New joint gridding and restoration method for SPIRE FTS data cube estimation

Hacheme Ayasso

Alain Abergel
Emilie Habart
Karin Dassas
Thomas Rodet
Melanie Koehler
Jeronimo Bernard-Salas

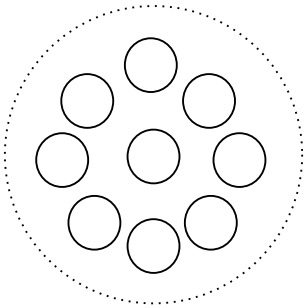
Institut d'Astrophysique Spatiale (UMR8617 CNRS-UNIV PARIS SUD 11)
Centre universitaire d'Orsay, Bat 120 -121, 91405 ORSAY CEDEX

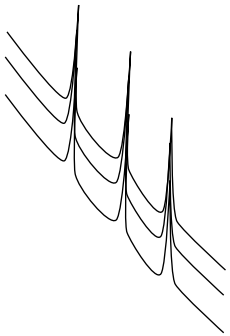
Journées SF2A, Nice , 05/06/2012

Context

Spectral cube reconstruction

- Herschel - SPIRE: Fourier Transform Spectrometer (FTS)
- Two bands: SSW $\in [194, 313]\mu m$, SLW $\in [303, 671]\mu m$
- Three observation modes: Sparse, Intermediate, Full

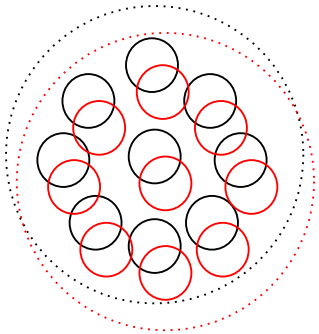


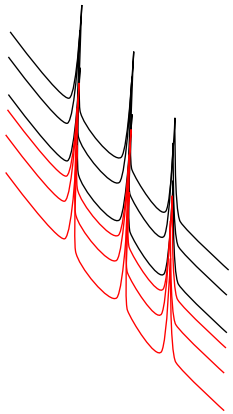


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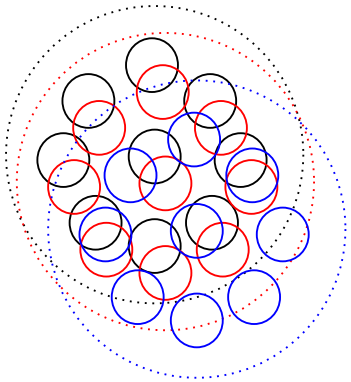


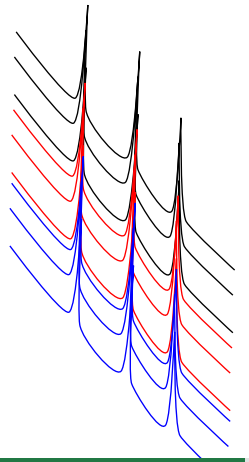


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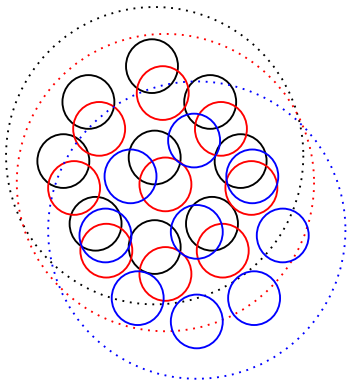


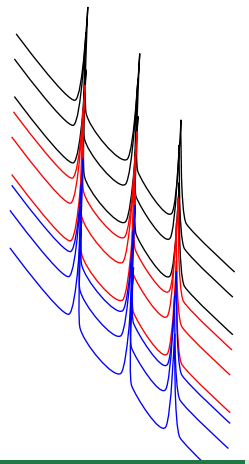


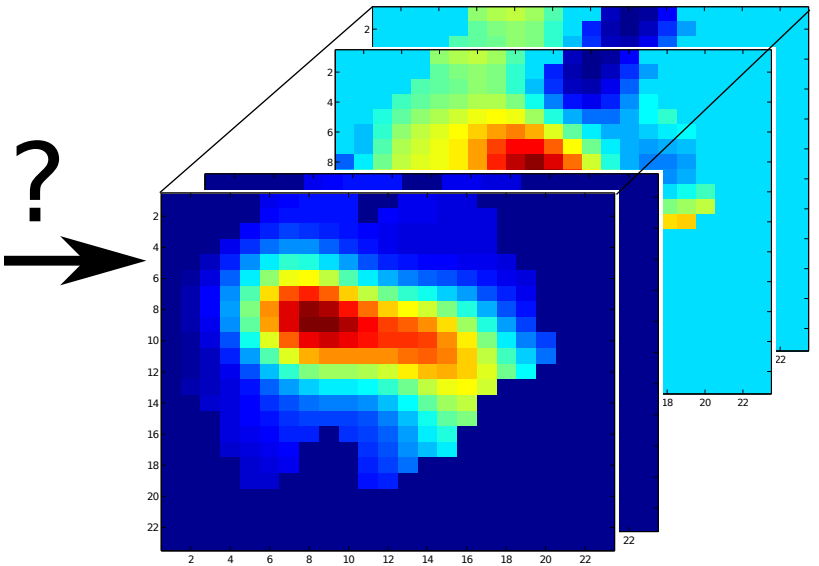
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Objectives

Data Model

$$\mathbf{y} = \mathbf{F}\mathbf{x}$$

- **y** : a collection of sky observations (data).
- **x** : unknown sky.
- **F** : system transfer function (instrument/forward Model).

Objective

1. Super-resolution: obtain **x** with a higher spatial resolution than the nominal resolution of the detector.
2. **BUT** calculating **x** given **y** & **F** $\rightarrow$ An ill-posed inverse problem (i.e. No unique stable solution).

Bayesian approach

use **instrument model** and the **prior information** to have a better **Cube estimation**.



Outline

1 Objectives

2 Instrument Model

3 Gridding methods (HIPE)

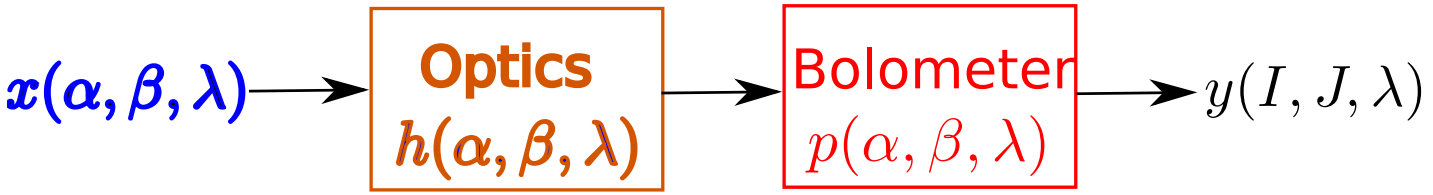
4 New Bayesian approach

5 Results

6 Conclusions

Instrument Model

- Optics: Mirror, Feedhorns, Filters, ...
- Pointing (Bolometers): scan process $\rightarrow$ only some part of the sky generates the data (Spatial discretization).
- Electronics: Electronic filters, ...



$$y(I,J,\lambda) = \iint_{\mathcal{B}} p(\alpha' - \alpha_I, \beta' - \beta_J, \lambda) \iint_{\mathbb{R}^2} h(\alpha,\beta,\lambda) x(\alpha' - \alpha, \beta' - \beta, \lambda) d\alpha d\beta d\alpha' d\beta'$$



Gridding methods (HIPE)

Gridding method

- Rearrange the data to sky pixels using a pointing model.

$$\hat{\mathbf{x}} = \mathbf{P}^t \mathbf{y}$$

- different pointing models $\rightarrow$ different methods

Limitations

- Reduced spatial resolution.
- Spectra contamination: Gaussian beam $h(\alpha, \beta, \lambda) = A \exp\left(-\frac{\alpha^2+\beta^2}{2c\lambda^2}\right)$
  - Point source $x(\alpha, \beta, \lambda) = \delta(\alpha, \beta) f(\lambda)$:

$$y(I, J, \lambda) = A f(\lambda) \delta(\alpha_I, \beta_J)$$

  - Extended source $x(\alpha, \beta, \lambda) = \mathbb{1}(\alpha, \beta) f(\lambda)$

$$y(I, J, \lambda) = 2\pi A c \lambda^2 f(\lambda) \delta(\alpha_I, \beta_J)$$



Bayesian approach

Bayes' rule:

$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{y})}$$

- $p(\mathbf{y}|\mathbf{x})$: Likelihood (instrument and error models),
- $p(\mathbf{x})$: Sky prior (Smoothness: slow variation, Smooth + point sources),
- $p(\mathbf{y})$: Evidence (Normalising factor).

