Large-field imaging

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Large-field imaging
The problems

- The field of view is limited by the antenna primary beam width

  Solution: observe a **mosaic** = several adjacent overlapping fields

- The field of view is limited because of the "2D approximation"

  Solution: use appropriate algorithm if necessary

- The largest structures are filtered out due to the lack of the short spacings

  Solution: add the **short spacing** information

- Deconvolution algorithms are not very good at recovering small- *and* large-scale structures

  Solution: try Multi-Scale CLEAN...

Interferometer field of view

Measurement equation of an interferometric observation:

$$\mathbf{F} = \mathbf{D} * (\mathbf{B} \times \mathbf{I}) + \mathbf{N}$$

$$\begin{aligned} F &= \text{dirty map} = \text{FT of observed visibilities} \\ D &= \text{dirty beam} \ (\longrightarrow \text{deconvolution}) \\ B &= \text{primary beam} = \text{FT of transfert function} \\ I &= \text{sky brightness distribution} = \text{FT of ``true'' visibilities} \\ N &= \text{noise distribution} \end{aligned}$$

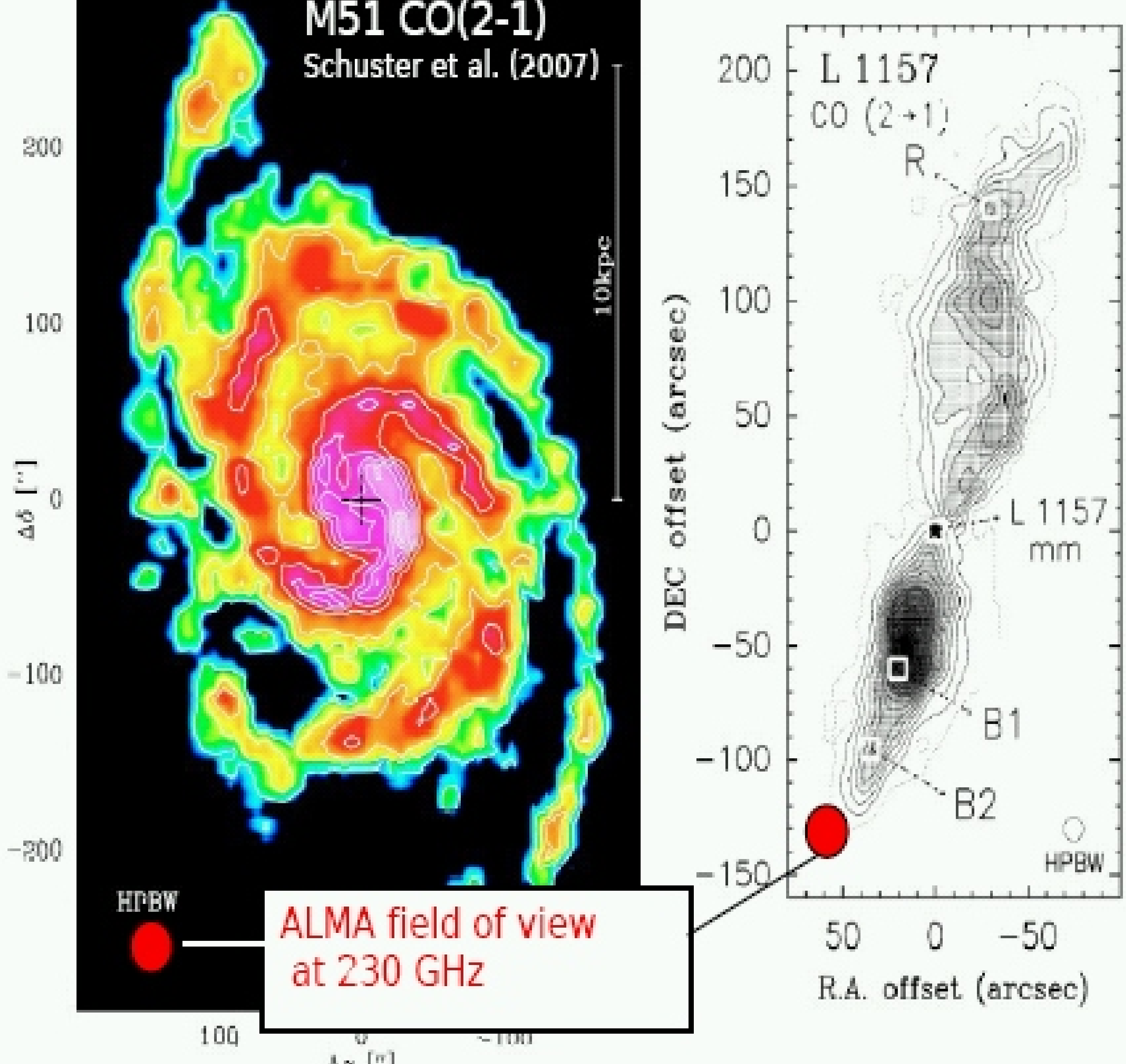
- **An interferometer measures the product $\mathbf{B} \times \mathbf{I}$**
- **$\mathbf{B}$ ∼ Gaussian** $\longrightarrow$ primary beam correction possible (proper estimate of the fluxes) but strong increase of the noise

Mosaics
Primary beam width

Gaussian illumination $\Longrightarrow$ B $\sim$ Gaussian Beam of $\mathbf{1.2\,\lambda/D}$ FWHM

Plateau de Bure
$D = 15$ m

Frequency	Wavelength	Field of View
85 GHz	3.5 mm	58″
100 GHz	3.0 mm	50″
115 GHz	2.6 mm	43″
150 GHz	2.0 mm	33″
230 GHz	1.3 mm	22″
345 GHz	0.8 mm	15″


M51 CO(2-1)
Schuster et al. (2007)
10kpc
HPBW
ALMA field of view
at 230 GHz
L 1157
CO (2→1)
R
L 1157
mm
B1
B2
HPBW
DEC offset (arcsec)
R.A. offset (arcsec)

Mosaicing with the PdBI

Mosaic :

- **Field spacing = half the primary beam FWHM** = $11''$ at 230 GHz

Observations :

- **Fields are observed in a loop**, each one during a few minutes $\longrightarrow$ similar atmospheric conditions (noise) and similar uv coverages (dirty beam, resolution) for all fields

Calibration :

- Procedure identical with any other observation (only the calibrators are used)
- Produce one dirty map per field

Mosaics

Mosaic reconstruction

- Forgetting the effects of the dirty beam:

$$F_i = B_i \times I + N_i$$

- This is similar to several measurements of I, each one with a "weight" B_i
- Best estimate of I in least-square formalism (assuming same noise):

$$\mathbf{J} = \frac{\sum_i \mathbf{B_i}\,\mathbf{F_i}}{\sum_i \mathbf{B_i^2}}$$

- J is homogeneous to I, i.e. the mosaic is **corrected for the primary beam attenuation**

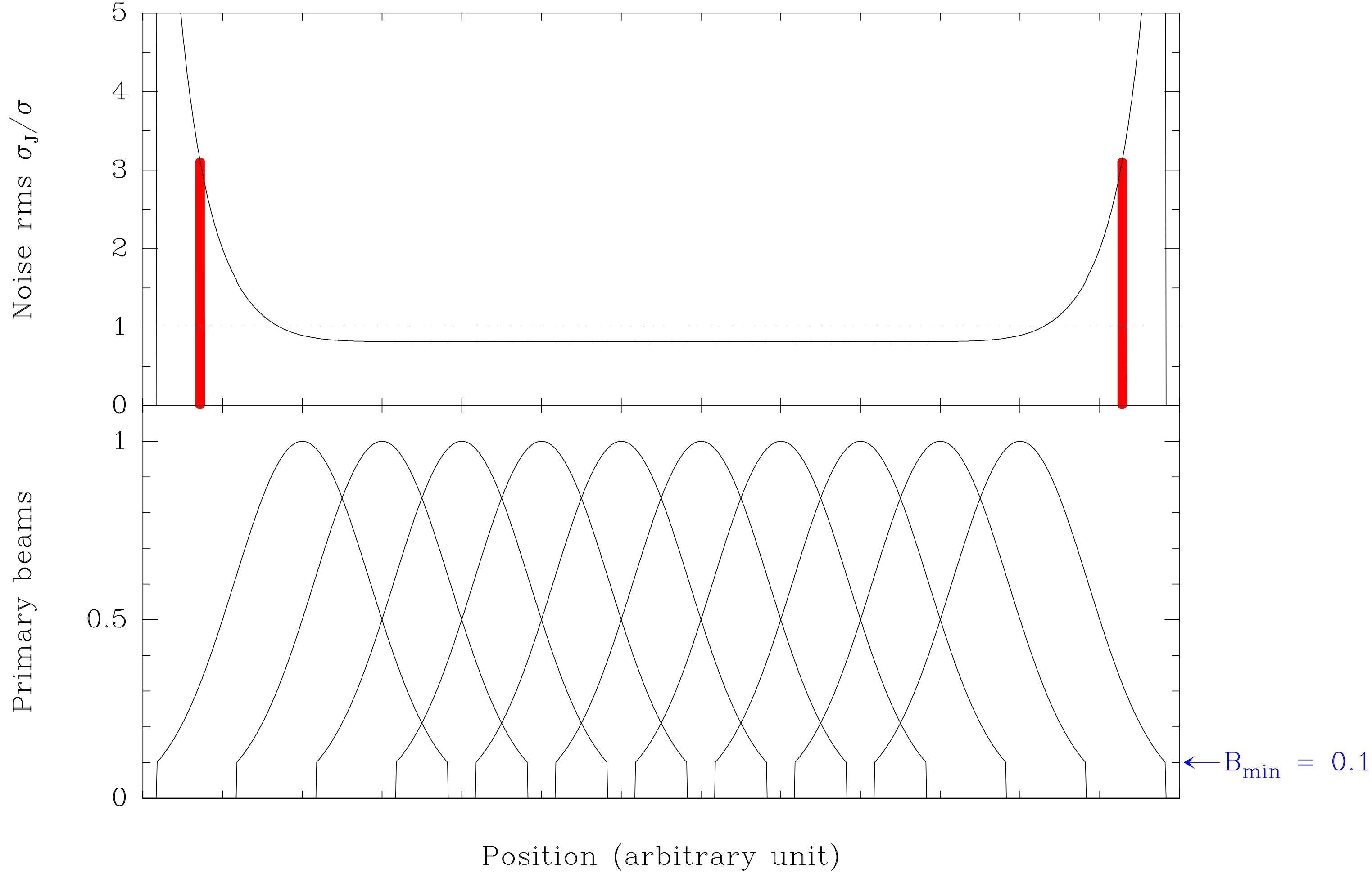
Mosaics
Noise distribution

$$J = \frac{\sum_i B_i\, F_i}{\sum_i B_i^2} \quad \Longrightarrow \quad \sigma_J = \sigma \frac{1}{\sqrt{\sum {B_i}^2}}$$

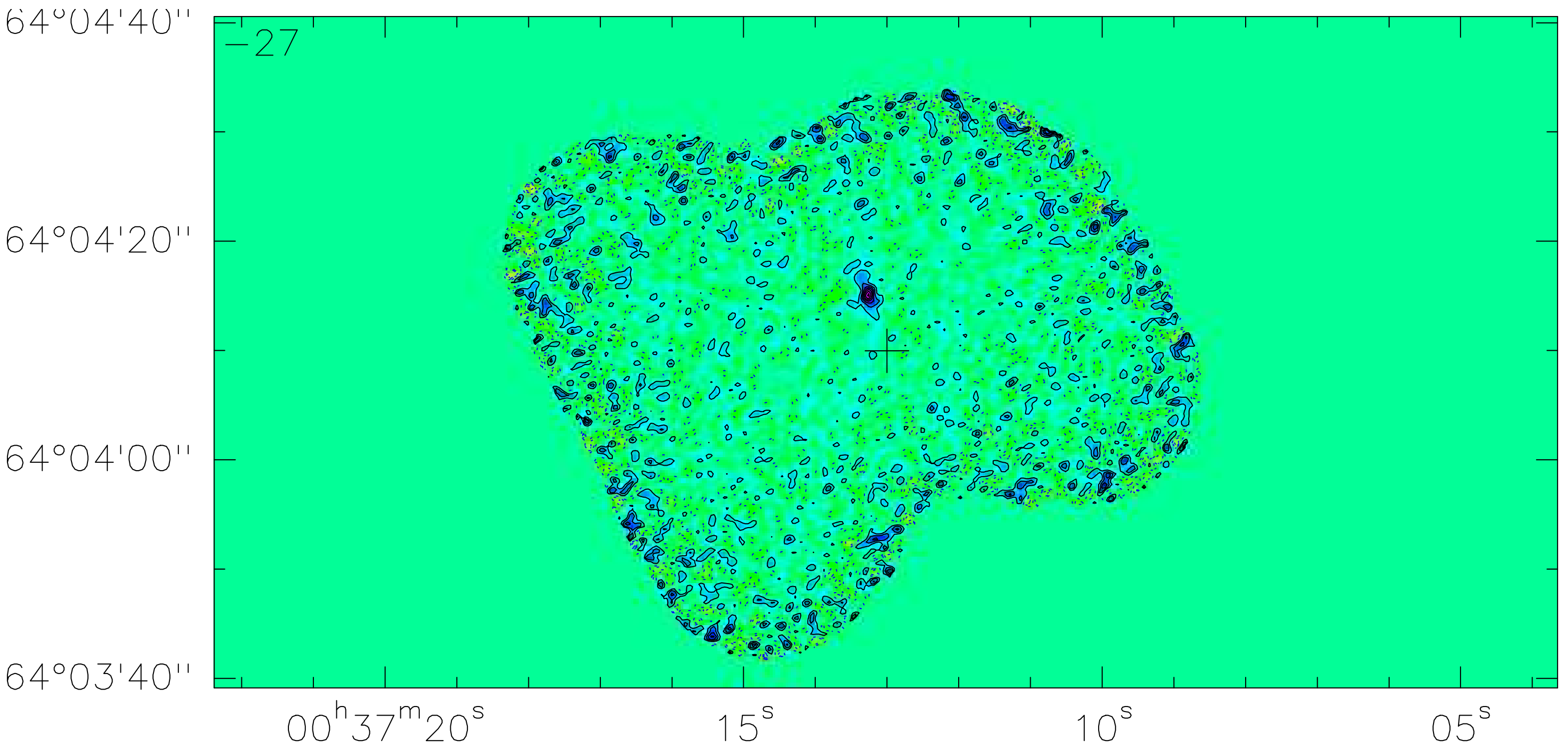
The noise depends on the position and strongly increases at the edges of the field of view

In practice :

- Use **truncated primary beams** $(B_{\min} = 0.1 - 0.3)$ to avoid noise propagation between adjacent fields
- **Truncate the mosaic**



5
4
3
2
1
0
Noise rms σ_J/σ
1
0.5
0
Primary beams
$\leftarrow B_{min} = 0.1$
Position (arbitrary unit)



−27
64°04'40''
64°04'20''
64°04'00''
64°03'40''
00h37m20s
15s
10s
05s

Mosaics

Mosaic deconvolution

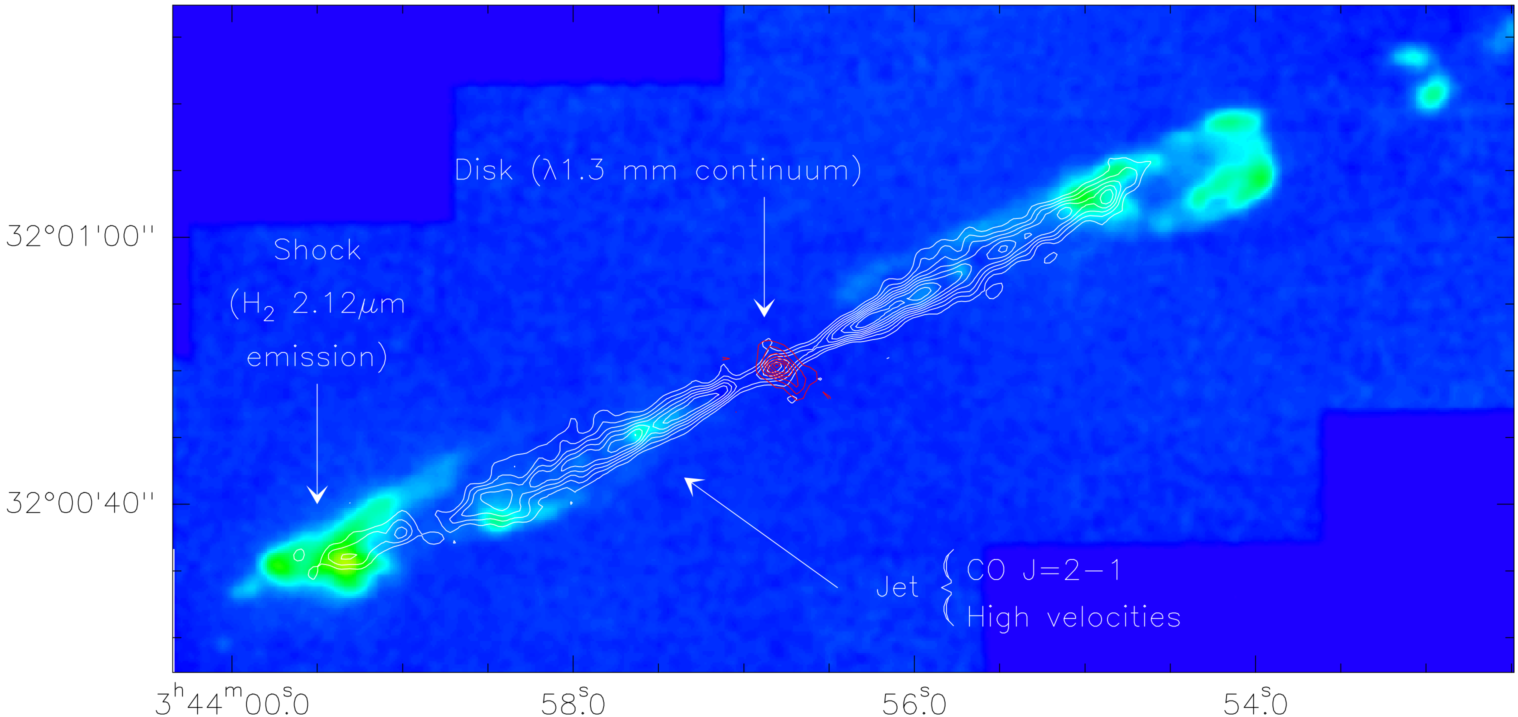
- **Linear mosaicing:** deconvolution of each field, then mosaic reconstruction

  Non-linear mosaicing: mosaic reconstruction, then global deconvolution
- The two methods are not equivalent, because the deconvolution algorithms are (highly) non-linear
- **Non-linear mosaicing gives better results**
  - sidelobes removed in the whole map
  - better sensitivity
- Plateau de Bure mosaics: **non-linear joint deconvolution based on CLEAN**

