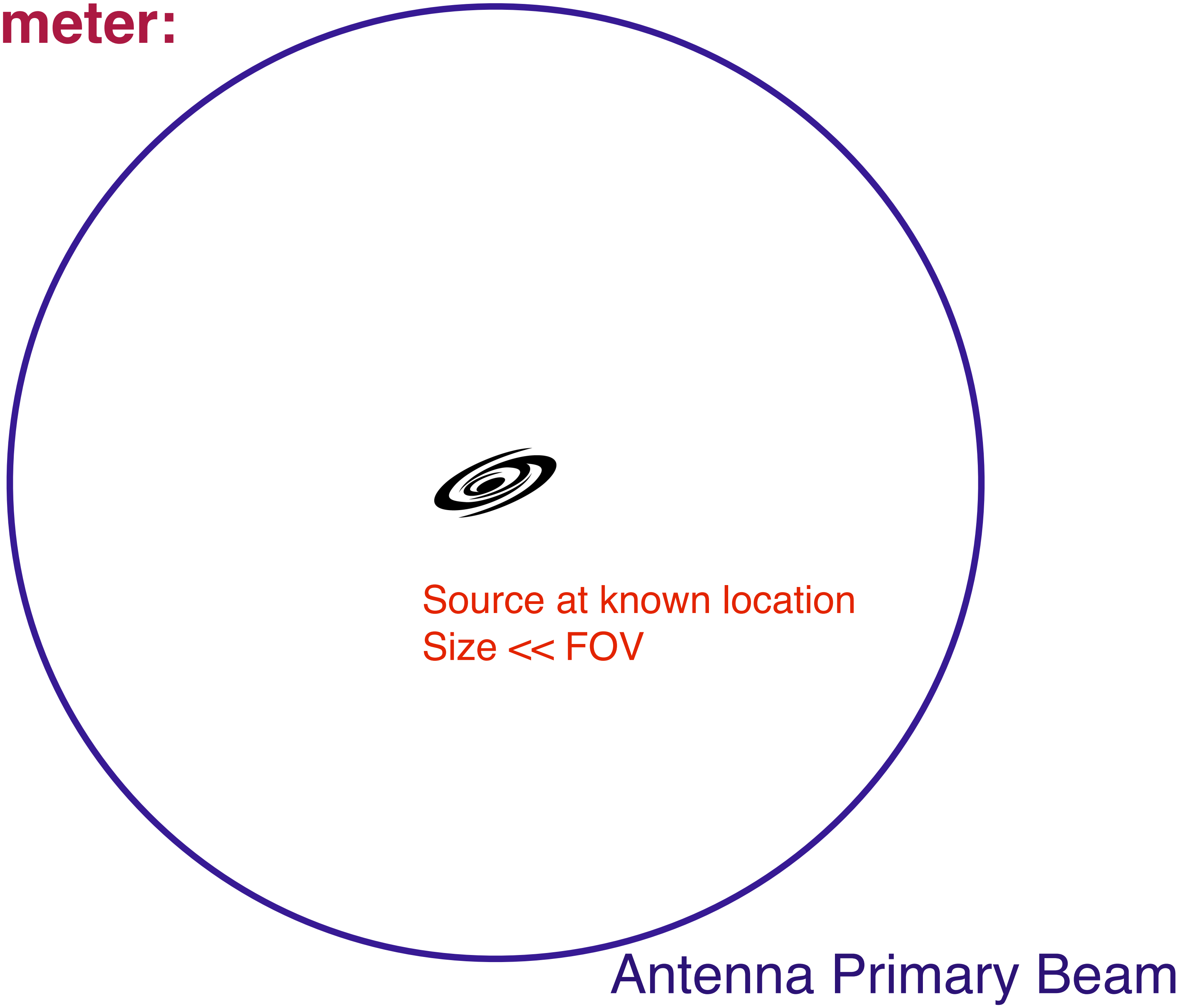
Mosaicking

Brian Mason (NRAO)

See also:
arXiv:2006.06549

18th Synthesis Imaging Workshop
19 May 2022

The simplest observing scenario for an interferometer:

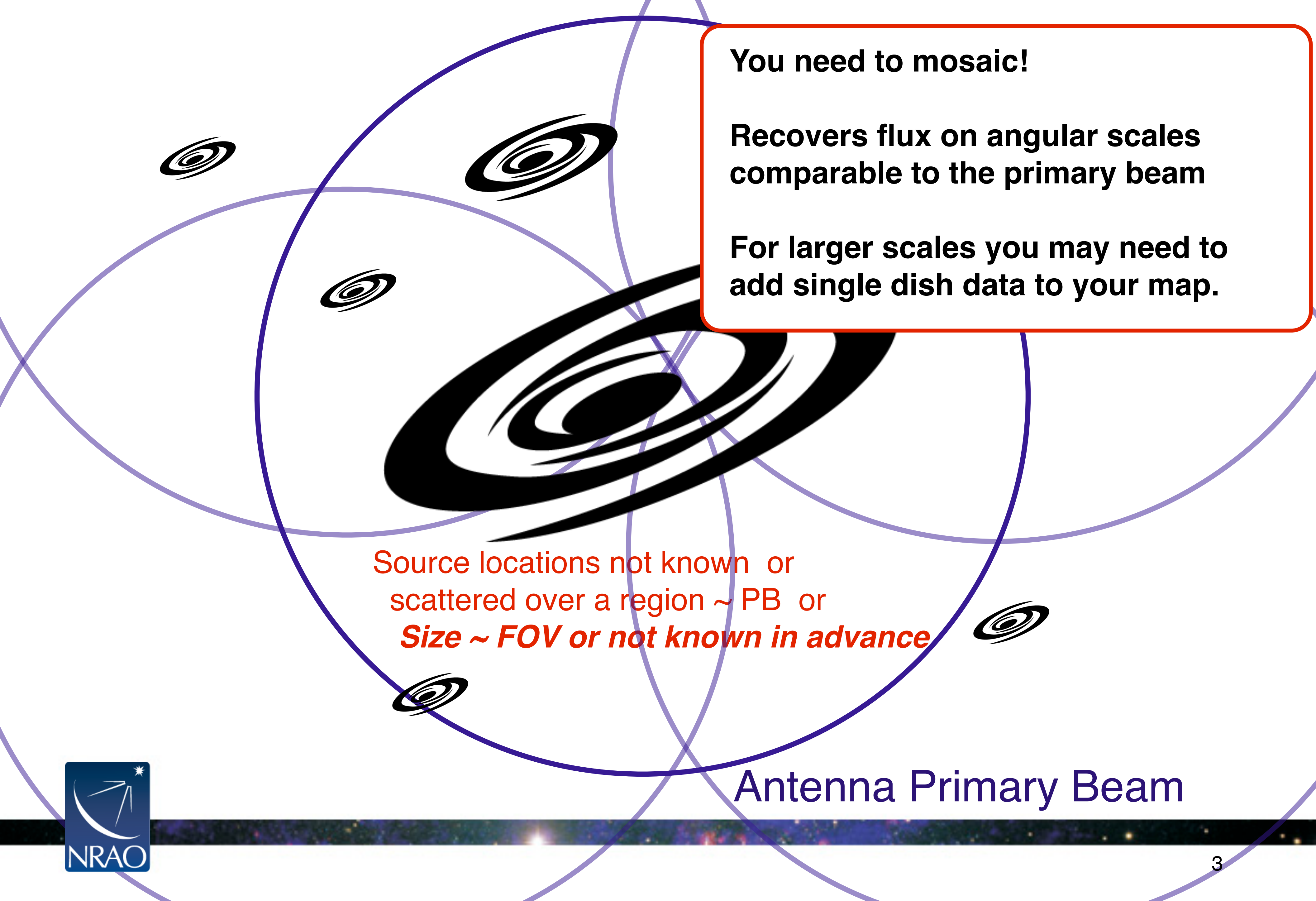


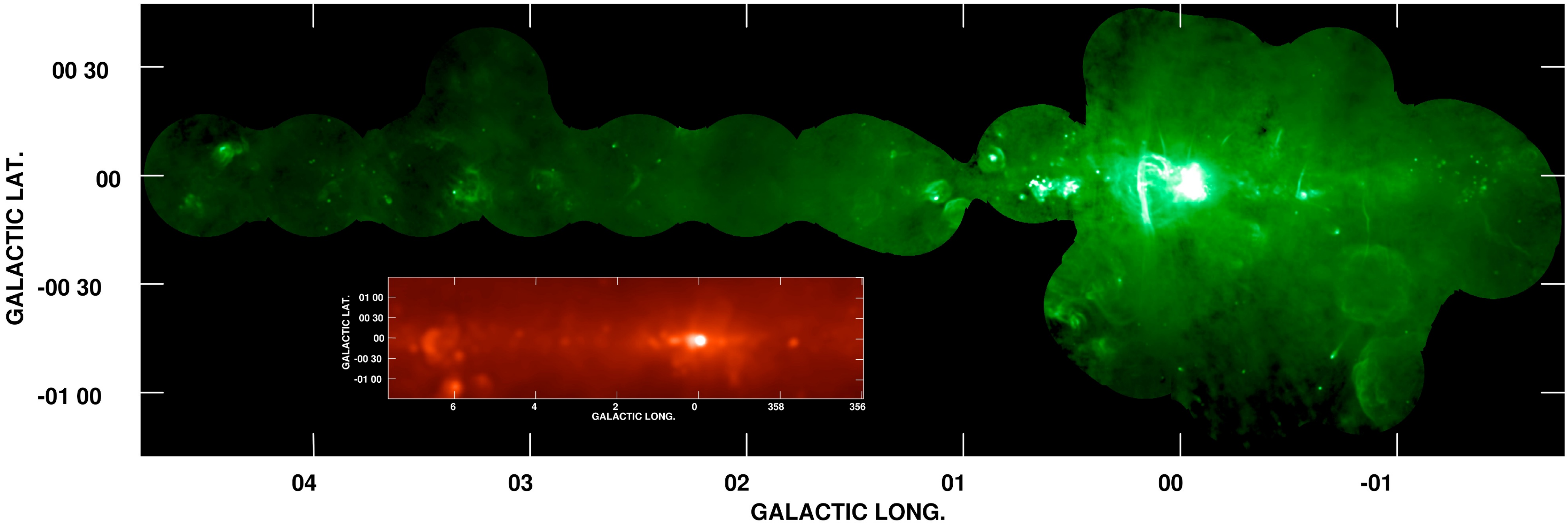
But that's often not the case...

You need to mosaic!

Recovers flux on angular scales comparable to the primary beam

For larger scales you may need to add single dish data to your map.



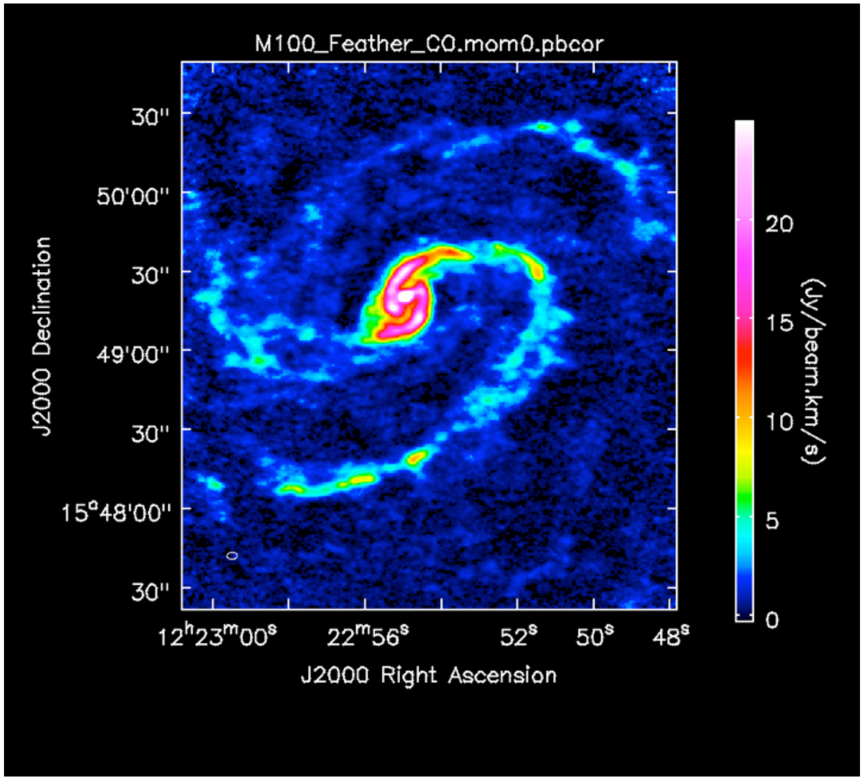


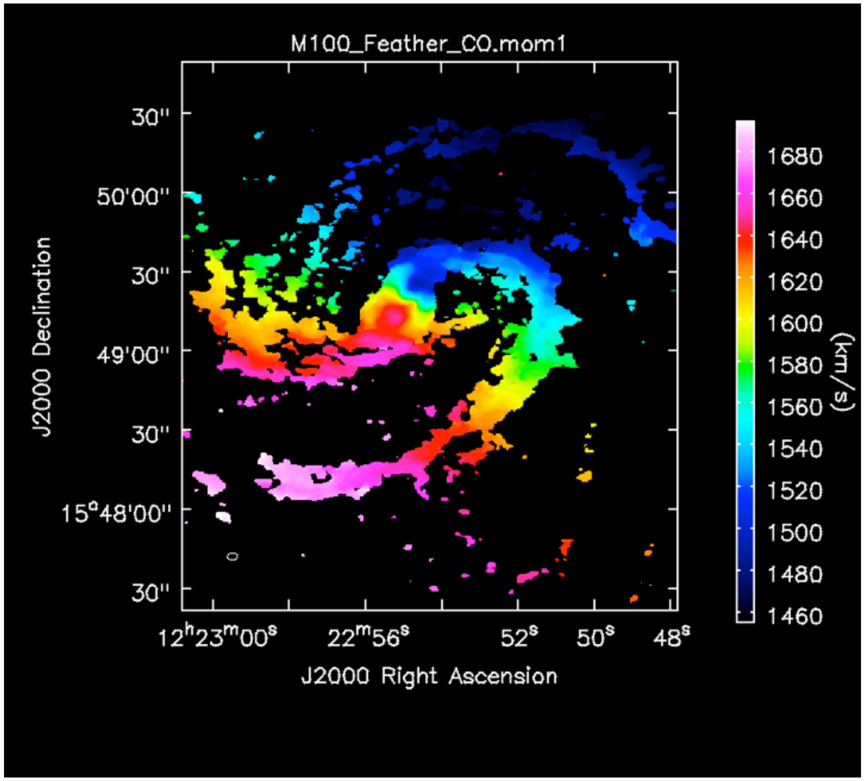
20cm VLA Mosaic+GBT Single Dish (green) (red inset :GBT only)

Law, Yusef-Zadeh, & Cotton (2008)

ALMA Science Verification: M100

12m array + 7m array + total power





Integrated CO line intensity line)
Band 3 (115 GHz, ~2.6mm)

1st moment map (velocity field of CO)

