antennas
 - ◆ Total Power Array: 4 x 12m antennas
 - ◆ Atacama Compact Array (ACA): 12 x 7m antennas
 - ◆ TP + ACA (Morita Array)
- Array Operations Site is located at 5000m elevation in the Chilean Andes
- Provides unprecedented imaging* & spectroscopic capabilities at mm/submm λ



What is ALMA?



ALMA Current Status

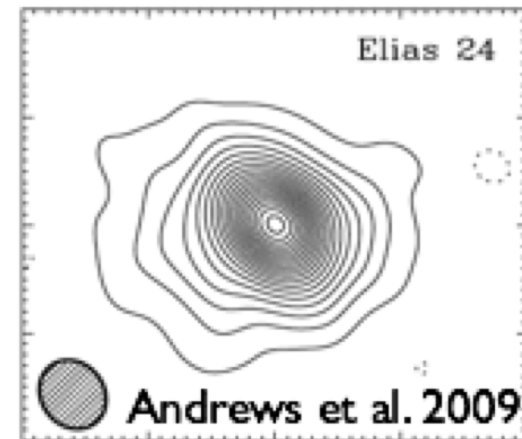
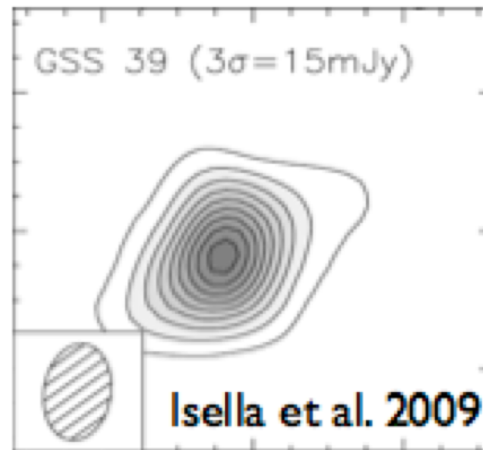
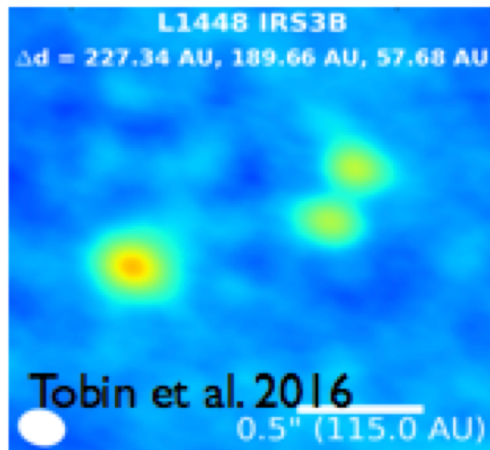
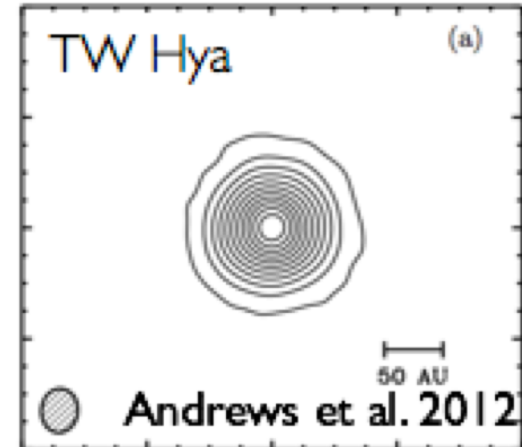
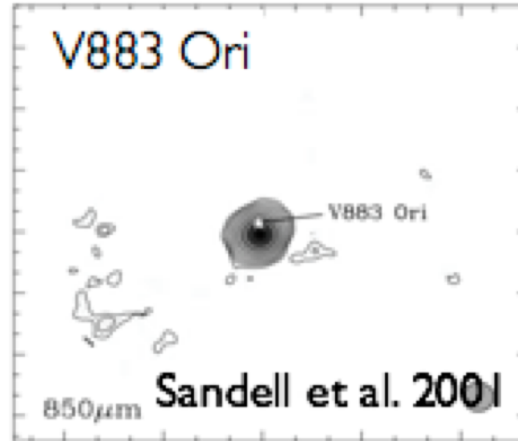
- Construction Project ended in September 2014
- Routine science observing has been out to **greater than 16 km baselines (C43-10)** thanks to the highly successful Long Baseline Campaigns in 2014 and 2015
- **All 66 antennas accepted**
 - Currently all 66 antennas are at the high site (AOS), of which ~47 on average (up to max ~66) are being used for Cycle 7 observations
 - Some construction and verification items remain to be finished (e.g., wide-field polarization; various observing modes)
- The ACA (Atacama Compact Array) or Morita Array – up to 12x7m antennas and 4x12m antennas for TP observations – is currently being used for Cycle 7 observations
- More on Capabilities later... however, first on to science!

Broad Science Topics with NRAO Telescopes

- ◆ **Sun** – coronal mass ejections, magnetic field activity
- ◆ **Solar system, KBOs** – atmospheres, astrometry, composition
- ◆ **Star-forming regions** – dust and gas environment, kinematics (infall, outflows, jets), proto-planetary disks, cores, chemistry, feedback, and natal cloud / star interactions
- ◆ **Exoplanets** – direct imaging, gaps in disks, kinematics
- ◆ **Pulsars** – neutron star physics, pulse morphology, gravity, ISM probe
- ◆ **Galactic structure** – spiral arms, bars, global atomic and molecular gas properties
- ◆ **Nearby galaxies** – molecular / atomic gas content and kinematics, dynamics of galaxies at high resolution, star formation, obscured SF, gas flow
- ◆ **Galaxy groups and clusters** – atomic and molecular gas across systems, star formation efficiency, kinematics, dynamical mass measurements
- ◆ **Black holes** – mass measurements, kinematics
- ◆ **High redshift galaxies** – extragalactic background light, source counts, star formation history and efficiency, evolution of gas content (atomic and molecular)
- ◆ **Cosmology** – H_0 measurement, SZE

ALMA Science Highlights: Protoplanetary Disks

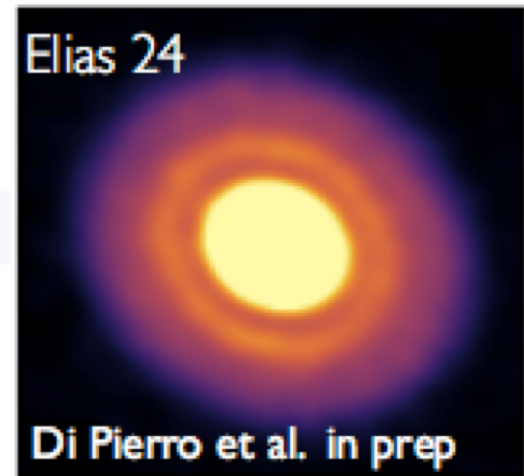
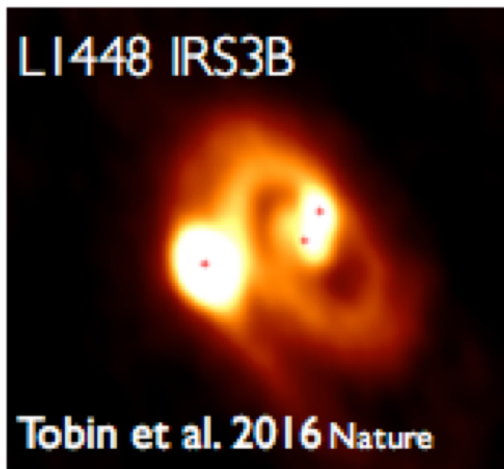
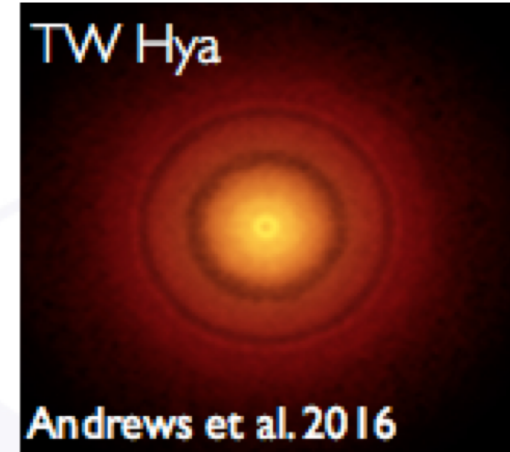
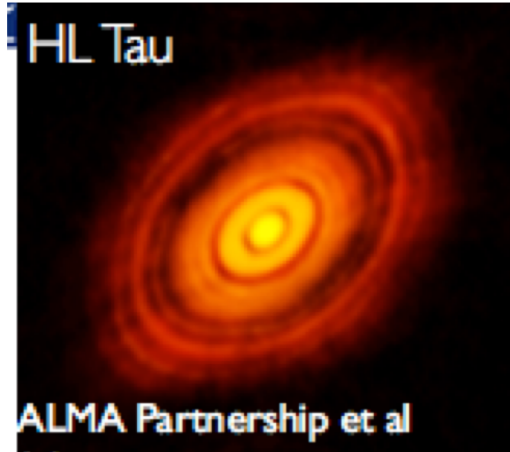
Protoplanetary Disks: Pre- ALMA



Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: Protoplanetary Disks

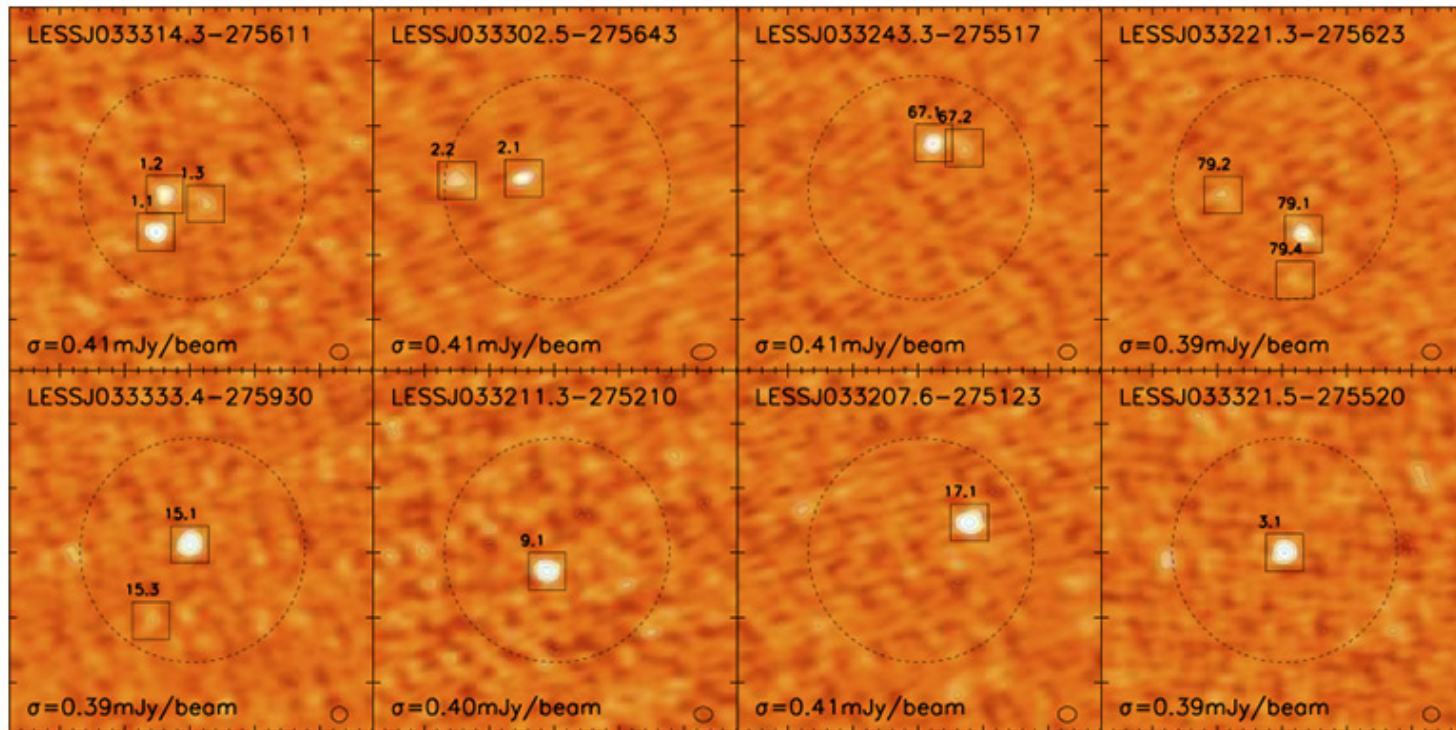
Protoplanetary Disks: With ALMA



Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

ALMA Science Highlights: the Distant Universe

Resolving High-z Submm Galaxies

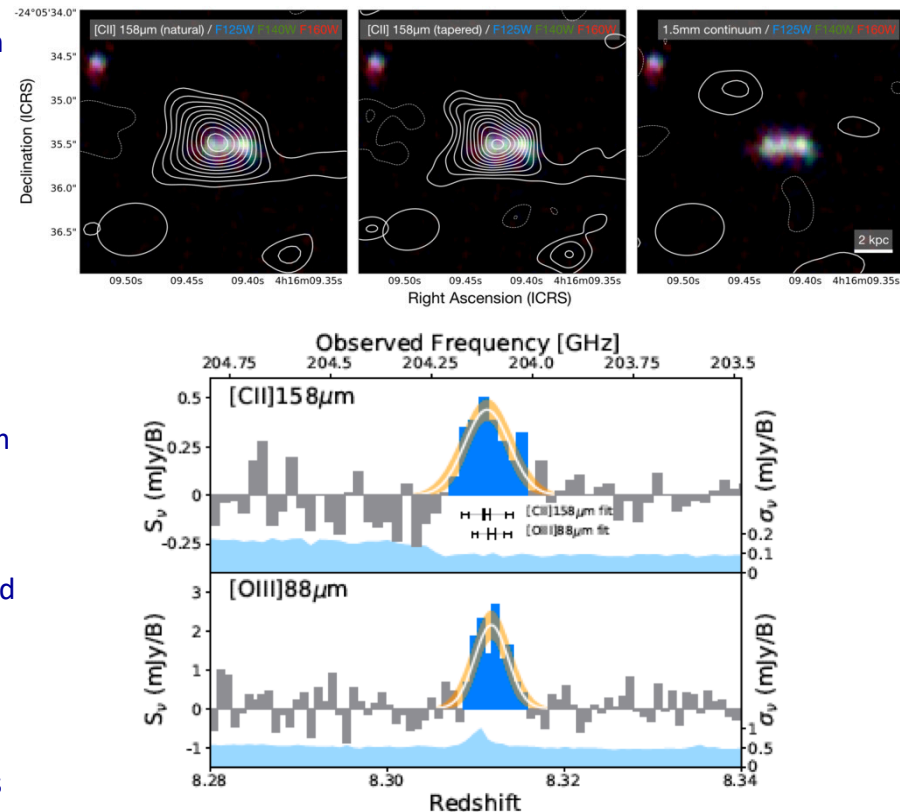


Hodge et al. 2013

- ◆ 126 submm sources observed with ALMA at 870 μm
- ◆ 2x deeper, 10x higher angular resolution than previous surveys
- ◆ **99 sources detected in 88 fields, integration time ~120 sec (!!)**
- ◆ Significant multiplicity (35-50%) found at 0.2'' resolution

ALMA uncovers the [CII] emission and warm dust continuum in a $z = 8.31$ Lyman break galaxy

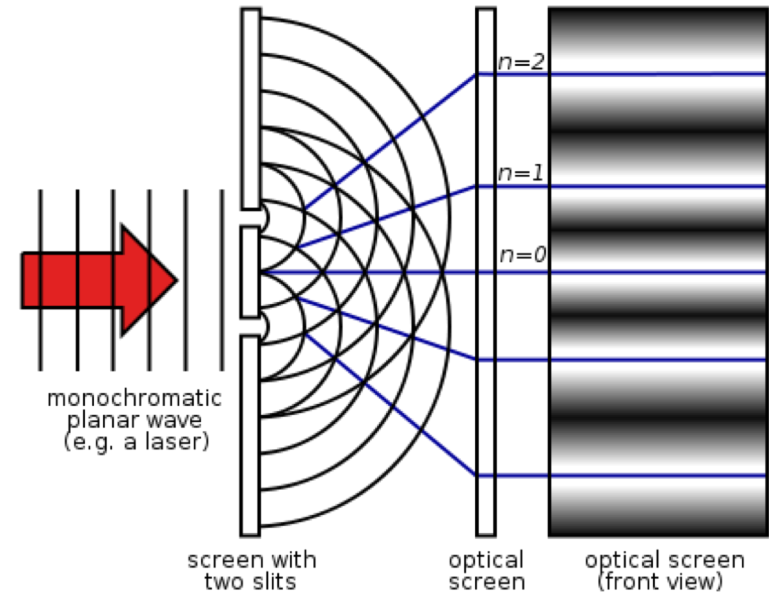
- ALMA detection of the [CII] $157.7 \mu\text{m}$ emission from the Lyman break galaxy (LBG) MACS0416_Y1 at $z = 8.3113$
- The luminosity ratio of [OIII] $88 \mu\text{m}$ to [CII] is 9.31 ± 2.6 ,
 - indicative of hard interstellar radiation fields and/or a low covering fraction of photo-dissociation regions.
 - The emission of [CII] is cospatial to the $850 \mu\text{m}$ dust emission ($90 \mu\text{m}$ rest-frame, from previous campaigns),
 - Peak [CII] emission does not agree with the peak [OIII] emission, suggesting that the lines originate from different conditions in the interstellar medium.
 - We fail to detect continuum emission at 1.5 mm ($160 \mu\text{m}$ rest-frame) placing a strong limit on the dust spectrum
 - suggests an unusually warm dust component ($T > 80 \text{ K}$, 90% confidence limit), and/or a steep dust-emissivity index $\beta_{\text{dust}} > 2$, compared to galaxy-wide dust emission found at lower redshifts (typically $T \sim 30 - 50 \text{ K}$, $\beta_{\text{dust}} \sim 1 - 2$).
- If such temperatures are common, this would reduce the required dust mass and relax the dust production problem at the highest redshifts.
- We recommend a more thorough examination of dust temperatures in the early Universe, and stress the need for instrumentation that probes the peak of warm dust in the Epoch of Reionization.



T. Bakx, Y. Tamura, T. Hashimoto, et. al. arxiv: 2001.02812

What is an interferometer?

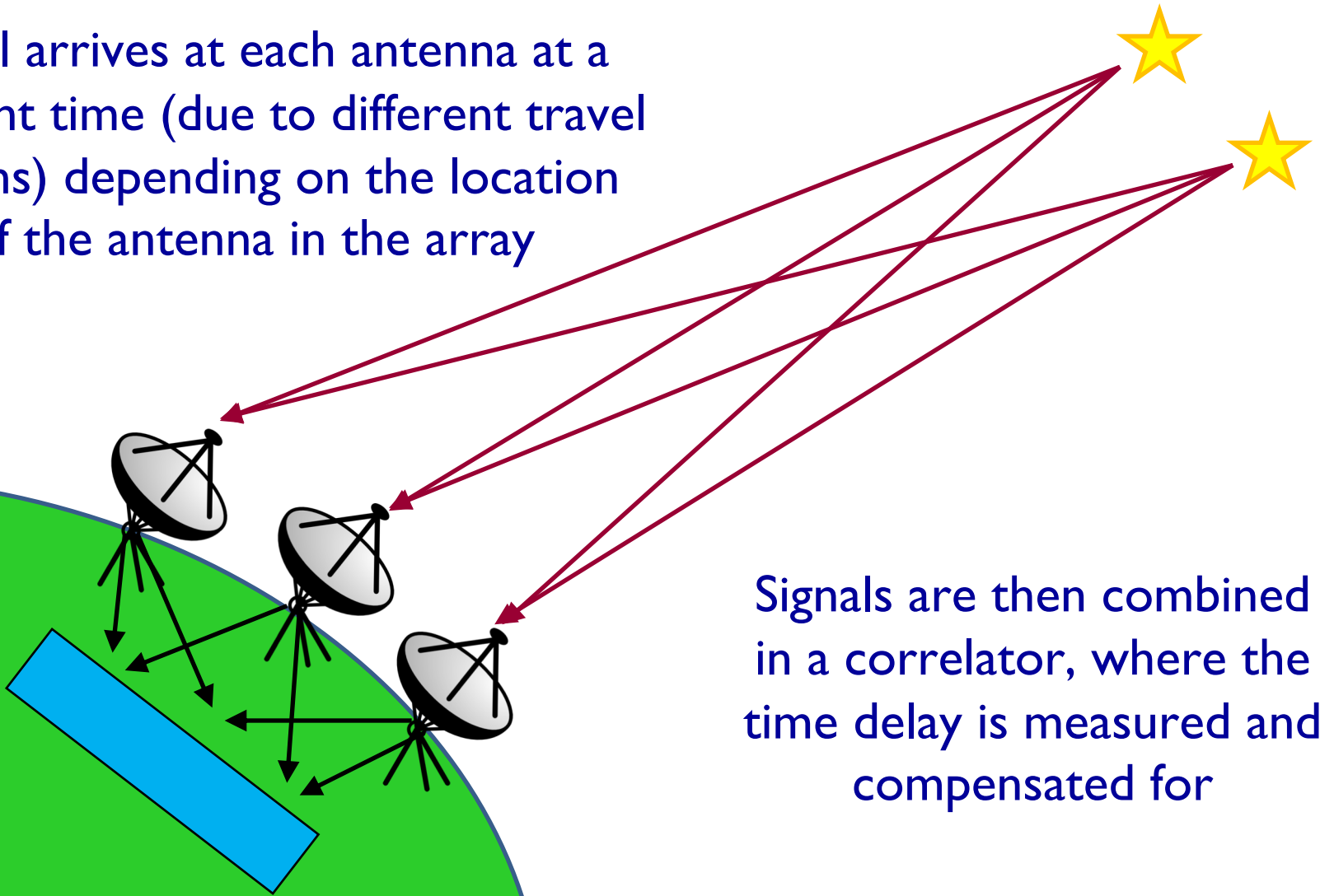
An *interferometer* measures the interference pattern produced by multiple apertures, much like a 2-slit experiment