Mosaics

Example

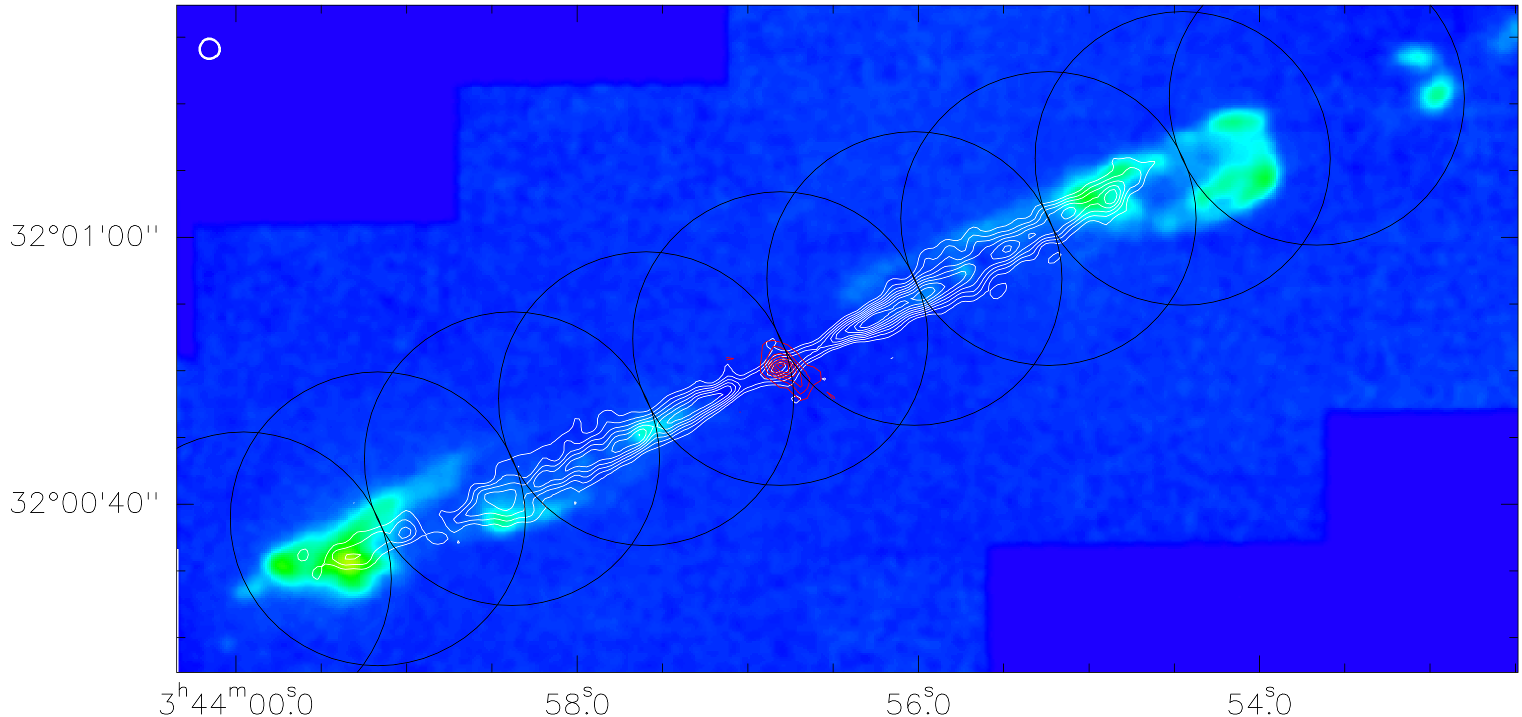
H_2 + CO(2−1) EHV + continuum 1.3 mm in HH211



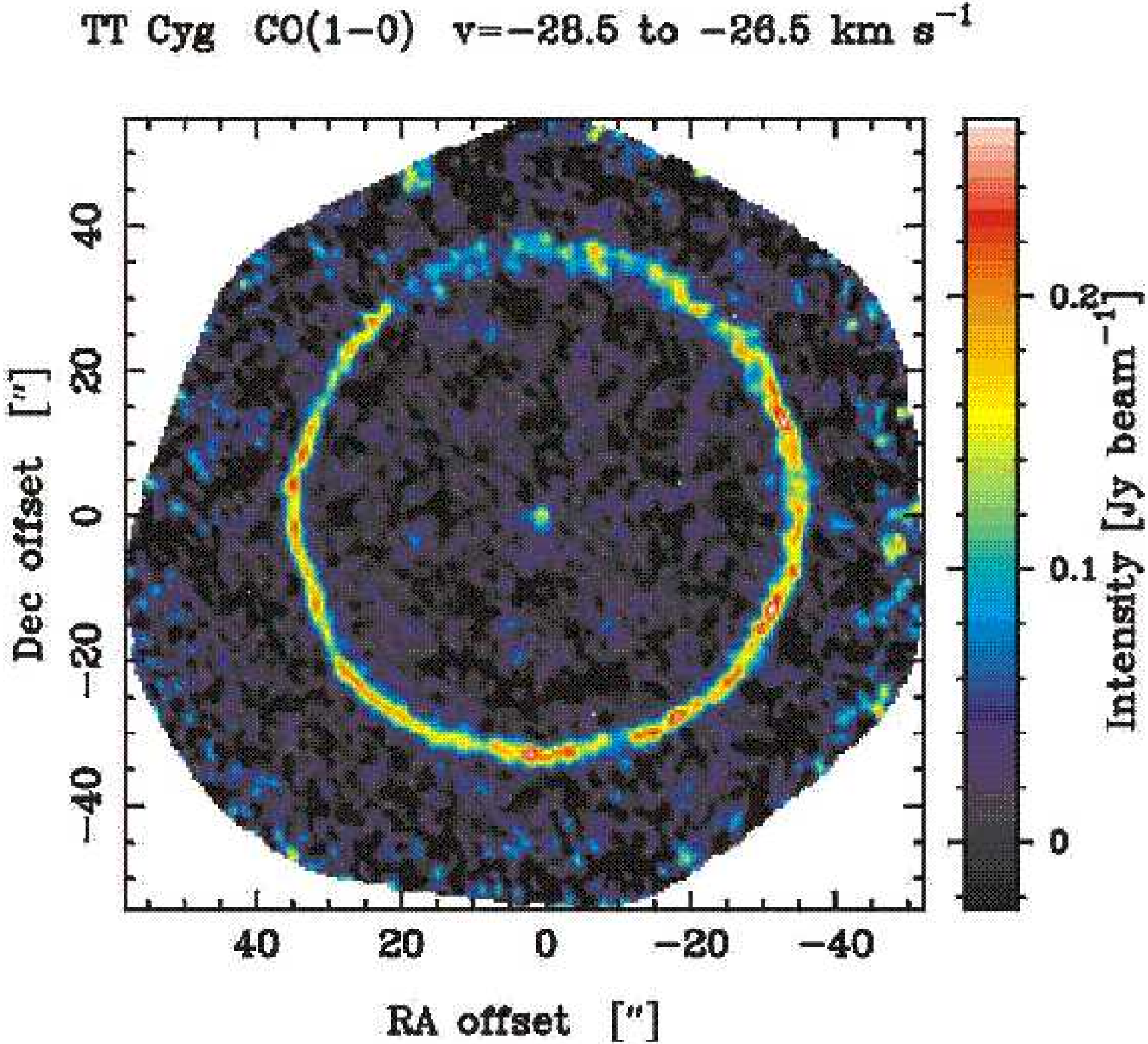
(Gueth & Guilloteau 1999)

Mosaics
Example

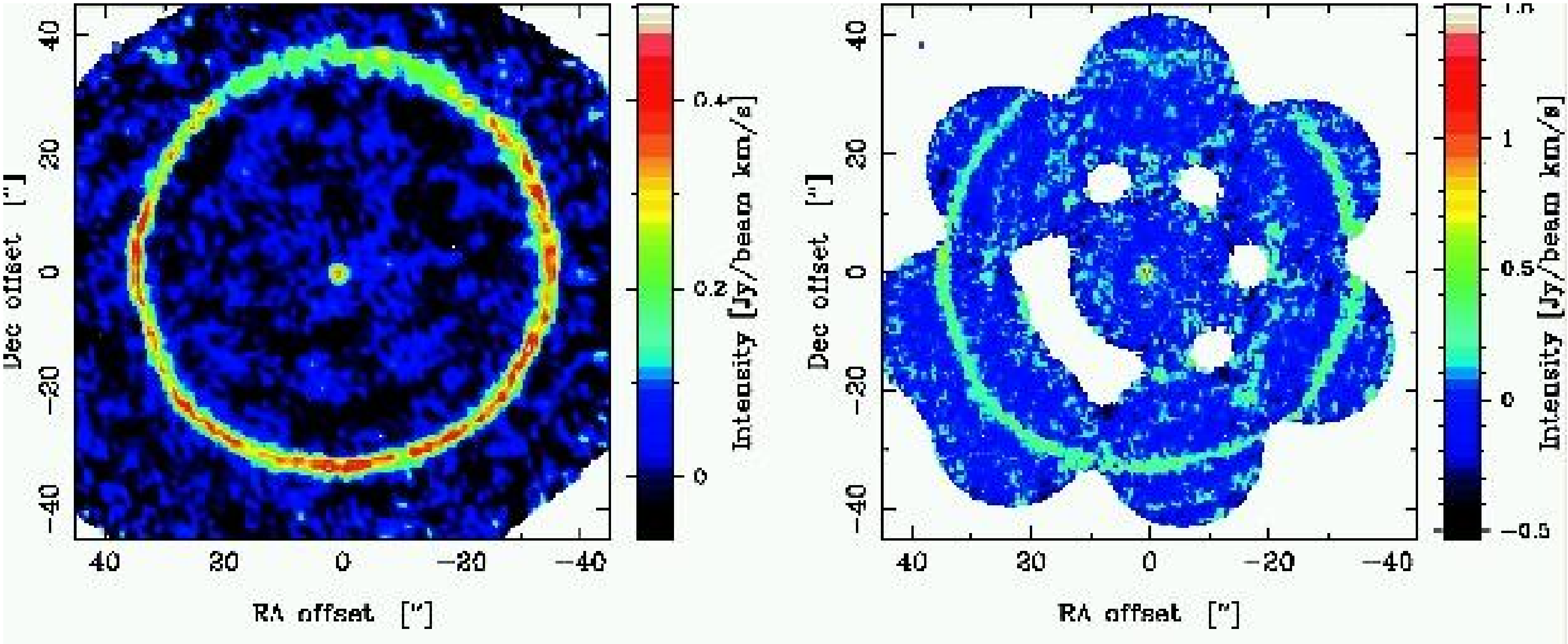
H_2 + CO(2−1) EHV + continuum 1.3 mm in HH211



(Gueth & Guilloteau 1999)

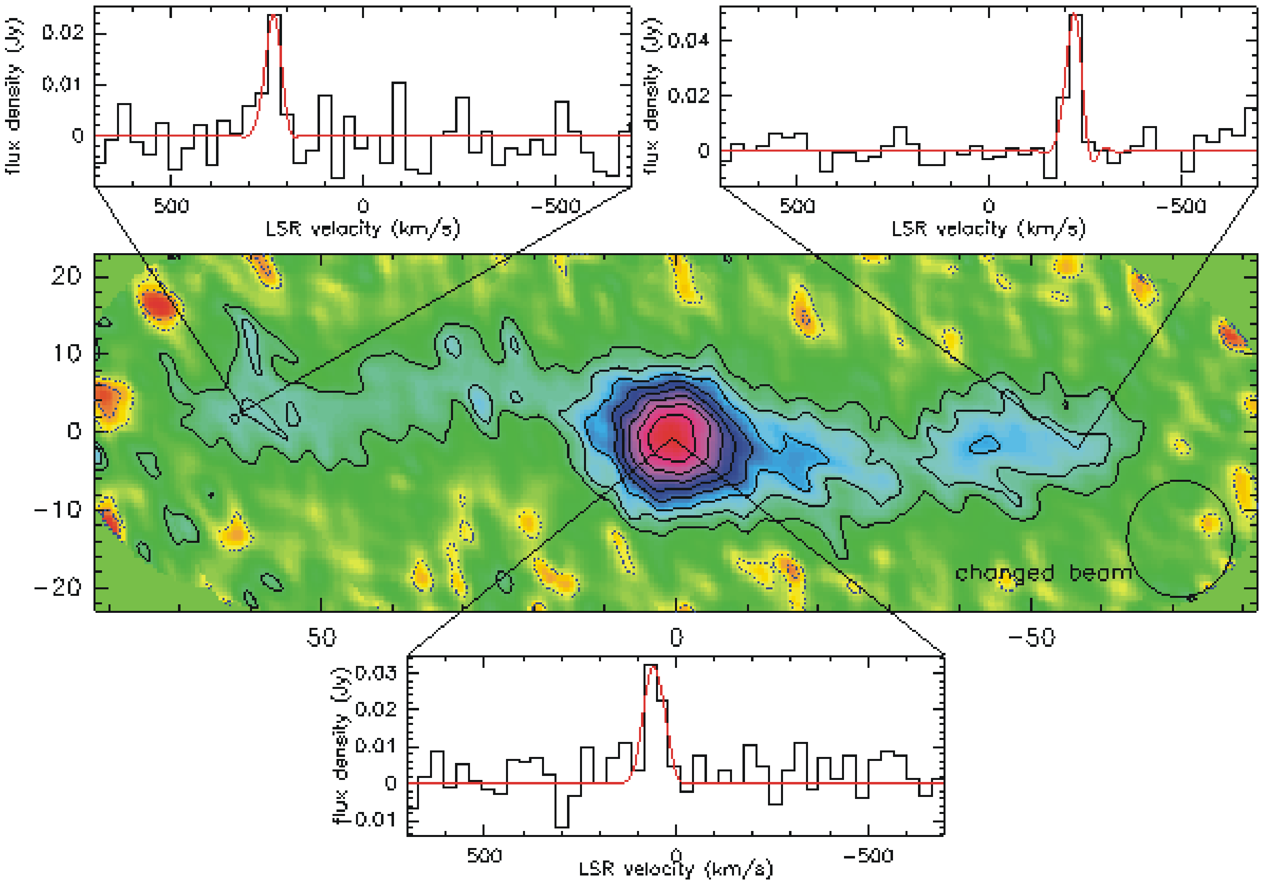


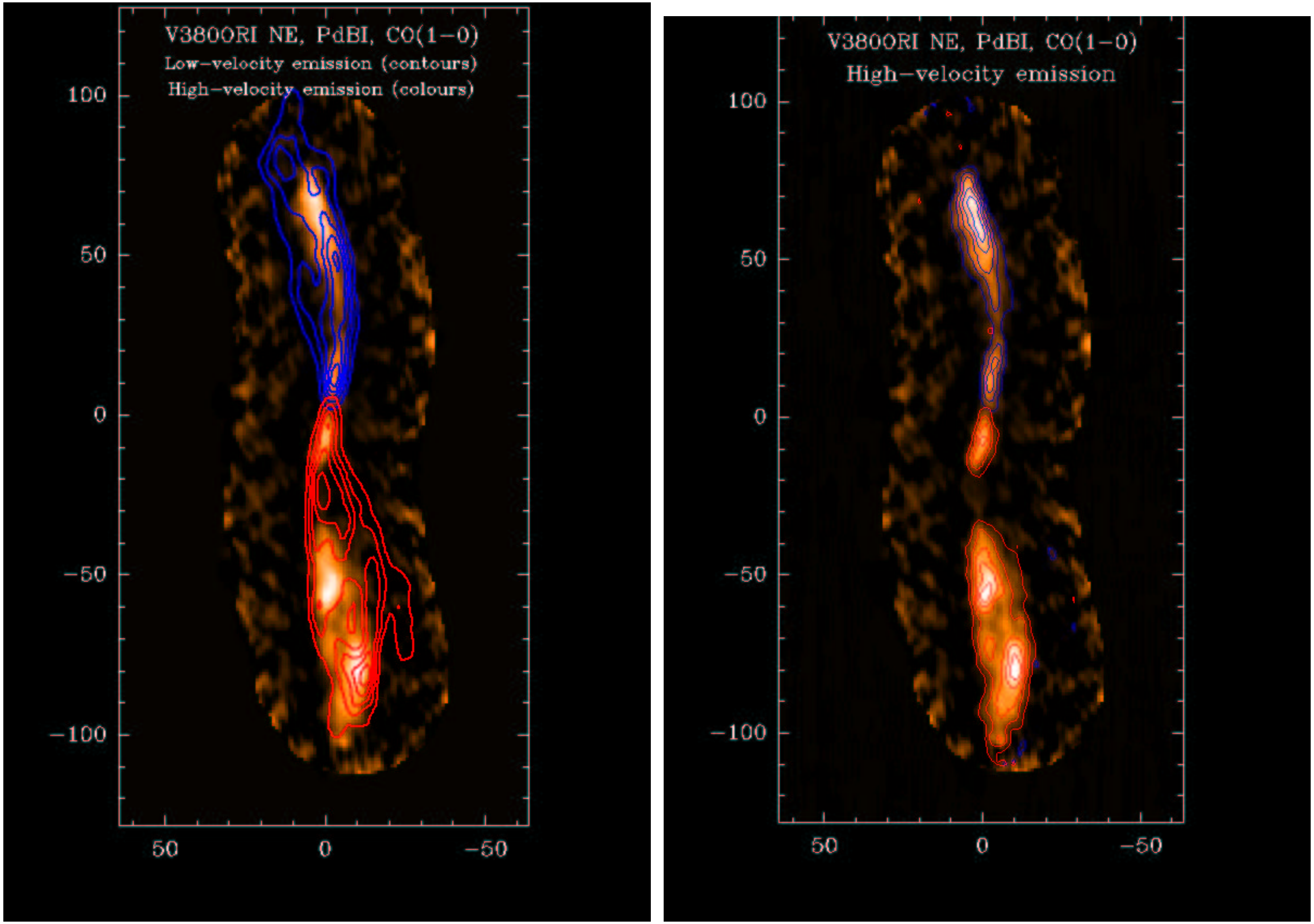
CO 1–0 in TT Cygni, Olofsson et al. 2000



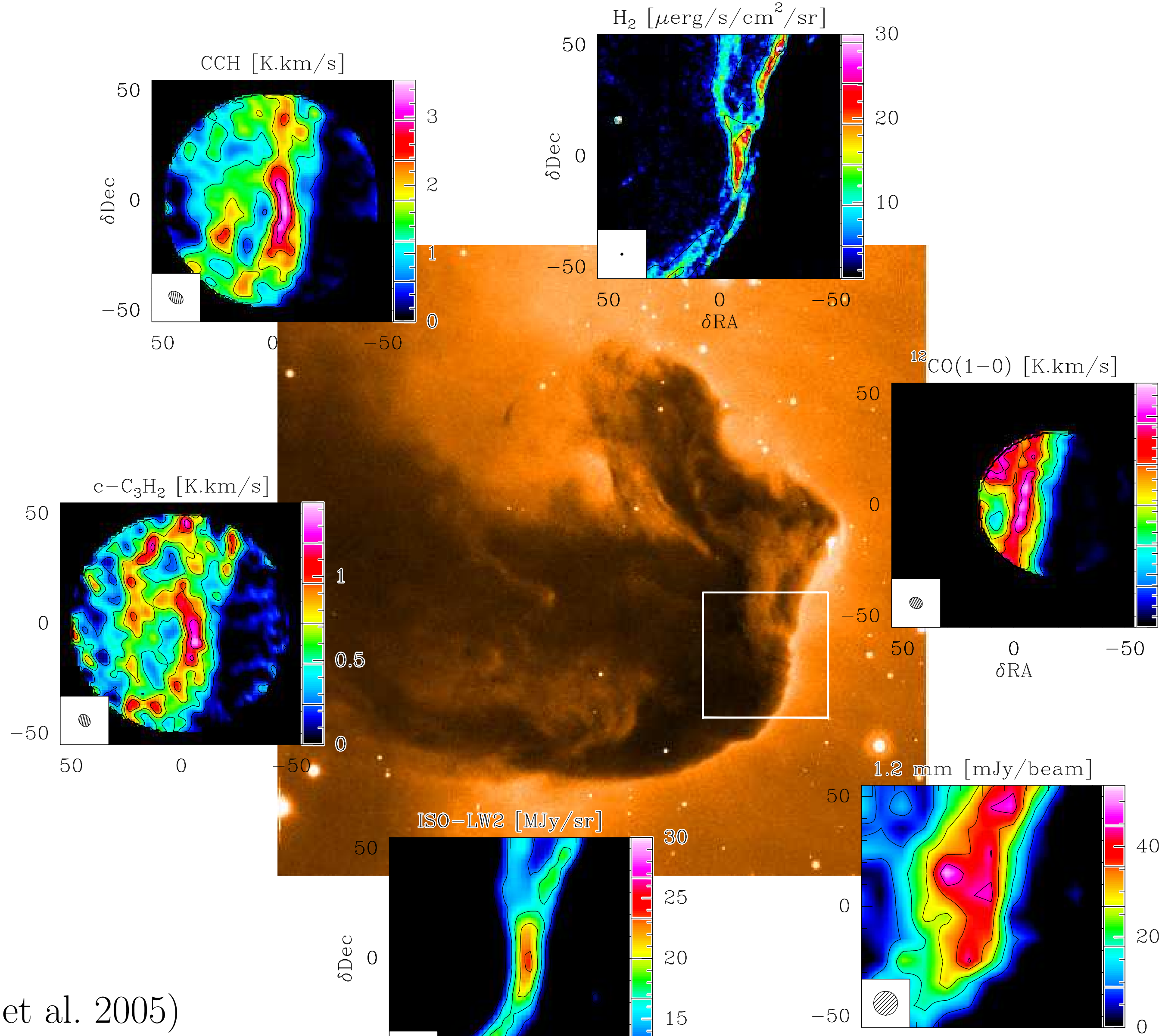
CO 1–0 in TT Cygni, Olofsson et al. 2000

