Inferring physical conditions in star forming regions with new Bayesian approach and spatial regularization

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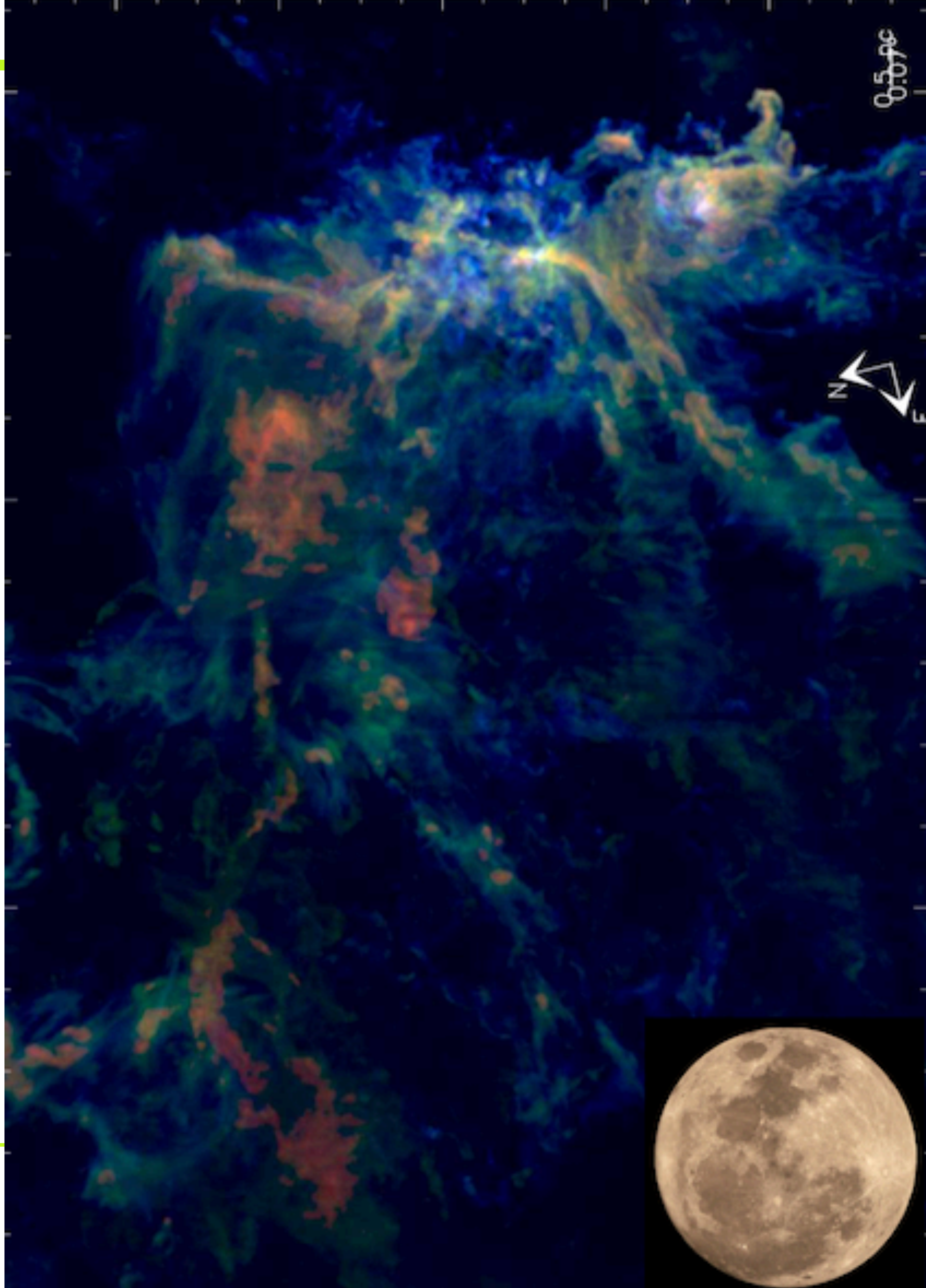


Point of the presentation

Effect of **radiative feedback** on parent cloud

↓

Efficient estimation of **physical conditions** in **star forming region**

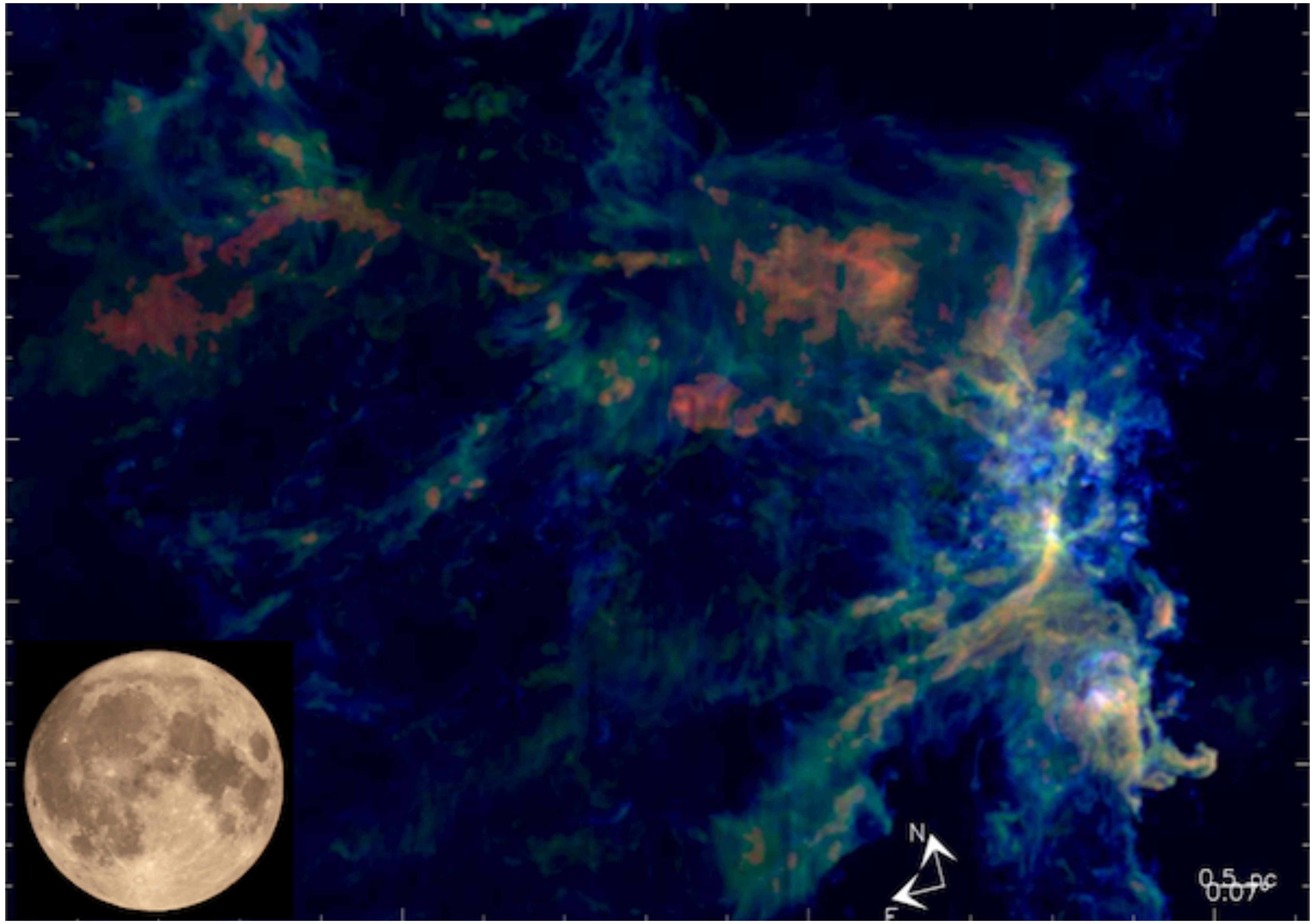
Carina nebula

Pillars of creation

Source: https://www.nasa.gov/

Example: the OrionB cloud

Source: IRAM-30m, J.Pety, M. Guerin, consortium Orion-B



Observations led by **OrionB Consortium**, (Pety et al., 2016)

Very rich dataset!

$\simeq 10^6$ pixels

$\simeq$ 100 pc^2

tens of lines

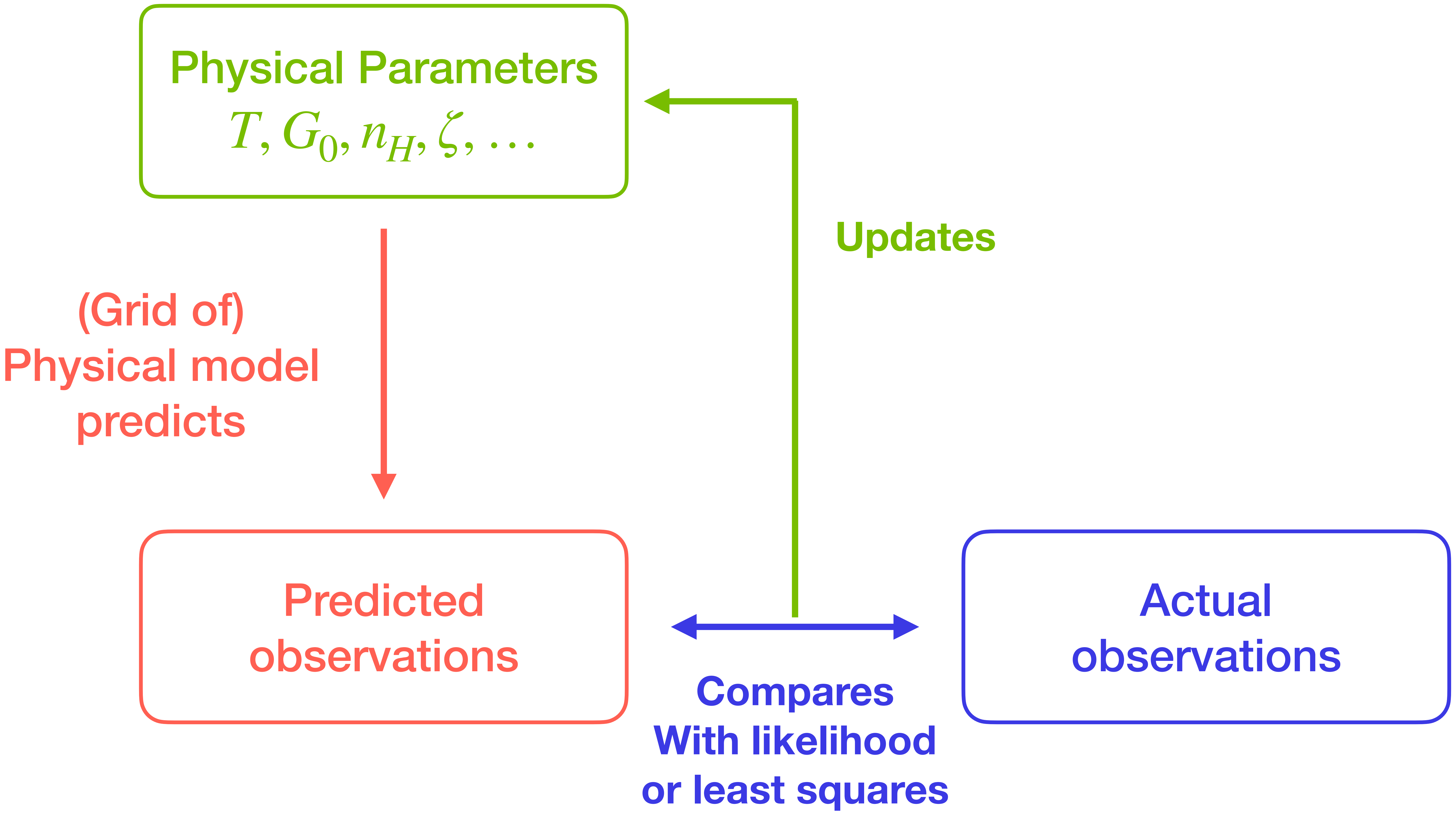
Great variations of SNR

$\Longrightarrow$ Between pixels

$\Longrightarrow$ Between lines

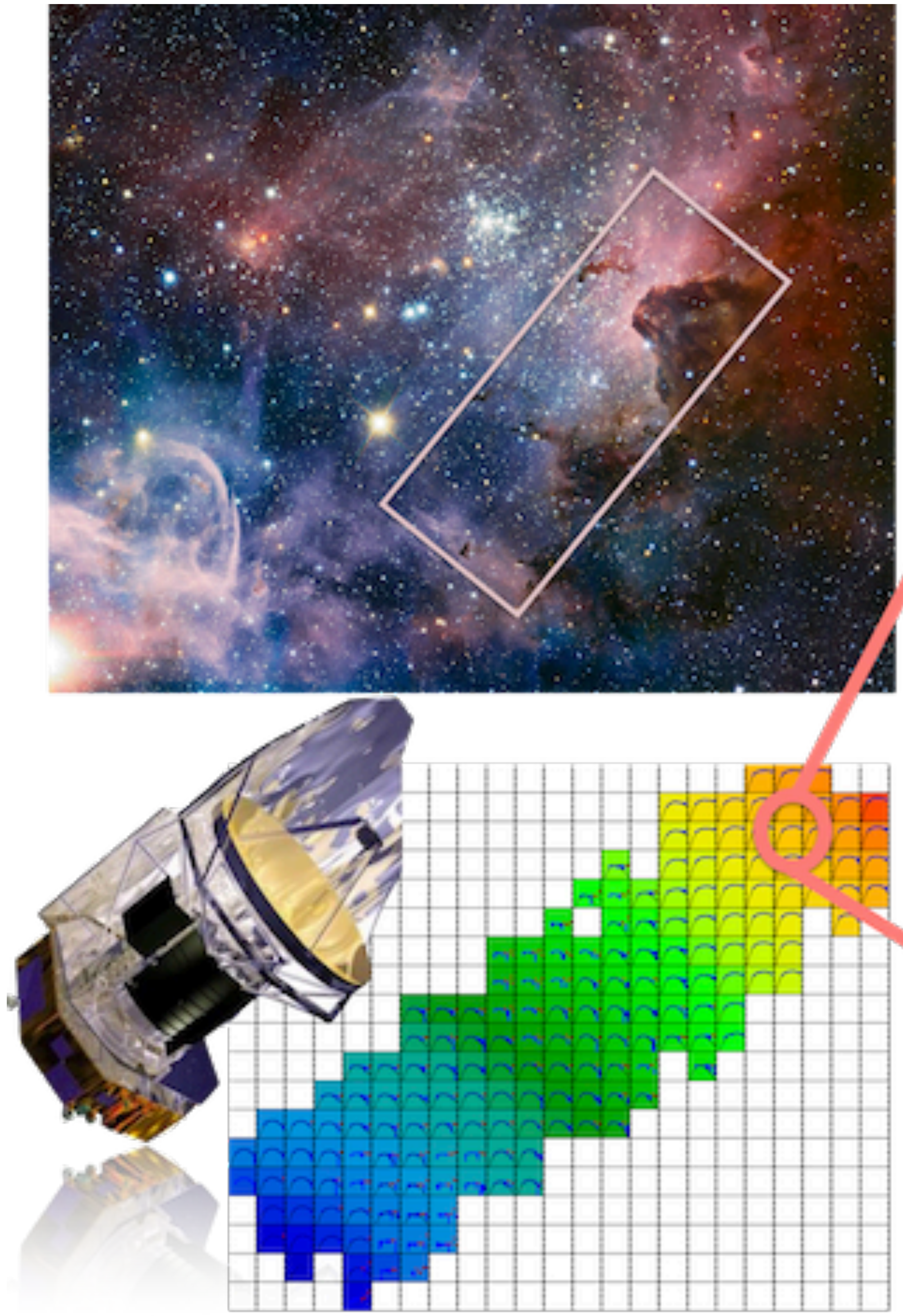
Estimation procedure

observations = Integrated intensities of molecular / atomic lines

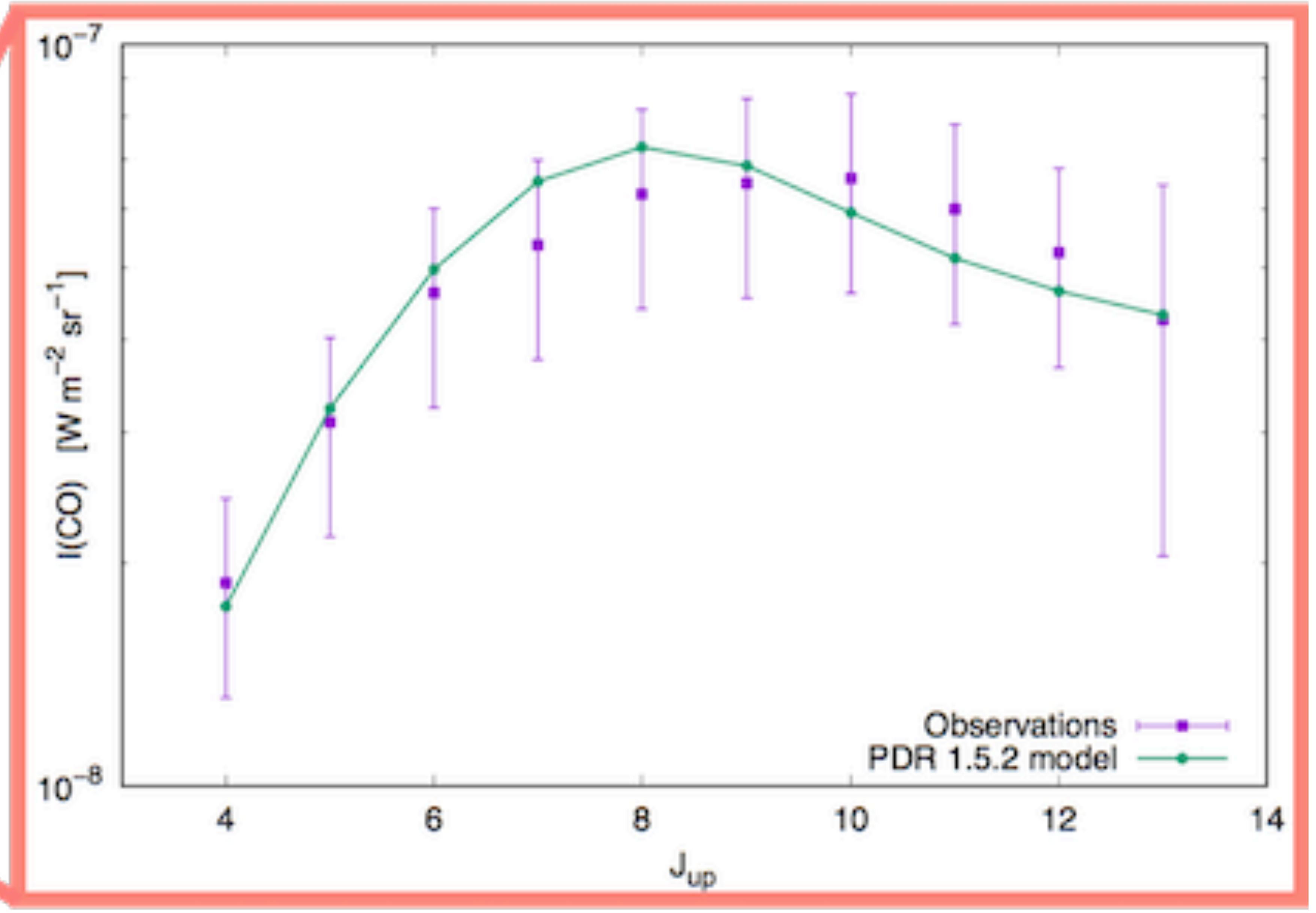


Carina nebula

(Wu et al., 2018)



