Mosaicking II: Large-Scale Imaging & Short Spacing Corrections

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NRAO

NEW MEXICO TECH
SCIENCE · ENGINEERING · RESEARCH · UNIVERSITY
The University of New Mexico

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

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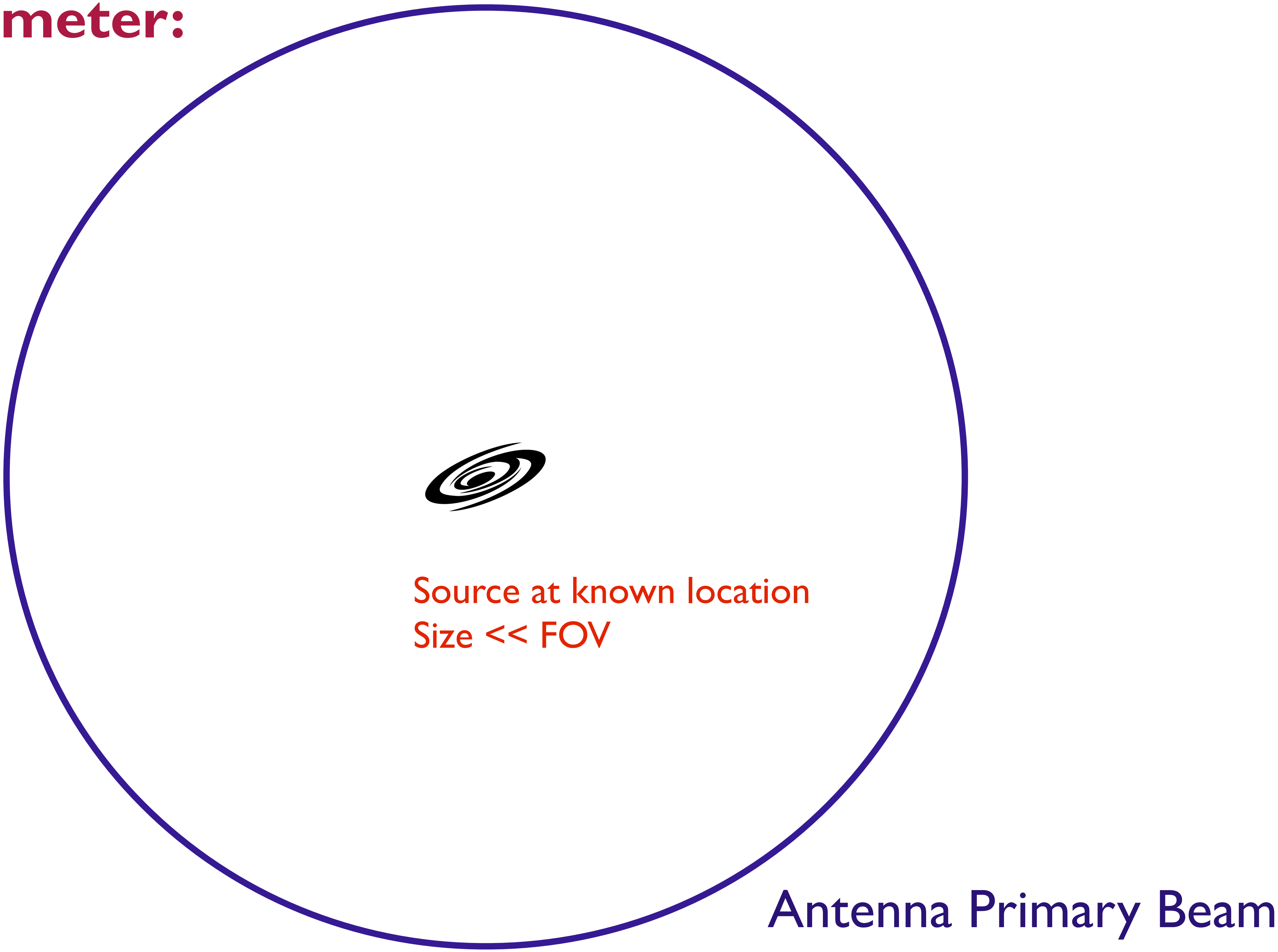
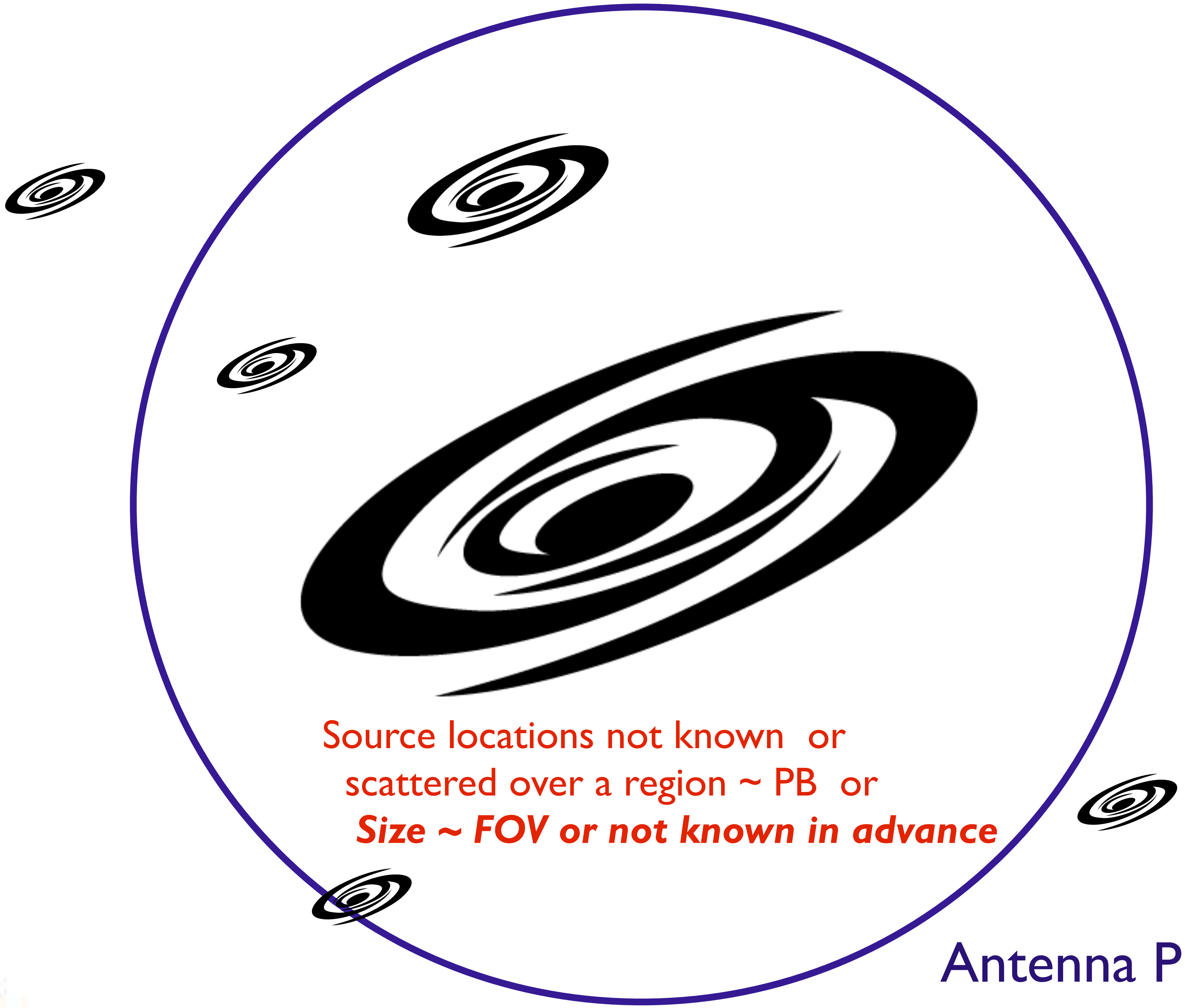
The simplest observing scenario for an interferometer:



But that's often not the case...



Source locations not known or
scattered over a region ~ PB or
Size ~ FOV or not known in advance

Antenna Primary Beam

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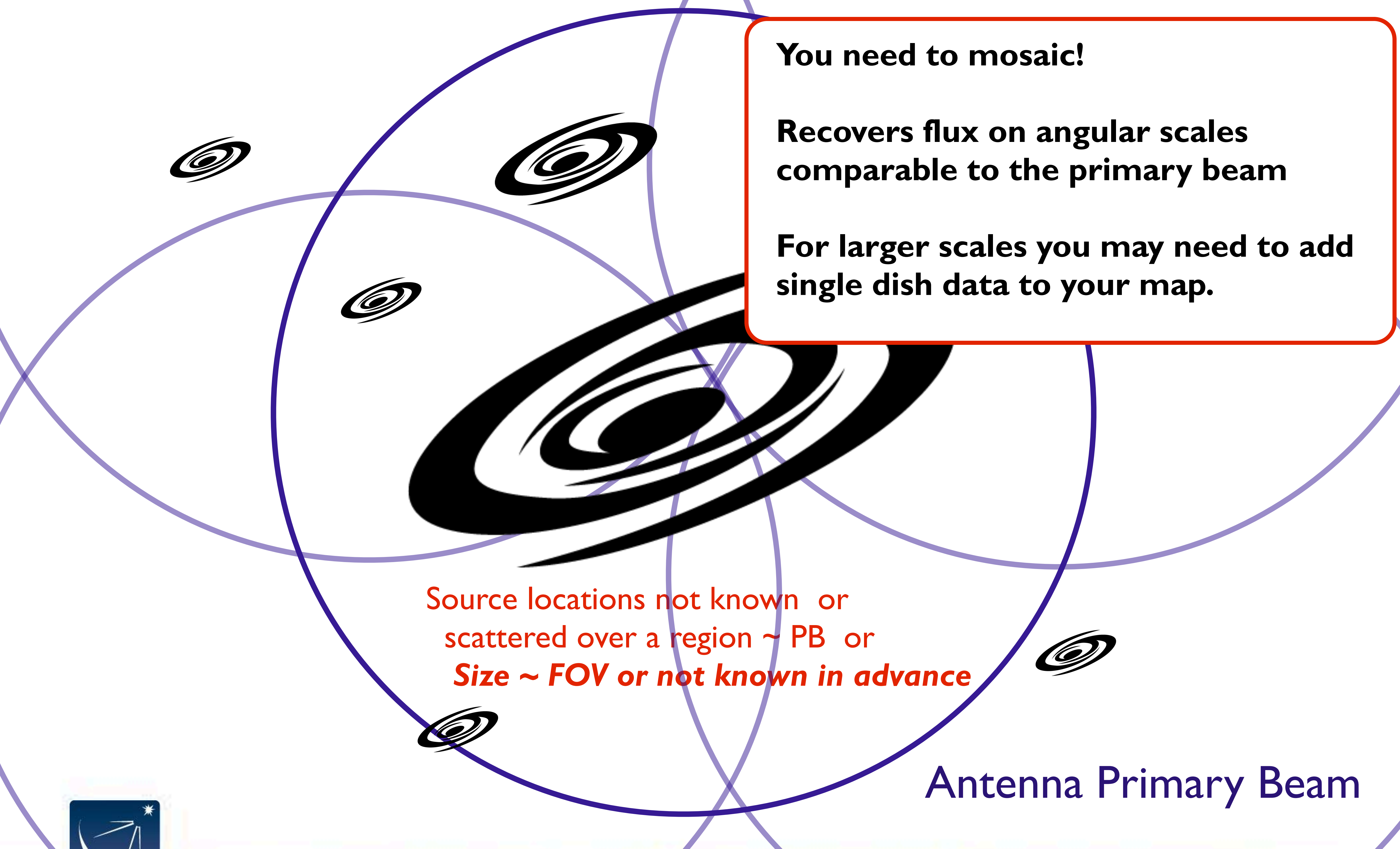
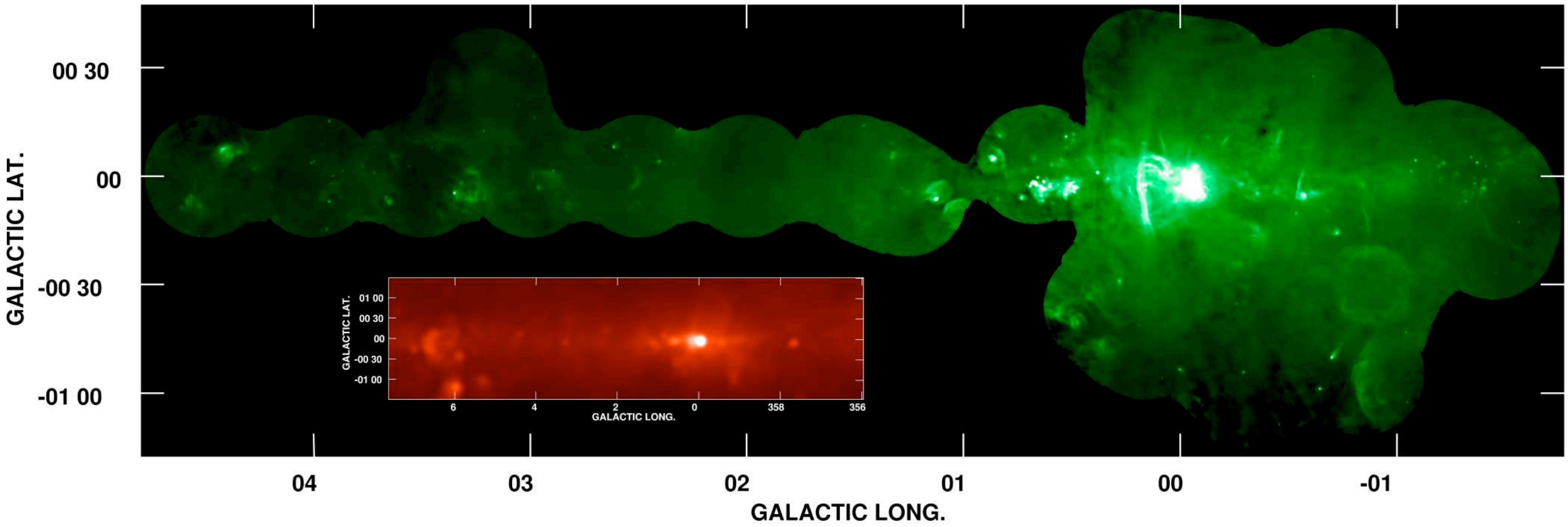
But that's often not the case...

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.

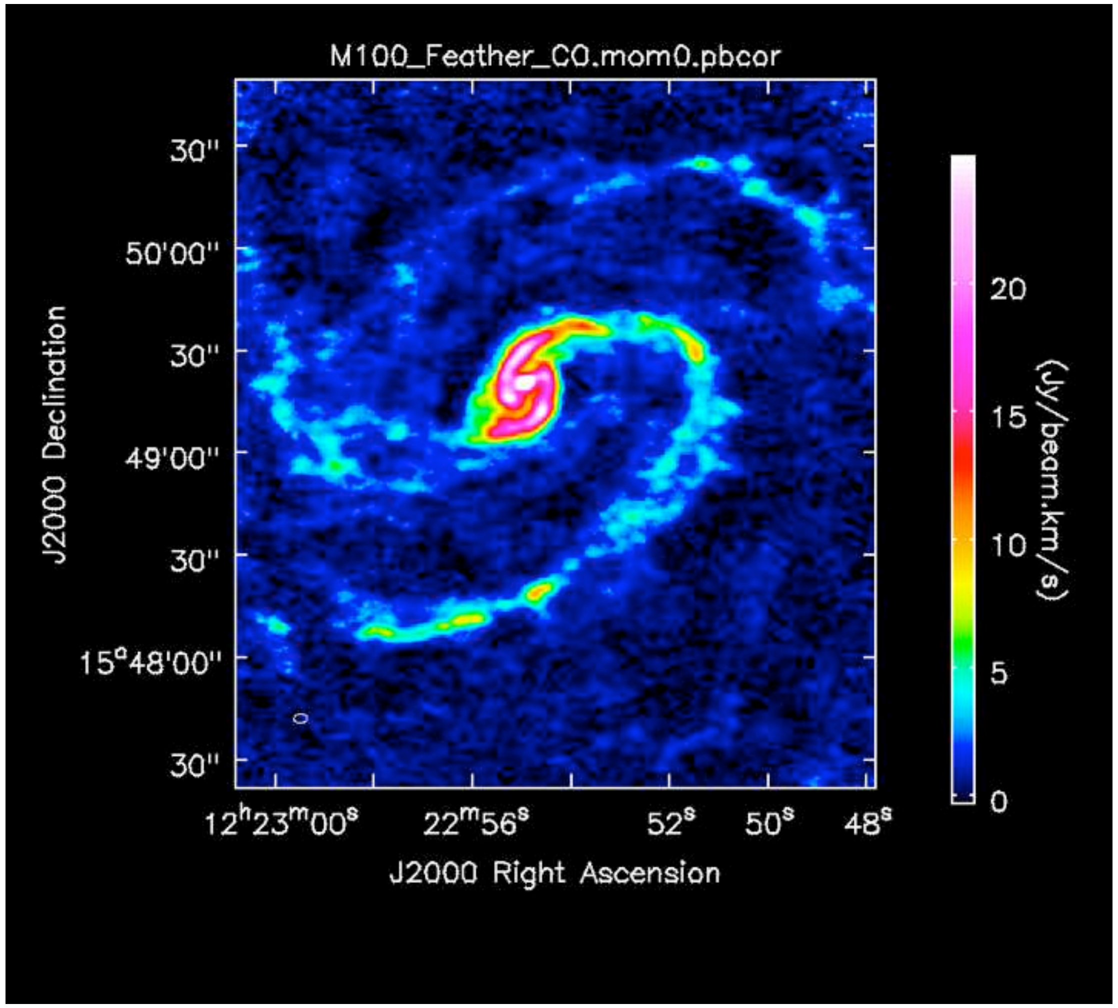




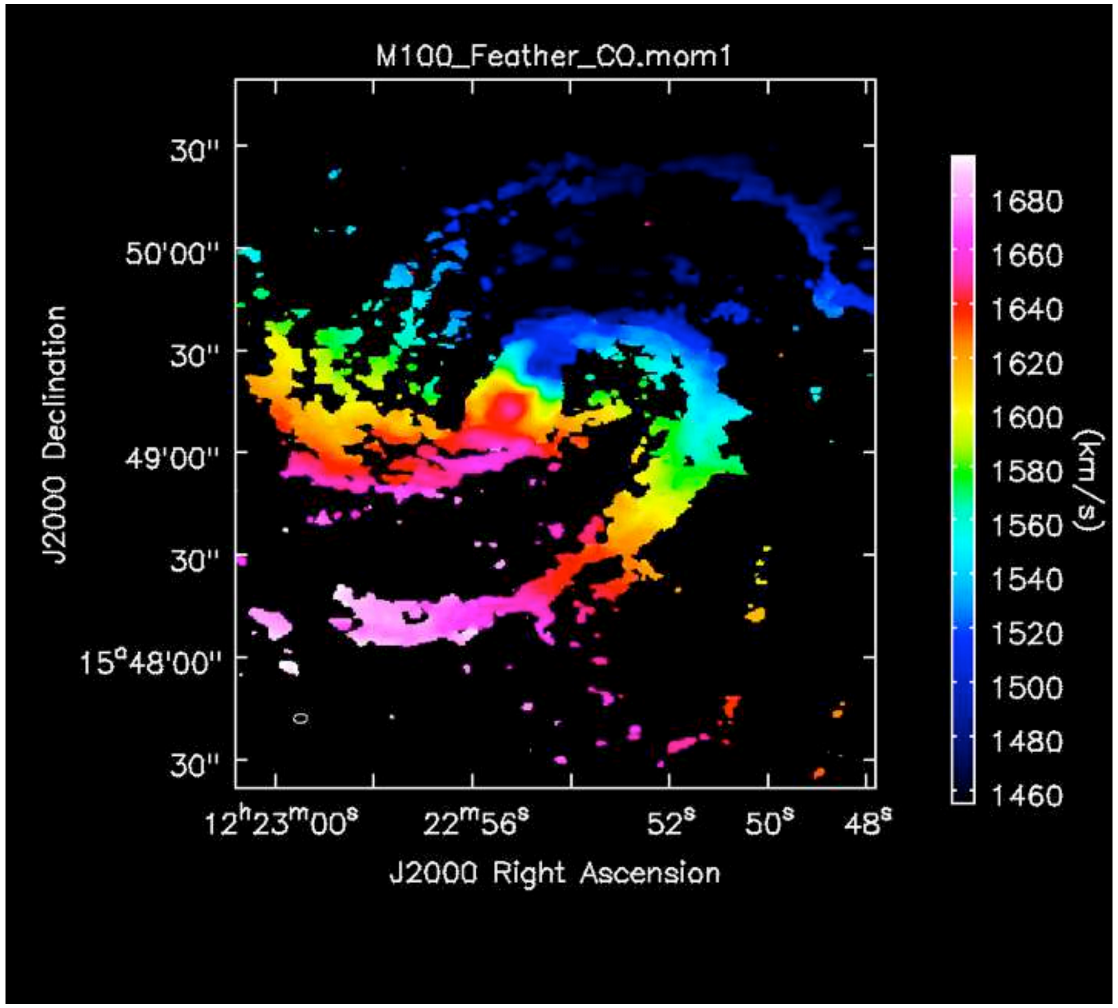
20cm VLA Mosaic+GBT Single Dish (green) (red inset :GBT only)

Law, Yusef-Zadeh, & Cotton (2008)

ALMA Science Verification: M100

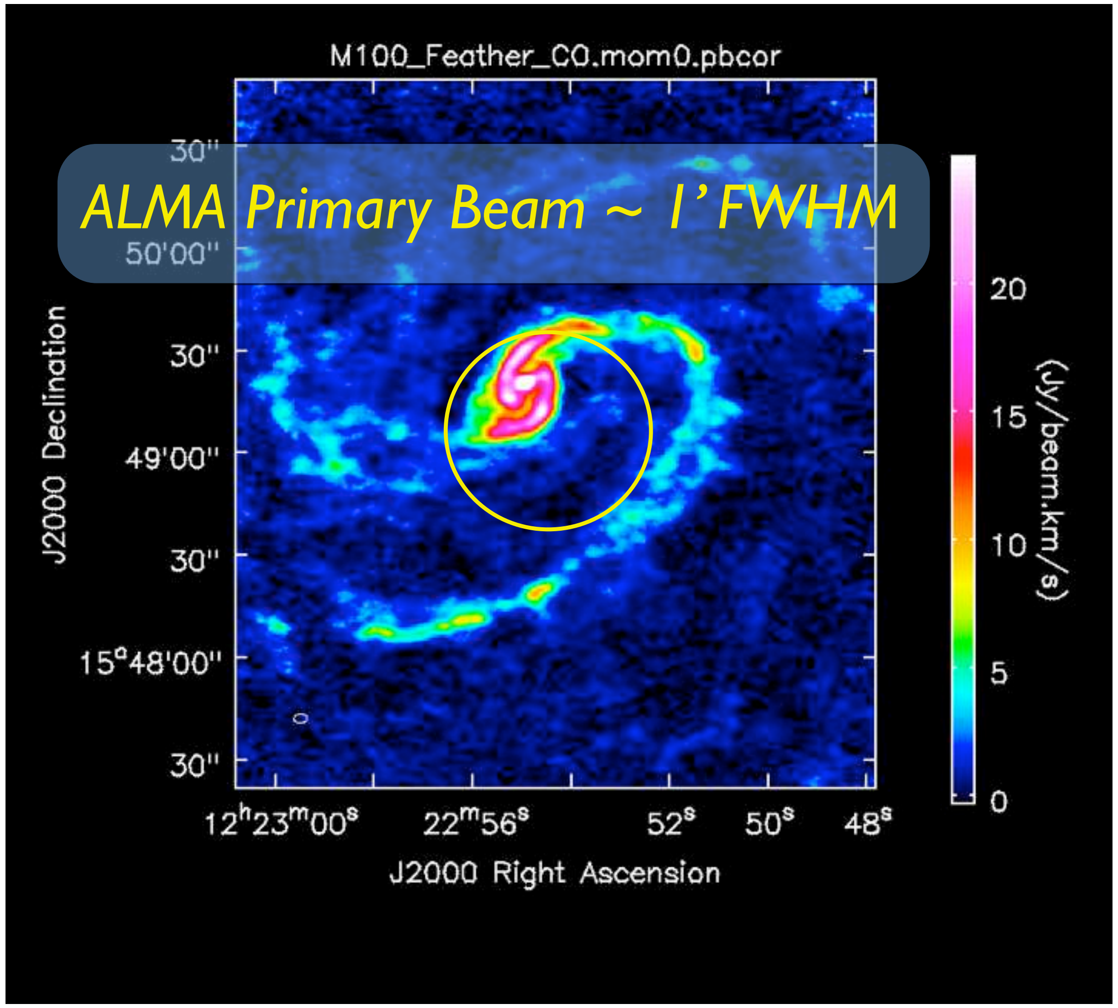


Integrated CO line intensity
Band 3 (115 GHz, ~2.6mm)



1st moment map (velocity field of CO line)

