Imaging & Deconvolution:
II. Mosaicking

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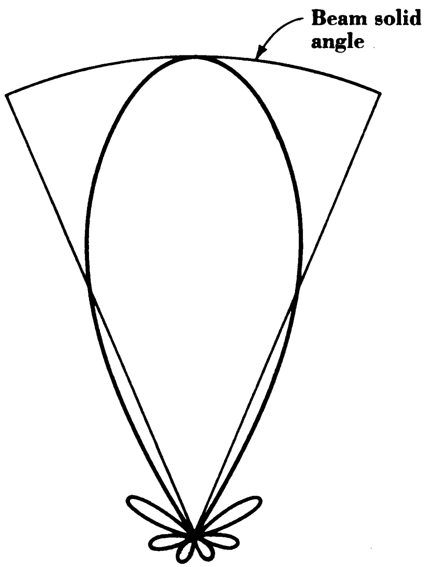
Towards Higher Resolution: Limited Instantaneous Field of View

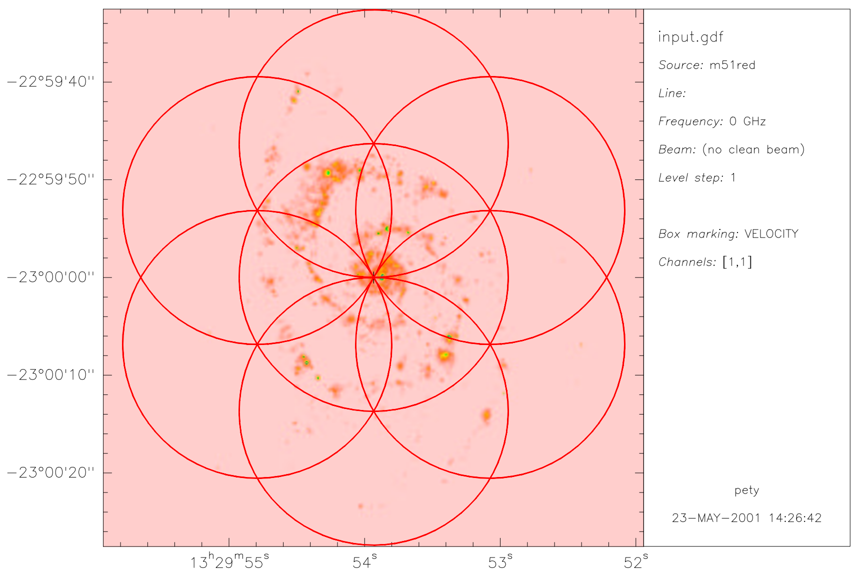
Measurement equation $I_{\text{meas}} = D \star (B_{\text{prim}}.I_{\text{source}}) + N.$

One pixel detector

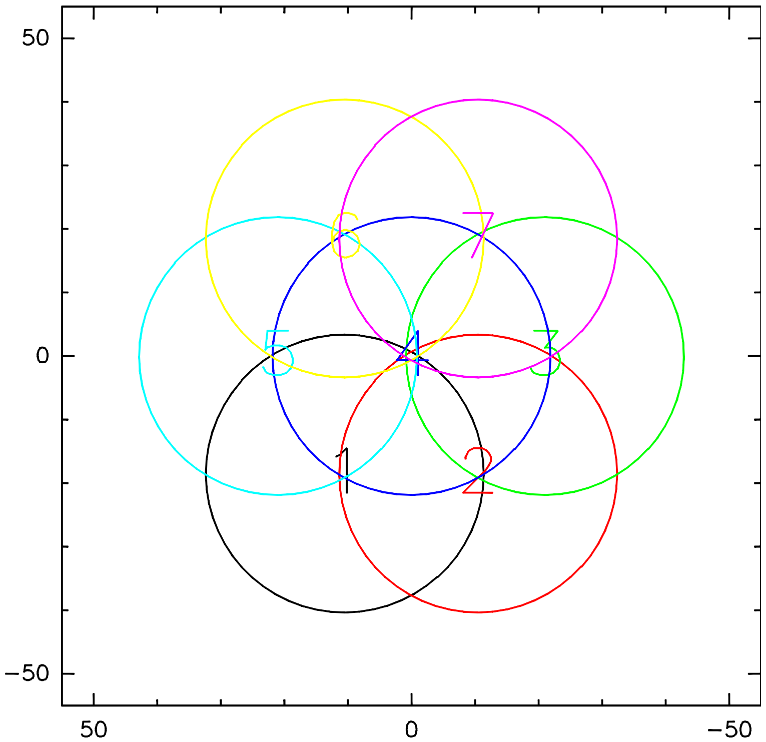
- Single Dish: one image pixel/telescope pointing;
- Interferometer: numerous image pixels/telescope pointing
  - Field of view = Primary beam size;
  - Image resolution = Synthesized beam size.

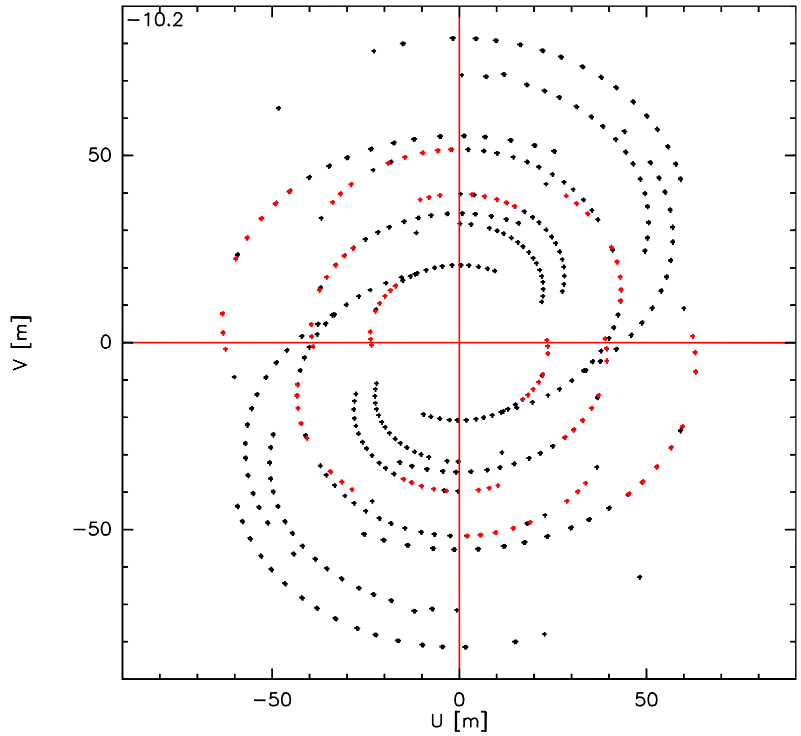
Wide-field imaging $\Rightarrow$ mosaicking.





Observing setup: I. Interferometry



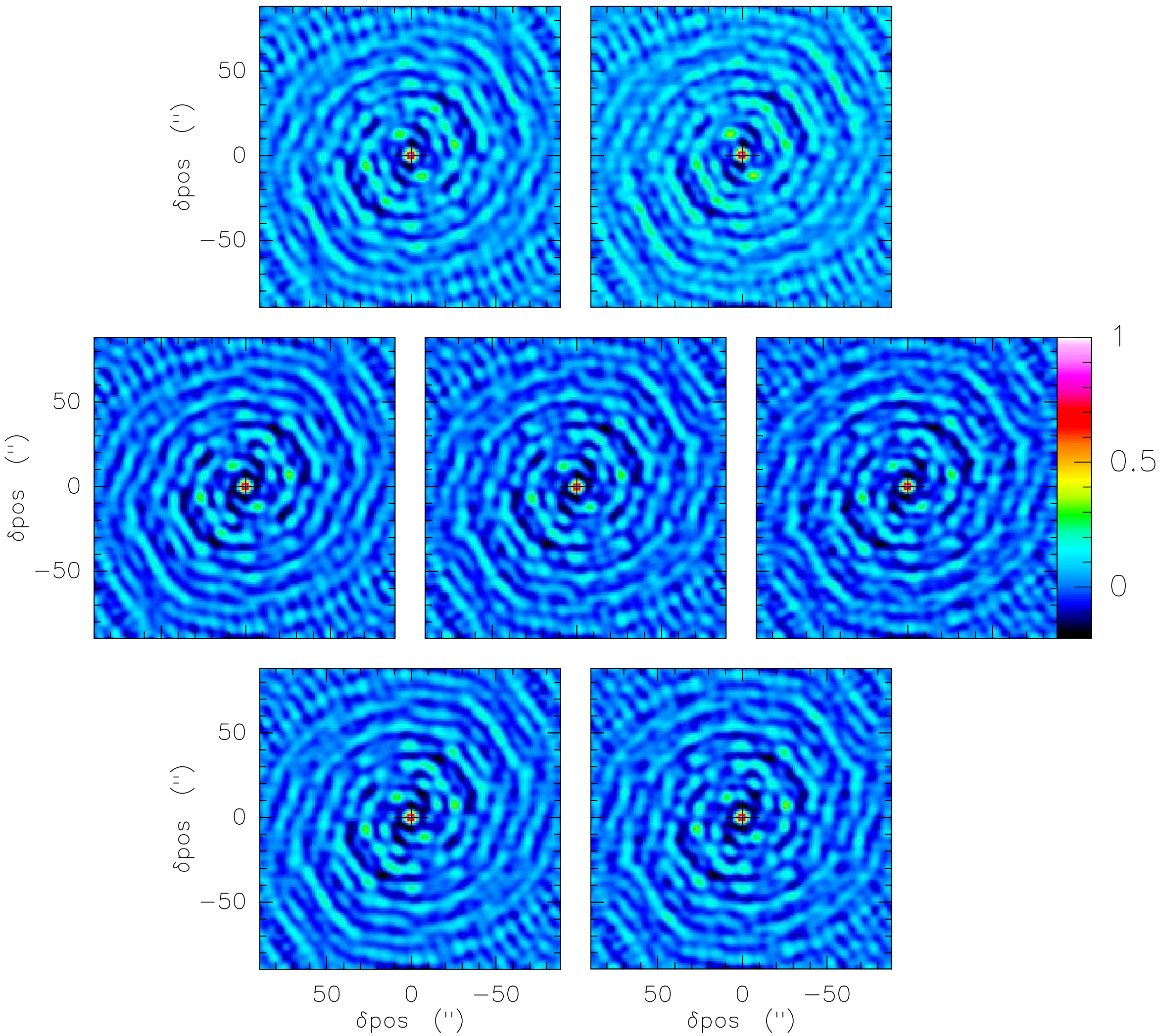


- Stop-and-go mosaicking setup:
  - Loop around field positions ⇒ similar uv coverage per field;
  - Contiguous time per field: Compromise between
    - ∗ Need of consistency between fields;
    - ∗ Minimization of dead times due to acceleration/deceleration.

- Example (setup during 8 hours)
  - 7 fields observed 3 minutes per fields in each loop;
  - Calibrator observed every 21 minutes;
  - Pointing and focus checked every hour.

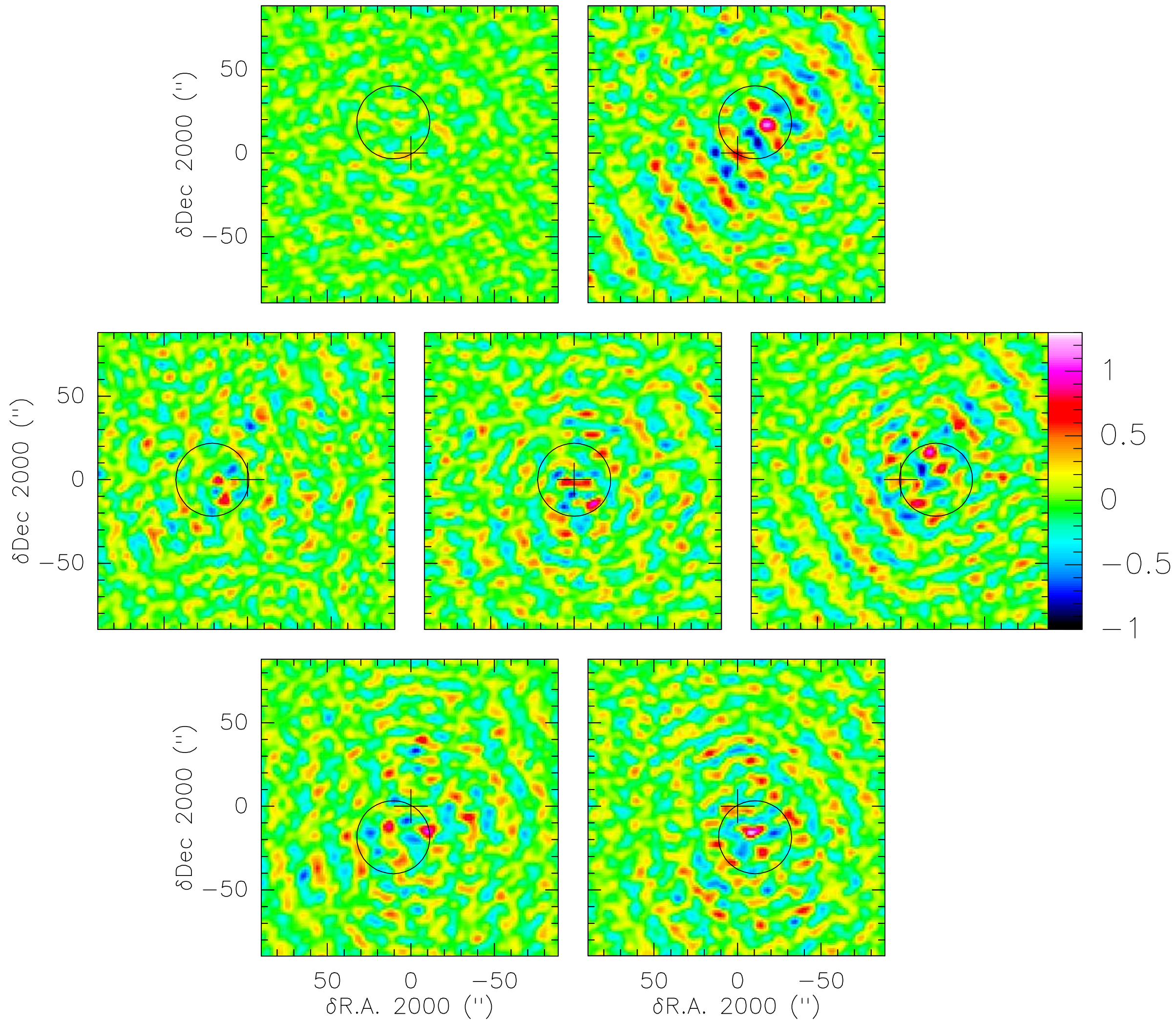
Imaging: Dirty beams

- One dirty beam per field (directly the final image size): $I_i = D_i \star (B_i.I_{\text{source}}) + N_i$.