Pixel-wise estimation:
reconstructs well observations



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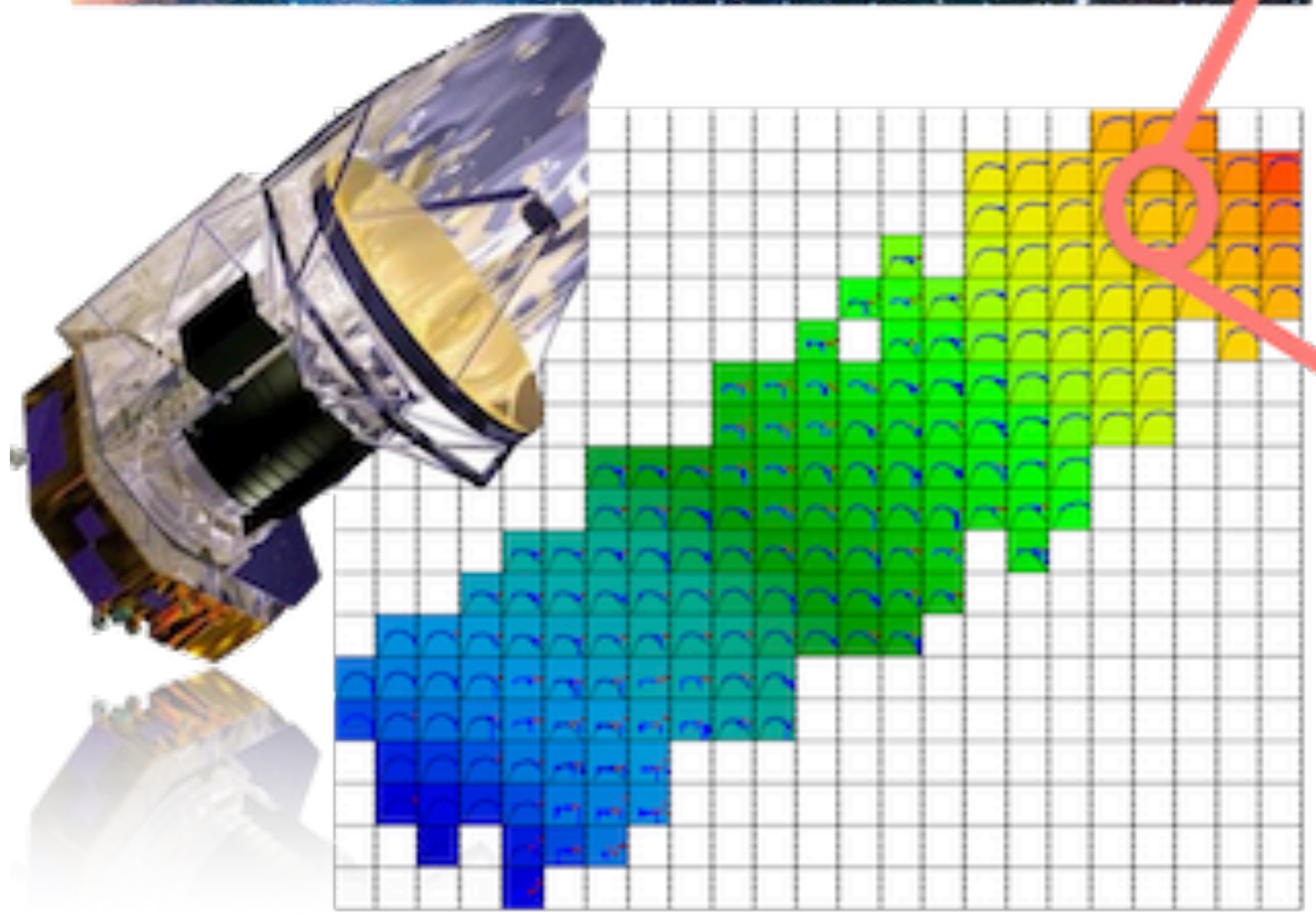

Pixel-wise estimation:
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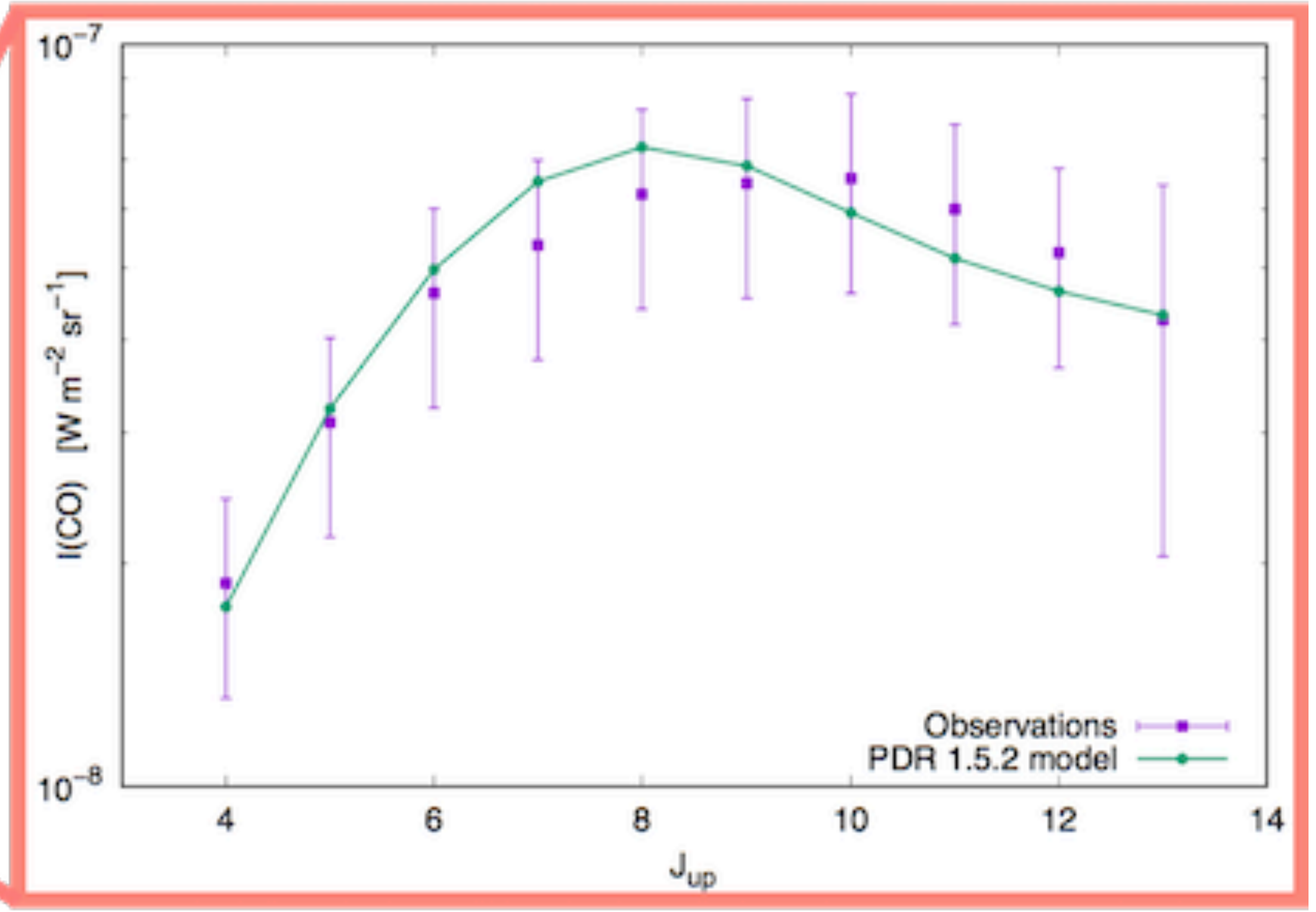
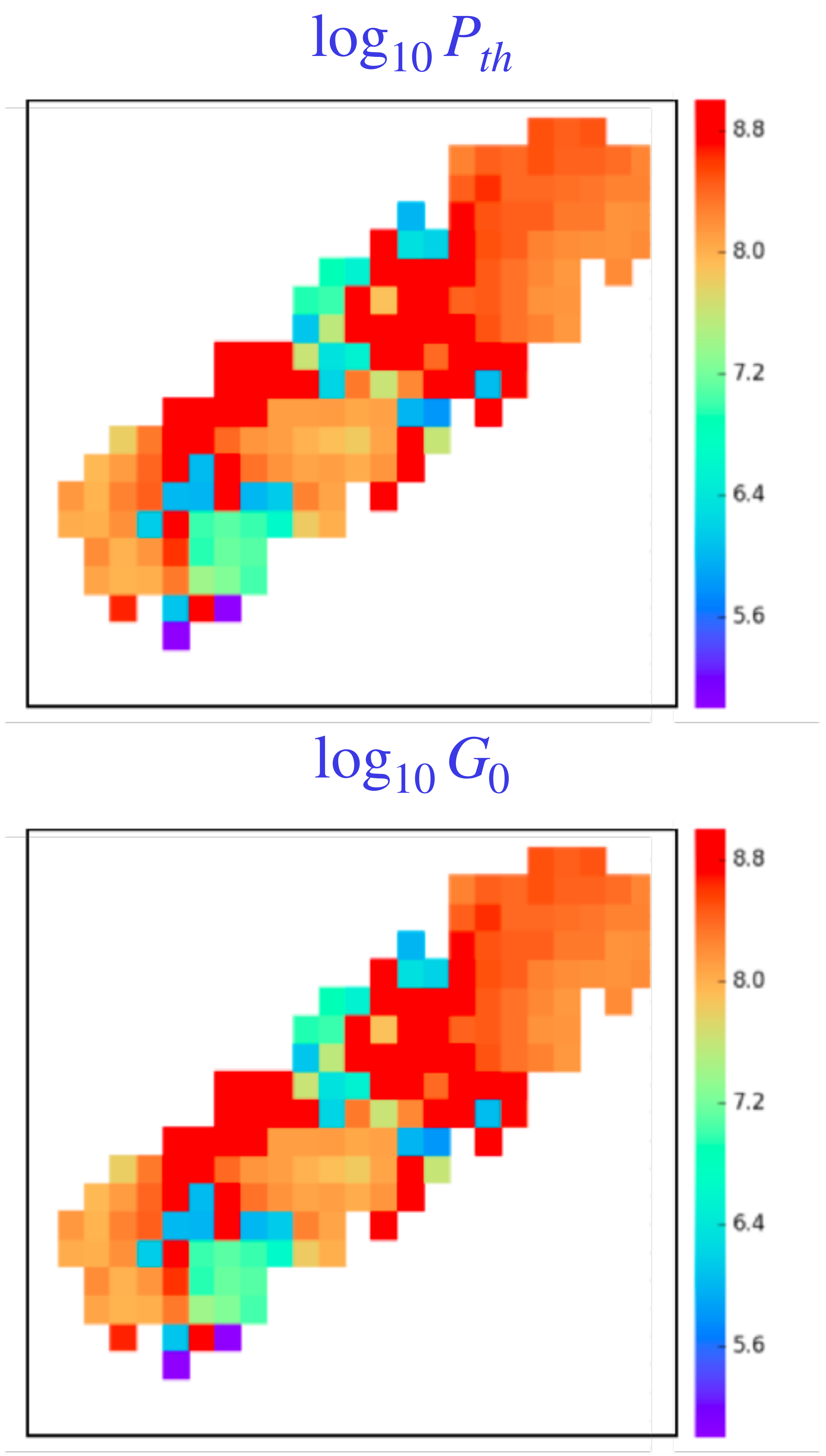
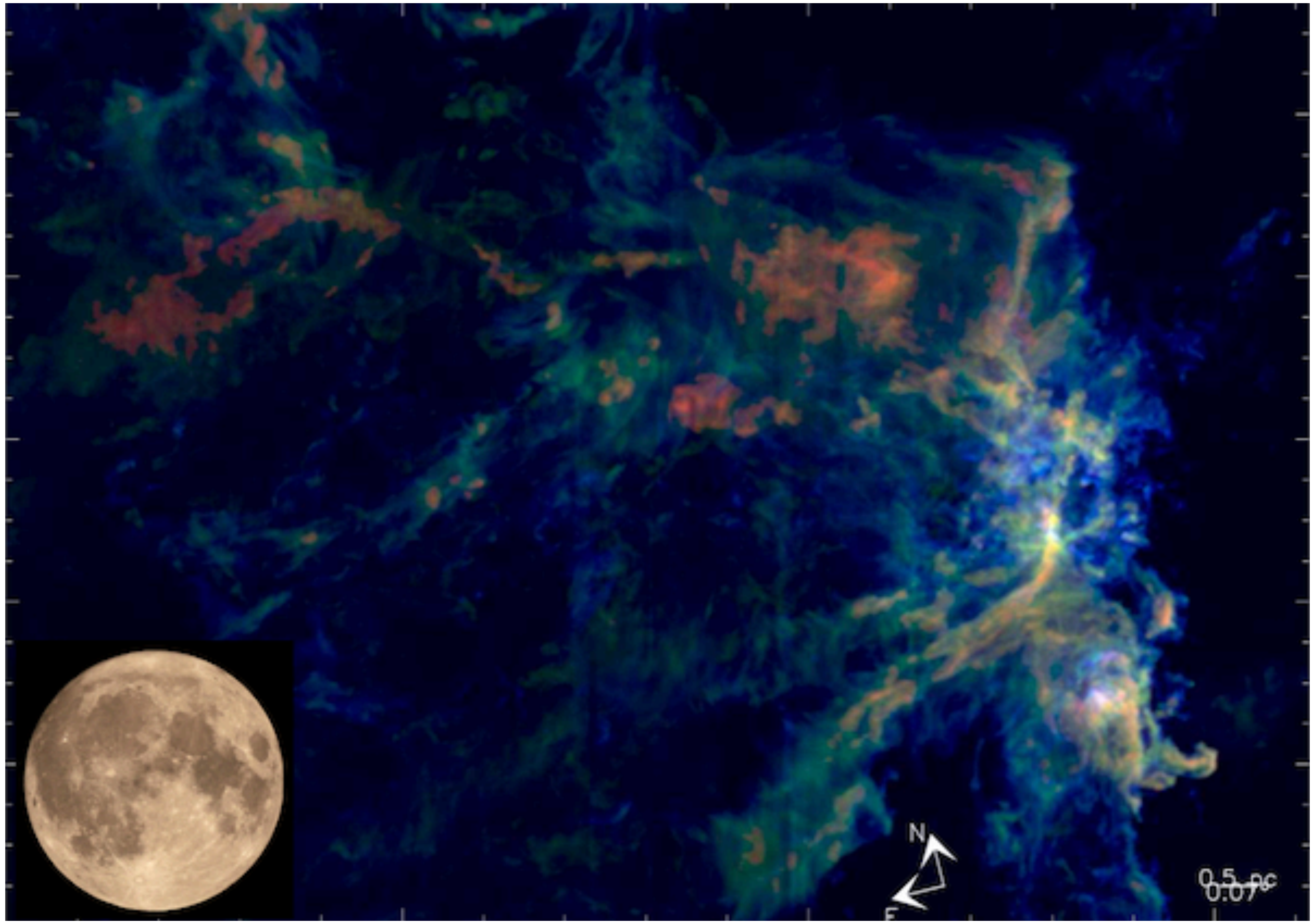


But reconstructed maps
have **no spatial coherence**
particularly in low SNR regions



Example: the OrionB cloud

Source: IRAM-30m, J.Pety, M. Guerin, consortium Orion-B



For better estimations:

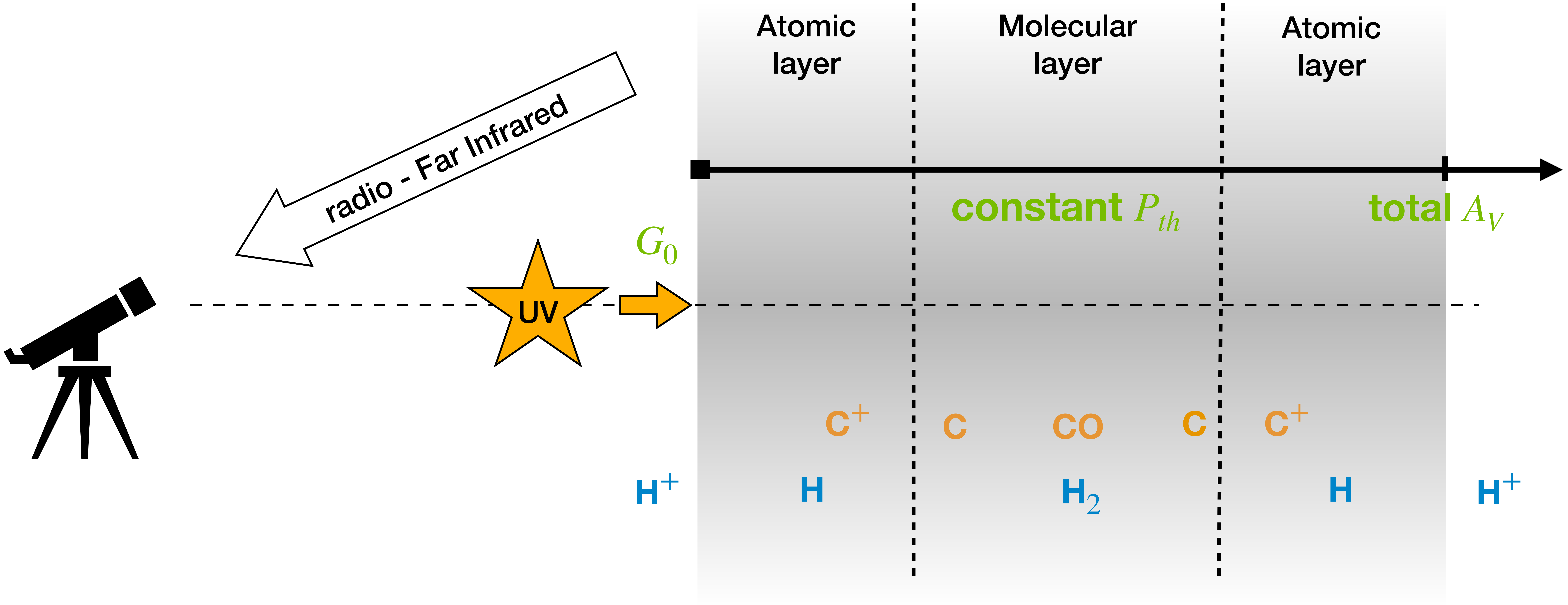
$\Longrightarrow$ Spatial regularization

