Other Imaging Techniques Like Self-Calibration and Data Combination

Slides by Dominic Ludovici and Emily Moravec for self-calibration, and
by Adele Plunkett and Emily Moravec for data combination

National Radio
Astronomy
Observatory

Self-Calibration

National Radio Astronomy Observatory

A Quick review of calibration

Interferometers measure “visibilities”: the amplitude and phase information of the cross-correlated signals between pairs of antennas.

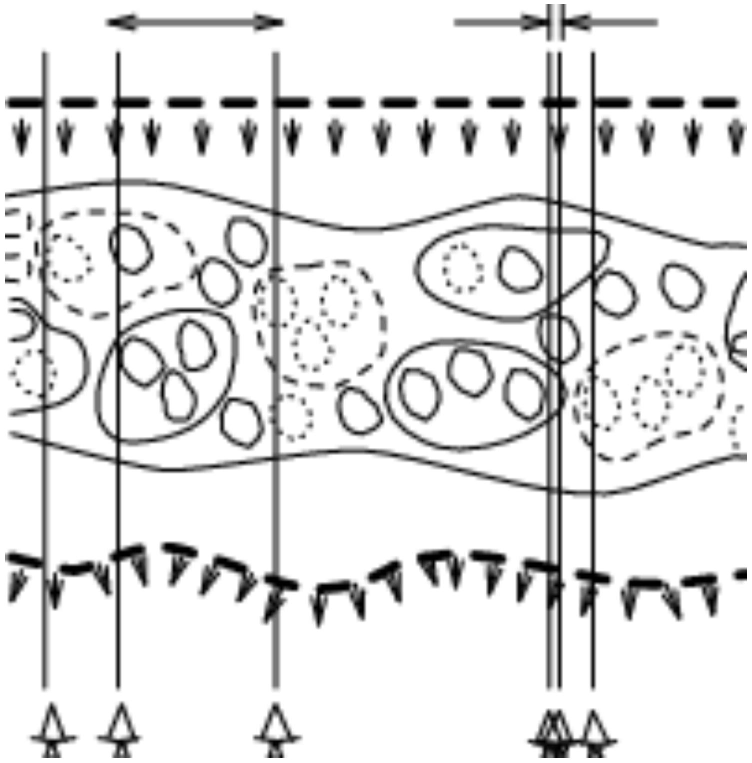
The true visibility is corrupted by many effects:

Antenna based:

- Atmospheric attenuation
- Radio “seeing”
- Variable pointing offsets
- Variable delay offsets
- Electronic gain changes
- Electronic delay changes
- Electronic phase changes

Baseline based:

- Radiometer noise
- Correlator malfunctions
- Most Interference signals



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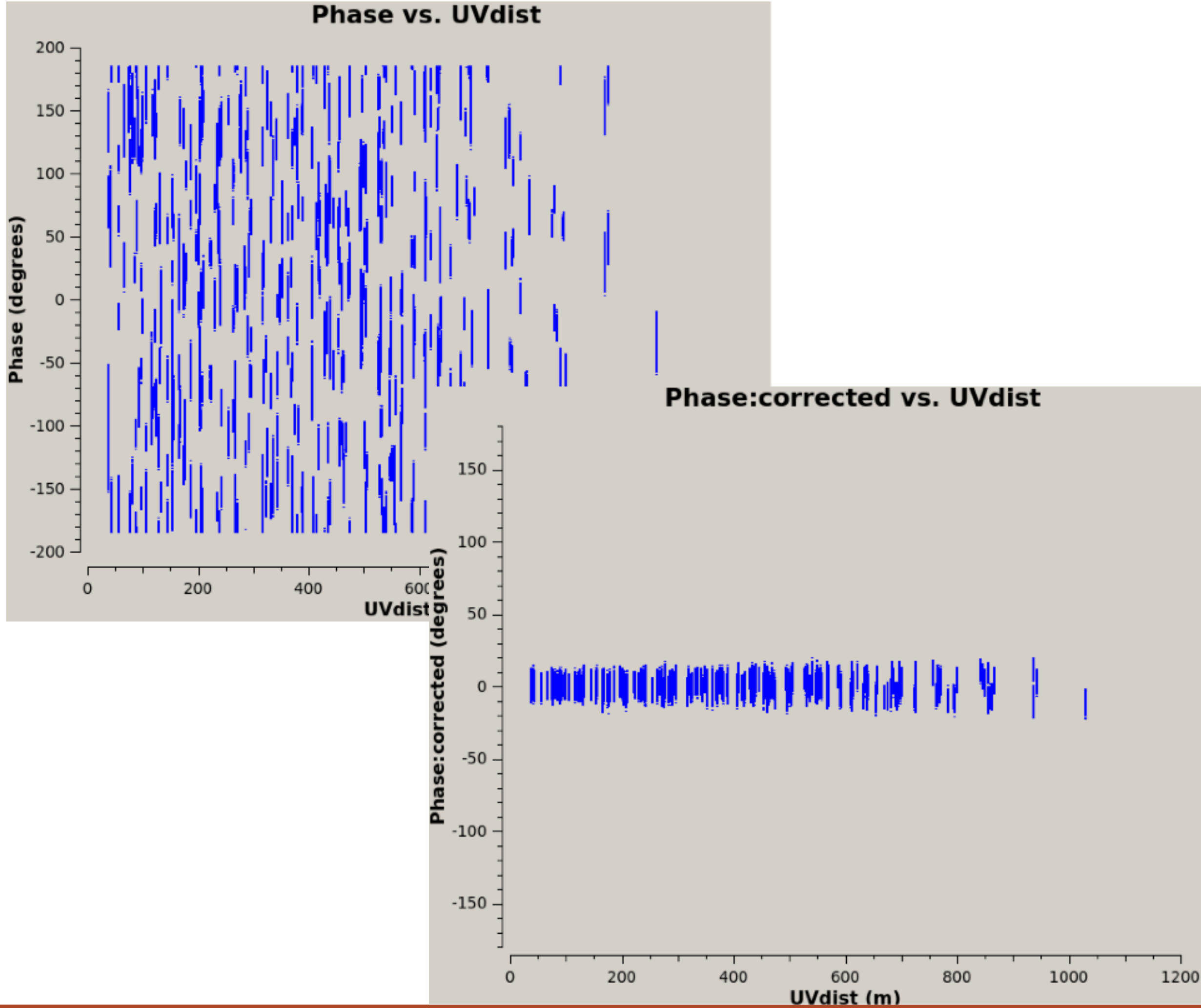
We calibrate these data by determining the complex gains (amplitude and phase) and the frequency response (bandpass) for each antenna. To do this, we observe a bandpass, flux, and phase calibrator

Discussion:

What is special about the calibrators?

There are lists of calibrators for both ALMA and VLA. What makes them special?



Phase vs UVdist

VLA Flux Calibrator 3C138

A Quick review of calibration

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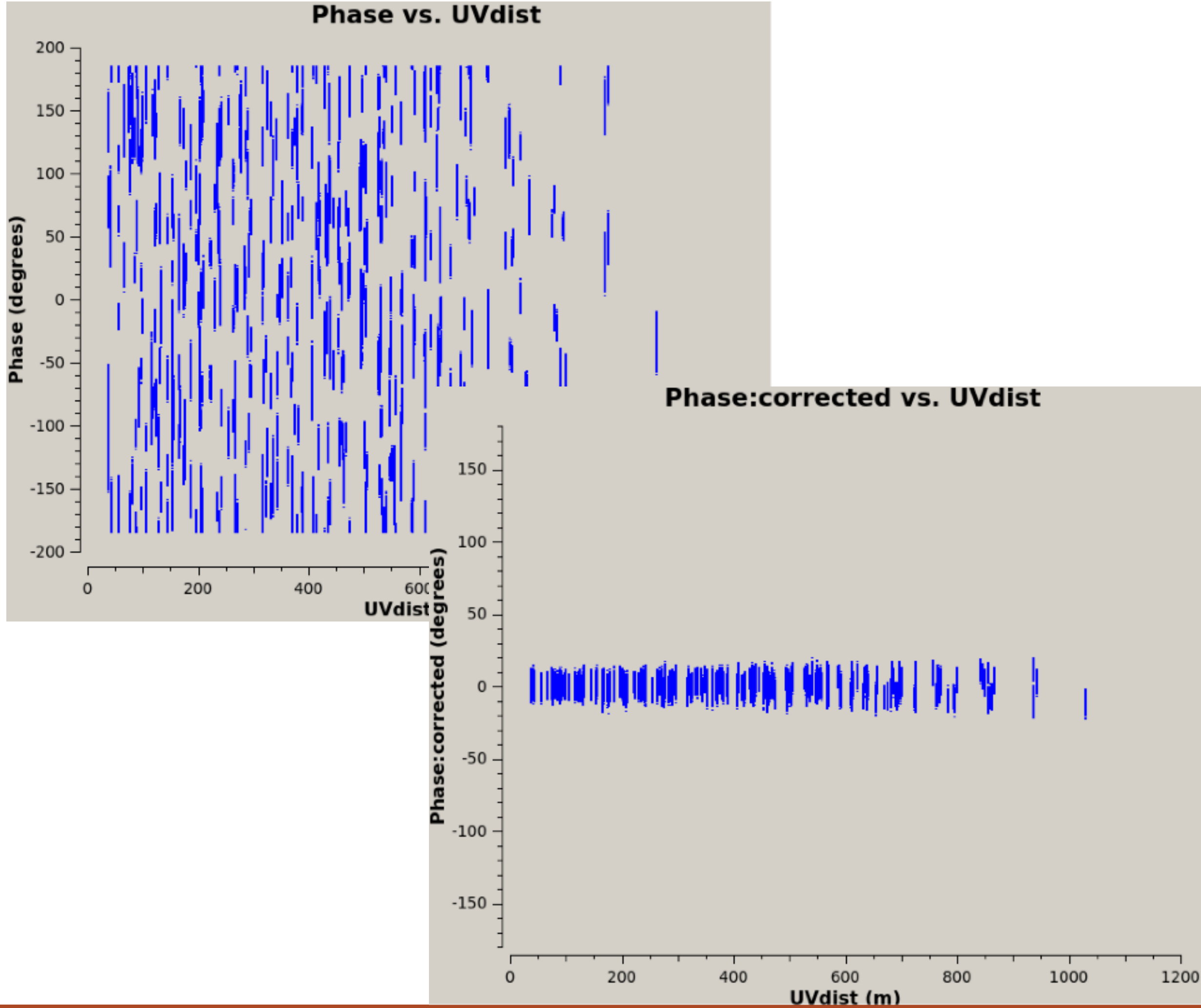
Discussion:

What is special about the calibrators?

There are lists of calibrators for both ALMA and VLA. What makes them special?

