Australian National University

Towards the zero-spacing: Mosaicing and Single Dish Combination

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The Australian National University

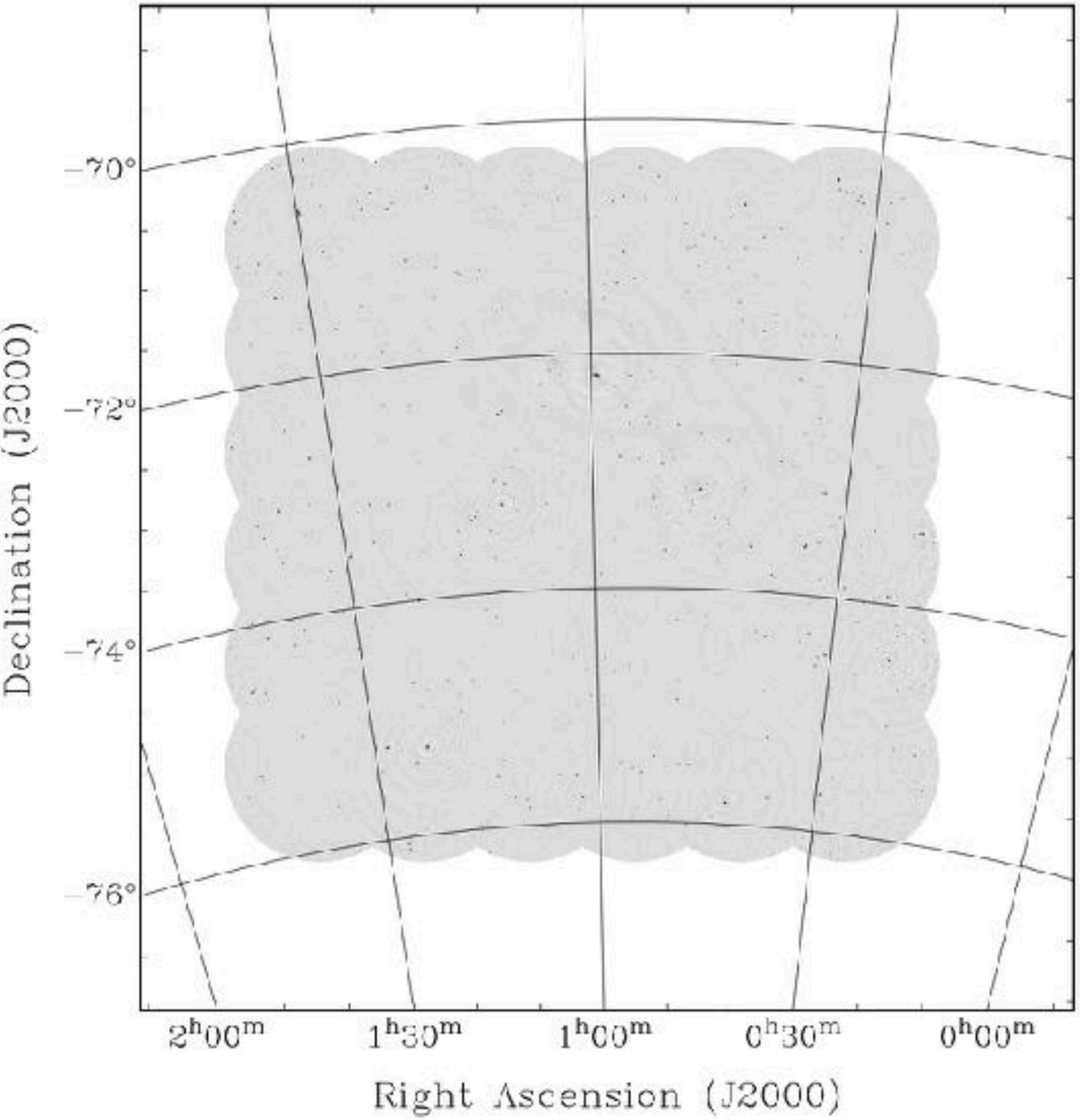
Outline

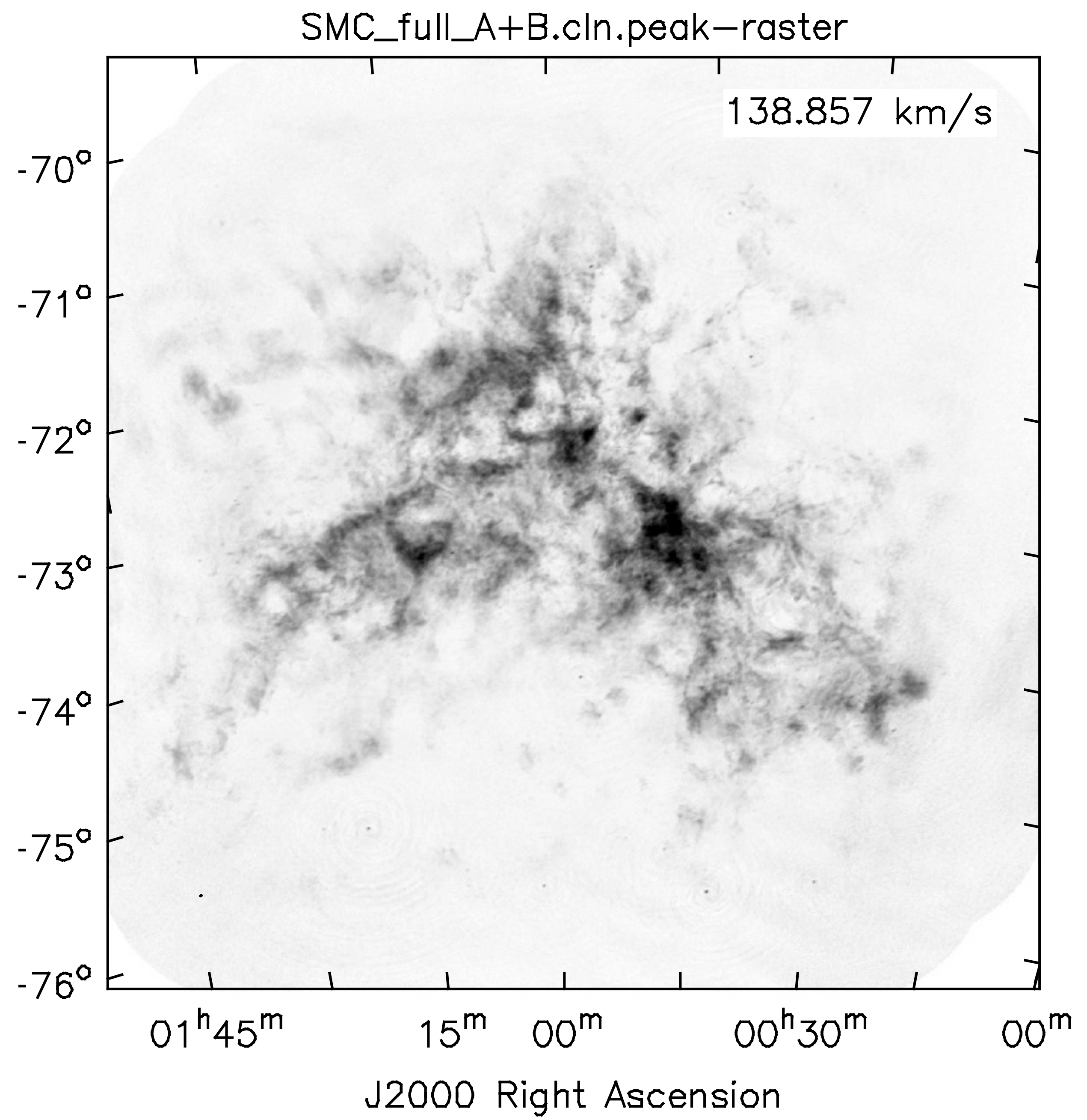
- Big images = mosaicing
- What is the zero-spacing problem?
  - Impacts on large-scale emission
  - Imaging artefacts
  - Total-power
- Solutions
  - Concept
  - Cross-calibration
  - Recipes

Why Mosaic?

- Wide-field imaging:
  - Interested in source that is larger than primary beam, $\theta > \lambda / D$
- Large scale structure:
  - Interested in structure on scales larger than that sampled by the shortest baseline: $\theta > \lambda / d_{min}$

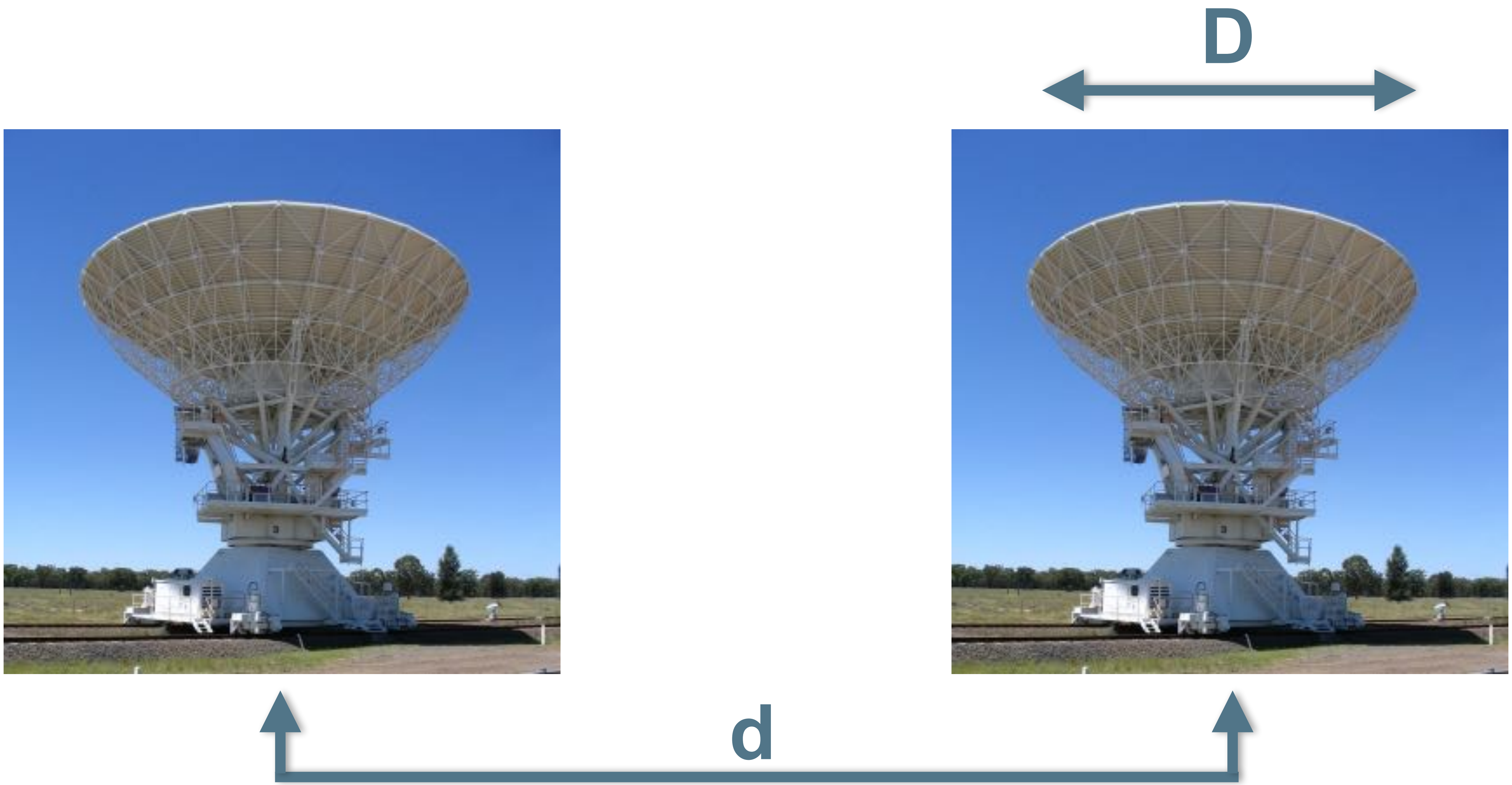
Two different reasons to mosaic:





An Interferometer samples angular scales:

$$\theta_{max} \lesssim \lambda / d_{min}$$



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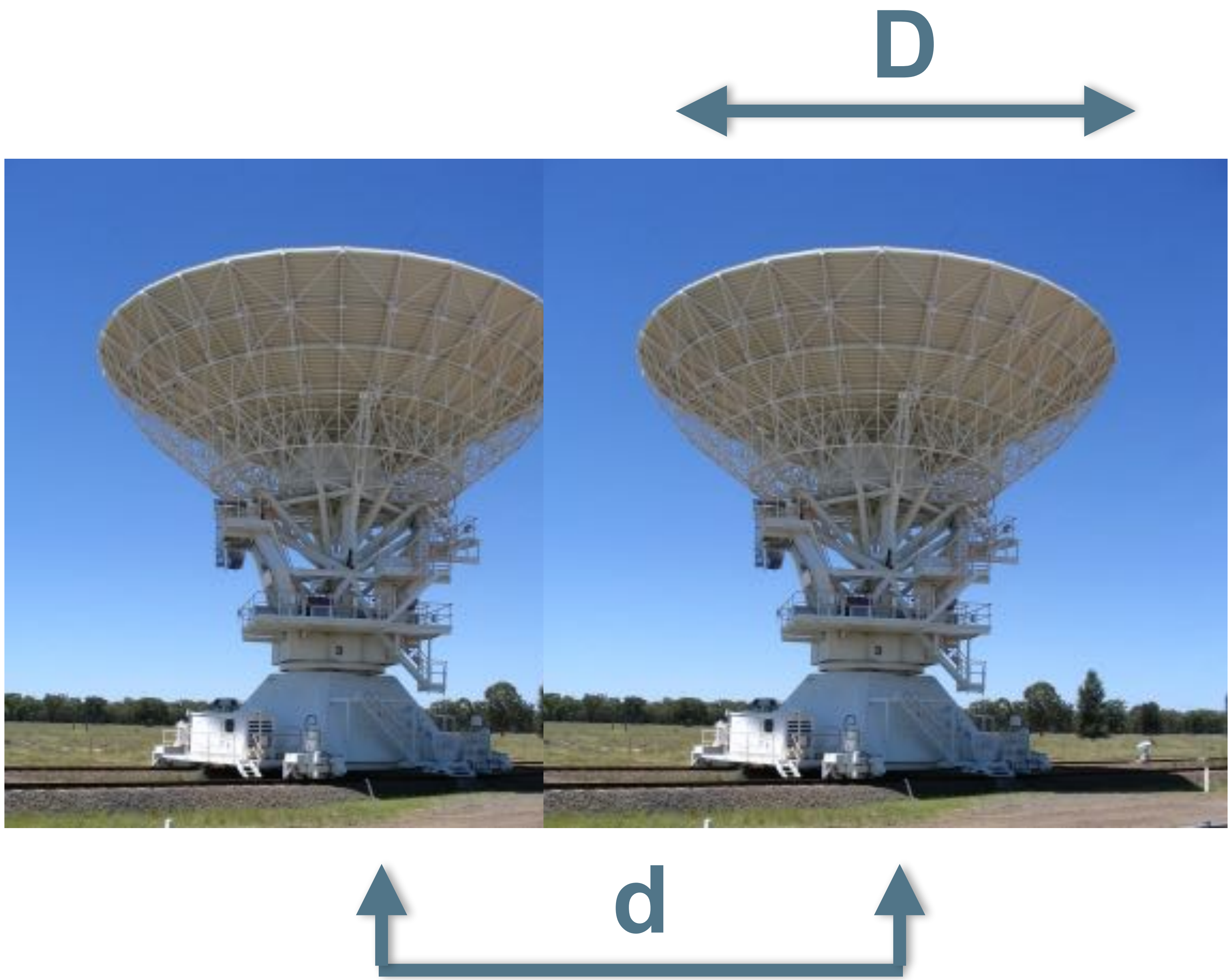
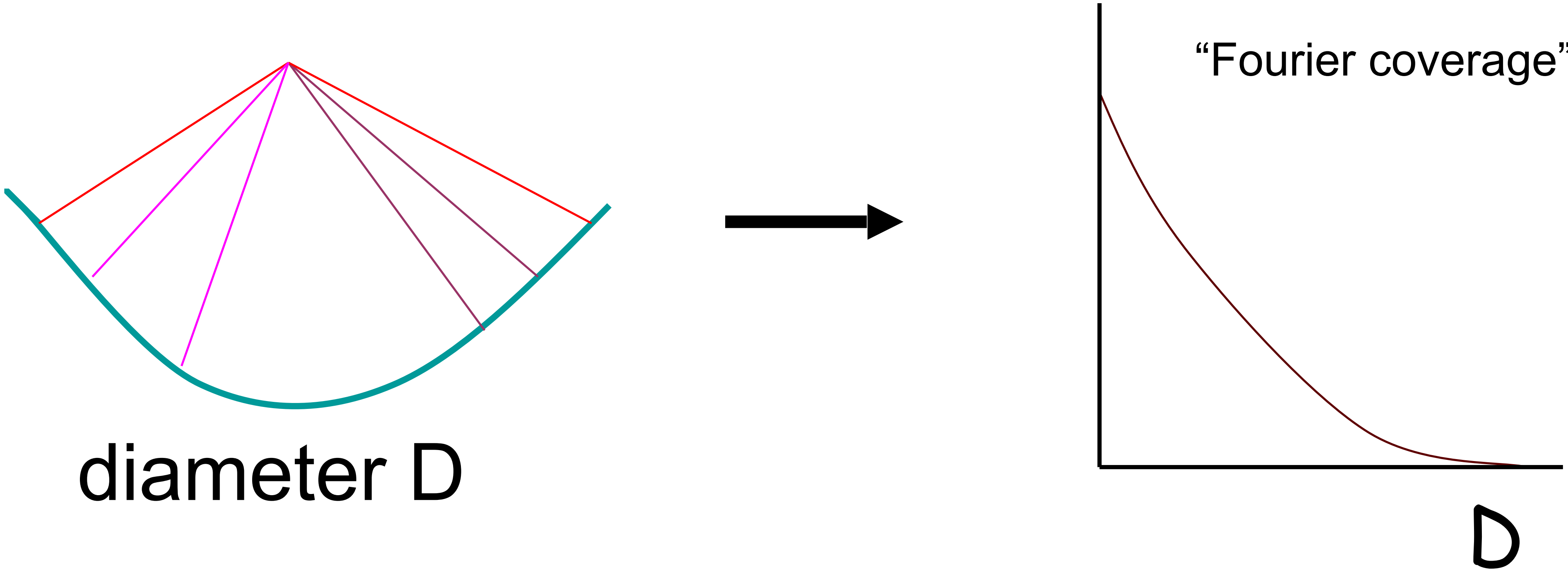
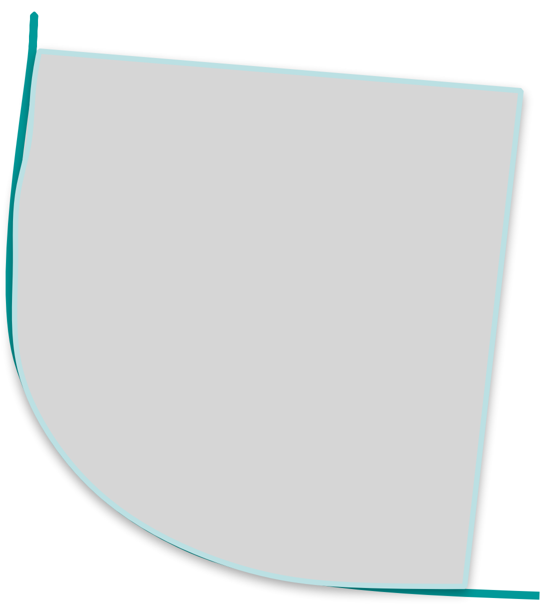


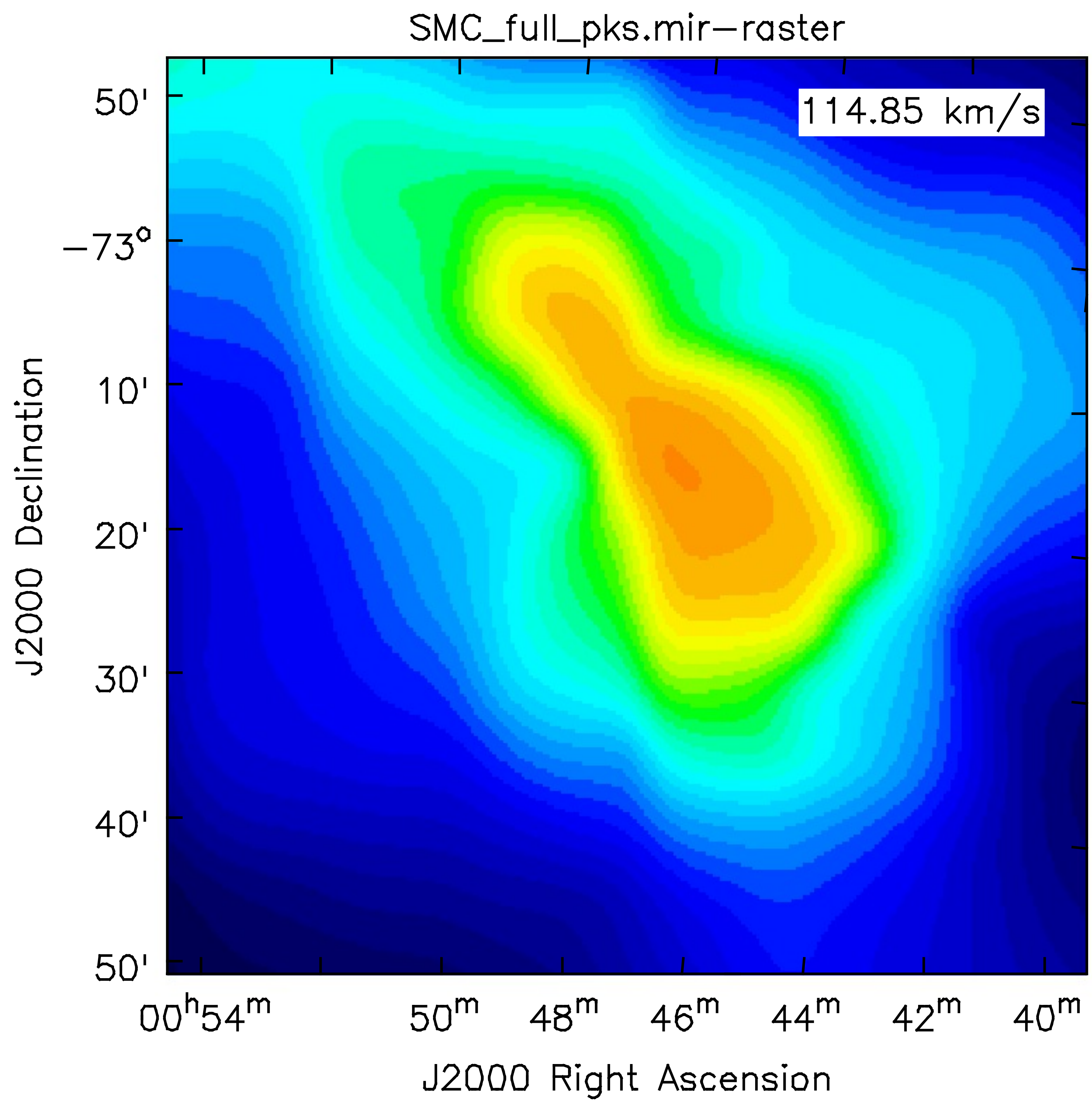
Mosaicing Fundamentals

- Background theory:
  - Ekers & Rots (1979) pointed out that one can think of a single dish as a collection of sub-interferometers.