$\Longrightarrow$ uncertainty quantification

$\Longrightarrow$ Fast

Method evaluated on a
synthetic PDR map

Photo-Dissociation Region (PDR)



Meudon PDR code

(Le Petit et al., 2006)

Parameters:

P_{th} - thermal pressure

G_0 - intensity of radiative field (in Habing units)

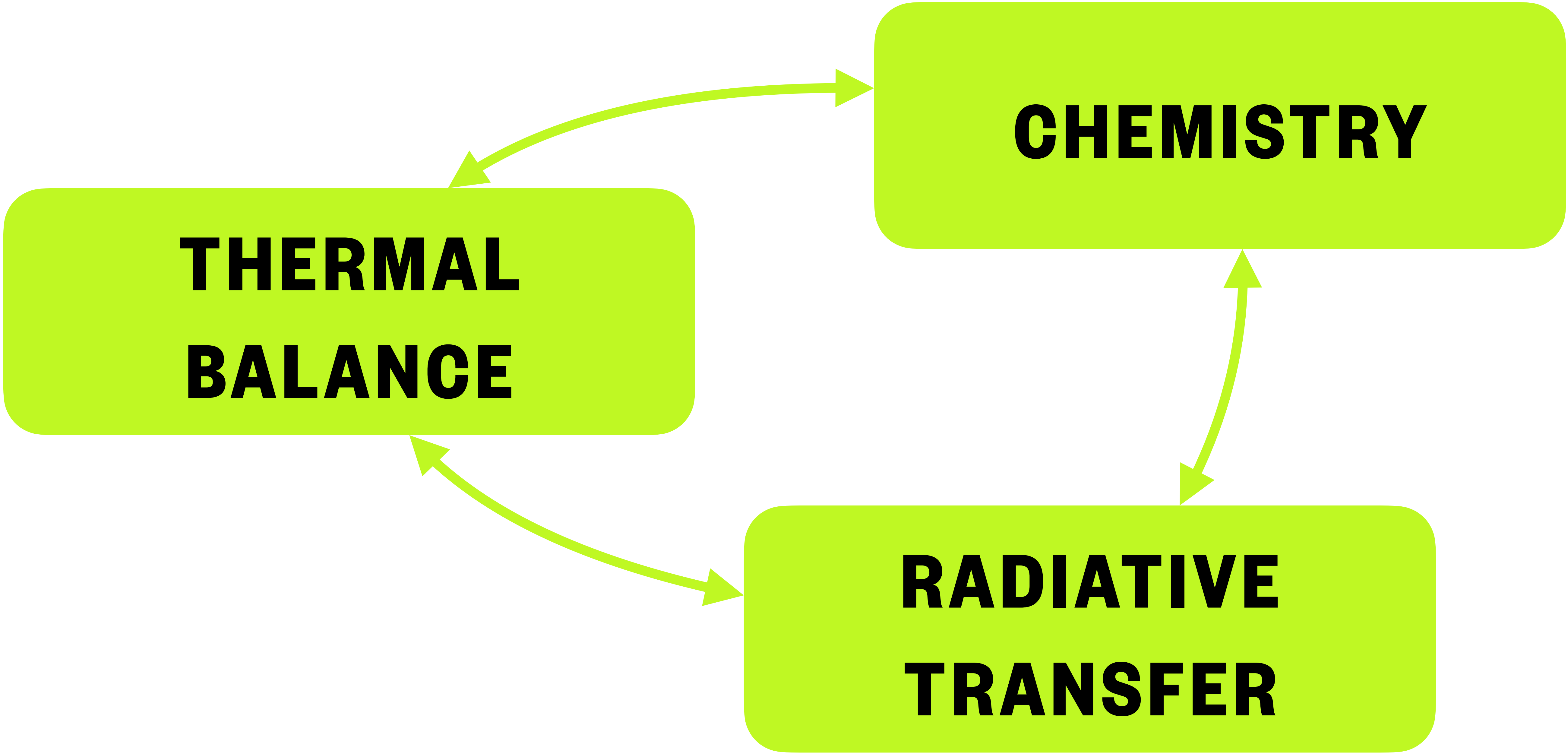
A_V - visual extinction

Code:

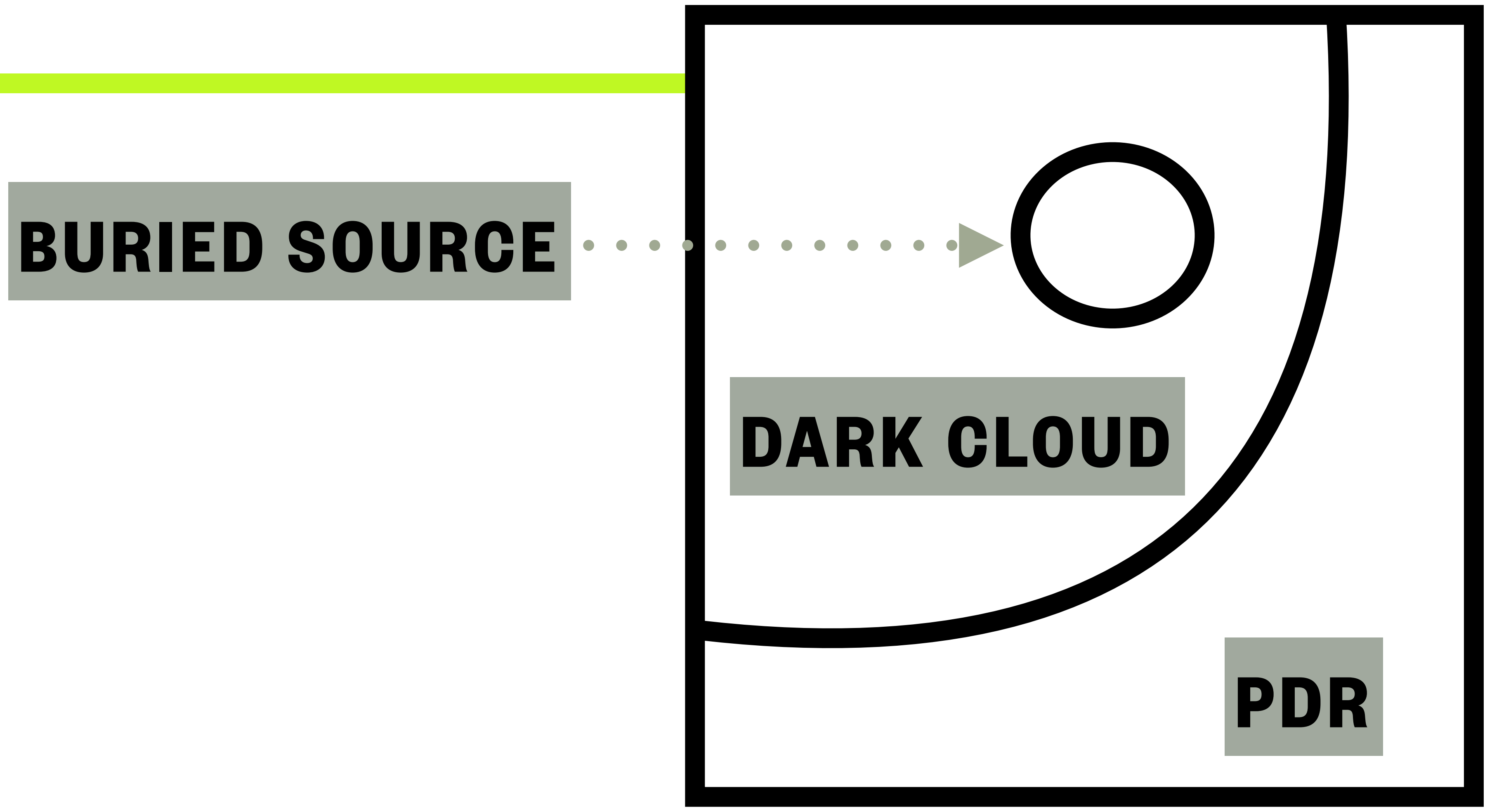
Iteratively Solves large set of partial differential equations

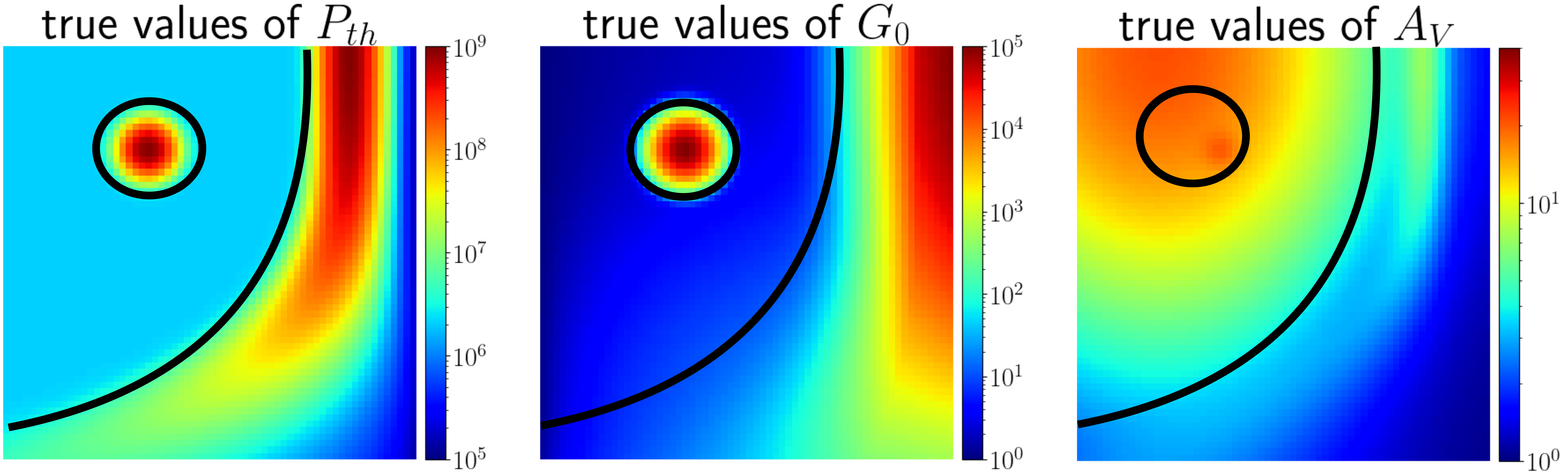
Observation:

