Short-Spacings Correction From the Single-Dish Perspective

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- Breath and depth of combining interferometer and single-dish data …
- A recipe for observing extended objects (with detours):
  1. the briefest possible intro to interferometry
  2. demonstration of the short-spacings problem
  3. what can we do about the short-spacings problem ?
  4. different methods for data combination
- Some recent examples
- Challenges at mm wavelengths

Single-dish and interferometer data frequently need to be combined …

- when observing **EXTENDED** objects (larger than ?/b_{min} or interferometer's primary beam) [you'll see why exactly]
- when **MOSAICING**: if you need to mosaic, you'll need to add single-dish data.
- especially at mm wavelengths where **TOTAL POWER** info is almost always needed.
- Data combination is routinely performed with a great success.
- Data combination has been the key driver for recent antenna designs (ALMA, CARMA).
- Data combination can be viewed as an 'artistic touch' to the interferometric data.
- Data combination helps greatly to bridge the historical gap between single-dishes and interferometers.

A Recipe for Observing Extended Objects:

- **Ingredients:**

1. an extended object (e.g. Small Magellanic Cloud)
2. an interferometer (e.g. VLA, ATCA, BIMA, ATA)
3. a single-dish (e.g. Arecibo, GBT, Parkes, 12m)

- **Procedure:**

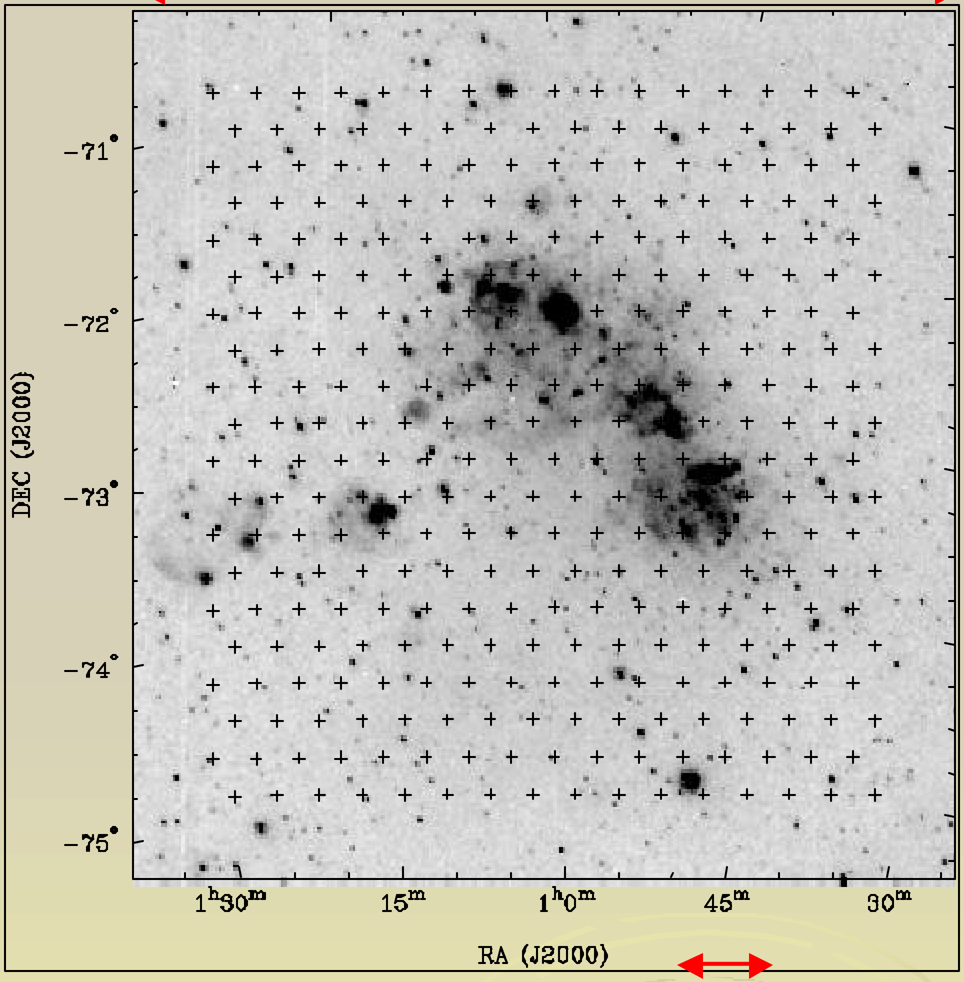
1. observe with an interferometer
2. observe with a single-dish
3. take advantage of both worlds: combine !

- **This recipe makes:**

1. pretty pictures: lots of resolution elements, no image artifacts
2. high resolution images with the TOTAL POWER information (accurate fluxes, masses etc.)
3. images sensitive to a wide range of spatial scales (very important for statistical studies)

Step 1: 'Mosaic' with an interferometer

4.5 deg = 4.7 kpc



34′ = ATCA primary beam

Australia Telescope Compact Array (ATCA) mosaic of the SMC at 1.4 GHz.

Mosaic of 320 different pointings.

Mosaic = point to many directions and paste all info together.

How does an interferometer actually work ?

Thompson (1994)

