Mosaicking and Data Combination

Adele Plunkett

NRAO Synthesis Imaging Workshop • 17 May 2024

NSF AUI National Radio Astronomy Observatory NRAO

Talk outline

I. Setting the stage

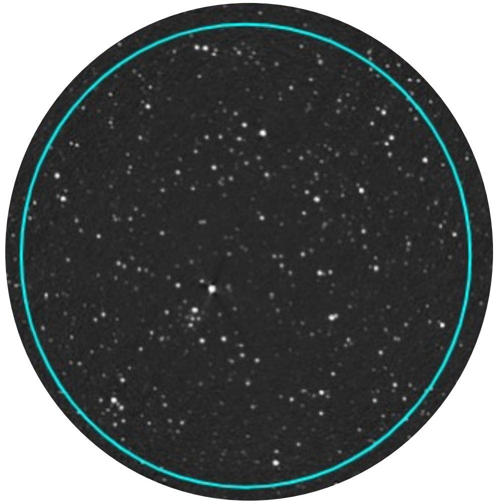
II. Mosaicking

III. Image combination

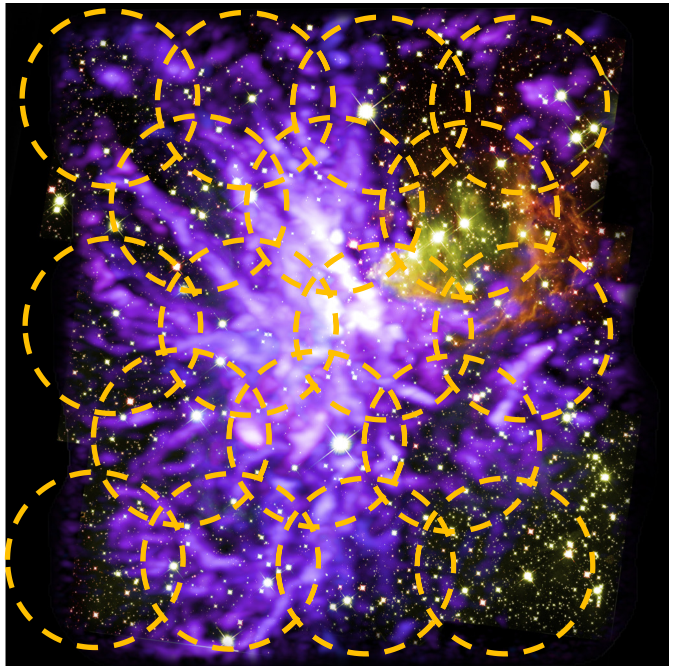
VI. Summary and resources

Where am I?
Look at the color of this band.

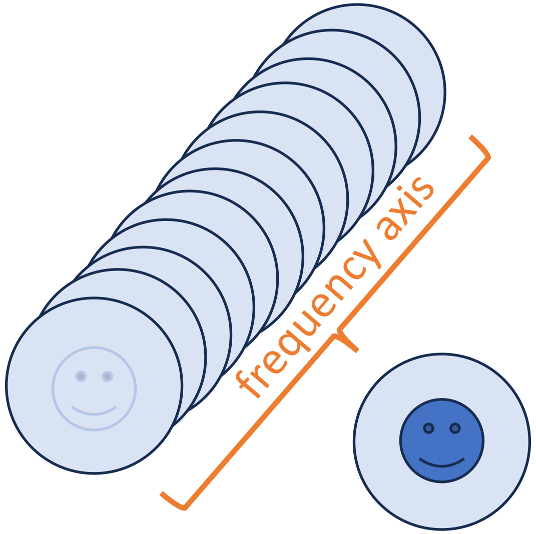
Wide field imaging
(Preshanth Jagannathan)



Narrow band mosaicking
and data combination
(Adele Plunkett)



Wide band imaging
(Joshua Marvil)



Talk outline

" There was a glut of information presented in the lectures. "

About me, briefly

Working with ALMA since ~2012


First visit to VLA in 2023

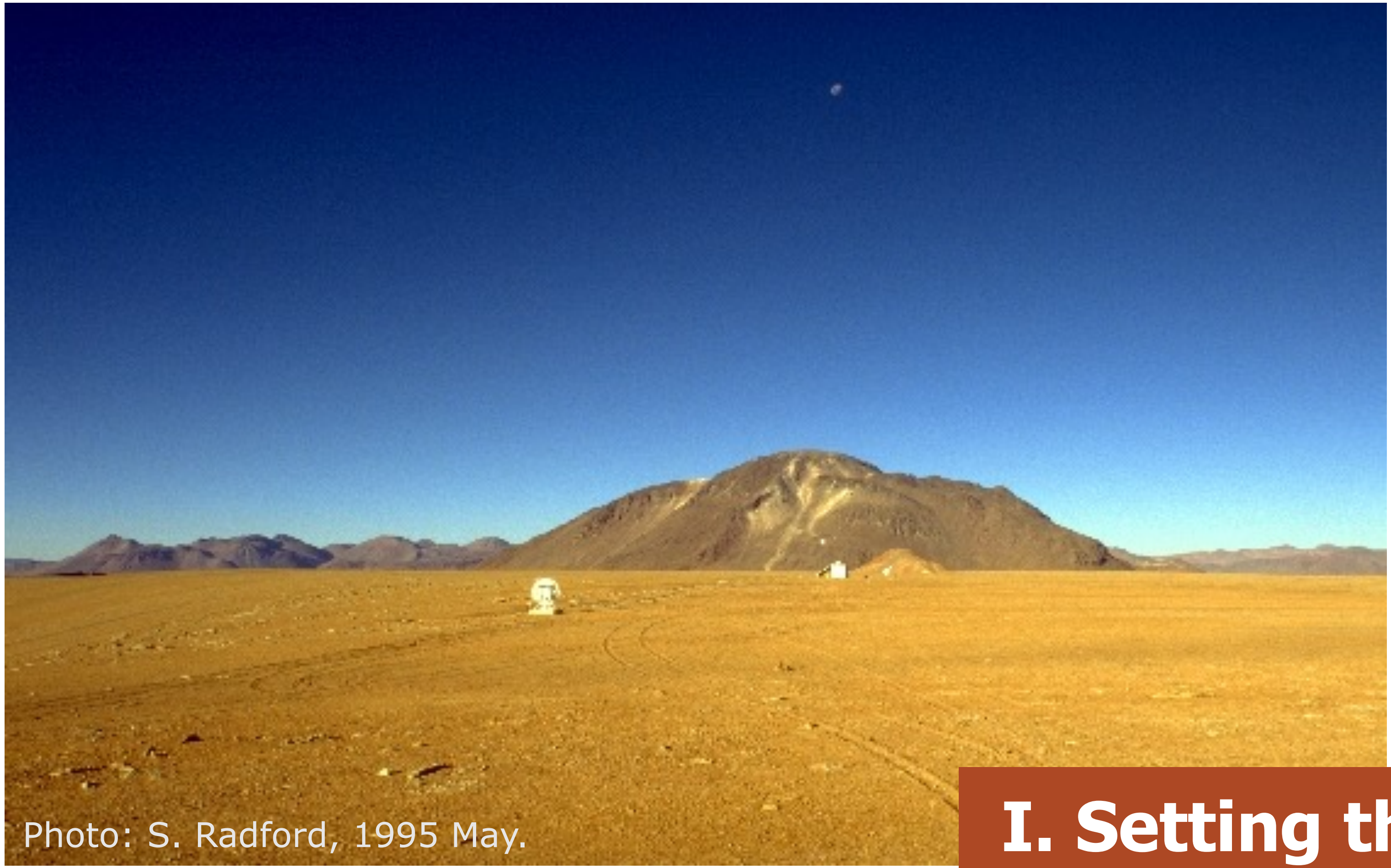


Photo: S. Radford, 1995 May.

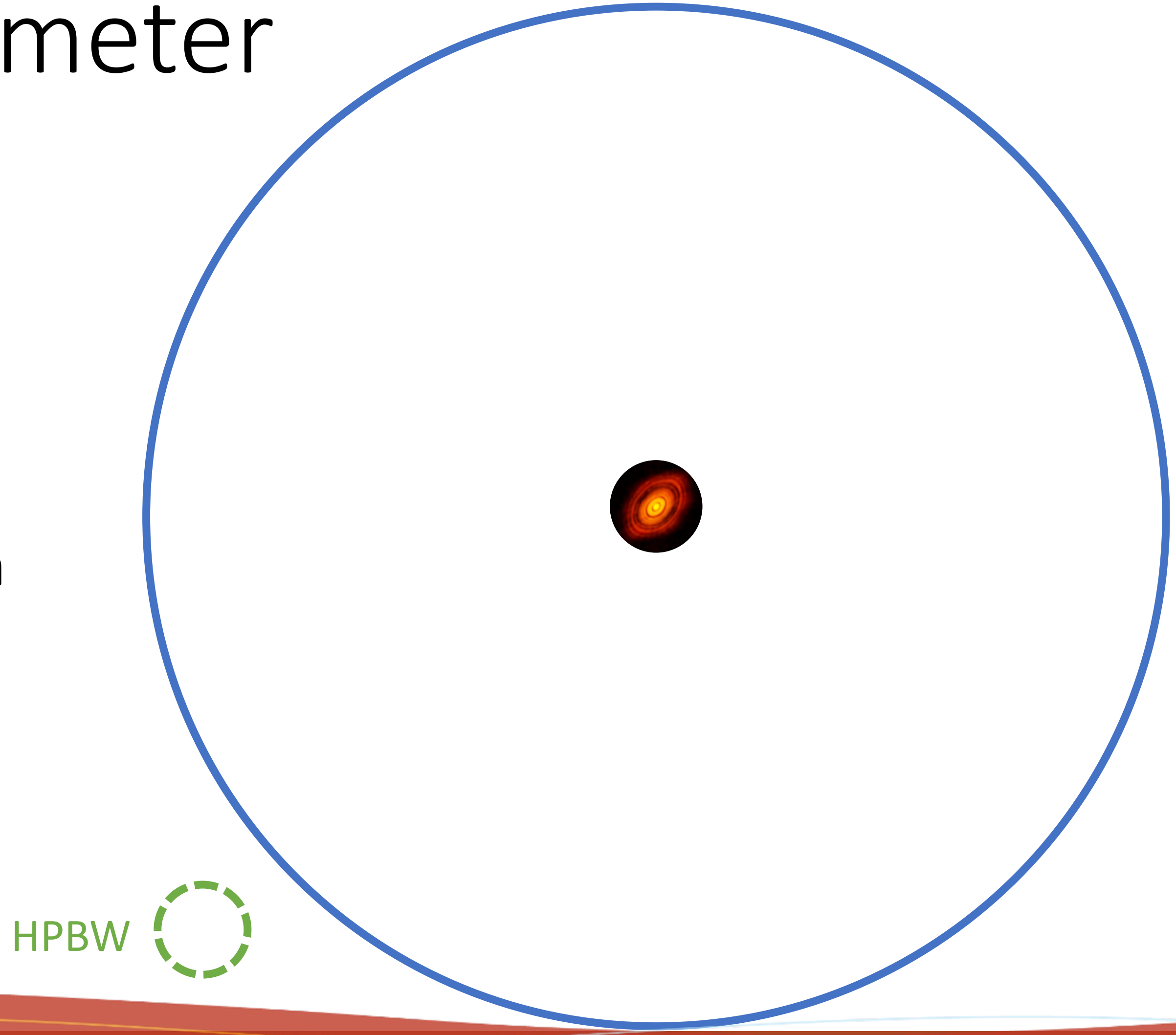
I. Setting the Stage

What to expect with interferometric imaging in practice, and why you might need to "think outside of the box" (primary beam)

The simplest observing scenario for an interferometer

Size: ~ HPBW

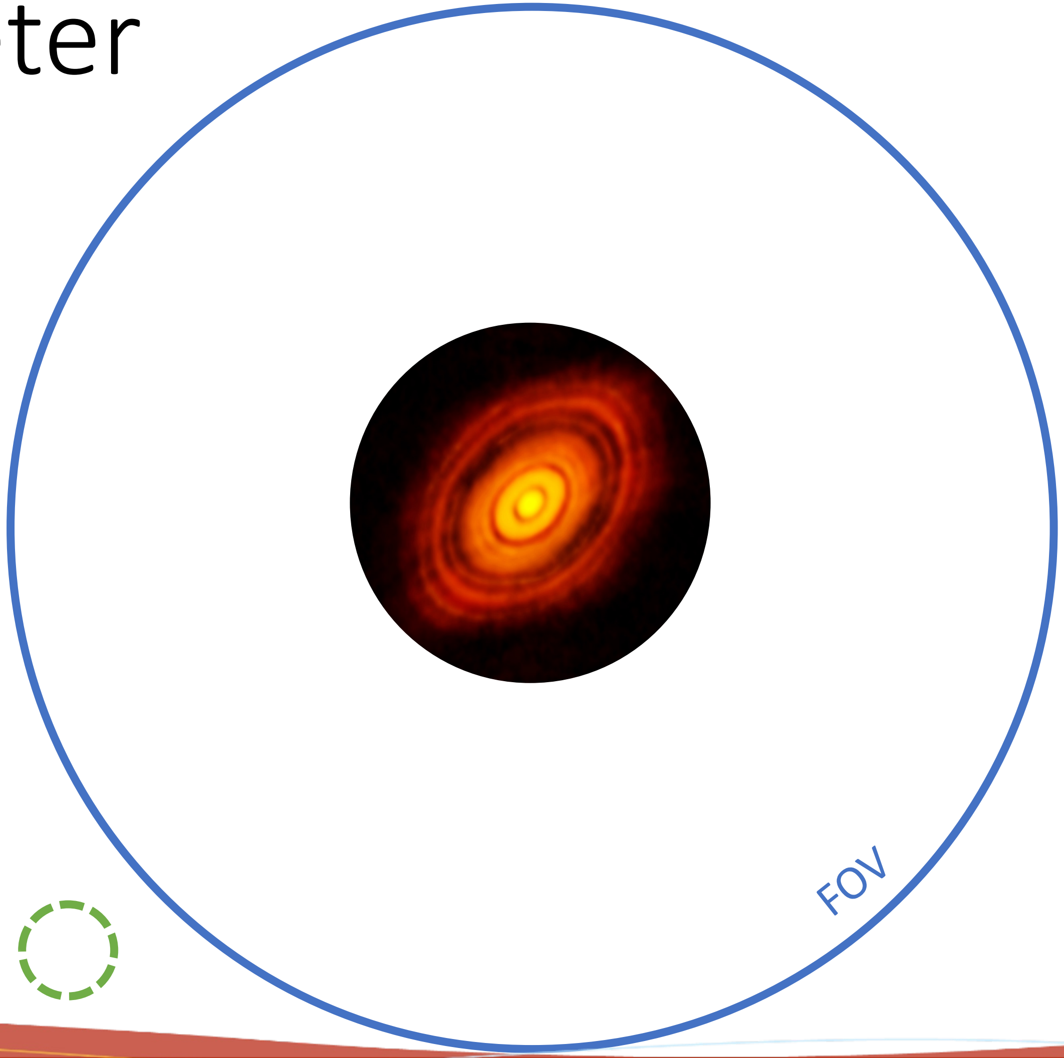
Location: known



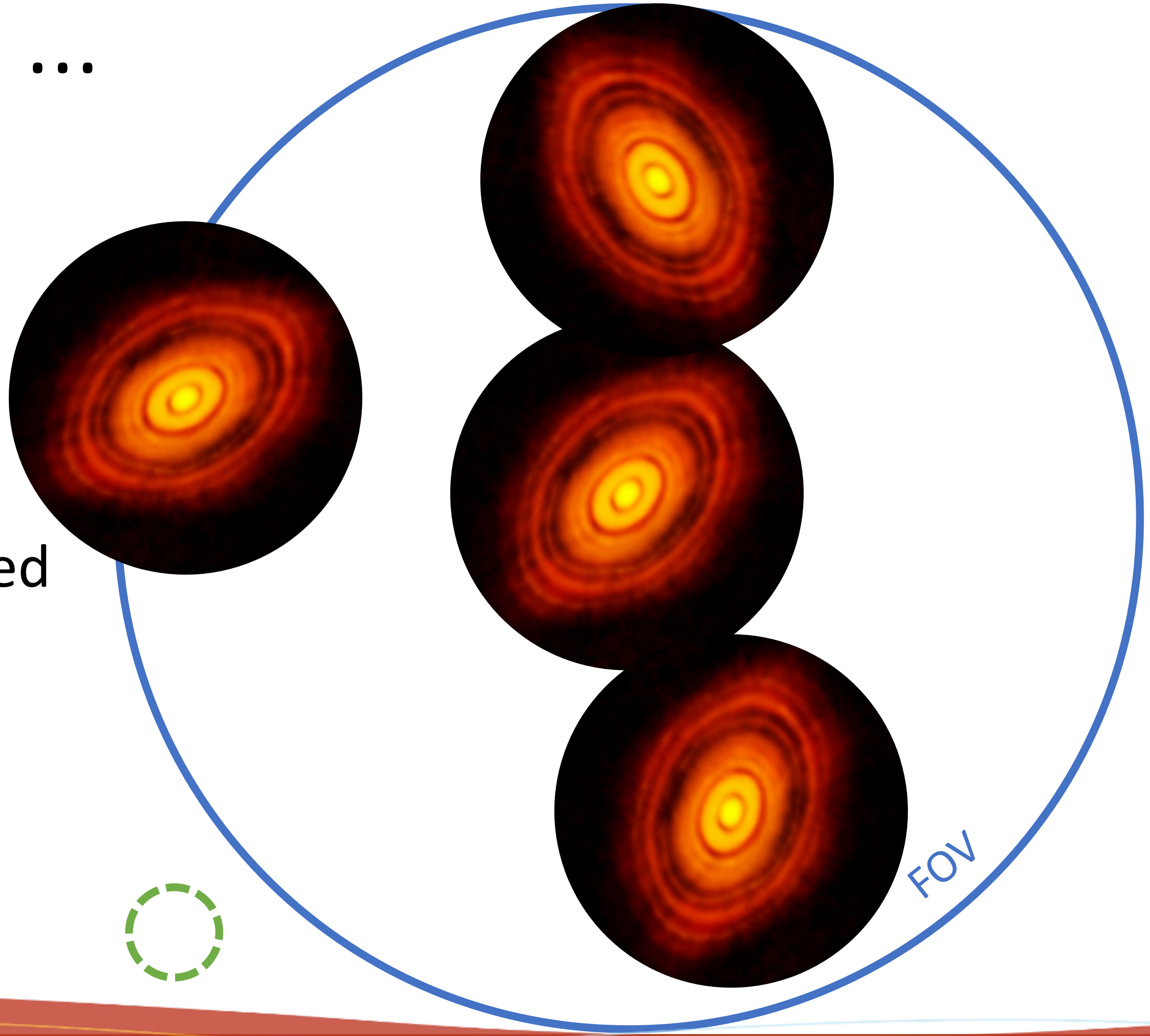
The next simplest observing scenario for an interferometer