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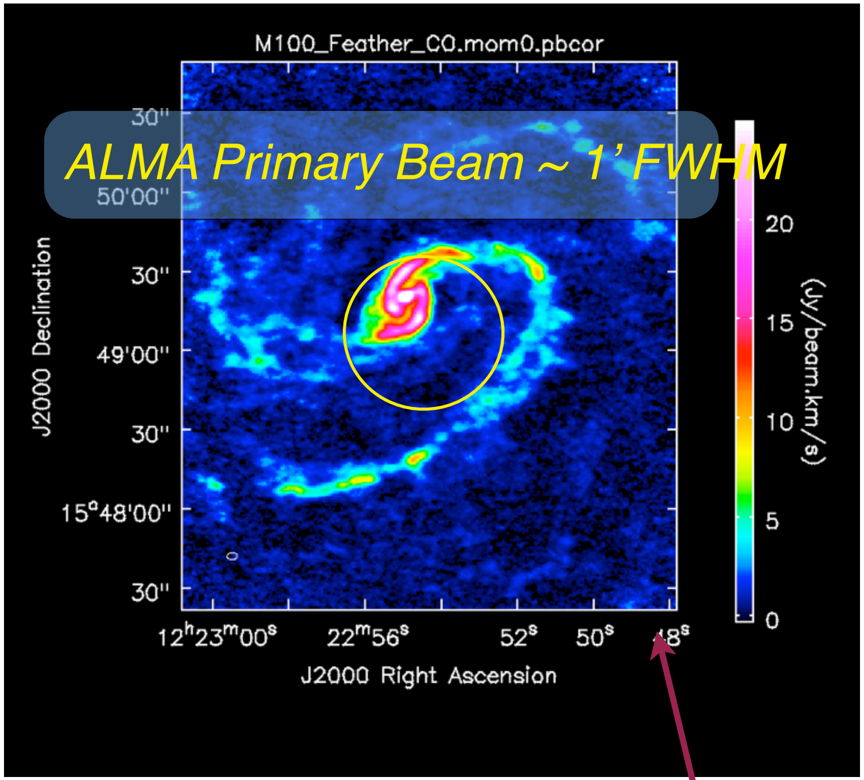

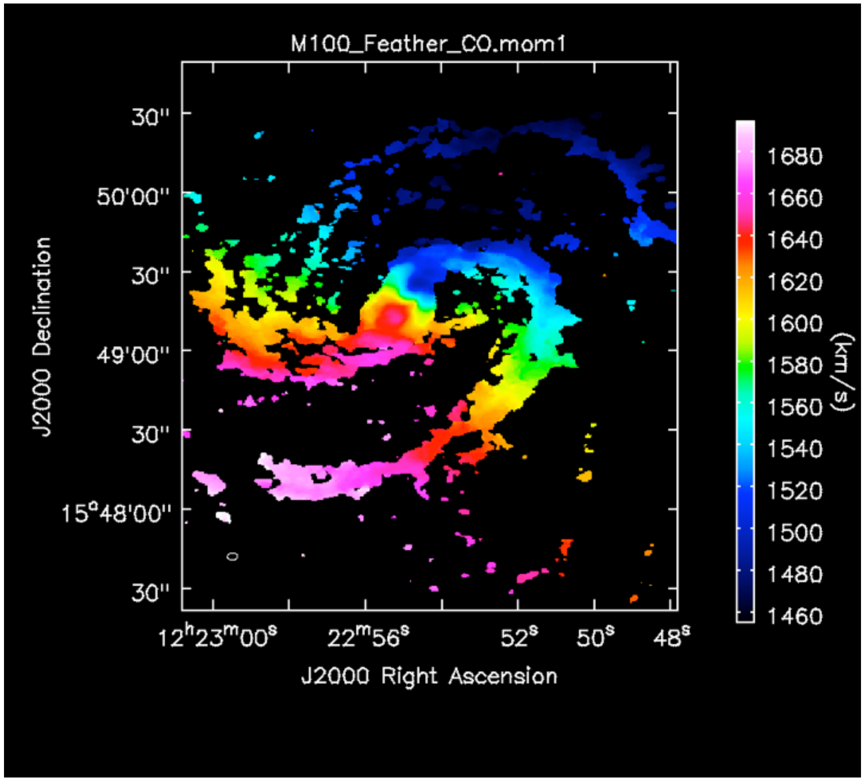

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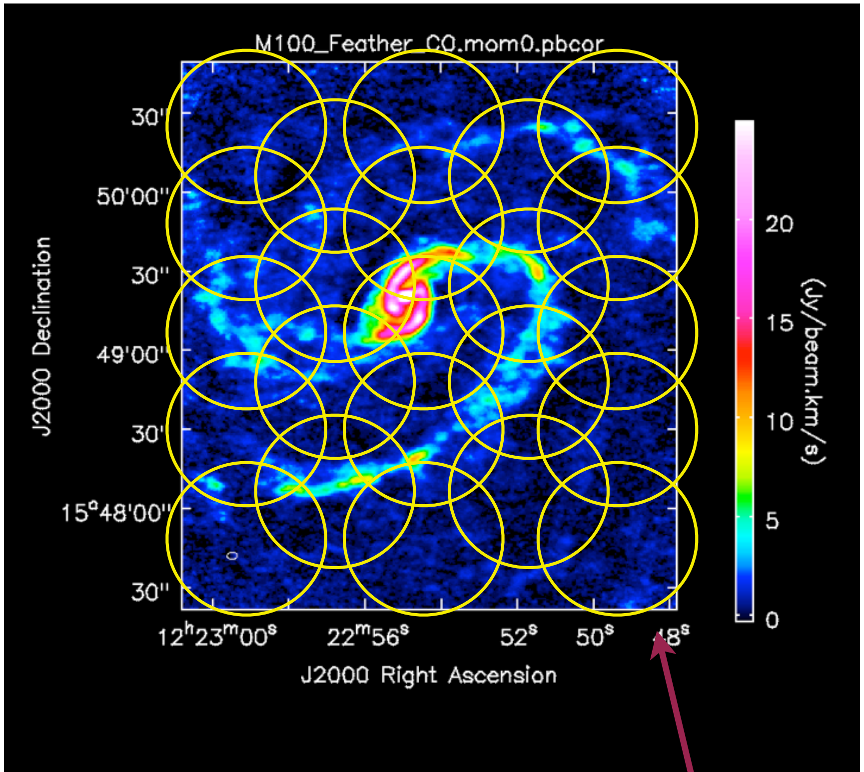

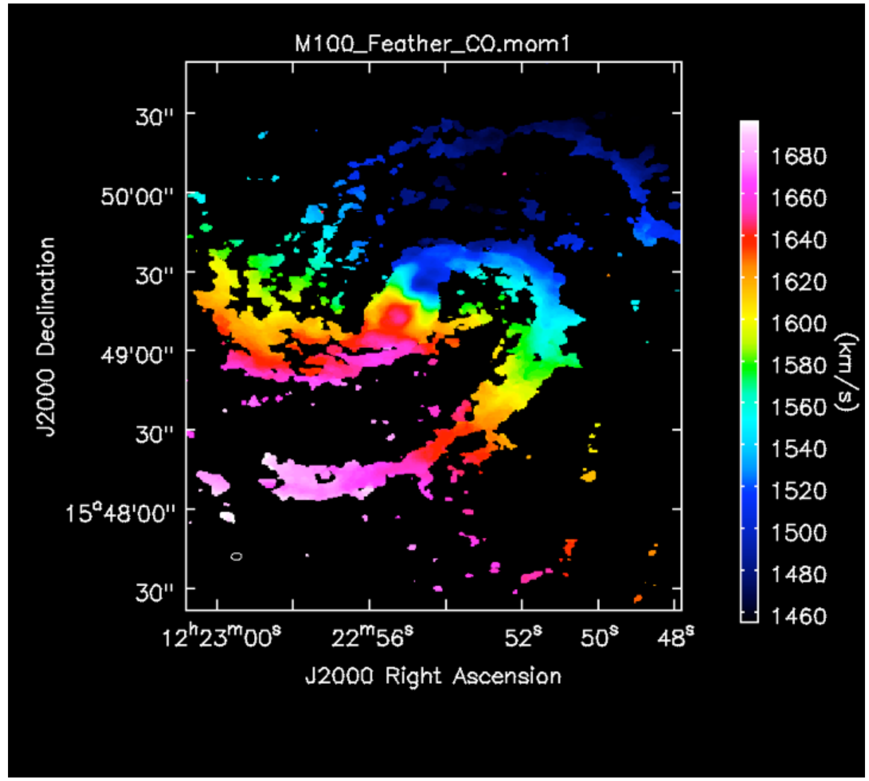

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Limiting Angular Scales for an Interferometer

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)

Largest recovered structure:

$$\theta_{LAS} = \frac{1}{2}\frac{\lambda}{b_{min}}$$

The “Spatial Period” of the largest angular scale Fourier component of the sky brightness measured by the interferometer

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

CAVEAT: a single short baseline doesn't do a lot of good — b_{min} should be taken to be the shortest spacing at which there is good uv-coverage

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Limiting Angular Scales for an Interferometer

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ALMA(12m): Band9 (0.44mm) = 9”

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

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VLA: Q-band (7mm), A-array = 1.2”

If the 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.

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$$\theta_{LAS} = \frac{1}{2}\frac{\lambda}{b_{min}} \leq \frac{1}{2}\frac{\lambda}{D}$$

Maximum possible LAS for an Interferometer with antennas of diameter D

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The ALMA Compact Array (ACA)

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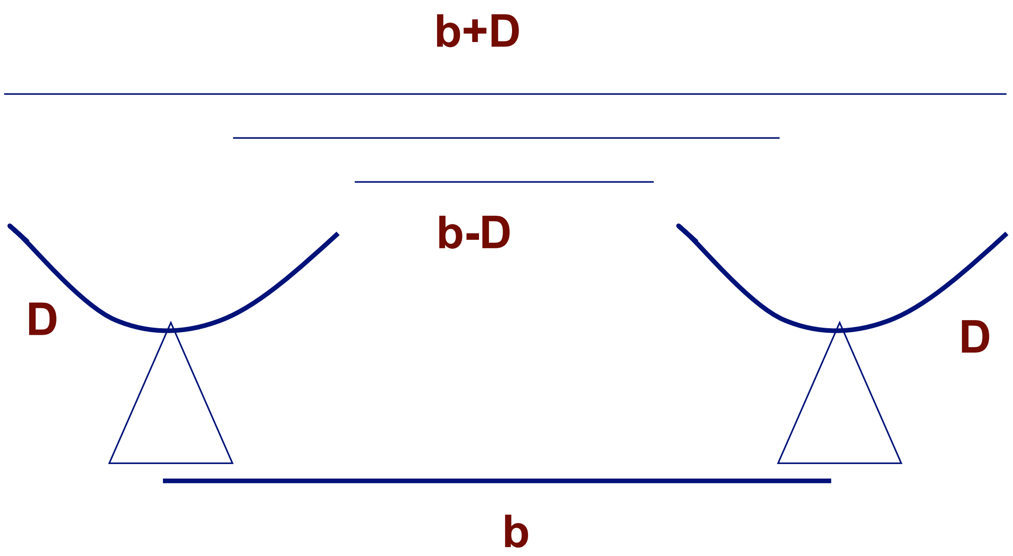
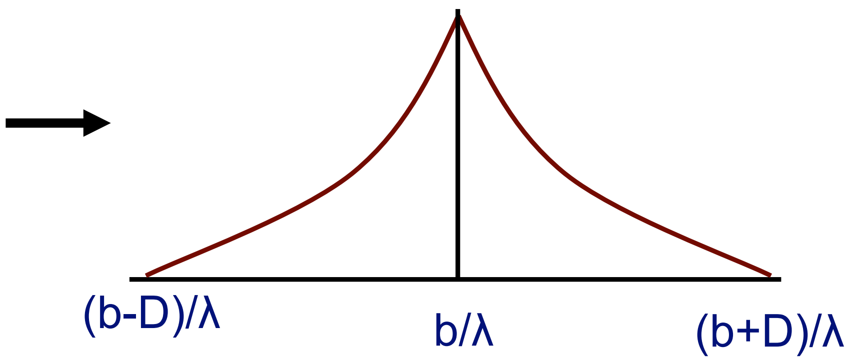
but there's a trick…

Theory of Mosaicking: Ekers & Rots Theorem

An interferometer doesn't just measure angular scales $\theta = \lambda/b$ it actually measures $\lambda/(b+D) < \theta < \lambda/(b-D)$



interferometer single baseline uv coverage:



Ekers & Rots (1979)

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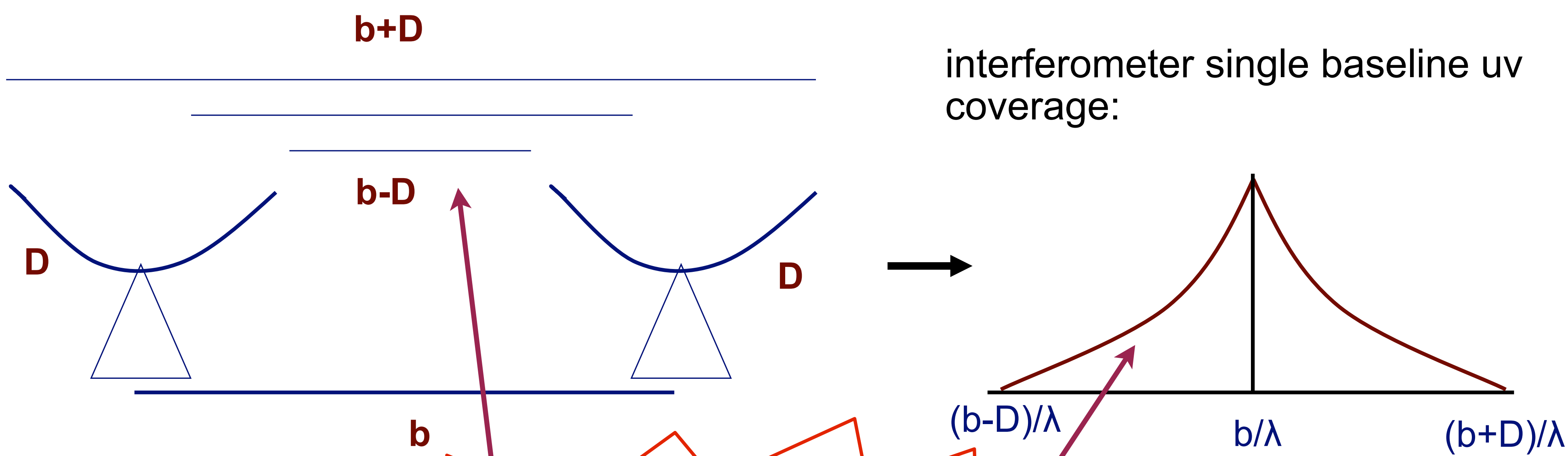


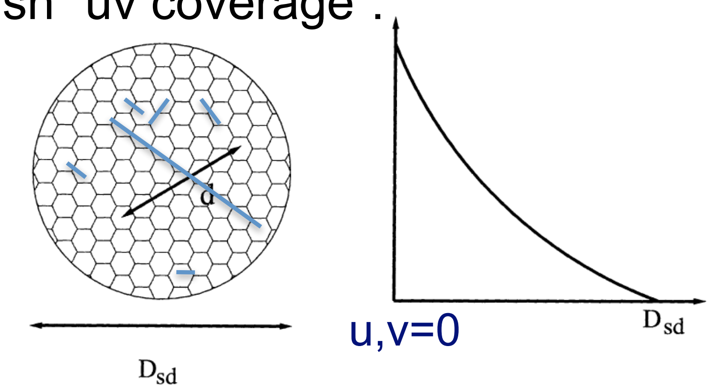
Information on scales larger than the shortest baseline

