Combining Interferometer & Single Dish Data

"Seeing the Forest *and* the Trees"

Jo Dawson

(Also thanks to Stezana Stanimirovic & Naomi McClure-Griffiths)

Parkes Radio Astronomy School

29th Sept 2011

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Stanimirovic et al. 2002,
ASPC, vol. 278, 375

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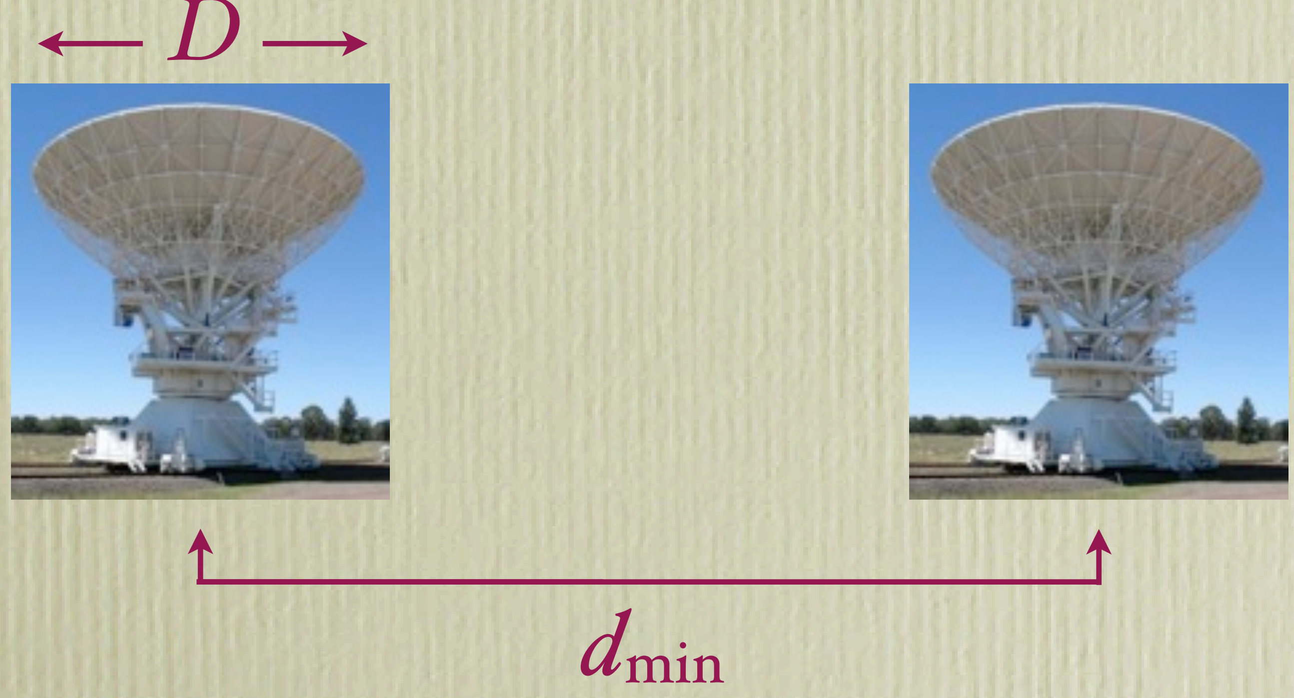
Outline

- The effect of missing short spacings
    - Missing large-scale structure
    - Artefacts
    - Missing flux
- Combining single dish & interferometer data:
    - Concepts
    - Calibration
    - Recipes for combining
- Requirements for single dish data

Missing Short Spacings

- Interferometer only sensitive to angular scales < ~ $\lambda / d_{\mathrm{min}}$ → lack of information about low spatial frequencies
    1. Cannot recover large-scale structure
    2. Problematic image artefacts in extended objects
    3. Cannot directly measure total flux (zeroth spacing)



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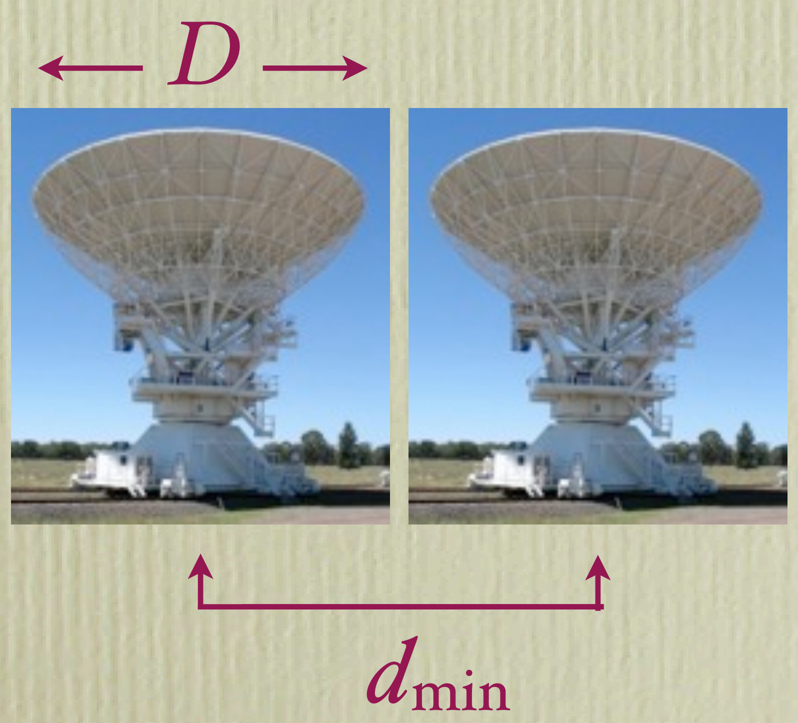

$d_{\mathrm{min}} > D$

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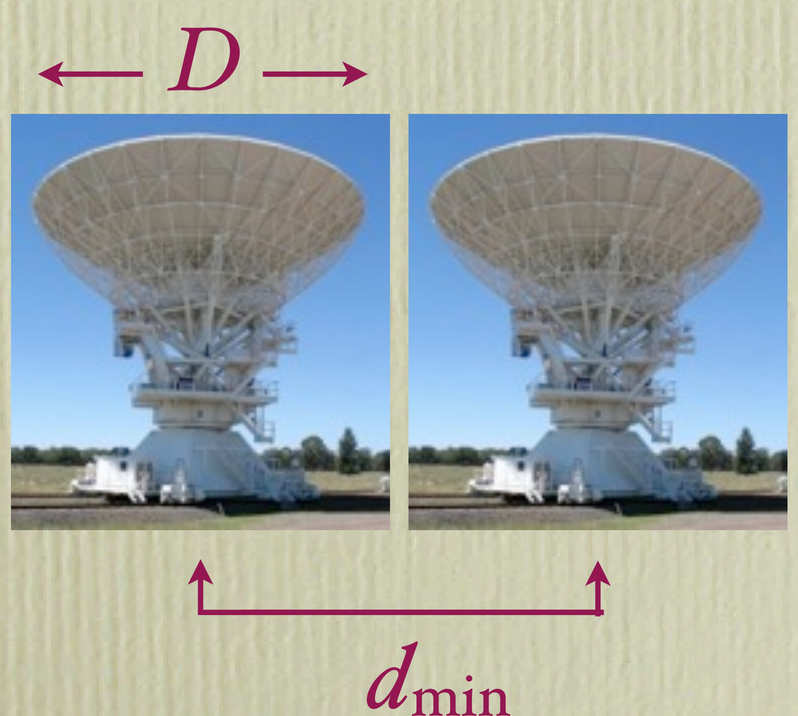
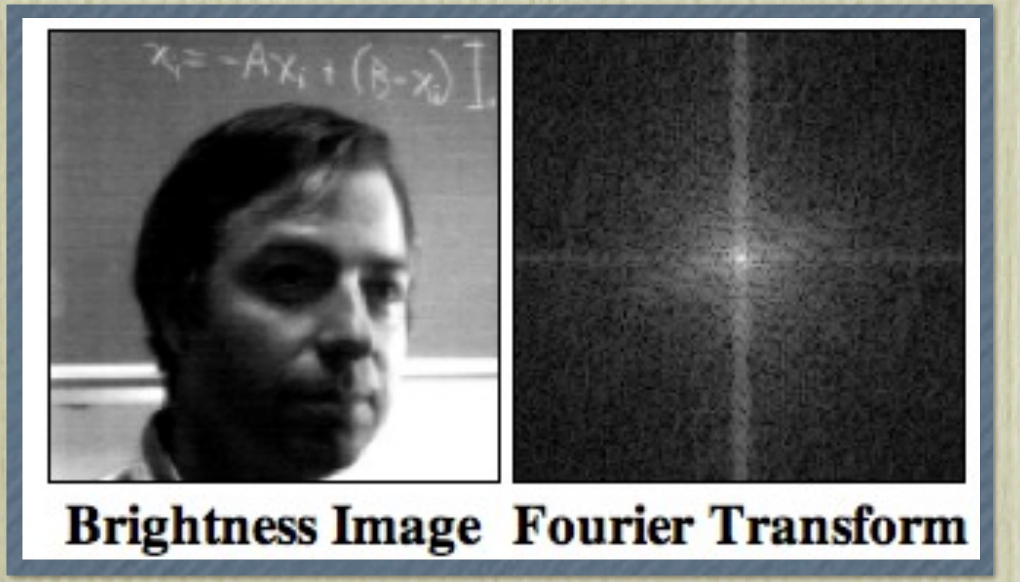


$d_{\mathrm{min}} > D$

When does all this matter?
When source is large compared to $\lambda / d_{\mathrm{min}}$

Missing Short Spacings

1. Missing Large Scale Structure



Sky brightness distribution

Visibilities in the u-v plane

Image credit: Steven Lehar (Internet Man!)

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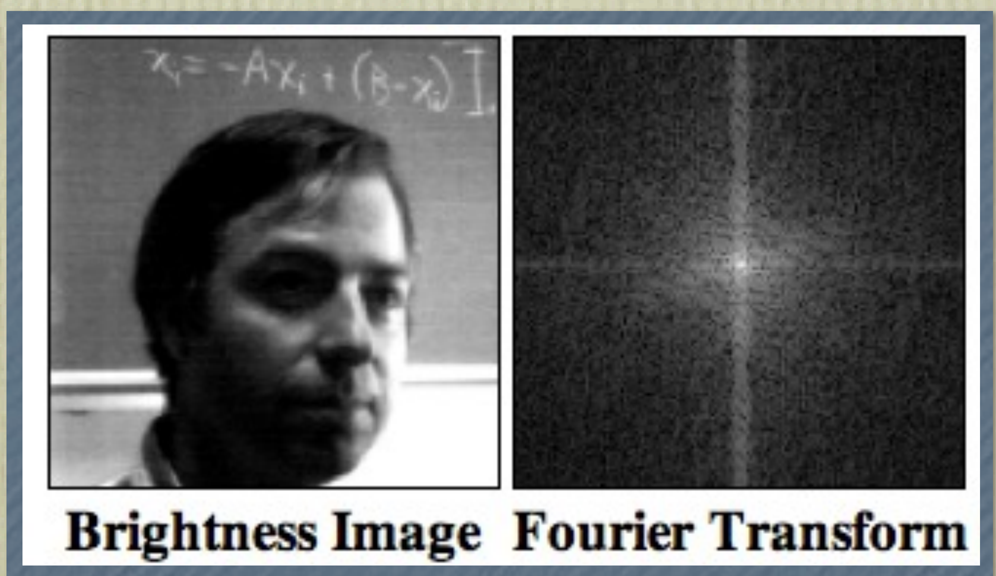

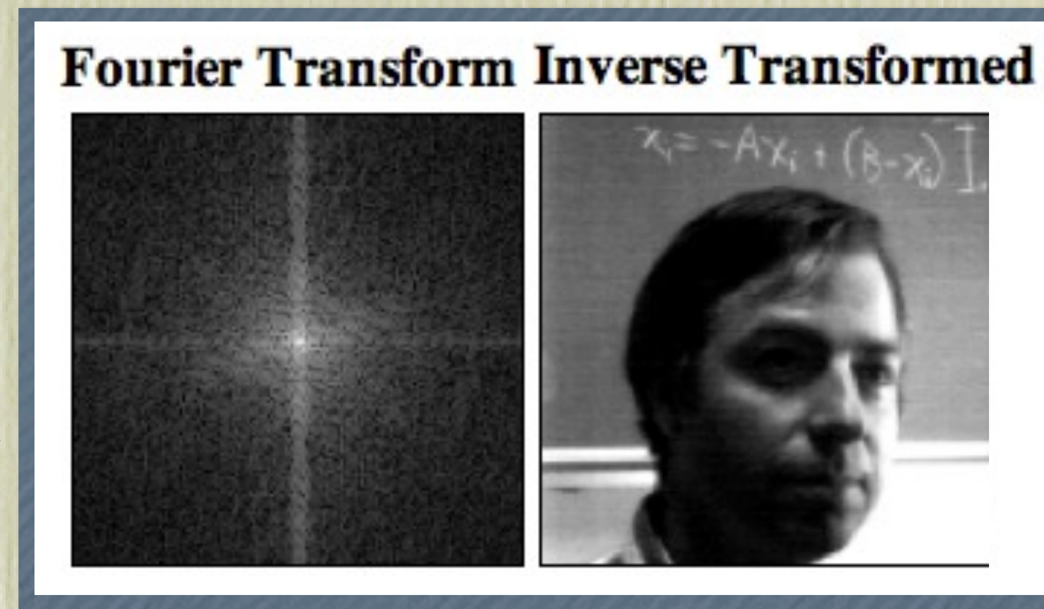

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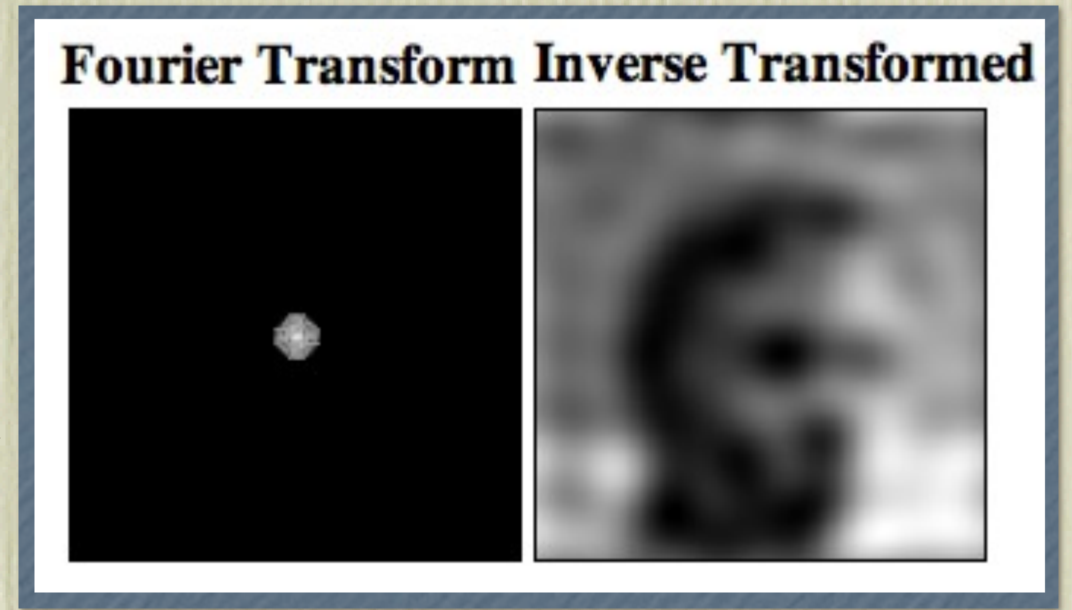
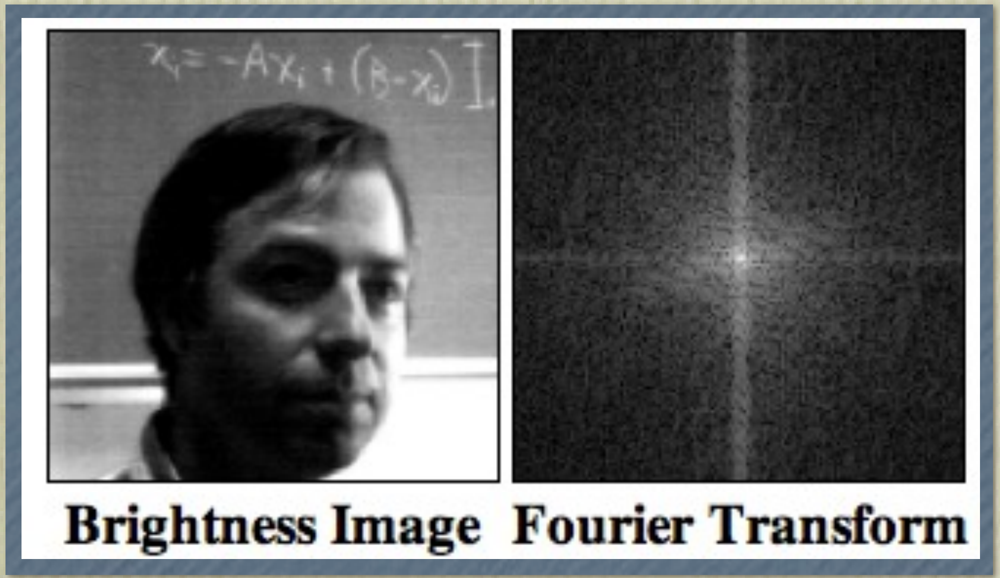


Low spatial frequencies only



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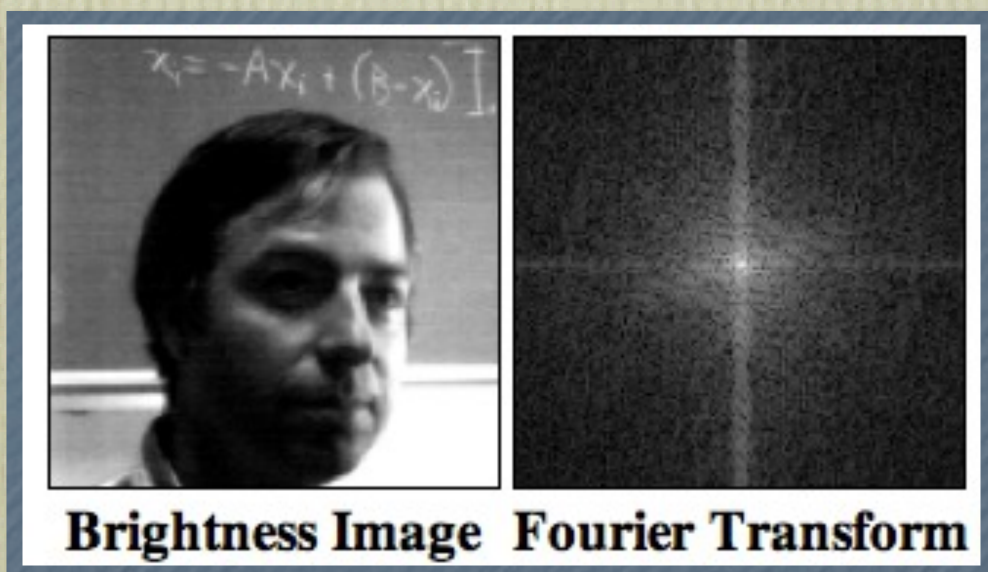