ALMA Science Verification: M100



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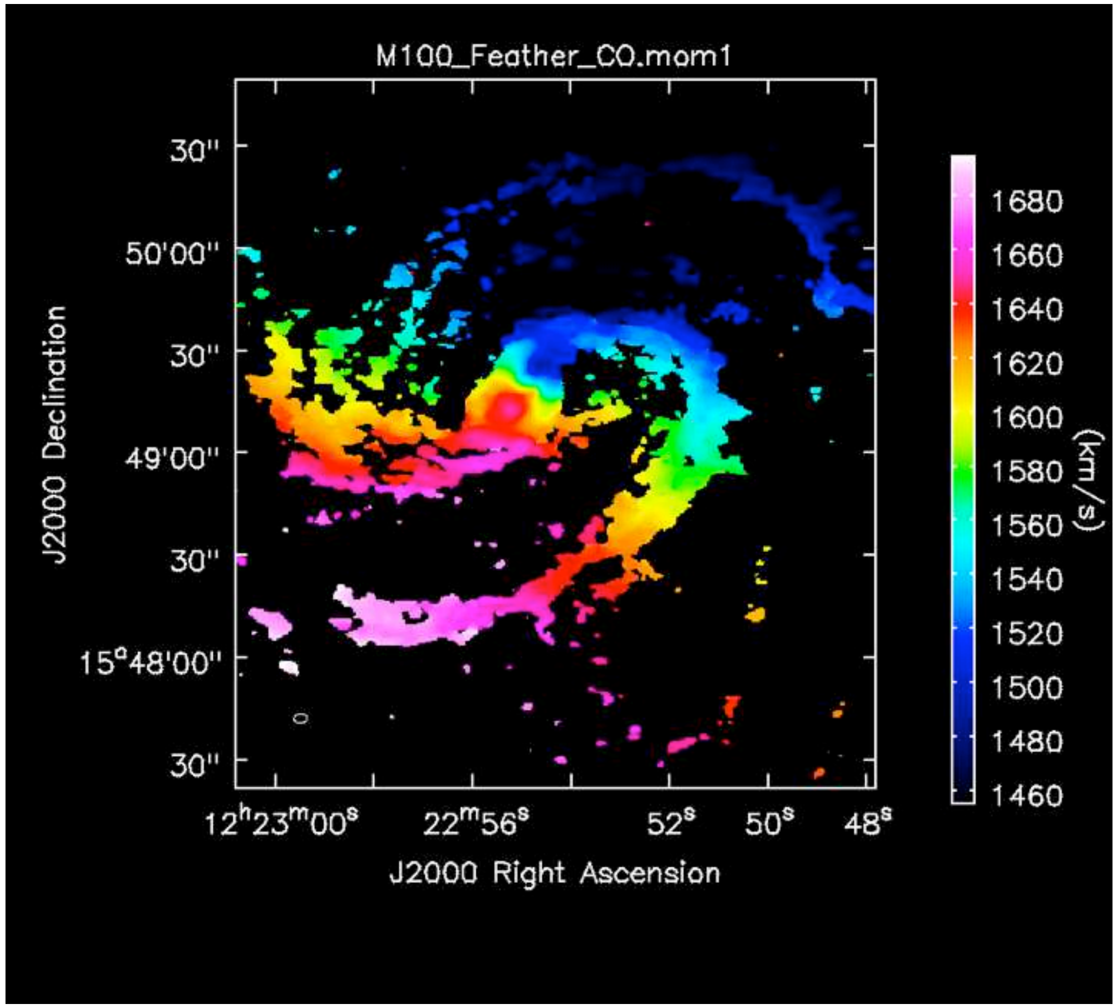

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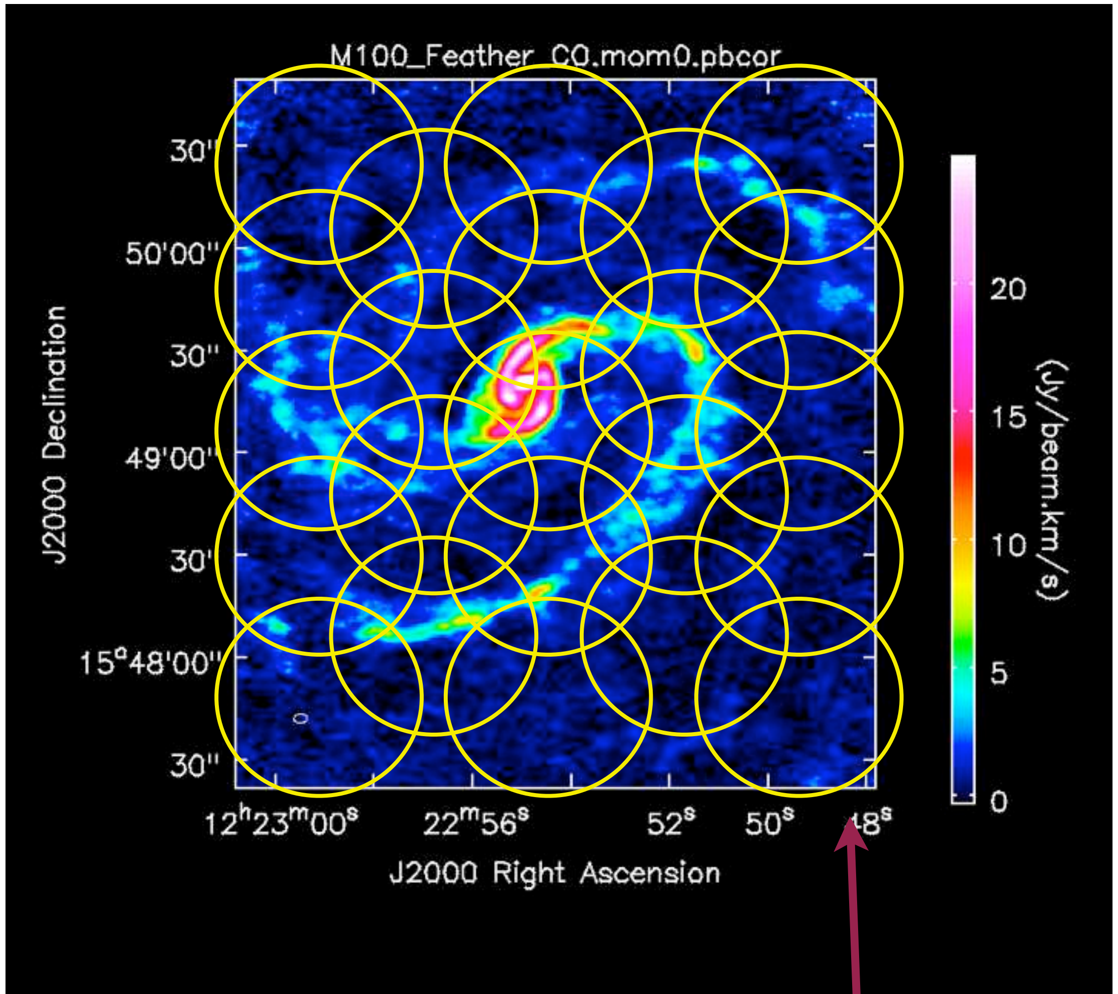

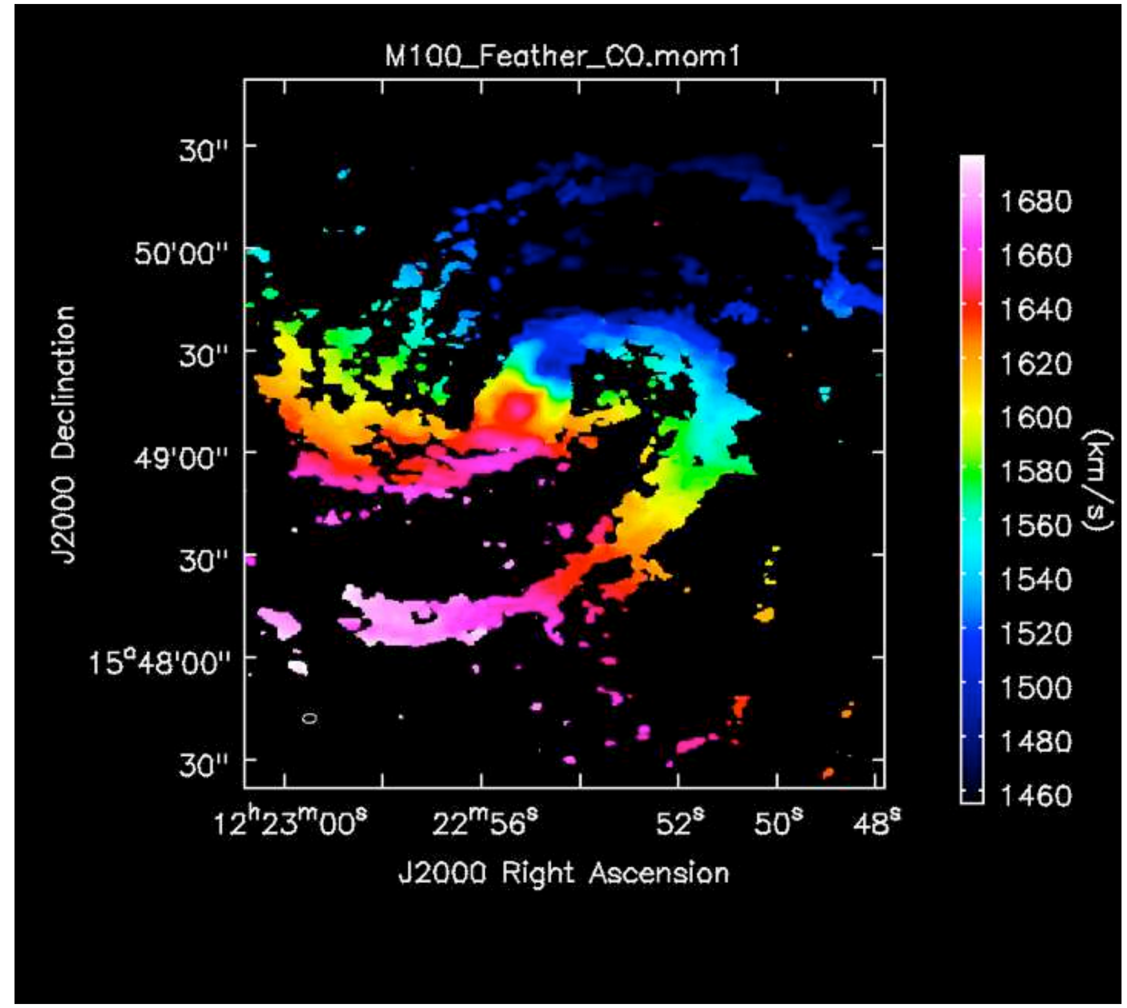

Integrated CO line intensity
Band 3 (115 GHz, ~2.6mm)

1st moment map (velocity field of CO line)

At short wavelengths, mosaicking is very commonly required

Limiting Angular Scales for an Interferometer

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

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

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

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

In practice, you only measure things *half* that big (say) very well.
(even that might be optimistic)

Exercise: you can quantify the LAS yourself using the "Gaussian Flux Loss" rule of thumb (D.Wilner lecture on deconvolution)

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Limiting Angular Scales for an Interferometer

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

VLA: L-band (20cm) = 30’ Q-band (7mm) = 1’

ALMA(12m): Band3 (3mm) = 1’ Band9 (0.44mm) = 9”

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

VLA: L-band (20cm), D-array = 16’ Q-band (7mm), A-array = 1.2”

30m *537m*

ALMA(12m): Band3 (3mm), compact cfg = 20” Band9 (0.44mm), ext.cfg= 1”

15m *43m*

(based on currently advertised capabilities)

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Limiting Angular Scales for an Interferometer

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

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

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

If the structures you are interested in are larger than this, you need to mosaic and/or get data from a more compact configuration of the interferometer or single dish.

VLA: L-band (20cm), D-array = 16' Q-band (7mm), A-array = 1.2"

30m *537m*

ALMA(12m): Band3 (3mm), compact cfg = 20" Band9 (0.44mm), ext.cfg= 1"

15m *43m*

(based on currently advertised capabilities)

Limiting Angular Scales for an Interferometer

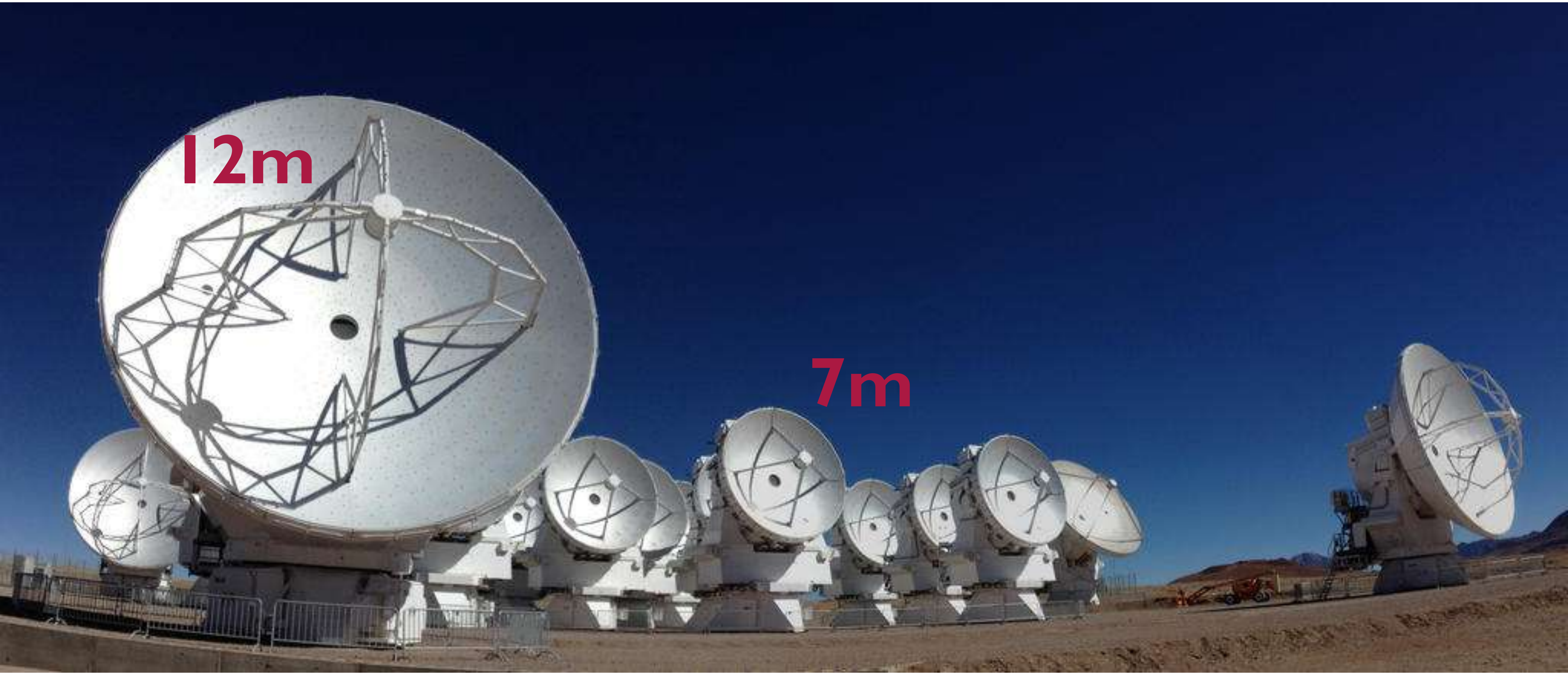
$$\theta_{PB} = (1.03 \rightarrow 1.2) \times \frac{\lambda}{D}$$

There is a limit to how compact a given interferometer can get

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

For angular scales much bigger than that you need smaller dishes, or data from a single dish telescope.

The ALMA Compact Array (ACA)

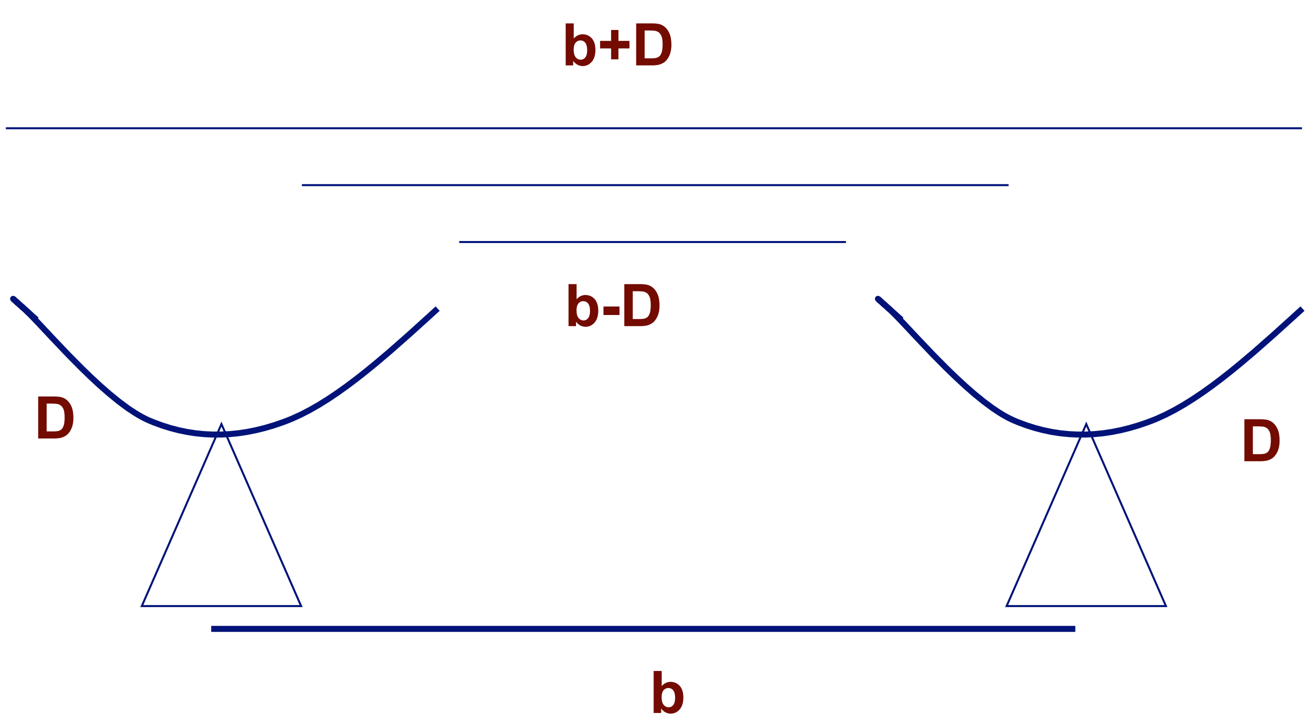


The ALMA Compact Array (ACA)

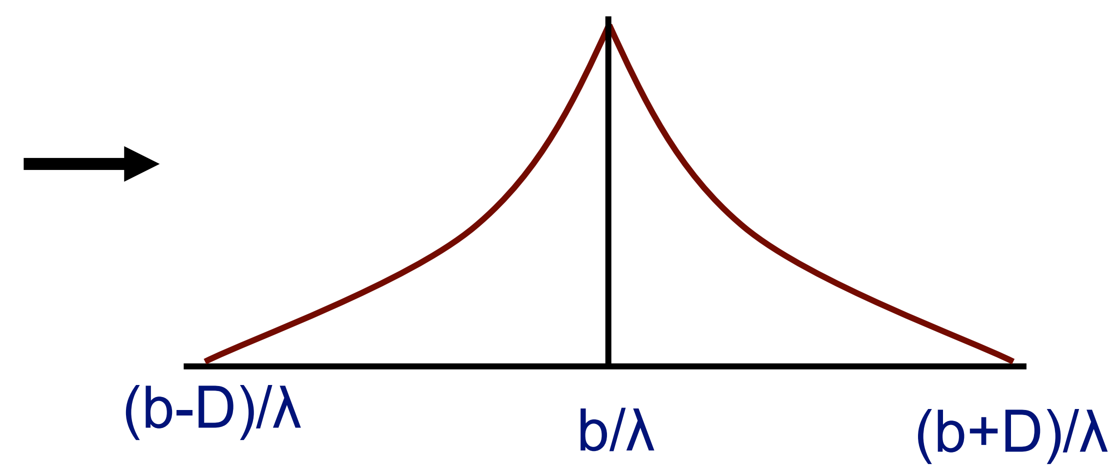
CARMA

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:



Theory of Mosaicking: Ekers & Rots Theorem

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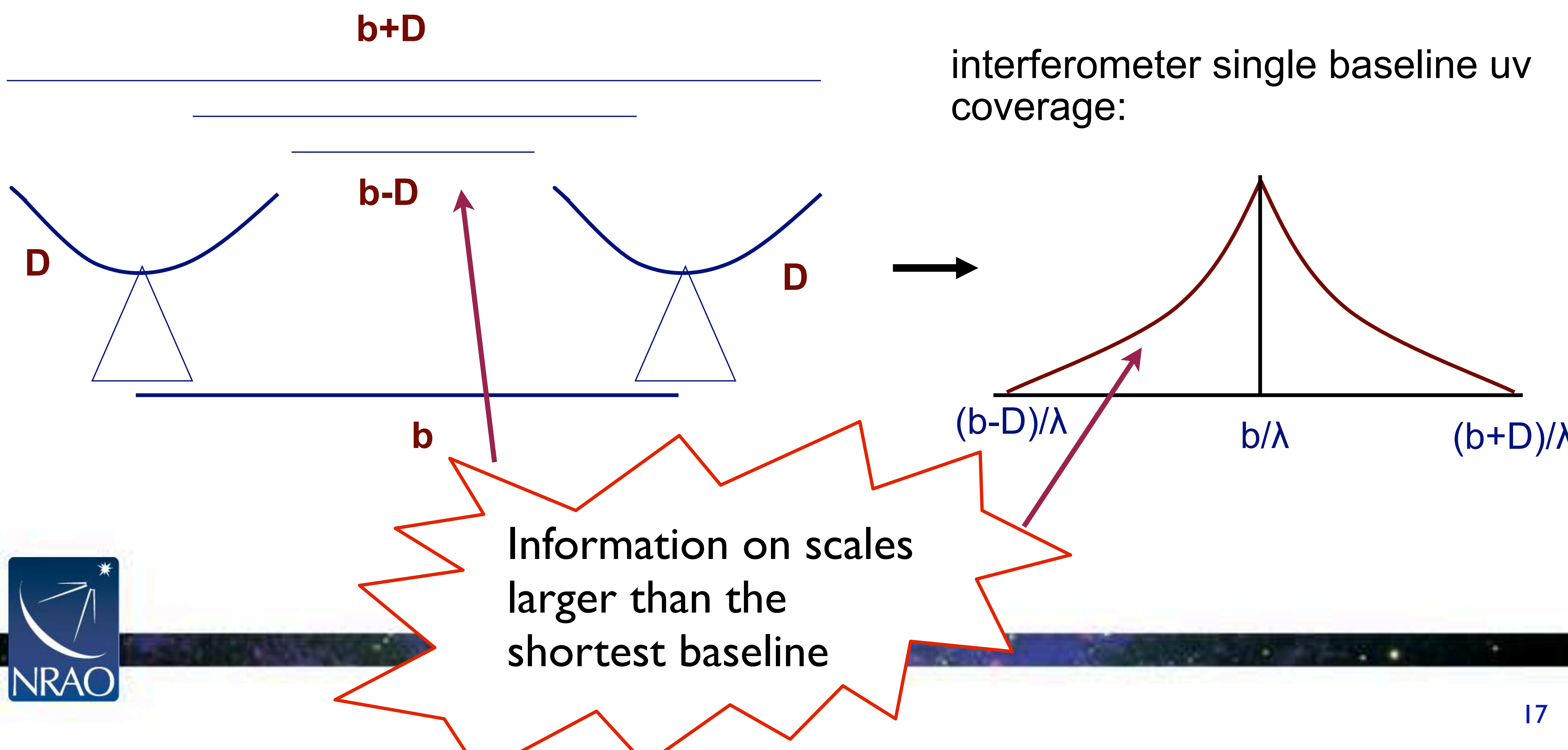
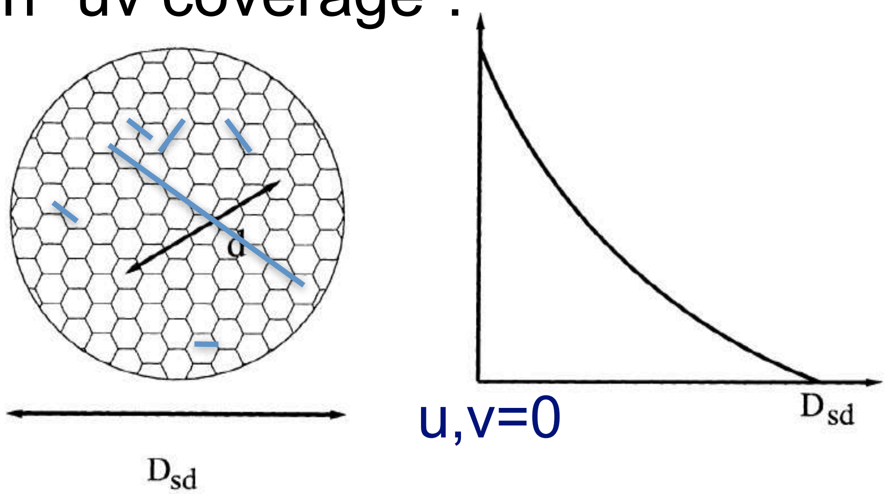


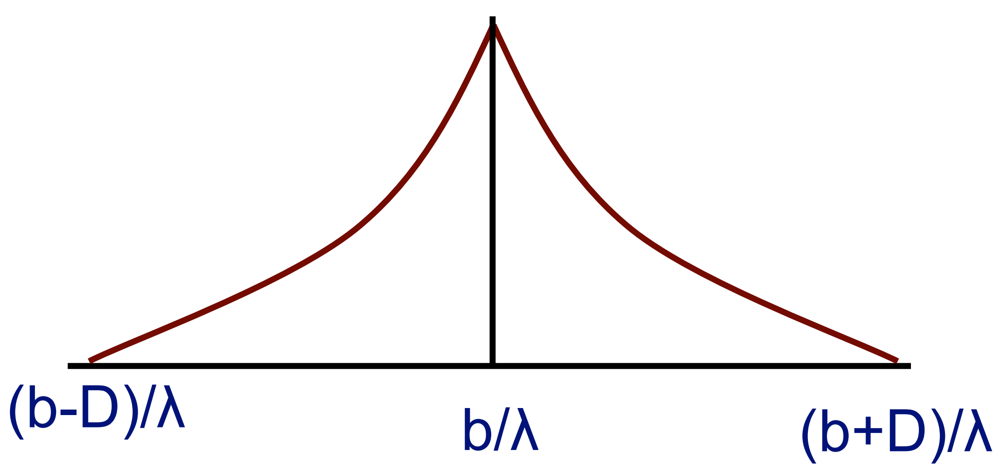
Theory of Mosaicking: Ekers & Rots Theorem

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:



Theory of Mosaicking: Ekers & Rots Theorem

"An interferometer measures $\lambda/(b\text{–}D) < \theta < \lambda/(b+D)$"

Motivation/Derivation:

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

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

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

Theory of Mosaicking: Ekers & Rots Theorem

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&= [E(u,v) \otimes E(u,v)] \otimes FT[I(\ell,m)]
\end{aligned}
$$