Integrated intensities of a line



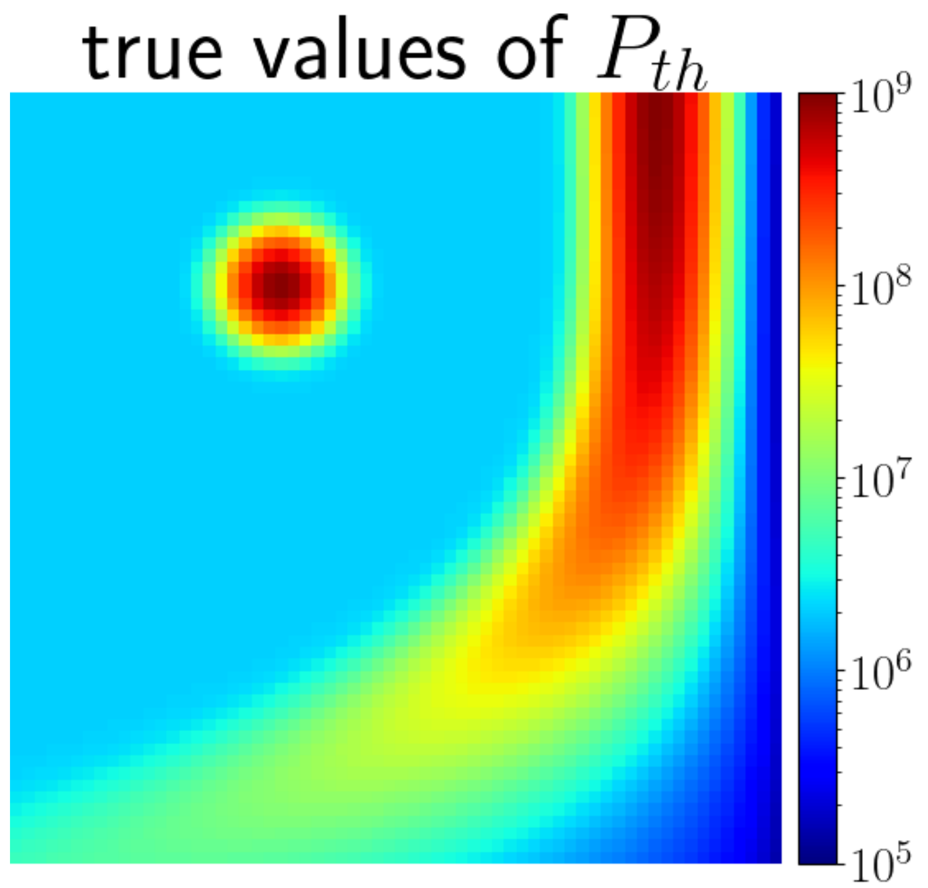
Synthetic PDR map

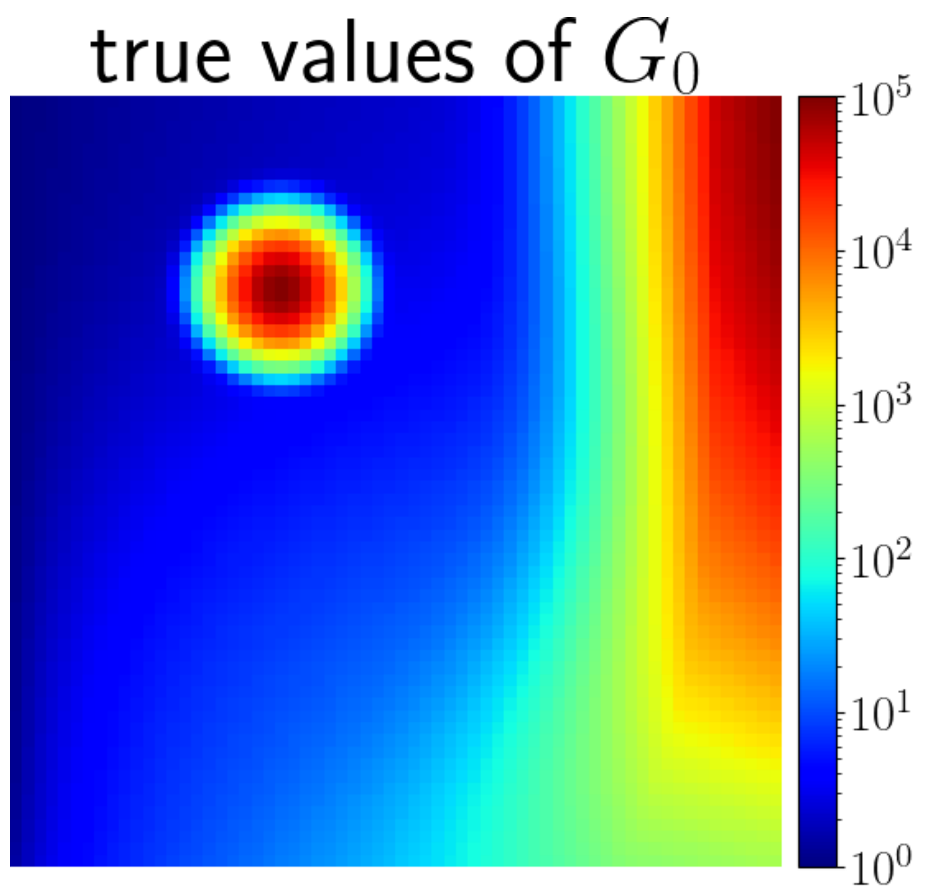




Synthetic PDR map

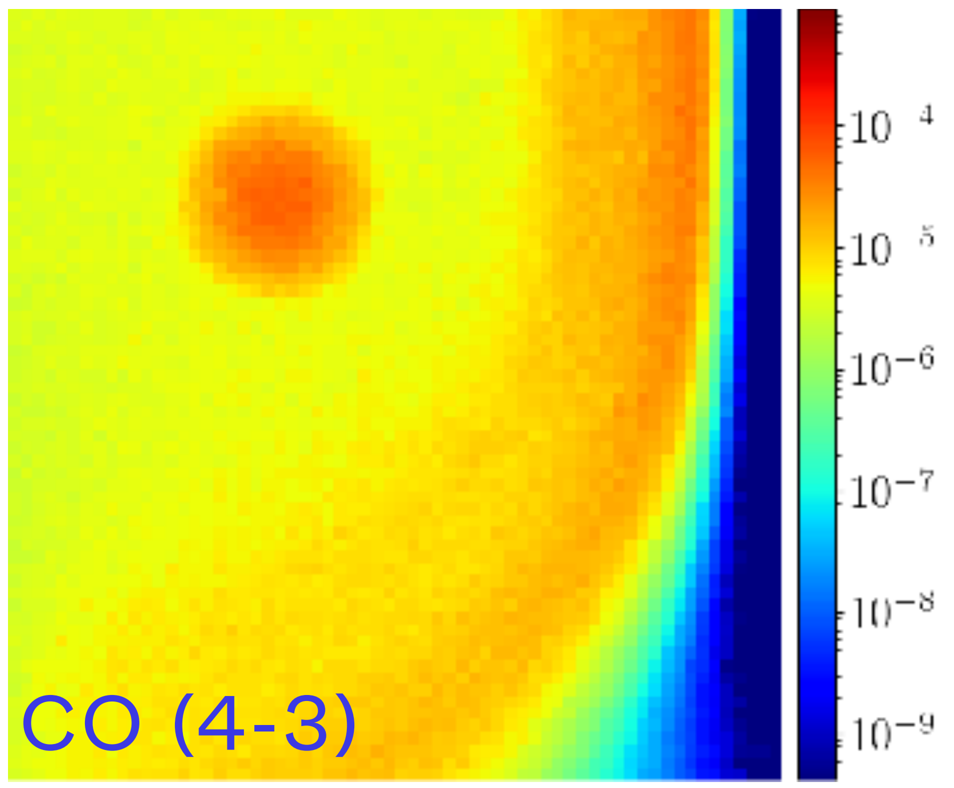
True maps





Meudon PDR
+
Noise

***Herschel*-like Observations**



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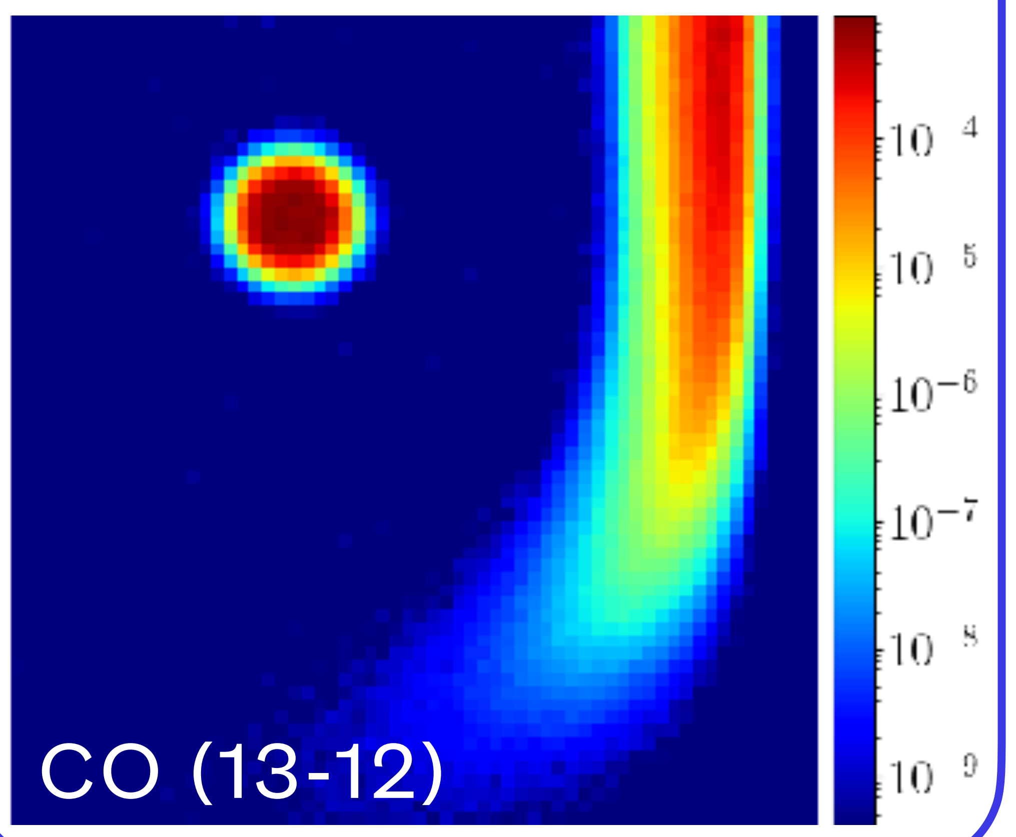
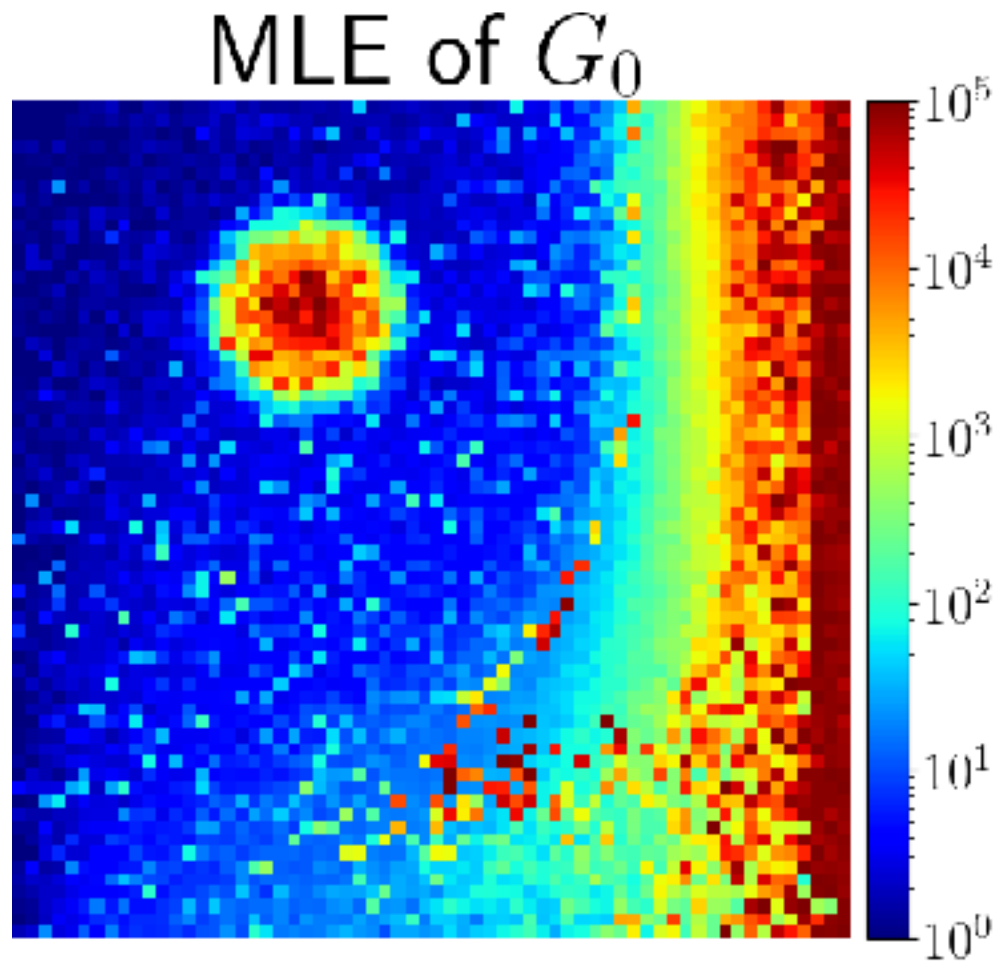


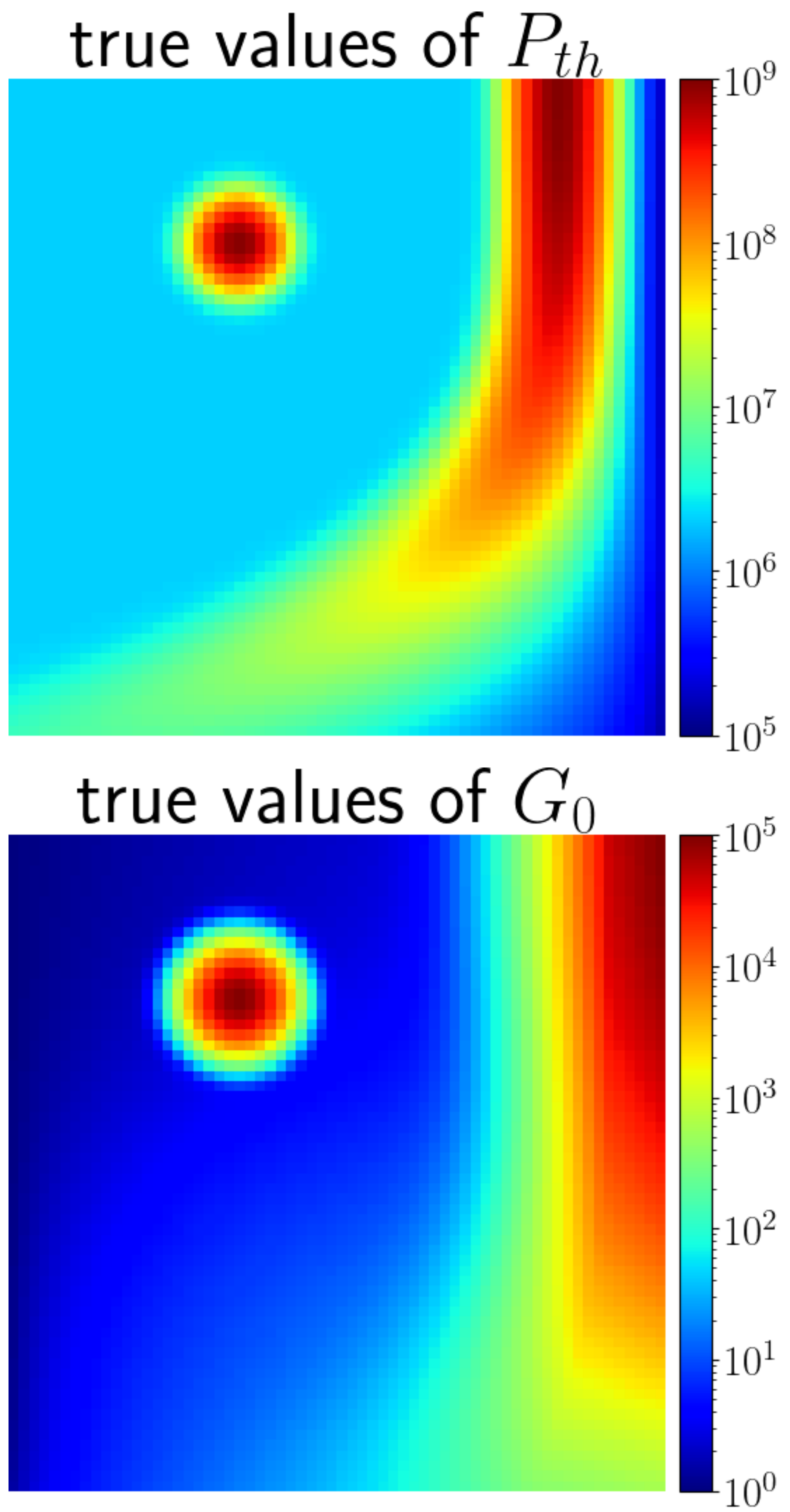
With previous method



Proposed method

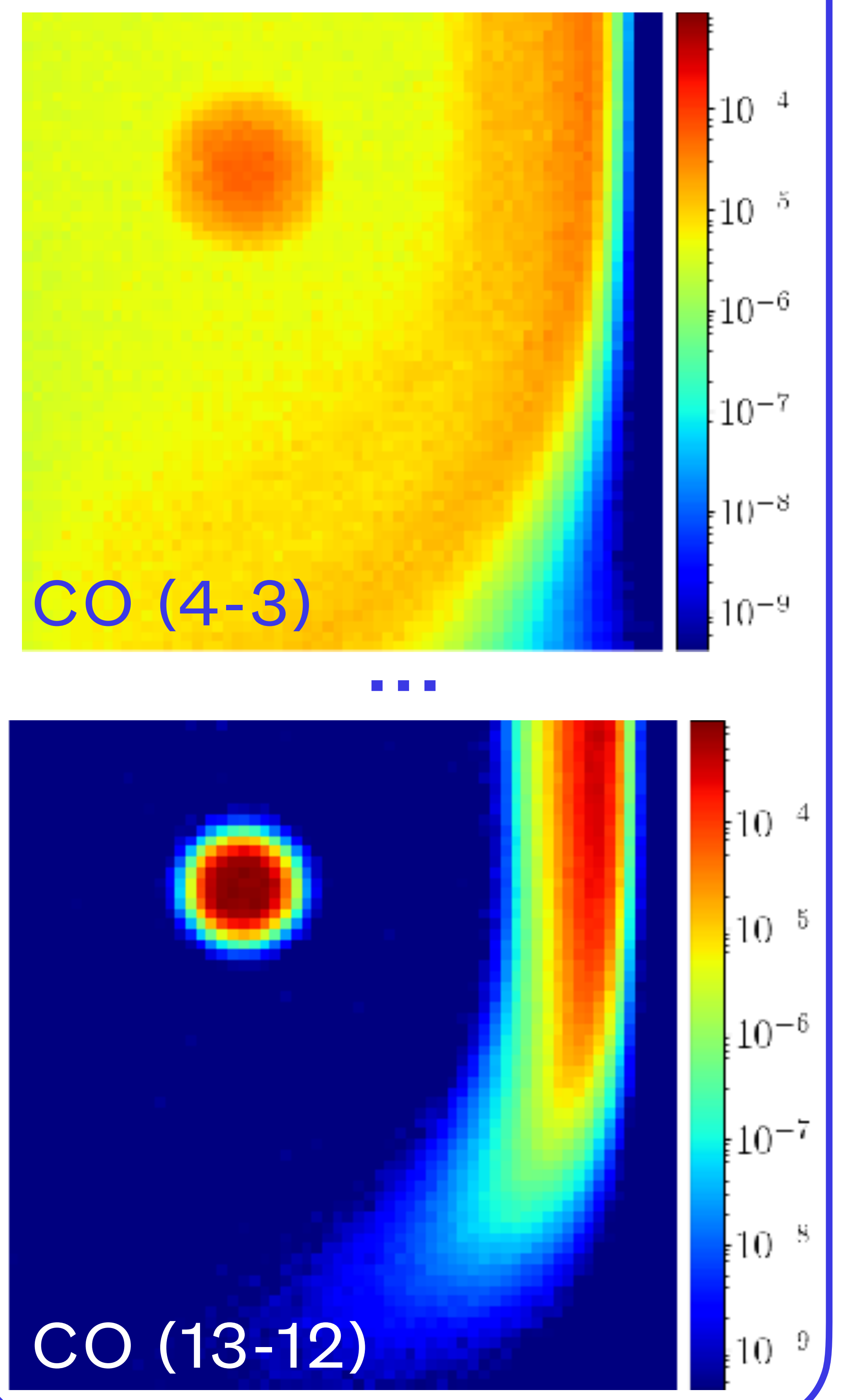
Synthetic PDR map

True maps

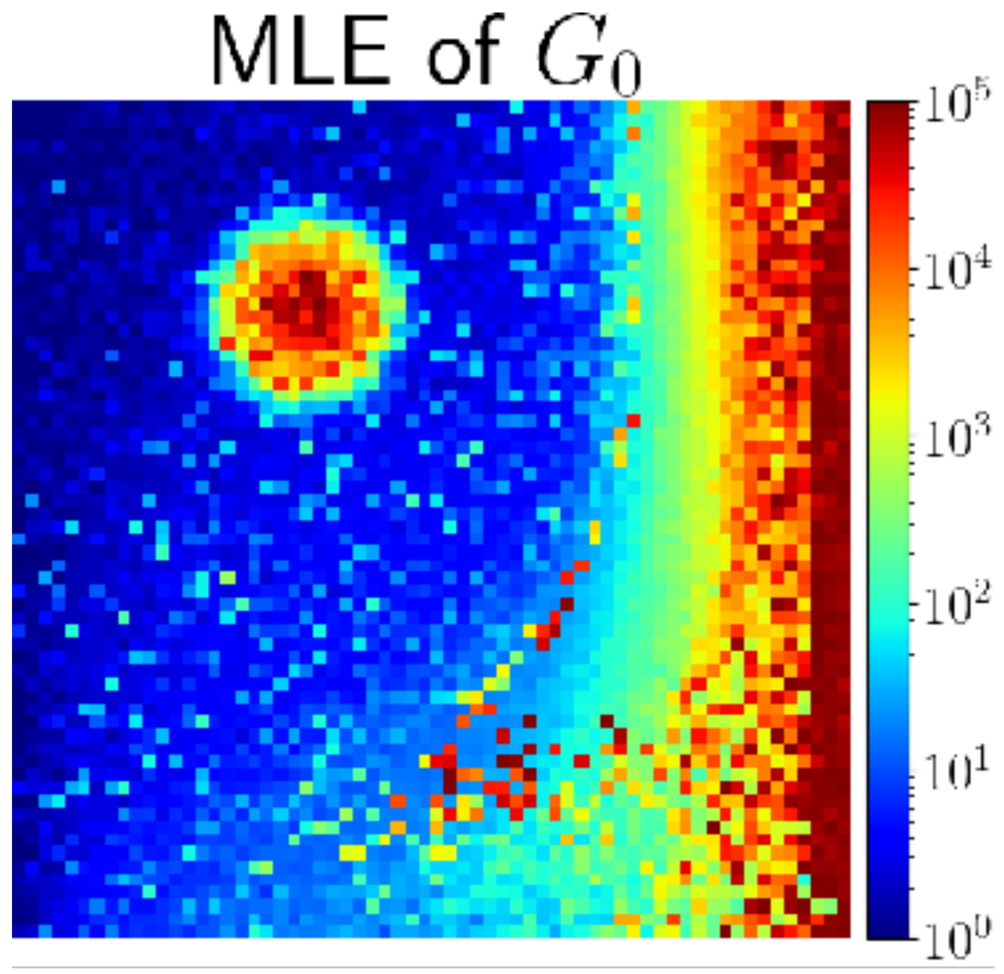


Meudon PDR
+
Noise

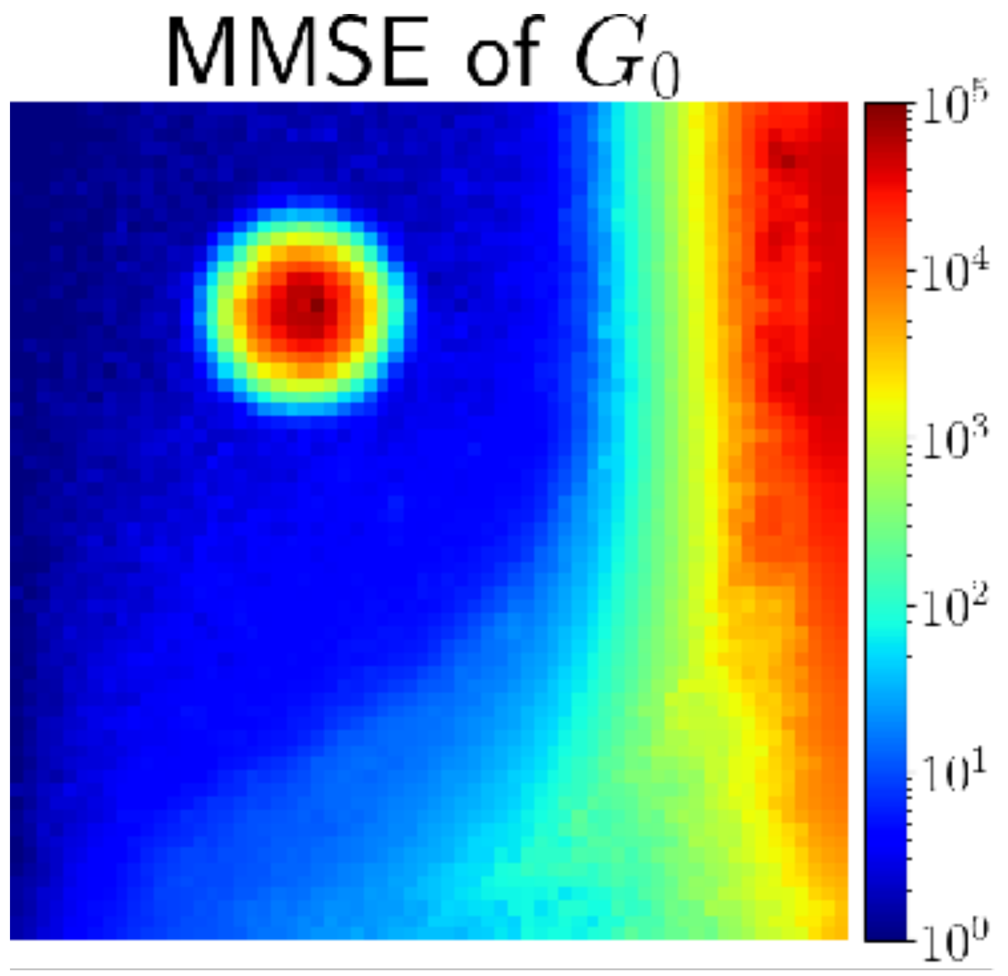
Herschel-like Observations



With previous method



Proposed method



Bayesian approach

Inference with **credibility intervals**
More complete description of parameter space
$\downarrow$