CO in the warped galaxy NGC 3718 (Krips et al. 2005)



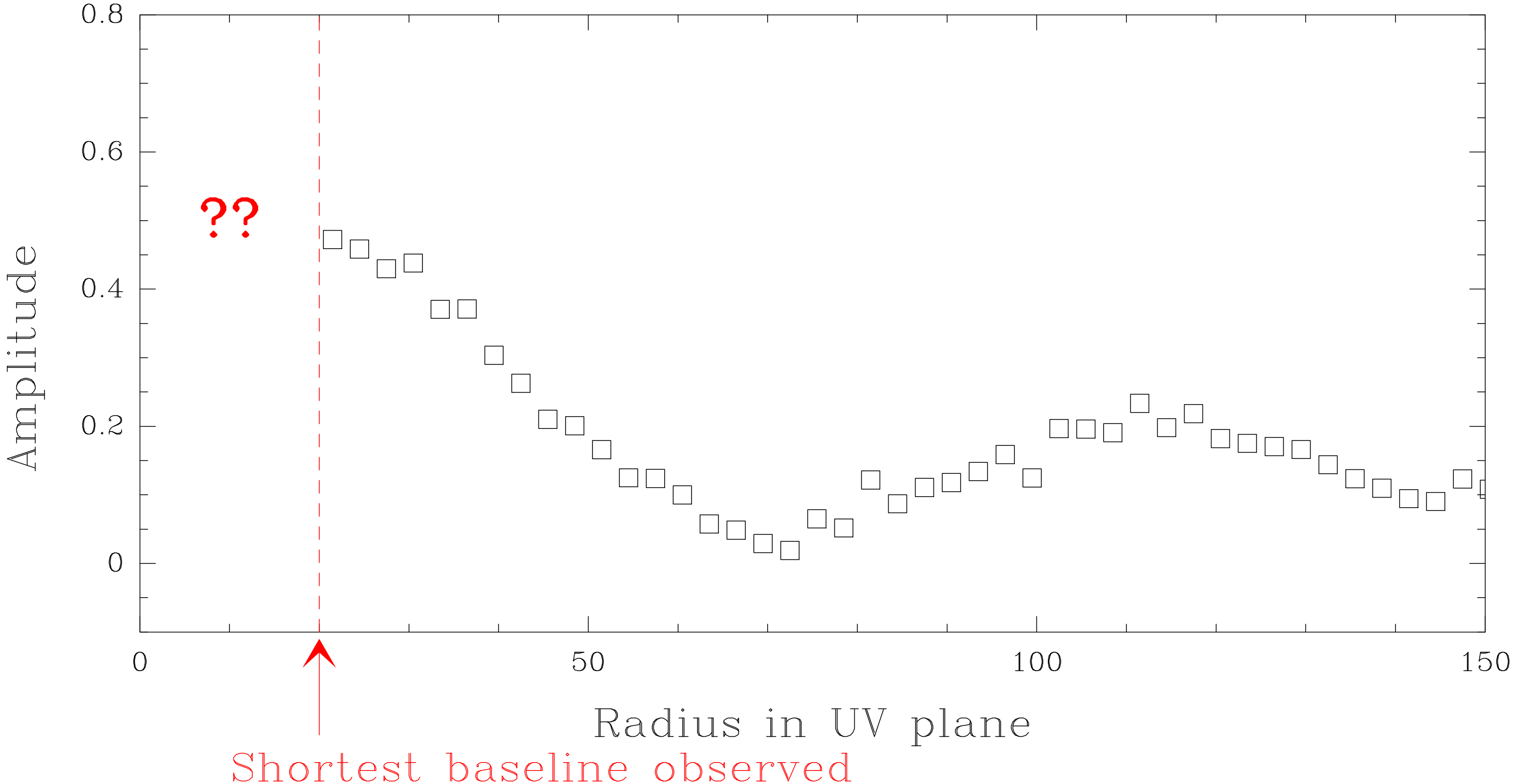


(Stanke et al. 2004)



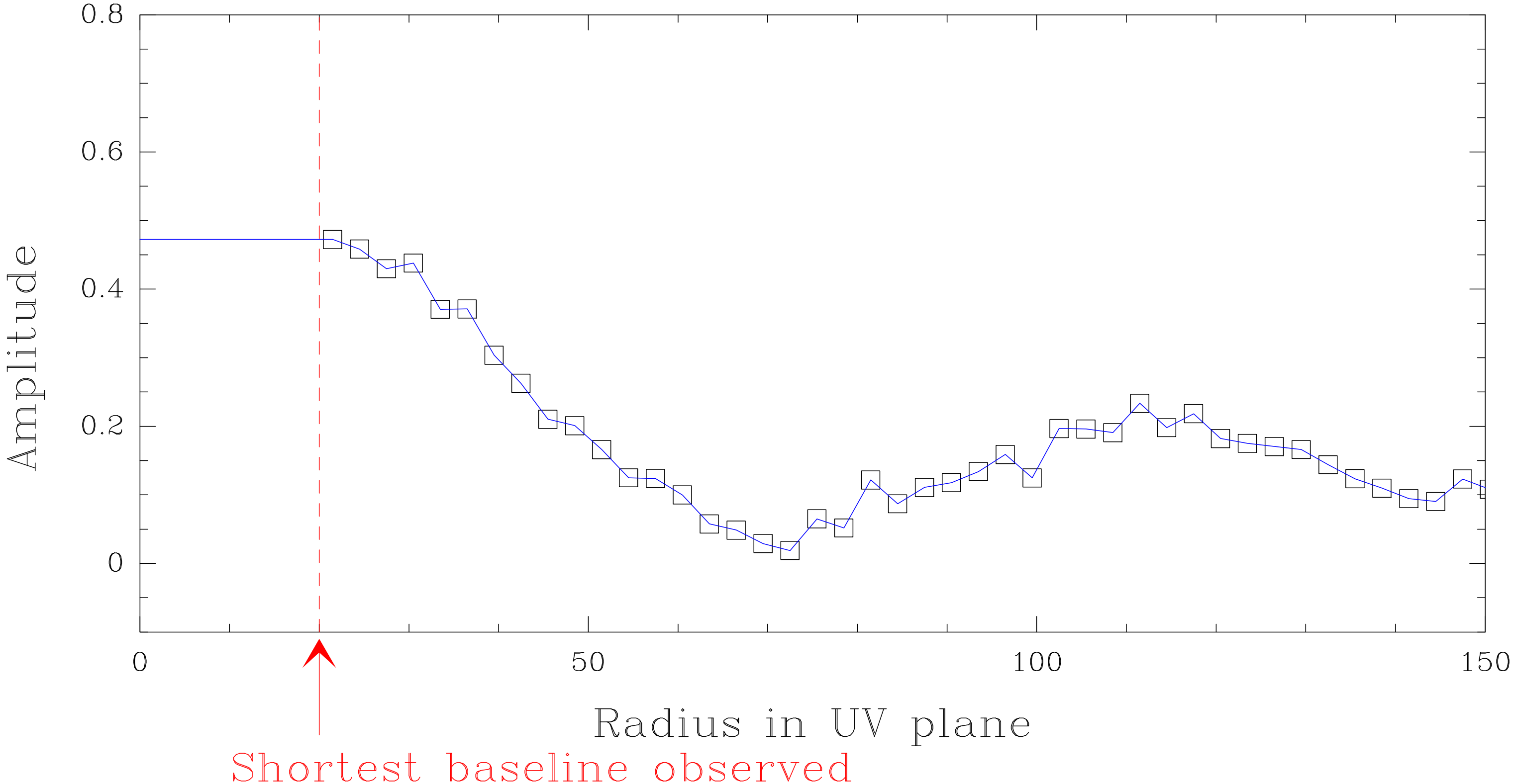
(Pety et al. 2005)

Short Spacings
Lack of the short spacings



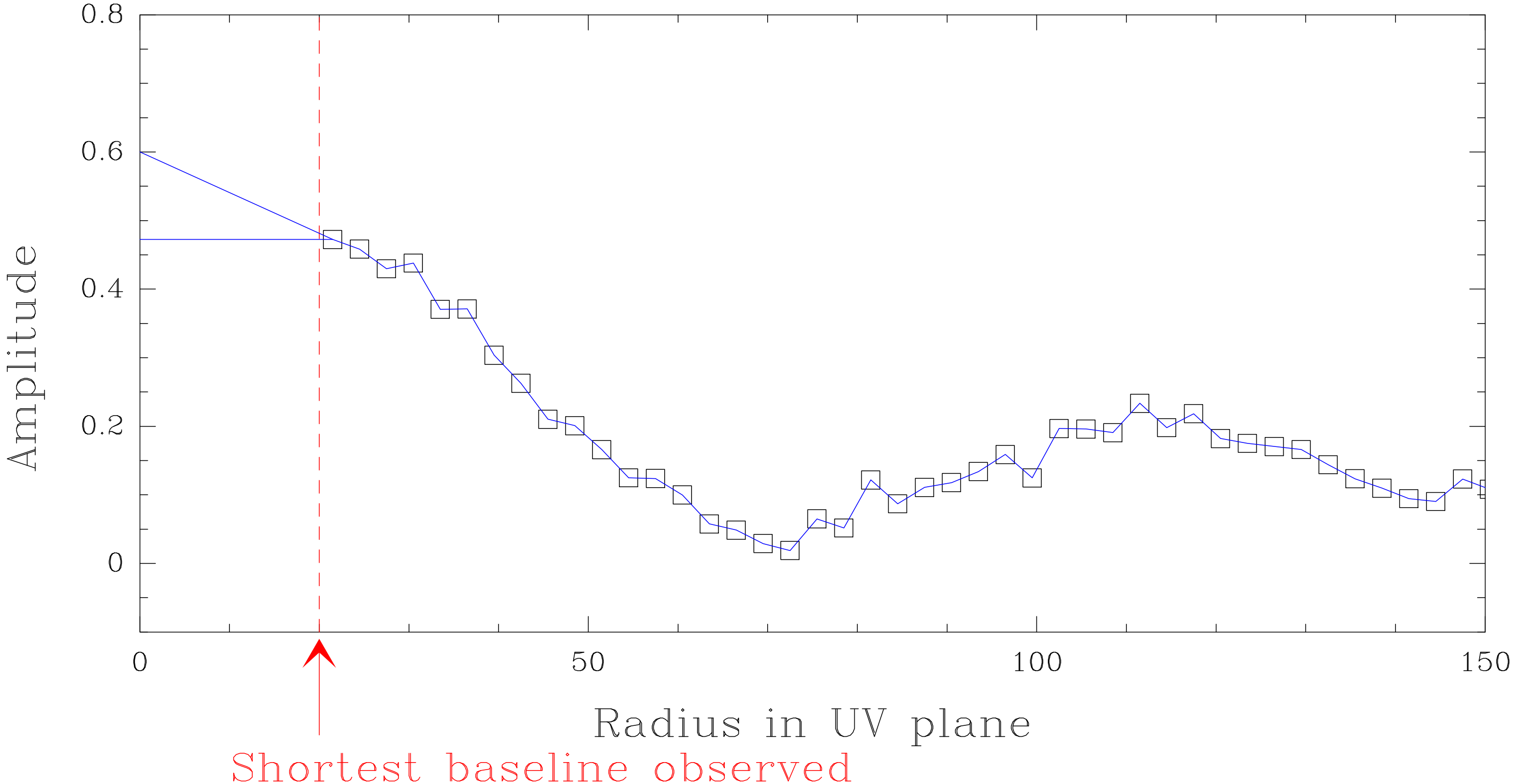
Short Spacings

Lack of the short spacings



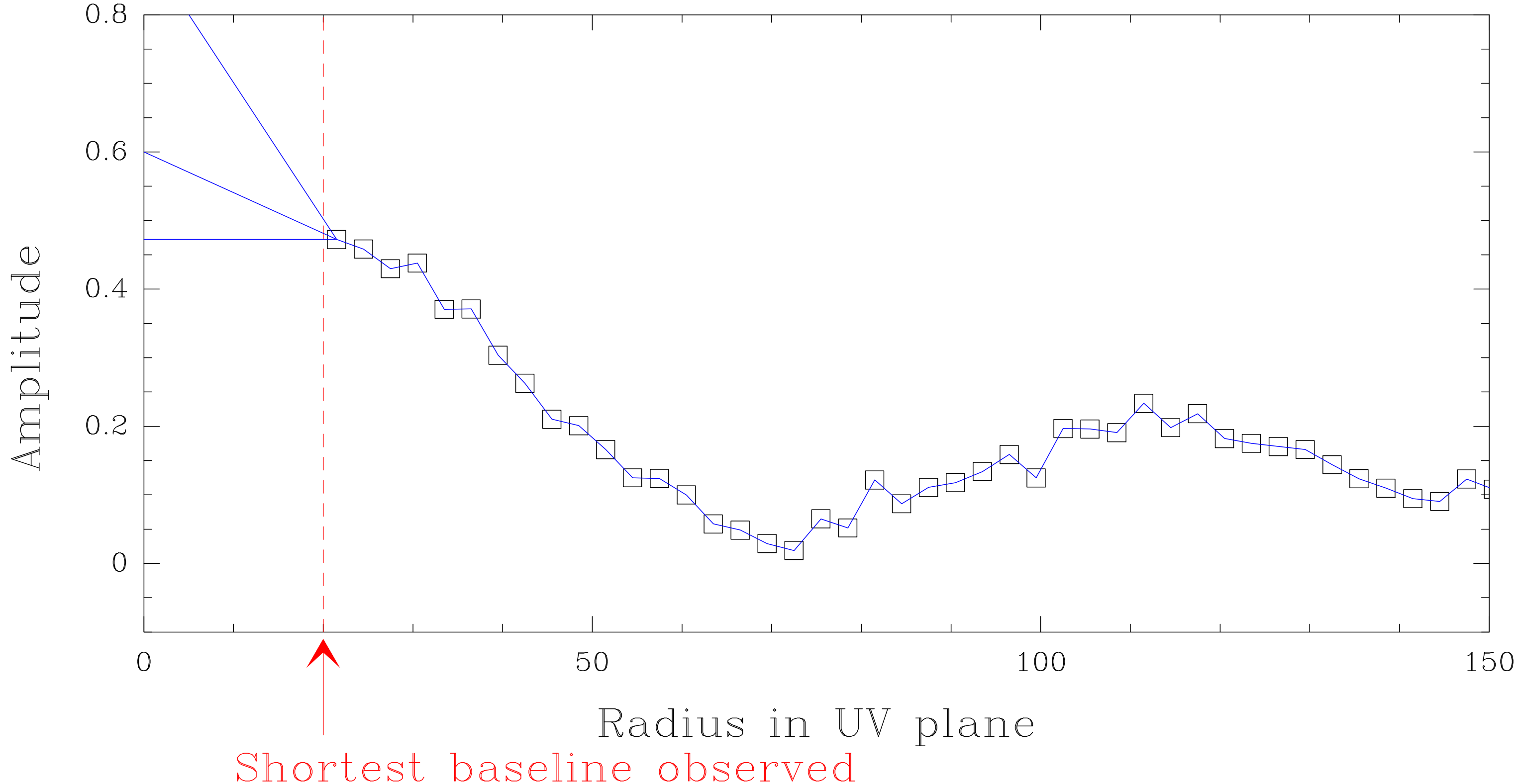
Short Spacings

Lack of the short spacings



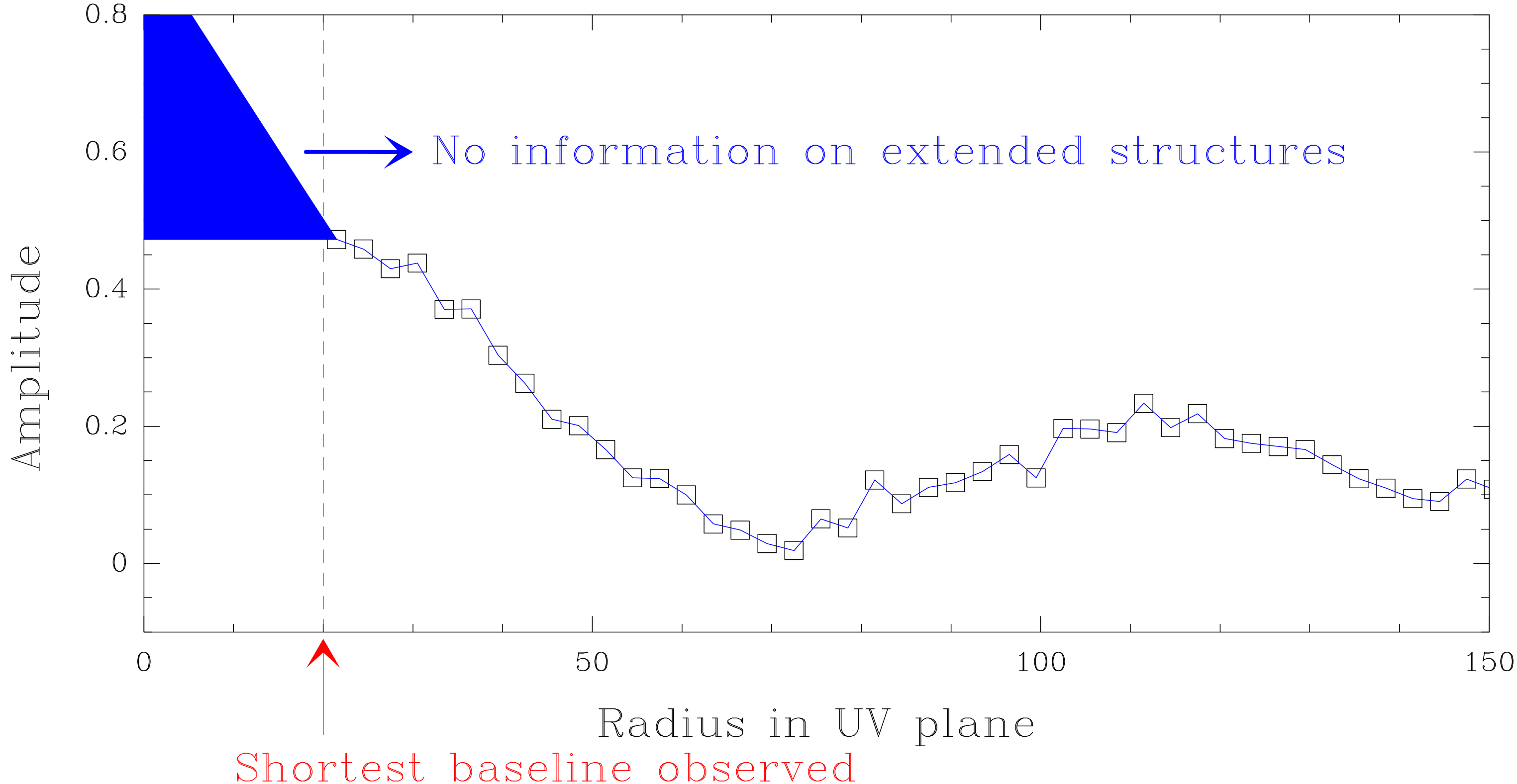
Short Spacings

Lack of the short spacings



Short Spacings

Lack of the short spacings



Short Spacings
The problem

Missing short spacings :