*Ron showed us this in his first talk

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114.85 km/s
50'
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J2000 Declination
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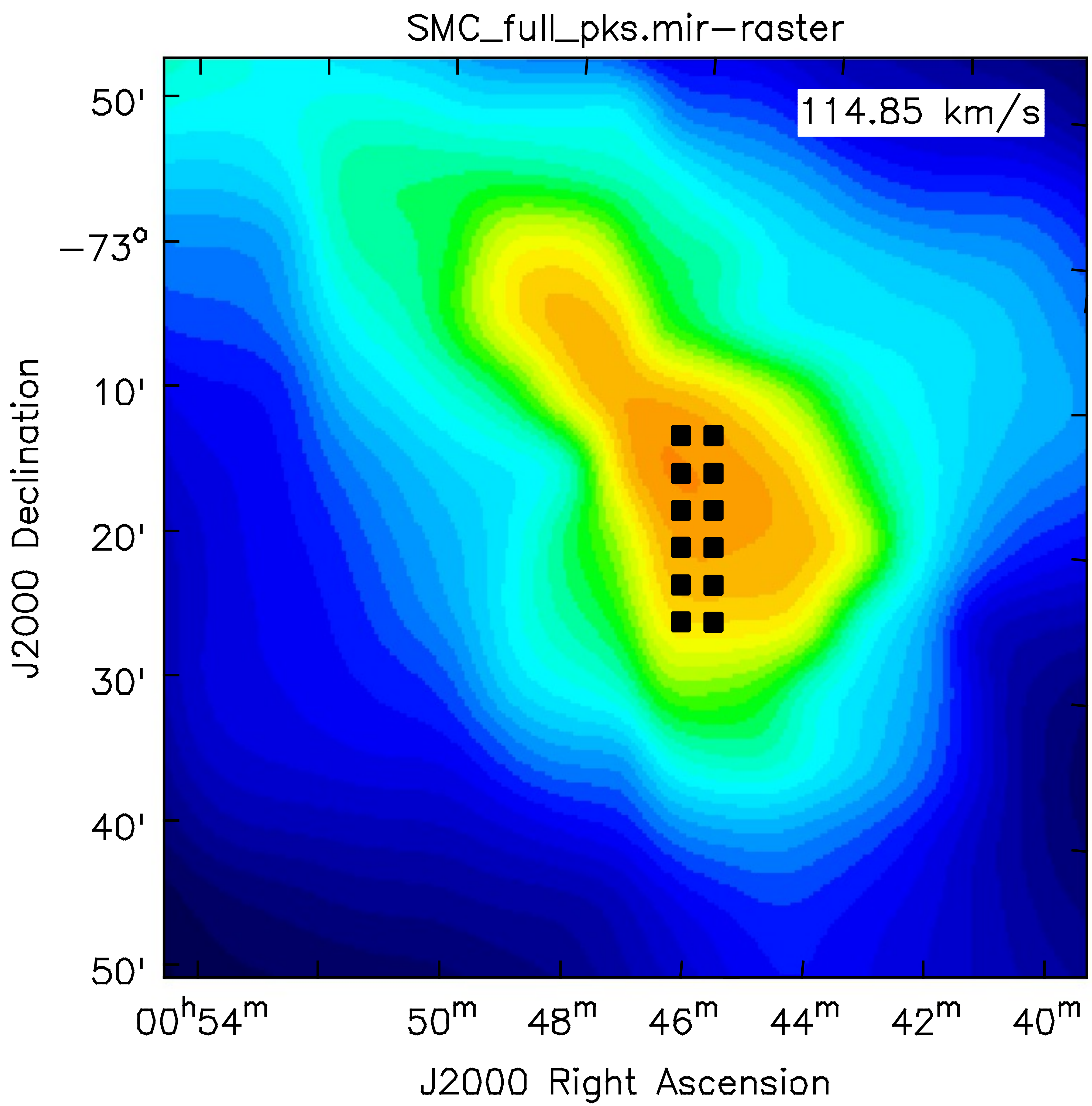
J2000 Right Ascension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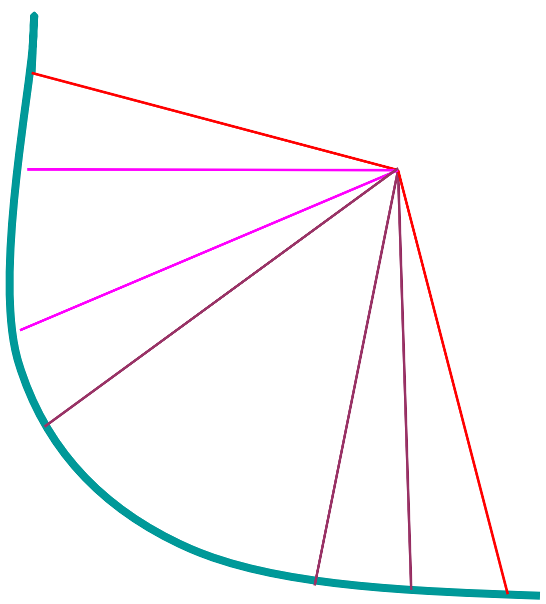

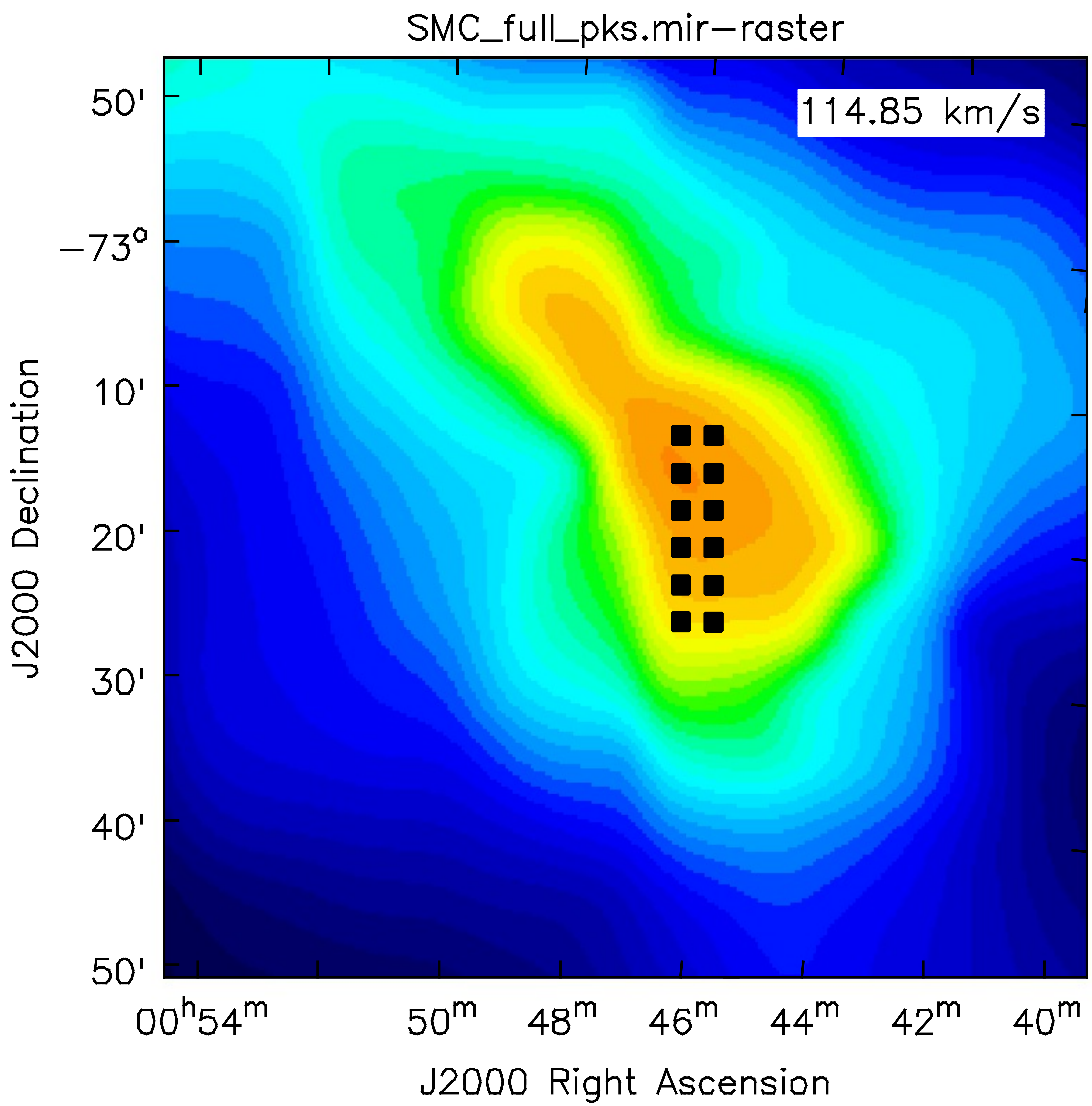
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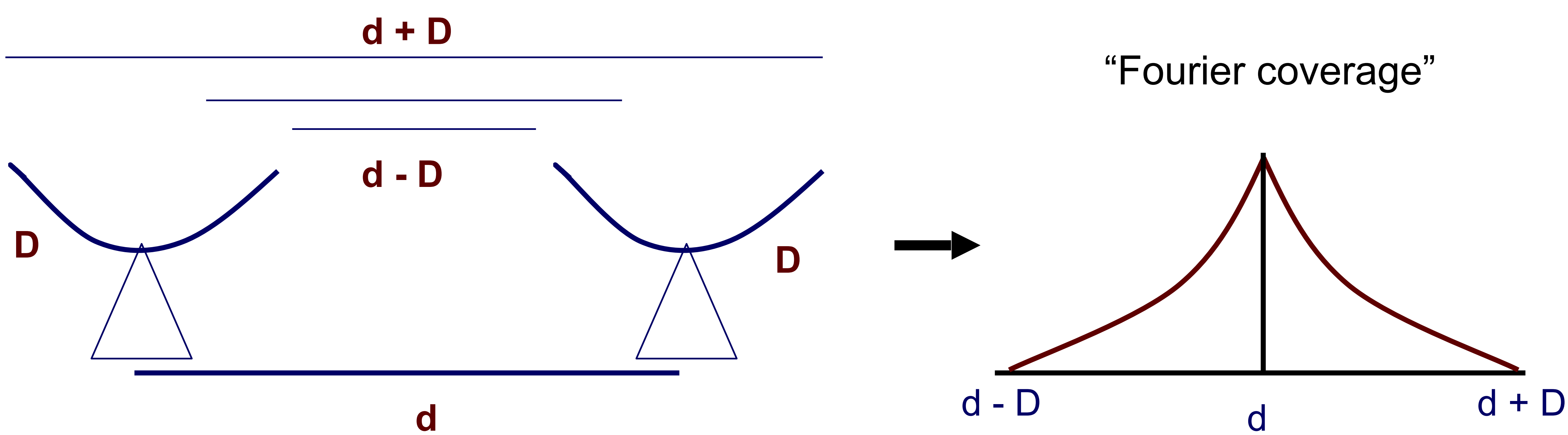
Mosaicing Fundamentals

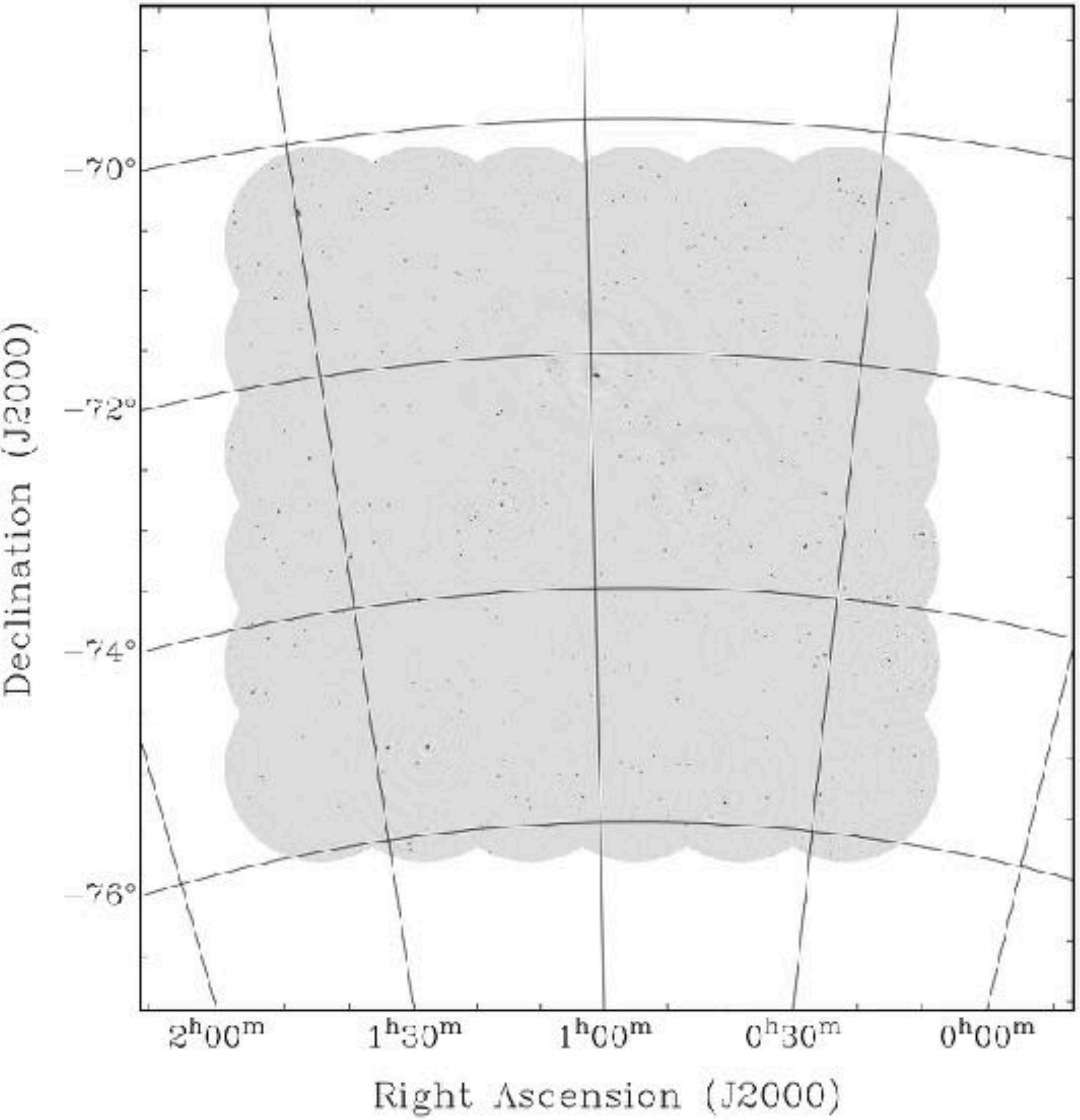
- Extending this formalism to interferometers, we find that an interferometer doesn't just measure angular scales $\theta = \lambda / d$ it actually measures $\lambda / (d - D) < \theta < \lambda / (d + D)$



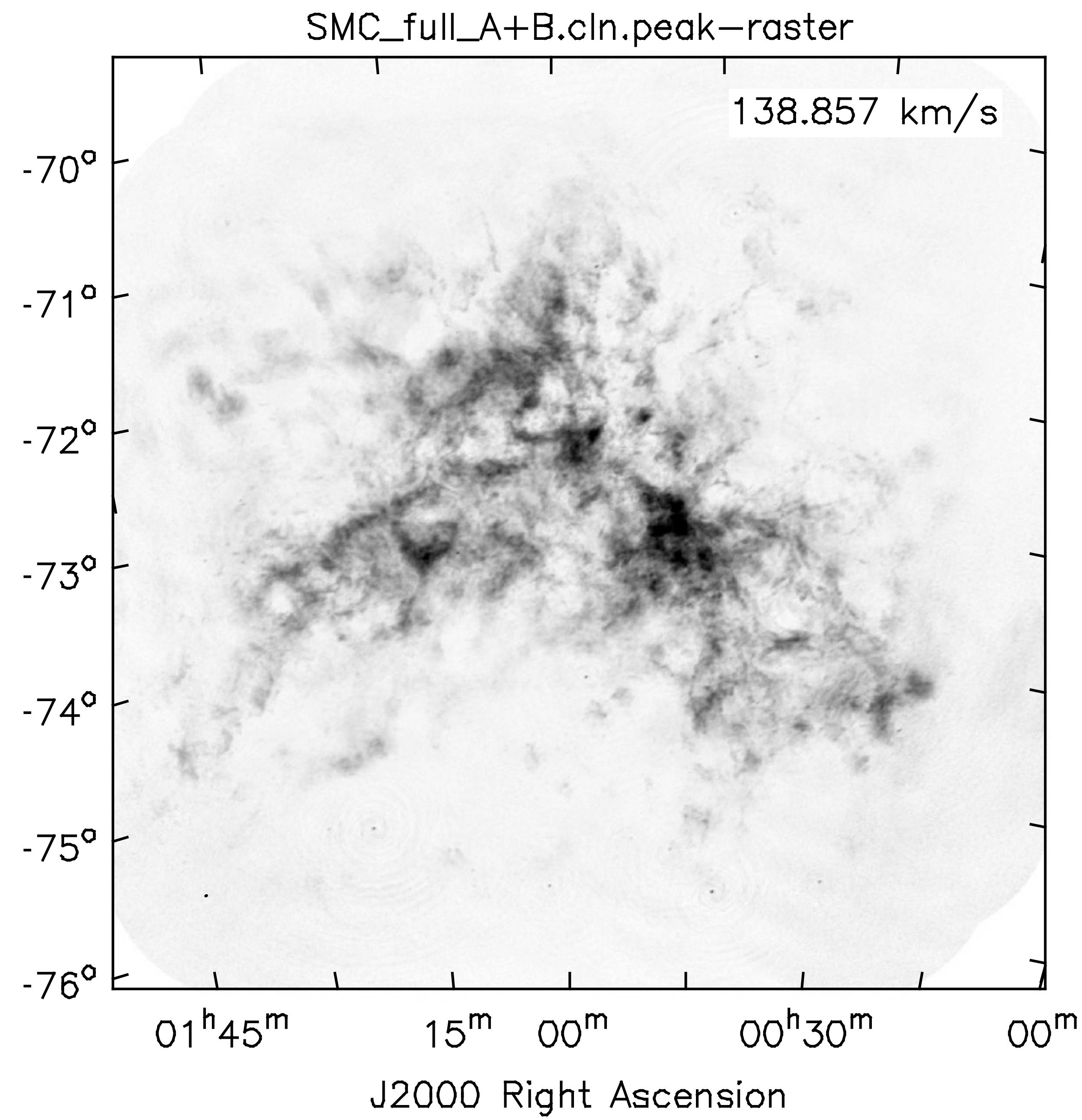
Mosaicing Fundamentals

- But you can't get all that extra info from a single pointing
  - As with a single dish, you have to scan to get the extra "spacings"
- Ekers & Rots showed that you can recover this extra information by scanning the interferometer
- The sampling theorem states that we can gather as much information by sampling the sky with a regular, Nyquist spaced grid (Cornwell 1988)

Linear mosaic



Joint deconvolution



Joint Deconvolution Approach

- Form a linear combination of the individual pointings, p:

$$I_{LM}(\ell) = W(\ell) \frac{\Sigma_p A(\ell - \ell_p) I_p(\ell)/\sigma_p^2}{\Sigma_p A^2(\ell - \ell_p)/\sigma_p^2}$$

- Here σ_p is the noise variance of an individual pointing and A(l) is the primary response function of an antenna
- W(l) is a weighting function that suppresses noise amplification at the edge of mosaic (amongst other things)

Sault, Brouw, & Staveley-Smith (1996)

Mosaicing: Joint Approach

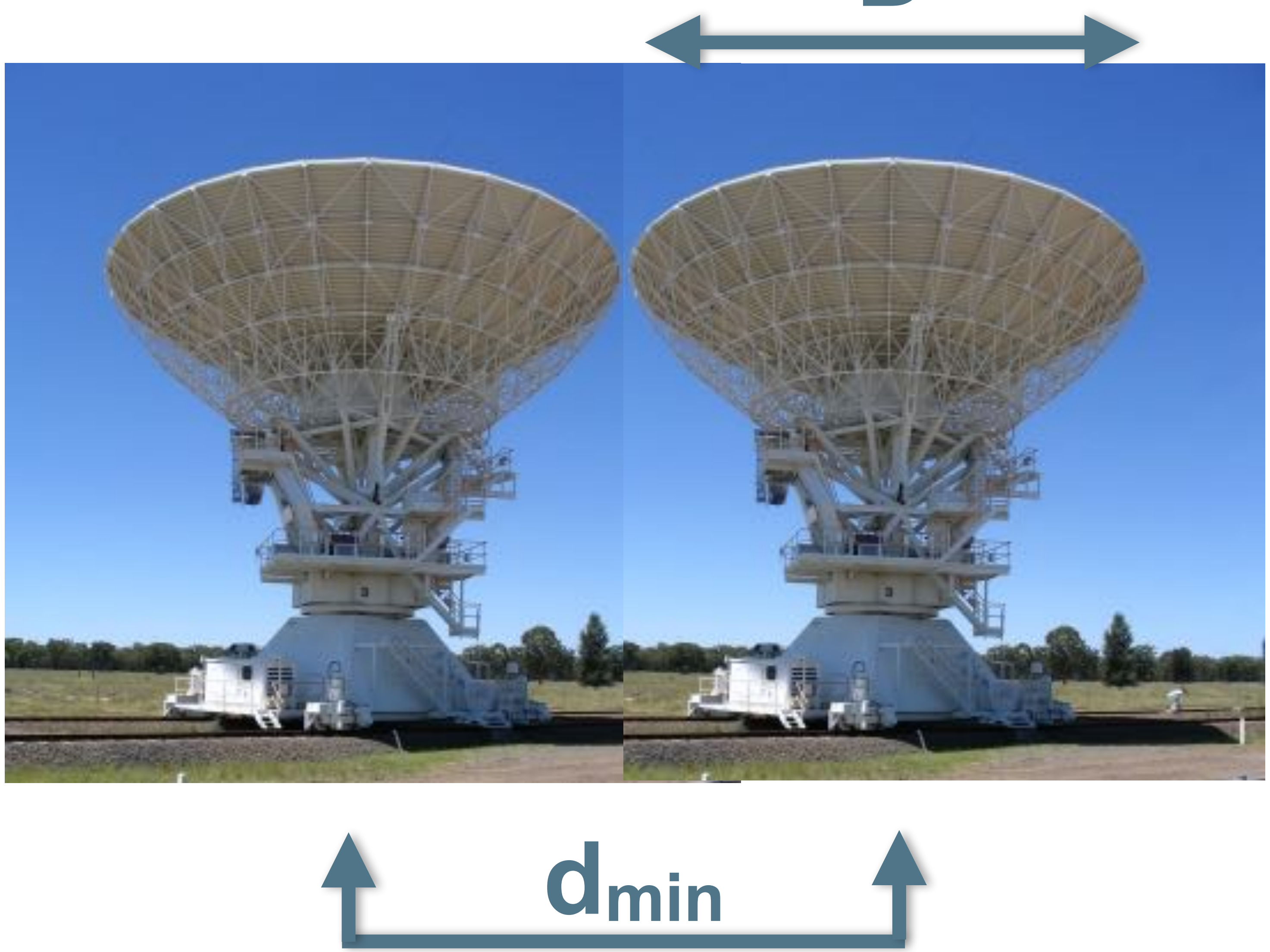
- Joint dirty beam depends on antenna primary beam:

$$B_{LM}(\ell;\ell_0) = W(\ell)\frac{\Sigma_p A(\ell_0-\ell_p)\,B_p(\ell-\ell_0)\,A(\ell-\ell_p)/\sigma_p^2}{\Sigma_p A^2(\ell-\ell_p)/\sigma_p^2}$$

- Use all u-v data from all points simultaneously
  - Extra info gives a better deconvolution

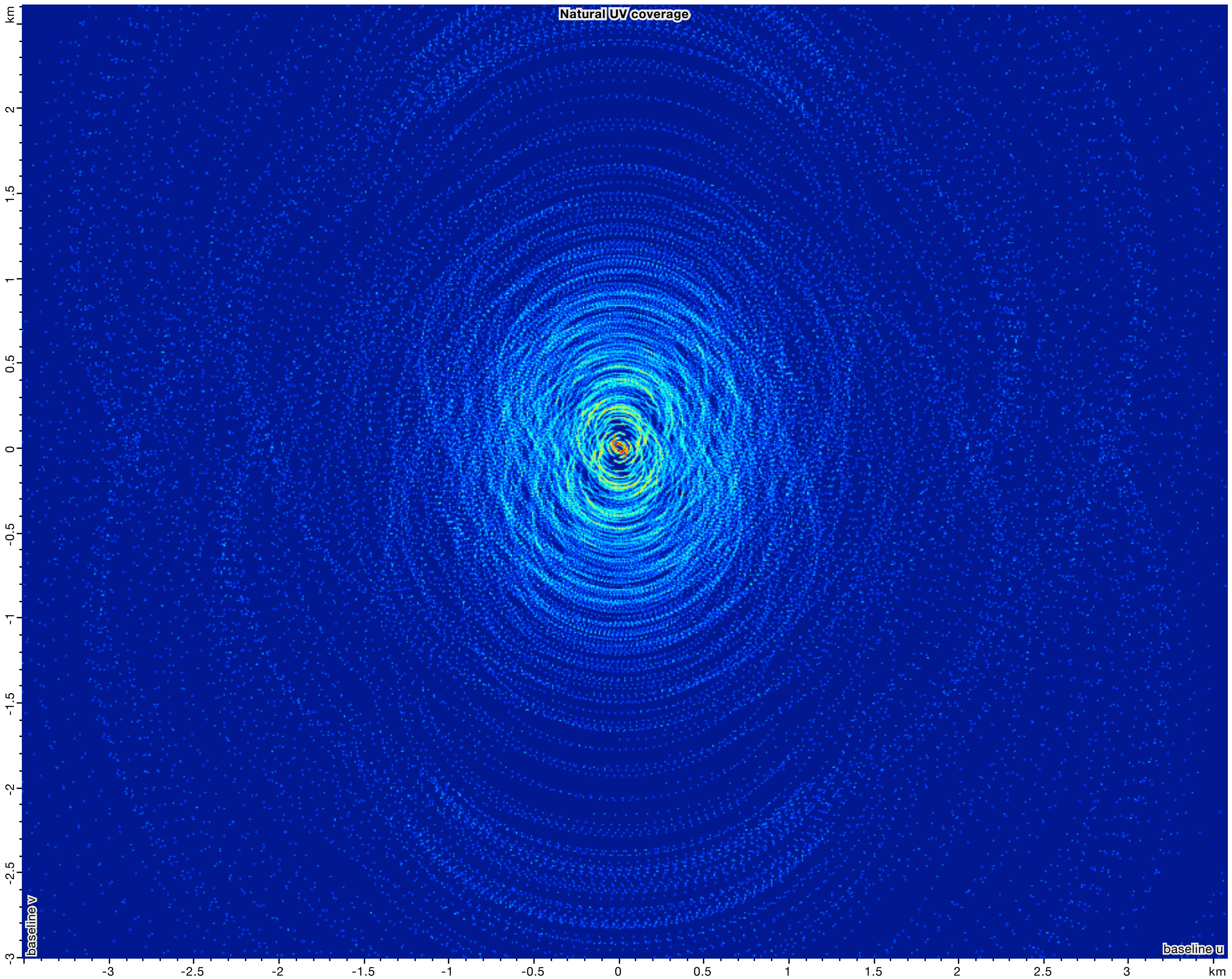
But…

– Maximum angular scale even with misaiming is: $\theta_{max} \sim \lambda/(d_{\min} - D)$