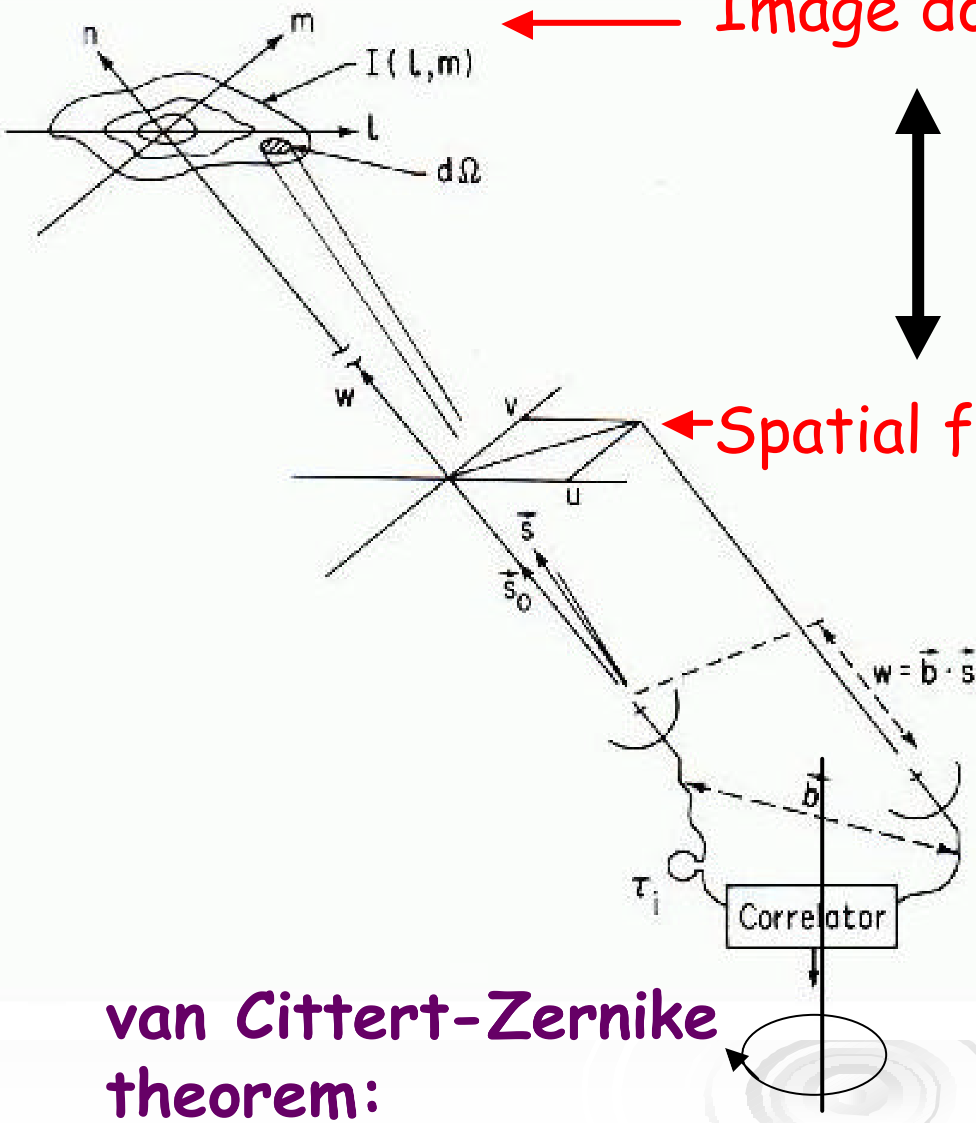


Image domain

Fourier transform

Spatial frequency domain

Sky brightness distribution

Spatial coherence function

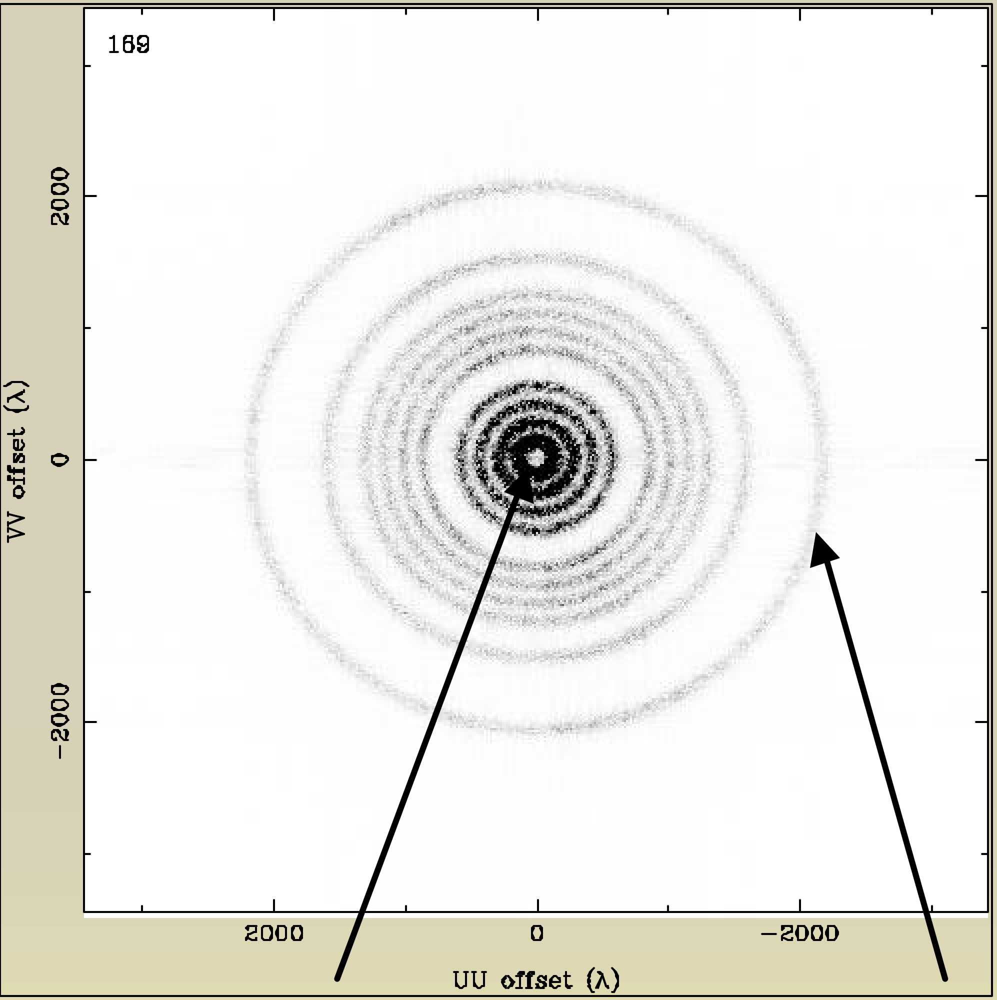
Antenna primary beam

van Cittert-Zernike theorem:

$$V(\vec{b}) = \int_{src} A(\vec{\sigma}) I(\vec{\sigma}) e^{-2\pi i \vec{b}.\vec{\sigma}/\lambda} d\Omega$$

$$V(u,v) = \int\int A(l,m) I(l,m) \times e^{-2\pi i(ul+vm)} \frac{dl\,dm}{\sqrt{1-l^2-m^2}}$$

More baselines, more u-v tracks!



Australia Telescope Compact Array (ATCA), an E-W linear array.

5 antennas, 5(5-1)/2

diff. baselines

Lowest spatial frequency: ~31m/0.21m

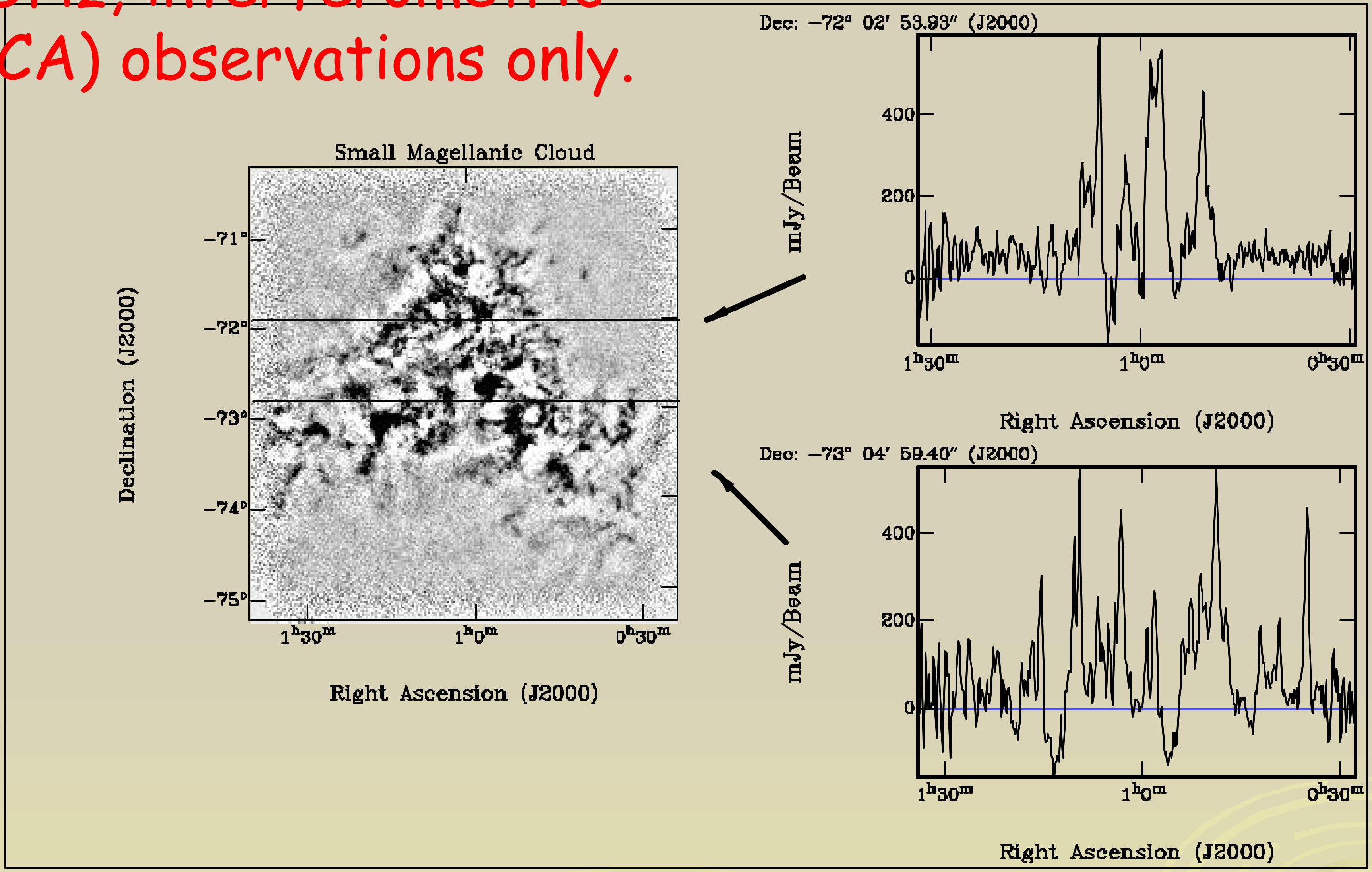
Can not see structure > 24'.

Highest spatial frequency: ~495m/0.21m

Angular resolution=1.6'

And what is the result ?

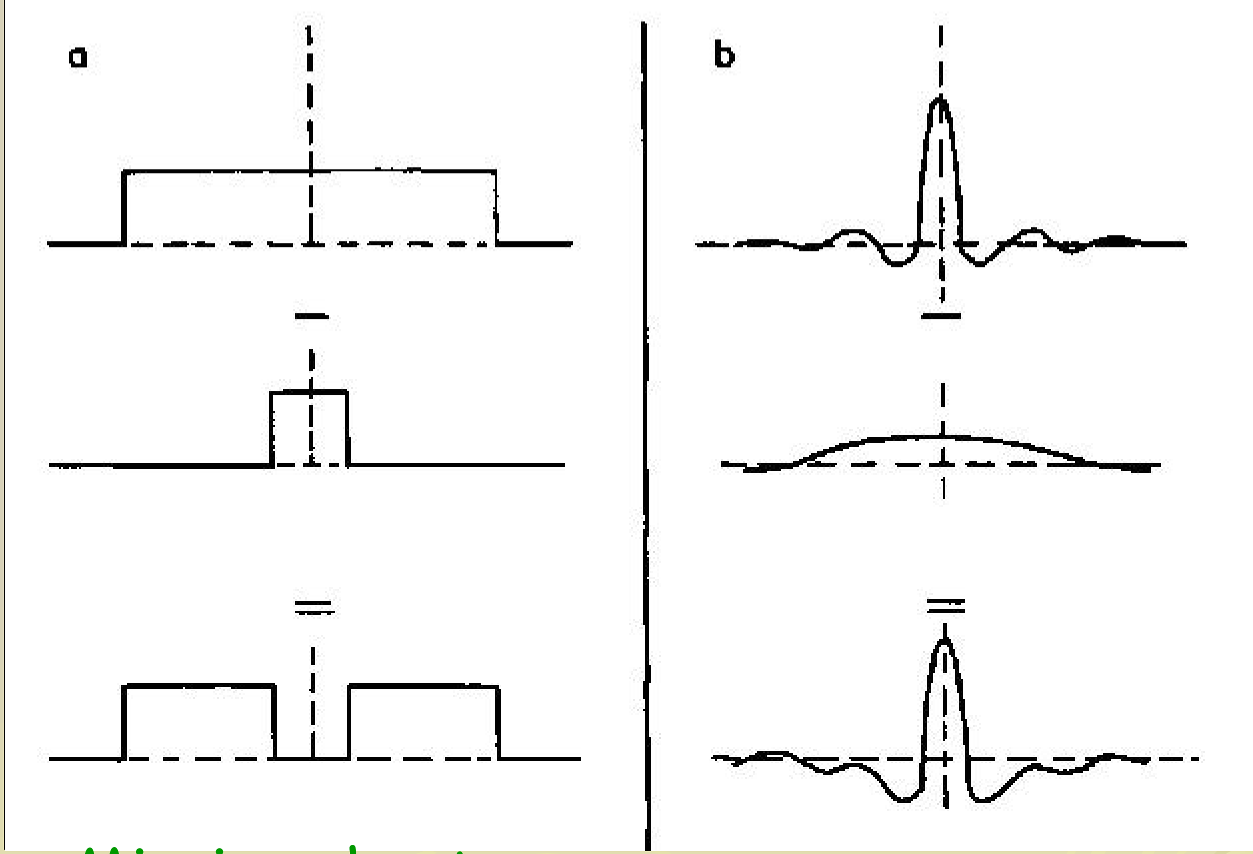
Small Magellanic Cloud at 1.4 GHz, interferometric (ATCA) observations only.