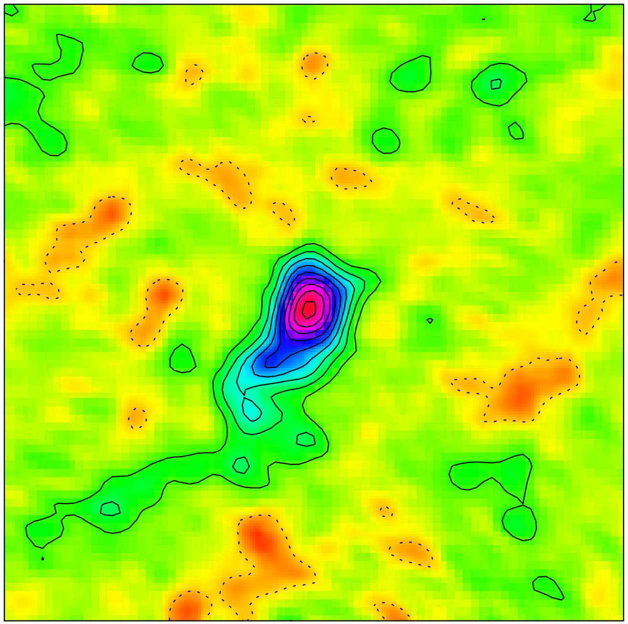
- Shortest baseline $B_{\mathrm{min}} = 24$ m at Plateau de Bure
- Projection effects can reduce the minimal baseline – but baselines smaller than antenna diameter D can never be measured
- In any case: **lack of the short spacings information**

Consequence :

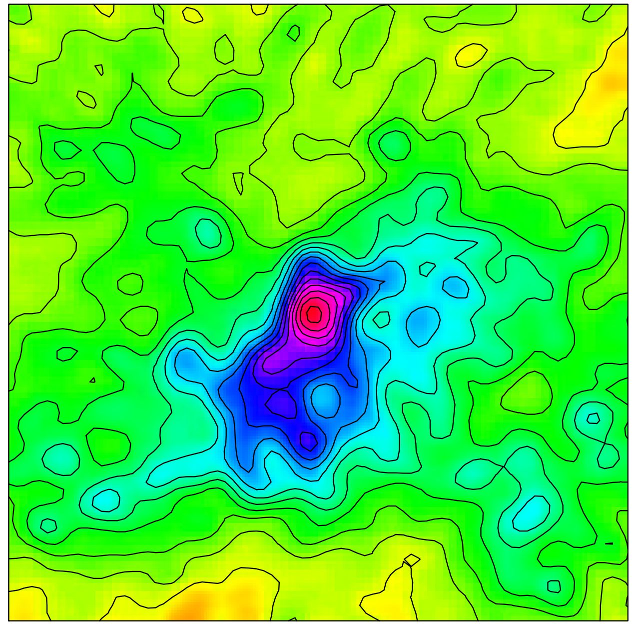
- **The most extended structures are filtered out**
- The largest structures that can be mapped are $\sim 2/3$ of the primary beam (field of view)
- Structures larger than $\sim 1/3$ of the primary beam may already be affected

Short Spacings
Example

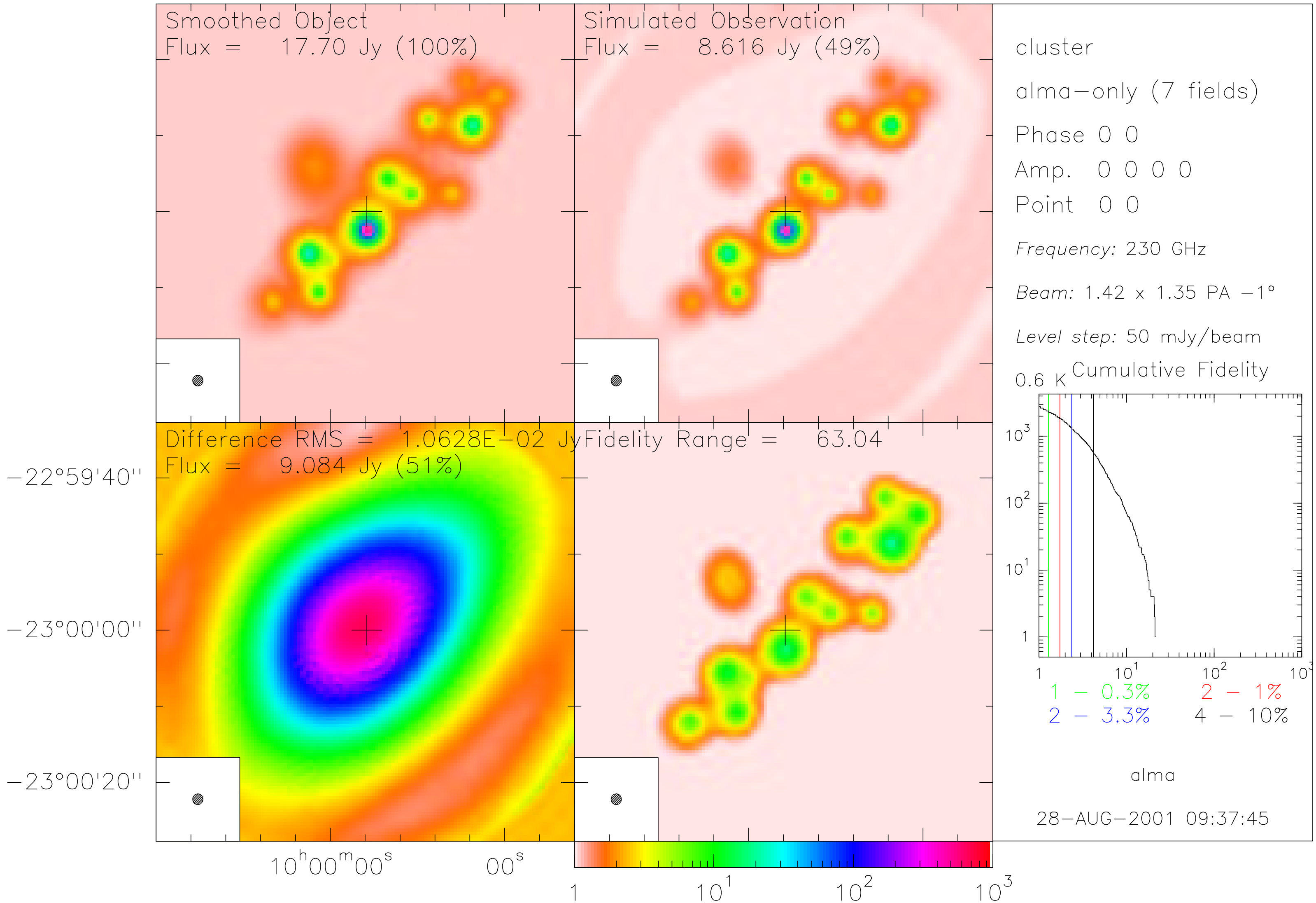
Without short spacings

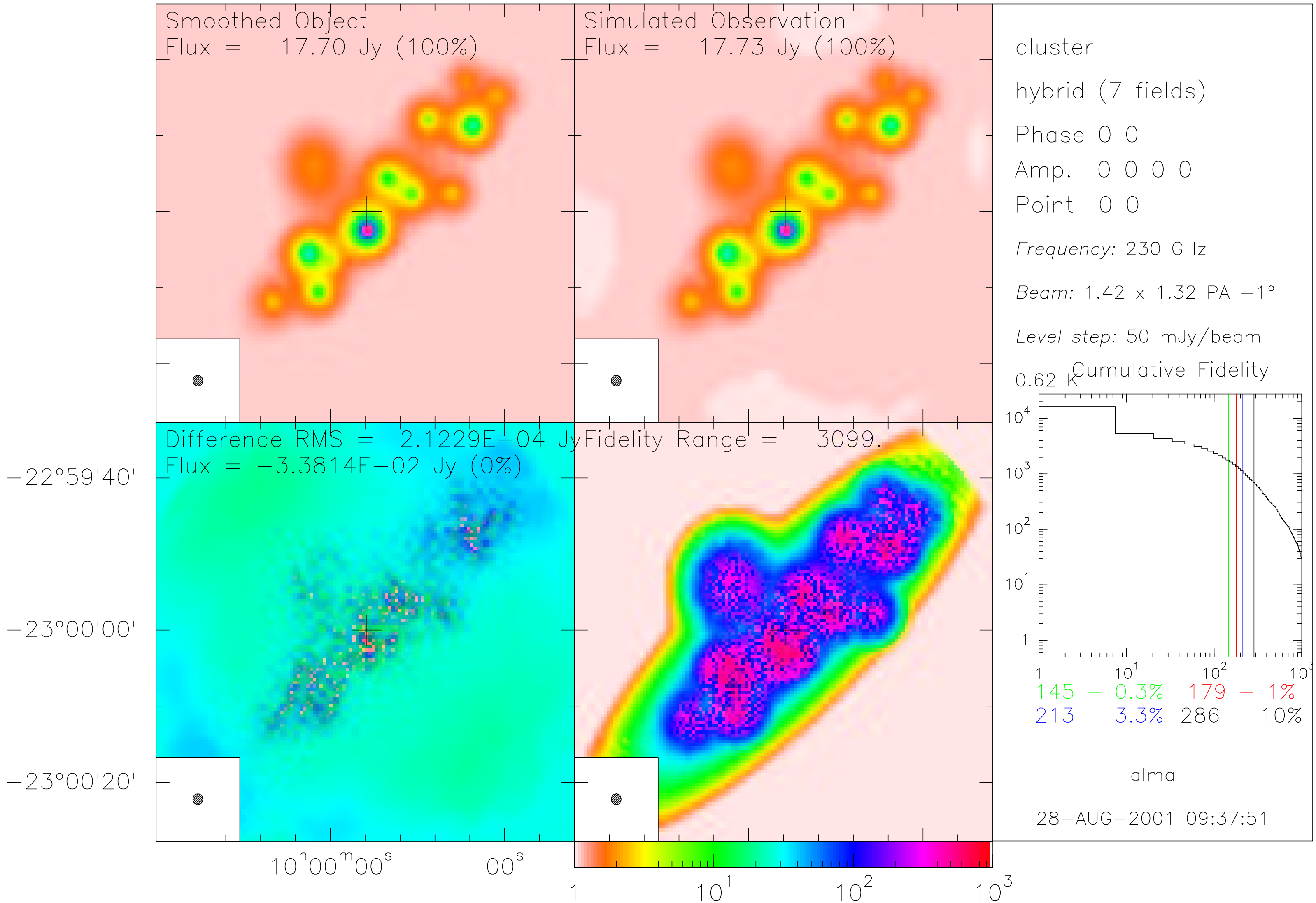


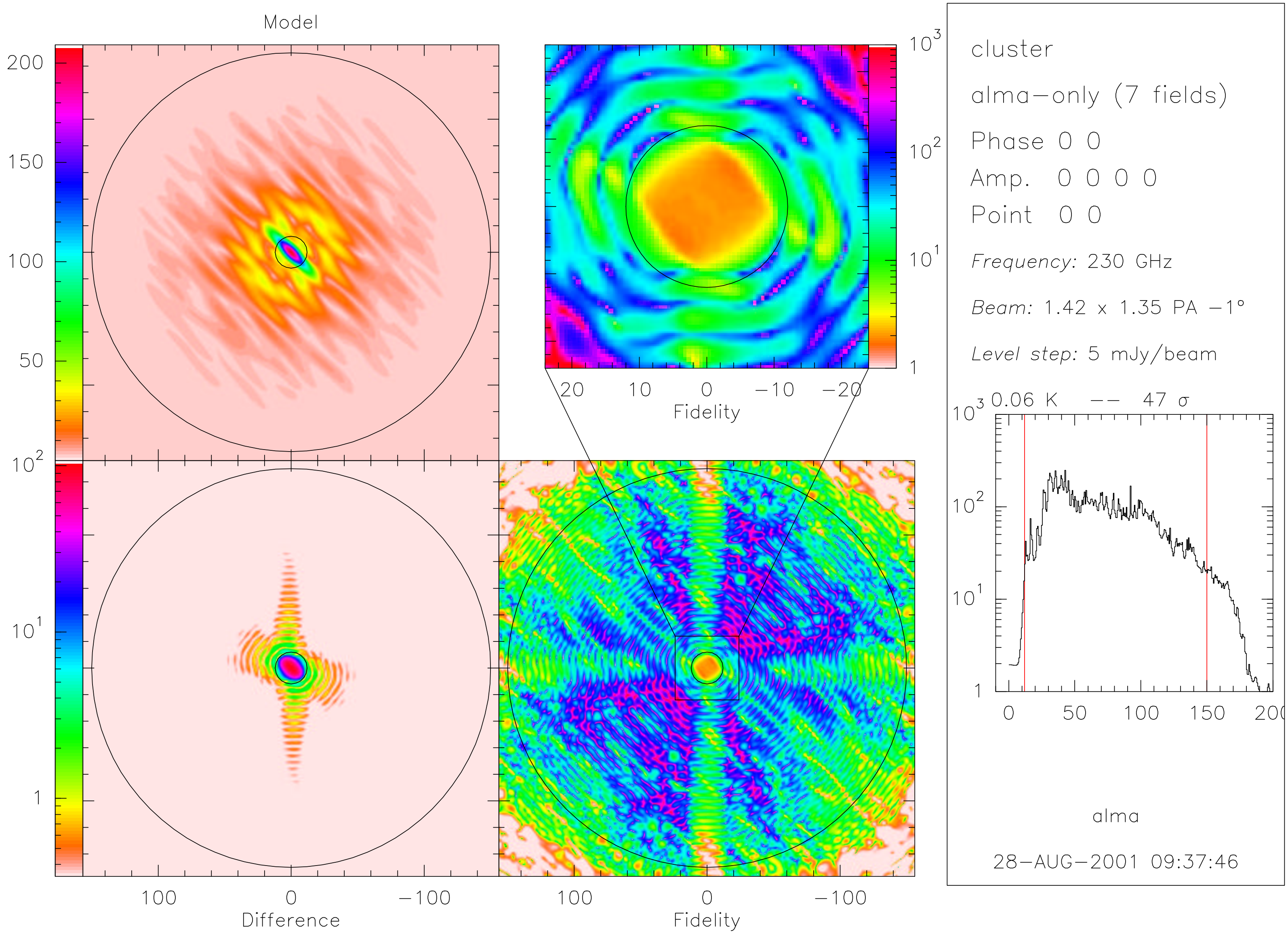
With short spacings



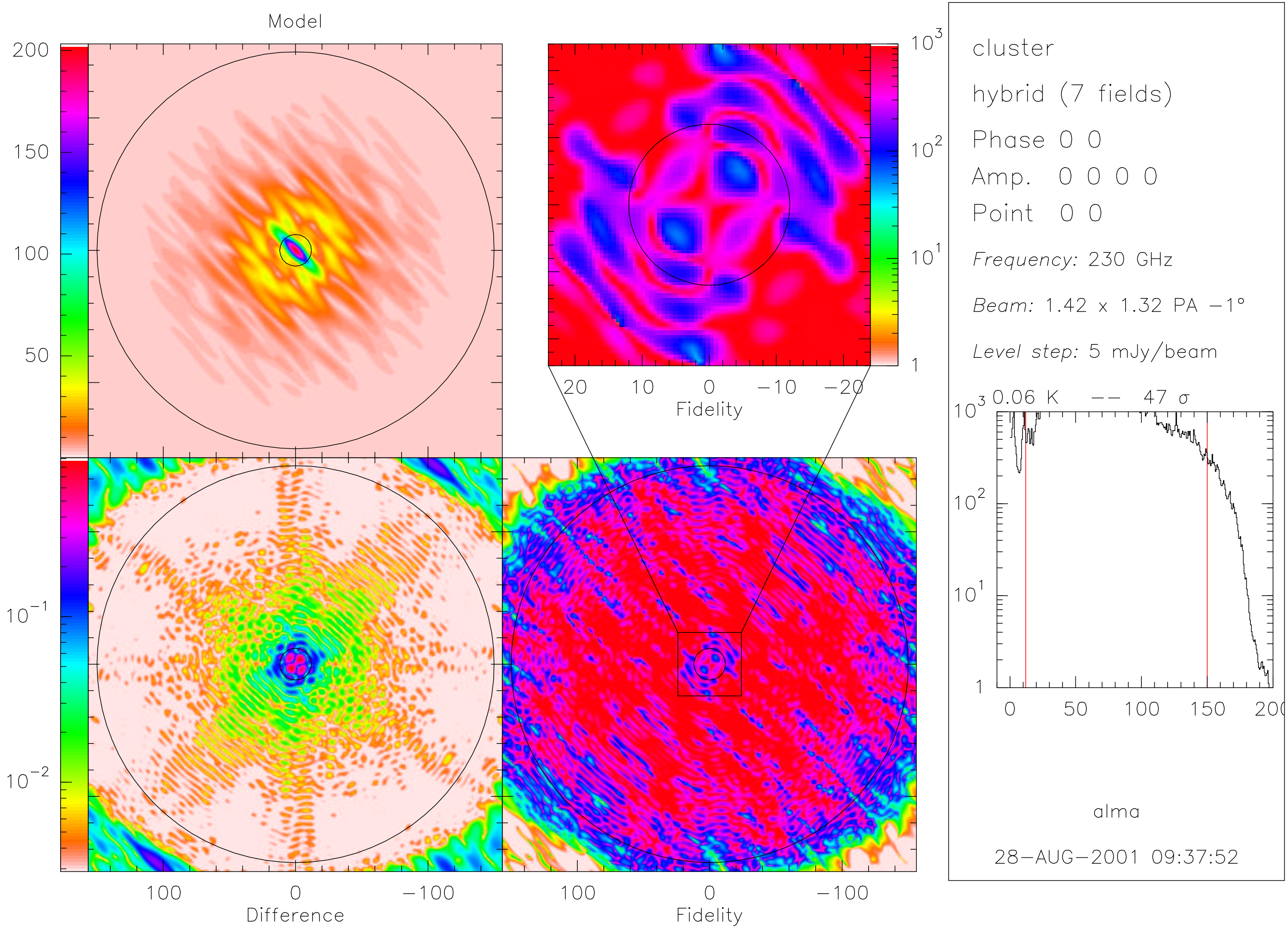
^{13}CO (1–0) in the L 1157 protostar (Gueth et al. 1997)