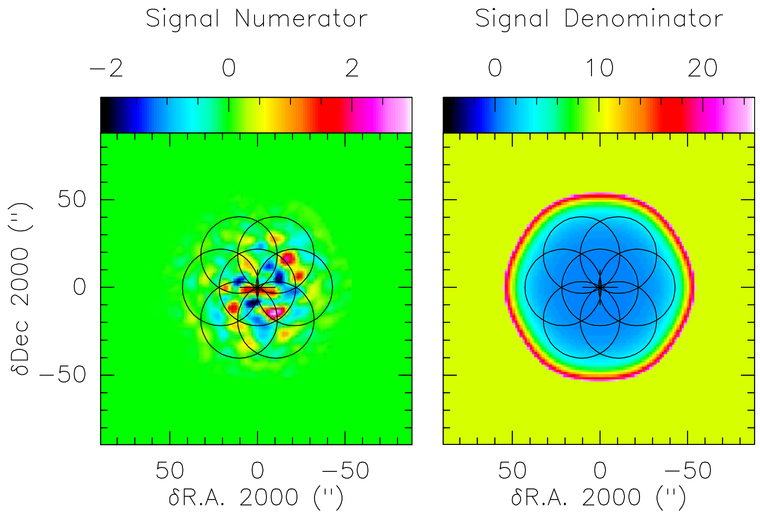


Imaging: Dirty image and noise

- One dirty image per field (directly the final image size): $I_i = D_i \star (B_i.I_{\text{source}}) + N_i$.



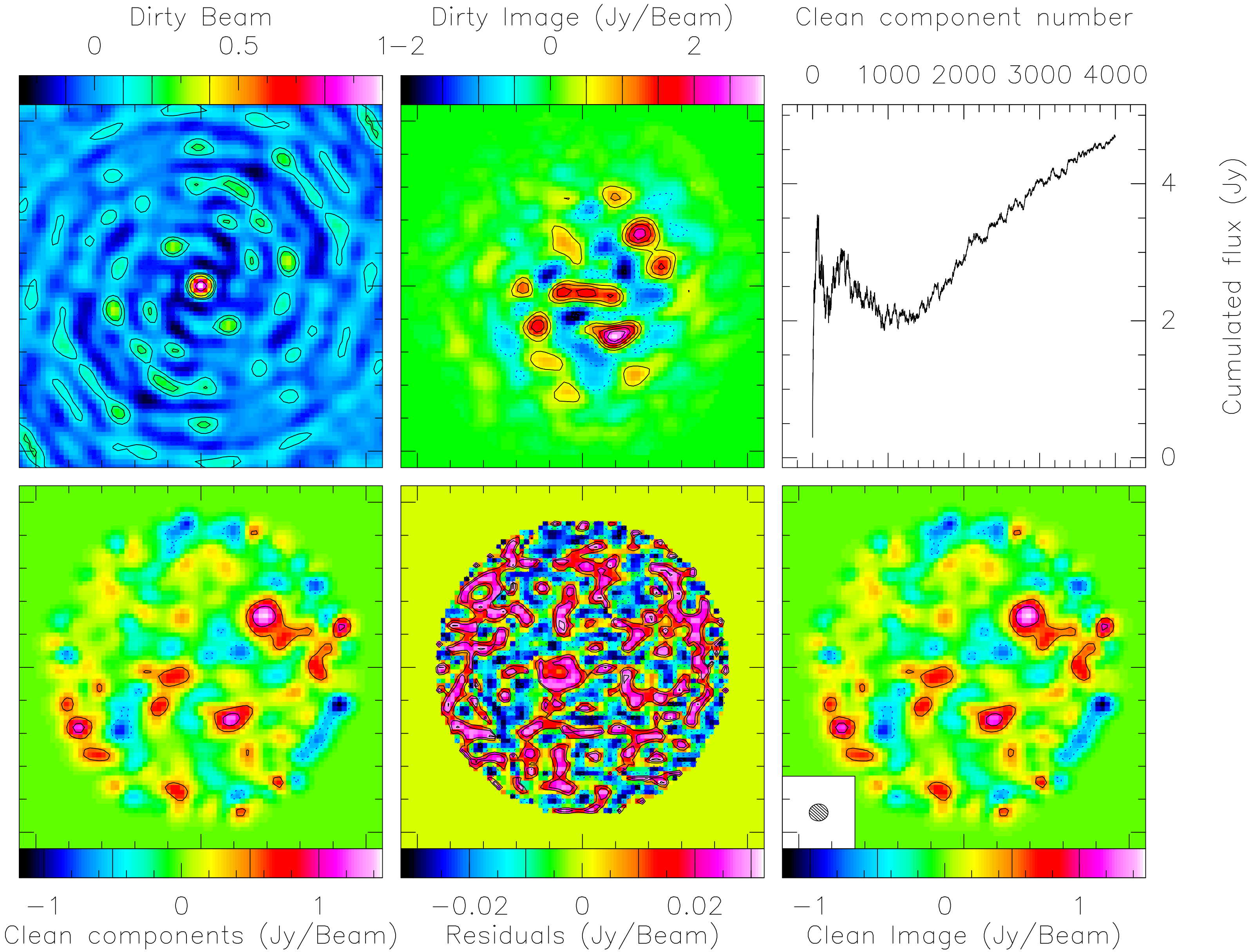
- Linear combination (optimal from signal-to-noise ratio point of view):
  - Signal:
    $$S(\alpha,\beta) = \frac{\sum_i \frac{B_i(\alpha,\beta)}{\sigma_i^2} I_i(\alpha,\beta)}{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}};$$
  - Noise:
    $$N(\alpha,\beta) = 1 \Big/ \sqrt{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}};$$
  - Signal-to-Noise Ratio: $\text{SNR}(\alpha,\beta) = \frac{S(\alpha,\beta)}{N(\alpha,\beta)}$.



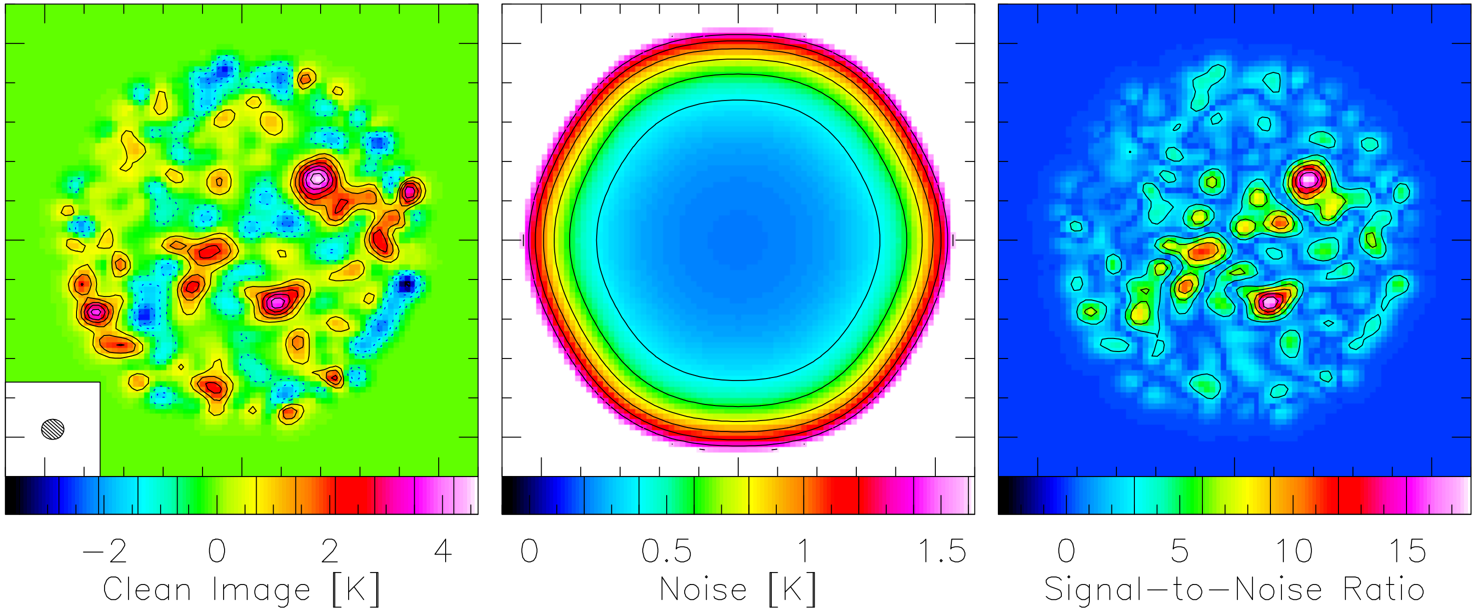
- Same as single field except:
  - The CLEAN components are searched on the SNR map;
  - The residual and SNR maps are iterated as:
    * $S_k(\alpha,\beta) = S_{k-1}(\alpha,\beta) - \frac{\sum_i \frac{B_i(\alpha,\beta)}{\sigma_i^2} \gamma \, I_k}{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}}$

      with $I_k = B_i \star \{B_i(\alpha_k,\beta_k).I_k.\delta(\alpha_k,\beta_k)\}$ and $\gamma \sim 0.2$;
    * $\mathrm{SNR}(\alpha,\beta) = \frac{S_k(\alpha,\beta)}{N(\alpha,\beta)}$.

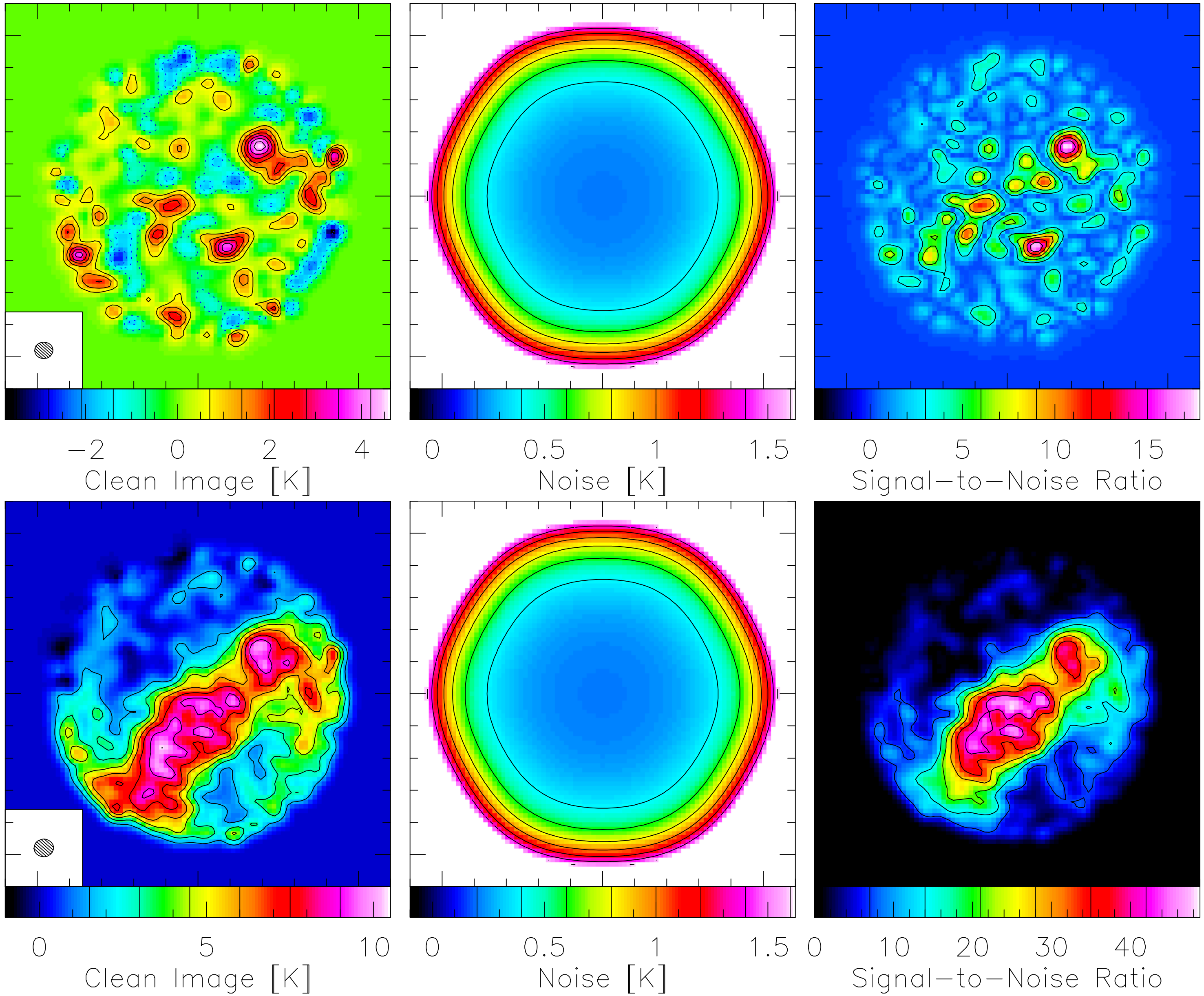
Deconvolution: II Practice



Results: Signal, Noise, and Signal-to-Noise Ratio



Comparison without and with short-spacings

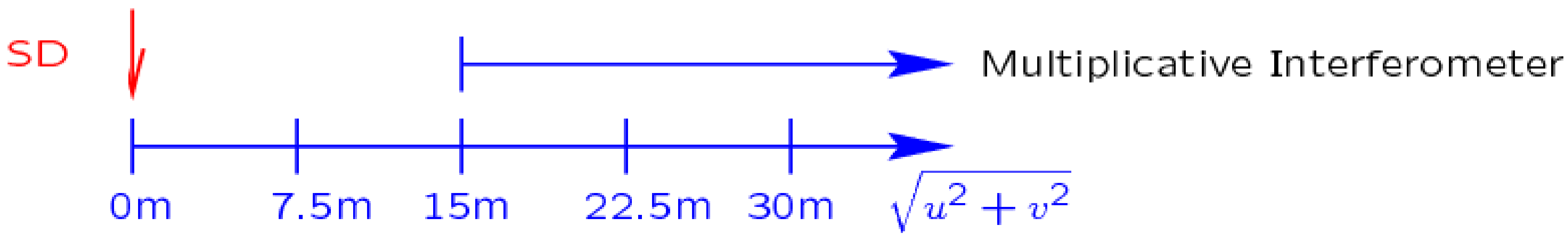


A radio-interferometer is a multiplicative interferometer

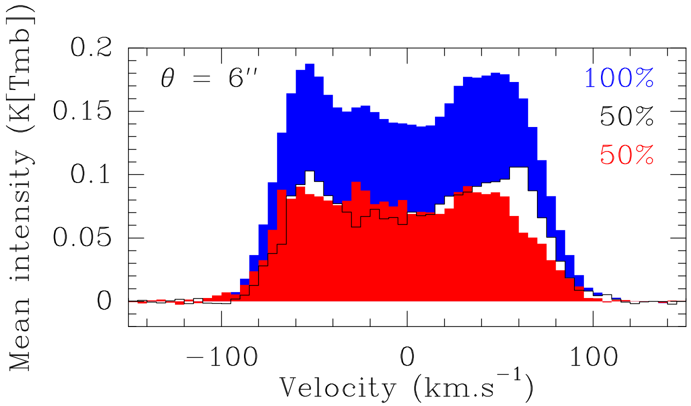
Avantage all offsets are irrelevant ⇒ Much easier;

