ALMA: MM Observing Considerations

Focus on Early Science (cycle 0)

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(NRAO/North American ALMA Science Center)

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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Overview of Talk

ALMA

- **Perspective:** Getting time on ALMA will be competitive!
  - The math: only ~600 hours for ES cycle 0
    at ~6 hours per project ➔ ~100 projects split over the world
- **Motivation:** While ALMA is for everyone, a technical justification is required for each proposal, so you need to know some of the details of how the instrument works
- **Goal:** Do the best job you can to match your science to ALMA's capabilities

Sky coverage available

ALMA

- ALMA is at a latitude of -23 degrees ➔ Southern sky!
- Antenna elevation limit is technically 3 degrees
- In practice, atmospheric opacity will cause significant degradation with lower elevation ➔ most severe at higher frequencies

Northern sources: Maximum length of observation (hours)

Dec	Elev > 10°	Elev > 15°	Elev > 20°	Elev > 30°
+55	2.7	-	-	-
+50	5.9	2.5	-	-
+40	7.0	5.8	4.3	-
+30	8.3	7.3	6.3	3.9
+20	9.2	8.4	7.5	5.7

Note: This table does not account for shadowing, which further complicates low elevation observations.

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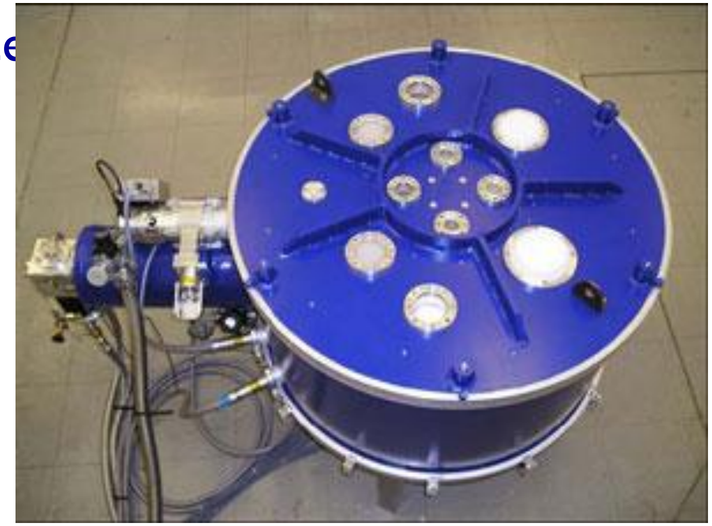
Receiver Bands Available

Bands:	3	4	5	6	7	8	9	10
Frequency (GHz)	84-116	125-163	163-211	211-275	275-373	385-500	602-720	787-950
Wavelength (mm)	3.57-2.59	2.40-1.84	1.84-1.42	1.42-1.09	1.09-0.80	0.78-0.60	0.50-0.42	0.38-0.32

3 mm **1.3 mm** **0.87 mm** **0.45 mm**

- Only 4 of 8 bands are available for Early Science all with dual linear polarization feeds

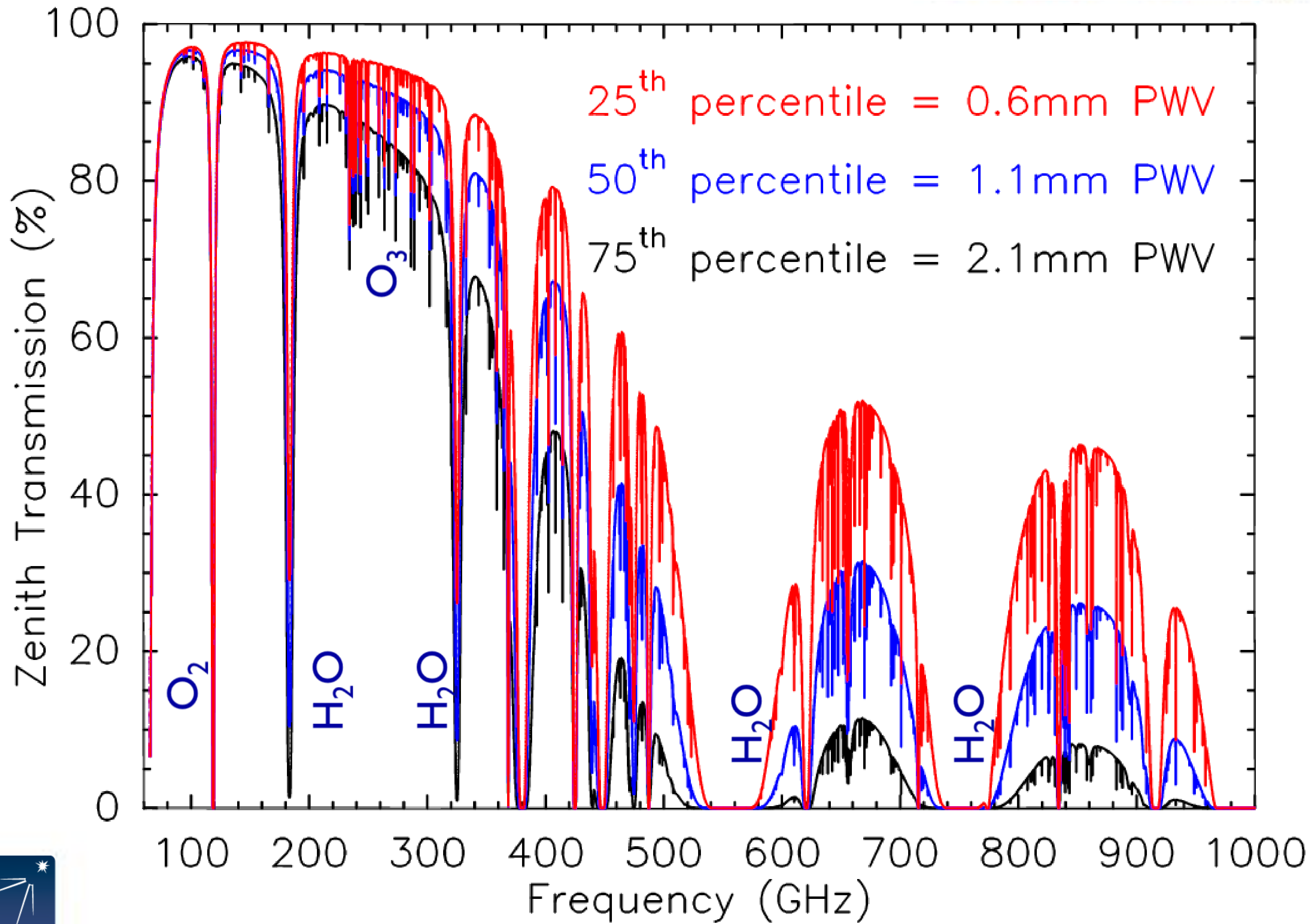


- Only 3 receiver bands can be "ready" at one time (i.e. amplifiers powered on and stable temperature achieved). Required lead time to stabilize a new band is about 20 minutes.
- With configurations of ~125m and ~400m, approximately matched resolution is possible between Bands 3 and 7, or between Bands 6 and 9
  - Matched resolution can be critical, for example to measure the SEDs of resolved sources.

Atmospheric Opacity

(PWV = Precipitable Water Vapor)

ALMA



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Sensitivity calculator

ALMA

http://www.eso.org/sci/facilities/alma/observing/tools/etc

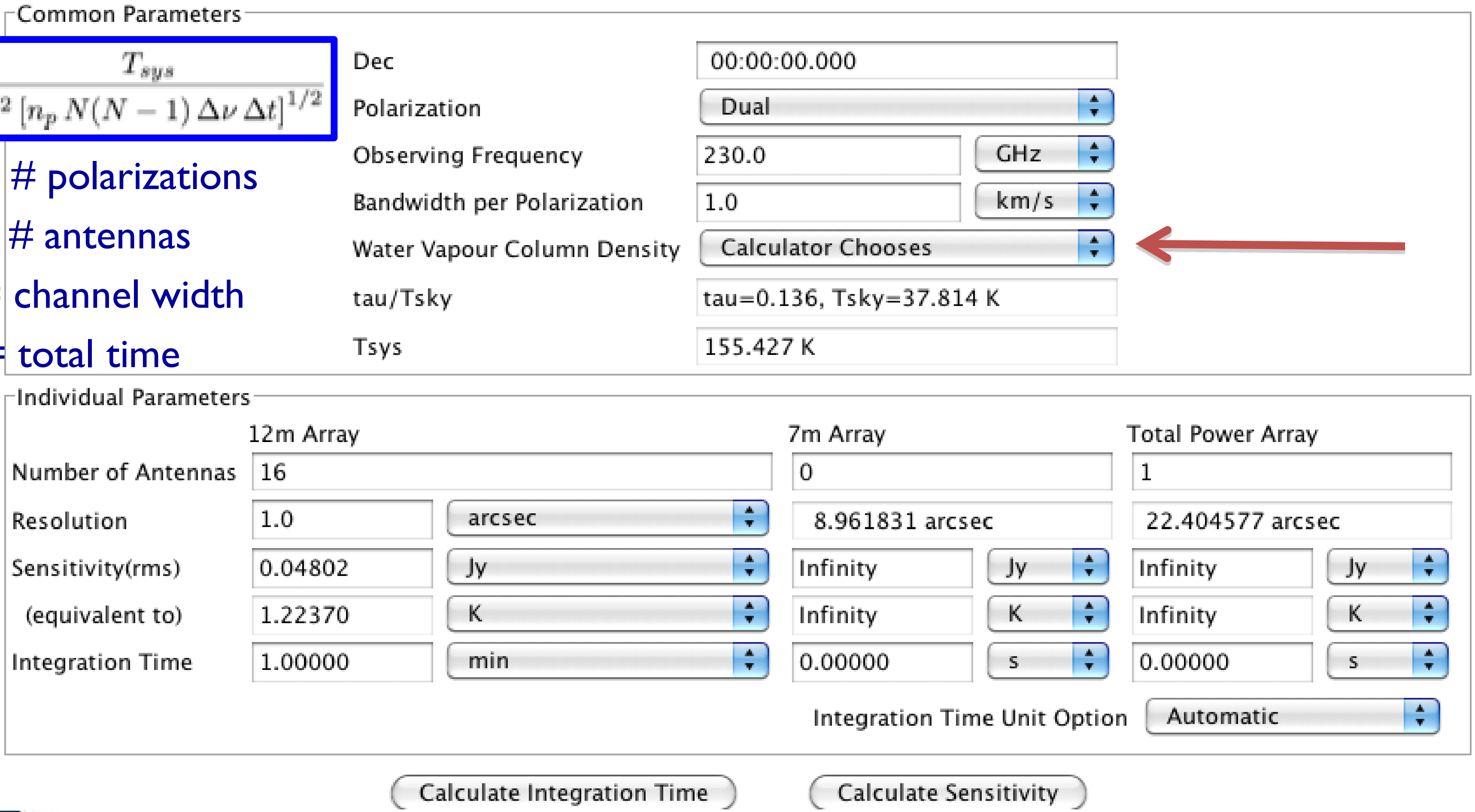
$$\Delta S \propto \frac{T_{sys}}{D^2 \left[n_p\, N(N-1)\, \Delta\nu\, \Delta t\right]^{1/2}}$$

n_p = # polarizations

N = # antennas

Δv = channel width

Δt = total time



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Choosing your bands – I
(constructed from sensitivity calculator)

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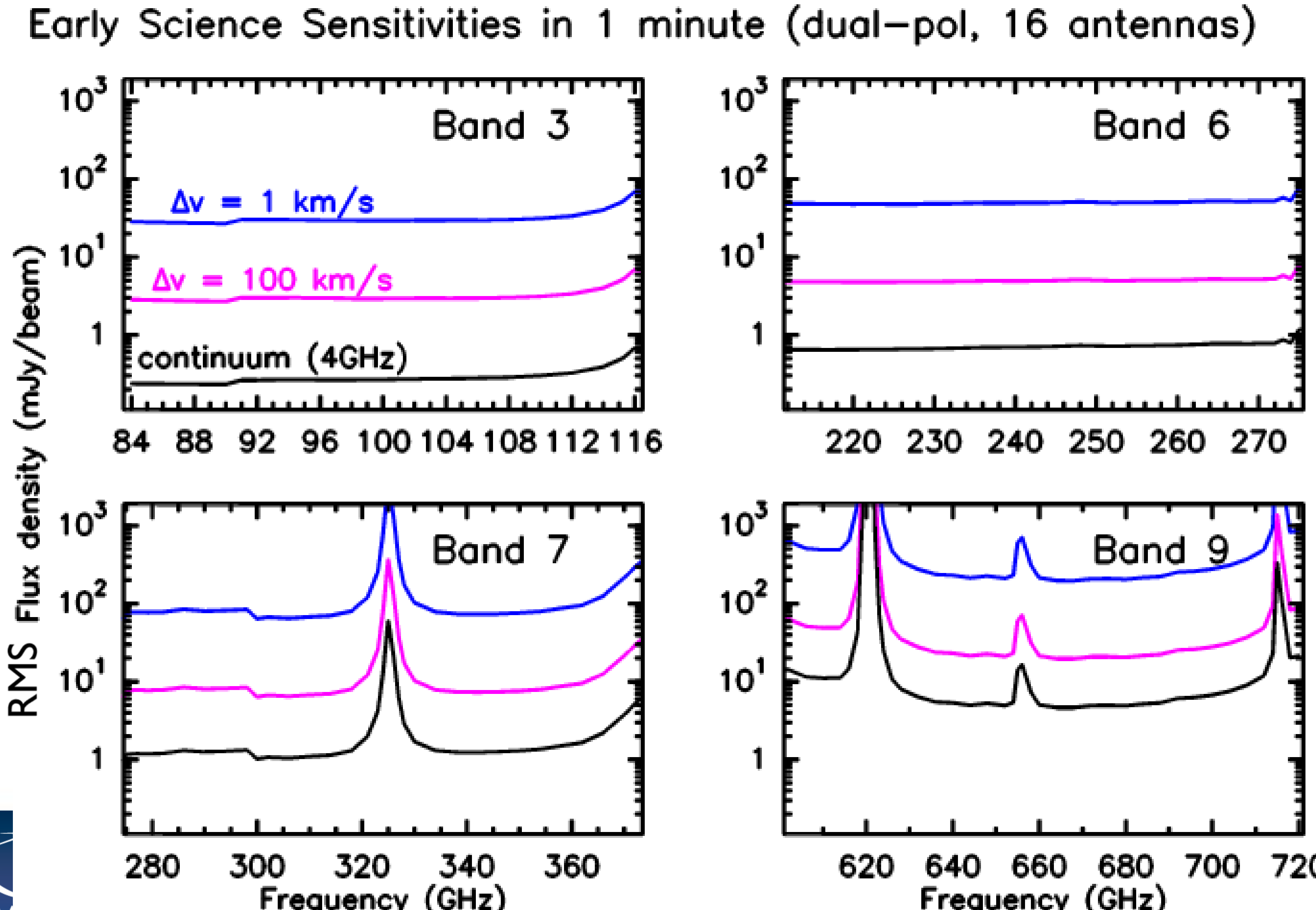
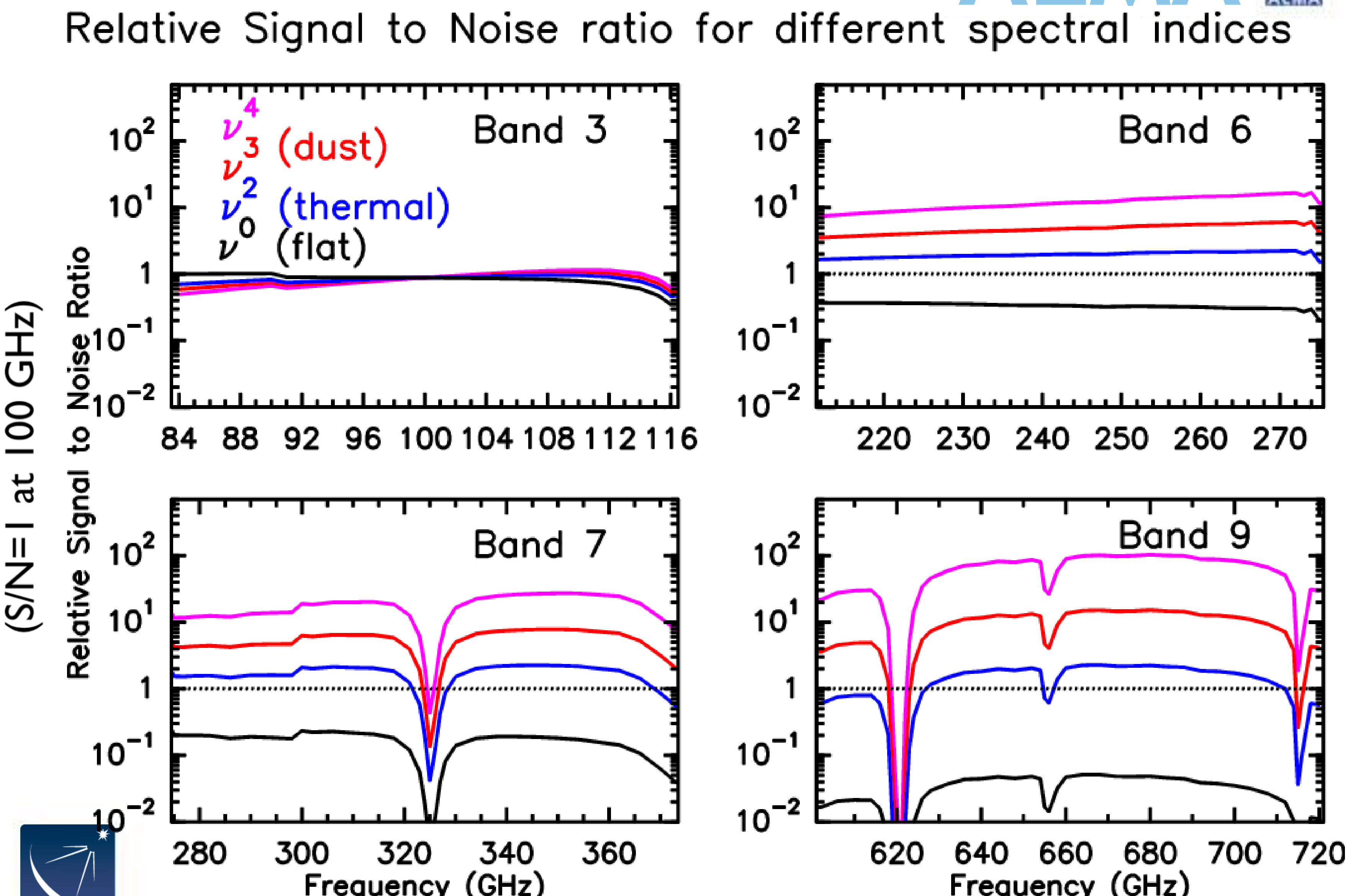