Ekers & Rots (1979)

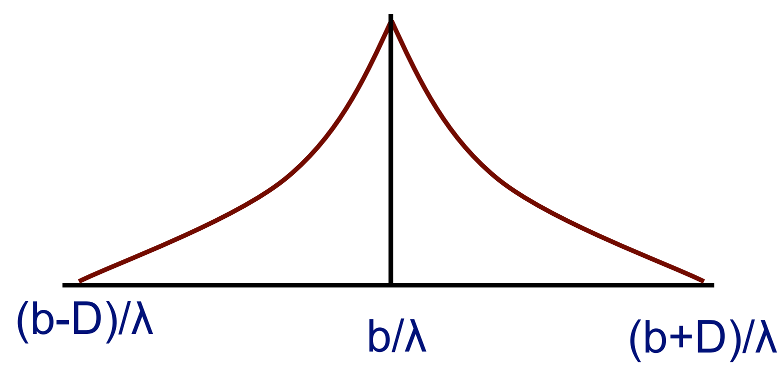
Theory of Mosaicking: Ekers & Rots Theorem

Similarly: a single dish measures a range of baselines from spatial frequencies of *zero* (the mean level of the sky) up to (the dish diameter)/λ

single dish "uv coverage":



interferometer single baseline uv coverage:



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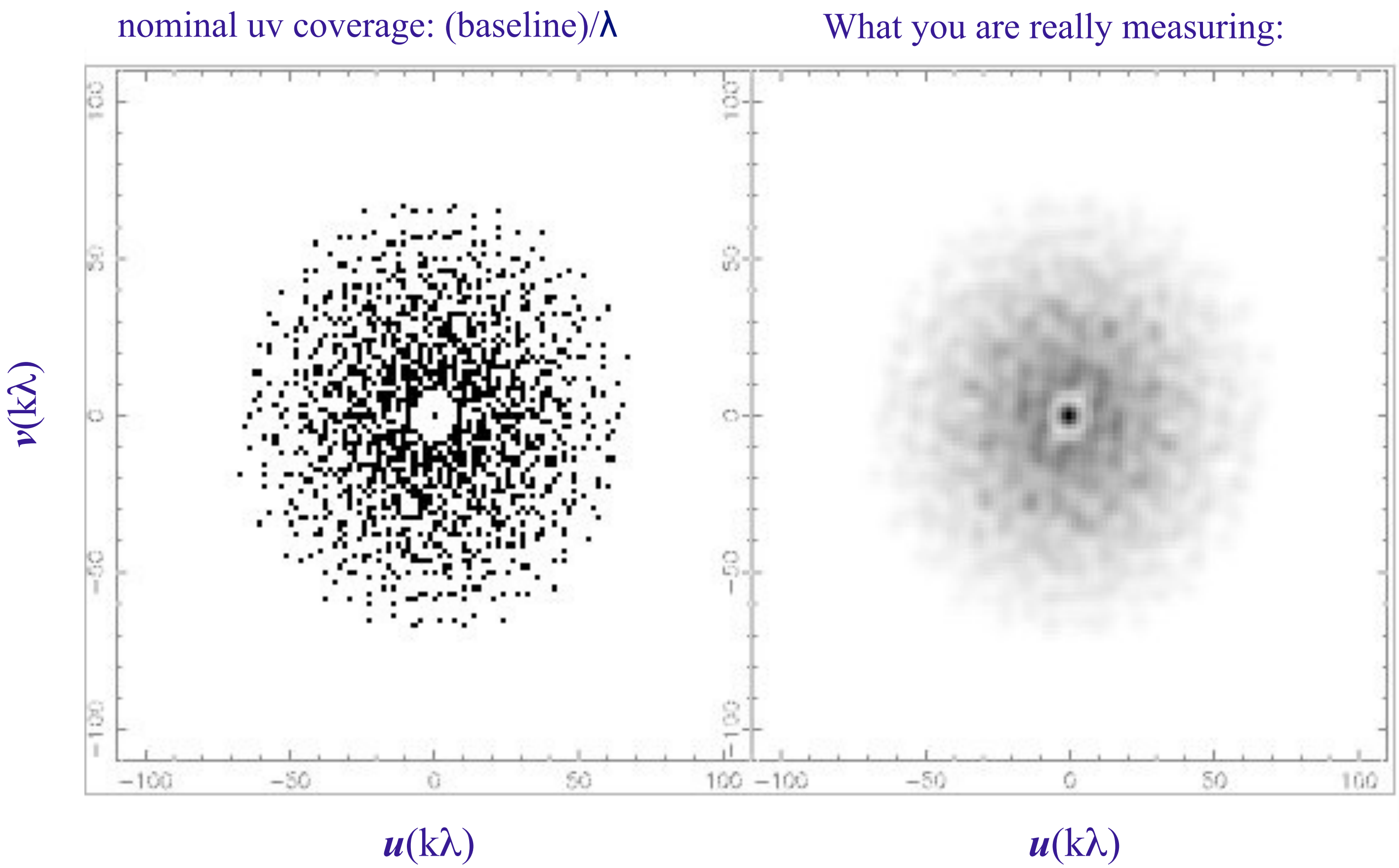


Interferometer + Single Dish

Theory of Mosaicking: Ekers & Rots

"An interferometer measures $\lambda/(b-D) < \theta < \lambda/(b+D)$"

Motivation/Derivation:

$$\begin{aligned} V(u,v) = \int\int d\ell\, dm\, A(\ell,m) I(\ell,m)\, e^{-2\pi(u\ell+vm)} &= FT[A(\ell,m) I(\ell,m)] \\ &= FT[A(\ell,m)] \otimes FT[I(\ell,m)] \\ &= [E(u,v) \otimes E(u,v)] \otimes FT[I(\ell,m)] \end{aligned}$$

$$\begin{aligned} A(\ell,m) &= \left| \int\int_{aperture} du\, dv\, E(u,v)\, e^{-2\pi(u\ell+vm)} \right|^2 \\ &= FT[E(u,v)]\, FT[E(u,v)] \\ &= FT[E(u,v) \otimes E(u,v)] \end{aligned}$$

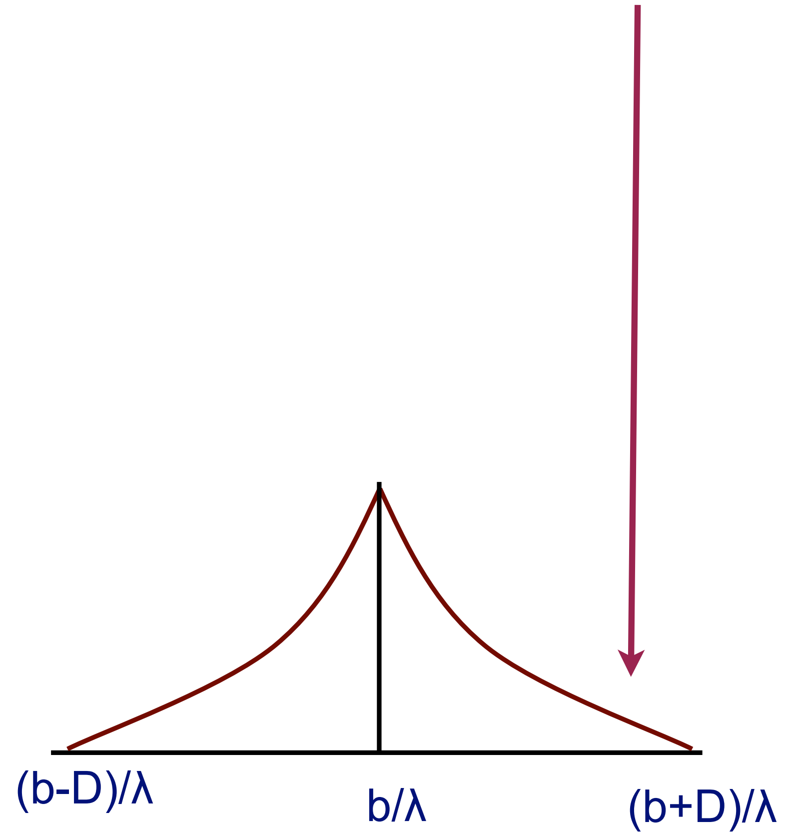
Auto-correlation of aperture plane illumination function; support within r=(0,+D)

$$FT[A(\ell,m)] = E(u,v) \otimes E(u,v)$$

The problem:

You want to separately estimate many Fourier component amplitudes between (b-D)/λ and (b+D)/λ, but you have measured only a single complex visibility!

(a single dish has the same problem)



The problem:

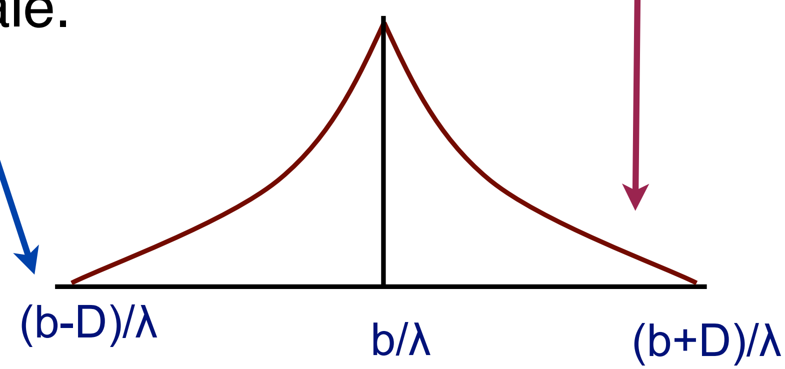
You want to separately estimate many Fourier component amplitudes between (b-D)/λ and (b+D)/λ, but you have measured only a single complex visibility!

Solution: scan the telescope over the sky and measure the visibility (V) multiple times.

i.e. - make a mosaic!

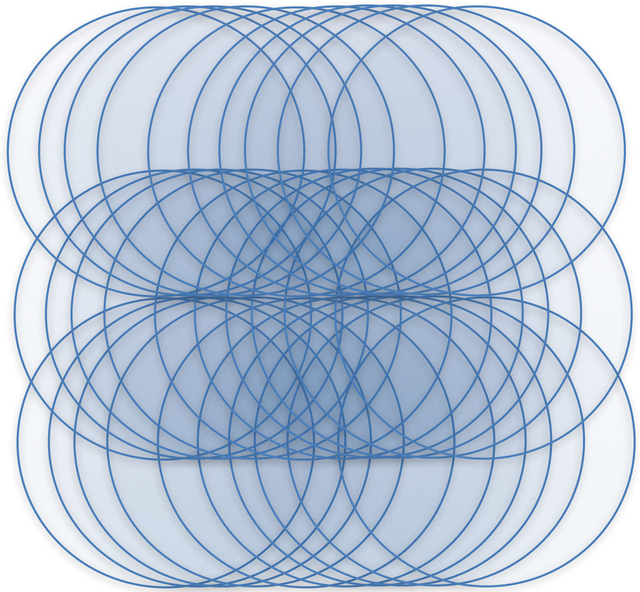
This allows you to separate out the the Fourier modes each measurement contains, increasing the maps' Fourier resolution & Largest (useful) Angular Scale.

Ekers & Rots (1979)



How to cover the sky (I)

- Scheme proposed by Ekers & Rots: scan continuously, dumping correlations & antenna position information rapidly
  - On-The-Fly Interferometry - analogous to single dish “On-the-fly Mapping”



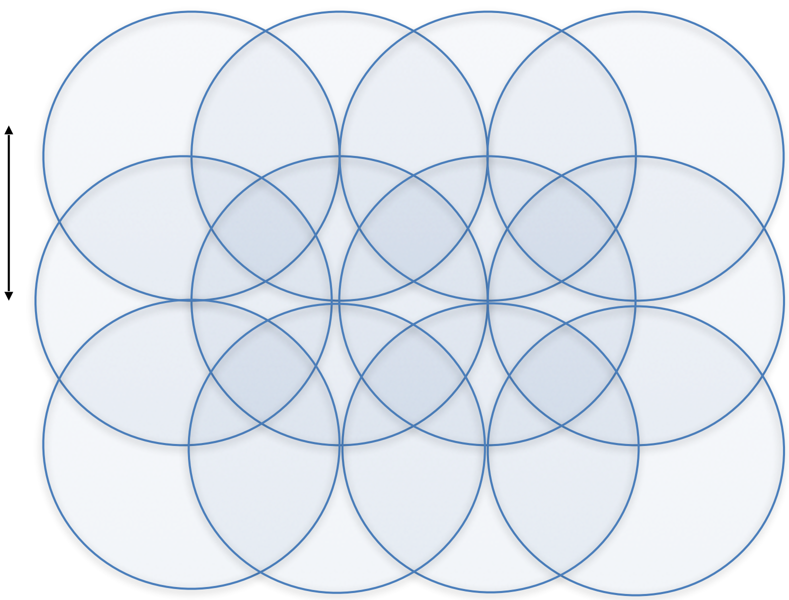
- Low observing overheads but high data rates
  - sometimes used today, especially for surveys (e.g. VLASS)

How to cover the sky (II)

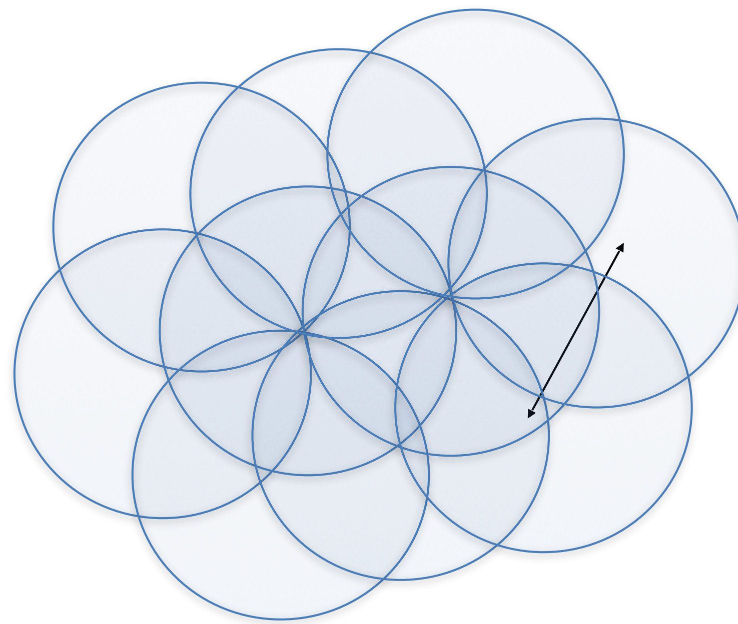
It's often more practical to tile the sky with discrete pointings; Cornwell (1988) showed that this provides the full E&R information if the sampling is sufficiently dense