That's the zero-spacing problem

ASKAP, 8h



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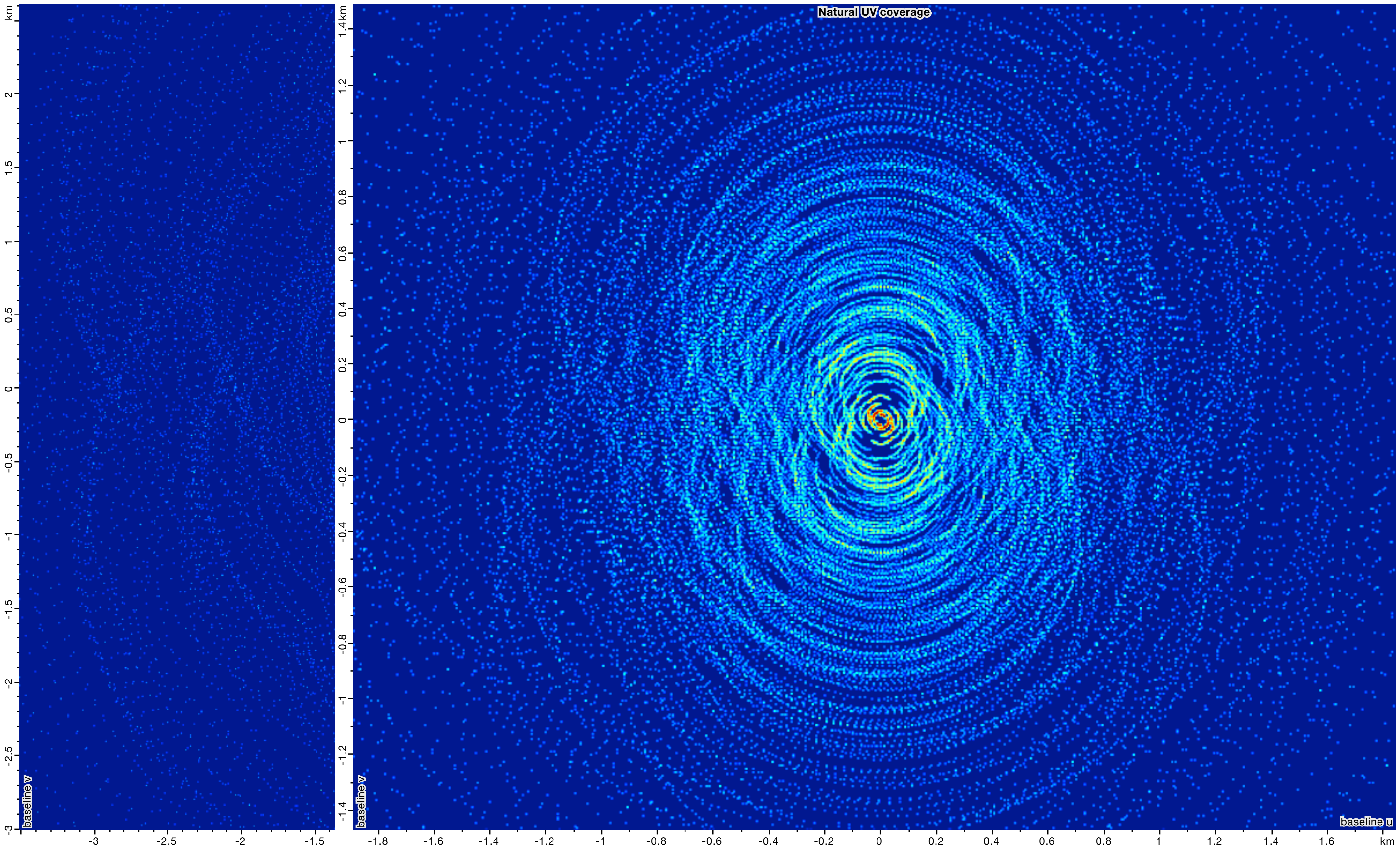

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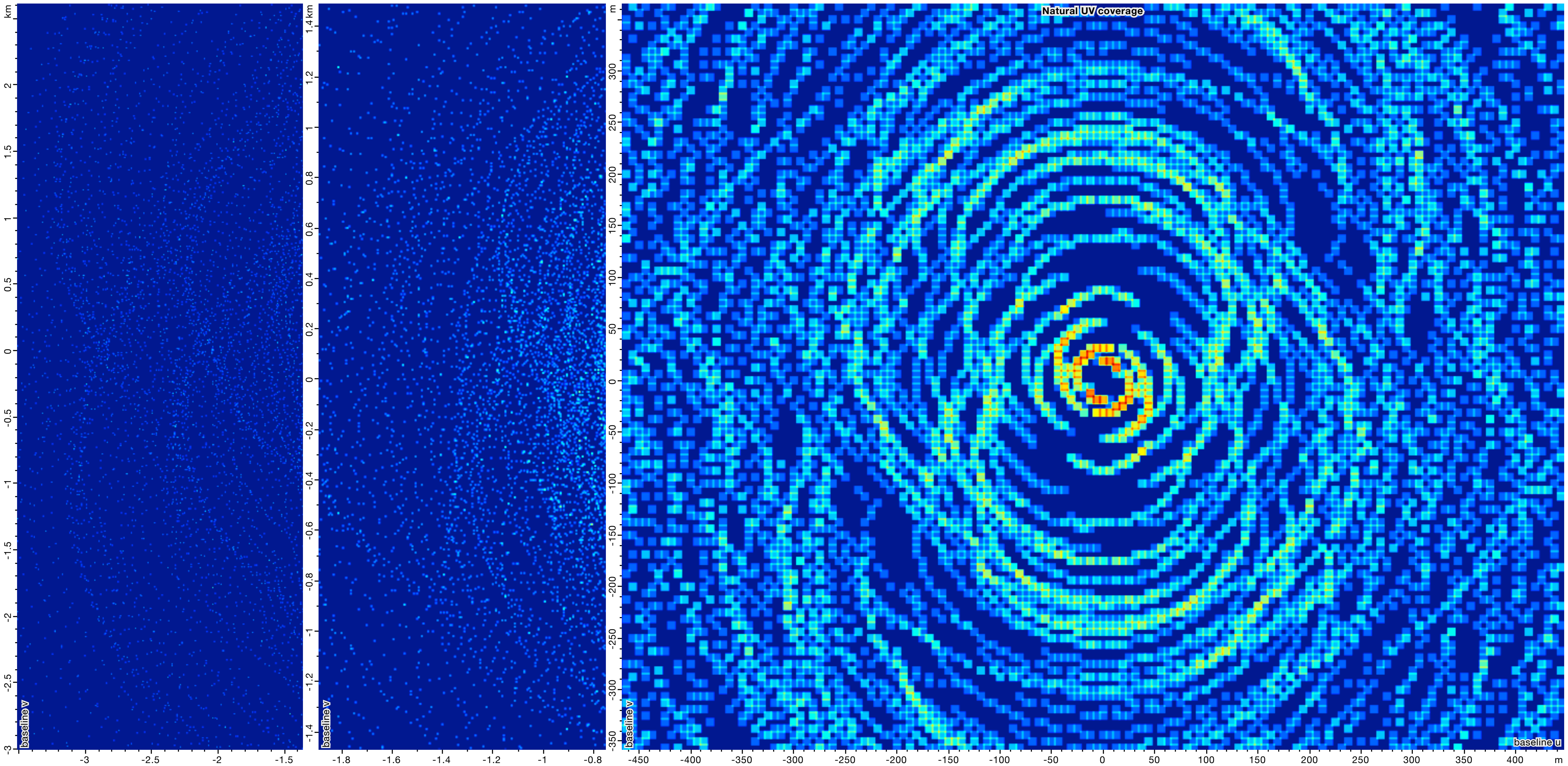


The zero-spacing problem

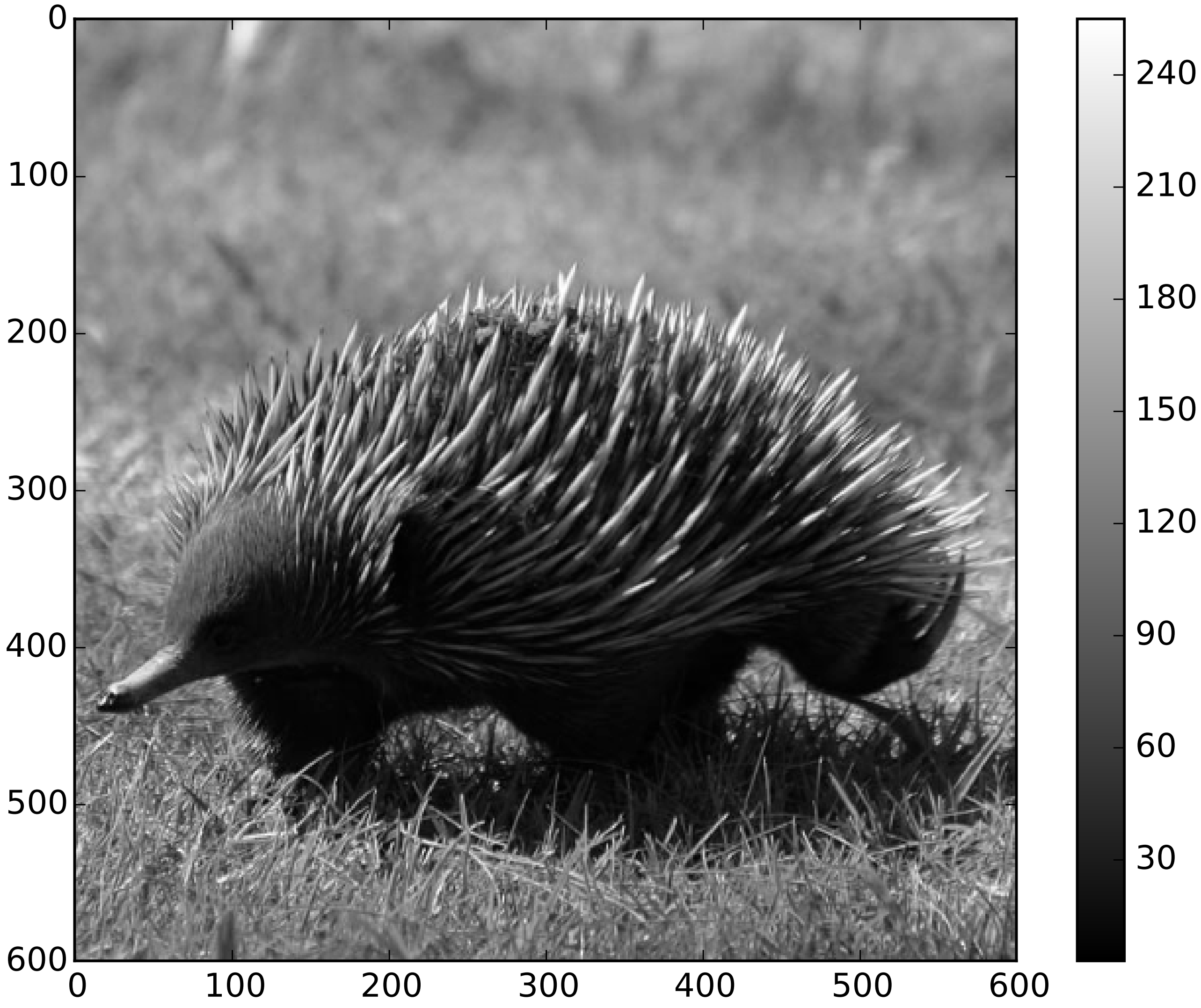
- So if the source is large compared to

$$\theta_{max} \sim \lambda / d_{min}$$

there's a problem that:

1. Limits ability to recover large-scale structure
2. Causes image artefacts around extended objects
3. Prevents total flux measurements

Echidna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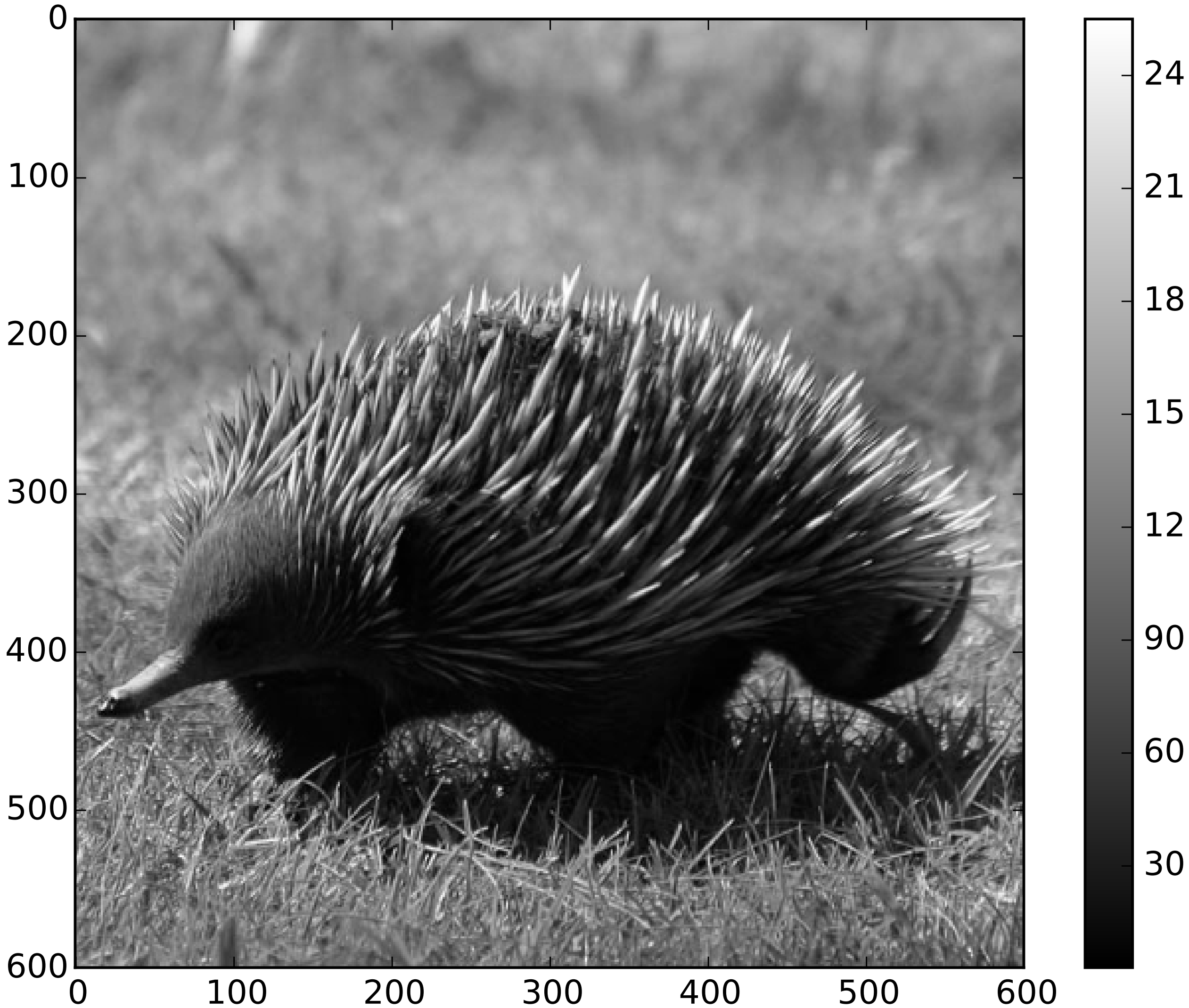
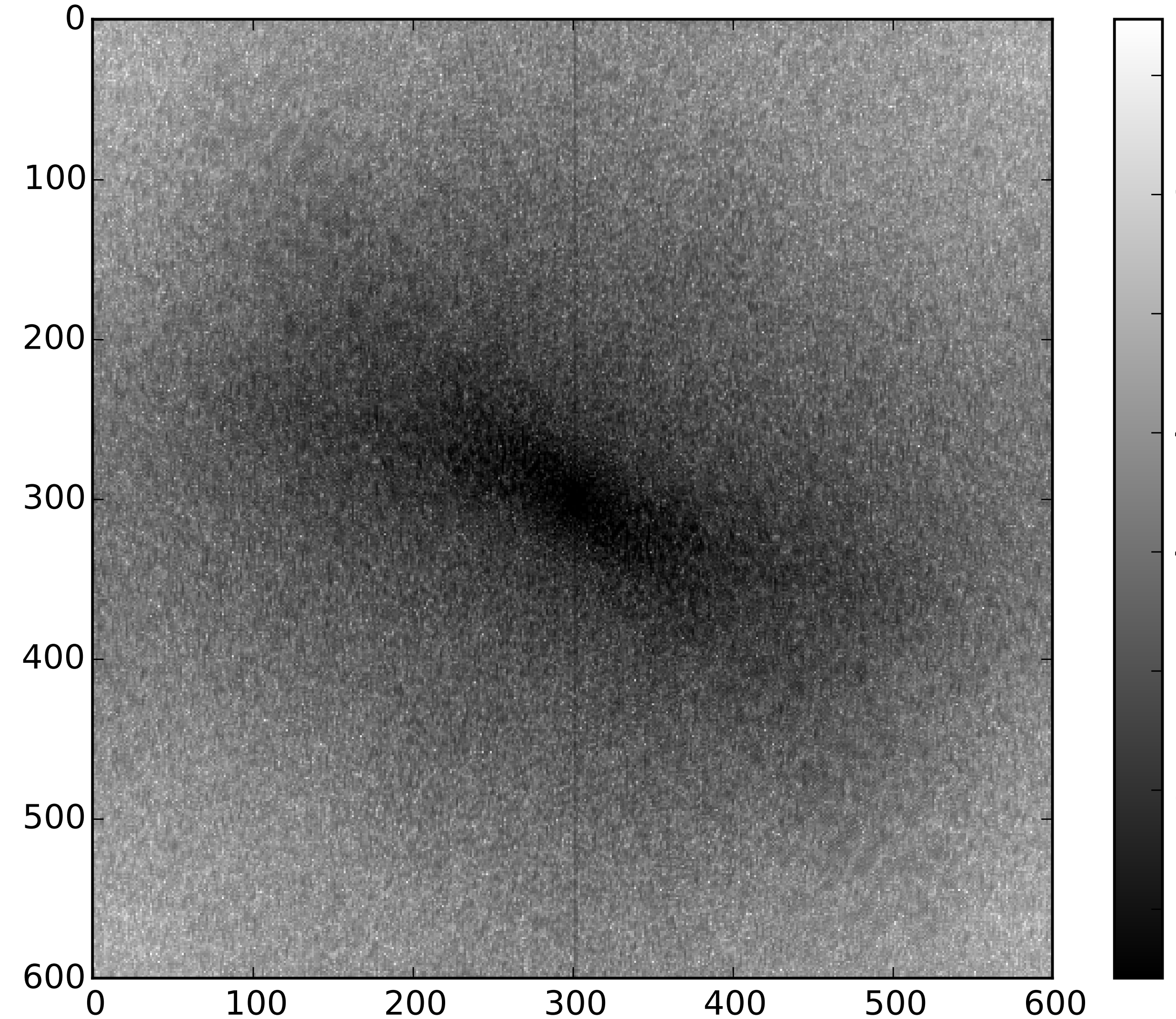
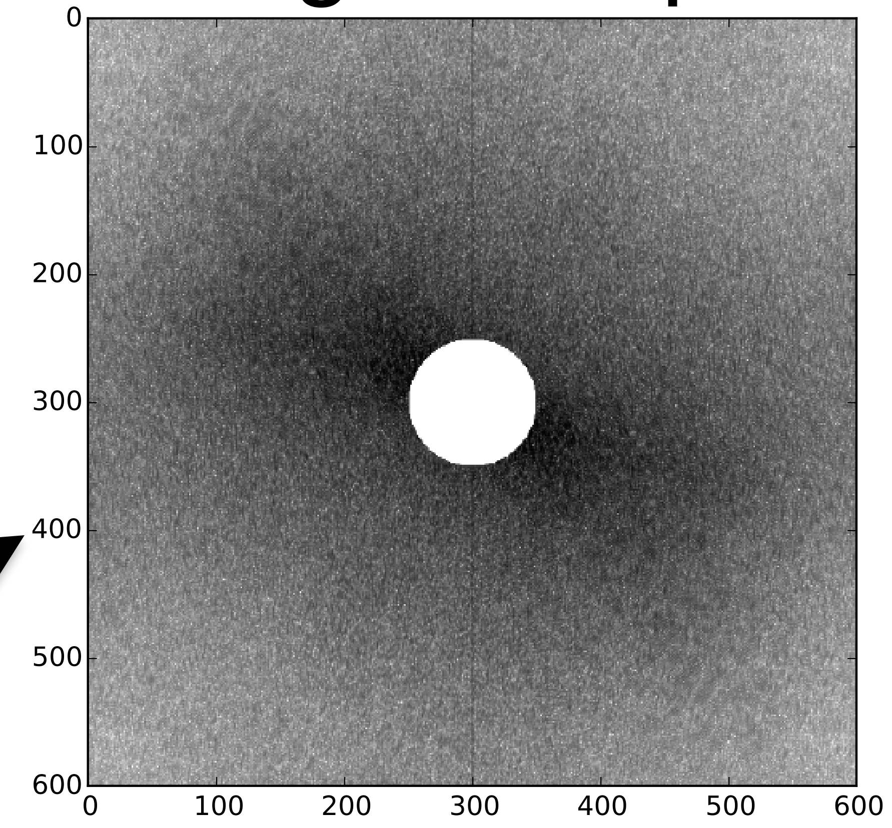
Echidna