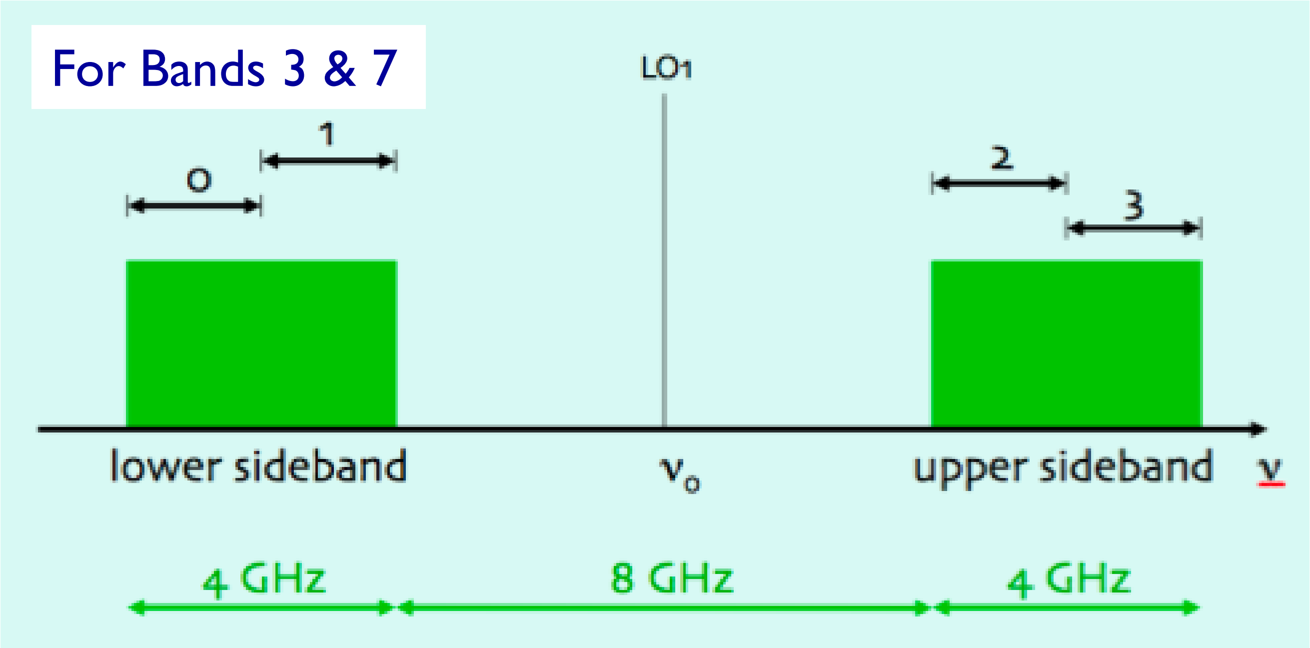
NOTE: For 8 GHz continuum bandwidth divide by √2

Choosing your bands - II



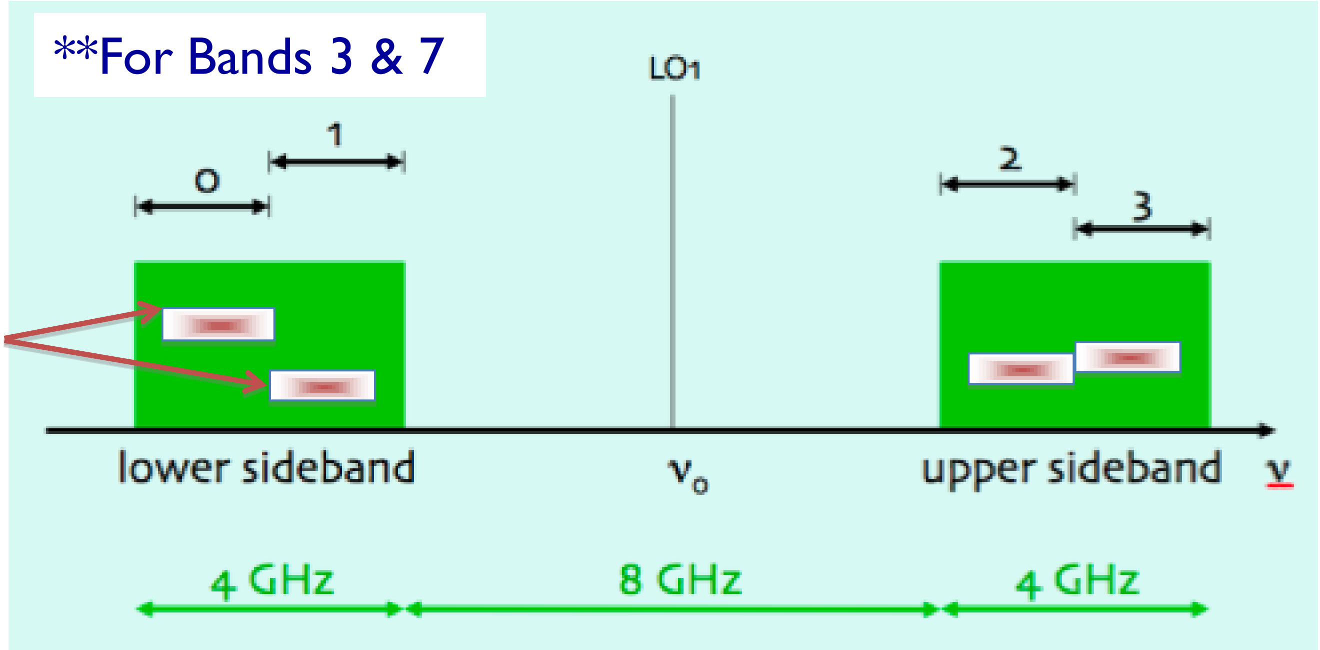
Correlator Modes, Spectral Resolution, Spectral Coverage - I

- Receivers are sensitive to two separate ranges of sky frequency: **sidebands**
- Each antenna has 4 digitizers which can each sample 2 GHz of bandwidth
- These 2 GHz chunks are termed **basebands**, and can be distributed among the sidebands (in ES: either all four in one, or two in both as shown below)



Correlator Modes, Spectral Resolution, Spectral Coverage - II

Spectral windows



- In order to collect data, you need to set up a spectral window within one (or more) basebands.
- In Early Science, only 4 spectral windows are available, i.e. one per baseband, and all must have the same resolution and bandwidth
- **Note: exact spacing between sidebands and sideband widths vary from band to band – OT will show correct one for each band

Correlator Modes, Spectral Resolution, Spectral Coverage - II

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Typical purposes:

Corr-elator Mode	Polari-zation	Bandwidth per baseband (MHz)	Number of channels per baseband	Channel Spacing (MHz)	Velocity width at 1mm (km/s)
7	Dual	1875	3840	0.488	0.48
8	Dual	938	3840	0.244	0.24
9	Dual	469	3840	0.122	0.12
10	Dual	234	3840	0.061	0.06
11	Dual	117	3840	0.0305	0.03
12	Dual	58.6	3840	0.0153	0.015
6	Single	58.6	7680	0.00763	0.008
69	Dual	2000	128	15.625	15.6

Spectral scans (modes 7–8)

Targeted imaging of moderately narrow lines: cold clouds / protoplanetary disks (modes 9–12, 6)

"Continuum" or broad lines (mode 69)

- These numbers are per baseband (you can use up to 4 basebands)
- Usually want to have several channels across narrowest line
- The required spectral resolution typically needs to be justified as does the number of desired spectral windows

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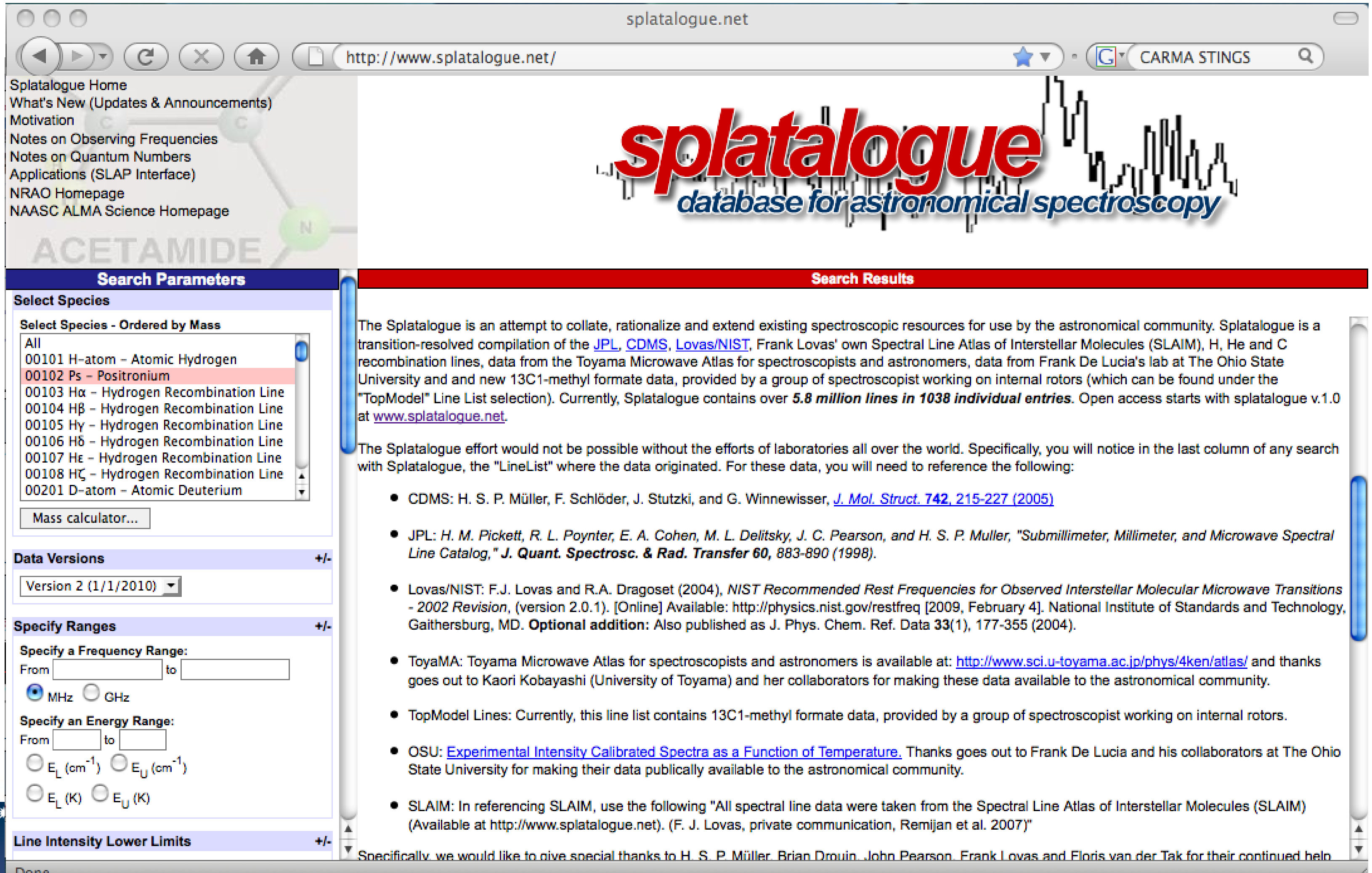
Spectral Lines in the ALMA bands

ALMA

http://www.splatalogue.net (large subset also available in OT)



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Spectral lines in the ALMA bands

SMA spectrum of Arp 220 (Band 6) (Martin et al. 2011)