However, the interference patterns measured by radio telescopes are produced by **multiplying - not adding - the wave signals measured at the different telescopes (i.e. apertures)*

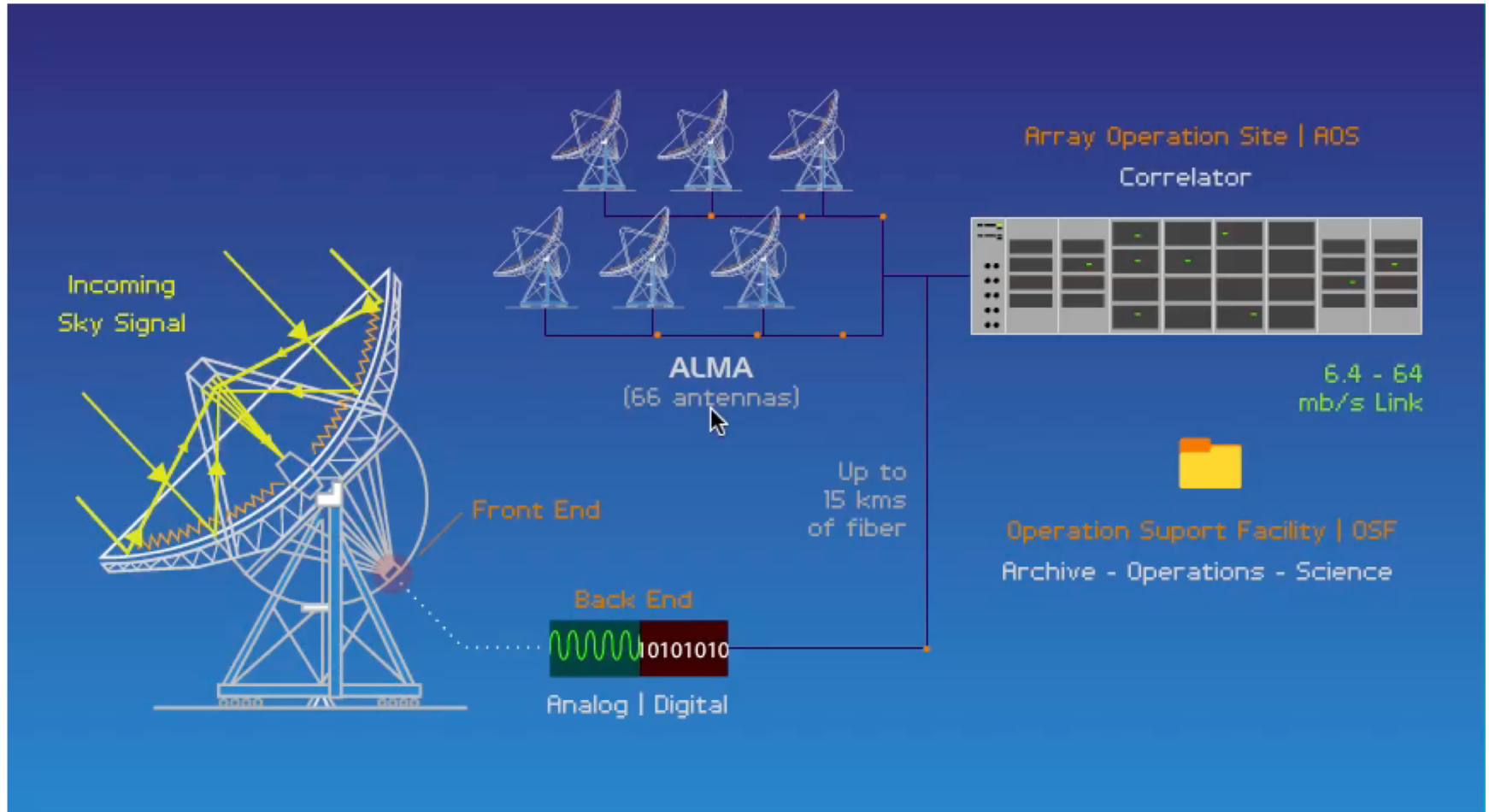
How Do We Use Interferometry?

Signal arrives at each antenna at a different time (due to different travel lengths) depending on the location of the antenna in the array



Signals are then combined in a correlator, where the time delay is measured and compensated for

An Interferometer In Action



Visibility and Sky Brightness

The van Cittert-Zernike theorem

Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)

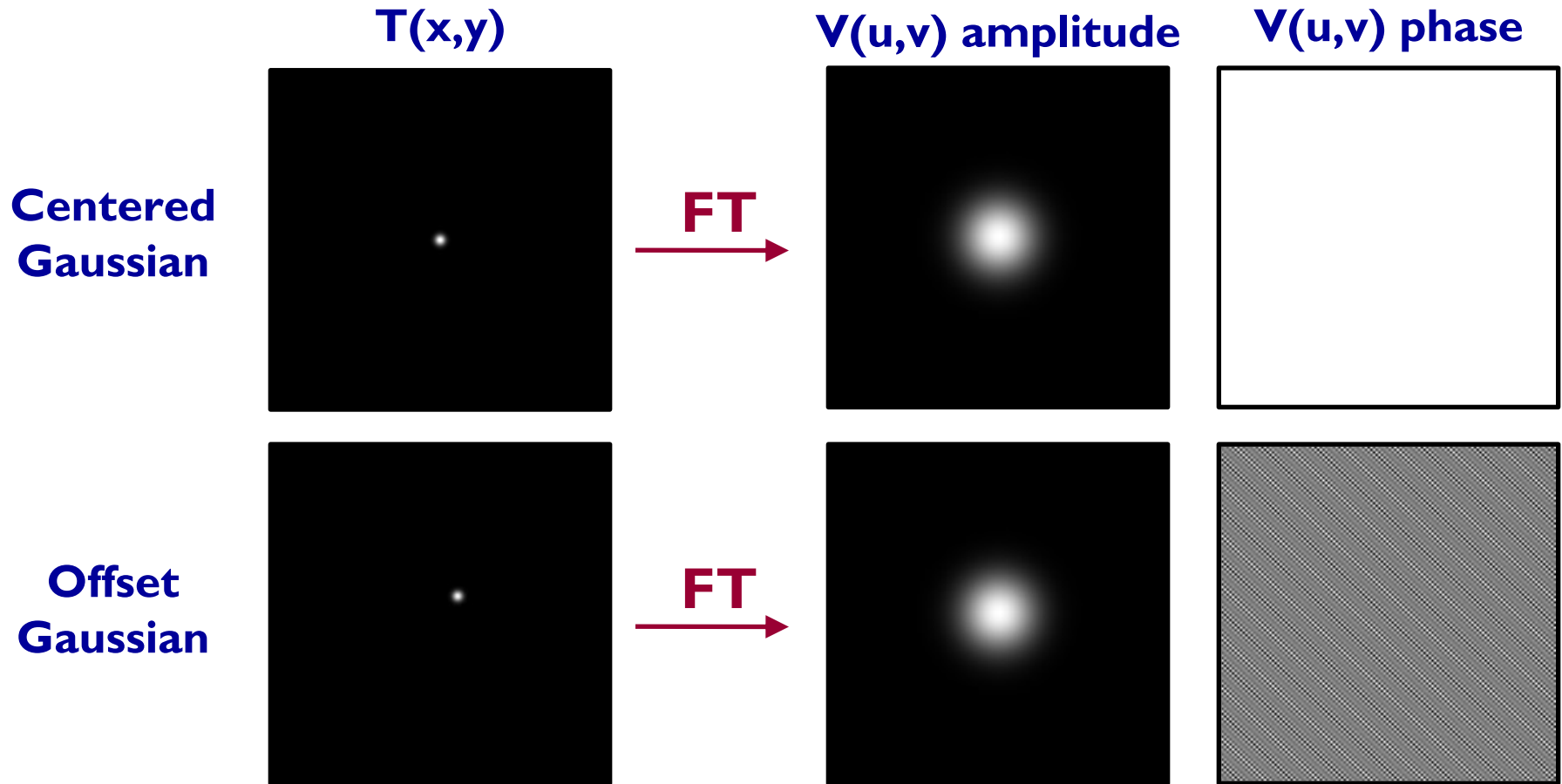
$$V(u, v) \xrightarrow{\text{FT}} T(x, y)$$

$$V(u, v) = \text{the complex visibility function} = \iint T(x, y) e^{2\pi i(ux+vy)} dx dy$$

$$T(x, y) = \text{the sky brightness distribution} = \iint V(u, v) e^{-2\pi i(ux+vy)} du dv$$



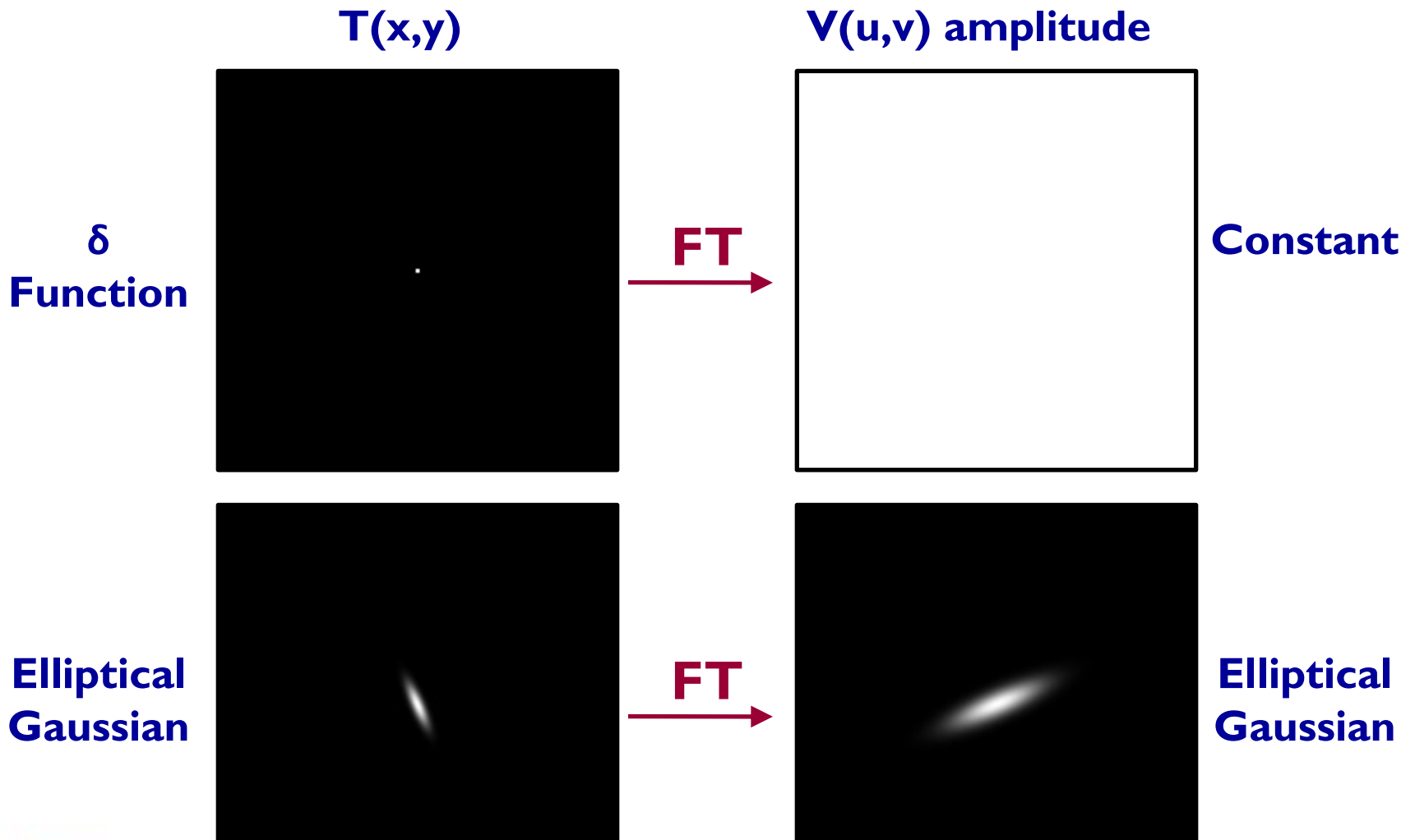
Examples of 2D Fourier Transforms



Rules of the Fourier Transform:

Amplitude tells you 'how much' of a spatial frequency
Phase tells you 'where' the spatial frequency is

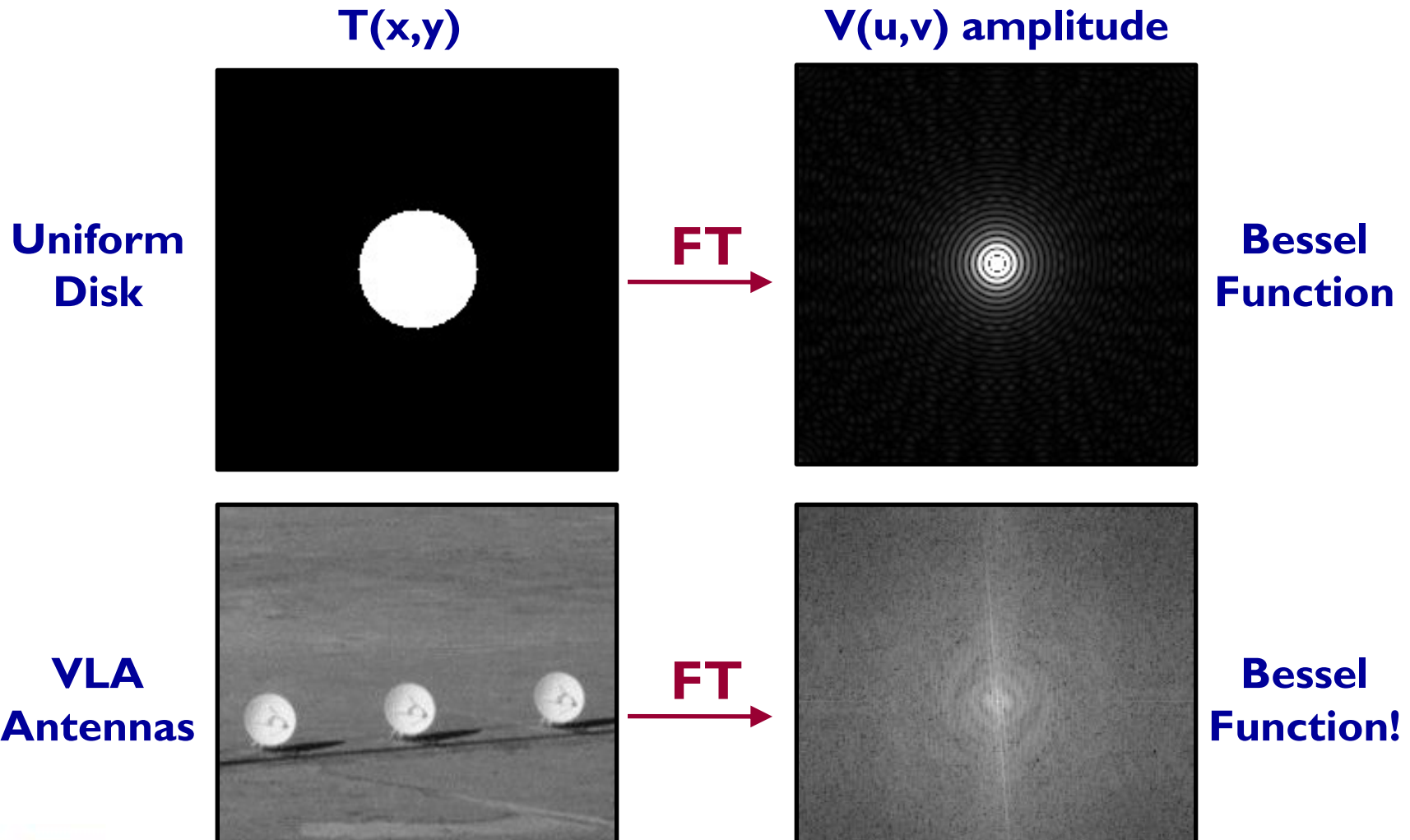
Examples of 2D Fourier Transforms



Rules of the Fourier Transform:

Narrow features transform to wide features (and vice versa)

Examples of 2D Fourier Transforms



Rules of the Fourier Transform:
Sharp features (edges) result in many high spatial features

What Are Visibilities?

Each $V(u,v)$ contains information on $T(x,y)$ everywhere

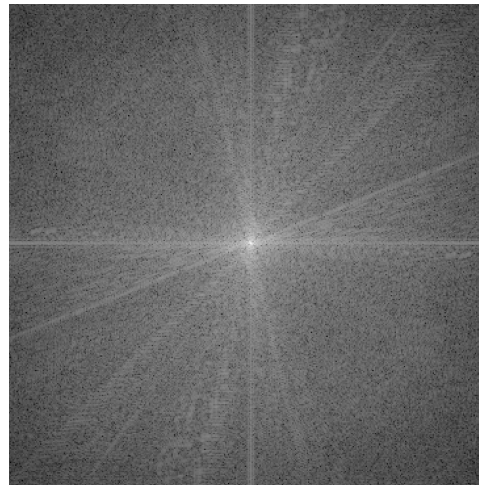
Each $V(u,v)$ is a complex quantity

Expressed as (real, imaginary) or (amplitude, phase)

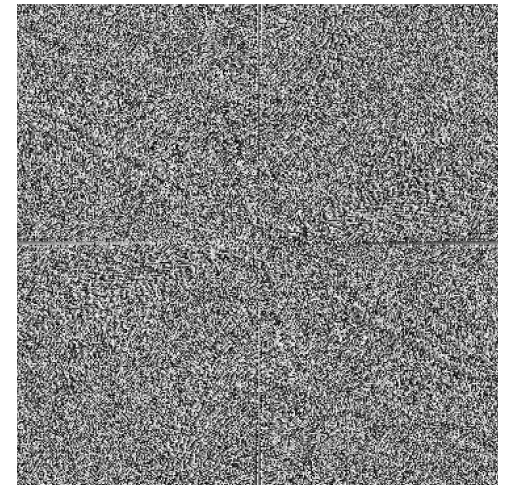


$T(x,y)$

FT
→



$V(u,v)$ amplitude



$V(u,v)$ phase

Visibility and Sky Brightness

The van Cittert-Zernike theorem

Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)

$$V(u, v) \xrightarrow{\text{FT}} T(x, y)$$

$$V(u, v) = \text{the complex visibility function} = \iint T(x, y) e^{2\pi i(ux+vy)} dx dy$$

THIS IS NOT A SMOOTH FUNCTION! DISCRETE SAMPLING OF FOURIER SPACE

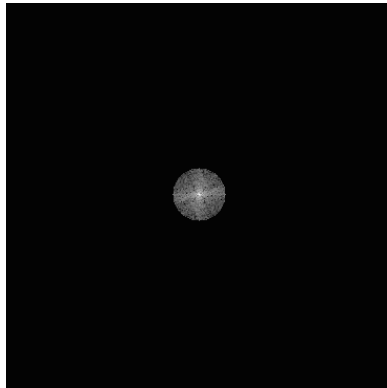
$$T(x, y) = \text{the sky brightness distribution} = \iint V(u, v) e^{-2\pi i(ux+vy)} du dv$$

Implications of (u,v) Coverage

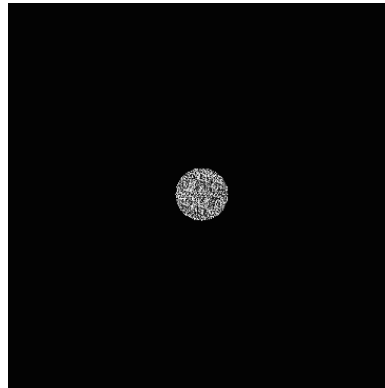
What does it mean if our (u,v) coverage is not complete?

Missing High
Spatial
Frequencies

$V(u,v)$ amplitude



$V(u,v)$ phase



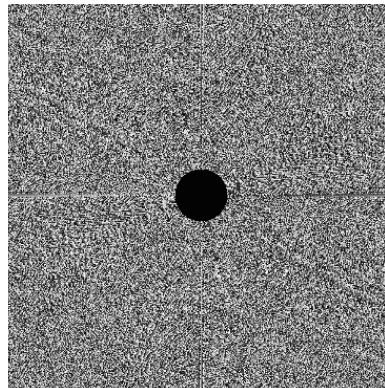
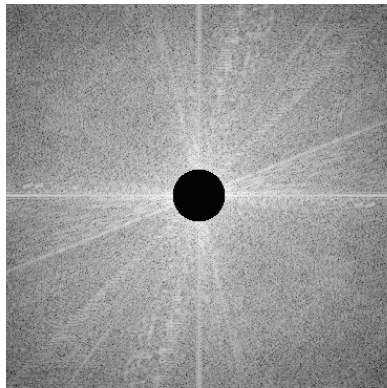
FT



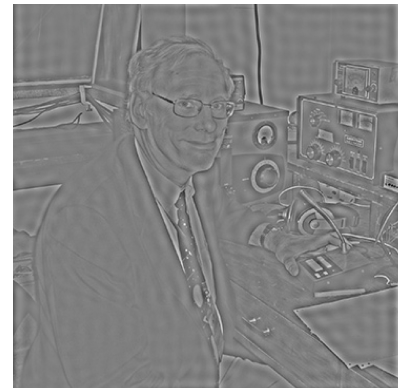
$T(x,y)$



Missing Low
Spatial
Frequencies



FT



Basics of Aperture Synthesis

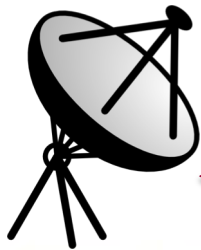
Idea: Sample $V(u,v)$ at an enough (u,v) points using distributed small aperture antennas to synthesize a large aperture antenna of size (u_{\max}, v_{\max})

One pair of antennas = one baseline

For **N** antennas, we get **$N(N-1)$** samples at a time

How do we fill in the rest of the (u,v) plane?