Estimation

- MAP: $\hat{\mathbf{x}} = \arg\max p(\mathbf{x}|\mathbf{y})$
- PM : $\hat{\mathbf{x}} = E\{\mathbf{x}\}_{p(\mathbf{x}|\mathbf{y})}$



Ingredients

Likelihood

$$\mathbf{y} = \mathbf{F}\mathbf{x} + \epsilon$$

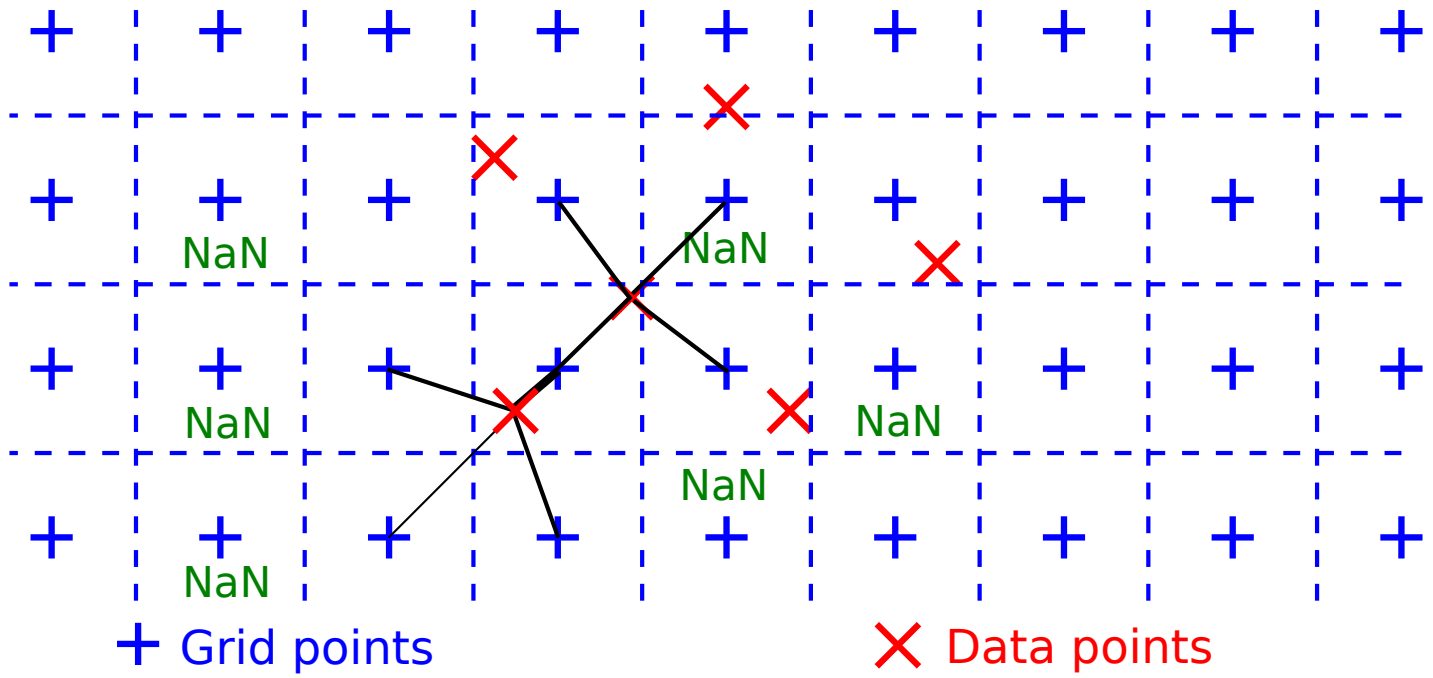
- White Gaussian noise $\rightarrow p(\mathbf{y}|\mathbf{x}) \sim \mathcal{N}(\mathbf{F}\mathbf{x}, \rho_n \mathbf{I})$
- $\mathbf{F} = \mathbf{P}\mathbf{H}$, $\mathbf{P}$ (bilinear interpolation), $\mathbf{H}$ (PSF : Lethbridge)
- ρ_n: noise variance unknown $\rightarrow$ joint estimation

Prior

$$p(\mathbf{x}|\rho_s) \propto \exp\left(-\frac{\rho_s}{2}\left[||D_\alpha \mathbf{x}||^2 + ||D_\beta \mathbf{x}||^2\right]\right)$$

- Extended emission $\rightarrow$ Markovian model for smooth variations
- ρ_s unknown $\rightarrow$ estimate it jointly with $\mathbf{x}$

Pointing model



- Point-Pixel approach ($p(\alpha, \beta, \lambda) = \delta(\alpha, \beta)$): account for data points inside a pixel (bilinear average).
- Flagged measurements eliminated automatically.
  - \+ Simple, fast and use redundancy
  - \+ bilinear averaging.
  - – Point representation of bolometer.

Joint estimation

Unsupervised approach

$$p(\mathbf{x}, \mathbf{p}, \rho_n, \rho_s|\mathbf{y}) \propto p(\mathbf{y}|\mathbf{x}, \rho_n)p(\mathbf{x}|\rho_s)p(\rho_n)p(\rho_s)$$

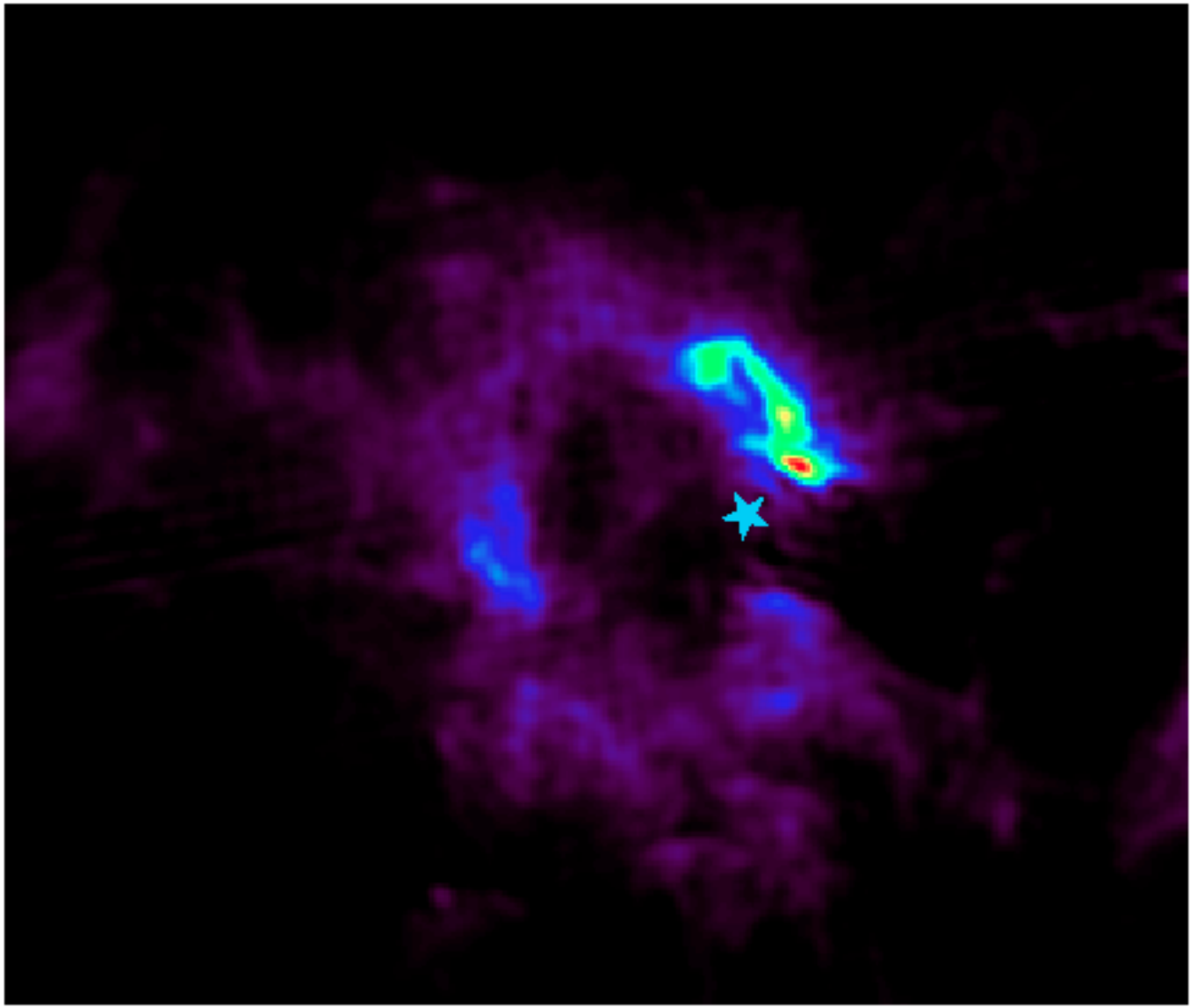
$$\begin{aligned}\log\left(p(\mathbf{x}, \rho_n, \rho_s|\mathbf{y})\right) = -0.5\Big(&\rho_n \left\|\mathbf{y} - \mathbf{H}(\mathbf{x})\right\|_2^2 + \rho_s \left(\left\|\mathbf{D}_\alpha \mathbf{x}\right\|_2^2 + \left\|\mathbf{D}_\beta \mathbf{x}\right\|_2^2\right) \\ &- N_y \log\left(\rho_n\right) + \frac{\rho_n}{\gamma_n} - \left(\phi_n - 1\right)\log\left(\rho_n\right) \\ &- N_s \log\left(\rho_s\right) + \frac{\rho_s}{\gamma_s} - \left(\phi_s - 1\right)\log\left(\lambda_s\right) + cte\Big)\end{aligned}$$