A posteriori probability distribution $\mathbb{P}[(P_{th}, G_0, A_V) \,|\, Y]$

$$\underbrace{\mathbb{P}[(P_{th}, G_0, A_V) \,|\, Y]}_{\text{A posteriori}} \propto \underbrace{\mathbb{P}[Y \,|\, (P_{th}, G_0, A_V)]}_{\textbf{Likelihood}} \; \underbrace{\mathbb{P}[(P_{th}, G_0, A_V)]}_{\textbf{Spatial prior}}$$

Complex distribution
$\Longrightarrow$ impossible to extract estimators as is

$\Longrightarrow$ sample from it with **MCMC algorithm**

Observation model

$$\begin{cases} \text{If detected: } y_{n,\ell} = \epsilon^{(m)}_{n,\ell} f_\ell(\theta_n) + \epsilon^{(a)}_{n,\ell} \\ \text{Otherwise: } y_{n,\ell} \leq \omega \end{cases}$$

With

$y_{n,\ell}$: actual observation

$f_\ell(\theta_n)$: predicted observation

$\epsilon^{(m)}_{n,\ell}$: multiplicative noise

$\epsilon^{(a)}_{n,\ell}$: additive noise

ω : telescope detectability limit

How to deal with **expensive numerical code** f ?

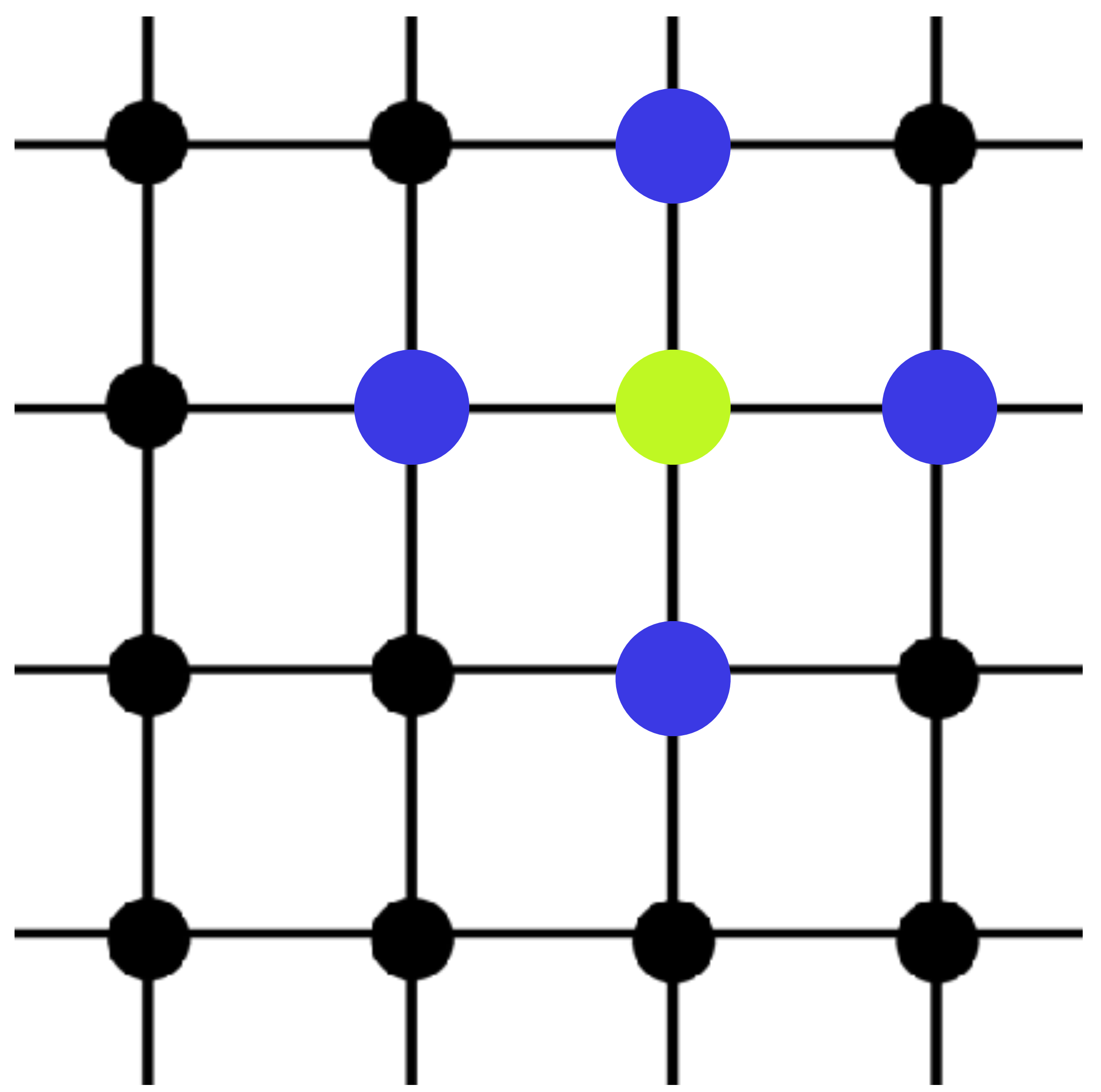
Approximation of f
(e.g., with a neural network)

How to deal with **both** additive and multiplicative noises ?