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

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

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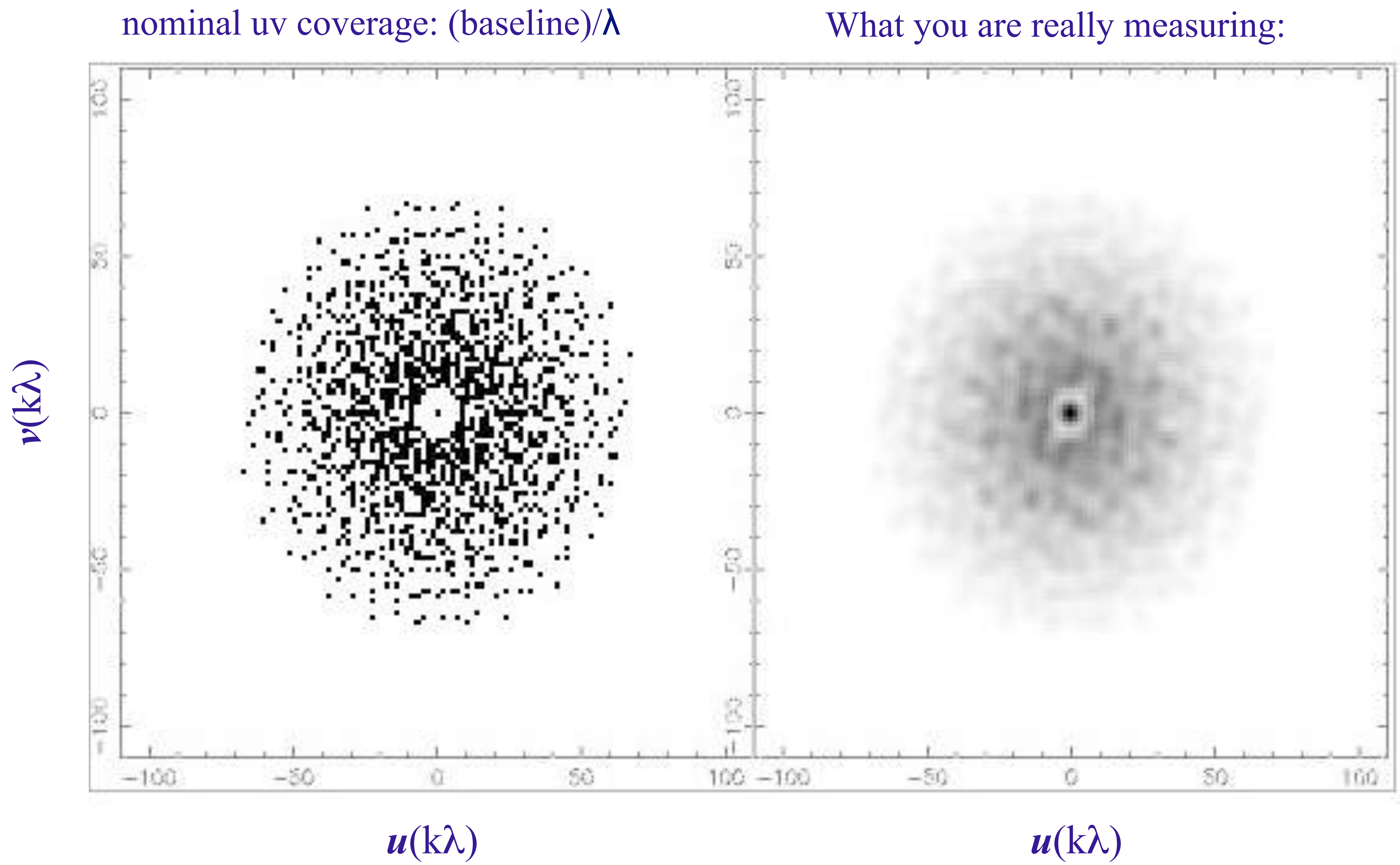
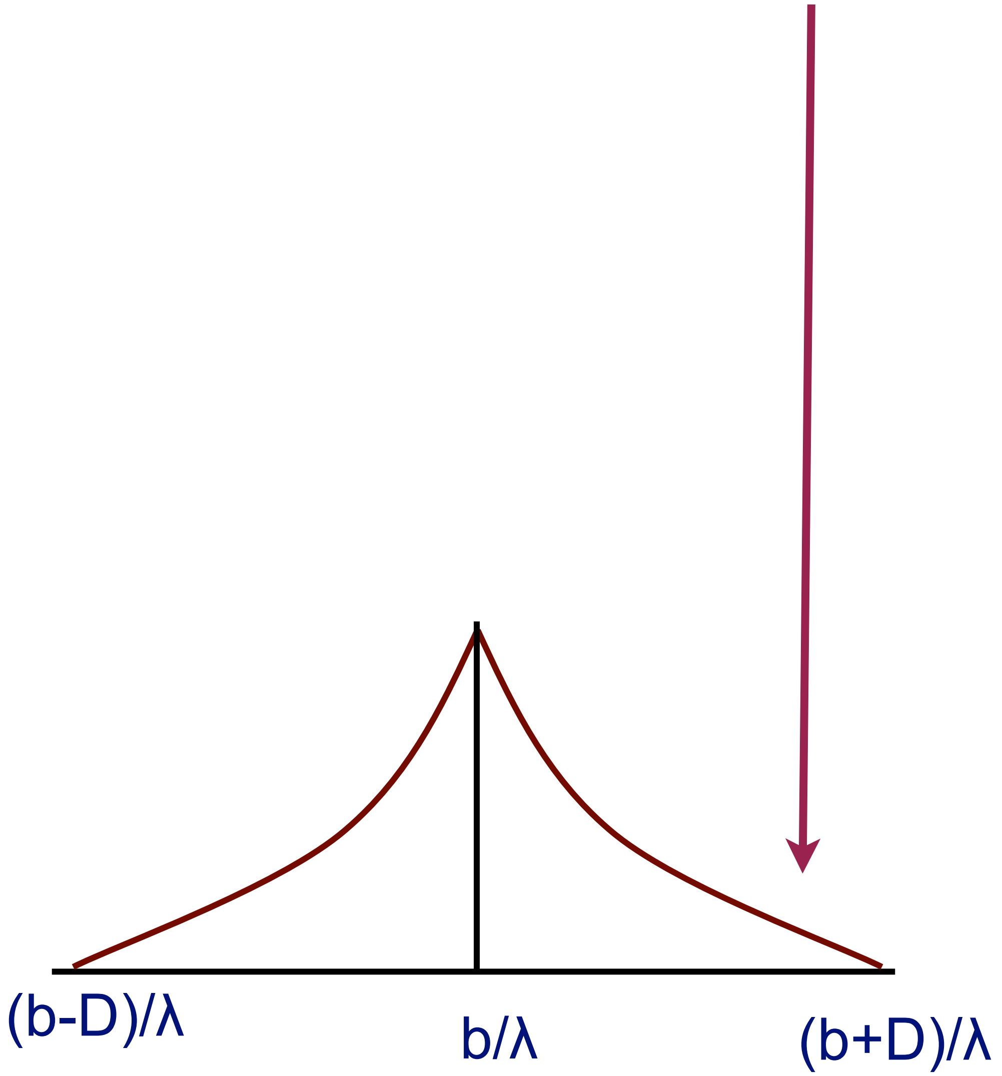


Interferometer + Single Dish

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)

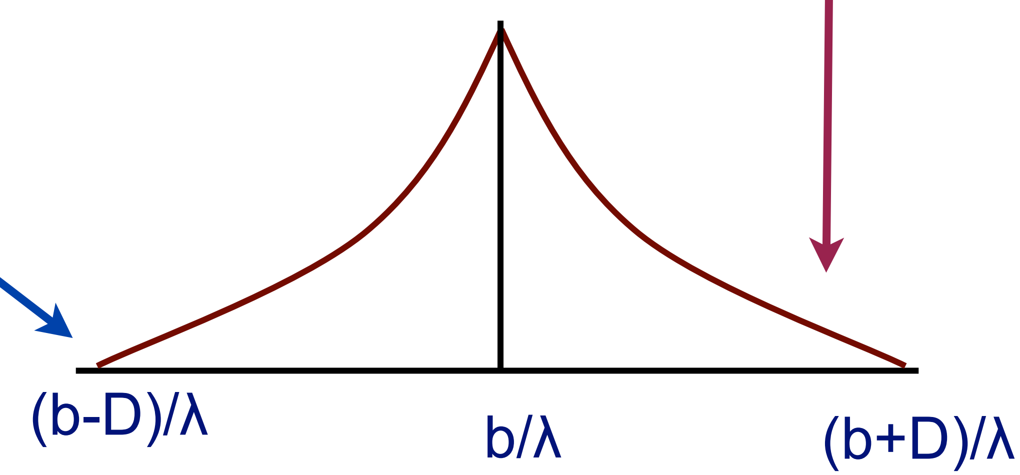


The problem:

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

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

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



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

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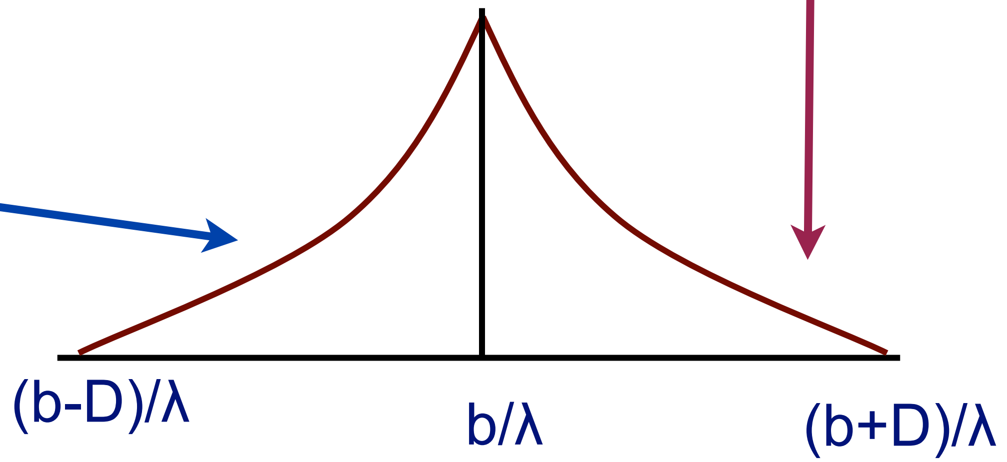
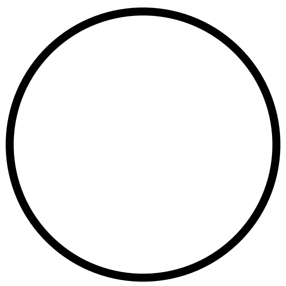
Caveat: *signals away from b are attenuated so not measured as well.*

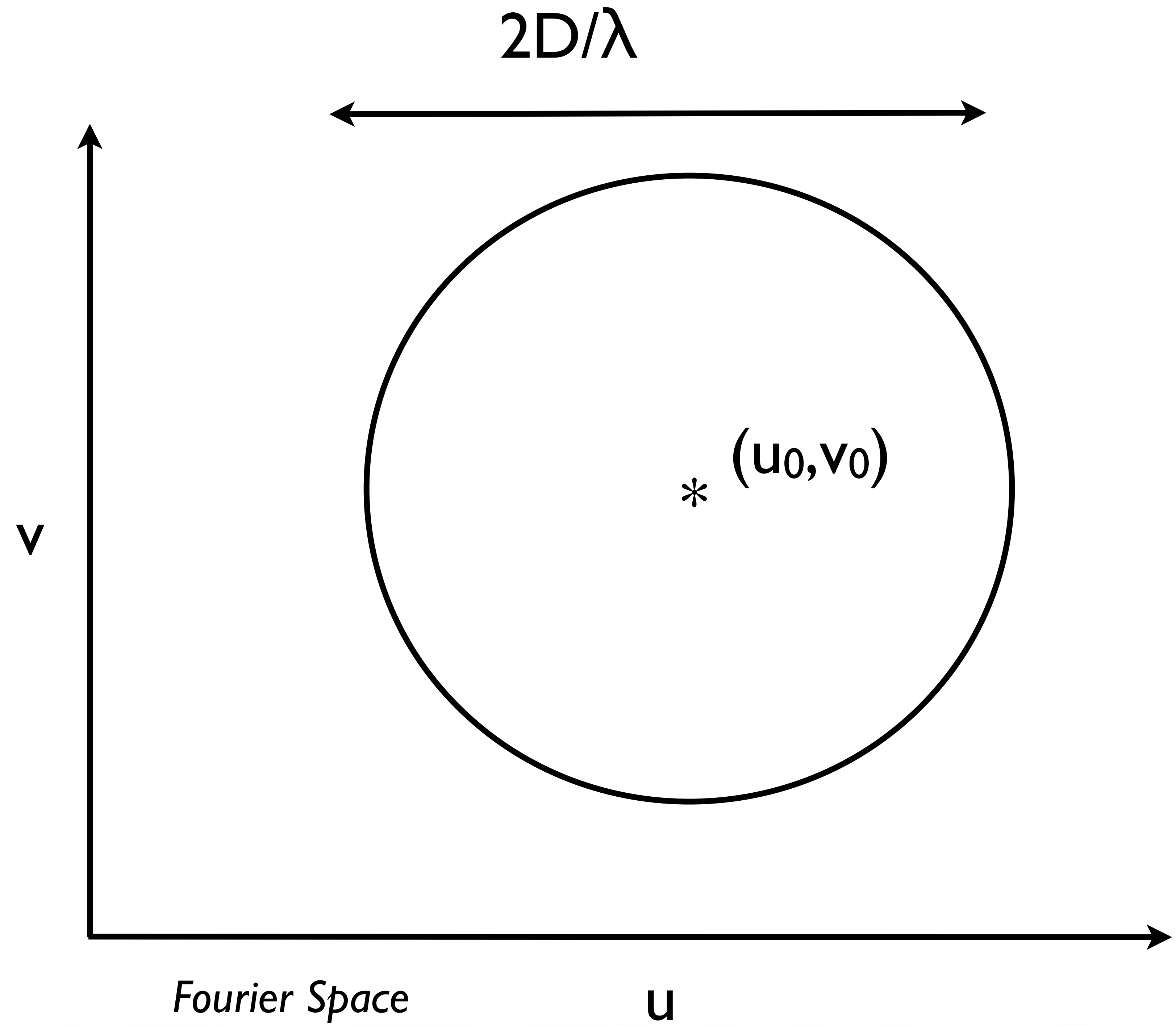




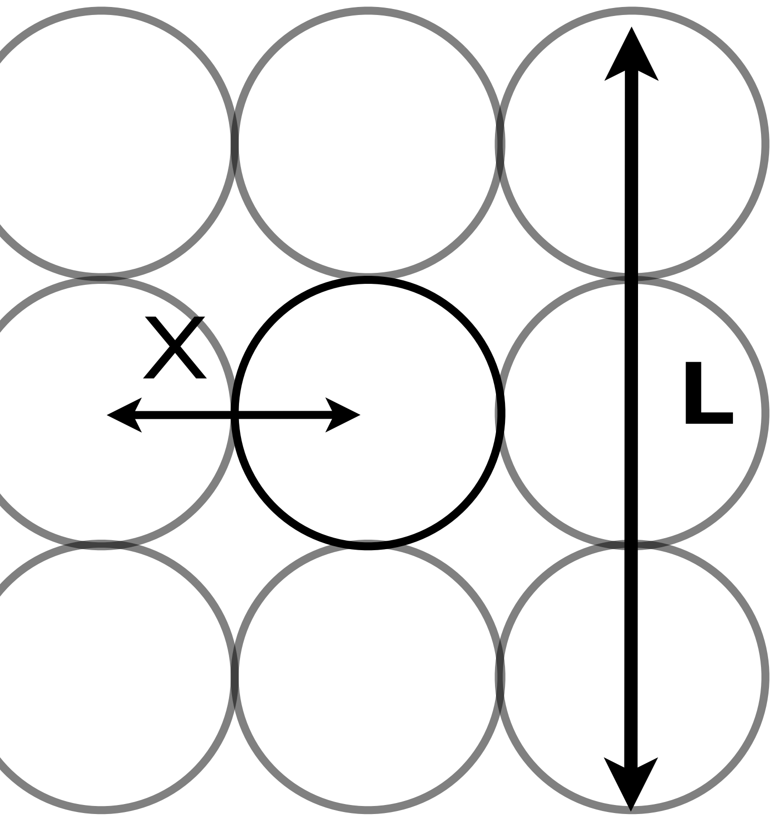
antenna primary beam

Real Space

One Pointing of the interferometer



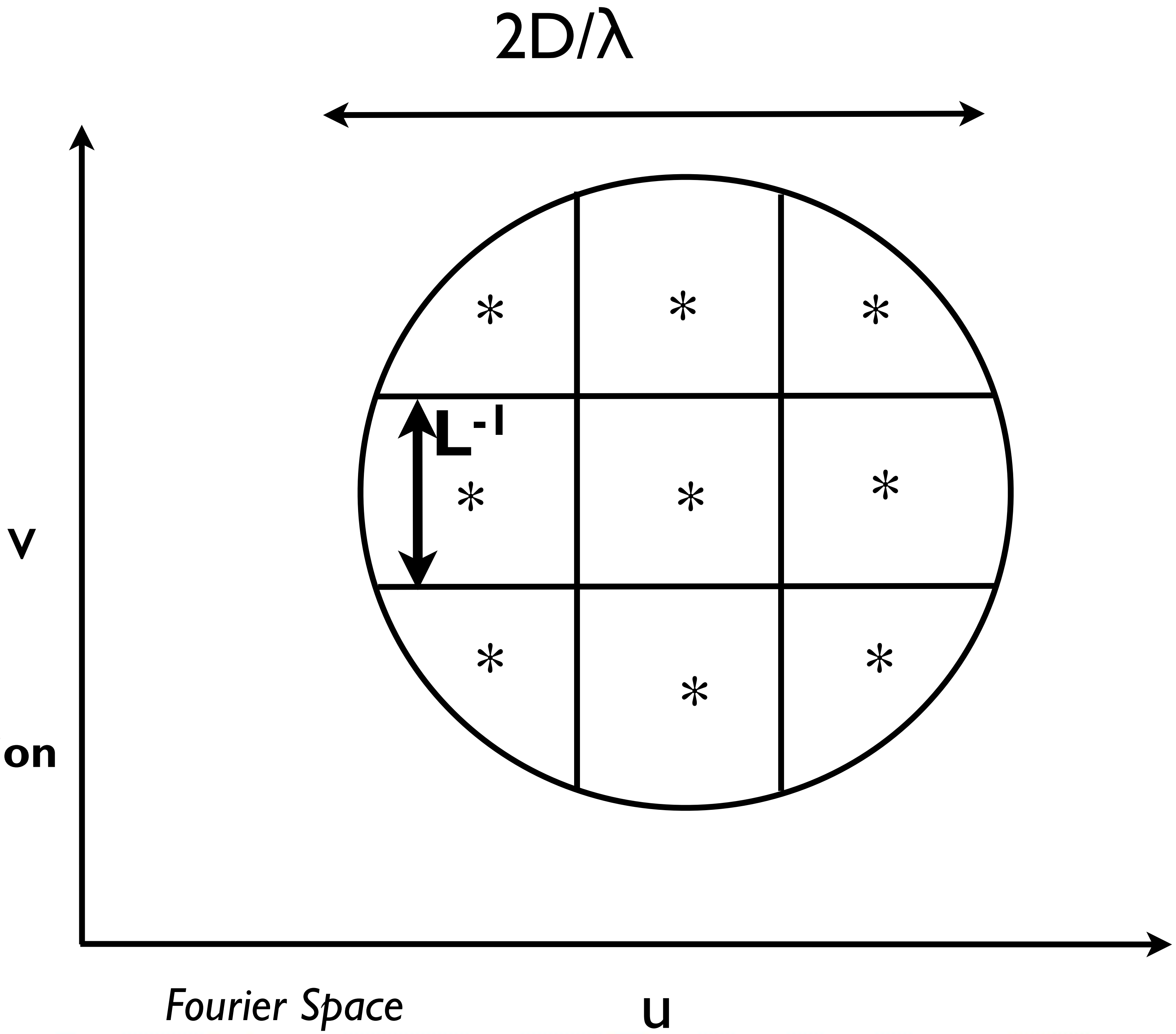
Fourier Space



Real Space

3x3 Pointings of the interferometer

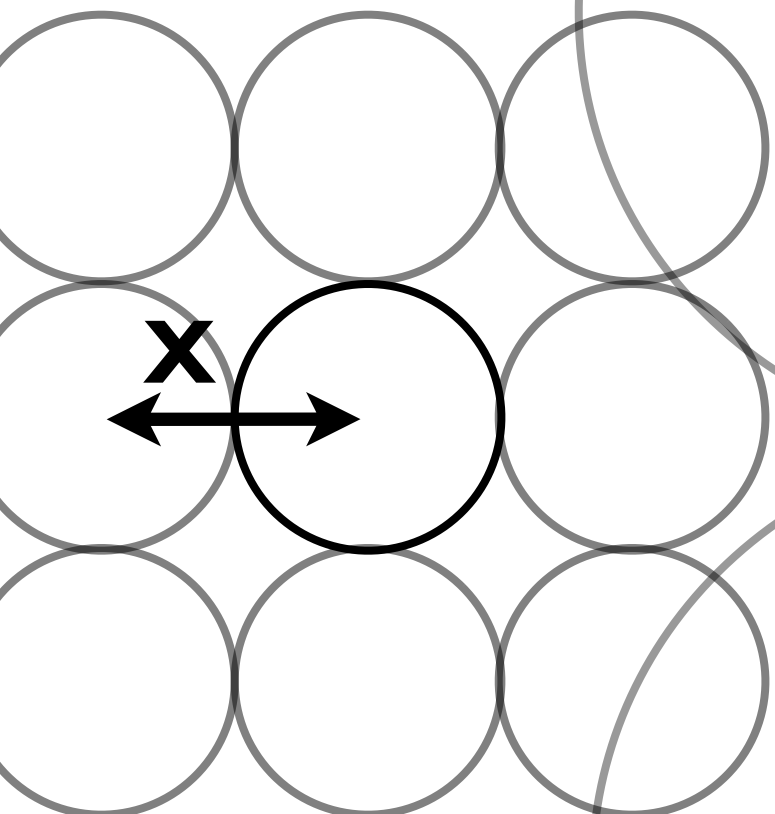
N PB Areas = Nx more resolution in Fourier Space



Fourier Space

ALIASES

$X <= \lambda/2D$



Real Space

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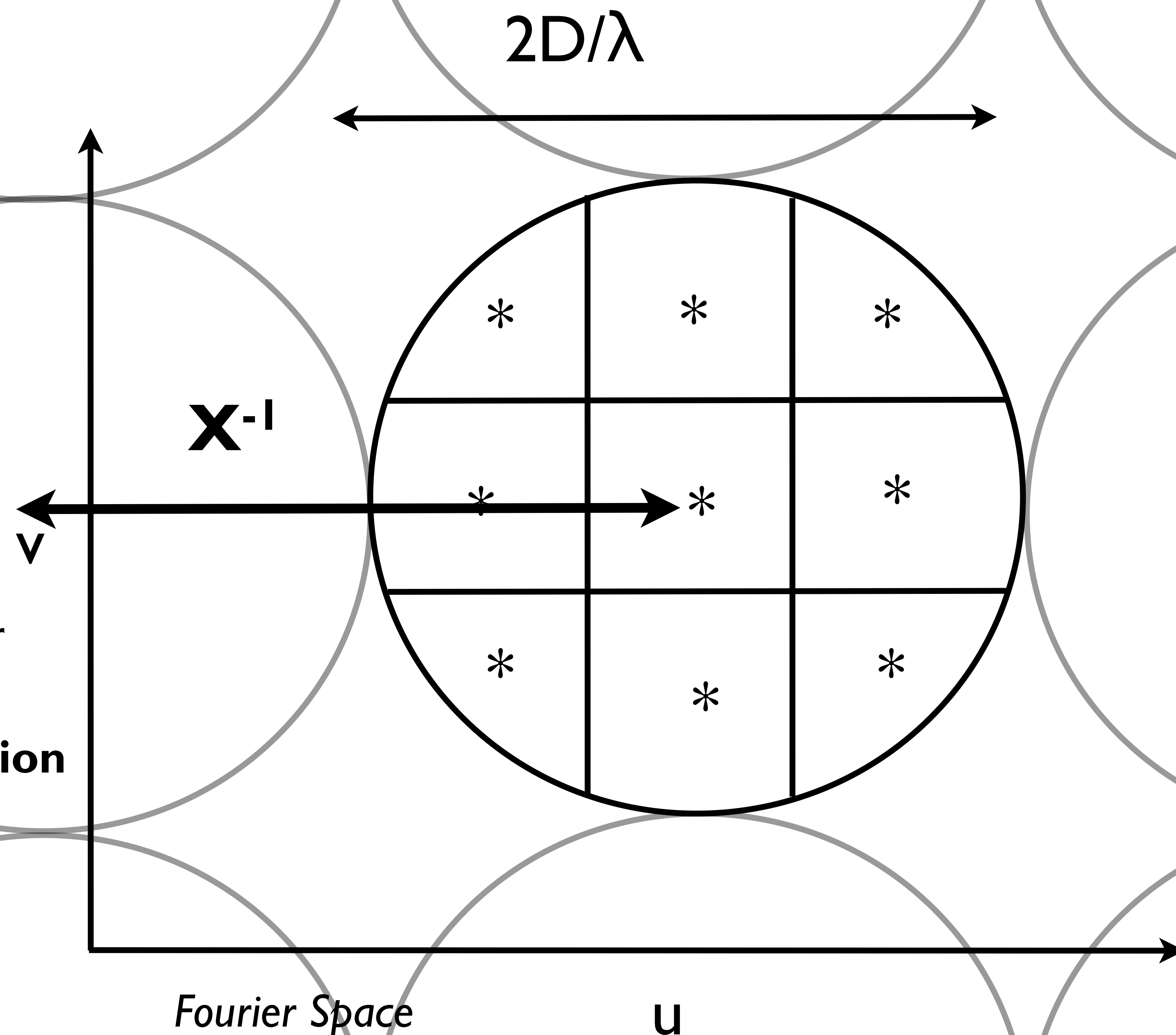


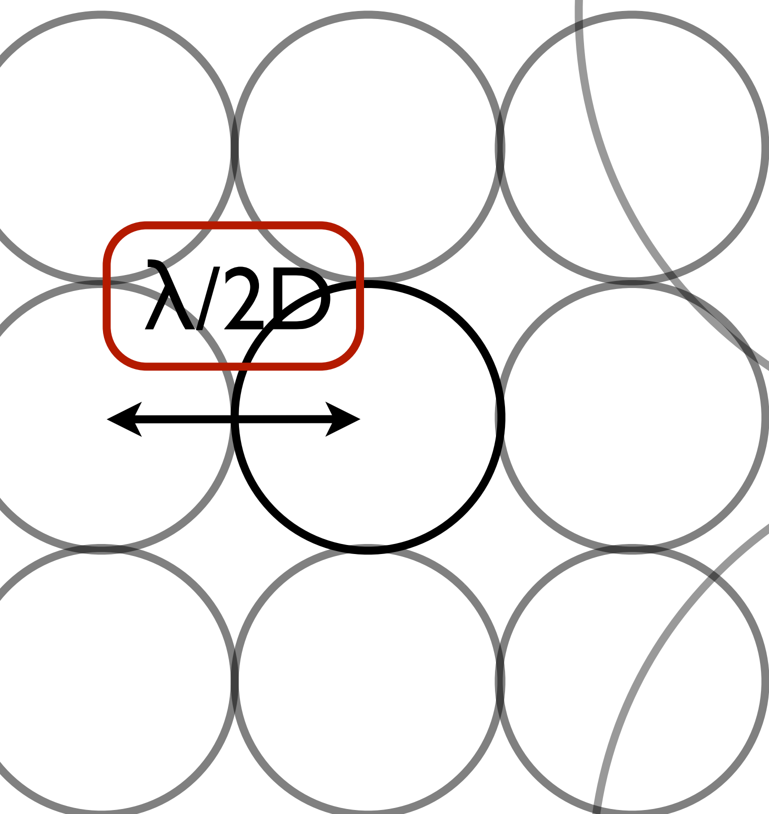
Fourier Space

*Pointing centers should be spaced by $\lambda_{shortest}/2D$ (not necessarily beam FWHM)

*For round dishes: aperture plane more densely tiled without overlap by hexagonal mosaic

real space slightly more sparsely sampled

*Good sampling also provides closer to uniform noise in the image.