Estimator

- Deterministic: Variational Bayesian Approach (VBA).
- Stochastic: Monte Carlo Markov Chains (MCMC).

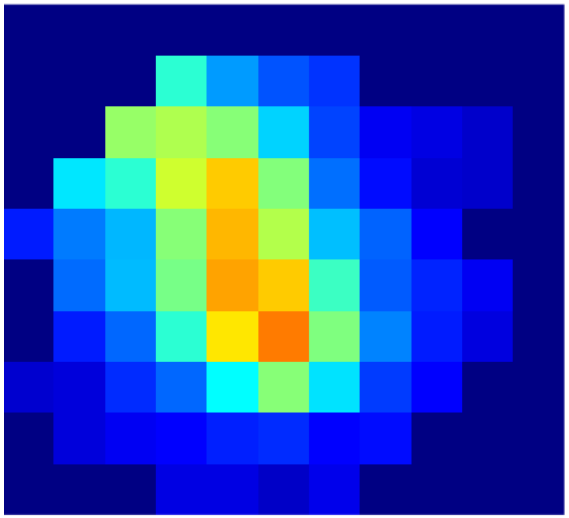
Results

NGC7023 : Full sampling



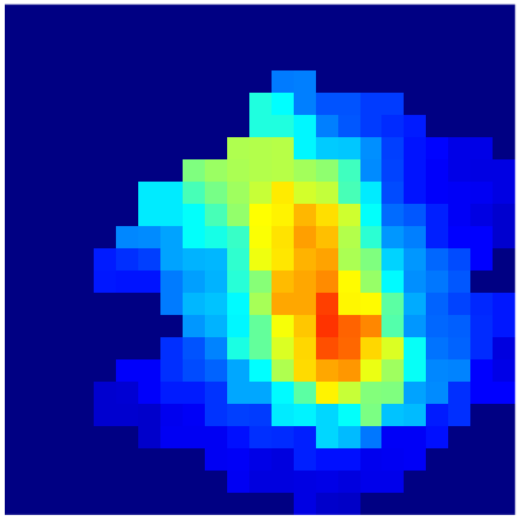
Results

HIPE

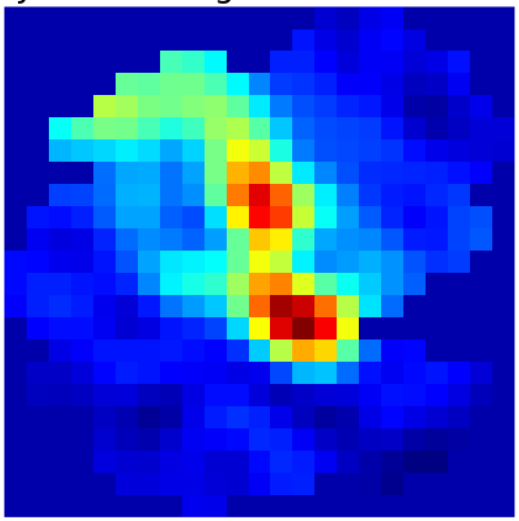


310 um

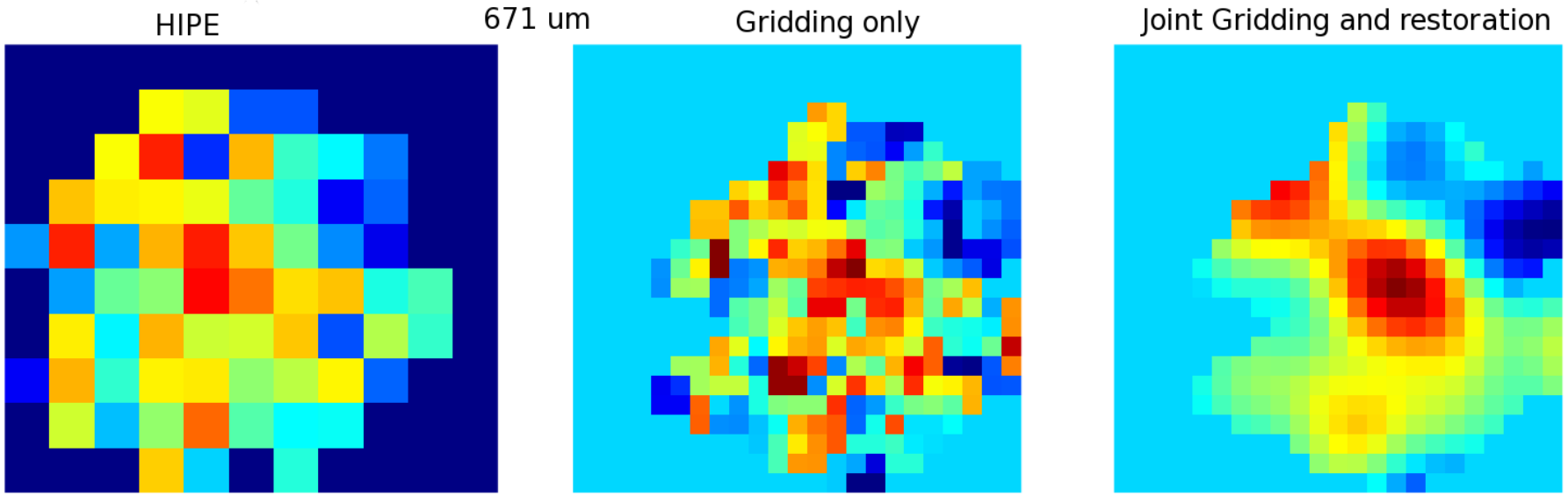
Gridding only

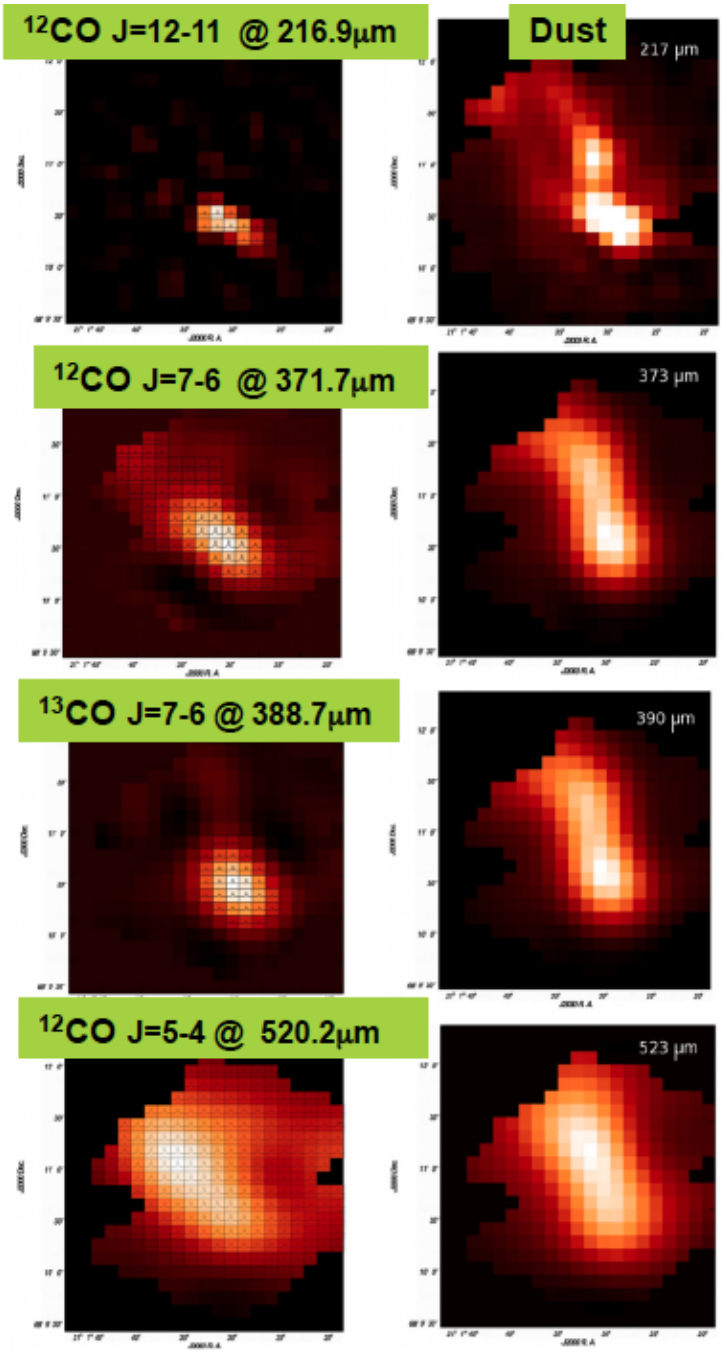


Joint Gridding and restoration



Results





Specific spatial behaviour of high-J and low-J ^{12}CO, ^{13}CO and dust emission:

✓ Dust emission peaks in two regions :

(1) Southern warm and dense condensation

(2) Northern colder condensation

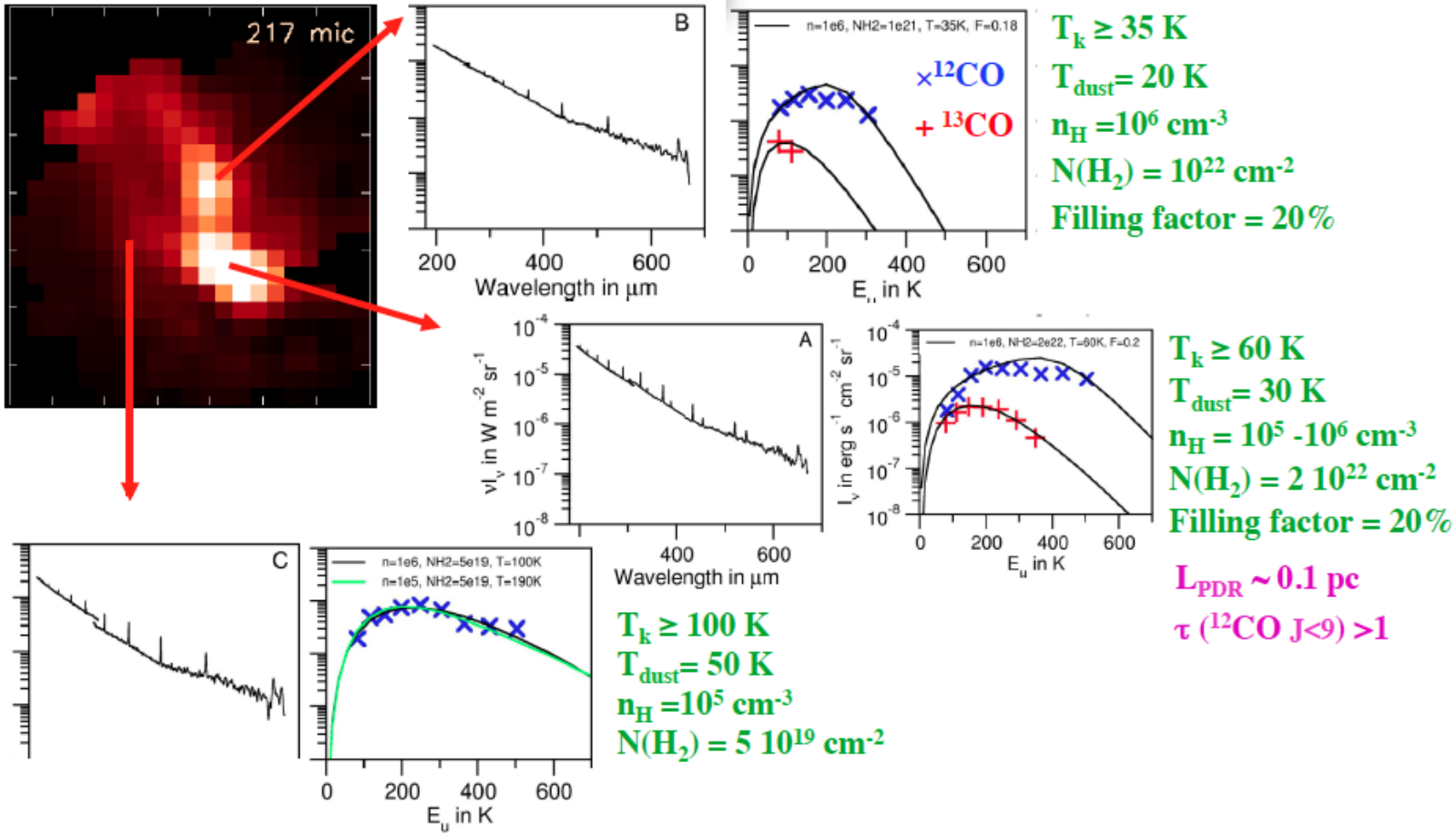
✓ ^{12}CO J=12-11: occurs only at the southern region