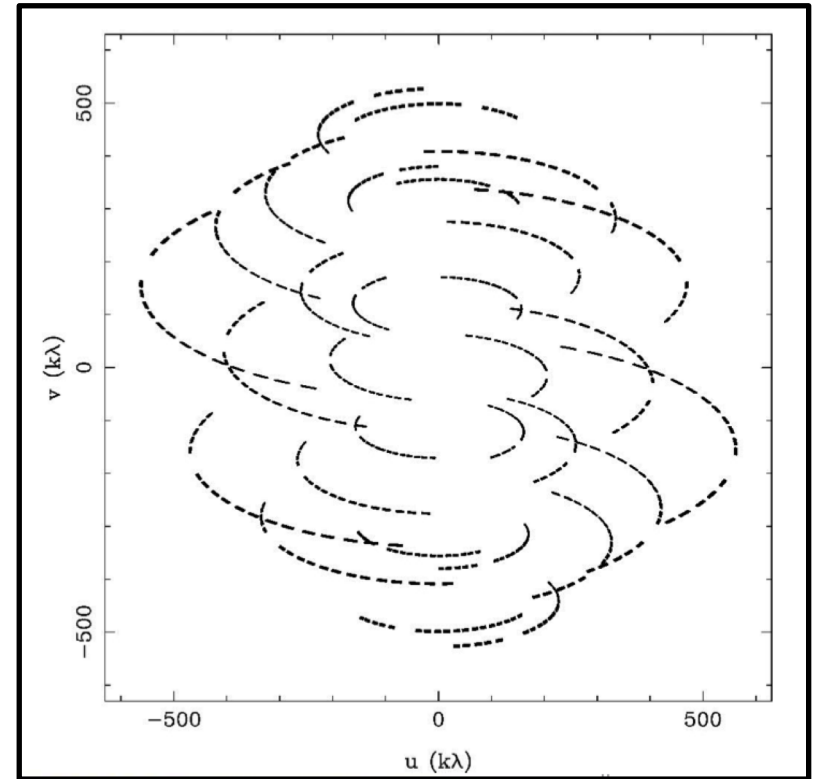
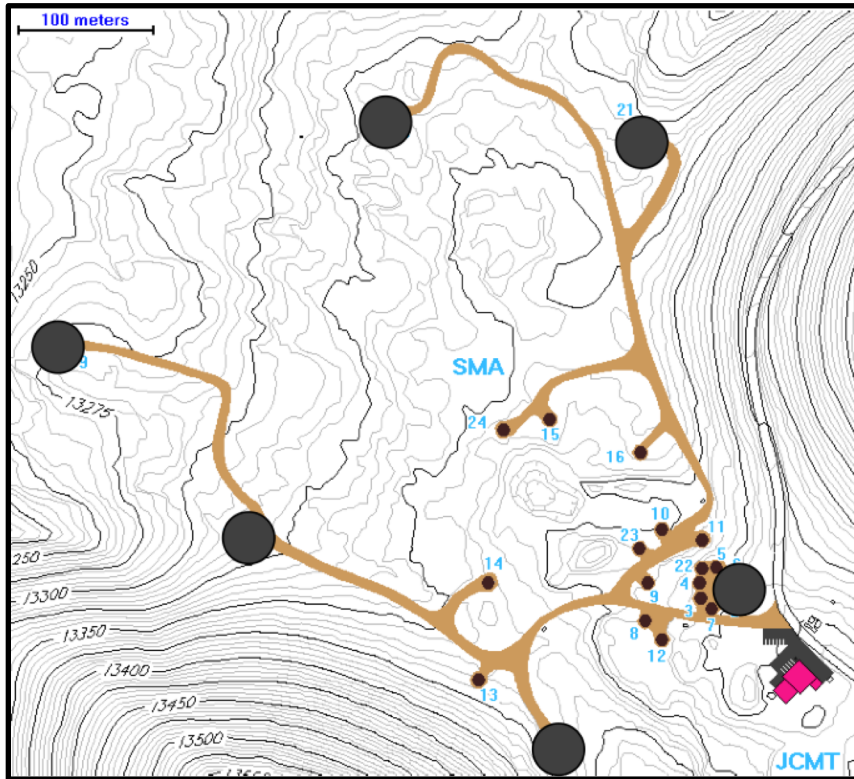
1. Earth's rotation
2. Reconfigure physical layout of N antennas



One baseline = 2 (u,v) points



(u,v) Plane Sampling

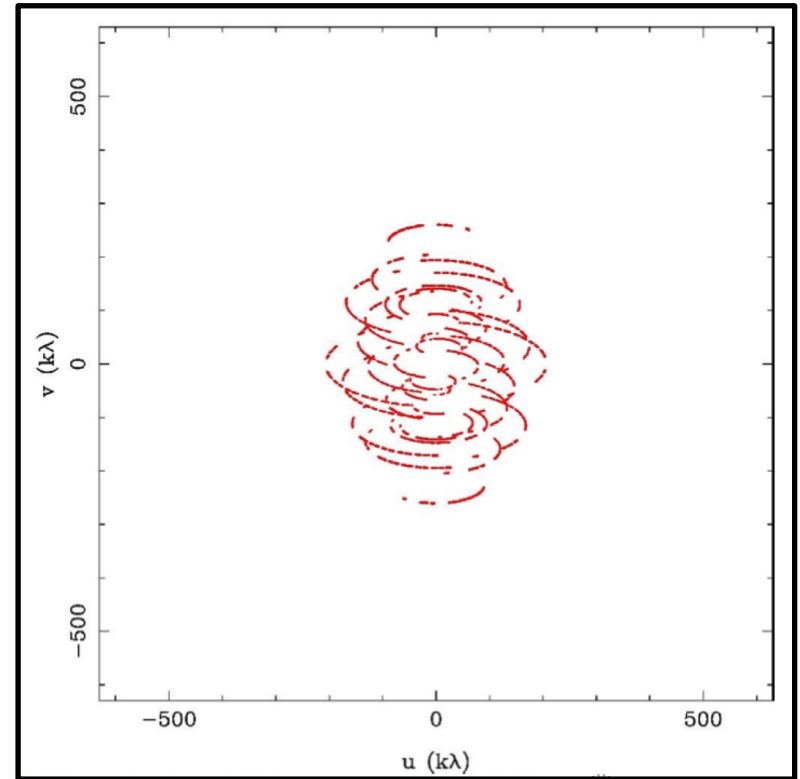
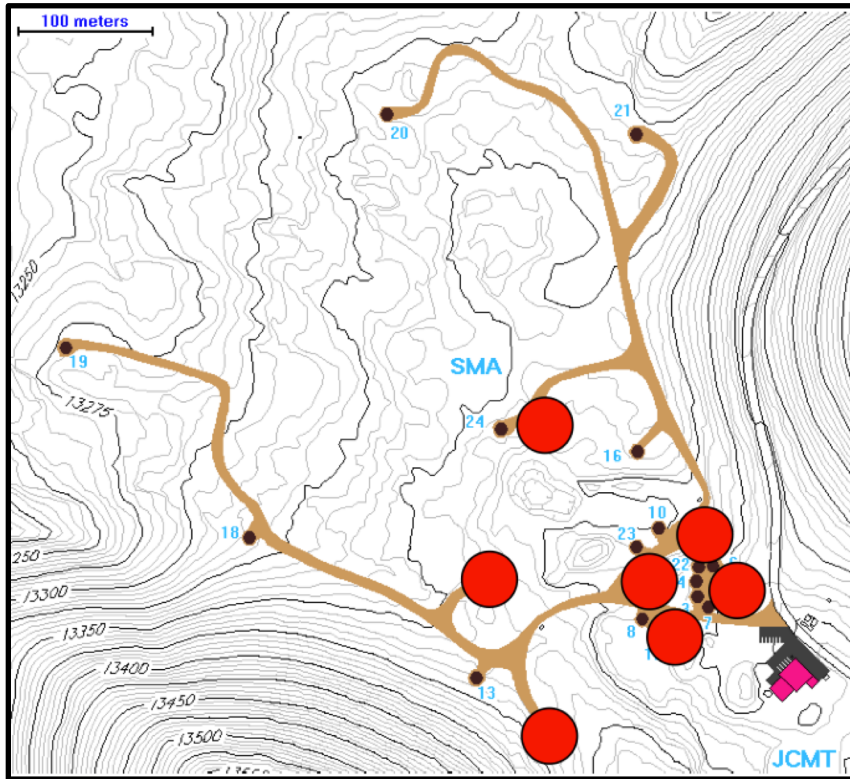


Very Extended SMA configuration

(most extended baselines)

345 GHz, DEC = +22

(u,v) Plane Sampling

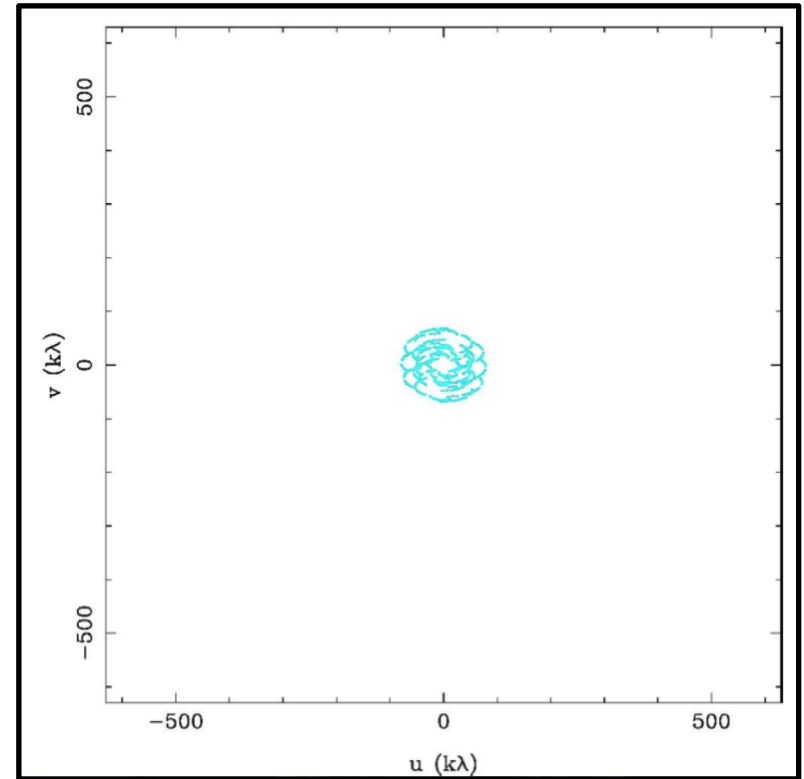
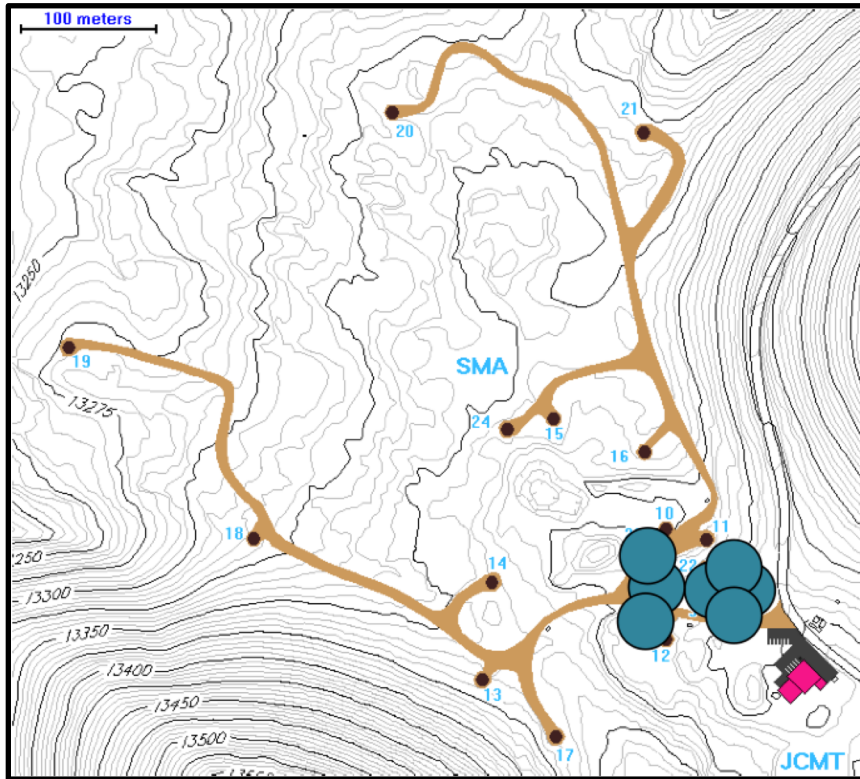


Extended SMA configuration

(extended baselines)

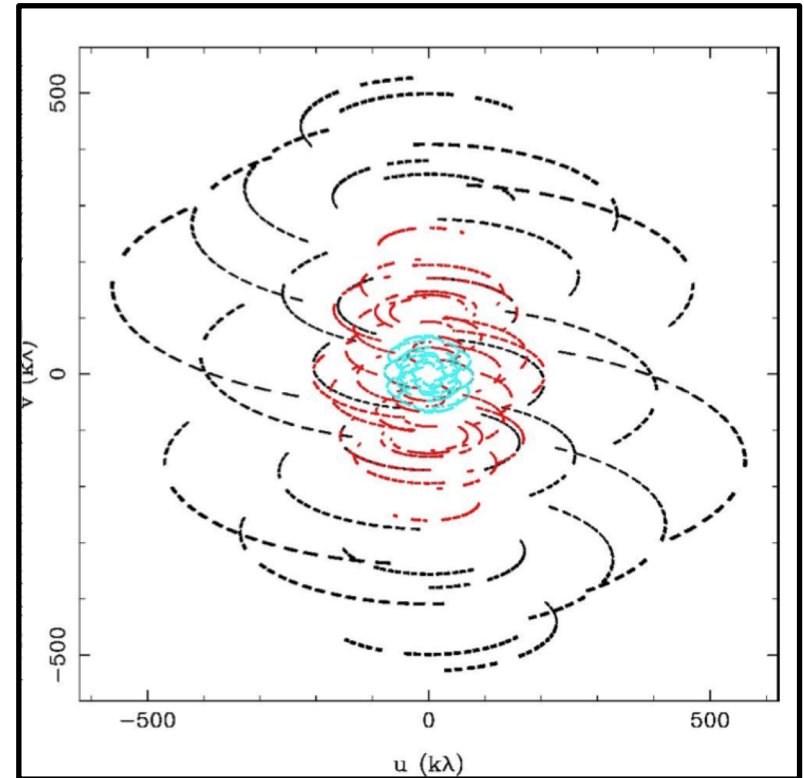
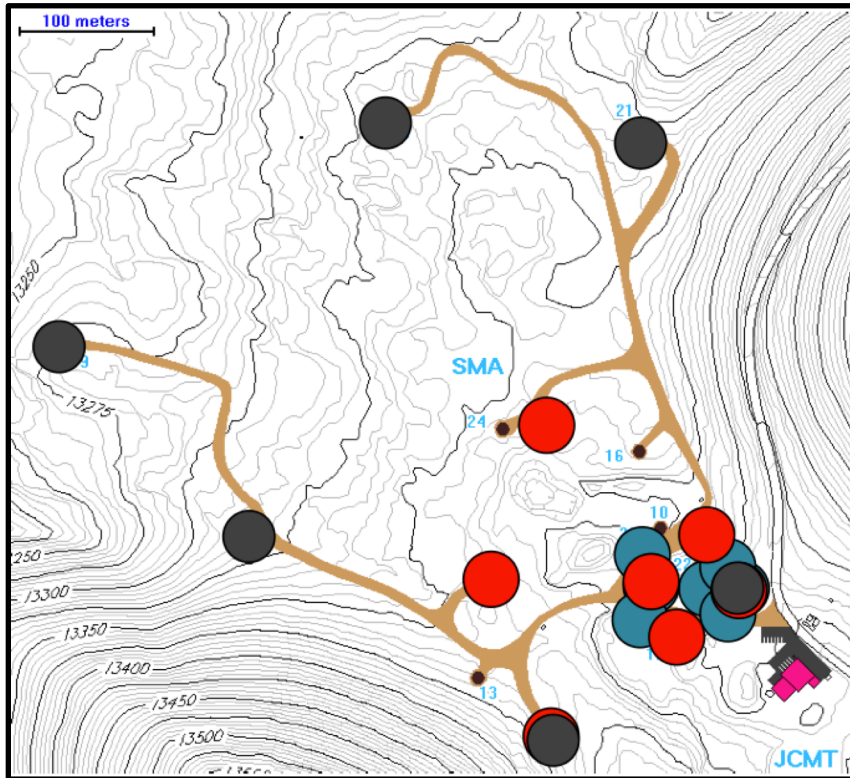
345 GHz, DEC = +22

(u,v) Plane Sampling



Compact SMA configuration
(compact baselines)
345 GHz, DEC = +22

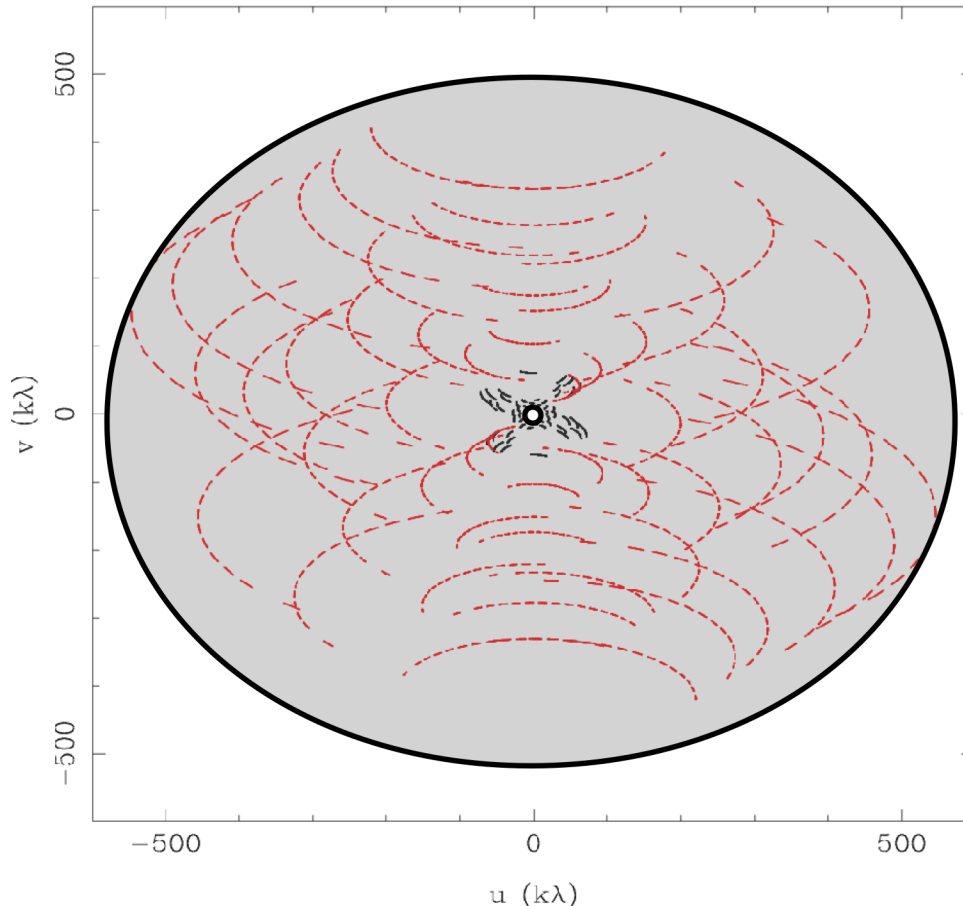
(u,v) Plane Sampling



Combine multiple configurations to get the most complete coverage of the (u,v) plane

(u,v) Plane Sampling

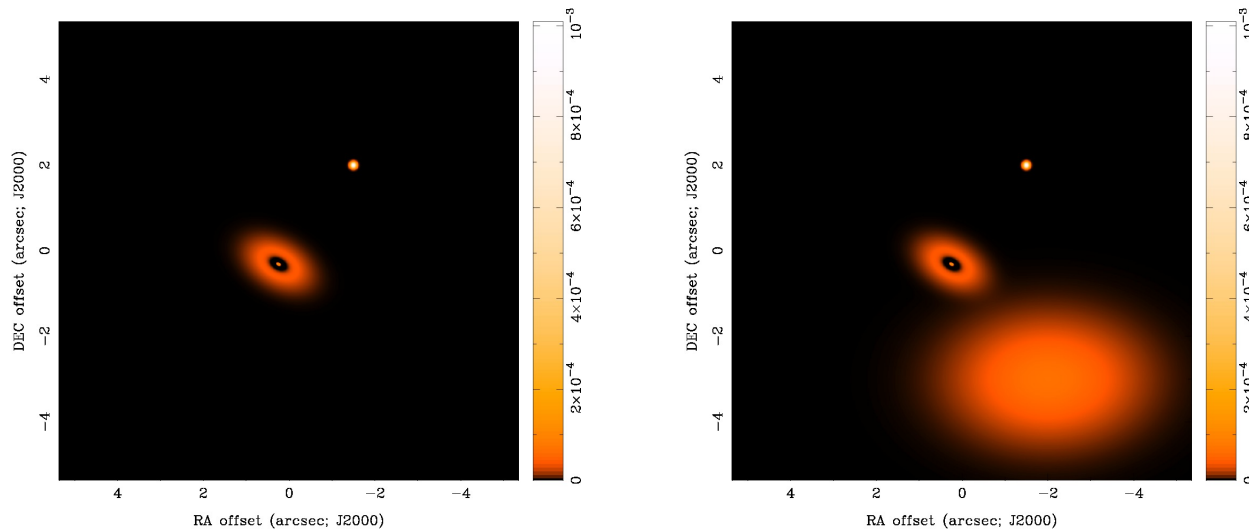
- in aperture synthesis, $V(u,v)$ samples are limited by number of telescopes, and Earth-sky geometry



- high spatial frequencies
 - maximum angular resolution
- low spatial frequencies
 - extended structures invisible
- irregular within high/low limits
 - sampling theorem violated
 - information missing

Remember: Important structure may be missed in central hole of (u,v) coverage

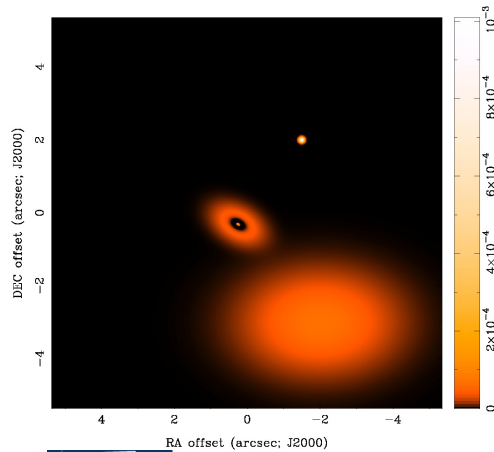
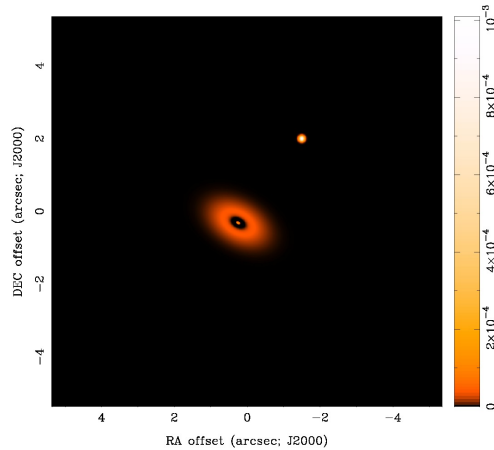
- Do the visibilities observed in our example discriminate between these two models of the sky brightness distribution $T(l,m)$?