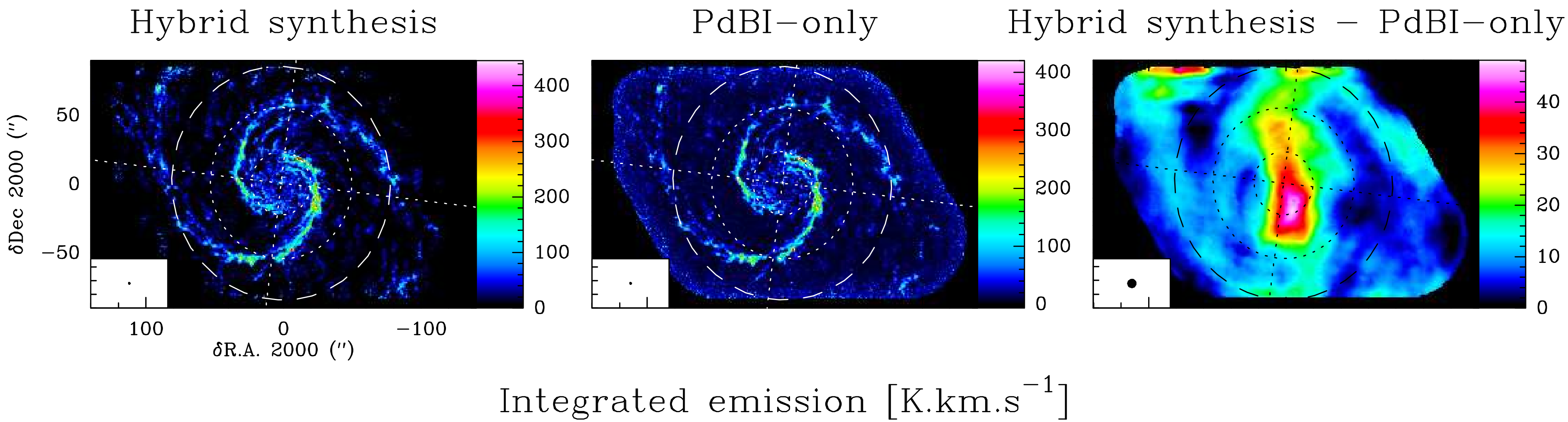
Inconvenient Radio interferometer = bandpass instrument;

⇒ Low spatial frequencies are filtered out.



Importance of Short-Spacings:
II.1 A CO diffuse thick disk in M51
$\sim$ 50% of the flux is resolved
at scales $\geq 36'' \sim 1.3$ kpc
(PAWS collaboration, Pety et al., 2013)





PdBI-only component

- **Bright** From 2 to 16 K with a median of 2.5 K.
- **Compact** It fills only $\sim$ 2% of the surface.

Filtered component

- **Faint** From 0.07 to 1.36 K with a median of 0.14 K.
- **Extended** It fills $\sim$ 30% of the surface.

Importance of Short-Spacings:
II.2 A CO diffuse thick disk in M51
A dense and diffuse components of very different vertical scale heights, which probably mix in the galactic plane.
(PAWS collaboration, Pety et al., 2013)

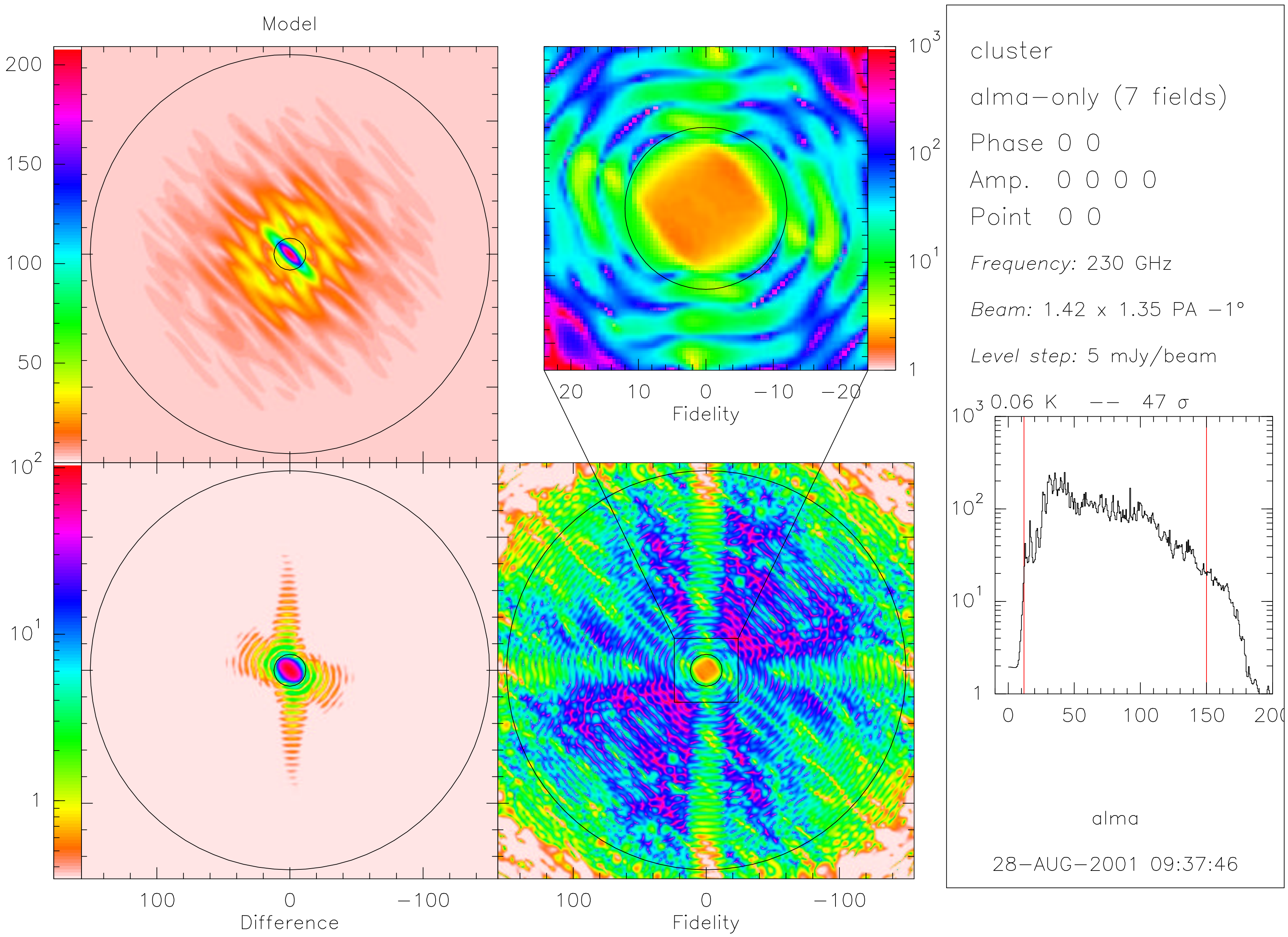
Relative linewidths

Fact The filtered component has a velocity dispersion at least twice as large as the compact component.

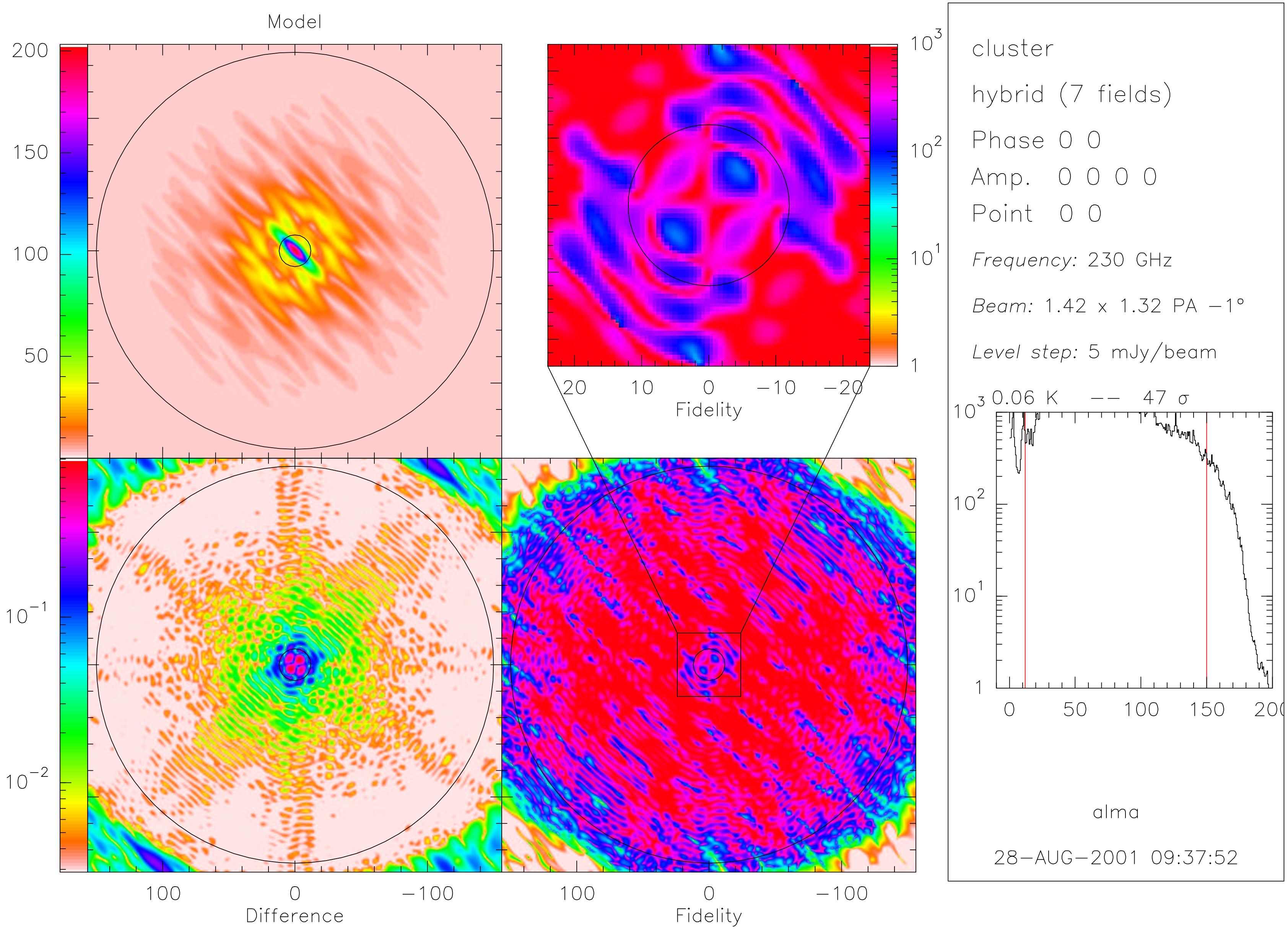
Interpretation (using Koyama & Ostriker 2009) The extended component has a Gaussian scale height ($\sim 200\,$pc) typically 5 times as large as the compact component one ($\sim 40\,$pc). The Galaxy scale height is 57 pc (Ferriere 2001, Cox 2005).

Consequence The extended component average density ($1 H_2\ cm^{-3}$) is one order of magnitude lower than the compact component one ($10 H_2\ cm^{-3}$). The Galaxy average density is $0.29 H_2\ cm^{-3}$ (Ferriere 2001, Cox 2005).