Size: << FOV

Location: known

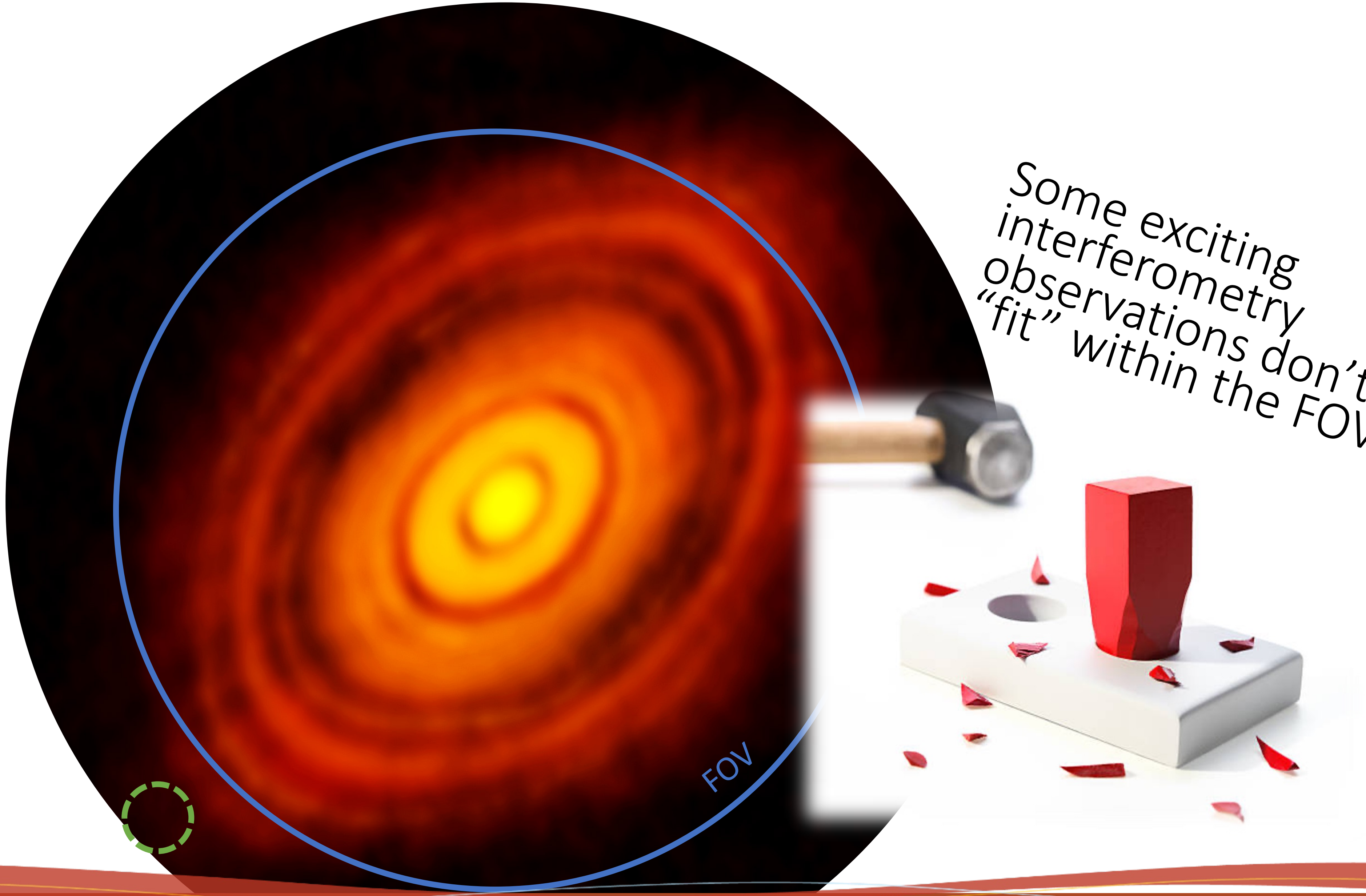


Now consider several more complex scenarios …



- **Size**: << FOV
- **Location**: dispersed

Or this…

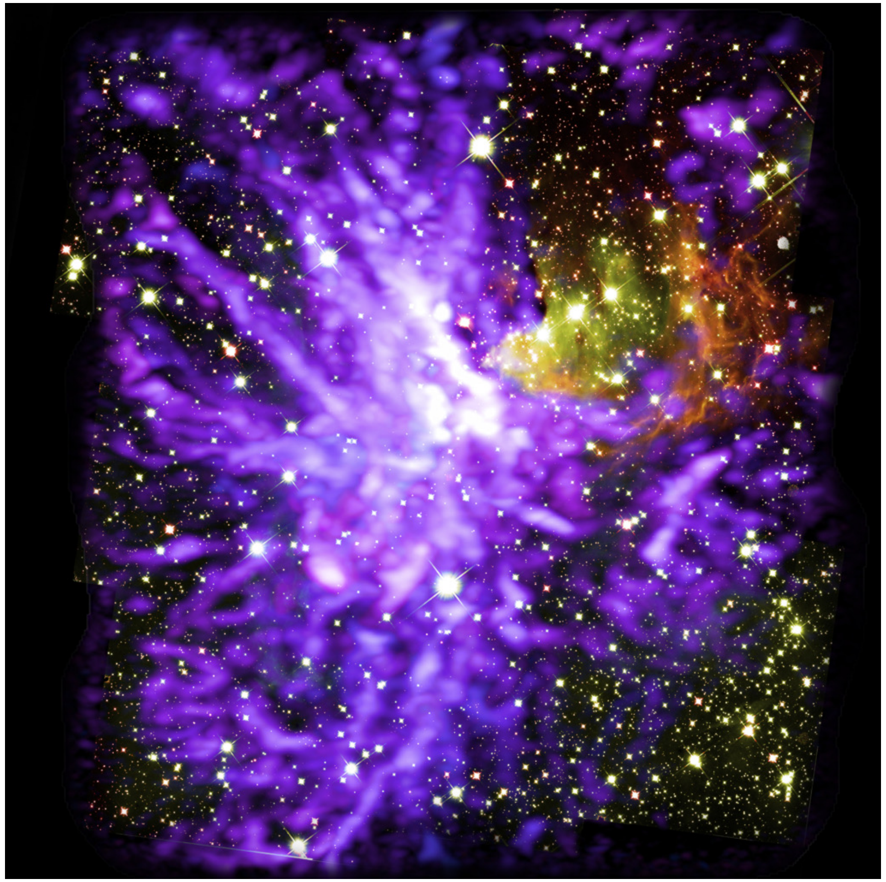


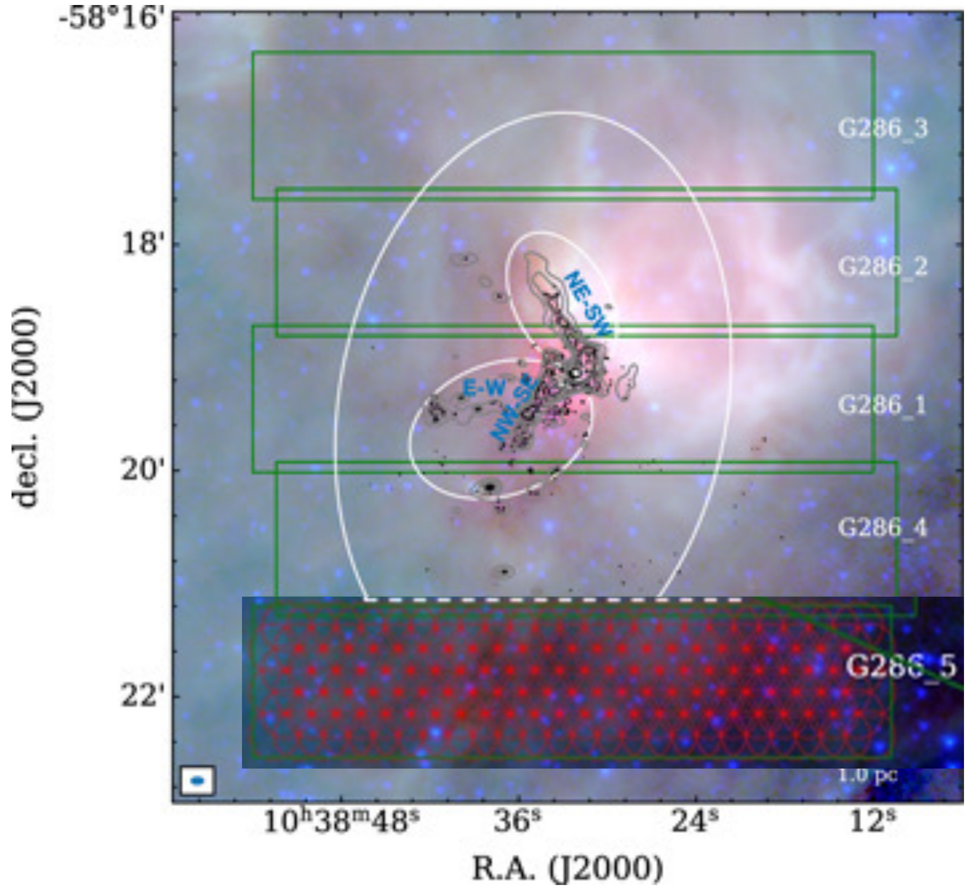
Some exciting interferometry observations don't "fit" within the FOV.

Size: ≳ FOV

Astronomical examples that cover a "large" area of the sky

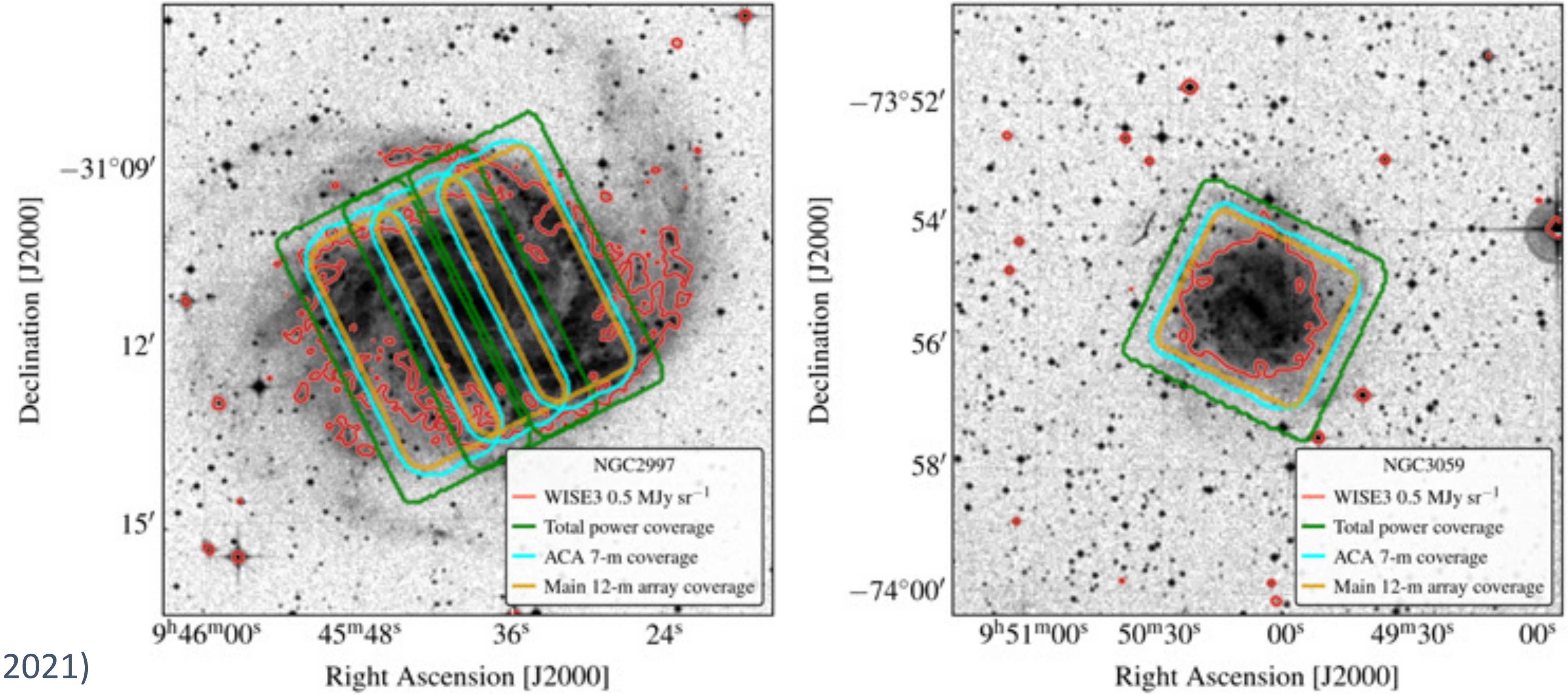
>FOV



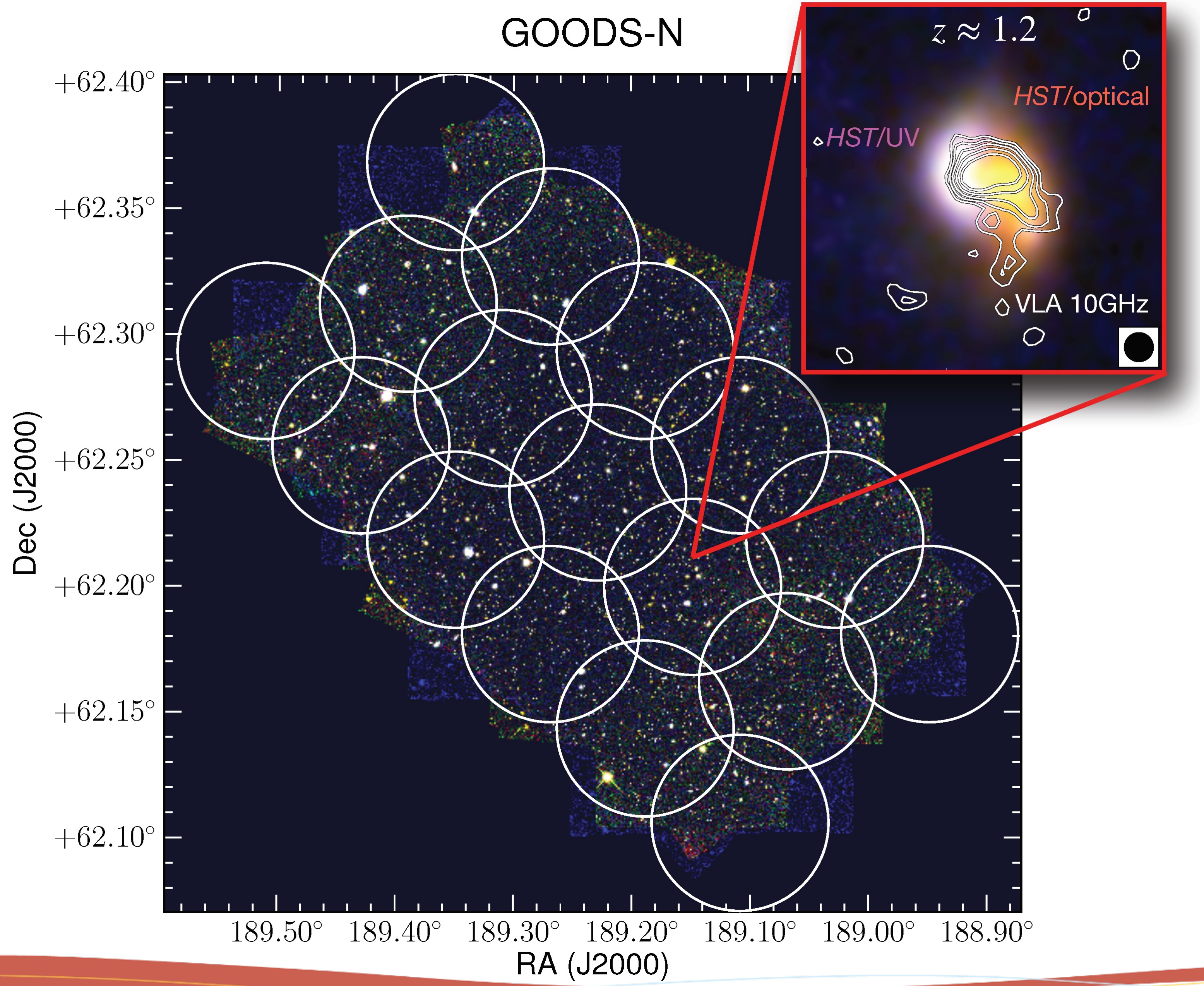


Cheng et al. (2020)

Astronomical examples that cover a "large" >FOV area of the sky



Leroy et al. (2021)



GOODS-N
Murphy et al. (2017)

I. Setting the stage: Scales

It's important to know what (angular) scales your observations will be sensitive to detect and discern.

Equations

Primary Beam (∝ Field of View):

$$\theta_{PB} = (1.03 \rightarrow 1.2) \times \frac{\lambda}{D}$$

~ the diameter of the area imaged by one pointing of the interferometer (instantaneous FOV defined at first null of PB)

Maximum Recoverable Scale (MRS):

$$\theta_{MRS} = \mathcal{L}\frac{\lambda}{b_{min}}$$

The "Spatial Period" of the **largest angular scale** Fourier component of the sky brightness measured by the interferometer.

*In practice, $\mathcal{L}$ represents what you can measure **well.** Quoted pre-factors vary, e.g. depending on uv-coverage; you can motivate $\mathcal{L} = 1/2$ with a simple toy model (Wilner & Welch 1994). ALMA uses $\theta_{MRS} = \frac{0.983\lambda}{L_5}$.*

*b_{min} should be taken to be the shortest spacing at which there is **good** uv-coverage. ALMA uses L_5.*

Equations

Primary Beam (∝ Field of View):

$$\theta_{PB} = (1.03 \rightarrow 1.2) \times \frac{\lambda}{D}$$

~ the diameter of the area imaged by one pointing of the interferometer (instantaneous field of view)

Maximum Recoverable Scale (MRS):

$$\theta_{MRS} = \mathcal{L}\frac{\lambda}{b_{min}} < \underbrace{\frac{\lambda}{D}}$$

The "Spatial Period" of the **largest angular scale** Fourier component of the sky brightness measured by the interferometer

Largest possible scale reliably recovered by an interferometer with antennas of diameter D

Angular Resolution:

$$\theta_{HPBW} = \frac{\lambda}{b_{max}}$$

Takeaway messages

Primary Beam (∝ Field of View):

*If your region of interest is larger than the FOV, you need to **mosaic** together many interferometer pointings.*

Maximum Recoverable Scale (MRS):

*If the **Largest Angular Scale (LAS)** of structures you are interested in are larger than this, you likely will need to get data from **a more compact configuration of the interferometer, and/or single dish.***

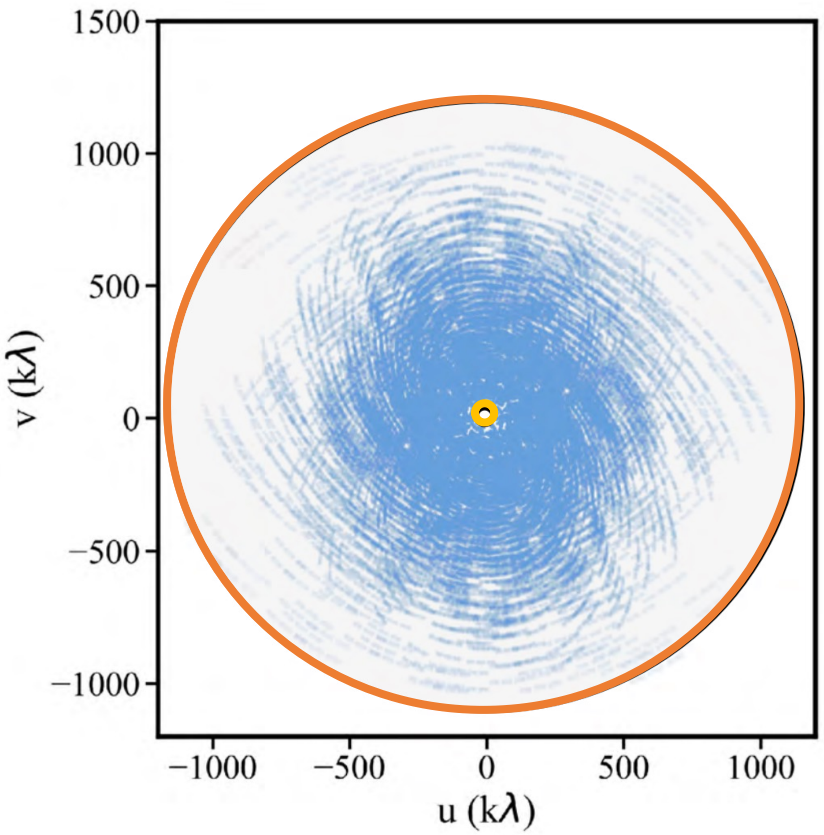
Angular Resolution:

Smallest scale structure you can distinguish.