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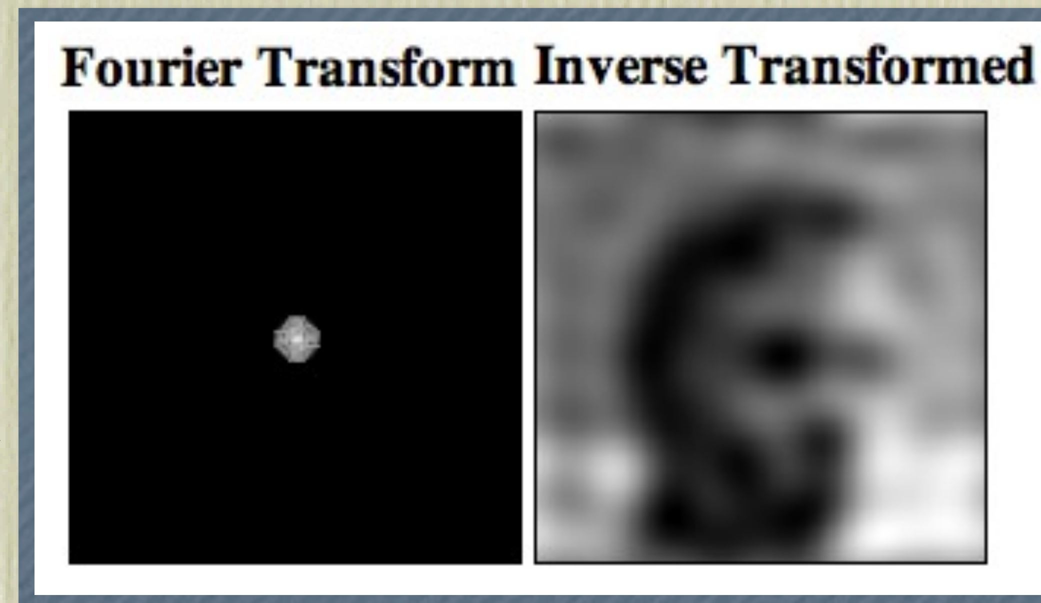

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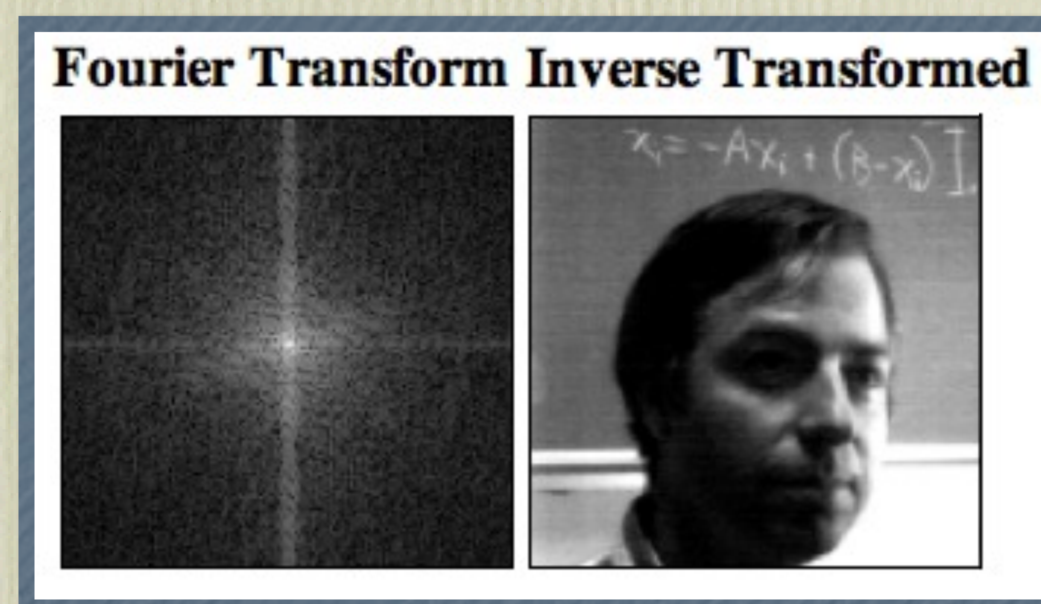

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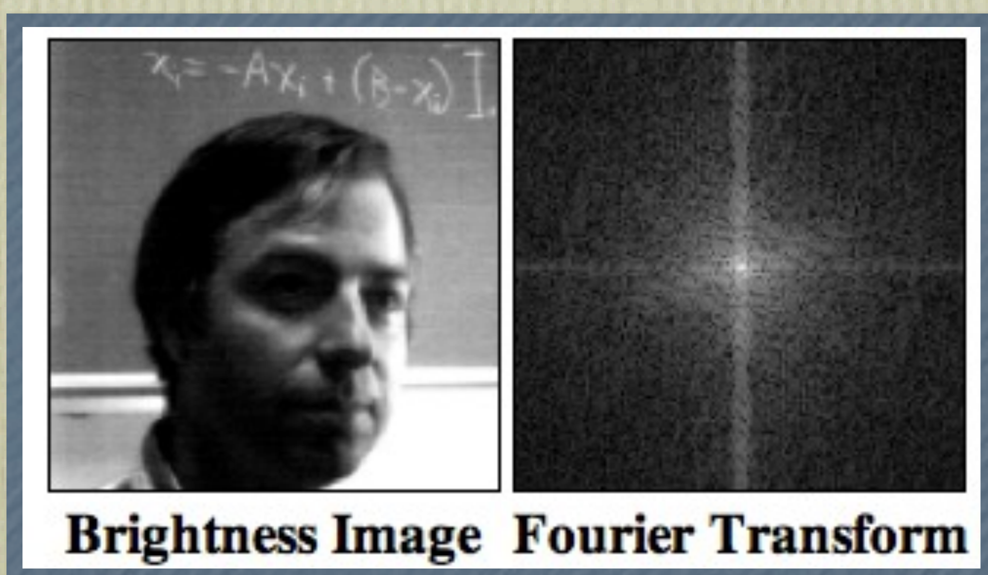

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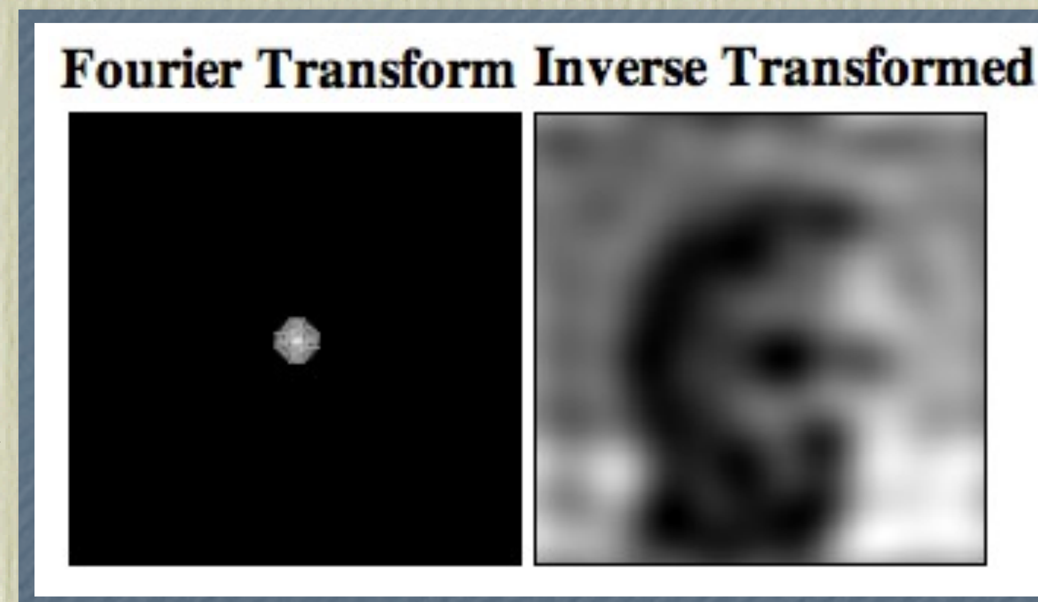

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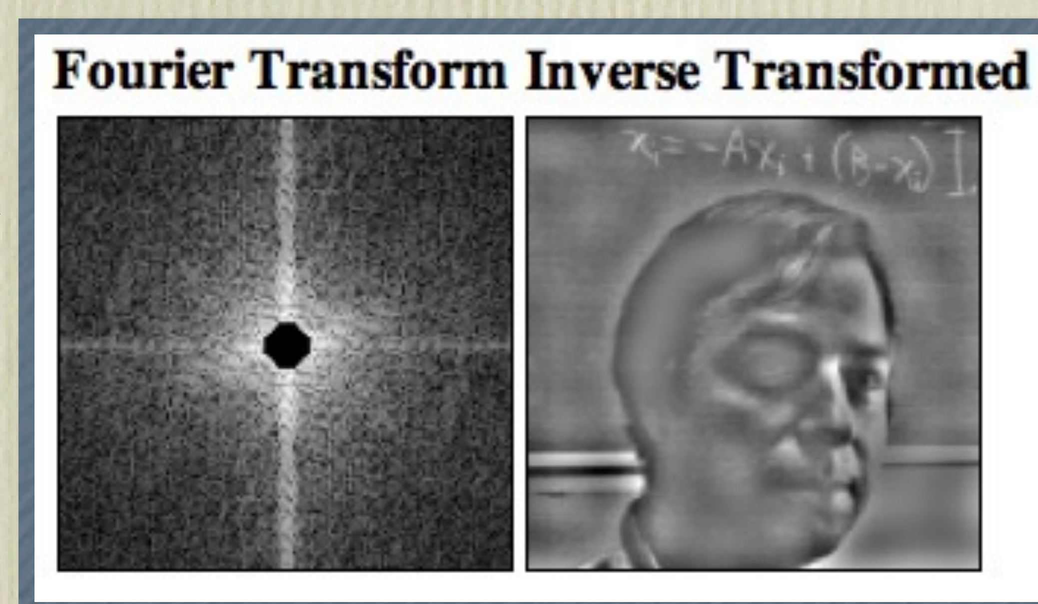

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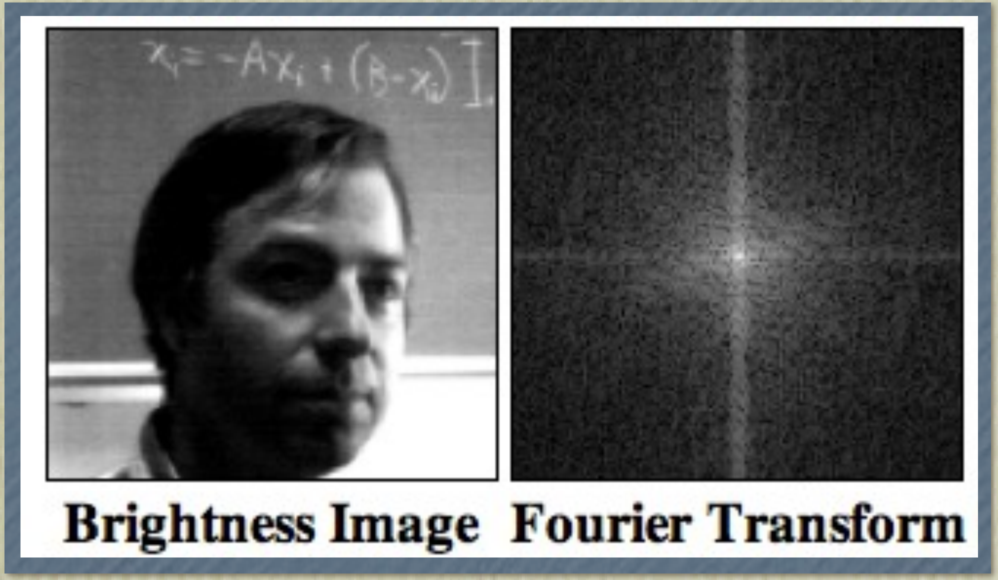

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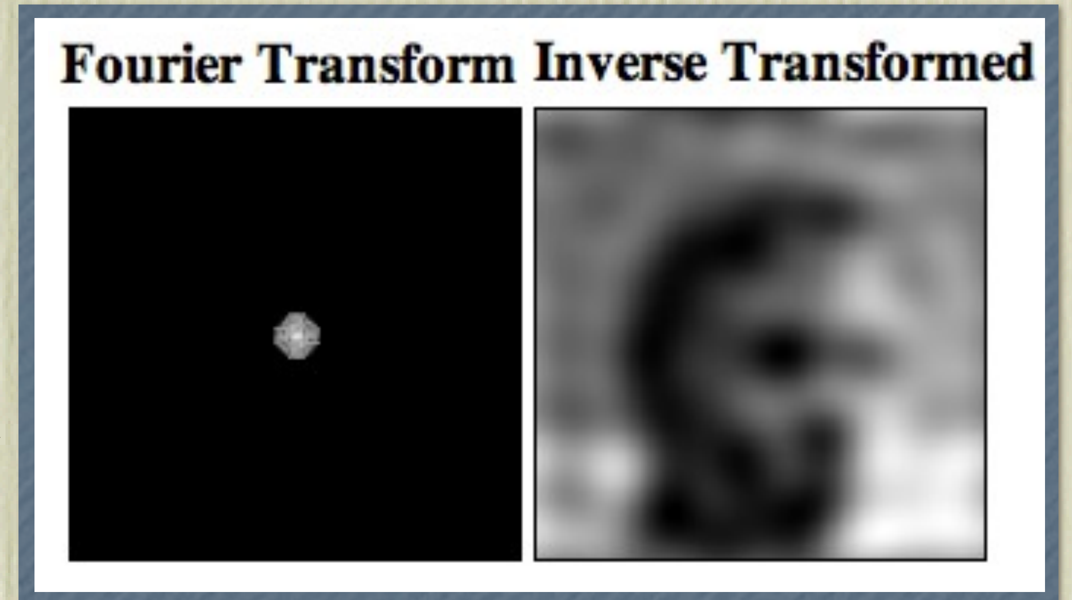

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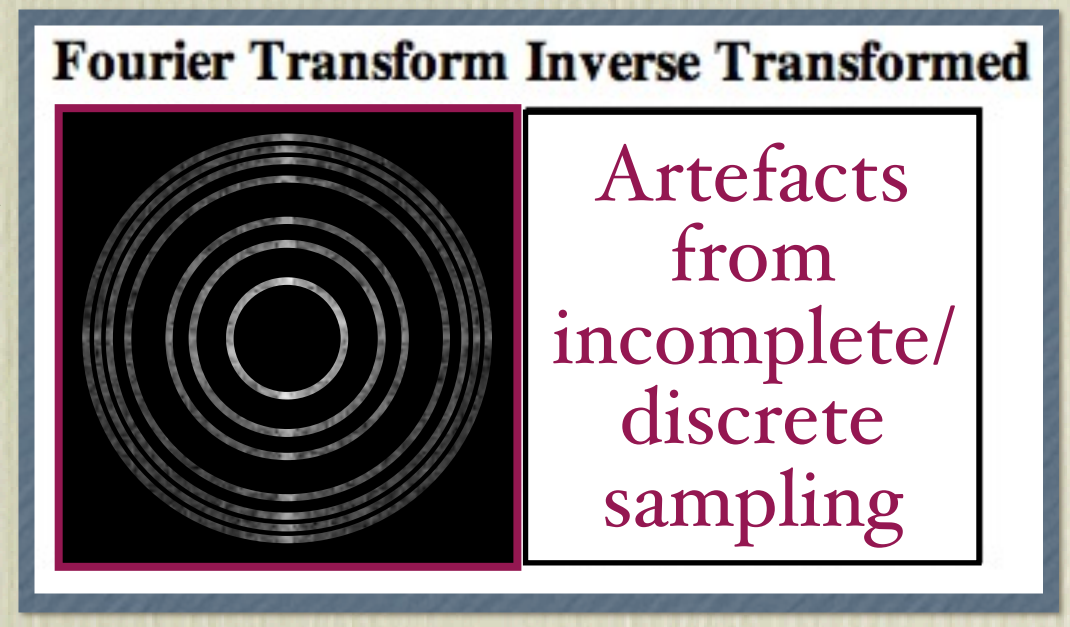

High spatial frequencies only

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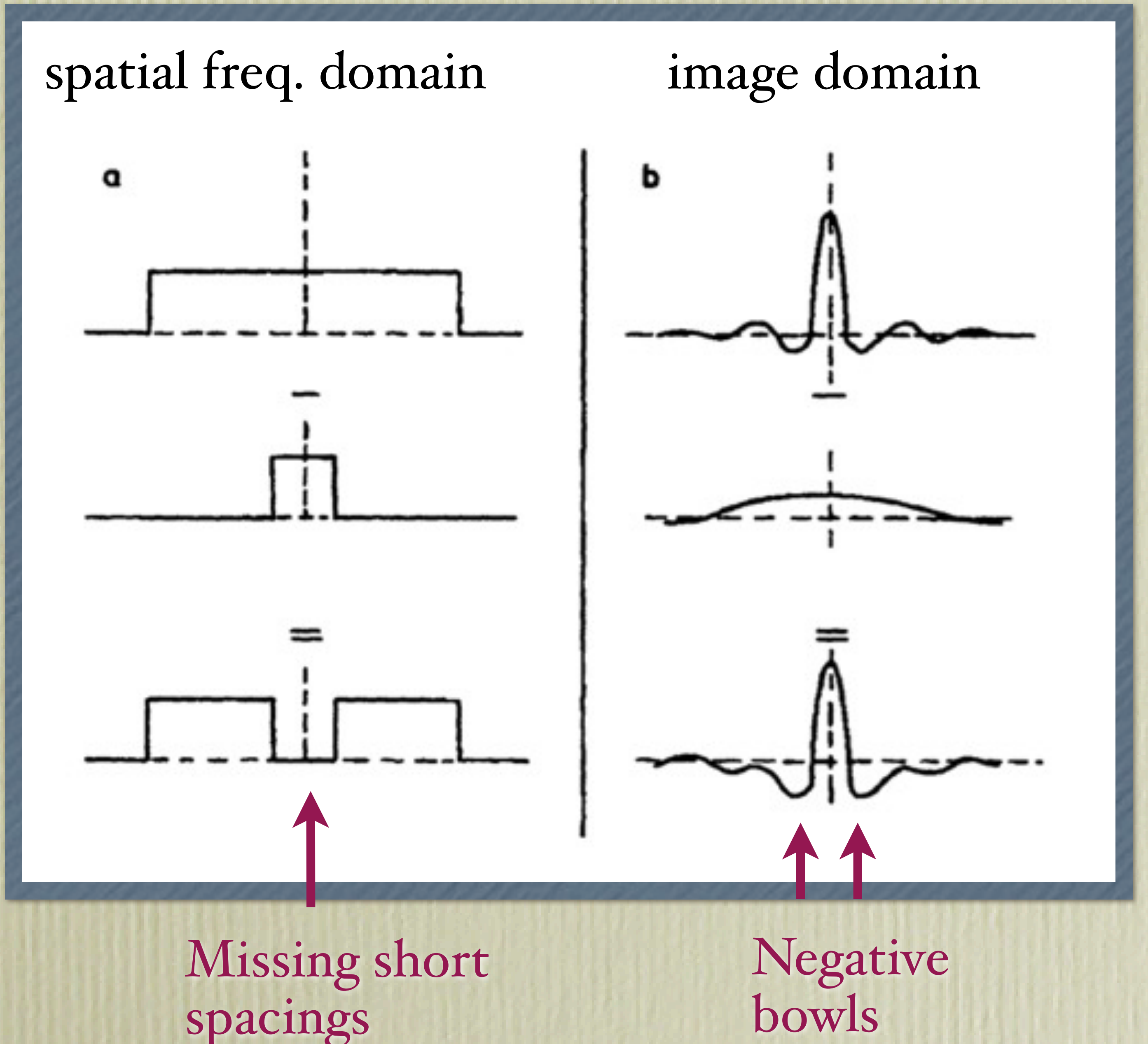
Missing Short Spacings