And what is the result ? WHY ?

Spatial frequency domain

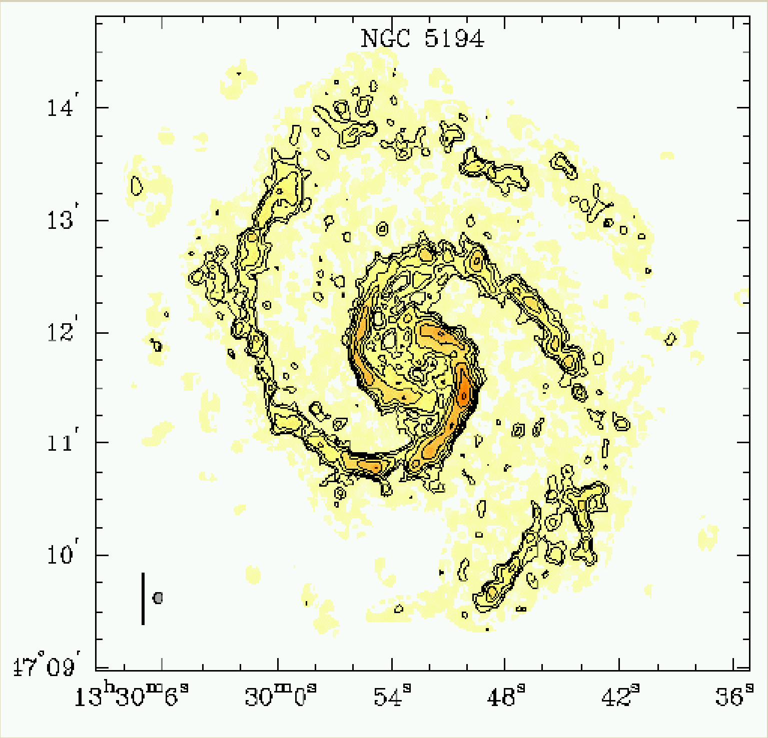
Image domain



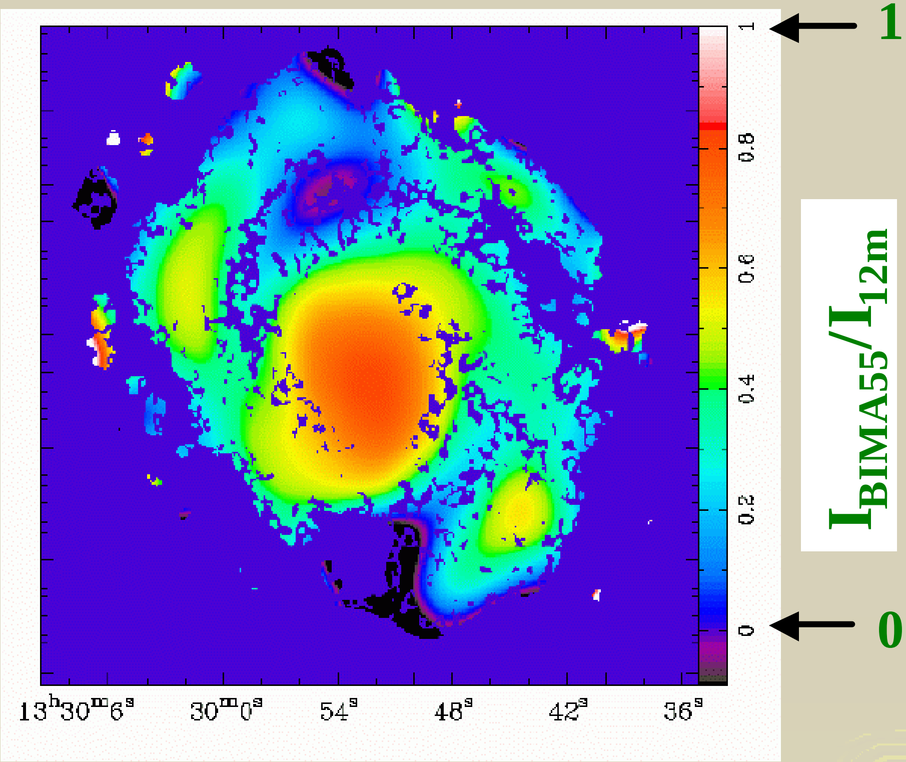
Missing short sp. frequencies

Negative bowls

How severe the problem is ?



BIMA SONG
CO map

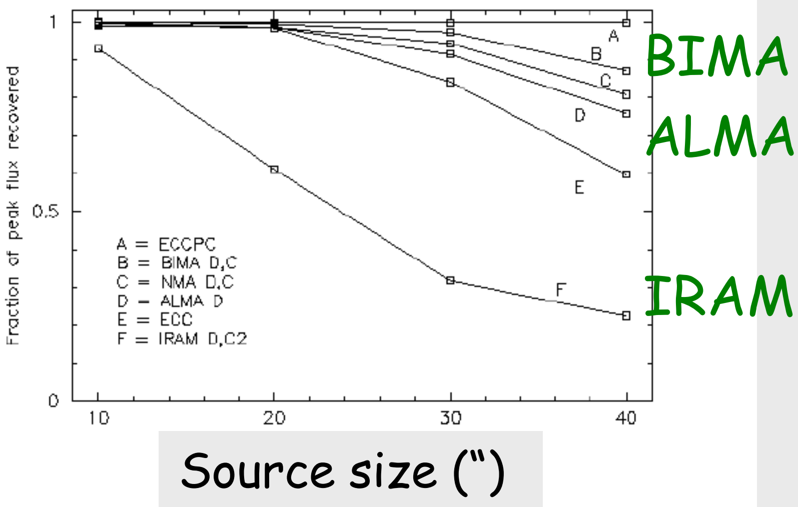


Flux recovery
ratio map

How much flux is missing ?

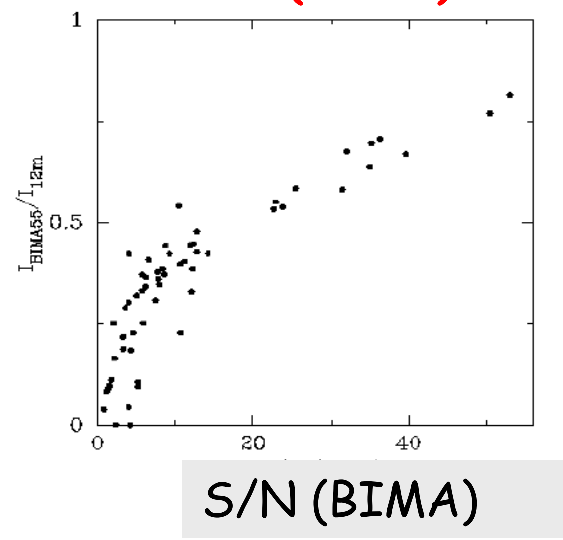
Simulations

Helfer et al. (2002)



BIMA SONG Data, > 30 galaxies

Helfer et al. (2003)



Large-scale flux recovery for a mosaic observation :

- depends on the minimum distance between the dishes, b_{min}-D
- is a function of the S/N
- varies from source to source, and spatially

→ Large-scale distribution can not be modeled, needs to be measured!

What can we do about the short-spacings problem ?

- ✓ How to provide missing short-spacings ?

  1. Homogeneous scheme = all antennas of the same size
  2. Heterogeneous scheme = different-sized antennas

- ✓ How to combine short-spacing data with that from an interferometer ?