A side note on MRS versus LAS:

- **ALMA** documentation distinguishes **MRS** as a property of the observations, and **LAS** as a property of the observed source.
- **VLA** documentation refers only to **LAS**, which applies to either case.

Implications of (*u*,*v*) plane sampling, visually



Samples of *V(u,v)* are limited by the array, and Earth-sky geometry.

Outer boundary (longest baselines):
- Information only DOWN TO a certain small scale
- Resolution limit (θ_{HPBW})

Inner boundary (shortest baselines):
- Information only UP TO a certain recoverable scale (MRS)
- Extended sources are invisible

Irregular coverage:
- Sampling theorem violated
- Information missing

Recall talk by J. Marvil (Thursday), adapted from slide by D. Wilner

Implications of (u,v) plane sampling, numerically **

Array	λ	PB	MRS	θ_{HPBW}
VLA	21 cm (L Band)	15’	36-970”	1-46”
	3.6 cm (X Band)	3’	5-145”	0.2-7”
	0.7 cm (Q Band)	40”	1-32”	0.04-1.5”
ALMA	1 mm (Band 6)	17.5”	0.2-12”	0.02-1.5”
	0.4 mm (Band 9)	7”	0.08-4”	0.007-0.5”
	Depends on:	Wavelength, antenna diameter	Wavelength, shortest baselines	Wavelength, longest baselines

*** Approximate reference values*

II. Mosaicking

The theory, (mostly) illustrated

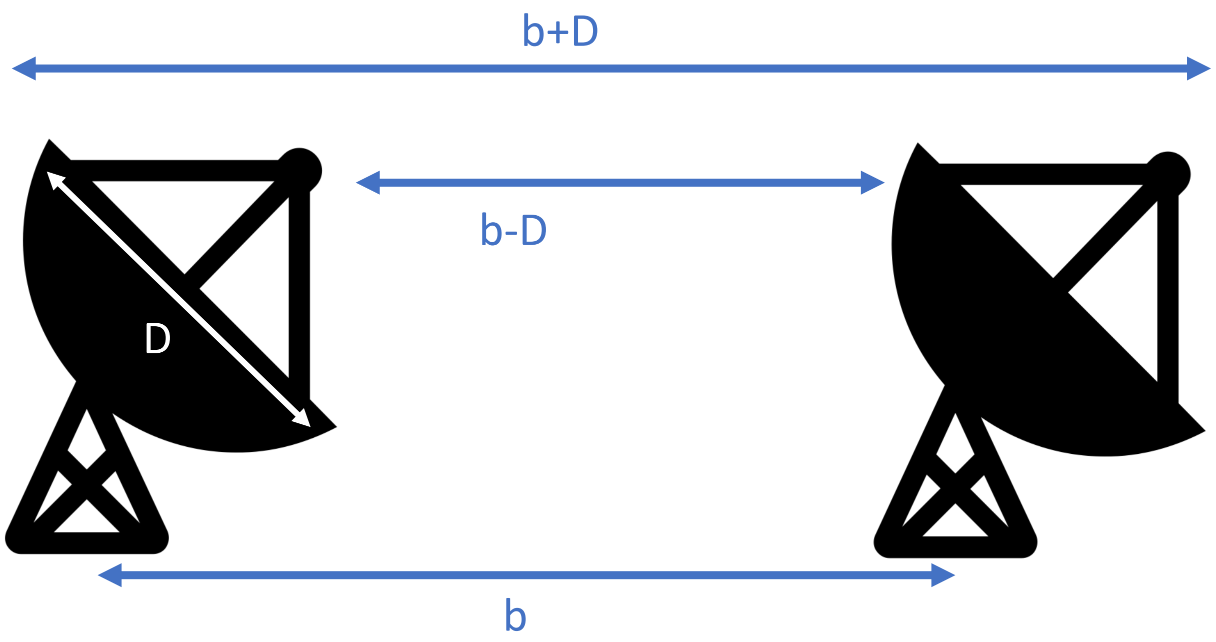
See talks by I. Heywood & P. Jagannathan for Radio Interferometer Measurement Equation

Theory of Mosaicking

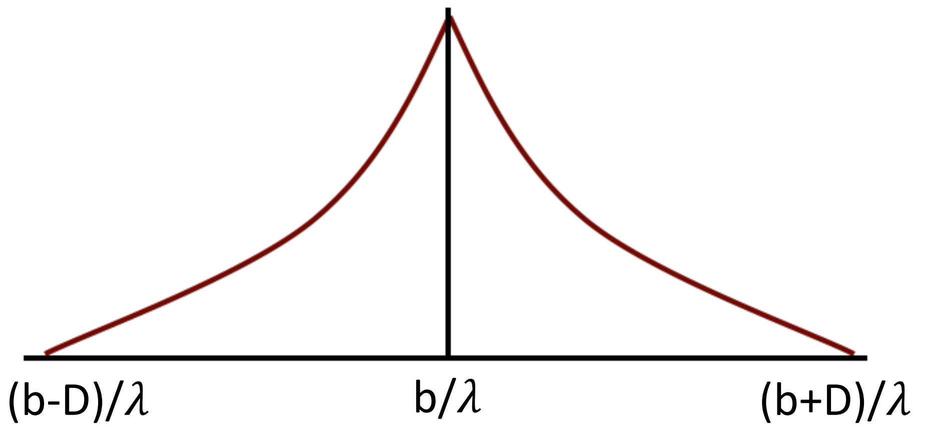
Ekers & Rots (1979)

Each 2-element interferometer (roughly) measures angular scales $\theta \sim \lambda/b$.

Actually, it measures $\frac{\lambda}{b+D} < \theta < \frac{\lambda}{b-D}$



A single baseline has the following (u,v) coverage:

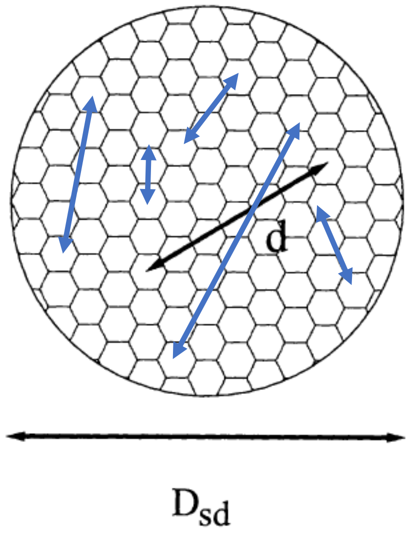


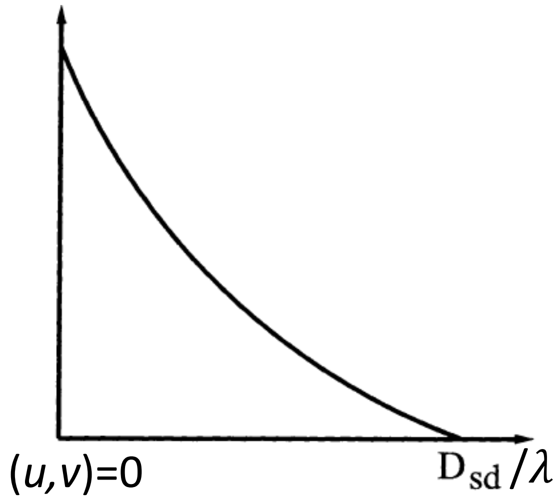
Theory of Mosaicking

Ekers & Rots (1979)

A single dish measures scales: $\frac{\lambda}{D_{SD}} < \theta < \infty$ (within FOV)

Single dish "(u,v)" coverage:





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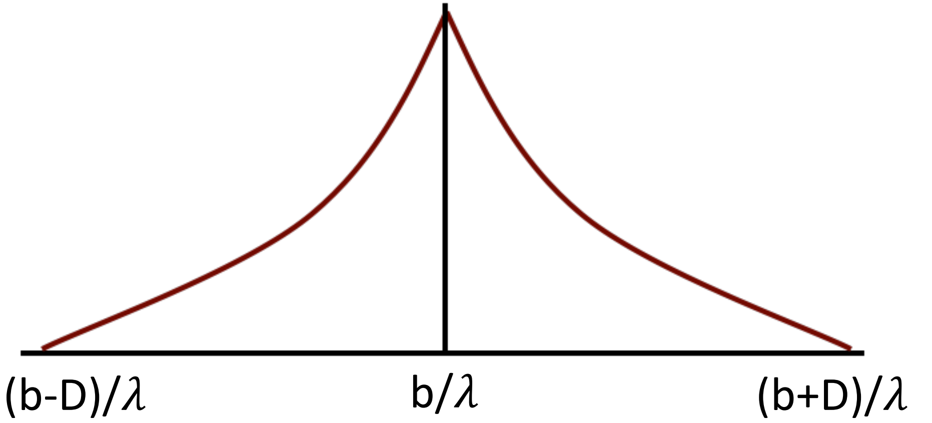
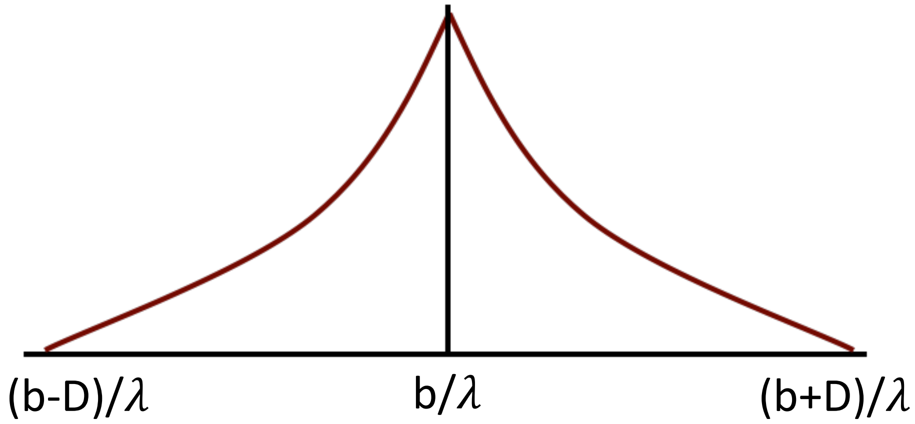


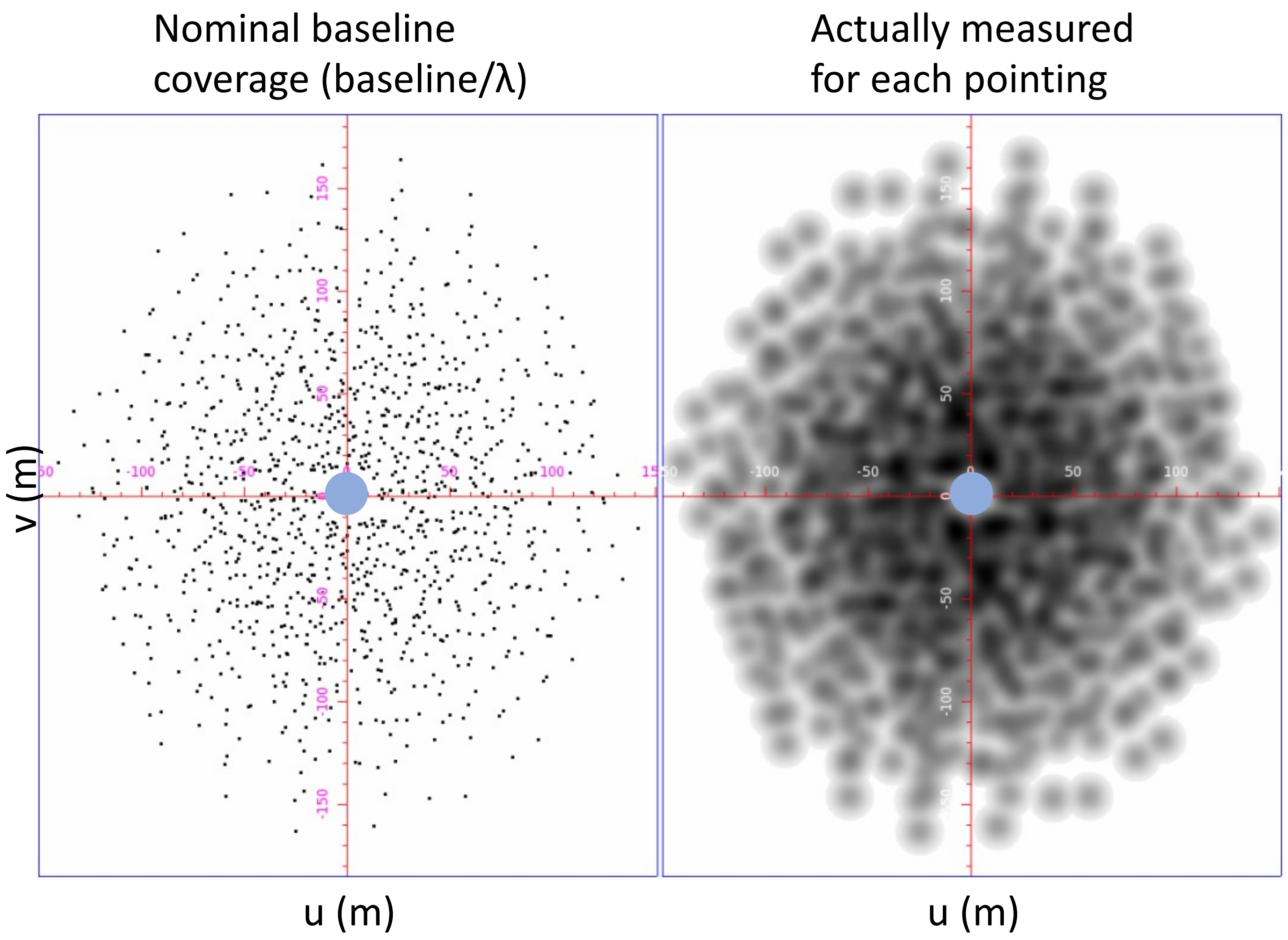
Theory of Mosaicking

The problem

- With each pointing of the interferometer, you measured only a single complex visibility $\left(\text{between} \frac{\lambda}{b+D} < \theta < \frac{\lambda}{b-D}\right)$
- SD observations have an equivalent problem…



Theory of Mosaicking



See memo by Mason (2020)
https://arxiv.org/pdf/2006.06549

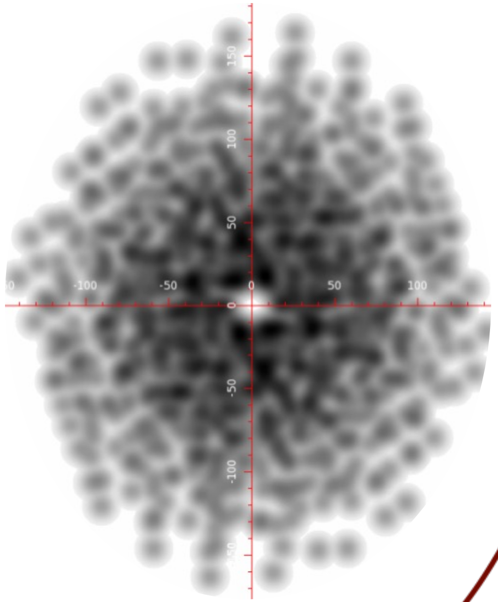
Theory of Mosaicking

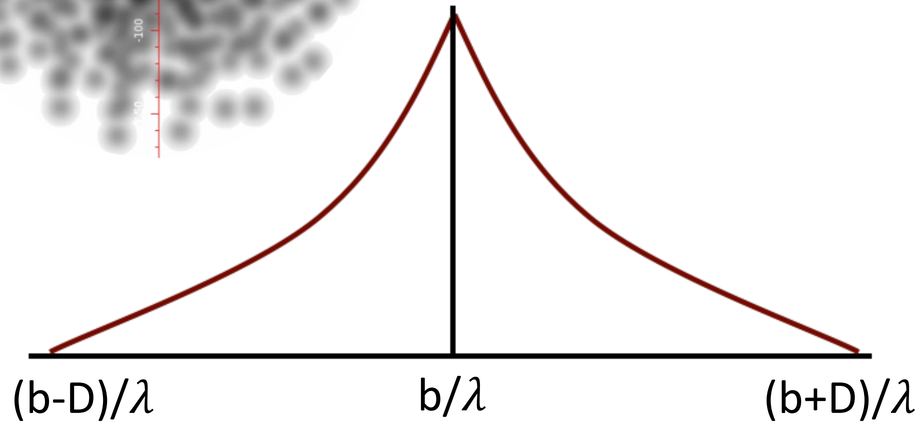
The problem

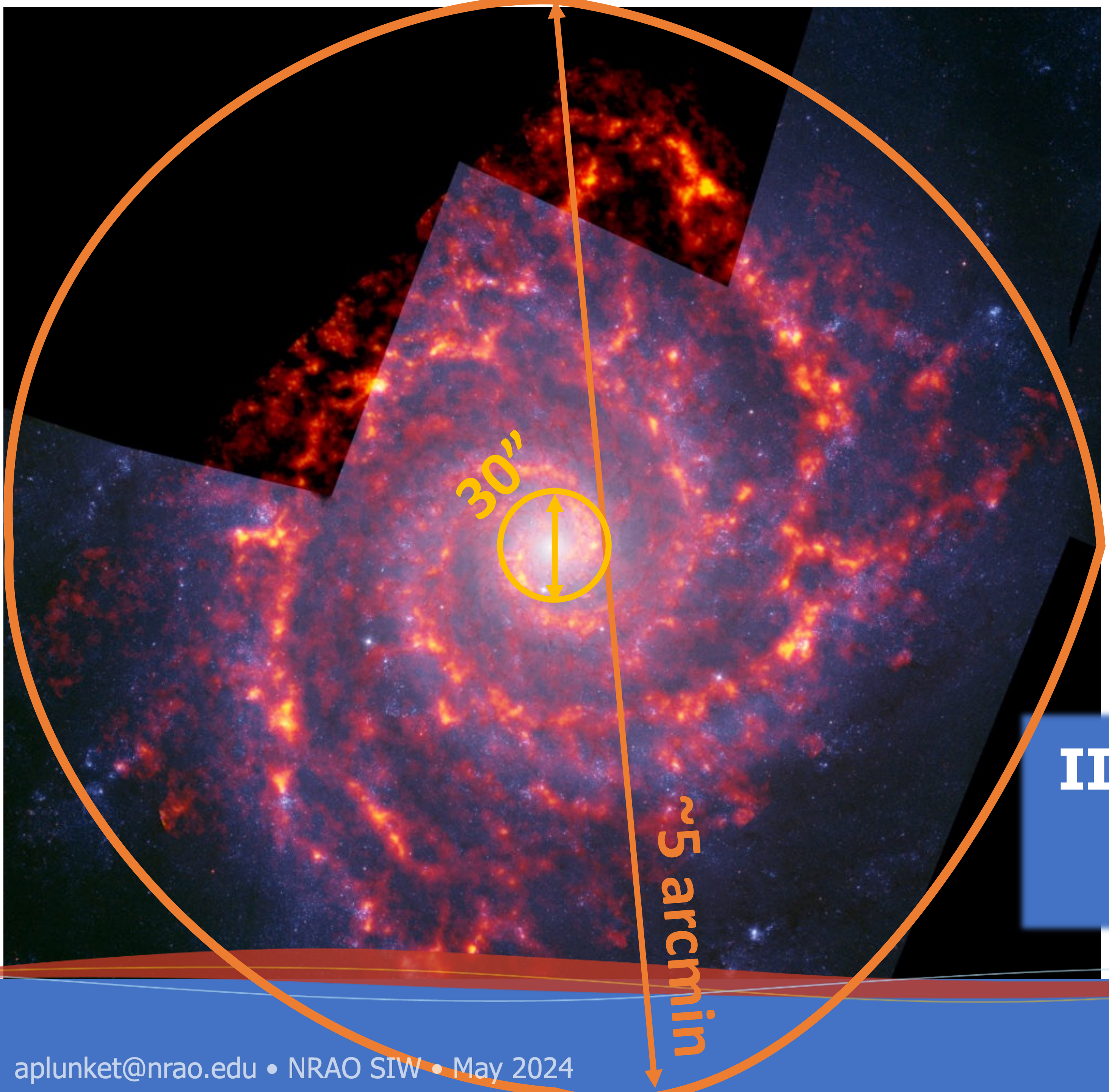
- With each pointing of the interferometer, you measured only a single complex visibility $\left(\text{between } \frac{\lambda}{b+D} < \ \theta < \ \frac{\lambda}{b-D}\right)$
- SD observations have an equivalent problem…