Smoothed Object
Flux = 17.70 Jy (100%)
Simulated Observation
Flux = 8.616 Jy (49%)
Difference RMS = 1.0628E−02 Jy
Flux = 9.084 Jy (51%)
Fidelity Range = 63.04
−22°59'40''
−23°00'00''
−23°00'20''
10h00m00s
00s
1
10^1
10^2
10^3
cluster
alma−only (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.35 PA −1°
Level step: 50 mJy/beam
0.6 K
Cumulative Fidelity
1 − 0.3%
2 − 1%
2 − 3.3%
4 − 10%
alma
28−AUG−2001 09:37:45


Smoothed Object
Flux = 17.70 Jy (100%)
Simulated Observation
Flux = 17.73 Jy (100%)
cluster
hybrid (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.32 PA −1°
Level step: 50 mJy/beam
0.62 K
Cumulative Fidelity
Difference RMS = 2.1229E−04 Jy
Flux = −3.3814E−02 Jy (0%)
Fidelity Range = 3099.
−22°59'40''
−23°00'00''
−23°00'20''
10h00m00s
00s
145 − 0.3%
179 − 1%
213 − 3.3%
286 − 10%
alma
28−AUG−2001 09:37:51



Model
Fidelity
Difference
Fidelity
cluster
alma−only (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.35 PA −1°
Level step: 5 mJy/beam
0.06 K -- 47 σ
alma
28−AUG−2001 09:37:46

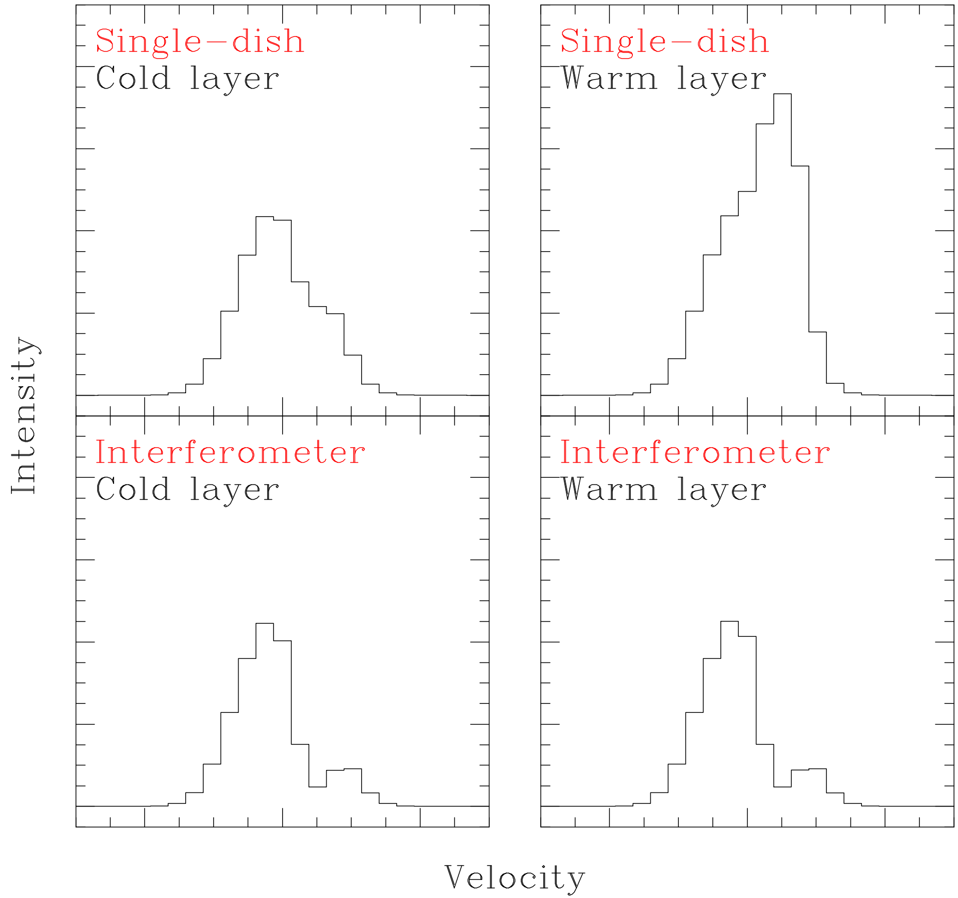

Model
Difference
Fidelity
Fidelity
cluster
hybrid (7 fields)
Phase 0 0
Amp. 0 0 0 0
Point 0 0
Frequency: 230 GHz
Beam: 1.42 x 1.32 PA −1°
Level step: 5 mJy/beam
0.06 K -- 47 σ
alma
28−AUG−2001 09:37:52

Short Spacings

Simulations

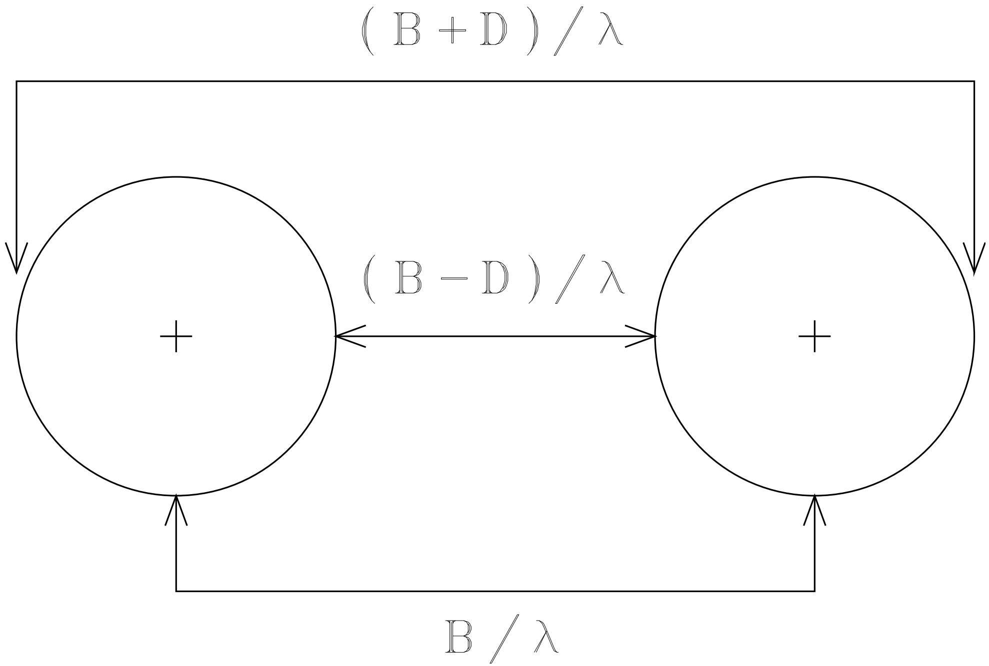
Simulations of small source + extended cold/warm layer with narrow line emission

Lack of short spacings can introduce complex artifacts **leading to wrong scientific interpretation**



Short Spacings
Spatial frequencies

- A single-dish of diameter D is sensitive to spatial frequencies from **0 to D**
- An interferometer baseline B is sensitive to spatial frequencies from $\mathbf{B-D}$ **to** $\mathbf{B+D}$



Short Spacings
Spatial frequencies

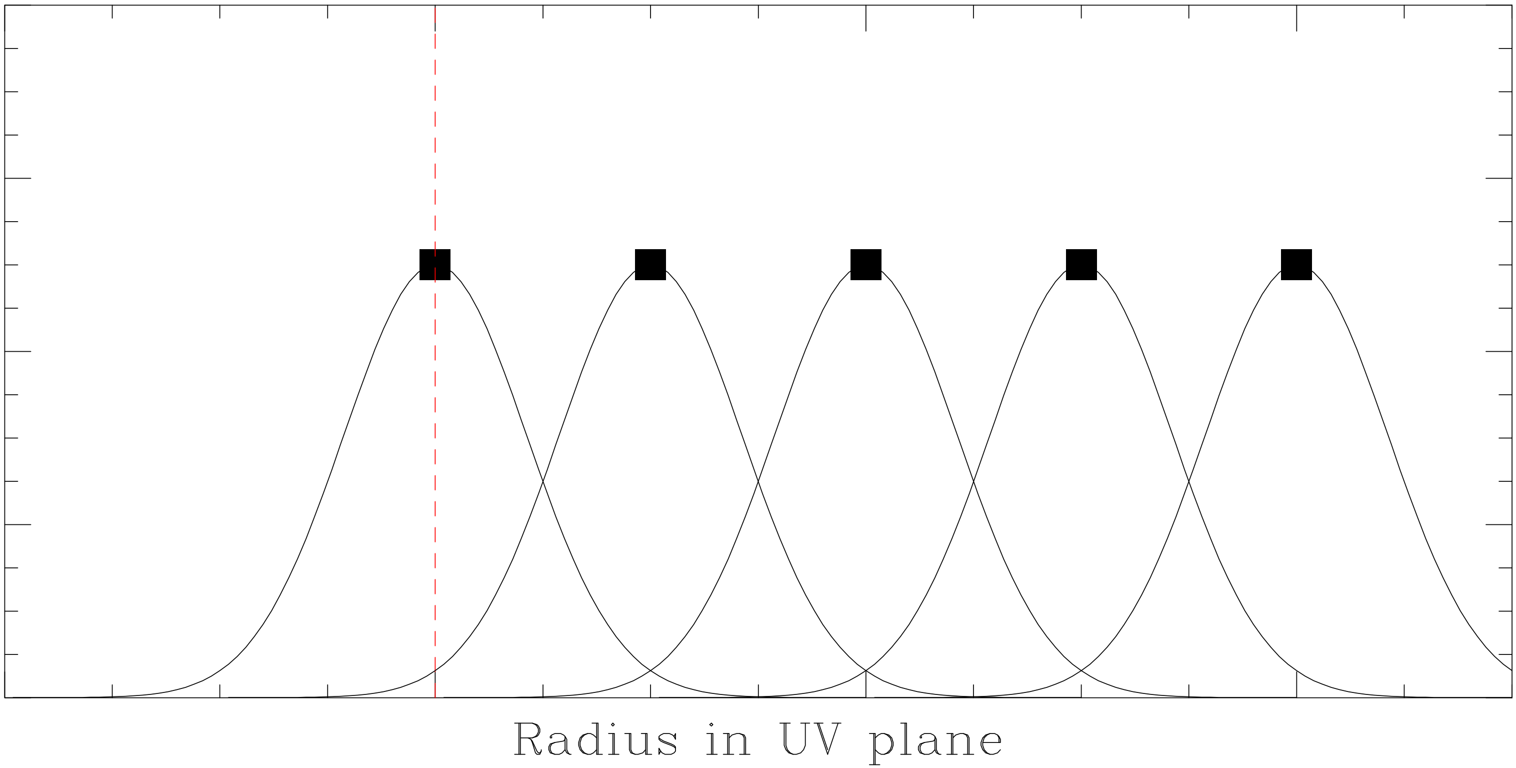
- A single-dish of diameter D is sensitive to spatial frequencies from **0 to D**
- An interferometer baseline B is sensitive to spatial frequencies from $\mathbf{B - D}$ **to** $\mathbf{B + D}$

- An inteferometer measures the product **primary beam** $\times$ **sky**
- In the uv plane: **transfert function** $*$ **true visibilities**

Short Spacings

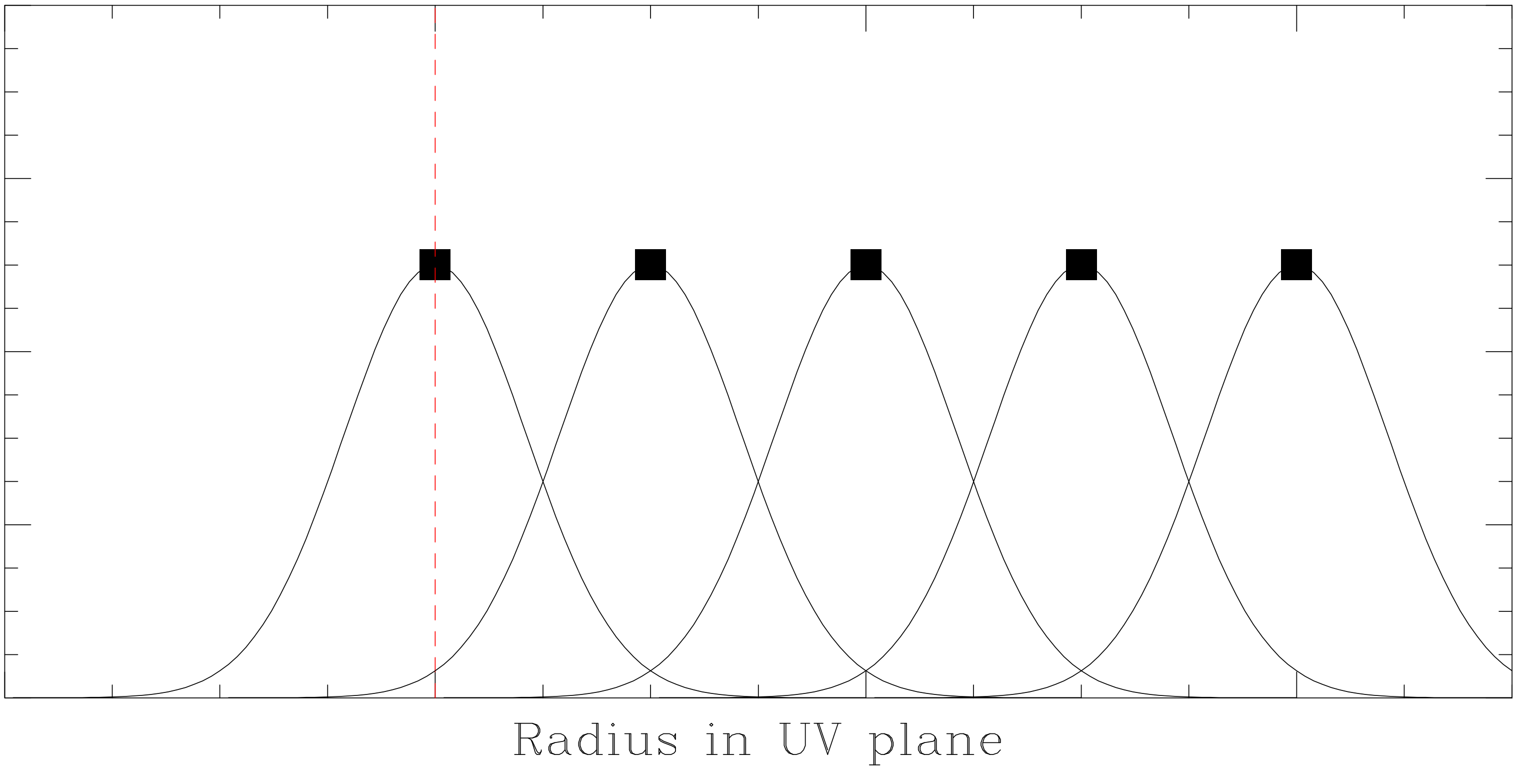
Measurements

An interferometer measures the **convolution** of the "true" visibility with the **antenna transfert function**



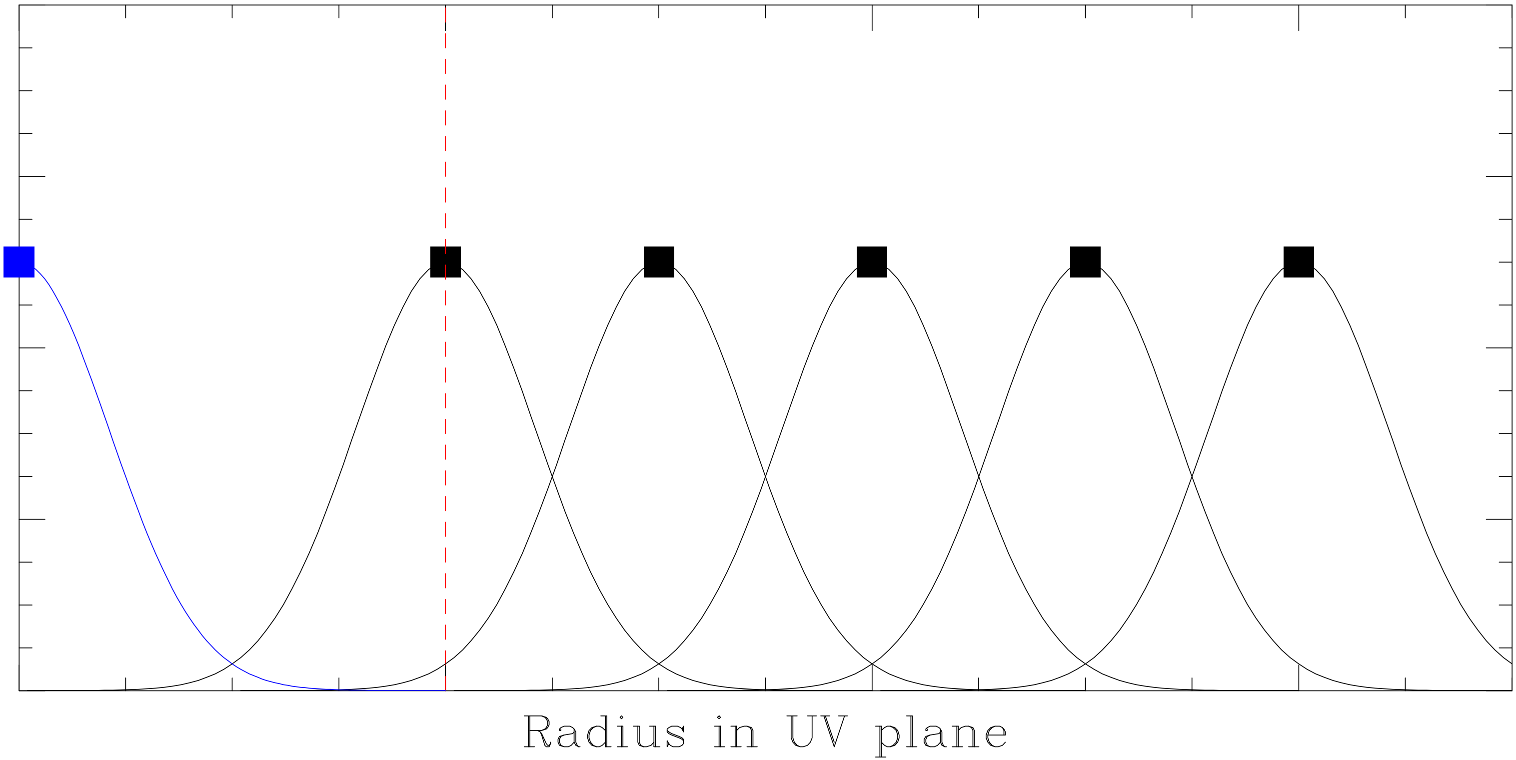
Short Spacings Measurements

No short-spacings



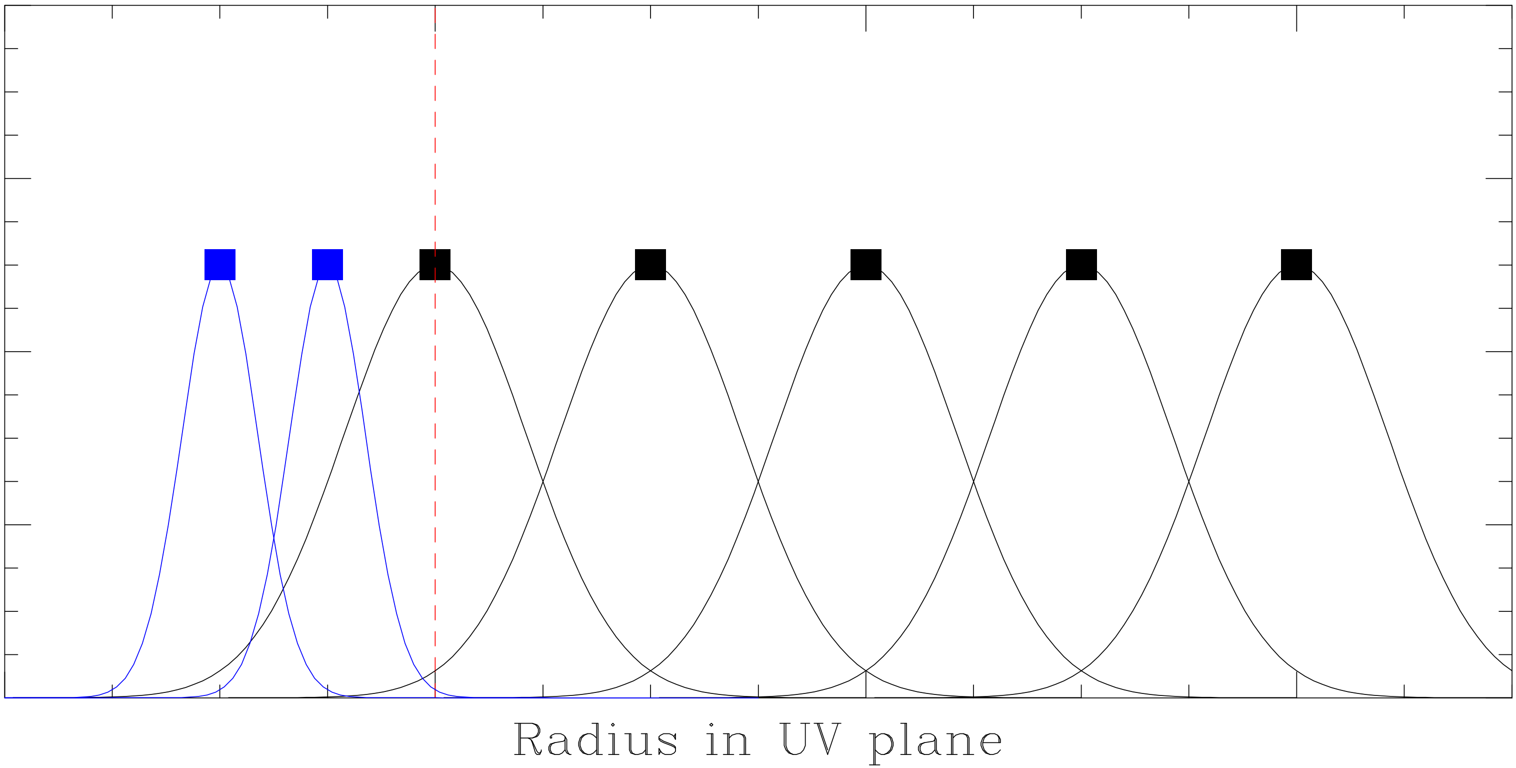
Short Spacings
Measurements

Single-dish measurement (same antenna diameter)