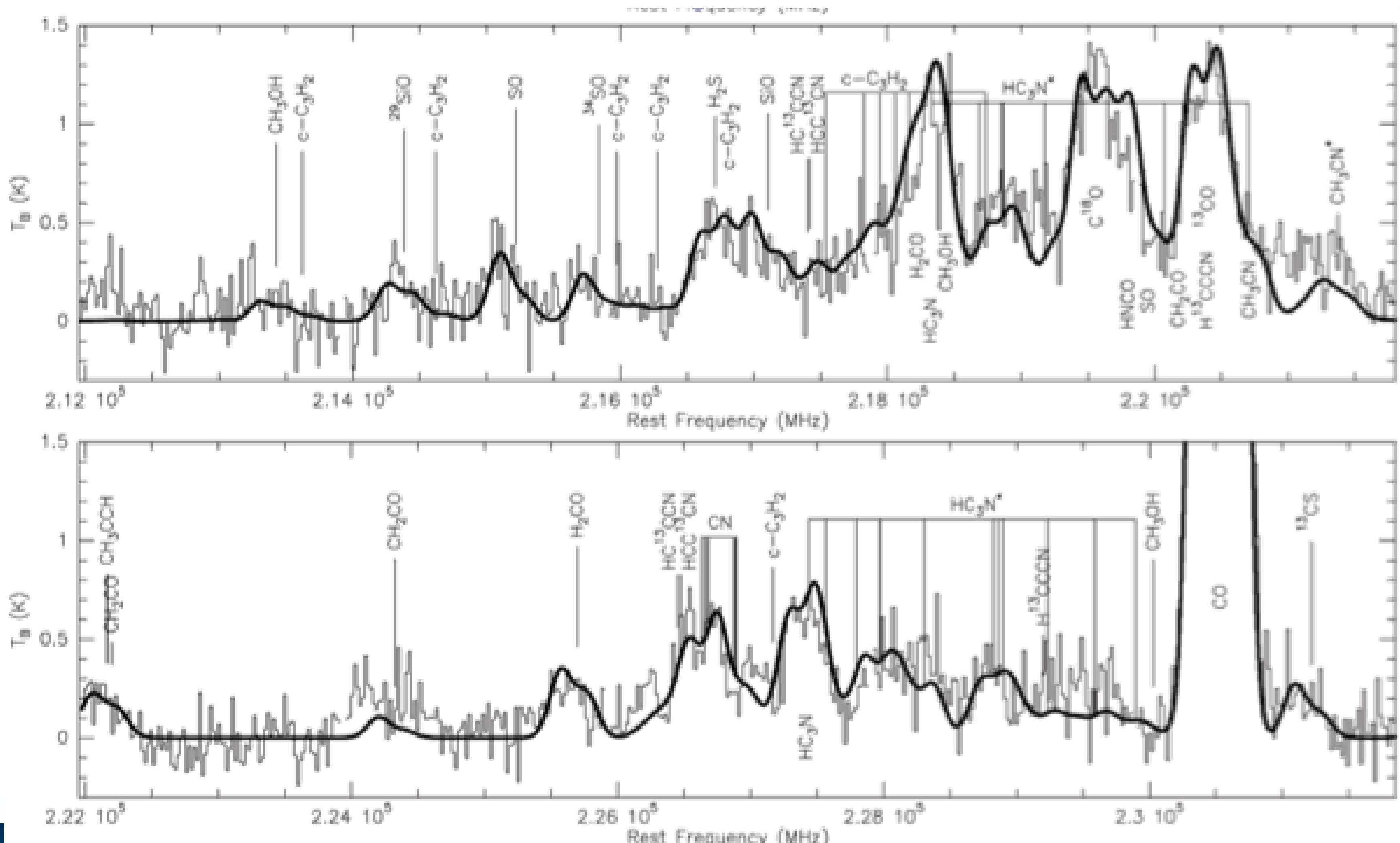


Image Quality

Sensitivity is not enough! Image quality also depends on:

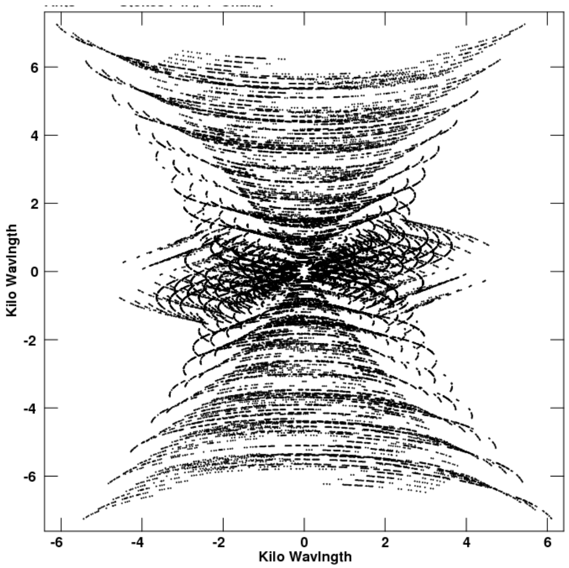
❖ *UV* coverage and density of *UV* samples

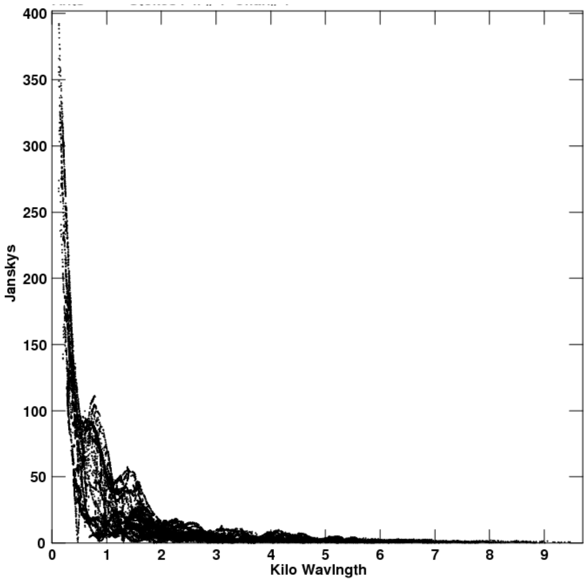
- Image fidelity is improved when high density regions of UV coverage are well matched to source brightness distribution

➔The required DYNAMIC RANGE can be more important than sensitivity

➔ALMA OT currently has no way to specify required image quality

➔Technical justification

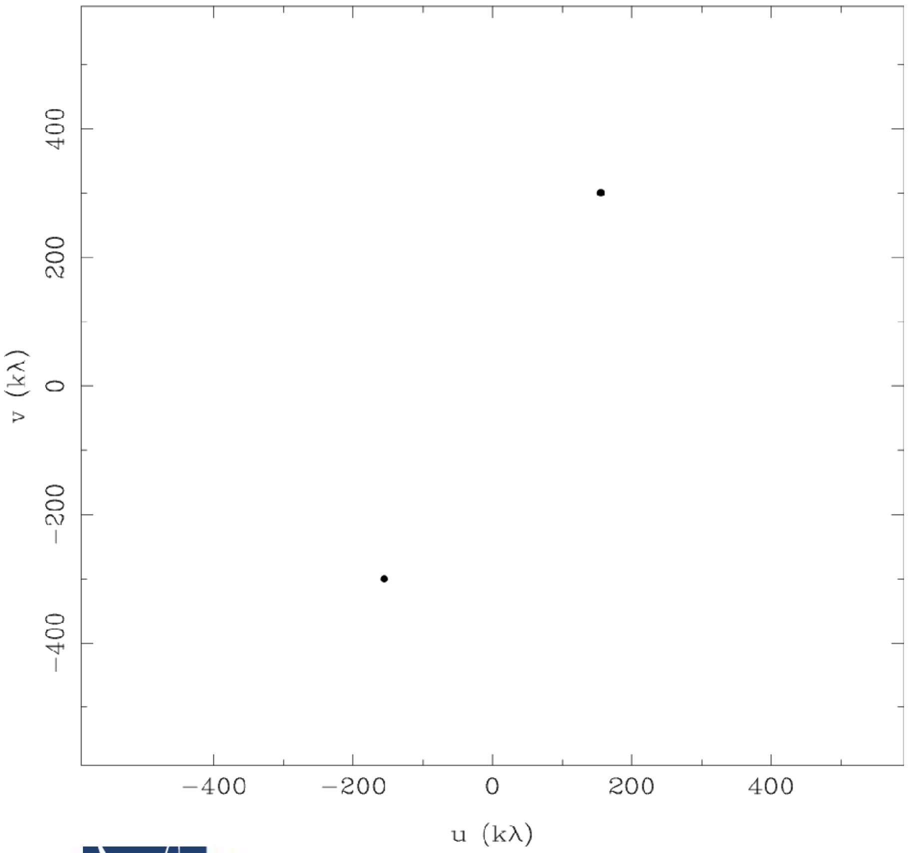


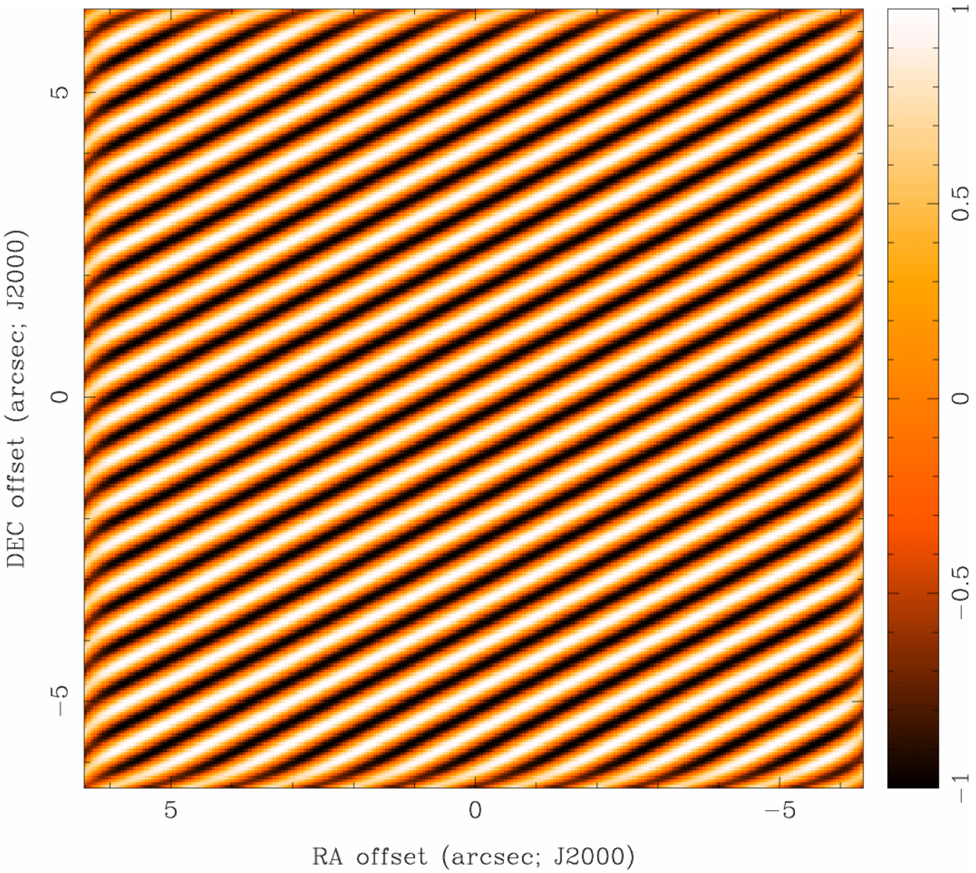


Dirty Beam Shape and N Antennas

(Image sequence taken from Summer School lecture by D. Wilner)