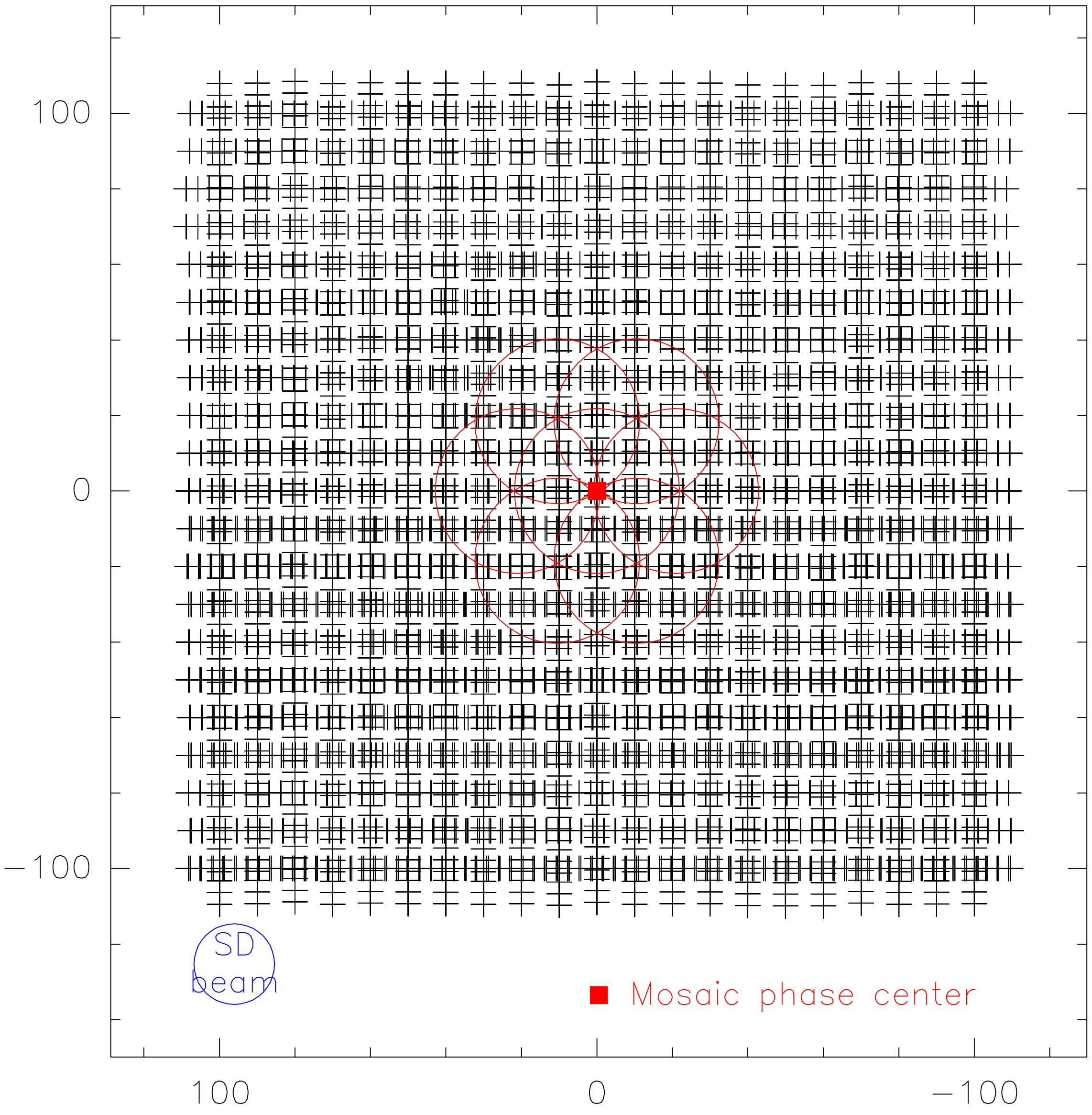
Importance of short-spacings: III.1 ALMA alone



Importance of short-spacings: III.2 ALMA + ACA + Short-spacings
Short-Spacings also help at large uv radius



Observing Setup: II. Single-Dish

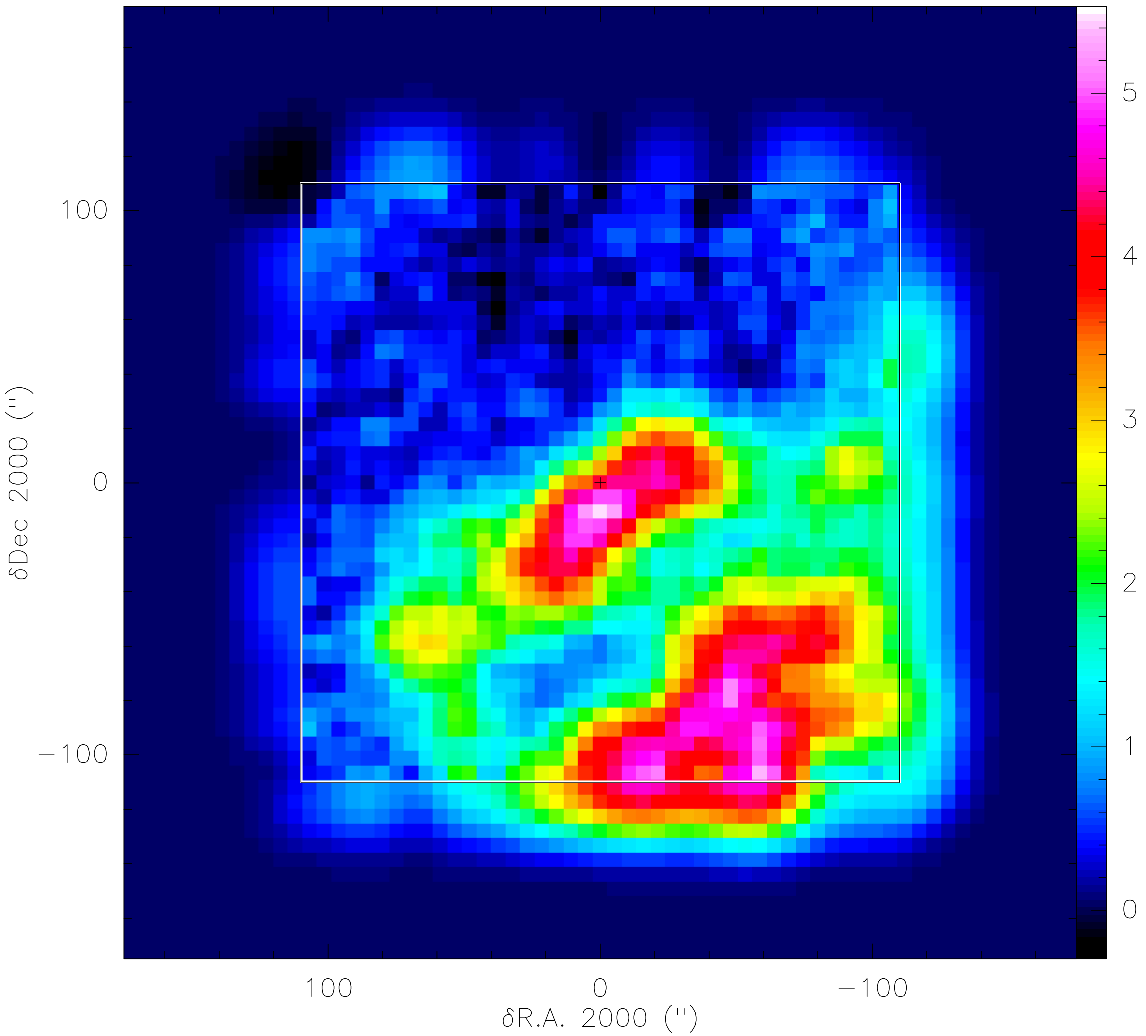


- On-The-Fly setup:
  - IRAM-30m resolution at 115 GHz: 22″.
  - Raster scanning in RA and then Dec
    - Speed: 3″/second;
    - Dump time: 1 second ⇒ 7 points/beam;
  - Separation between rasters: 8″ ⇒ Nyquist sampling.
- Calibration:
  - ON-OFF switching;
  - Hot/cold/atm measurement every 15 minutes;
  - Chopper wheel method;
  - Factor from T_A^* to T_{mb}: F_{eff}/B_{eff}

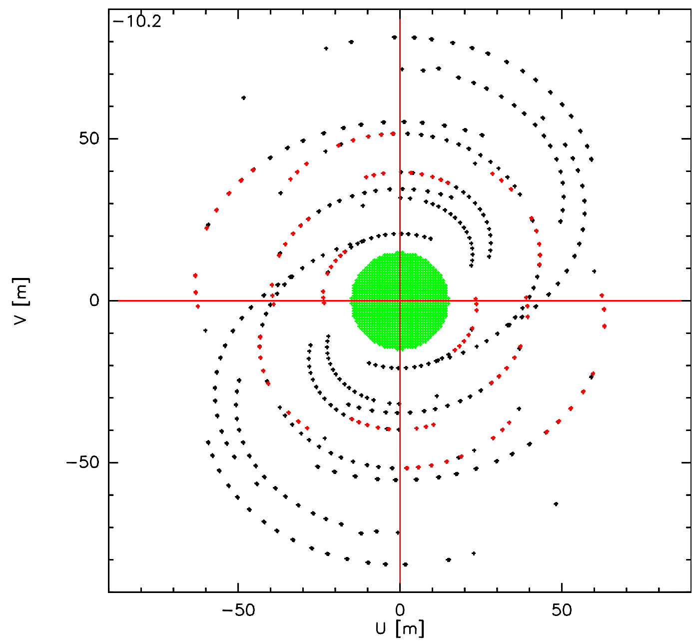
Short-Spacings Processing: I. Pseudo-visibilities

From $I_{\text{meas}} = B_{\text{30m}} \star I_{\text{source}} + N$

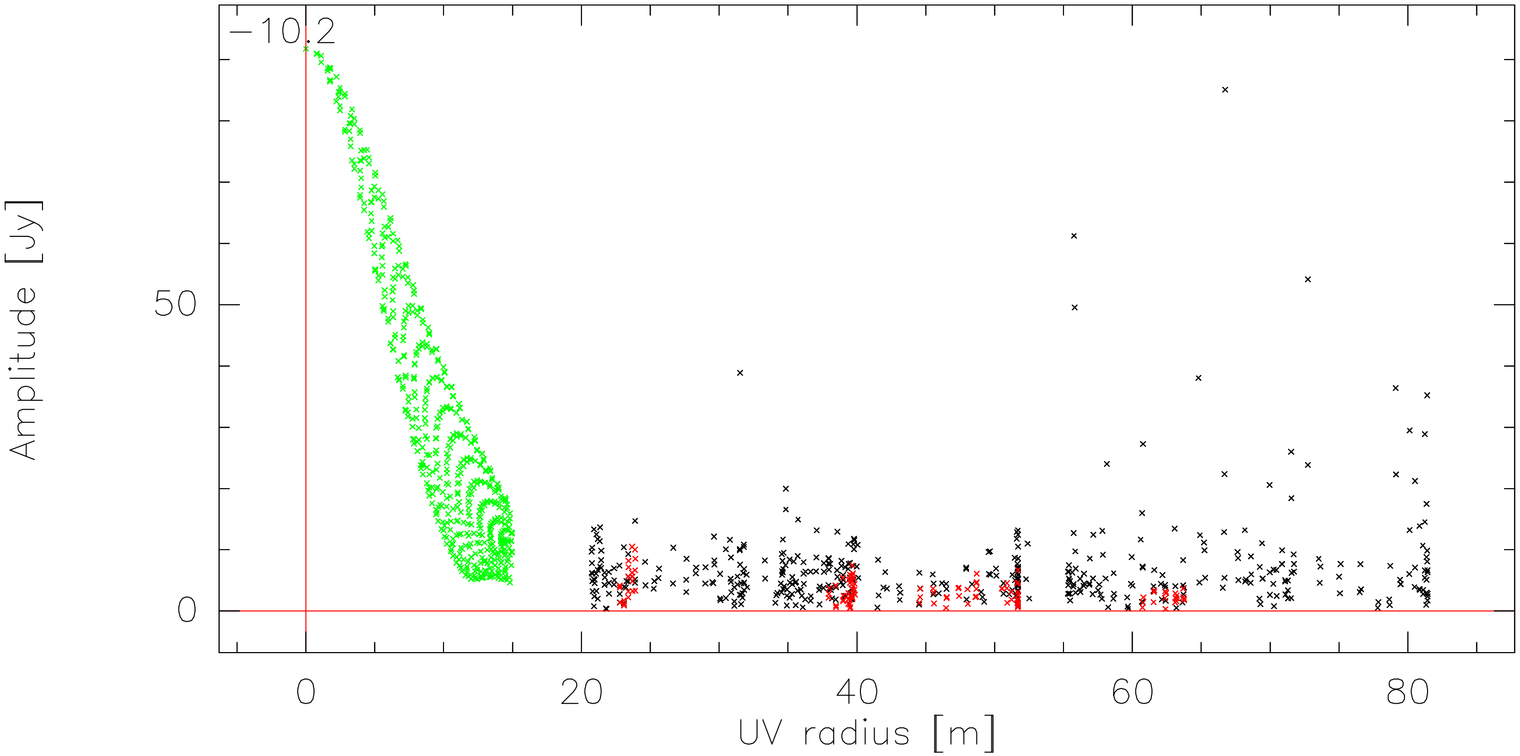
To $V_{\text{pseudo}}(u,v) = \textbf{FT}\left\{B^{15m}_{\text{primary}}.I_{\text{source}}\right\}(u,v) + N$



1. Gridding + Apodization;
2. Deconvolution of B_{30m} in uv plane;
3. Multiplication by B^{15m}_{primary} in image plane;
4. Sampling of pseudo-visibilities in uv plane.



Short-Spacings:
II.1 Merging (Amplitude cross calibration)

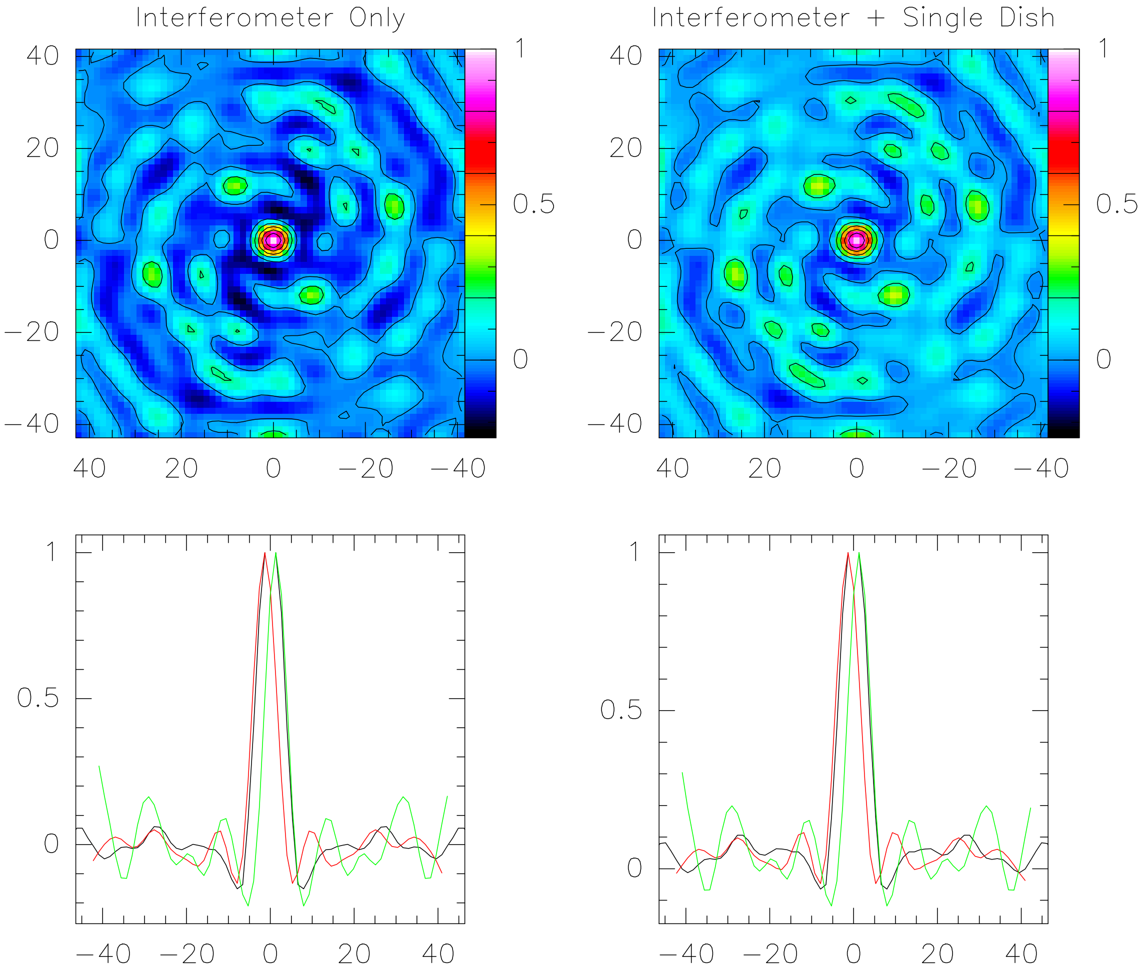


- Amplitude cross calibration:
  - Extremely important (wrong ⇒ distortion);
  - Difficult to achieve (no overlap).