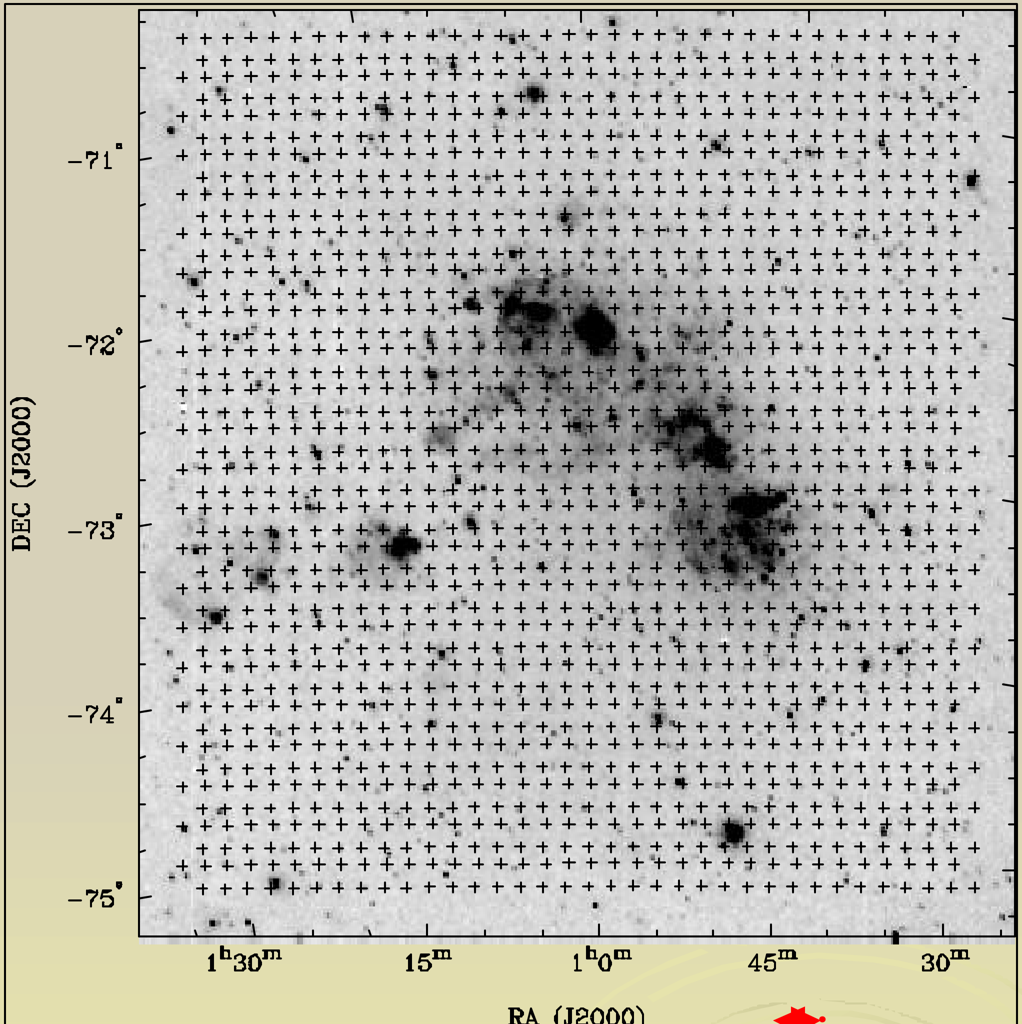
- ✓ As few gaps in the u-v plane as possible !

  Single-dish diameter > min. interferometer baseline.

- ✓ Must match flux scales of both data sets.

Step 2: 'Mosaic' with a single-dish

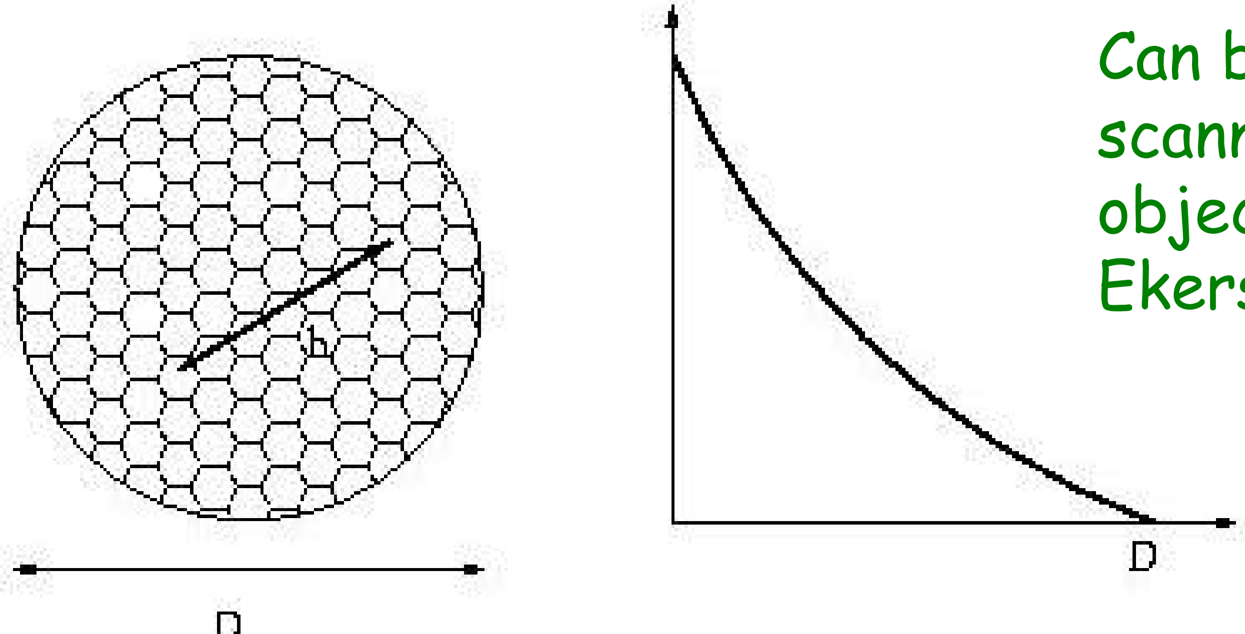
4.5 deg = 4.7 kpc



Parkes primary beam=15′

- Point to many directions & grid all spectra.
- **1540** different pointings with the Parkes (64 m) telescope!
- Multi-beam systems can help here greatly!

Single-dish as an interferometer!



Can be retrieved by scanning across your object, based on Ekers & Rots (1979).

'Phased array' → continuous range of baselines available from 0 to D.

Similar mathematical representation for both interferometers and single-dishes!

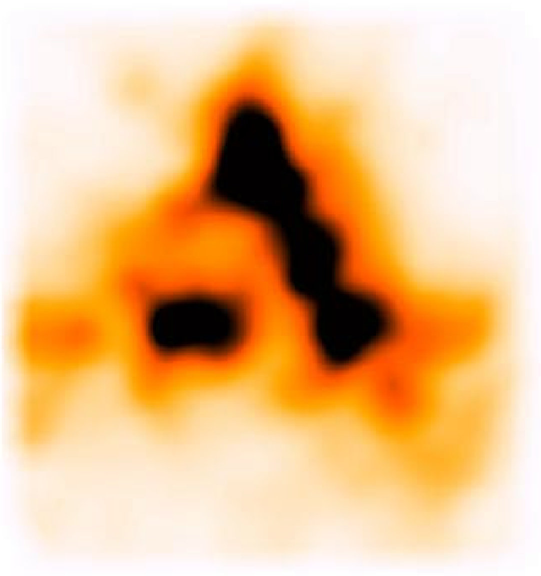
$$I^{\mathrm{D}}_{\mathrm{int}}(x,y) = I(x,y) * B_{\mathrm{int}}(x,y)$$
$$V'_{\mathrm{int}}(u,v) = V(u,v) \times b_{\mathrm{int}}(u,v)$$

&

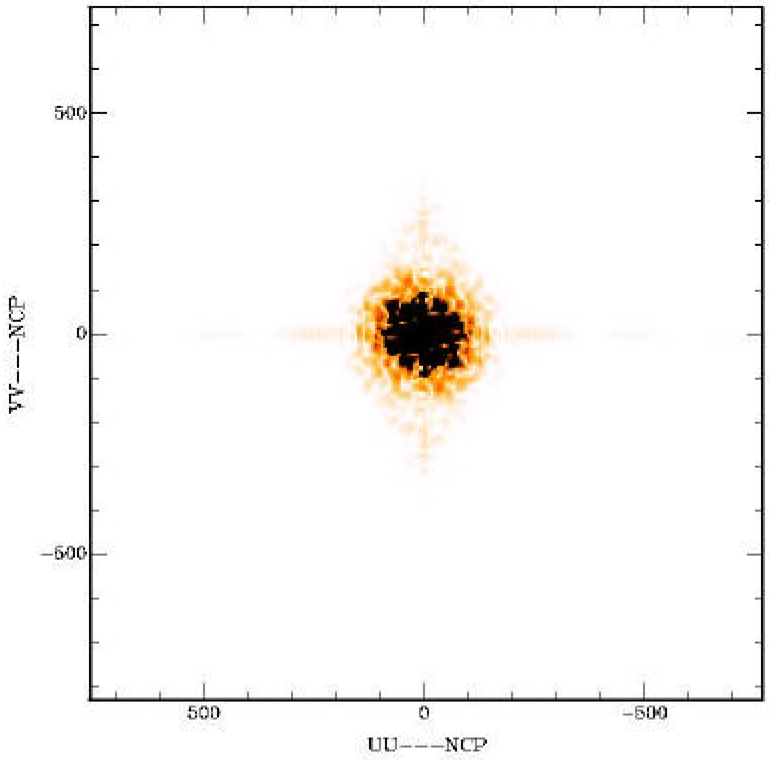
$$I^{\mathrm{D}}_{\mathrm{sd}}(x,y) = I(x,y) * B_{\mathrm{sd}}(x,y)$$
$$V'_{\mathrm{sd}}(u,v) = V(u,v) \times b_{\mathrm{sd}}(u,v)$$

And what is the result ?