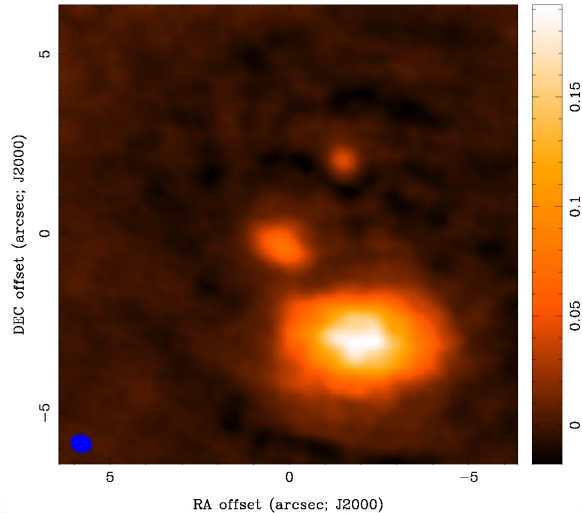
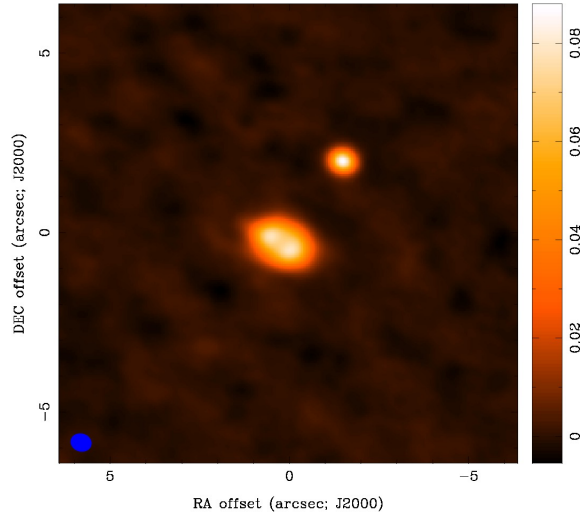
- Yes... but only on baselines shorter than about $75 \text{ k}\lambda$

Missing Short Spacings: Demonstration

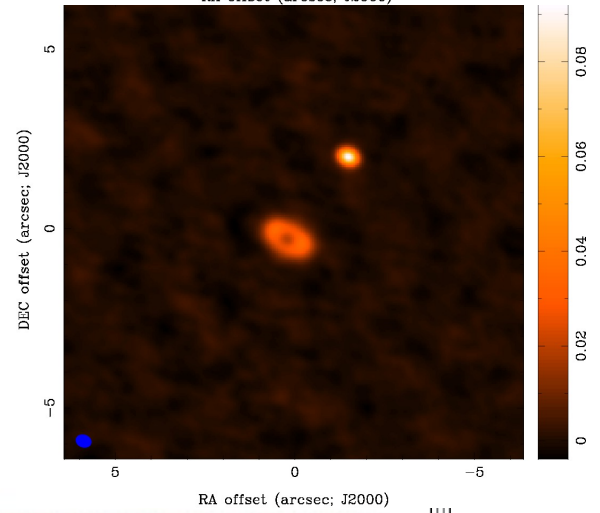
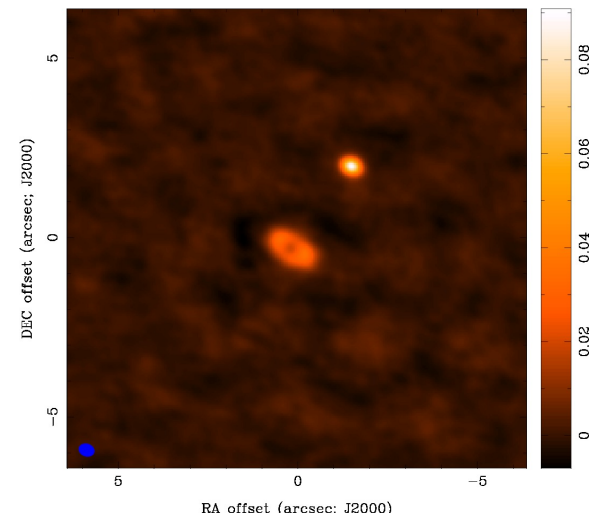
Sky Model



Full range of spatial scales



cutting out a central hole



Angular Scales — A Proposal Tip!

Interferometers act as spatial filters - shorter baselines are sensitive to larger targets, so remember ...

Spatial scales larger than the smallest baseline cannot be imaged

Spatial scales smaller than the largest baseline cannot be resolved

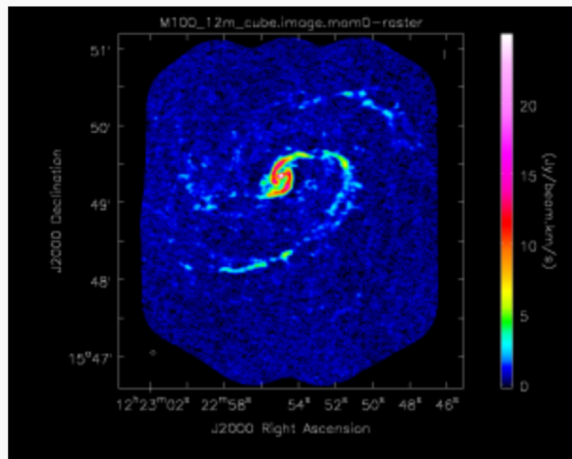
Config	Lmax		Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin		100 GHz	150 GHz	185 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m	45 m	AR	12.5"	8.4"	6.8"	5.5"	3.6"	2.7"	1.9"	1.4"
	9 m	MRS	66.7"	44.5"	36.1"	29.0"	19.3"	14.5"	10.3"	7.7"
C-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	28.5"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C-6	2.5 km	AR	0.31"	0.20"	0.17"	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"	2.2"	1.8"	1.2"	0.89"	0.63"	0.47"
C-7	3.6 km	AR	0.21"	0.14"	0.11"	0.092"	0.061"	0.046"	0.033"	0.024"
	64 m	MRS	2.6"	1.7"	1.4"	1.1"	0.75"	0.56"	0.40"	0.30"
C-8	8.5 km	AR	0.096"	0.064"	0.052"	0.042"	0.028"	N/A	N/A	N/A
	110 m	MRS	1.4"	0.95"	0.77"	0.62"	0.41"			



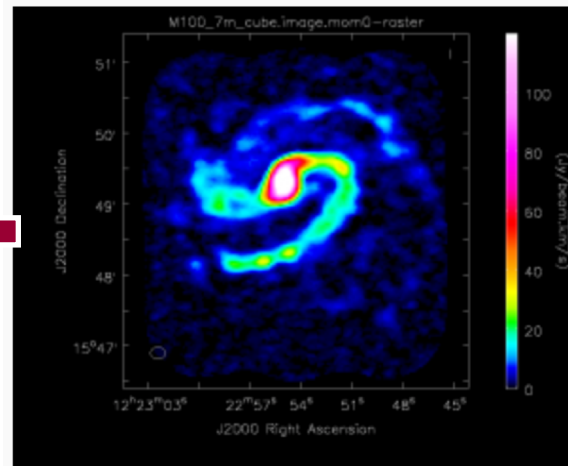
From the ALMA Cycle 8 Proposal Guide

Characteristic Angular Scales: M100

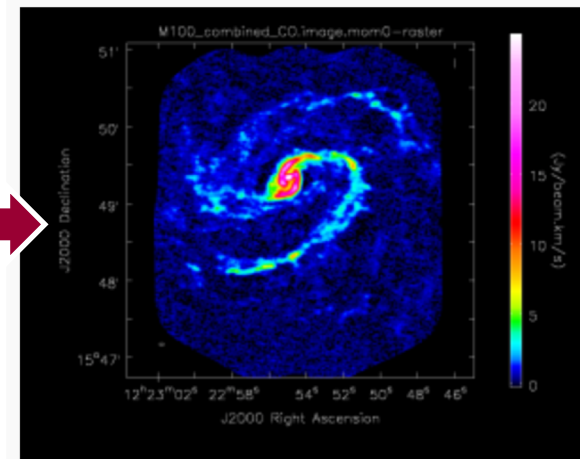
ALMA 12m



ACA 7m



Combined



ALMA 12m shows smaller spatial scales (denser, clumpier emission)
ACA 7m data shows larger spatial scales (diffuse, extended emission)

To get both — you need a combined image!

Interferometry: Spatial Scales

- The **sensitivity** is given by the number of antennas times their area
- The **field of view** is given by the beam of a single antenna (corresponding to the resolution for a single dish telescope or the primary beam)
- The **resolution** is given by the largest distance between antennas (called the synthesized beam)
- The **largest angular scale** that can be imaged is given by the shortest distance between antennas

Characteristic Angular Scales

Angular resolution of telescope array:

$$\sim \lambda/B_{\max} \text{ (} B_{\max} = \text{longest baseline)}$$

Maximum angular scale:

$$\sim \lambda/B_{\min} \text{ (} B_{\min} = \text{shortest distance between antennas)}$$

Field of view (FOV):

$$\sim \lambda/D \text{ (} D = \text{antenna diameter)}$$

*Sources more extended than the FOV can be observed using multiple pointing centers in a mosaic

An interferometer is sensitive to a range of angular sizes: $\lambda/B_{\max} < \theta < \lambda/B_{\min}$

Configuration Combinations

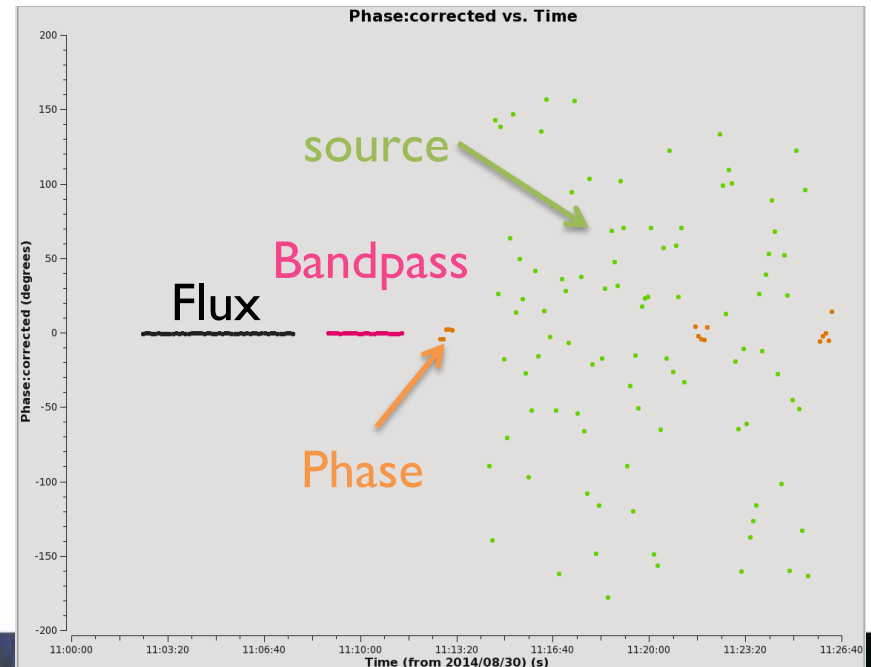
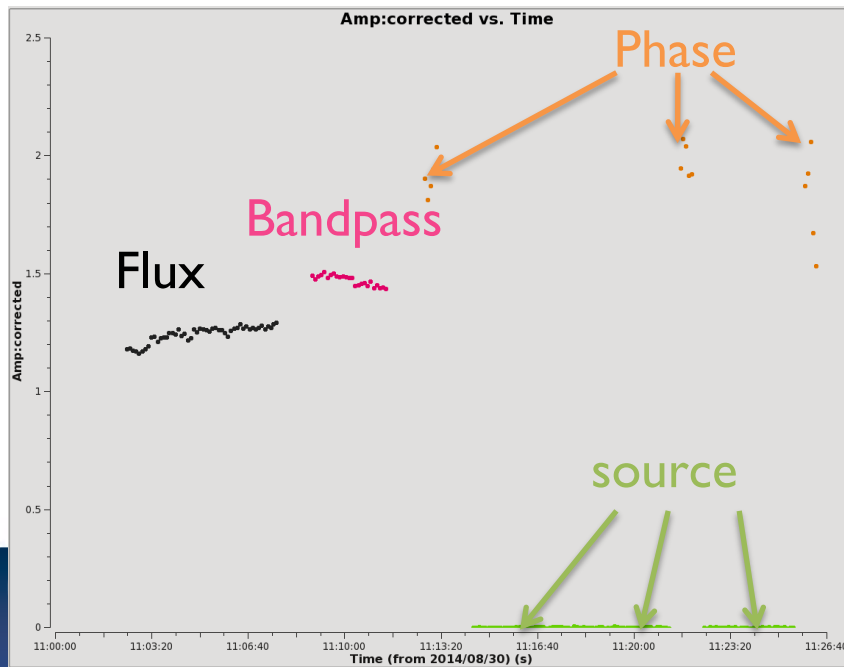
(The need for the ACA and TP)

Table A-2: Allowed Array Combinations and Time Multipliers

Most Extended configuration	Allowed Compact configuration pairings	Extended 12-m Array Multiplier	Multiplier if compact 12-m Array needed	Multiplier if 7-m Array needed	Multiplier if TP Array needed and allowed
7-m Array	TP			1	1.7
C-1	7-m Array & TP	1		7.0	11.9
C-2	7-m Array & TP	1		4.7	7.9
C-3	7-m Array & TP	1		2.4	4.1
C-4	C-1 & 7-m Array & TP	1	0.34	2.4	4.0
C-5	C-2 & 7-m Array & TP	1	0.26	1.2	2.1
C-6	C-3 & 7-m Array & TP	1	0.25	0.6	1.0
C-7	C-4	1	0.23		
C-8	C-5	1	0.22		

A Brief Word on Calibration

- Interferometers measure visibilities, i.e., the amplitude and phase of the cross-correlated signals between pairs of antennas, as a function of time and frequency.
- We calibrate these data by determining the complex gains (amplitude and phase), the frequency response (bandpass) and flux scale for each antenna.



A Brief Word on Calibration

Calibration requirements (Handled by ALMA):

Gain calibrator

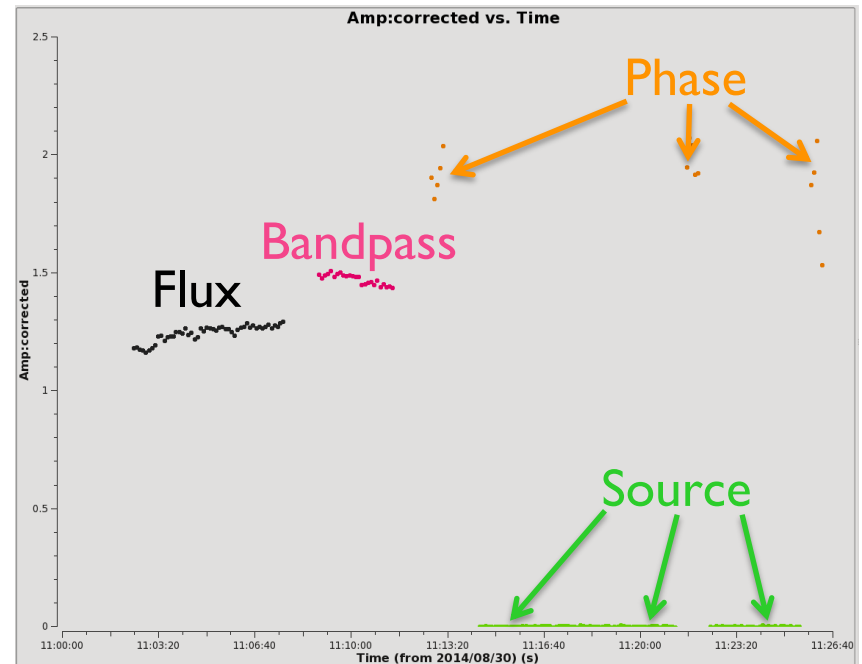
Bright quasar near science target
Solves for atmospheric and
instrumental variations with time

Bandpass calibrator

Bright quasar
Fixes instrumental effects and
variations vs frequency

Absolute flux calibrator

Solar system object or quasar
Used to scale relative amplitudes
to absolute value



Visibility and Sky Brightness

The van Cittert-Zernike theorem

Visibility as a function of baseline coordinates (u,v) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates (x,y)

$$V(u, v) \xrightarrow{\text{FT}} T(x, y)$$

$$V(u, v) = \text{the complex visibility function} = \iint T(x, y) e^{2\pi i(ux+vy)} dx dy$$

THIS IS NOT A SMOOTH FUNCTION! DISCRETE SAMPLING OF FOURIER SPACE

$$T(x, y) = \text{the sky brightness distribution} = \iint V(u, v) e^{-2\pi i(ux+vy)} du dv$$

Imaging Your ALMA Data

Dirty beams, dirty images, and how to “clean” them.

We want to do science on $T(x,y)$, the sky brightness distribution, but we measure $V(u,v)$, the complex visibility function.

In principle: $T(x,y) = \iint V(u,v) e^{-2\pi i(ux+vy)} du dv$

With incomplete u,v coverage you create an ‘incomplete’ image. This is called the “dirty image”, $T_D(x,y)$

In practice:

$$- T_D(x,y) = \iint V(u,v) S(u,v) W(u,v) e^{-2\pi i(ux+vy)} du dv$$

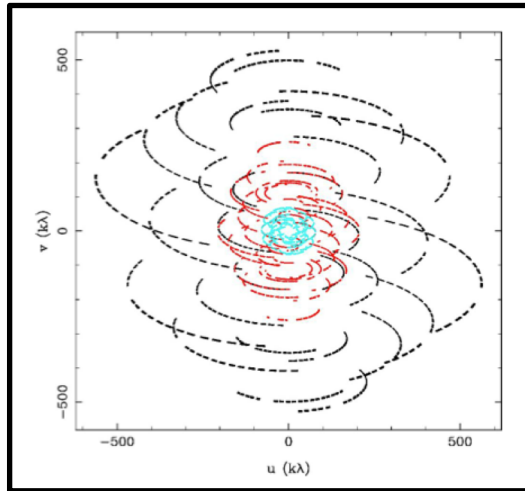
$S(u,v)$ – Sampling Function (1 where we have u,v coverage, 0 elsewhere)
(determined by array configuration and exposure time)

$W(u,v)$ - Weighting function (e.g., Natural, Uniform, Robust)



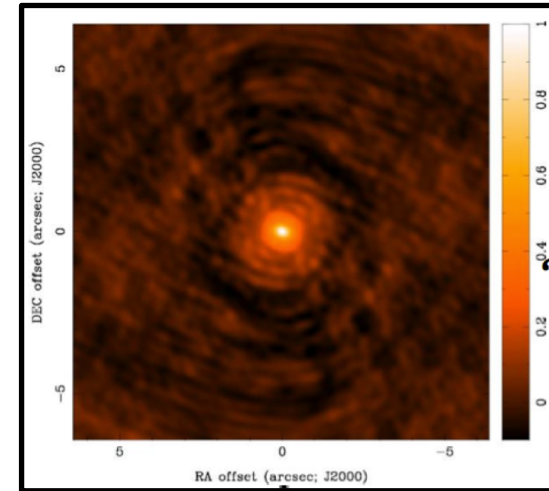
The Dirty Beam

$S(u,v)$

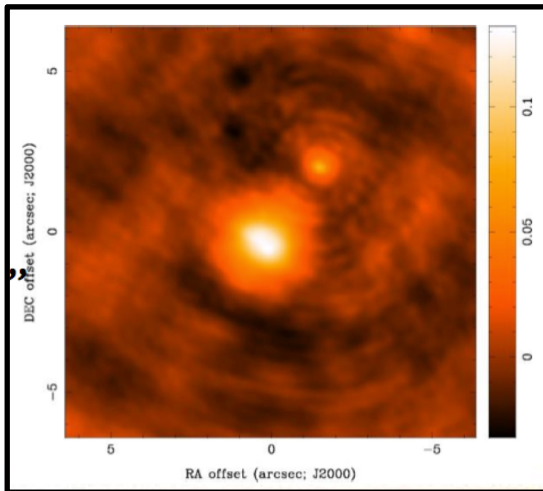


FT
→

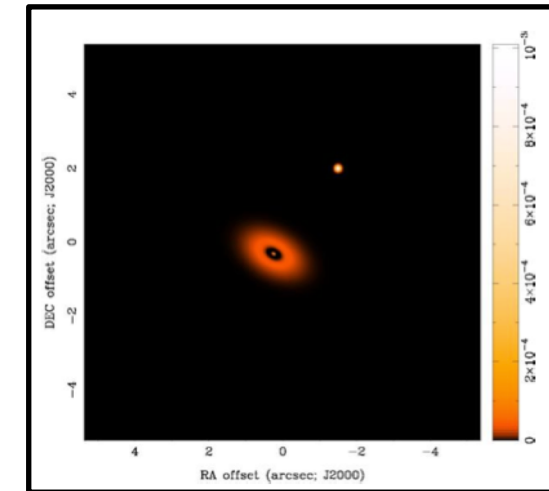
$s(x,y)$
“Dirty Beam”



* (Convolution)



←



$T_D(x,y)$
“Dirty Image”

$T(x,y)$

Imaging Your ALMA Data

Dirty beams, dirty images, and how to “clean” them.