  ⇒ Careful independent work needed.

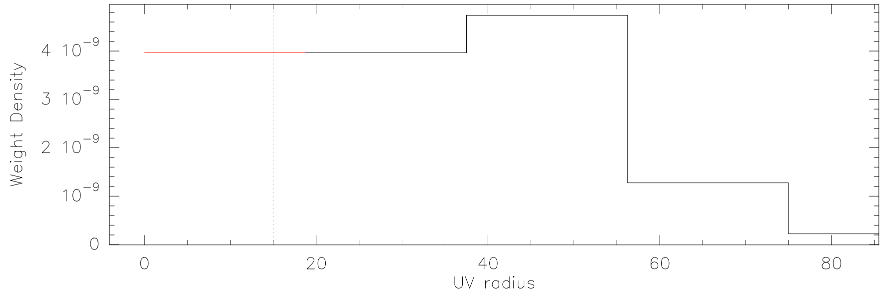
- Outlier points have extremely low weights ⇒ No need to clip them out.

Short-Spacings:
II.2 Merging (Weight density and dirty beam shape)



- Dirty beam = FFT of weight density;
- Single-dish total weight: A free parameter (as long as it is down-weighted...)

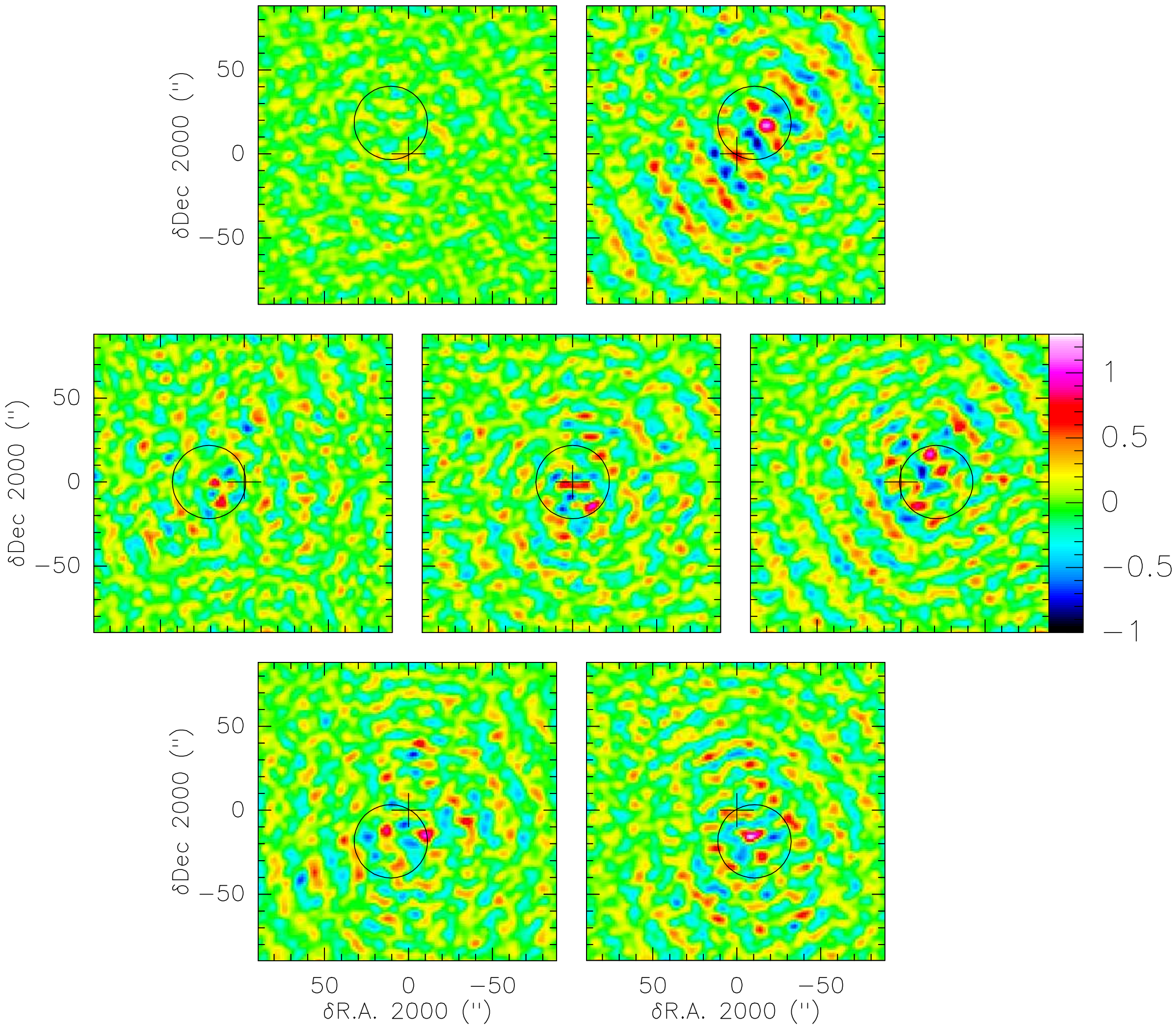
⇒ Single-dish total weight set to get a roughly Gaussian shape for the circularly averaged weight density.



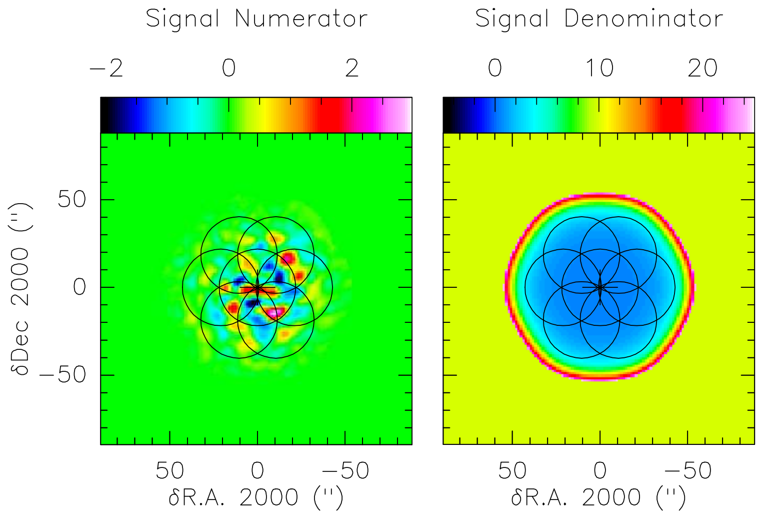
- Minimum visual change of the dirty beam;
- Dirty beam integral > 0 after addition of short-spacings.

Imaging: Dirty image and noise (Without short-spacings)

- One dirty image per field (directly the final image size): $I_i = D_i \star (B^{15m}_{\text{primary}}.I_{\text{source}}) + N_i$.

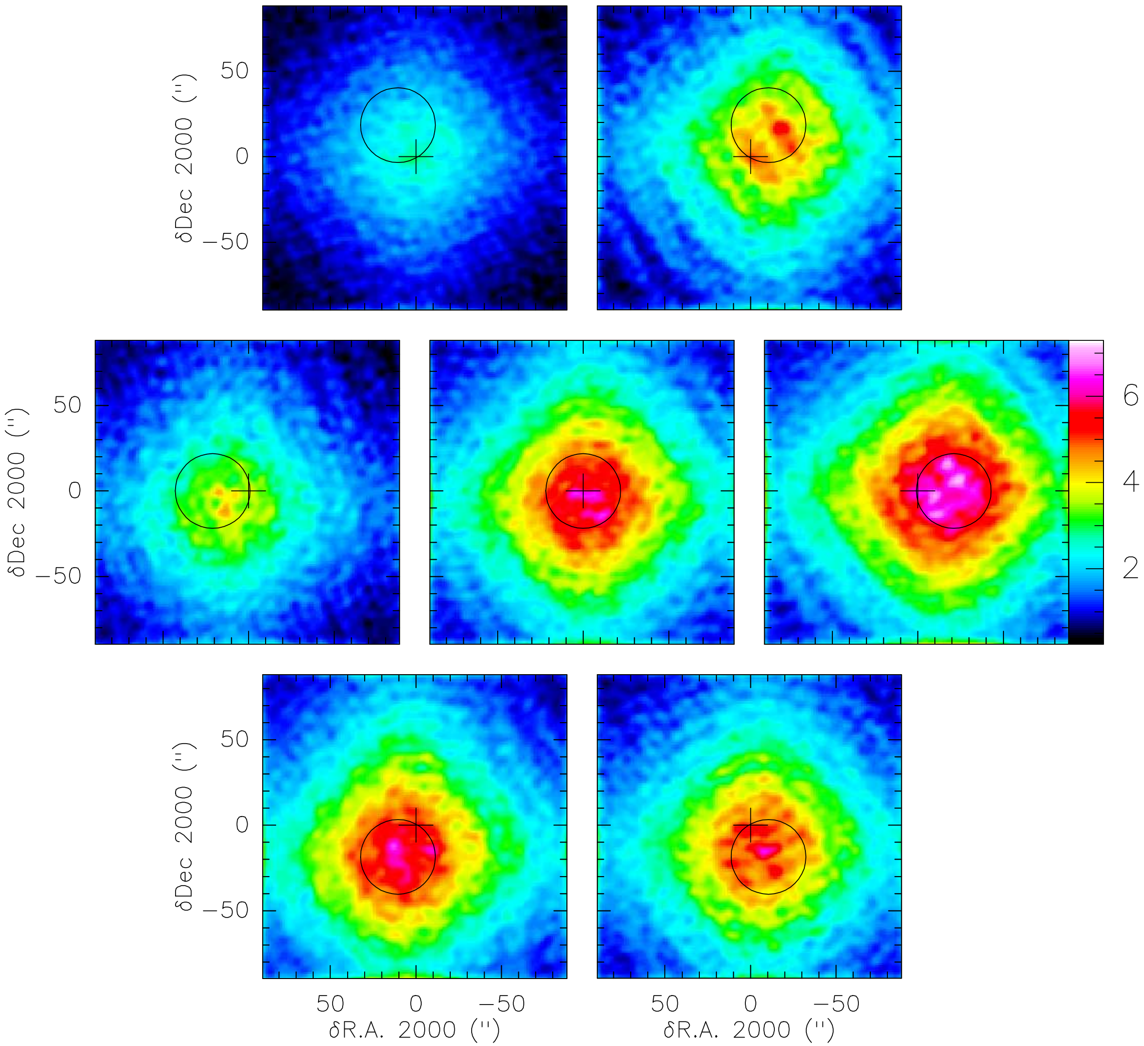


- Linear combination (optimal from signal-to-noise ratio point of view):
  - Signal:
  $$S(\alpha,\beta) = \frac{\sum_i \frac{B_i(\alpha,\beta)}{\sigma_i^2} I_i(\alpha,\beta)}{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}};$$
  - Noise:
  $$N(\alpha,\beta) = 1 \Big/ \sqrt{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}};$$
  - Signal-to-Noise Ratio: $\text{SNR}(\alpha,\beta) = \frac{S(\alpha,\beta)}{N(\alpha,\beta)}$.



Imaging: Dirty image and noise (With short-spacings)

- One dirty image per field (directly the final image size): $I_i = D_i \star (B^{15m}_{\text{primary}}.I_{\text{source}}) + N_i$.