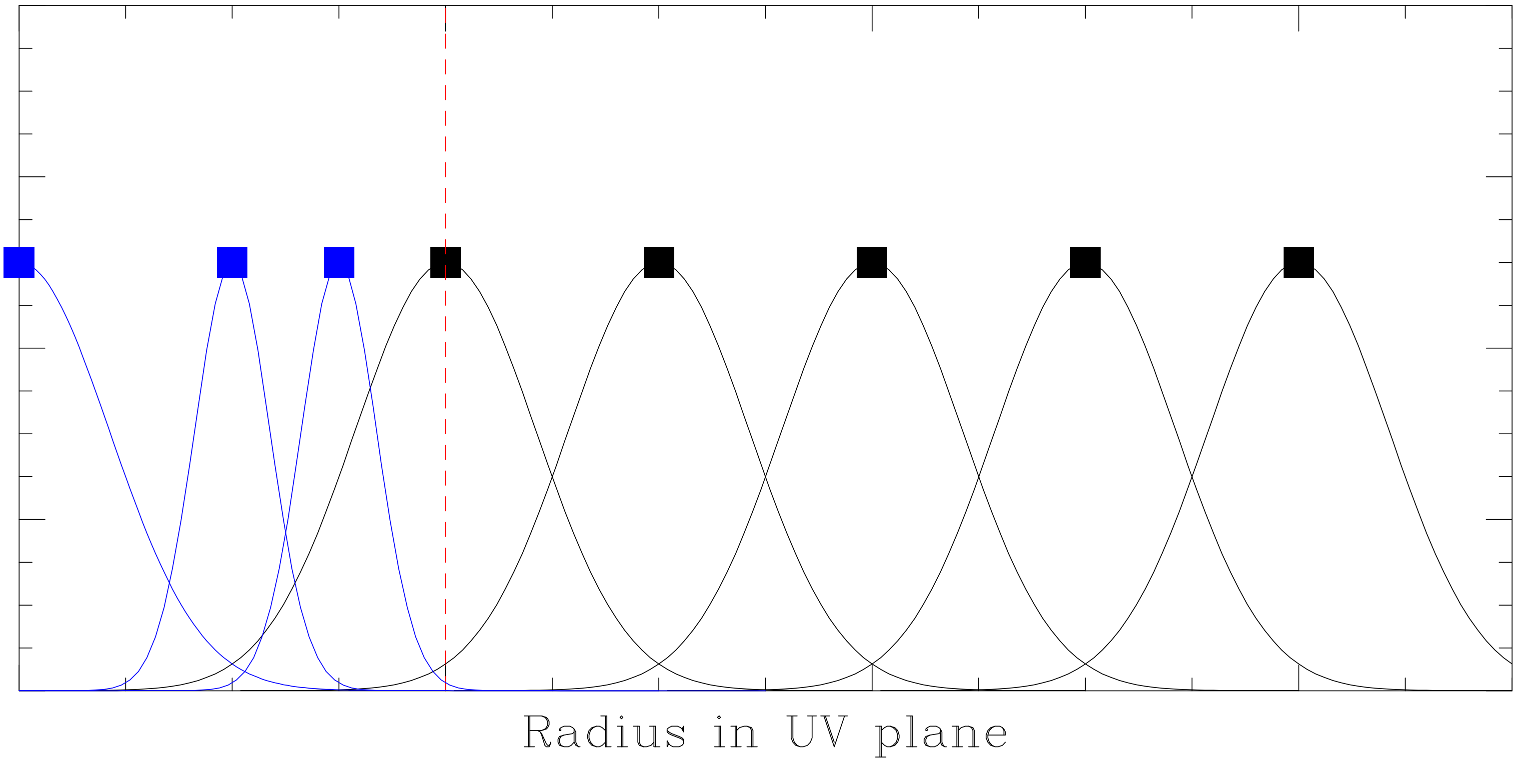
Short Spacings
Measurements

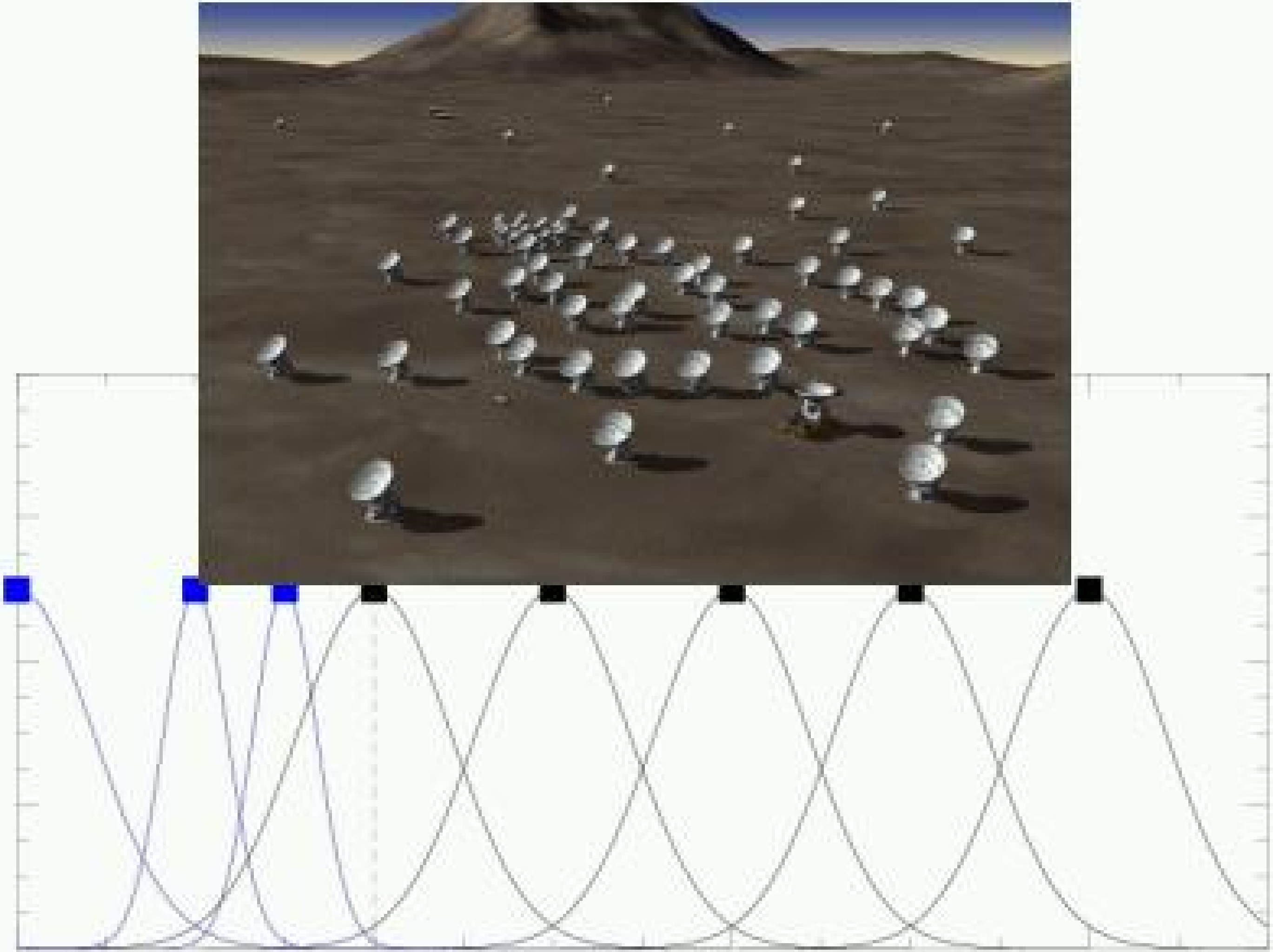
Interferometer with smaller antennas



Short Spacings
Measurements

Small interferometer + Single-dish measurement

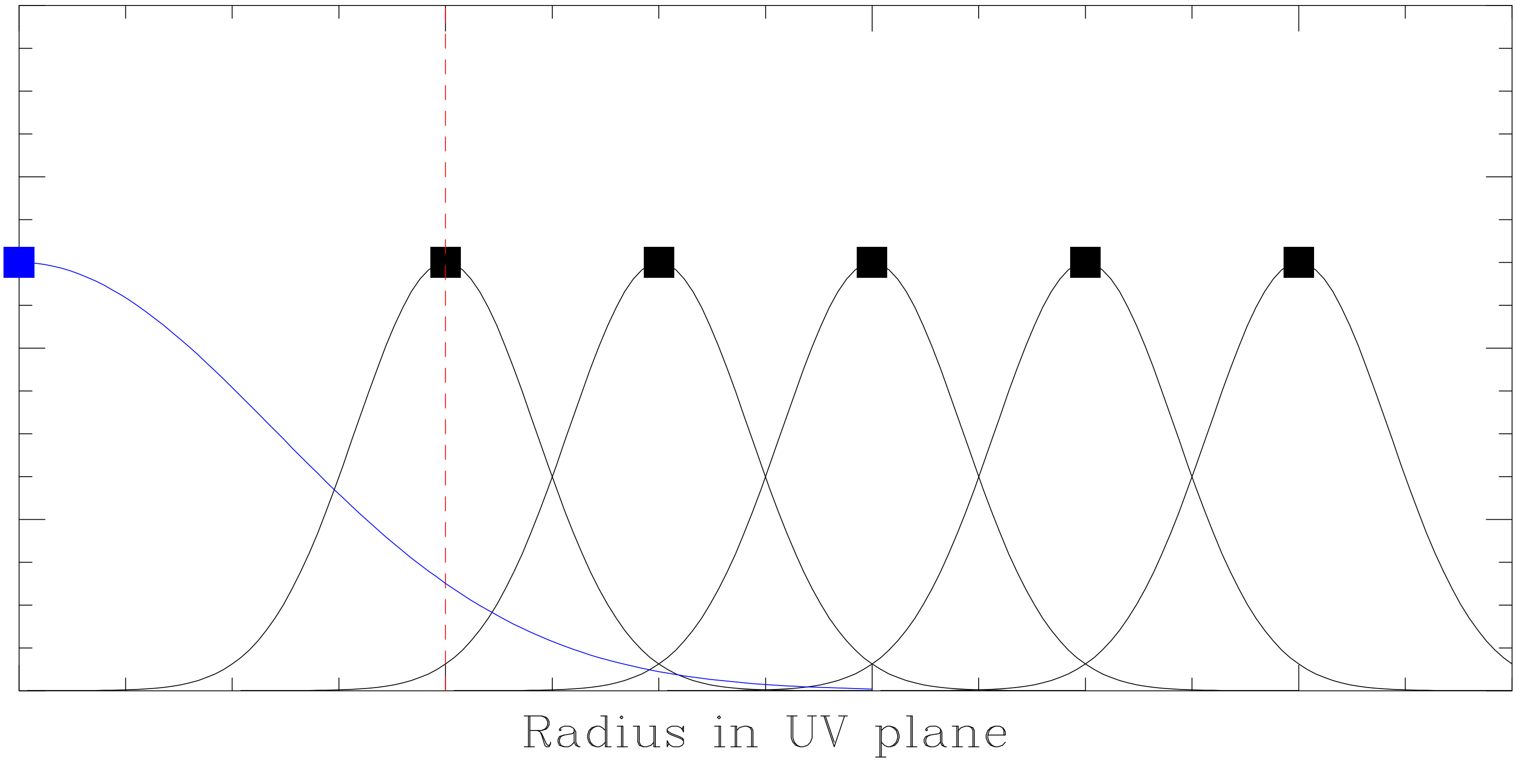


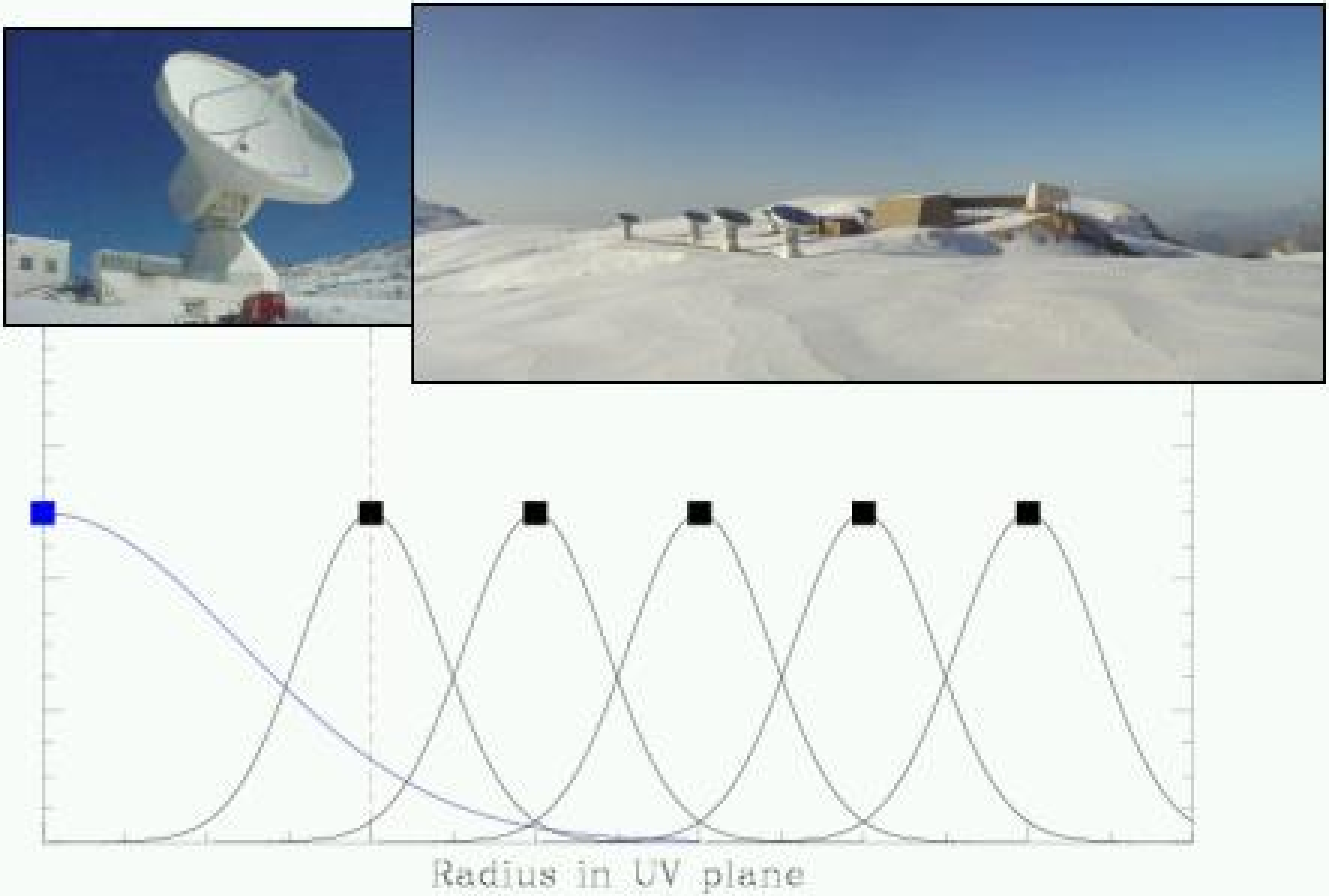


ALMA = 4 12m + 12 7 m + 50 12 m

Short Spacings
Measurements

Single-dish measurement (larger antenna diameter)




Radius in UV plane

Short Spacings

Short spacings from SD data

- Combine SD and Interferometric maps in the **image plane**
- **Joint deconvolution** (MEM or Multi-scale CLEAN)
- **Hybridization** (aka feather): Combine SD and Interferometric maps in the *uv* plane
- **Combine data in the uv plane before imaging**

  1. Use the 30–m map to simulate what would have observed the PdBI, i.e. extract "pseudo-visibilities"
  2. Merge with the interferometer visibilities
  3. Process (gridding, FT, deconvolution) all data together

  This **drastically improves the deconvolution**

Short Spacings
Extracting visibilities

$$\text{SD map} = \textbf{SD beam} * \textbf{Sky}$$

$$\text{Int. map} = \text{Dirty beam} * (\textbf{Int beam} \times \textbf{Sky})$$

- Image plane Gridding of the single-dish data $\longrightarrow$ SD Beam $*$ Sky
- uv plane Correction for single-dish beam $\longrightarrow$ Sky
- Image plane Multiplication by interferometer primary beam $\longrightarrow$ Int Beam $\times$ Sky
- uv plane Extract visibilities up to $\mathbf{D_{SD} - D_{Int}}$
- uv plane Apply a **weighting factor** before merging with the interferometer data