Solution

- Scan the telescope over the sky and measure the visibility *V(u,v)* function multiple times in different locations.
- Separate out the the Fourier modes contained in each measurement, increasing the mapped Fourier resolution & Maximum (useful) Recoverable Scale.





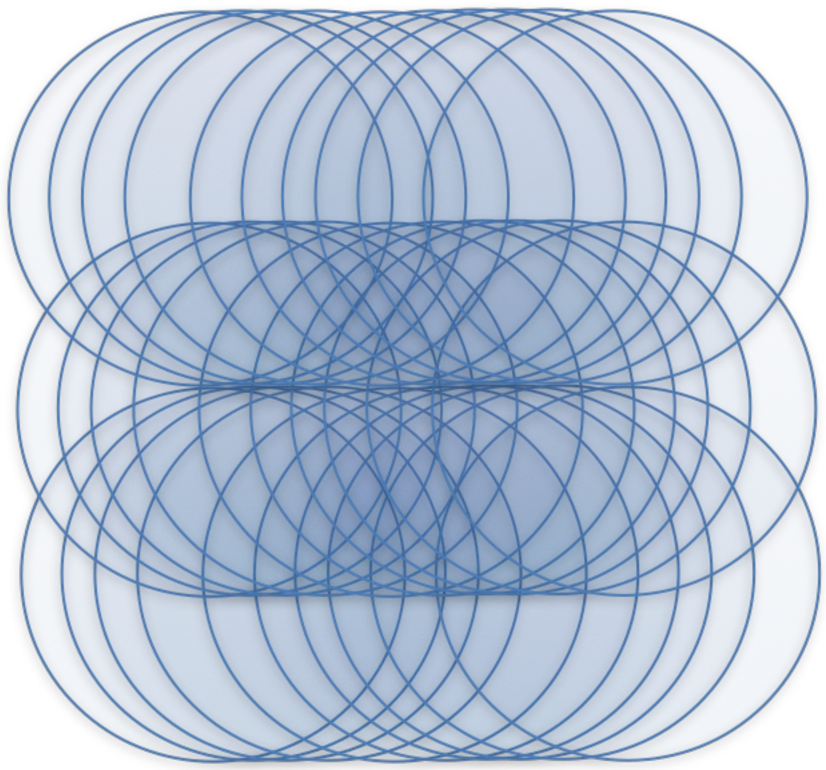


See talk by P. Jagannathan for widefield imaging

II. Mosaicking

Several techniques for mapping a larger field of view (FOV)

How to observe a larger FOV?



Option 1: Scan continuously, dumping correlations & antenna position information rapidly (scheme proposed by Ekers & Rots 1979)

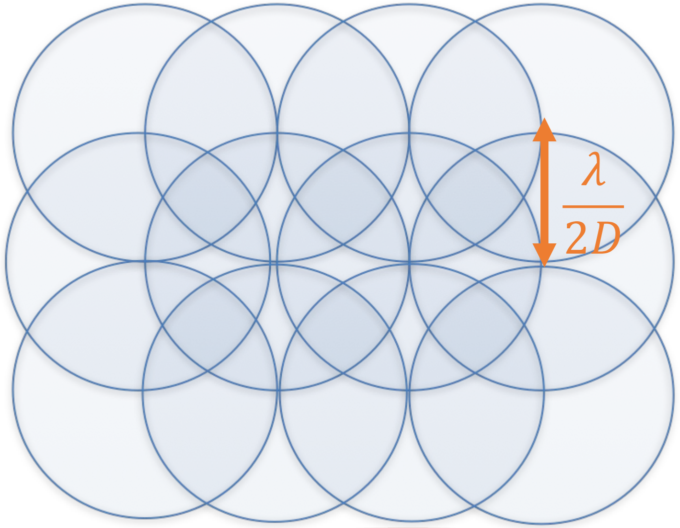
- On-The-Fly Interferometry - analogous to single dish "On-the-fly Mapping"
- Low observing overheads but high data rates
- Sometimes used today, especially for surveys at VLA (e.g. VLASS)

How to observe a larger FOV?

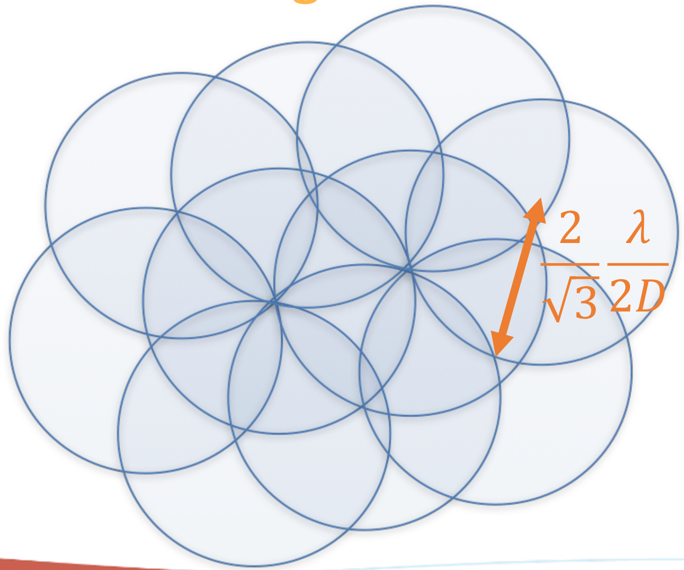
Option 2: Tile the sky with discrete pointings;

- Cornwell (1988) showed that this provides the full E&R (1979) information if the sampling is sufficiently dense

Rectangular Grid



Hexagonal Grid



Hexagonal is preferred for uniform image domain noise.

However, effects of more sparse sampling are modest, and often a viable option to increase survey speed, e.g. NVSS

Making the mosaic image ("map")

Two widely-used methods for mosaic image reconstruction:

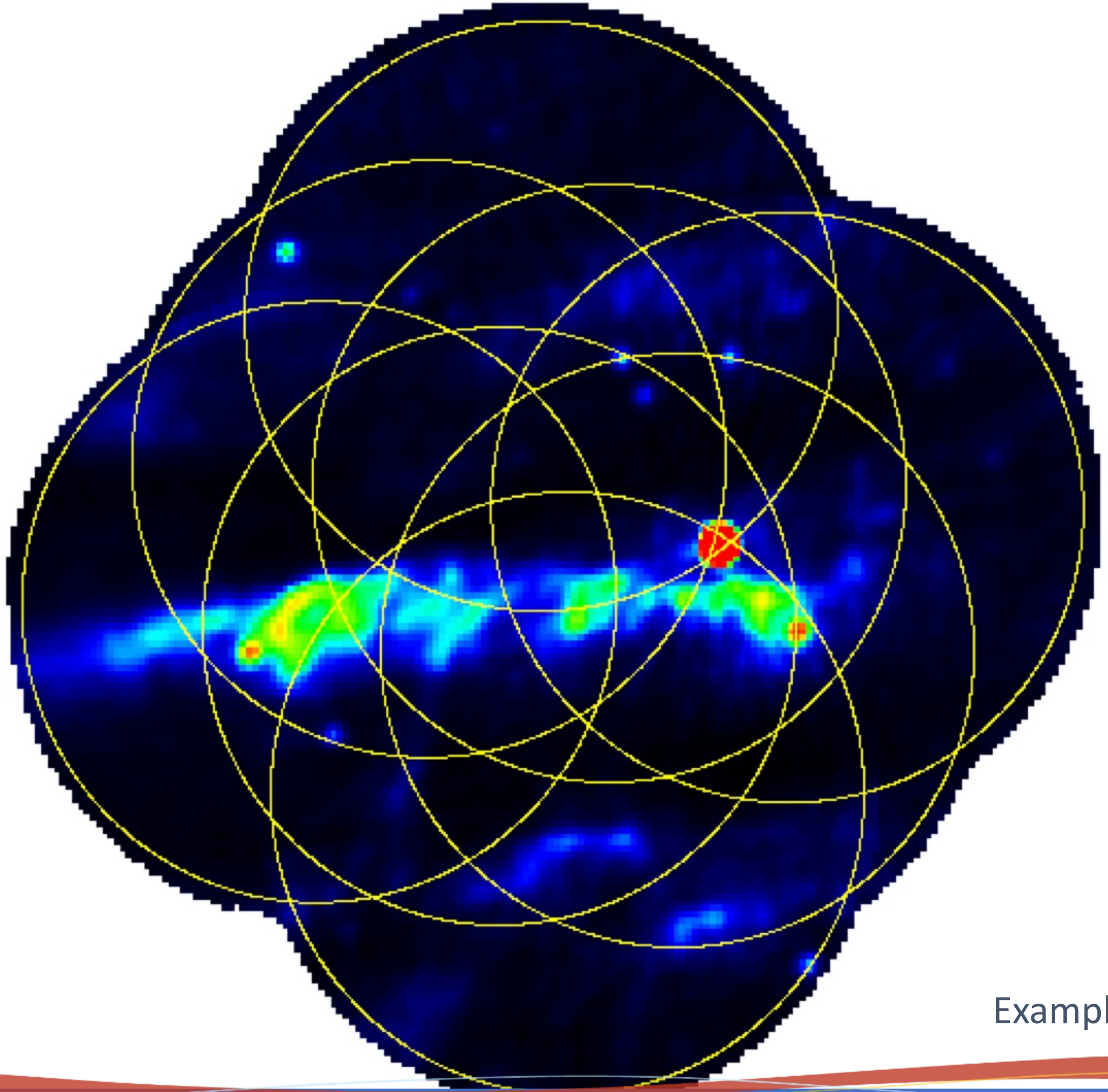
A.) Linear mosaic (AKA "stitching")

- Make dirty maps of each individual pointing
- Deconvolve individually
- Combine deconvolved maps with some PB correction

B.) Joint Mosaic Imaging

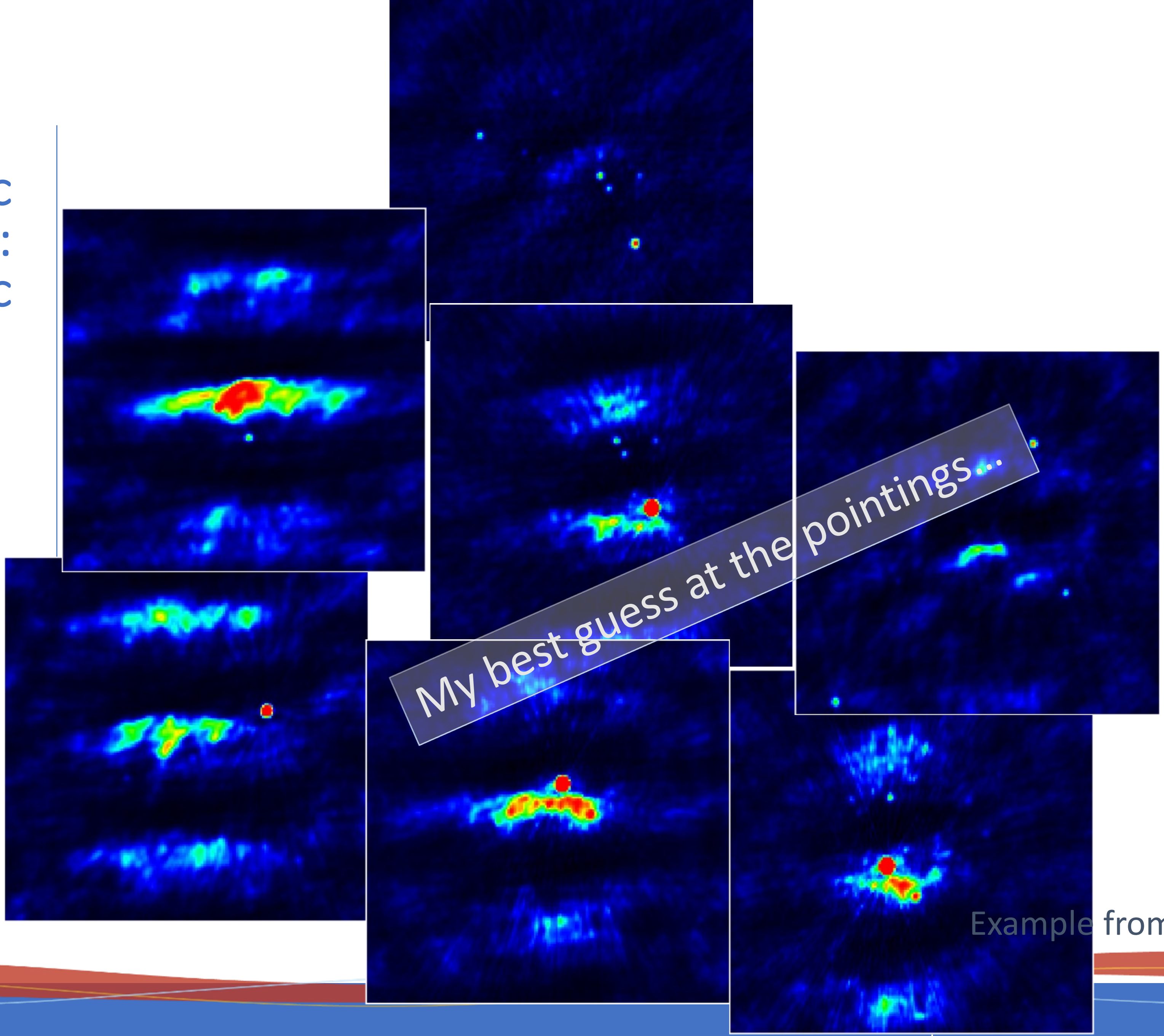
- Combine visibilities from all pointings in uv-space
- Generate single dirty map
- Deconvolve jointly

Making the mosaic image ("map"): A.) Linear mosaic



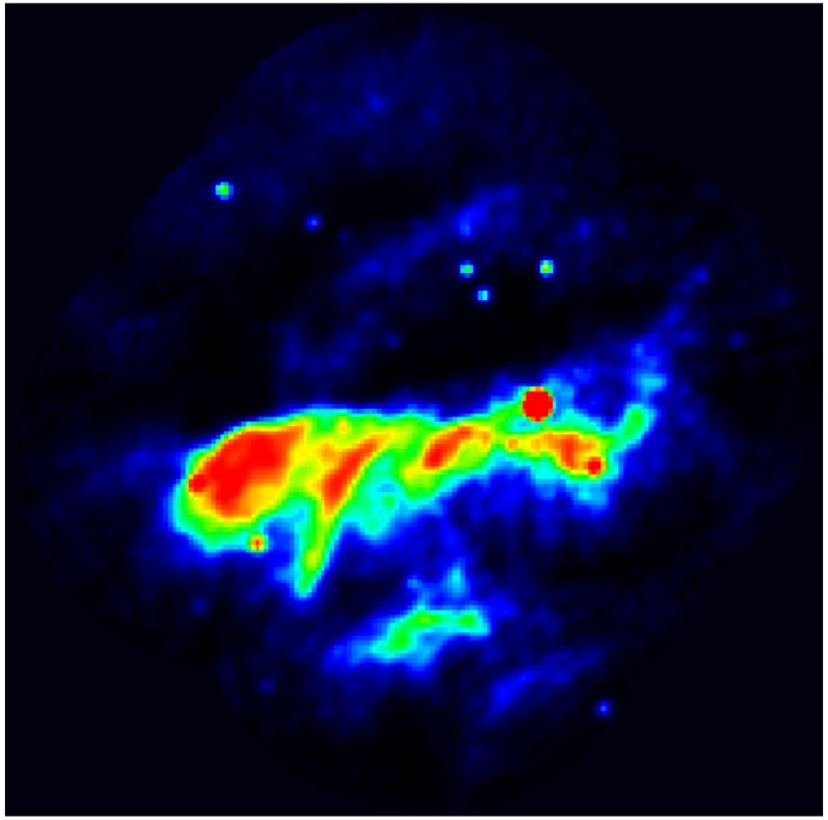
Example from J. Ott

Making the mosaic image ("map"): A.) Linear mosaic



Example from J. Ott

Making the mosaic image ("map"): A.) **Linear mosaic**



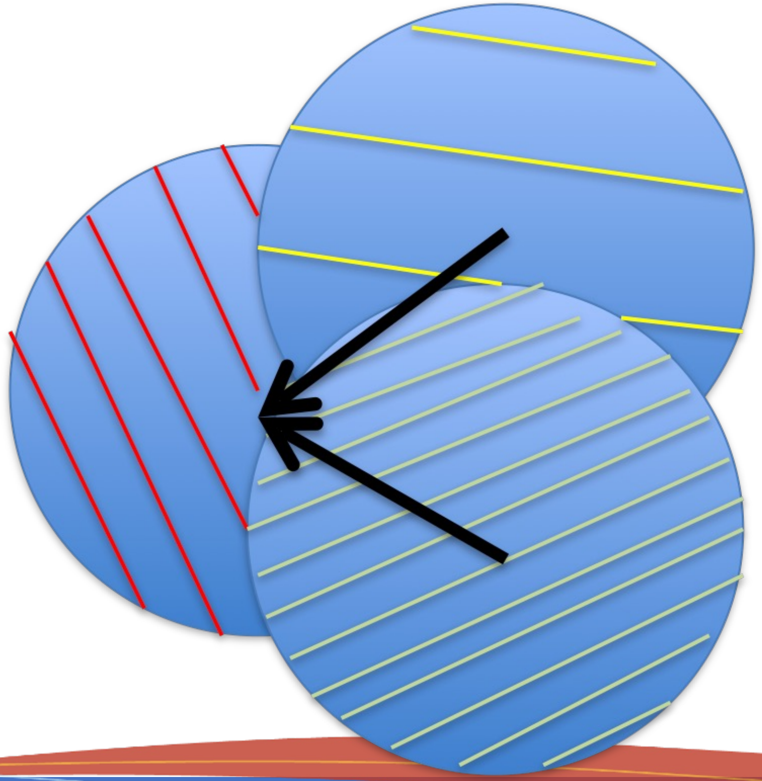
Advantages

- Conceptually straightforward
- Each pointing can be calibrated and optimized individually: useful for ***low frequency imaging*** (high dynamic range, ionosphere)