- Sources are monitored
- Well known Flux and structure
    - High SNR
    - Point source (preferred)
    - No spectral Features (Bandpass)
    - No short term variability



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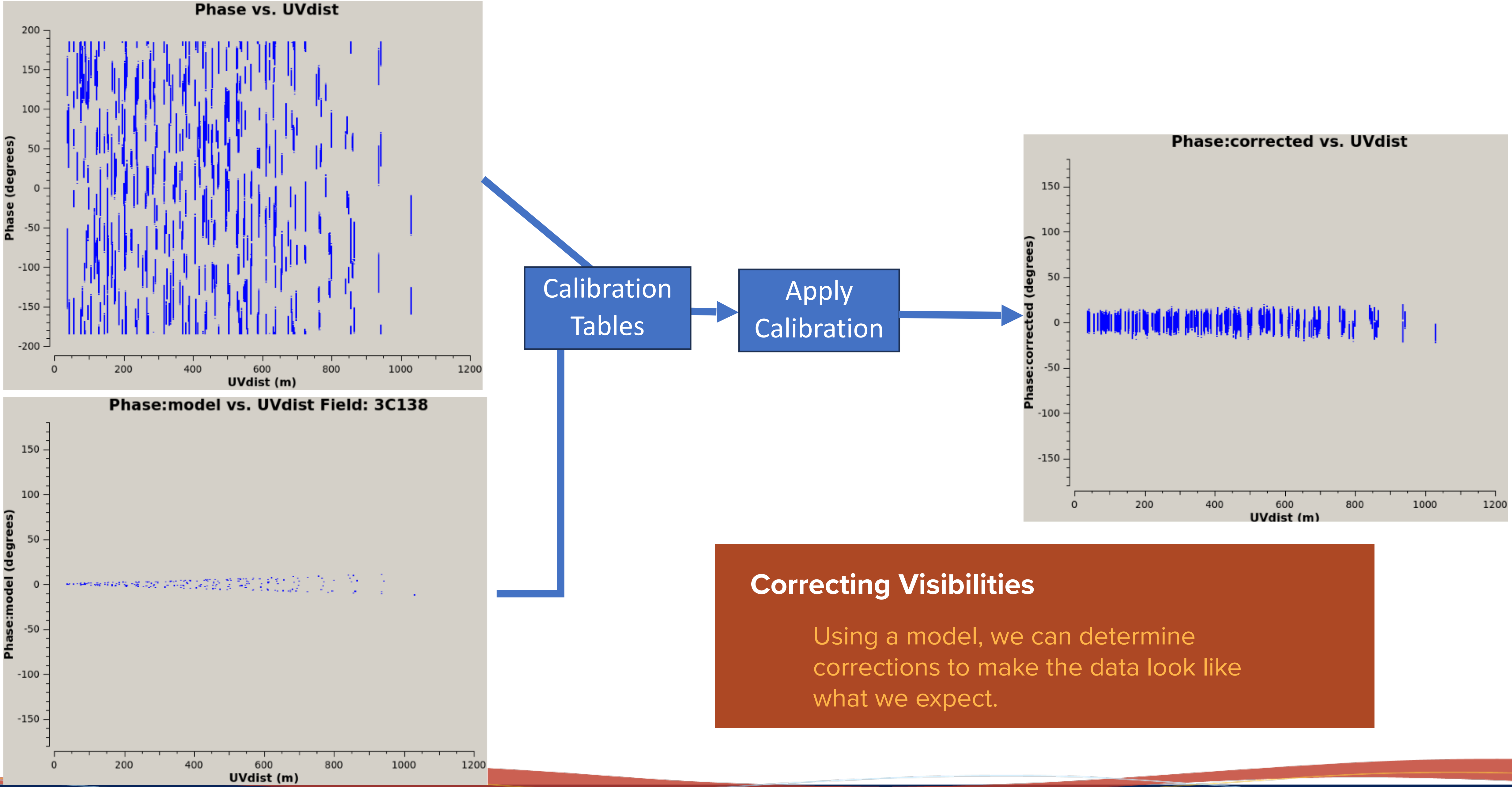
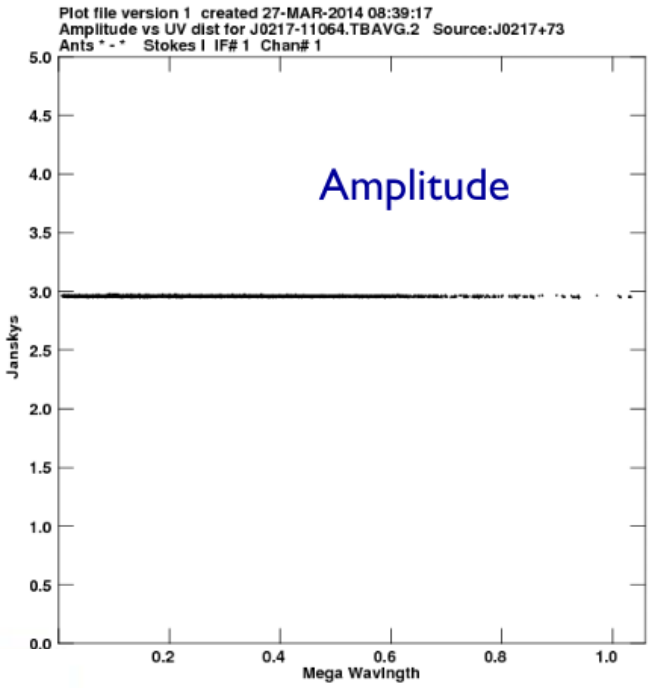


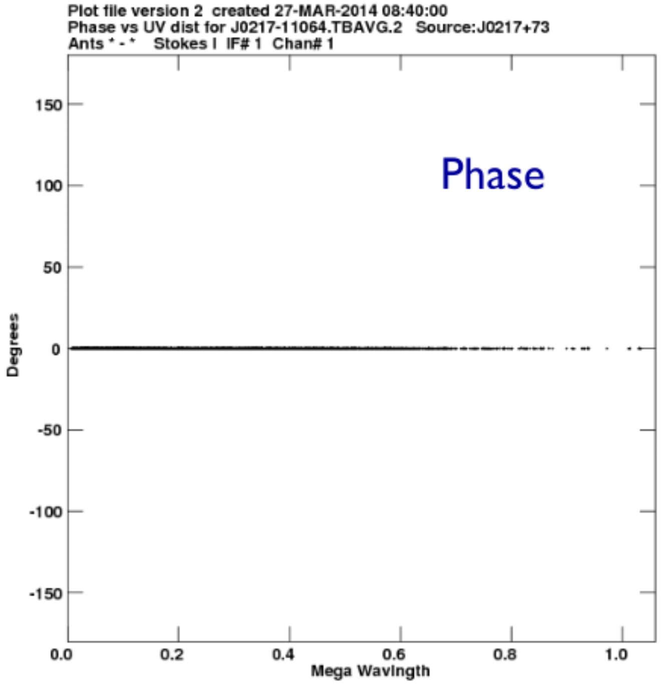
Calibration Tables

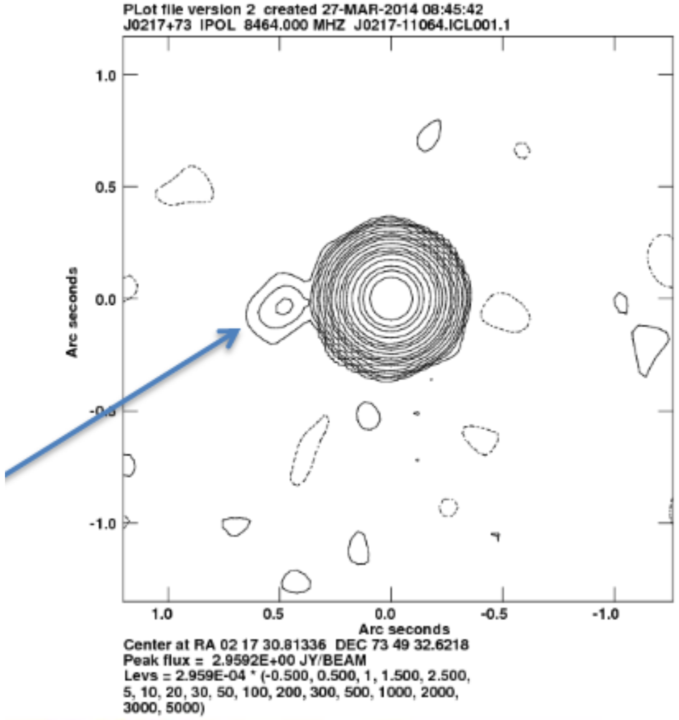
Apply Calibration

Correcting Visibilities

Using a model, we can determine corrections to make the data look like what we expect.

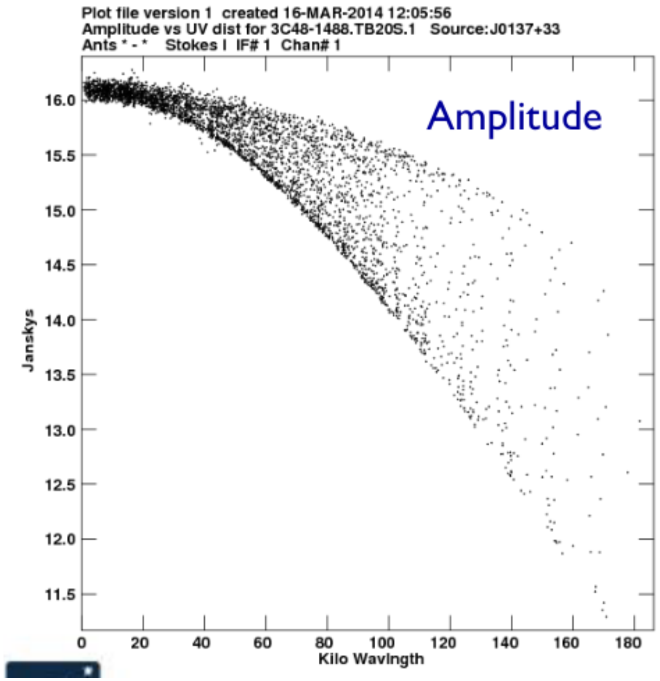


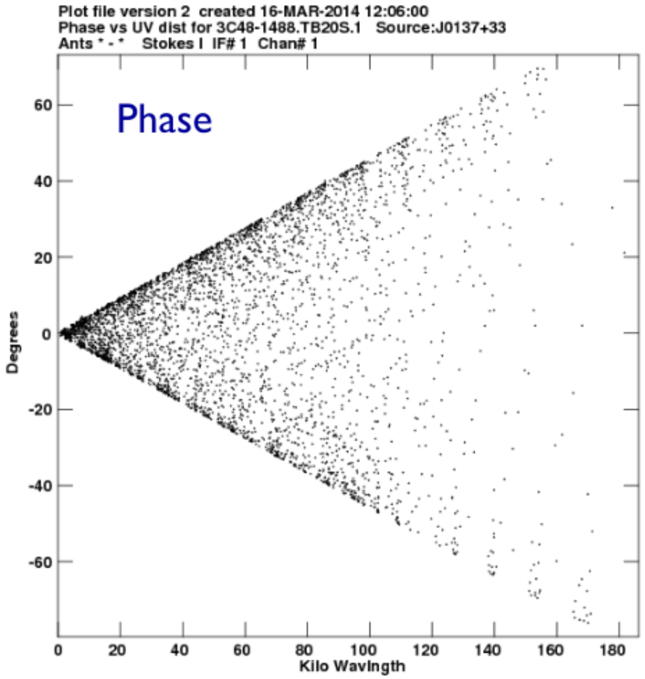


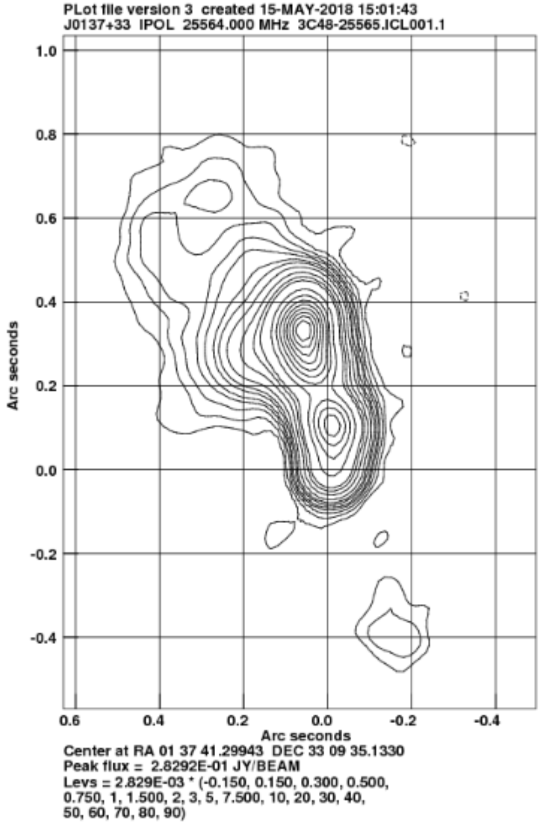


Models: Point Source

Fundamental Radio Astronomy II, Synthesis Imaging Workshop 2023, Rick Perley, NRAO/Socorro