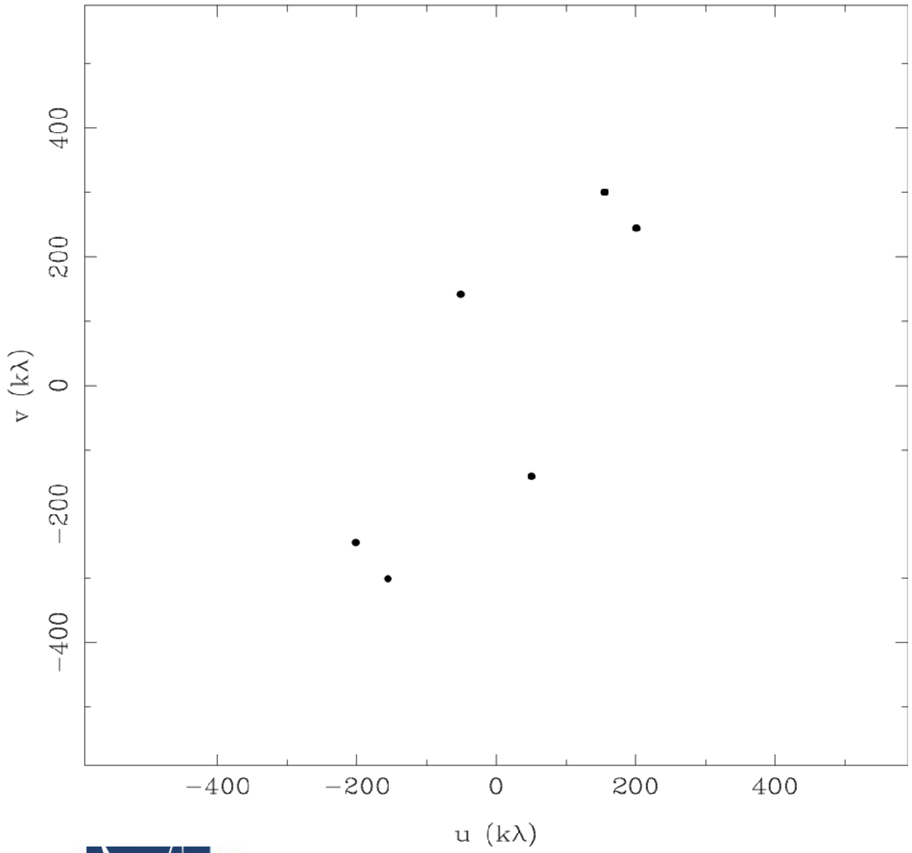
2 Antennas

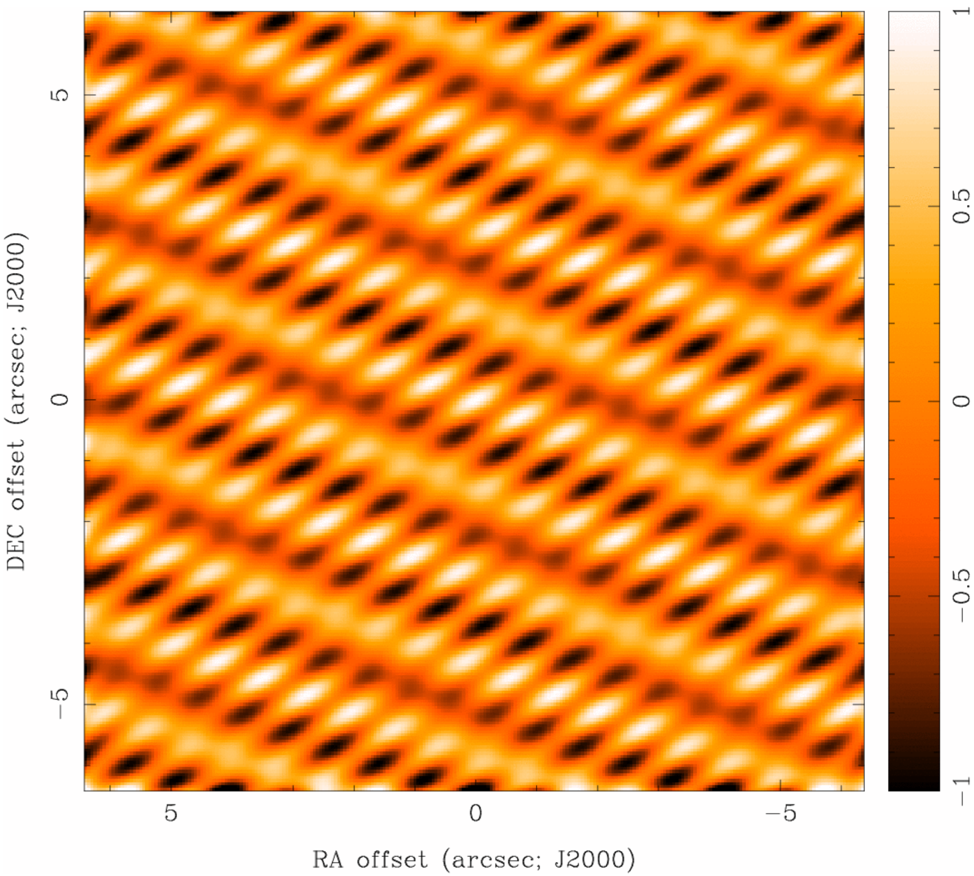




Dirty Beam Shape and N Antennas

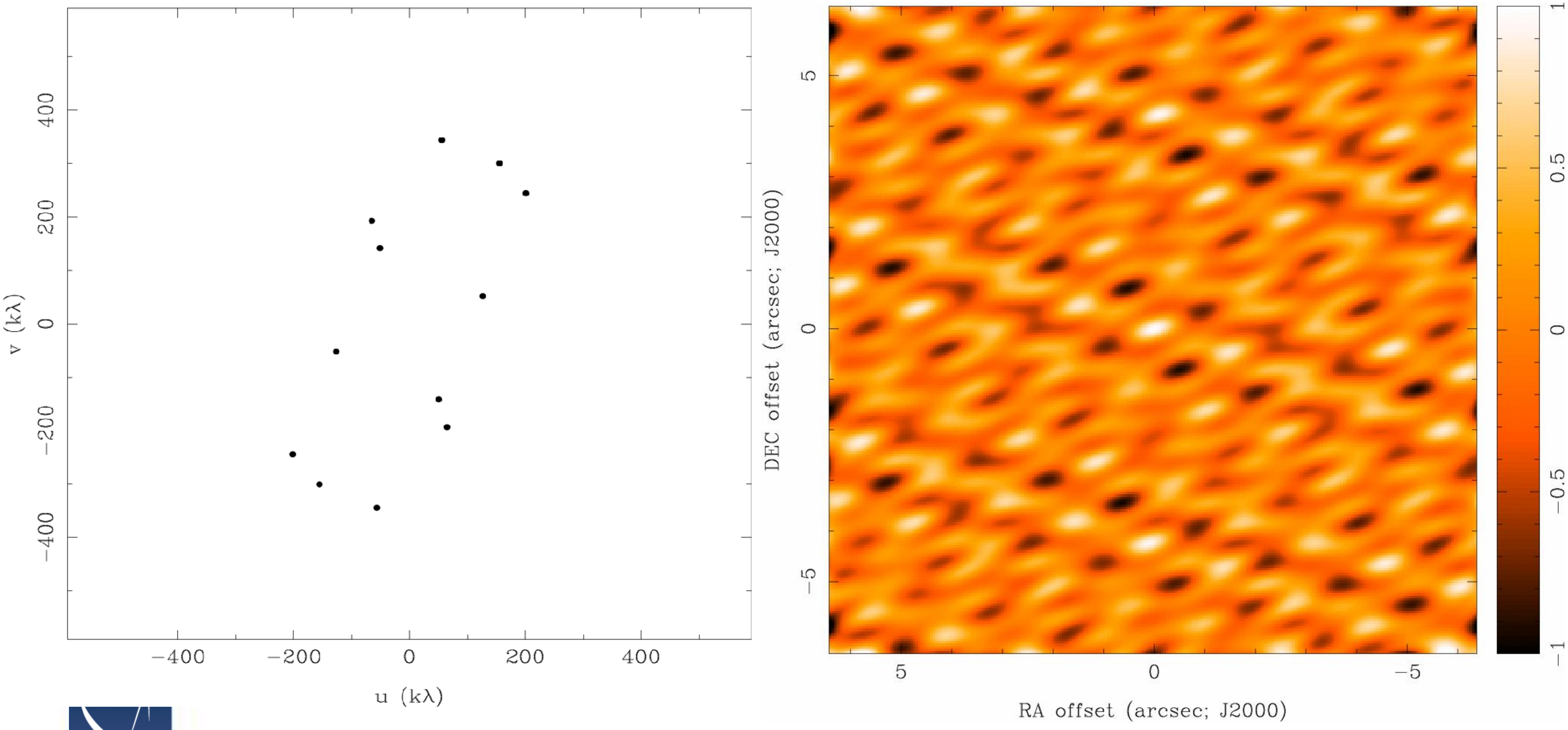
3 Antennas





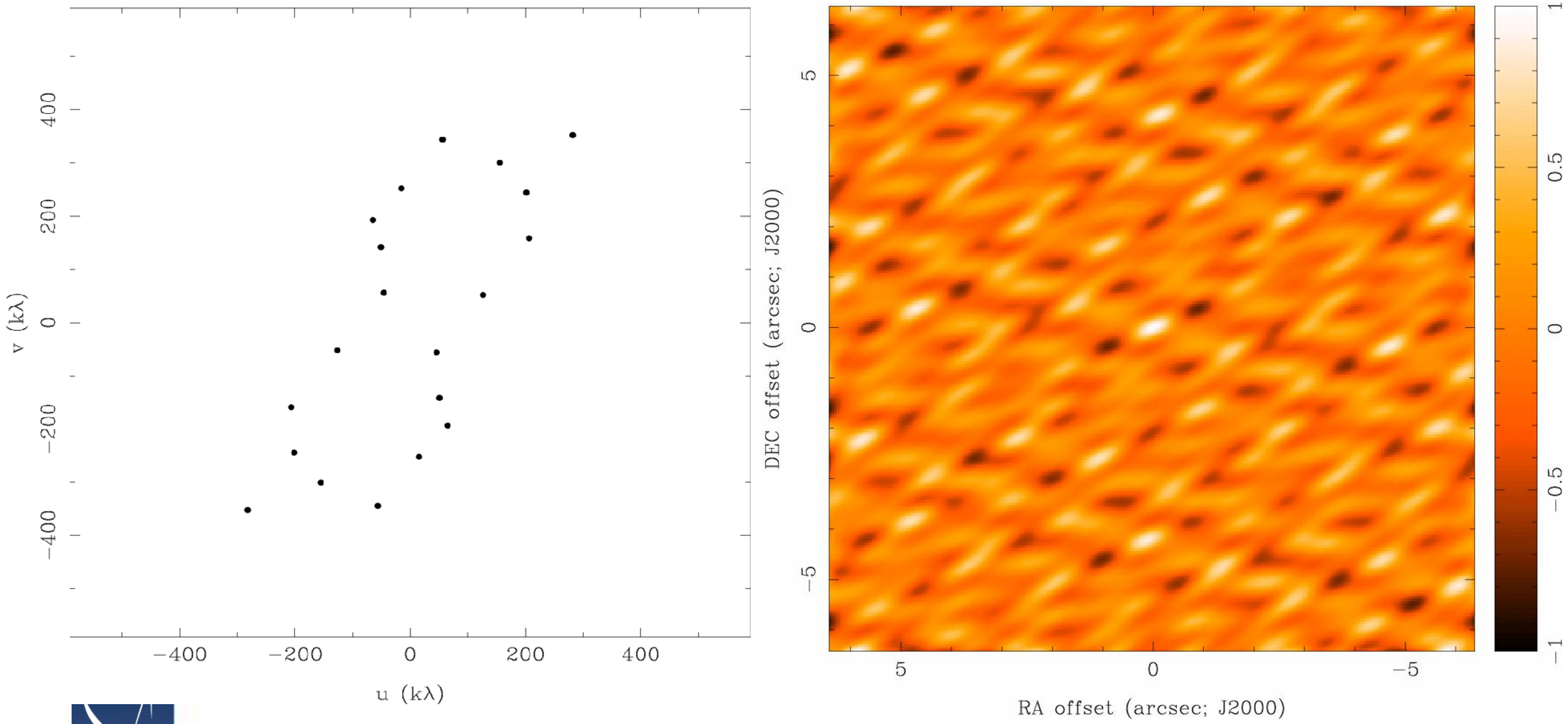
Dirty Beam Shape and N Antennas

4 Antennas



Dirty Beam Shape and N Antennas

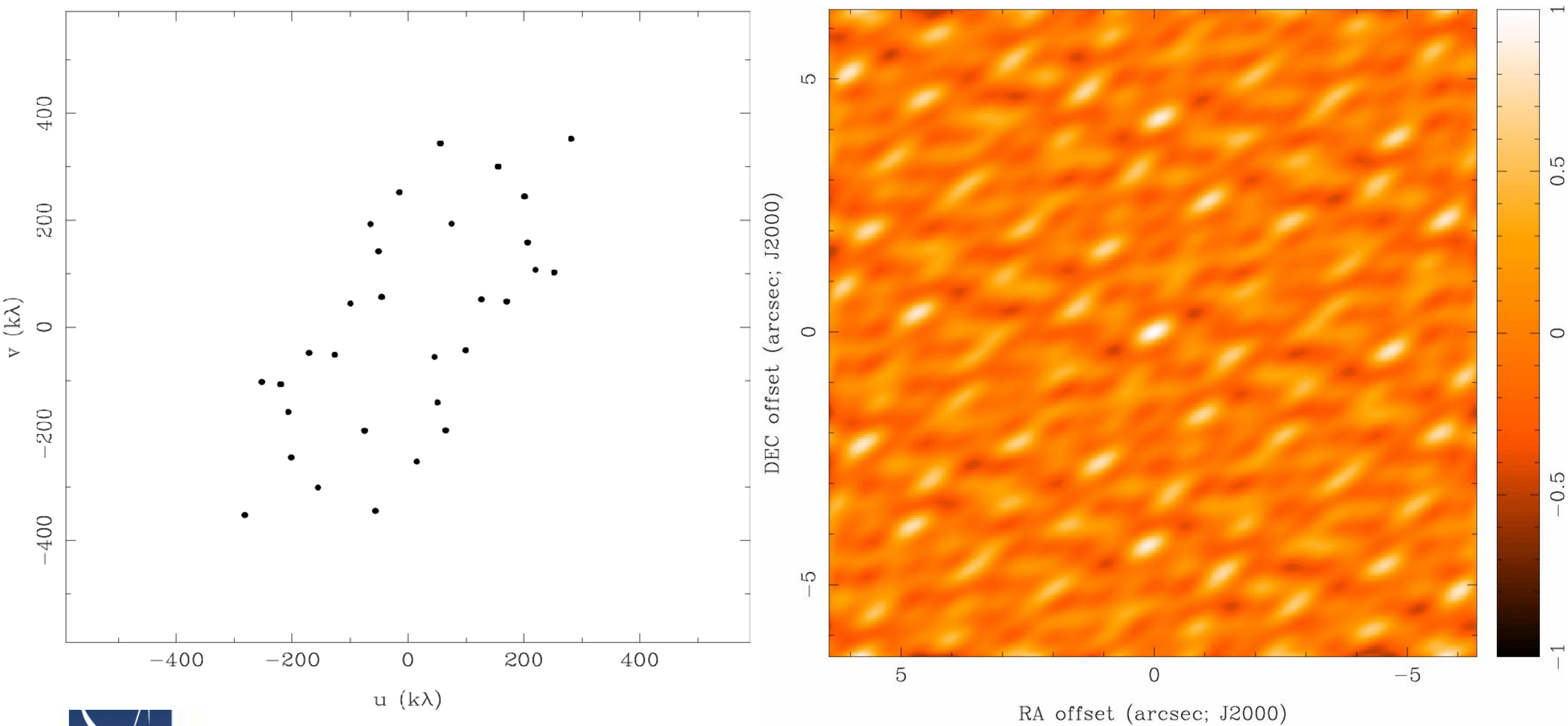
5 Antennas



Dirty Beam Shape and N Antennas

ALMA

6 Antennas



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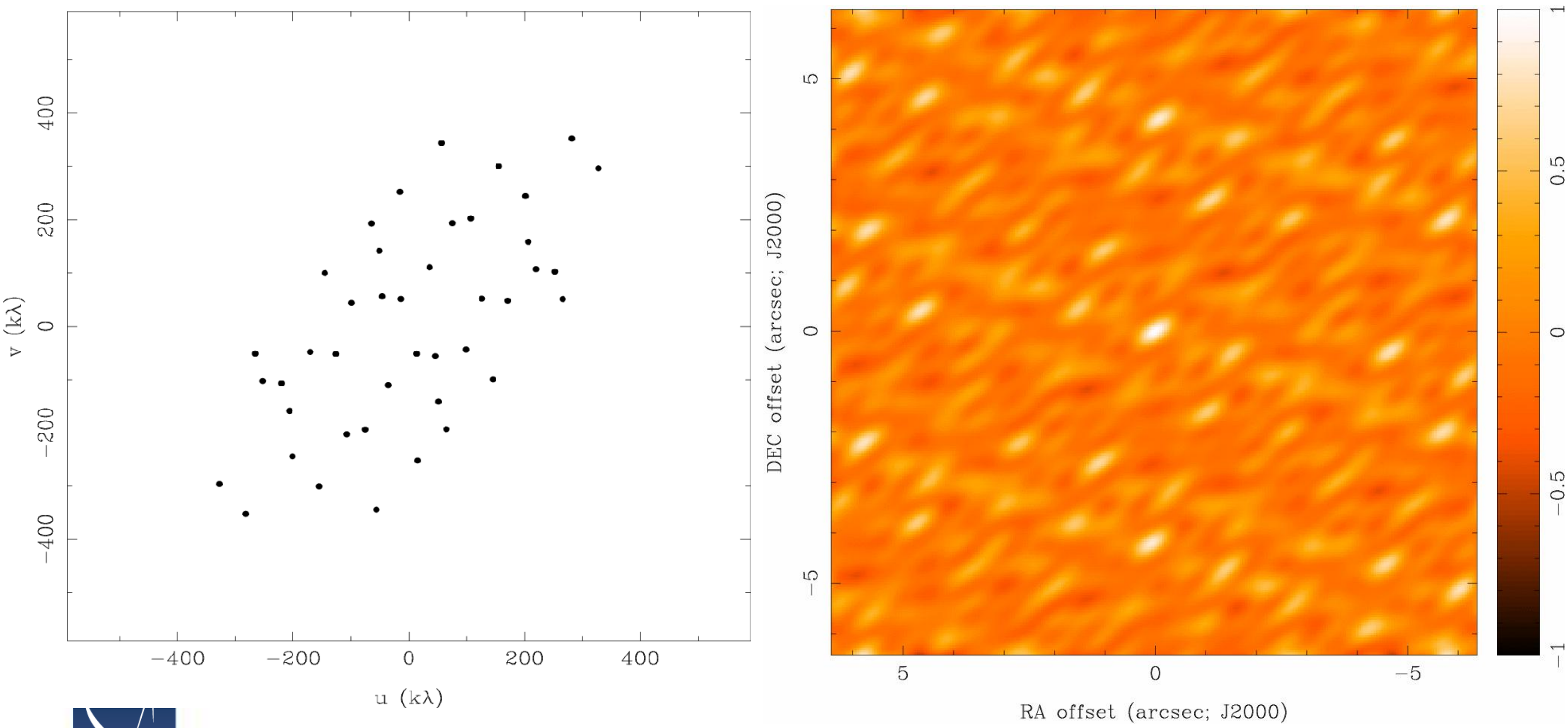
Dirty Beam Shape and N Antennas