Disadvantages

- Deconvolution is possible only to the depth of the individual pointings
- Not as effective at recovering shorter spacings (no Ekers & Rots information in the deconvolution)

Making the mosaic image ("map"): B.) **Joint mosaic imaging**



Advantages

- Uses all *(u,v)* info per overlap → better beam, deeper clean
- All the (Ekers-Rots) information at every point in the sky utilized in deconvolution → more large-scale structure recovered
- Works well with on-the-fly interferometry data (many, many pointing centers)
- Naturally works well with heterogeneous arrays (antennas of different sizes)

Disadvantages

- You need to know your PB well
- Assumes a fairly stable PSF

Making the mosaic image (“map”): B.) **Joint mosaic imaging**

In practice… *

- Calibrate as you would do for a single pointing (e.g. pipeline)
- In **tclean()** use *gridder=‘mosaic’* for joint mosaic imaging
  - Uses Cotton-Schwab (major/minor cycle) algorithm
  - Specify the “deconvolver” parameter
    - *deconvolver=‘hogbom’* - default, good for poor psf and compact sources
    - deconvolver=‘multiscale’ - for complex, extended emission.
    - *deconvolver=‘clark’ - faster*
  - *gridder=‘mosaic’* is necessary for any “heterogeneous array” imaging using **tclean()** in CASA (even single field!)
    - Fully supported for ALMA; possible for other telescopes if you use a little bit of care.
- Other recommended **tclean()** parameter choices: *mosweight=True*; and for cubes, *perchanwtdensity=True + briggsbwtaper=True*.

** For “Widefield Imaging”, see talk by P. Jagannathan*

Deconvolution

Deconvolution of extended sources (a primary scenario for mosaicking) is tricky. **

Why? In general the "CLEAN model" is not your best estimate of the sky; the reconvolved CLEAN model+residuals is.

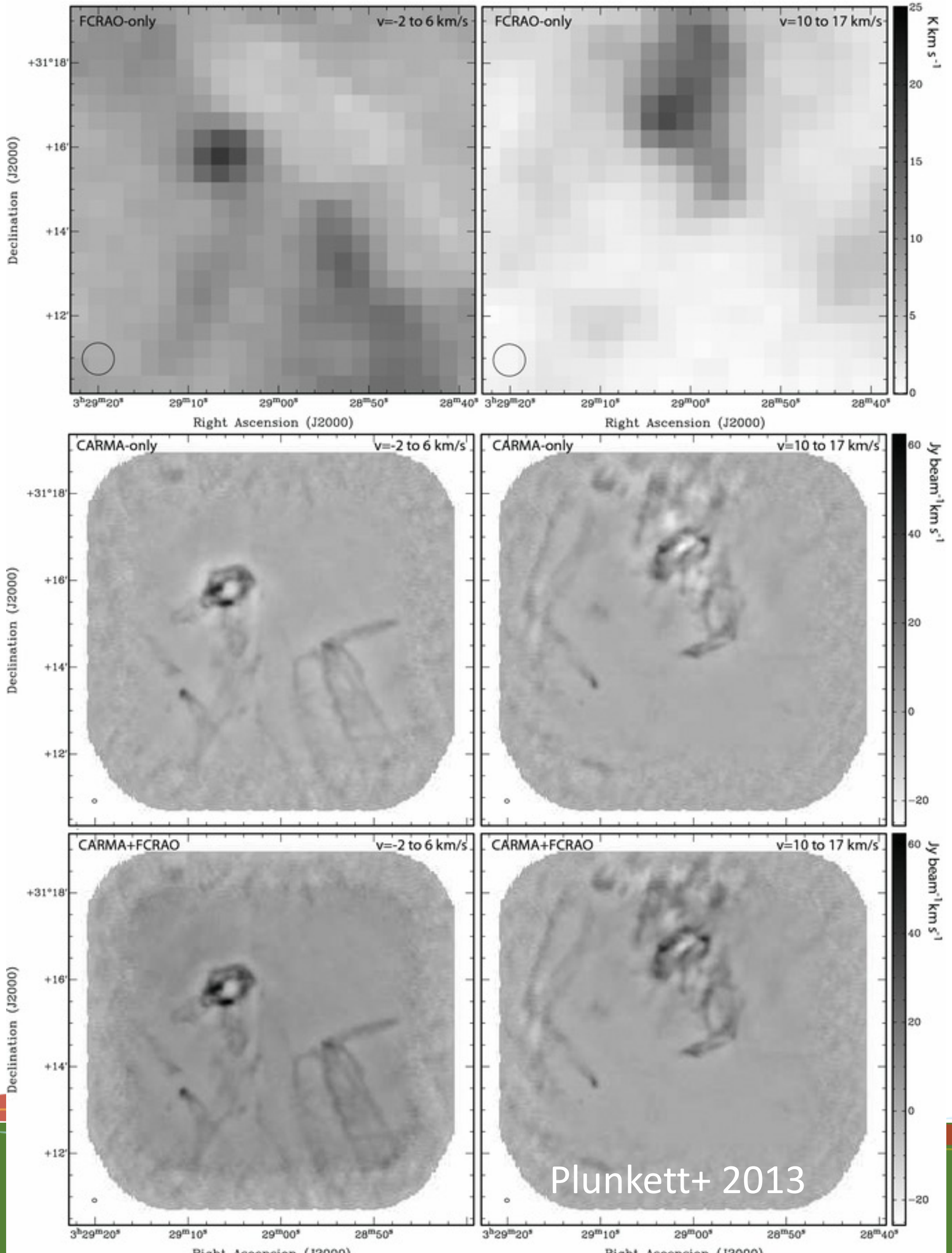
As a result…

- It may take a long time to clean a spectral line cube
- Multi-scale is often a good option tclean(deconvolver='multiscale') [Cornwell+ 2008]
- It helps to have good uv coverage, a judiciously chosen clean box, & careful monitoring (interactive)
- Automatic CLEAN masking can help a lot! tclean(mask='auto-multithresh') [Kepley+ 2020]
- You may need to clean deeply (e.g. 1.5σ) for extended emission.
- For self-cal using the CLEAN model for a mosaic, clean more conservatively.

*** For "Widefield Imaging", see talk by P. Jagannathan*

III. Image Combination: Motivation

Some words (pictures) on why single dish is important for “synthesis imaging”

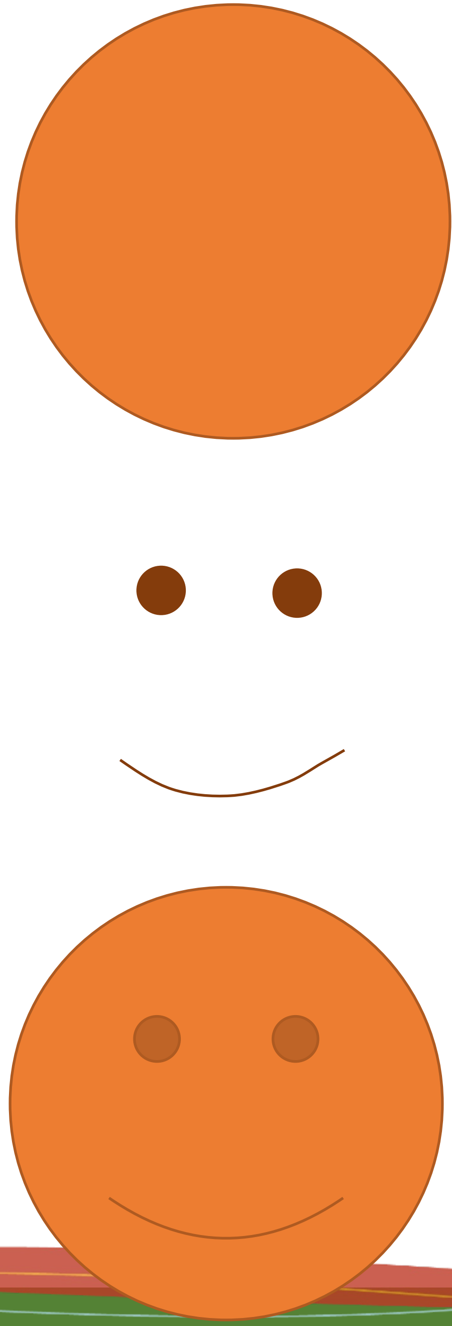


Single dish ⟷ Large structures

Interferometry ⟷ Small structures

Combined ⟷ ALL(?) structures

National Radio Astronomy Observatory

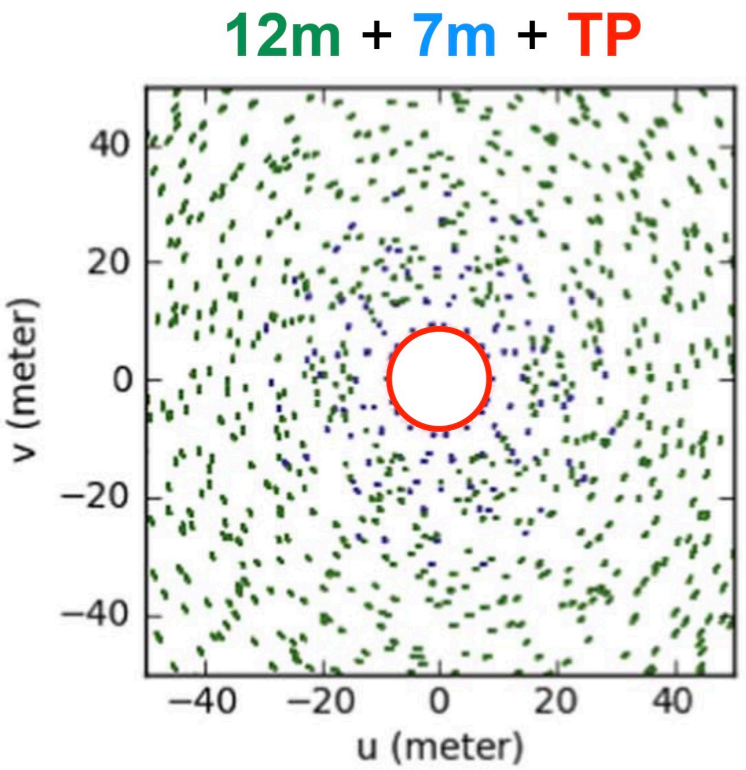


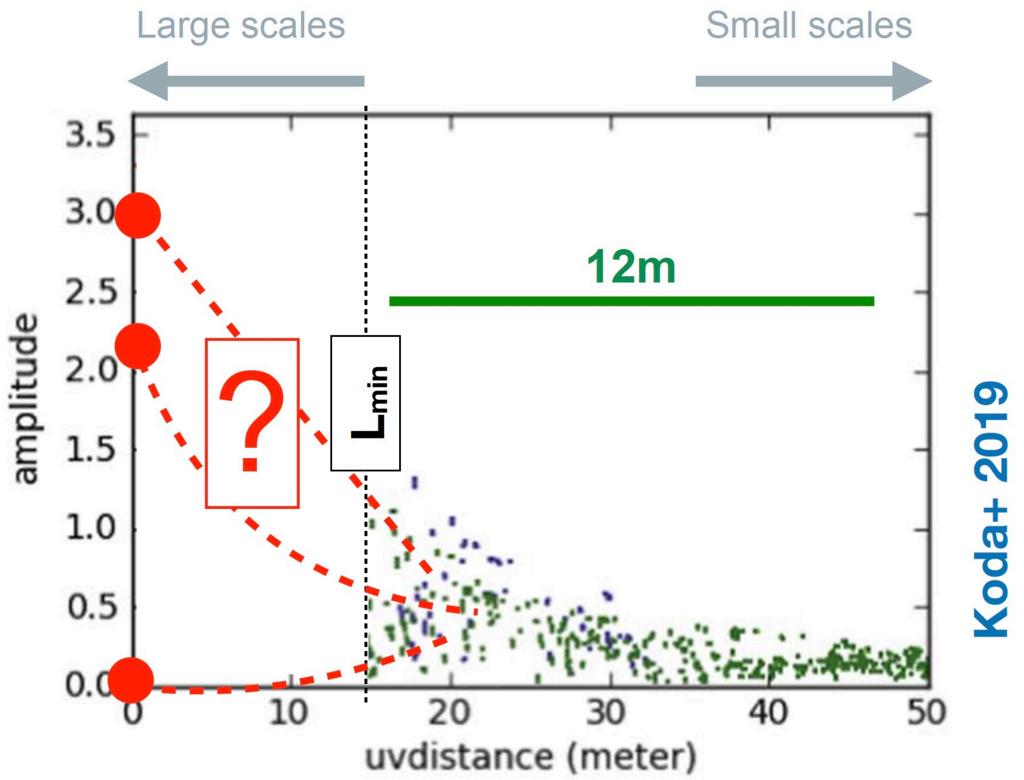
Single dish ⟷ Large structures

Interferometry ⟷ Small structures

Combined ⟷ ALL(?) structures

Data Combination: An illustrated need

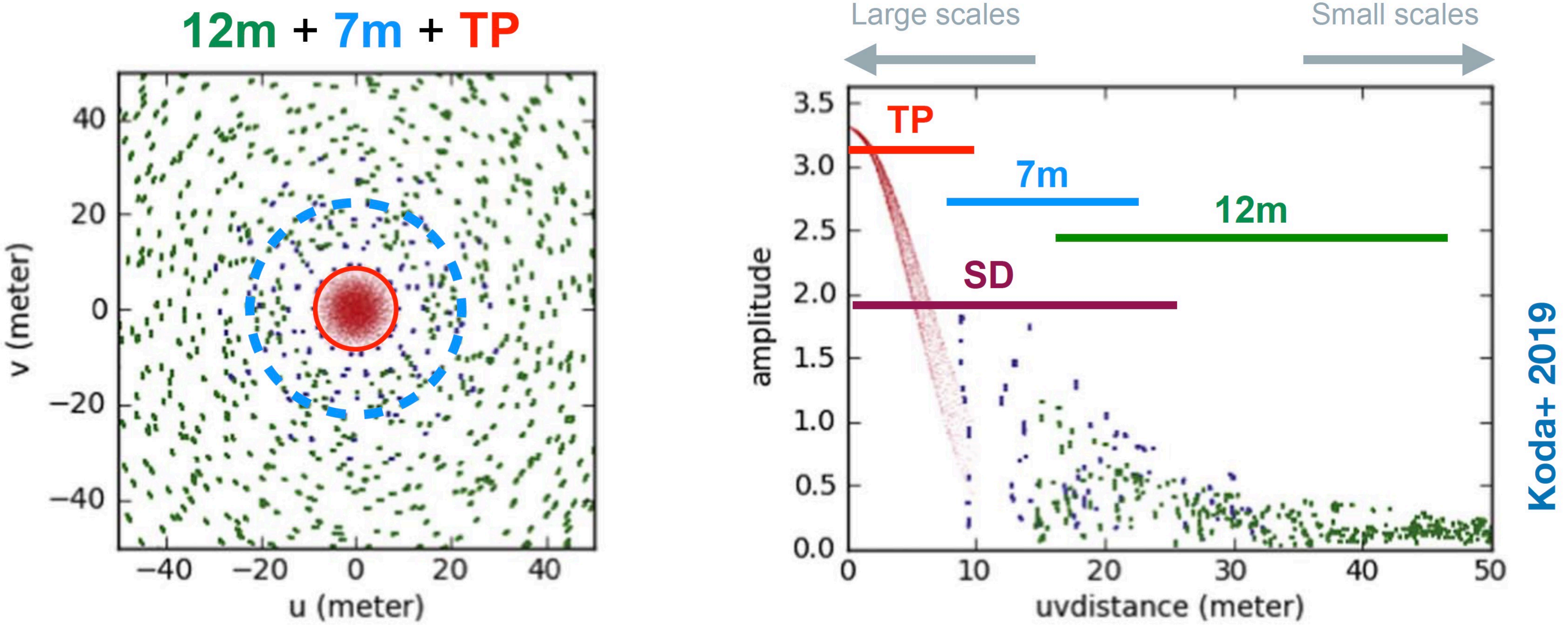




- Zero-spacing problem = missing information at short baselines (<L_{min})