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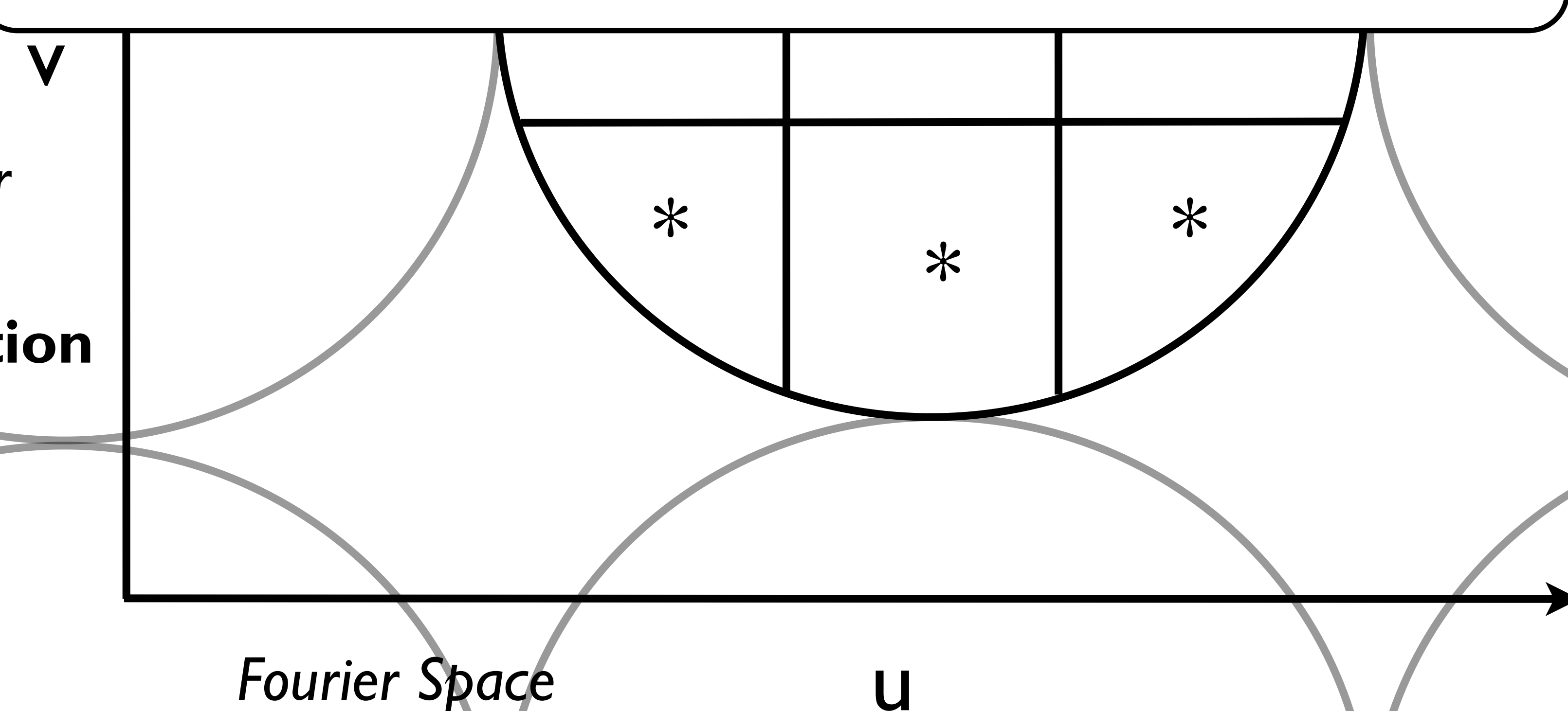

Fourier Space

Stitching the Interferometer Maps together: Mosaic Imaging Algorithms in Practice

Widely-used methods for mosaic image reconstruction:

- **Linear combination**

  Make individual ptg dirty maps → deconvolve individually → combine deconv'd maps

- **Joint deconvolution**

  Make individual ptg dirty maps → combine into one dirty map → deconvolve together (w/spatially varying PSF)

- **Widefield Imaging by regridding of all visibilities before FFT into a single map**

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

Stitching the Interferometer Maps together: Mosaic Imaging Algorithms in Practice

Widely-used methods for mosaic image reconstruction:

- **Linear combination**

  Make individual ptg dirty maps → deconvolve individually → combine deconv'd maps

  Advantages:
  - Careful imaging of each pointing separately
  - Depends less on the exact knowledge of primary beam shape.
  - Good when the field is crowded or confused (e.g., low frequency)

  Disadvantages:
  -Deconvolution algorithm doesn't have access to Ekers-Rots information!
  - " " has lower SNR data in overlap regions

These are significant shortcomings for a nonlinear algorithm

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Stitching the Interferometer Maps together: Mosaic Imaging Algorithms in Practice

Widely-used methods for mosaic image reconstruction:

- **Joint deconvolution / Wide field Imaging**

  Make individual ptg dirty maps → combine into one dirty map → deconvolve together

  [or co-grid all UV data]

Advantages:

-Deconvolution Algorithm explicitly makes use of Ekers-Rots information (same "visibility" measured at different sky pointings):

Improves Fourier resolution, LAS, and synthesized beam

Disadvantages:

-Requires a good PB model

Recommended unless special considerations guide you to another approach.

ftmachine='mosaic' in CASA clean() task.

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Interferometric Mosaicking Issues

- Pointings are in a time sequence:
  - Each pointing has a different uv-coverage
  - Atmospheric water vapor/Ionospheric variations from pointing to pointing
- Pointing is more critical than for non-mosaicked observation with an isolated source in the beam center
- Know your primary beam!

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Deconvolution

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

Deconvolution in this case is tricky.

Deconvolution

Mosaicking is typically done for ***extended*** sources.
Deconvolution in this case is tricky.

CLEAN: Preferably Cotton-Schwab, with small gain.

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.

- may require good uv coverage, a judiciously chosen clean box, & careful monitoring (interactive): beware of clean bias
- may take a long time for a spectral line cube.
- **Do not do this** if you are going to self-cal using the CLEAN model!

Deconvolution

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

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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Deconvolution

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

Deconvolution in this case is tricky.

Multi-Scale CLEAN

- Generalize CLEAN to allow components of multiple sizes

- Obviously better suited to extended emission!
- Several parameters need to be chosen for it to work well (list of component scales, small-scale bias)
- Fully supported in CASA clean() task

Deconvolution

"Entropy" $\mathcal{H}$ maximized by $I_k=M_k$

Mosaicking is typically done for ***extended*** sources.
Deconvolution in this case is tricky.

Maximum Entropy

- Vary pixel values I_K in deconvolved image to ***jointly***
  - Maximize match to a default image M_K

$$\mathcal{H} = -\sum_k \left[I_k \ln \left(\frac{I_k}{M_k\, e} \right) \right]$$

  - while maximizing the match of the FT of the model image to the visibility data (by minimizing Chi^2)
  - subject to $I_K>0$

$$\chi^2 = \sum_k \frac{|V(u_k, v_k) - V_{mod}(u_k, v_k)|^2}{\sigma_k^2}$$

- If M_K=const. this tends to maximize the "smoothness" of the image
  - ***A better choice: set M_K=(single dish image)***
- Does well with extended emission but not bright compact sources embedded in extended emission.
    - Available at toolkit (expert) level in CASA; as VM and VTESS in AIPS
    - See Cornwell, Braun & Briggs (1999) & references therein.

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Mosaicking in CASA

- Done in the imaging (deconvolution) stage; most of the fancy algorithms are implemented under the hood.
- Calibrate individual pointings as you would for a single pointing
- **CLEAN** supports joint deconvolution & widefield imaging (including w-term)
  – also offers multi-scale CLEANing
- *Image domain Linear Mosaicking & Maximum Entropy deconvolution are currently only available in the toolkit (lower-level, expert interface)*

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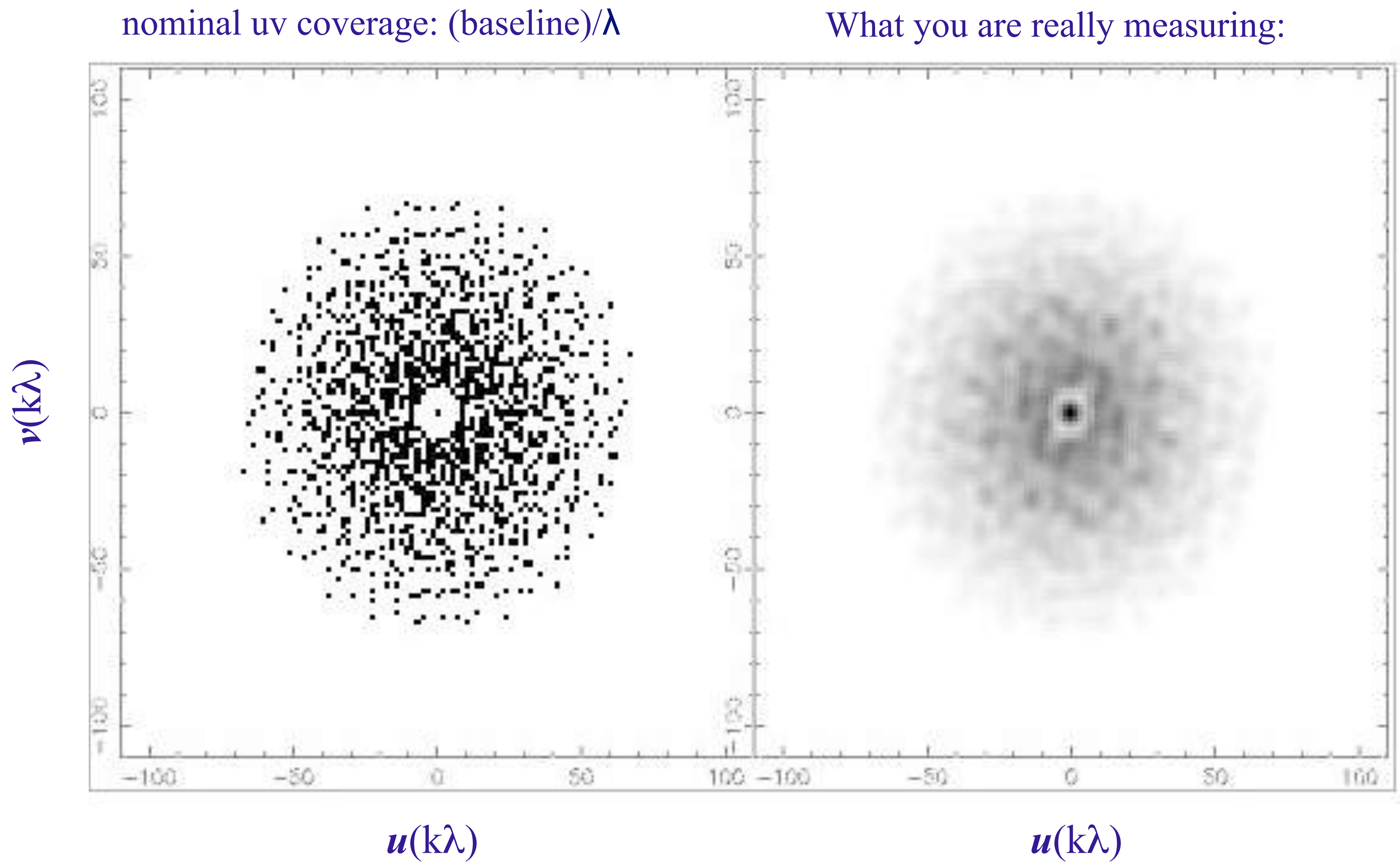
Effects of Missing Short & Zero Spacings

Interferometer + Single Dish

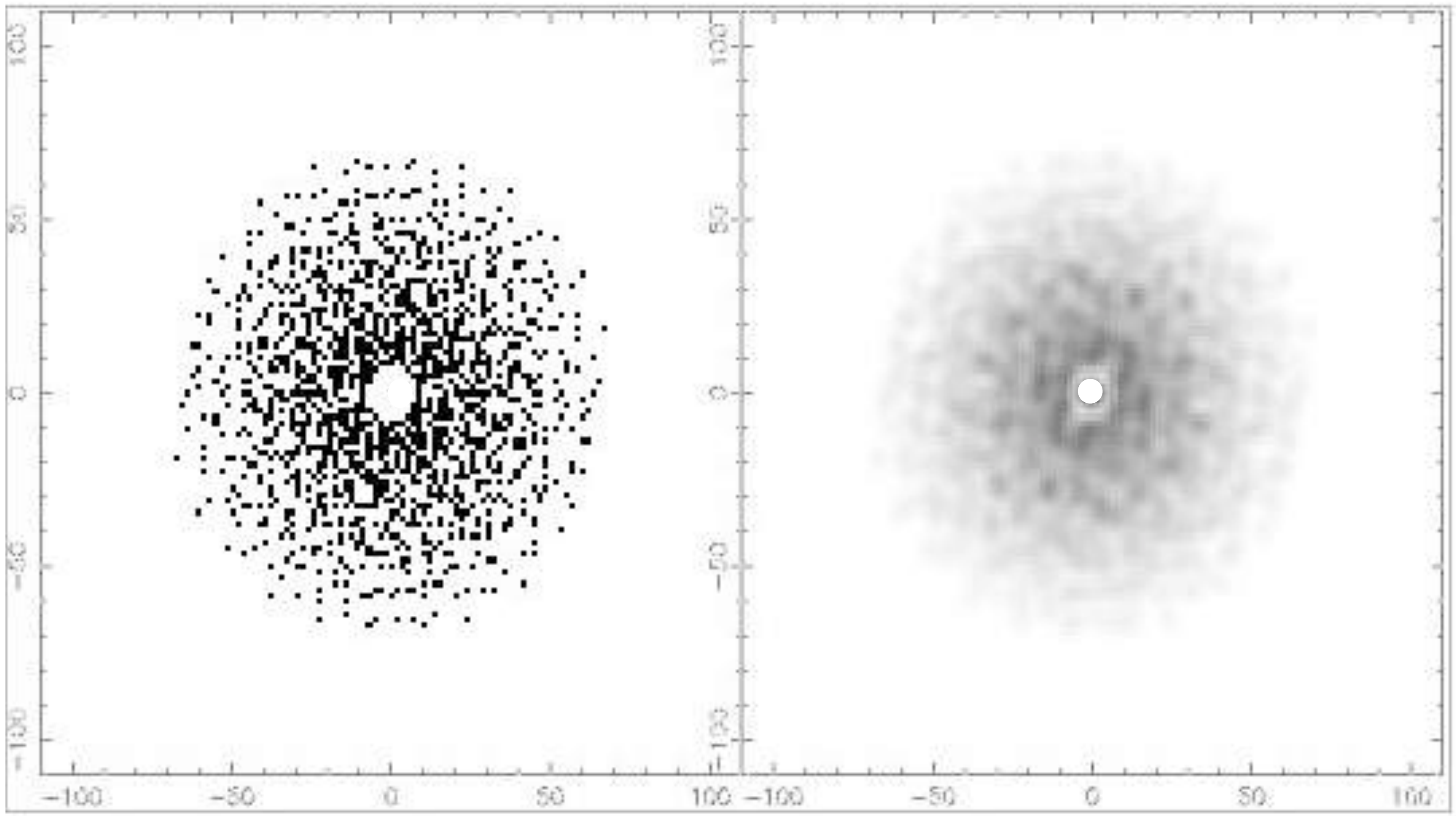


Effects of Missing Short & Zero Spacings

Interferometer + ~~Single Dish~~

nominal uv coverage: (baseline)/λ

What you are really measuring:



v(kλ)

u(kλ) u(kλ)

Effects of Missing Short & Zero Spacings

Interferometer + ~~Single Dish~~

nominal uv coverage: (baseline)/λ

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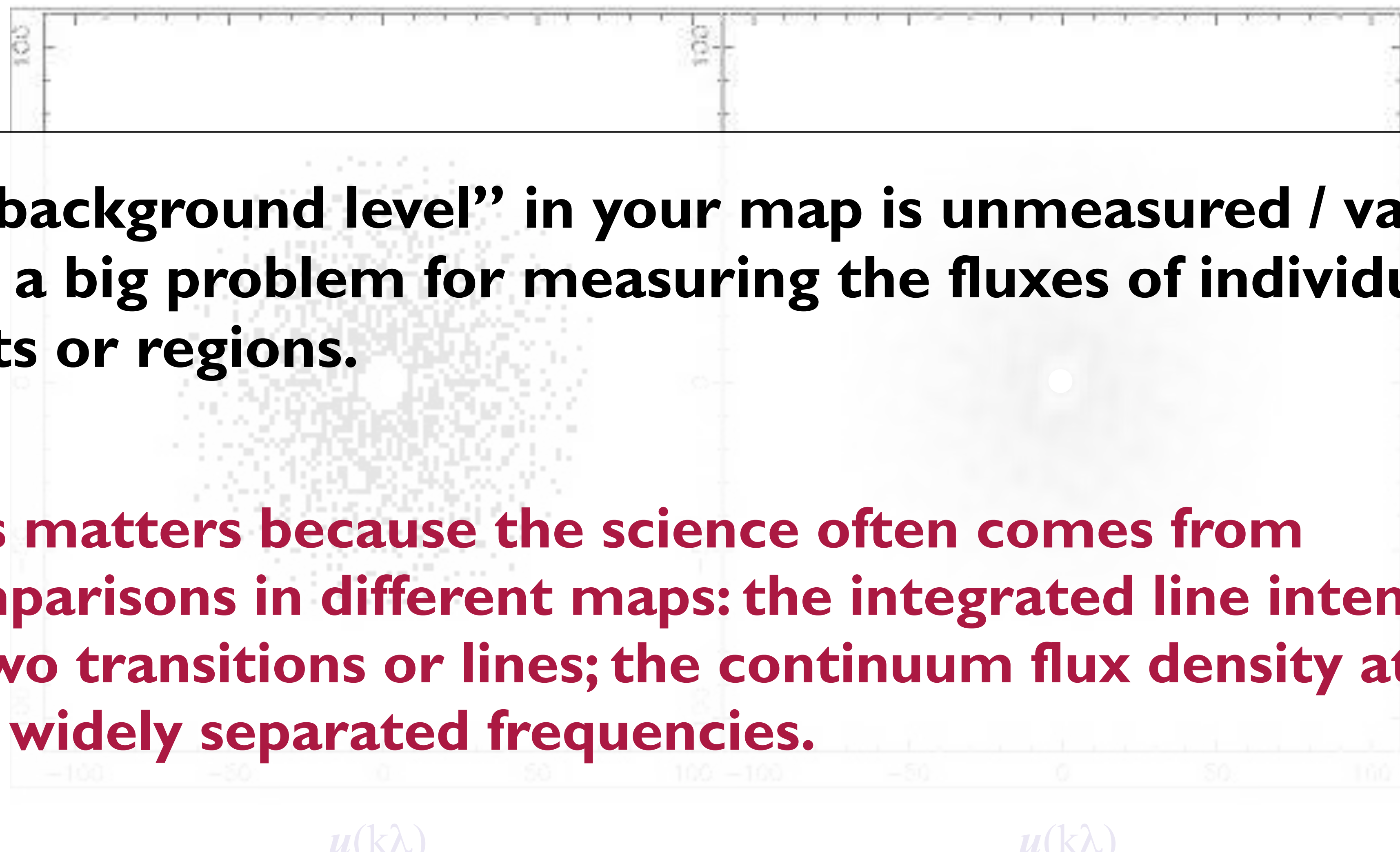


The "background level" in your map is unmeasured / variable: this is a big problem for measuring the fluxes of individual objects or regions.

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...)

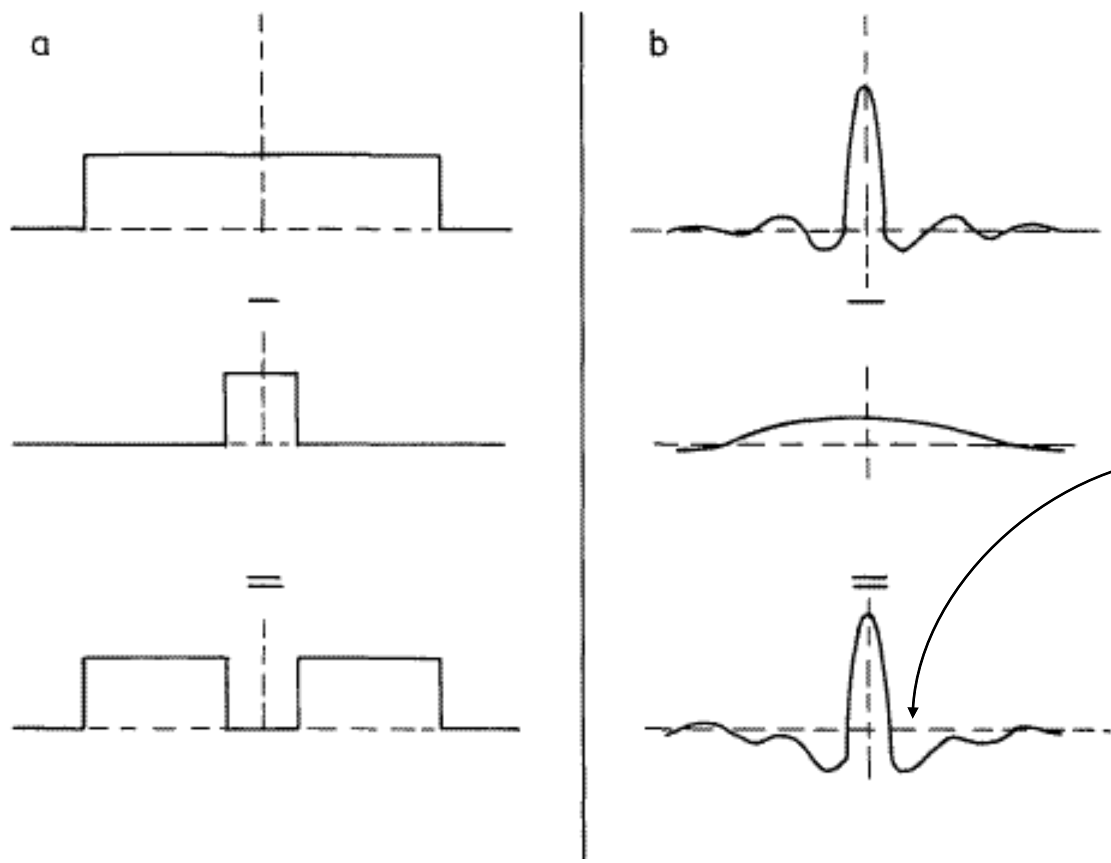
Effects of Missing Short & Zero Spacings