✓^{12}CO J=7-6: occurs in elongated regions, emission extended over cloud edge

✓^{13}CO J=7-6: occurs only where warm dust emission peaks at the south

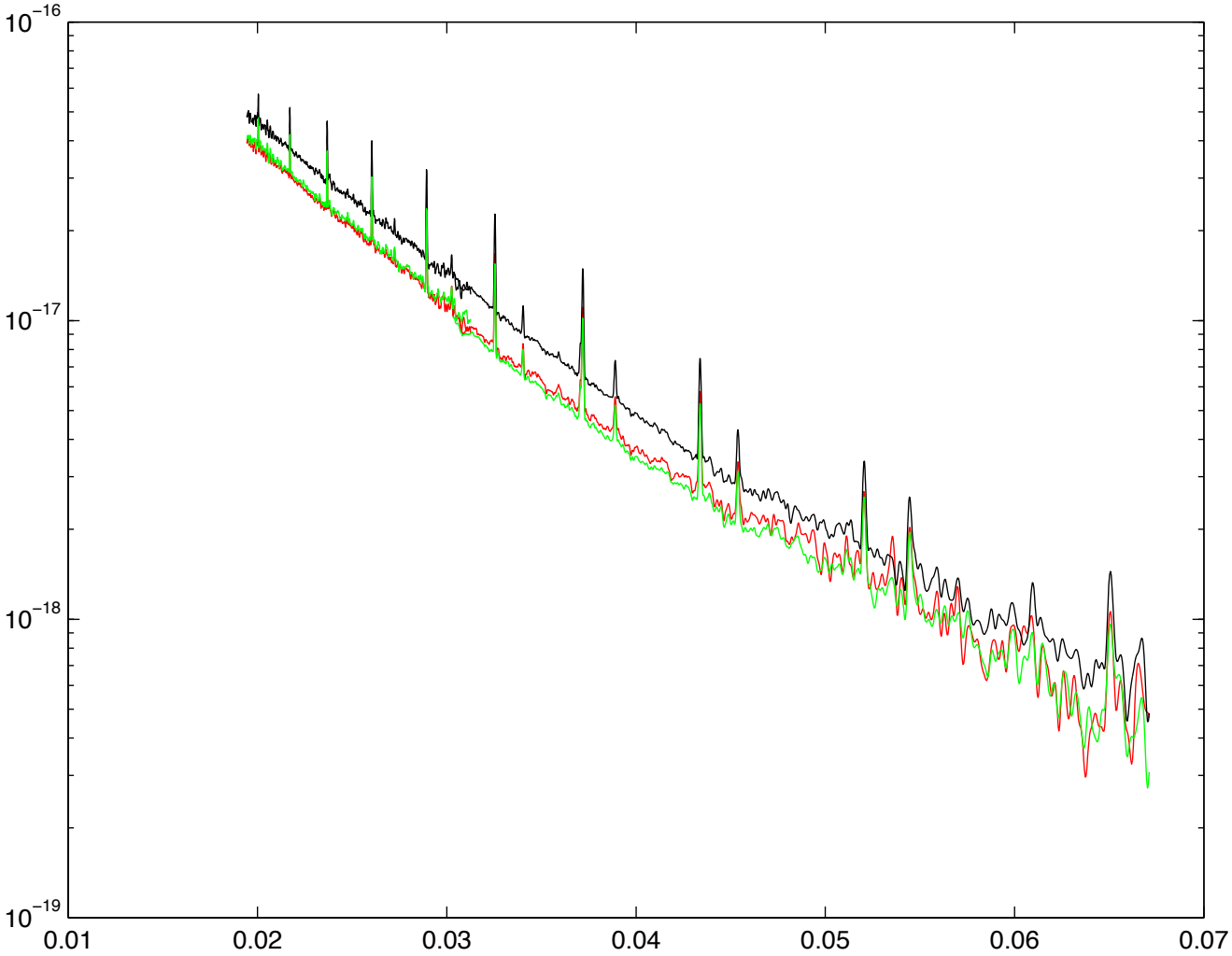
✓^{12}CO J=5-4: occurs over all the cloud, in elongated region

Results



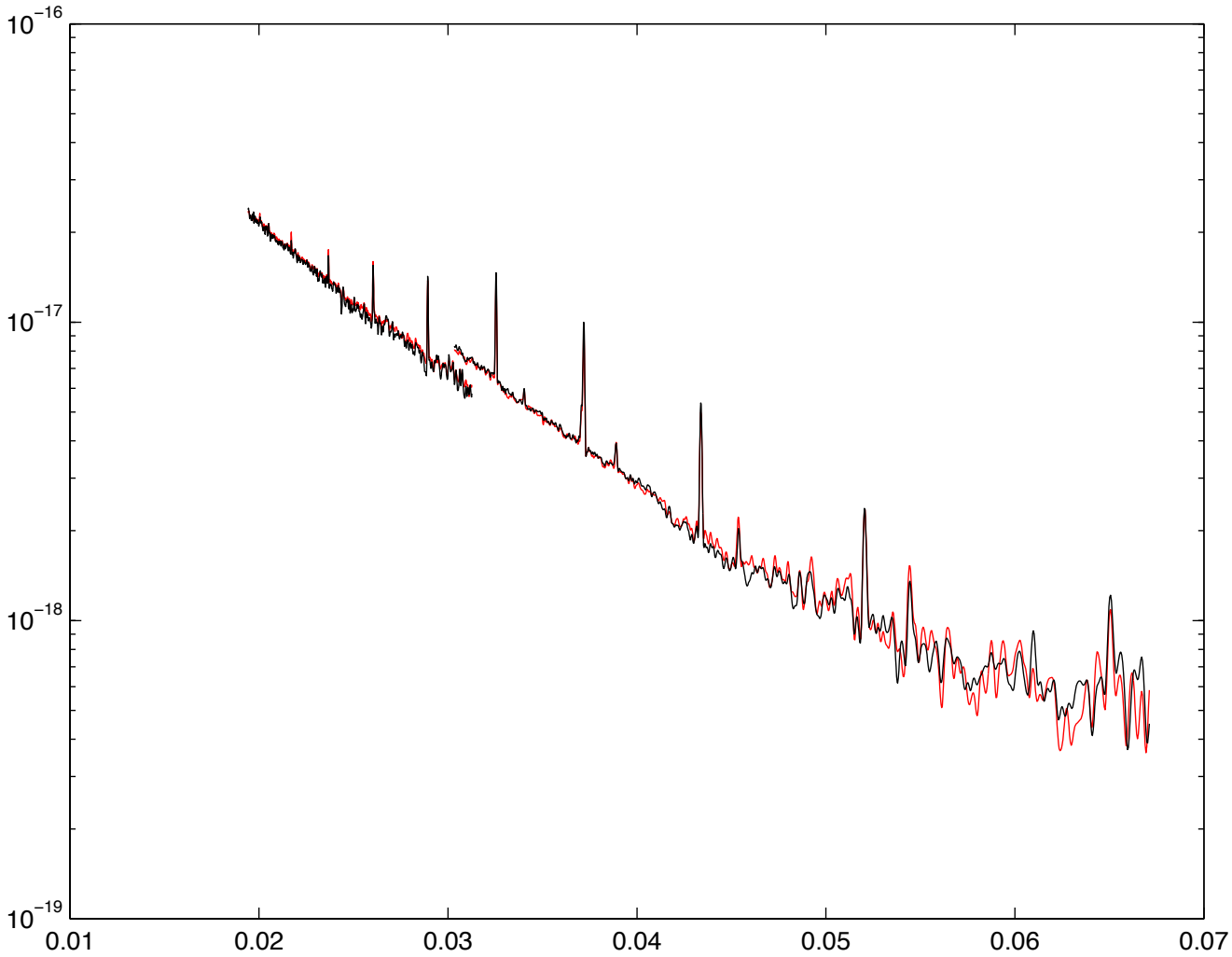
In preparation: 'Dust and gas in the NGC 7023 photodissociation region using FTS spectroscopy' **M. Koehler, E. Habart**, H. Arab, H. Ayasso, J. Bernard-Salas, A. Abergel, K. Dassas, Annie Zavagno, Jean-Paul Baluteau (IAS, LAM, SAG4)

Results



Spectra for maximum point: Green (HIFI), Red (Bilinear), Black (New method)

Results



Spectra for a point form a flat region: Red (Bilinear), Black (New method)



Conclusions

Key points

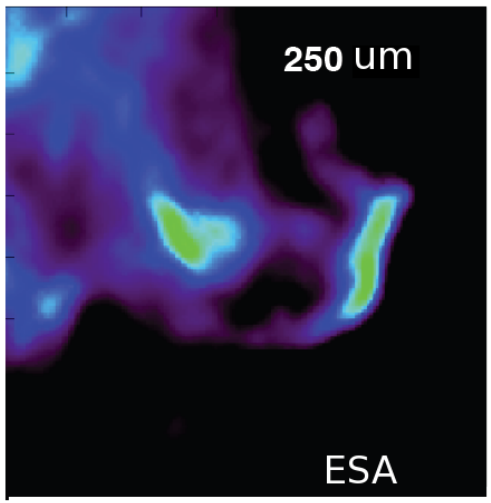
- Joint reconstruction
- Gridding based on bilinear model (avoid simplicity of Naive one and the over smoothing of the HIFI gridder)
- Correction of the PSF: model provided by Lethbridge
- Mask included (flagged data are eliminated seamlessly)
- Automatic parameters estimation (unsupervised method)
- Best resolution for each wavelength and controlled unique equivalent PSF