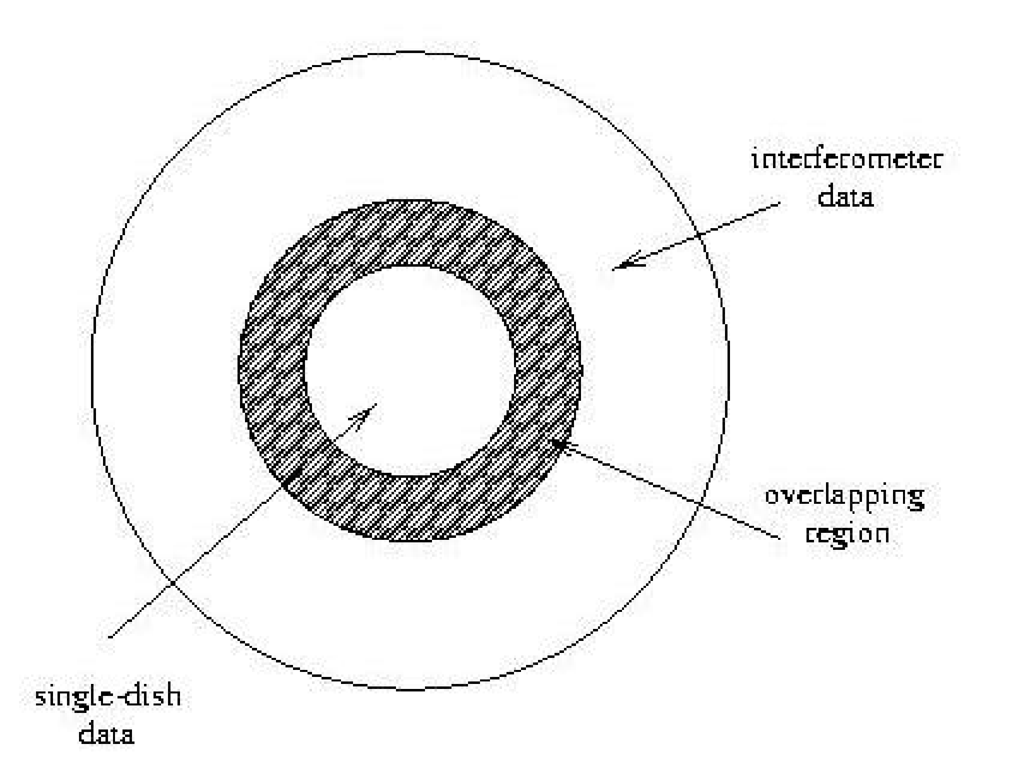
Small Magellanic Cloud at 1.4 GHz, single-dish (Parkes) observations only.



… and its Fourier transform



Step 3: Cross-calibration of two data sets



Interferometer and single-dish data should have the same flux density scale.

Calibration scaling factor:

$f_{cal}=S_{int}/S_{sd}$

Compare surface brightness of your object in the ovarlap region in the u-v plane.

Do it yourself or use Miriad's immerge

Step 4: Combination of single-dish and interferometer data

- Data combination in the Fourier domain:

Miriad's IMMERGE, Aips' IMERG, aips++'s IMAGER

Bajaja & Albada (1979); Vogel et al. (1984); Sault & Killen (2003)

- Data combination in the image domain:

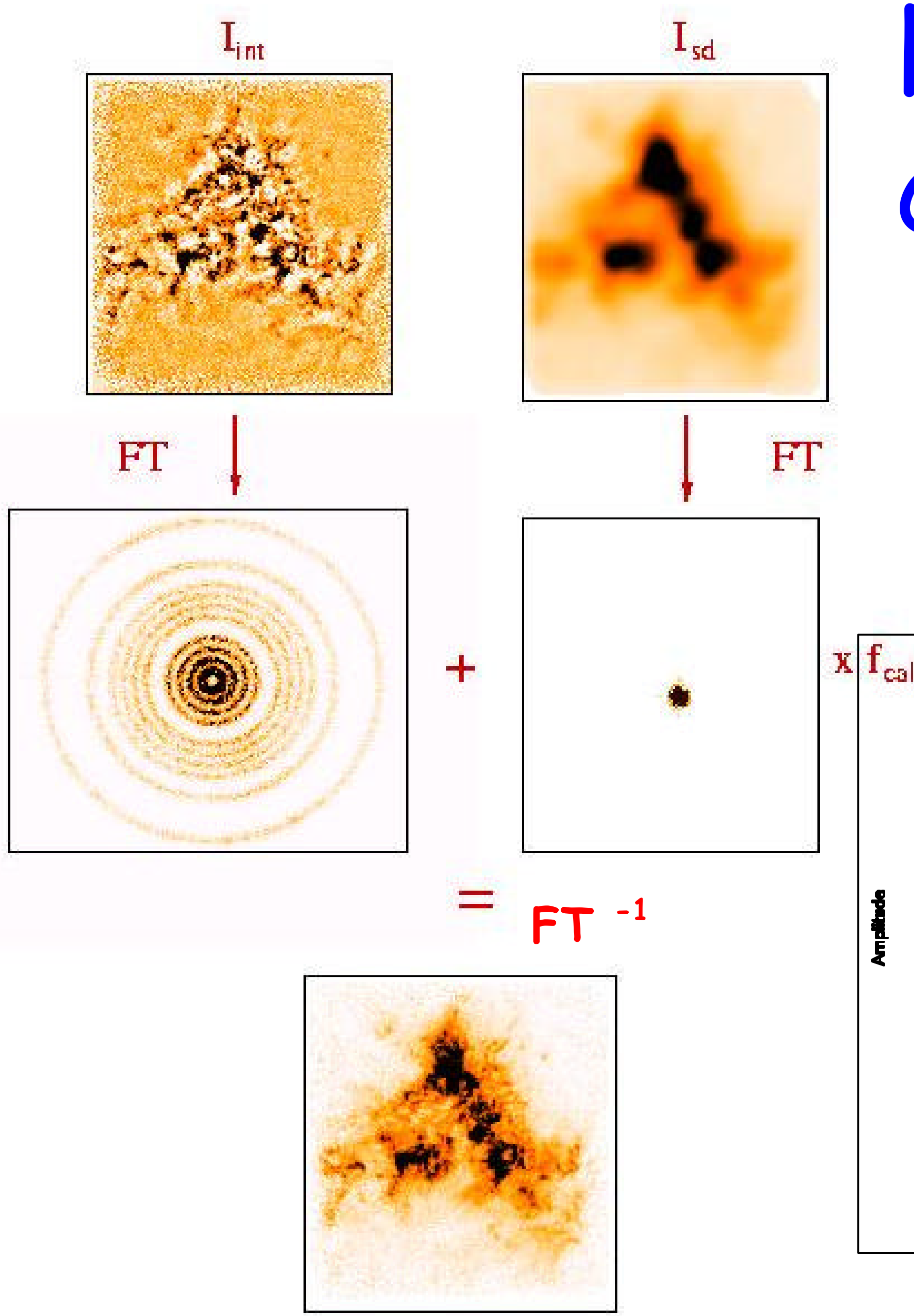
1. 'Linear Combination'

a combination of tasks, Ye & Turtle (1991); Stewart et al. (1993); Stanimirovic et al. (1999)

2. 'Non-linear combination' or 'Merging during deconvolution'

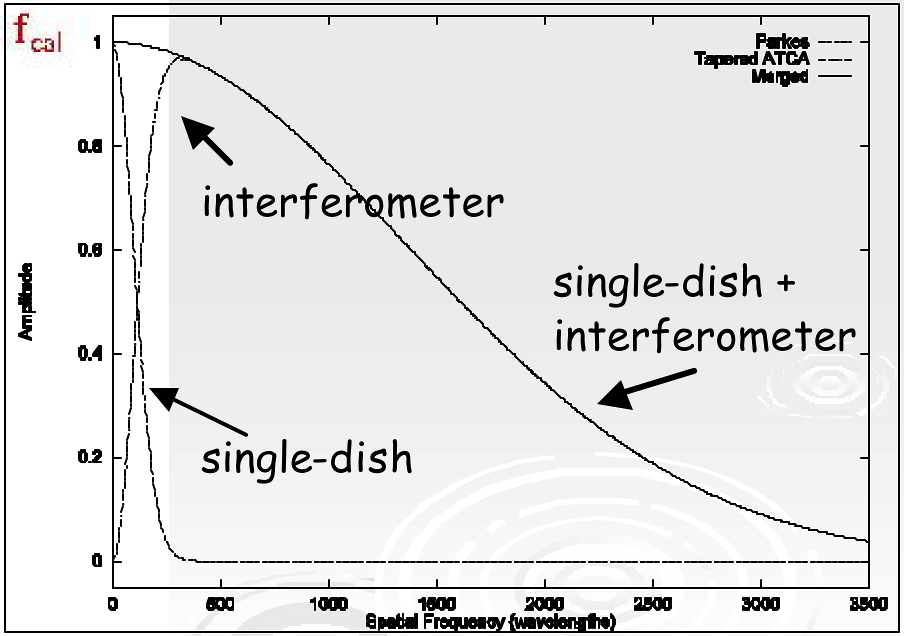
Miriad's MOSMEM through either 'default image' capability or 'joint deconvolution'