Interferometer + ~~Single Dish~~

- UV plane
- PSF

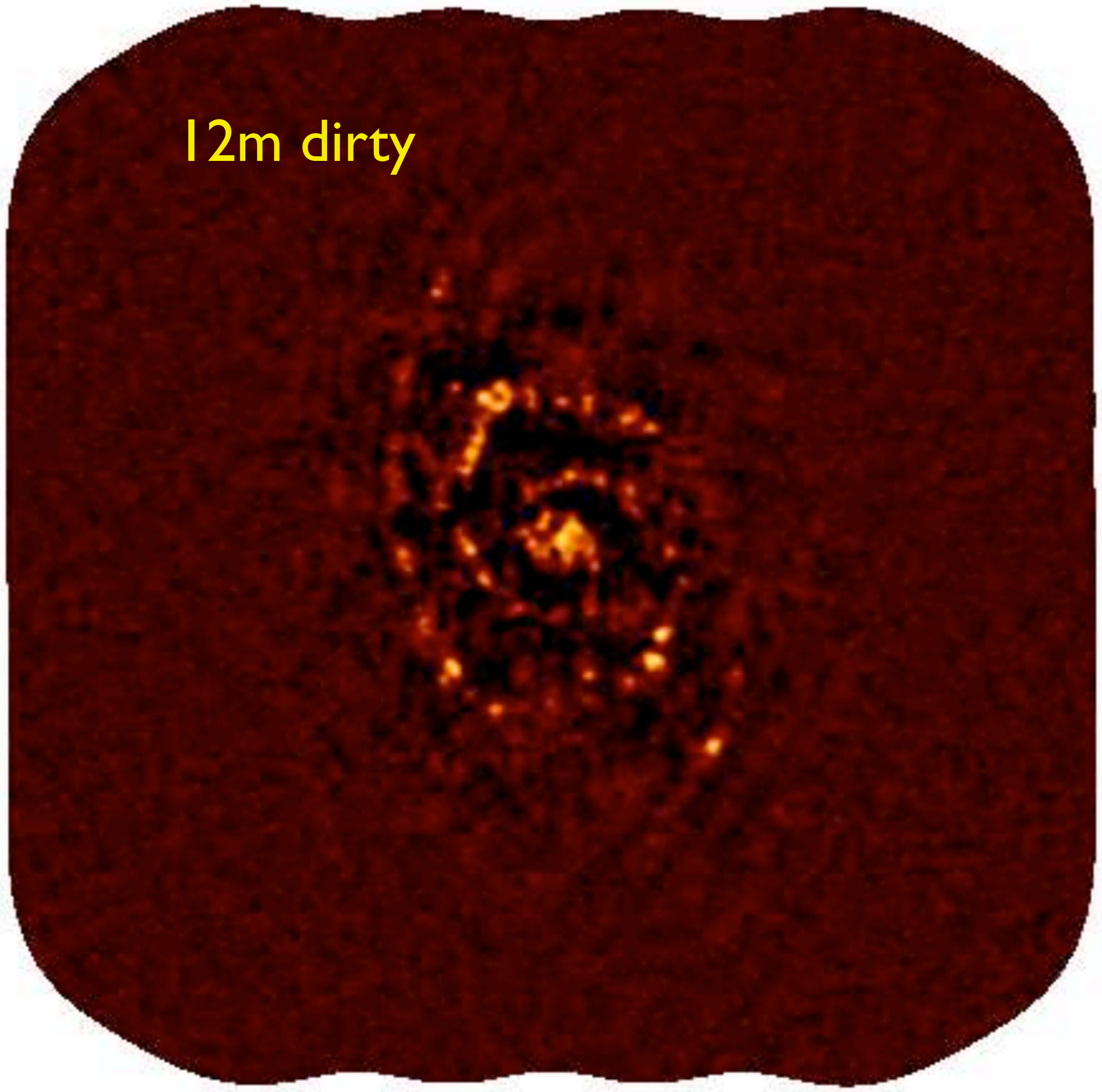
- Braun & Walterbos (1985)

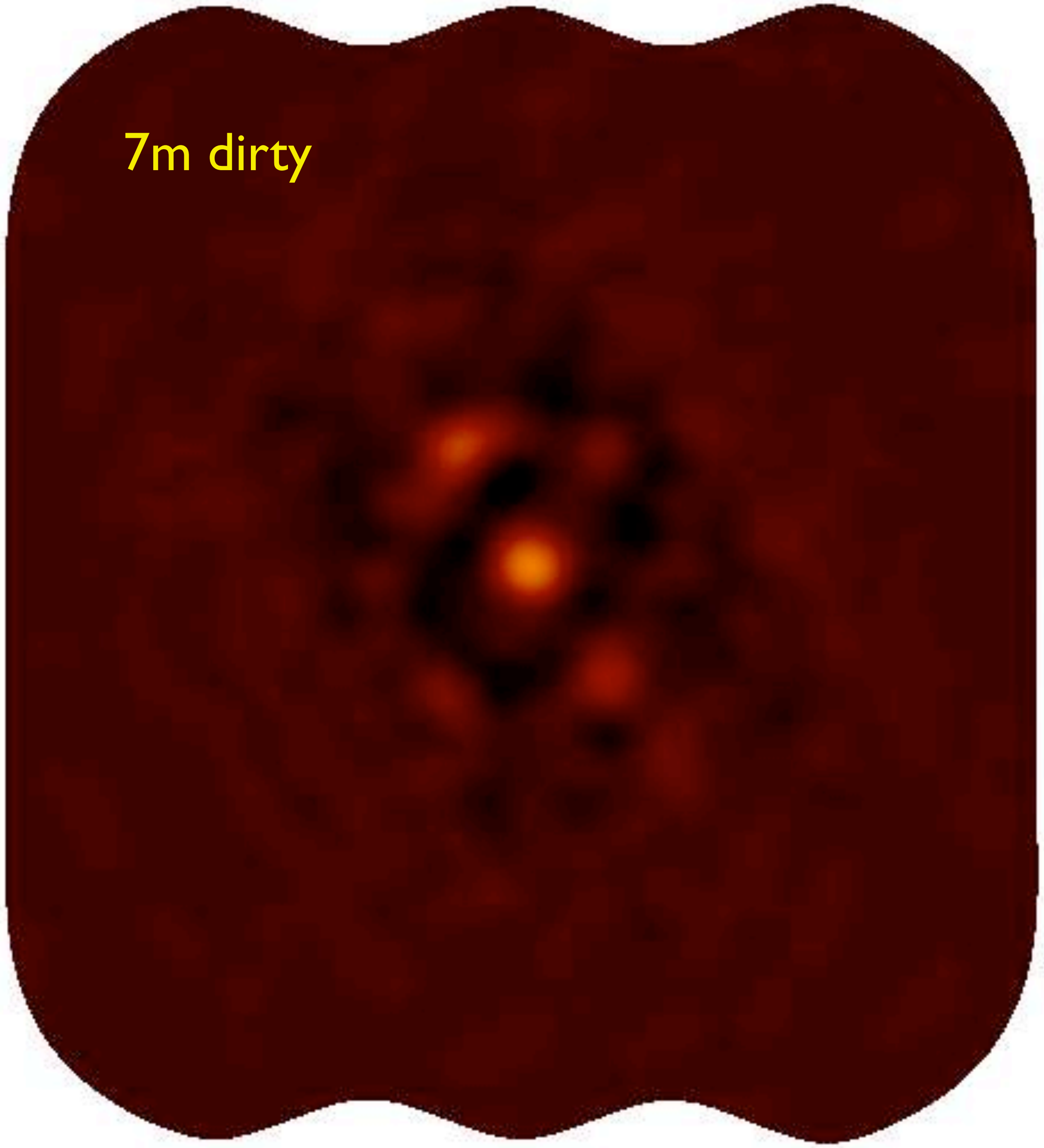
- ideal
- Central hole
- Typical interfero-meter



- Negative 'bowl'

Effects of Missing Short & Zero Spacings

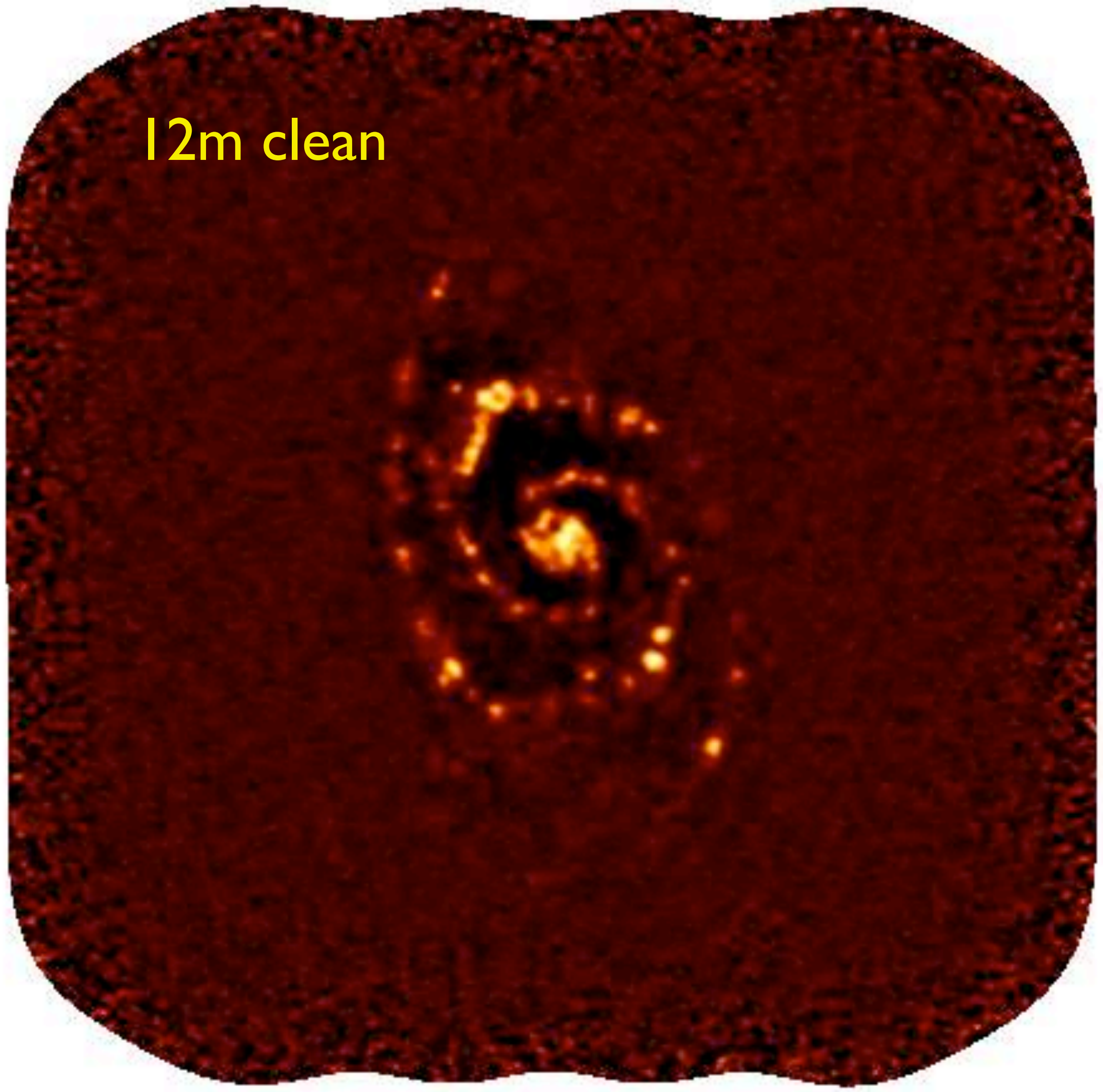


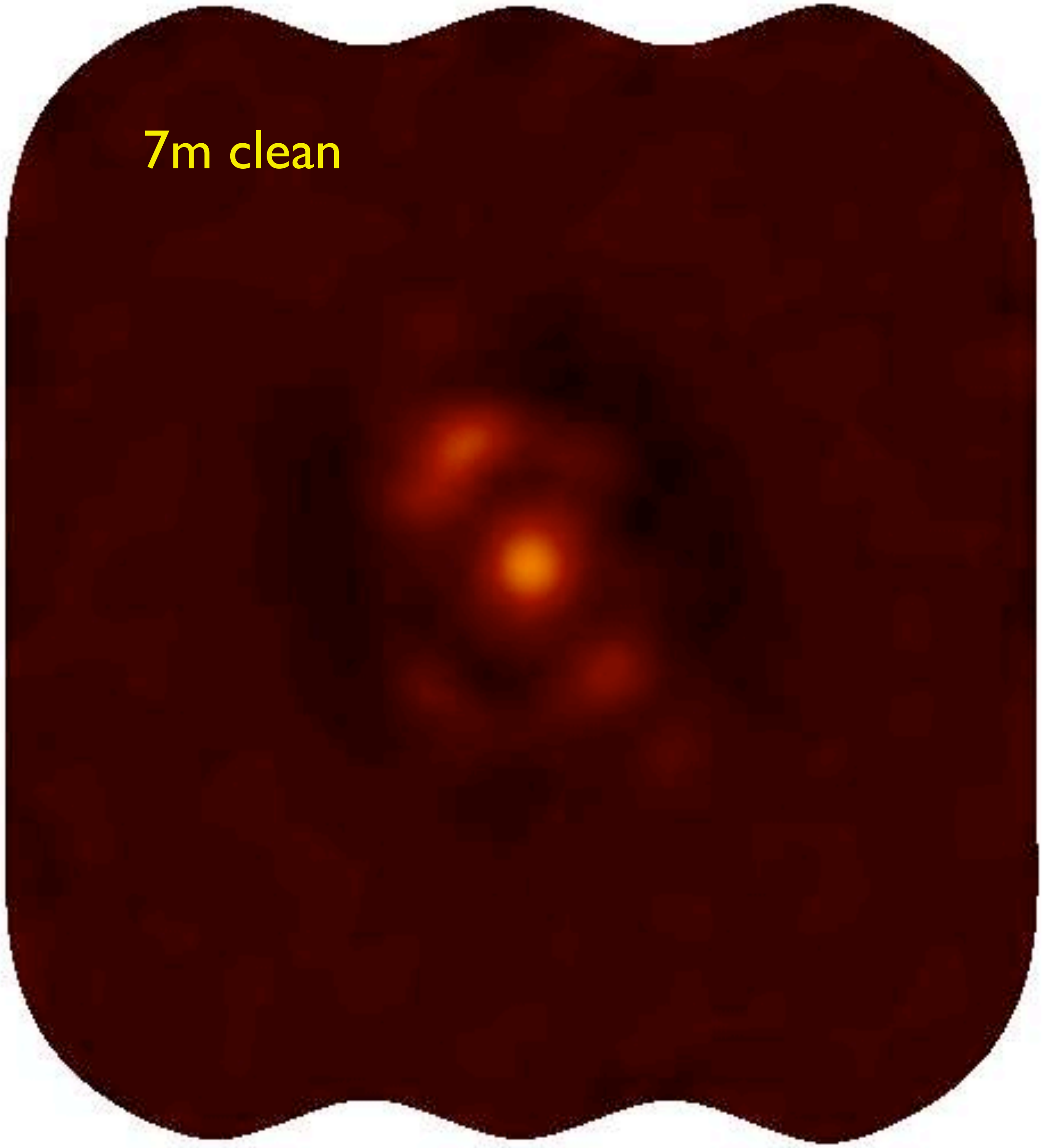


Based on the M51 ALMA simulation at

http://casaguides.nrao.edu

Effects of Missing Short & Zero Spacings





Based on the M51 ALMA simulation at

http://casaguides.nrao.edu

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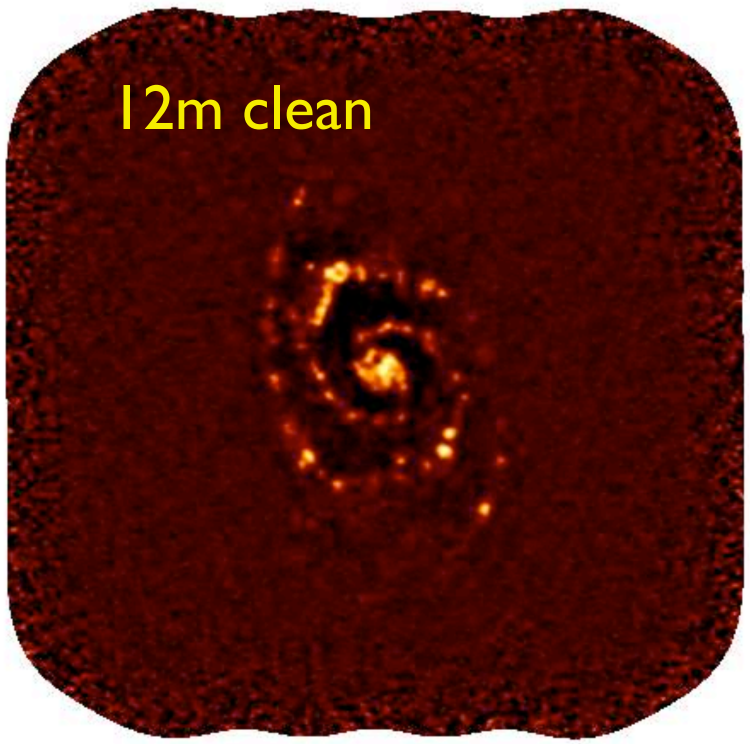
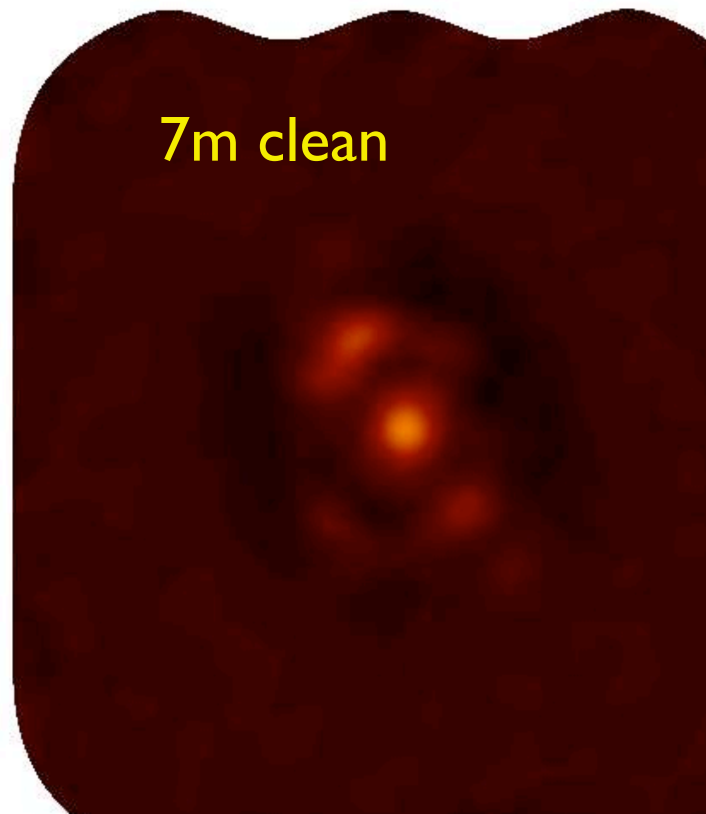
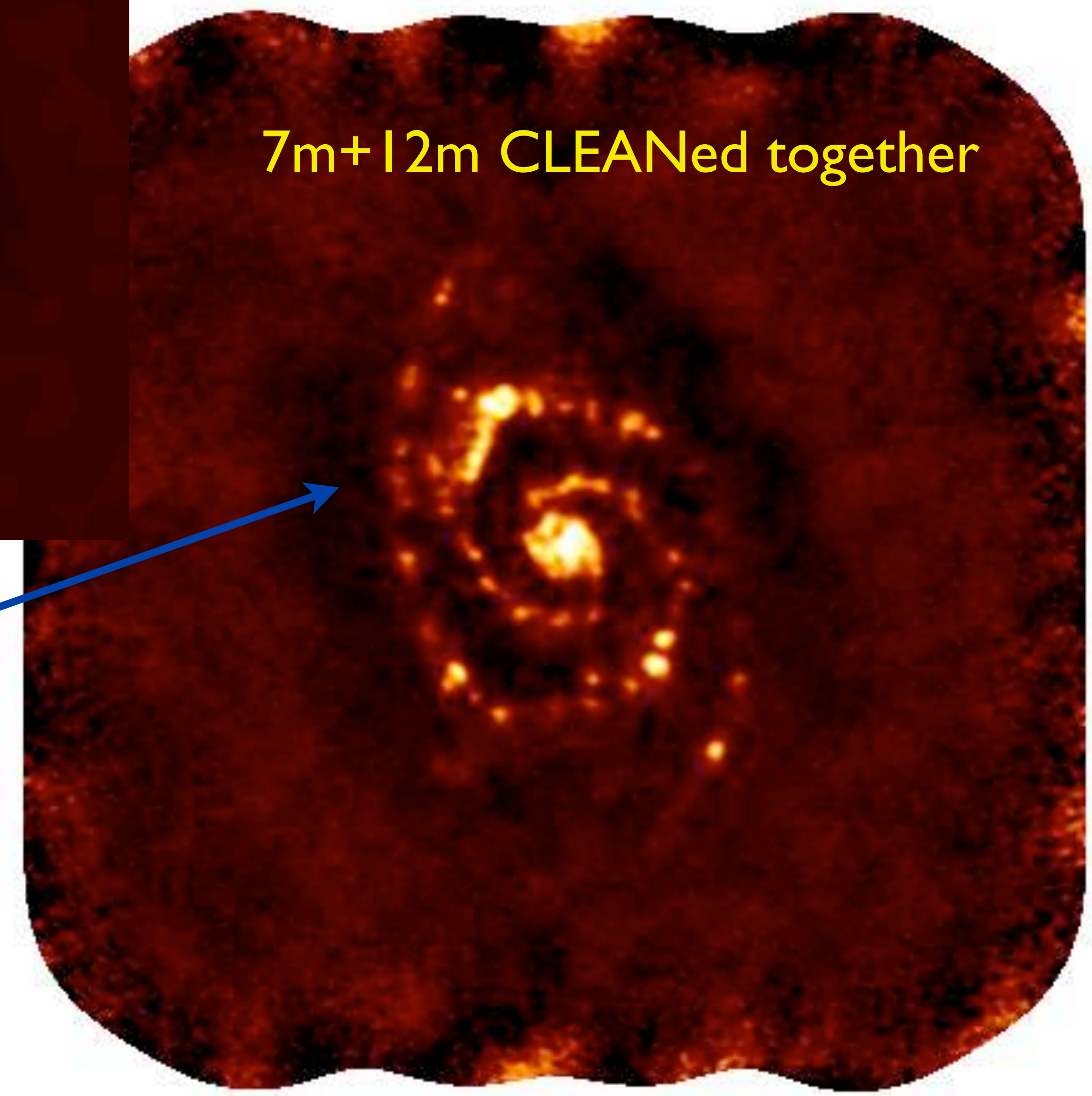
Effects of Missing Short & Zero Spacings

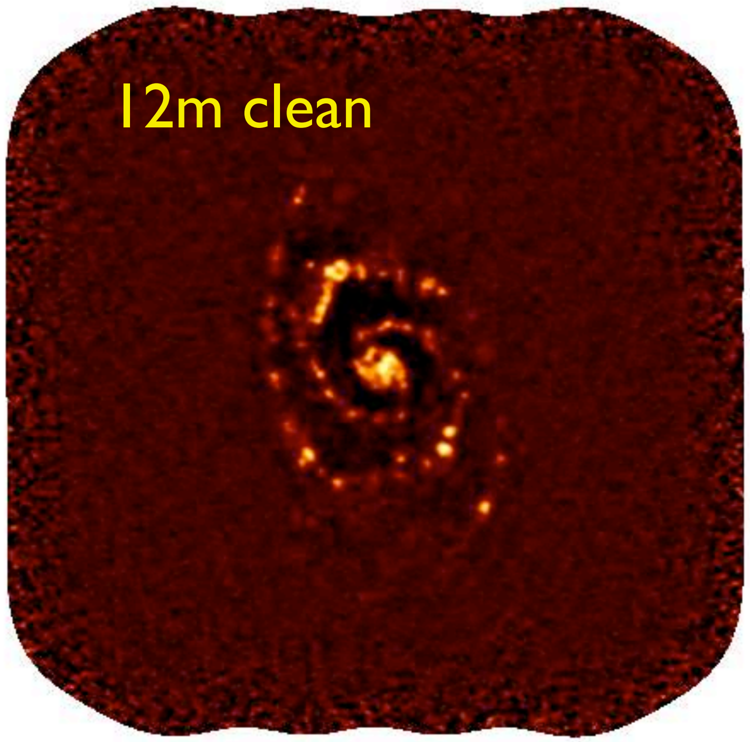


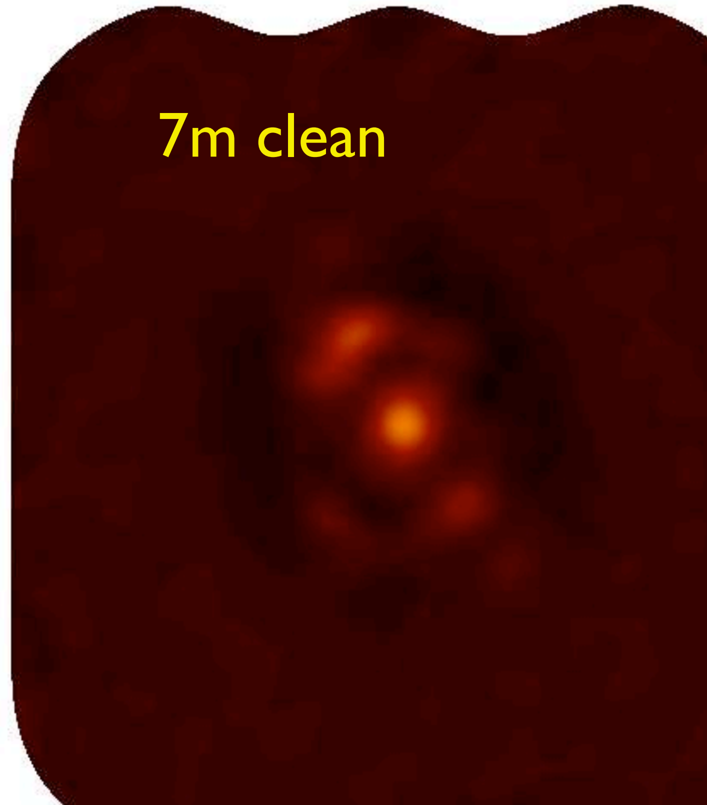




Combination of residual sidelobes (incomplete deconvolution) and poorly constrained short spacings.

