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Estimation of physical conditions in PDRs Bayesian approach with spatial regularization

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Aims and contributions

New large hyper-spectral surveys in radio-astronomy: game changer for study of star formation, feedback mechanisms and chemistry of interstellar gas.
 \Rightarrow now possible to observe full molecular clouds (10 pc size) at dense core scale (<0.1 pc) spatial resolution. For instance, the IRAM-30m Large Program «Orion B» [1] provides a 10^6 pixel observation map, covering ~ 250 pc² of the Orion B cloud with emission of dozens of molecules.

Goal To estimate maps of thermal pressure P_{th} , UV radiation intensity G_0 , visual extinction A_V , scaling factor κ and the associated uncertainties.

Challenge Variability of the SNR: the brightest regions can be well constrained, but the regions with low SNR lead to degenerate solutions.

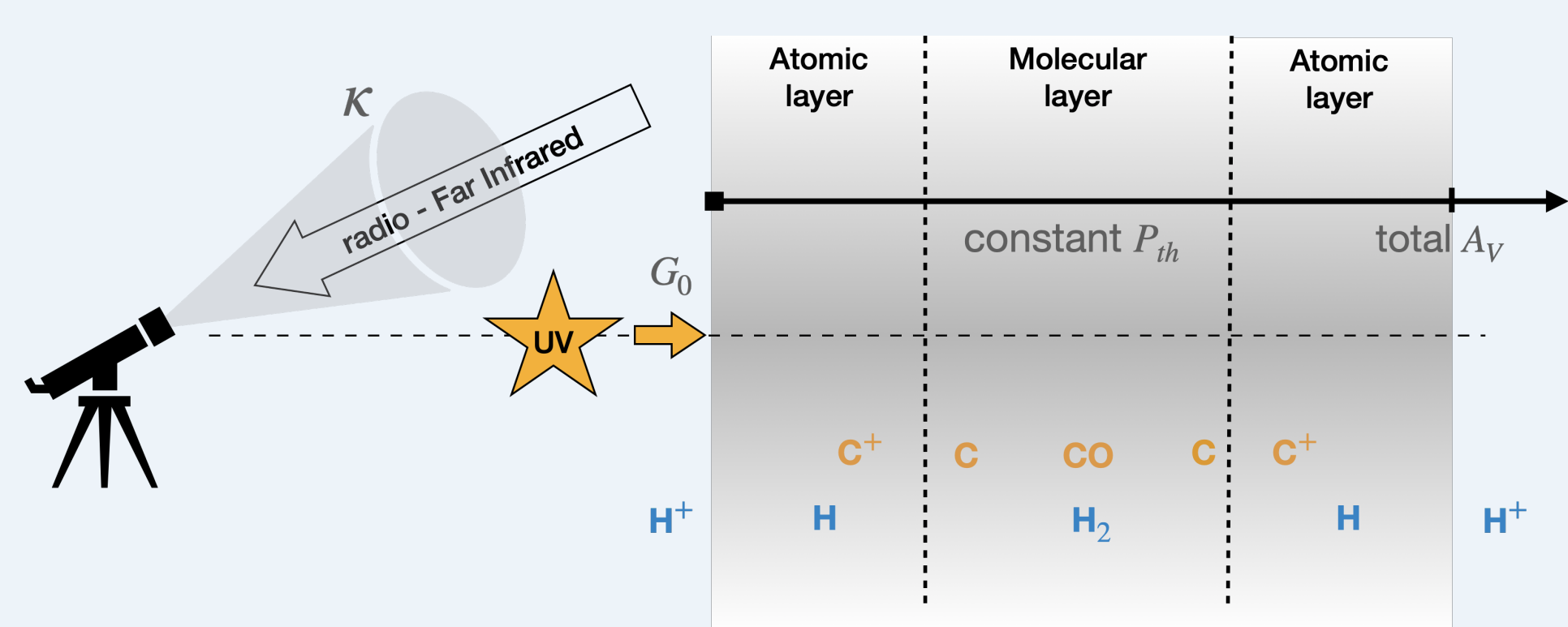
Approach ★ Mixture of both additive and multiplicative noises + limited detectability \Rightarrow more realistic observation model

★ Spatial regularization \Rightarrow exploitation of the information contained in neighbouring pixels.

★ Bayesian approach \Rightarrow access to accurate credibility intervals.

Problem formulation

\rightarrow Meudon PDR code [2]: solves radiative transfer, chemistry, thermal balance on stationary 1D plane-parallel model.