Fourier domain combination

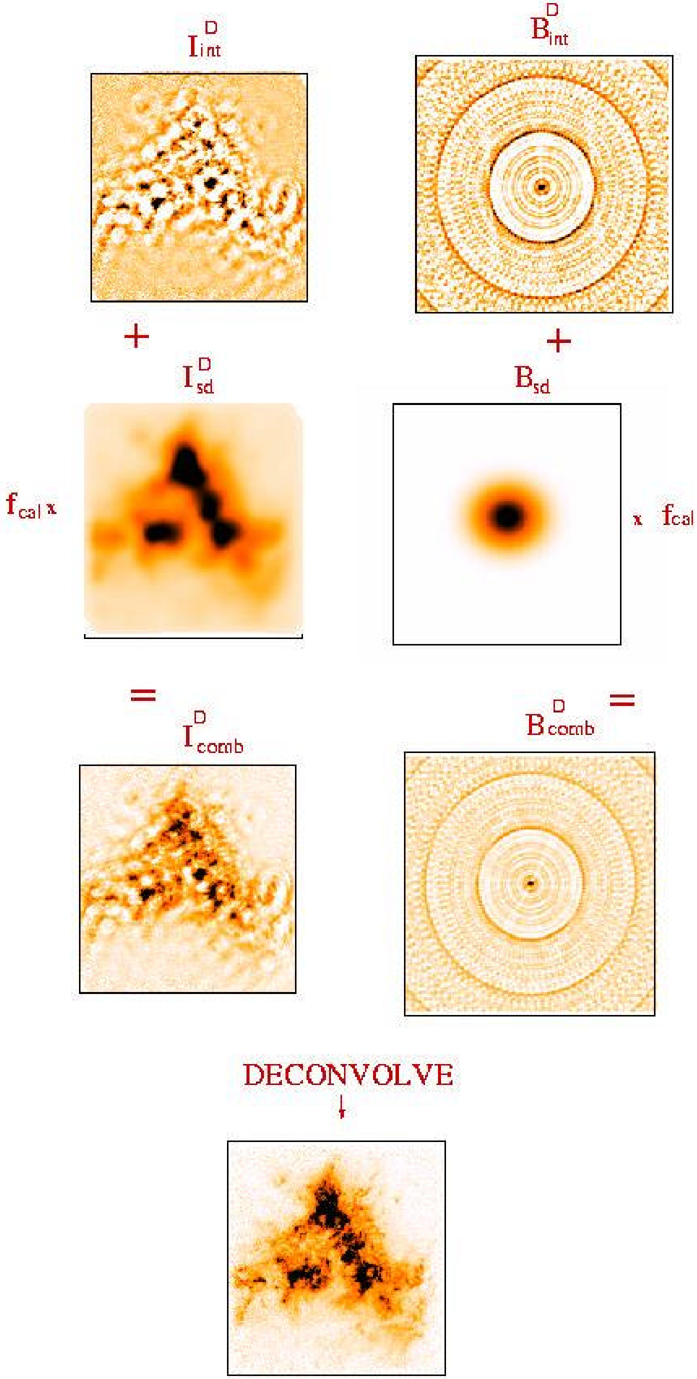


$$V_{\rm comb}(k) = w_{\rm int}(k)V_{\rm int}(k) + f w_{\rm sd}(k)V_{\rm sd}(k)$$

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



Linear combination

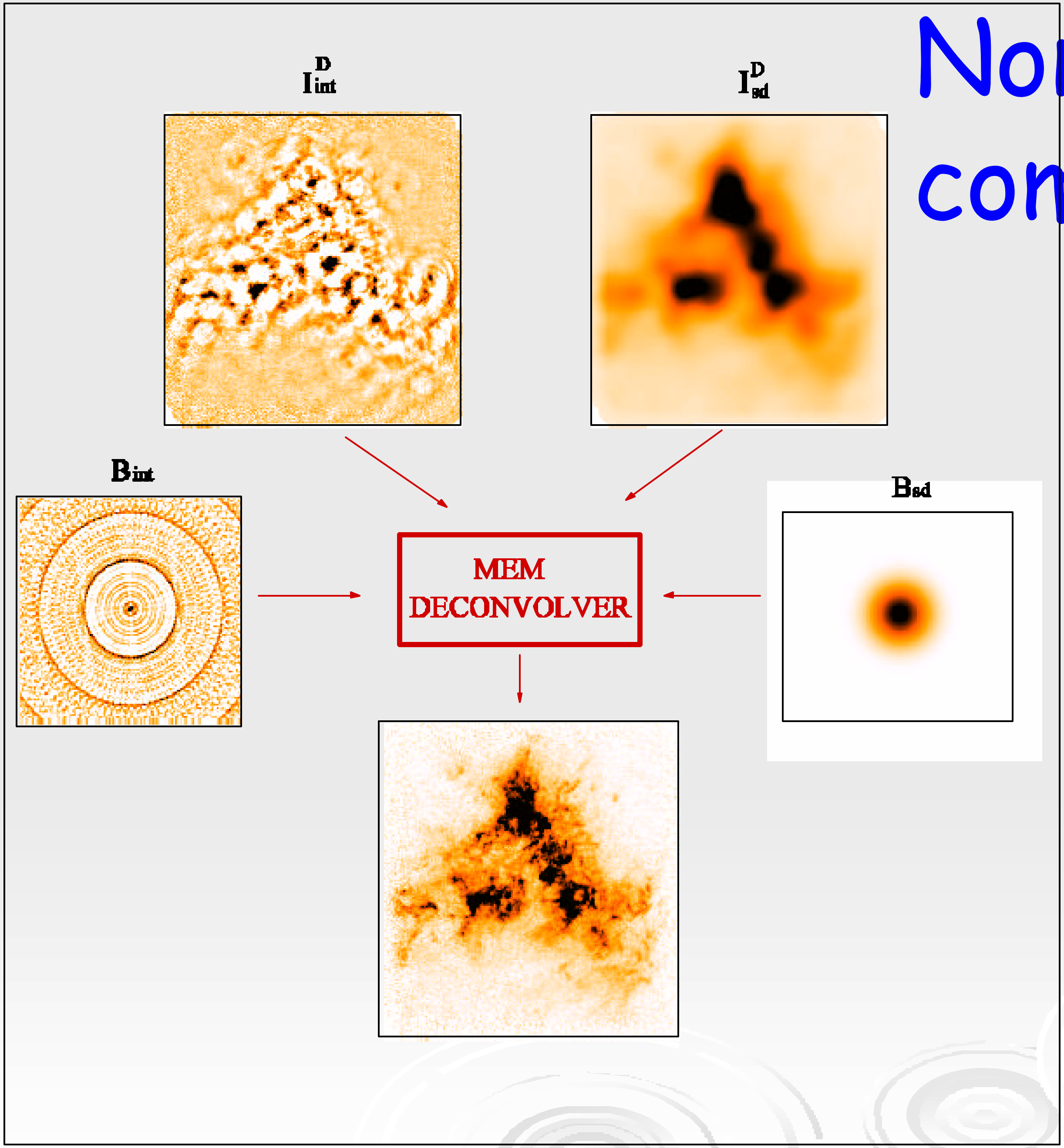


$$I^D_{\rm comb} = w_{\rm int} I^D_{\rm int} + w_{\rm sd} f I^D_{\rm sd}$$

$$B_{\rm comb} = w_{\rm int} B_{\rm int} + w_{\rm sd} B_{\rm sd}$$

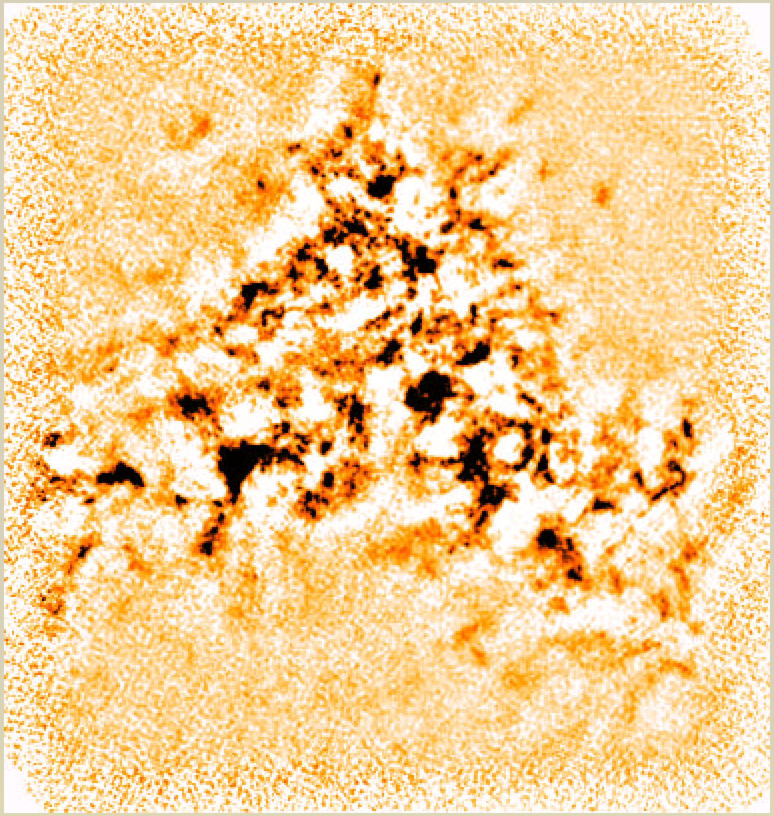
$$w_{\rm int} = \frac{\Omega_{\rm sd}}{\Omega_{\rm int}+\Omega_{\rm sd}} \quad w_{\rm sd} = \frac{\Omega_{\rm int}}{\Omega_{\rm int}+\Omega_{\rm sd}}$$