- Linear combination (optimal from signal-to-noise ratio point of view):
  - Signal:
    $$S(\alpha,\beta) = \frac{\sum_i \frac{B_i(\alpha,\beta)}{\sigma_i^2} I_i(\alpha,\beta)}{\sum_i \frac{B_i^2(\alpha,\beta)}{\sigma_i^2}};$$
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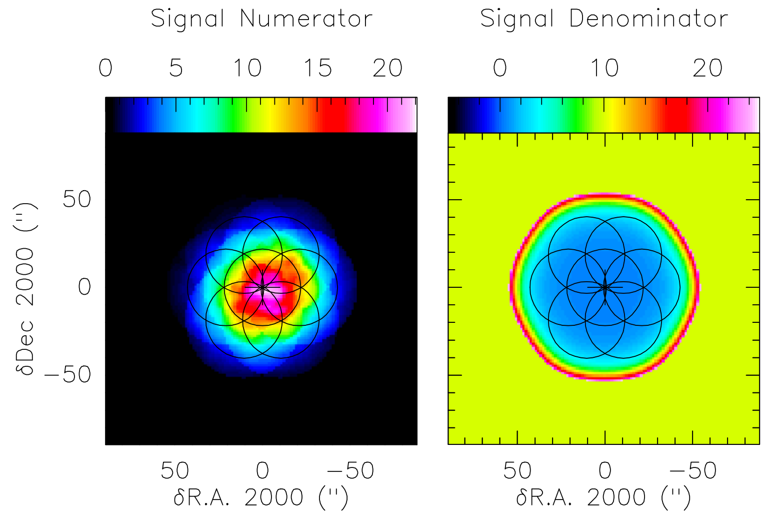
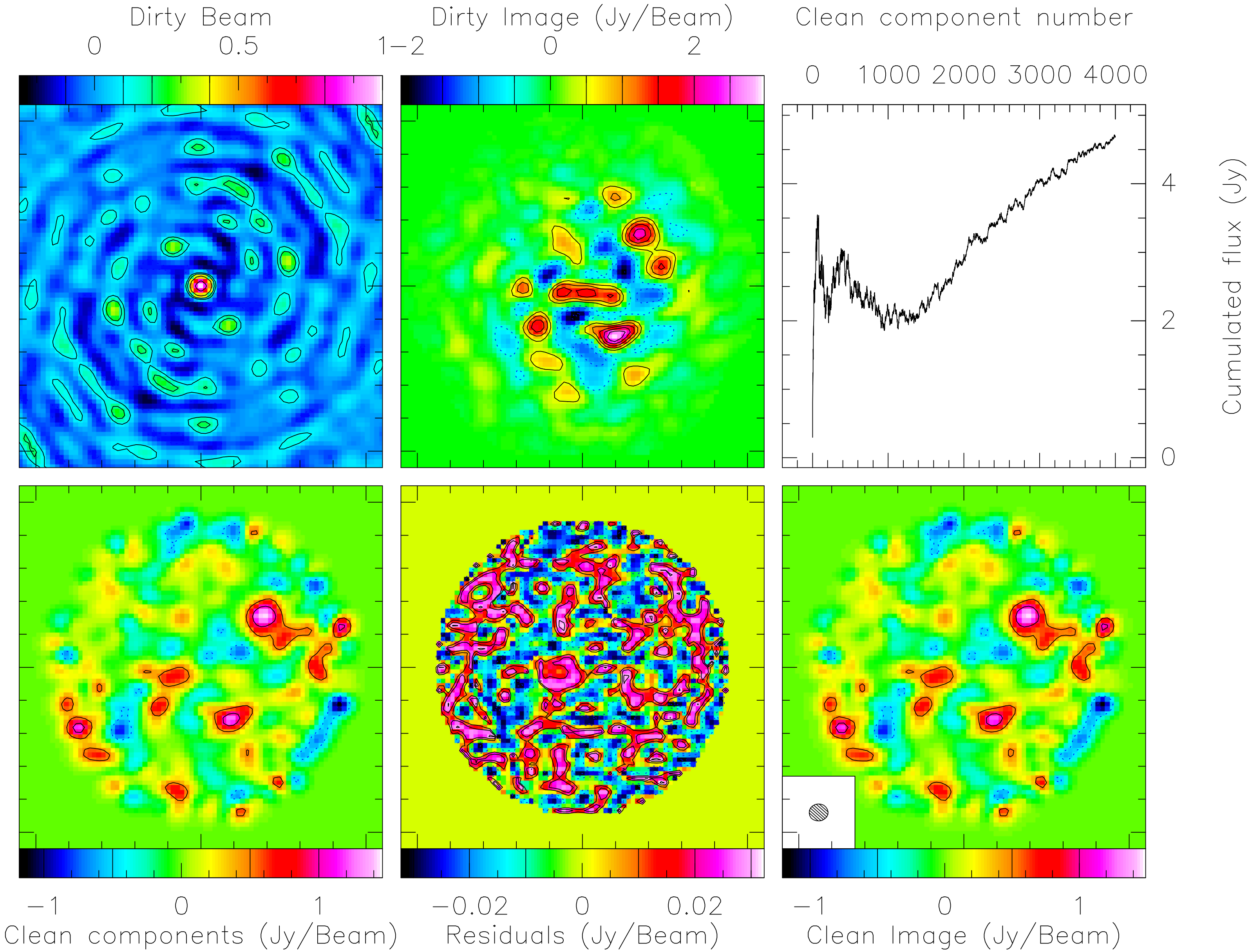
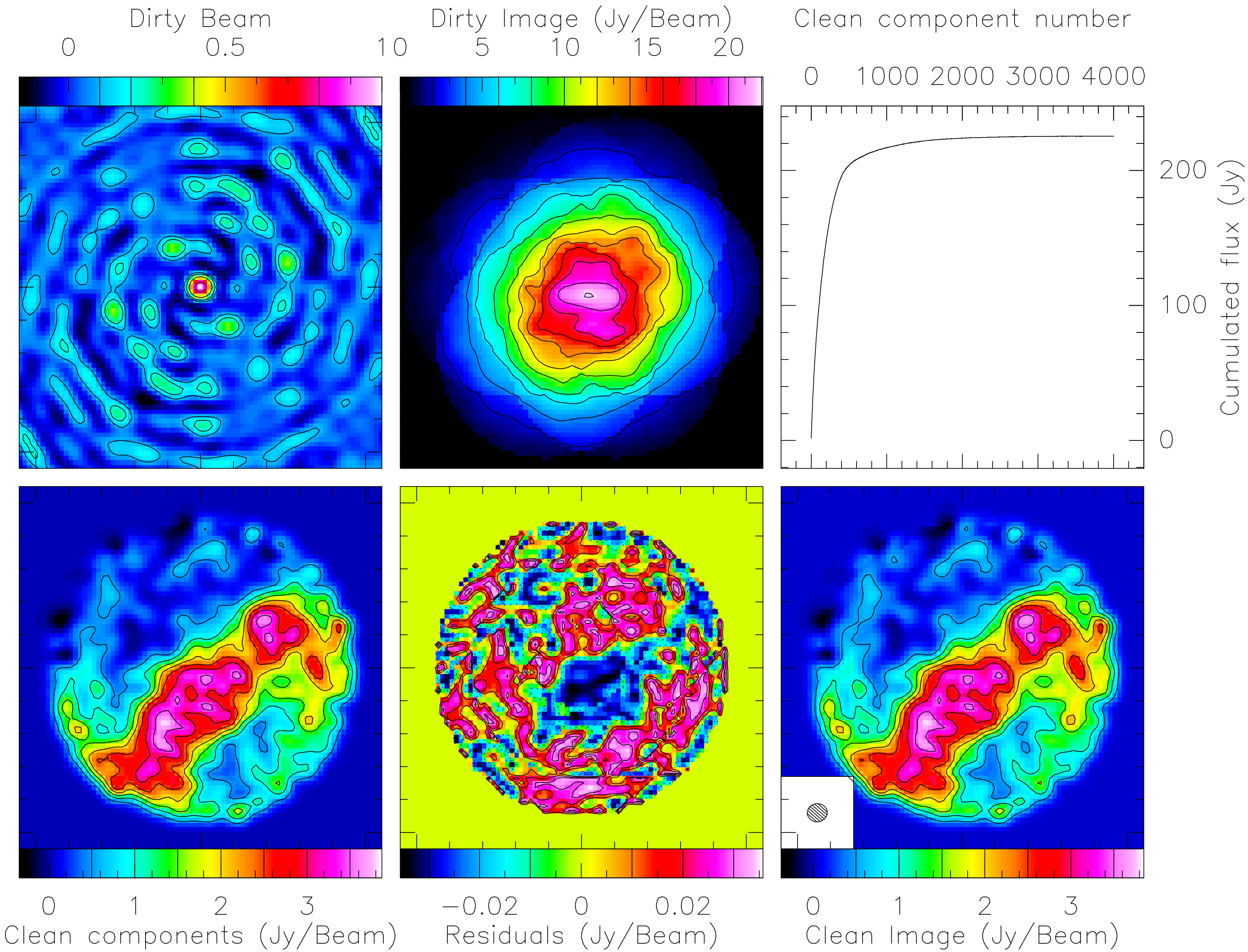


Deconvolution: II.1 Practice (Without short-spacings)



Deconvolution: II.2 Practice (With short-spacings)



FAQ

When observing/adding the short-spacings?

- **source size $<$ 1/3 primary beamwidth** Short-spacings are superfluous.
- **1/3 primary beamwidth $<$ source size $<$ 1/2 primary beamwidth** A single spectrum in the direction of the source is OK.
- **1/2 primary beamwidth $<$ source size** An OTF map is required.

Field of view PdBI field of view + PdBI half primary beam bandguard $\Rightarrow$ Double the field of view for a 7 field mosaic. But there is no need to integrate on empty sky...

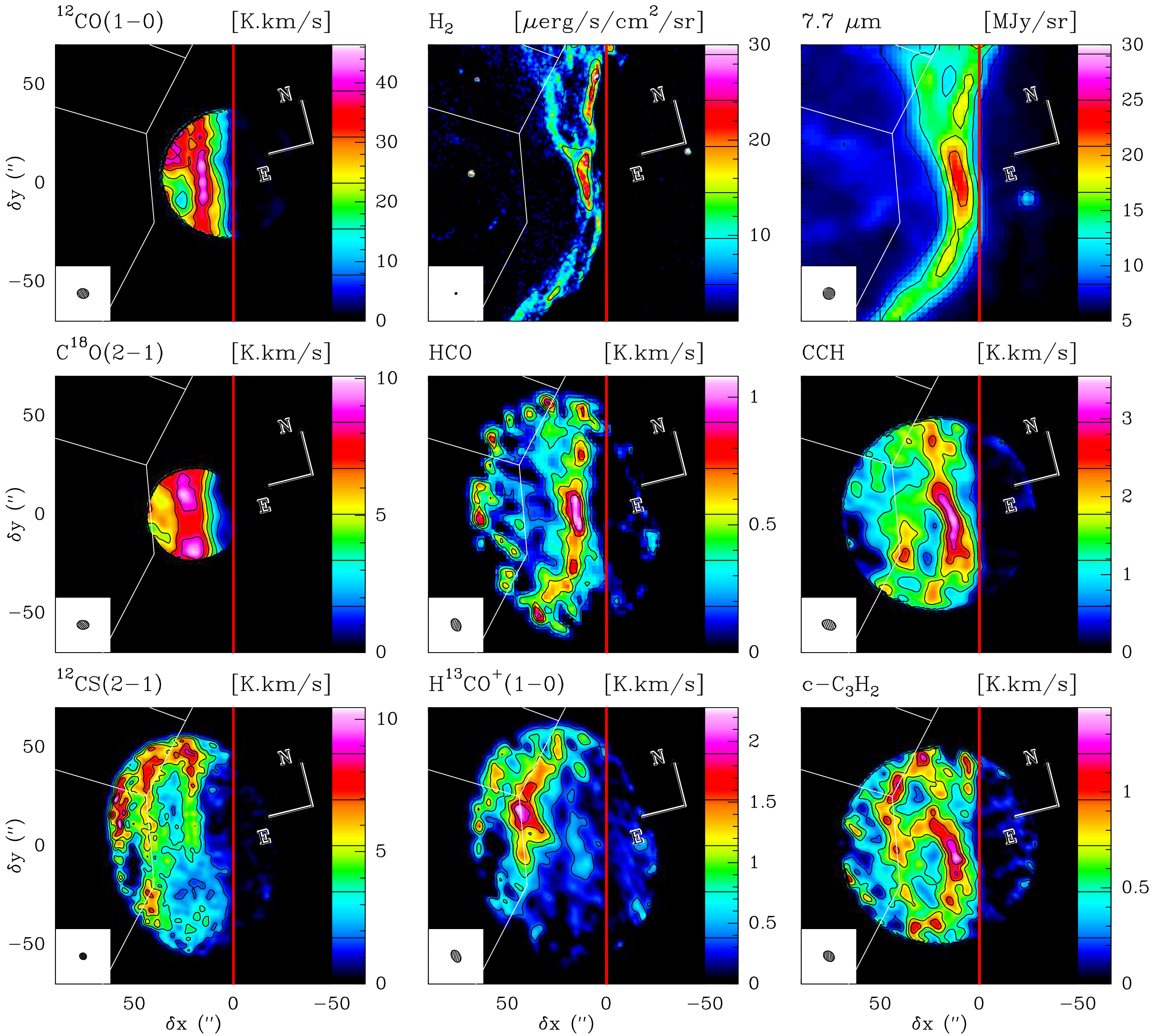
Single dish integration time Same time as the PdBI compact (D) configuration (assuming 6 antennas and similar receiver system at both observatories).

Needed data quality As good as possible (pay attention to data consistency, e.g., coordinate system, frequency tuning)... Don't spoil your interferometric data with crap single-dish data.

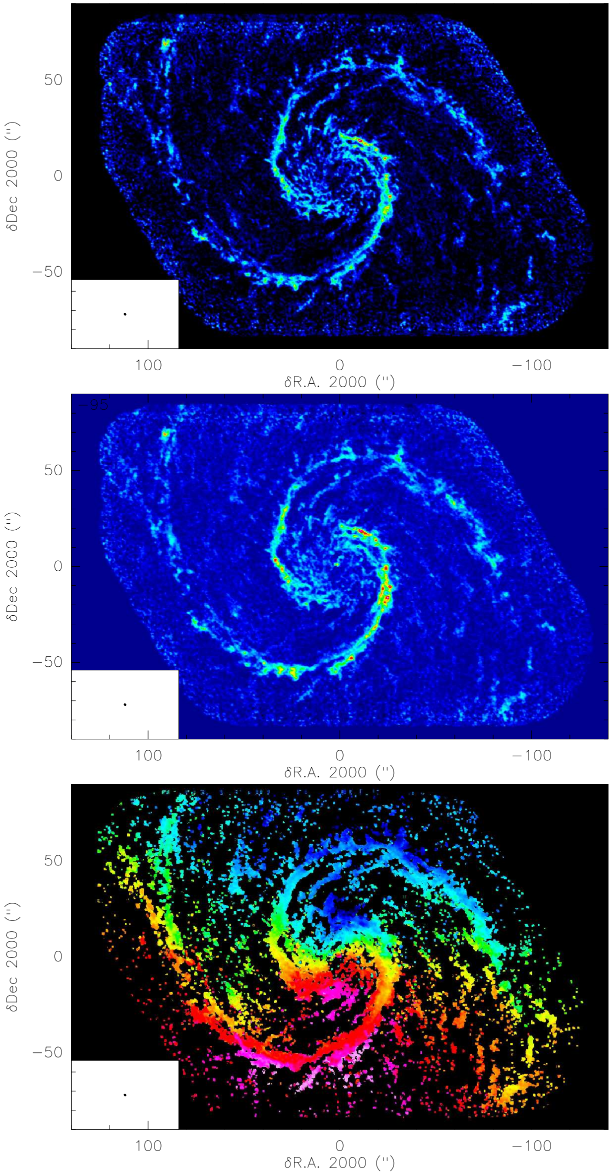
There is signal with PdBI but only noise at the 30m Your source may be a collection of point sources diluted in the 30m beam. This is the case where adding the short-spacings may just add noise.

Mosaicking: A standard observing mode

An example among many: The Horsehead PDR



Mosaicking: State-of-the-art with PdBI in 2010
I. PAWS (PdBI Arcsecond Whirlpool Survey, PI: E.Schinnerer)



Past:

- Revolution 1 (1997-2007): Mosaicking.
- Revolution 2 (2009-Today): Large programs.