7 Antennas



Dirty Beam Shape and N Antennas

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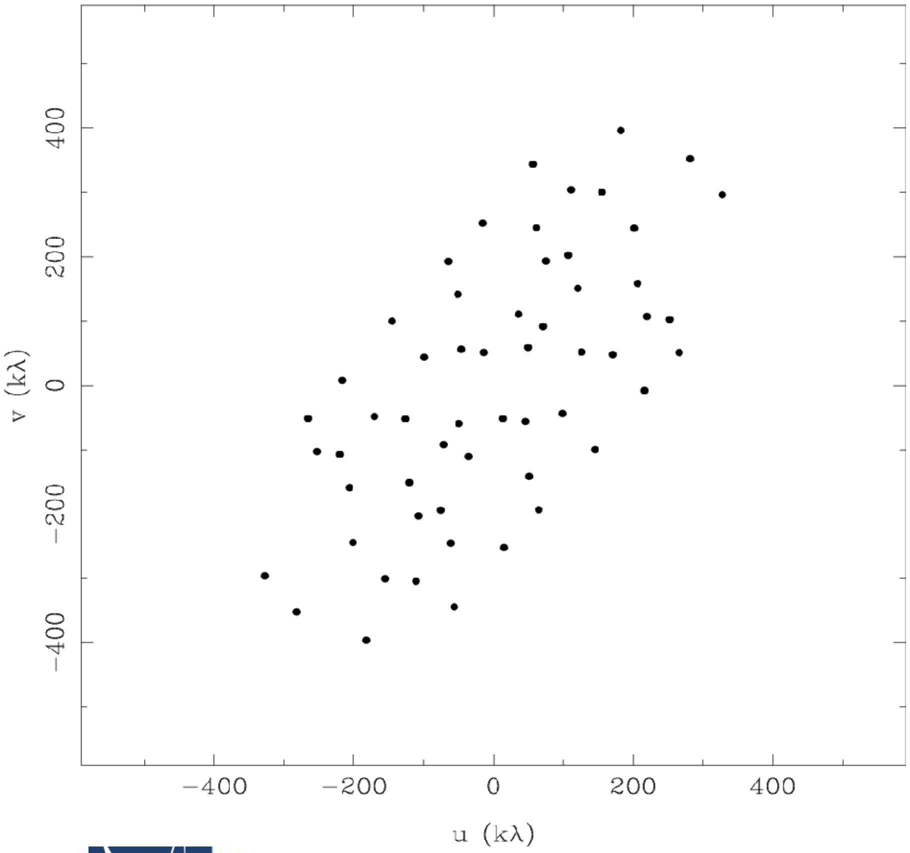
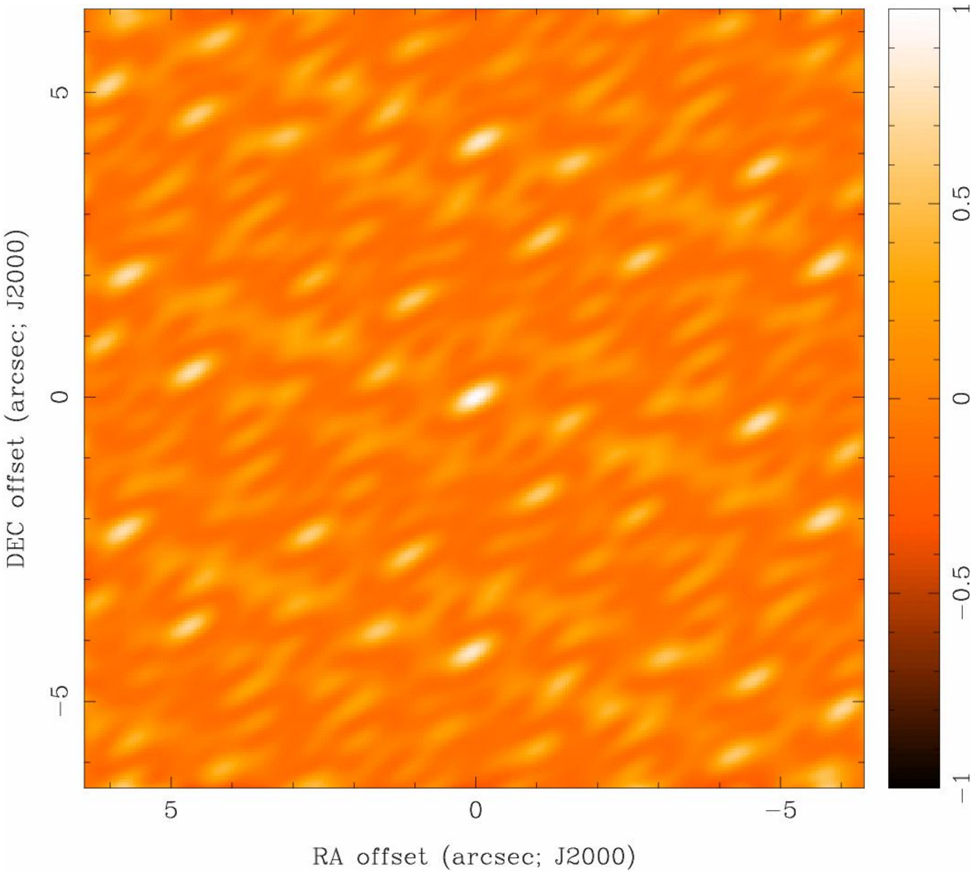
8 Antennas





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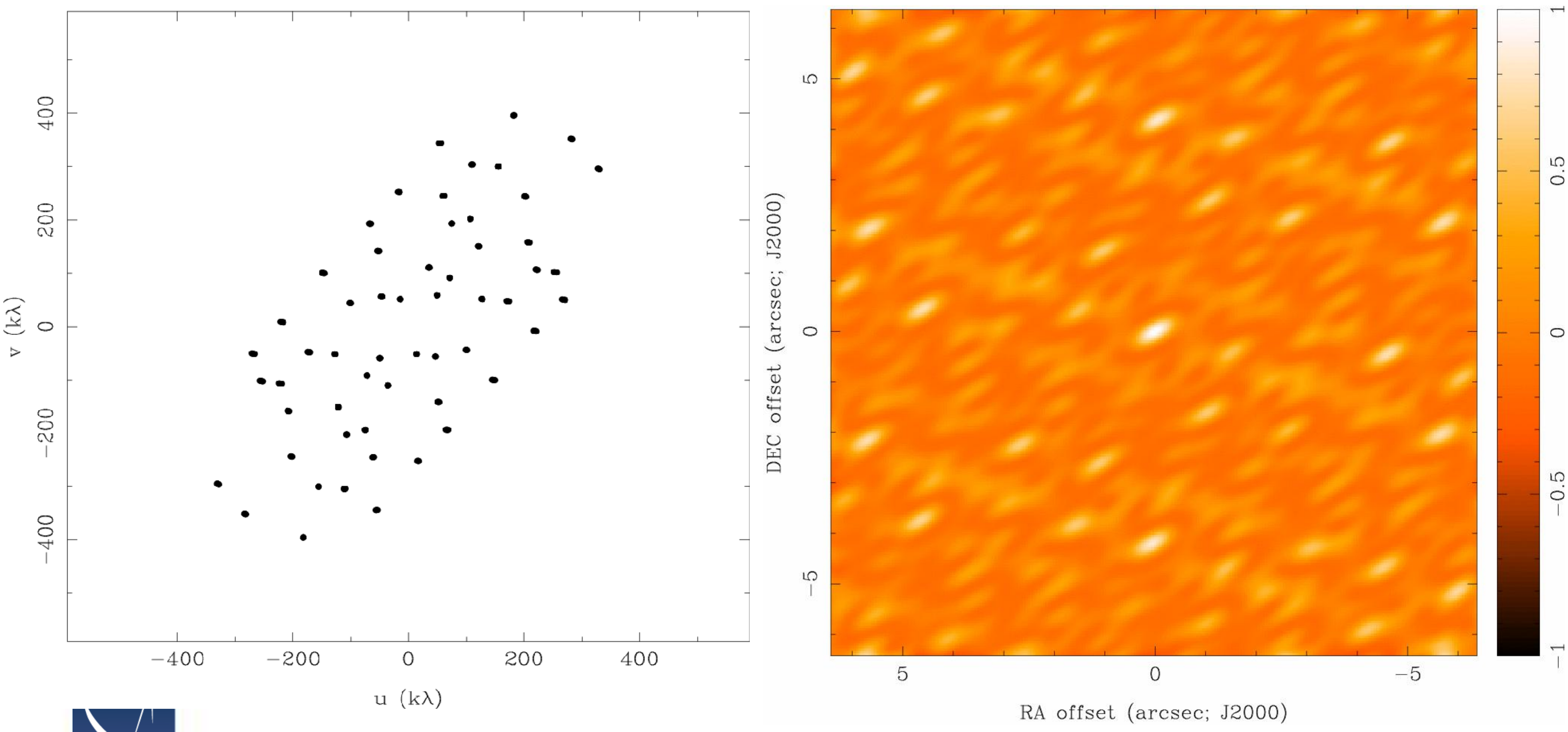
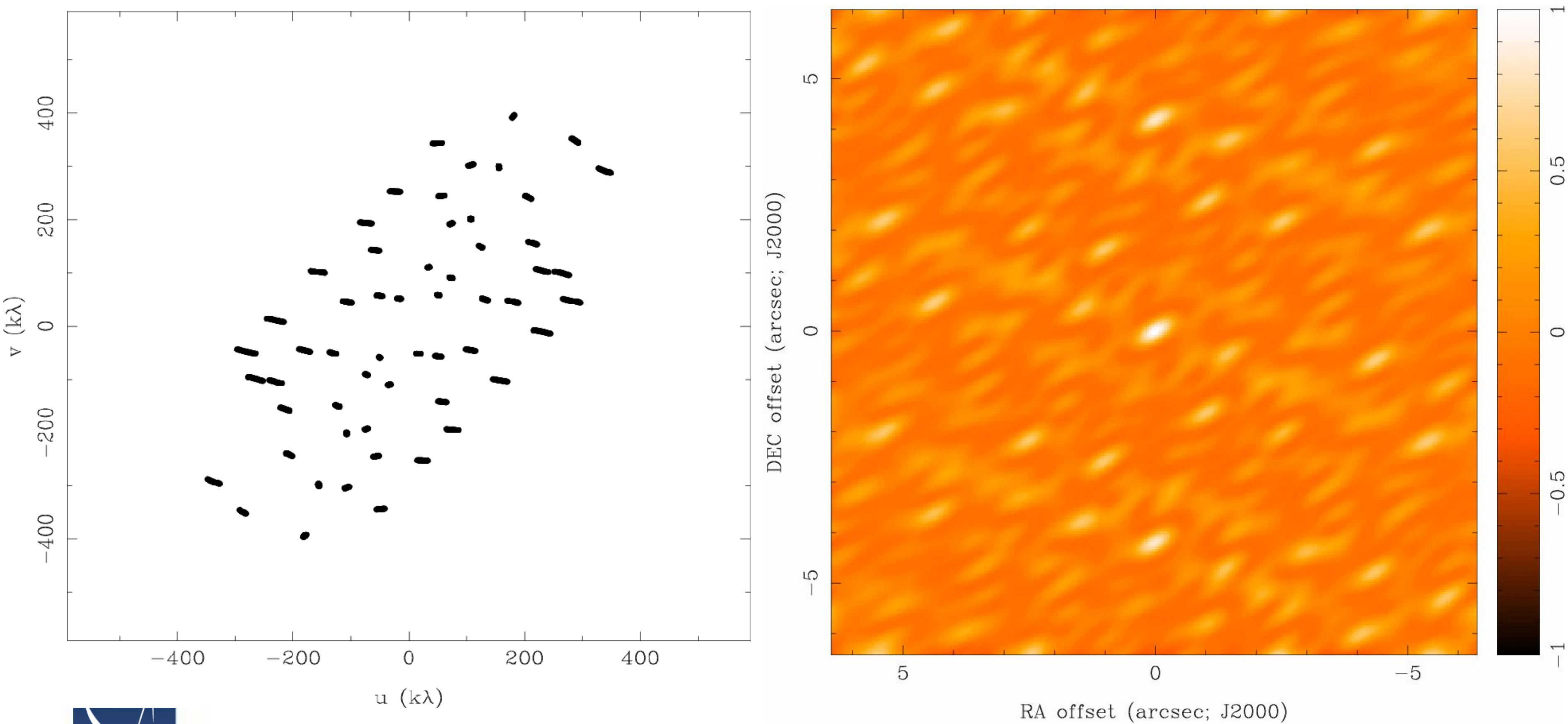
Dirty Beam Shape and N Antennas