Models: Slightly resolved source

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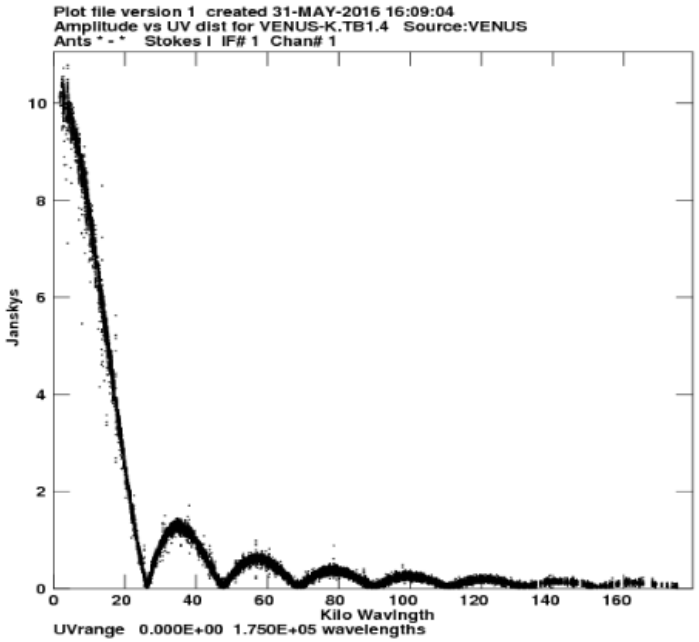
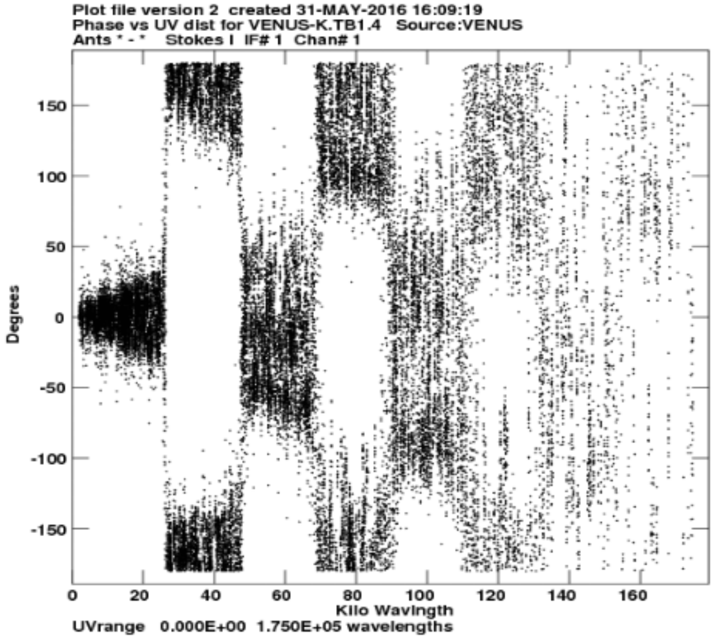
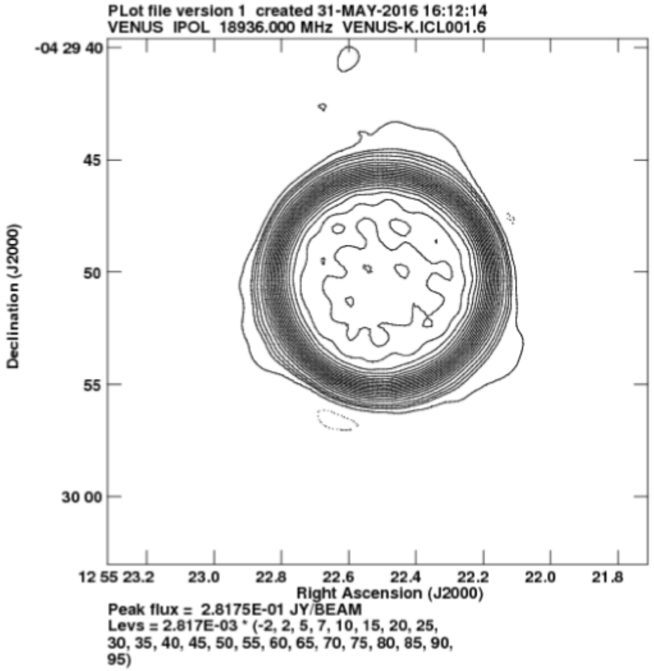




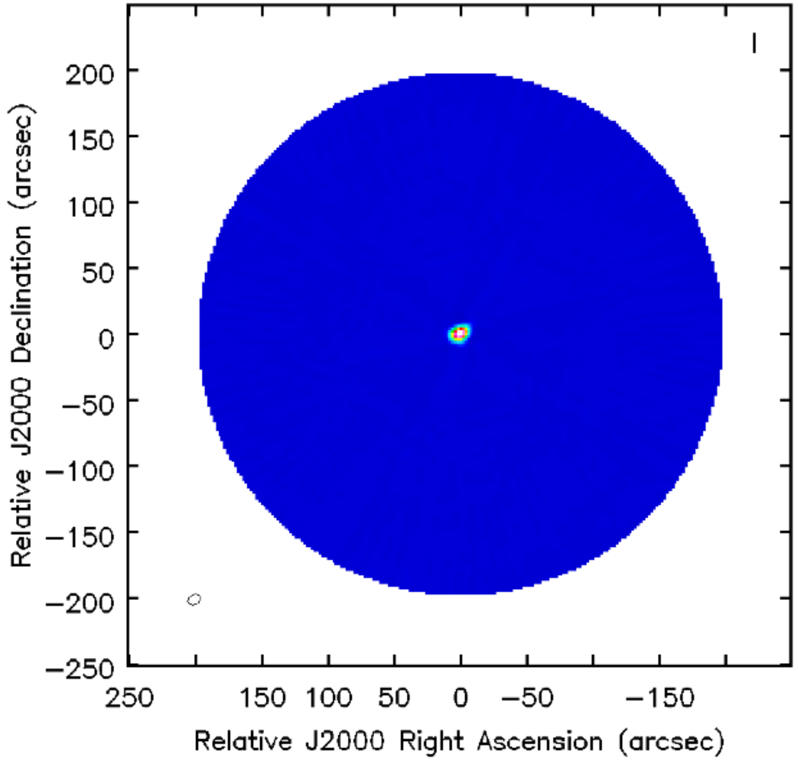


Models: Disk

Fundamental Radio Astronomy II, Synthesis Imaging Workshop 2023, Rick Perley, NRAO/Socorro

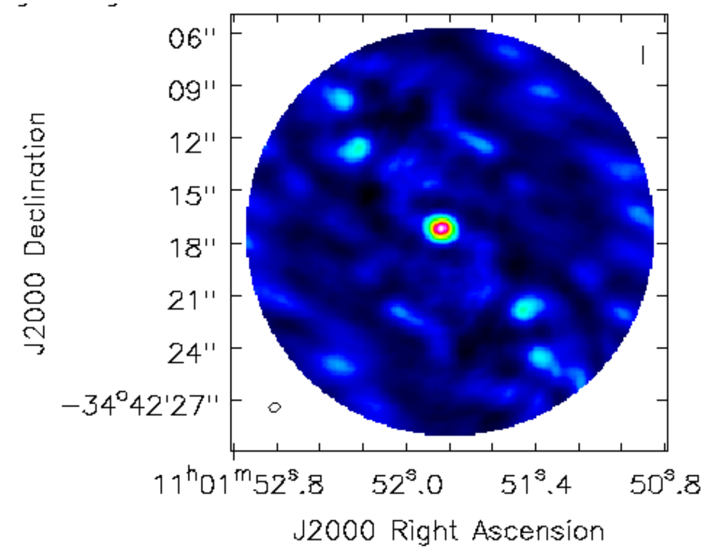
Not a calibrator!

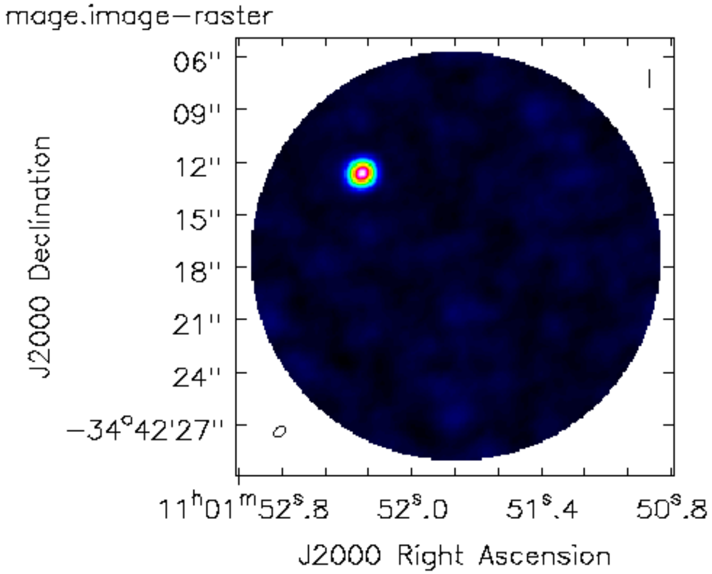
- This source is not a calibrator, it is a science target.
- **Discussion: What is stopping you from using this source as a calibrator?**
- Good news! YOU CAN!
    - Any source can be a calibrator if you have a good model of the source.