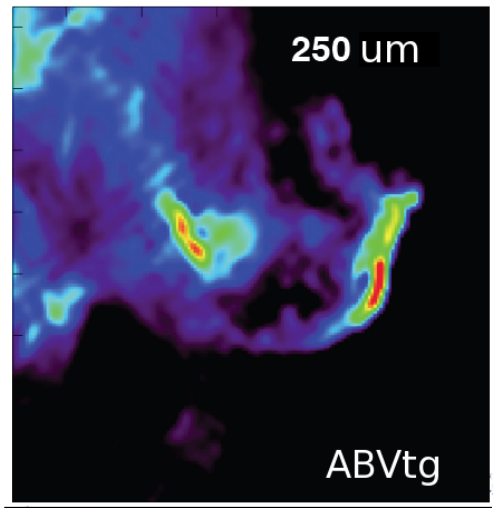
Still to do

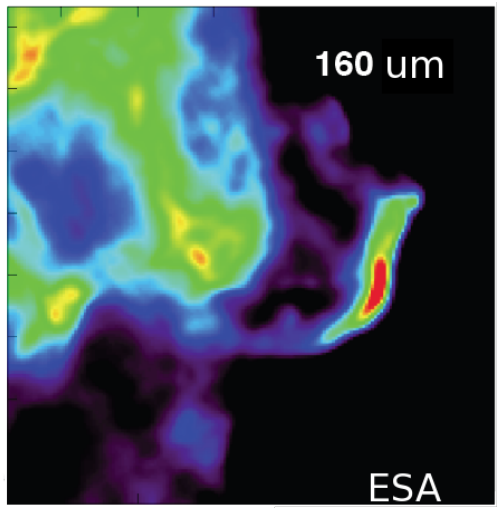
- Enhanced noise model based on Lethbridge measurements
- Tests, verification and validation (Photometer and spectrometer cross validation)

Merci

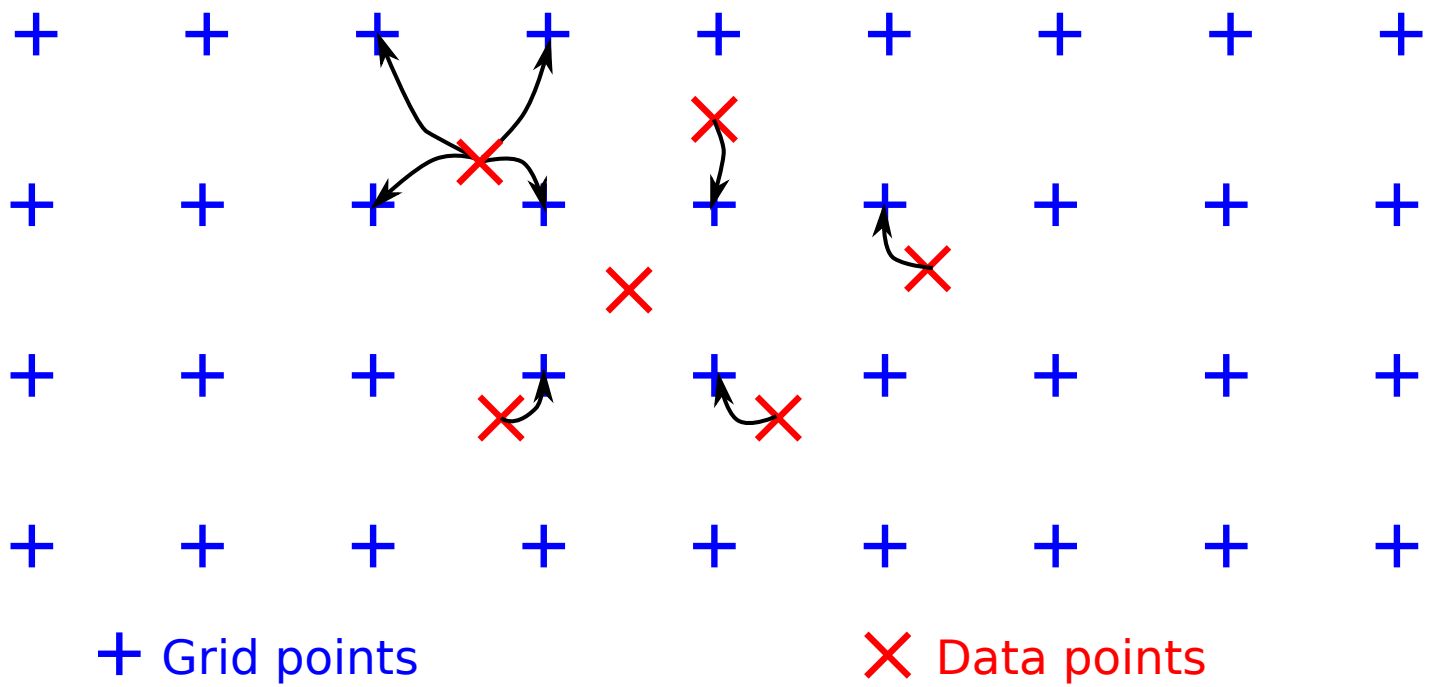
Available also for SPIRE photometer.