Present:

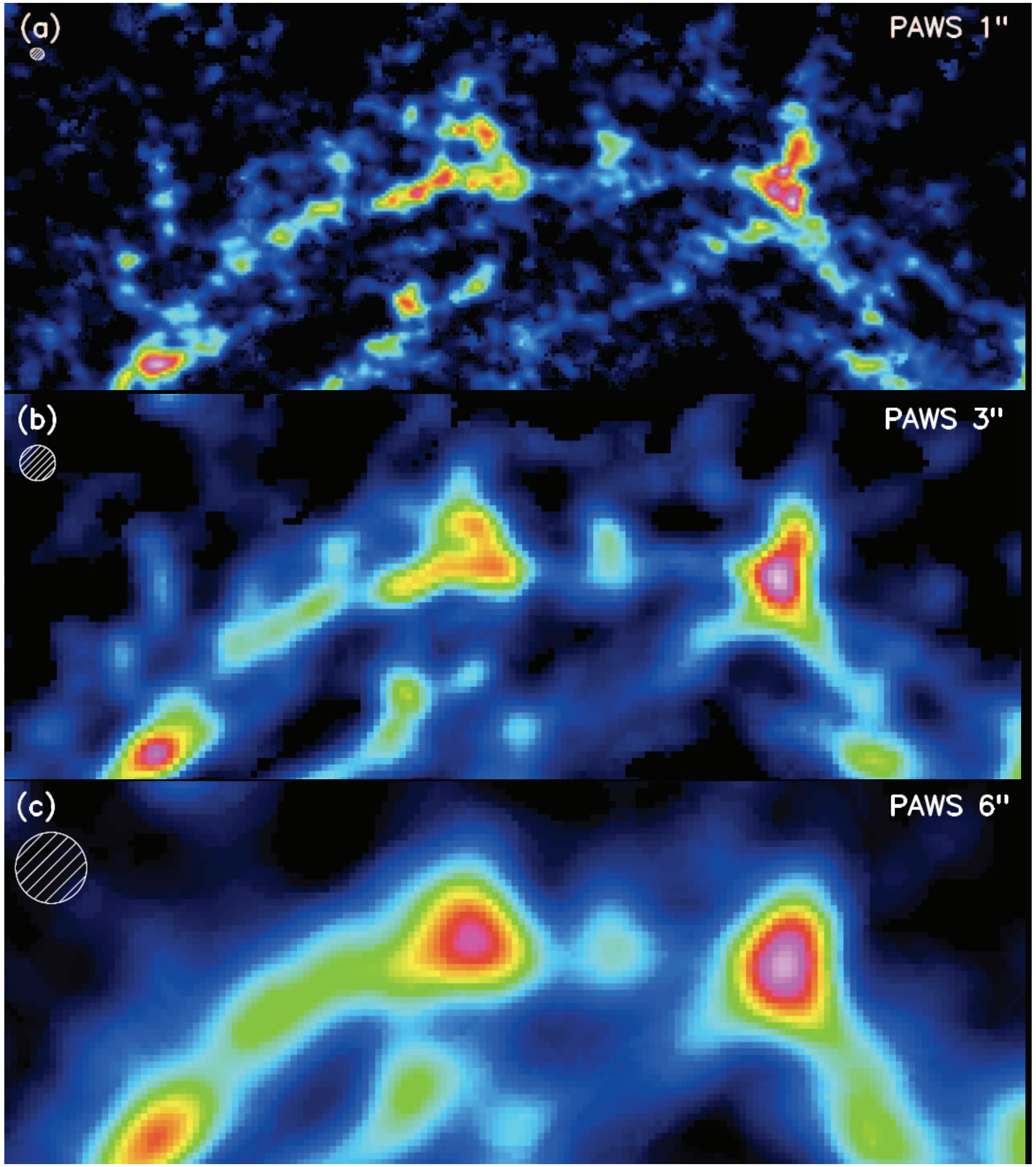
- Mosaic of 60 fields at 3 mm ⇒ Field of view: $3.5' \times 2.8'$.
- 8 hr in D, 15 hr in C, 43 hr in B and 60 hr in A ⇒ 454 000 visibilities × 1024 channels and a final resolution of $\sim 1''$.
- Imaging and deconvolution require images of 2 Mpixels (in fine: only 36 000 fully independant pixels). ⇒ 8 days and 14 hours to deconvolve 20 channels (320 000 components per channel).
- Mosaicking ∼ Raster mapping for a single-dish. ⇒ 8-9 seconds lost when moving from one field to the next one.

Future:

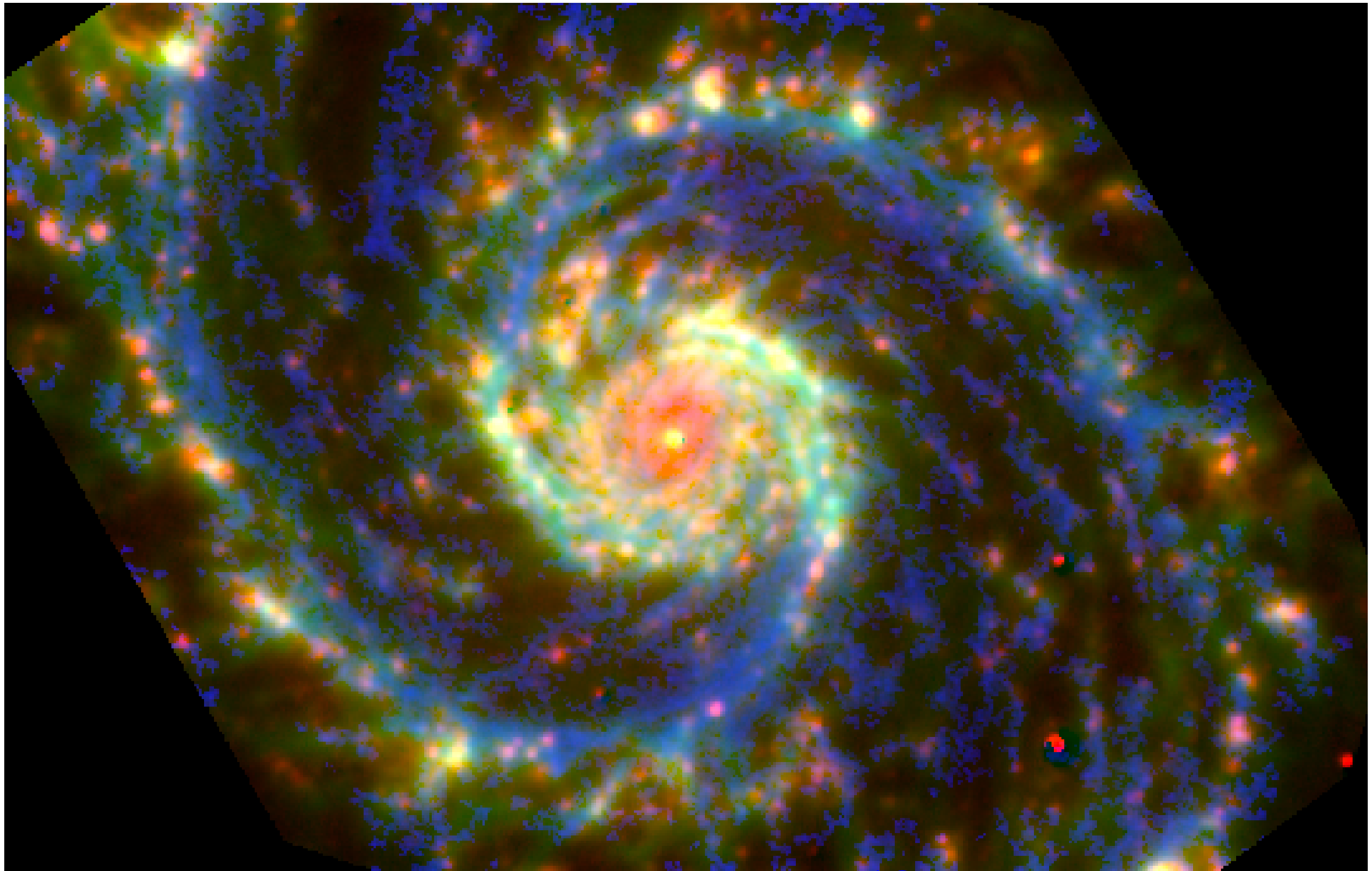
- Interferometric On-The-Fly.
  - New observing mode + new imaging algorithm.

Mosaicking: State-of-the-art with PdBI in 2010

II. Why/How HD TV changes your life



Mosaicking: State-of-the-art with PdBI in 2010
III. Multi-wavelength comparison
(Schinnerer et al. 2013, Meidt et al. 2013)



SINGS Hα Spitzer 8 μm ^{12}CO (J=1–0)

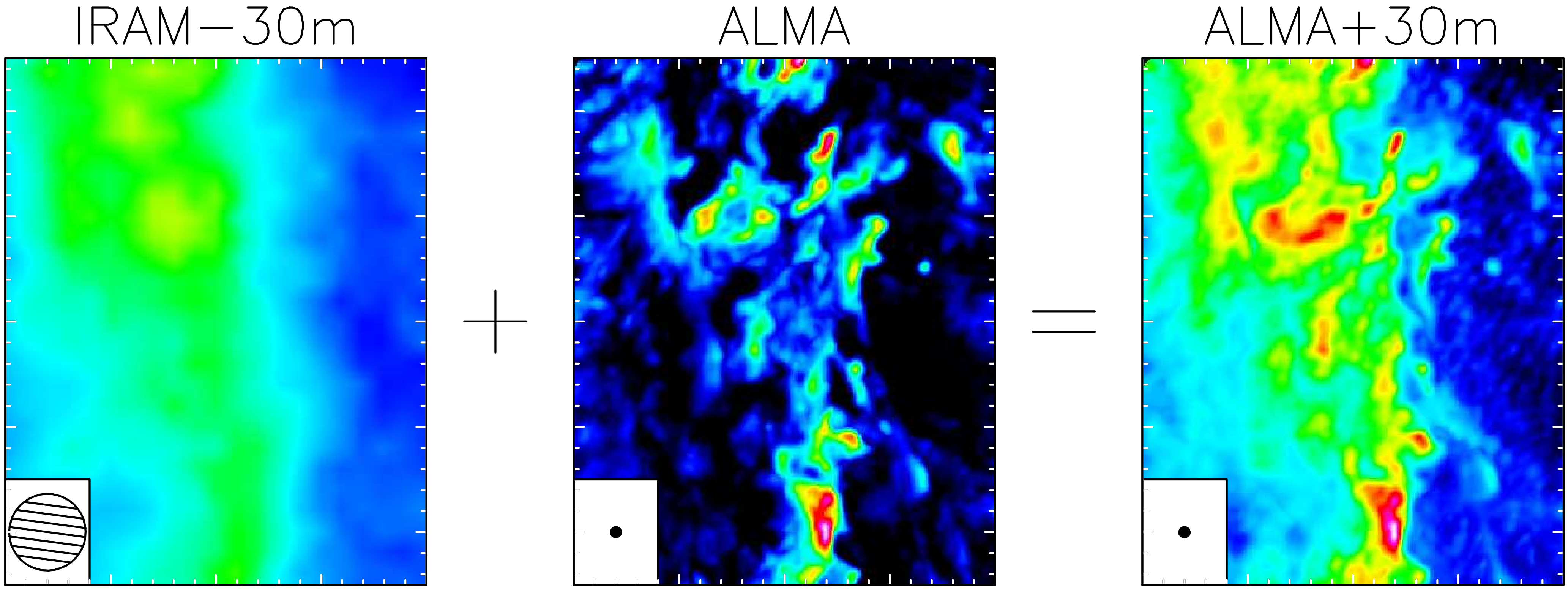
Molecular ring Coincident star formation

Spiral arm, inside spiral corotation Suppressed star formation.

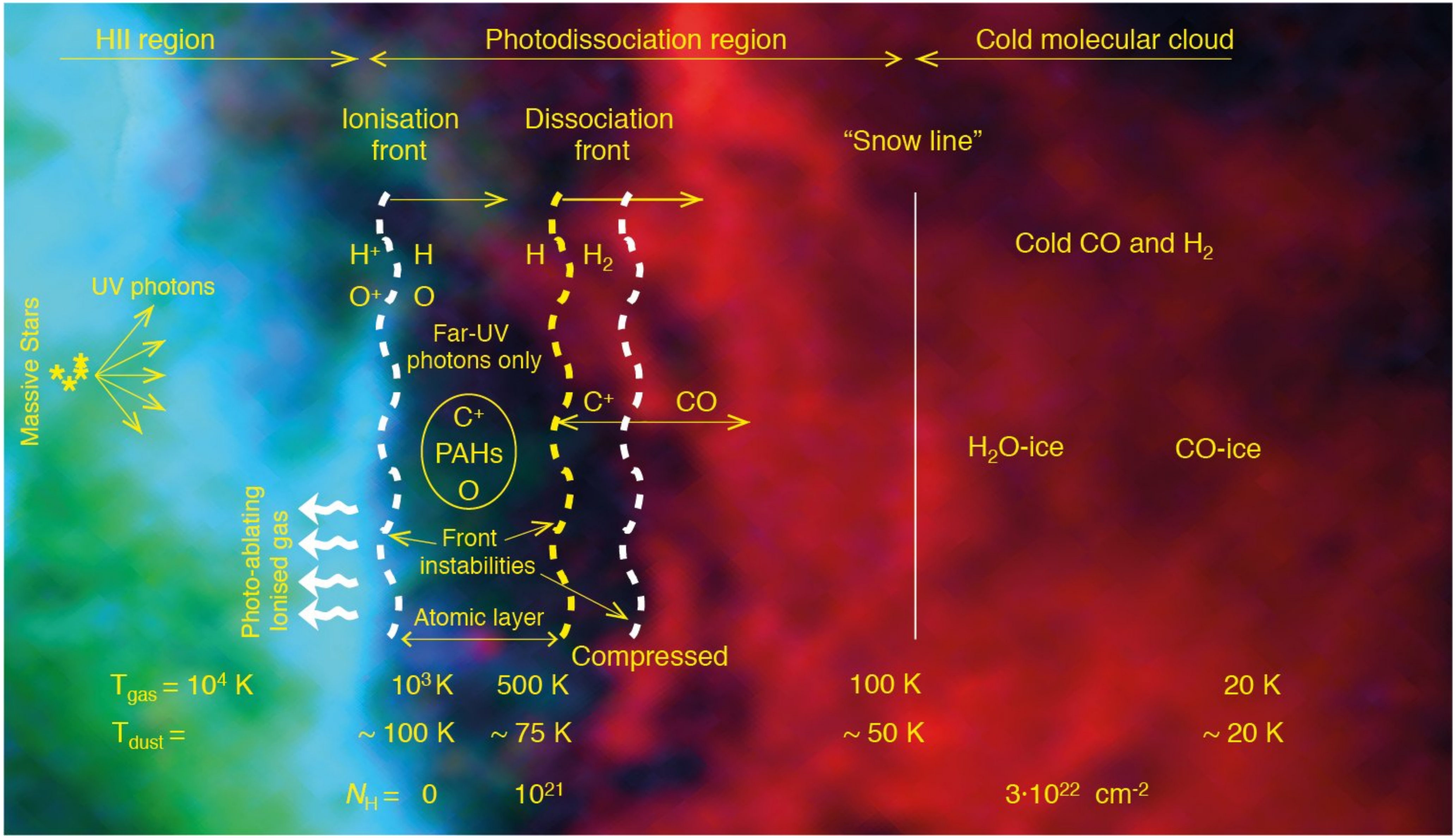
Spiral arm, outside spiral corotation Offset star formation.