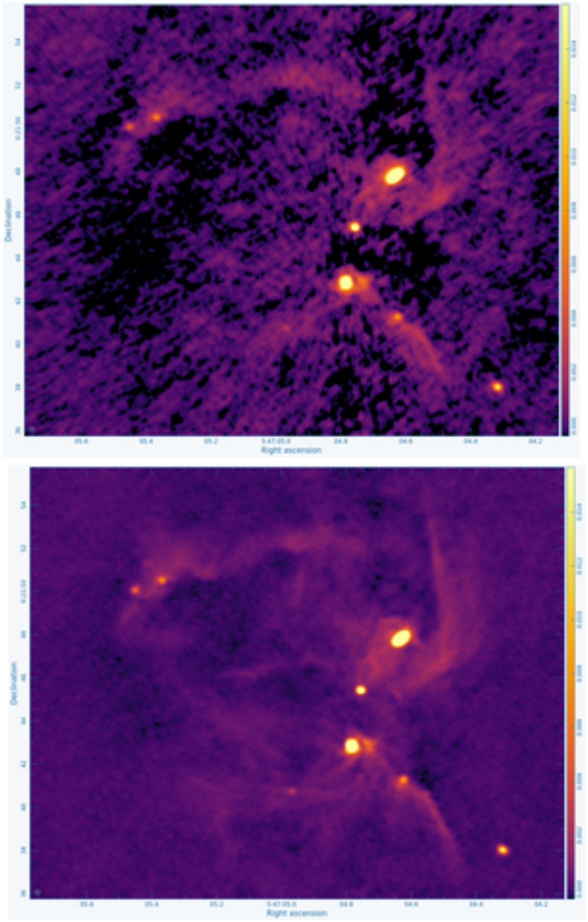
Creating your own model

- Tclean creates models using the clean components when running.
  - **<u>If</u>** what you clean is real, you can use the model for calibration.
  - CAUTION: If you add sources that are not real, you can create fake structure in your data.
    - This is more of a concern if the array has a small number of antennas such as the ACA, GMVA, EHT, or VLBA





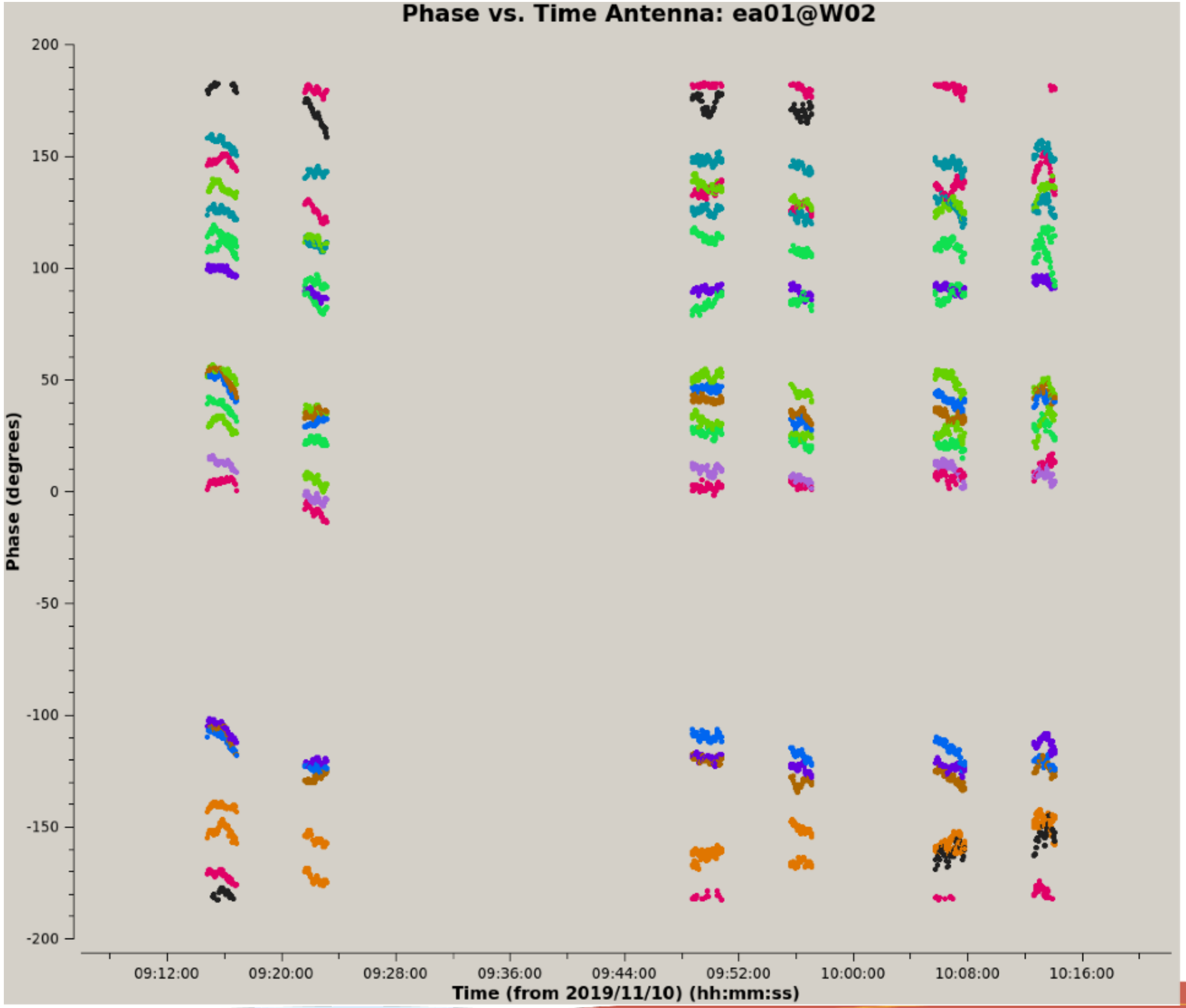
Why self calibration?



- ALMA (and the JVLA) have such impressive sensitivity that what you achieve is often limited by residual calibration errors!
- To surpass this, many objects have enough Signal-to-Noise (S/N) that they can be used to calibrate ***themselves*** to obtain a better image. This is self-calibration.
  - Sometimes, the increase in effective sensitivity may be an *order of magnitude!*
- It is not a circular trick to produce the image that you want. It works because the number of baselines is much larger than the number of antennas so that an approximate source image does not stop you from determining a better temporal gain calibration which leads to a better source image.
- Self-calibration may not be included in the data pipelines, for now...
  - …so, it’s best you learn how to do it

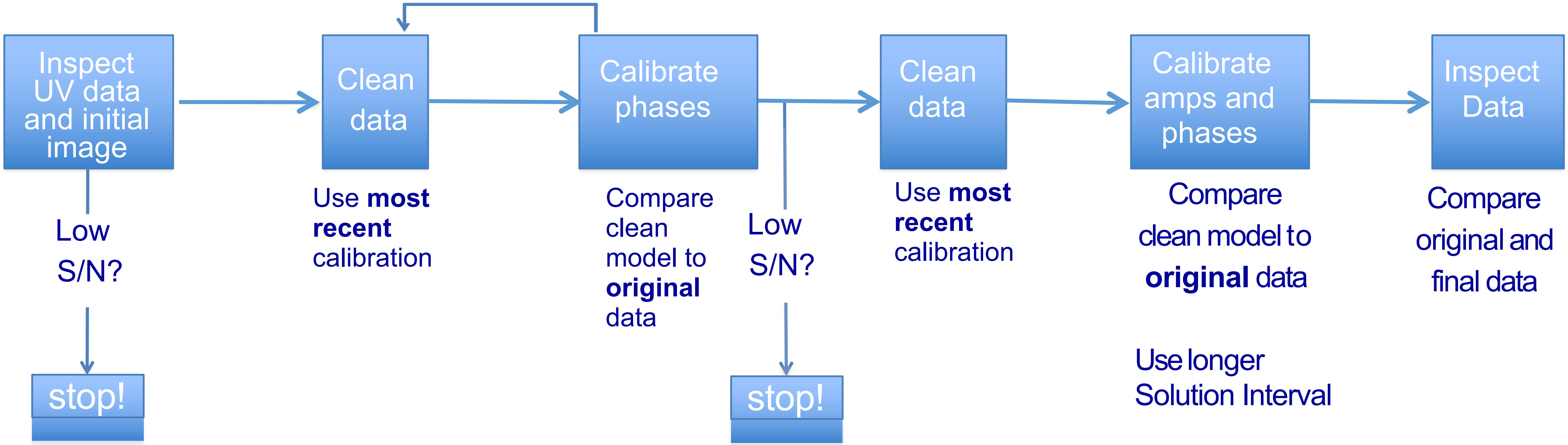
Why self calibration?

- The Phase calibrator brackets the target observations.



Outline of Self-Calibration Process:

Repeat with deeper cleans and
shorter solution intervals
until phases no longer improve



Inspect UV data and initial image

Low S/N?

stop!

Clean data

Use **most recent** calibration

Calibrate phases

Compare clean model to **original** data

Low S/N?

stop!

Clean data

Use **most recent** calibration

Calibrate amps and phases

Compare clean model to **original** data

Use longer Solution Interval

Inspect Data

Compare original and final data

SNR for self-calibration:

- **For phase only self-cal:** Need to detect the target with a S/N > 3 in a solution time (**solint**) less than the time for significant phase variations for all baselines to **a single antenna.**
- **For amplitude self-cal:** Need to detect the target with a S/N > 10 with only the baselines to a single antenna in a solution time (solint) less than the time for significant amplitude variations. For 25 antennas, an antenna based S/N > 10 will lead to a 10% amplitude error.
  - Amplitude corrections are more subject to deficiencies in the model image. Check results carefully!
  - For example, if clean model is missing significant flux compared to uv-data, give uvrange for amplitude solution that excludes short baselines.

- Additional S/N for self-cal can be obtained by:
- Increase solint (solution interval)
  - If errors that are directional rather than time dependent, self-calibration solutions can yield surprising improvement even for solints that span the entire observation. Antenna position errors are a good example.
- gaintype= ‘T’ to average polarizations
  - Caveat:Only if your source is unpolarized
- Combine = ‘spw’ to average spw’s (assumes prior removal of spw to spw offsets)
  - Caveat:If source spectral index/morphology changes significantly across the band, do not combine spws, especially for amplitude self-cal
- Combine = ‘fields’ to average fields in a mosaic (use with caution, only fields with strong signal)

SNR for self calibration:

- **For amplitude self-cal:** Need to detect the target with a S/N > 10 with only the baselines to a single antenna in a solution time (solint) less than the time for significant amplitude variations. For 25 antennas, an antenna based S/N > 10 will lead to a 10% amplitude error.
  - Amplitude corrections are more subject to deficiencies in the model image. Check results carefully!
  - For example, if clean model is missing significant flux compared to uv-data, give uvrange for amplitude solution that excludes short baselines.