8 Antennas x 6 Samples



Dirty Beam Shape and N Antennas

8 Antennas x 30 Samples



Dirty Beam Shape and N Antennas

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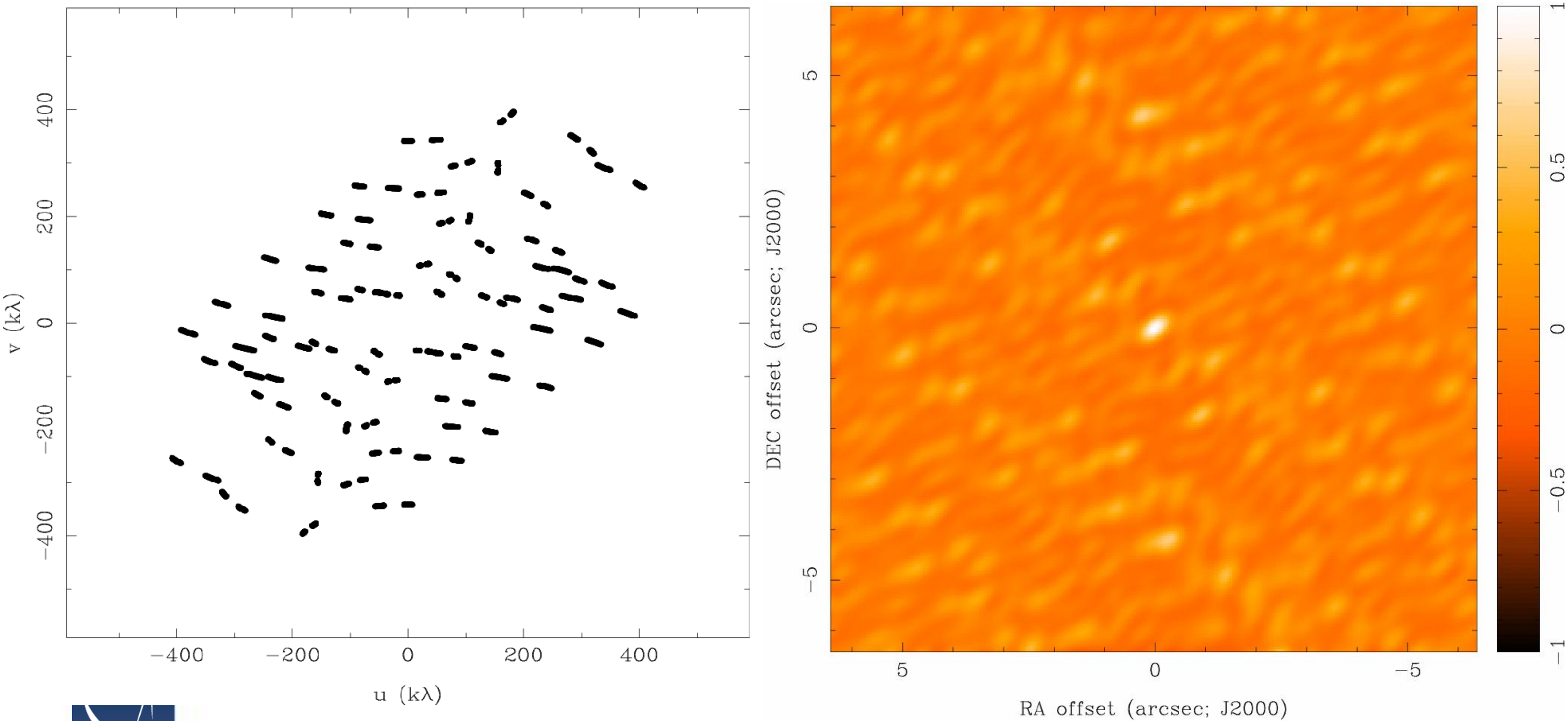
8 Antennas x 60 Samples



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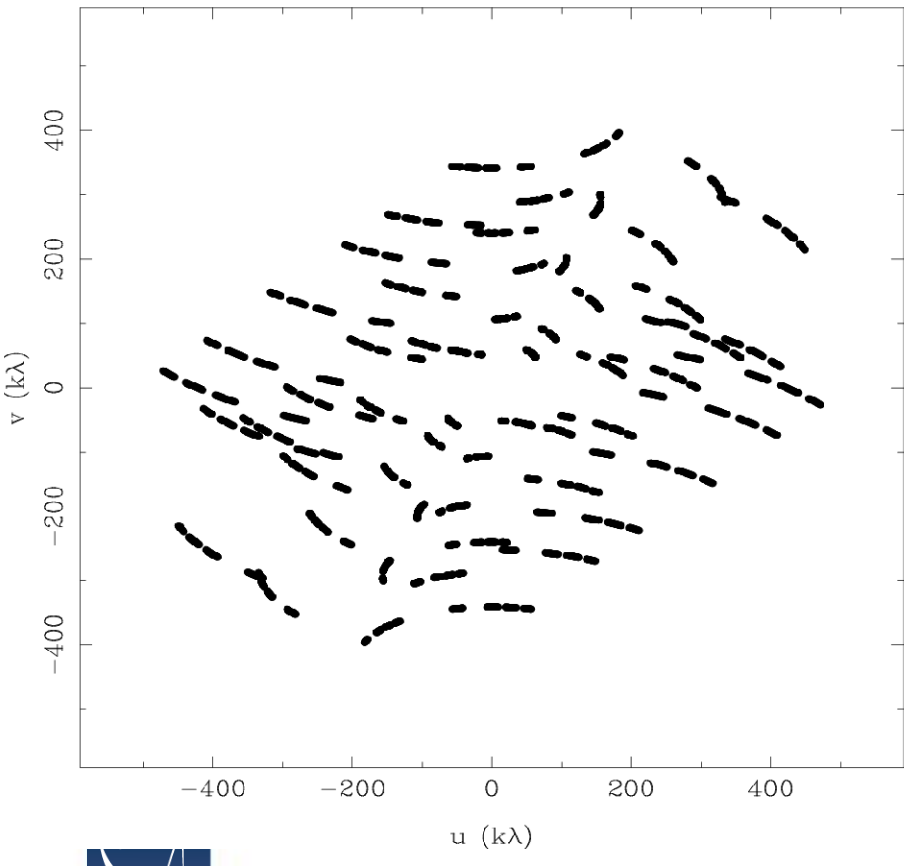
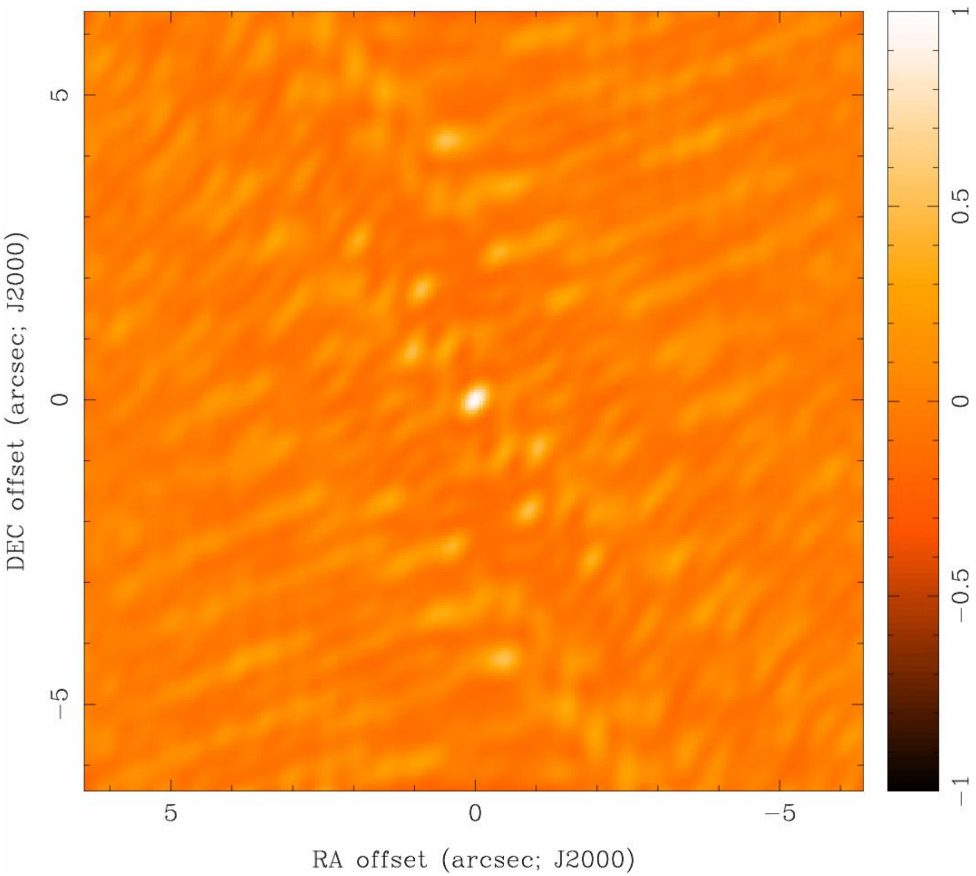
Dirty Beam Shape and N Antennas

8 Antennas x 120 Samples





Dirty Beam Shape and N Antennas

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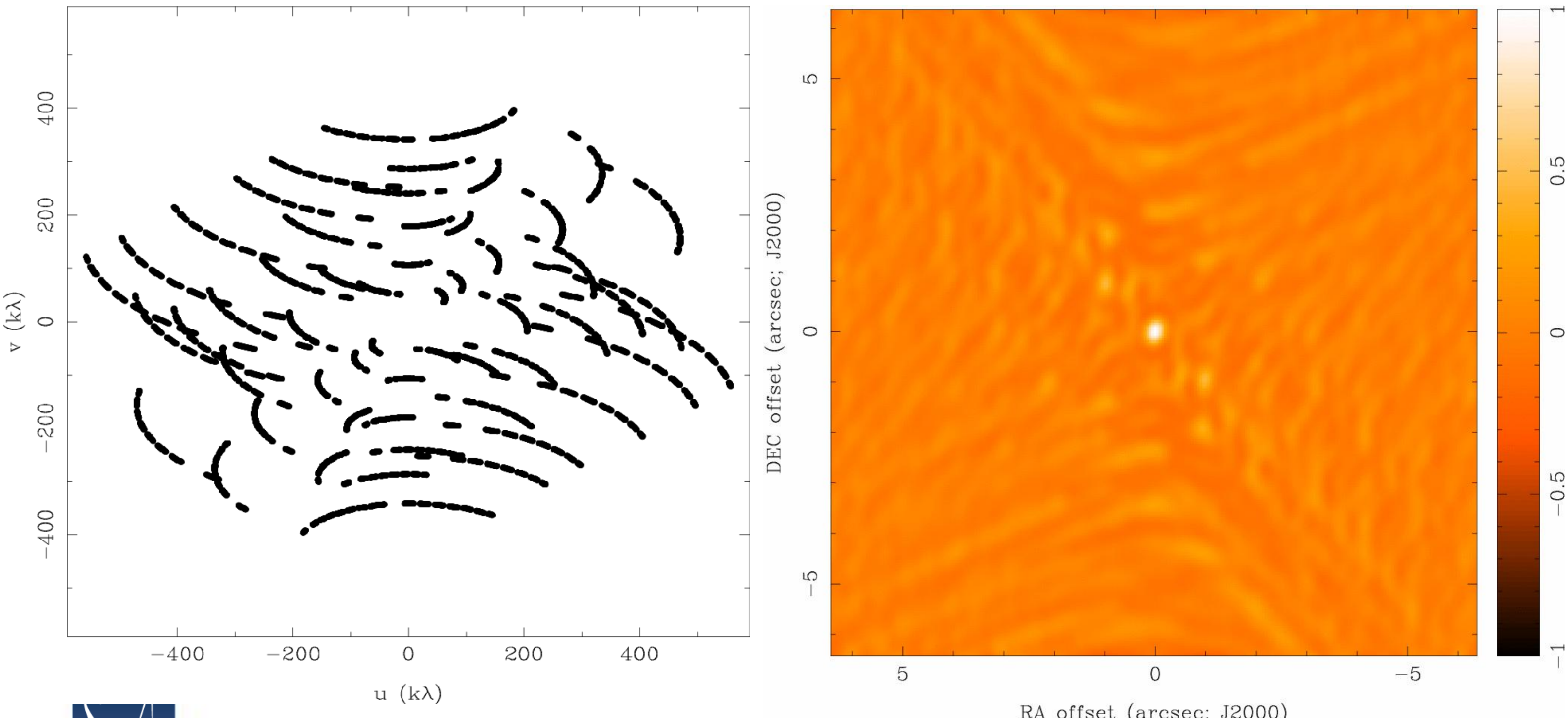
8 Antennas x 240 Samples



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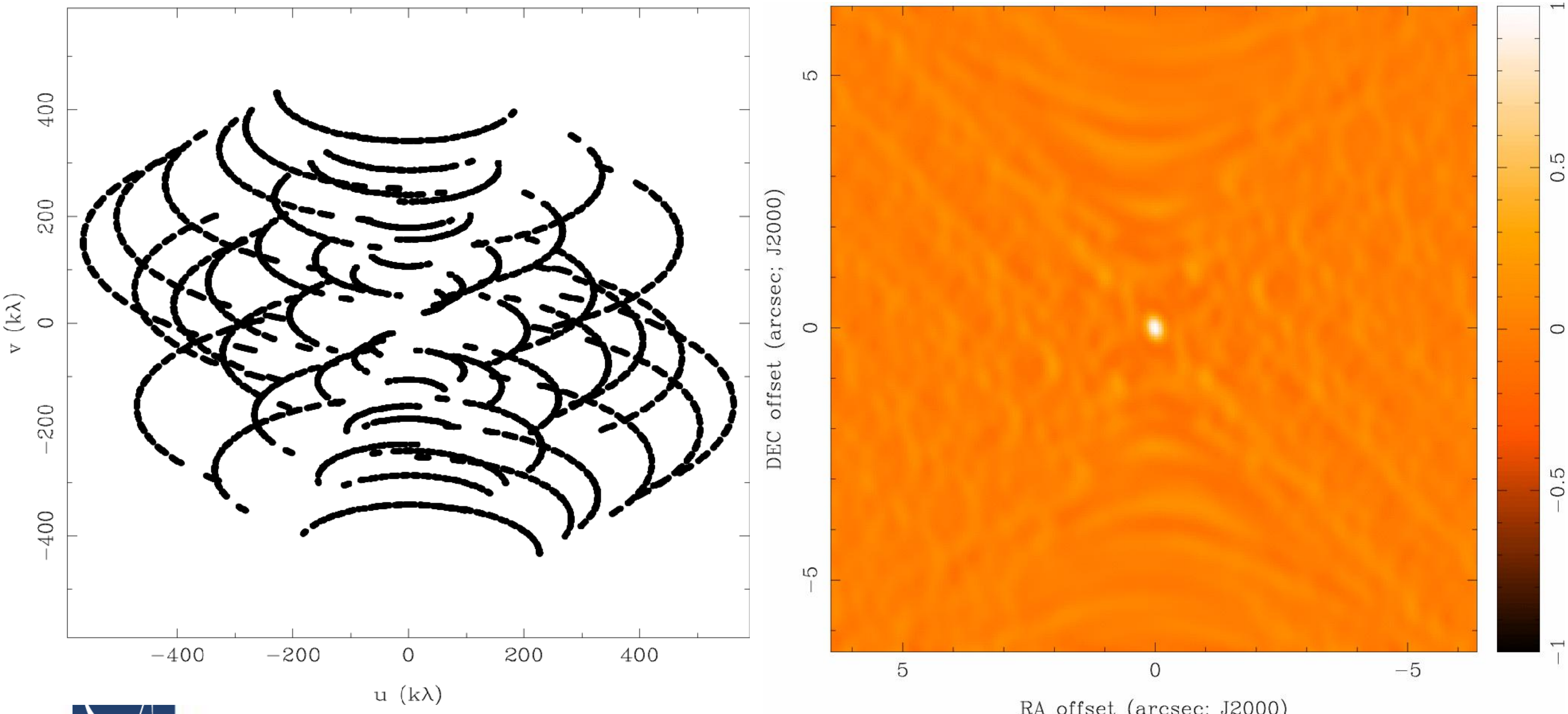
Dirty Beam Shape and N Antennas