Mosaicking: ALMA in 2014

Orion Bar PDR (Goicoechea et al. 2016)



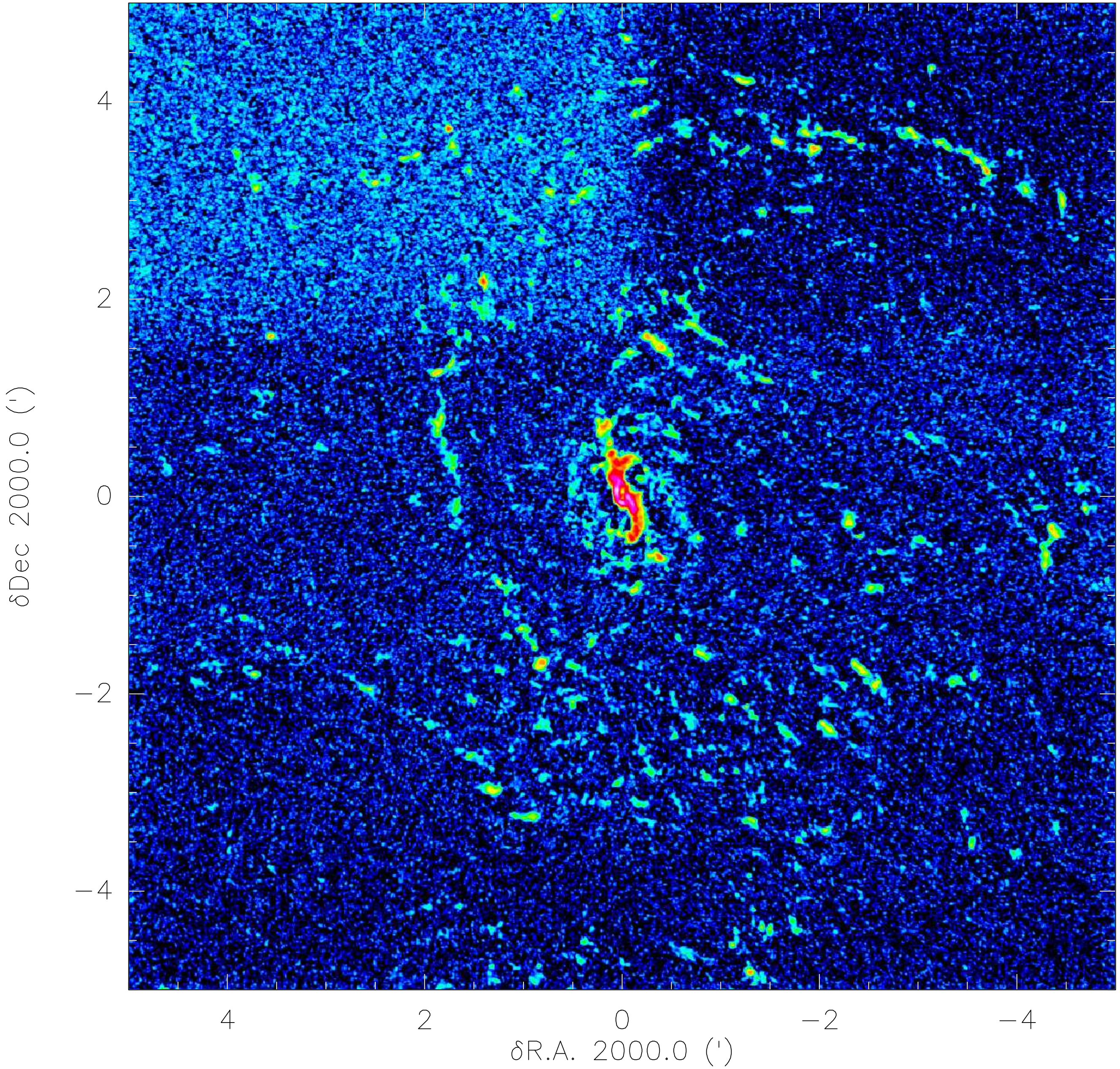
Mosaicking: ALMA in 2014
Orion Bar PDR (Goicoechea et al. 2016)



HCO^+ J=3-2 (ALMA+IRAM-30m), [Oi] 6,300 A (VLT/MUSE), [Sii] 6,731 A (VLT/MUSE)

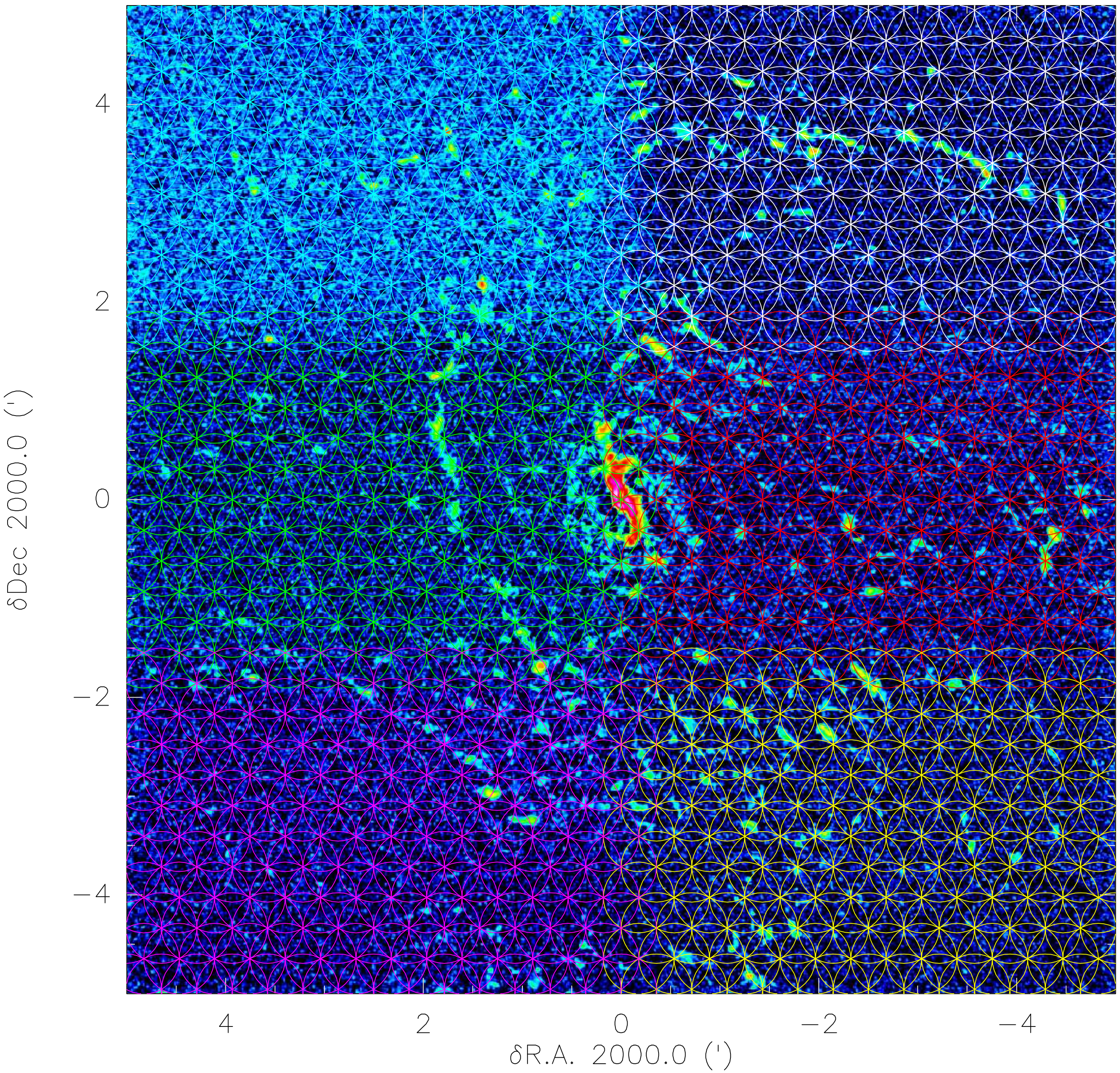
Mosaicking: State-of-the-art with NOEMA in 2016

$10' \times 10'$ on IC 342 (PI: A.Schruba)



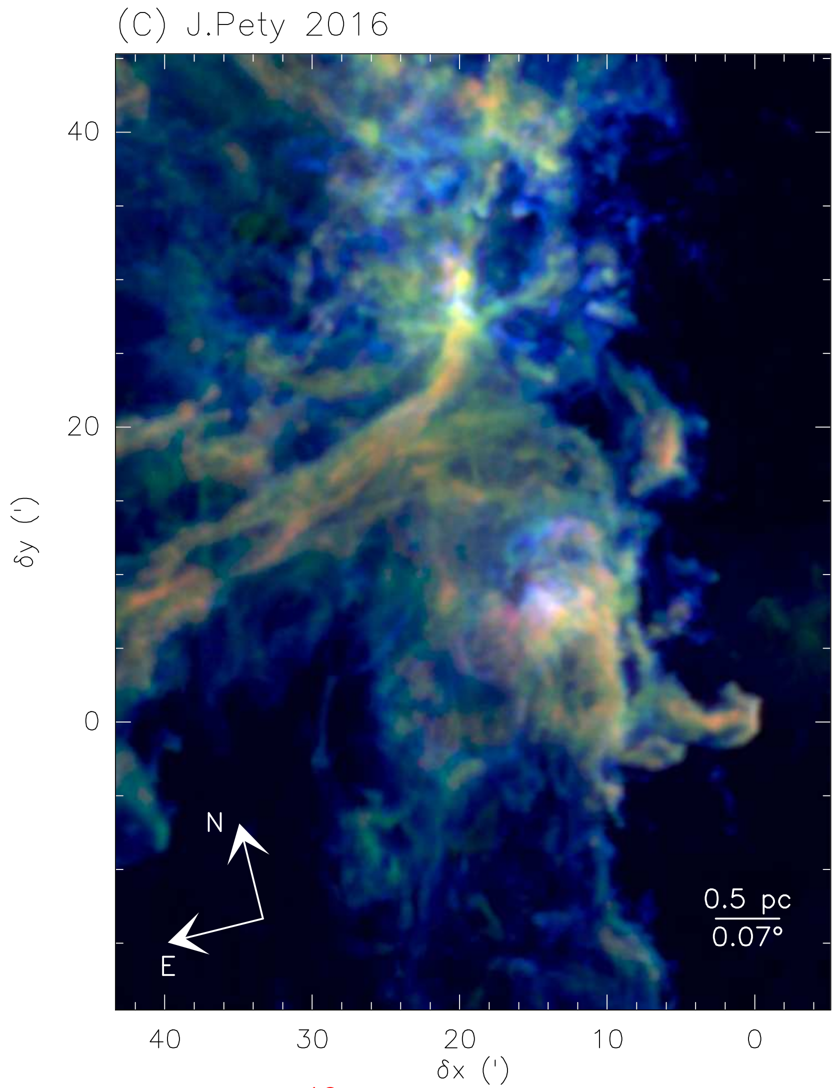
Mosaicking: State-of-the-art with NOEMA in 2016

941 fields in 6 tracks

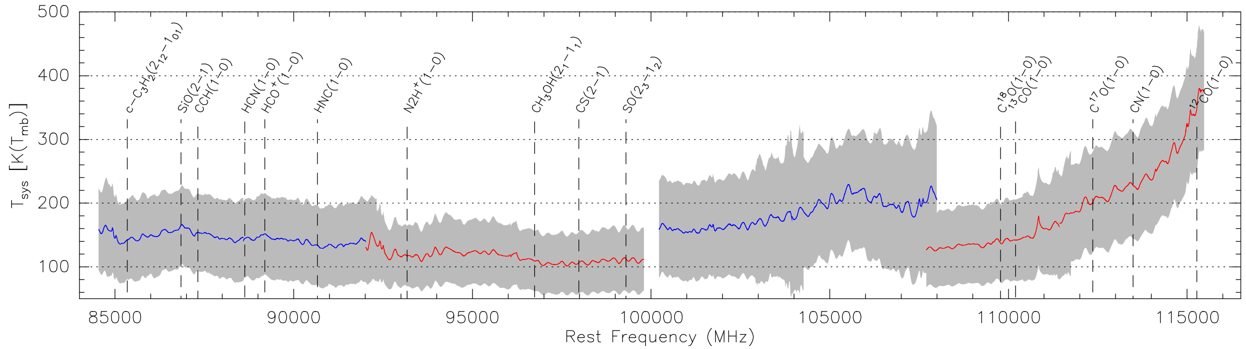


Next step: Mapping wide fields over wide bandwidths, e.g., Orion B

PI: J.Pety, J.Orkisz, E.Bron, V.Guzman et al.



$C^{18}O$ (J=1–0),
^{13}CO (J=1–0),
^{12}CO (J=1–0)



Integration time 133 hours.

Field of view 5 × 7 pc at a distance of 400 pc.

Spatial resolution 50 mpc or 10^5 AU ⇒ images of 315 × 420 pixels.

Bandwidth 32 GHz from 84 to 116 GHz.

Spectral resolution 200 kHz resolution.

Number of channels ⇒160 000 channels, *i.e.*, at 24 images per seconds, it makes a movies of 1h50!

Field of view × channels 144 000 channel x square degree (*i.e.*, the equivalent of twice of the sky in 5 days!).

Median noise level 0.1 to 0.5 K ($T_{\rm mb}$).

A sea of noise Clear signal detected in ∼ 800 channels, or 0.5% of the data (a video of about 30 seconds).

Data size 900 GB of raw data.