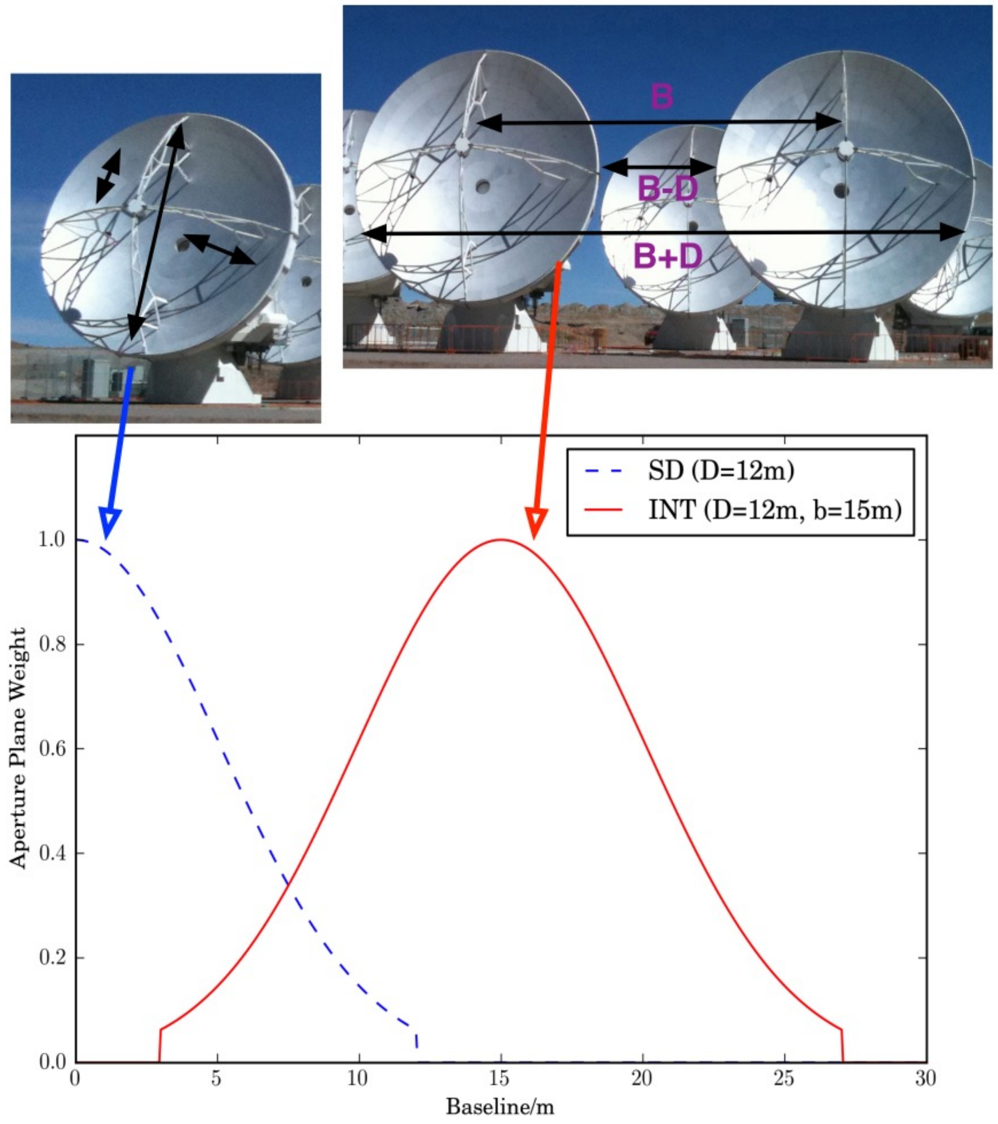
Slide by Alvaro Hacar

Data Combination: An illustrated need



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

Slide by Alvaro Hacar



See memo by Mason (2020)
https://arxiv.org/pdf/2006.06549

III. Image Combination: In practice

"Short-spacing correction"

Image combination: Antennas

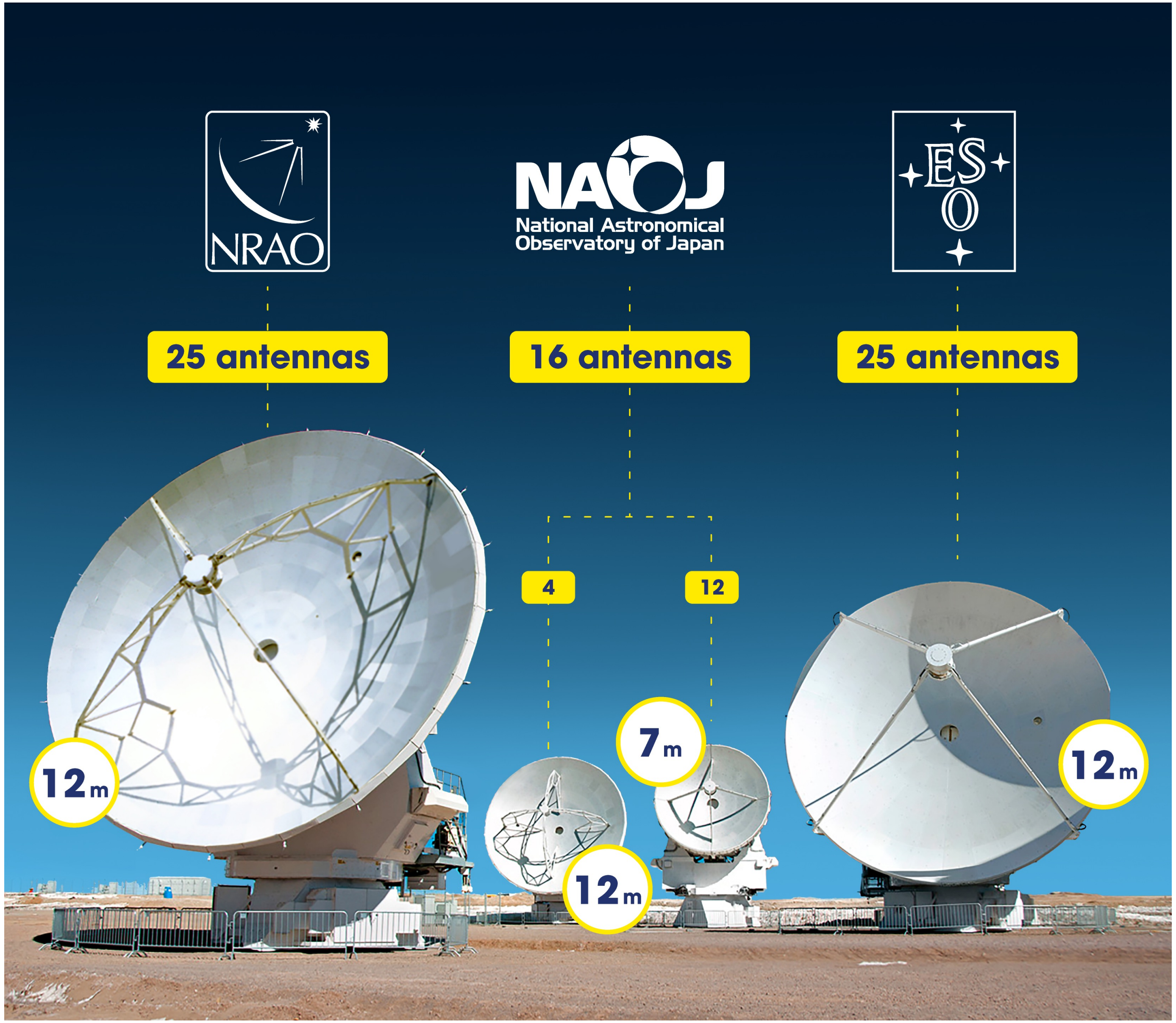
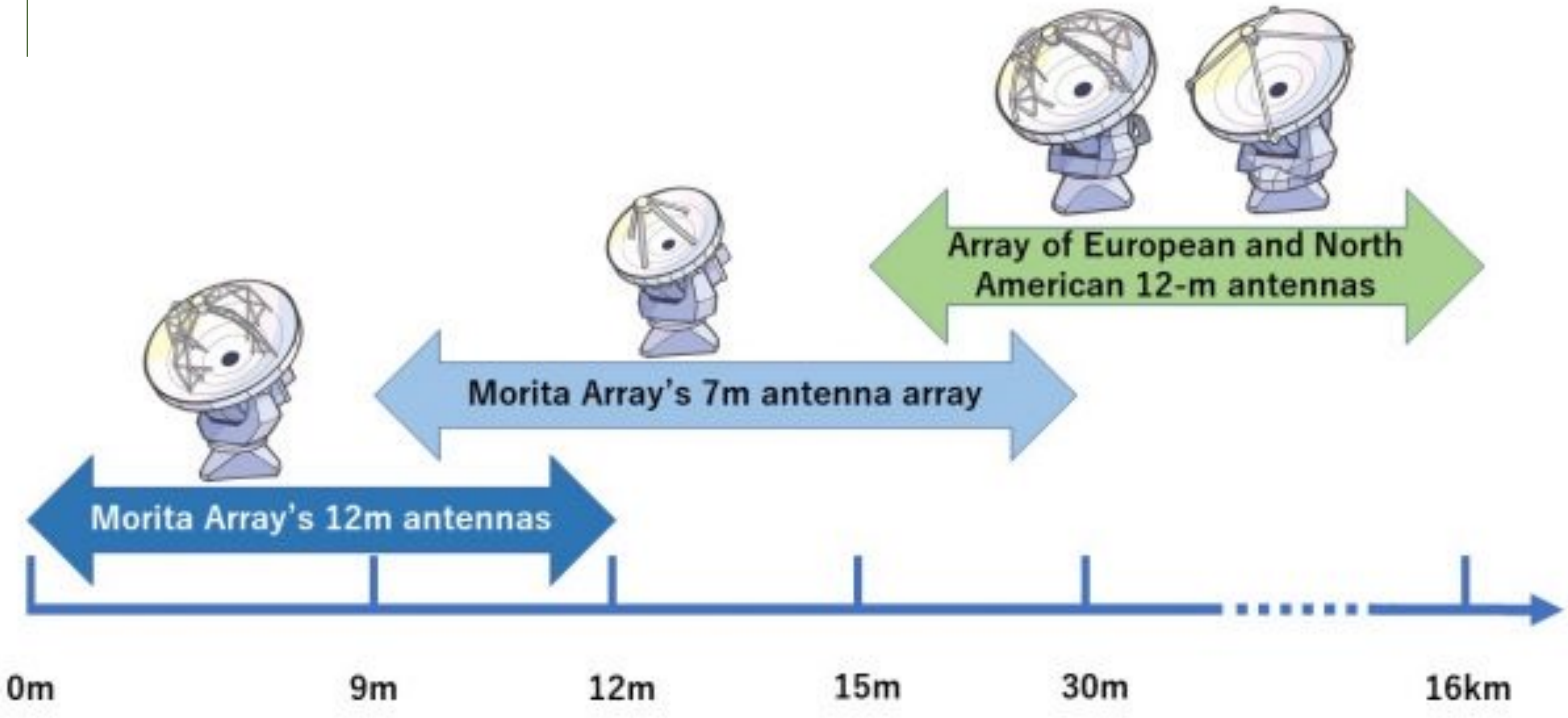


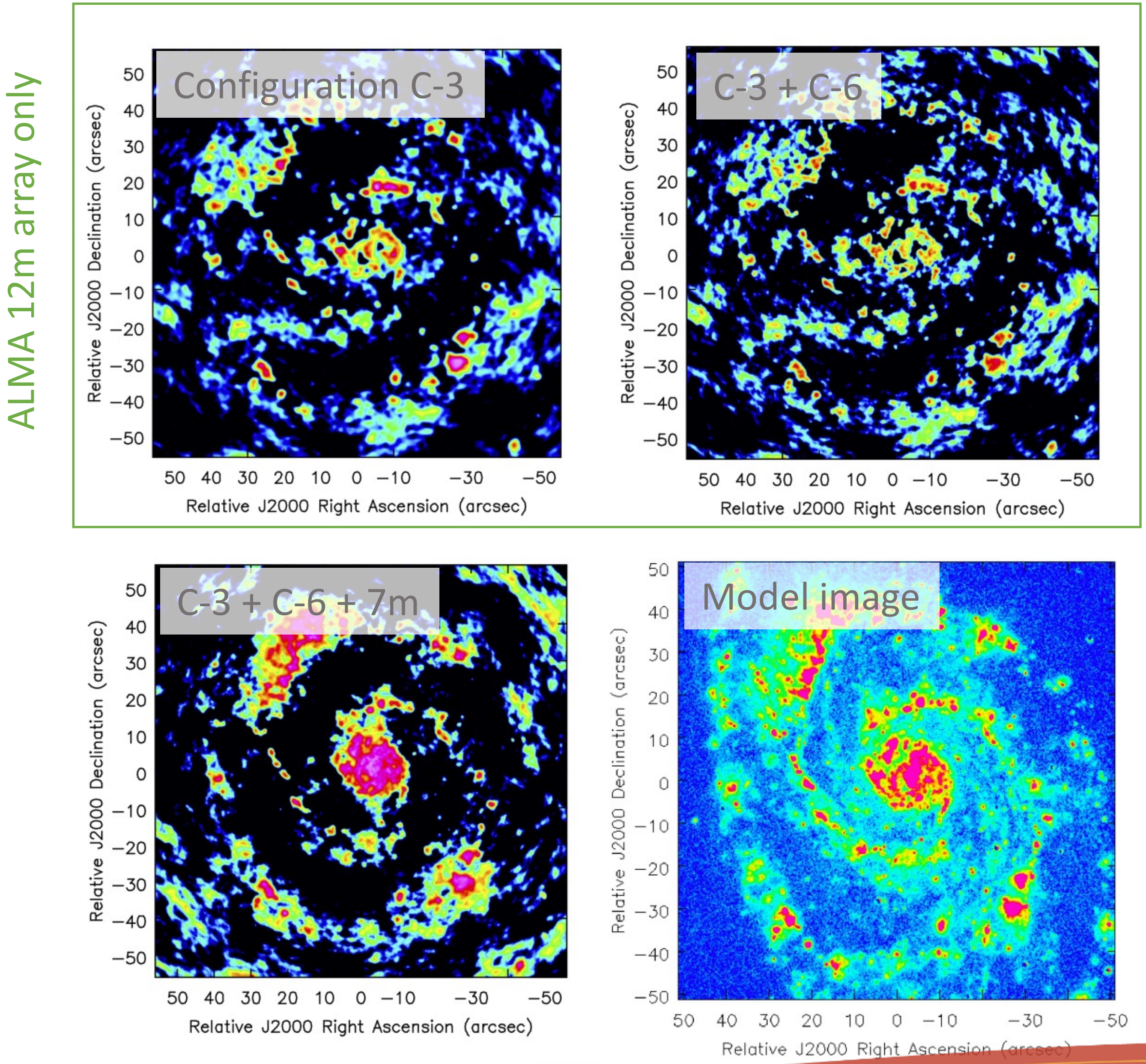
Image combination: Configurations



"baselines"

Diagram credit: ALMA (ESO/NAOJ/NRAO)

But first… Image combination does not *have* to include antennas of different sizes.



See ALMA Technical Handbook, Section 7.8-7.9

But first… Image combination does not *have* to include antennas of different sizes.

ALMA 12m array only

ALMA interferometry (12m+7m) only

Includes Total Power (TP)

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	$2.7 \times \Delta_{extended}$

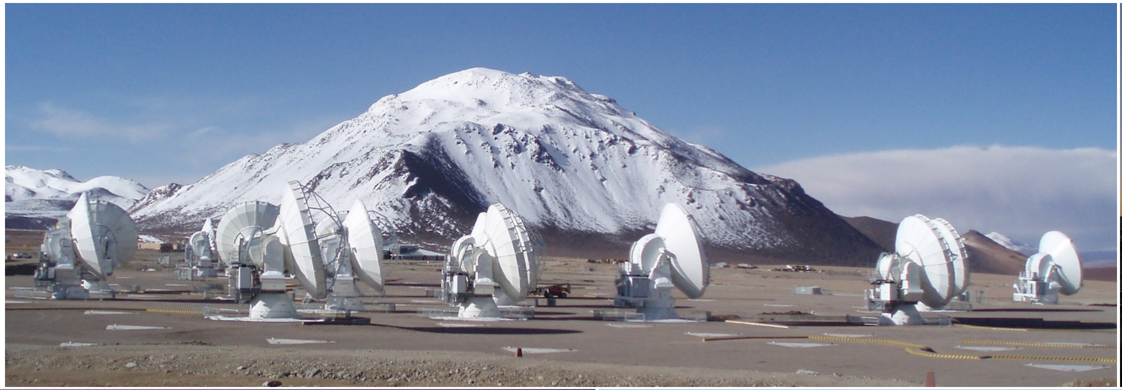
See: *ALMA Technical Handbook, Table 7.5 (for 100 GHz)*
For VLA: https://science.nrao.edu/facilities/vla/proposing/configpropdeadlines

Configuration changes at VLA and ALMA

WIRED


NRAO

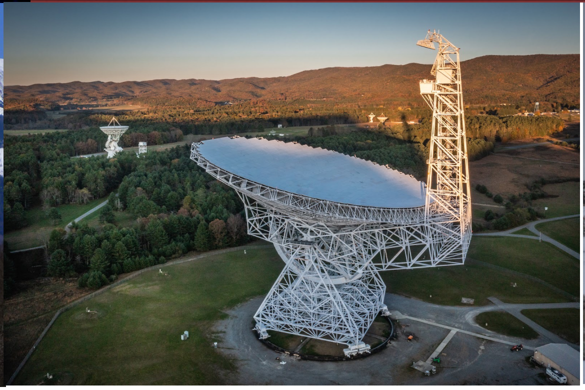
So many combination options…











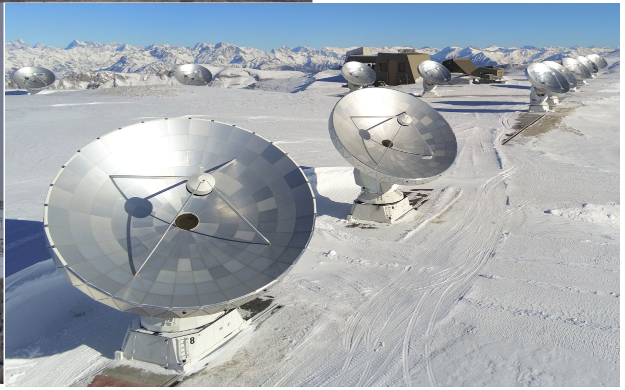
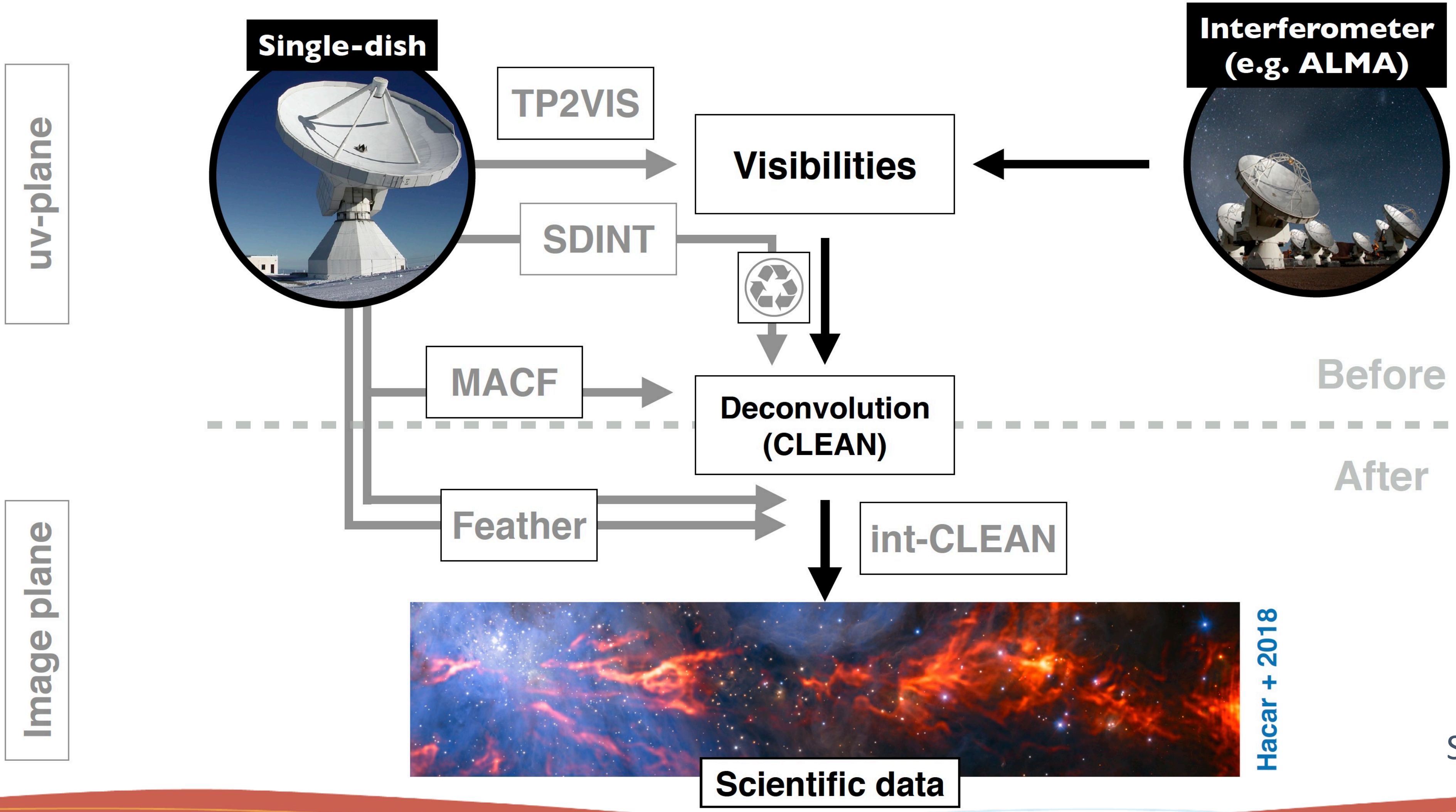