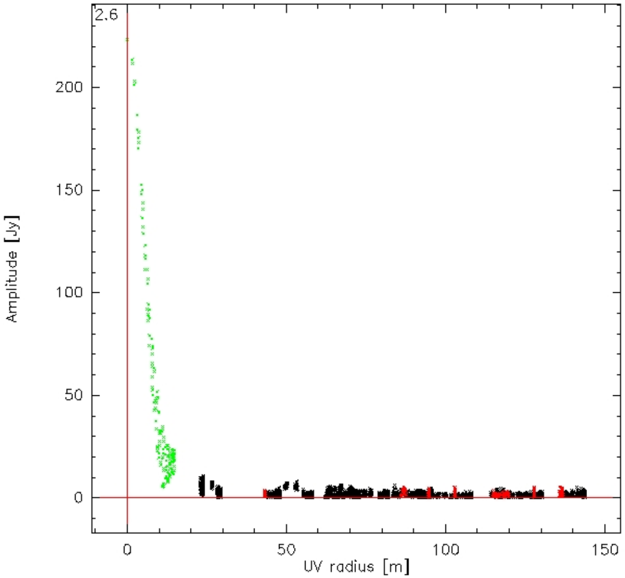
Short Spacings
Extracting visibilities

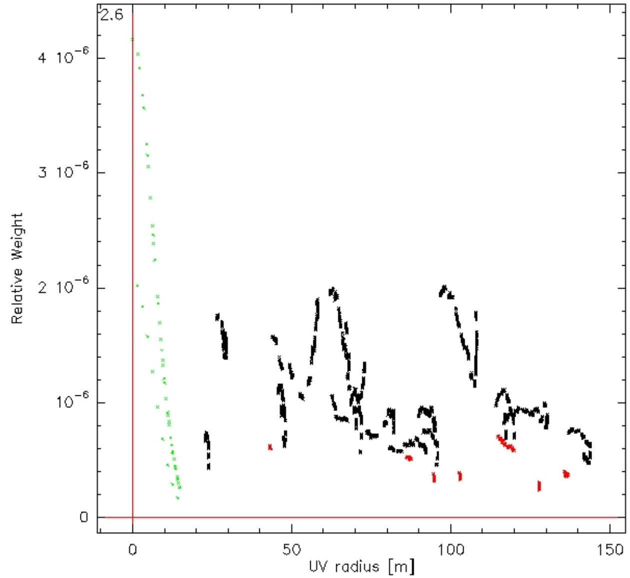
Weighting factor to SD data :

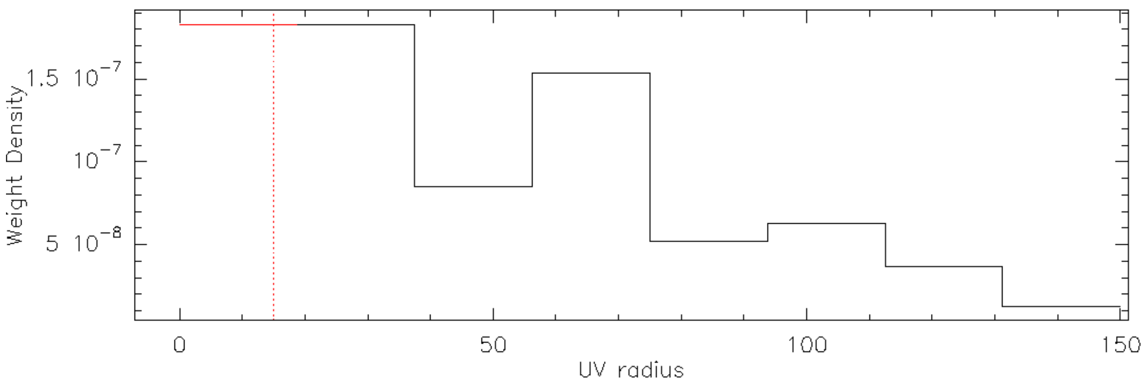
- Produce different images and dirty beams
- Methods are not perfect, noise $\longrightarrow$ weight to be optimized
- Usually, it is better to **downweight the SD data** (as compared to natural weight)

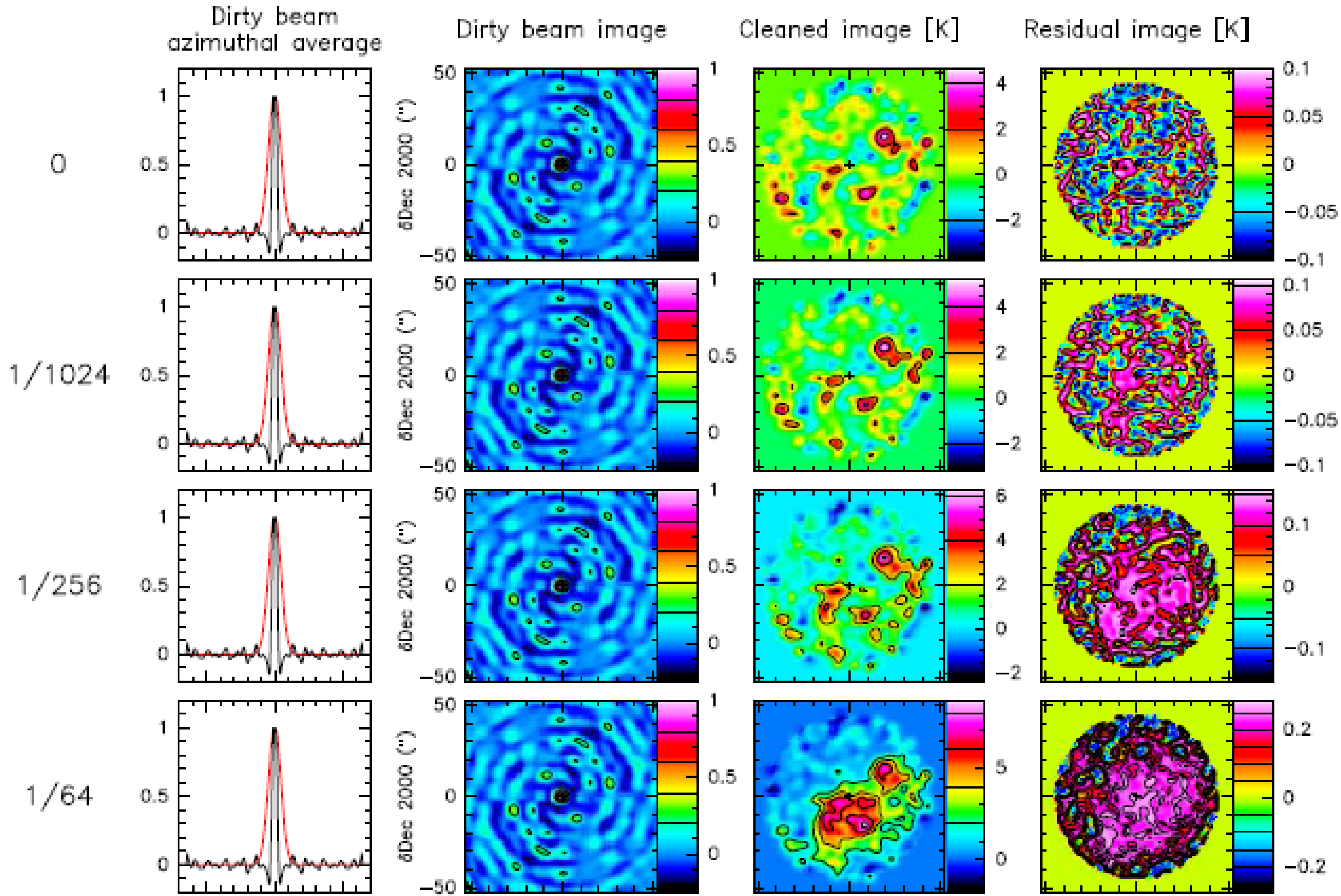
Optimization :

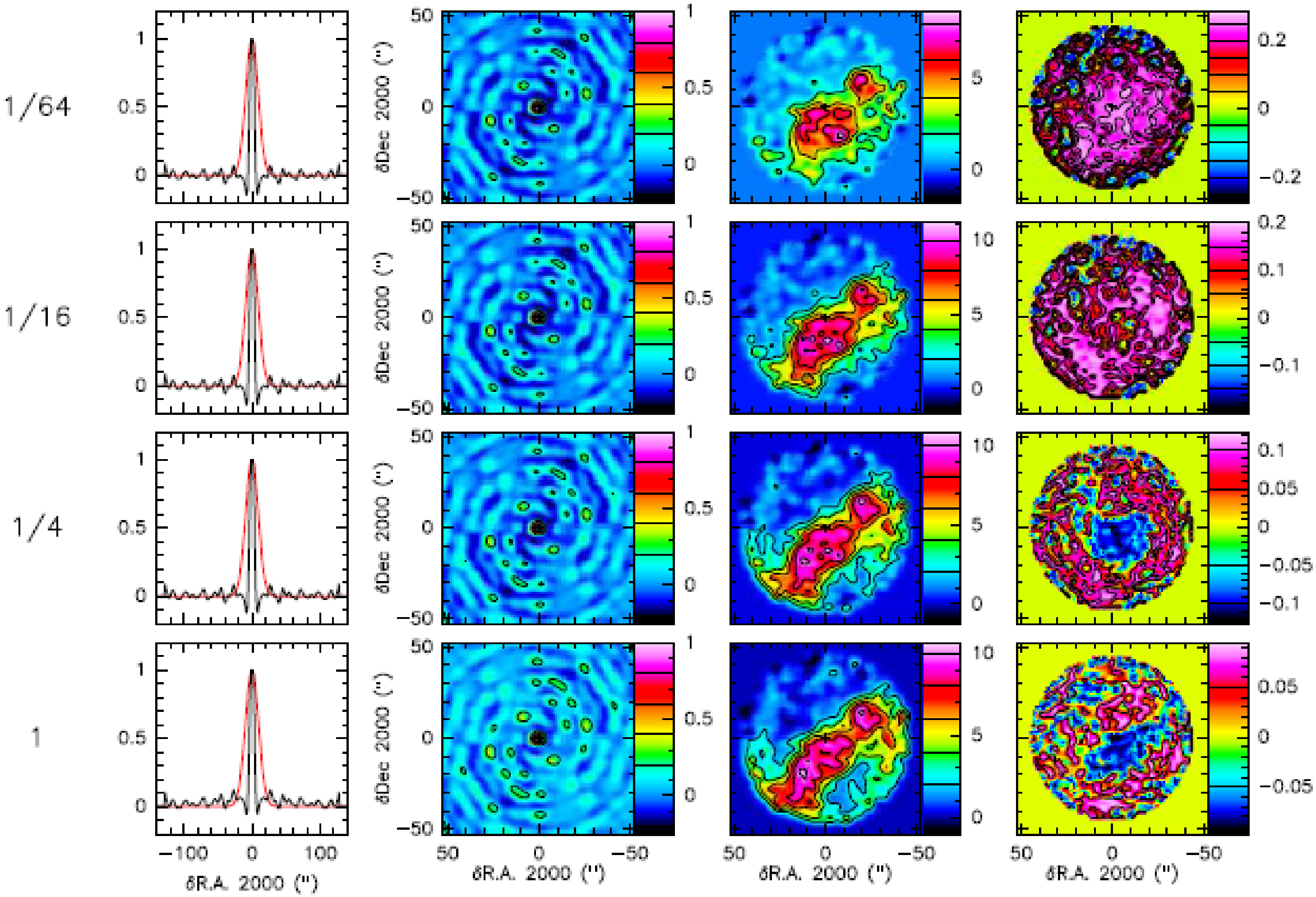
- Adjust the weights so that there is almost **no negative sidelobes** while keeping the highest angular resolution possible
- Adjust the weights so that the **weight densities in 0–D and D–2D** areas are equal $\longrightarrow$ mathematical criteria


2.6
200
150
100
50
0
Amplitude [Jy]
0
50
100
150
UV radius [m]

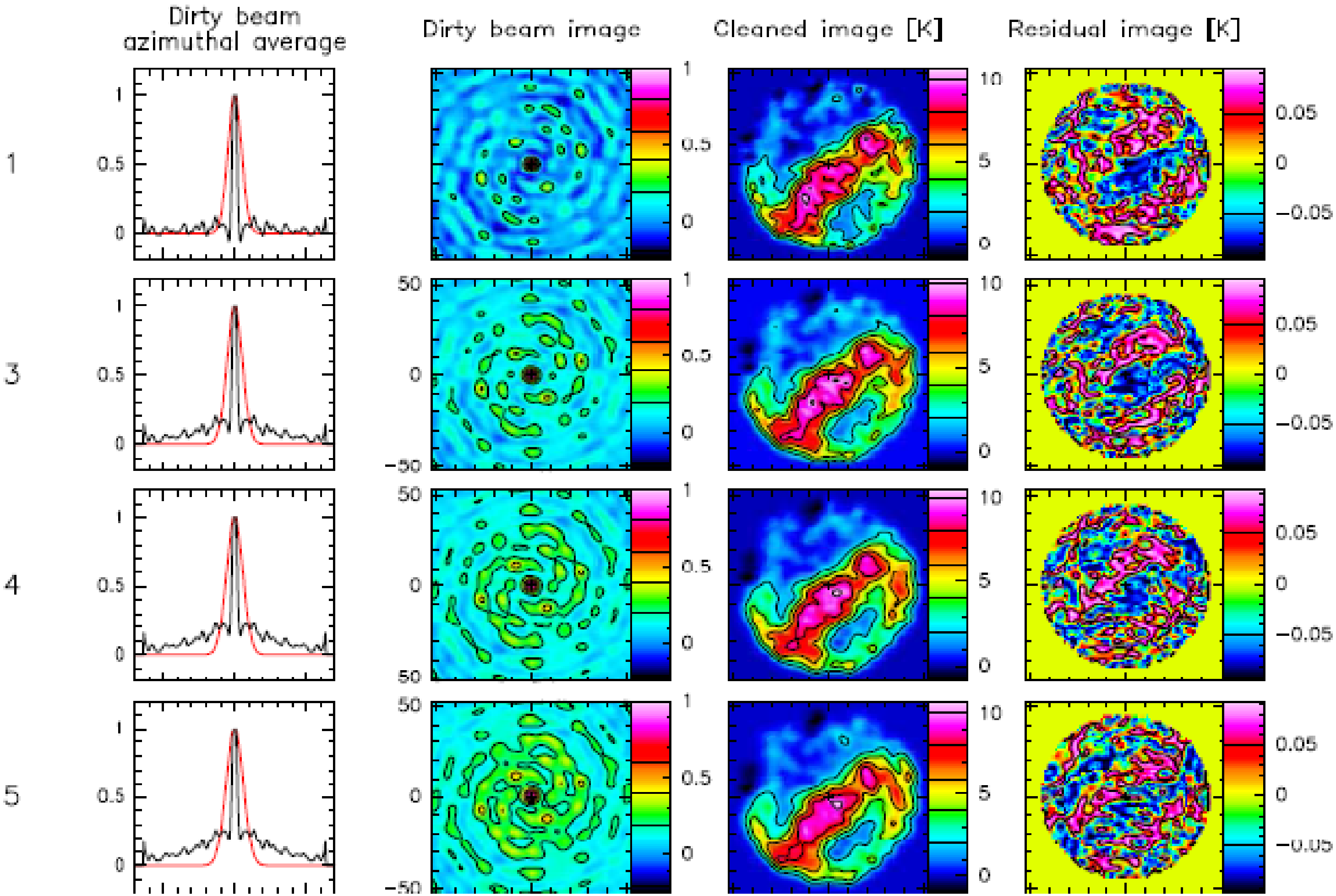

2.6
4 10^{-6}
3 10^{-6}
2 10^{-6}
10^{-6}
0
Relative Weight
0
50
100
150
UV radius [m]


1.5 10^{-7}
10^{-7}
5 10^{-8}
Weight Density
0
50
100
150
UV radius


Dirty beam azimuthal average
Dirty beam image
Cleaned image [K]
Residual image [K]
0
1/1024
1/256
1/64
δDec 2000 (")



1/64
1/16
1/4
1
δDec 2000 (″)
δR.A. 2000 (″)

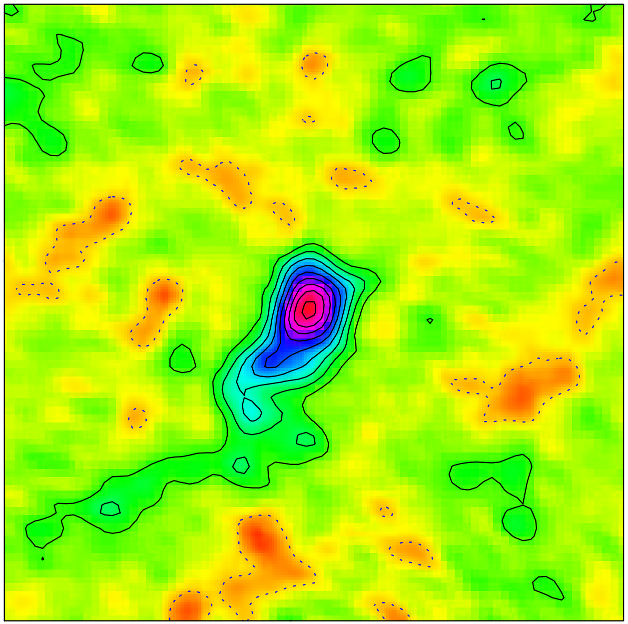


Dirty beam azimuthal average
Dirty beam image
Cleaned image [K]
Residual image [K]
1
3
4
5
0.5
0
1
50
-50
10
5
0.05
-0.05