Incomplete sampling of point source:



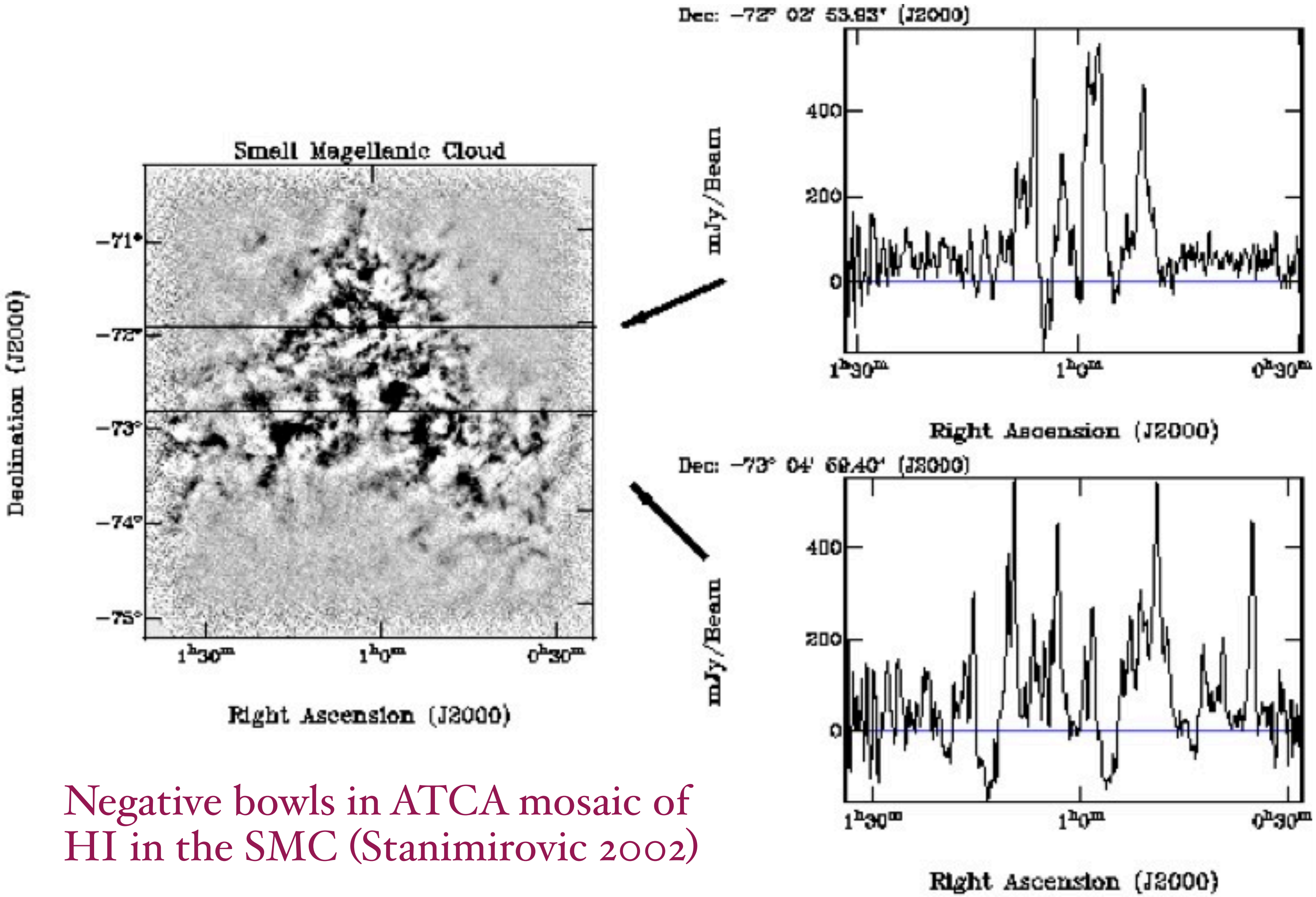
2. Artefacts

Incomplete sampling always causes image plane artefacts.

Missing short spacings cause characteristic negative bowls.

Increasingly problematic for extended sources - cleaning cannot easily disentangle real structure and artefacts.

Missing Short Spacings



Negative bowls in ATCA mosaic of HI in the SMC (Stanimirovic 2002)

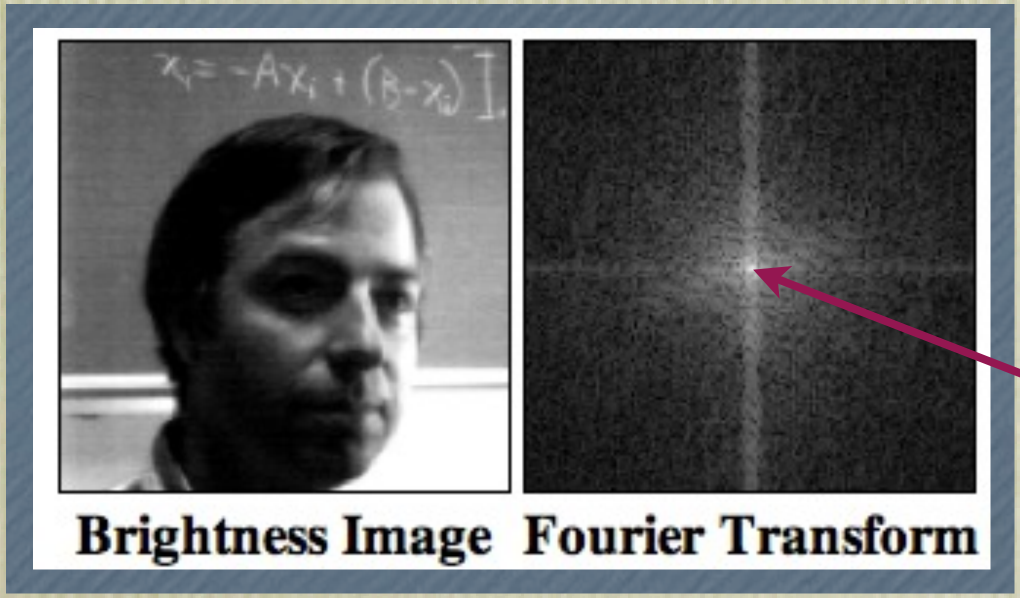
Missing Short Spacings

3. The Problem of Missing Flux

$$V_\nu(u,v) = \iint I_\nu(l,m) e^{-2\pi i(ul+vm)}\ dl\ dm$$

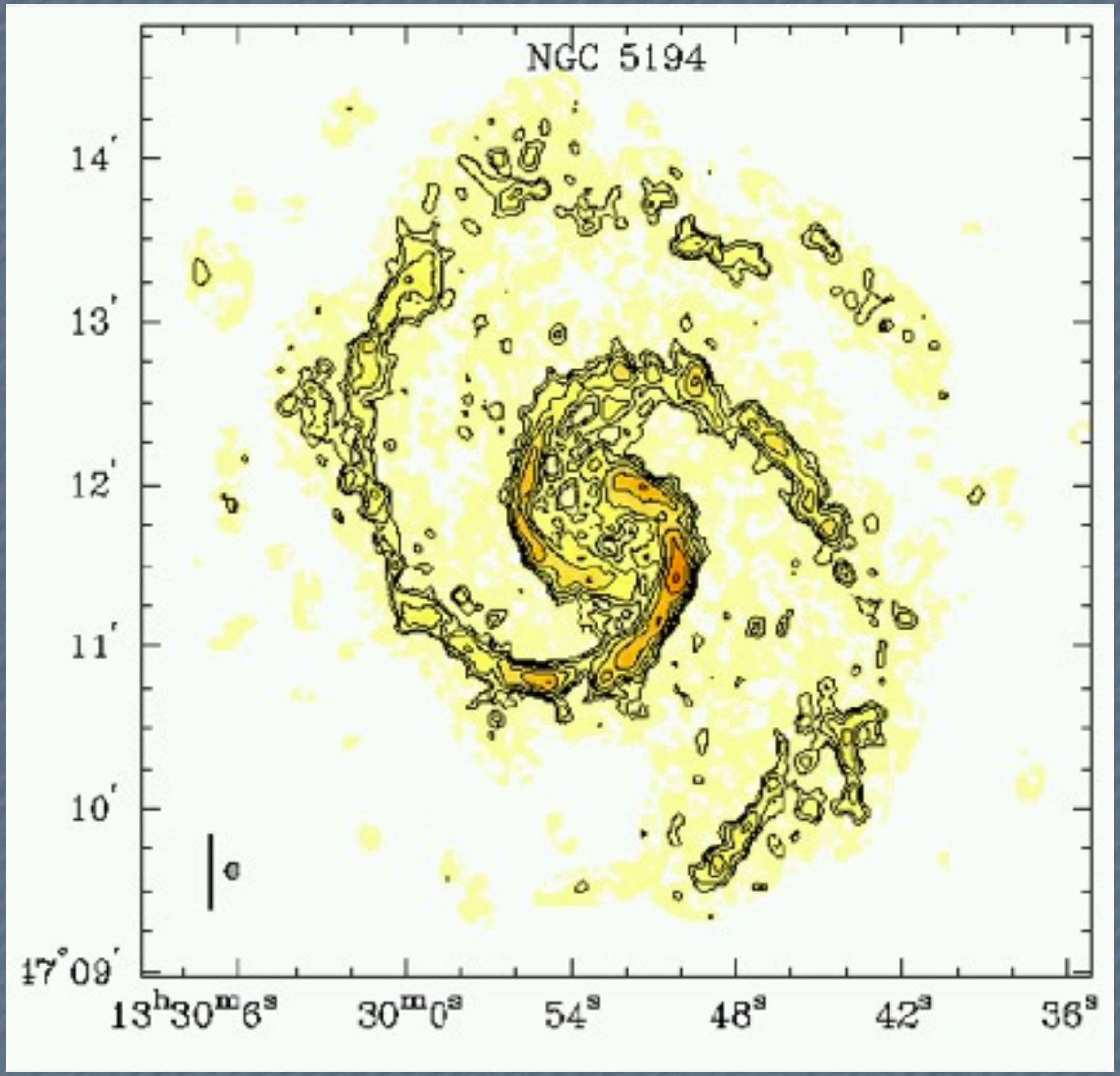
$$V_\nu(0,0) = \iint I_\nu(l,m)\ dl\ dm$$

- Total flux equal to value of visibility at (u,v) = (0,0) "zero spacing"
- Deconvolution tries to estimate missing u,v information. But this cannot be modelled; has to be measured!

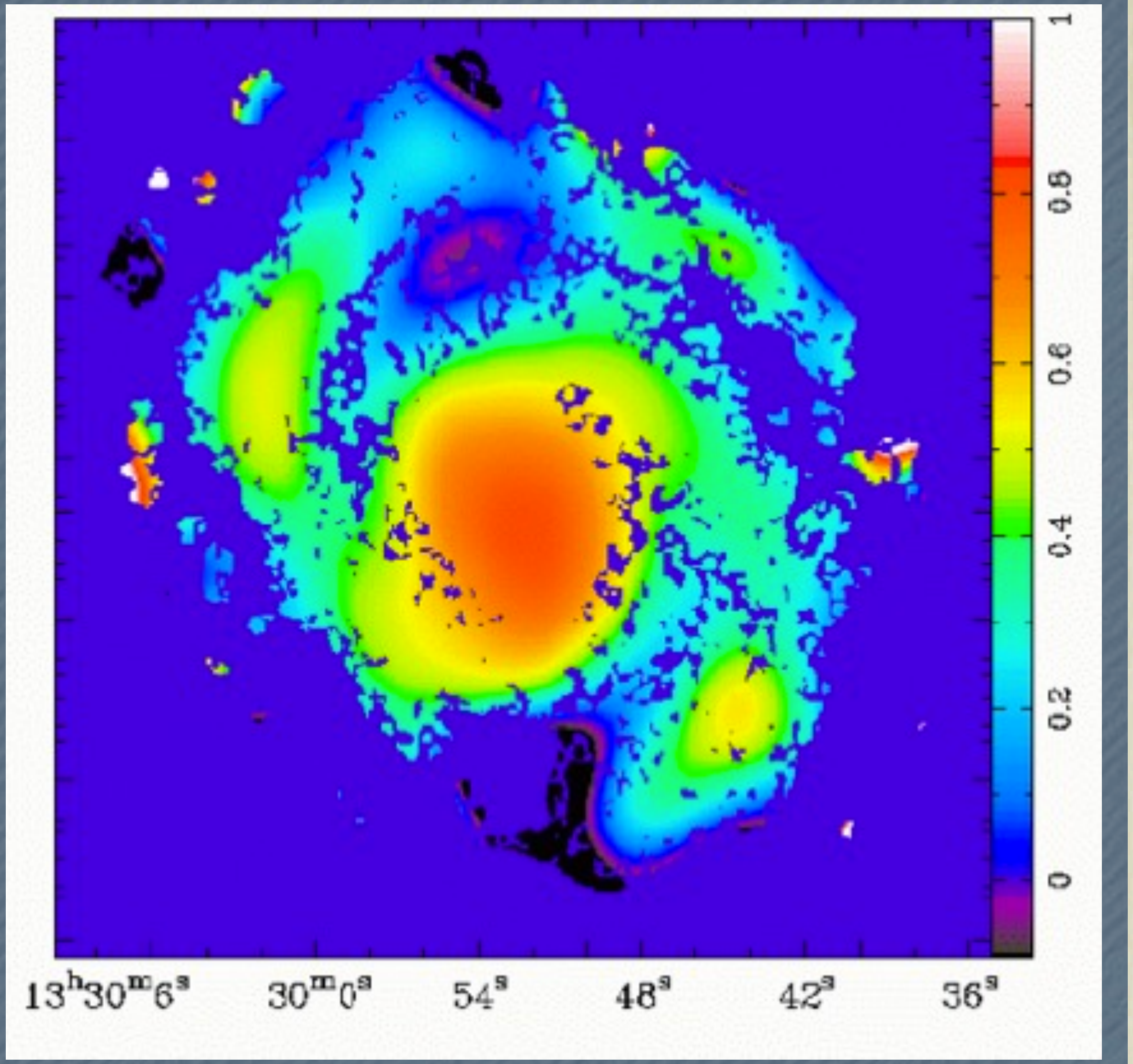


zero spacing

Missing Short Spacings



BIMA SONG CO map

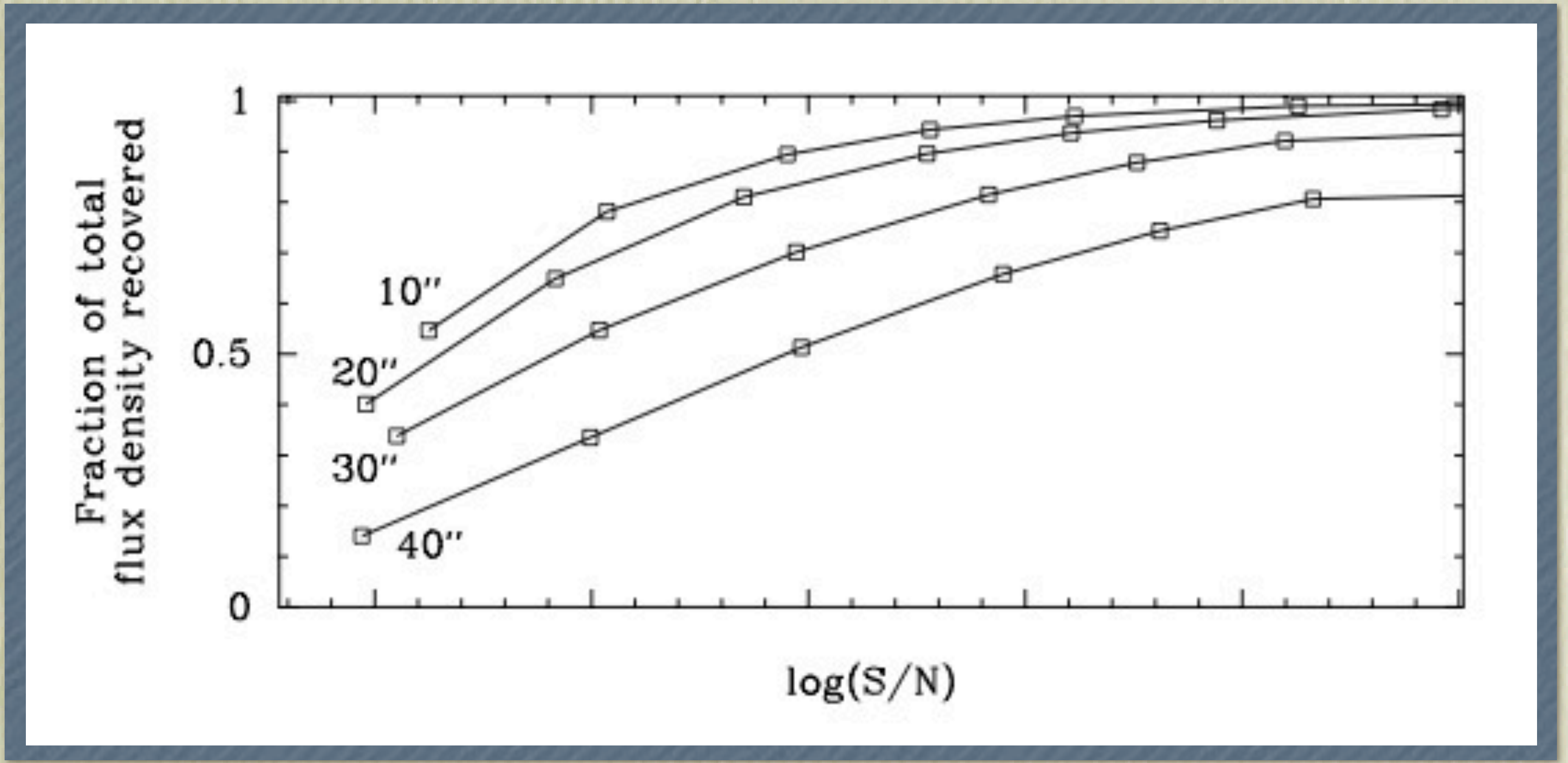


Flux recovery ratio
(I_{BIMA55}/I_{12m})

Helfer et al. (2002), Stanimirovic (2005; talk)