Result!

Obtain $T(x,y)$ by deconvolving the dirty image, $T_D(x,y)$, with the dirty beam, $B(x,y)$!

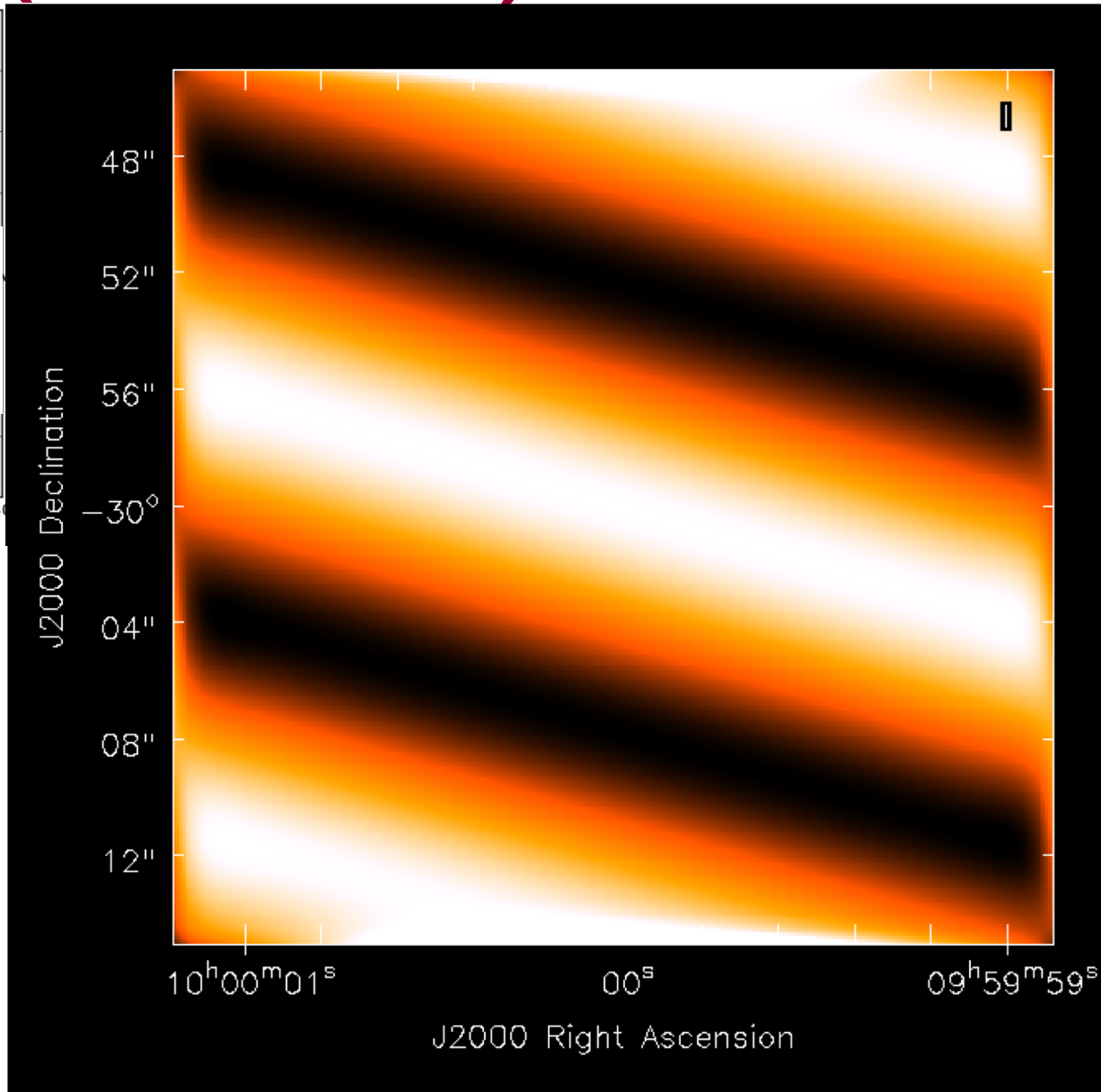
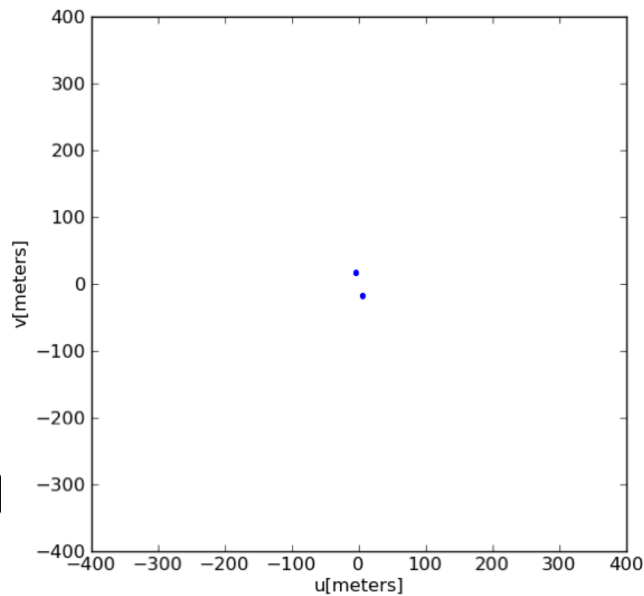
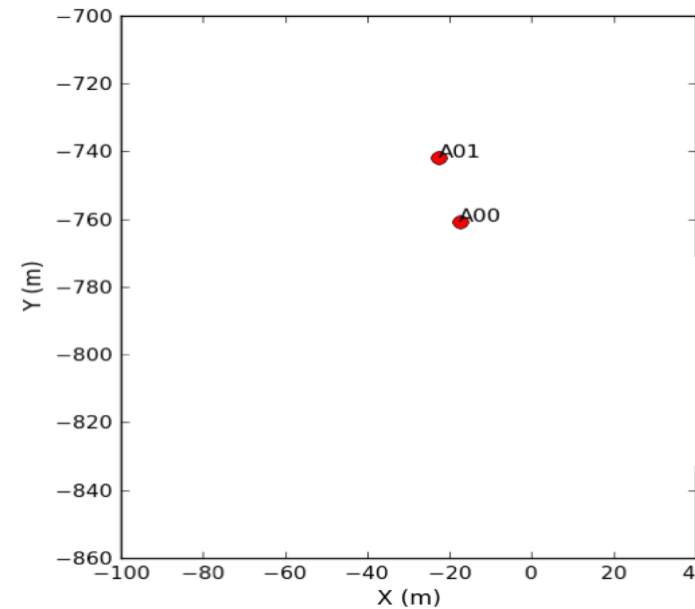
Not so fast

- There is no unique solution! There exist an infinite number of $T(x,y)$ that are compatible with $V(x,y)$

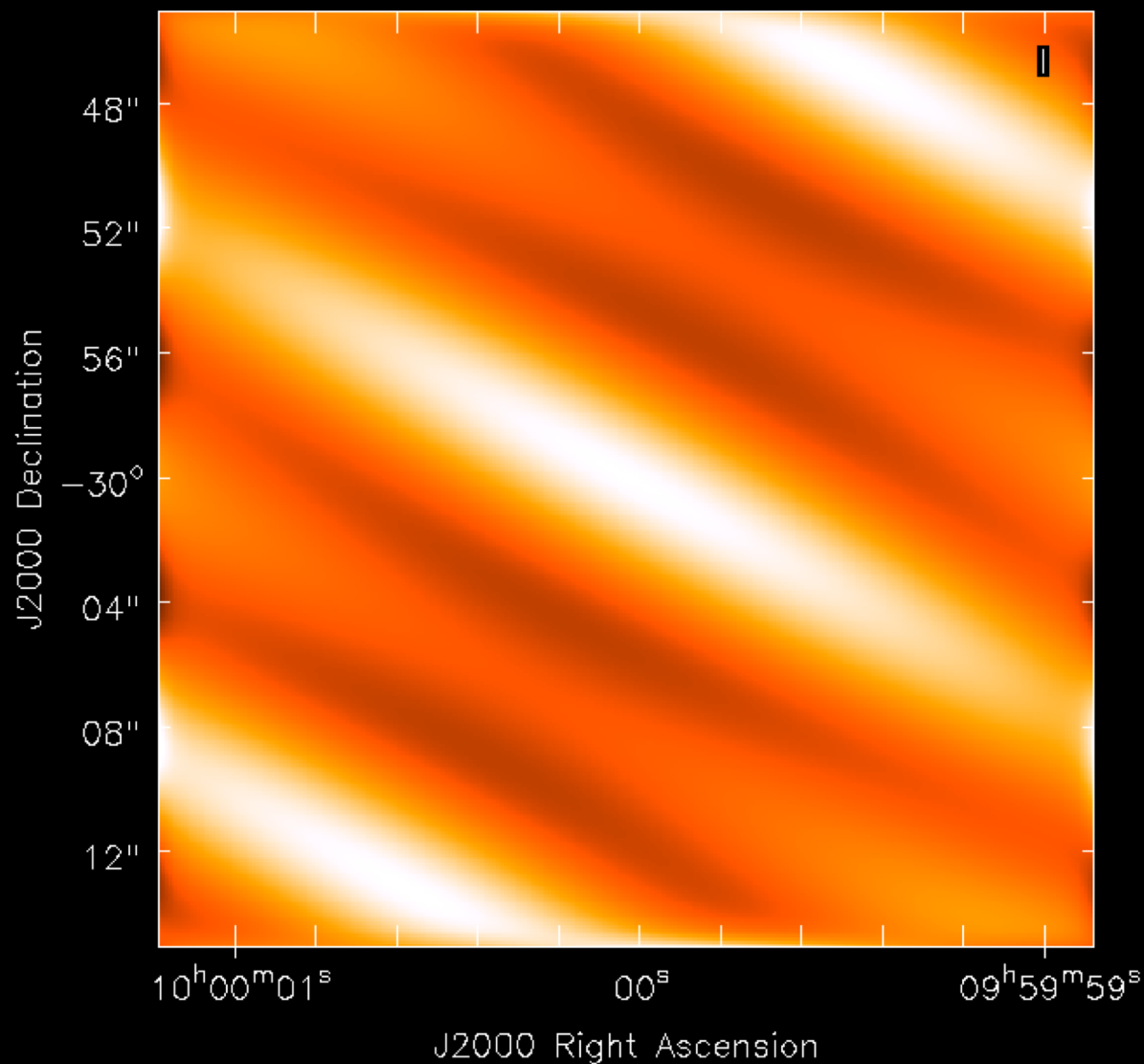
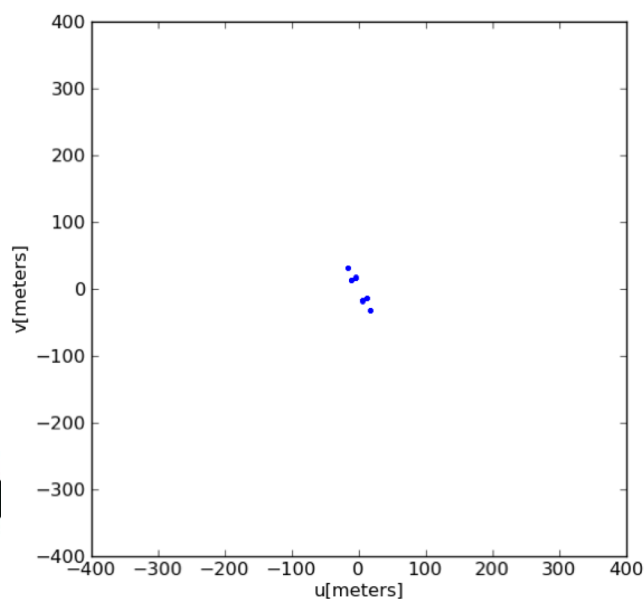
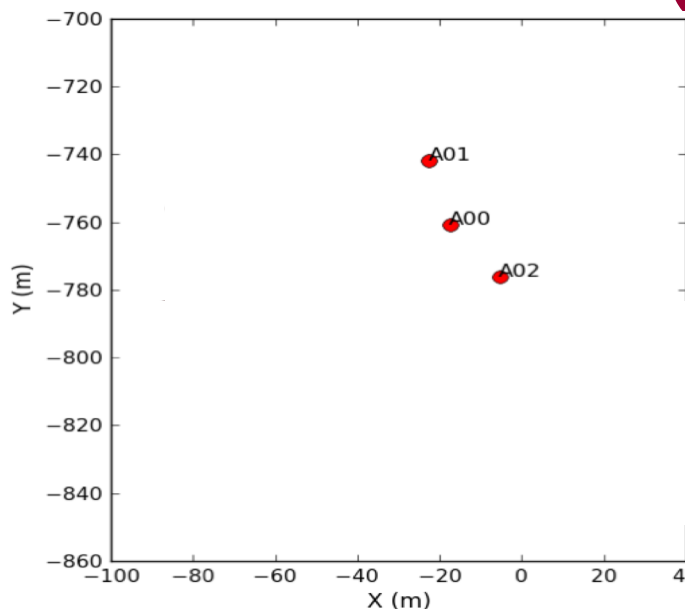
Goal of the Deconvolution:

- Find a sensible model of $T(x,y)$ using a priori assumptions about $T(x,y)$

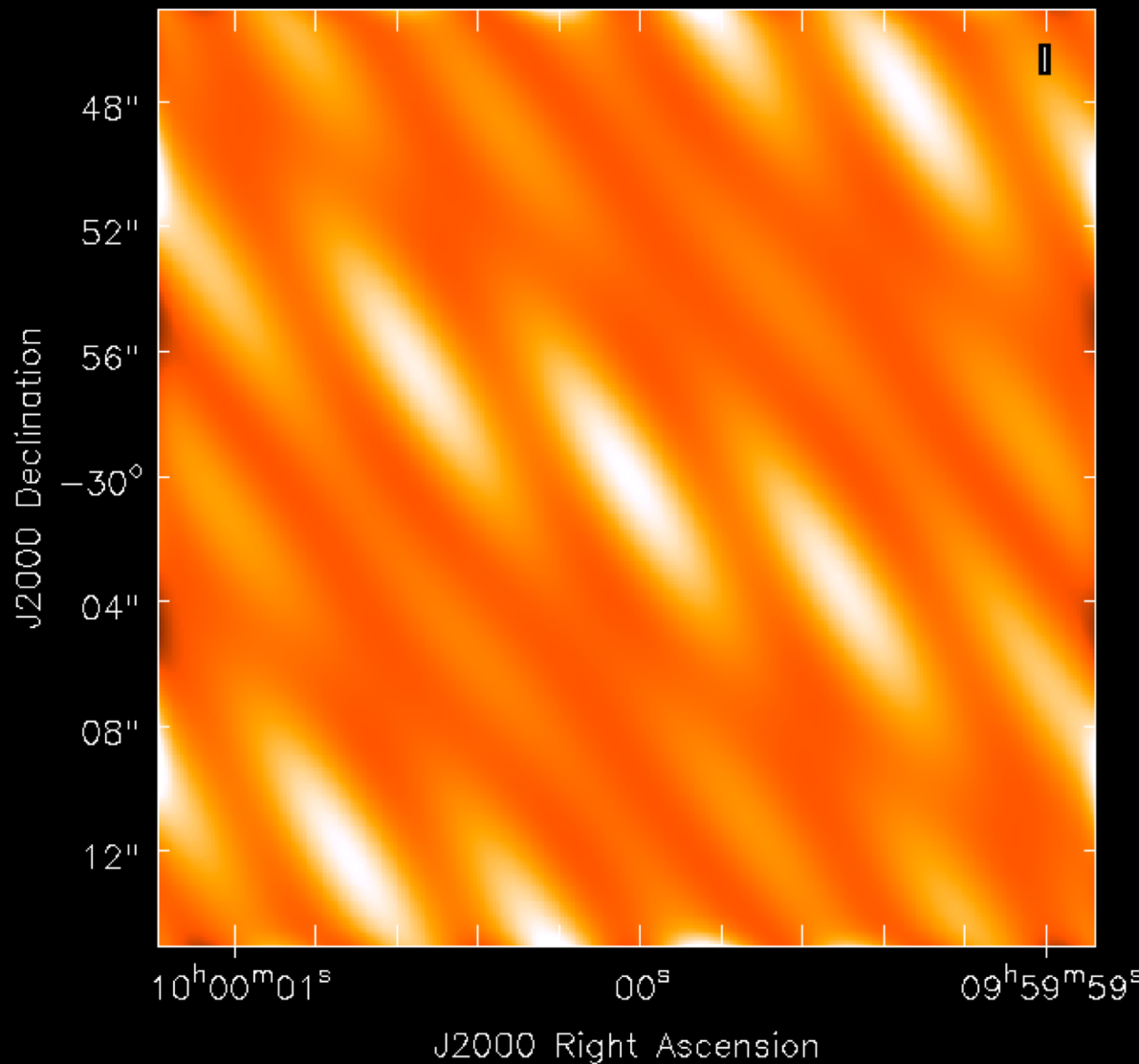
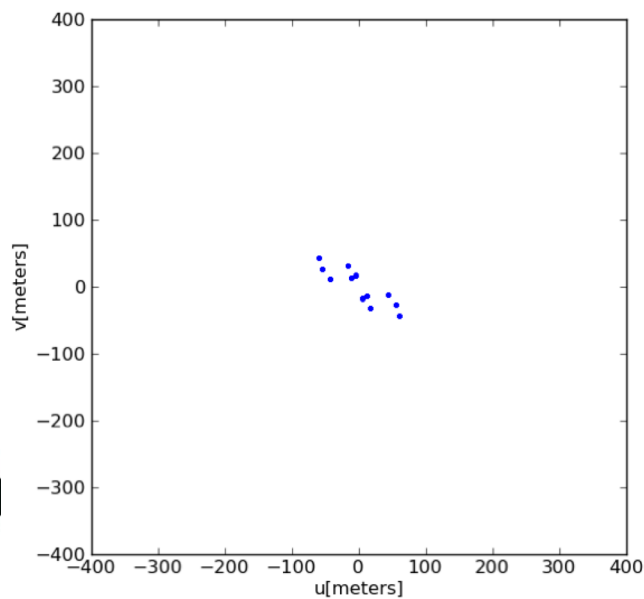
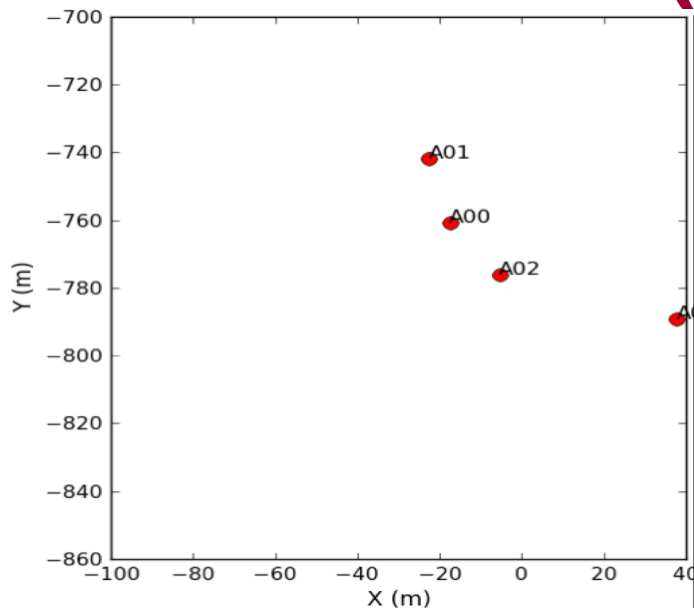
Example: Fringe pattern with 2 Antennas (one baseline)