Rectangular grid

$$\frac{\lambda}{2D}$$



Hexagonal grid



$$\frac{2}{\sqrt{3}}\frac{\lambda}{2D}$$

Preferred - very uniform image domain noise

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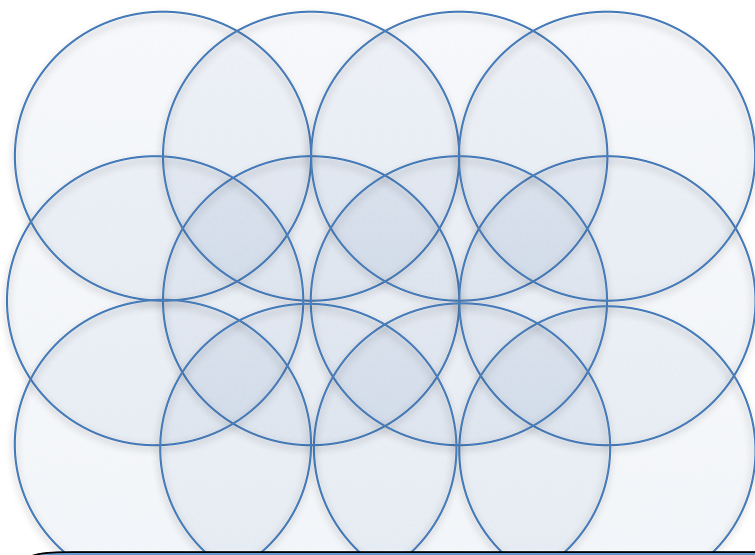

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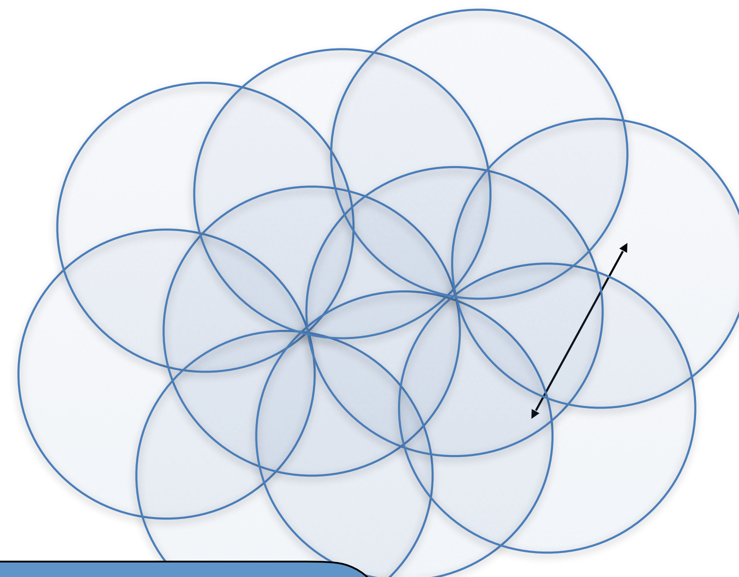


$\frac{2}{\sqrt{3}} \frac{\lambda}{2D}$

Effects of more sparse sampling are modest — often a viable option if you want to increase survey speed, e.g. NVSS

ry uniform image
se

Making the images: Mosaicking Algorithms

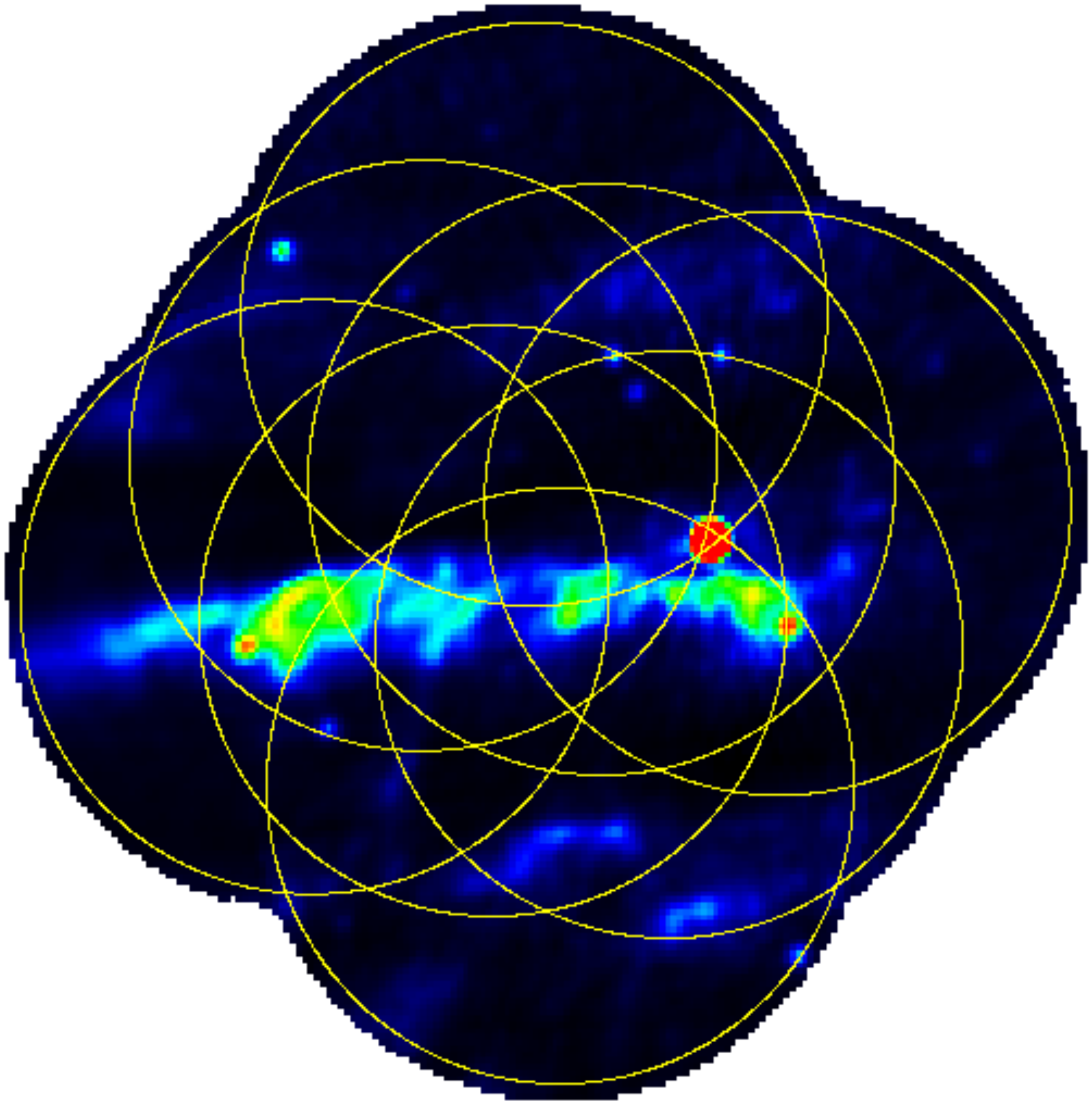
Widely-used methods for mosaic image reconstruction:

- **Linear mosaic (AKA "stitching")**

  Make individual ptg dirty maps → deconvolve individually → combine deconvolve maps

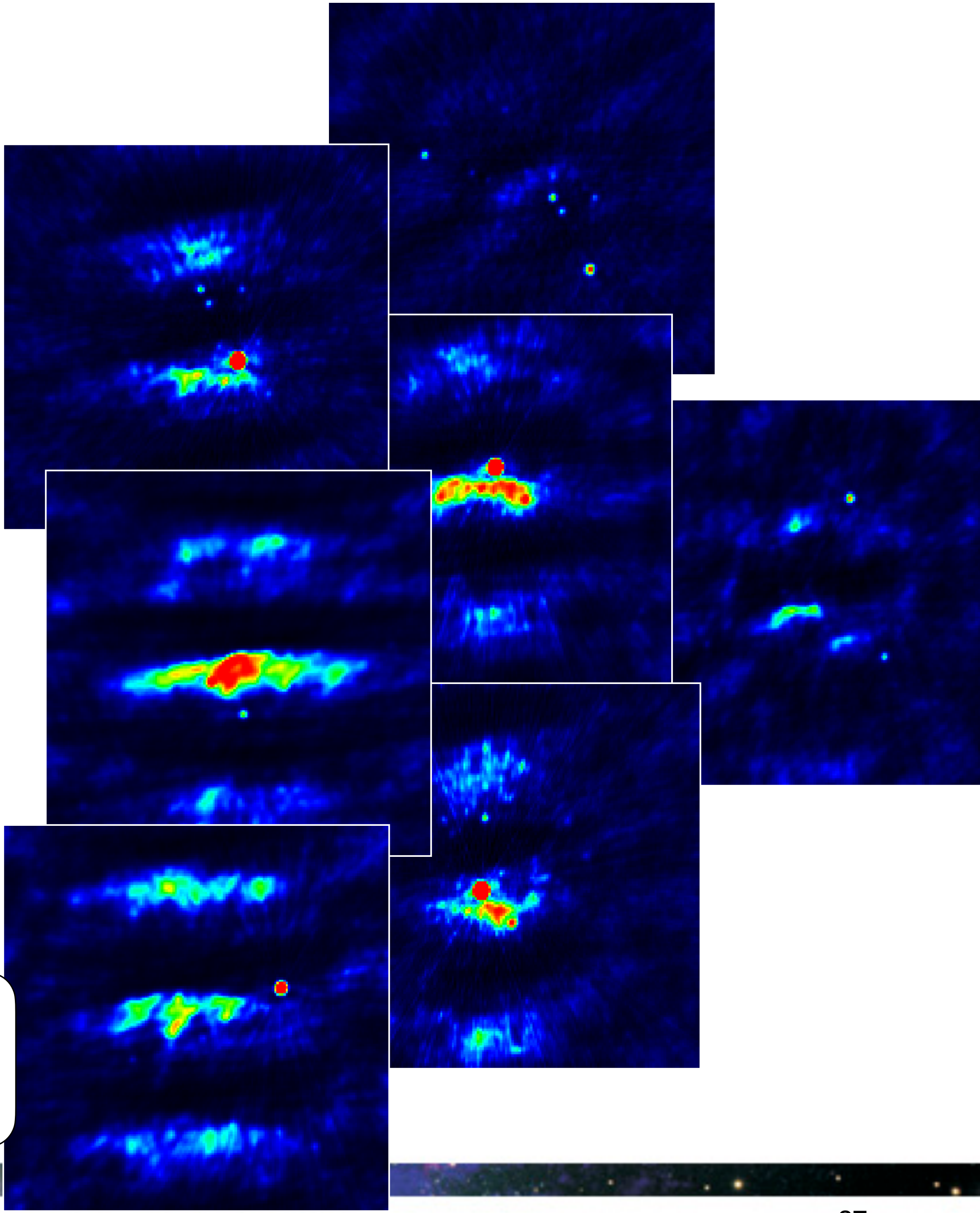
- **Joint Mosaic Imaging**

  Combine visibilities from all pointings in uv-space → single dirty map → deconvolve



Linear Mosaic – individual pointings images

- Treat each pointing separately
- Image & deconvolve each pointing
- Stitch together linearly with optimal pointing weights from noise and primary beam



$$I(\mathbf{x}) = \frac{\sum_p A(\mathbf{x}-\mathbf{x}_p) I_p(\mathbf{x})}{\sum_p A^2(\mathbf{x}-\mathbf{x}_p)}$$

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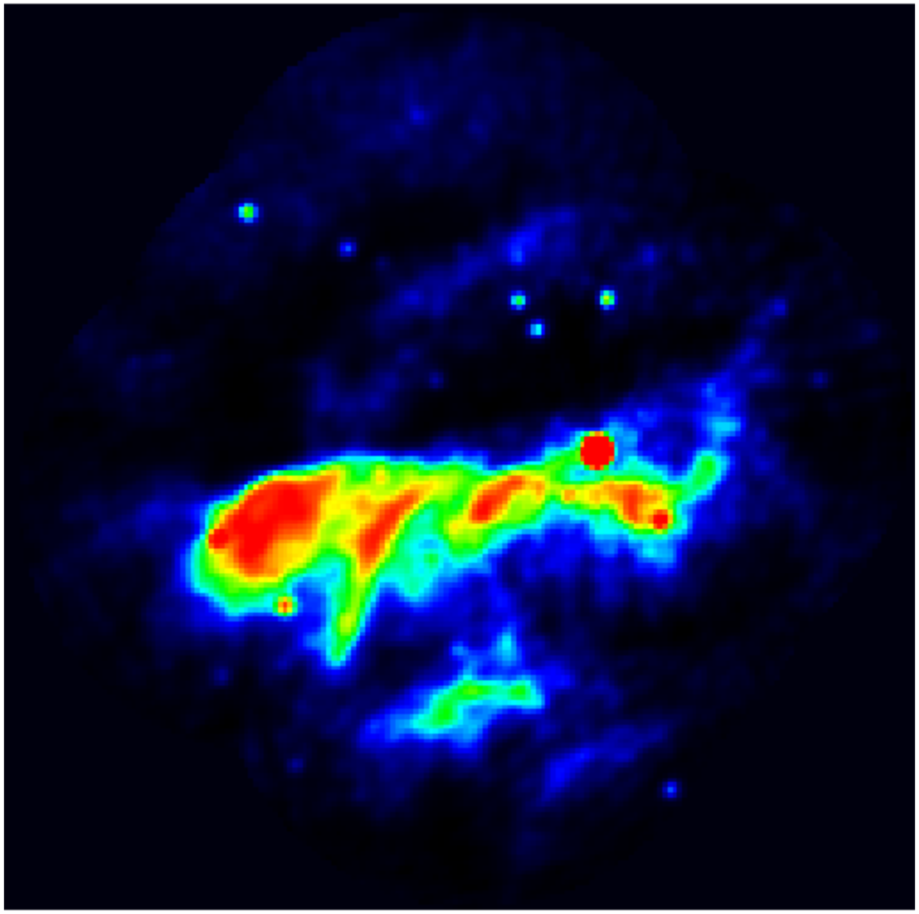
Linear Mosaic – combine pointings



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)

Linear mosaicking of cleaned images is available in the CASA toolkit (im.linearmosaic). [AIPS FLATN]

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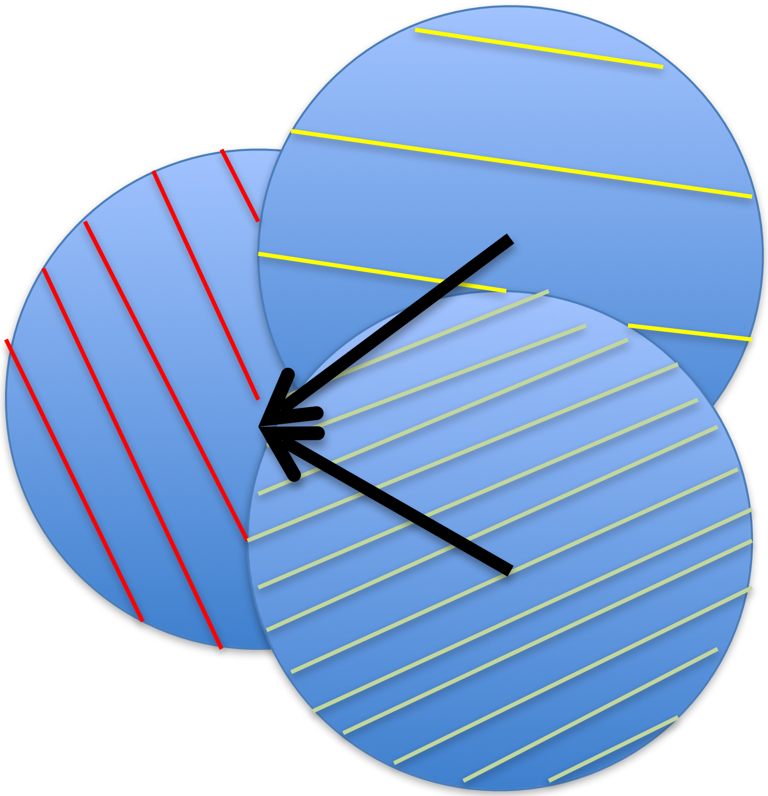
Joint Mosaic Imaging

Combine data from different pointings in uv domain, then deconvolve

- Take each uv data for each pointing and shift to a common phase reference center



Joint Mosaic Imaging

Combine data from different pointings in uv domain, then deconvolve

- Take each uv data for each pointing and shift to a common phase reference center.
- re-grid all visibilities to a common UV plane (PB kernel).
- FT to a single “dirty image” with a common PSF
  - » *Deconvolve*

ADVANTAGES

- Uses all uv info per overlap → better beam, deeper clean
- deconv. has all the (Ekers-Rots) information at every point in the sky: more large-scale structure recovered
- Works well with on-the-fly interferometry data (many, many pointing centers)
- Naturally works well with heterogeneous arrays (different sized antennas)

Cost: you need to know your PB well; assumes PSF fairly stable

Joint Mosaicking in CASA (*ALMA cases**)

- Calibrate as you would do for a single pointing (e.g. pipeline)
- Use **tclean** use *gridder='mosaic'* for joint mosaic imaging
  - Uses Cotton-Schwab (major/minor cycle) algorithm
  - Use *deconvolver='hogbom'* (default, good for poor psf and compact sources) *or 'clark' (faster)*
    - *deconvolver='multiscale' — helpful for complex, extended emission.*
  - *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 wide-field (i.e. non-coplanar i.e. $\lambda B/D^2 > 1$), wide-band cases c.f. talks by U.Rao & Preshanth Jagannathan*

Deconvolution

Mosaicking is often done for ***extended*** sources.