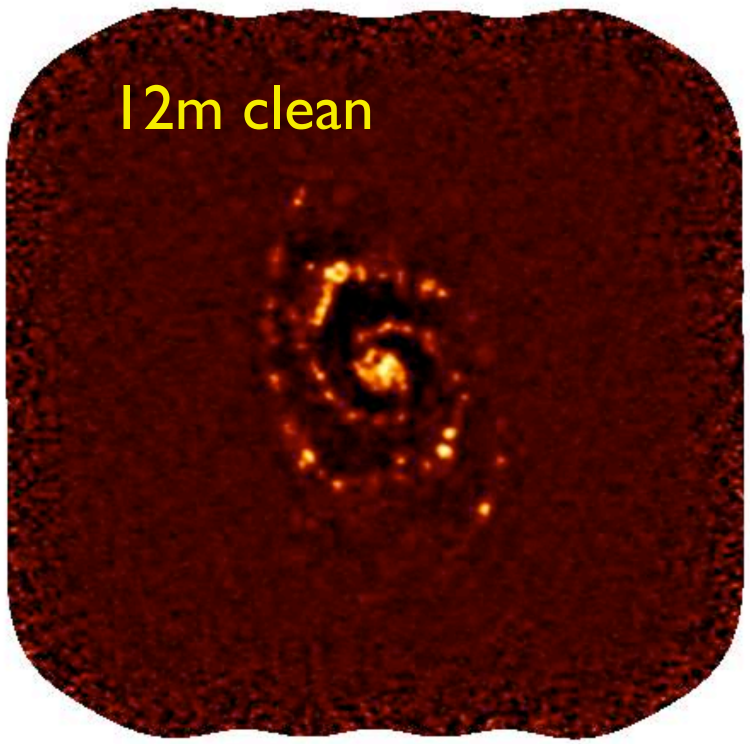
Effects of Missing Short & Zero Spacings

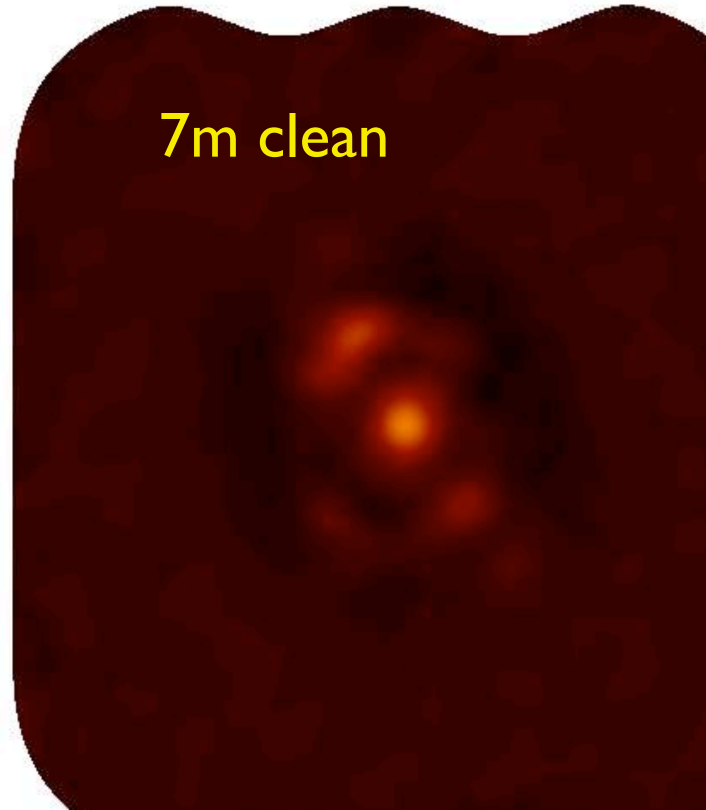




Measured total fluxes in any aperture will underestimate the true total fluxes.

Effects of Missing Short & Zero Spacings



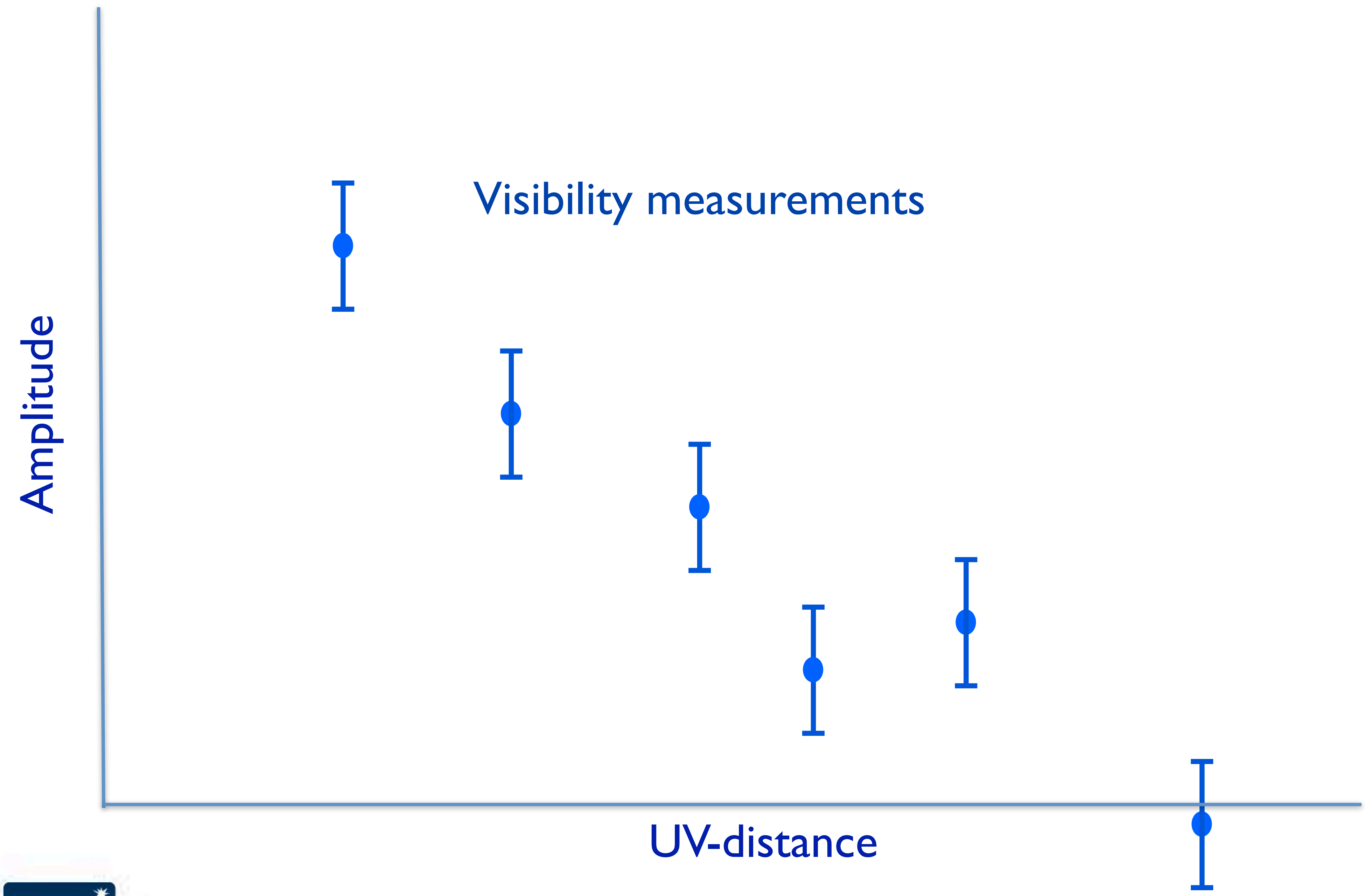


Measured total fluxes in any aperture will underestimate the true total fluxes.

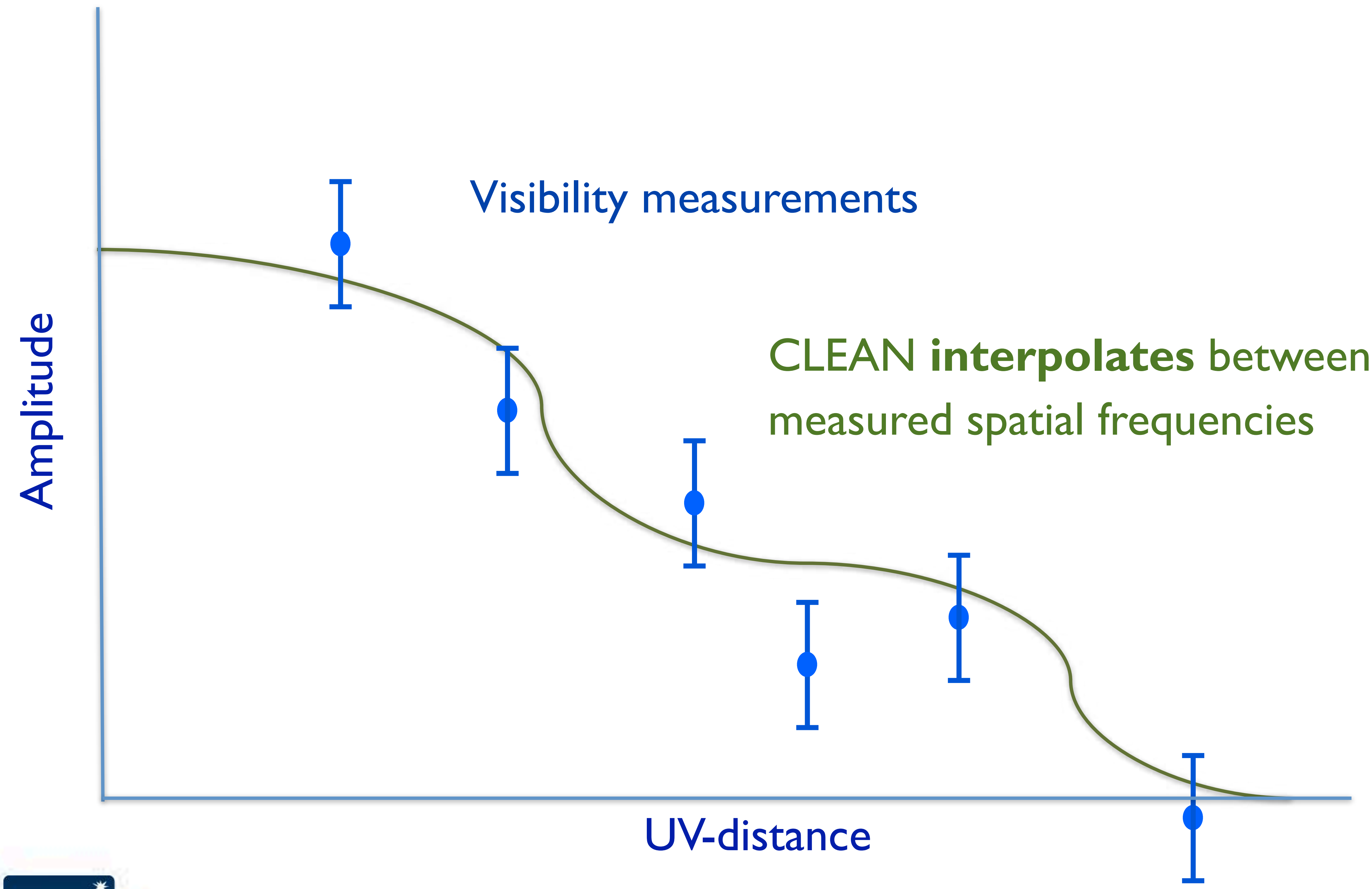
maybe MS clean could do better but the ***real problem is that the short spacings are poorly constrained***.

Add single dish data to the map!

Feathering

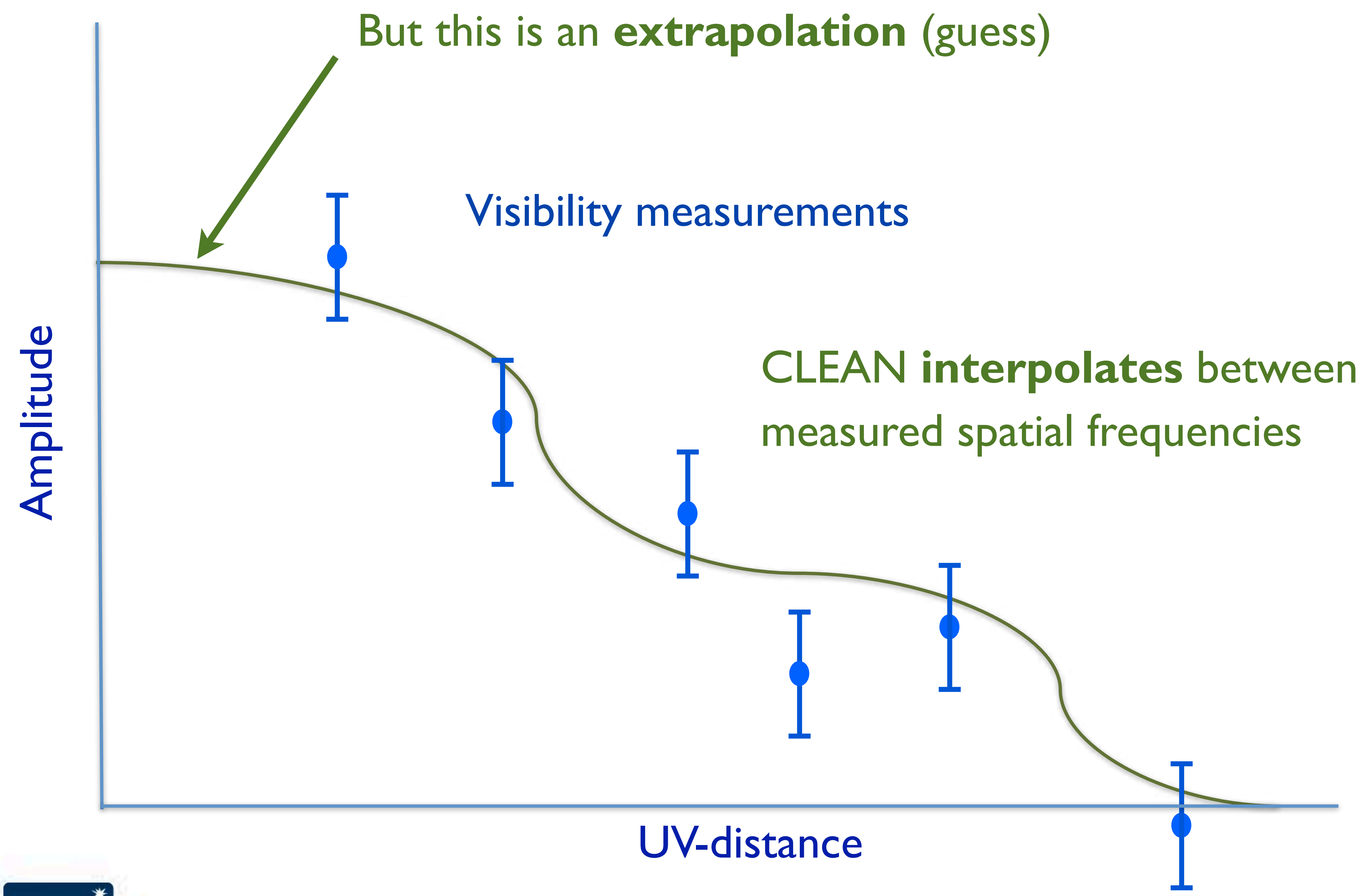


Feathering

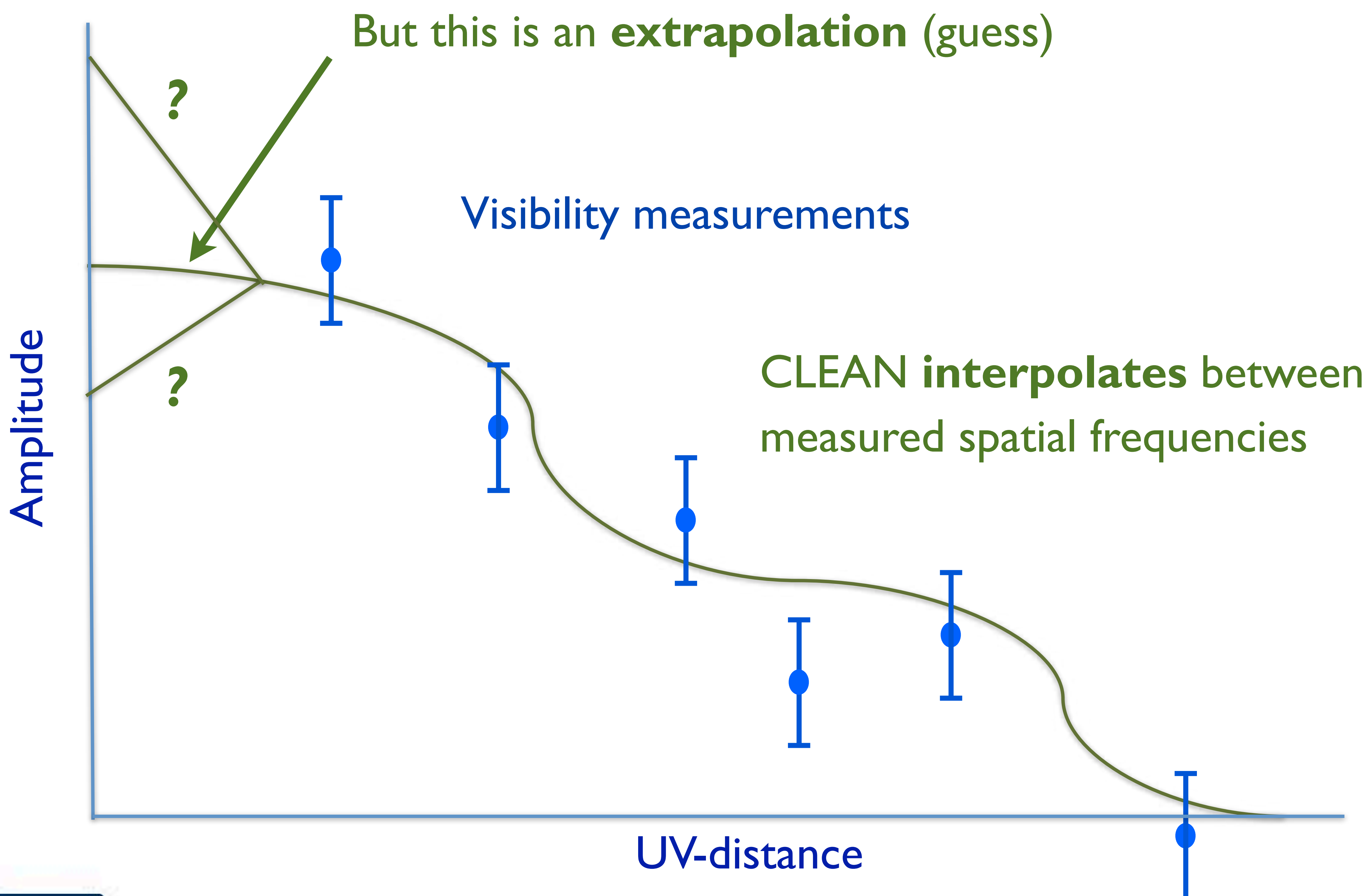


Visibility measurements
CLEAN **interpolates** between measured spatial frequencies
Amplitude
UV-distance

Feathering


But this is an **extrapolation** (guess)
Visibility measurements
CLEAN **interpolates** between measured spatial frequencies
Amplitude
UV-distance

Feathering


But this is an **extrapolation** (guess)
?
?
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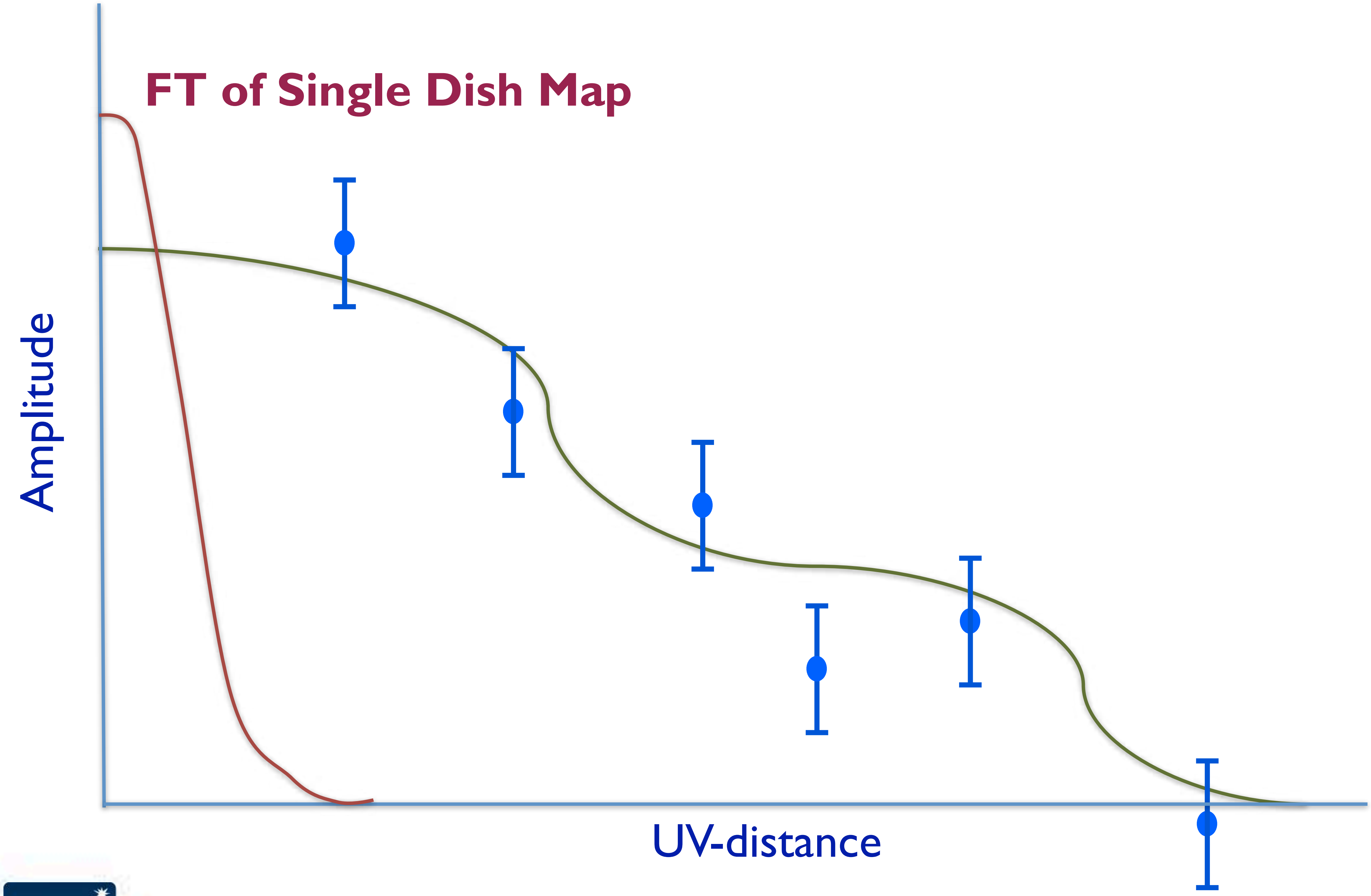
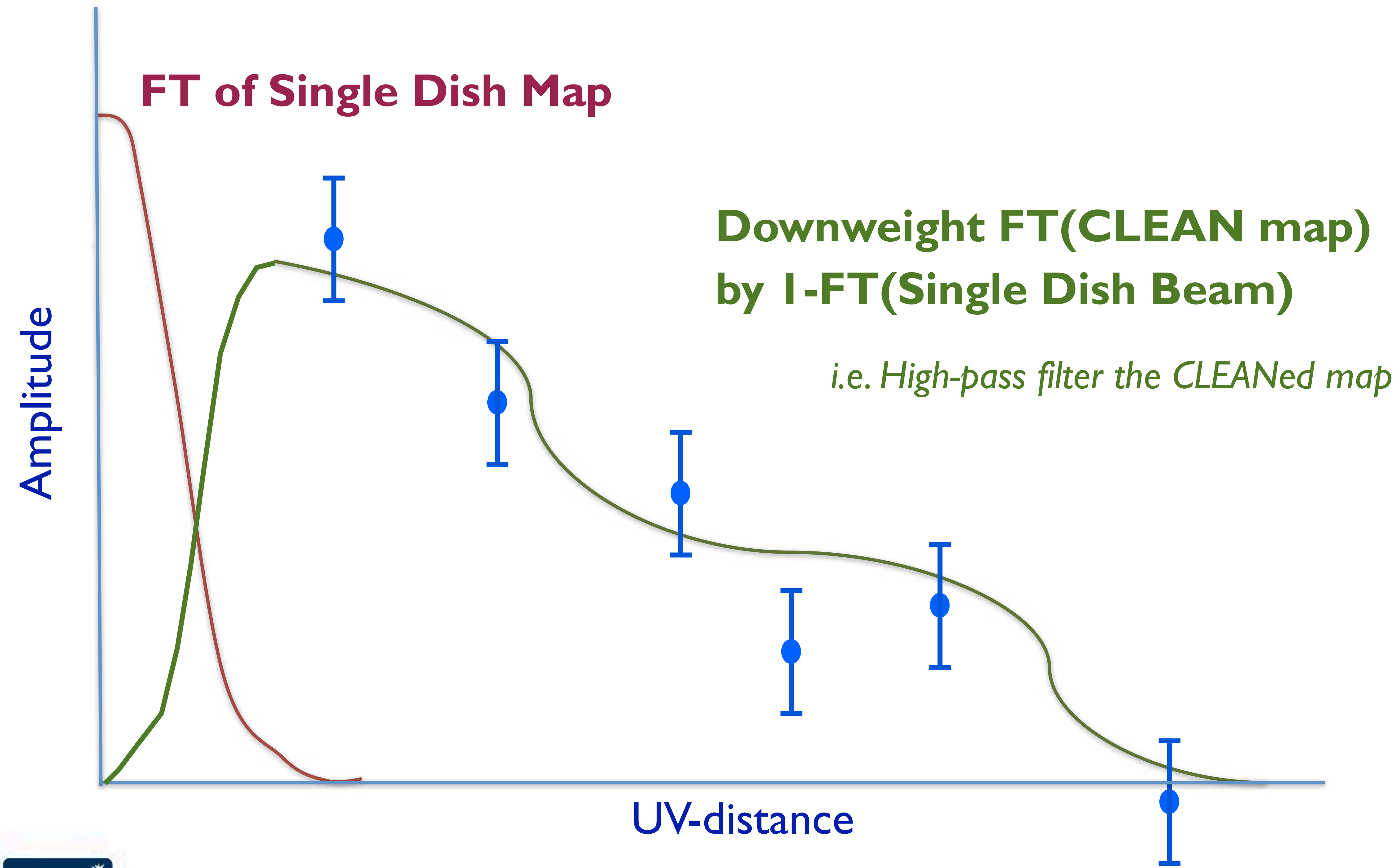
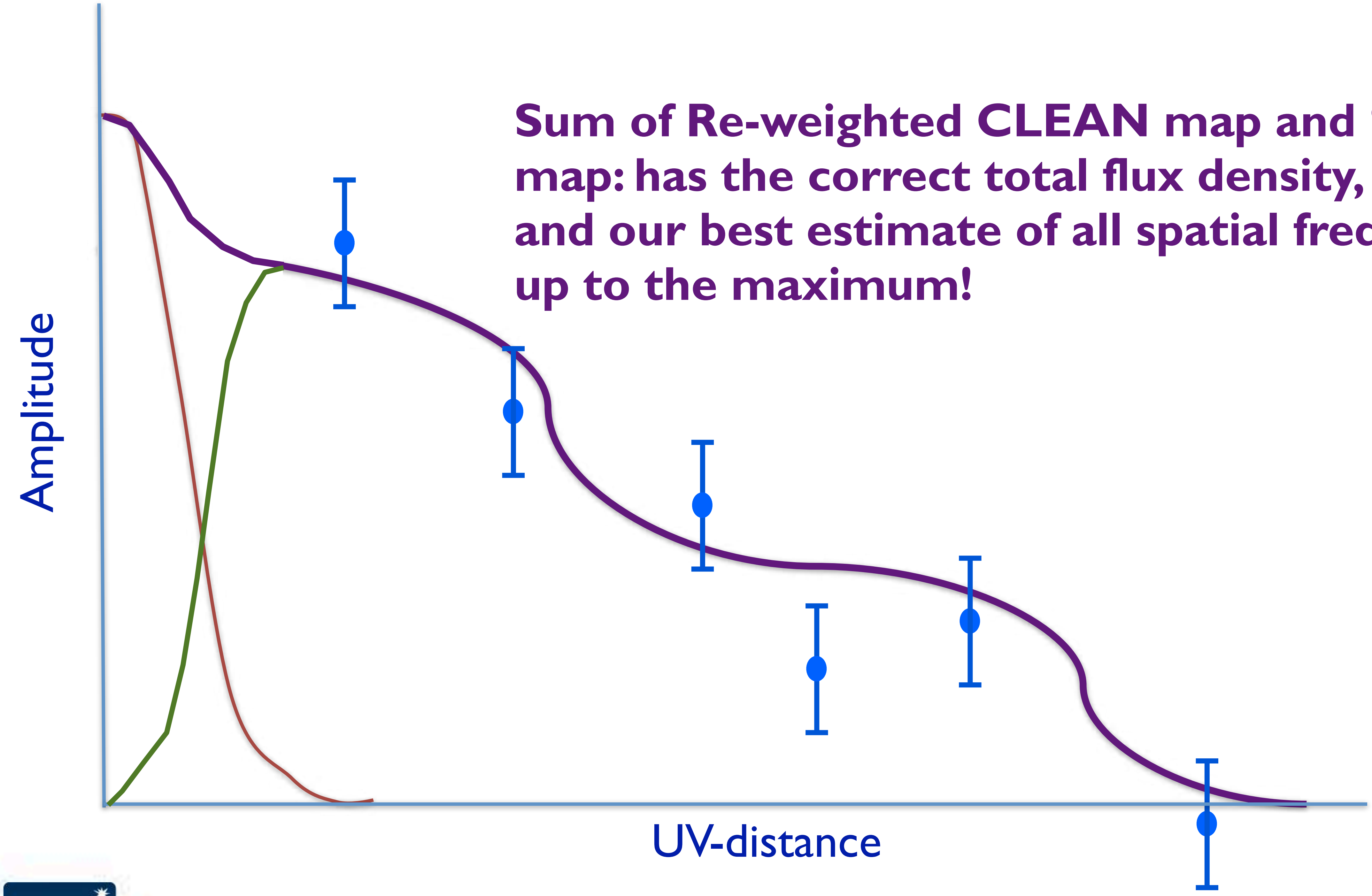
Feathering