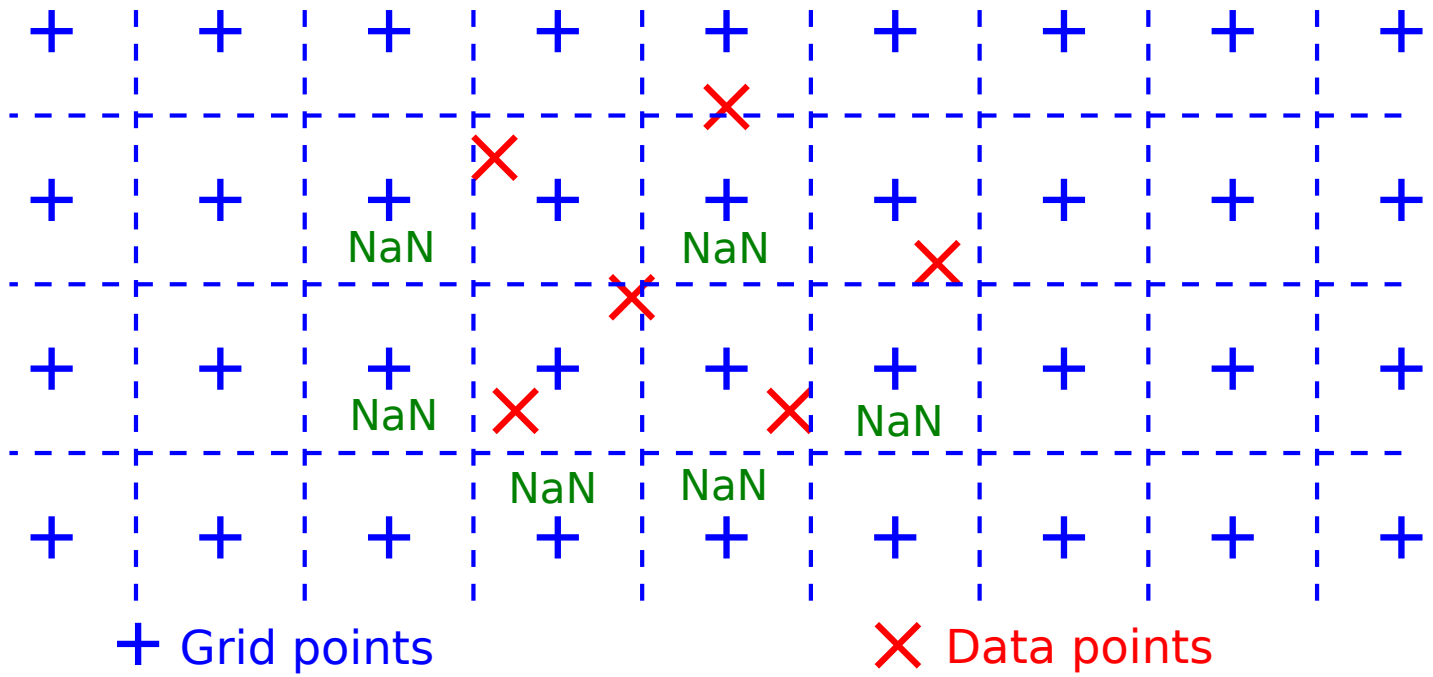


Nearest Neighbour



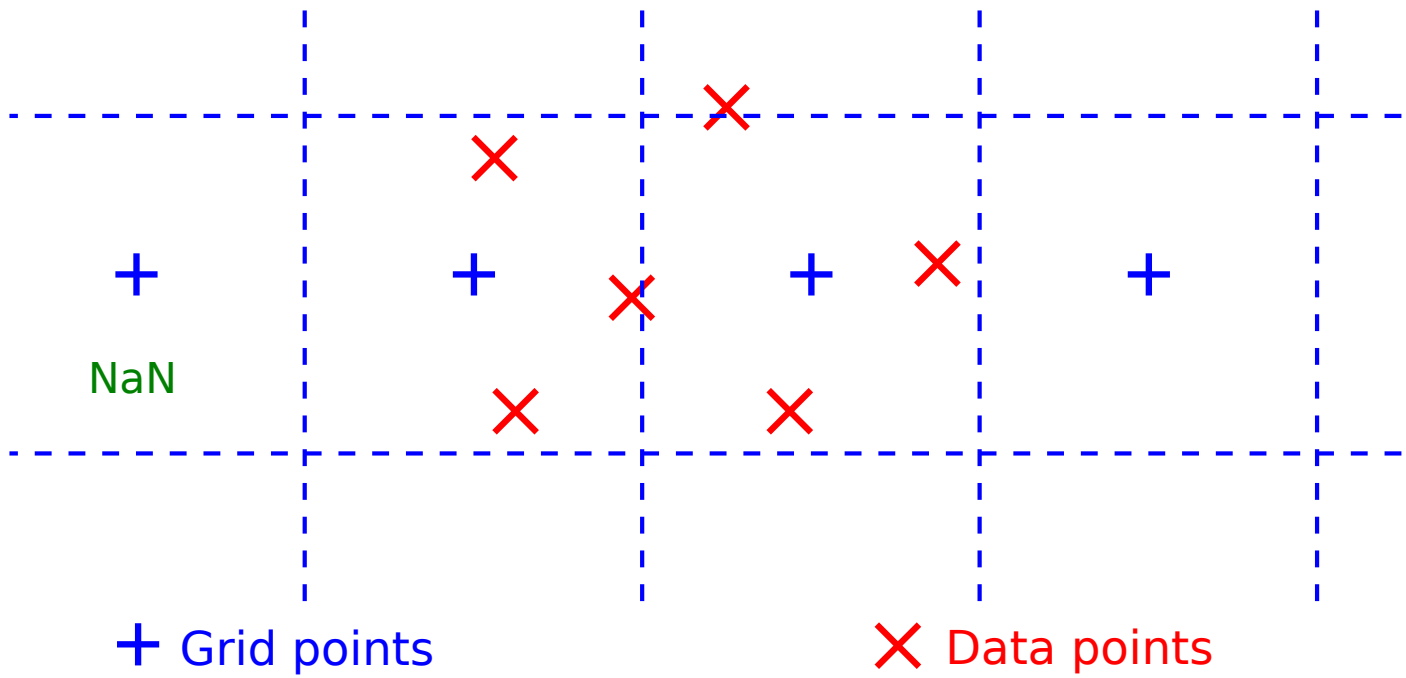
- Point-Point approach ($p(\alpha, \beta, \lambda) = \delta(\alpha, \beta)$) using interpolation by nearest neighbour.
- Optional elimination of flagged data.
  - \+ Full filling of all maps points with nearest point
  - – Lose redundancy in data.

Naive method



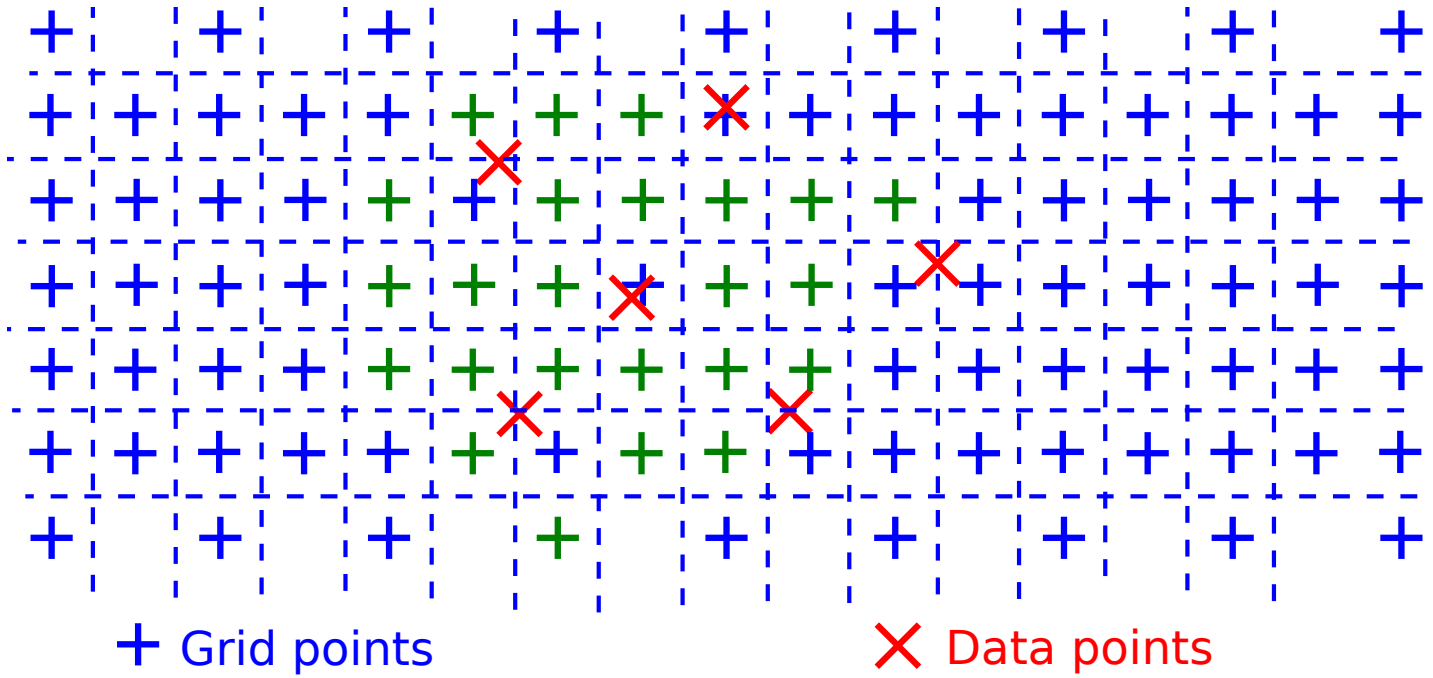