Approximation of likelihood

SNR	Noise model
Low	Additive
High	Multiplicative
Intermediate	Mixture

Spatial Regularization

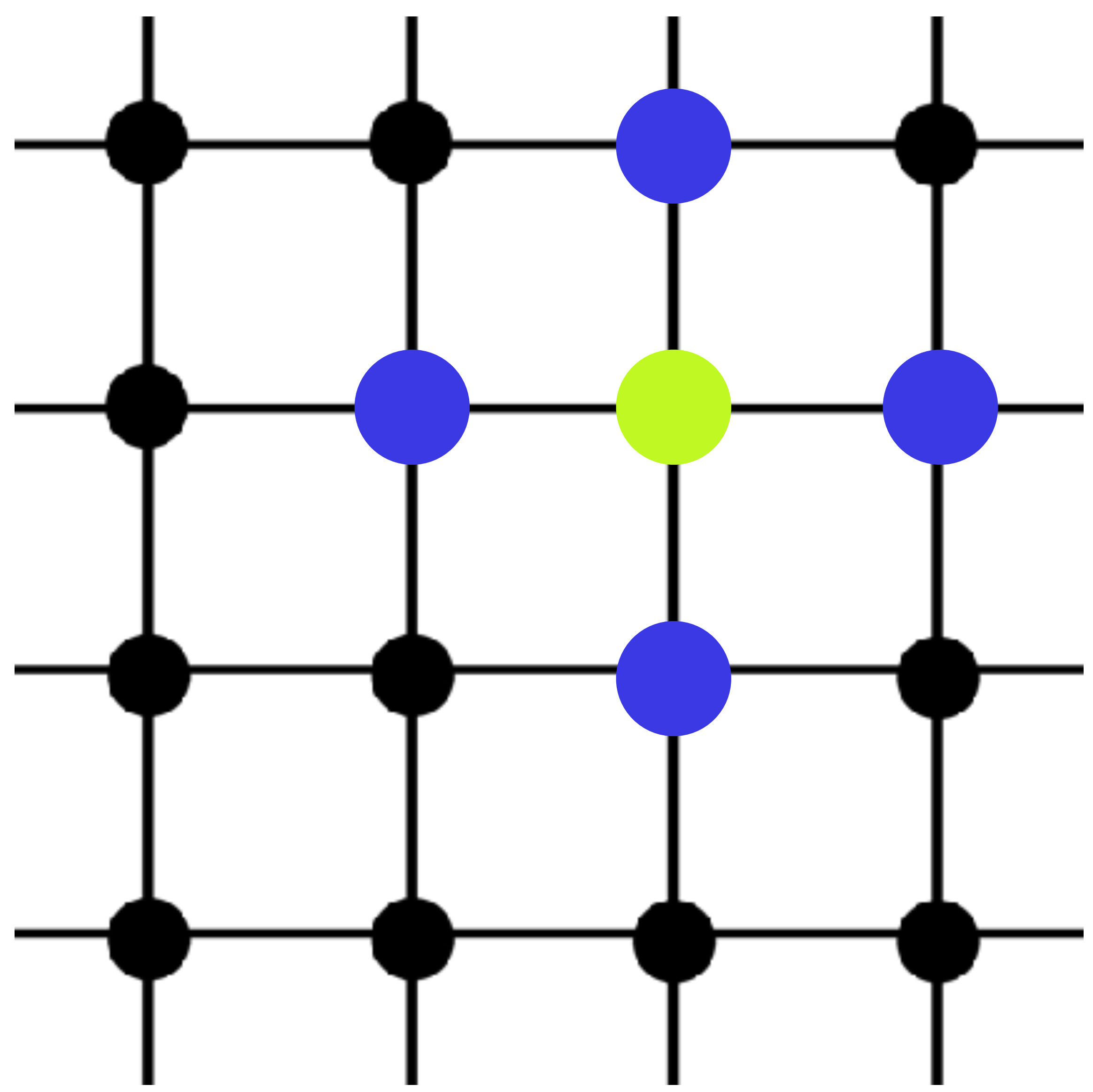


Neighbour of

Should be close to the average of

$\simeq$ **adaptive stacking**

Spatial Regularization

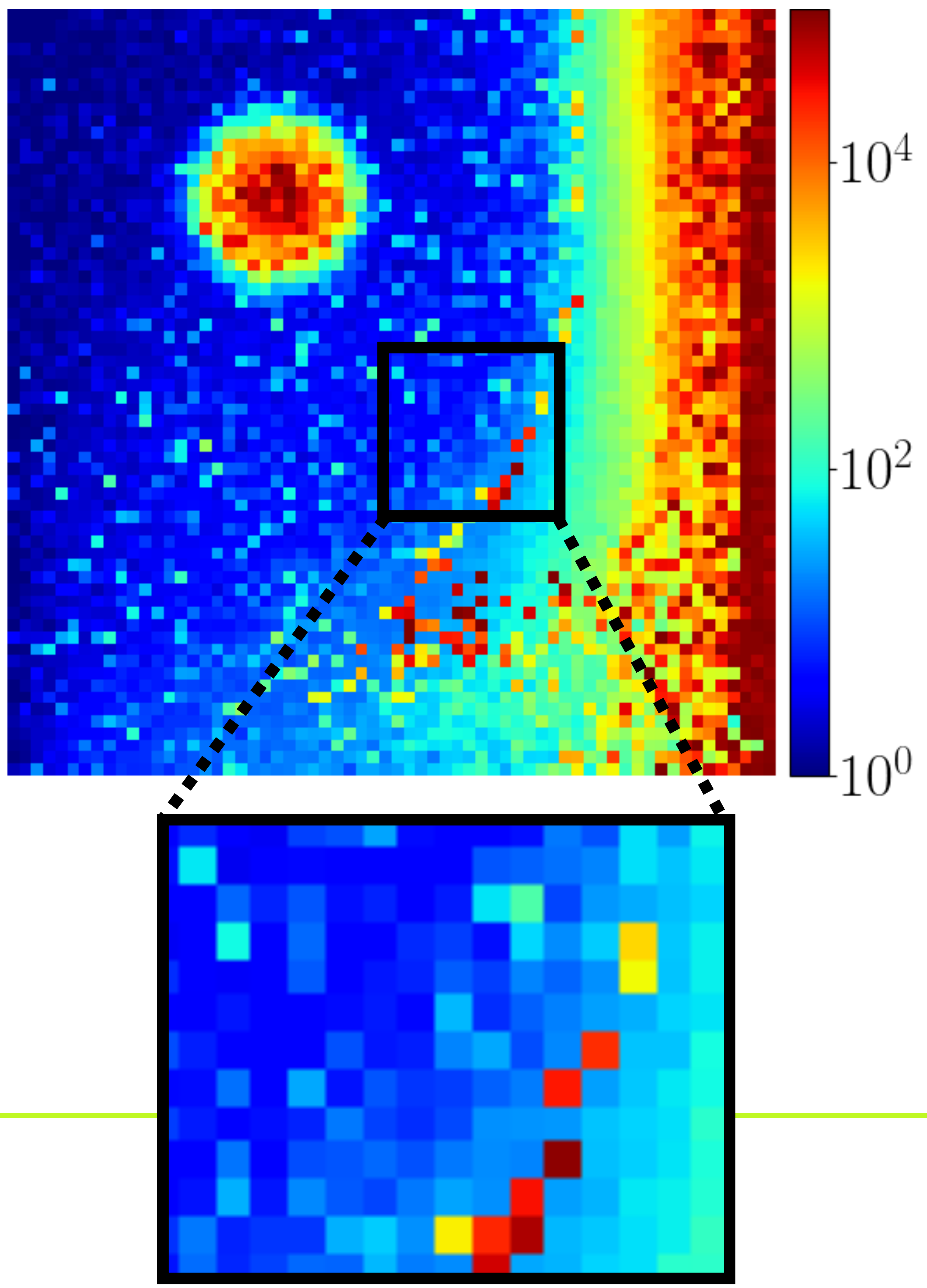


Neighbour of

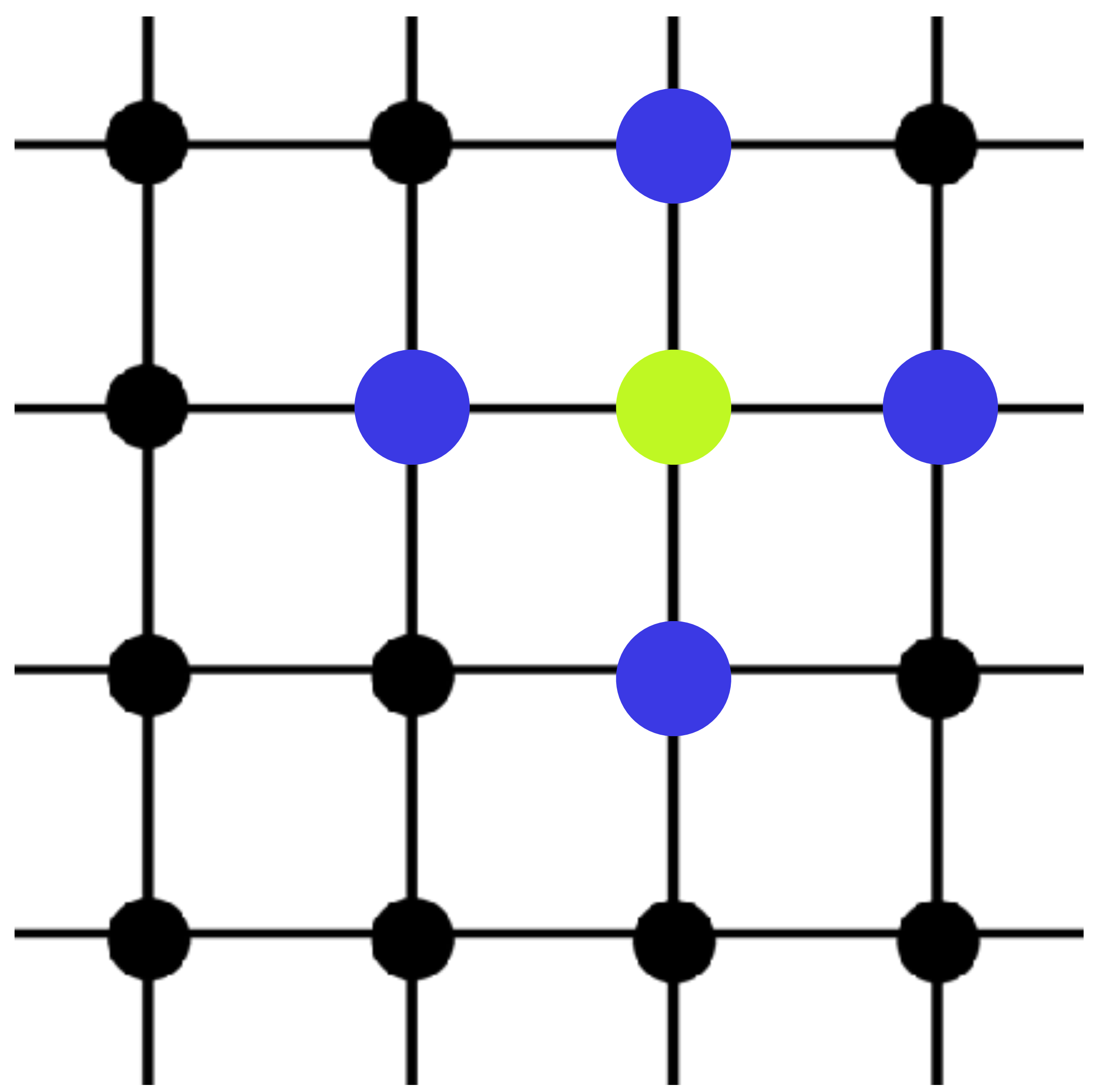
Should be close to the average of

$\simeq$ **adaptive stacking**

Not smooth $\implies$ High penalty ❌



Spatial Regularization

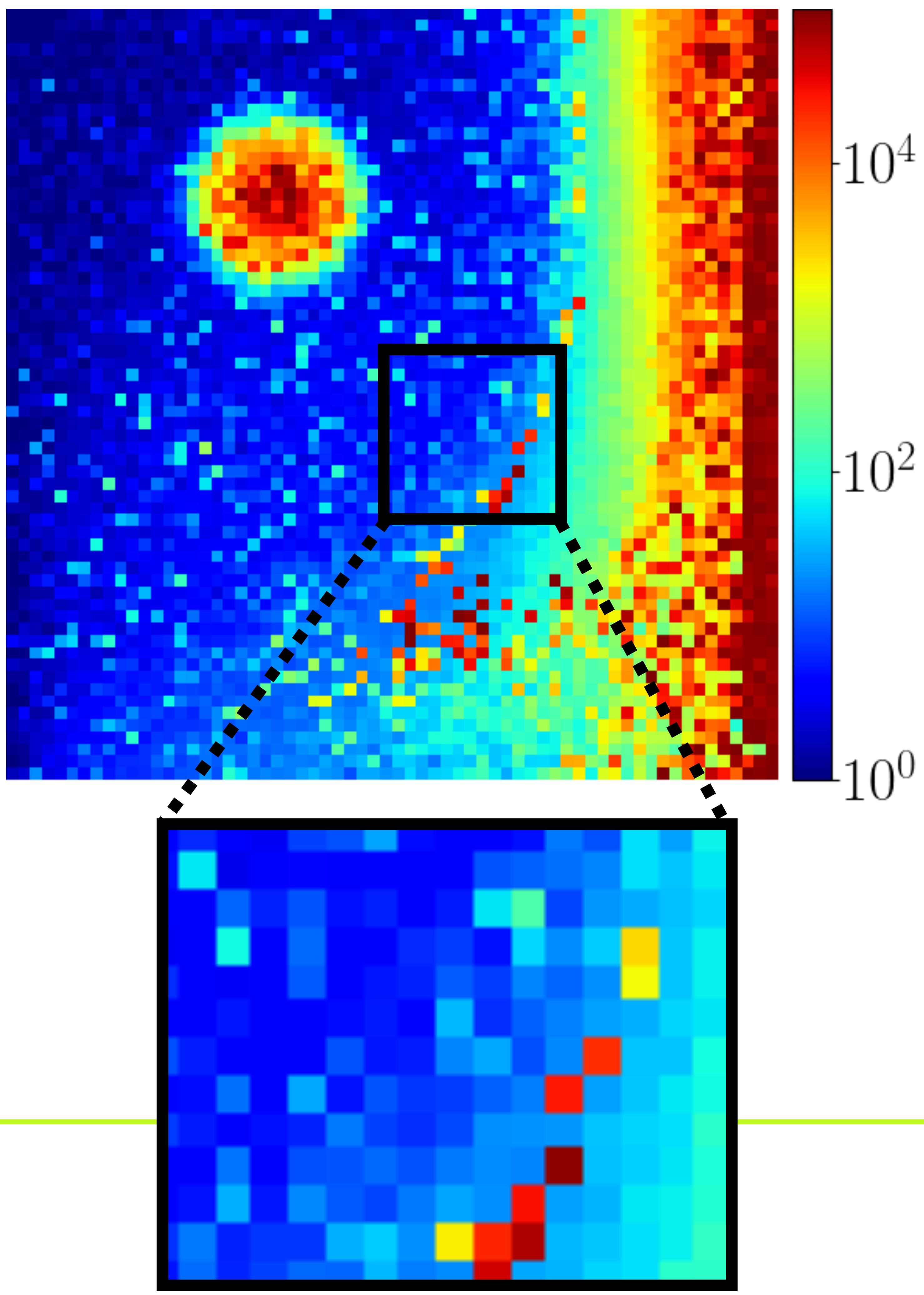


Neighbour of

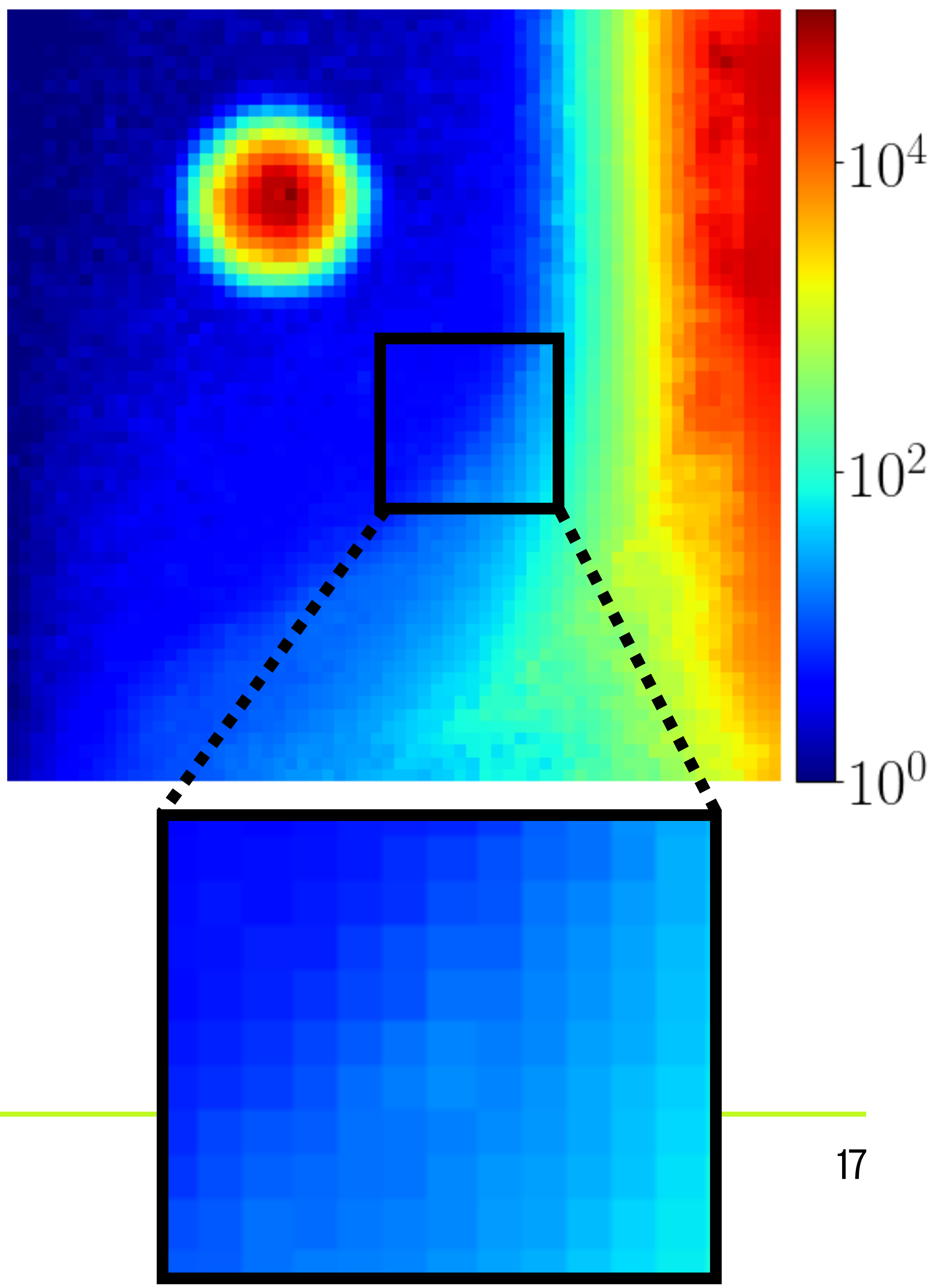
Should be close to the average of

$\simeq$ **adaptive stacking**

Not smooth $\Longrightarrow$ High penalty ✗

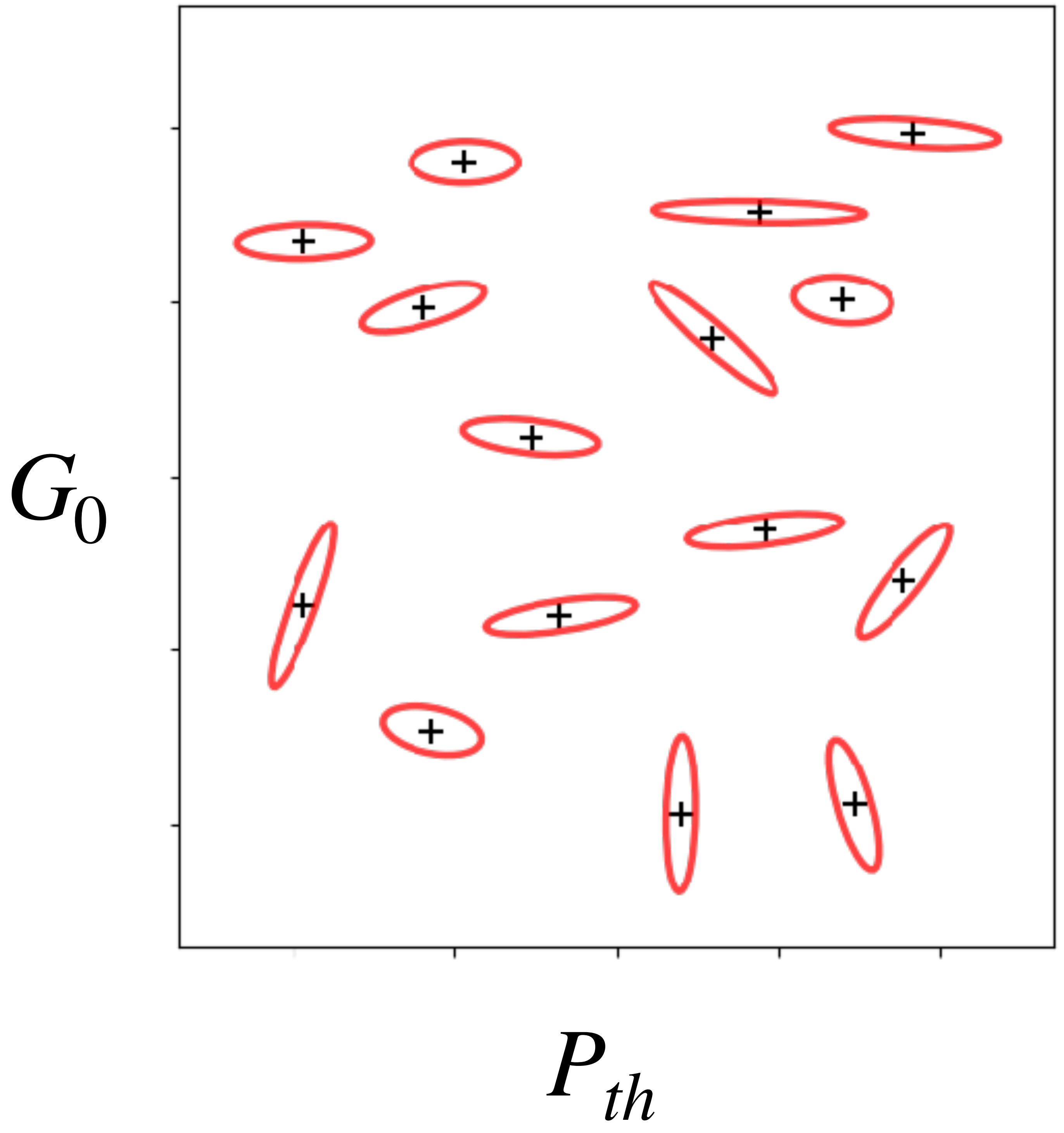


Smooth $\Longrightarrow$ Low penalty ✓



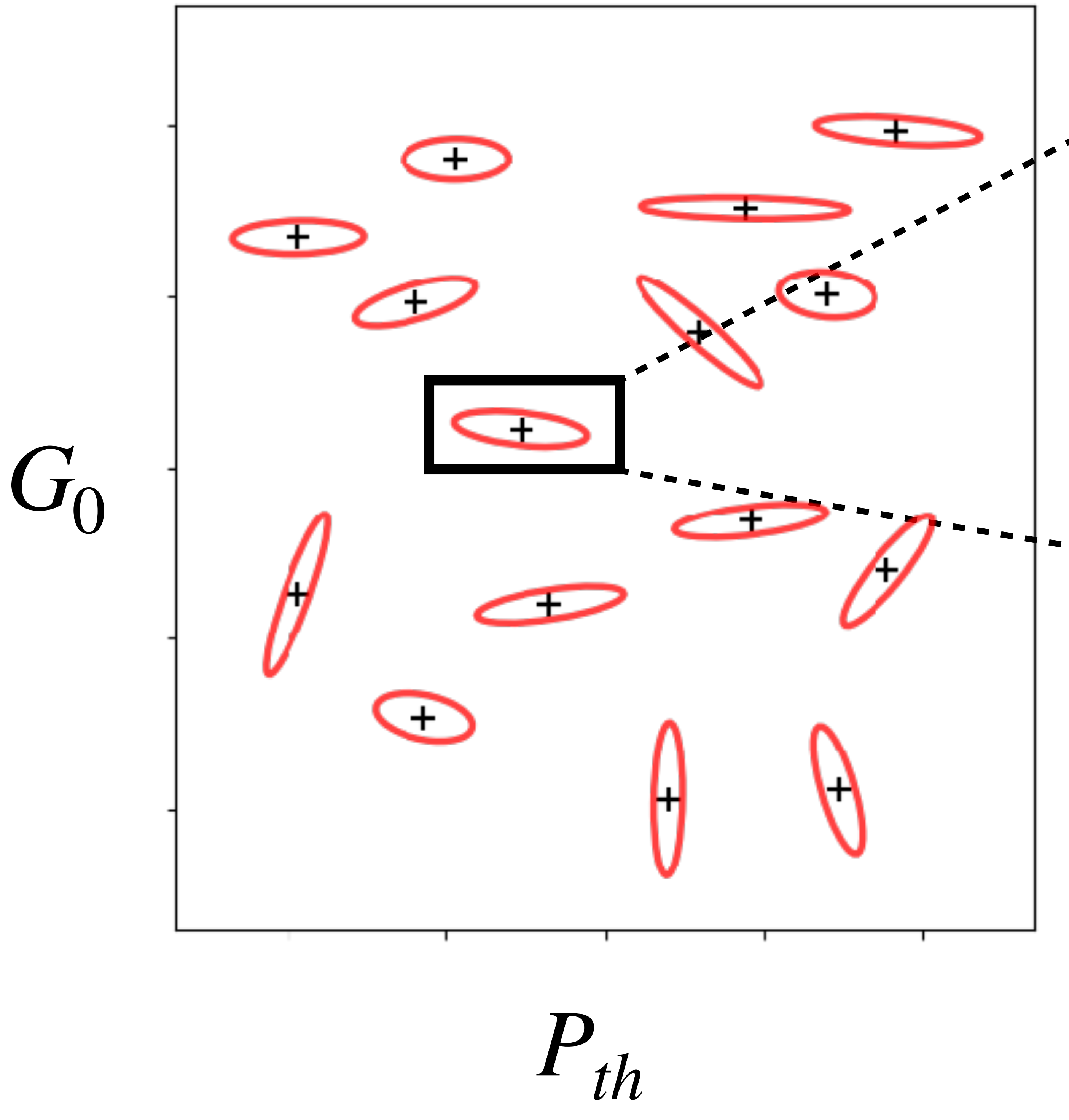
Markov Chain Monte Carlo

Some Gaussian Mixture
How to explore all modes?

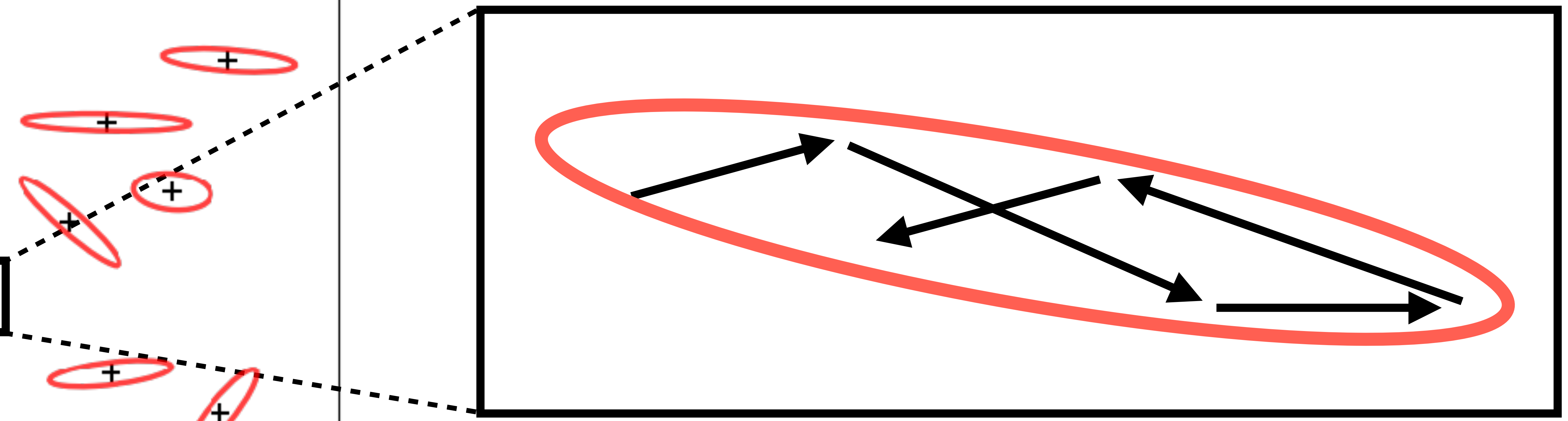


Monte Carlo Markov Chain

Some Gaussian Mixture
How to explore all modes?