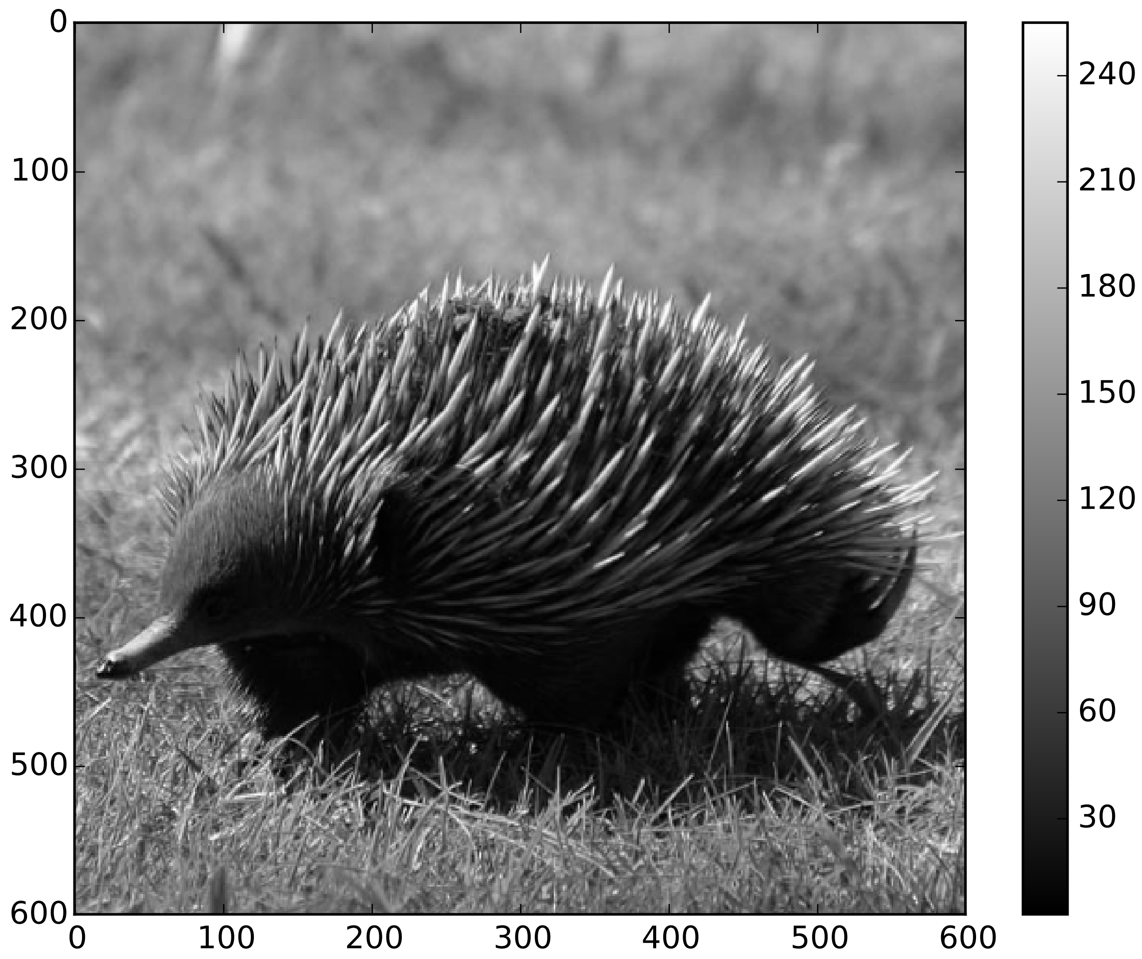
FT(Echidna)



missing zero-spacing



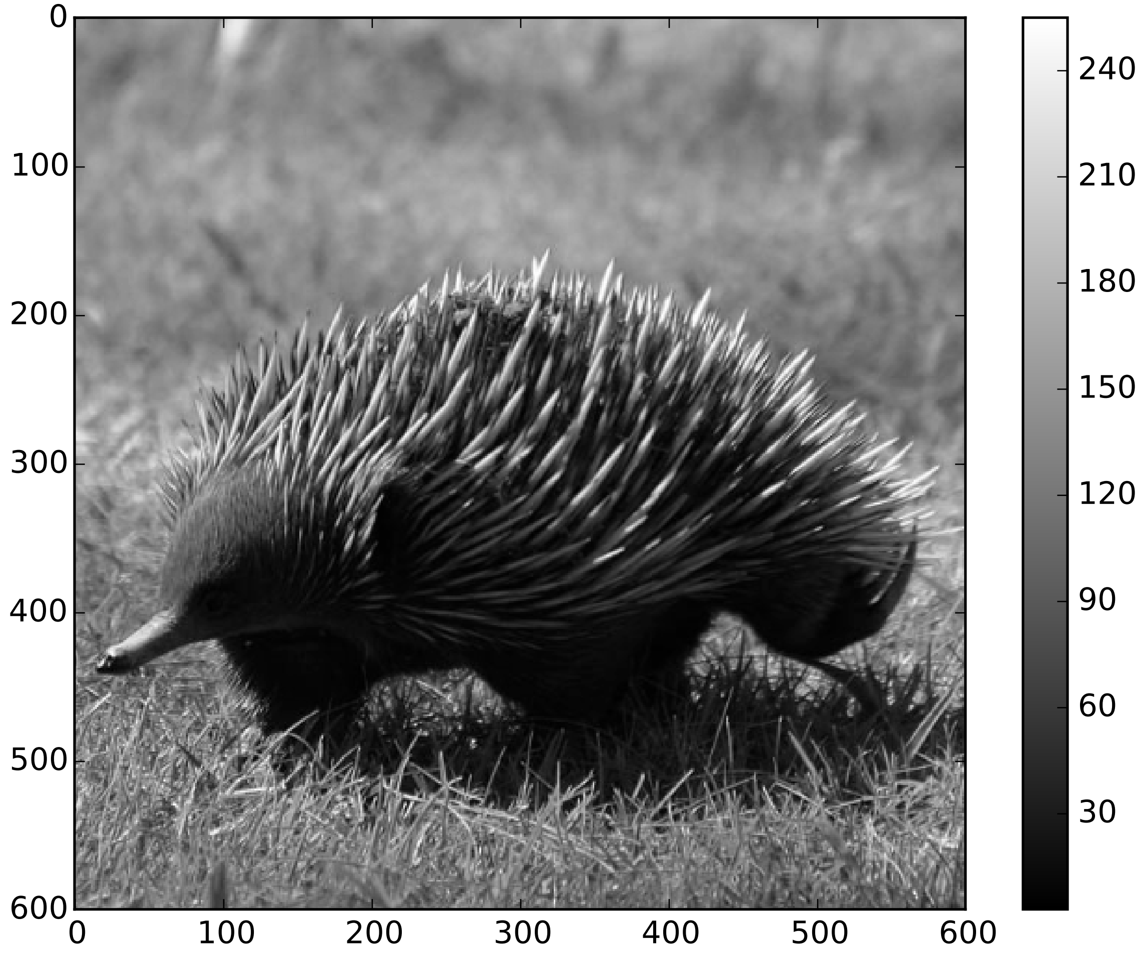
Echidna



FT

missing zero-spacing

Echidna



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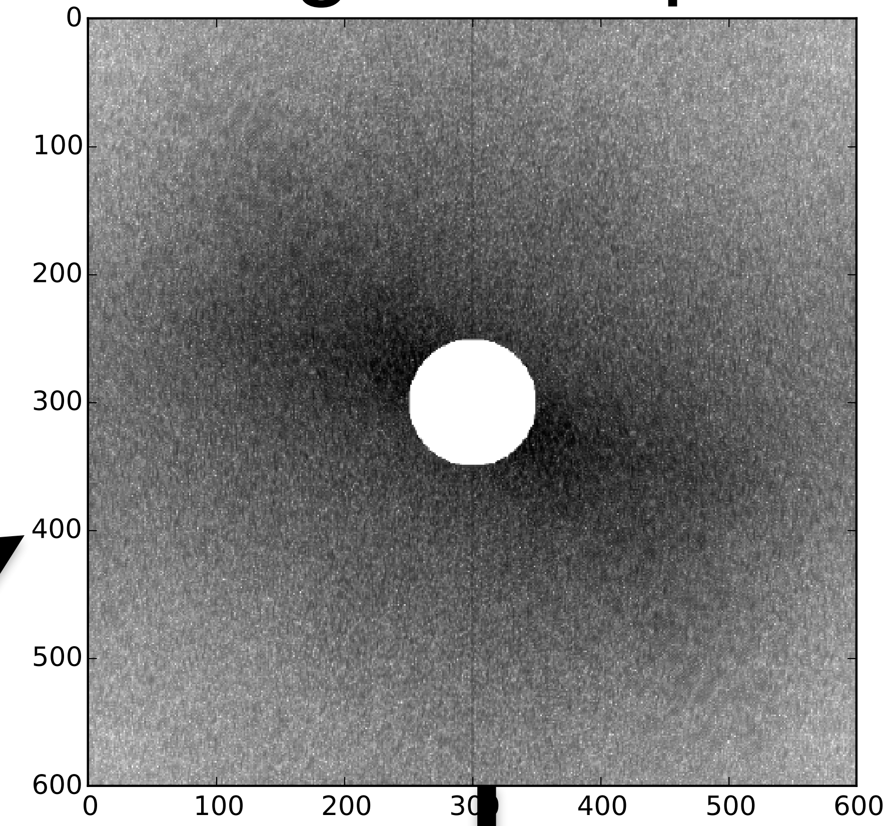
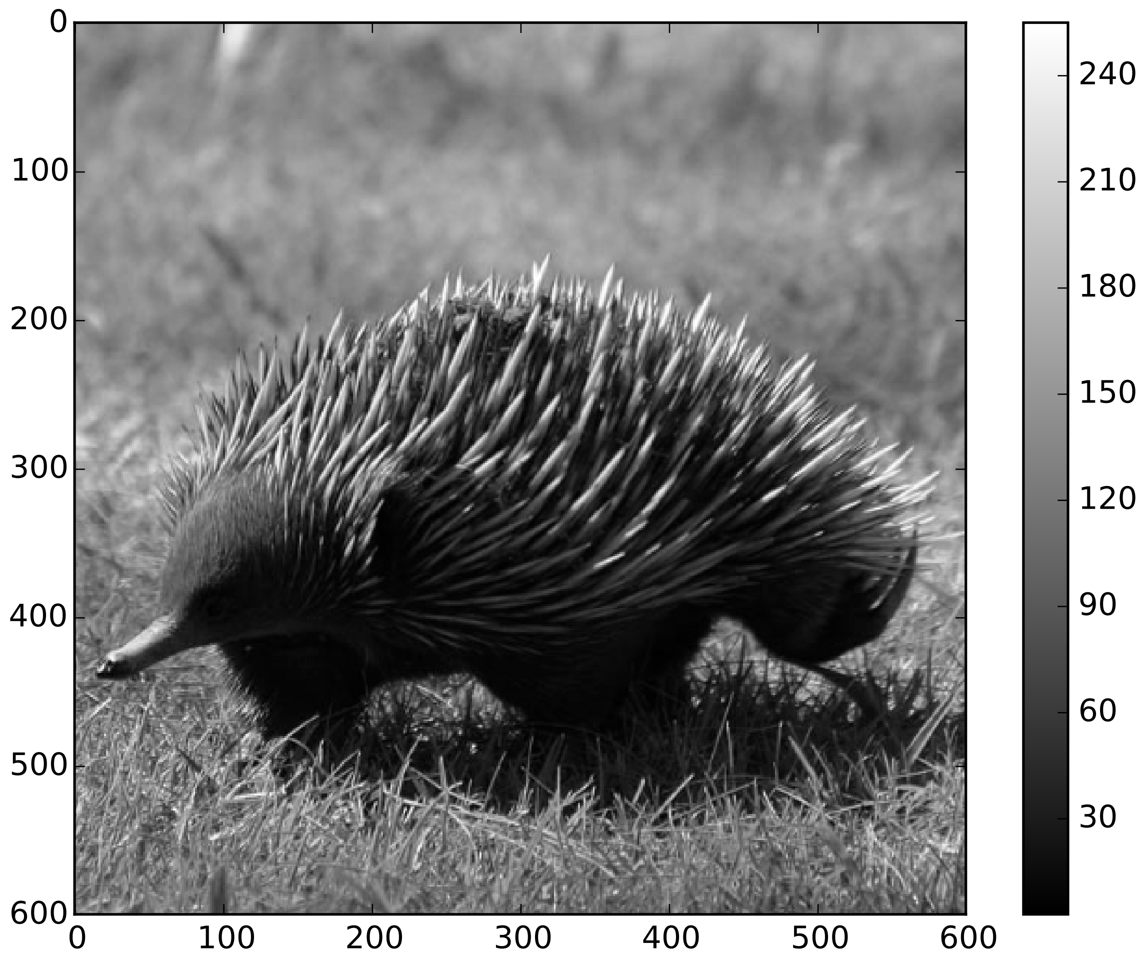


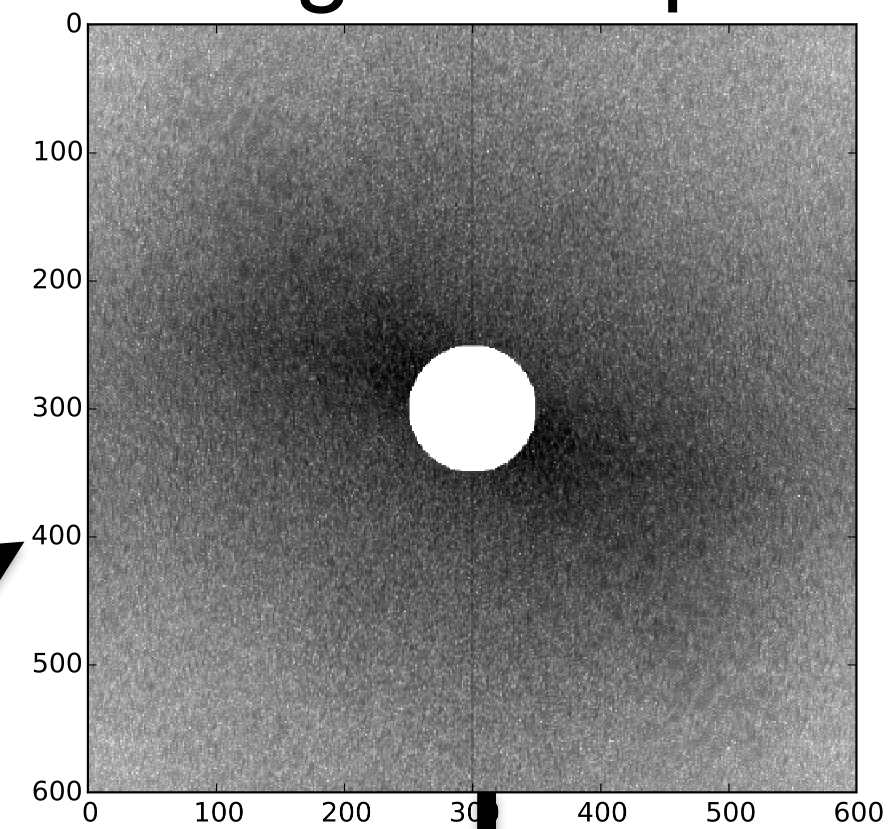
FT^{-1}

missing zero-spacing

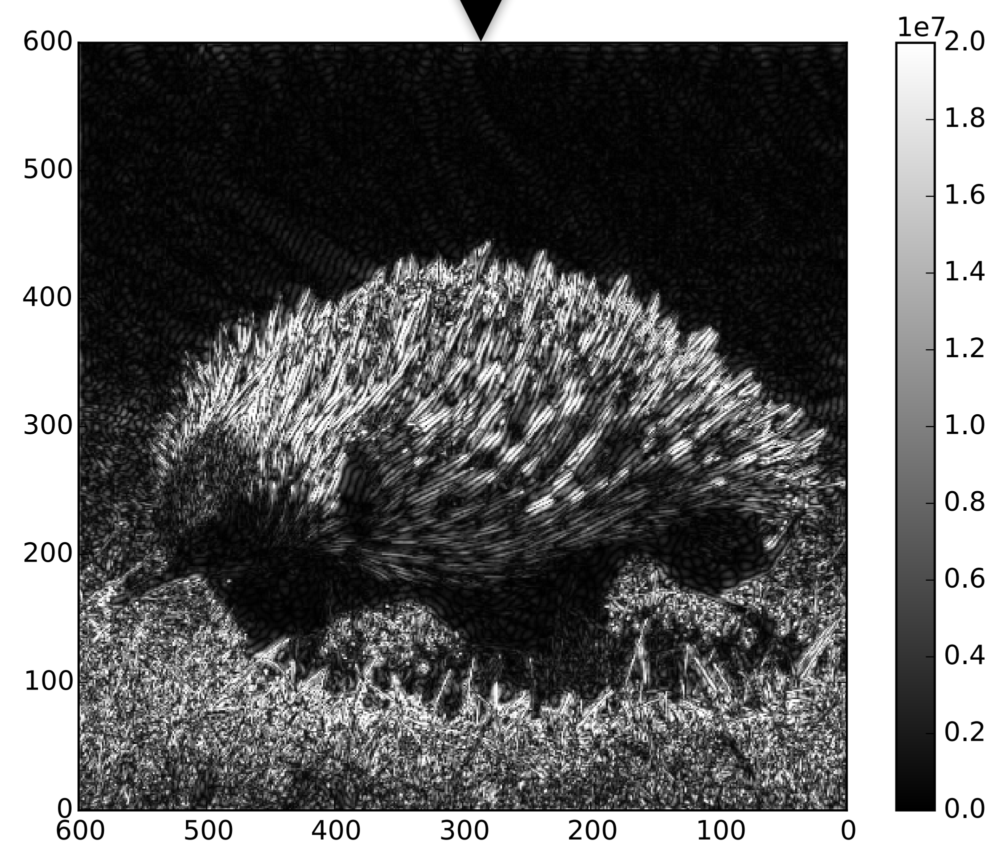
Echidna



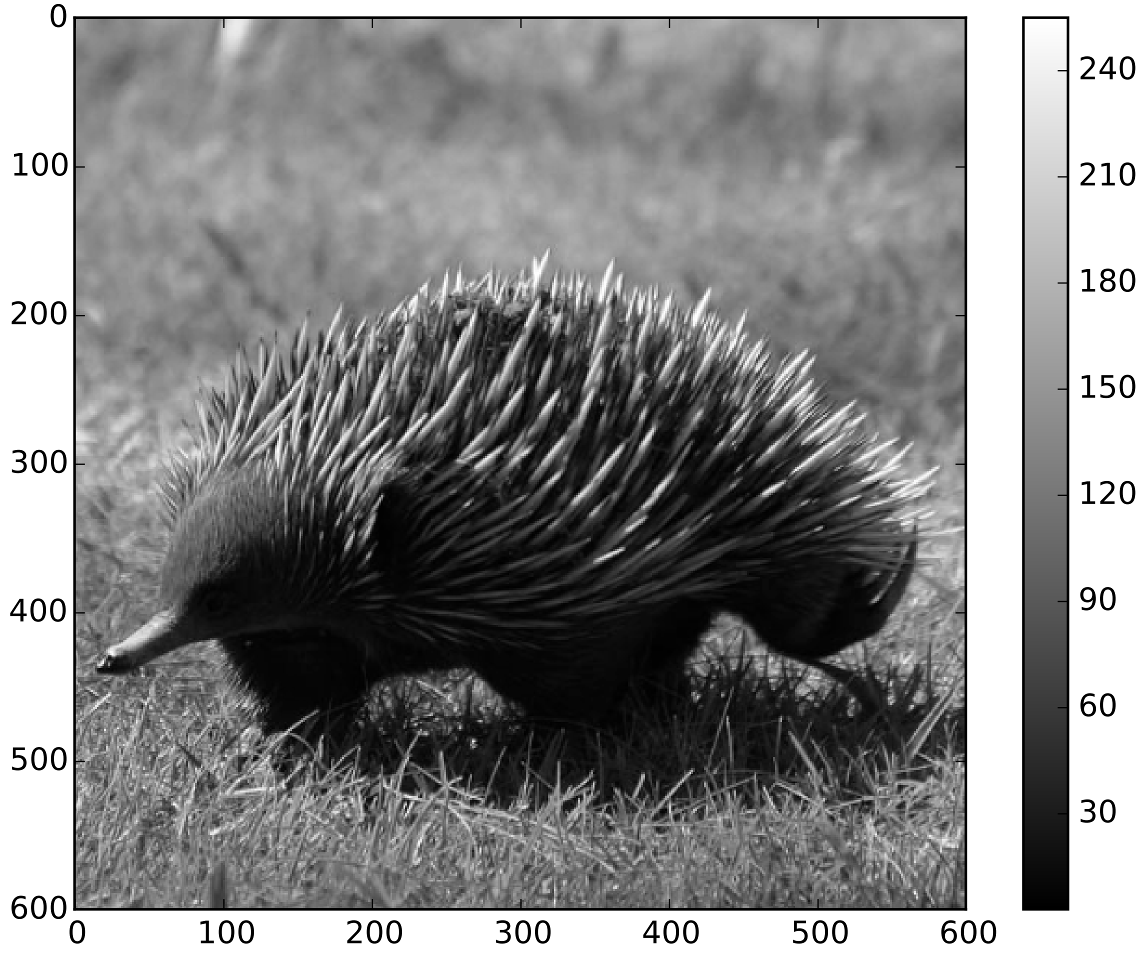
FT



FT^{-1}

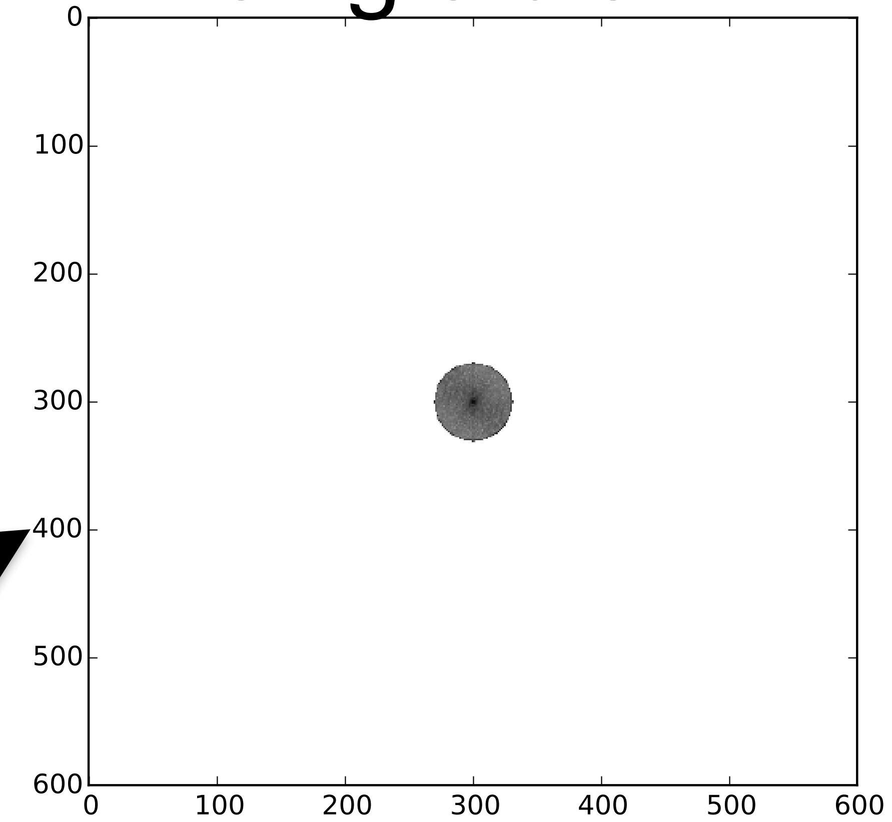


Echidna



FT

“single dish”



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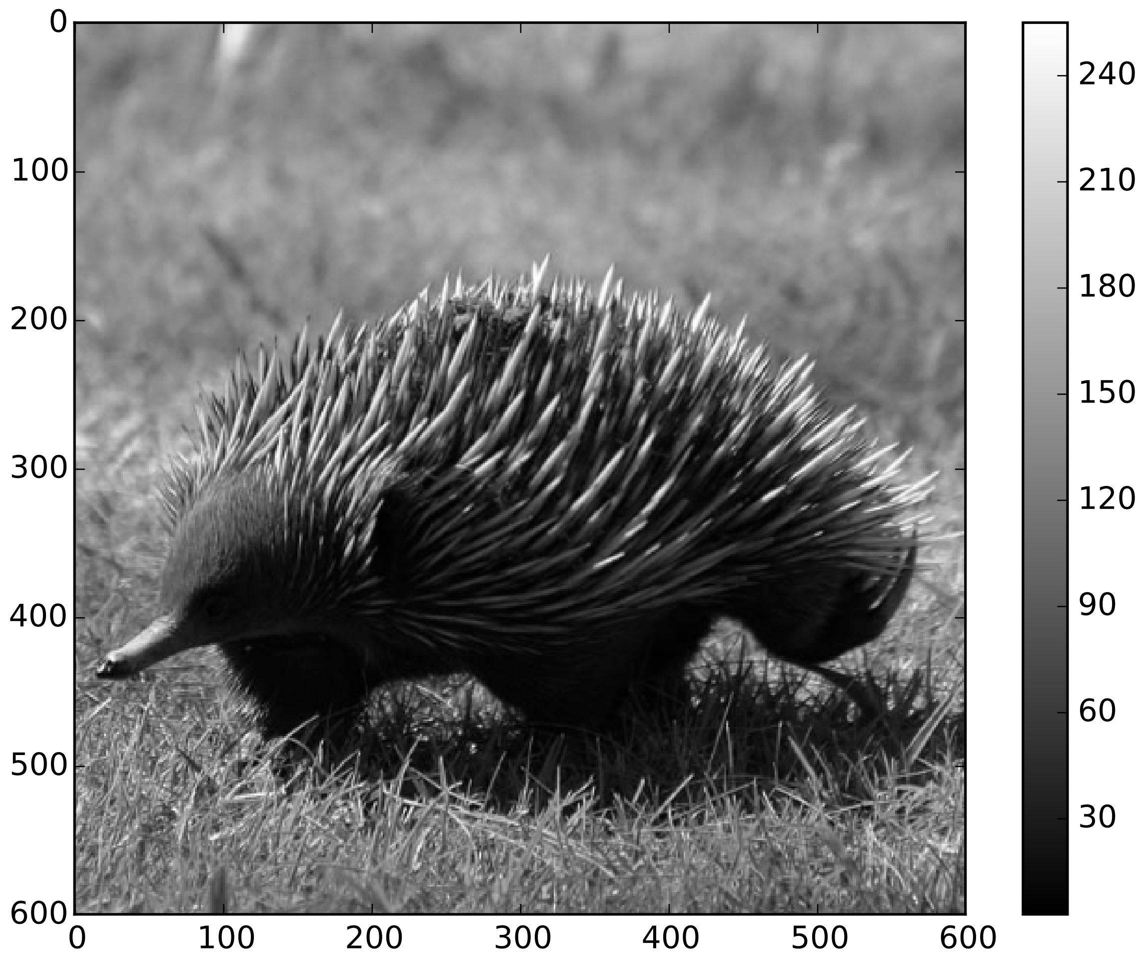