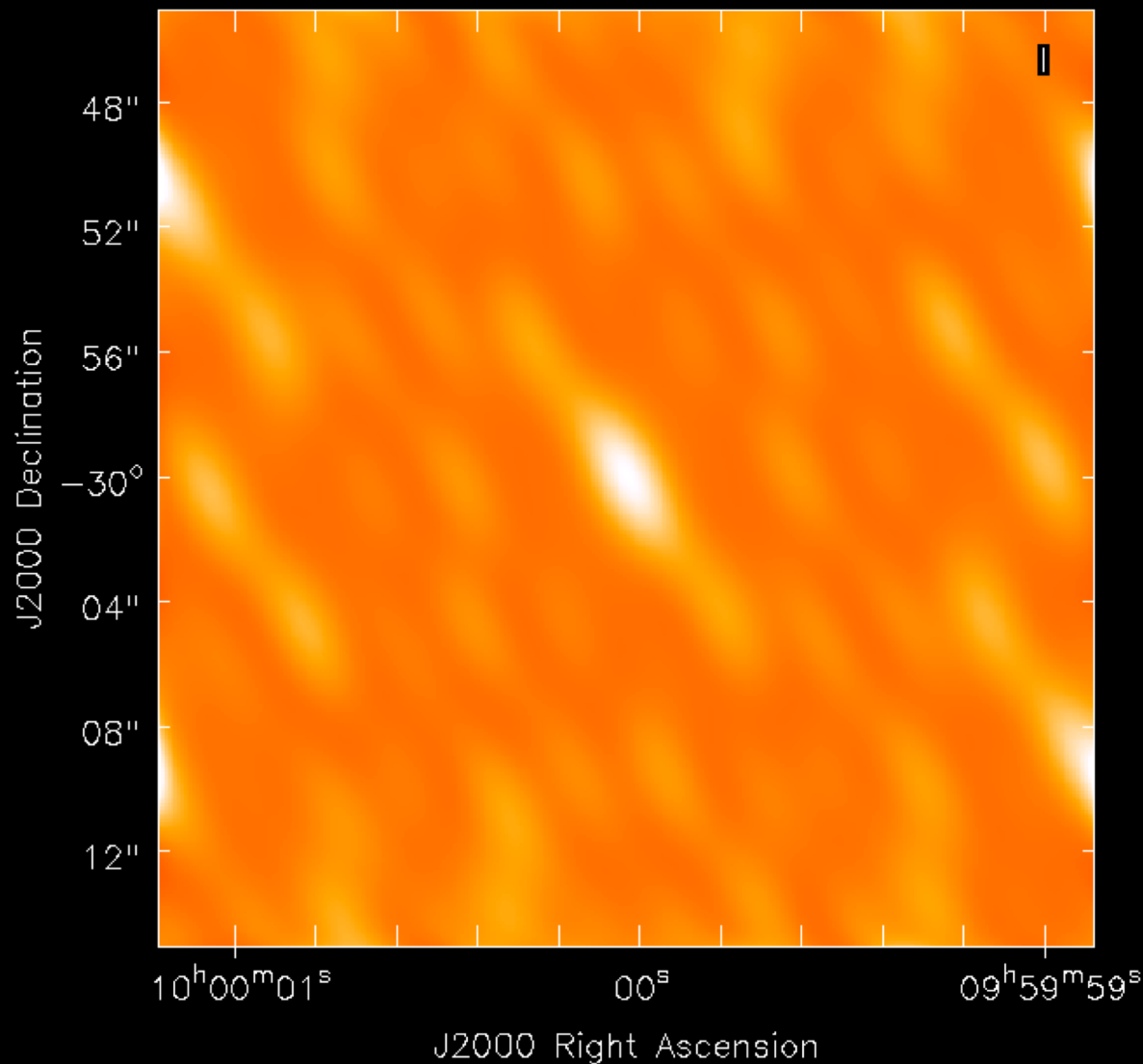
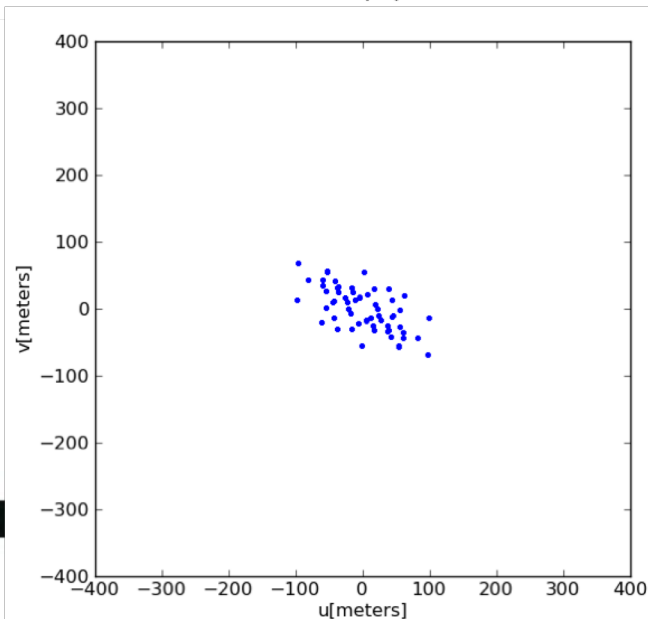
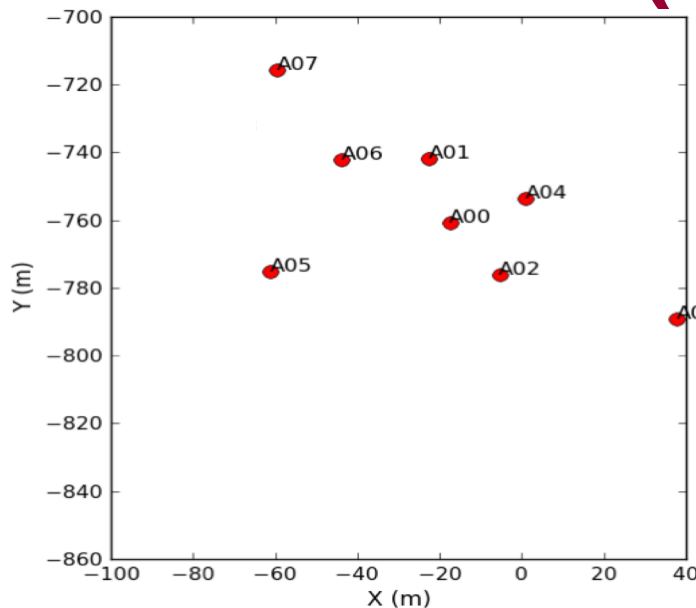
Example: Fringe pattern with 3 Antennas (3 baselines)



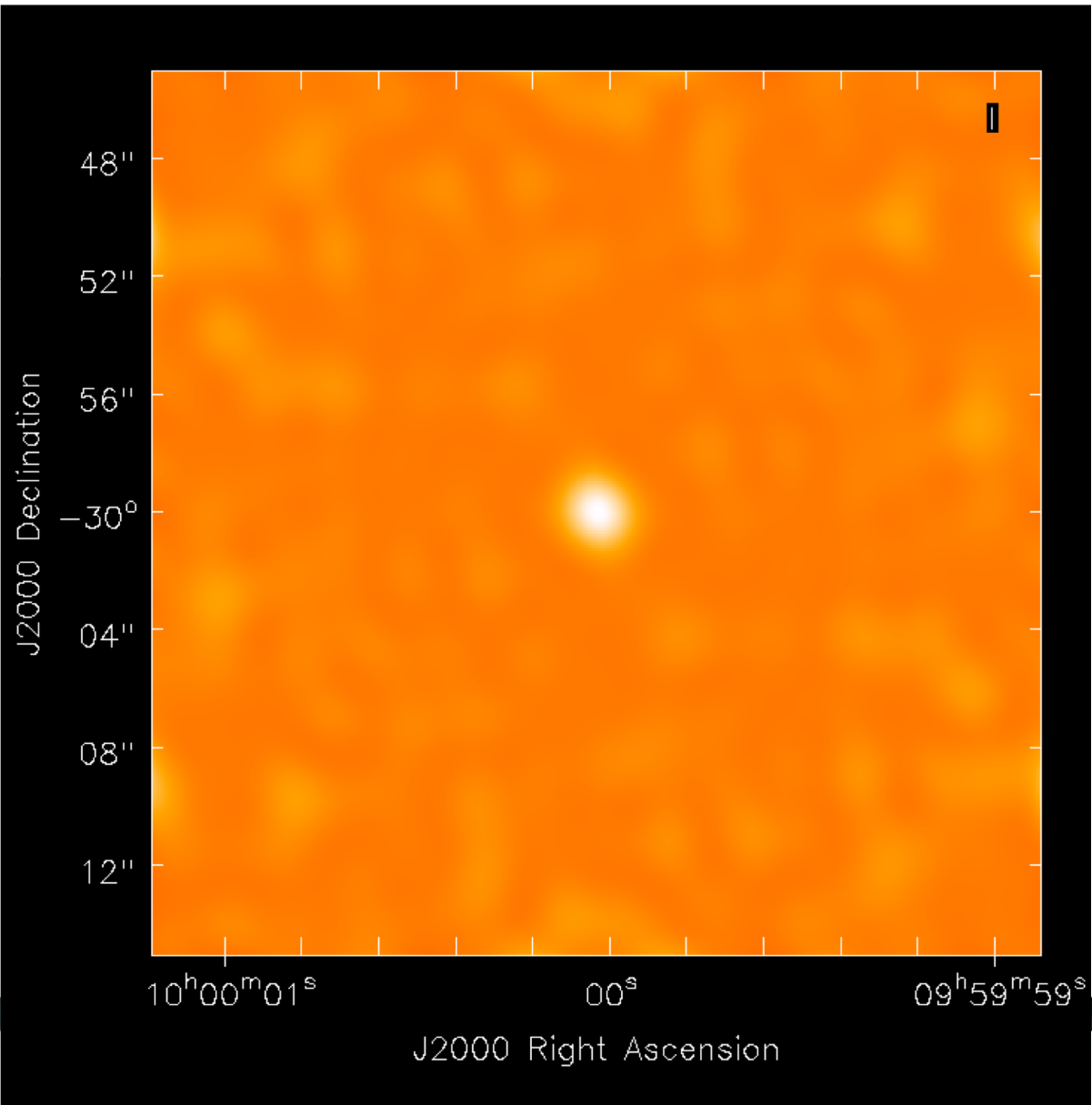
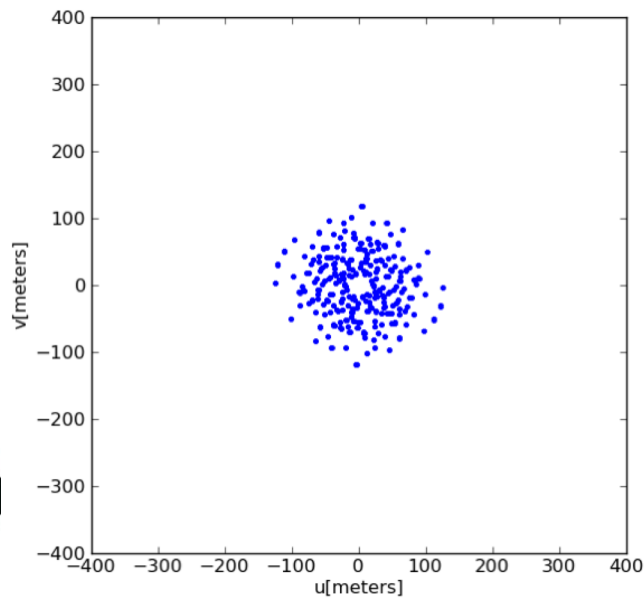
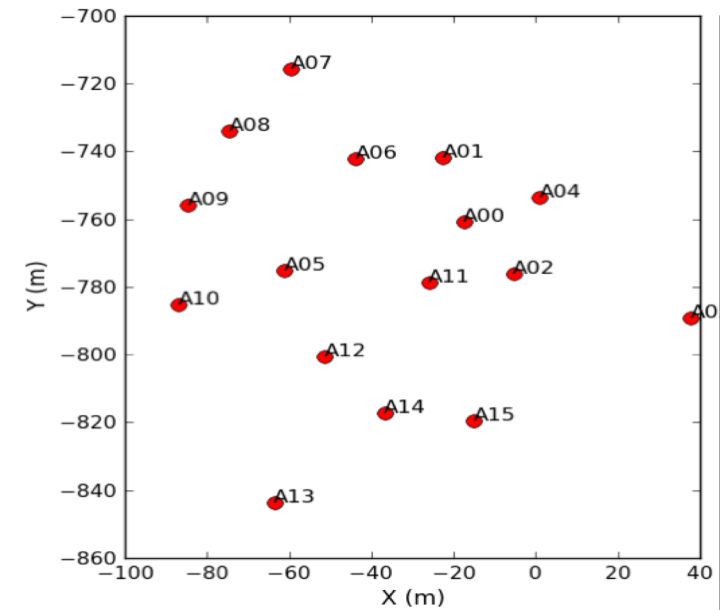
Example: Fringe pattern with 4 Antennas (6 baselines)



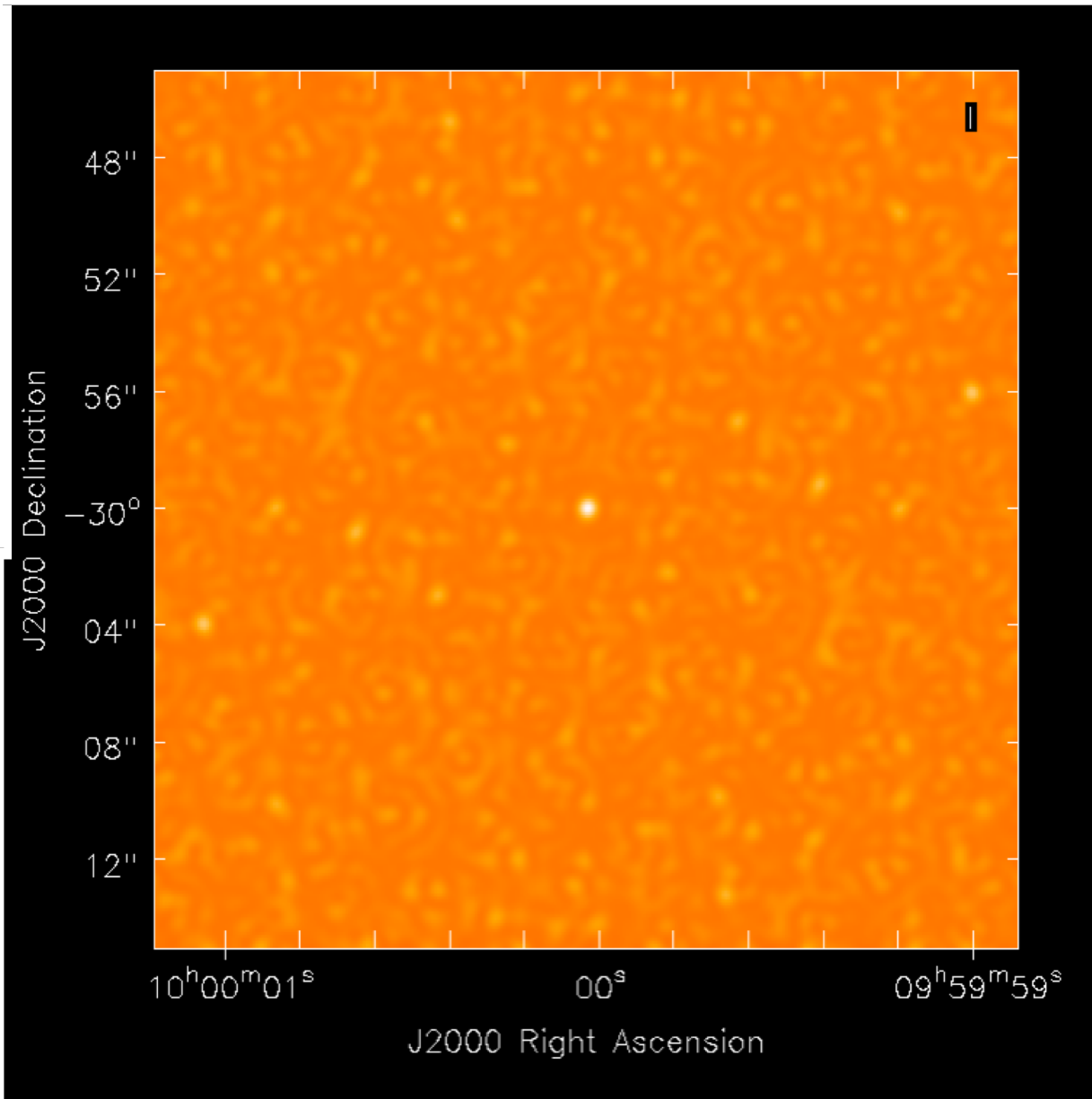
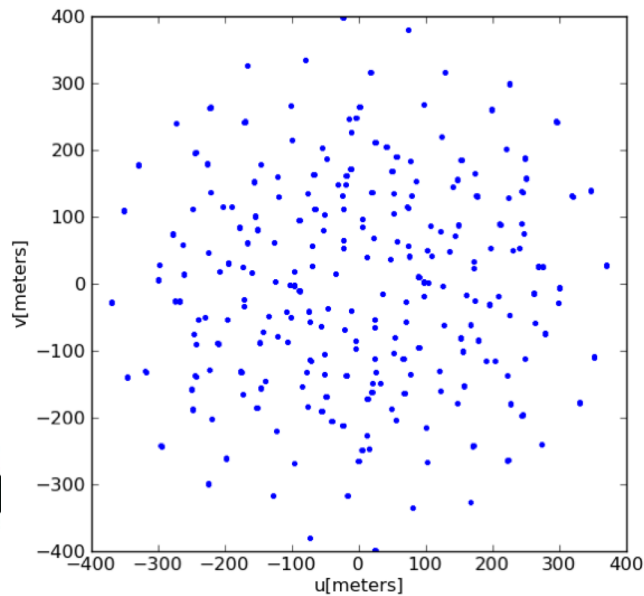
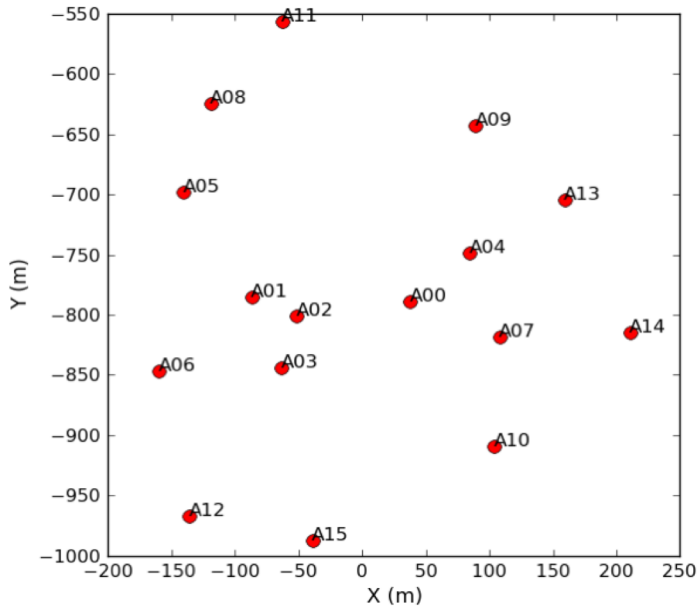
Example: Fringe pattern with 8 Antennas (28 baselines)



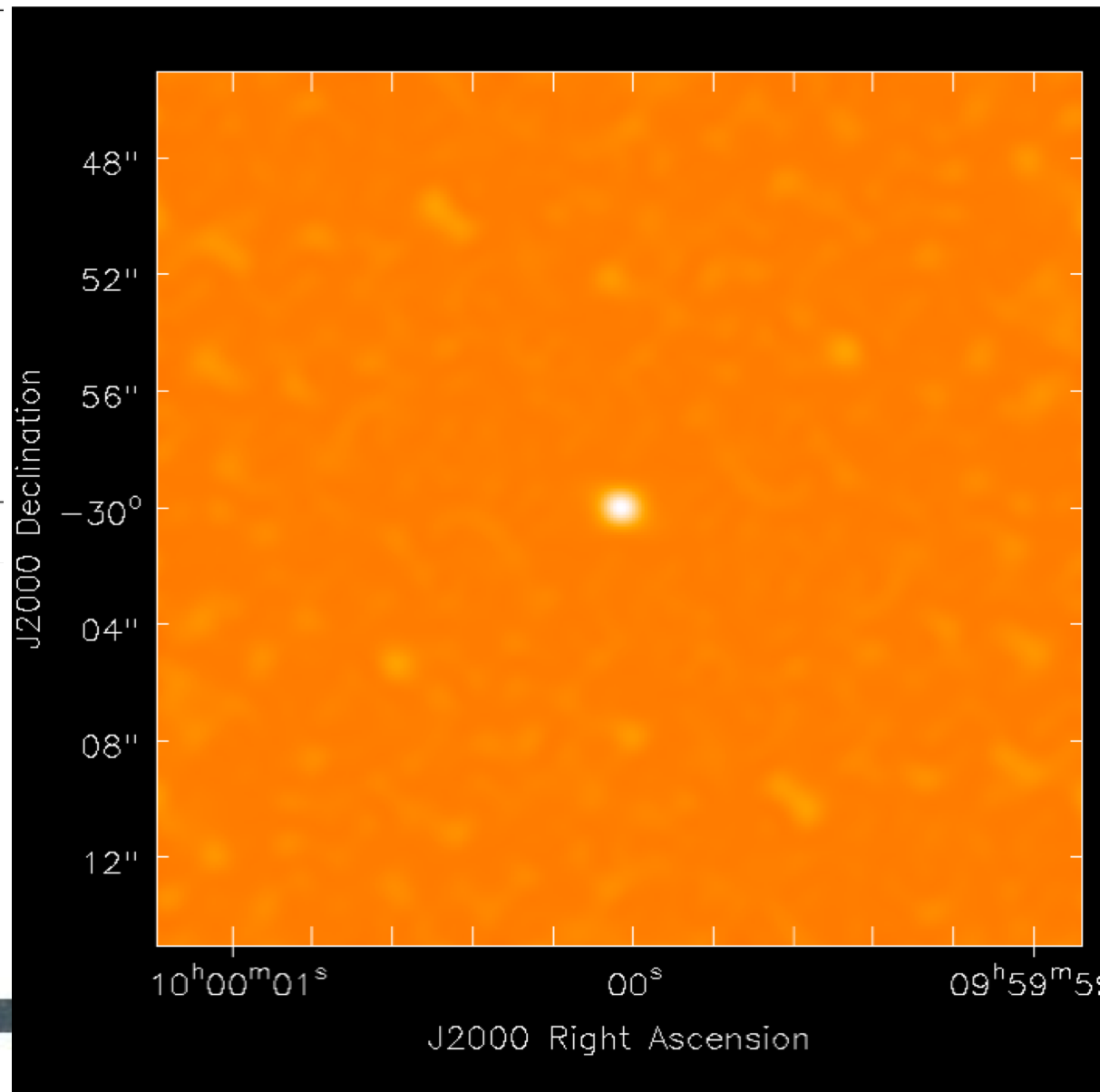
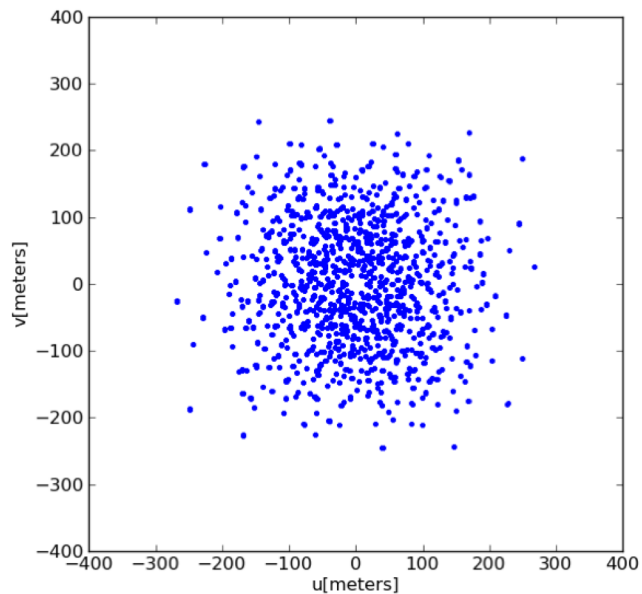
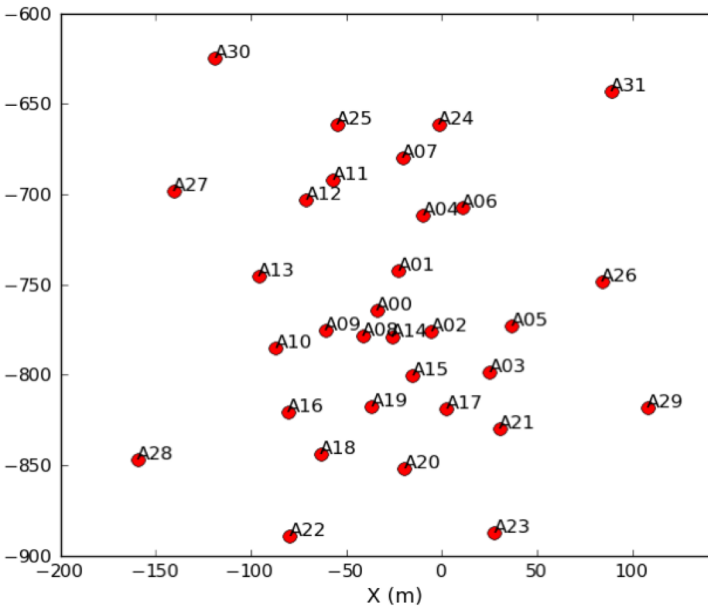
16 Antennas – Compact Configuration