Deconvolution in this case is tricky.

Multi-scale is often a good option (see D. Wilner's lecture)

You need to clean deeply (~1σ) for extended emission.

Justification: in general the "CLEAN model" is not your best estimate of the sky; the reconvolved CLEAN model+residuals is.

- This may not be optimal if you are going to ***self-cal*** using the CLEAN model! (***Clean more conservatively***)
- helps to have good uv coverage, a judiciously chosen clean box, & careful monitoring (interactive)
- may take a long time for a spectral line cube

Deconvolution

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Deconvolution in this case is tricky.

CLEAN: Issues to be aware of

- "CLEAN Bias": constructive interference of synthesized beam sidelobes can make them appear higher than the main lobe of the synth. beam.
  - Reduces the apparent source fluxes recovered
  - most severe for extended sources
  - *mitigated by good UV coverage (lower sidelobes), **good masking**.*
  - see Condon et al. (1998) [NVSS survey paper]

- Mismatch of Clean & Dirty Beams: beam areas differ within relevant apertures, biasing integrated flux density values upward.
  - mitigated by **deeper cleaning**, correction factor
  - see Jorsater & VanMoorsel (1995) and Walter et al. (2008)

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automatic clean masking can be helpful, e.g. tclean(mask=‘auto-multithresh’) [Kepley+ 2020]

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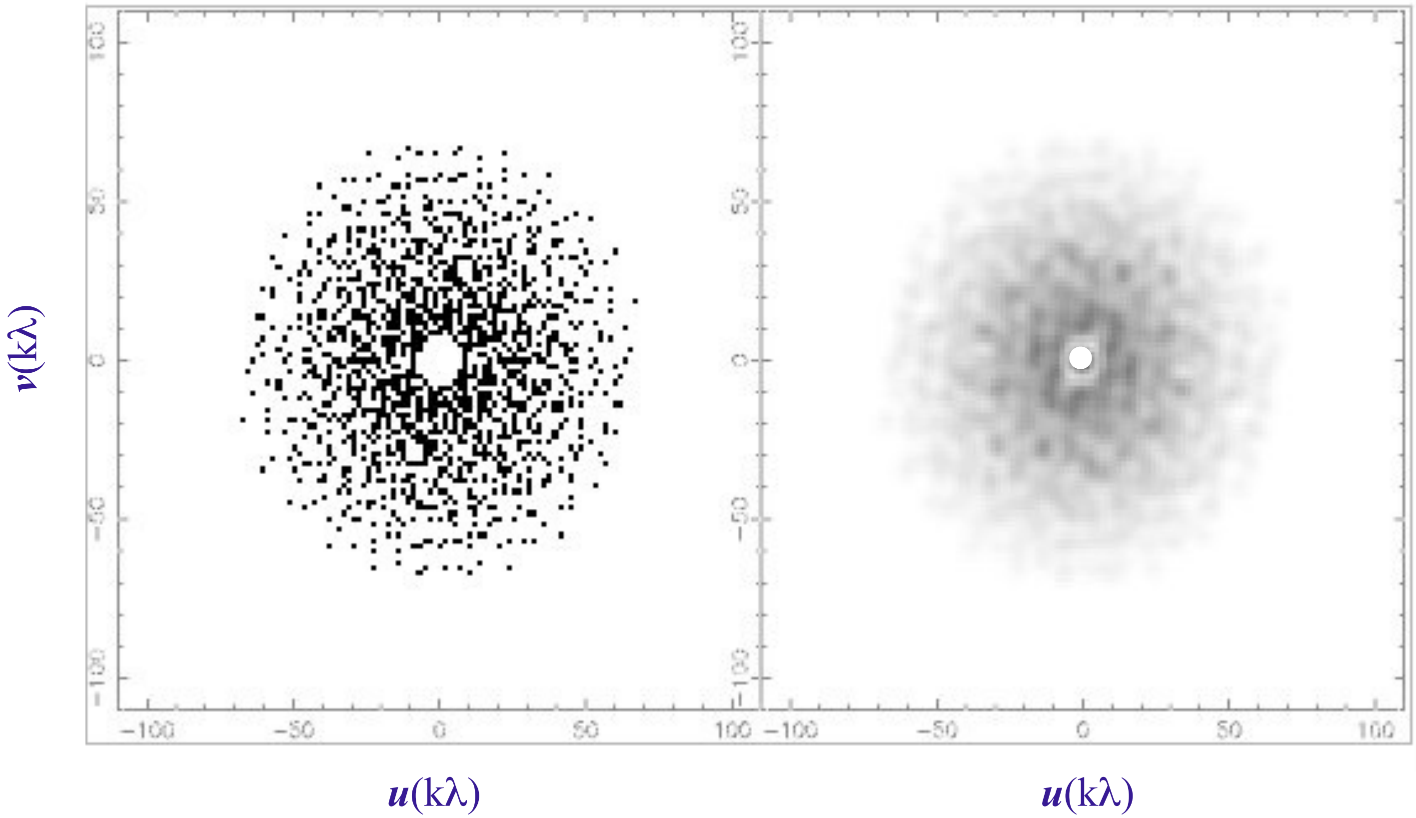
Effects of Missing Short & Zero Spacings

Interferometer ~~+ Single~~ Dish

nominal uv coverage: (baseline)/λ

What you are really measuring:

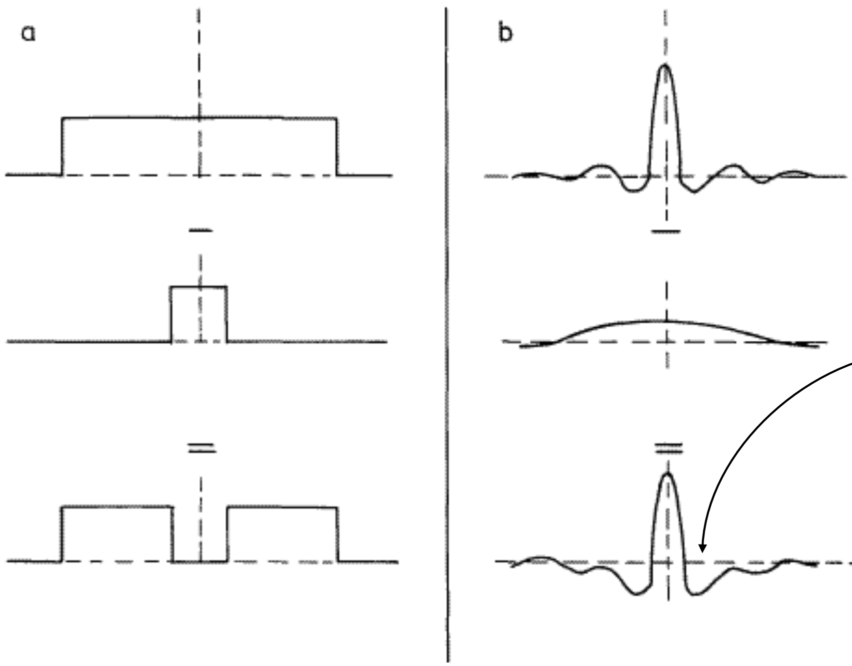


Effects of Missing Short & Zero Spacings

Interferometer ~~+ Single~~ Dish

- UV plane
- PSF
- Braun & Walterbos (1985)

- ideal
- Central hole
- Typical interfero-meter



- Negative 'bowl'

Effects of Missing Short & Zero Spacings

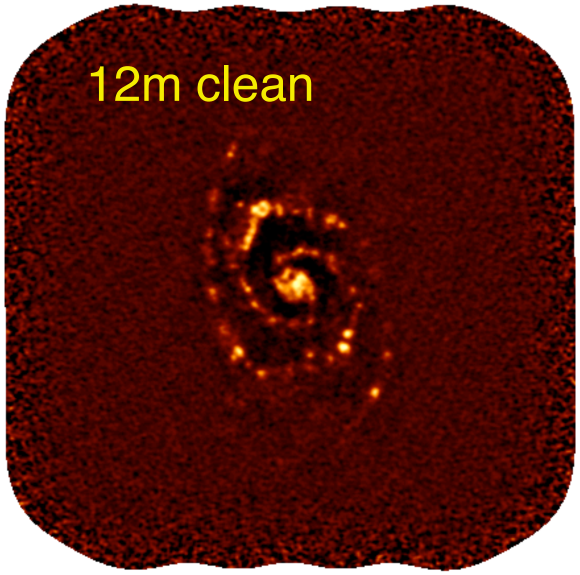
Interferometer ~~+ Single~~ Dish

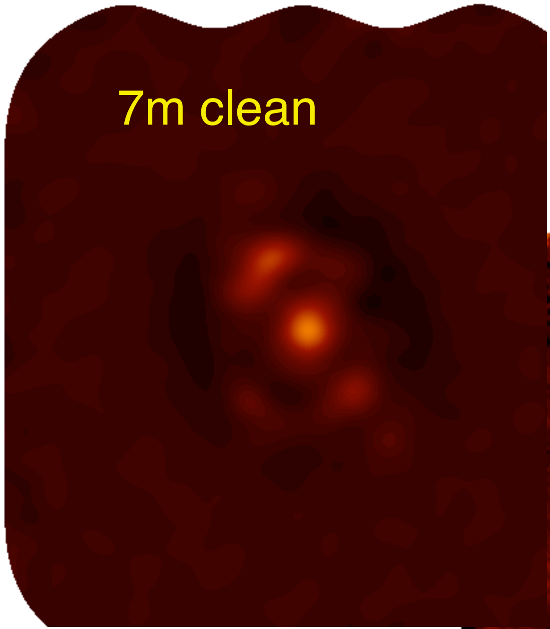
The "background level" in your map is unmeasured / variable: this is a big problem for measuring the fluxes of individual objects or regions.

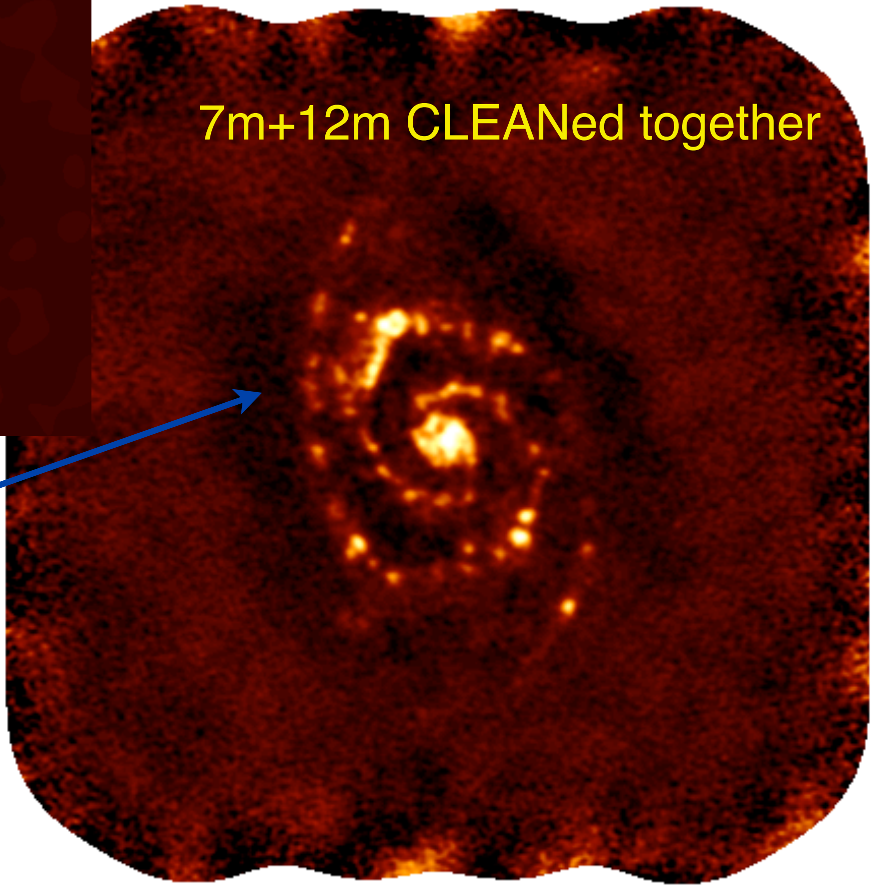
This matters because the science often comes from comparisons in different maps: the integrated line intensity in two transitions or lines; the continuum flux density at two widely separated frequencies.

(Often using data from completely different instruments...)