PMALA transition kernel
Fast local exploration



Pressure P_th	G_0
Not constrained	Well constrained
Large steps	Small steps

Monte Carlo Markov Chain

Some Gaussian Mixture
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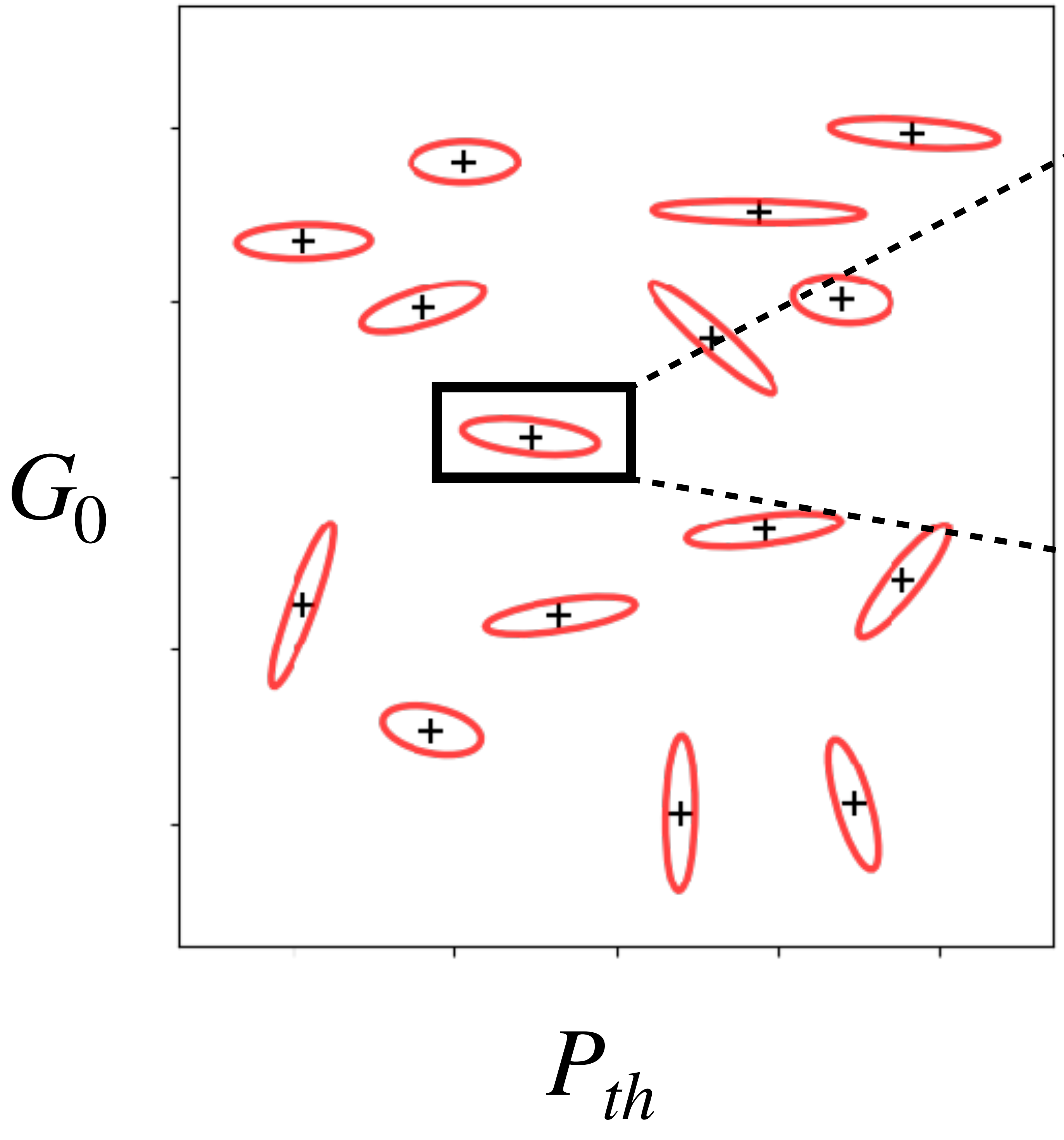

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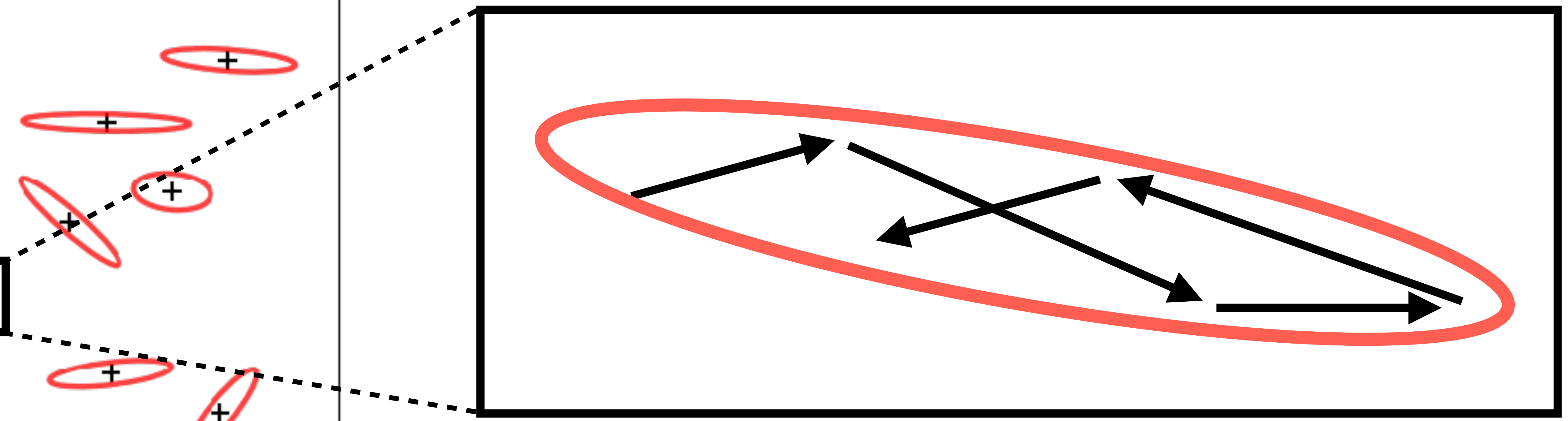


Pressure P_th	G_0
Not constrained	Well constrained
Large steps	Small steps

MTM transition kernel
Jumps between modes

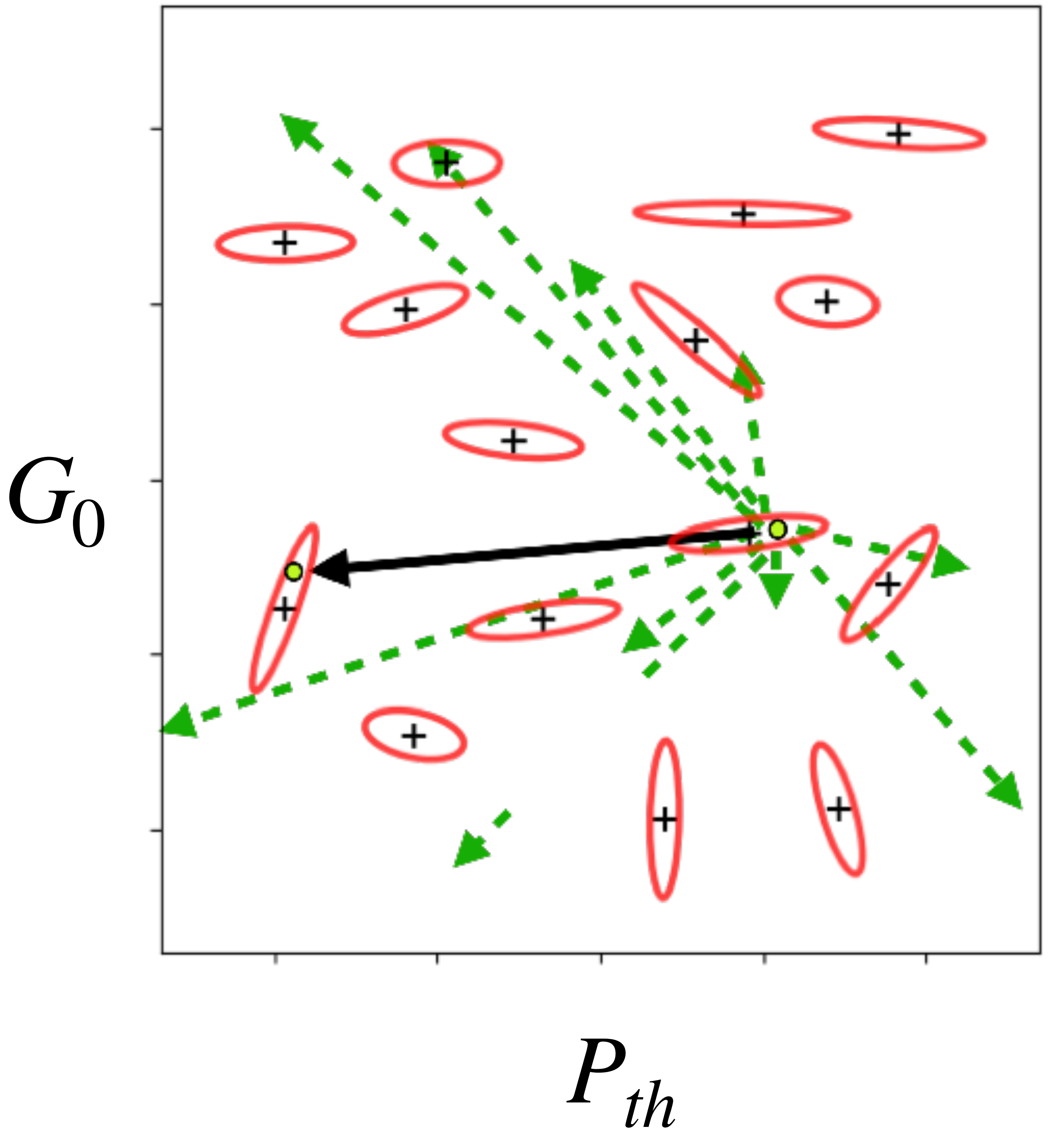
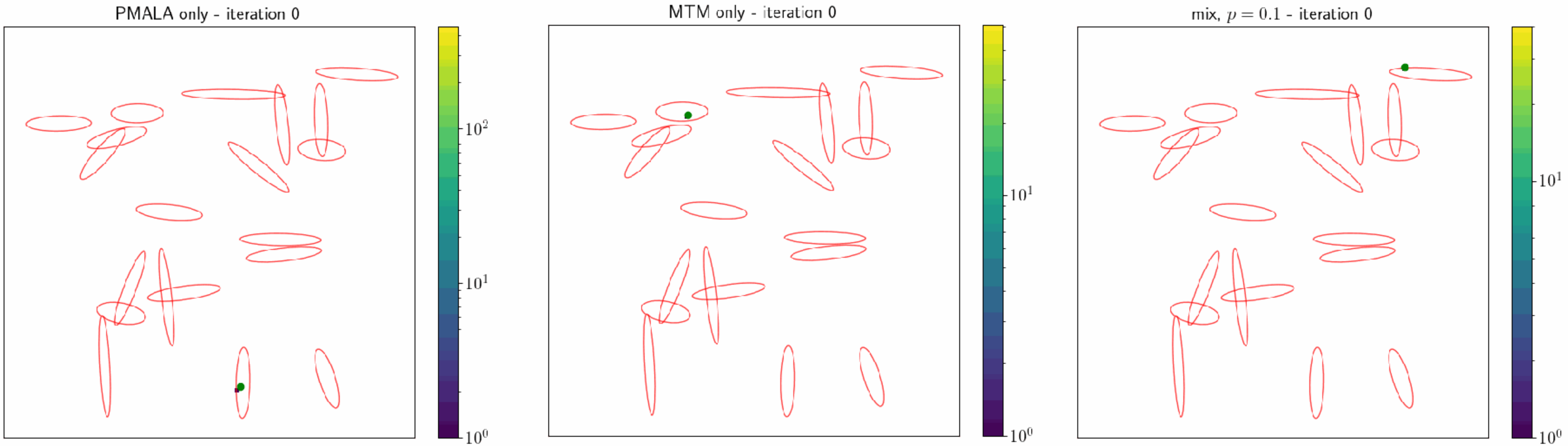
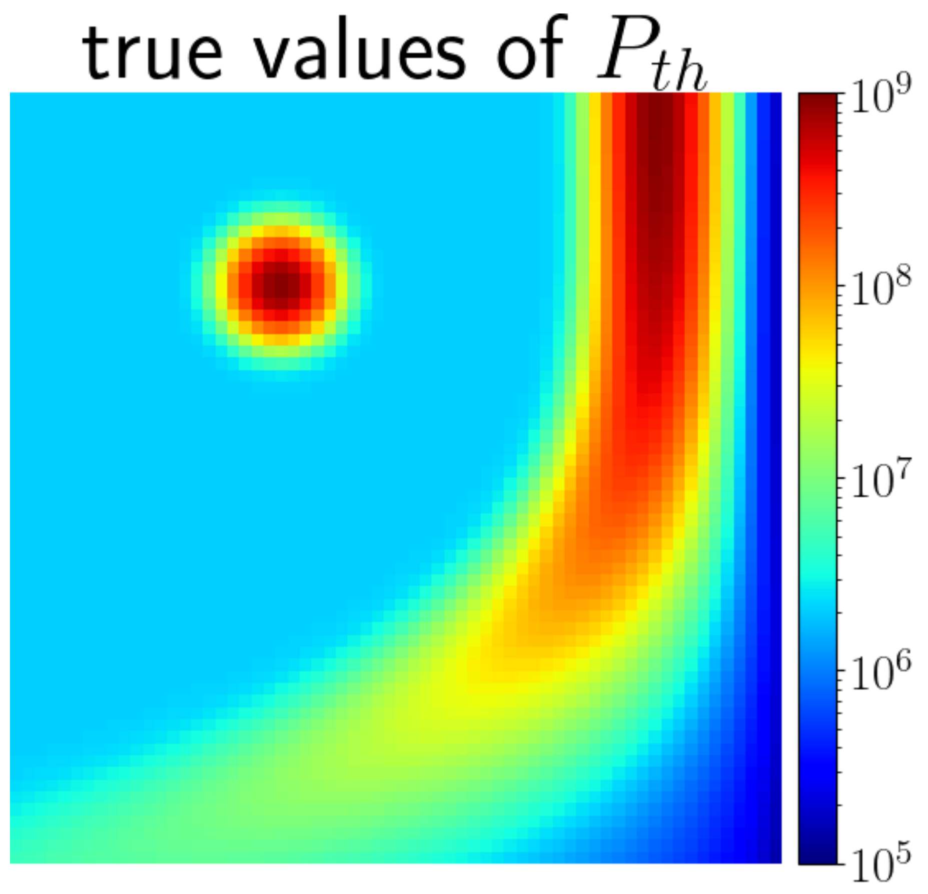


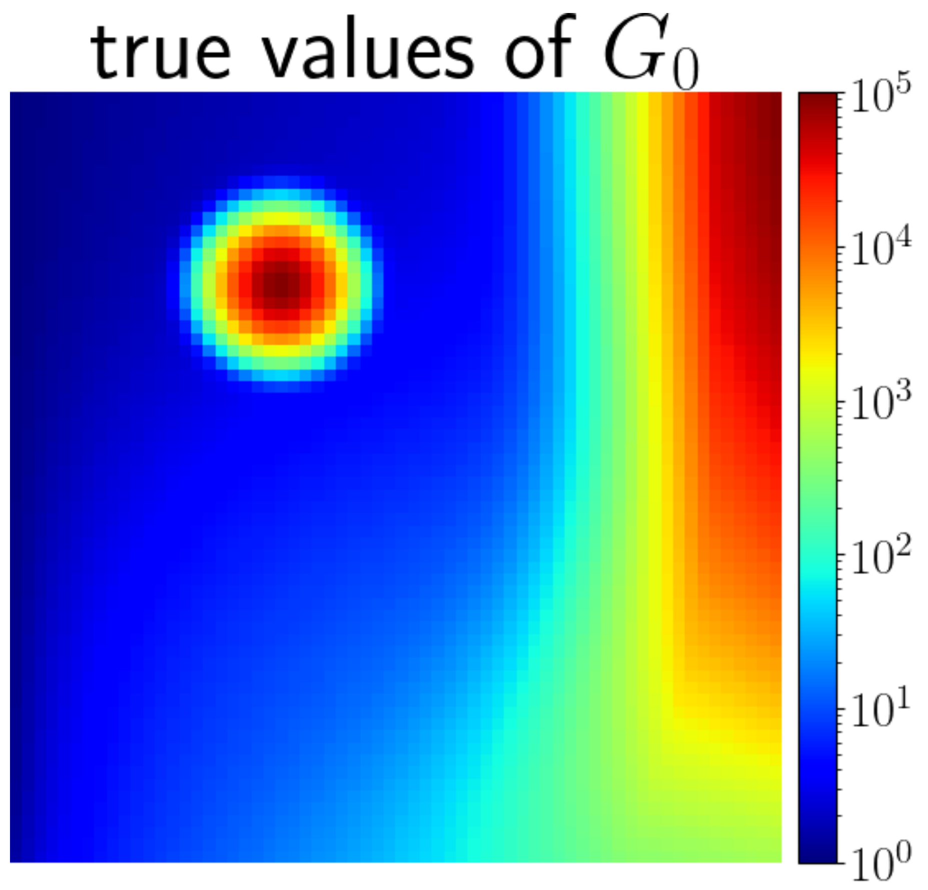
Illustration on Gaussian mixture



Synthetic PDR map

True maps





Meudon PDR
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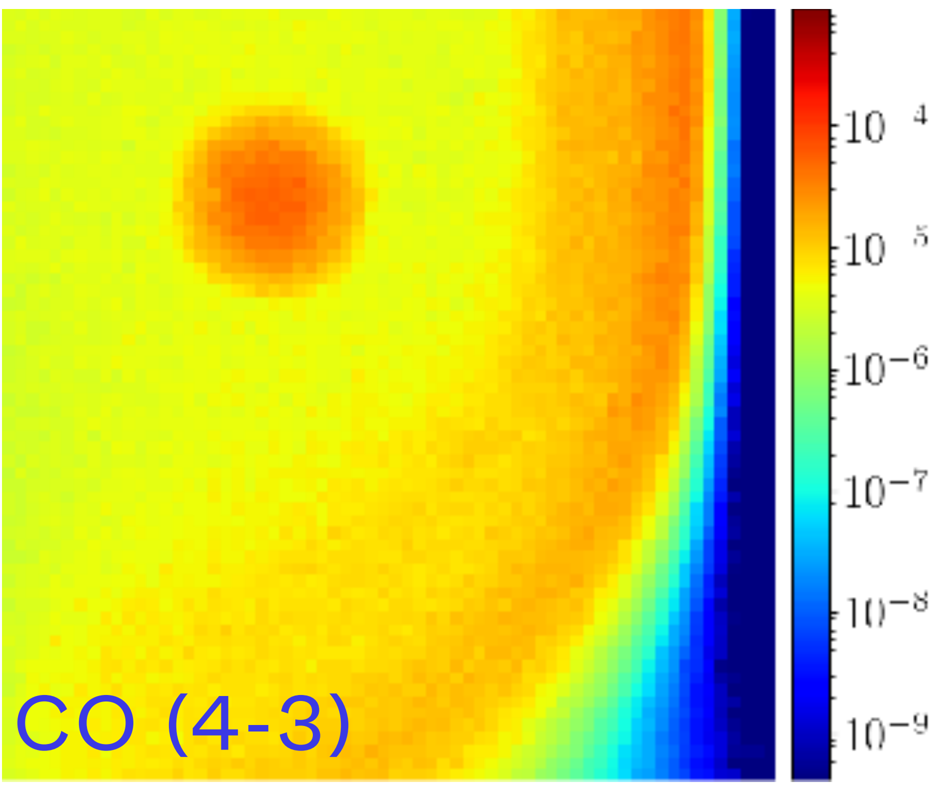
Noise