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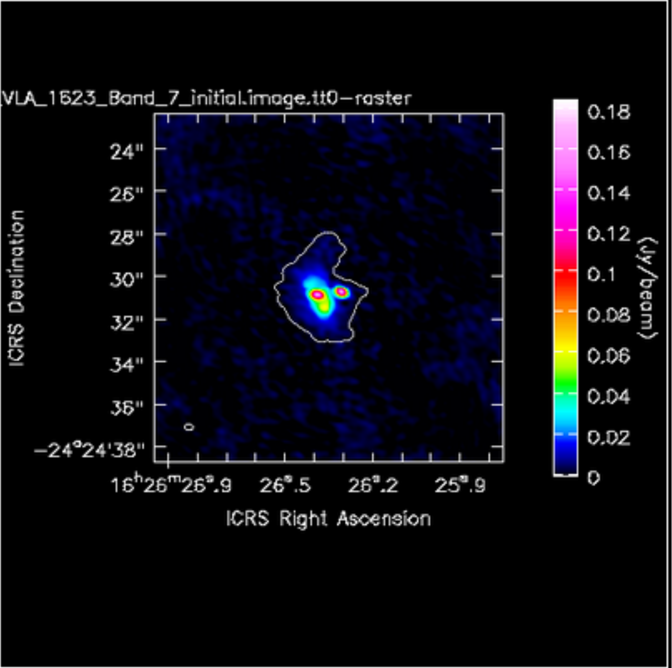
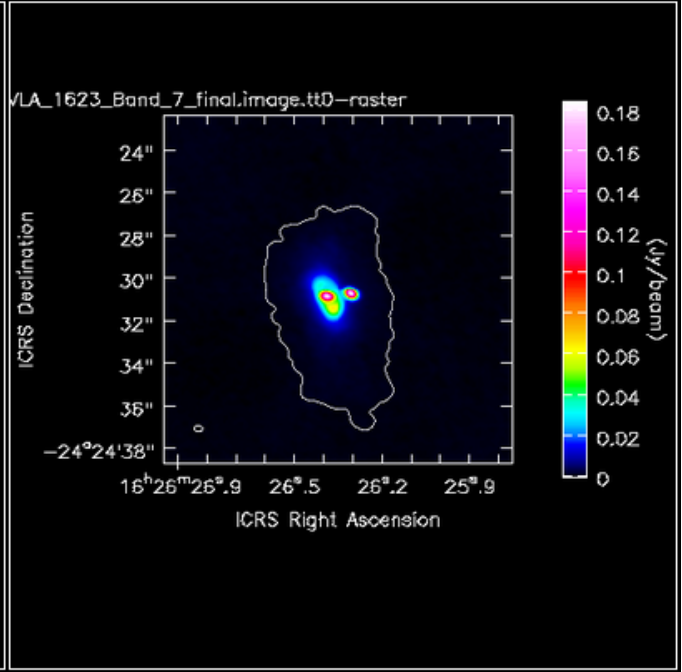
Automated Self-Cal

- There is now Automated self-cal for individual pointing continuum observations (Not mosaics).
- Will also be available in the cycle 10 pipeline.

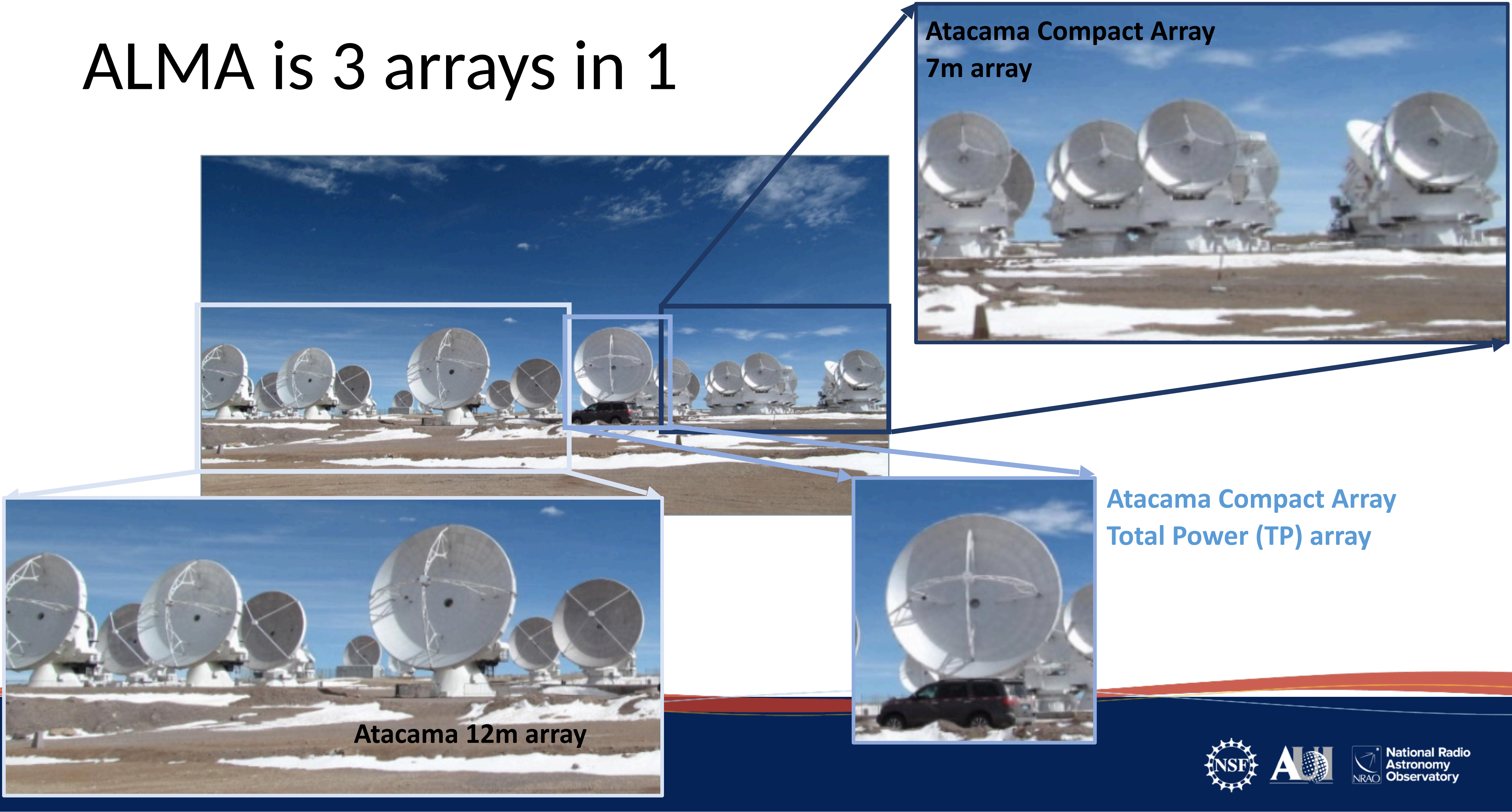
Data:	Initial	Final
Image:		
Integrated Flux:	1376.06 +/- 28.49 mJy	1754.46 +/- 28.52 mJy
SNR:	113.68	1042.15
SNR (near-field):	111.37	981.68
RMS:	1.42 mJy/beam	0.18 mJy/beam
RMS (near-field):	1.45 mJy/beam	0.19 mJy/beam
Beam:	0.37"x0.30" -87.51 deg	0.37"x0.30" -87.47 deg

Self-Cal Resources

- ALMA Self-cal Tutorial
  - https://casaguides.nrao.edu/index.php?title=First_Look_at_Self_Calibration_CASA_6
- VLA Self-cal Tutorial
  - https://casaguides.nrao.edu/index.php?title=VLA_Self-calibration_Tutorial-CASA6.4.1
- I-TRAIN #6: Improving image fidelity through self-calibration
  - Video, scripts, and data
  - https://almascience.eso.org/tools/eu-arc-network/i-train
- ALMA memo 620
  - https://library.nrao.edu/alma.shtml - #620
- Crystal Brogan's 2018 paper
  - Brogan, C. L., Hunter, T. R., & Fomalont, E. B. 2018, arXiv e-prints, arXiv:1805.05266