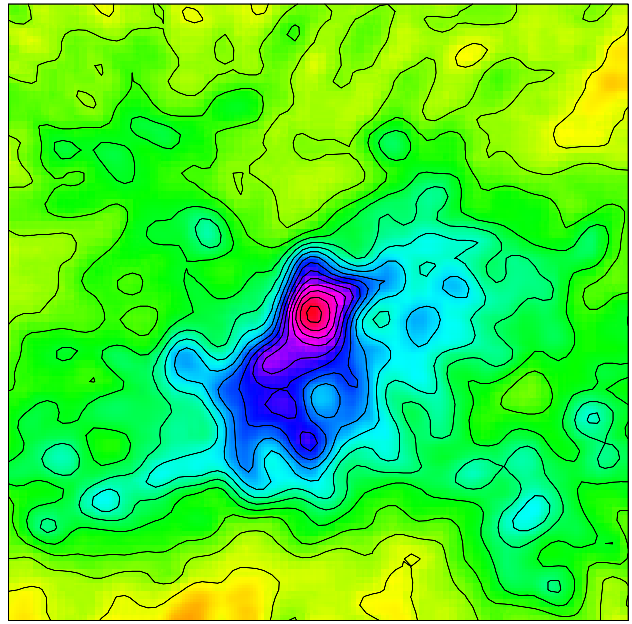
Short spacings

Example

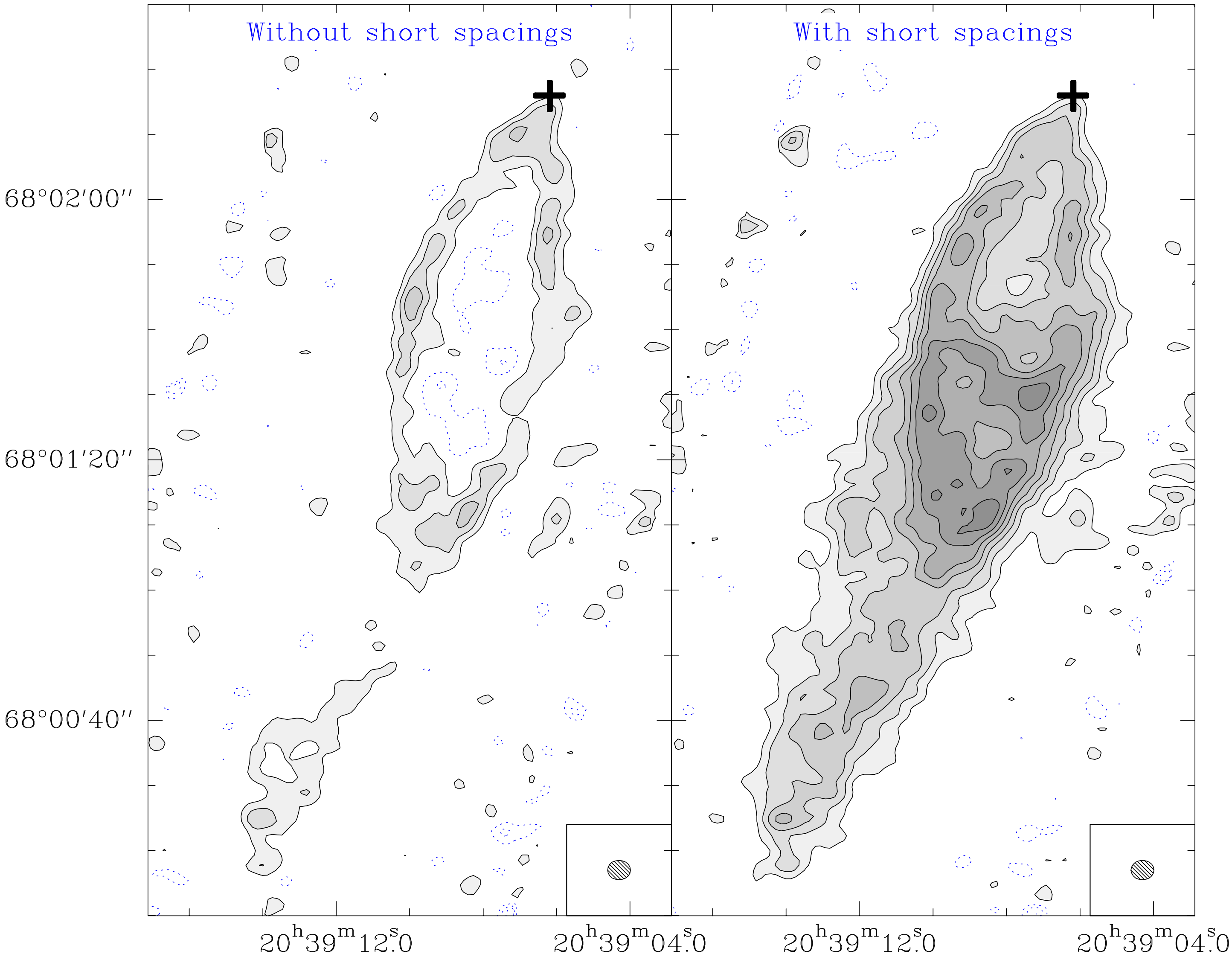
Without short spacings



With short spacings

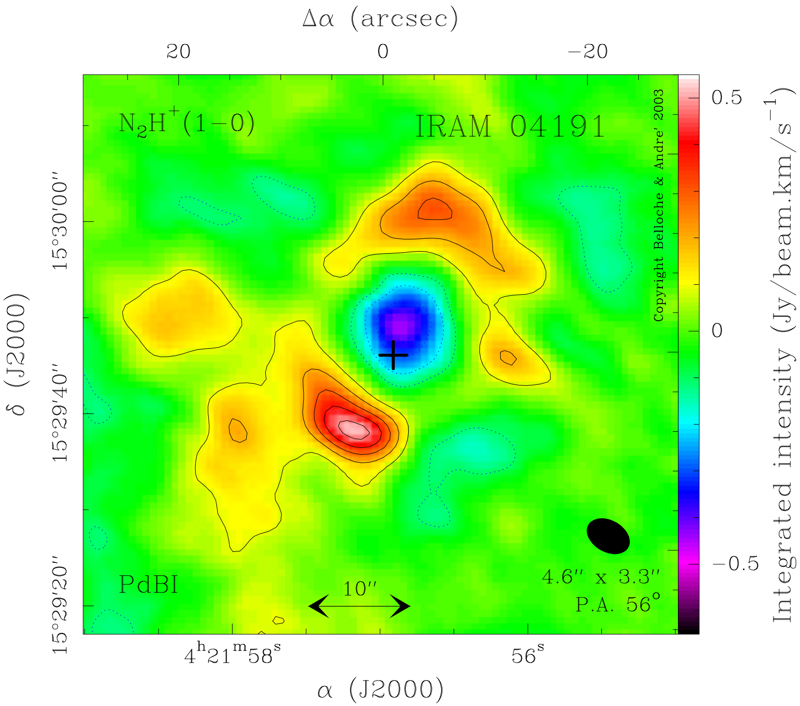


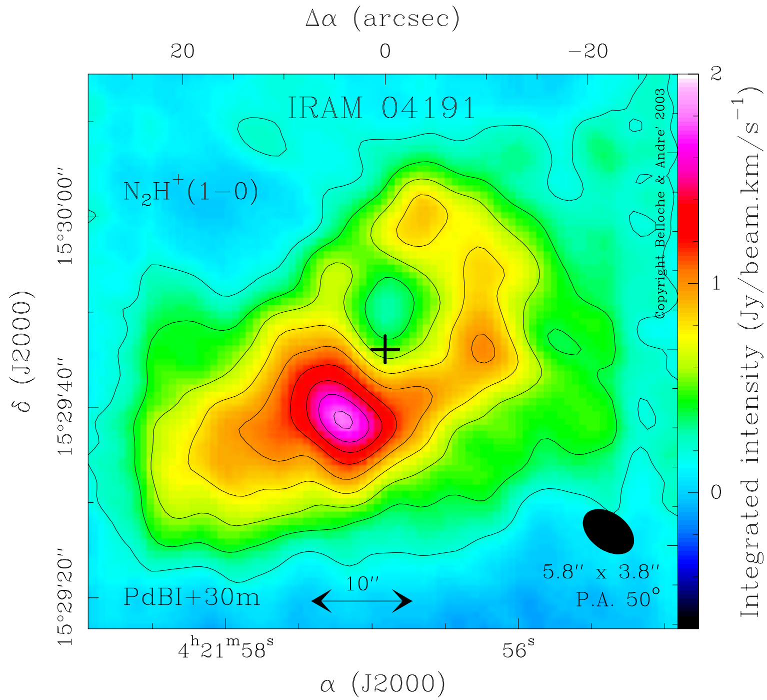
^{13}CO (1–0) in the L 1157 protostar (Gueth et al. 1997)



Without short spacings
With short spacings
68°02′00″
68°01′20″
68°00′40″
20h39m12.s0
20h39m04.s0
20h39m12.s0
20h39m04.s0

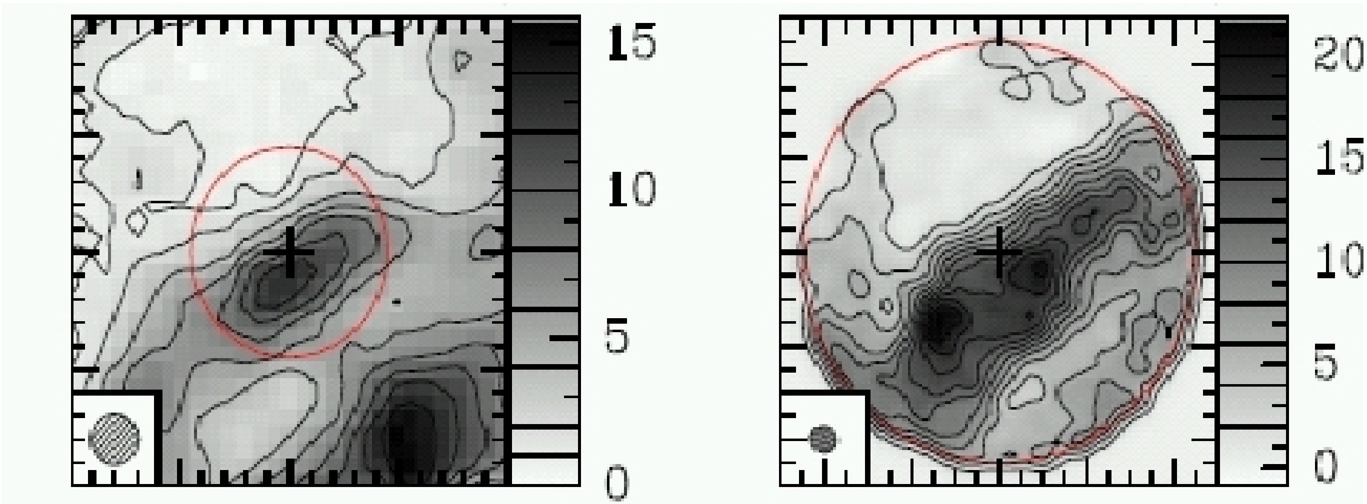
Short spacing
Example





N_2H^+ in the IRAM 04191 protostar (Belloche et al. 2004)

Short spacing
Example



CO 1–0 in the direction of NRAO 530, Pety et al. 2008

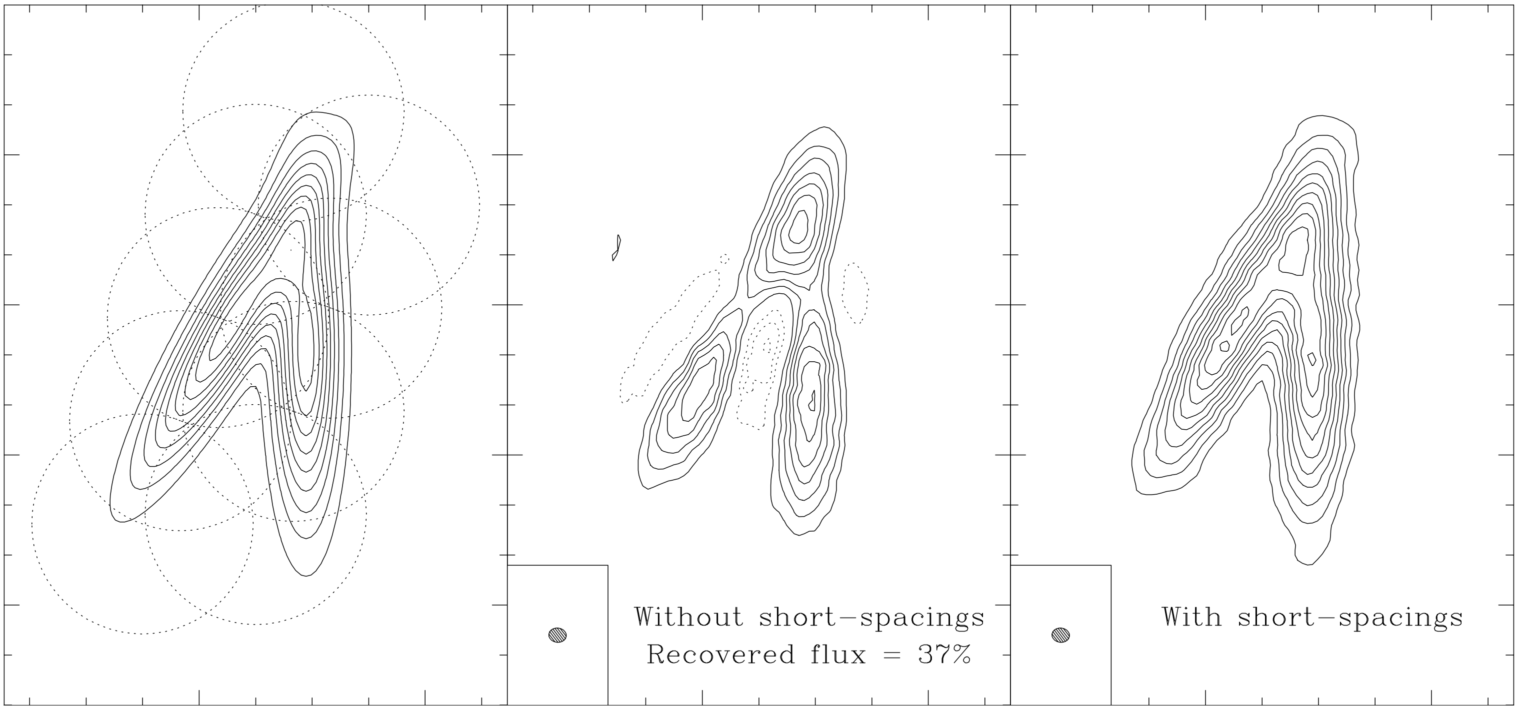
Mosaics and short spacings
The problem

Effect of missing short spacings more severe on mosaics than on single-field images:

- Extended structures are filtered out **in each field**
- Lack of information on an **intermediate scale** as compared to the mosaic size
- Possible artefact: extended structures split in several parts
- **In most cases cases, adding the short spacings is required**

Mosaics and short spacings

Simulations



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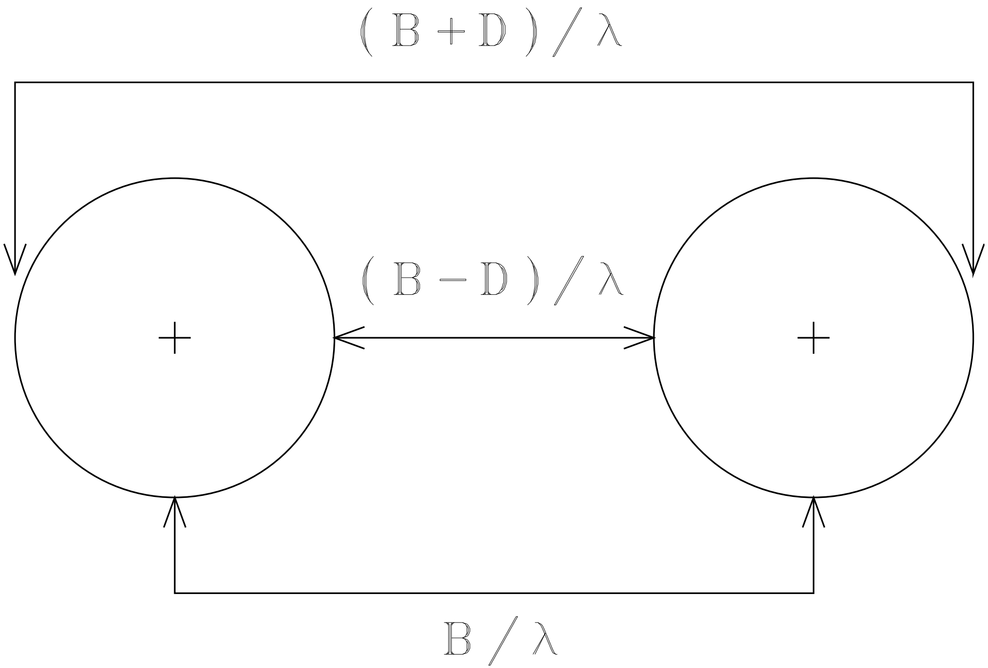
However, **mosaics are able to recover part of the short spacings information**

Image formation

- An interferometer is sensitive to all spatial frequencies from **B–D** to **B+D** $\Longrightarrow$ it measures a **local average** of the "true" visibilities



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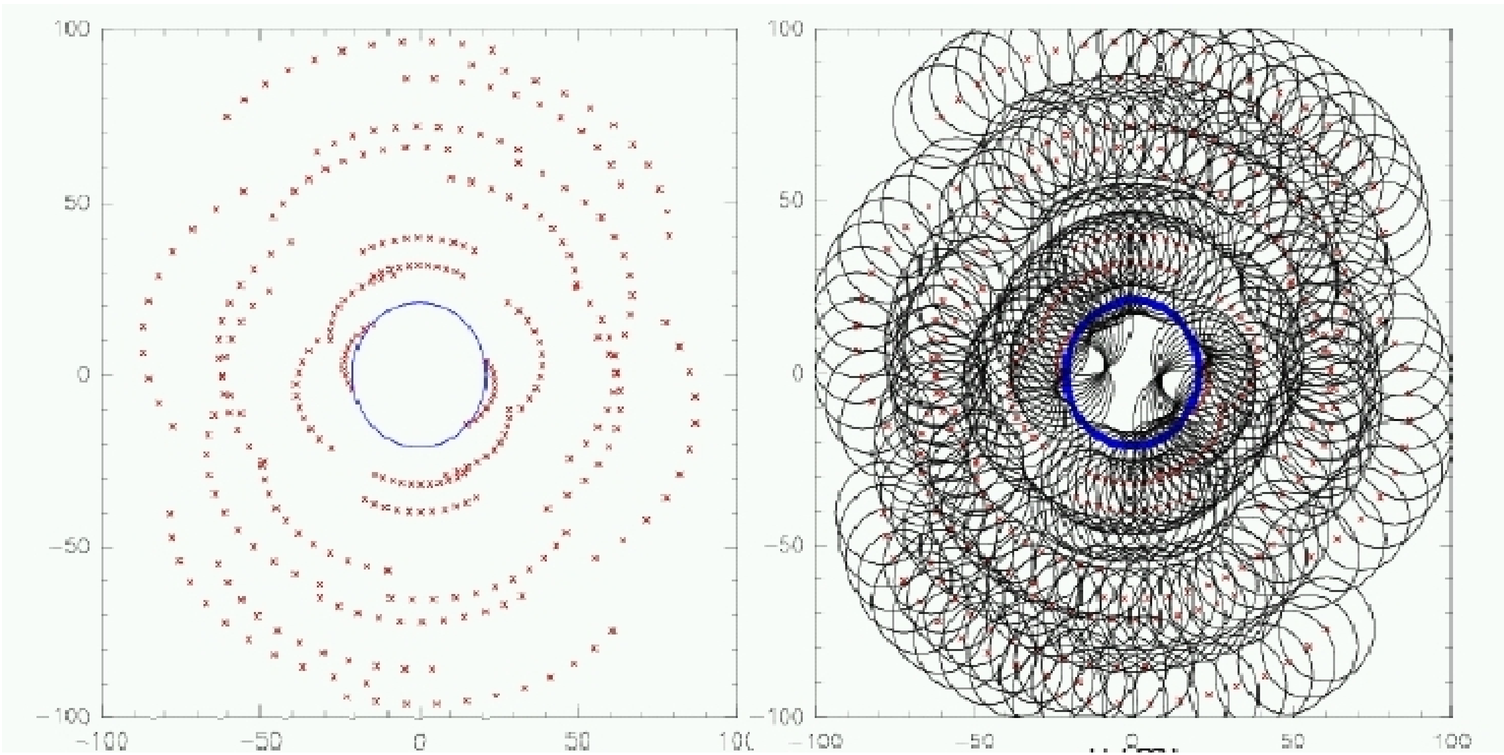
- Measured visibilities: $V_{\rm mes} = {\rm FT}(B \times I) = \mathbf{T} * \mathbf{V}$ where T is the transfert function of the antenna

- Pointing center $(\ell_p, m_p) \neq$ Phase center: phase gradient across the antenna aperture

$$V_{\rm mes}(u,v) = \left[T(u,v)\, {\rm e}^{-2i\pi(u\ell_p + v m_p)}\right] * V(u,v)$$

- **Combination of measurements at different (ℓ_p, m_p) should allow to derive V**

- The recovery algorithm is a simple Fourier Transform (Ekers & Rots)



100
50
0
−50
−100
−100
−50
0
50
100

Conclusions

- Mosaicing is a **standard observing mode** at Plateau de Bure
- Adding short spacings from the IRAM 30–m is an **standard procedure** (box in proposal form)
- ALMA designed from the beginning to include the short-spacings (ACA, SD antennas) – but not for all projects
- New developments to come: on-the-fly interferometry