Photo credits: ALMA: A. Plunkett; VLA: NRAO/AUI/NSF; IRAM 30m: © IRAM,K.Zacher; FCRAO: https://www.umass.edu/; SMA: SMA; ACA: A. Plunkett; LMT: http://lmtgtm.org/; NRO: NAOJ; GBT : Jay Young; CARMA: A. Plunkett; NOEMA: IRAM

Data Combination methods



Slide by Alvaro Hacar

Methods: We tested and evaluated 5 methods

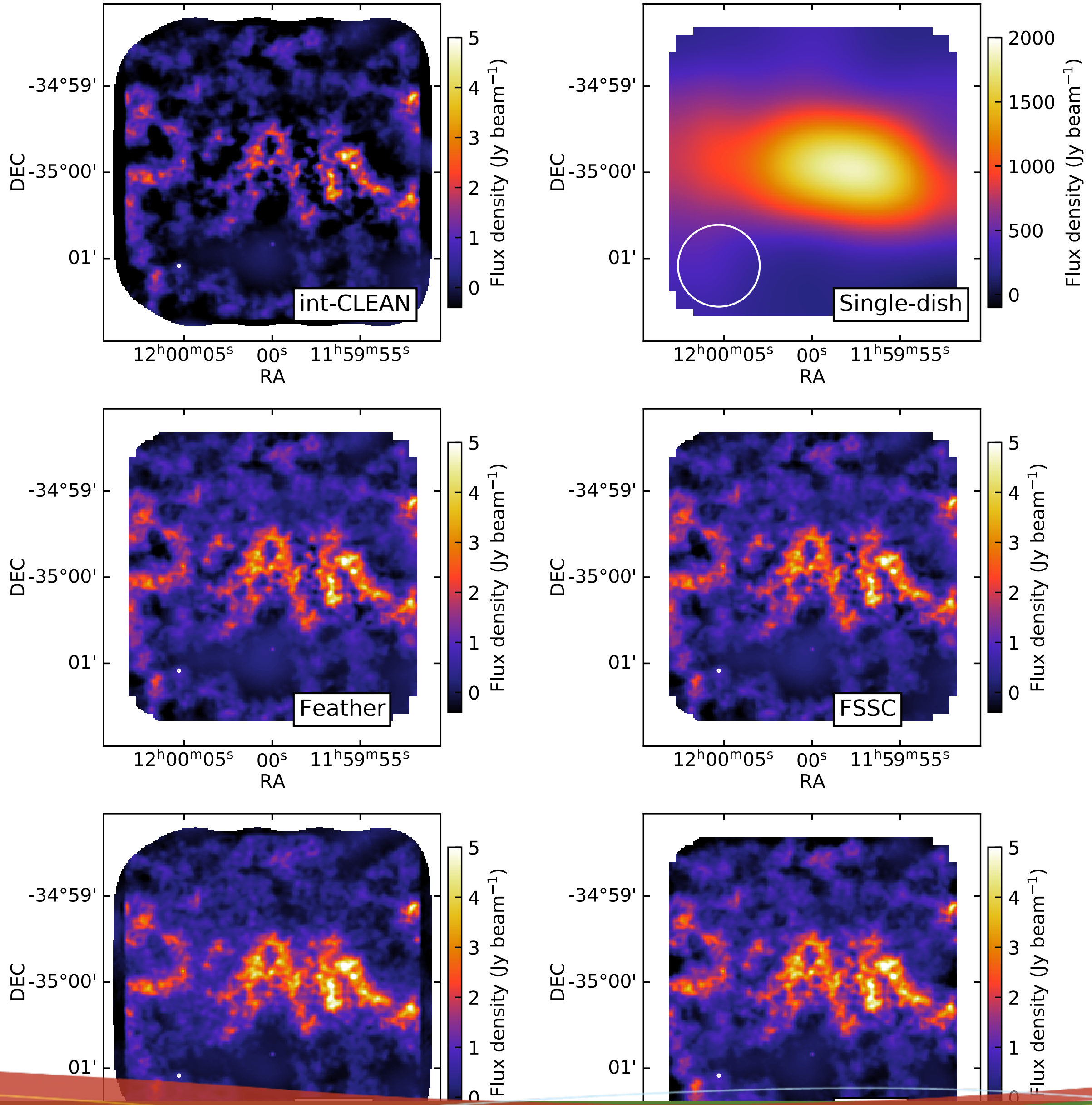
Table 1
Summary of Data Combination Methods

Methodology[a]	Domain[b]	Method	Task Name	Input		Output
				Interferometry	SD	
Before	F/I	SDINT	`sdintimaging`	Vis.	Image	Image
	F	TP2VIS	`tp2vis`[c]	Vis.	SD image	Pseudovisibilities
			`tclean`	Vis.	Pseudovisibilities	Image
During	F + I	MACF	`tclean`	Vis.	Image as model	Image
			`feather`	Image	Image	Image
After	F	Feather	`feather`	Image	Image	Image
	I	FSSC	(script)	Image	Image	Image

Notes.
[a] Indicates combination before, during, or after image deconvolution.
[b] Fourier ("F") or image ("I") domain in which the method operates.
[c] Only available in CASA after importation of the TP2VIS package.

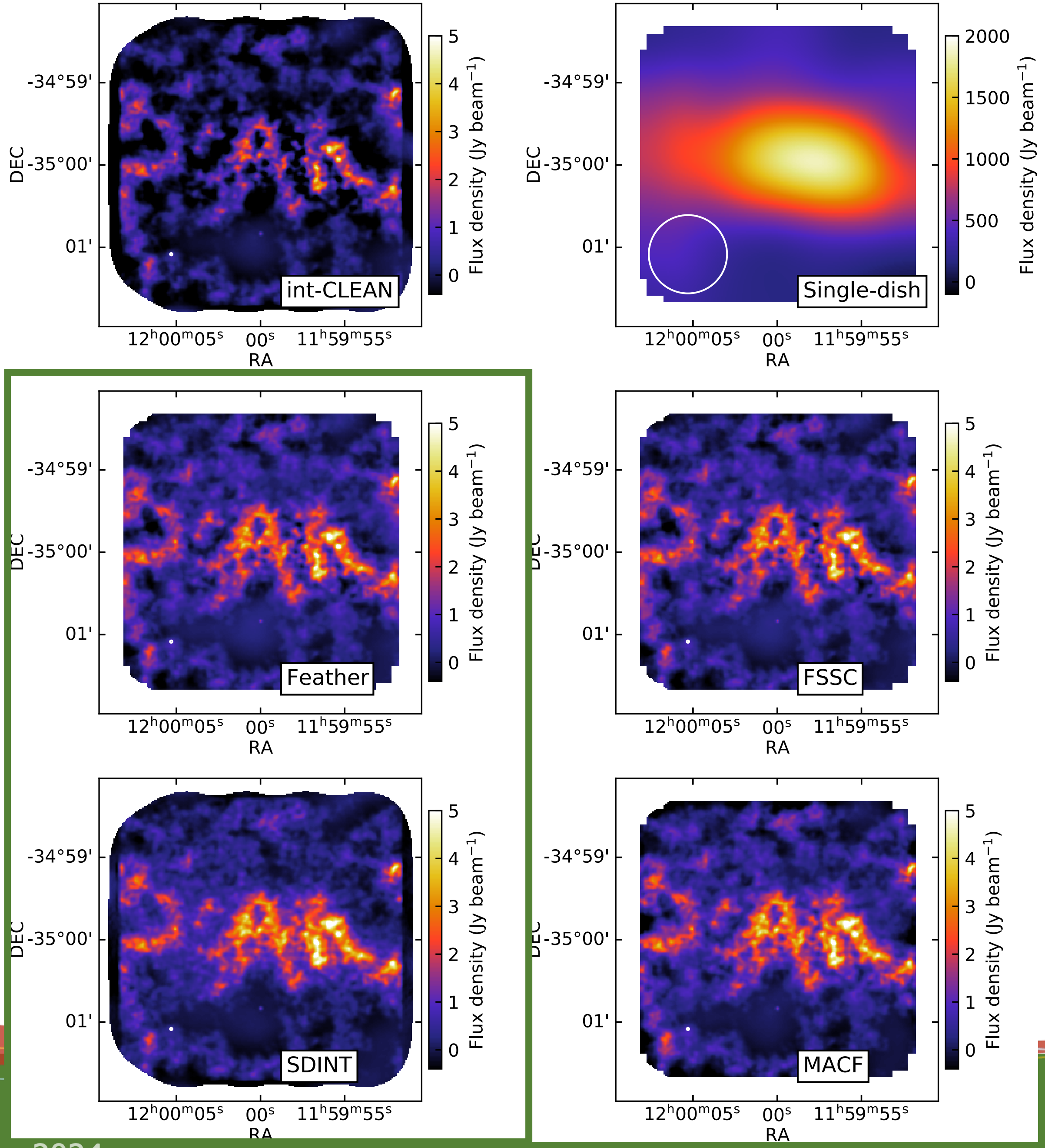
See Plunkett et al. (2023)

Results (qualitative)



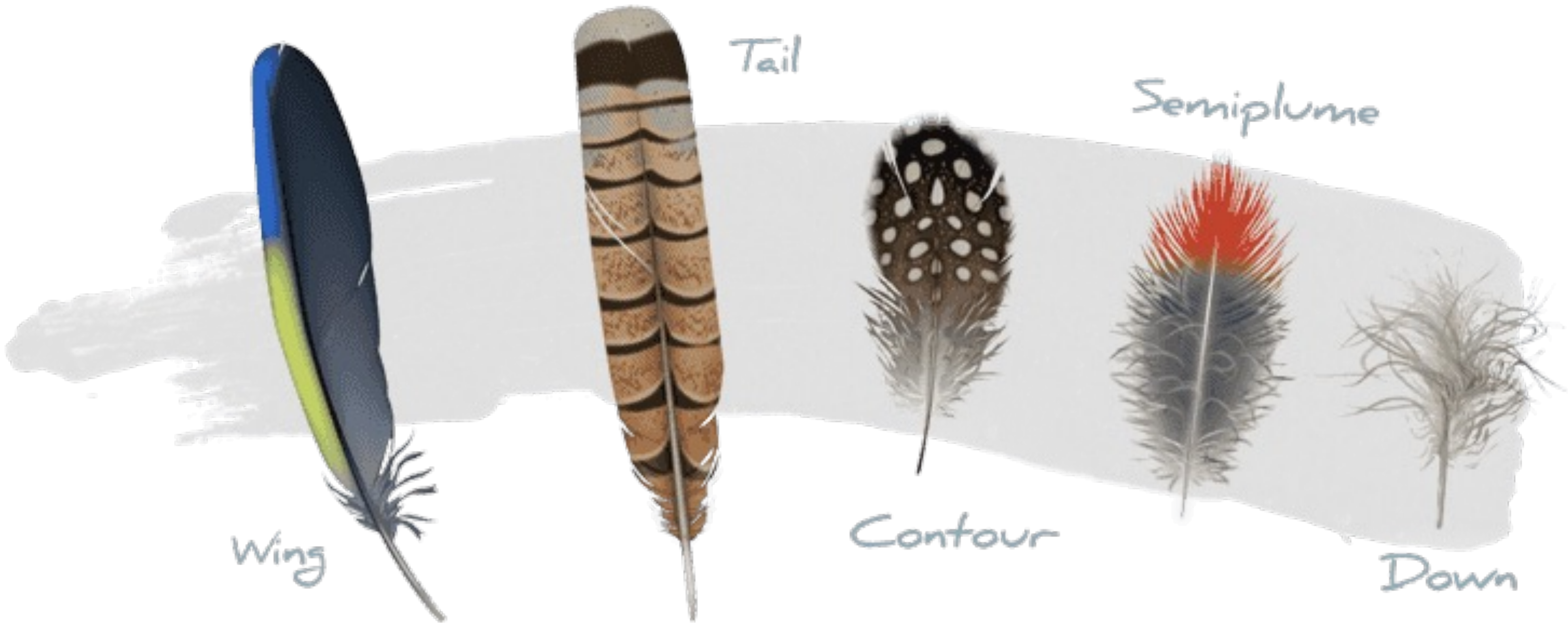
See Plunkett et al. (2023)

Results (qualitative)



We'll focus here on `Feather` and `Sdintimaging` (two methods in CASA)

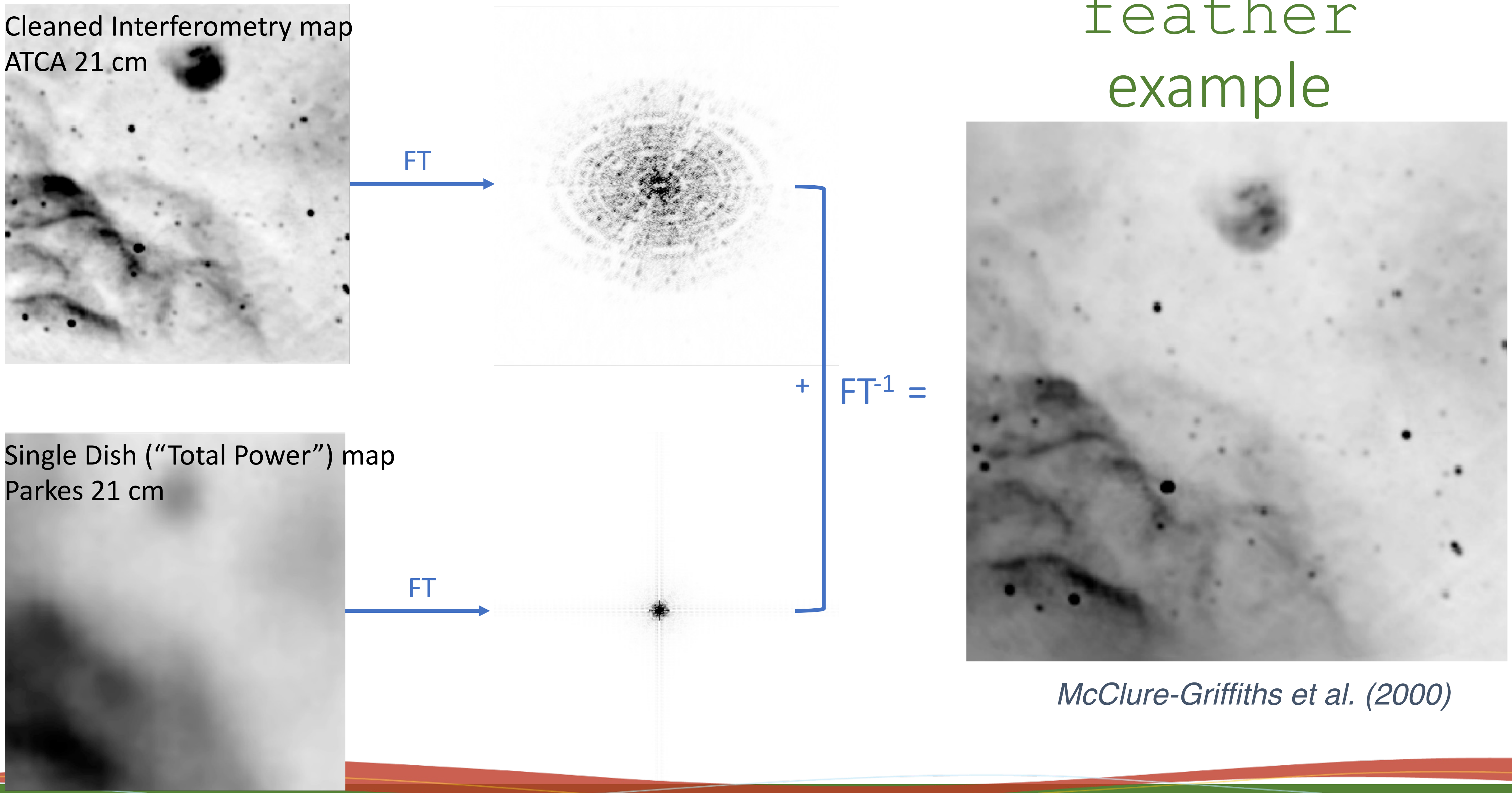
See Plunkett et al. (2023)