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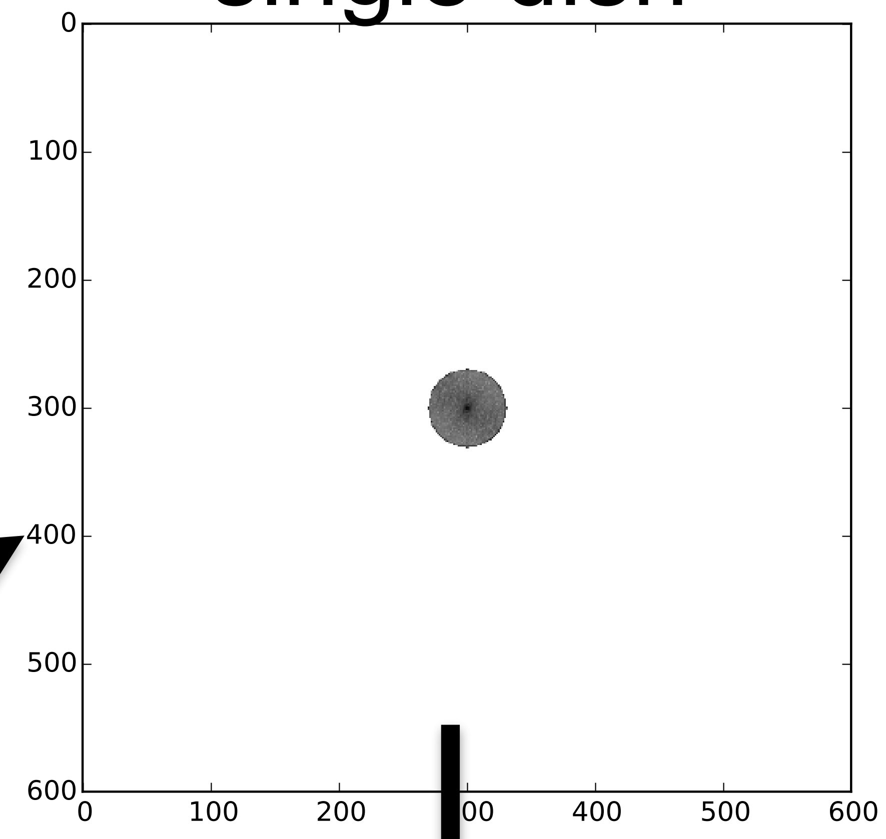

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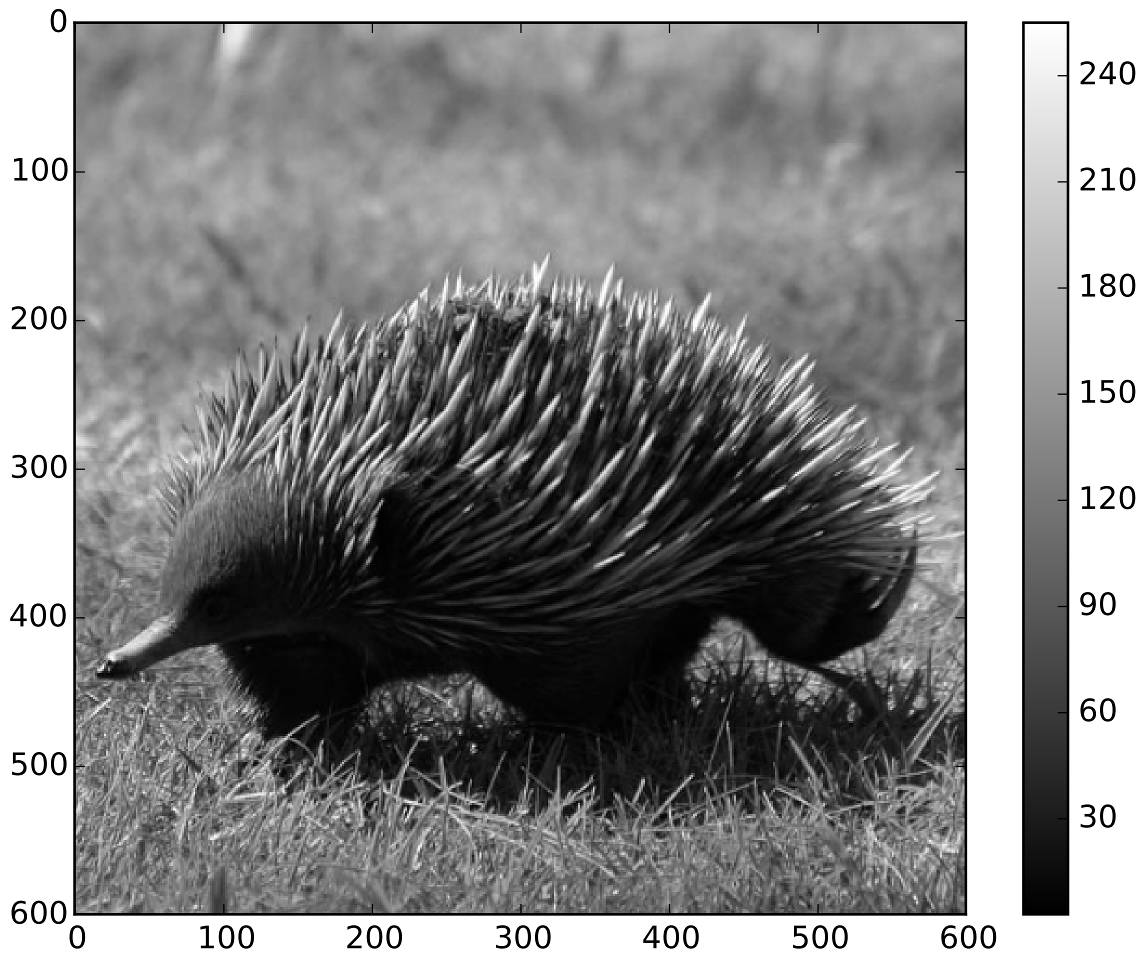

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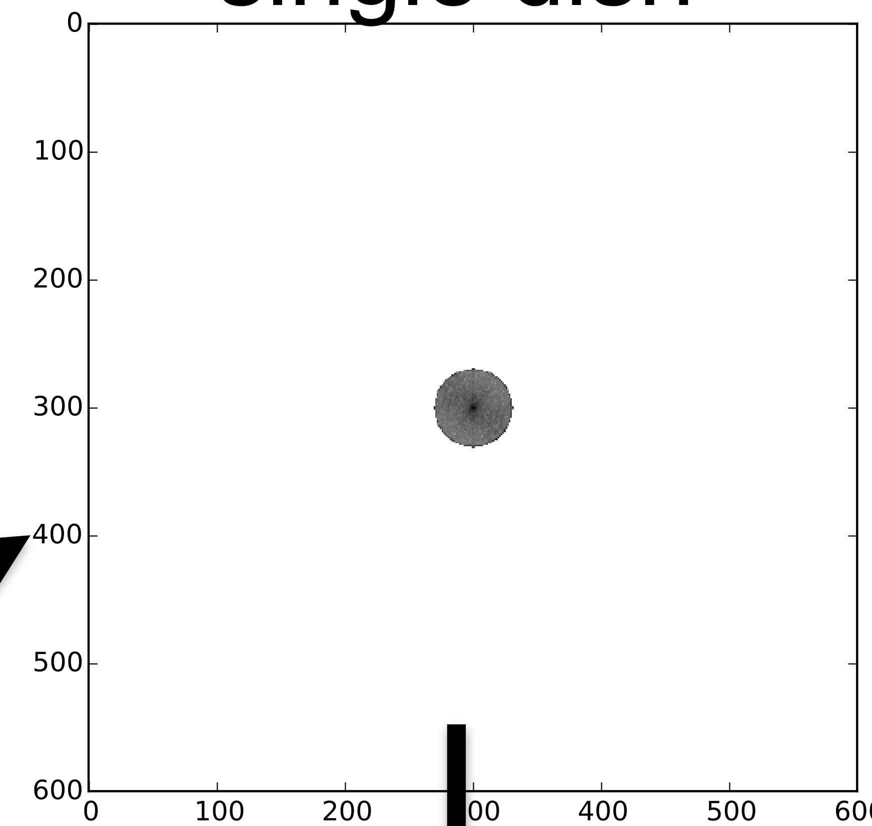


FT^{-1}

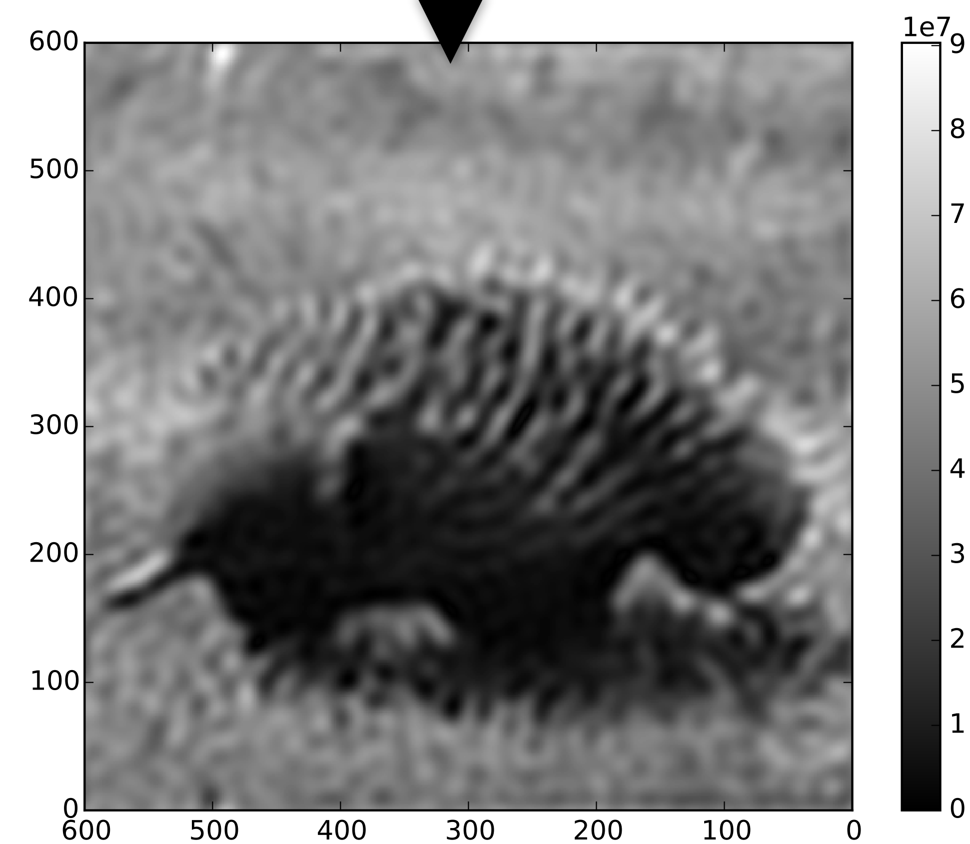


Image Artefacts

Fourier domain | Spatial domain

- Cause of "negative bowls"
- Cleaning algorithms try to recover this without information

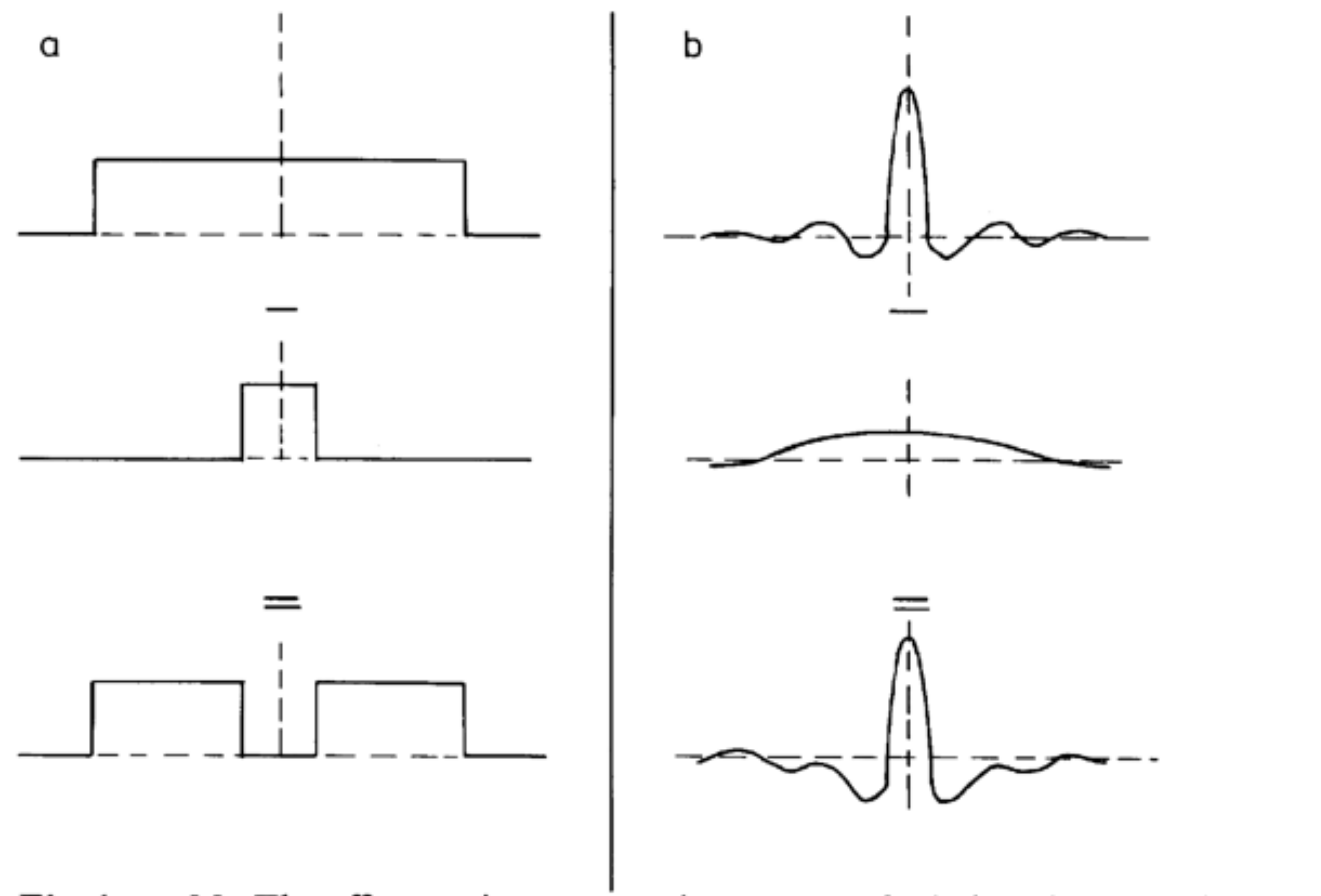
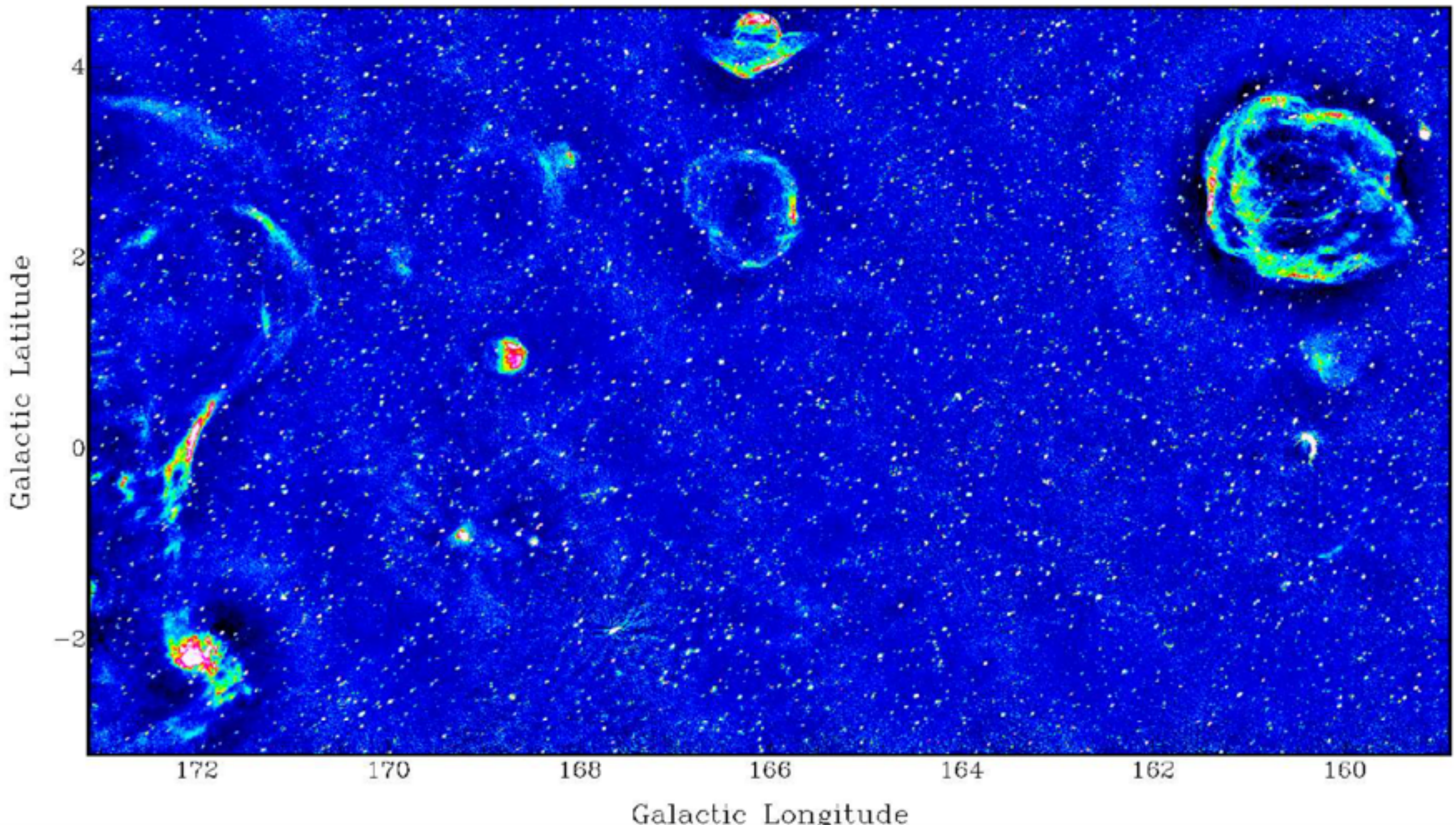


Fig. 1a and b. The effect on instrumental response of missing short spacings. **a** Observed spatial frequencies and **b** the corresponding instrumental response

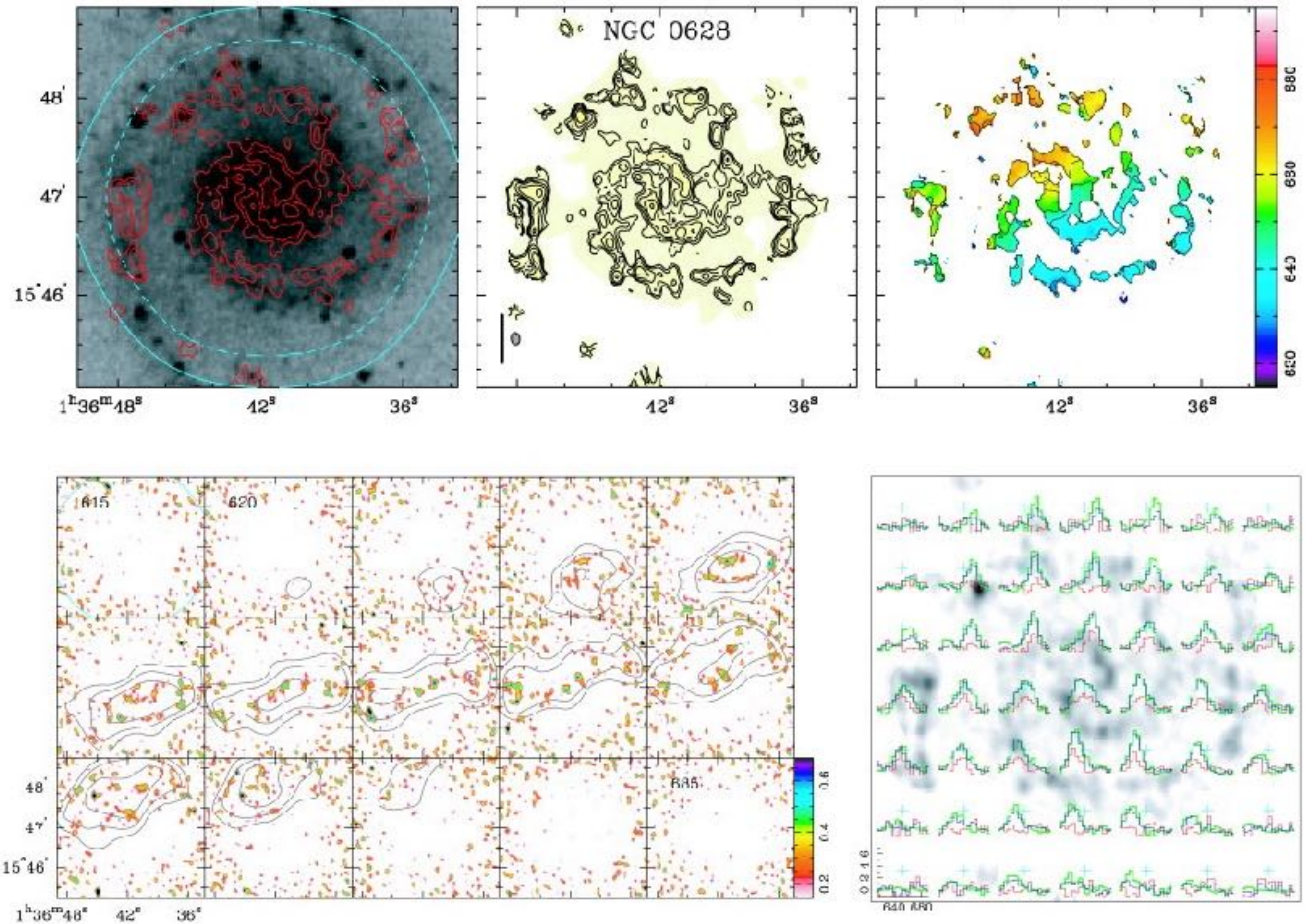
Braun & Walterbos (1985)