Effects of Missing Short & Zero Spacings



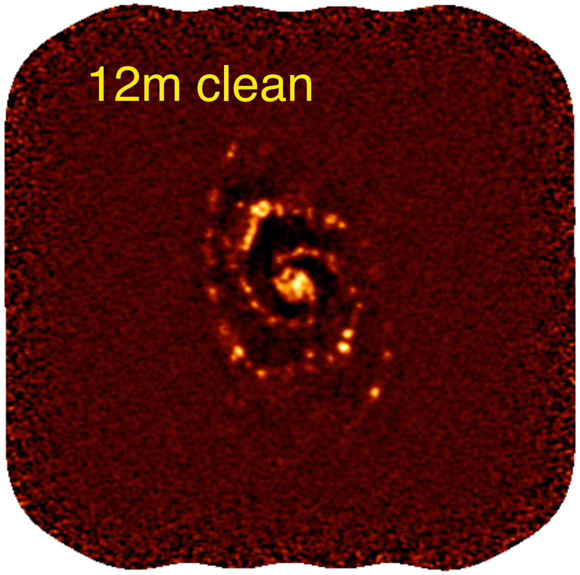


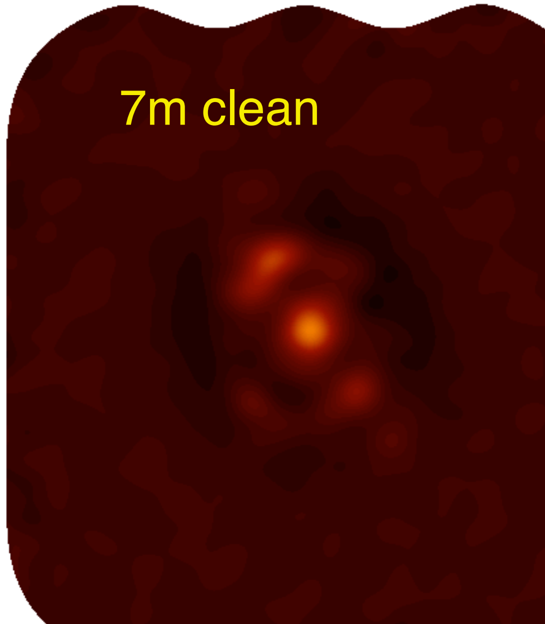


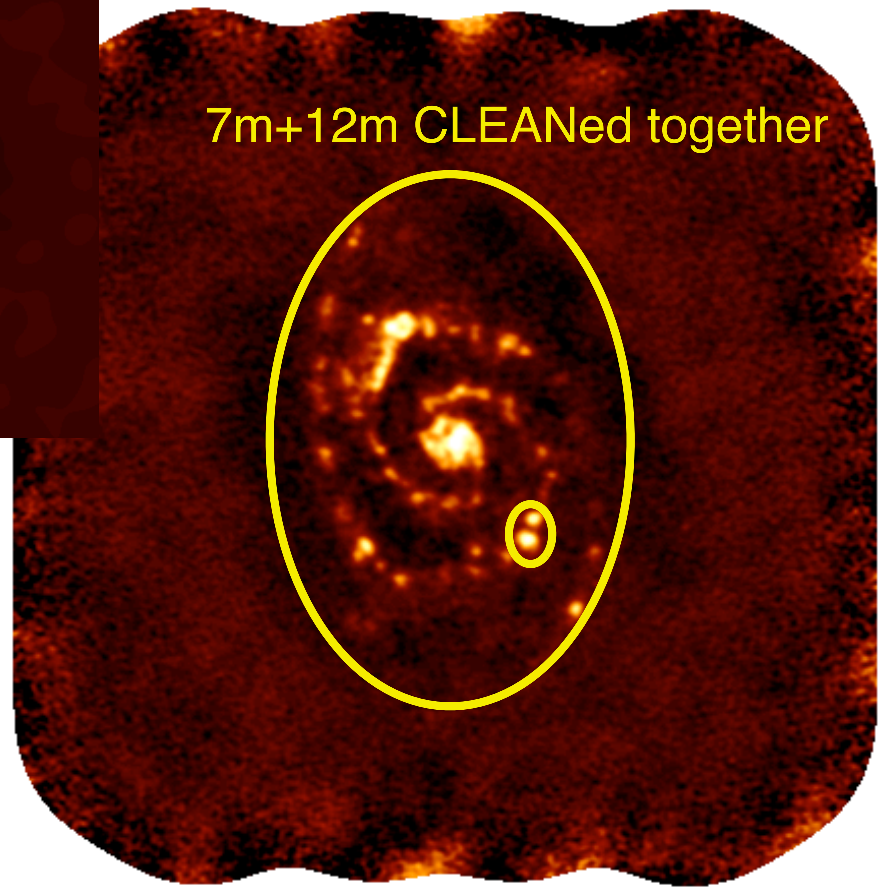
Combination of residual sidelobes (incomplete deconvolution) and poorly constrained short spacings.

https://casaguides.nrao.edu/index.php?title=Simulating_Observations_in_CASA_5.4

Effects of Missing Short & Zero Spacings







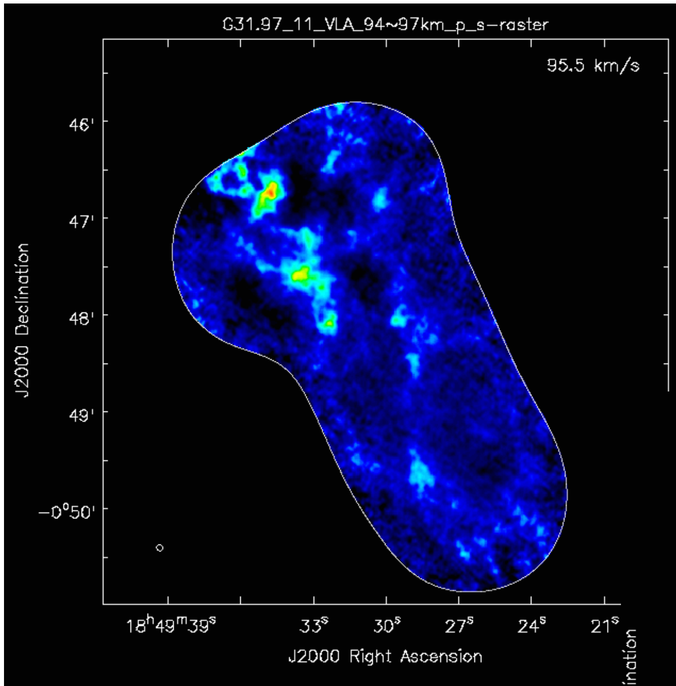
Measured total fluxes in any aperture will underestimate the true total fluxes.

maybe MS clean could do better but the ***real problem is that the short spacings are poorly constrained***.

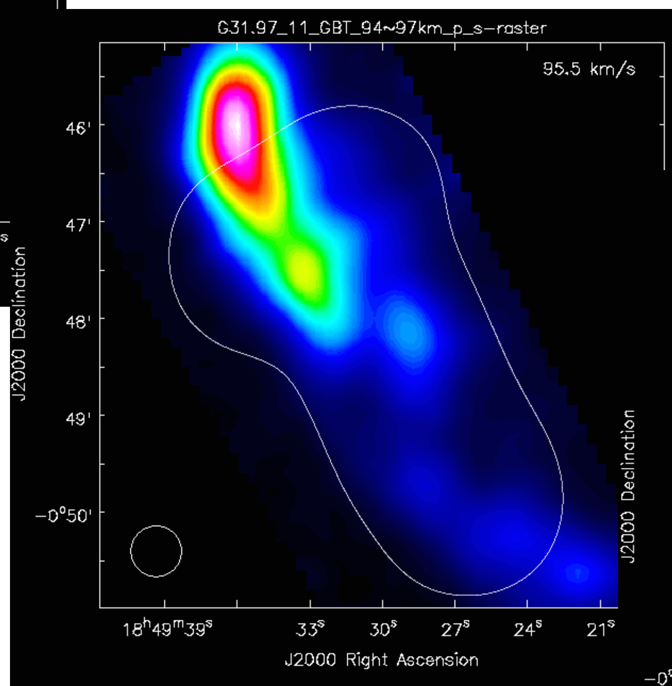
Add single dish data to the map!

https://casaguides.nrao.edu/index.php?title=Simulating_Observations_in_CASA_5.4

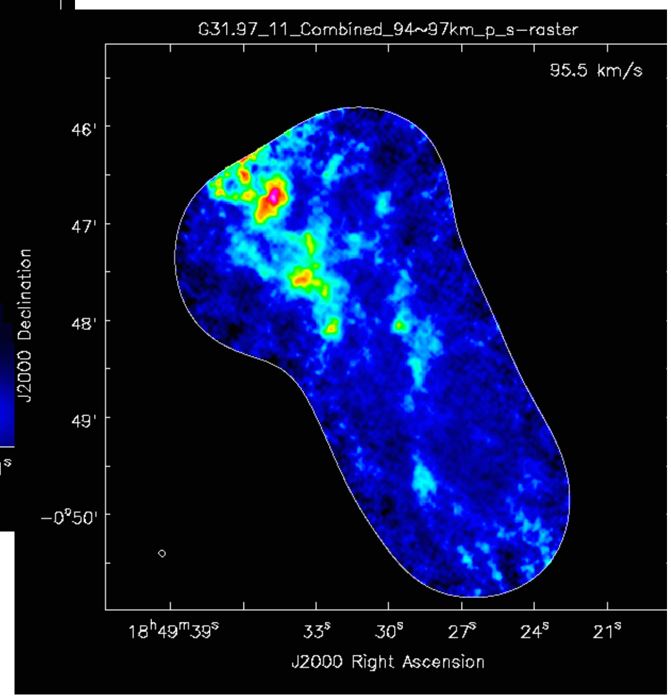
EVLA NH_3 (multi-scale CLEANed)



GBT NH_3

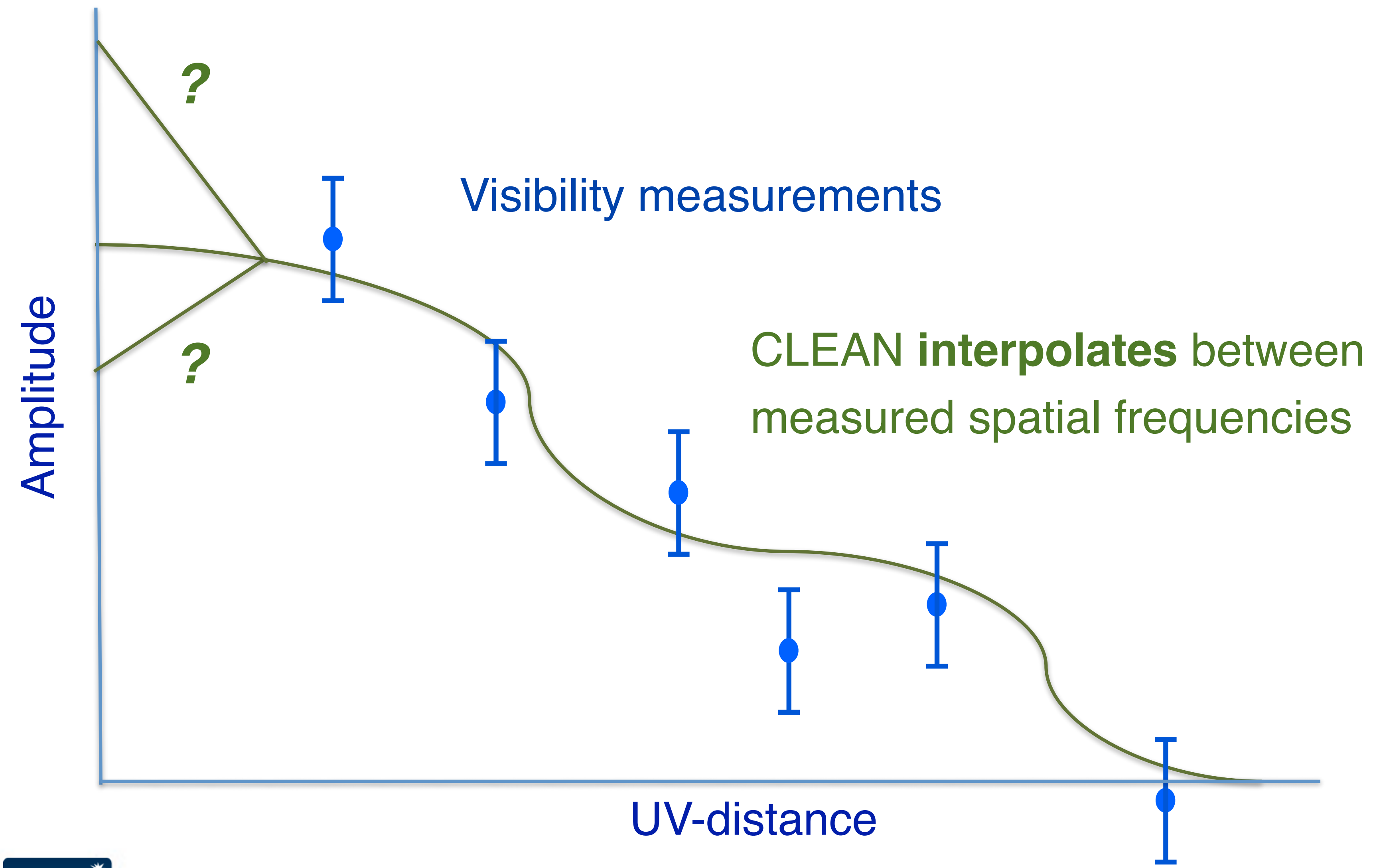


Feathered



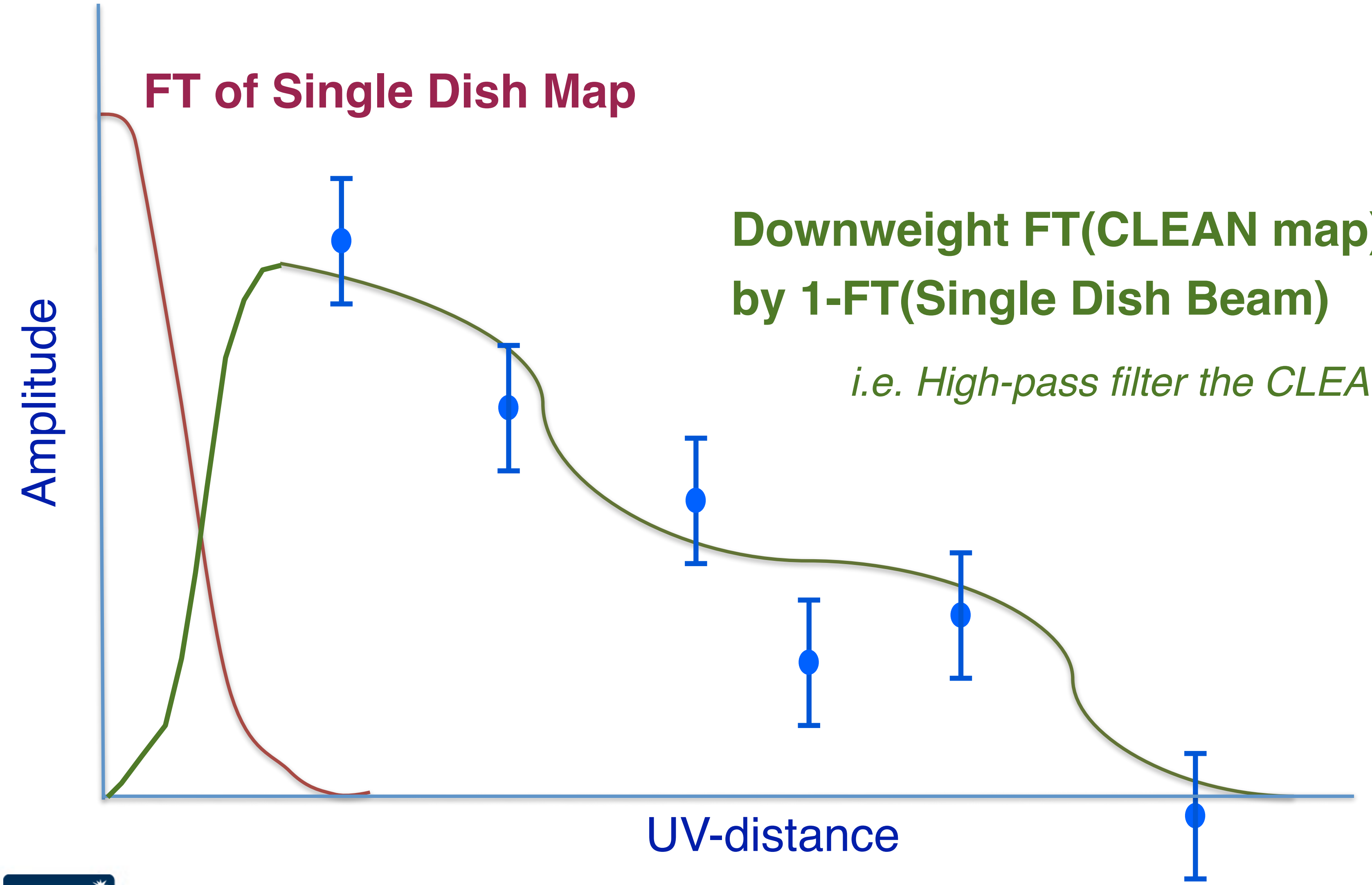
DiRienzo et al. (2015)