Missing Short Spacings

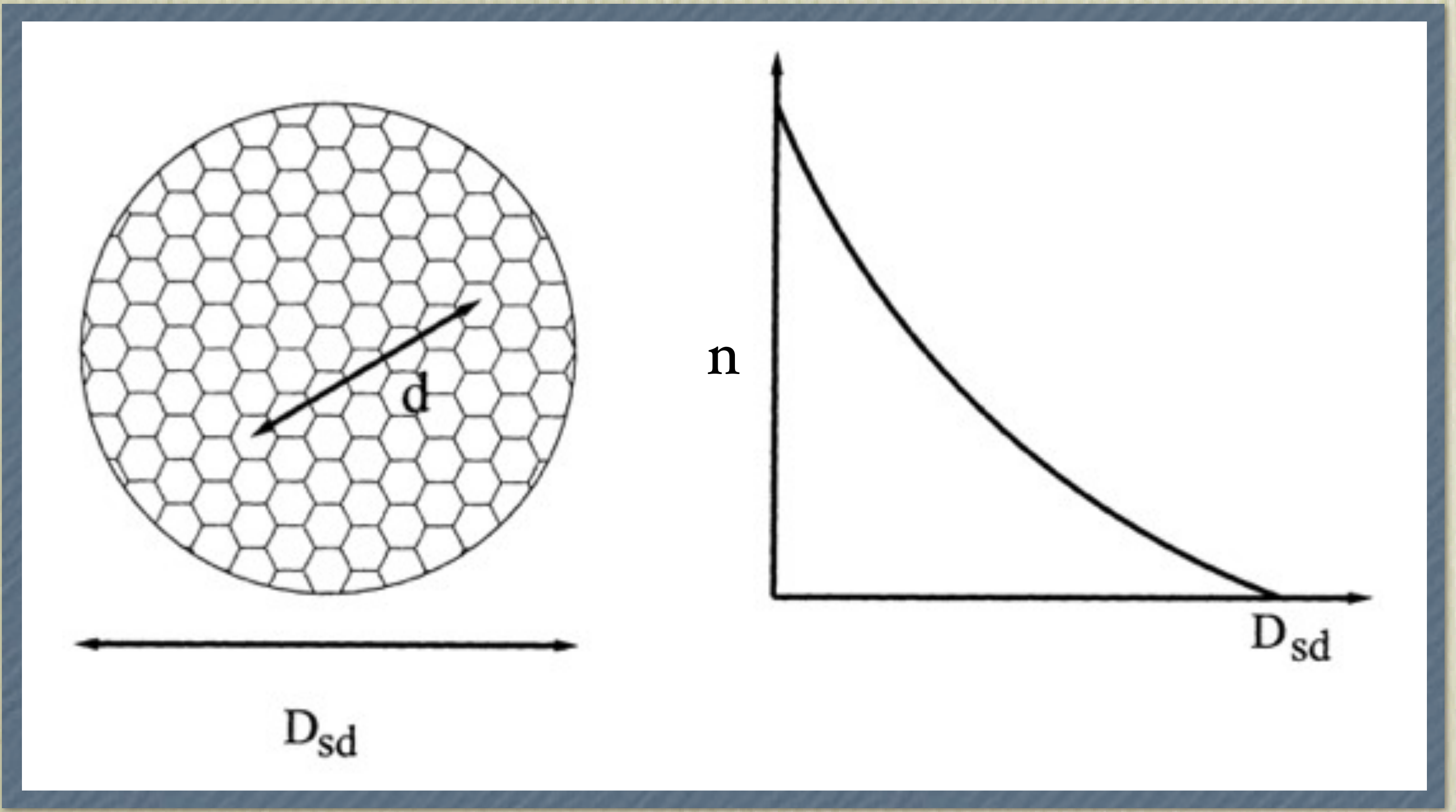
- Rule of thumb: Larger source/noisier data = worse flux recovery
- But in general cannot be predicted without detailed knowledge of source structure



Simulations for BIMA SONG survey (beam FWHM ~ 5-10”)
Helfer et al. (2003). Sizes are spiral arm widths.

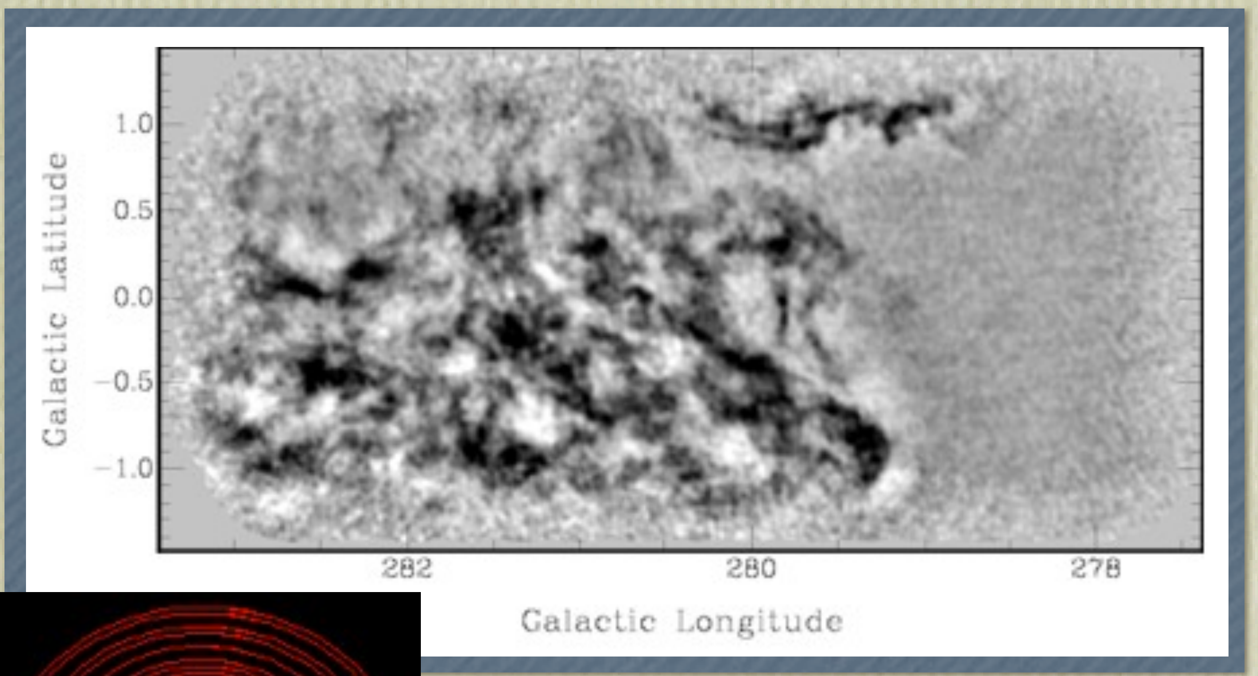
Short Spacings from Single Dish Data

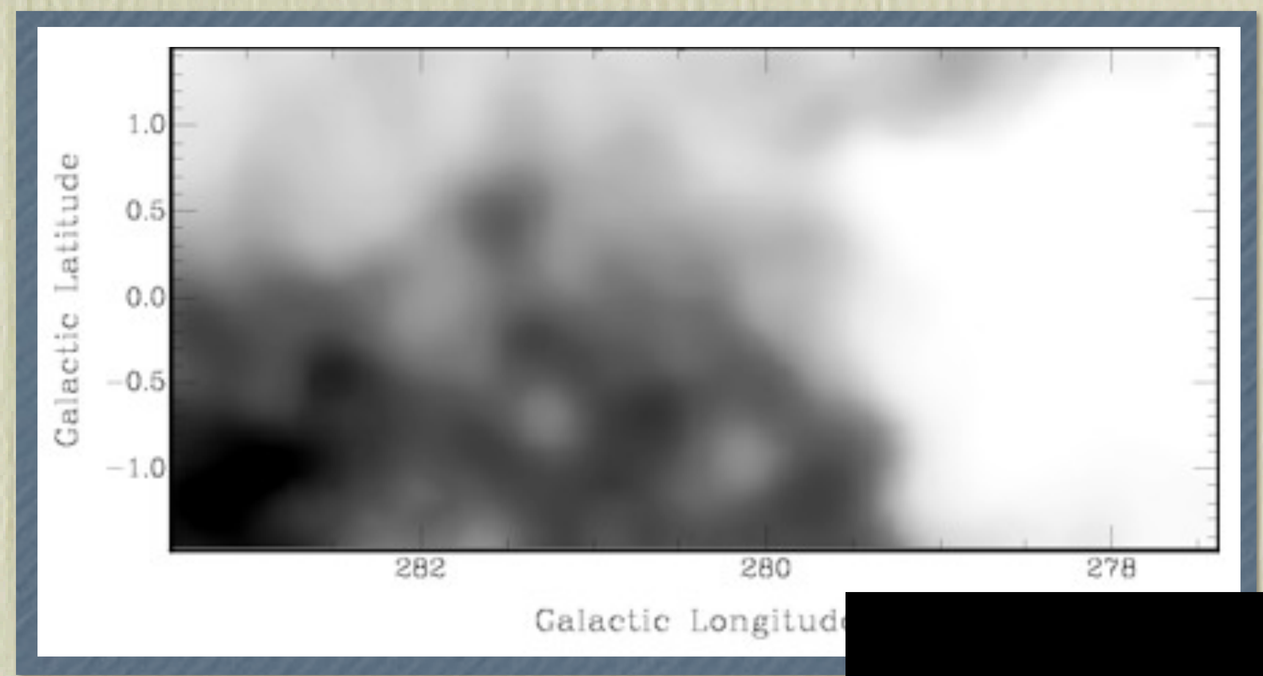
- A single antenna samples the u-v plane on spacings from zero to its diameter D_{sd} (recovered when scanning across source).
- Combine single dish with interferometer data to provide short spacings and recover total flux!

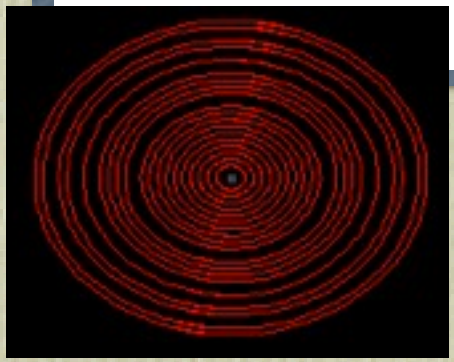


Stanimirovic (2002)

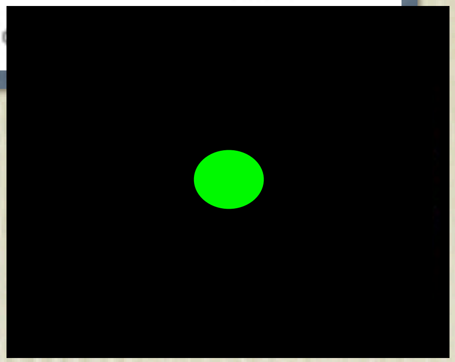
Short Spacings from Single Dish Data







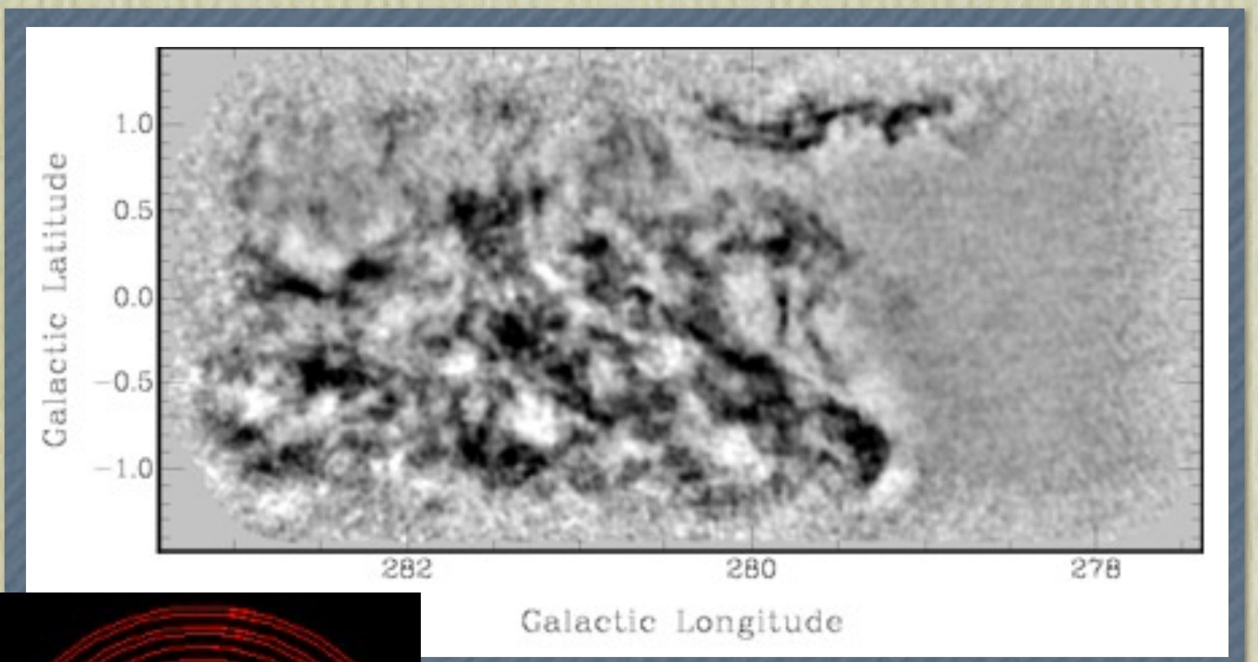
u-v coverage

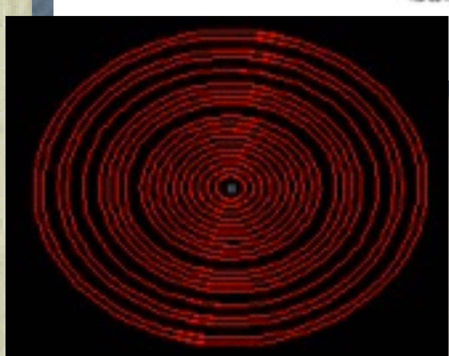


u-v coverage

McClure-Griffiths
(2001; talk)

Short Spacings from Single Dish Data





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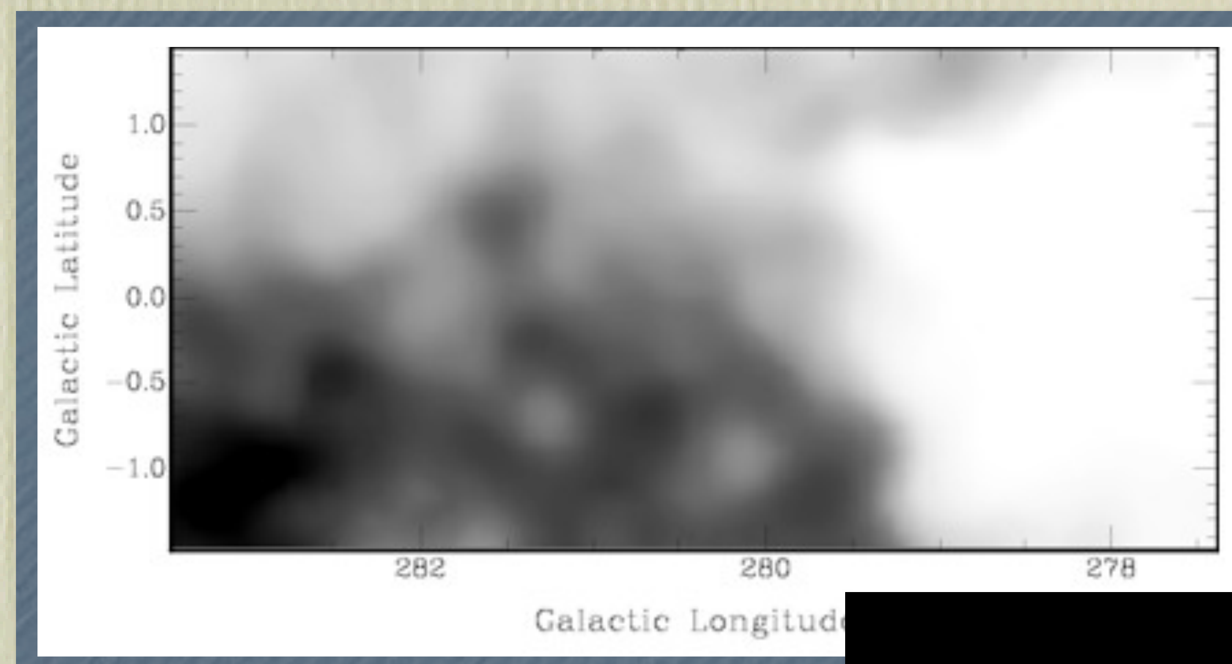

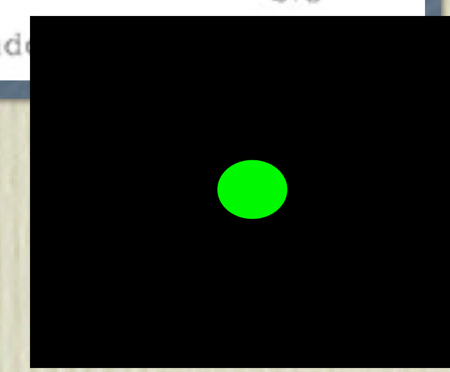

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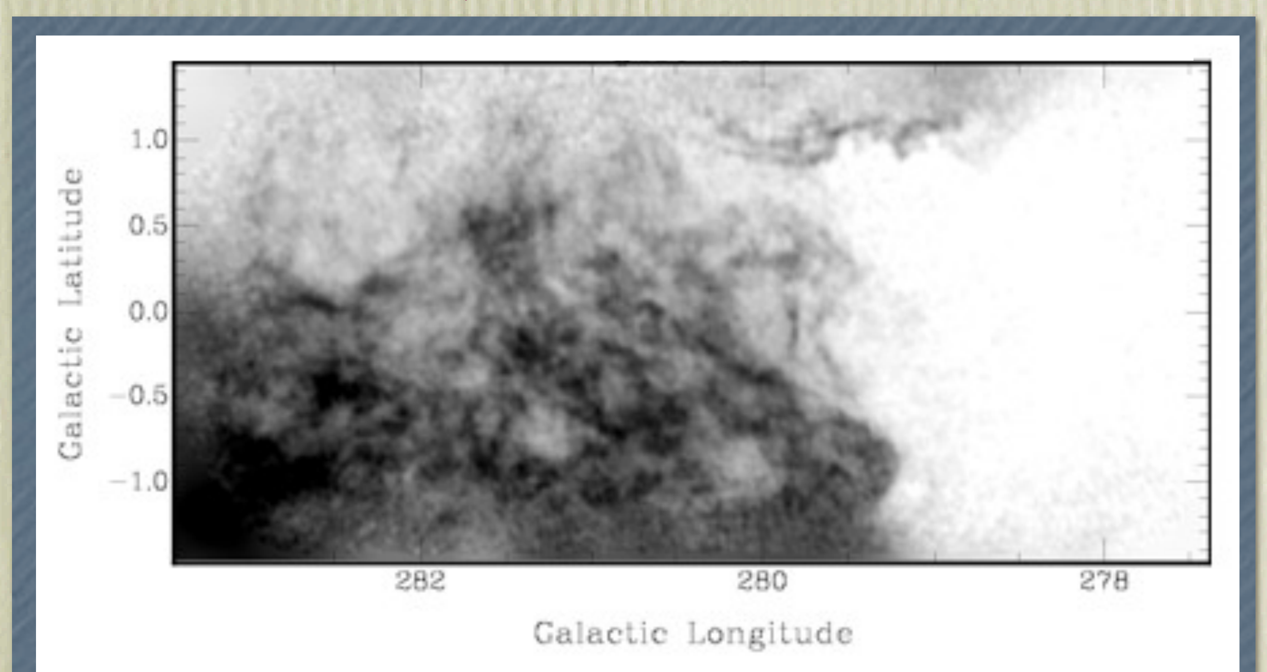