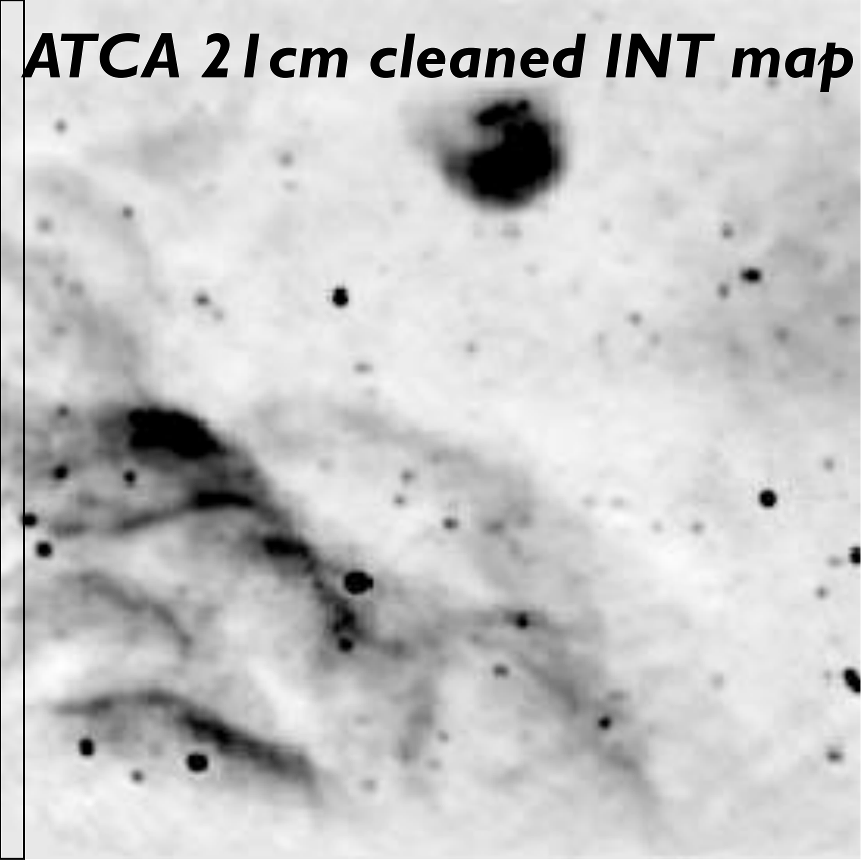
Feathering


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

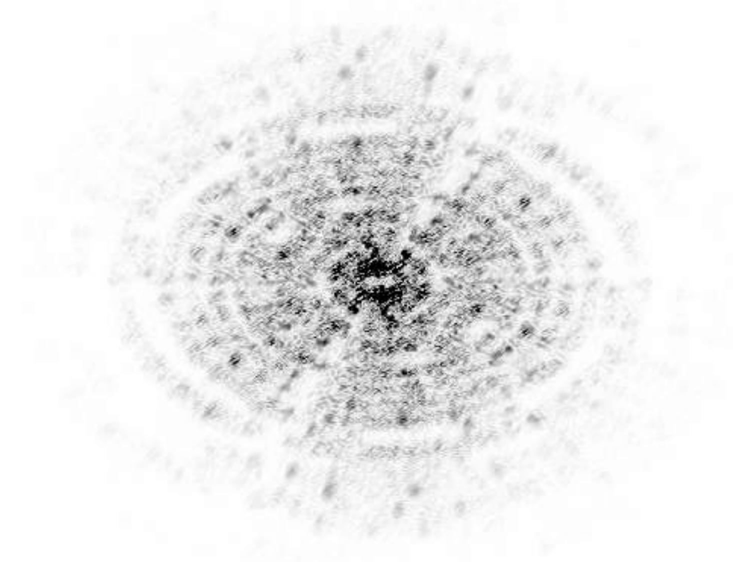
Feathering



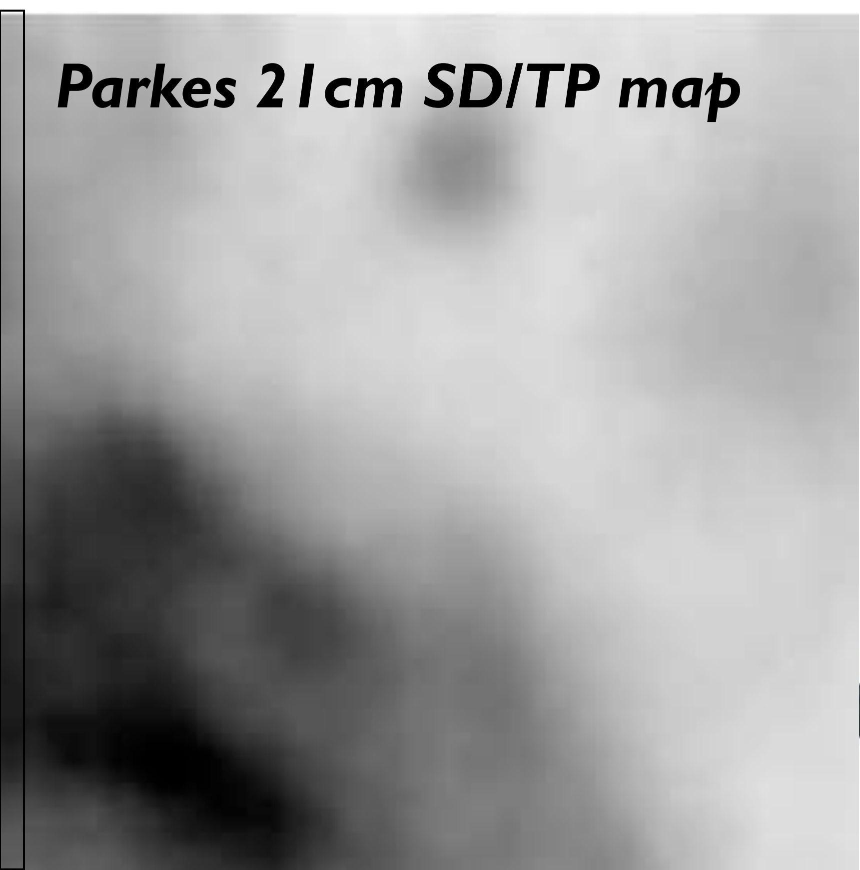
Sum of Re-weighted CLEAN map and SD map: has the correct total flux density, and our best estimate of all spatial frequencies up to the maximum!
Amplitude
UV-distance



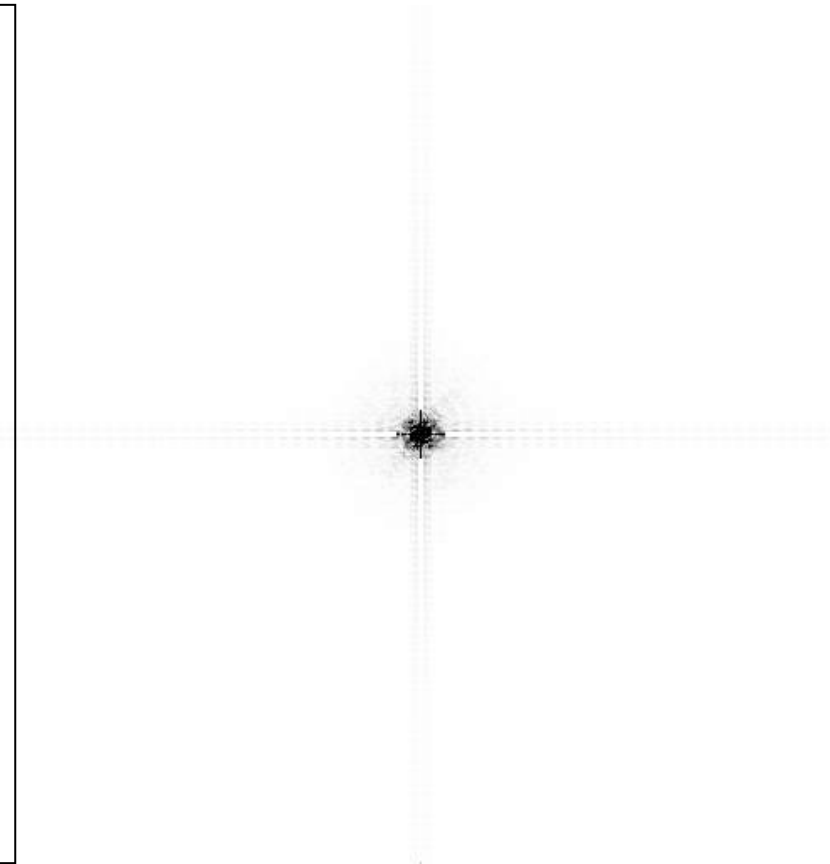
FT $\longrightarrow$



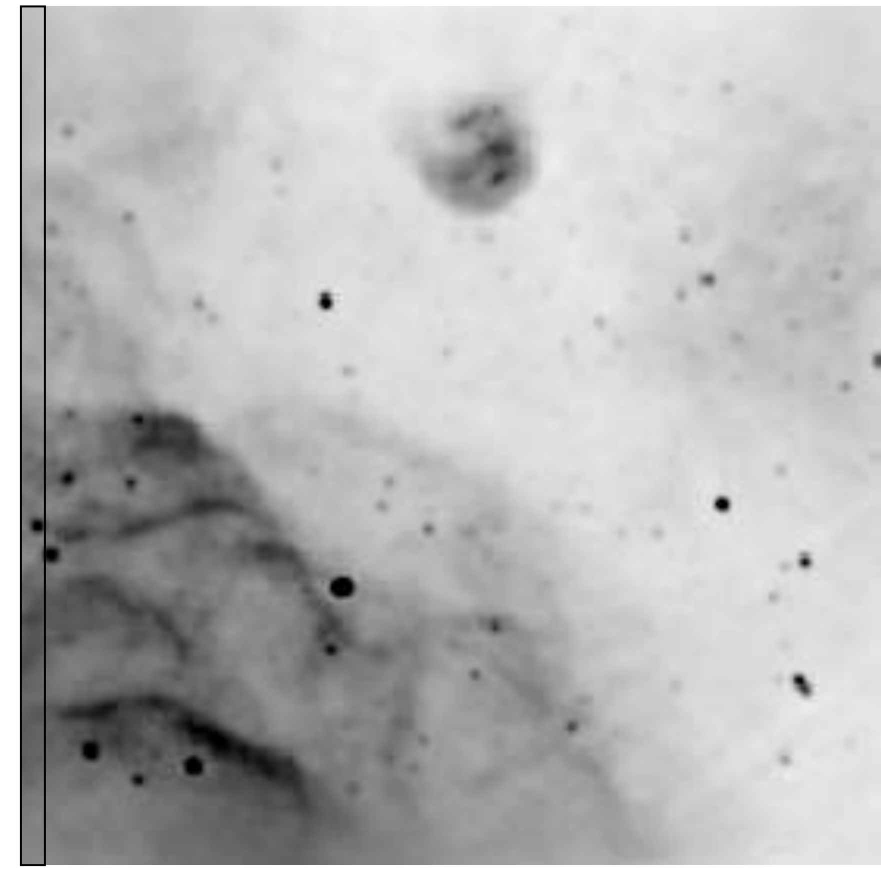
+



FT $\longrightarrow$

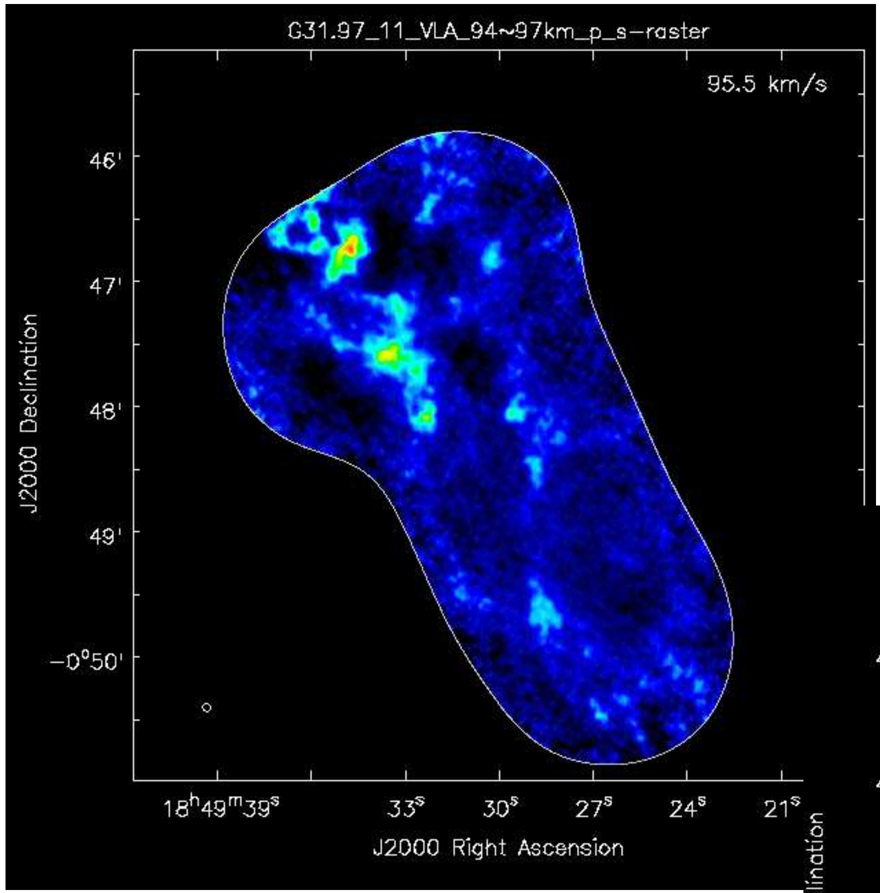


$\mathbf{FT^{-1}=}$

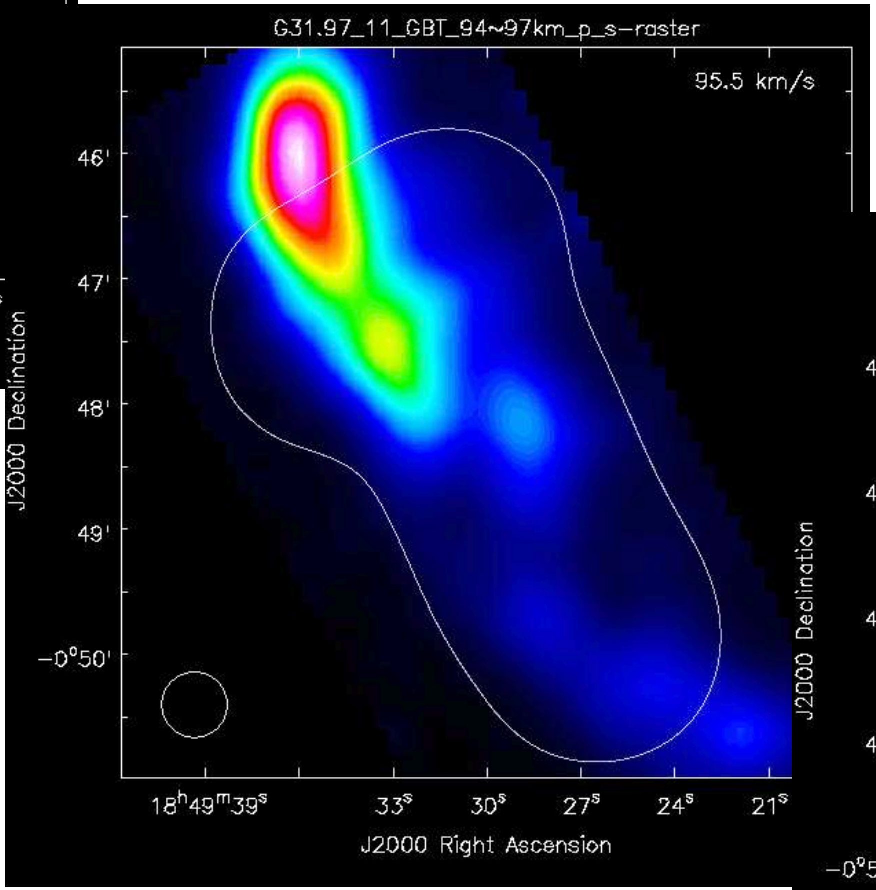


McClure-Griffiths et al.

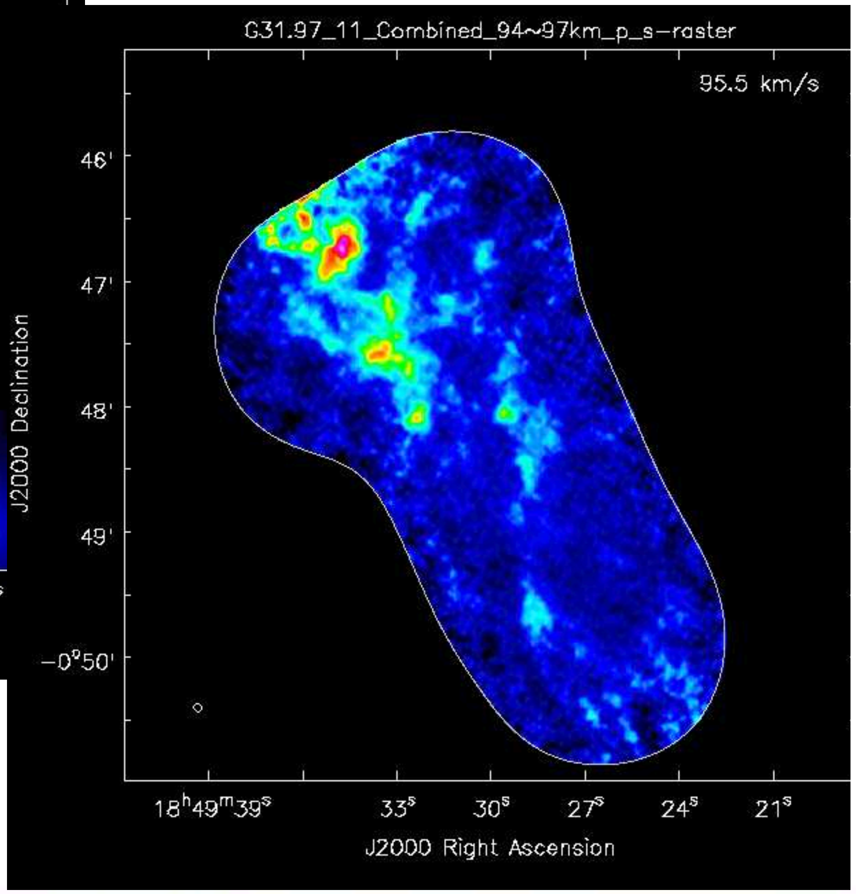
EVLA NH_3 (multi-scale CLEANed)



GBT NH_3

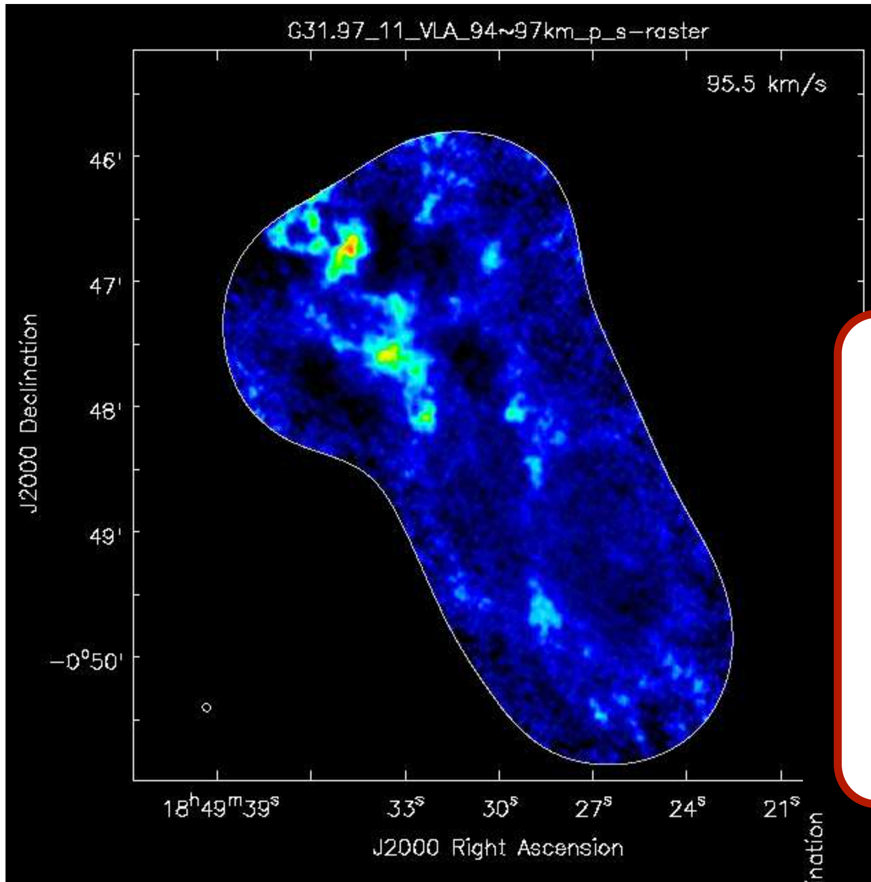


Feathered

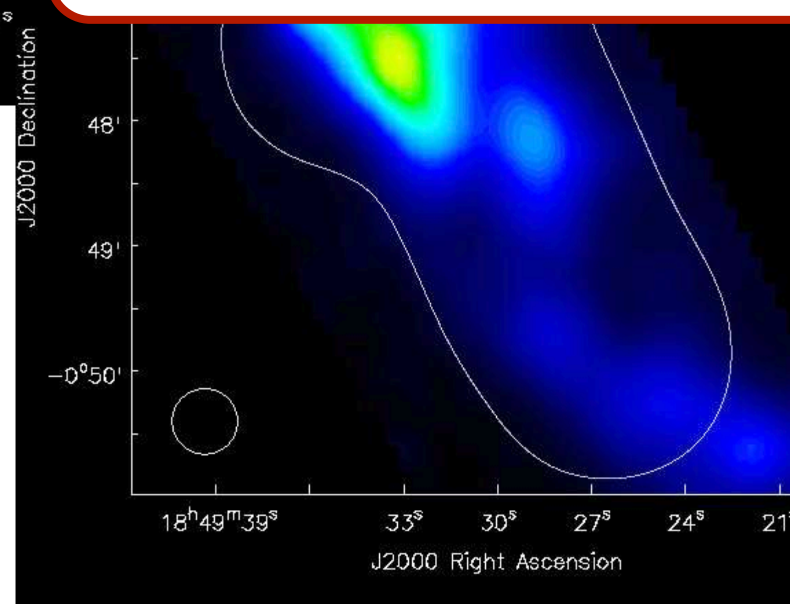


Courtesy W. DiRienzo et al. (in prep.)