Non-Linear combination



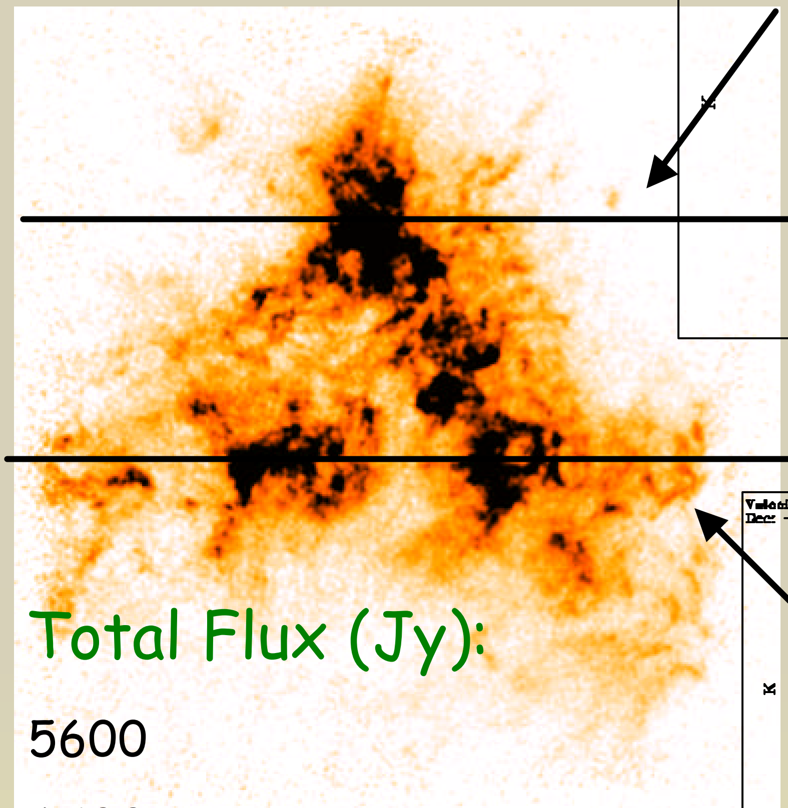
Final Results:

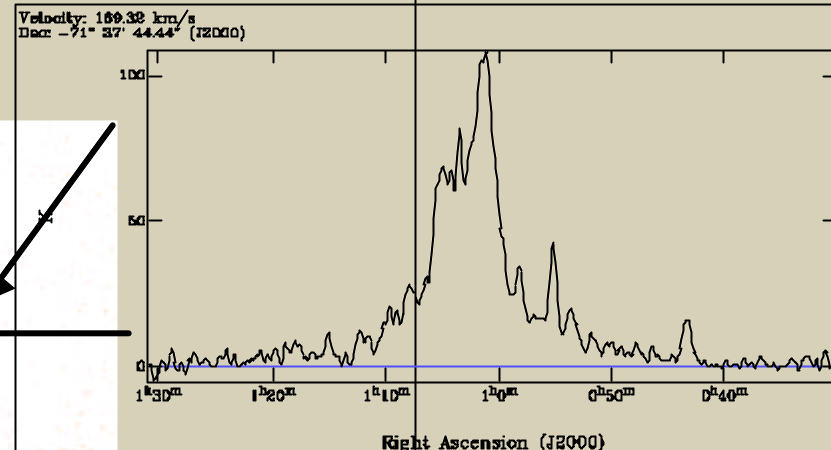
Small Magellanic Cloud BEFORE short-spacings correction.

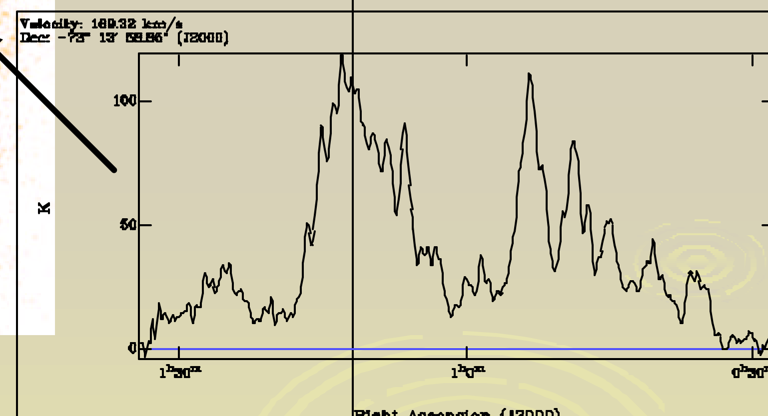


Final Results:

Small Magellanic Cloud AFTER short-spacings correction.







Method	Total Flux (Jy):
1.	5600
2.	6500
3.	6300
Parkes only	6100
ATCA only	3200

Some Recent Examples:

Array	B_{min}(m)	SD	D(m)	? (GHz)	Method	Ref.
ATCA	25	Parkes	64	1.4	linear	Stanimirovic et al. 1999
ATCA	25	Parkes	64	1.4	immerge	Muller et al. 2003
ATCA	25	Parkes	64	1.4	immerge	McClure-Griffiths 2000
OVRO	15	IRAM	30	8.8	immerge	Lang et al. 2002
BIMA	8	FCRAO	14	115	linear	Pound et al. 2003
BIMA	8	12m	12	113	mosmem	Welch et al. 2000
BIMA	8	12m	12	115	linear	Helfer et al. 2003
VLA D	35	GBT	100	8.4	feathering, aips++	Shepherd et al. 2003
VLA D	35	AO	305	1.4	-	Koo et al.; Robishaw et al.
Future:						
ALMA	15	ACA	7-12	30-950	short spacings high priority!	
CARMA	4-8	SZ	3.5	115, 230, 345	no total power at the start	
ATA	8-11	?	?	1.4-11.12	no total power at the start most likely	

Remarks on different methods:

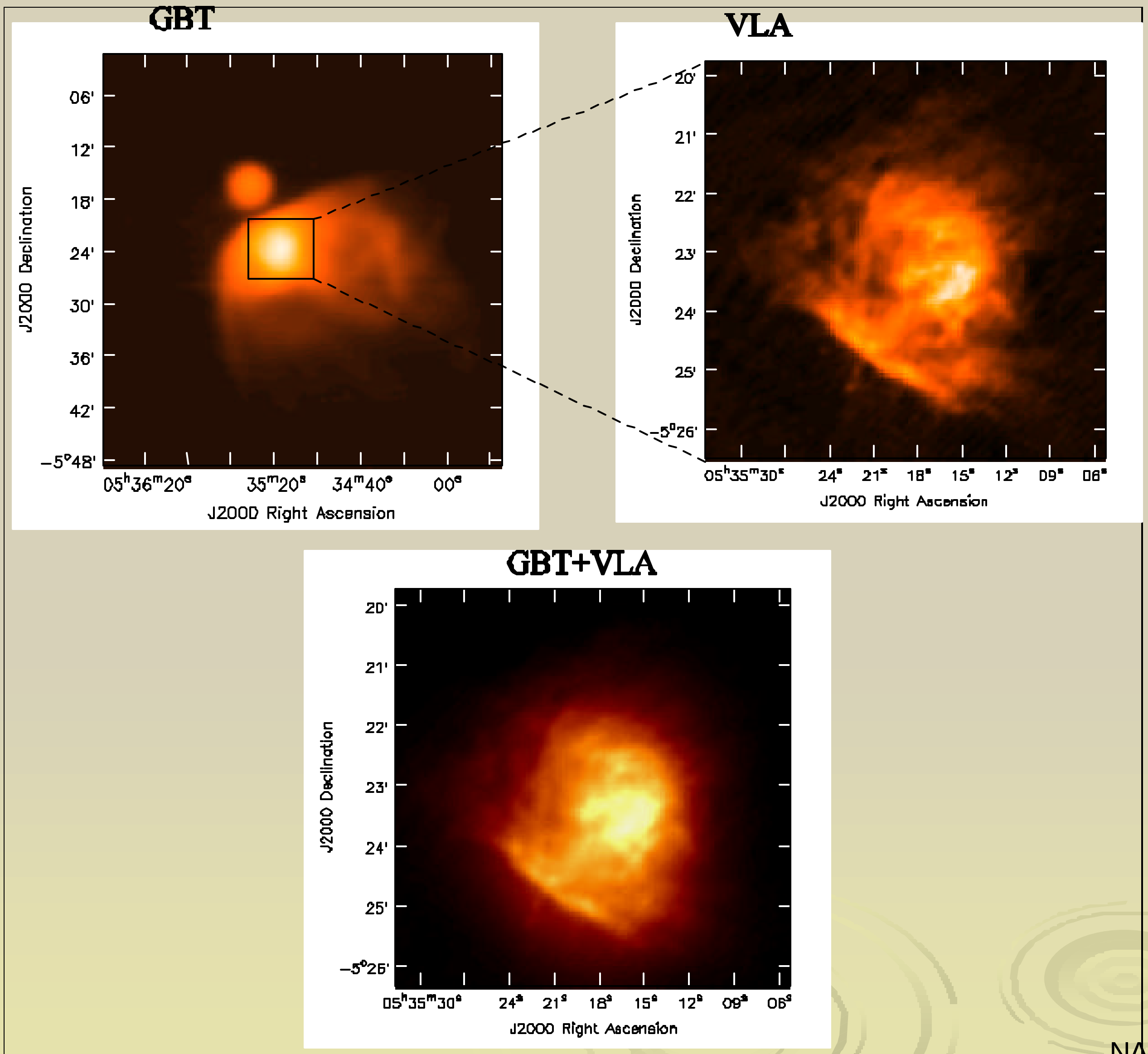
- In recent years, all methods are commonly used from small 7-point to huge >1000-point mosaics.
- All methods produce comparable results in the case of high S/N data (e.g. SMC).
- 'Feathering' method is the fastest and the least computer intensive, great results.
- For low S/N data, as is often case at mm wavelengths, 'linear' method seems advantageous: no need for deconvolution by the single-dish beam nor deconvolution of int. dirty maps, it is easy to implement and automate.
- 'MEM' method is theoretically the best way but heavily dependant on noise estimate which may vary across an image.
- Future trend: multi-scale SD+INT. deconvolution.