\rightarrow Assumption: physics in PDR = interpolation of a grid of simulations of Meudon PDR code. Defines function f s.t. for one pixel n :

$$f : \underbrace{x_n = (\kappa, P_{th}, G_0, A_V)}_{\text{physical parameters (to estimate)}} \mapsto \underbrace{(y_{n,\ell})_{\ell=1}^L}_{\text{integrated intensities (observed)}}$$

\rightarrow observation model involves detectability limit ω , gaussian noise $\varepsilon_{n,\ell}^{(a)}$ and lognormal noise $\varepsilon_{n,\ell}^{(m)}$

$$y_{n,\ell} = \begin{cases} \omega & \text{if } \varepsilon_{n,\ell}^{(m)} f_{\ell}(x_n) + \varepsilon_{n,\ell}^{(a)} \leq \omega \\ \varepsilon_{n,\ell}^{(m)} f_{\ell}(x_n) + \varepsilon_{n,\ell}^{(a)} & \text{else} \end{cases}$$

\Rightarrow defines a **likelihood** function $\pi(y | x)$.

Bayesian approach

\rightarrow State-of-the-art in millimeter/IR astronomy estimations: Maximum Likelihood Estimates (MLE) \Rightarrow very sensitive to noise

\rightarrow For robust estimators: spatial regularization **prior** $\pi(x)$ (norm of image gradient or laplacian)

\rightarrow **Posterior** probability density function:

$$\pi(x | y) \propto \pi(y | x)\pi(x)$$

\rightarrow To derive estimators and credibility intervals from posterior distribution: **sample** from it with Monte Carlo Markov Chain (MCMC).

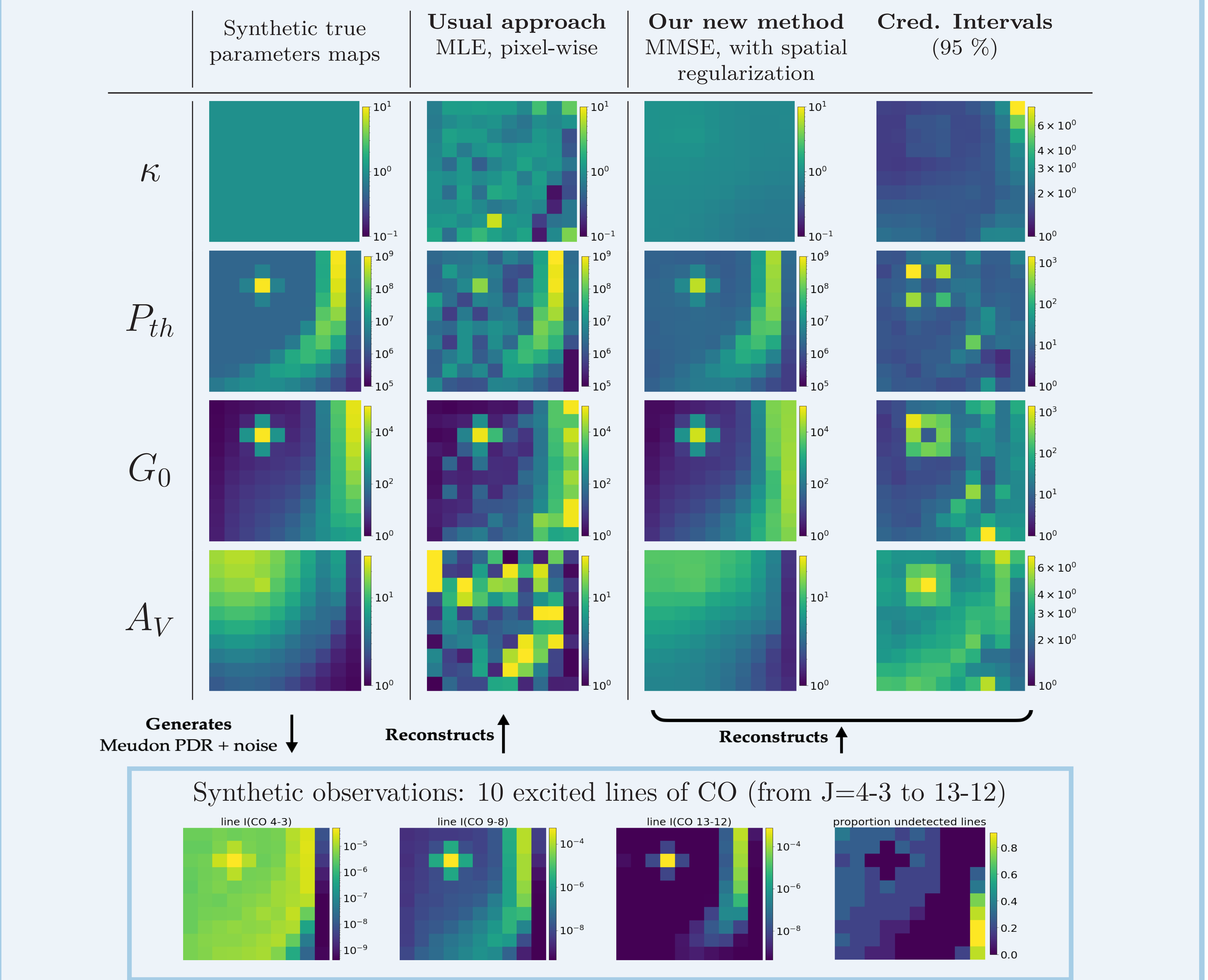
\rightarrow Our sampler mixes two kernels: one identifies local minima, one efficiently explores them.