Feathering



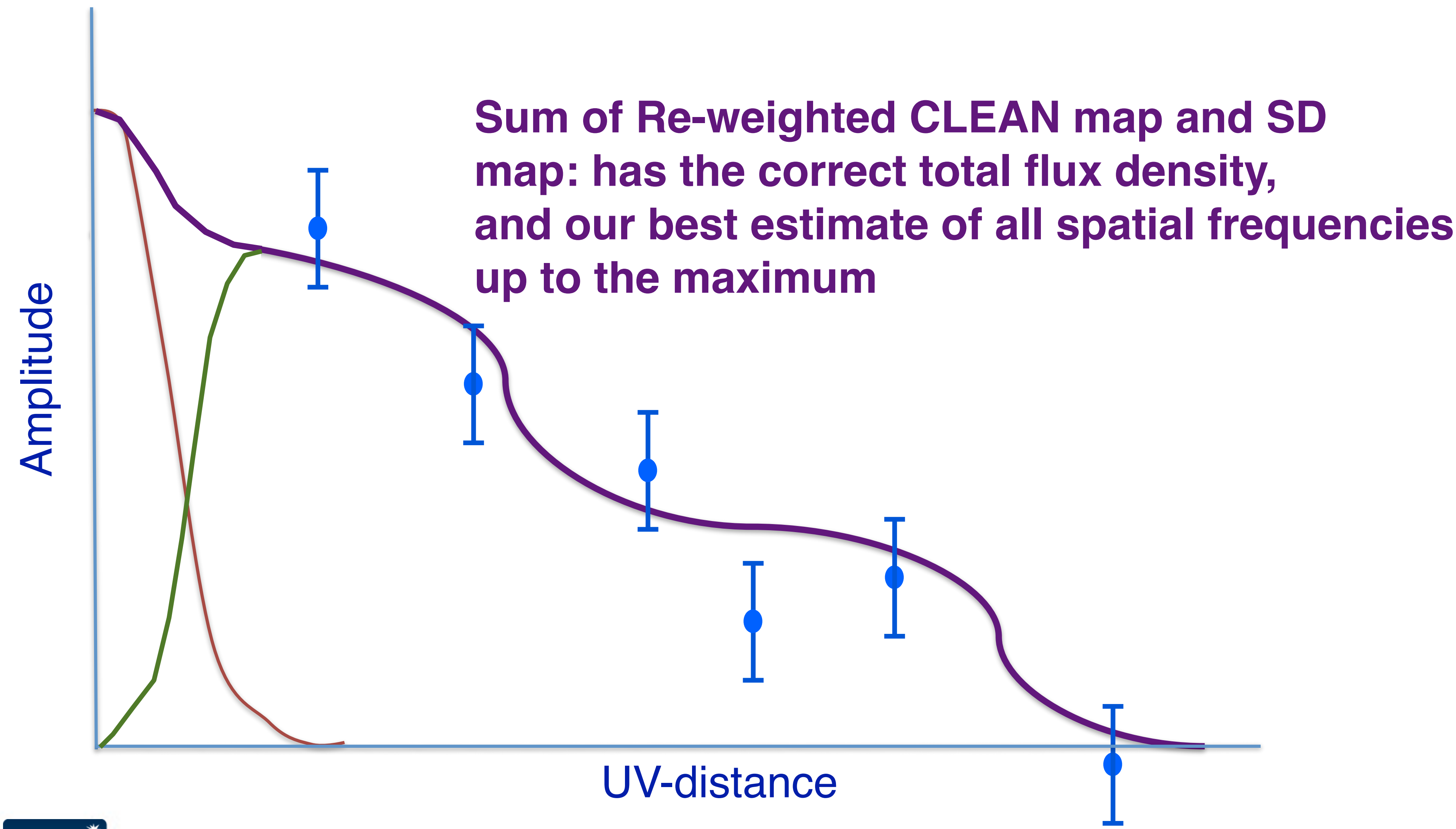
?
Visibility measurements
CLEAN **interpolates** between
measured spatial frequencies
Amplitude
?
UV-distance

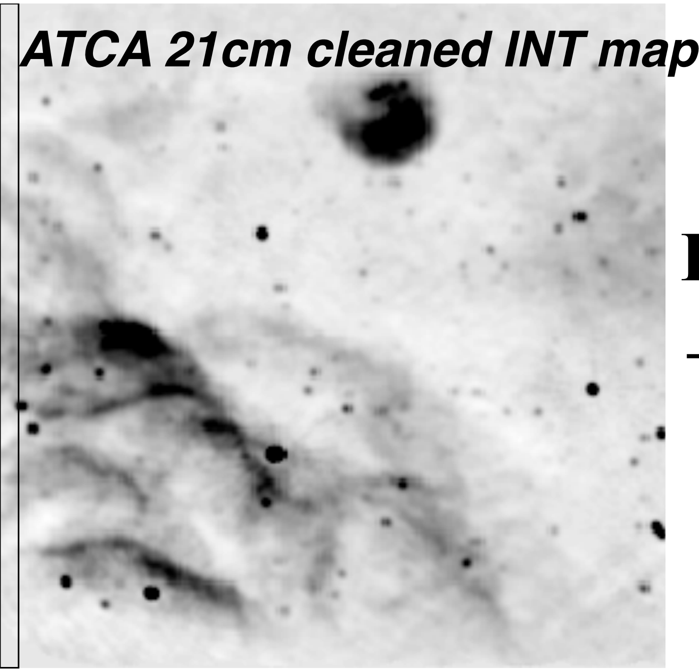
Feathering



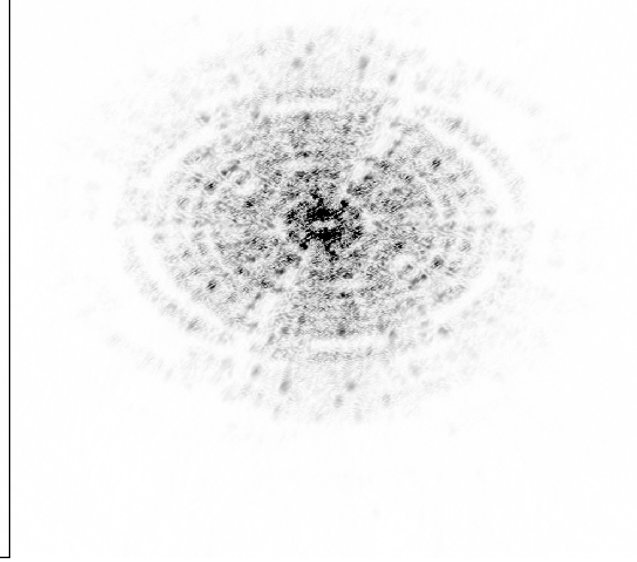
FT of Single Dish Map
Downweight FT(CLEAN map)
by 1-FT(Single Dish Beam)
i.e. High-pass filter the CLEANed map
Amplitude
UV-distance

Feathering

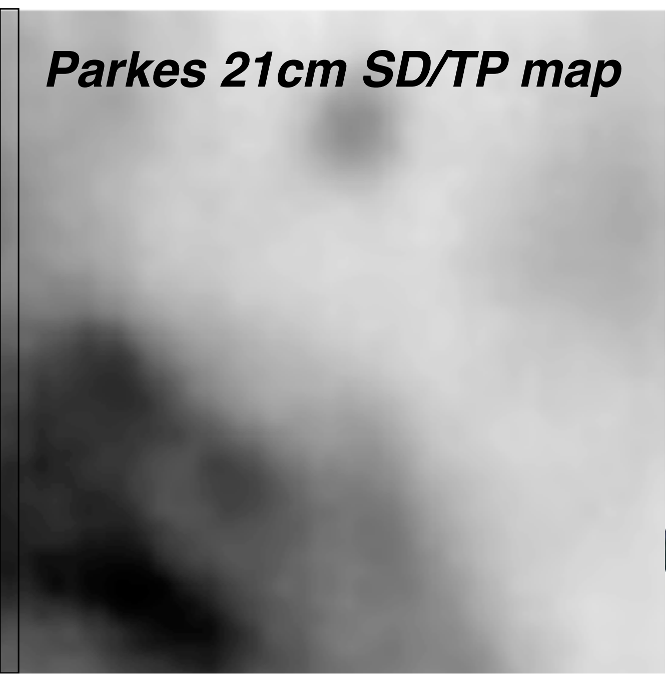

Sum of Re-weighted CLEAN map and SD map: has the correct total flux density, and our best estimate of all spatial frequencies up to the maximum
Amplitude
UV-distance



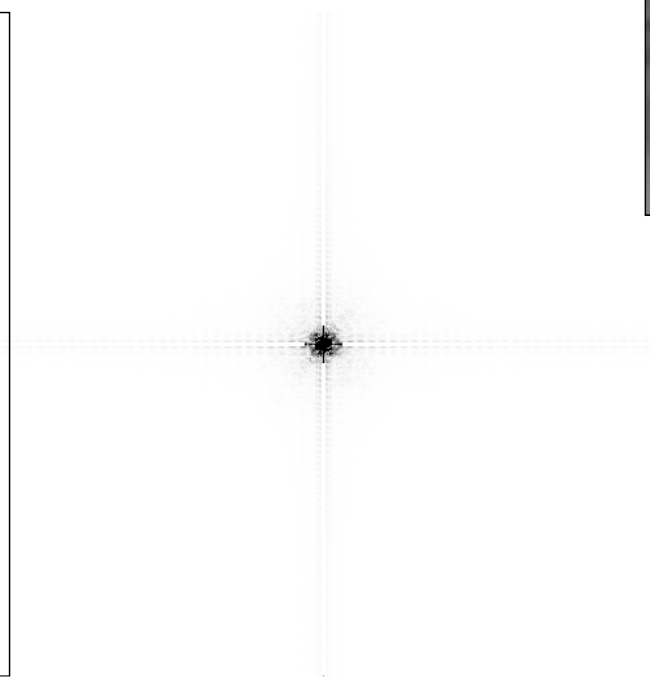
FT →



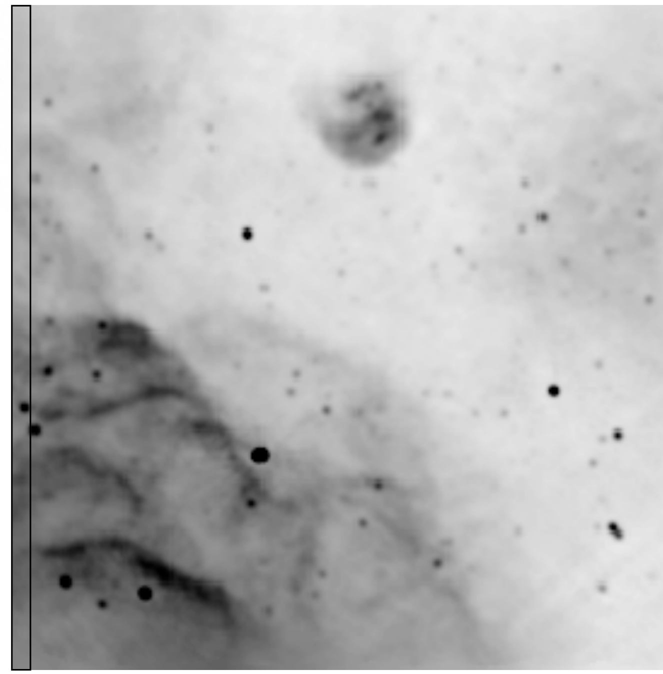
+



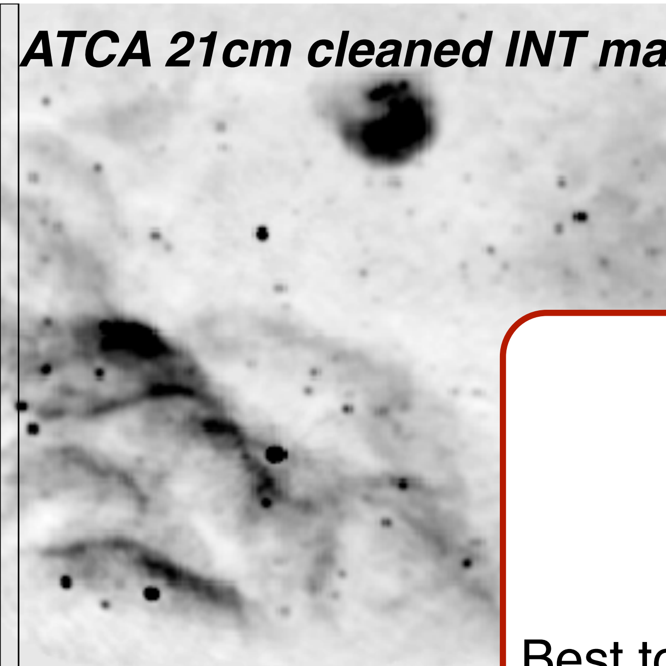
FT →



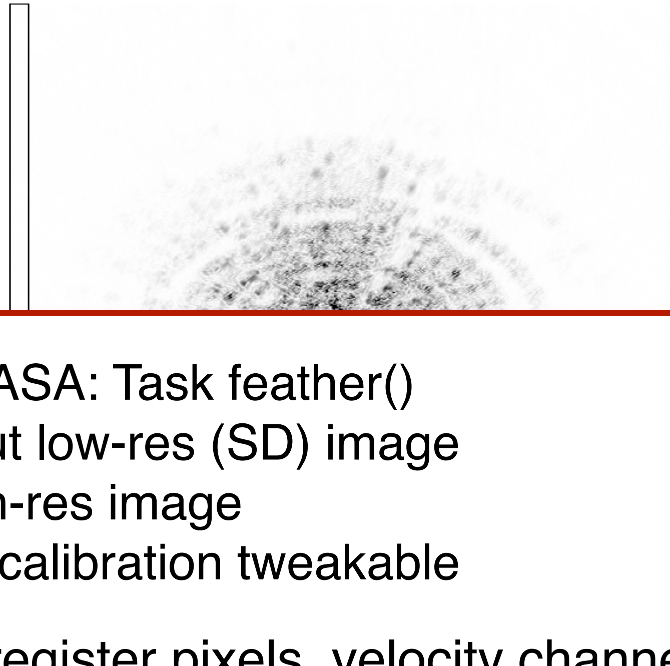
$FT^{-1}=$



McClure-Griffiths et al.