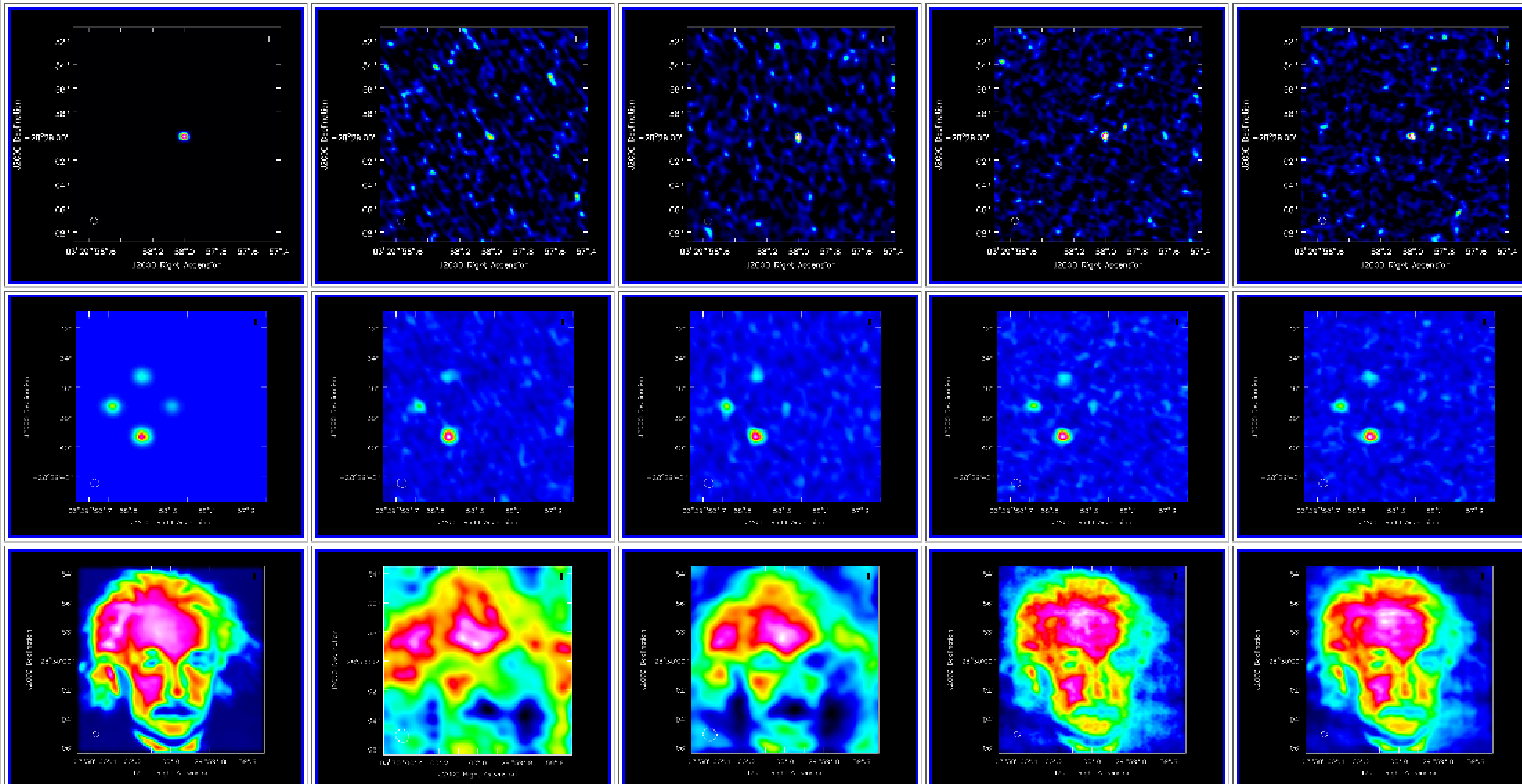
8 Antennas x 480 Samples

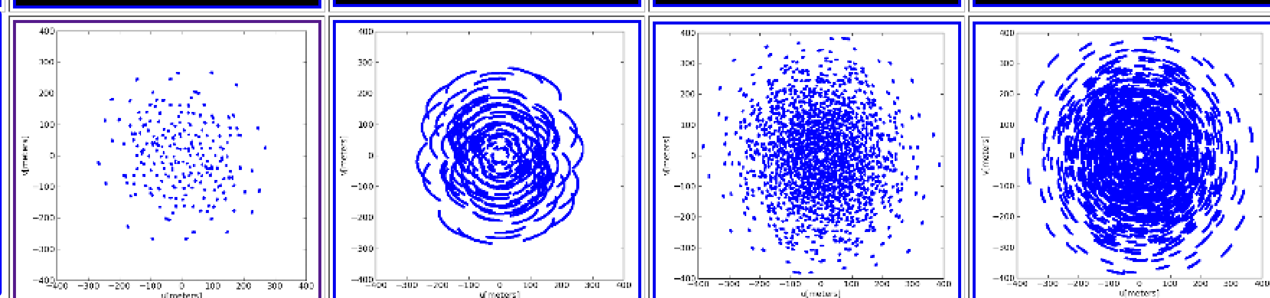


Effects of UV Coverage

ALMA

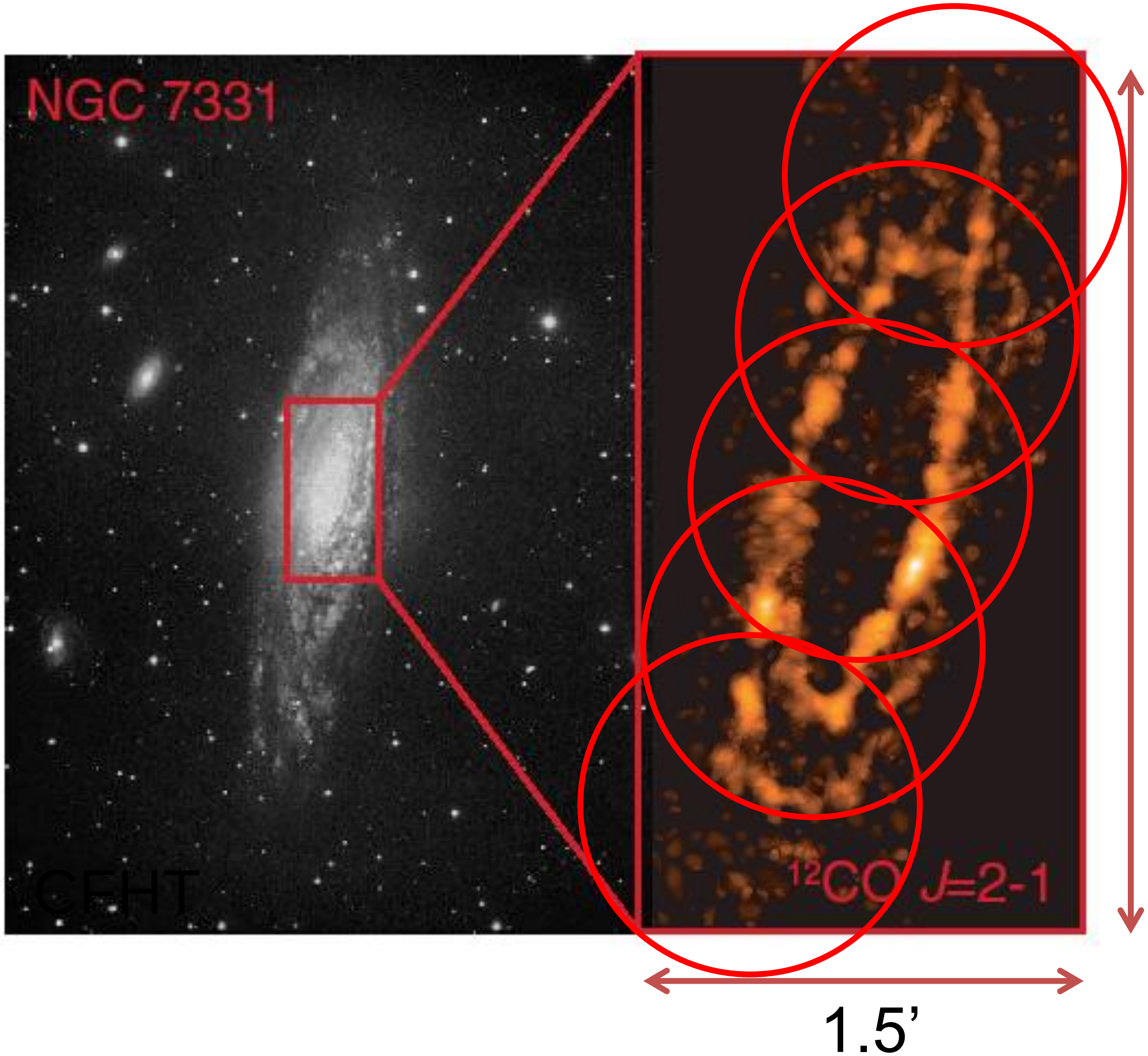
Convolved source models	Early Science (16)		Full Science (50)	
	10 minutes (0.47 mJy rms)	4 hours (0.091 mJy rms)	10 minutes (0.14 mJy rms)	1 hour (0.057 mJy rms)





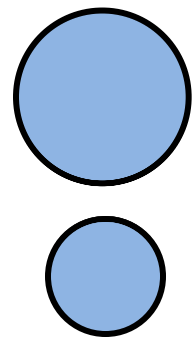
Note improved uv-coverage with time for same config.

Source Size: Single Field or Mosaic



Example: SMA 1.3 mm observations: 5 pointings

- Primary beam ~1’
- Resolution ~3”



Petitpas et al.

In ES, the number of pointings will be limited

Largest Angular Scale

Band	Frequency (GHz)	Primary beam (“)	Approximate Largest Angular Scale in compact configuration (“)
3	84-116	72 - 52	37
6	211-275	29 - 22	18
7	275-373	22 - 16	12
9	602-720	10 – 8.5	6

- **Smooth** structures larger than LAS are completely resolved out
- Begin to loose total recovered flux for objects on the order of half LAS
- The LAS of the 400m configuration will likely be smaller than the 125m configuration

Sensitivity and Brightness Temperature

ALMA

- There will be a factor of 10 difference in brightness temperature sensitivity between the 2 configurations offered in Early Science. Very important to take into account for resolved sources.

The conversion from brightness temperature T to flux S_ν with synthesized beam solid angle Ω_s is

$$S_\nu = \frac{2\,\nu^2\,k\,T}{c^2}\Omega_s.$$

An alternate formulae that is often useful is

$$\left(\frac{T}{1K}\right) = \left(\frac{S_\nu}{1\ \mathrm{Jy\ beam}^{-1}}\right)\left[13.6\left(\frac{300\ \mathrm{GHz}}{\nu}\right)^2\left(\frac{1''}{\theta_{max}}\right)\left(\frac{1''}{\theta_{min}}\right)\right]$$

Example: 1 minute integration at 230 GHz with 1 km/sec channels:

Configuration	Beamsize	Flux density Sensitivity	Brightness sensitivity
125 m	3”	48 mJy/beam	0.14 K
400 m	1”	48 mJy/beam	1.2 K

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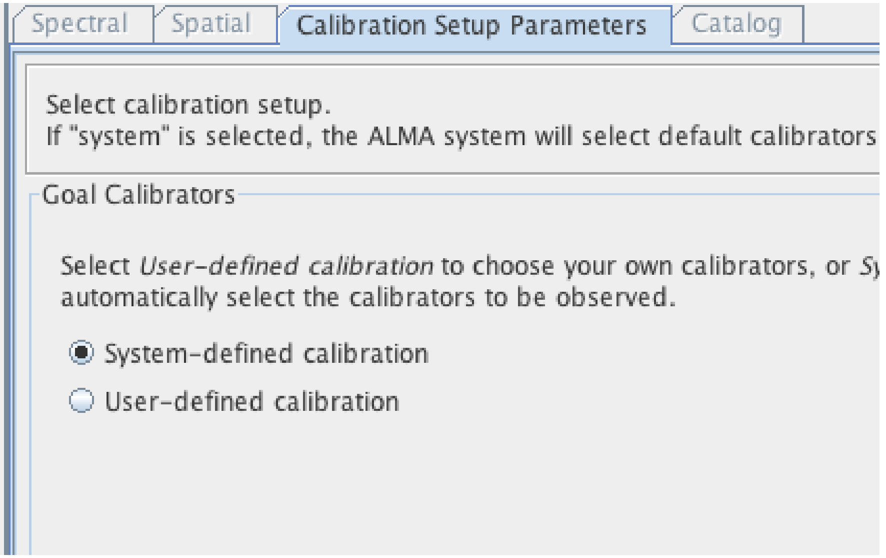
Observatory Default Calibration

- Need to measure and remove the (time-dependent and frequency-dependent) atmospheric and instrumental variations.

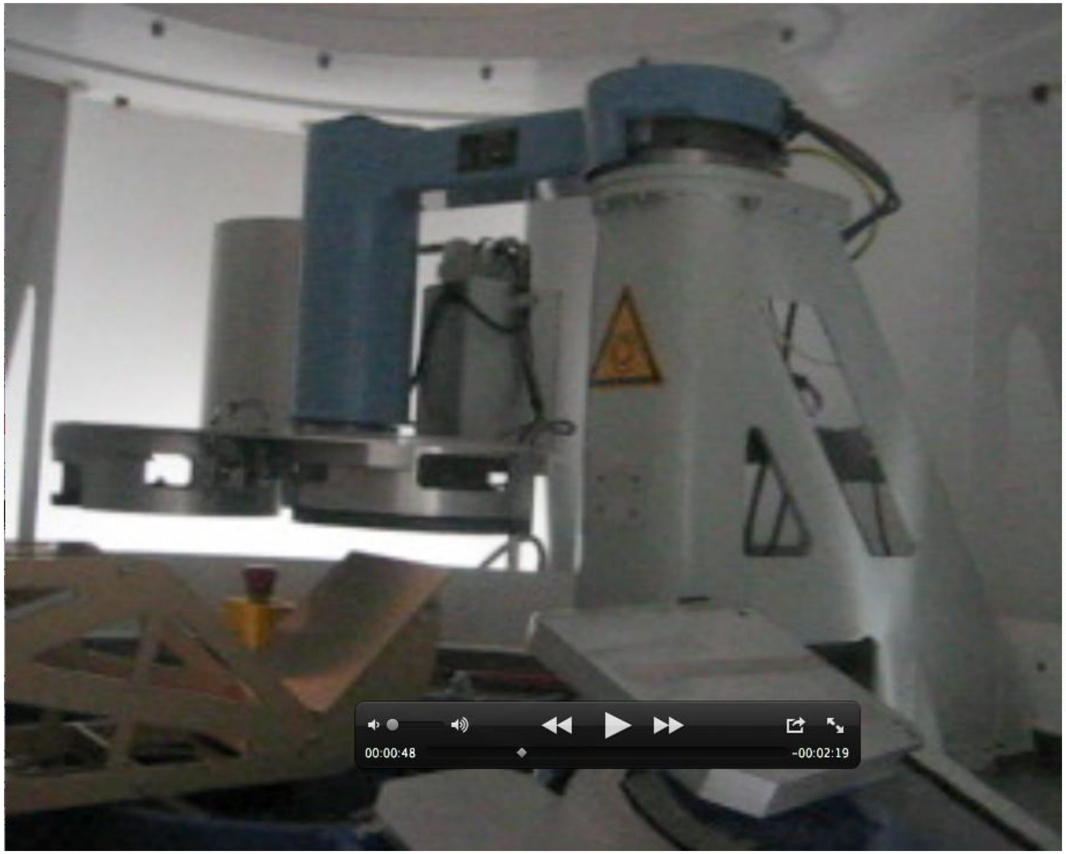
- Set calibration to **system-defined calibration** unless you have very specific requirements for calibration (which then must be explained in the Technical Justification). Defaults include (suitable calibrators are chosen at observation time):