\rightarrow Our punctual estimator: MMSE (Minimum Mean Squared Error) = mean of posterior.

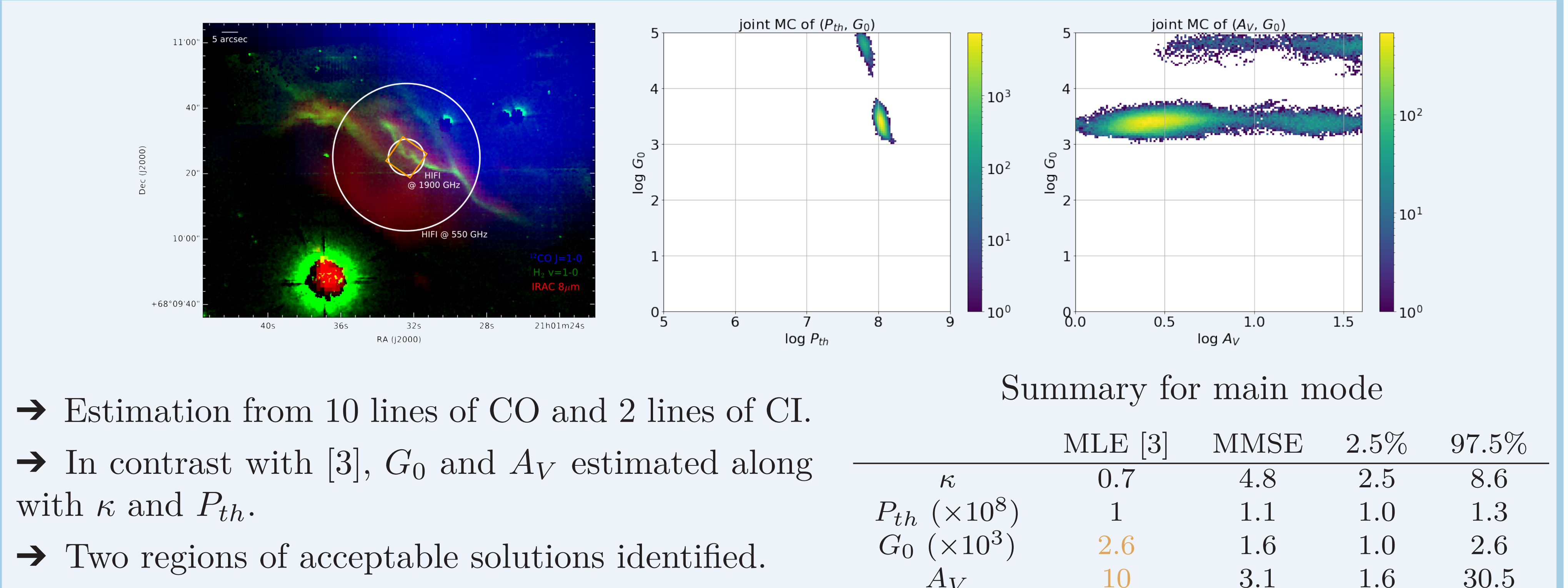
References

[1] Pety *et al.*, *The anatomy of the Orion B Giant Molecular Cloud: A local template for studies of nearby galaxies*, 2016
 [2] Le Petit *et al.*, *A model for atomic and molecular interstellar gas the Meudon PDR code*, 2009
 [3] Joblin *et al.*, *Structure of photodissociation fronts in star-forming regions revealed by Herschel observations of high-J CO emission lines*, 2018

Application on toy dataset (100 pixels)



NGC 7023 (1 pixel)



Conclusions

Achieved:

- ✓ Spatial regularization \Rightarrow more robust estimations of maps of parameters,
- ✓ Bayesian approach \Rightarrow more complete description than punctual estimators.

Future Work:

- \rightarrow Application to other environments than PDR (shocks, dark clouds, etc.),
- \rightarrow Code acceleration to scale to $\sim 10^6$ pixel observations (e.g., Orion B IRAM Large Programm).