- Point-Pixel approach ($p(\alpha, \beta, \lambda) = \delta(\alpha, \beta)$): account for data points inside a pixel (uniform average).
- Flagged pixels eliminated automatically.
  - \+ Simple, fast and use redundancy
  - – Uniform averaging.
  - – Point representation of bolometer.

Naive method



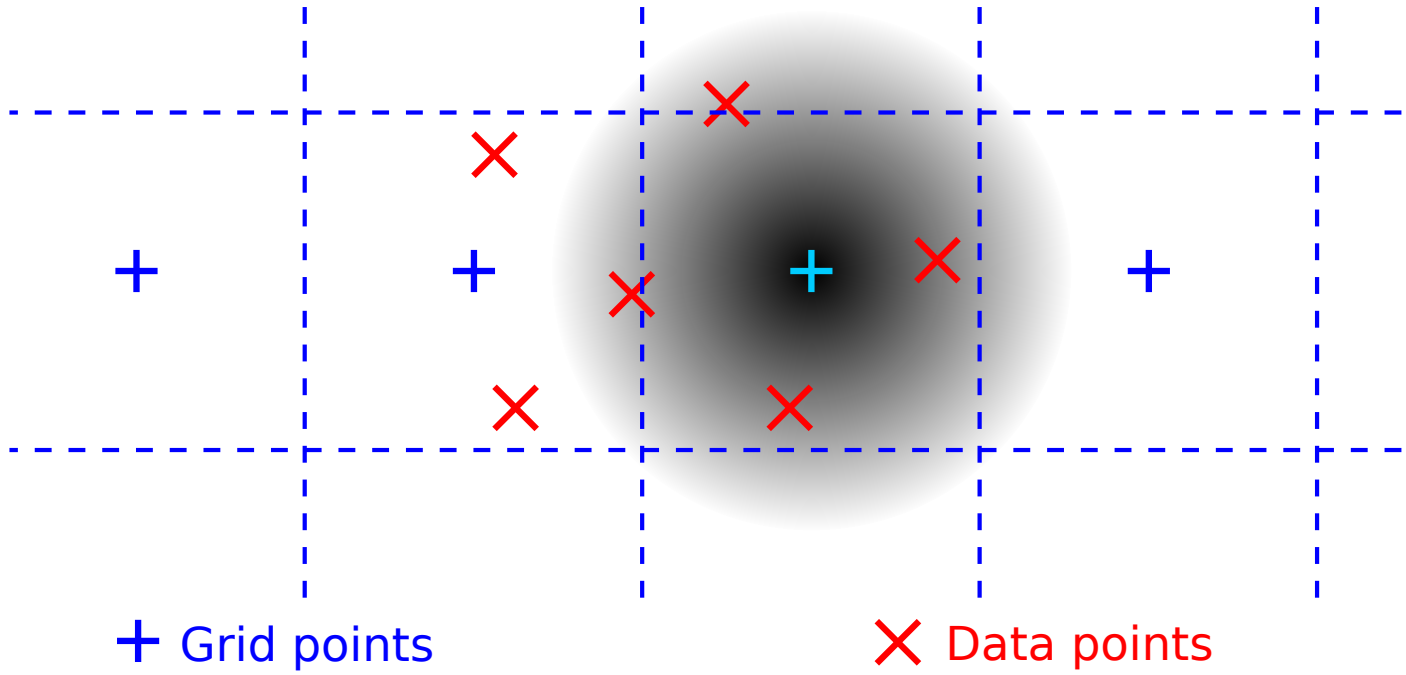
- Bigger pixels contains more data points but has less spatial resolution