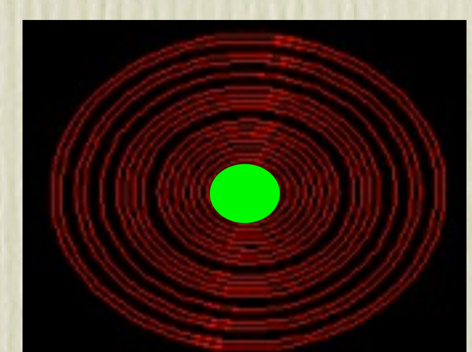

McClure-Griffiths (2001; talk)

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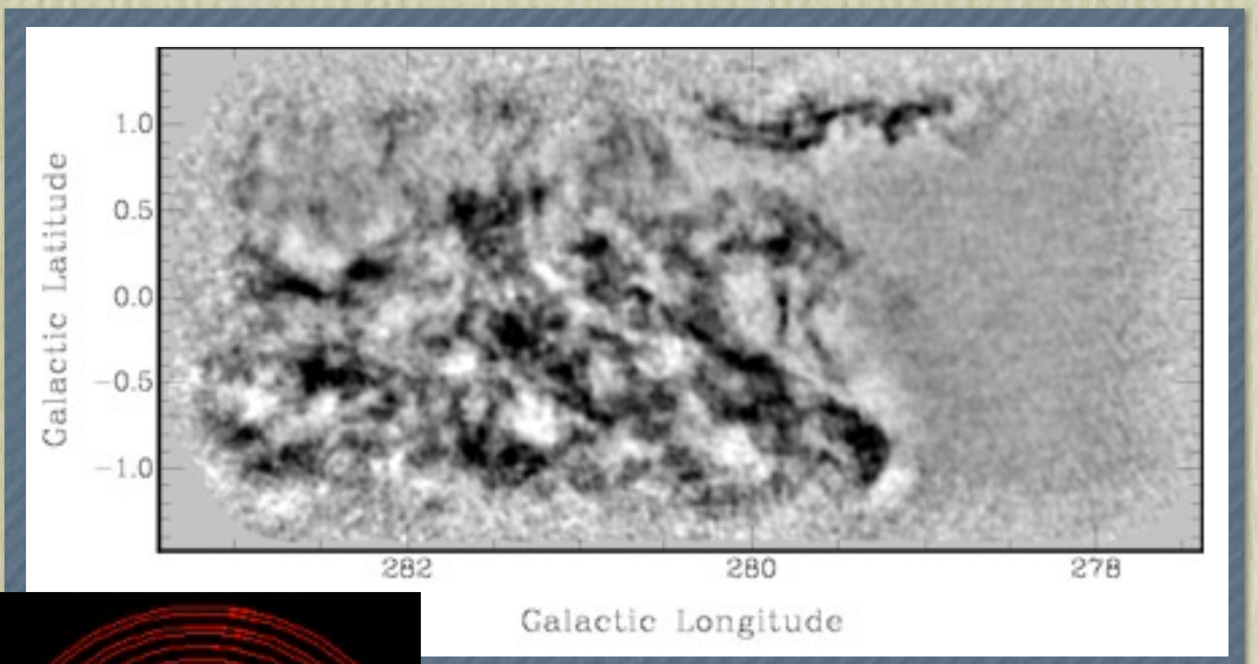

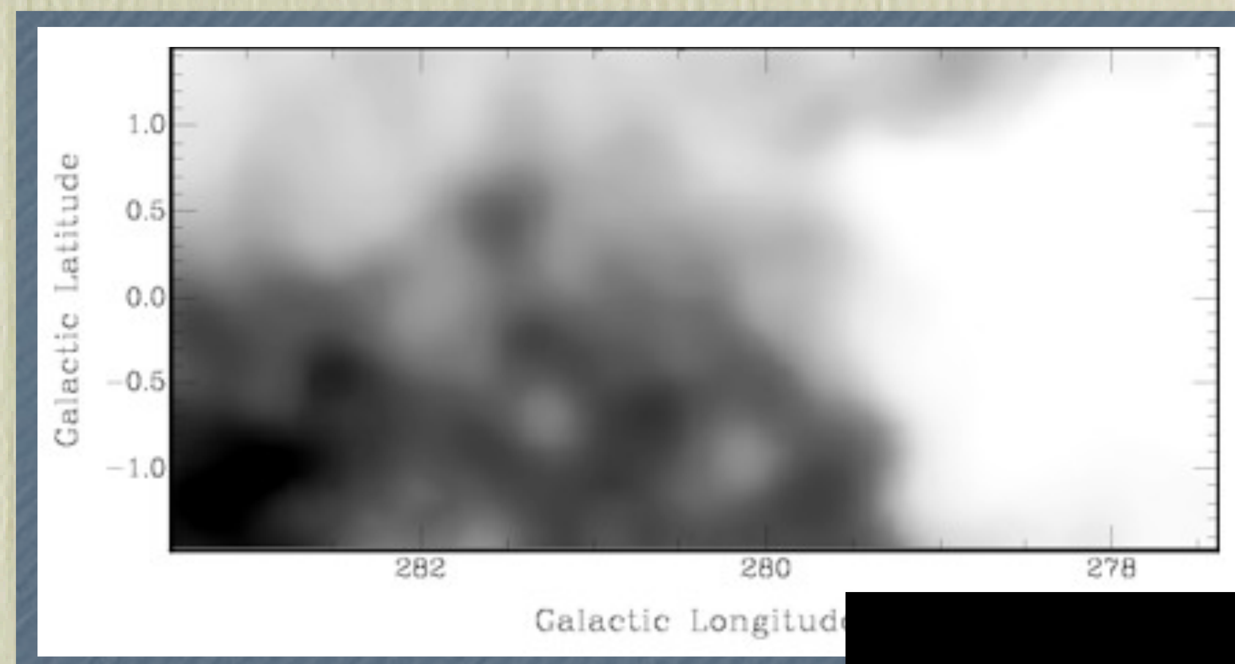

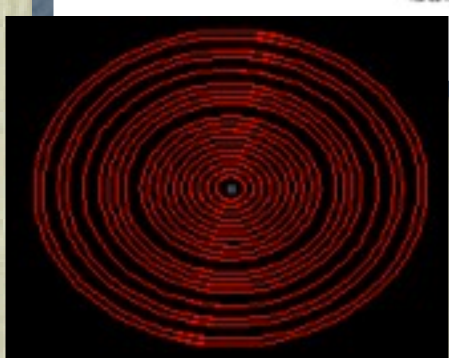

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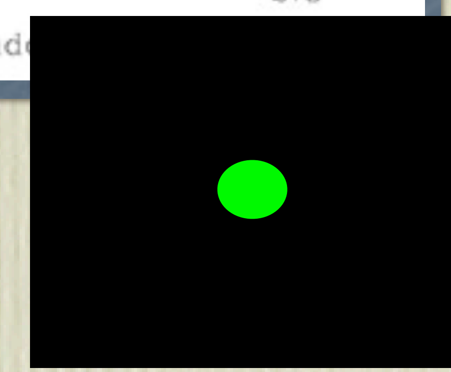
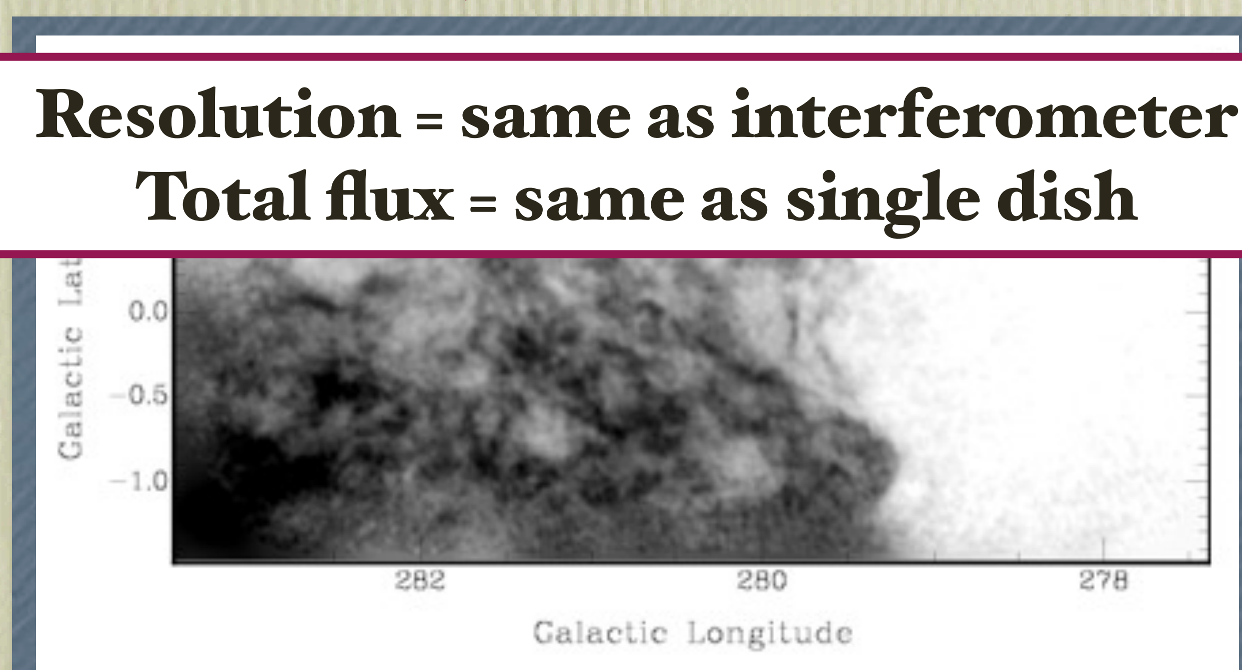
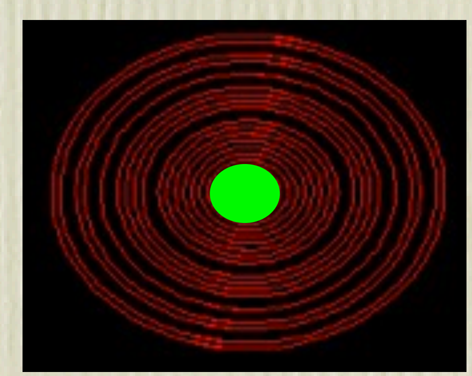


u-v coverage

Resolution = same as interferometer
Total flux = same as single dish





McClure-Griffiths (2001; talk)

Short Spacings from Single Dish Data

- Observe same region separately with a large single dish (ideally $D_{sd} > 2d_{min}$)
  - Observing is technically straightforward.
  - Single dish observations sensitive to systematic errors.

- Use autocorrelations from single elements of a homogeneous array.
  - Theoretically simple.
  - Tricky to implement. (Must find a way to observe simultaneously in single dish and interferometric modes.)

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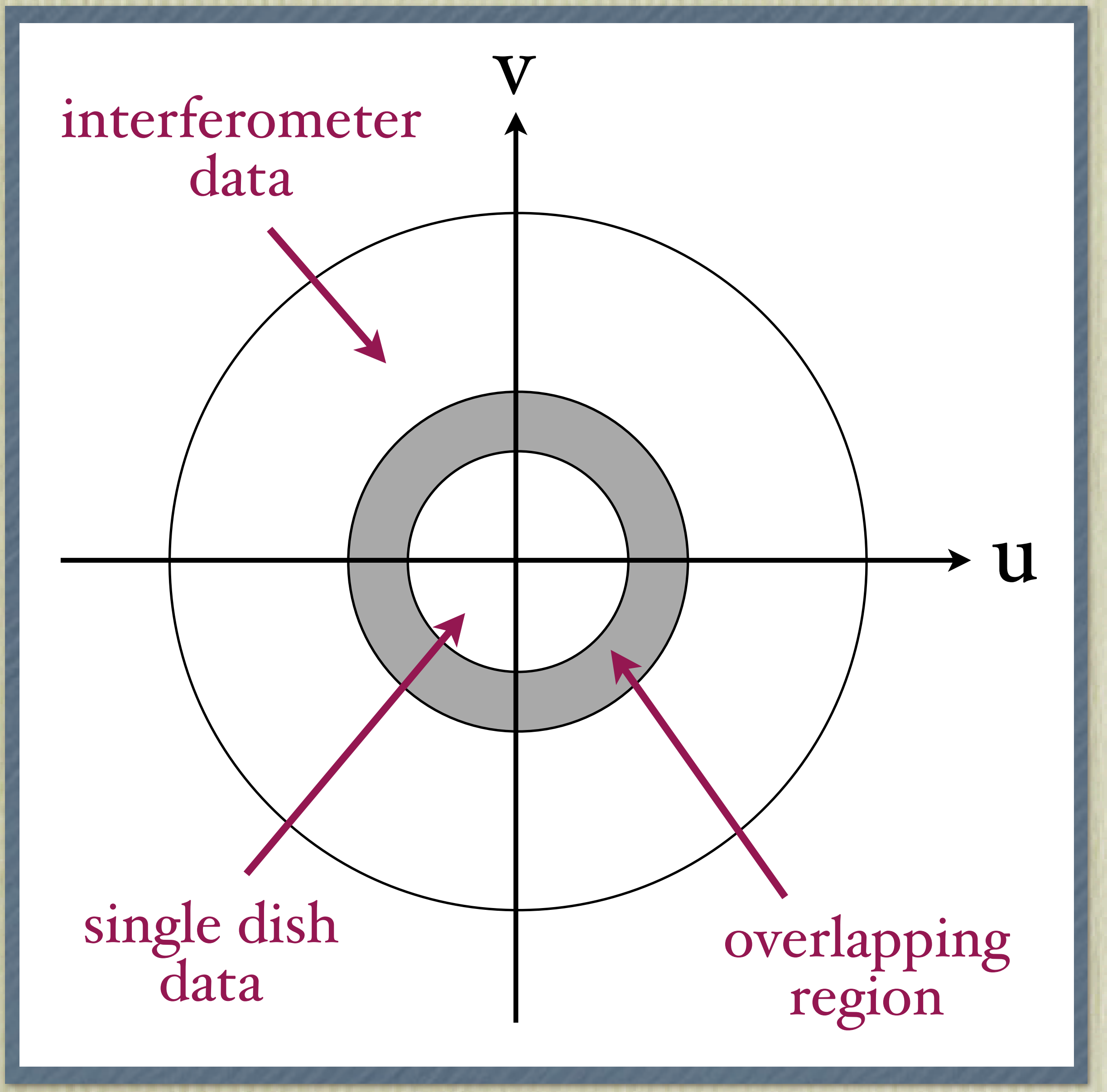
Calibration: Basics

- Flux density scales for interferometer and single dish datasets must be identical.
- Interferometer is usually better calibrated - easier to track gain variations, uncorrelated fluctuations not retained...
- Define flux calibration factor by which to "correct" single dish data:

$$f = \frac{S_{\rm int}}{S_{\rm sd}}$$

- Determine f by comparing data at spatial frequencies sampled by both instruments...

Calibration: Basics



1. FT interferometer and single dish images.

2. Deconvolve single dish data by dividing by FT of single dish beam.

(Remember:)

$$I_{\mathrm{sd}}^{\mathrm{D}}(l,m) = I(l,m) * B_{\mathrm{sd}}(l',m')$$

observed — sky — beam

$$V'_{\mathrm{sd}}(u,v) = V(u,v) \times b_{\mathrm{sd}}(u,v)$$

3. Compare "visibilities" in overlapping region.

Calibration: Further Points

- Intensity expressed in units of Jy/beam. Must convert to same per-solid-angle scale before comparison.

$$\alpha = \Omega_{\text{int}}/\Omega_{\text{sd}}$$

- Single dish of $D_{\text{sd}} > 2d_{\text{min}}$ required for reliable cross calibration.
- Requires good knowledge of single dish beam pattern. Errors have effect on calibration factor that varies non-linearly with distance in u-v plane.

(See Stanimirovic 2002 for more information...)

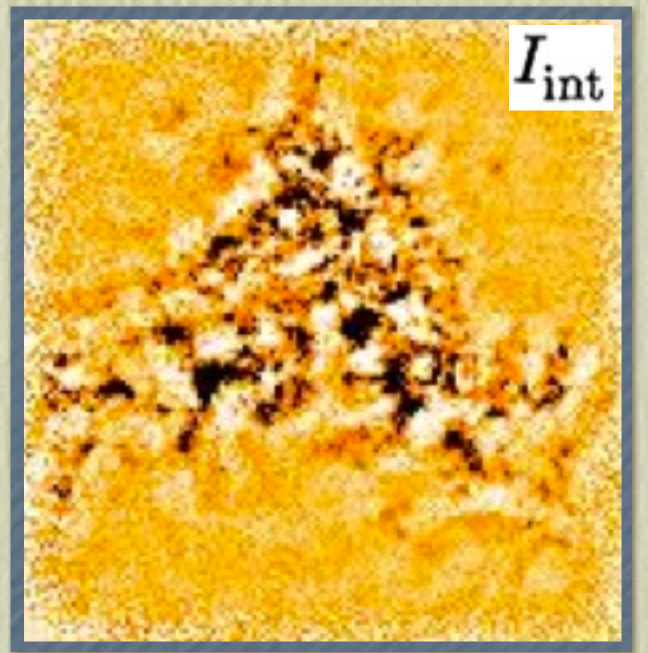
Combining Single Dish Data

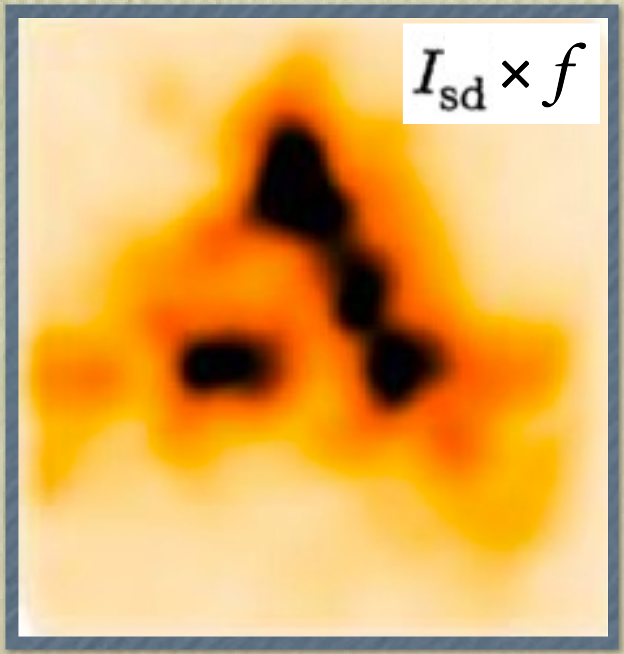
- When? Before, during or after deconvolution?
- How? Combination in the image plane? In the spatial frequency plane? As part of the deconvolution process?