Negative bowls



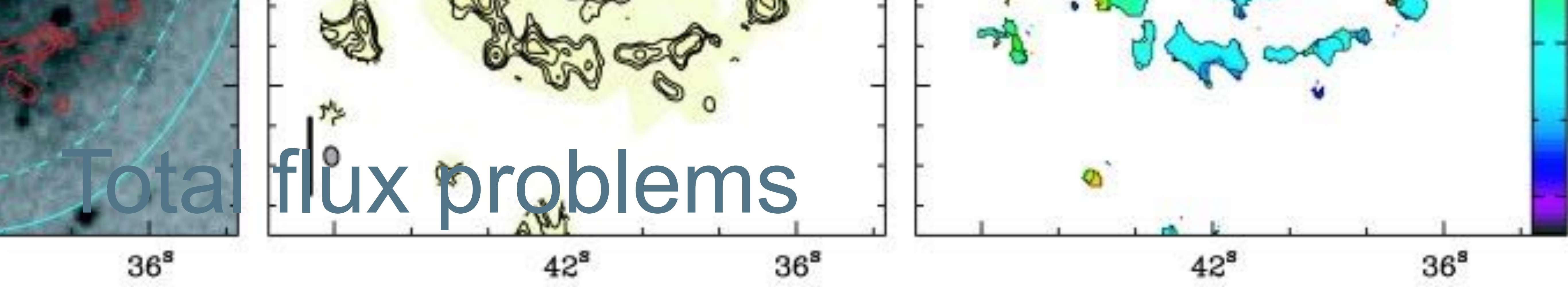
from the CGPS

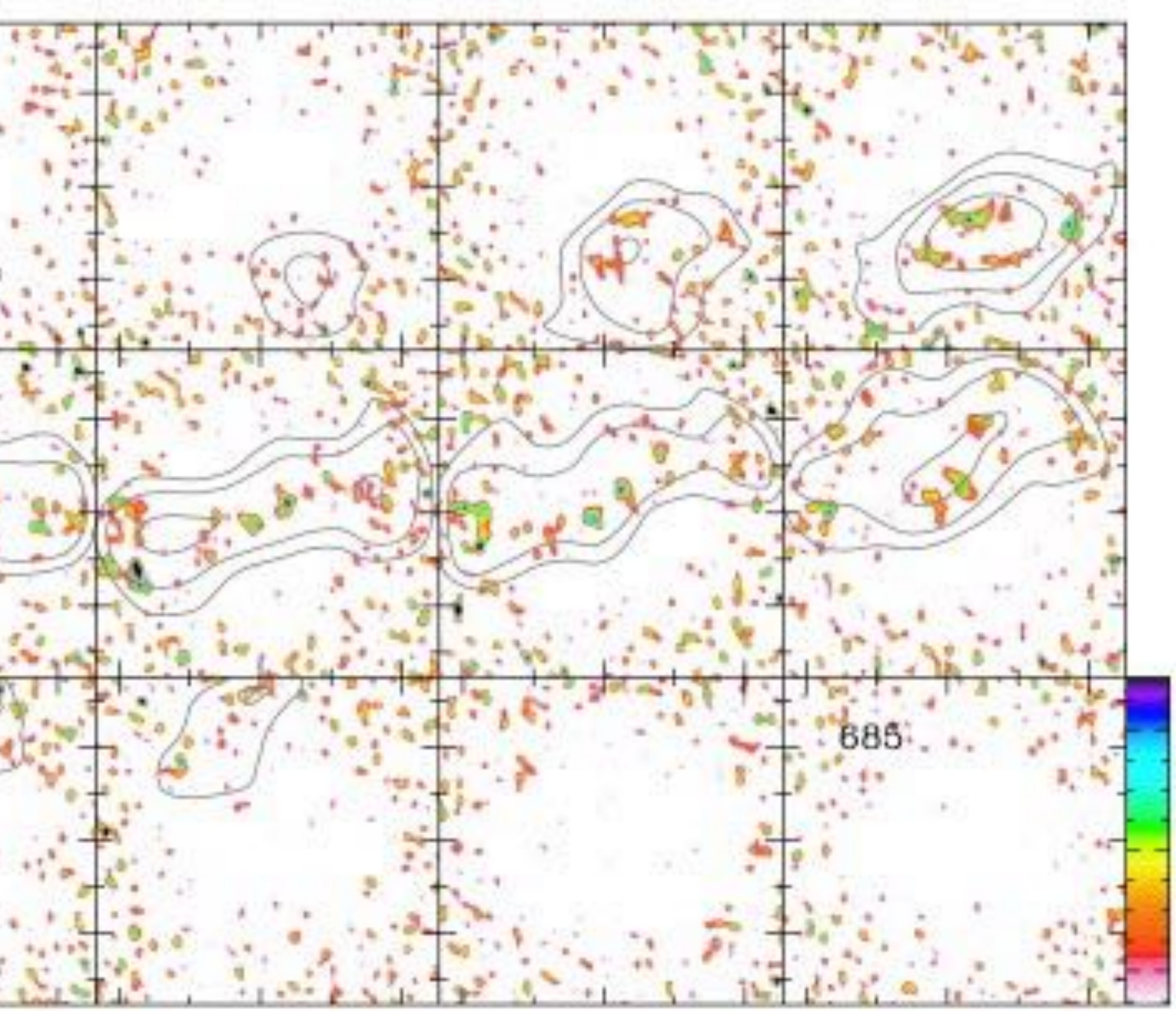
Total flux problems

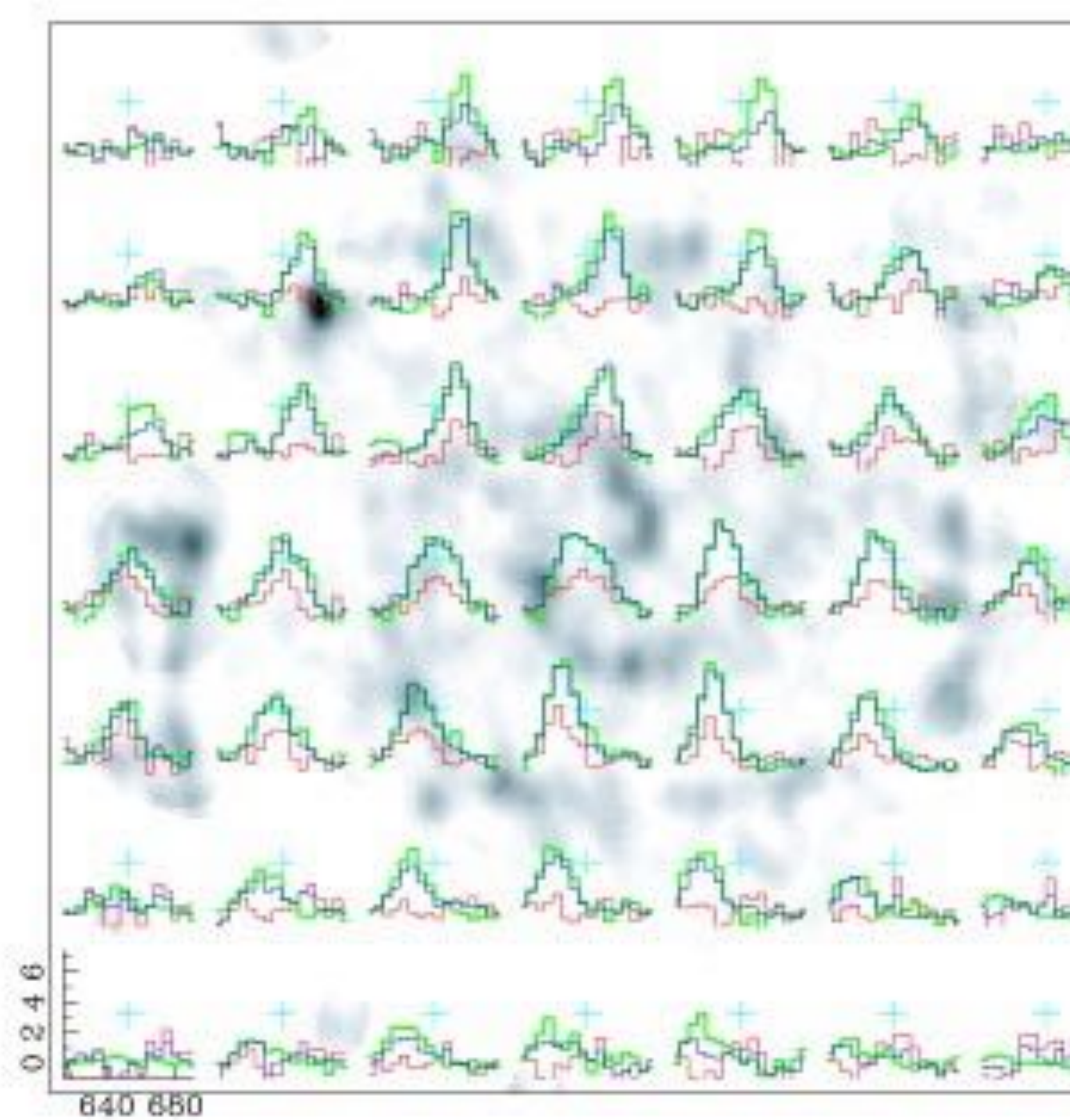


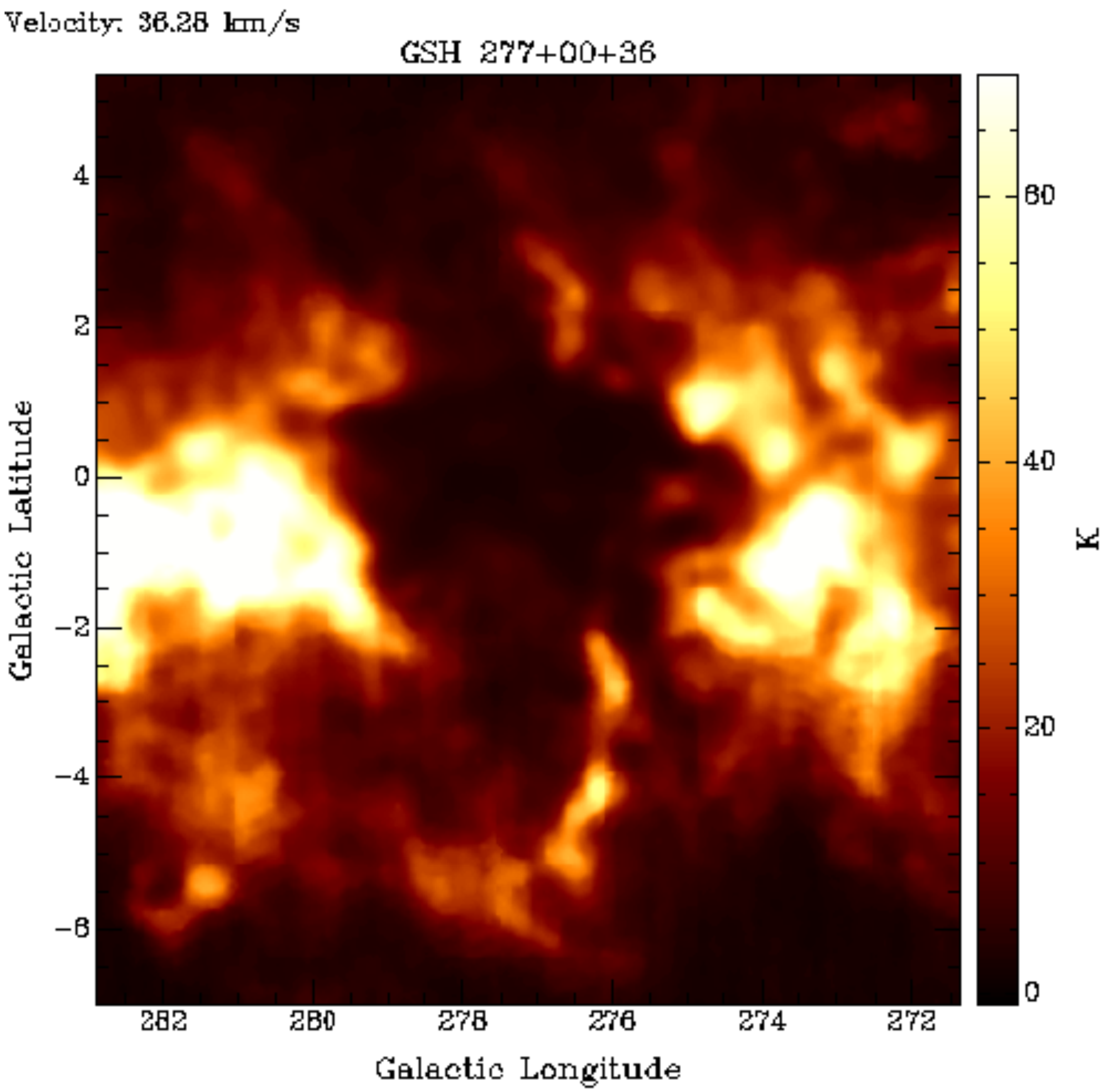
Helfer et al (2003)

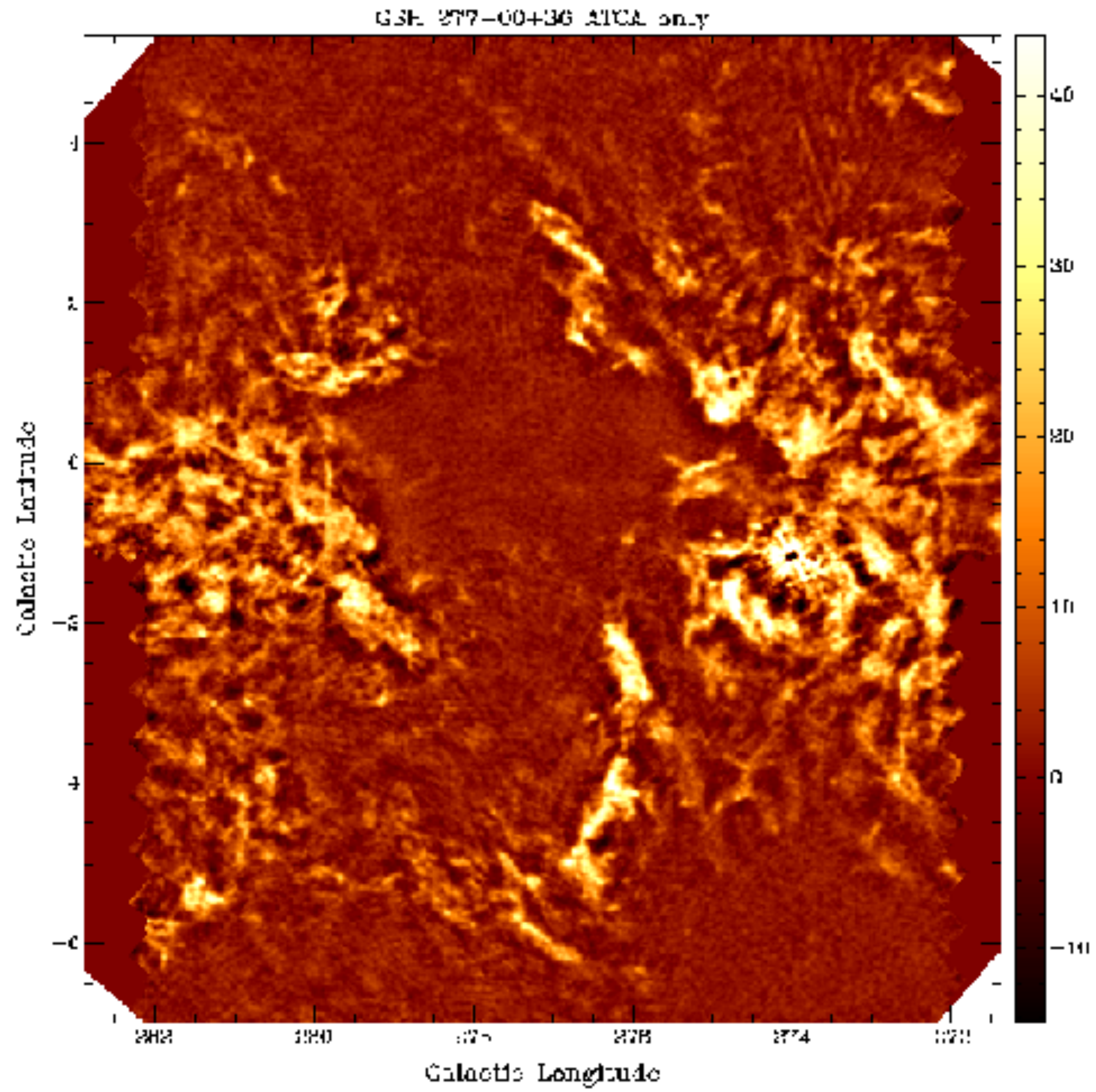
Total flux problems





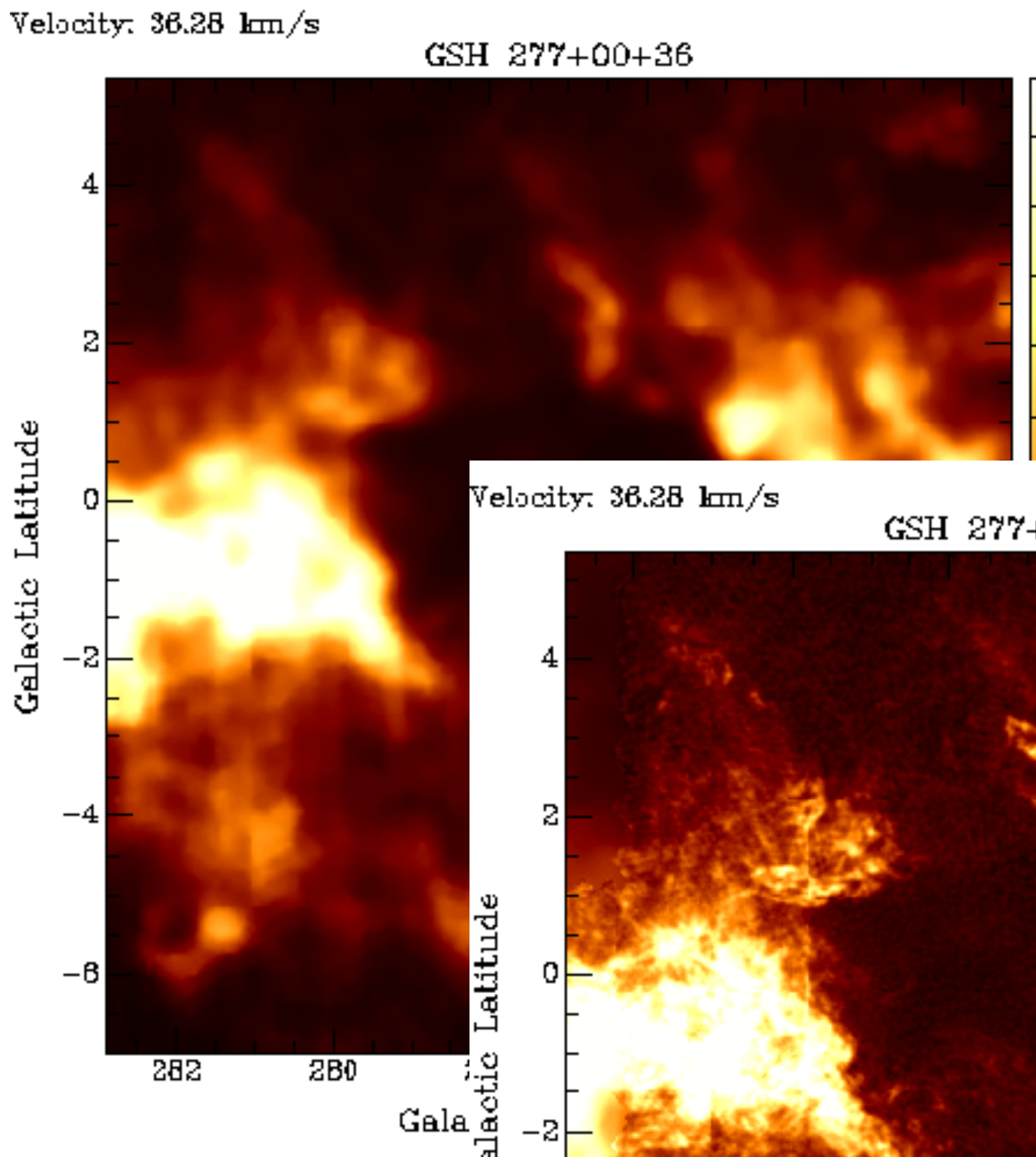


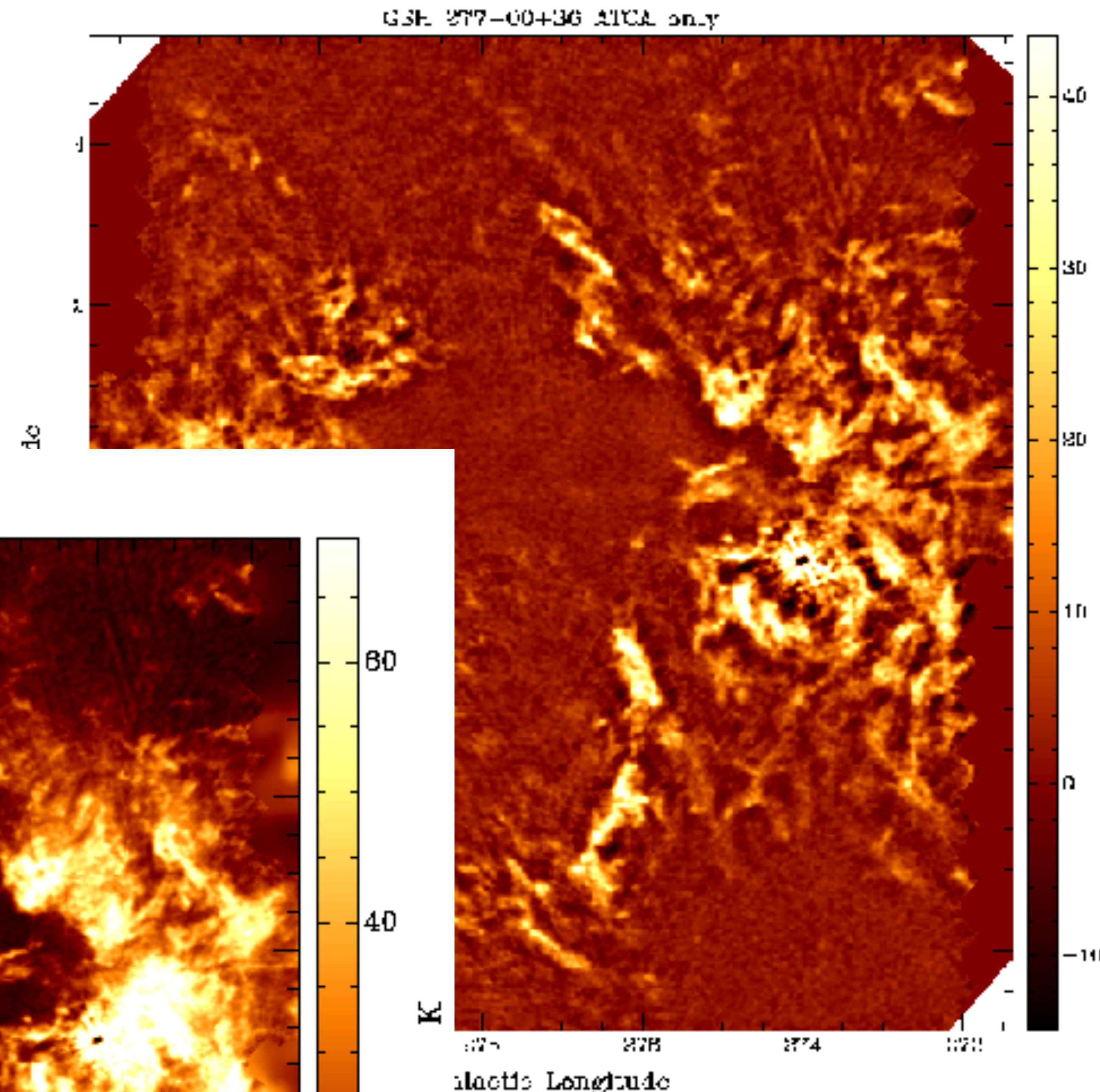


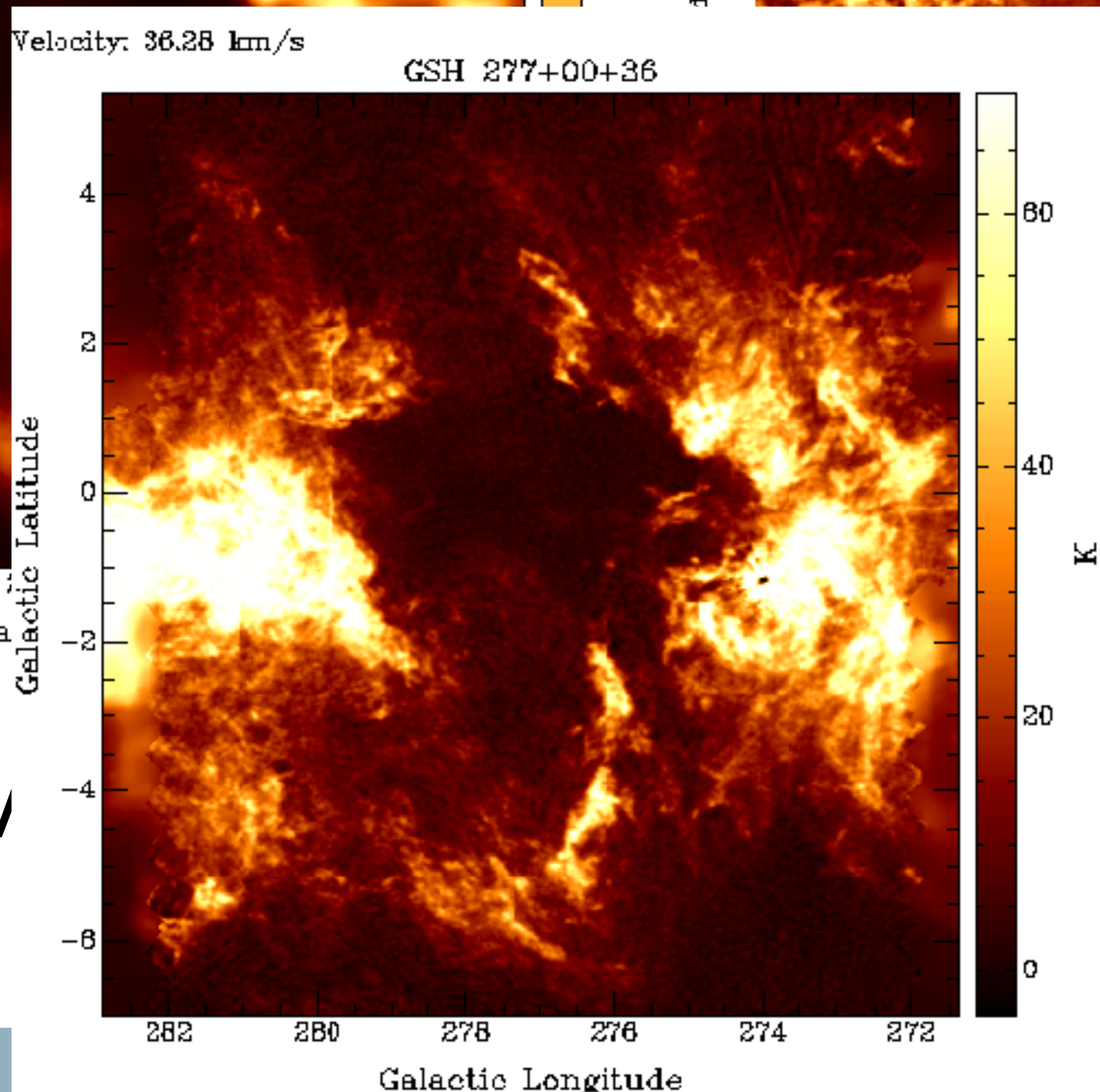


Recovering large-scale diffuse emission

McClure-Griffiths et al (2003)