Naive method



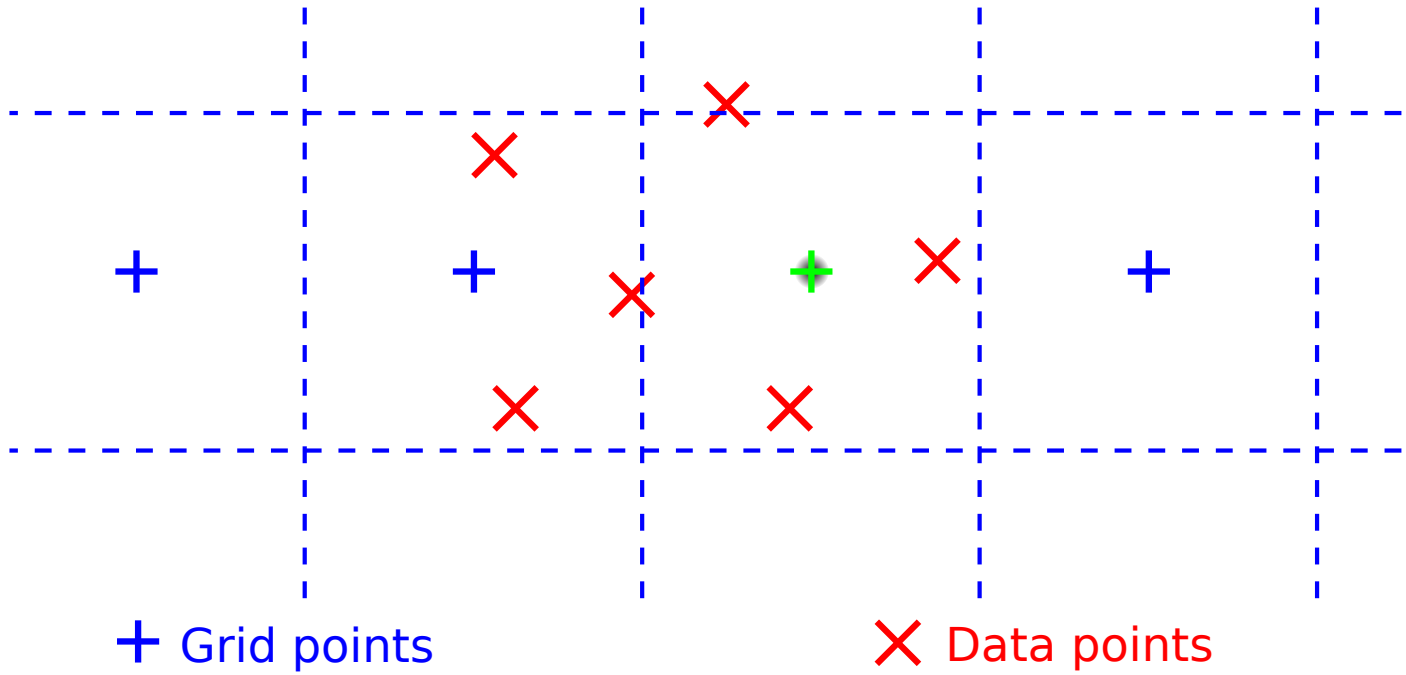
- Smaller pixels give a lot of NaN

Hifi gridding



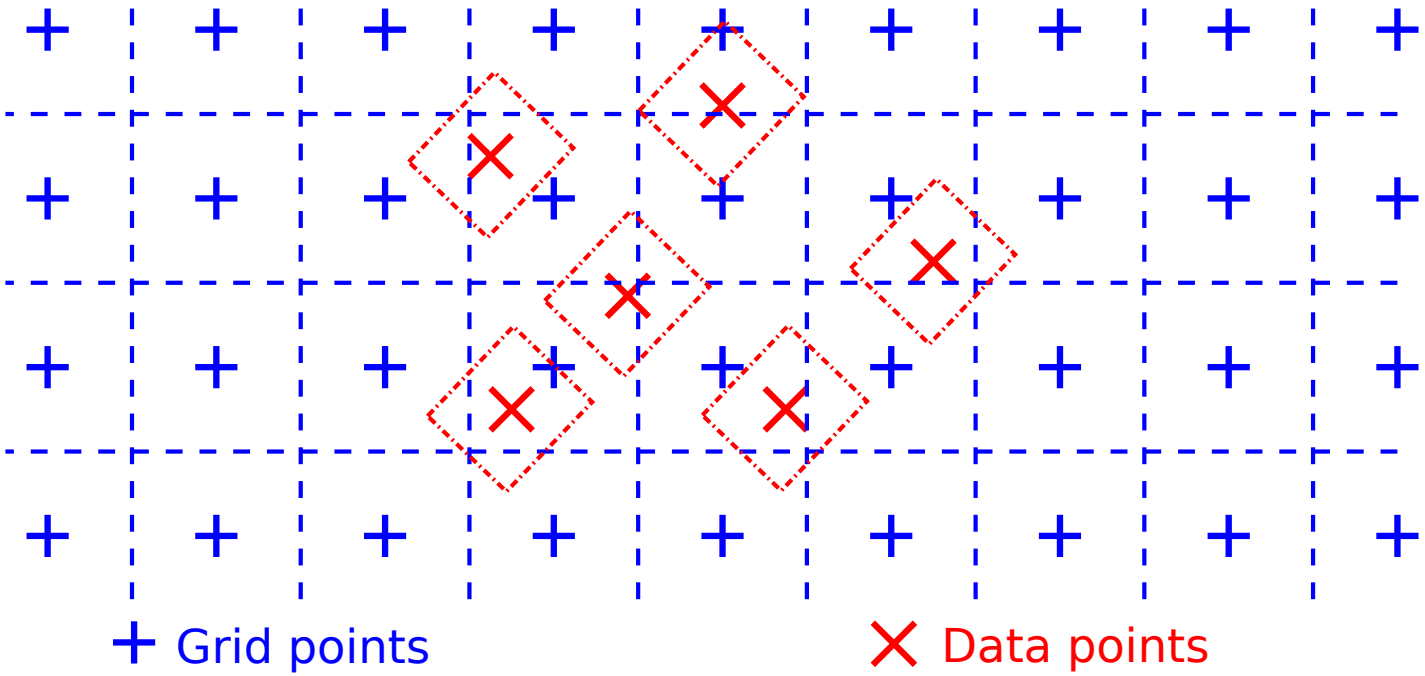
- Point-Point approach ($p(\alpha, \beta, \lambda) = \delta(\alpha, \beta)$): define grid point by filtering the data points with a low-pass filter $\mathcal{L}$.
- $\mathcal{L}$ is Gaussian which width is calculated from beams width.
  - \+ Automatic smoothing for the data (Can not be eliminated !! see below)
  - – ATTENTION minimum smoothing factor is 4% (fixed by the algorithm)
  - – No separation between gridding and filtering.

Hifi gridding



- Beam width only used to calculate smoothing. Beam form is not accounted for in this method (No Decovolution)
- Reducing the smoothing factor will leads to NaN pixels everywhere

PACS gridding



- Pixel-Pixel approach ($p(\alpha, \beta, \lambda) = \Pi(\alpha, \beta)$): average data points base on the intersection area between sky pixel and detector pixel.
  - \+ Weighted average with spatial coverage of detector pixel.
  - – No deconvolution.
  - – Calculation time.