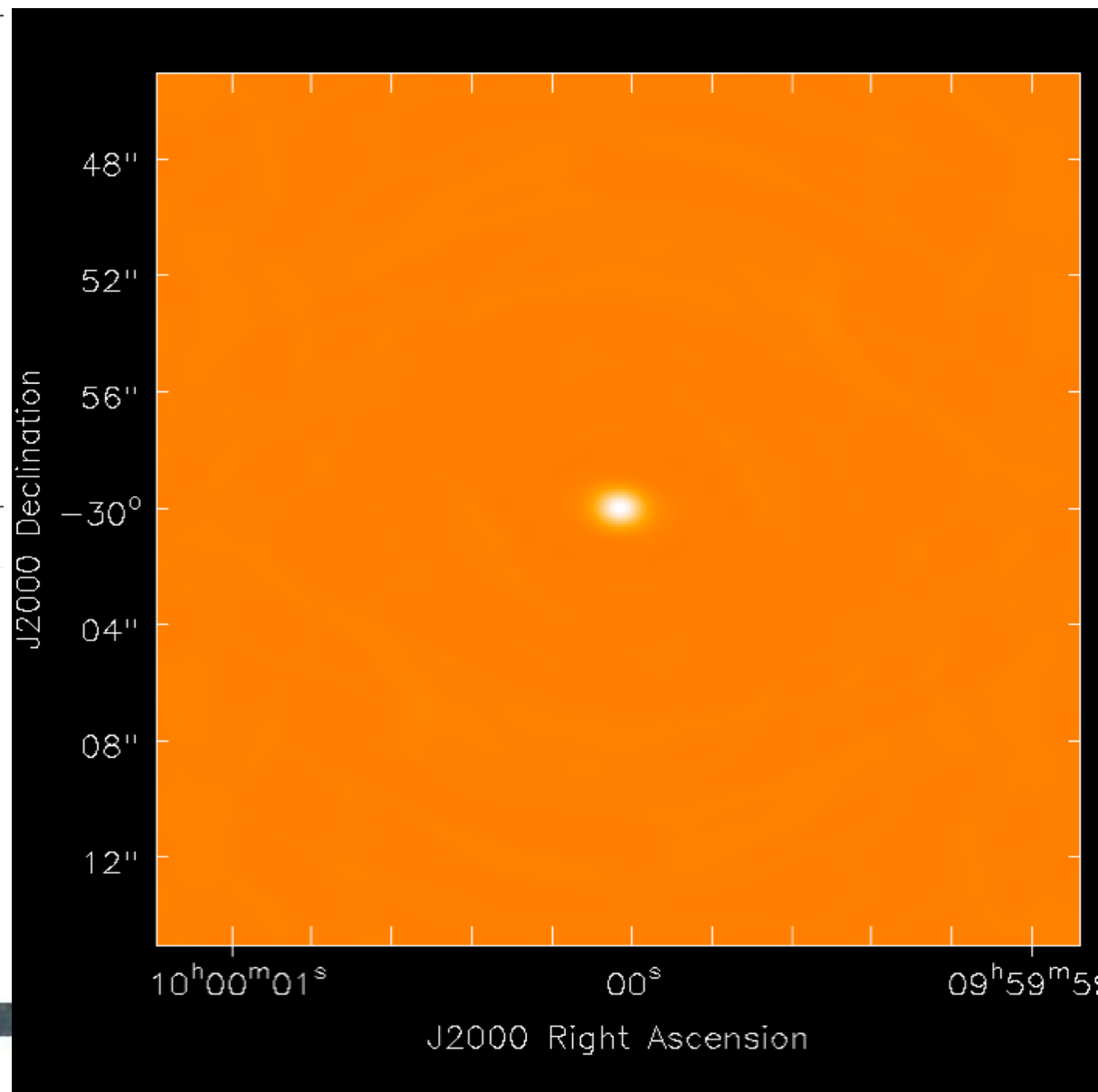
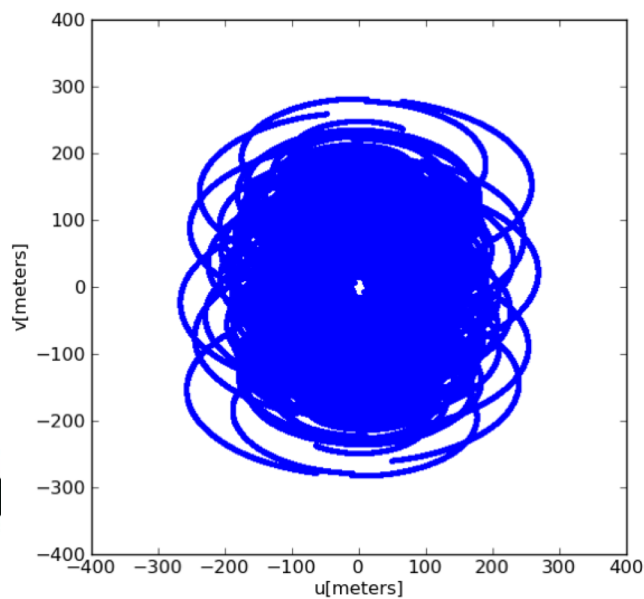
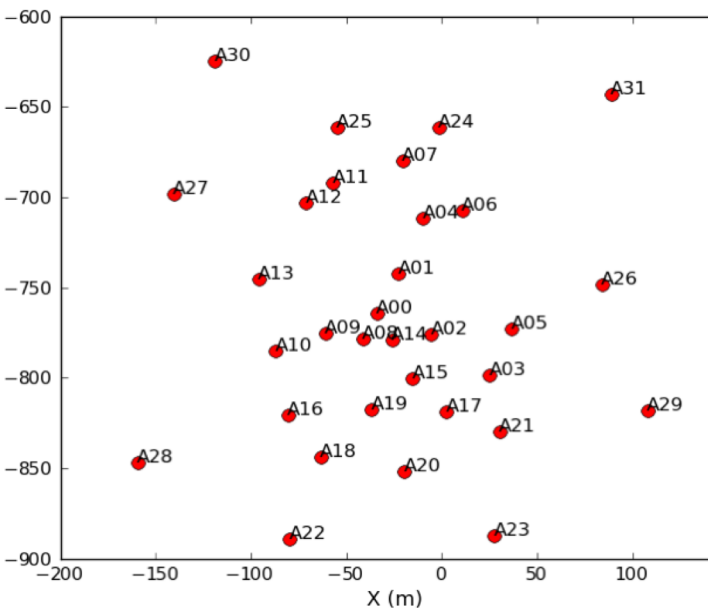
16 Antennas – Extended Configuration



32 Antennas – Instantaneous



32 Antennas – 8 hours

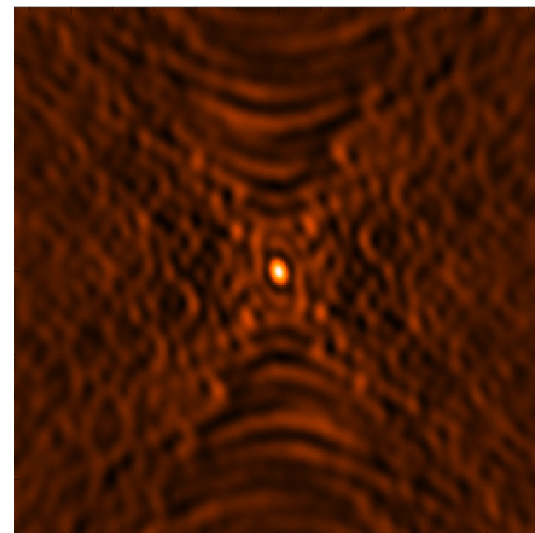
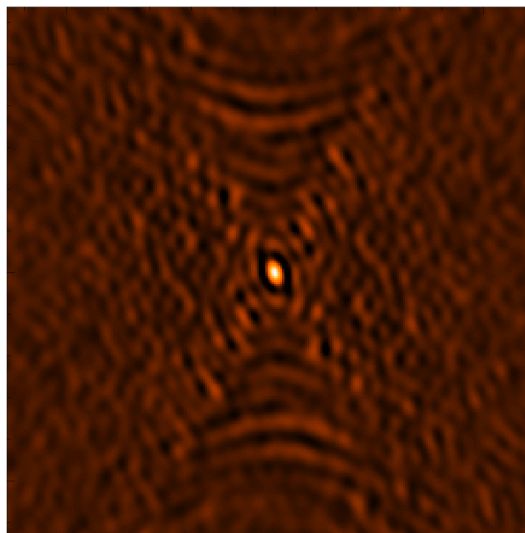
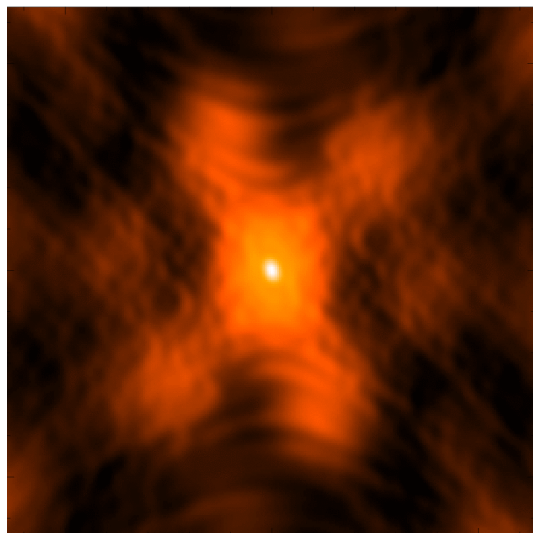


Natural

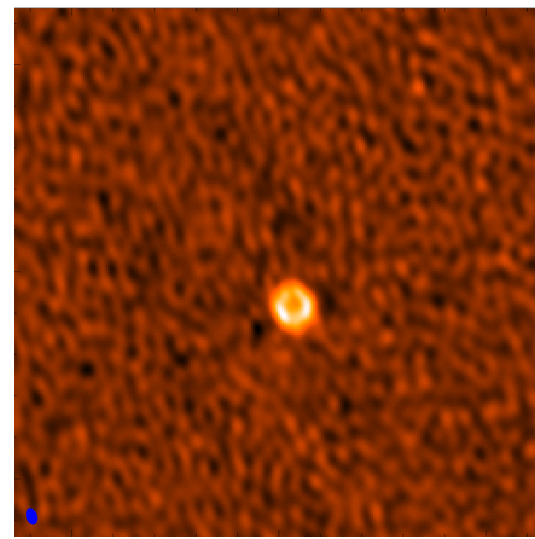
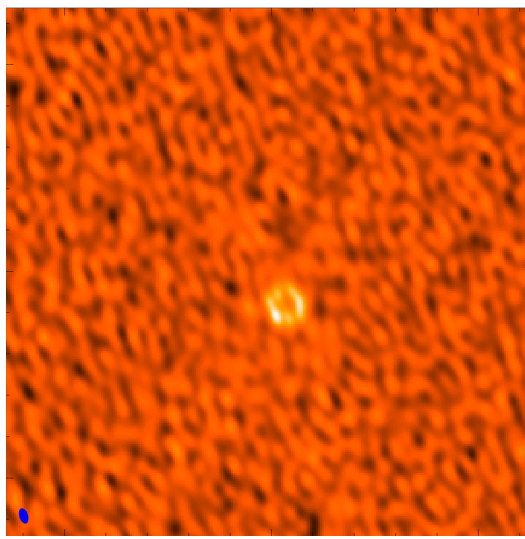
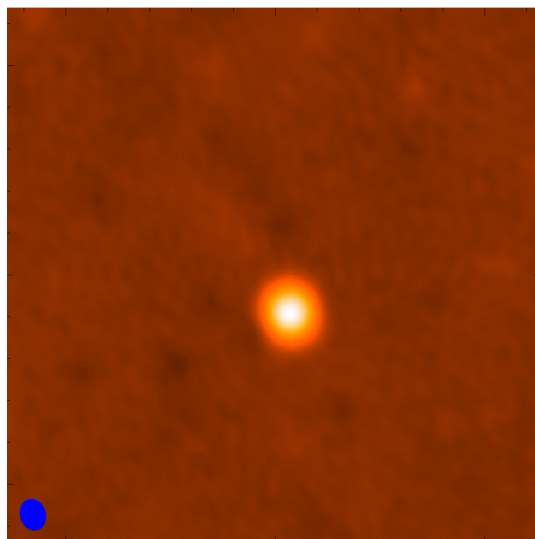
Uniform

Robust=0

Beam



CLEAN
image



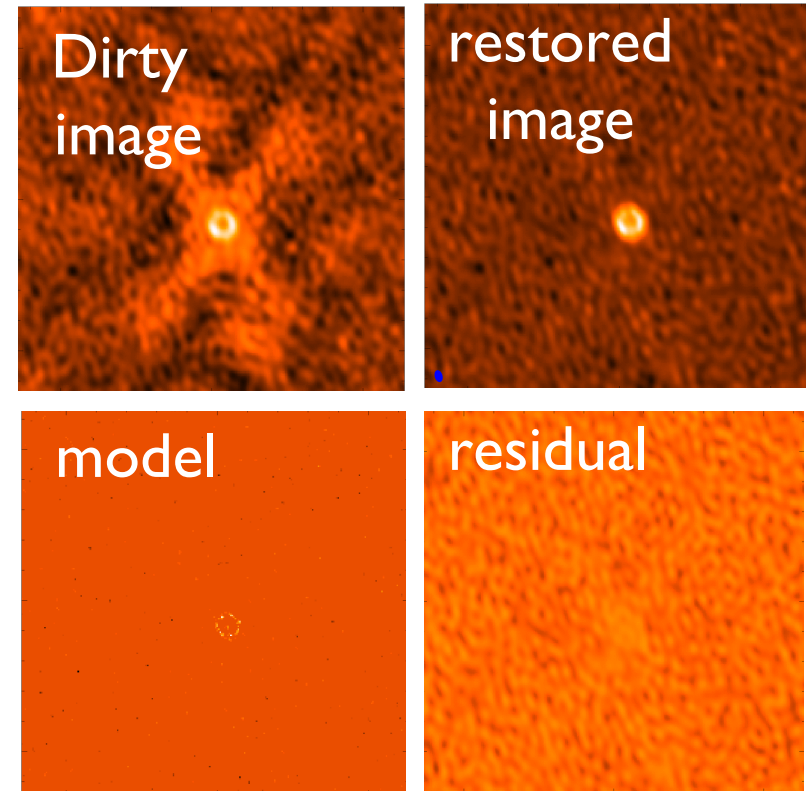
Clean is the most common deconvolution algorithm.

Sky Model : List of delta-functions

- (1) Construct the observed (dirty) image and PSF
- (2) Search for the location of peak amplitude.
- (3) Add a delta-function of this peak/location to the model
- (4) Subtract the contribution of this component from the dirty image - a scaled/shifted copy of the PSF

Repeat steps (2), (3), (4) until a stopping criterion is reached.

- (5) Restore : Smooth the model with a 'clean beam' and add residuals

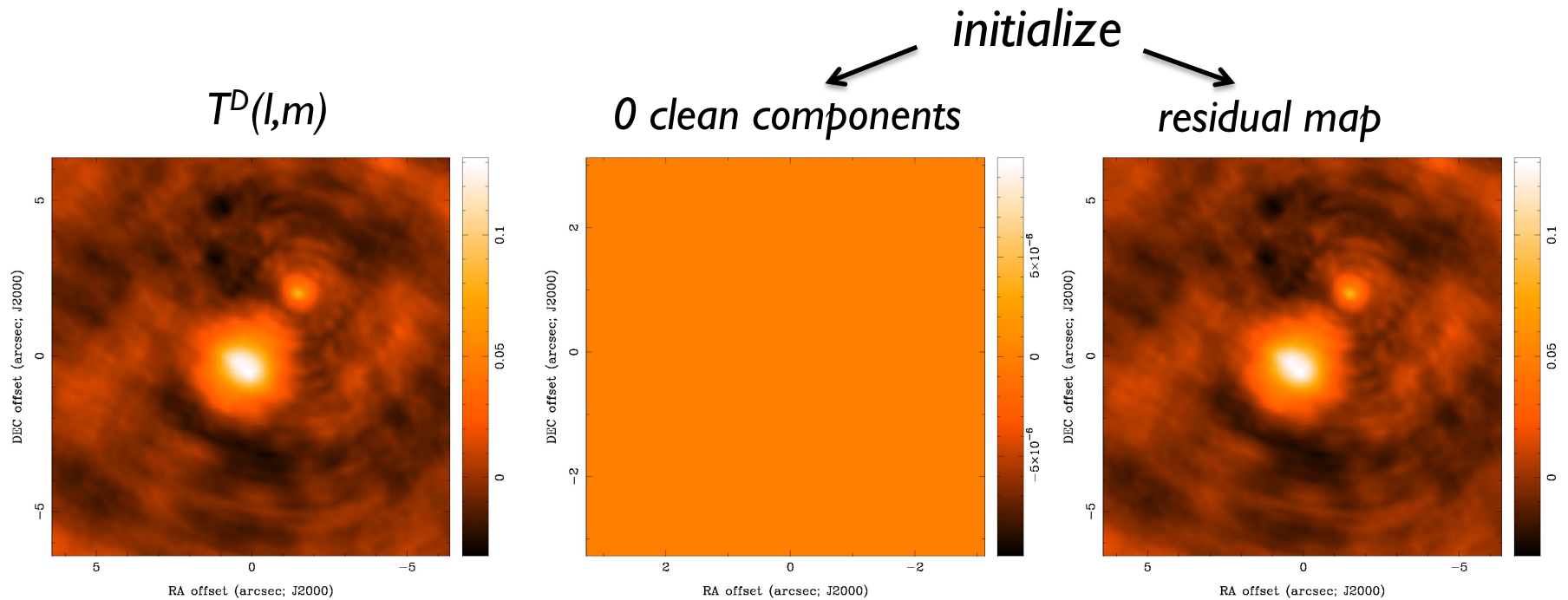


Choices: what and how much PSF to subtract and when to stop

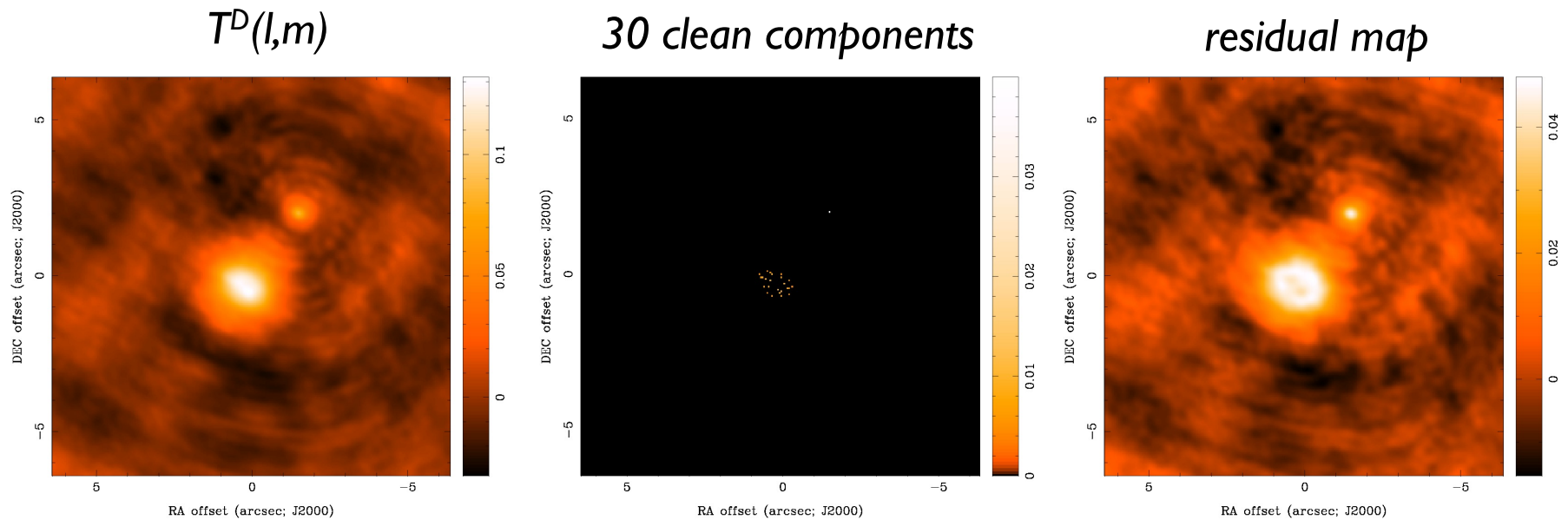
The supported CASA implementation of this algorithm is “**tclean**”.

DO NOT USE THE “clean” FUNCTION!