We will look at:

1. Linear combination in the u-v plane after deconvolution
2. Linear combination in the image plane prior to deconvolution
3. Non-linear combination during deconvolution:
   3.1. Using the single dish as a default image
   3.2. Joint deconvolution

1. Linear Combination in the u-v Plane





SMC, Stanimirovic (2002; 2005)

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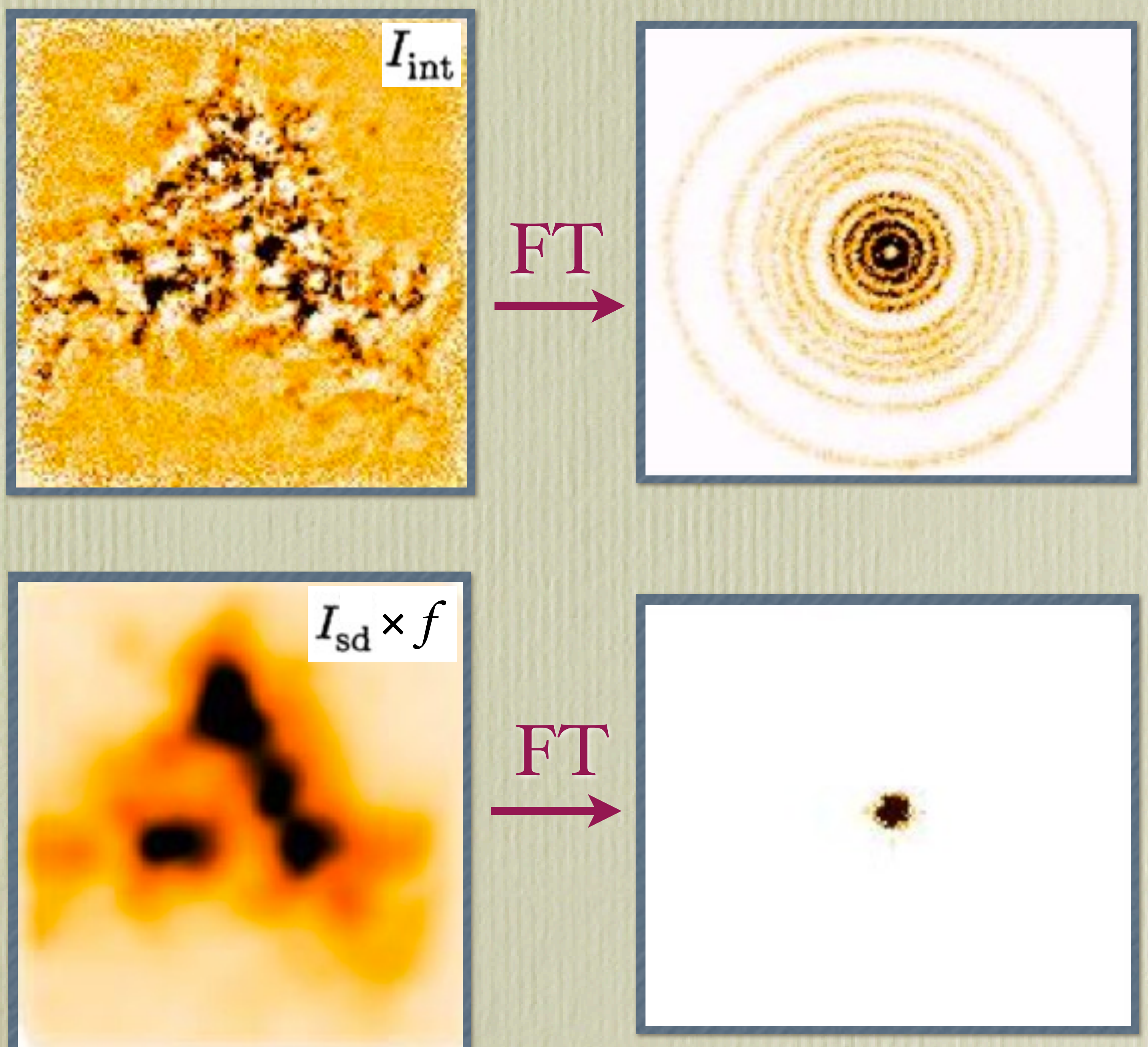

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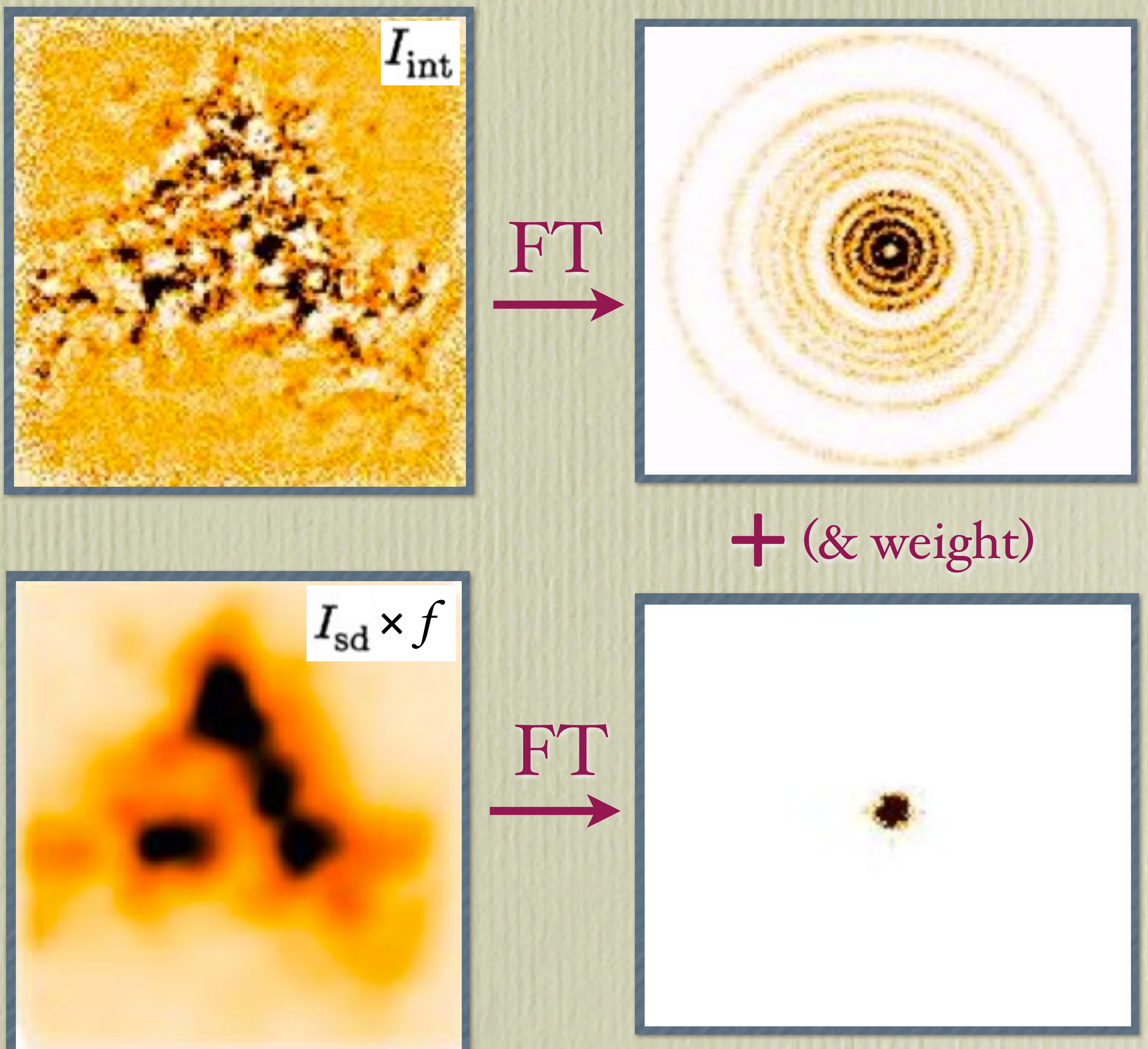

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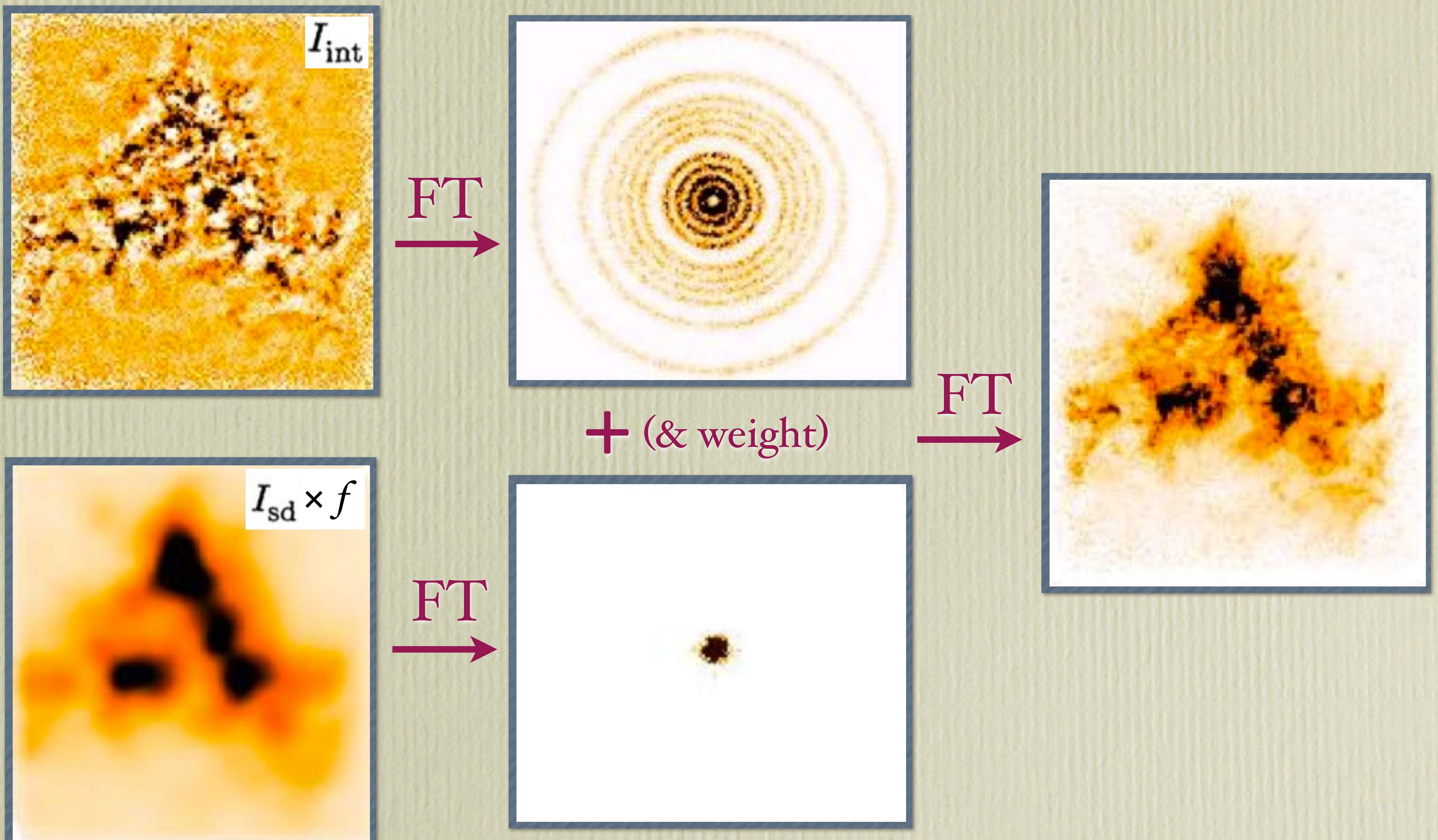


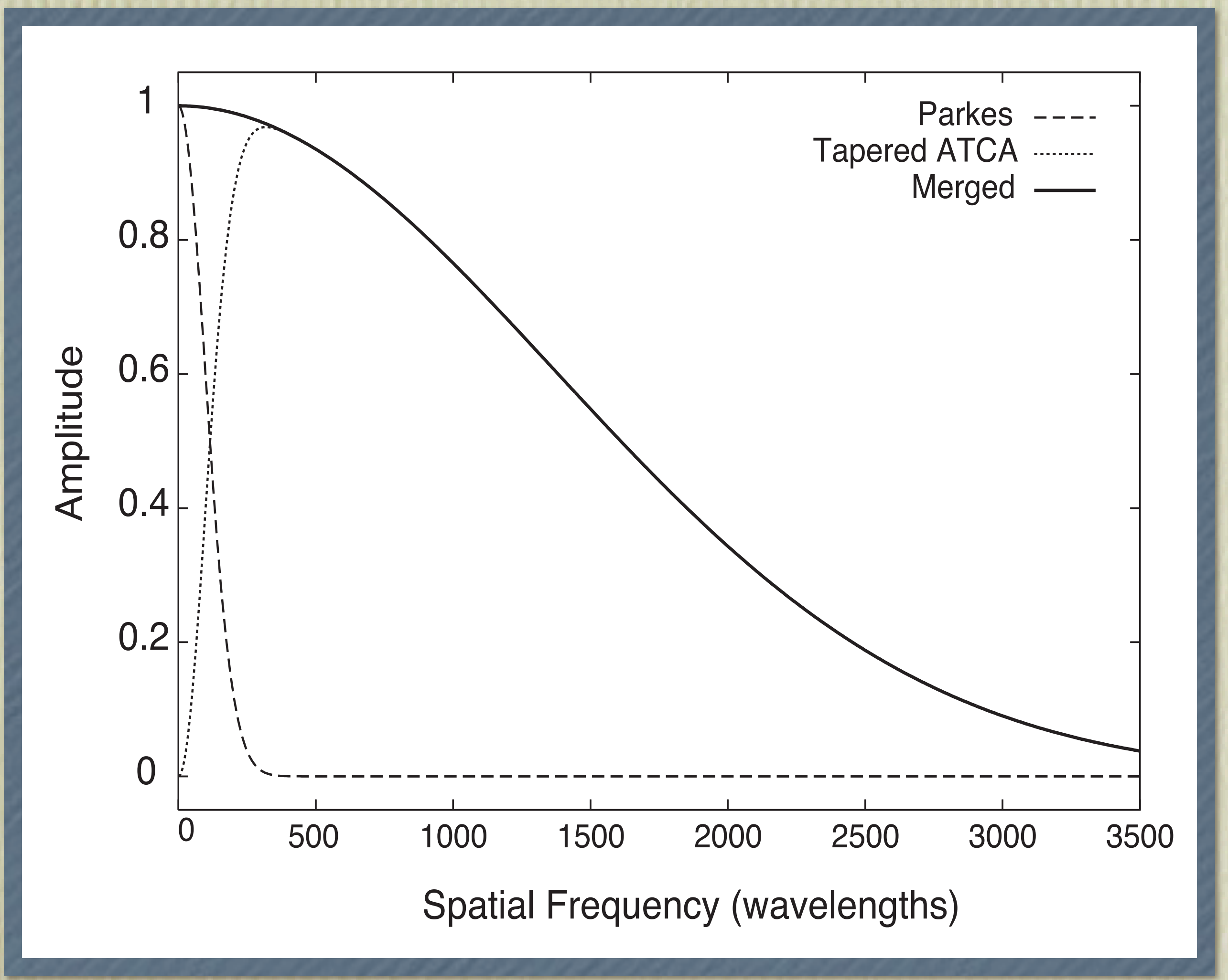
SMC, Stanimirovic (2002; 2005)

1. Linear Combination in the u-v Plane

- Start with **deconvolved interferometer image** and single dish image.
    1. FT both images
    2. Weight in u-v plane
    3. Add weighted data in u-v plane
    4. FT back to image plane
- Implementation: *immerge* in Miriad, *imerg* in AIPS, *imager* in AIPS++, *feather* in CASA...
- Sometimes called “feathering”.

1. Linear Combination in the u-v Plane

- Visibilities must be weighted where there is overlap



- Combine according to

calibration factor

$$V_{\text{comb}}(k) = w'(k)V_{\text{int}}(k) + f w''(k)V'_{\text{sd}}(k)$$

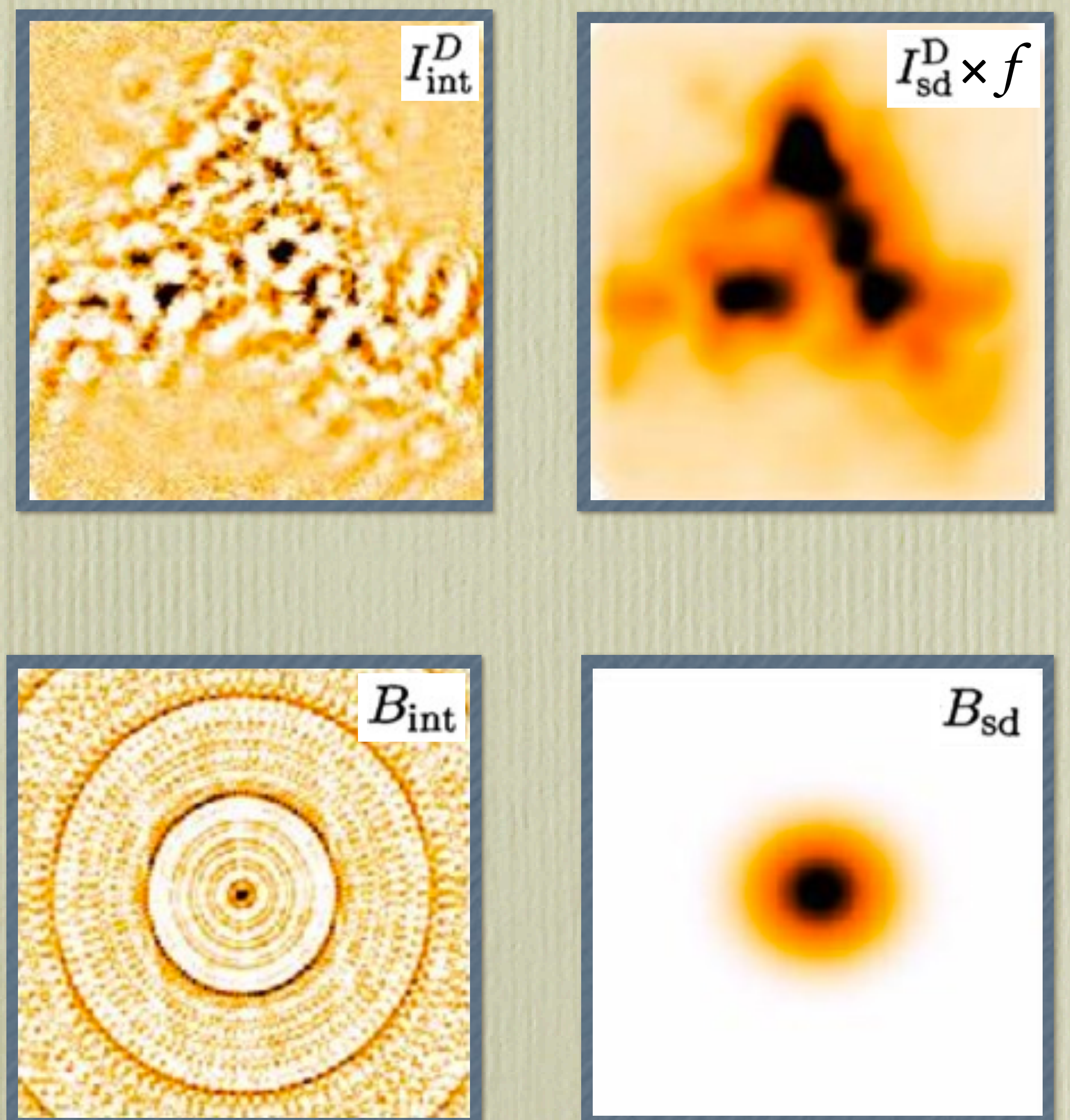
tapering functions (weights)