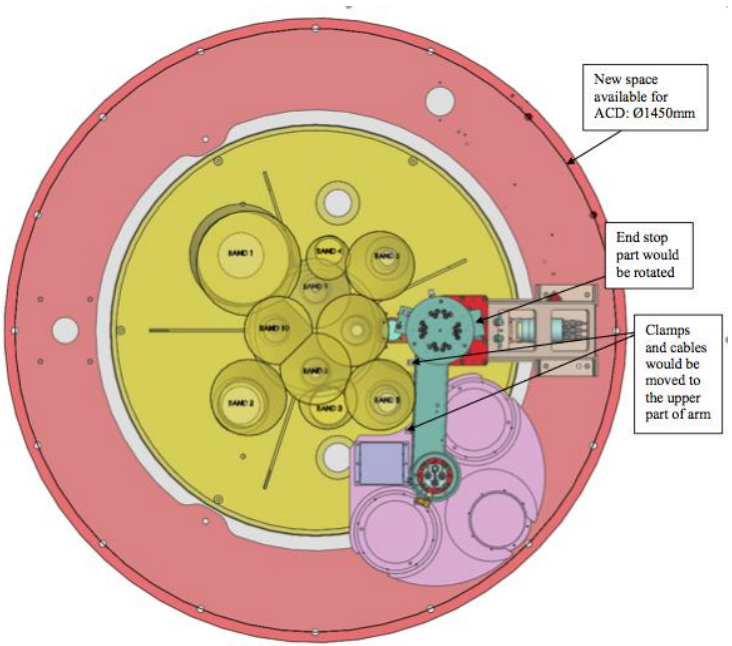
1. Pointing, focus, and delay calibration
2. Phase and amplitude gain calibration
3. Absolute flux calibration
4. Bandpass calibration
5. System Temperature calibration
6. Water-vapor radiometry correction



ALMA Calibration Device

Two-temperature load system (100C & ambient) maneuvered by robotic arm (shown in a Melco antenna below)





$$T_{sys} \approx T_{atm}(e^{\tau}-1) + T_{rx}e^{\tau}$$

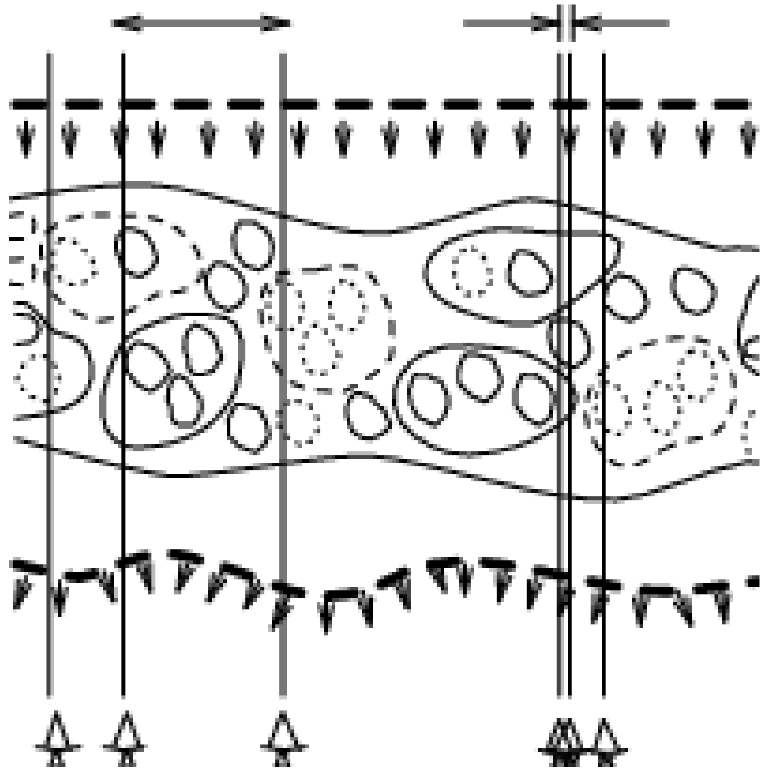
$$\tau = \tau_o \sec(el)$$

Atmospheric phase fluctuations

ALMA

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths (higher frequencies), and result in
  - Low coherence (loss of sensitivity)
  - Radio "seeing", typically 1″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

You can observe in apparently excellent submm weather (in terms of transparency) and still have terrible "seeing" i.e. phase stability.



Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

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Phase fluctuation correction methods

- **Fast switching:** used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

	Band 9 (690 GHz)	Band 7 (345 GHz)
50 antennas, 2pol, 8GHz, 1 minute	0.64 mJy/beam	0.10
1 baseline, 2pol, 8GHz, 1 minute	15 mJy	2.5
1 baseline, 1pol, 2 GHz	60 mJy	10 mJy
3-sigma	180 mJy	30 mJy

- Traditional calibrators (quasars) are more scarce at high frequency
- But ALMA sensitivity is high, even on a per baseline basis
- Key will be calibrator surveys (probably starting with ATCA survey)

Phase fluctuation correction methods

ALMA

- Fast switching: used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

However, the atmosphere often varies faster than the timescale of Fast Switching. The solution = WVR

- **Water Vapor Radiometry (WVR) concept**: measure the rapid fluctuations in T_B^{atm} with a radiometer at each antenna, then use these measurements to derive changes in water vapor column (w) and convert these into phase corrections using:

$$\otimes\phi_e \approx 12.6\pi\otimes w/\lambda$$

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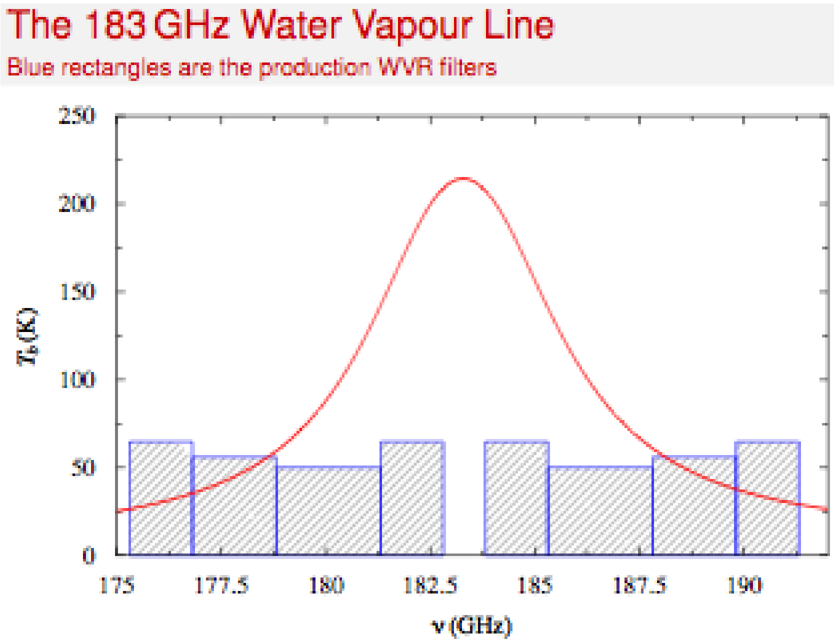
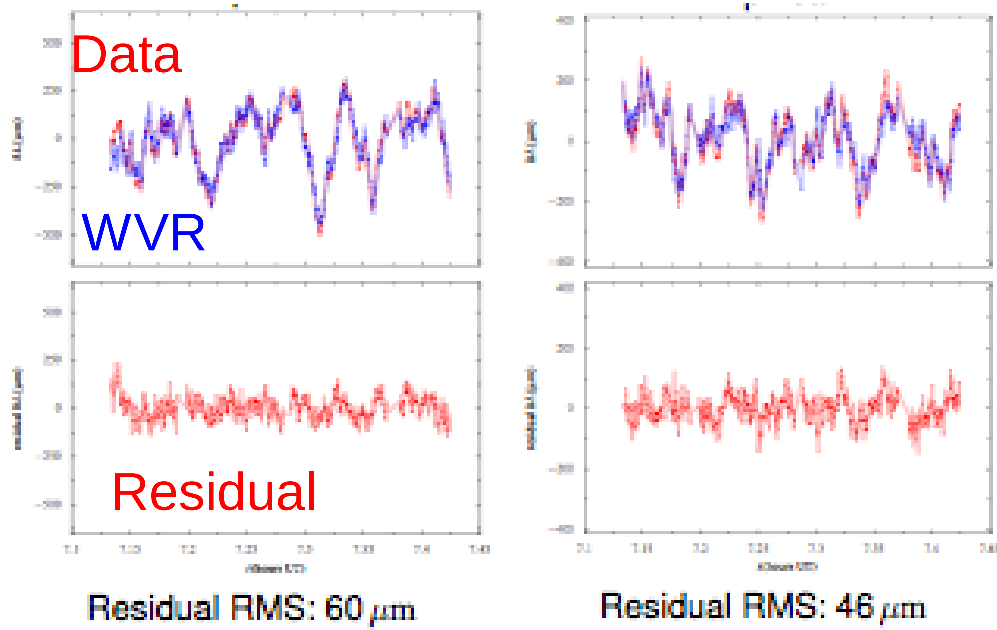
Tests of ALMA WVR Correction

Two different baselines Jan 4, 2010



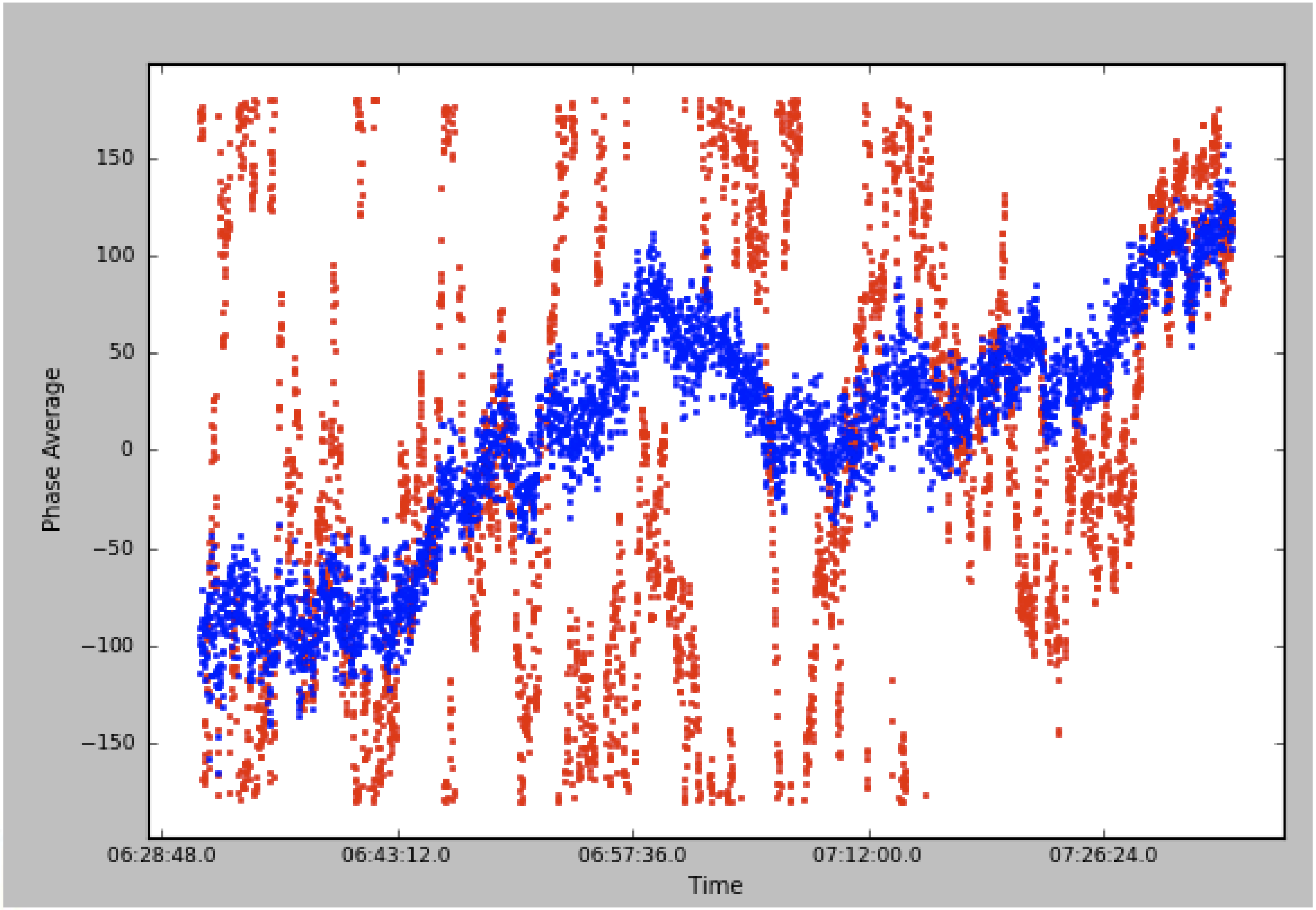


There are 4 “channels” flanking the peak of the 183 GHz water line

- Matching data from opposite sides are averaged
- Data taken every second, and are written to the ASDM (science data file)
- The four channels allow flexibility for avoiding saturation
- Next challenges are to perfect models for relating the WVR data to the correction for the data to reduce residual phase noise prior to performing the traditional calibration steps.

Tests of ALMA WVR Correction

600m baseline, Mar 2011 (red=raw, blue=corrected)



Phase fluctuation correction methods

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- **Fast switching**: used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

- **Water Vapor Radiometry**: measure rapid fluctuations in T_B^{atm} with a radiometer, then use these to derive changes in water vapor column (w) and convert these into phase corrections using: $\otimes\phi_e \approx 12.6\pi\otimes w/\lambda$

- **Phase transfer:** alternate observations at low frequency (calibrator) and high frequency (science target), and transfer scaled phase solutions from low to high frequency. Can be tricky, requires well characterized system due to differing electronics at the frequencies of interest.

- **Self-calibration**: for bright sources. Need S/N per baseline of a few on short times scales (typically a few seconds).

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Future Capabilities

ALMA

- >3x better sensitivity with 50 x 12m antennas in main array
    - Fantastic "snapshot" uv-coverage (1225 baselines)
    - Imaging fidelity ~10x better!
- Higher angular resolution: baselines ~15km, matched beams possible in all bands
- Better imaging of resolved objects and mosaics
    - TPA: 4 x 12m antennas with subreflector nutators
    - ACA: Atacama Compact configuration 12 x 7m antennas
    - "On-the-Fly" mosaics: quickly cover larger areas of sky
- More receiver bands: 4, 8, 10 (2mm, 0.7mm, 0.35mm)
- Polarization: magnetic fields and very high dynamic range imaging
- "Mixed" correlator modes (simultaneous wide & narrow, see A&A 462, 801)
- ALMA development program ➔ studies just beginning
    - mm VLBI
    - More receiver bands
    - Higher data rates

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ALMA

ATACAMA LARGE MILLIMETER ARRAY

www.almaobservatory.org

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership among Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).