Data Combination

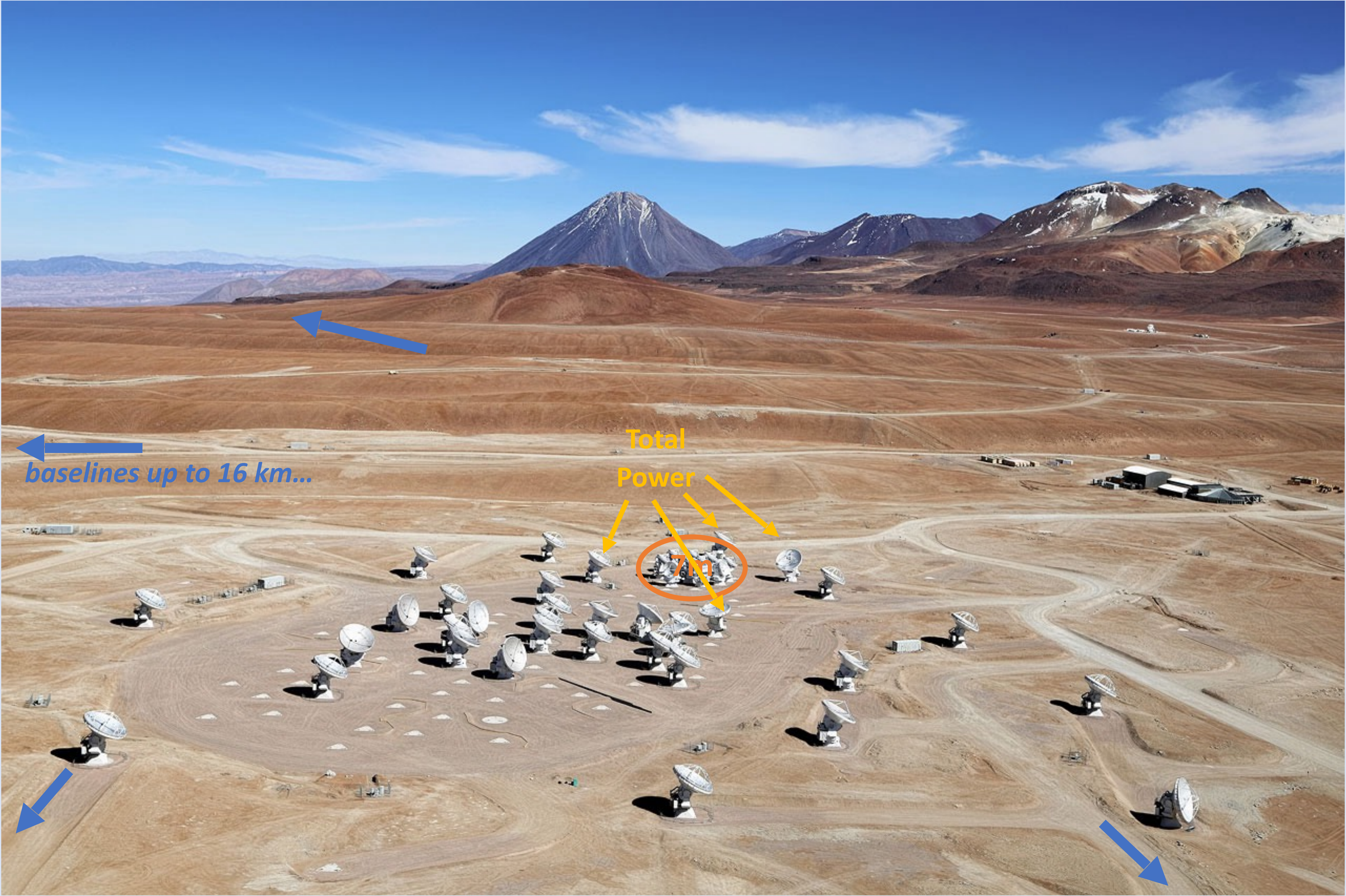
ALMA is 3 arrays in 1



Atacama Compact Array
7m array

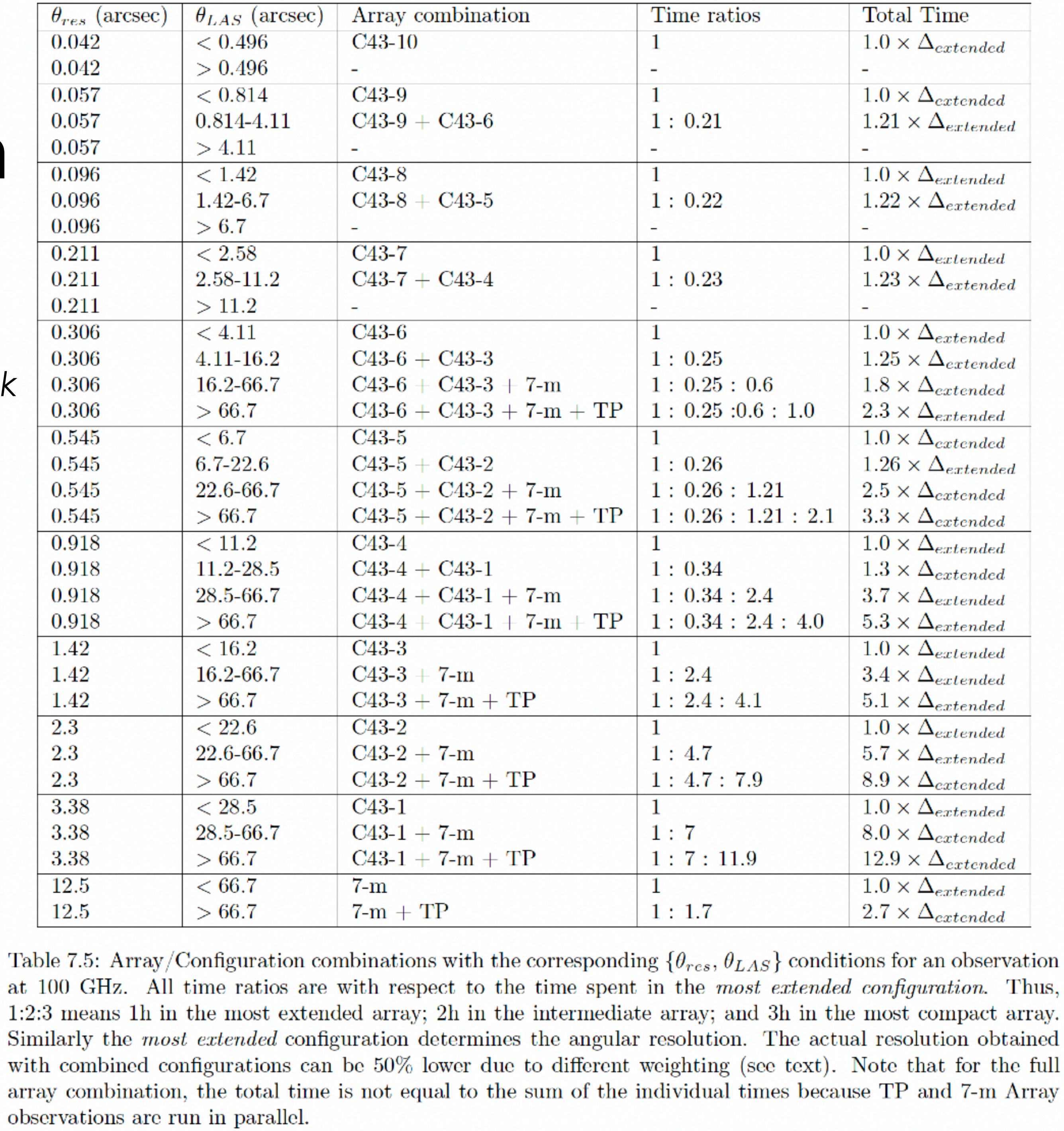
Atacama Compact Array
Total Power (TP) array

Atacama 12m array


baselines up to 16 km...
Total
Power
7m

Array combination setup

Source: Cycle 10 Technical Handbook

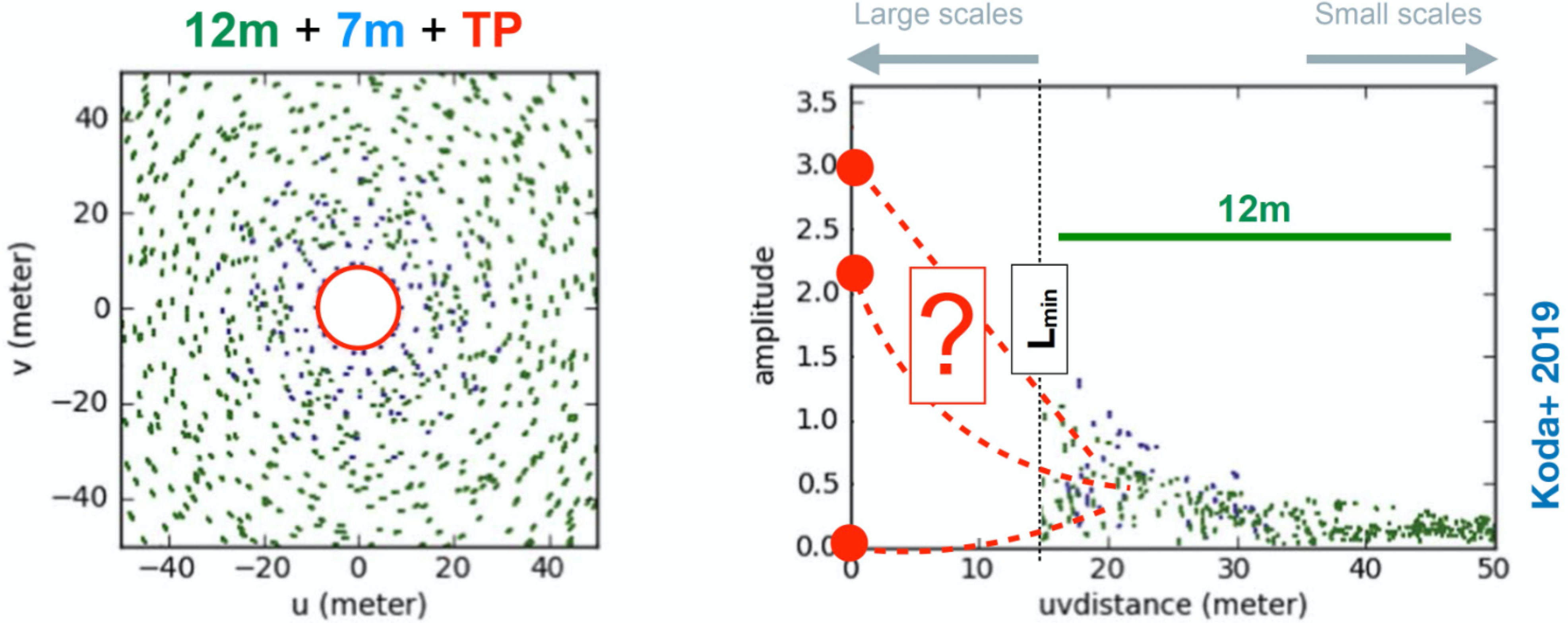


θ_{res} (arcsec)	θ_{LAS} (arcsec)	Array combination	Time ratios	Total Time
0.042	< 0.496	C43-10	1	$1.0 \times \Delta_{extended}$
0.042	> 0.496	-	-	-
0.057	< 0.814	C43-9	1	$1.0 \times \Delta_{extended}$
0.057	0.814-4.11	C43-9 + C43-6	1 : 0.21	$1.21 \times \Delta_{extended}$
0.057	> 4.11	-	-	-
0.096	< 1.42	C43-8	1	$1.0 \times \Delta_{extended}$
0.096	1.42-6.7	C43-8 + C43-5	1 : 0.22	$1.22 \times \Delta_{extended}$
0.096	> 6.7	-	-	-
0.211	< 2.58	C43-7	1	$1.0 \times \Delta_{extended}$
0.211	2.58-11.2	C43-7 + C43-4	1 : 0.23	$1.23 \times \Delta_{extended}$
0.211	> 11.2	-	-	-
0.306	< 4.11	C43-6	1	$1.0 \times \Delta_{extended}$
0.306	4.11-16.2	C43-6 + C43-3	1 : 0.25	$1.25 \times \Delta_{extended}$
0.306	16.2-66.7	C43-6 + C43-3 + 7-m	1 : 0.25 : 0.6	$1.8 \times \Delta_{extended}$
0.306	> 66.7	C43-6 + C43-3 + 7-m + TP	1 : 0.25 :0.6 : 1.0	$2.3 \times \Delta_{extended}$
0.545	< 6.7	C43-5	1	$1.0 \times \Delta_{extended}$
0.545	6.7-22.6	C43-5 + C43-2	1 : 0.26	$1.26 \times \Delta_{extended}$
0.545	22.6-66.7	C43-5 + C43-2 + 7-m	1 : 0.26 : 1.21	$2.5 \times \Delta_{extended}$
0.545	> 66.7	C43-5 + C43-2 + 7-m + TP	1 : 0.26 : 1.21 : 2.1	$3.3 \times \Delta_{extended}$
0.918	< 11.2	C43-4	1	$1.0 \times \Delta_{extended}$
0.918	11.2-28.5	C43-4 + C43-1	1 : 0.34	$1.3 \times \Delta_{extended}$
0.918	28.5-66.7	C43-4 + C43-1 + 7-m	1 : 0.34 : 2.4	$3.7 \times \Delta_{extended}$
0.918	> 66.7	C43-4 + C43-1 + 7-m + TP	1 : 0.34 : 2.4 : 4.0	$5.3 \times \Delta_{extended}$
1.42	< 16.2	C43-3	1	$1.0 \times \Delta_{extended}$
1.42	16.2-66.7	C43-3 + 7-m	1 : 2.4	$3.4 \times \Delta_{extended}$
1.42	> 66.7	C43-3 + 7-m + TP	1 : 2.4 : 4.1	$5.1 \times \Delta_{extended}$
2.3	< 22.6	C43-2	1	$1.0 \times \Delta_{extended}$
2.3	22.6-66.7	C43-2 + 7-m	1 : 4.7	$5.7 \times \Delta_{extended}$
2.3	> 66.7	C43-2 + 7-m + TP	1 : 4.7 : 7.9	$8.9 \times \Delta_{extended}$
3.38	< 28.5	C43-1	1	$1.0 \times \Delta_{extended}$
3.38	28.5-66.7	C43-1 + 7-m	1 : 7	$8.0 \times \Delta_{extended}$
3.38	> 66.7	C43-1 + 7-m + TP	1 : 7 : 11.9	$12.9 \times \Delta_{extended}$
12.5	< 66.7	7-m	1	$1.0 \times \Delta_{extended}$
12.5	> 66.7	7-m + TP	1 : 1.7	$2.7 \times \Delta_{extended}$

Table 7.5: Array/Configuration combinations with the corresponding $\{\theta_{res}, \theta_{LAS}\}$ conditions for an observation at 100 GHz. All time ratios are with respect to the time spent in the *most extended configuration*. Thus, 1:2:3 means 1h in the most extended array; 2h in the intermediate array; and 3h in the most compact array. Similarly the *most extended* configuration determines the angular resolution. The actual resolution obtained with combined configurations can be 50% lower due to different weighting (see text). Note that for the full array combination, the total time is not equal to the sum of the individual times because TP and 7-m Array observations are run in parallel.