- Weights add such that

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

Gaussian with FWHM of interferometer beam in spatial frequency domain

2. Linear Combination in the Image Plane



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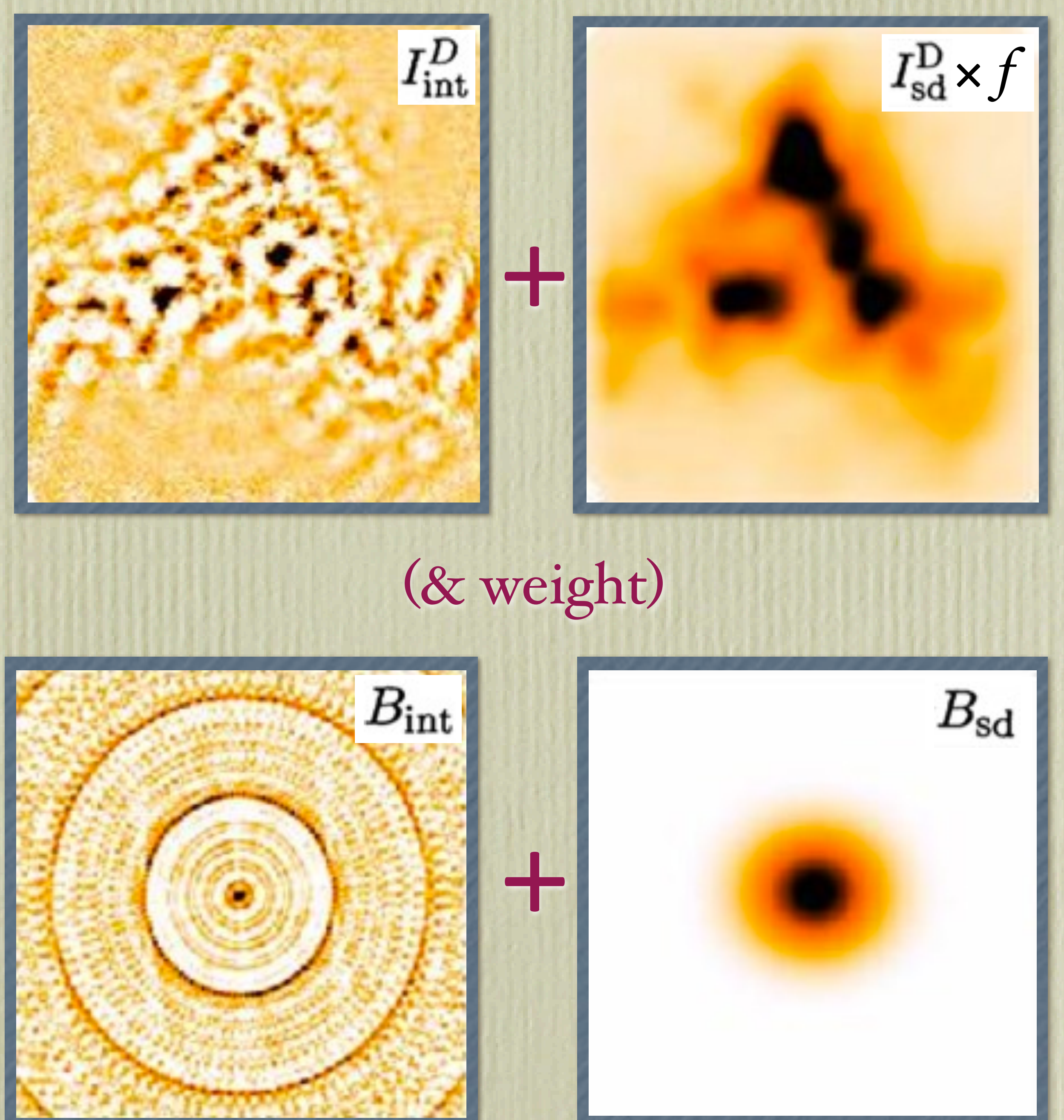

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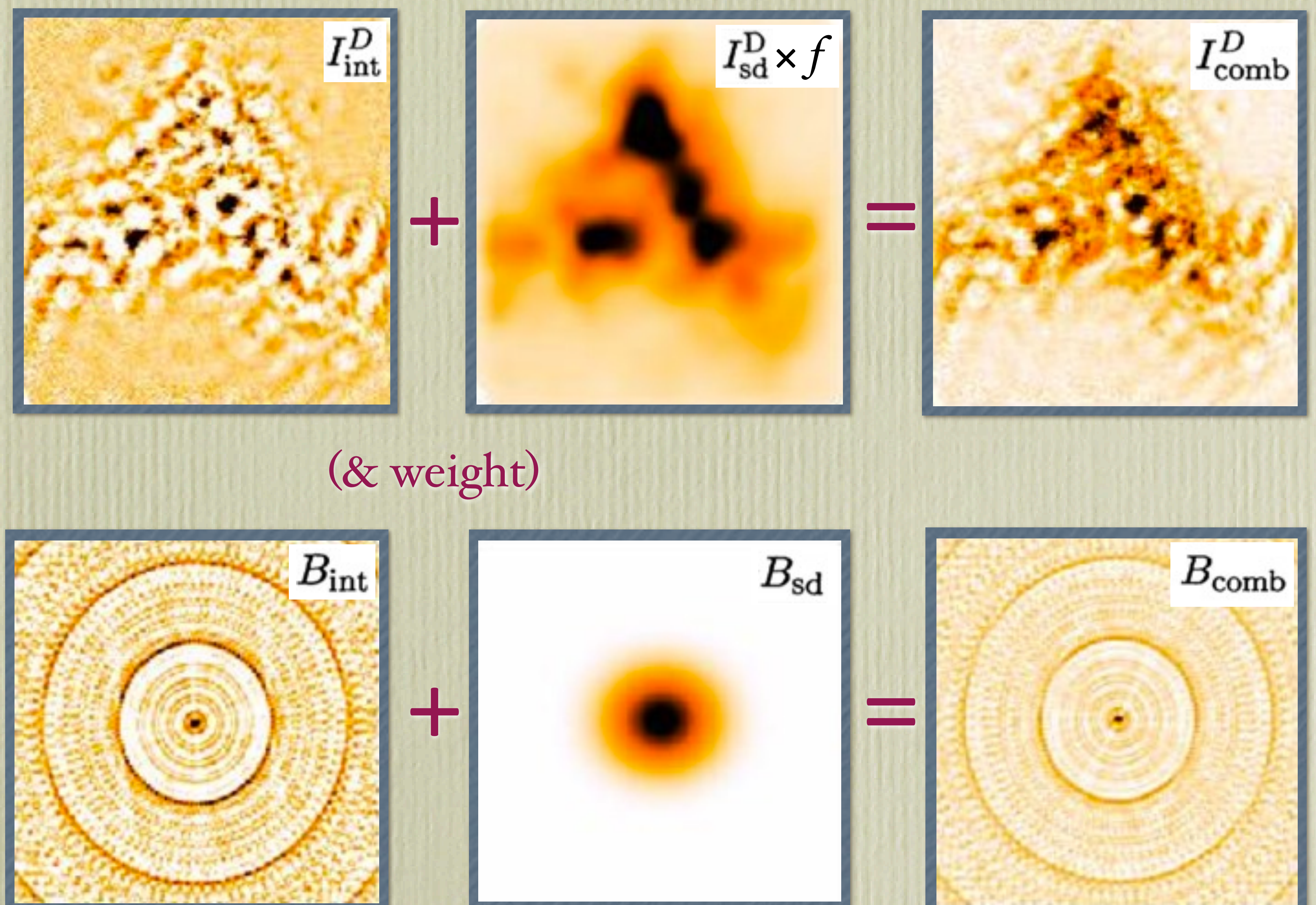

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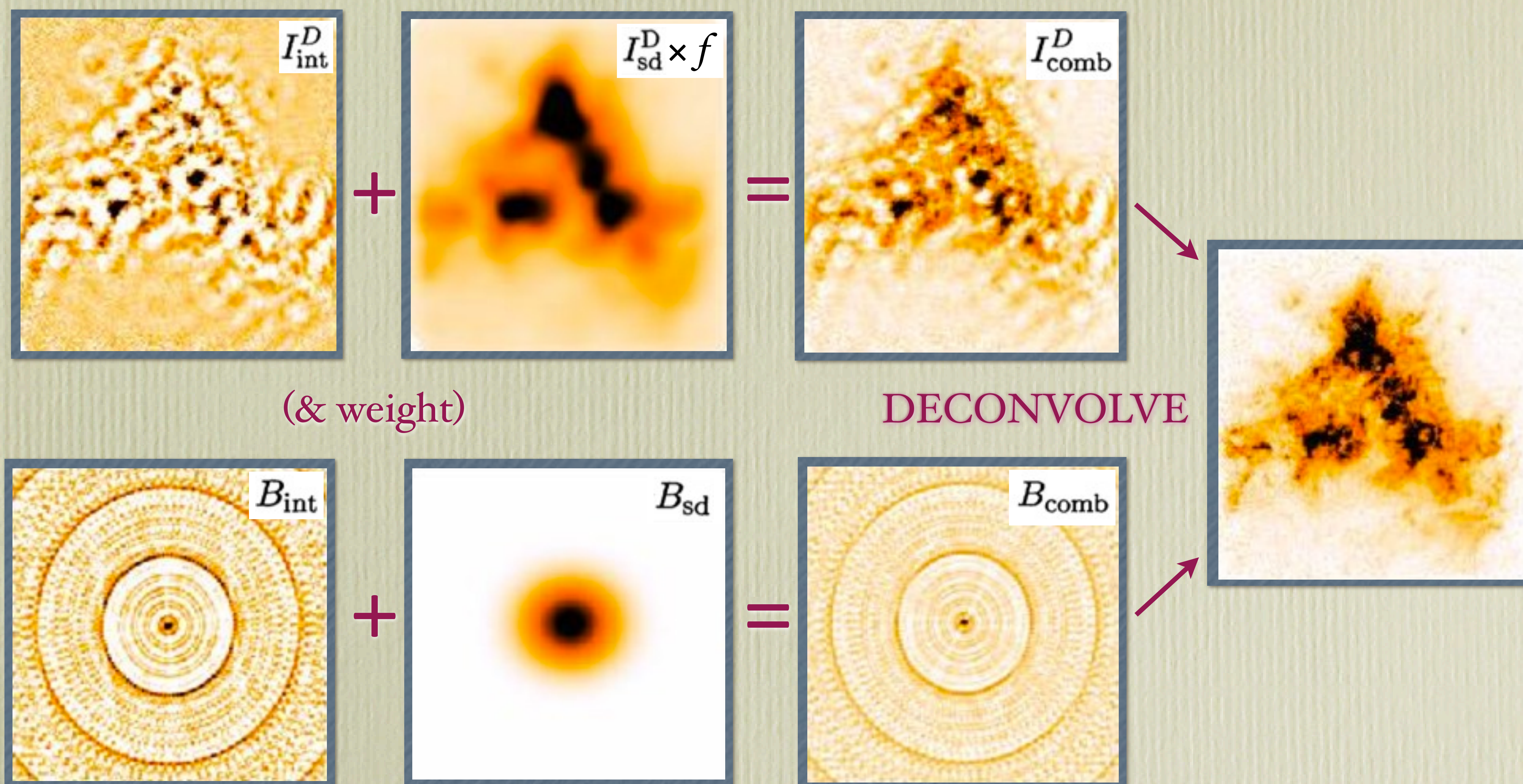


SMC, Stanimirovic (2002; 2005)

2. Linear Combination in the Image Plane

- We can do this because fourier transforms are linear: i.e. FT (A+B) = FT(A)+FT(B), and the convolution relationship between the beam and the sky still holds for the combined data. i.e.

$$I^D_{\text{comb}} = B_{\text{comb}} * I$$

- A good choice for weighting is to weight by difference in beam size:

$$I^D_{\text{comb}} = (I^D_{\text{int}} + \alpha f I^{\text{D}}_{\text{sd}})/(1+\alpha)\ ,$$
$$B_{\text{comb}} = (B_{\text{int}} + \alpha B_{\text{sd}})/(1+\alpha),$$

$$\alpha = \Omega_{\text{int}}/\Omega_{\text{sd}}$$

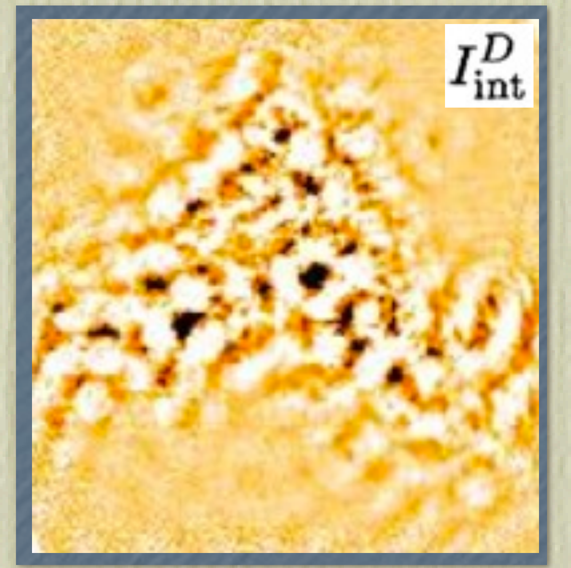
2. Linear Combination in the Image Plane

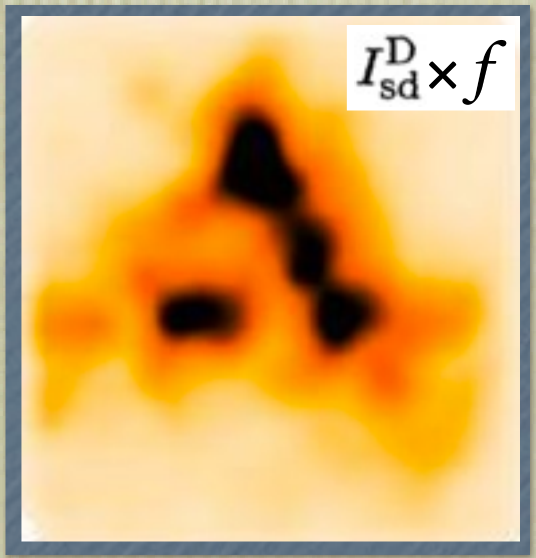
- Start with **dirty interferometer image** and single dish image.

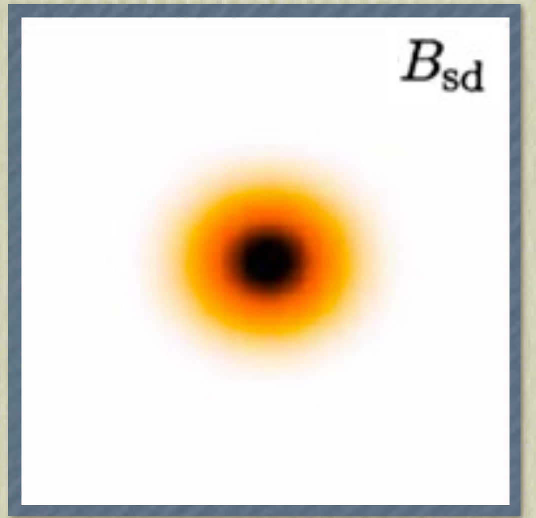
    1. Add data in the image plane
    2. Add beam patterns in the image plane
    3. Deconvolve combined image with combined beam

- Implementation: No dedicated tasks for weighting and combination, but easy to carry out manually in most data reduction packages.