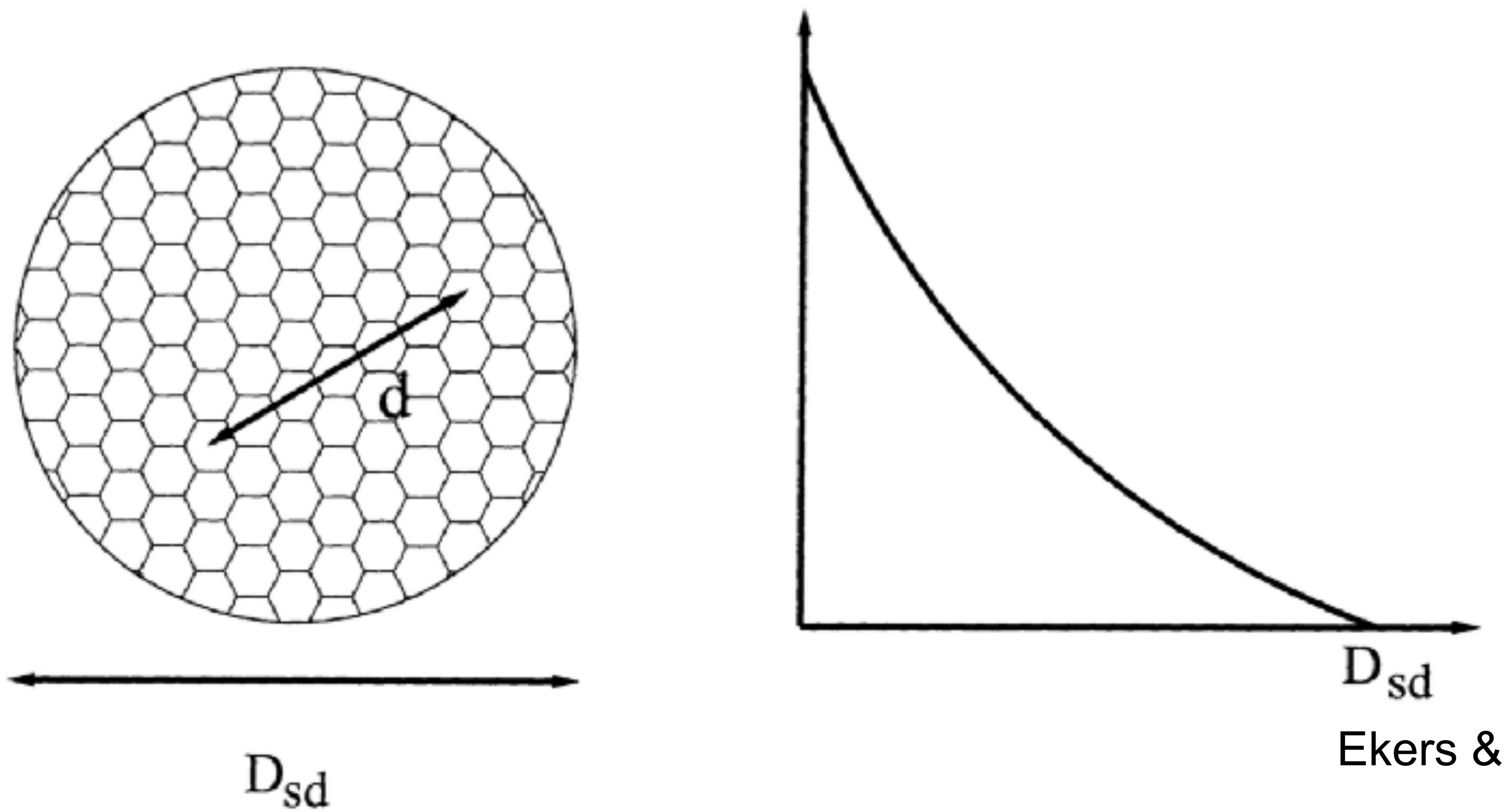
Recov … emission

McClure-Griffiths et al (2003)

Solution Methods:

- Basic methods:
  - Combine dirty data in u-v plane then image and deconvolve
  - Image, deconvolve, then combine
- Variants:
  - Combine during maximum entropy (“joint” deconvolution)
  - Combine during deconvolution with single-dish as model (“default” method)

Using a single-dish as an interferometer



Ekers & Rots (1979)

Single dish gives “visibilities” from zero-spacing to D

$$I^D_{sd}(l,m) = I(l,m) * B_{sd}(l',m')$$
$$V'_{sd}(u,v) = V(u,v) \times b_{sd}(u,v)$$

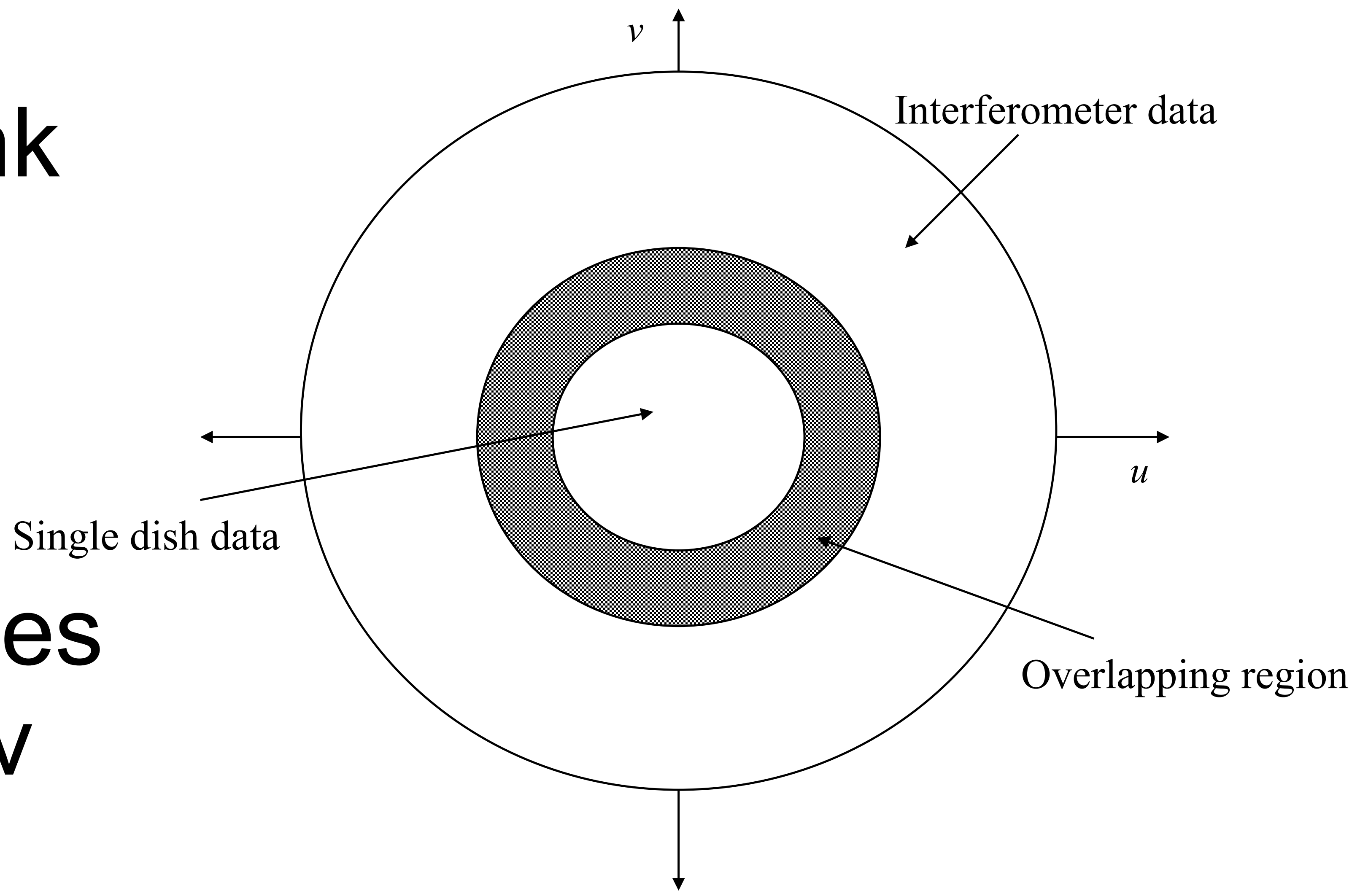
Cross-calibration

- Scale factor to link flux scales:

$$f_{cal} = \frac{S_{int}}{S_{sd}}$$

- Measure intensities in overlapping u-v space

$$f_{cal} = \frac{I_{int}}{I_{sd}}$$



Combine Dirty Images, then Deconvolve

- Combine the dirty images, I_{int}^{D} and I_{sd}^{D}

$$I_{comb}^{D} = \frac{I_{int}^{D} + \alpha\, f_{cal}\, I_{sd}^{D}}{1+\alpha}$$

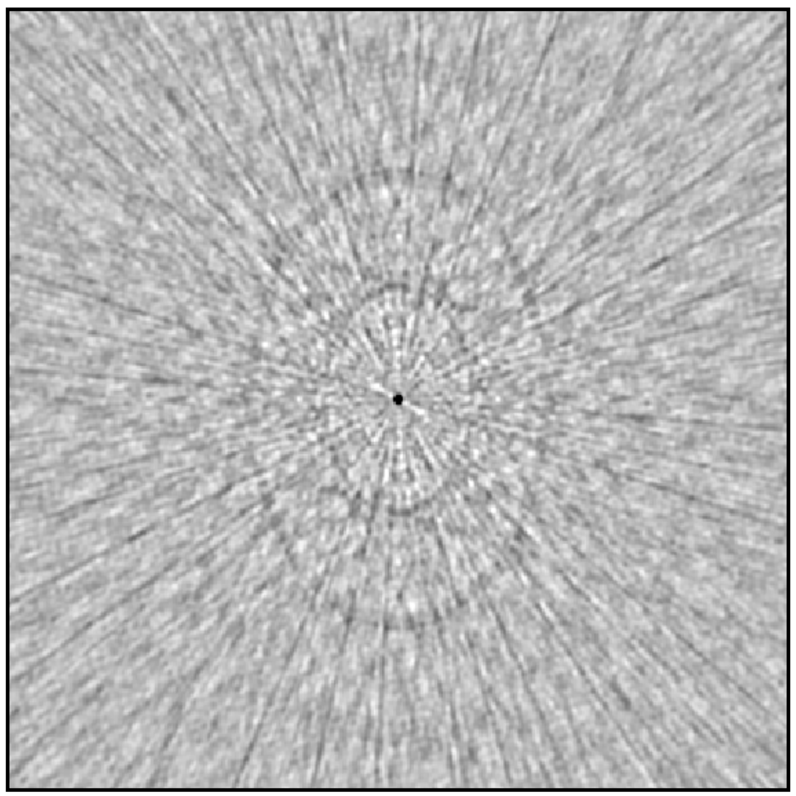
- where the ratio of beam solid angles gives

$$\alpha = \frac{\Omega_{int}}{\Omega_{sd}}$$

- and similarly combine the beams
  - Implemented in miriad's *mosmem*, casa clean(?)

Beam combination

ATCA



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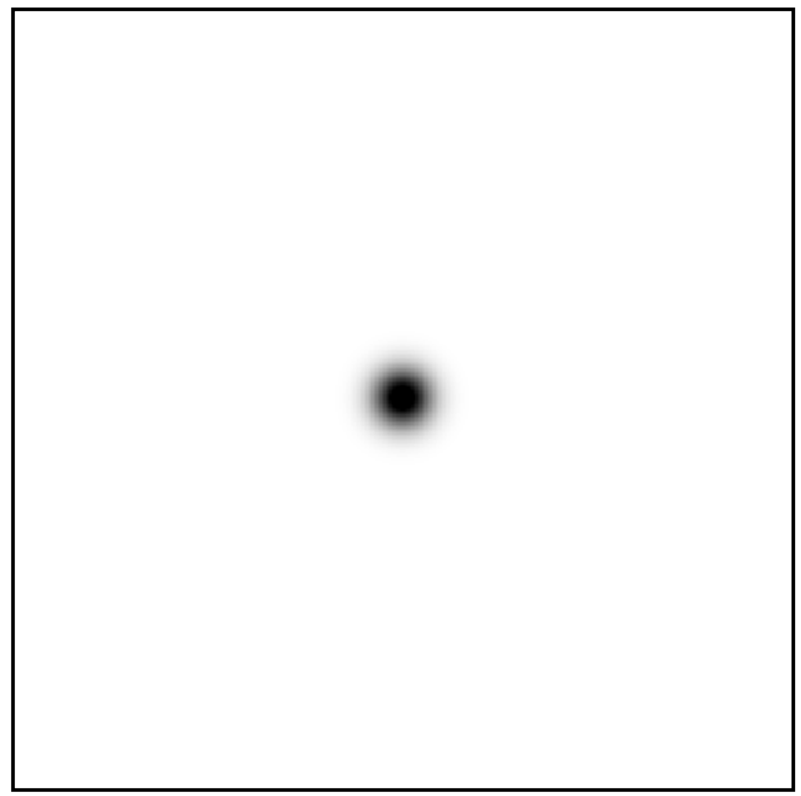
Parkes



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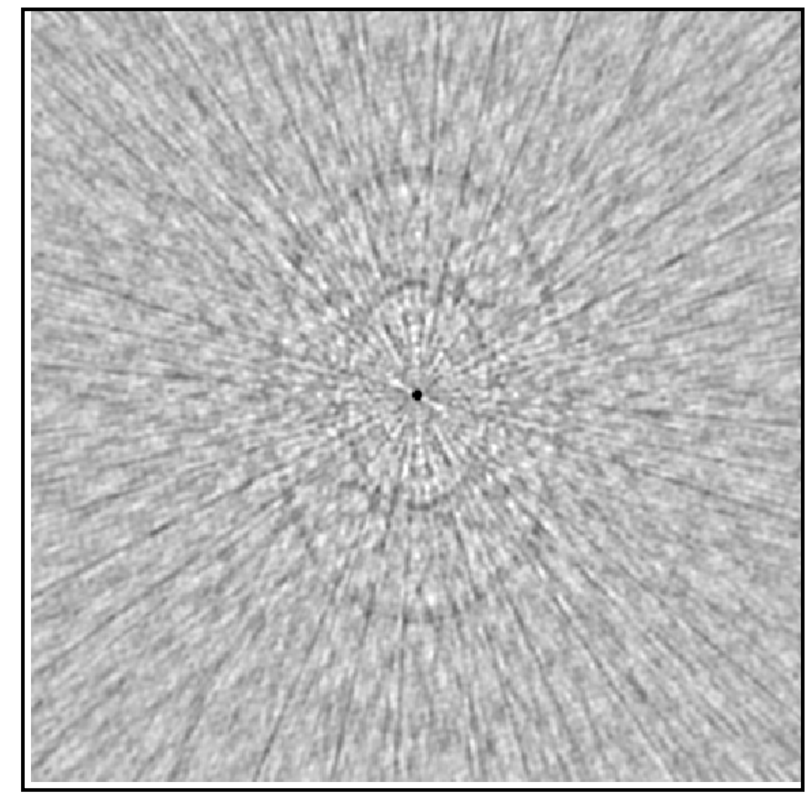
ATCA+Parkes



$$B_{comb} = \frac{B_{int} + \alpha\, B_{sd}}{1 + \alpha}$$

Combination after deconvolution

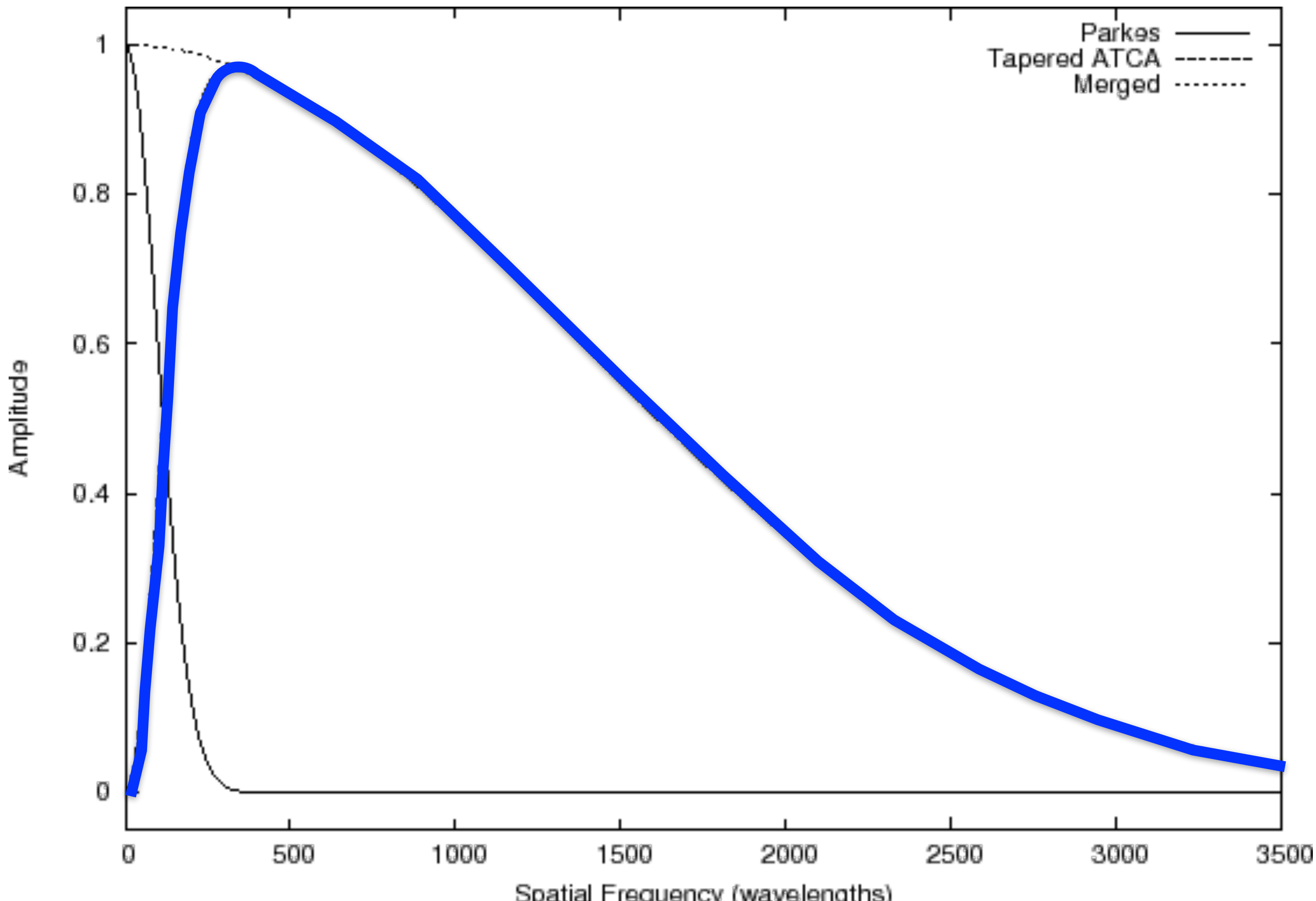
- "Feathering" technique combines deconvolved image in Fourier space

$$V_{comb}(k) = \omega'(k)\, V_{int}(k) + f_{cal}\, \omega''(k)\, V'_{sd}(k)$$

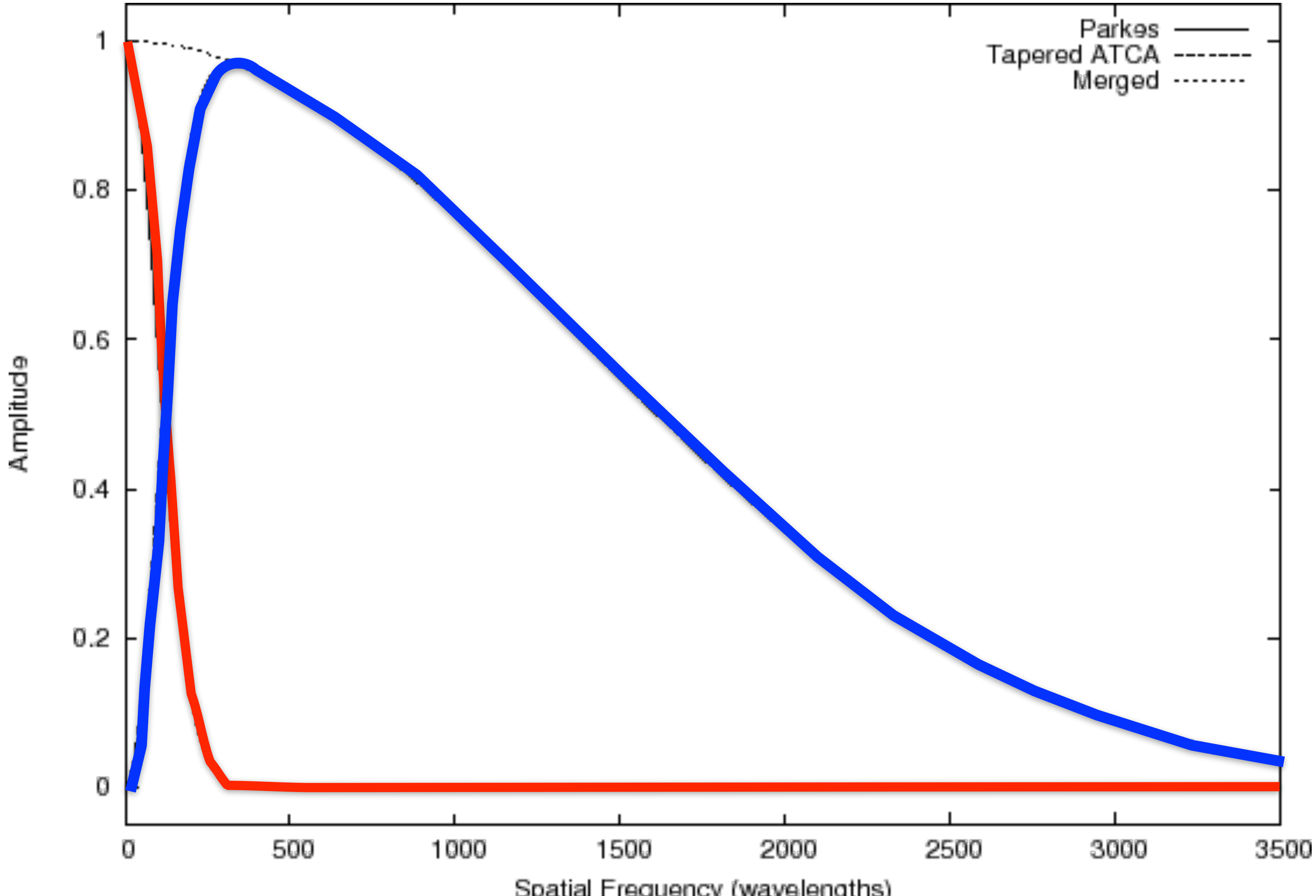
where

$$\omega'(k) + \omega''(k) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_{int}^2 k^2}{4\ln 2}\right)$$