Particular single-dish needs:

- A large enough area must be covered with single-dish observations (edge-effect issue).
- Nyquist sampling is important to avoid aliasing during deconvolution (Vogel et al. 1984).
- S/N ratio of interferometer and single-dish data should be comparable.
- In general, and especially for the cross-calibration a very good knowledge of the single-dish beam is required (can start with a Gaussian first).
- At mm wavelengths main issues are: pointing and calibration accuracy (e.g. pointing cross-correlation).

Future trends in providing short-spacings seem to be towards **heterogeneous arrays** using arrays of smaller dishes. Smaller dishes have lower systematic errors and larger field of view so are faster than large single dishes (Holdaway & Helfer 1999).

Recent Examples: VLA + GBT

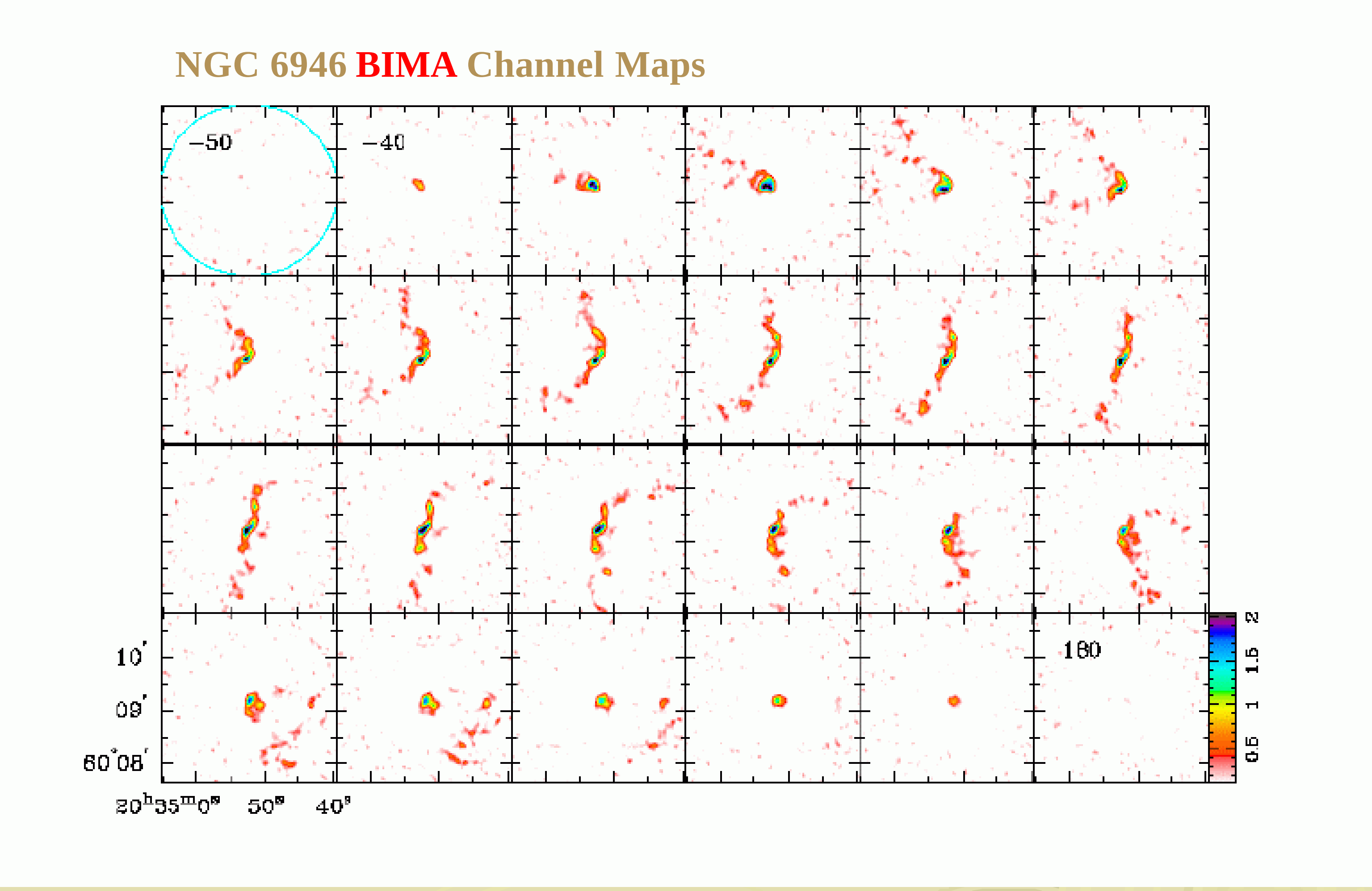


Orion nebula at 8.4 GHz

Shepherd, Maddalena, McMullin (2003)

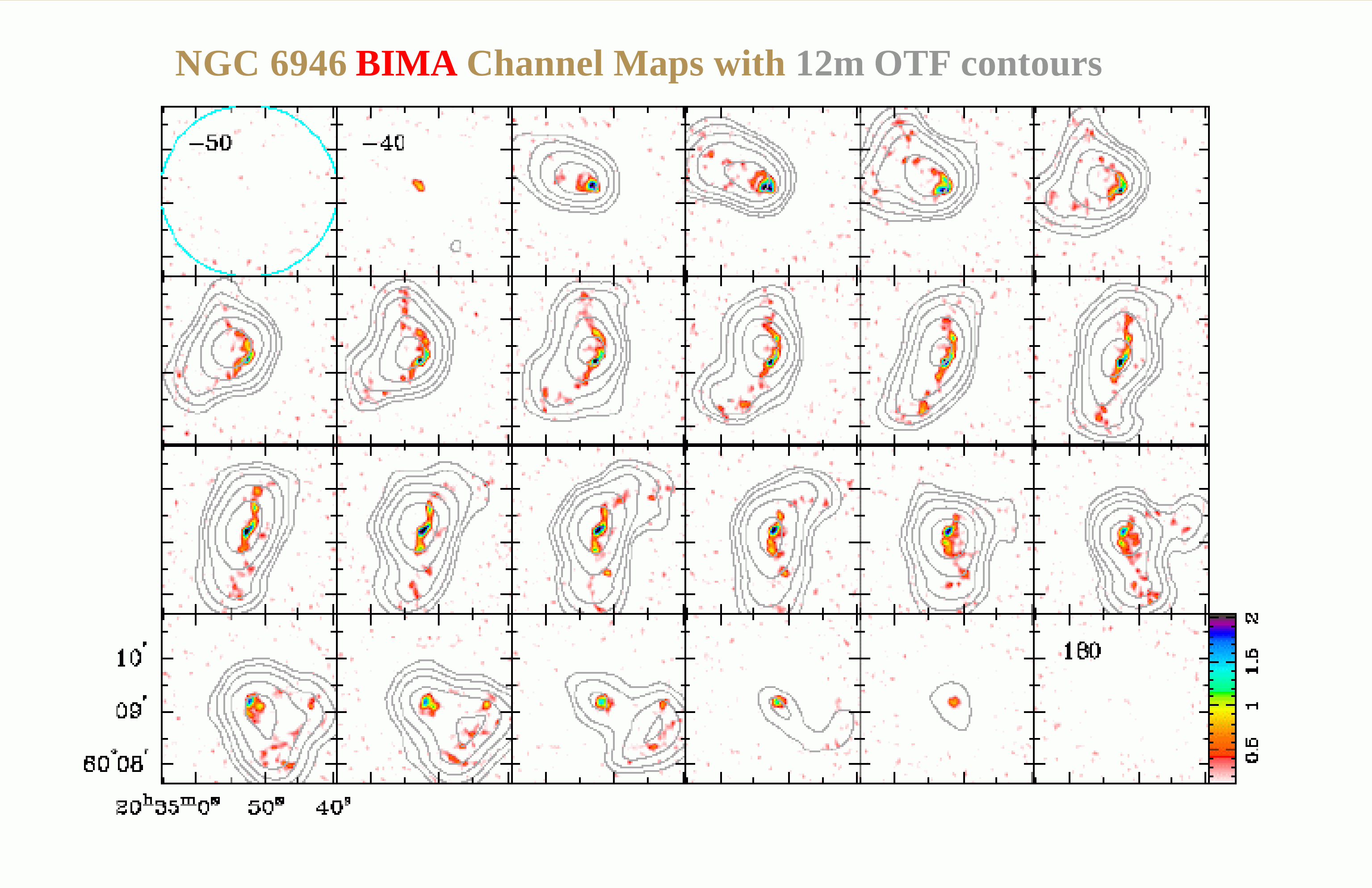
SEE POSTER !

Recent Examples: BIMA SONG



Helfer et al., ApJS, 145, 259

Recent Examples: BIMA SONG



Helfer et al., ApJS, 145, 259

Summary:

- Single-dishes have a huge role in providing information that complements interferometric observations.
- Short-spacings correction is a MUST in most of observations at mm wavelengths and may soon become a part of general observing scheme (e.g. ALMA).
- Easy combination of single-dish and interferometer data available.
- Routinely done for different telescopes and for sources of greatly varying sizes.
- 4 discussed methods work fine and with comparable results.
- Overlap of spatial frequencies is crucial for cross-calibration.

Bibliography:

- Stanimirovic 2002, ASP Conf. Ser. 278
- Sault & Killeen 2003, Miriad Users Manual
- Holdaway 1999, ASP Conf. Ser. 180
- Holdaway & Helfer 1999, ASP Conf. Ser. 180
- Helfer et al. 2002, PASP, 114, 350

- 'Interferometry and Synthesis in Radio Astronomy' Thompson, Moran & Swenson (2001)
- 'Synthesis Imaging in Radio Astronomy' Taylor, Carilli & Perley (1999)
- Sault & Killeen 2003, Miriad Users Manual