3. Combination During Deconvolution

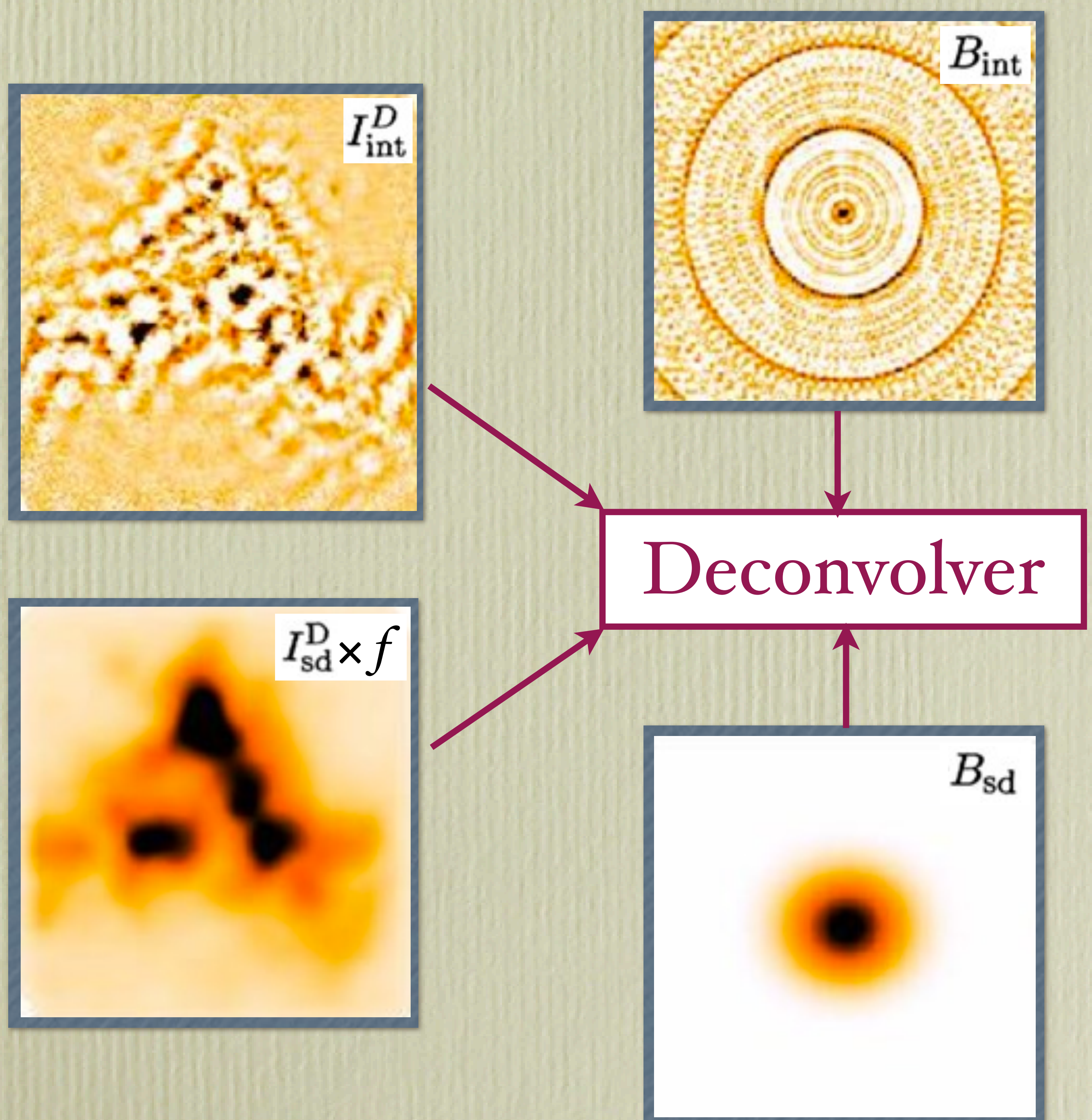






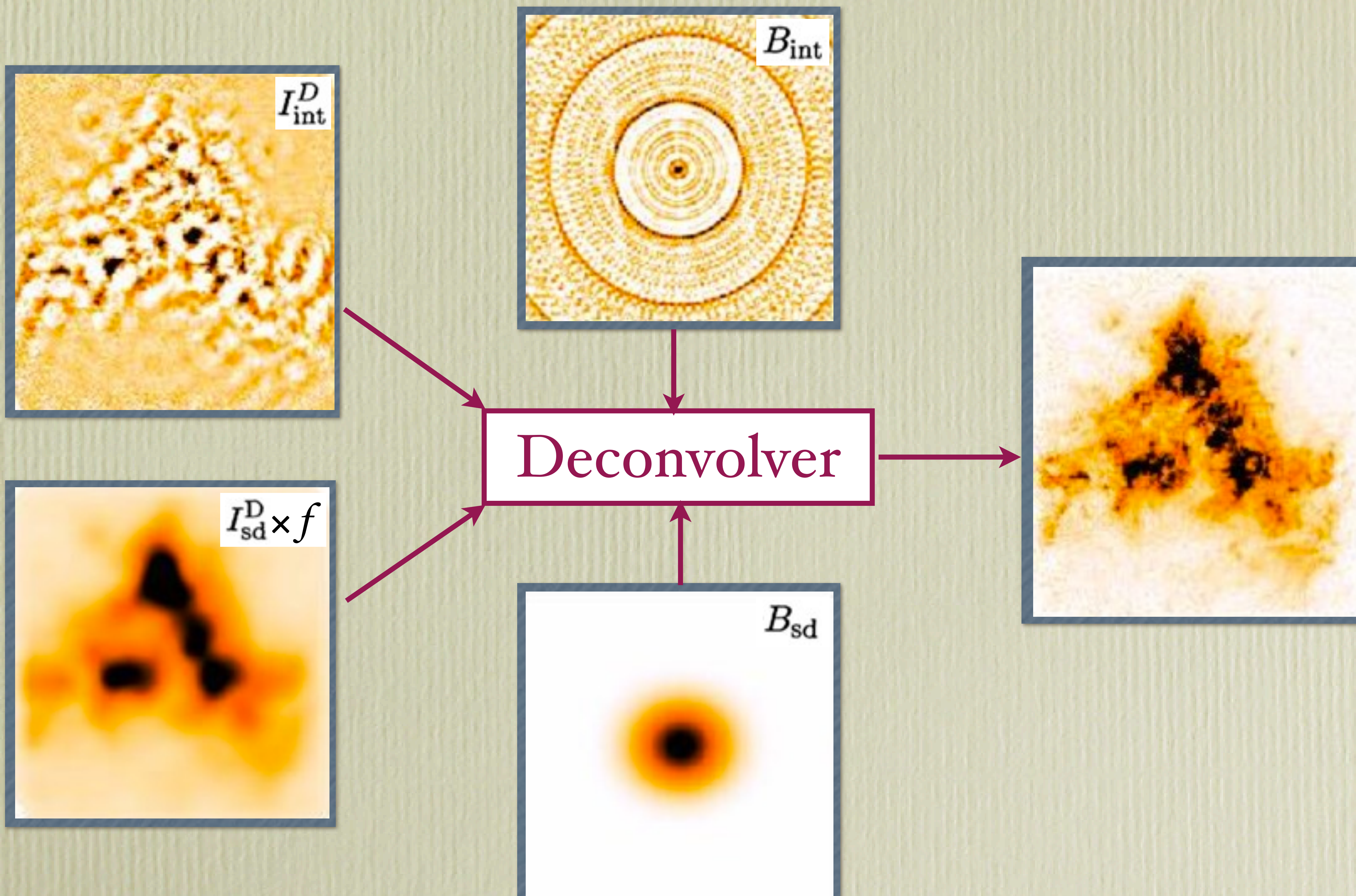
SMC, Stanimirovic (2002; 2005)

3. Combination During Deconvolution



SMC, Stanimirovic (2002; 2005)

3. Combination During Deconvolution



SMC, Stanimirovic (2002; 2005)

3. Combination During Deconvolution

- Start with **dirty interferometer image** and single dish image.
  - **Option 1: Use the single dish data as an default image**

    Implementation: Most standard deconvolution algorithms (both MEM and CLEAN-based), e.g. *mosmem* in Miriad, *clean* in CASA, *vtess* in AIPS...
  - **Option 2: "True" joint deconvolution** - simultaneously deconvolve both images.

    Implementation: Presently implemented in Miriad's *mosmem* only?

3.1. Single Dish as a Model Image

- **Maximum entropy deconvolution** (e.g. Miriad's *mosmem, maxen*): maximises the quantity

"Relative entropy" →

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

brightness of ith pixel of solution

brightness of ith pixel of model image

iterates until χ2 falls below:

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

noise variance

no. of pixels

- Use single dish image as $M_i \rightarrow$ **Solution is forced to resemble single dish** as far as interferometer data constraints allow

3.1. Single Dish as a Model Image

- **CLEAN**-based algorithms: single dish image is subtracted off before cleaning begins. i.e. used to calculate first residuals before cleaning.

  Final solution = single-dish model + clean components found during deconvolution

- For both MEM and CLEAN-based algorithms, a large overlap between the interferometer and single dish data is recommended.

3.2. "True" Joint Deconvolution

- In *mosmem*, "true joint deconvolution" finds the model which maximises the entropy subject to two separate χ^2 constraints:

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

interferometer χ^2 ⟶

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

single dish χ^2 ⟶

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

Combination During Deconvolution: Further Reading

Help!

All about MEM deconvolution: Cornwell et al. (1985), plus many other Tim Cornwell papers...

Practical information on deconvolution algorithms: **Miriad**, **CASA**, **AIPS** User's Guides...

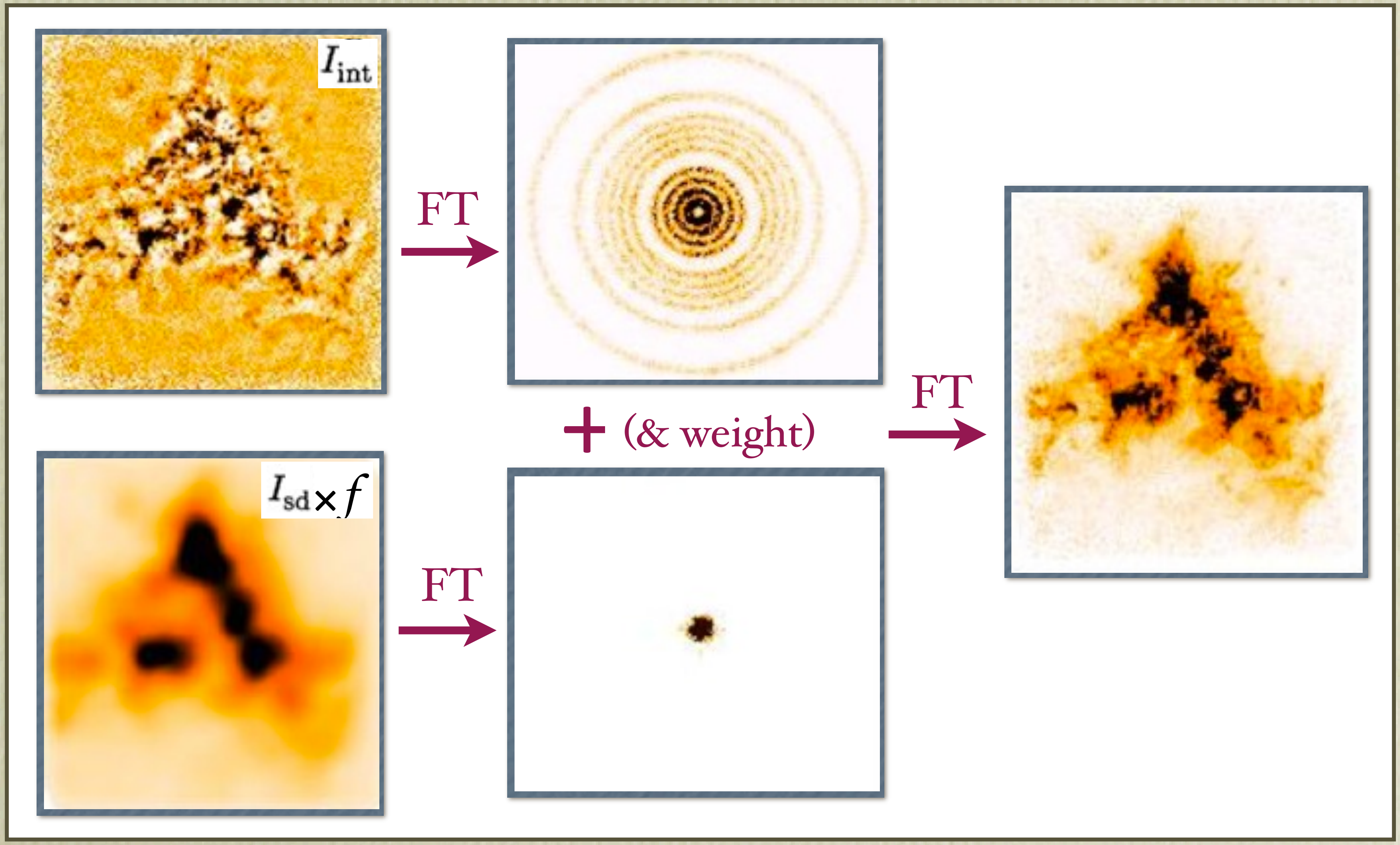
More generally: Thompson, Moran & Swenson. (The Interferometry bible!)

Comparing Different Schemes

All methods produce comparable results for high S/N data.

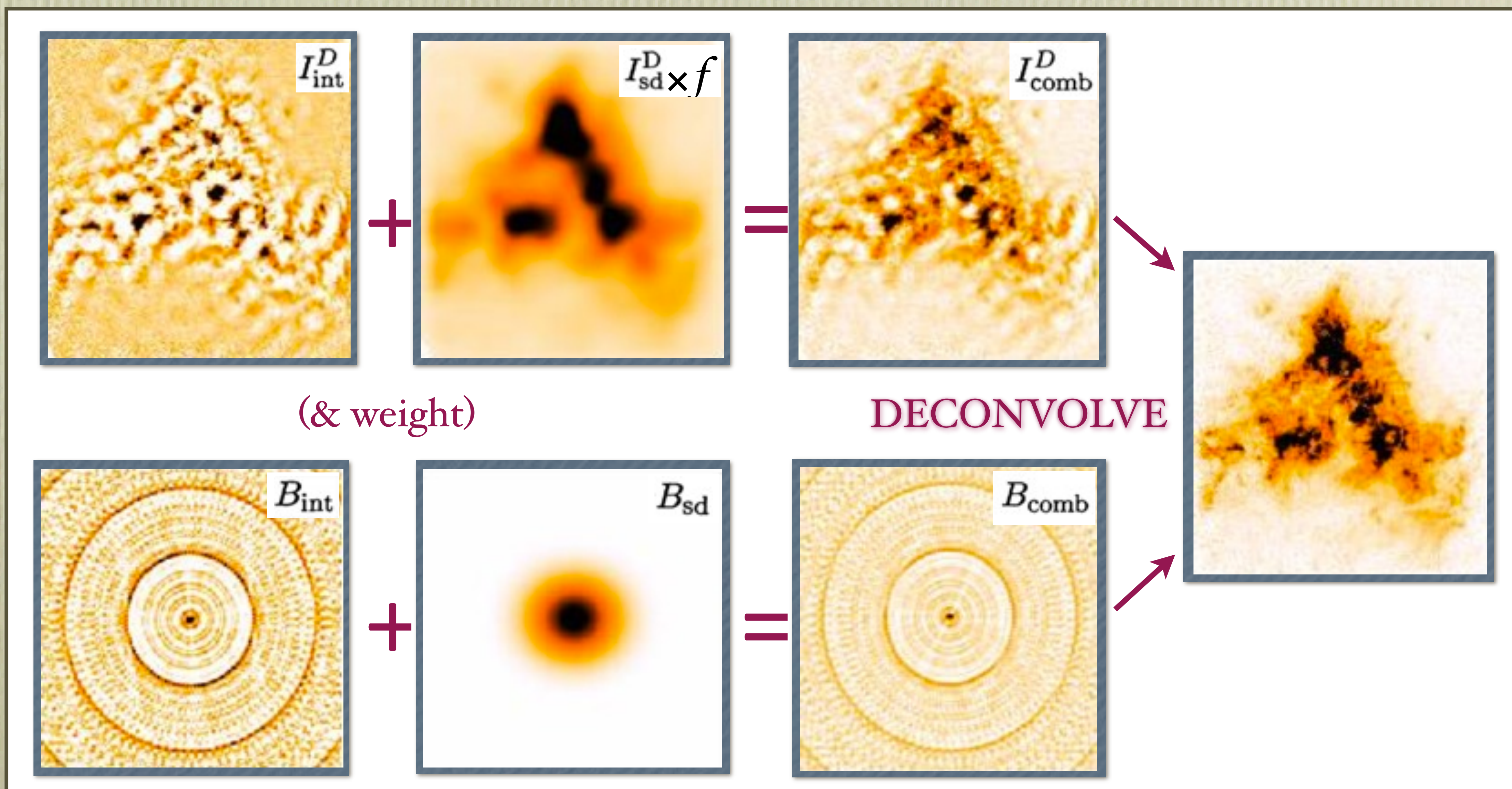
Comparing Different Schemes

1. Linear combination in the u-v plane:
   - Fastest, least computer-intensive, very robust. Slightly weights up interferometer data over single dish.



Comparing Different Schemes

2. Linear combination in the image plane:
   - Simple, easy to implement/automate. Particularly good for low S/N data (e.g. mm). Weights up SD data over interferometer.



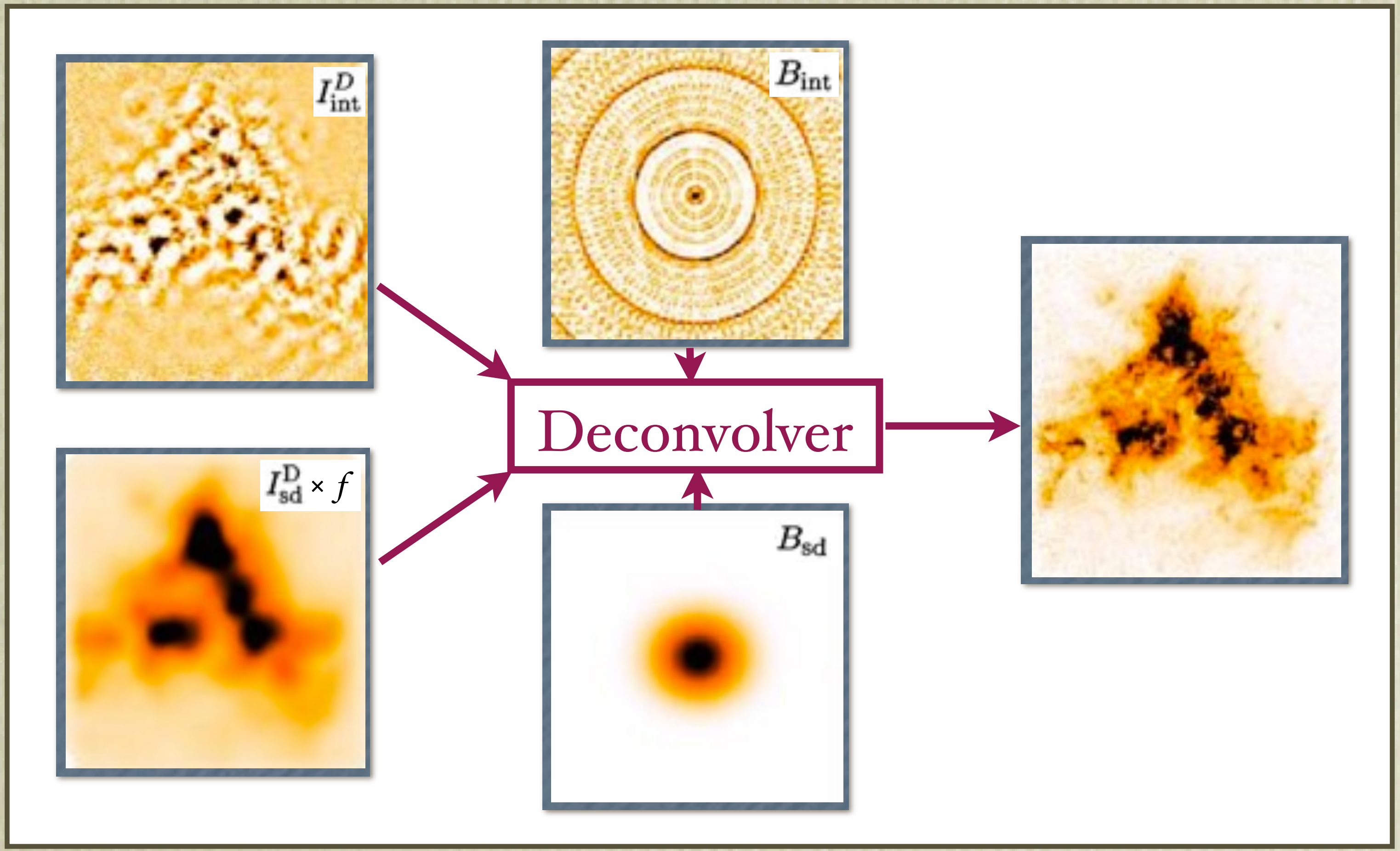
Comparing Different Schemes

3.1. Combination during deconvolution - SD as default image:

- Included in most deconvolution tasks. Fast where there is significant overlap between datasets.

3.2. Combination during deconvolution - Joint deconvolution

- Theoretically the best option. But highly sensitive to single dish data quality & beam shape.



Practical Requirements for Single Dish Data

- **Single dish diameter of at least $D_{sd} > 2d_{min}$** to allow accurate calculation of flux calibration factor, f.
- **Data must be Nyquist sampled** to avoid aliasing during deconvolution.
- Observed **field should be larger than target object** to avoid edge effects.
- **S/N should be comparable to interferometer data**.
- In general, need **good knowledge of the single dish beam**

Summary

- For extended objects missing short spacings are a problem.
- Combing with single dish data provides this missing information.
- Four main methods to choose from. Needs will vary, but all provide comparable results and are easy to implement!

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