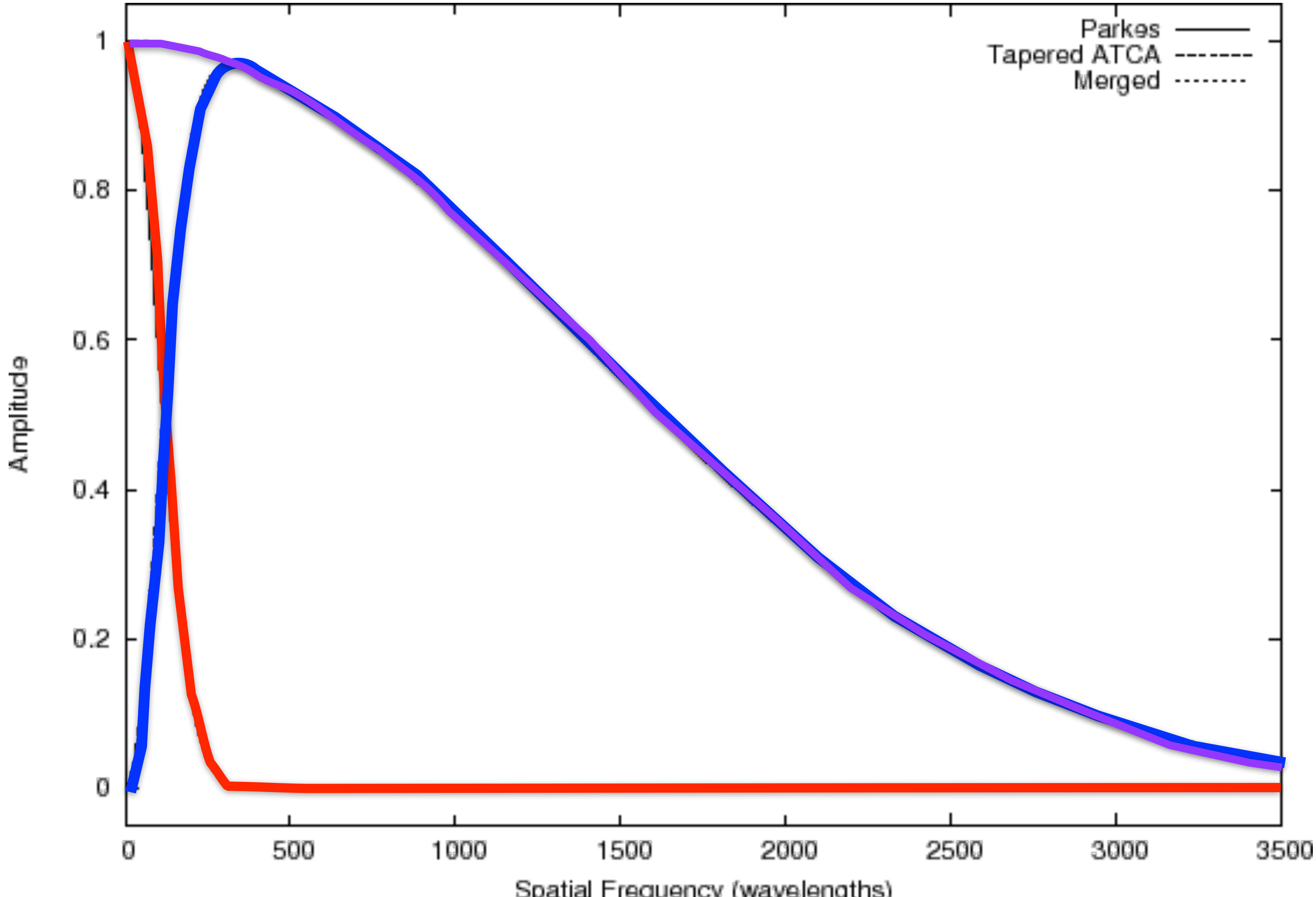
Weighting functions



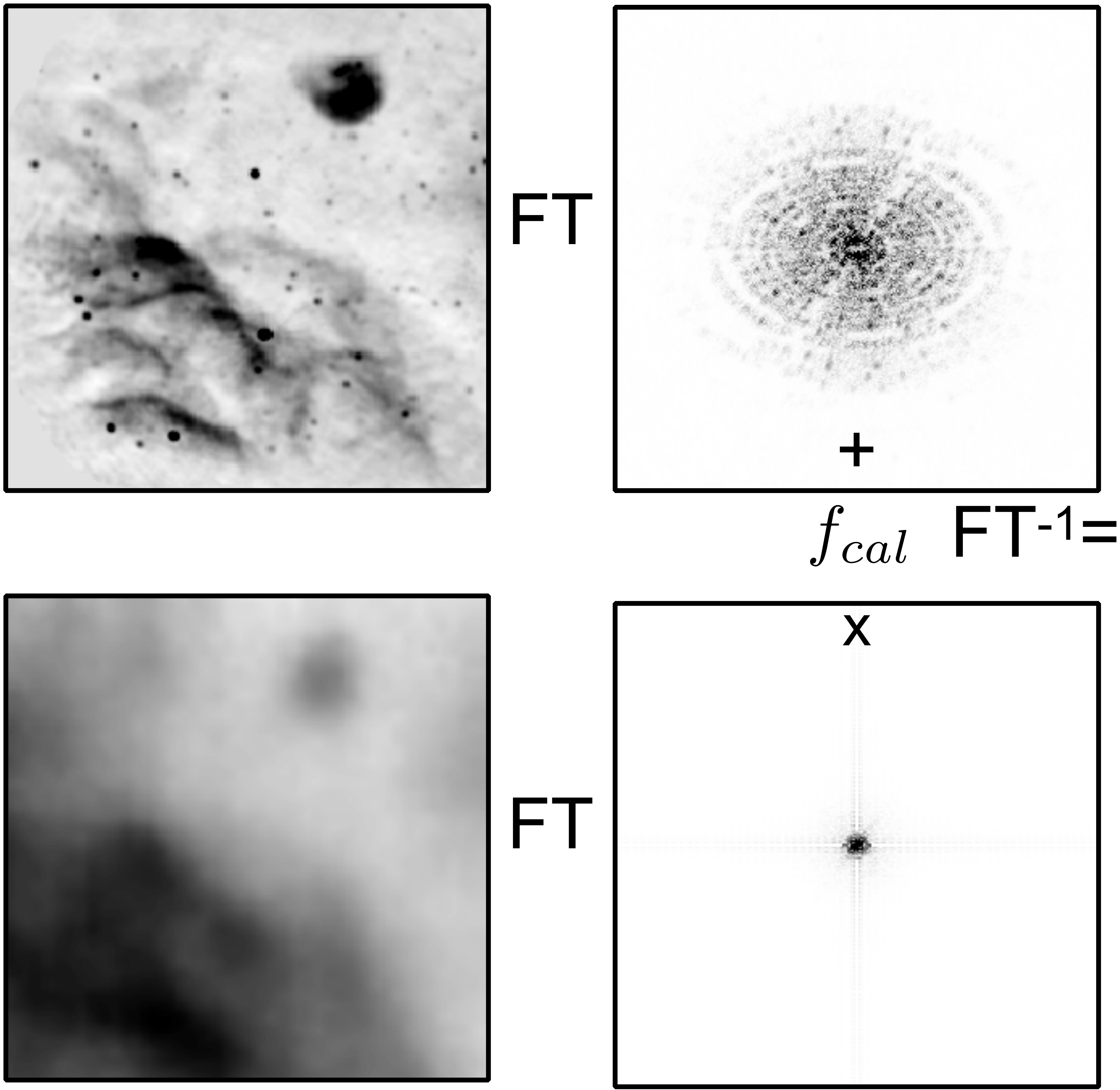
Weighting functions

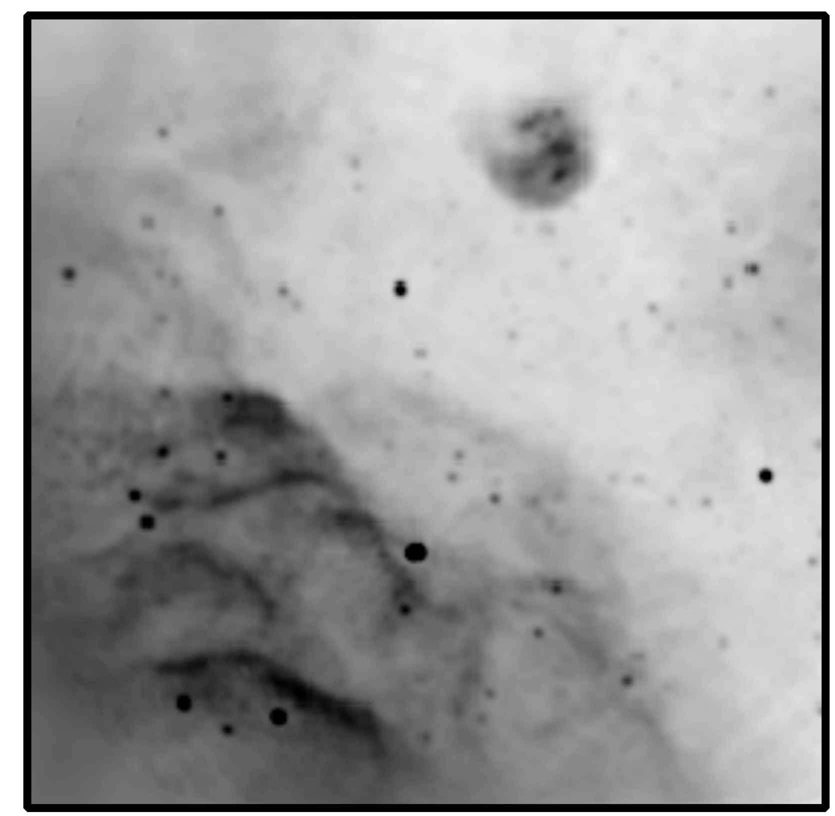


Weighting functions



Image, deconvolve, then combine

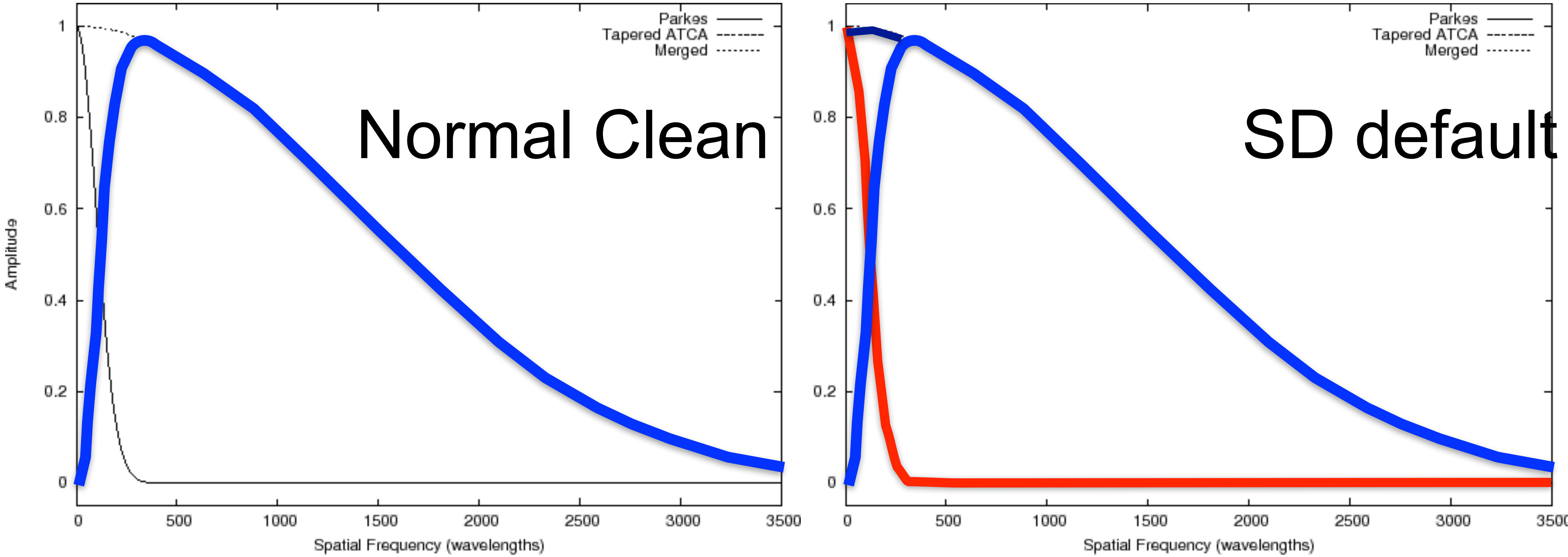




Implemented in miriad's *immerge*, casa *feather*

Combination during Deconvolution: I

- Use the SD image as a “default” in deconvolution
  - Implemented in miriad’s mosmem, casa’s *clean* and *ASKAPsoft* (at least it was!)



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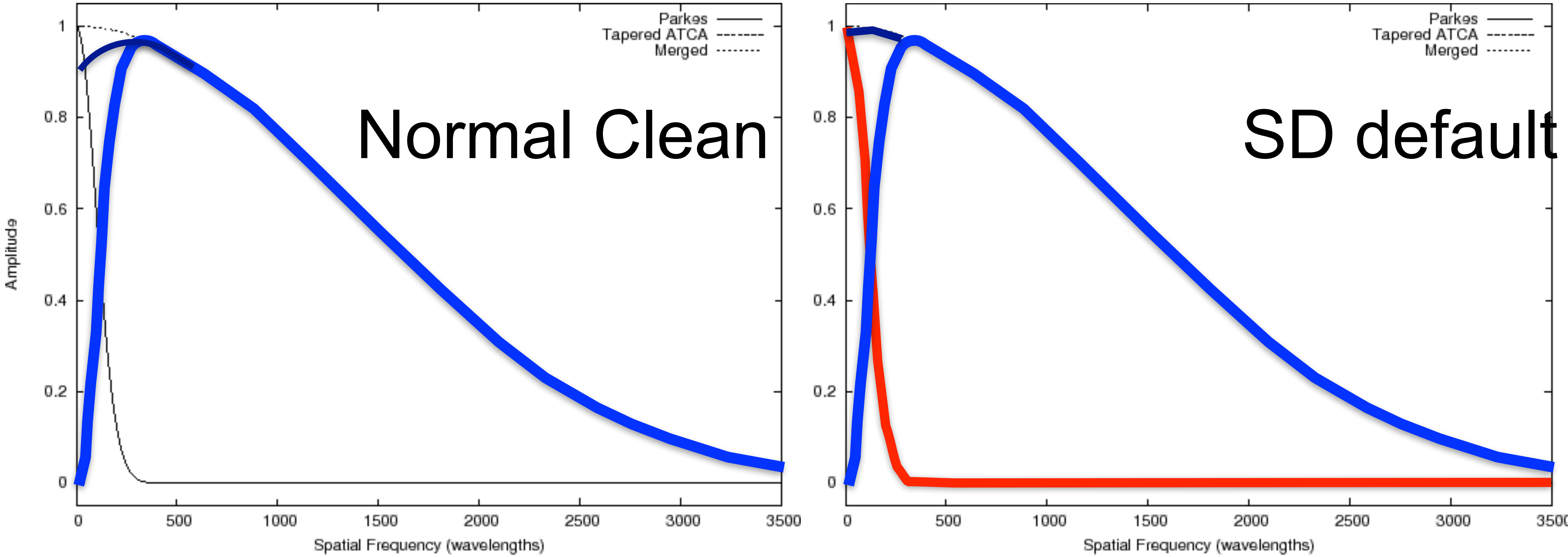
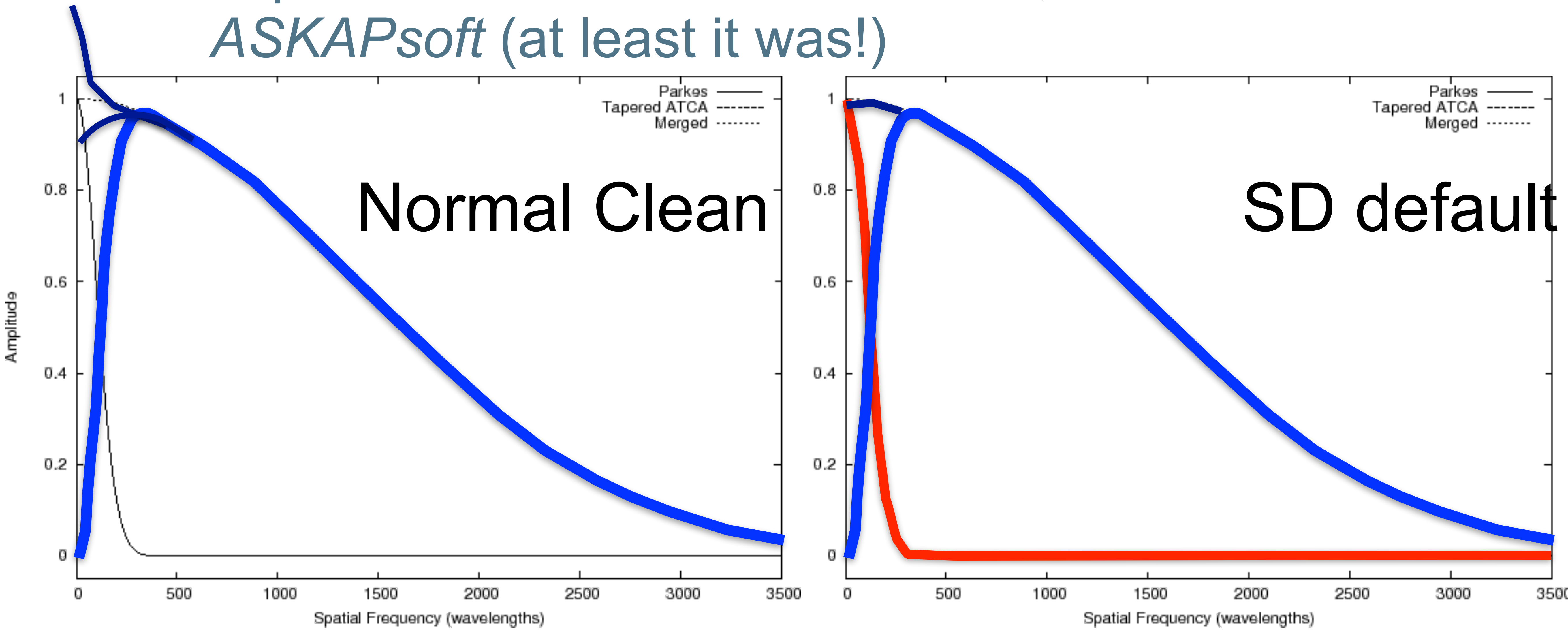


Combination during Deconvolution: I

- Use the SD image as a "default" in deconvolution
  - Implemented in miriad's mosmem, casa's *clean* and *ASKAPsoft* (at least it was!)



Combination during Deconvolution: II

- Jointly deconvolve both images using a maximum entropy technique
- Where we maximise

$$\varkappa = -\sum_i I_i \ln\left(\frac{I_i}{M_i e}\right)$$

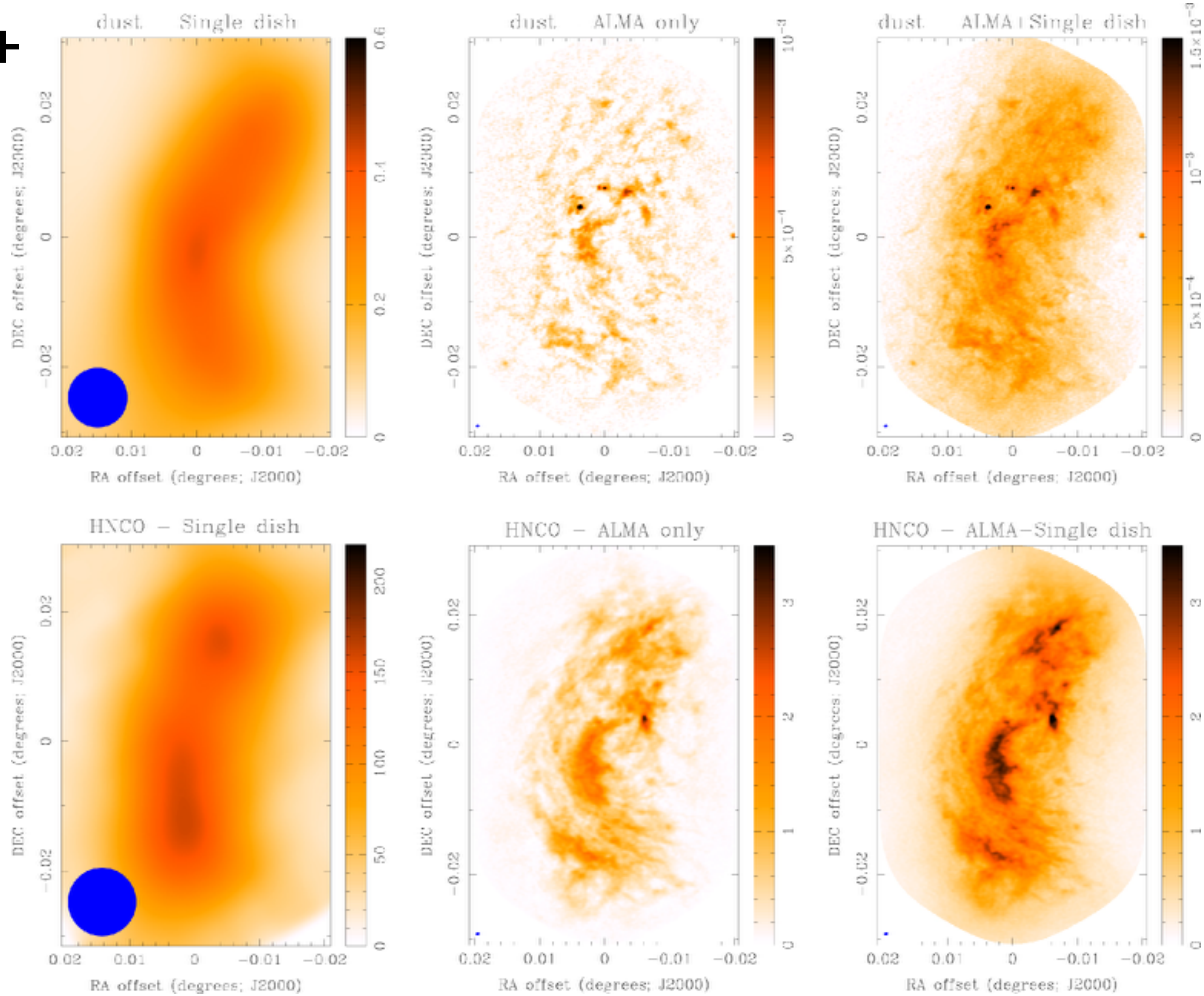
- subject to:

$$\sum_i \left\{I^D_{int} - B_{int} * I\right\}^2_i < N\,\sigma^2_{int}$$

$$\sum_i \left\{I^D_{sd} - \frac{B_{sd} * I}{f_{sd}}\right\}^2_i < M\,\sigma^2_{sd}$$

  – Implemented in miriad's *mosmem*

ALMA + Mopra

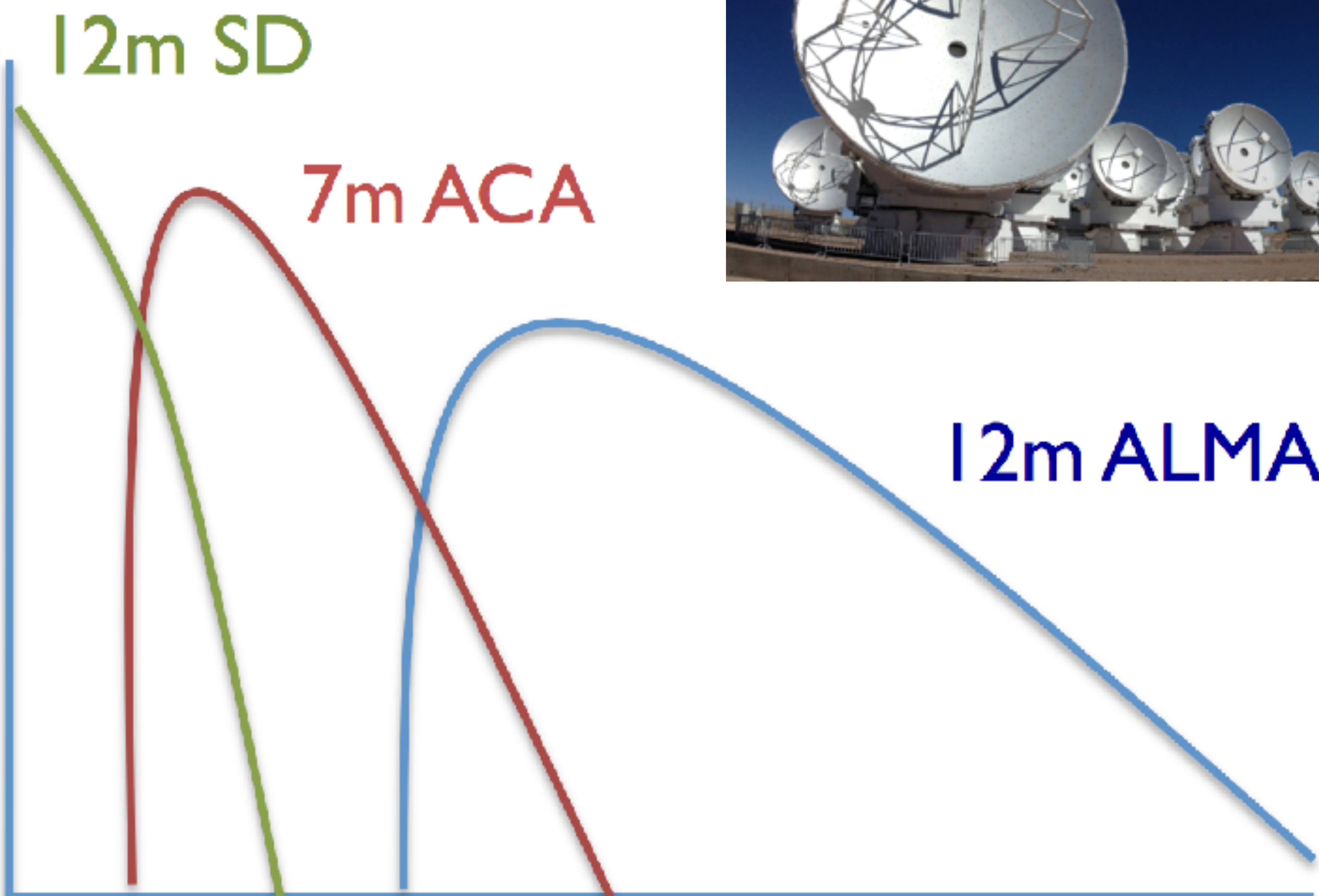


Rathborne et al (2015)

Some Complications

- Noise matching
- Need big single dish for overlapping u-v coverage:
  - rule-of-thumb D_{sd}~$2*d_{min}$
- Cross-calibration very-much subject to ratio of beam sizes
- Single dish image not larger than interferometer or aliasing
- Single dish is not well-defined:
  - elevation effects, sidelobes (<70% efficiency)
  - certainly not a perfect Gaussian beam so any method that deconvolves SD suffers, e.g. joint deconvolution
  - Brightness temperatures vs Jy/Bm

The ALMA + ACA solution



From J Ott

Summary

- Widefield imaging can include the desire to recover extended emission
  - Mosaic-ing can help with this
- Lack of “zero”-spacing in interferometers leads to:
  - lack of sensitivity to large scale emission
  - imaging artefacts (negative bowls)
  - inability to measure total flux
- Can be solved by combining interferometer with single dish data via
  - “joint” or “default”deconvolution
  - “feathering”
  - combination then deconvolution

Some useful literature

- Stanimirovic (2002) ASP Conf. Series 278
- Sault & Killeen (2003) Miriad Users Manual
- Holdaway (1999) ASP Conf. Series 180
- Ekers & Rots (1979) Image Formation, IAU Coll 49, 61.
- Cornwell (1988) A&A, 202, 316.
- Cornwell (1989) ASPC 6.
- Cornwell, Holdaway & Uson (1993) A&A, 271, 697.
- Sault, Staveley-Smith & Brouw (1996) A&A Suppl., 120, 375.
- Holdaway (1998) ASPC 180, ch.20.
- Subrahmanyan (2004) MNRAS, 348, 1208.
- Bhatnagar, Golap & Cornwell (2005) ASPC 347, 96