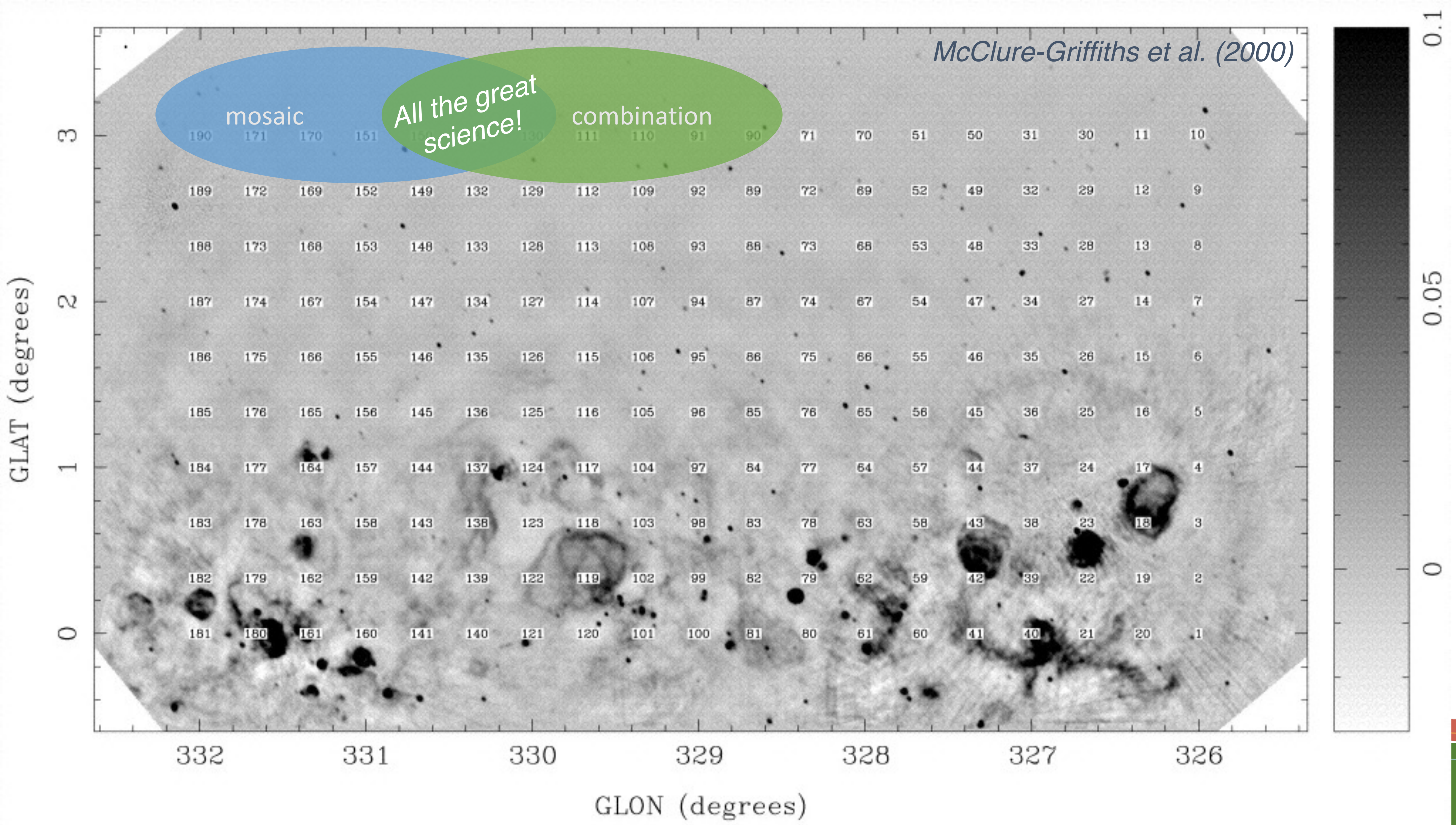
III. Image Combination: Feather

"The term "feathering" is likely derived from the similarity with birds' feathers, which are dense at the center and very light at the edge." Cotton (2017)

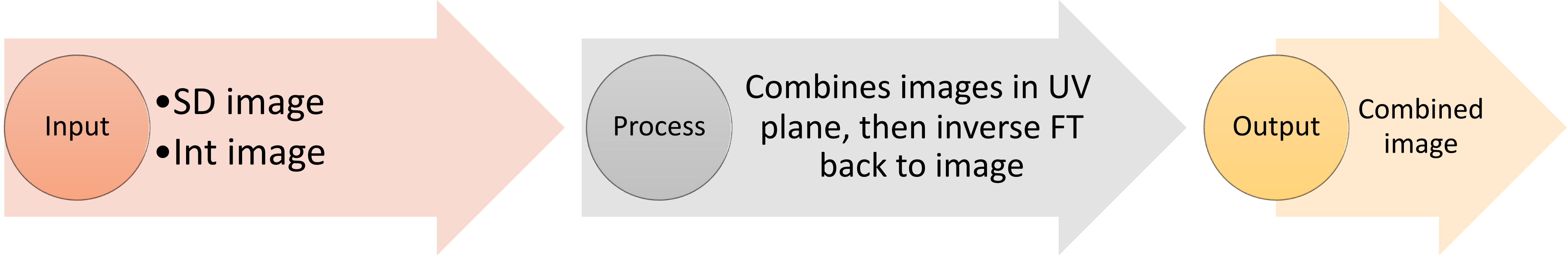
feather example



McClure-Griffiths et al. (2000)


McClure-Griffiths et al. (2000)
mosaic
All the great science!
combination
GLAT (degrees)
GLON (degrees)
332
331
330
329
328
327
326
0
1
2
3
0.1
0.05
0

Feather: A basic schema



MACF: Model Assisted CLEAN with `Feather`: A basic schema

Input
- SD image
- Int image

Process

Combines images in UV plane, then inverse FT back to image

Output

Combined image

TCLEAN with SD image as "startmodel"

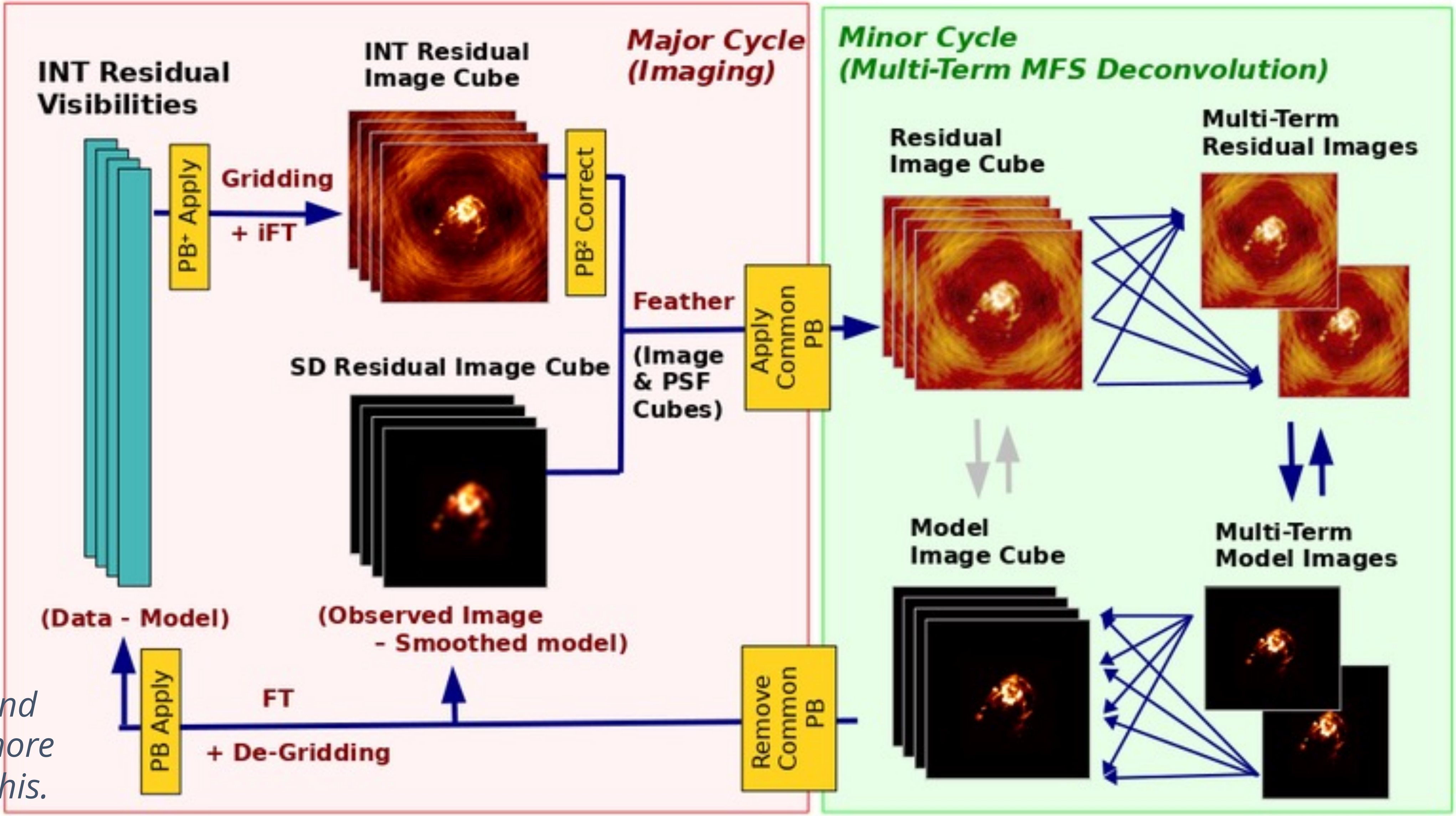
```
tclean(vis='myvis.vis', imagename='myimage', …
        startmodel='SD.image')
```

- Essentially, this helps guide the `TCLEAN` process.
- `TCLEAN` will (generally) recover more extended flux, with fewer negatives.
- Zero-spacing flux is unconstrained. You MUST run `FEATHER` after this.
- Better input image to `FEATHER` leads to better combined image.

III. Image Combination: SDIntImaging

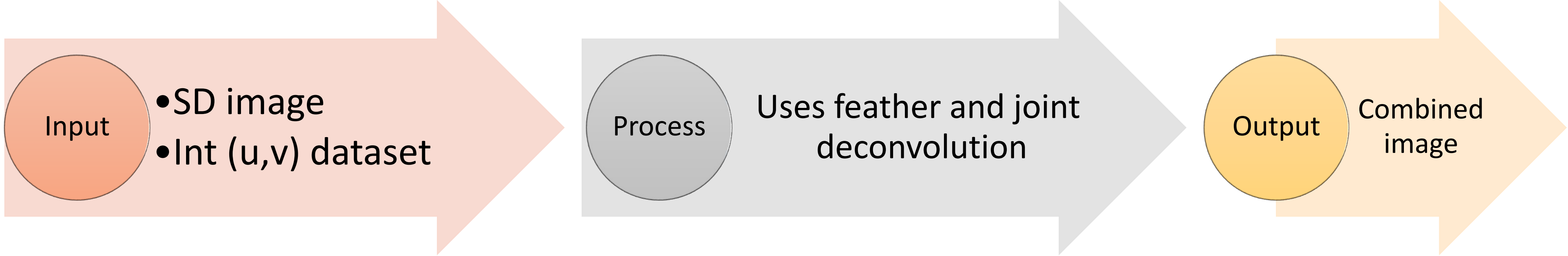
The newest combination technique in CASA

sdintimaging



See talks by P. Jagannathan and J. Marvel for more diagrams like this.

sdintimaging
An over-simplified schematic...



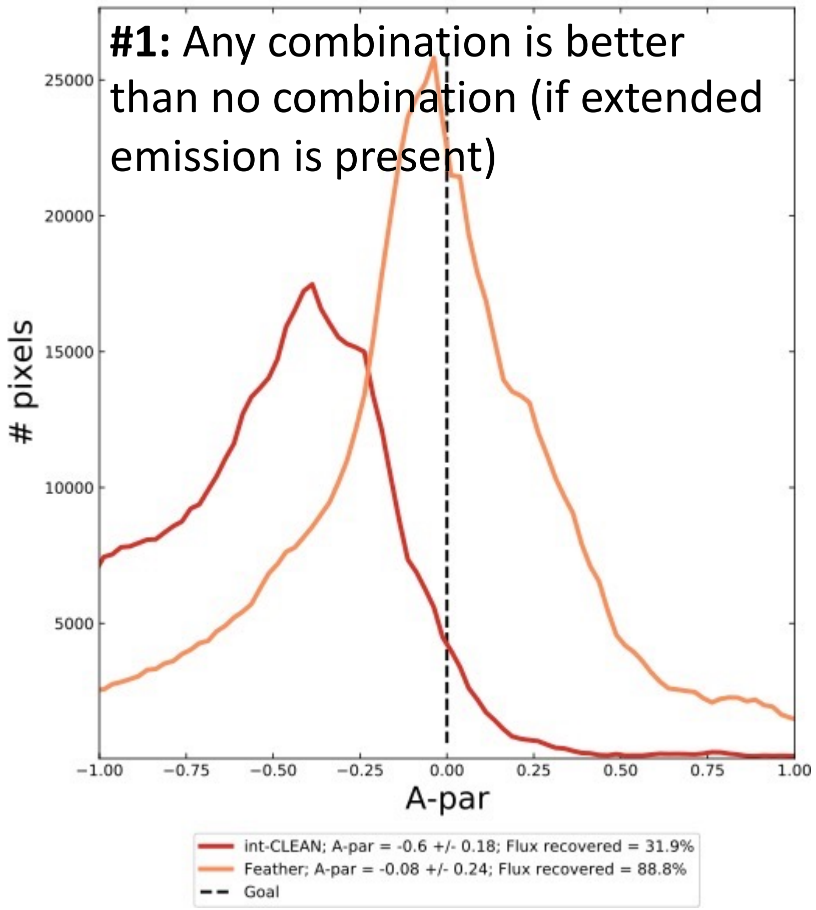
Learn more:
https://casadocs.readthedocs.io/en/stable/api/tt/casatasks.imaging.sdintimaging.html

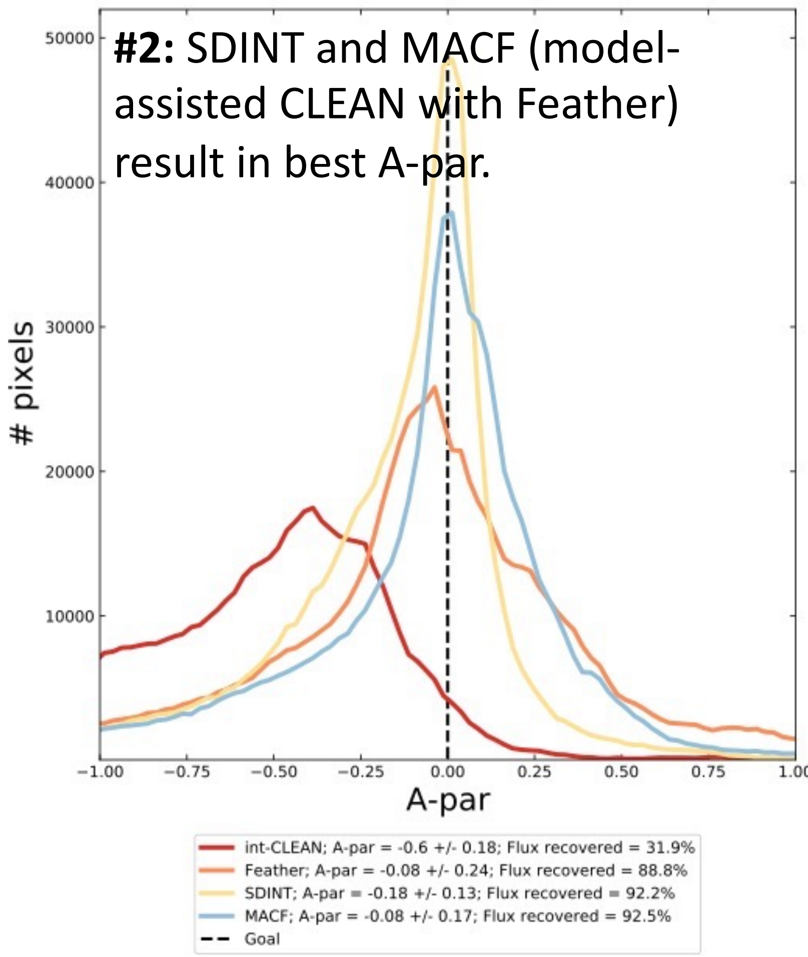
Image analysis [[some definitions]]

	Formula:	*Ideal:*
A-par	$A_\nu(x, y) = \frac{I_\nu(x, y) - R_\nu(x, y)}{\lvert R_\nu(x, y) \rvert}, \quad -\infty < A_\nu(x, y) < \infty.$	A~0
Fidelity	$F_\nu(x, y) = \left\lvert \frac{R_\nu(x, y)}{I_\nu(x, y) - R_\nu(x, y)} \right\rvert, \quad 0 < F_\nu(x, y) < \infty.$	F~∞

See Plunkett et al. (2023), *Sec. 5.2: Accuracy Parameter and Fidelity: Assessing Flux Recovery*

A few results on data combination testing





Plunkett et al. (2023)

Image combination considerations

- ALMA Observing Tool helps the user set up the observations on multiple configurations; VLA users should independently indicate which configurations are needed
- Sensitivities should be comparable among the images that are being combined, therefore integrations times should scale accordingly.
- There are a few scale factors (sdfactor in feather, sdgain in sdintimaging) that can be tested.
- The greater the overlap in baselines/ SD diameter, the better.
- If you know that there is extended emission beyond your FOV, you should consider image combination with SD (even if you only care about smaller scales).
- Make the SD map extend beyond the interferometry map.

Summary

- Consider FOV, PB, MRS, LAS, and HPBW *
- If your region of interest is larger than the FOV, you need to **MOSAIC** together many interferometer pointings.
- For ”large” structures, you likely will need to **COMBINE** data from a more compact configuration of the interferometer, and/or single dish.
  - `Feather` and `sdintimaging` are two techniques

** Abbreviations?! Next slide.*

Abbreviations

- **HPBW**: Half-power beam width (like FWHM)
- **FOV**: Field of view
- **PB**: Primary Beam
- **MRS**: Maximum Recoverable Scale
- **LAS**: Largest Angular Scale
- **PSF**: Point spread function

Resources

- Essentials of Radio Astronomy (link), especially section 3.7
- Ekers & Rots (1979) (link)
- Mason (2020) "Imaging Spatially Extended Objects with Interferometers: Mosaicking and the Short Spacing Correction" (link)
- Cotton (2017) on Feather (link)
- Rau et al. (2019) on Sdintimaging (link)
- Plunkett et al. (2023) (link)
  - Try out Data Combination using scripts at DataComb Github.
- ALMA Technical Handbook (Cycle 10 link)
- VLA configurations and mosaicking guide
  - VLA interactive configuration visualizations

Getting started

1. Check your interferometry and SD images.
2. Run FEATHER
   - **a.** **INPUTS**: interferometry image; SD image
   - *b.* *Advantage*: It's fast!
   - *c.* *Disadvantage*: If your interferometry image isn't great, the negatives might remain.
3. Run SDINTIMAGING
   - **a.** **INPUTS**: interferometry calibrated measurement set; SD image
   - *b.* *Advantage*: It's making the interferometry image as you go.
   - *c.* *Disadvantage*: It will take more time than feather, because you're "CLEANing" again.
4. Test out MACF
   - **a.** **INPUTS** (TCLEAN): calibrated measurement set as "vis", SD image as "startmodel"
   - b. Then run FEATHER (see #1)
   - *c.* *Advantage/disadvantage*: Does a better clean because it starts out with a model, but sometimes this still isn't enough to make a good interferometry image.

FEATHER, a few notes

https://casaguides.nrao.edu/index.php?title=M100_Band3_Combine_6.5.4

- Inputs should be "*.image" (casa images) format
  - importfits and exportfits
- In Tclean step: Combined 12m+7m image, or any interferometry image, should have restoration=True, restoringbeam='common'
  - Otherwise
- To make a quick assessment of the images, smooth to a common beamsize (the larger beam size).
  - Use `imsmooth` for the two input images and the output image of `Feather`
  - Then plot the spectra
- Check units of input Single Dish image (mJy/beam, Jy/beam, Jy/pixel, mK, K?)
  - When making any comparisons, make sure the units are the same.

SDINTIMAGING, a few notes

https://casadocs.readthedocs.io/en/latest/notebooks/image_combination.html

- **SD image needs “per channel beams”**
- *If imaging a cube:* SD image must be a cube with the same spectral grid as the one you are trying to create.
- Units of SD image should (*probably?*) be Jy/beam
- `SDINTIMAGING` uses many parameters common to `TCLEAN` (check weblog to see what TCLEAN parameters were used)
  - Possibly, masking can be less specific (i.e. a pb-based mask at the 0.3 gain level)
- There was once an issue with CASA '6.2.0’ and MFS mode. *Not sure if that was resolved…*