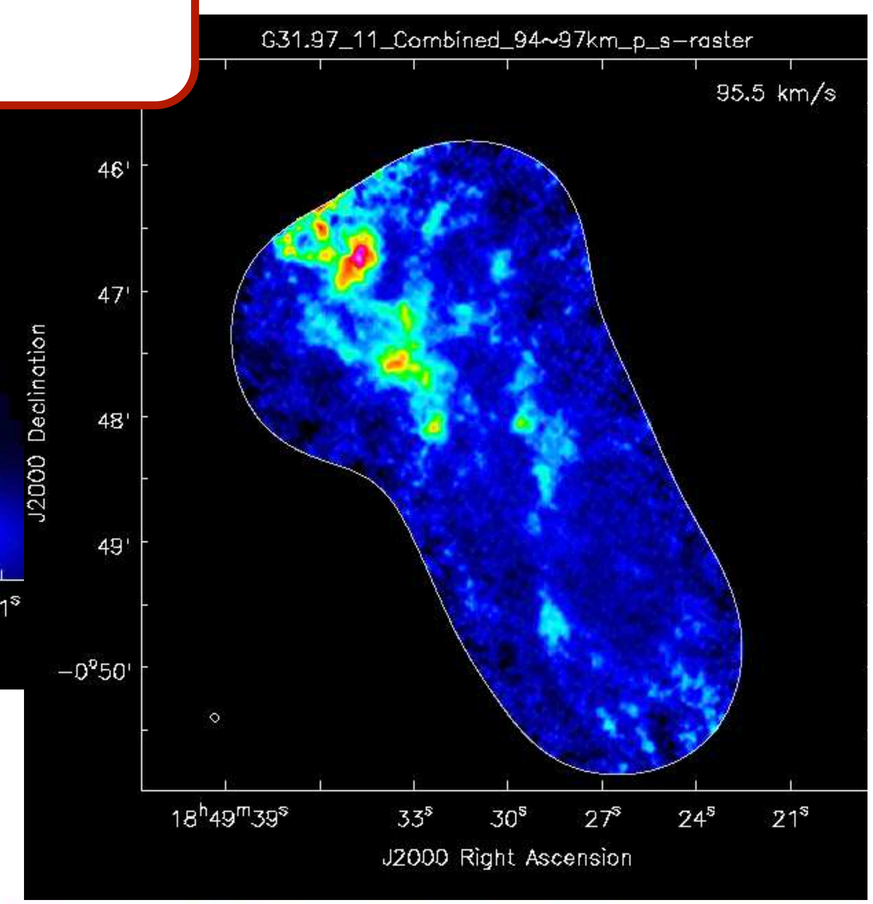
EVLA NH_3 (multi-scale CLEANed)



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

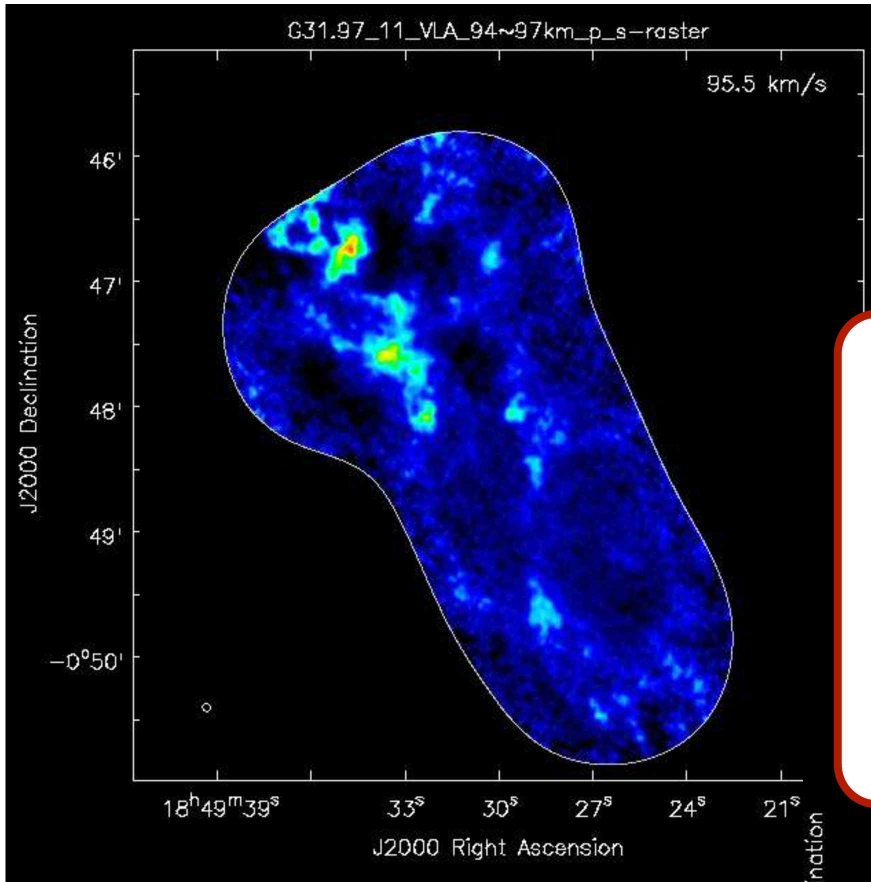


Feathered

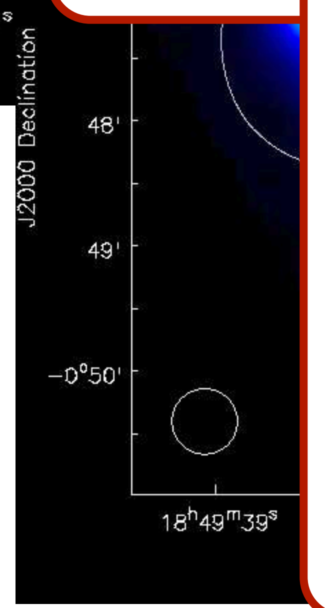


Courtesy W. DiRienzo et al. (in prep.)

EVLA NH_3 (multi-scale CLEANed)



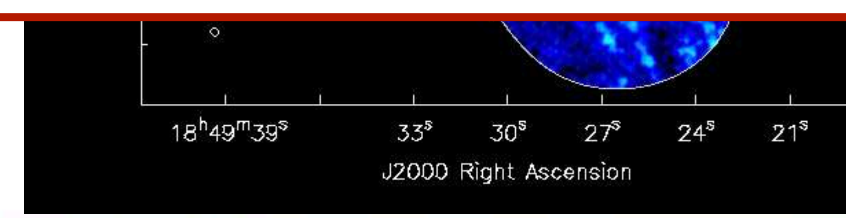
In CASA: Task feather()
*input low-res (SD) image
*high
*SD c



Feathering is widely used and fairly robust … but not the only way to do this!

*MEM default image
*Turn SD into pseudo-visibilities, jointly deconvolve together (e.g., Koda et al.2011)

*See S. Stanimirovic article in *Single Dish Summer School* Proceedings

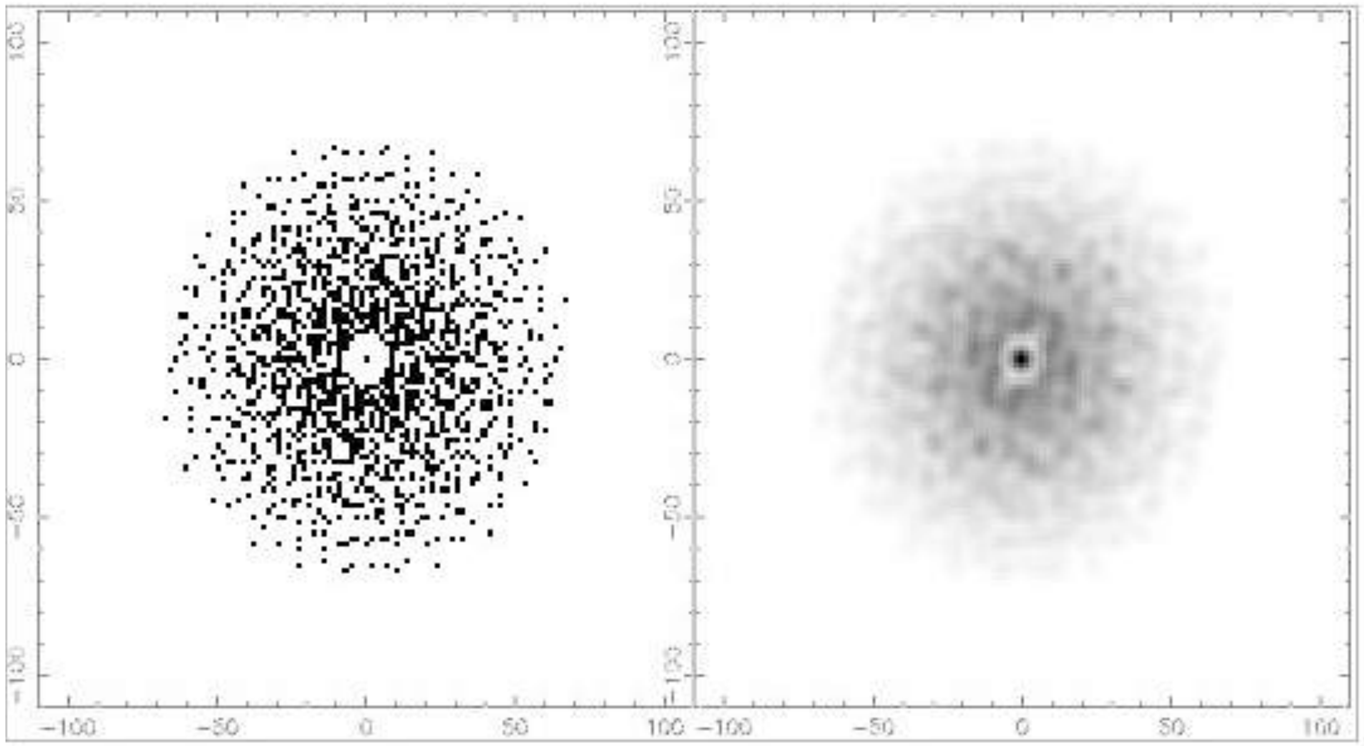


Courtesy W. DiRienzo et al. (in prep.)

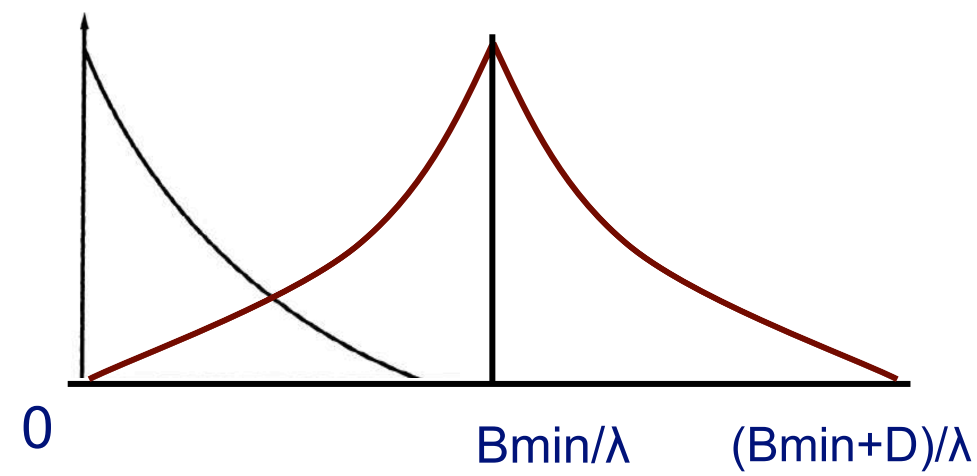
Single Dish Issues

- Pointing errors
  - minimize; smooth to mitigate somewhat
- Striping
  - Scan rapidly and include signal-free "off" regions (spatial and/or spectral)
    - more of an issue for continuum than spectral line
  - use appropriate calibration & imaging algorithms.
- Sidelobes
  - if significant, you may need to deconvolve the single-dish data before combination (e.g., single-dish clean)
  - at short wavelengths, an "error beam" around the main beam is not uncommon
  - at long wavelengths, aperture blockage can be an issue (clear aperture is better)
- SD Image may *not* have all spatial frequencies down to u=v=0 (e.g., millimeter-wavelength continuum)
- Relative Calibration

What Single Dish Data do I Need?

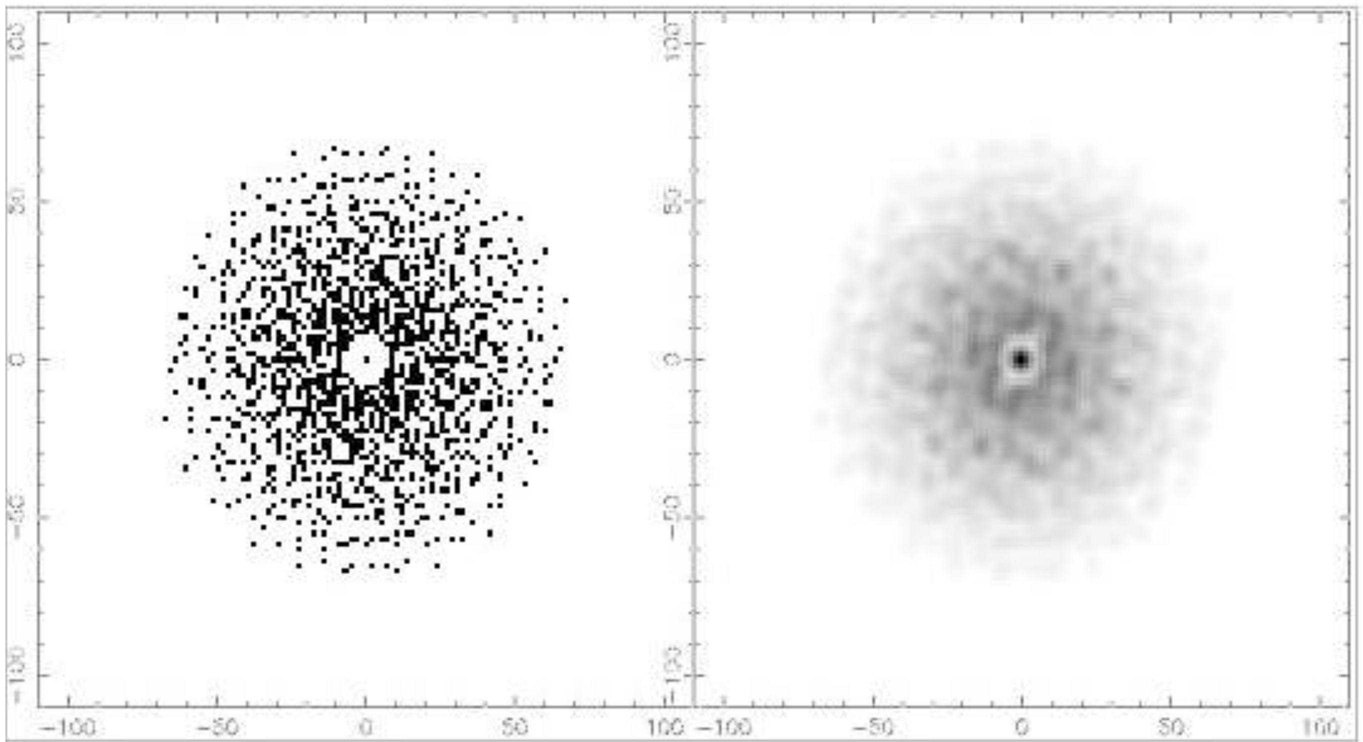


UV Space Sensitivities of interferometer (D) and single dish (D):

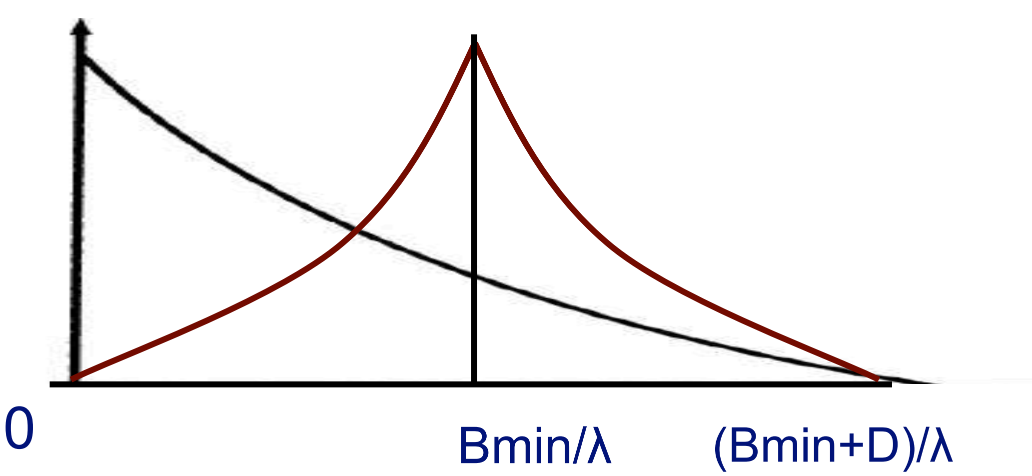


Problems:
****You still have a "hole" between (0,0) and Bmin***
****No common, well-measured spatial freq's***

What Single Dish Data do I Need?



UV Space Sensitivities of interferometer (D) and single dish (2D):



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}

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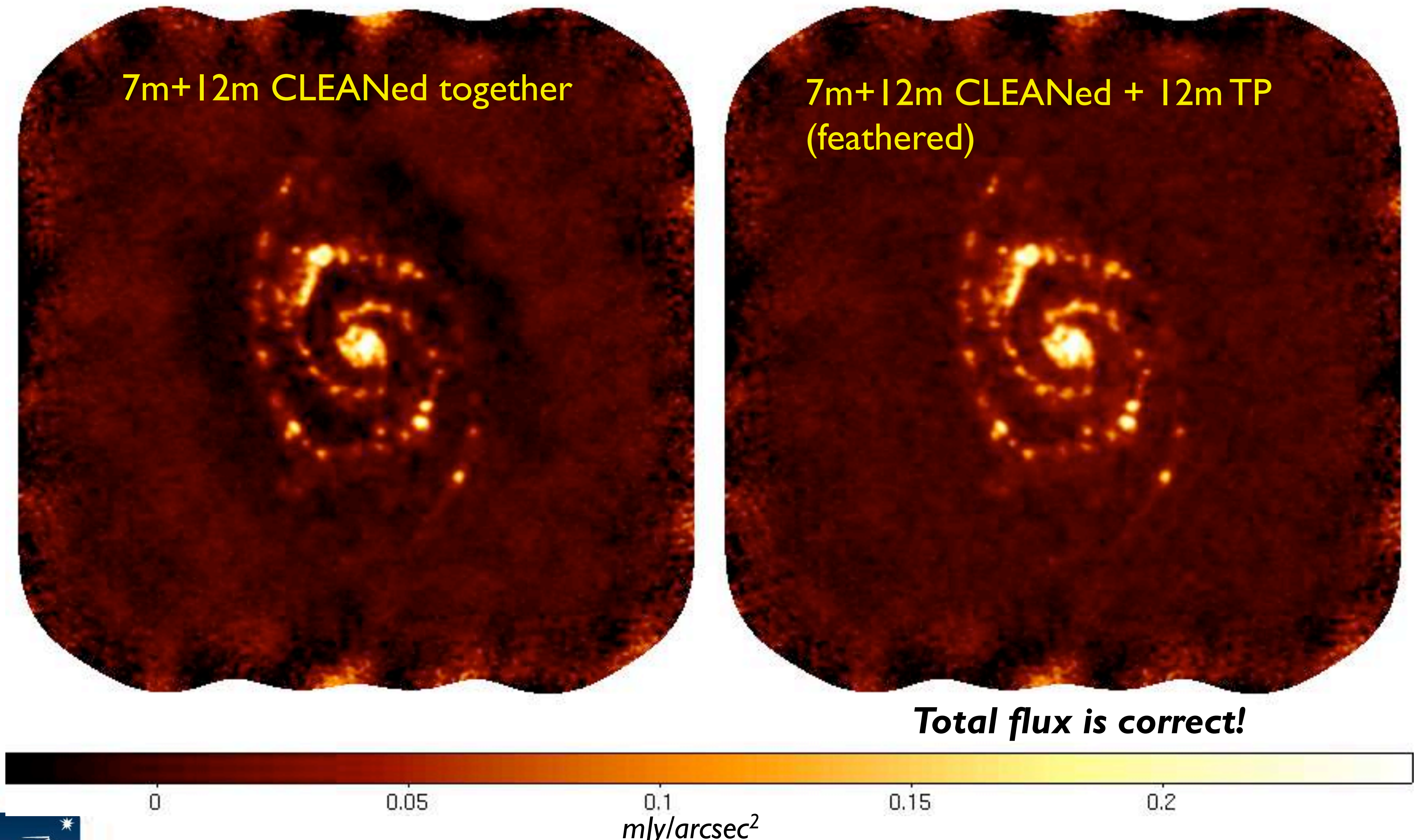
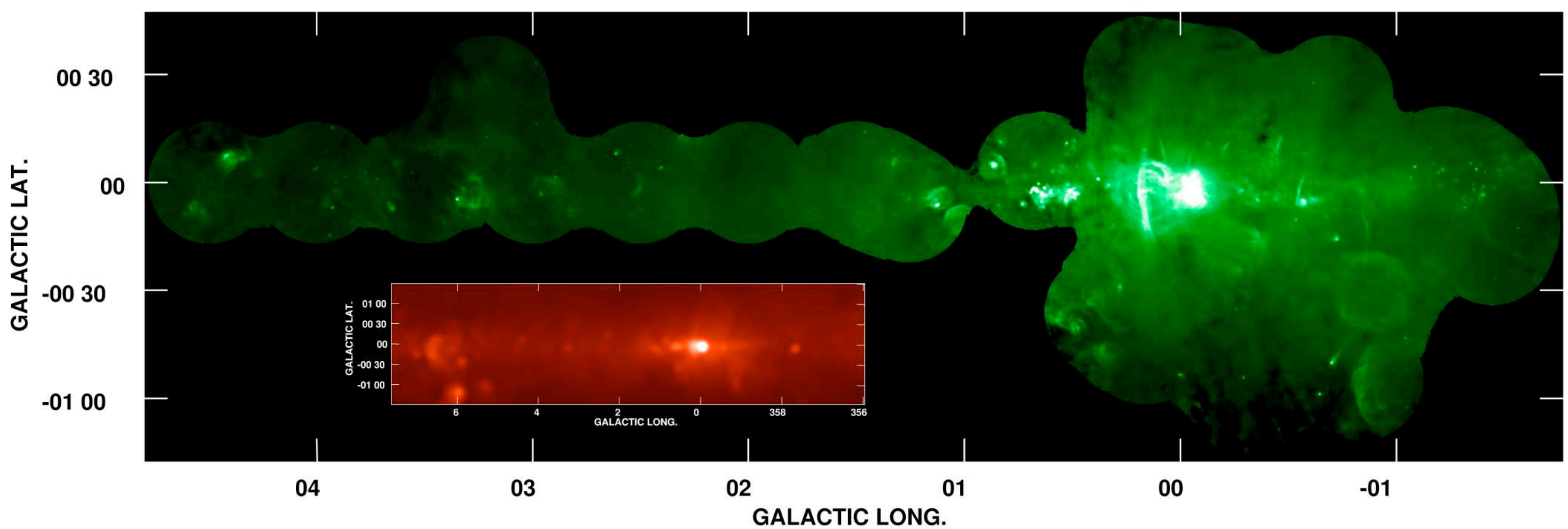


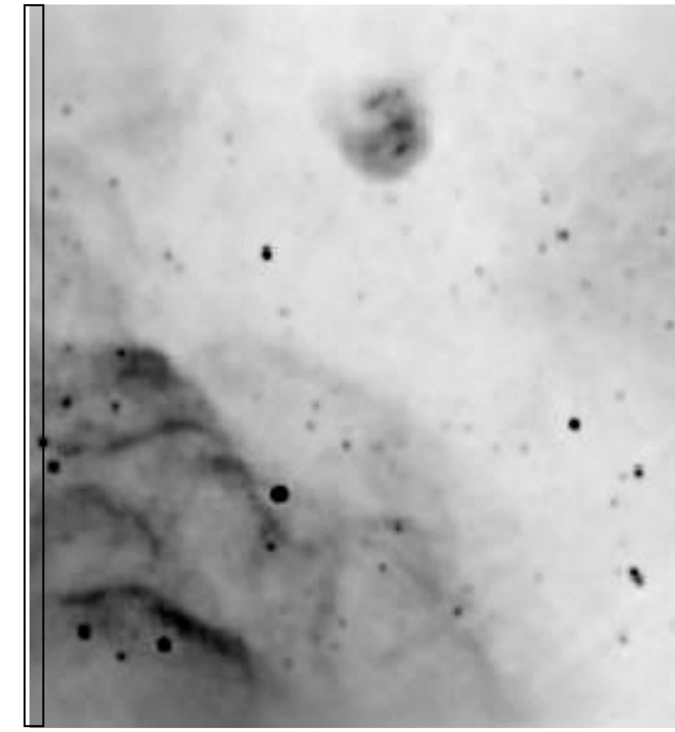
Total flux is correct!

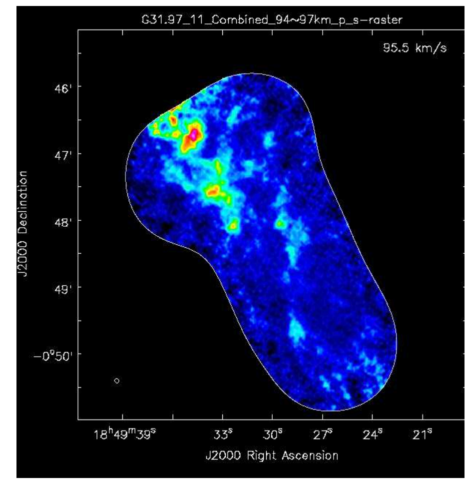
Summary

- Each visibility of an interferometer measures a range of spatial frequencies
- By mosaicking, you can recover some of this information and make gorgeous, scientifically useful images!
  - Adding single dish data can make them even more useful
- There is no cookie-cutter approach to imaging extended emission with an interferometer, or to adding in single dish data
  - read up, experiment, and talk to some people who have done it before!



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)
- 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)
- Useful discussions with C.Brogan, U.Rao, J.Ott, & others

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