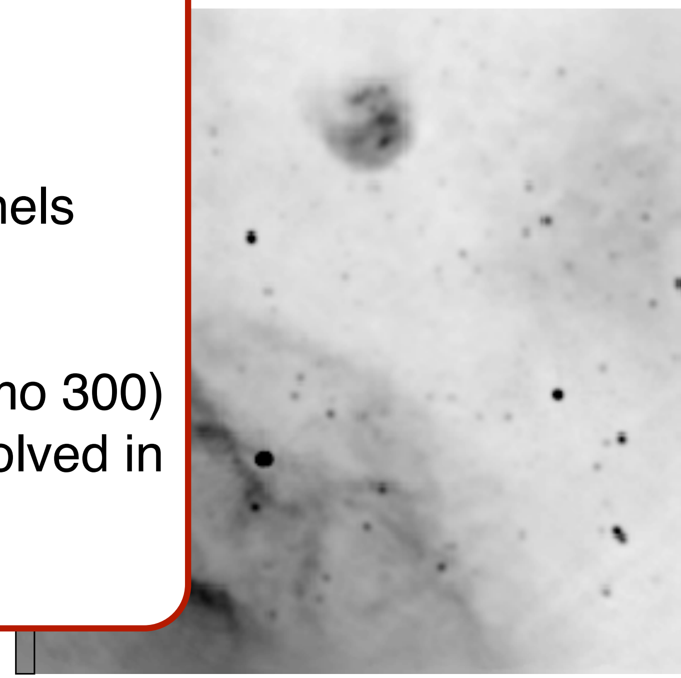
FT

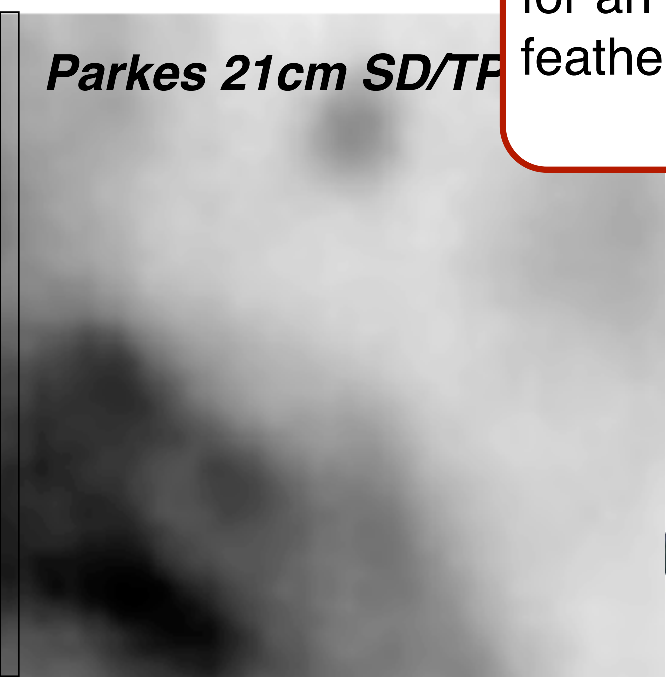


In CASA: Task feather()
*input low-res (SD) image
*high-res image
*SD calibration tweakable

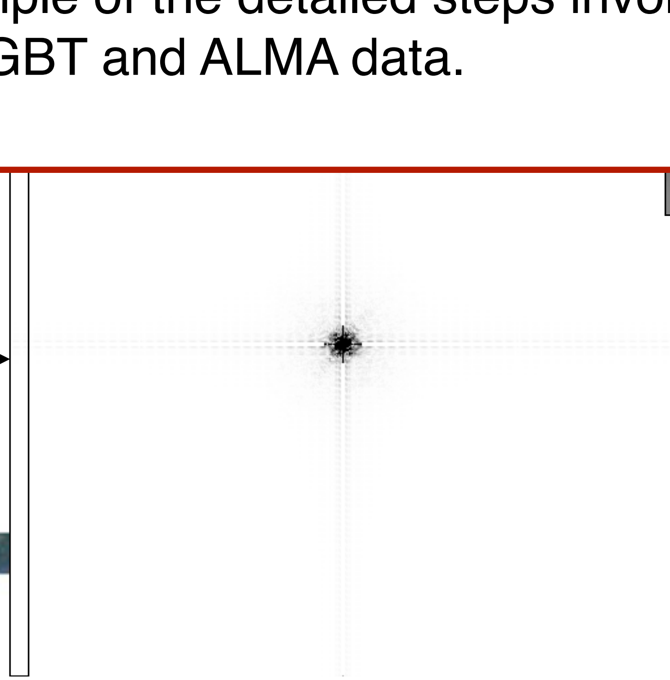
Best to co-register pixels, velocity channels first.

See Hoffman & Kepley (2018, GBT Memo 300) for an example of the detailed steps involved in feathering GBT and ALMA data.



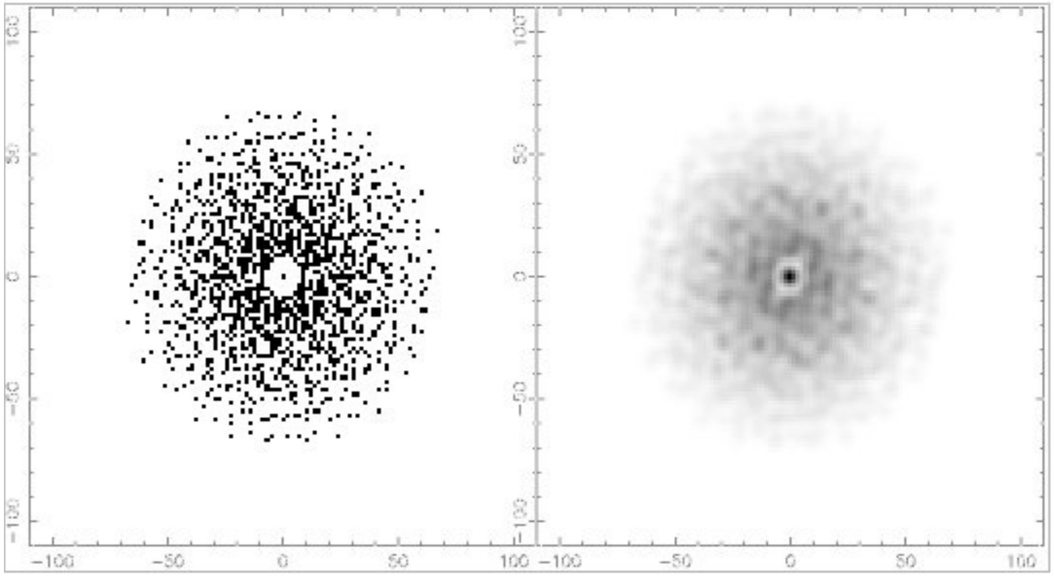


FT



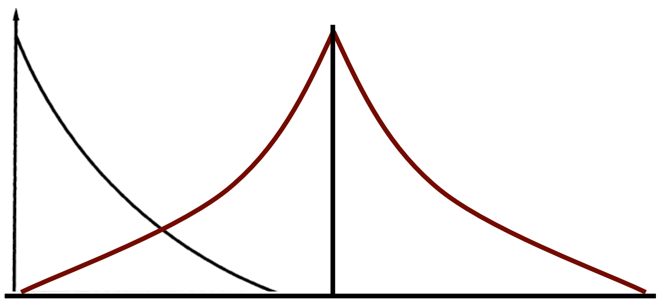
McClure-Griffiths et al.

What Single Dish Data do I Need?



interferometer diameter D

single dish diameter D



Problems:
****You still have a "hole" between (0,0) and Bmin***
****No common, well-measured spatial freq's***

To maximize flux recovery and image quality, you want a single dish of D > 1.5xB_{min}

This also facilitates verifying and linking the telescopes' calibrations

Alternatives to Feather

- **Feathering is computationally cheap and fairly robust but there are other approaches**
- Maximum Entropy (**MEM**) - use TP as a default image to reconstruct INT image
- Turn the TP image or cube into visibilities and deconvolve jointly with INT vis. ("**Pseudo-vis**" approach - Koda et al. 2011)
  - See S.Stanimirovic's article in the Single Dish Summer School proceedings (2000)
- New experimental task in CASA: **sdintimaging()**
  - Incorporates TP data into the interferometric CLEANing process via feathering
  - See Rau, Naik & Braun (2019)
- "DataComb 2019" collaboration has been working on a quantitative comparison of different TP+INT combination methods — watch for a manuscript soon (Plunkett et al. in prep.)

Practical issues (interferometric)

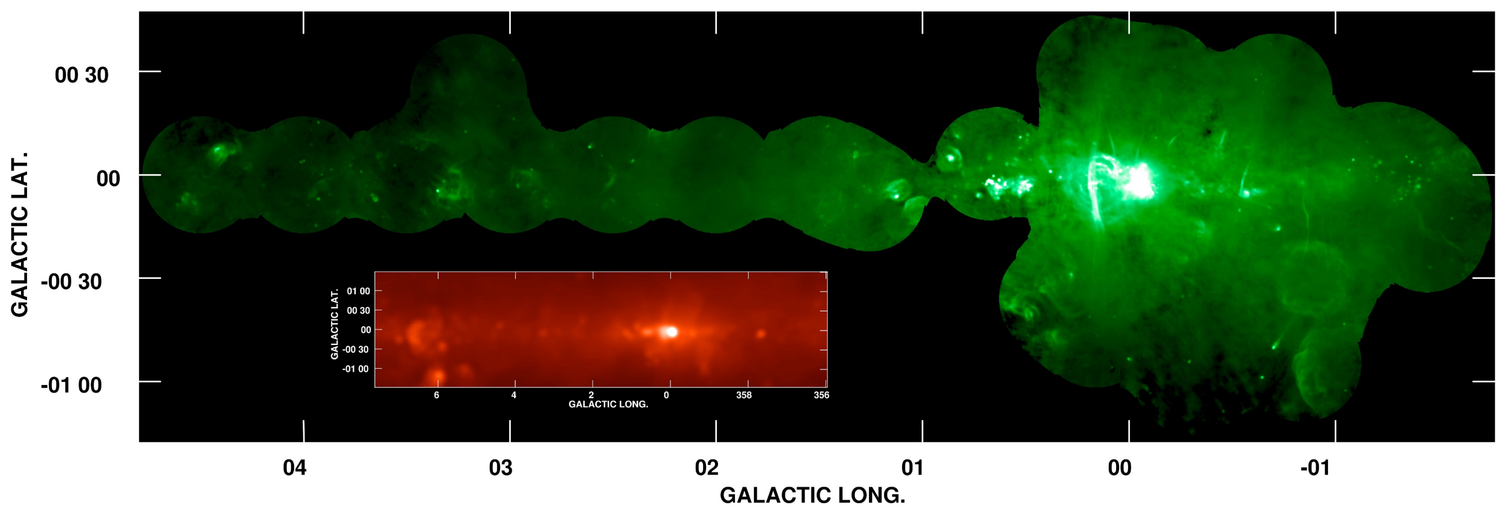
- ***Mosaic pointings are in a time sequence***:
  - Each pointing has a different uv-coverage; atmospheric water vapor/ Ionospheric variations from pointing to pointing
  - If the variation is significant (e.g., CLEAN seems not to be converging) you may want to consider deconvolving individual pointings or executions separately & linear-mosaicking them together
- ***Antenna positioning/tracking errors*** are more critical than for non-mosaicked observation with an isolated source in the beam center
  - Most applicable in the telescope design & observation planning phase
  - If bright (DR-limiting/self-cal-able) sources are sparsely distributed (< 1 per PB), self-cal might help
  - If bright emission is pervasive in the mosaic, you need *antenna pointing self-cal* (no current production implementation in CASA, though see Bhatnagar & Cornwell 2017)

Practical Issues (Single Dish)

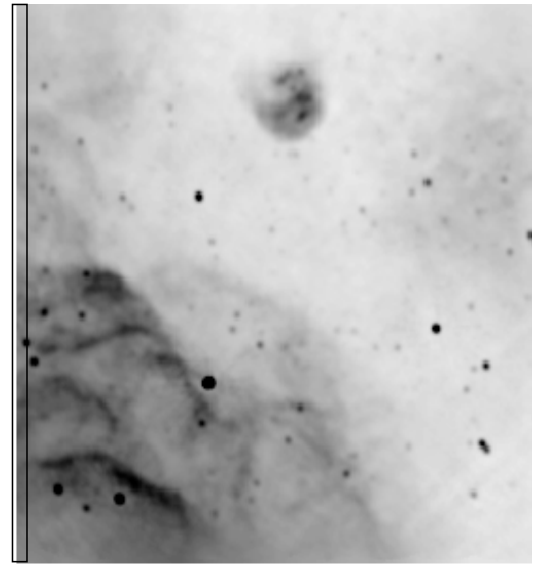
- ***SD Image may not have *all* spatial frequencies*** (down to u=v=0)
  - SD map is not usually all-sky, so “true DC level” may not be well known
  - In addition most TP observing strategies use some form of differencing (e.g. ON-OFF reference position), so it is still a differential measurement
- ***Absolute Calibration*** may not be the same as your interferometric map; you can in principle check this provided the overlap in uv-space is sufficient.
  - In CASA the feather() parameter “sdscale” can be used to address a mismatch
- **TP antenna side-lobes**: the SD primary beam is the PSF of your TP map (it acts like a synthesized beam not a primary beam) — if it is not compact and simple, you may need to deconvolve it or at least account for it in your calibration.
- ***Striping & Pointing errors:*** can introduce spurious small scale features to your TP map. Best managed in the observation planning & data collecting stage; can be mitigated somewhat by smoothing.

Summary

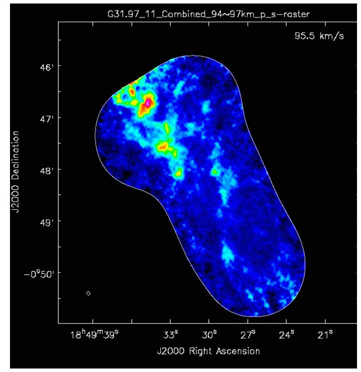
- Each visibility of an interferometer measures a range of spatial frequencies.
- By mosaicking, you can recover some of this information and make beautiful, scientifically useful images.
  - Adding single dish data can enhance them further.
- Don’t be afraid to try it! Do experiment, review documentation & talk to some people who have done it before.
  - If you have questions contact our helpdesk, or come for a face to face visit!



References & Acknowledgements



- Synthesis Imaging Summer School proceedings
  - mosaicking article by M. Holdaway
  - deconvolution article by T.Cornwell
  - previous lectures by J.Ott, D.Shepherd
- Single Dish Summer School
  - article by S.Stanimirovic
- Theory of Mosaicking: Ekers & Rots (1979)



- Joint Deconvolution: Saul, Stavely-Smith, & Brouw (1996)
- https://casadocs.readthedocs.io/en/latest/notebooks/synthesis_imaging.html
- CLEANing: Jorsater & VanMoorsel (1995); Walter et al. (2008); Condon et al. (1998); MS Clean: Cornwell (2008)
- Joint Mosaic UV Gridding: Myers et al. (2003)
- Example of Pseudo-Visibility Joint Deconvolution approach to SD+INT combo: Koda et al. (2011)
- Heterogeneous array / SD relative integration times:
  - Pety-Guth et al. (2008); Kurono et al. (2009); Mason & Brogan (2013; ALMA memo 598)
- Useful discussions with C.Brogan, U.Rao, J.Ott, & others