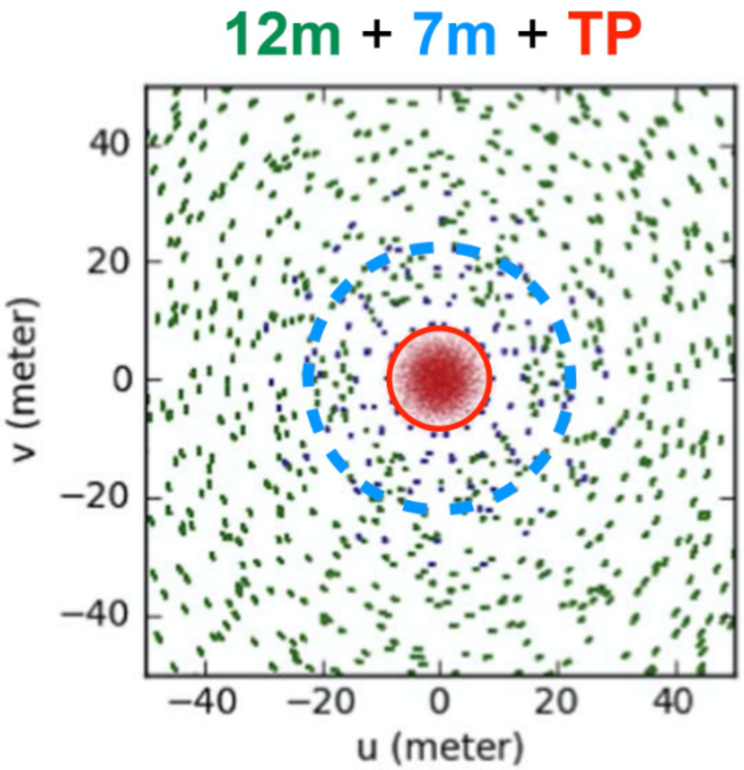
Why do we want to combine configurations?

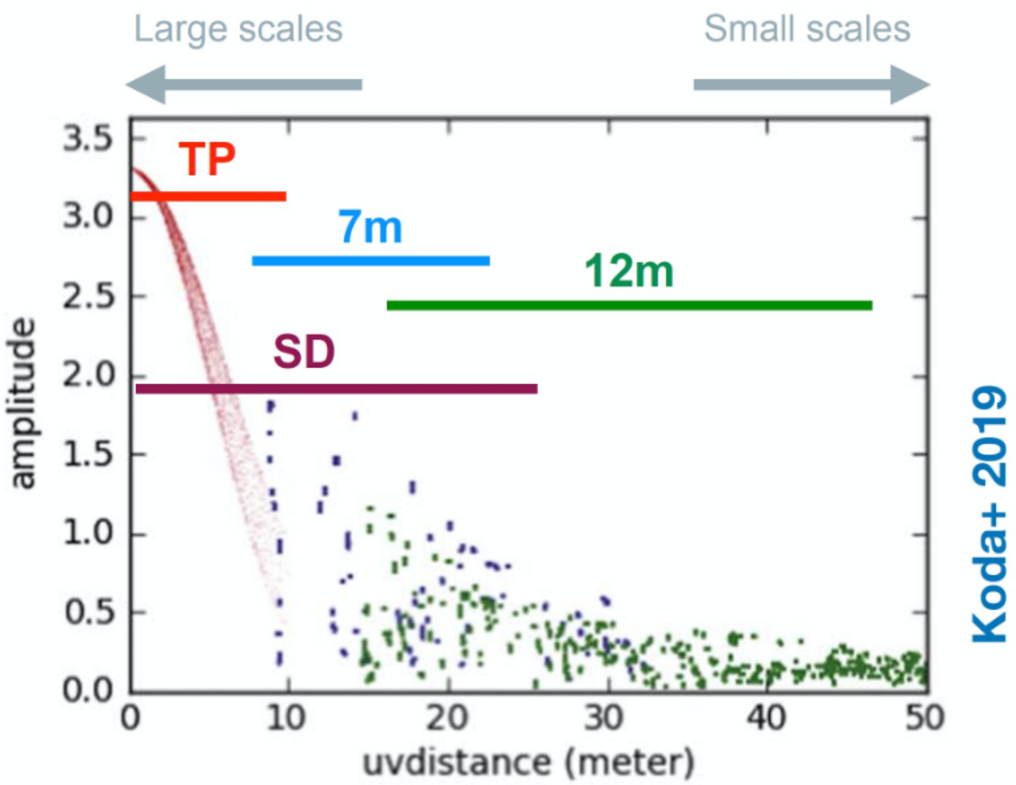
Zero-spacing problem



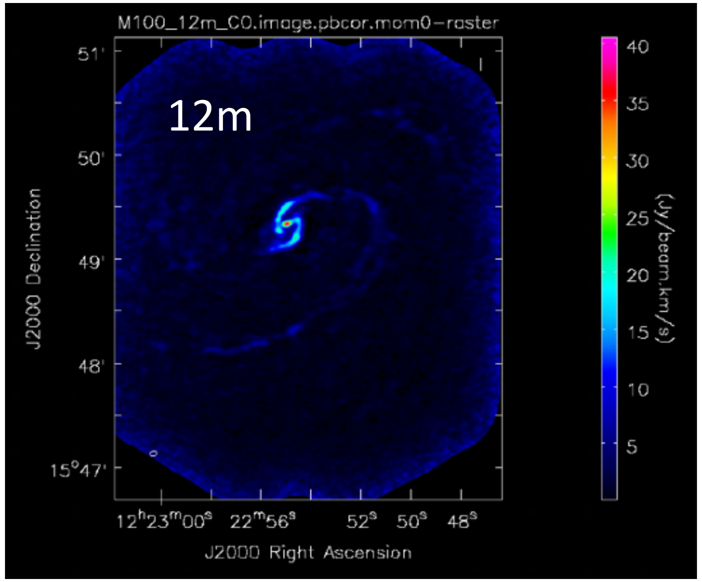
- Zero-spacing problem = missing information at short baselines (<L_{min})

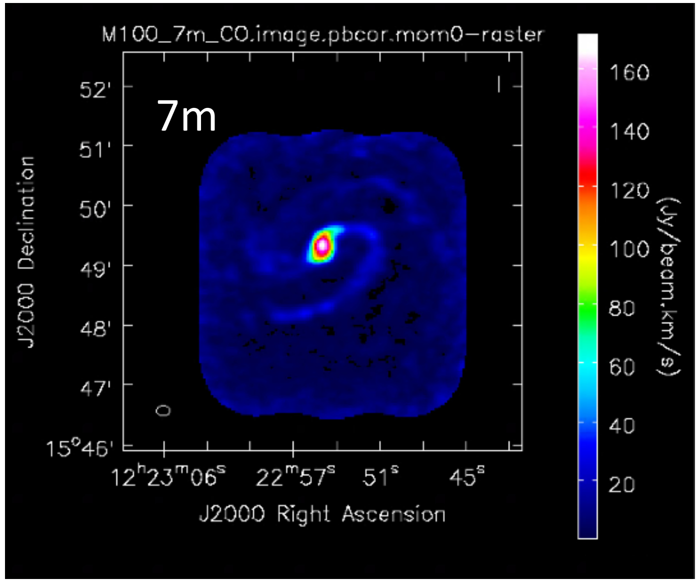
Zero-spacing problem

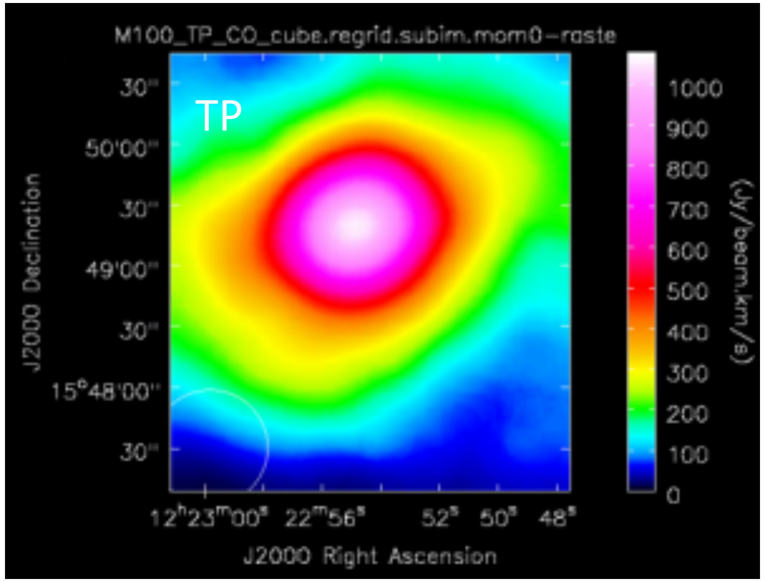


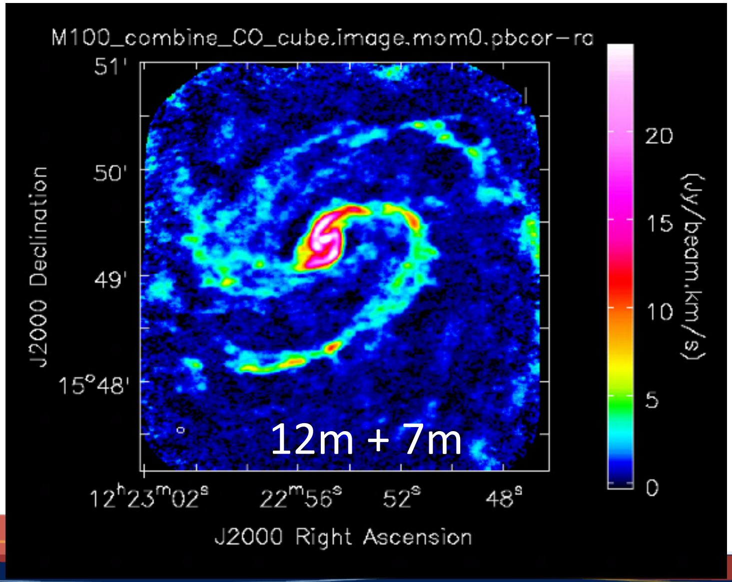


- Zero-spacing problem = missing information at short baselines ($<L_{min}$)
- **Solution:** Fill up the gap combining config./arrays/telescopes