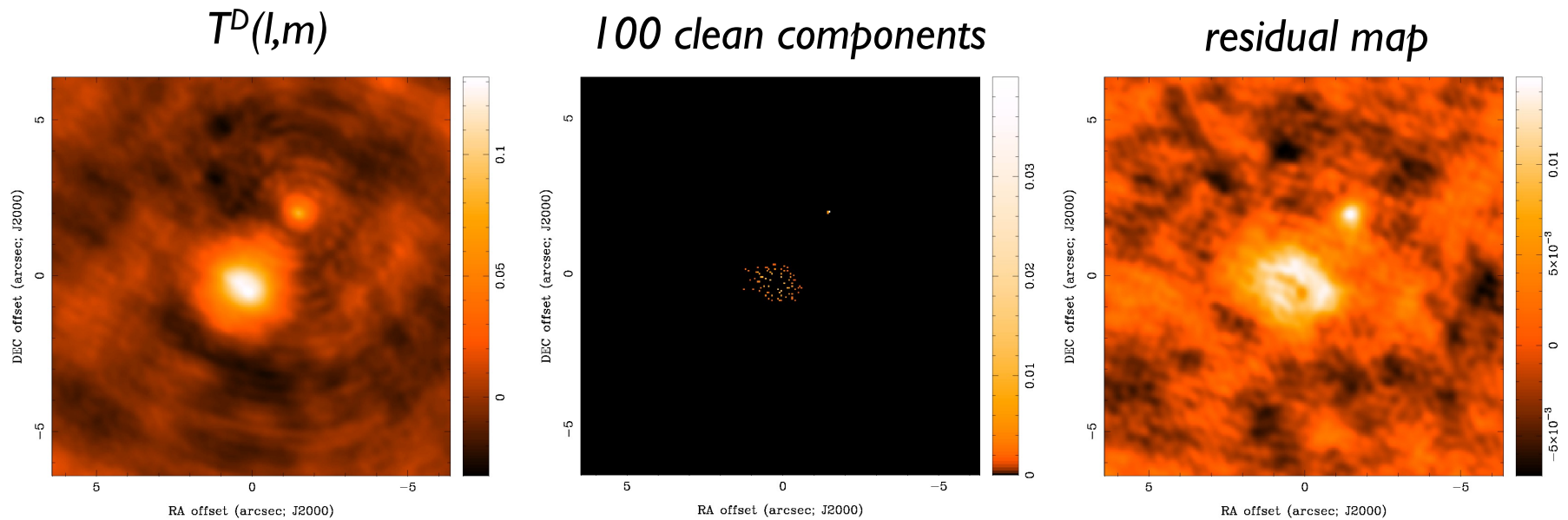
clean example



clean example

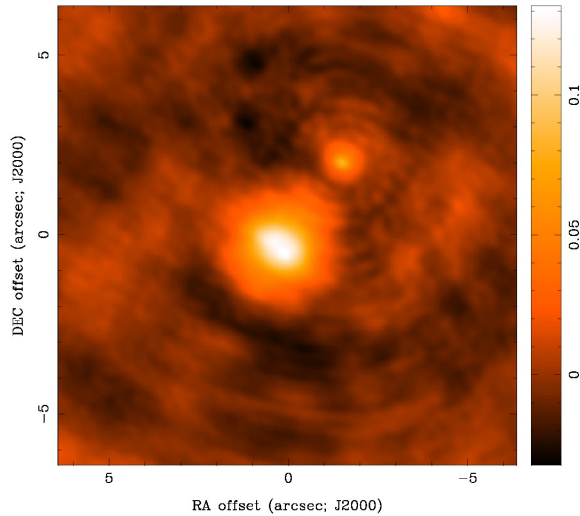


clean example

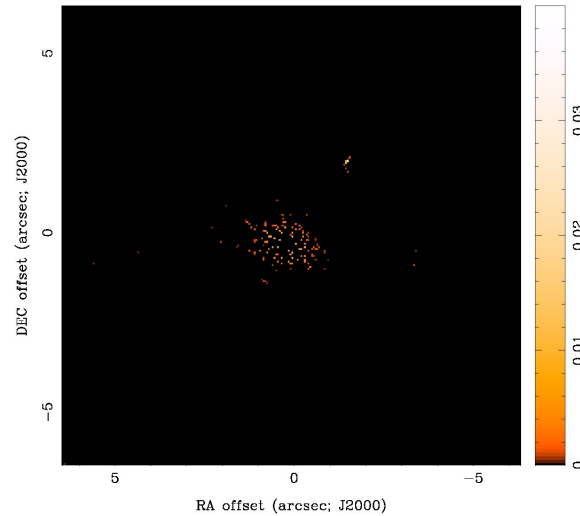


clean example

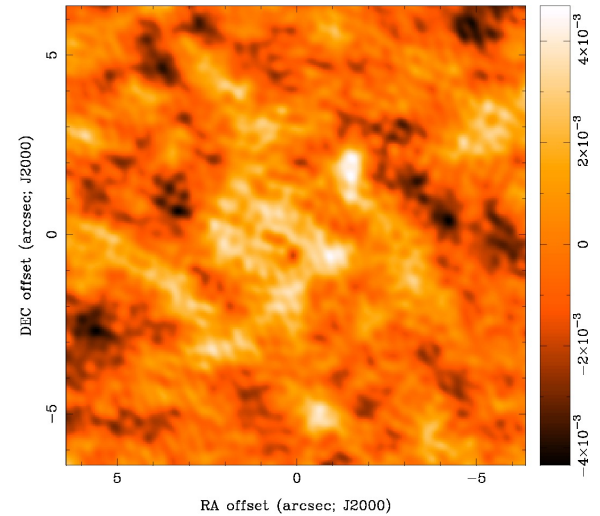
$T^D(l,m)$



300 clean components

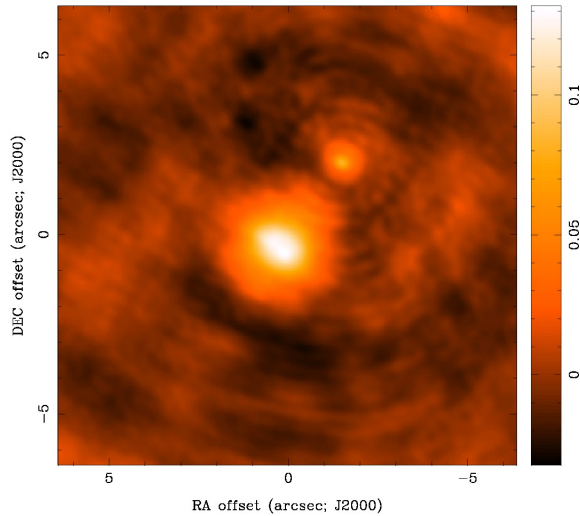


residual map

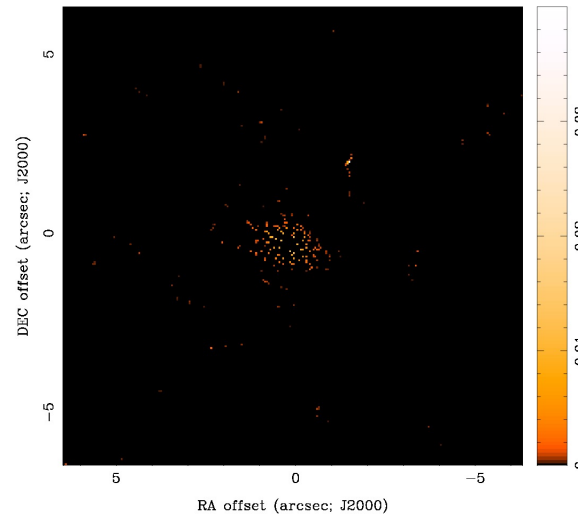


clean example

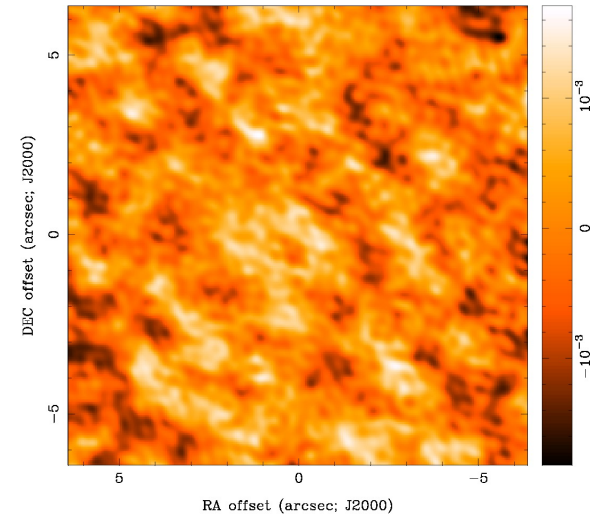
$T^D(l,m)$



583 clean components

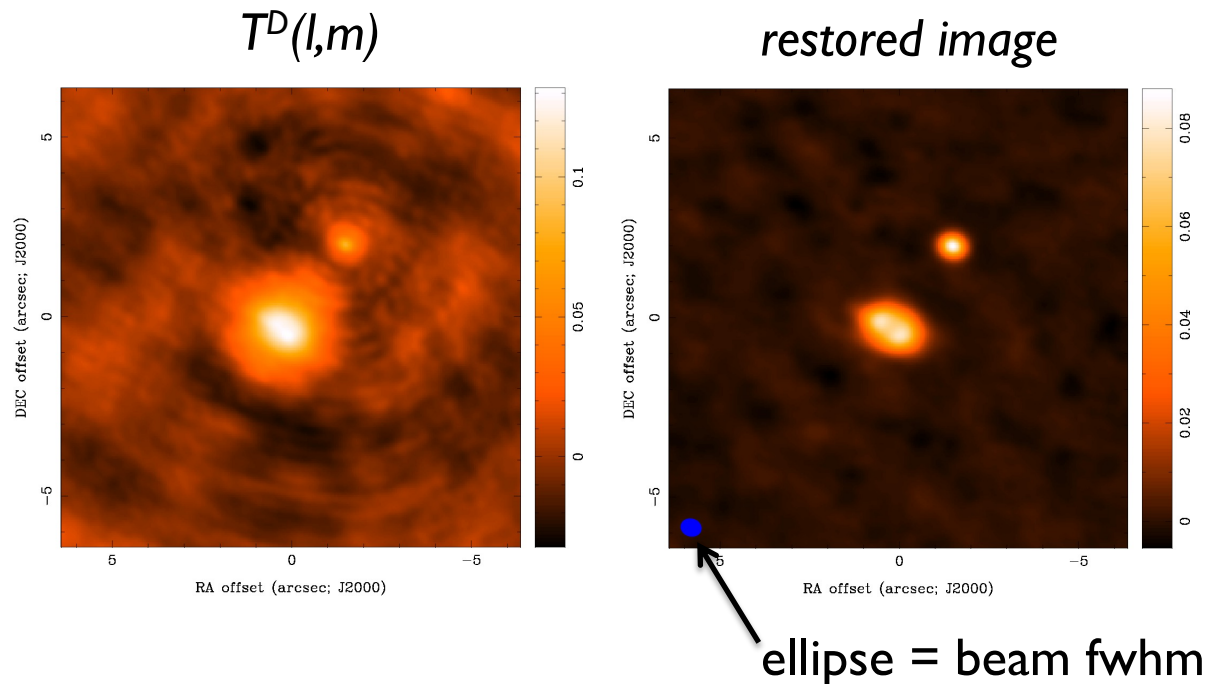


residual map



threshold reached

clean example



final image depends on

*imaging parameters (pixel size, visibility weighting scheme, gridding)
and deconvolution (algorithm, iterations, masks, stopping criteria)*

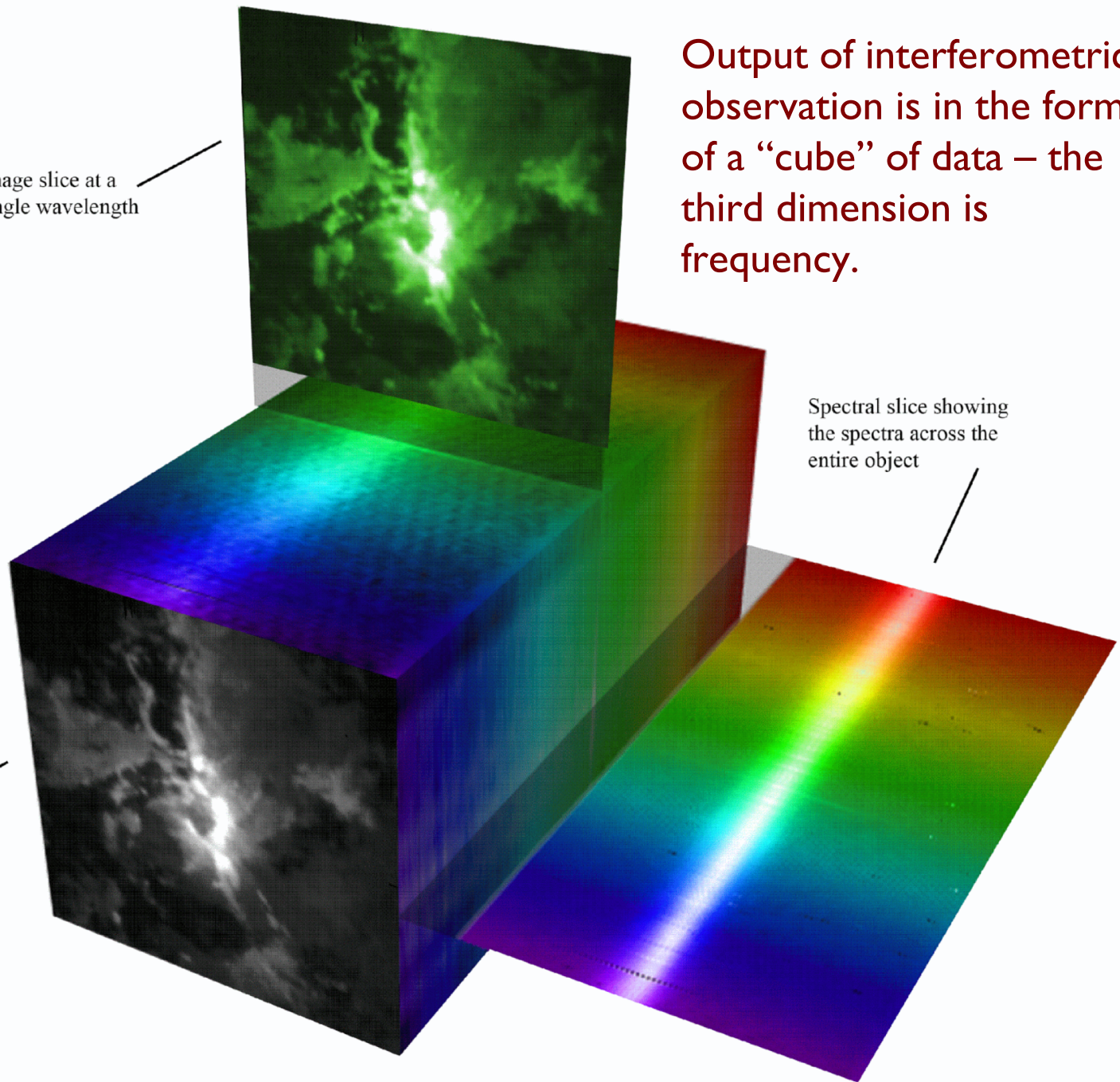
Not only 2D imaging, but 3D

Output of interferometric observation is in the form of a “cube” of data – the third dimension is frequency.

Image slice at a single wavelength

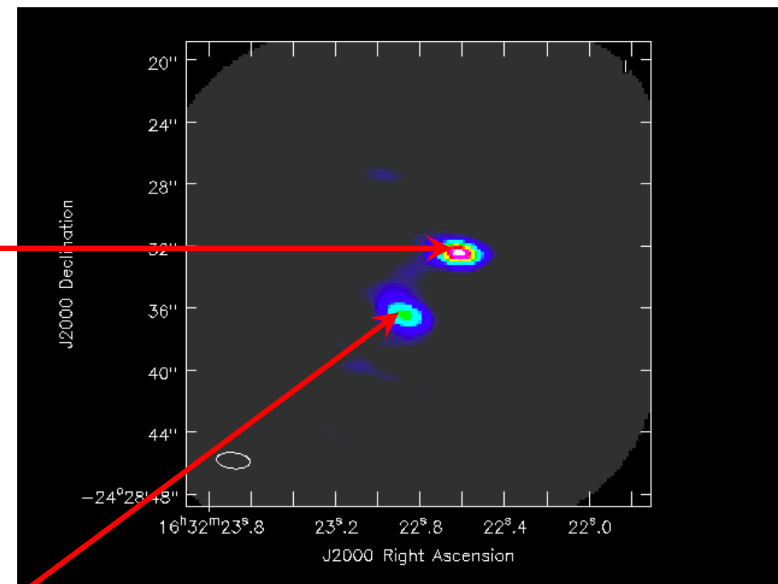
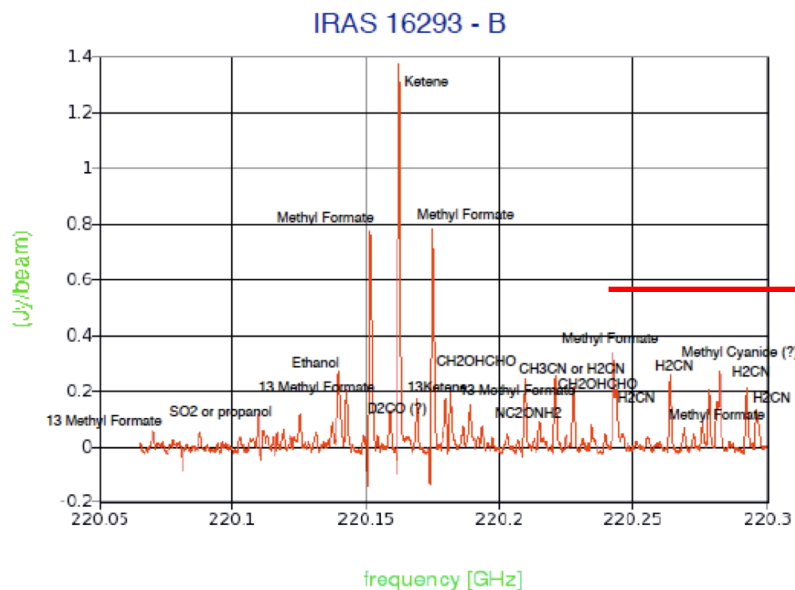
Object seen in combined light

Spectral slice showing the spectra across the entire object



Sometimes the most interesting science lies in the third dimension

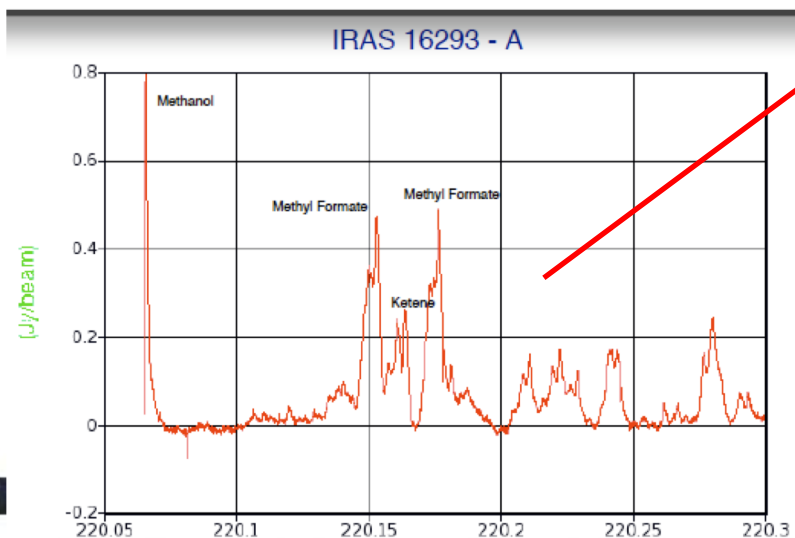
Band 6



J. Turner & ALMA CSV team

Young Low Mass Stars: IRAS 16293

- Note narrow lines toward preprotostellar core B (top) with infall apparent in methyl formate and ketene lines.



Feeling Overwhelmed?

NAASC is there to help!

- **ALMA Helpdesk:** User support is a priority so questions are usually answered within 48 hours (with around the clock staffing in the week leading up to the proposal deadline) - <https://help.almascience.org>
- **Student Observing Support:** Successful ALMA proposals will be invited to apply for up to \$35k to support undergraduate or graduate student involvement - <https://science.nrao.edu/opportunities/student-programs/sos>
- **NAASC Financial Support for Workshop/Conferences:** The NAASC invites scientists to apply for funding in support of upcoming conferences and workshops. - <https://science.nrao.edu/facilities/alma/community1/NAASC-Conference-and-Workshop-Support>
- **Page Charges:** Upon request NRAO covers page charges for authors at US institutions when reporting results from ALMA/VLA - <https://library.nrao.edu/pubsup.shtml>
- **Face-to-face Visitor Support:** Upon request NRAO will cover the travel expenses of up to 2 people from 2 teams per week to come to the NAASC to get support for data reduction, proposal preparation, etc... We also have long term visitor support as well - <https://science.nrao.edu/facilities/alma/visitors-shortterm>
- **ALMA Ambassadors:** You too can become an ALMA Ambassador. For program eligibility visit - <https://science.nrao.edu/facilities/alma/ambassadors-program>

Good Future References

Thompson, A.R., Moran, J.M., Swensen, G.W. 2017 “Interferometry and Synthesis in Radio Astronomy”, 3rd edition (Springer)

<http://www.springer.com/us/book/9783319444291>

Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 “Synthesis Imaging in Radio Astronomy” (San Francisco: ASP)

www.aoc.nrao.edu/events/synthesis

IRAM Interferometry School proceedings

www.iram.fr/IRAMFR/IS/IS2008/archive.html



Good Future References

NRAO Synthesis Imaging Workshop

<https://science.nrao.edu/science/meetings/2018/16th-synthesis-imaging-workshop/16th-synthesis-imaging-workshop-lectures>

Examples of UV coverage from Ian Czekala

<https://drive.google.com/file/d/1fy3edrjNATo175WopB49-3mZ7QeZPK5O/view>





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