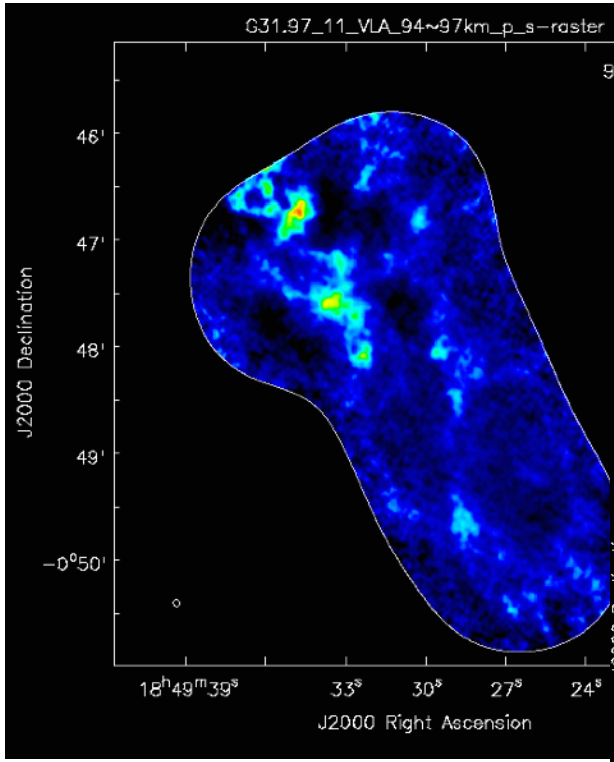


Source: https://casaguides.nrao.edu/index.php?title=M100_Band3_Combine_6.4

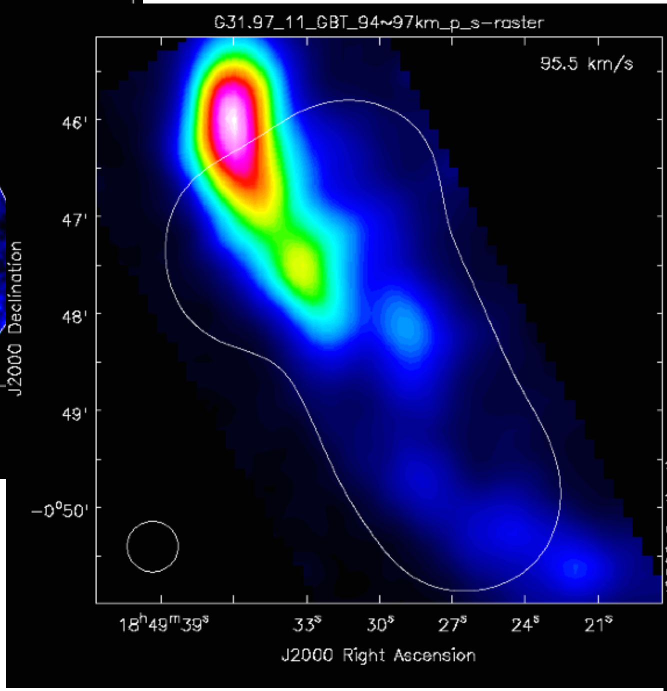
Example: DiRienzo+15

+

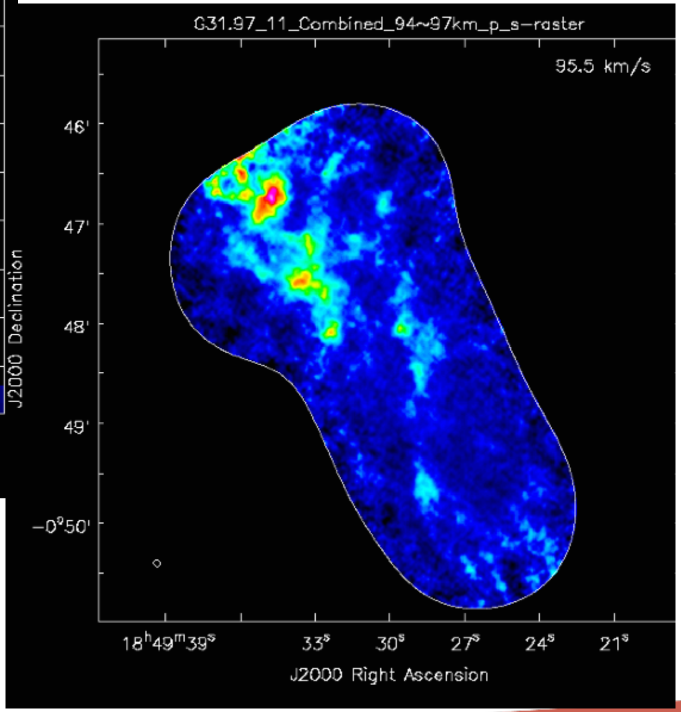
Interferometer: EVLA NH$_3$



Single Dish: GBT NH$_3$



SD + Int



To maximize flux recovery and image quality
you want a single dish size of D> 2 x B$_{\mathrm{min}}$
VLA D-config B$_{\mathrm{min}}$ 35m -> 75m

Plunkett et al. (2023) - Data Combination: Interferometry and Single-dish Imaging in Radio Astronomy
See also: https://github.com/teuben/DataComb

Aims:

- Uniform, reproducible method to perform several data combination techniques
- Which method(s) results in the “best” image quality?
  - How do we quantify the image quality of data combination?
  - In what scenarios do we need data combination?

Combination methods

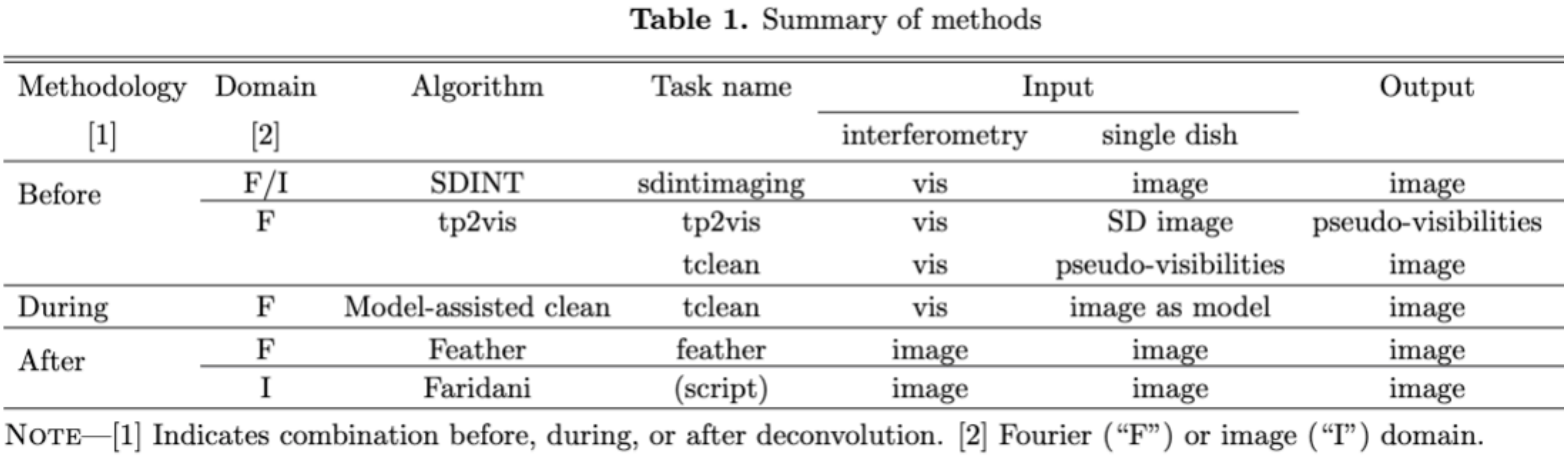


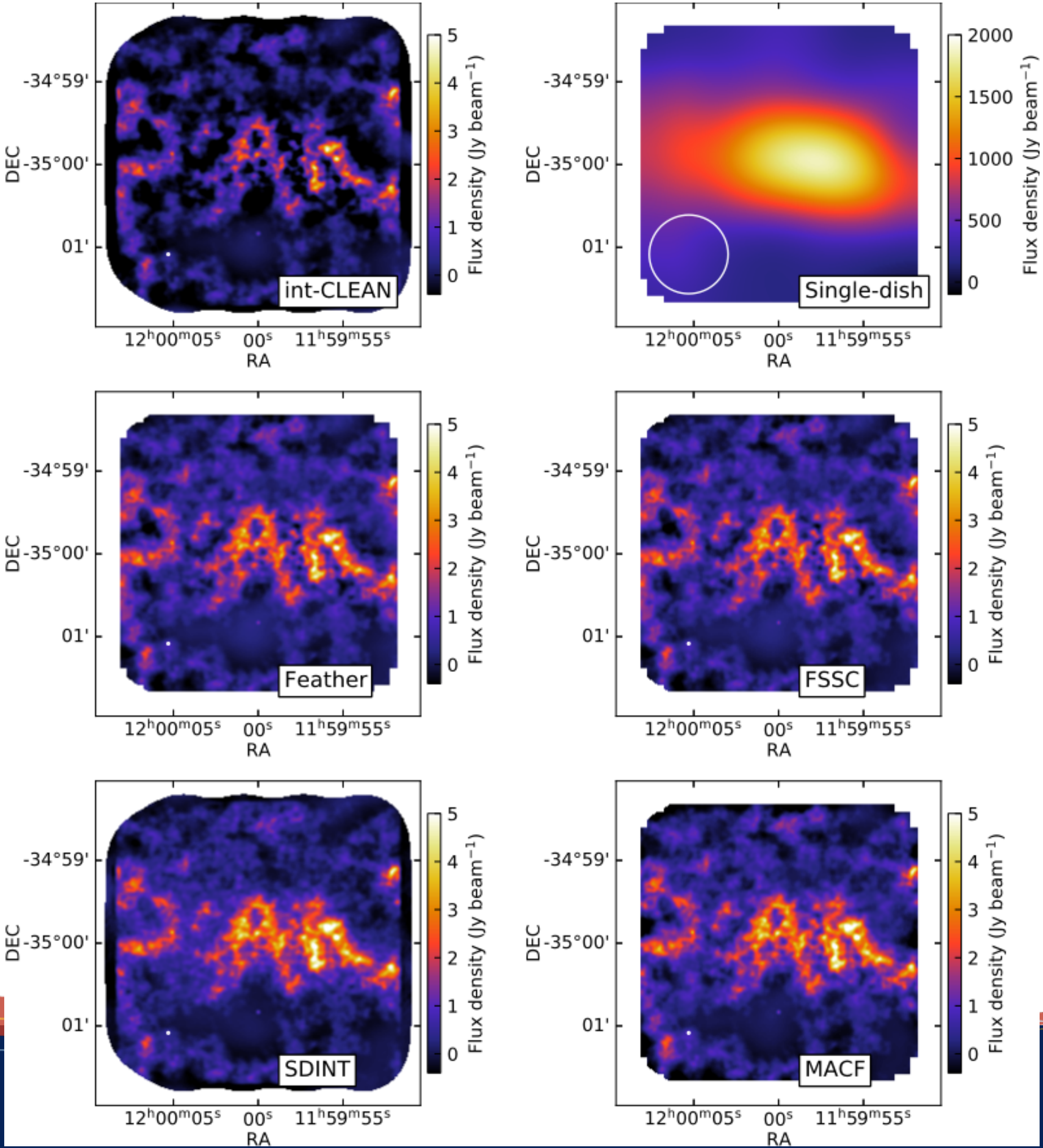
Table 1. Summary of methods

Methodology	Domain	Algorithm	Task name	Input		Output
[1]	[2]			interferometry	single dish	
Before	F/I	SDINT	sdintimaging	vis	image	image
	F	tp2vis	tp2vis	vis	SD image	pseudo-visibilities
			tclean	vis	pseudo-visibilities	image
During	F	Model-assisted clean	tclean	vis	image as model	image
After	F	Feather	feather	image	image	image
	I	Faridani	(script)	image	image	image

Note—[1] Indicates combination before, during, or after deconvolution. [2] Fourier ("F") or image ("I") domain.

Results

(qualitative)



Results:

- Uniform, reproducible method
  - Plunkett et al. (2023) and https://github.com/teuben/DataComb
- Which method(s) results in the “best” image quality?
  - SDINT and MACF methods show subtly better quality than others.
  - ALMA recommends feather currently as the task SDINT is under testing
- How do we quantify the image quality of data combination?
  - Accuracy-parameter (A-Par)
  - See Plunkett et al. (2023), *Sec. 5.2: Accuracy Parameter and Fidelity: Assessing Flux Recovery*
- In what scenarios do we need data combination?
  - If extended emission present, then any combination seems to help
  - **Examine**: spatial power spectrum; source structure; spectral shape

Data Combination Resources

- ALMA Data Combination CASA Tutorial
  - https://casaguides.nrao.edu/index.php?title=M100_Band3_Combine_6.4
- Plunkett et al. (2023) - Data Combination: Interferometry and Single-dish Imaging in Radio Astronomy
  - See also: https://github.com/teuben/DataComb - scripts
  - https://ui.adsabs.harvard.edu/abs/2023PASP..135c4501P/abstract