Herschel-like Observations



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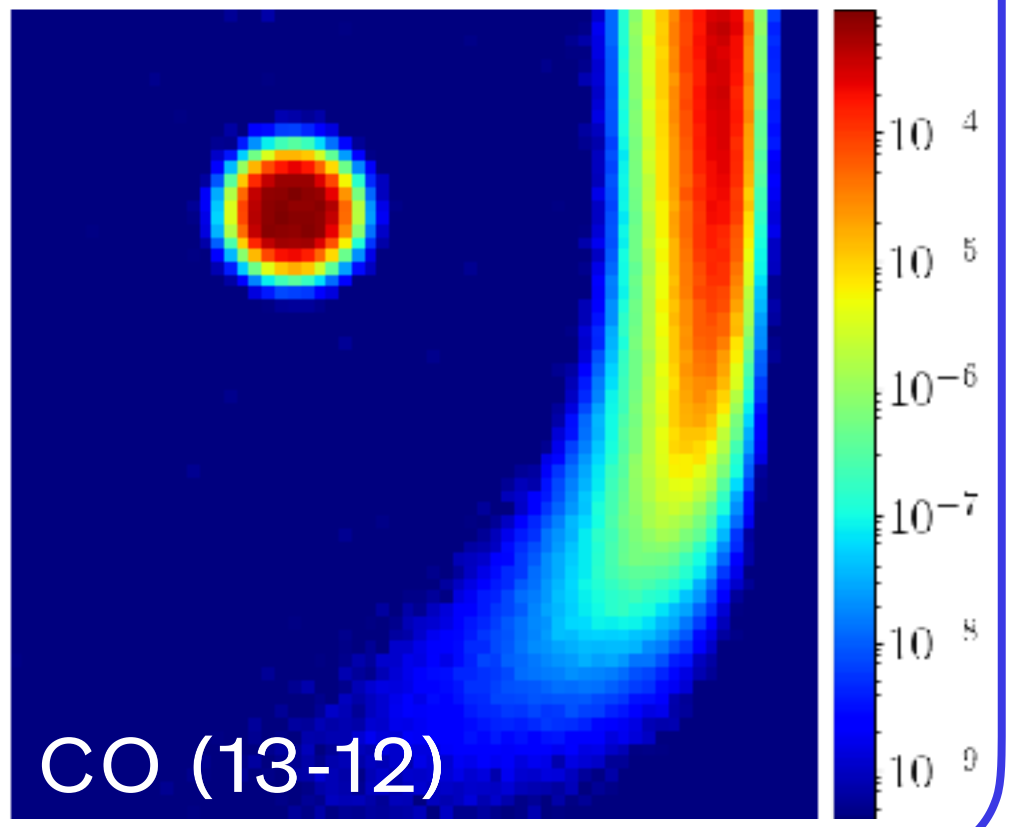
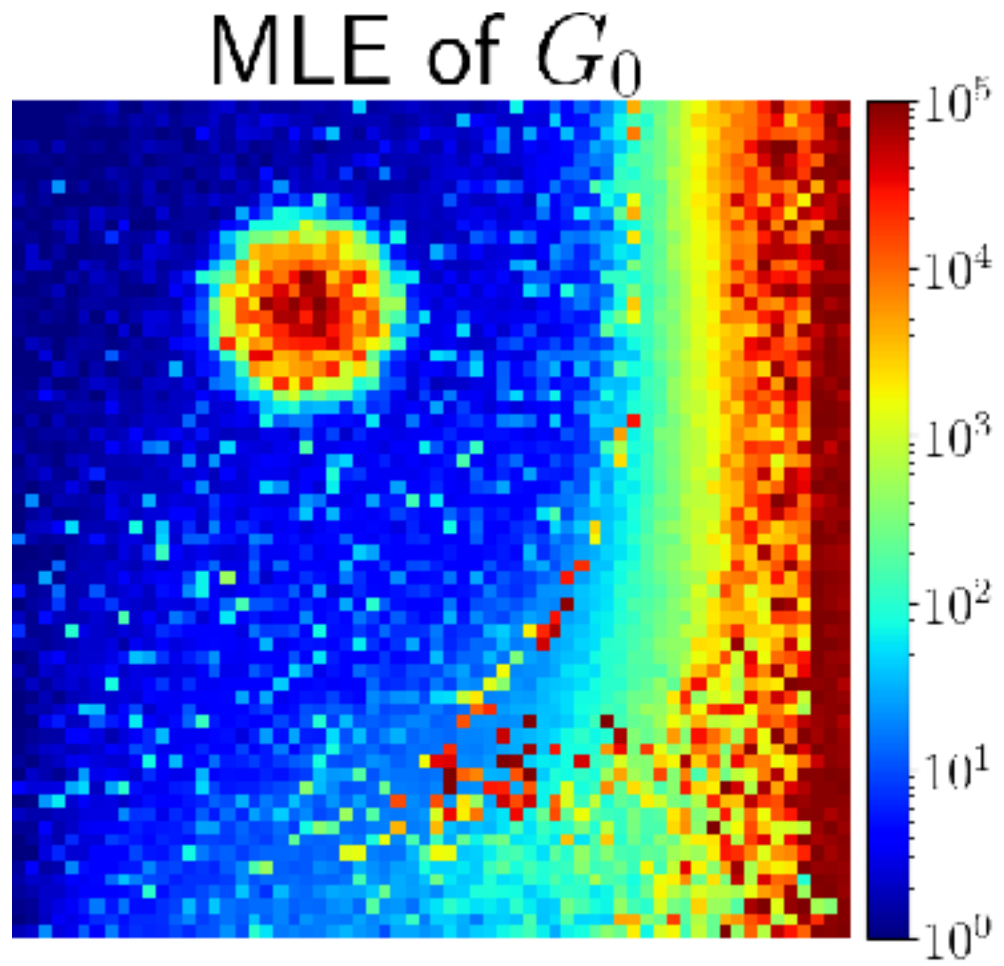
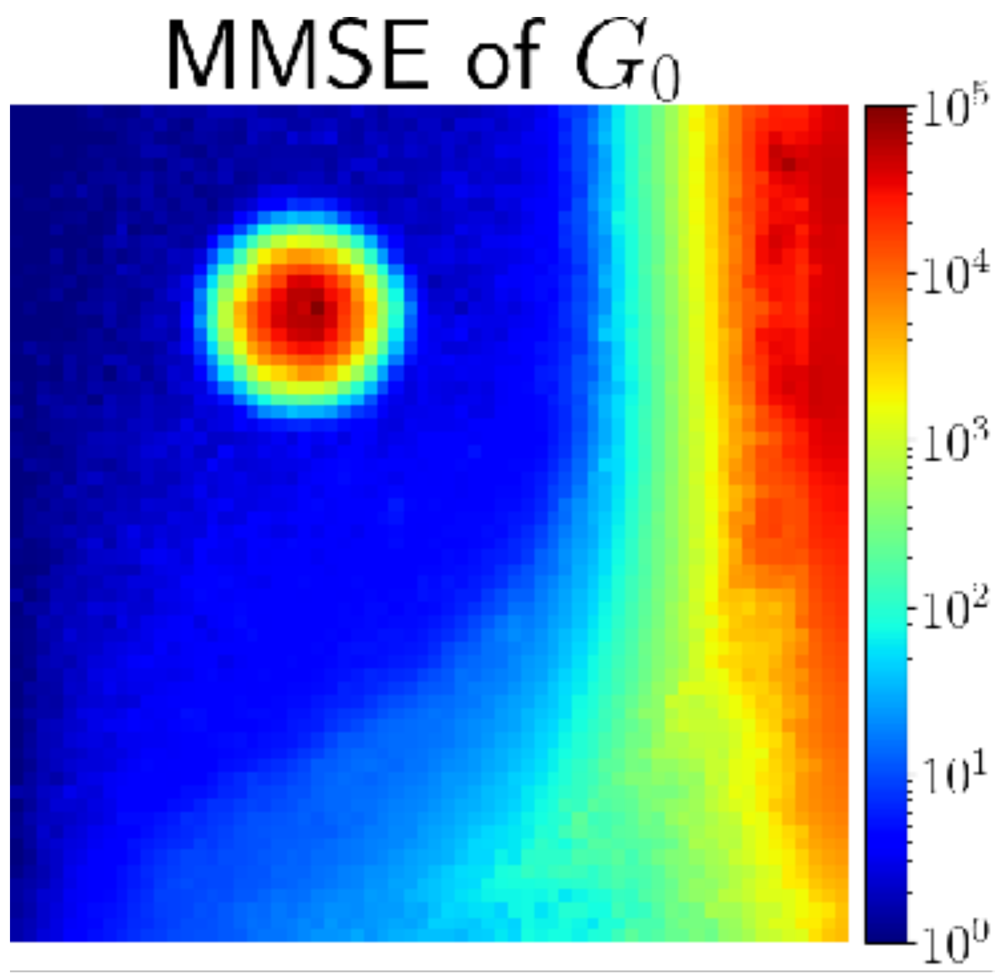


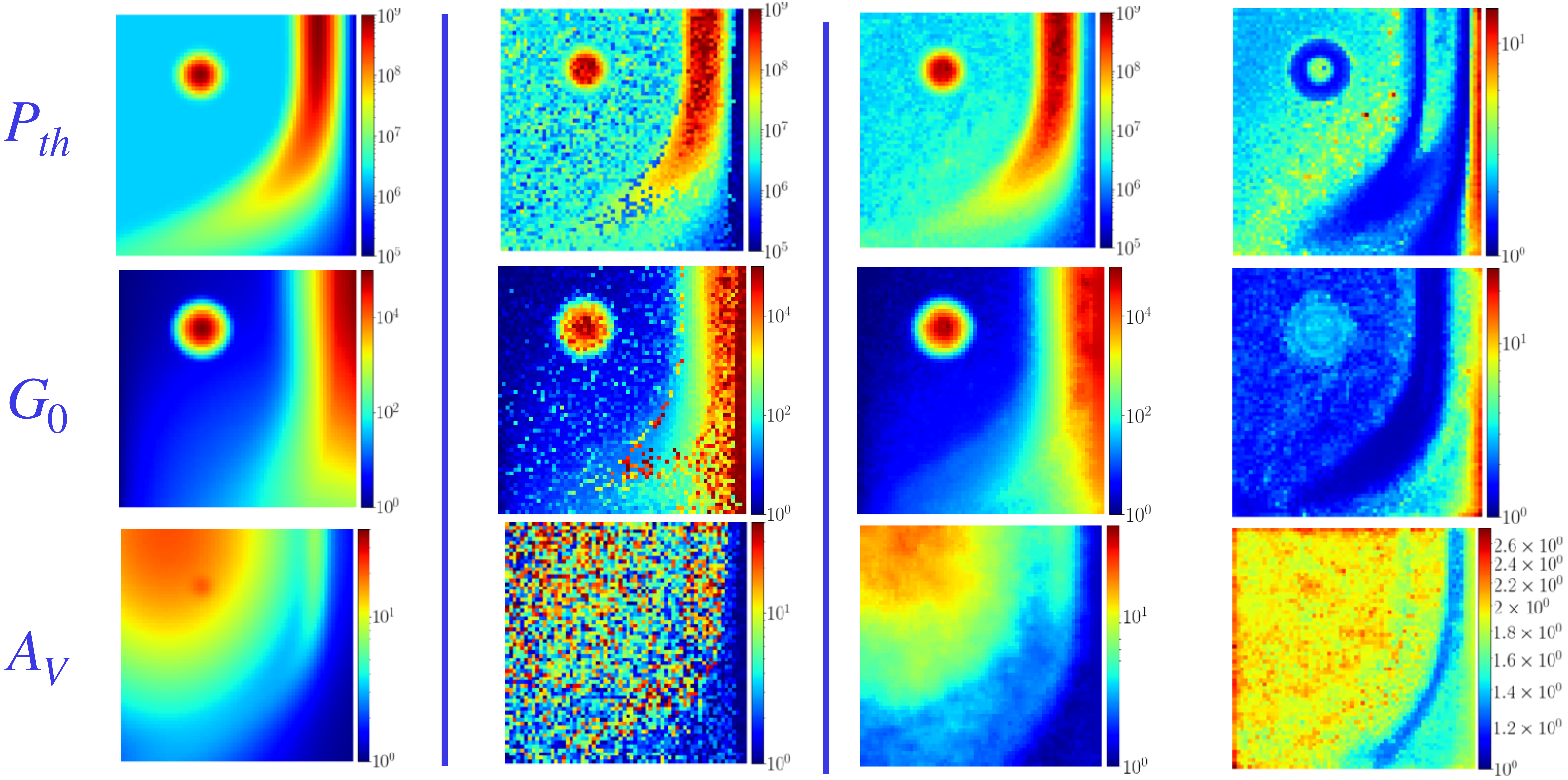
With previous method



Proposed method



True values | Classic method | Proposed method | Credibility Intervals



Application to real data: NGC 7023

One of the most studied PDR

Close to us (~ 320 pc)

Edge-on geometry

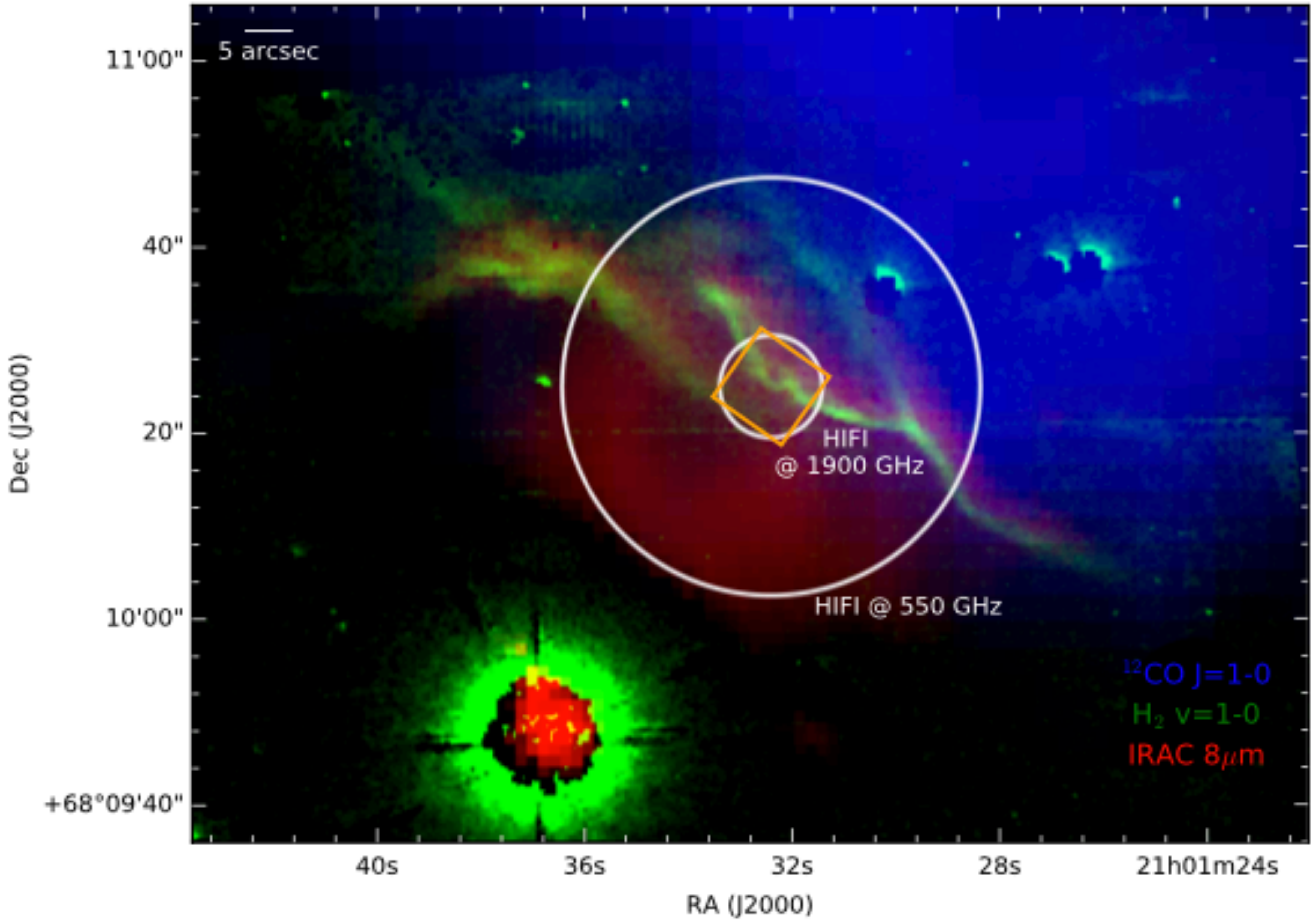
Illuminated by a spectroscopic binary system (B3Ve and B5)

Previous estimations:

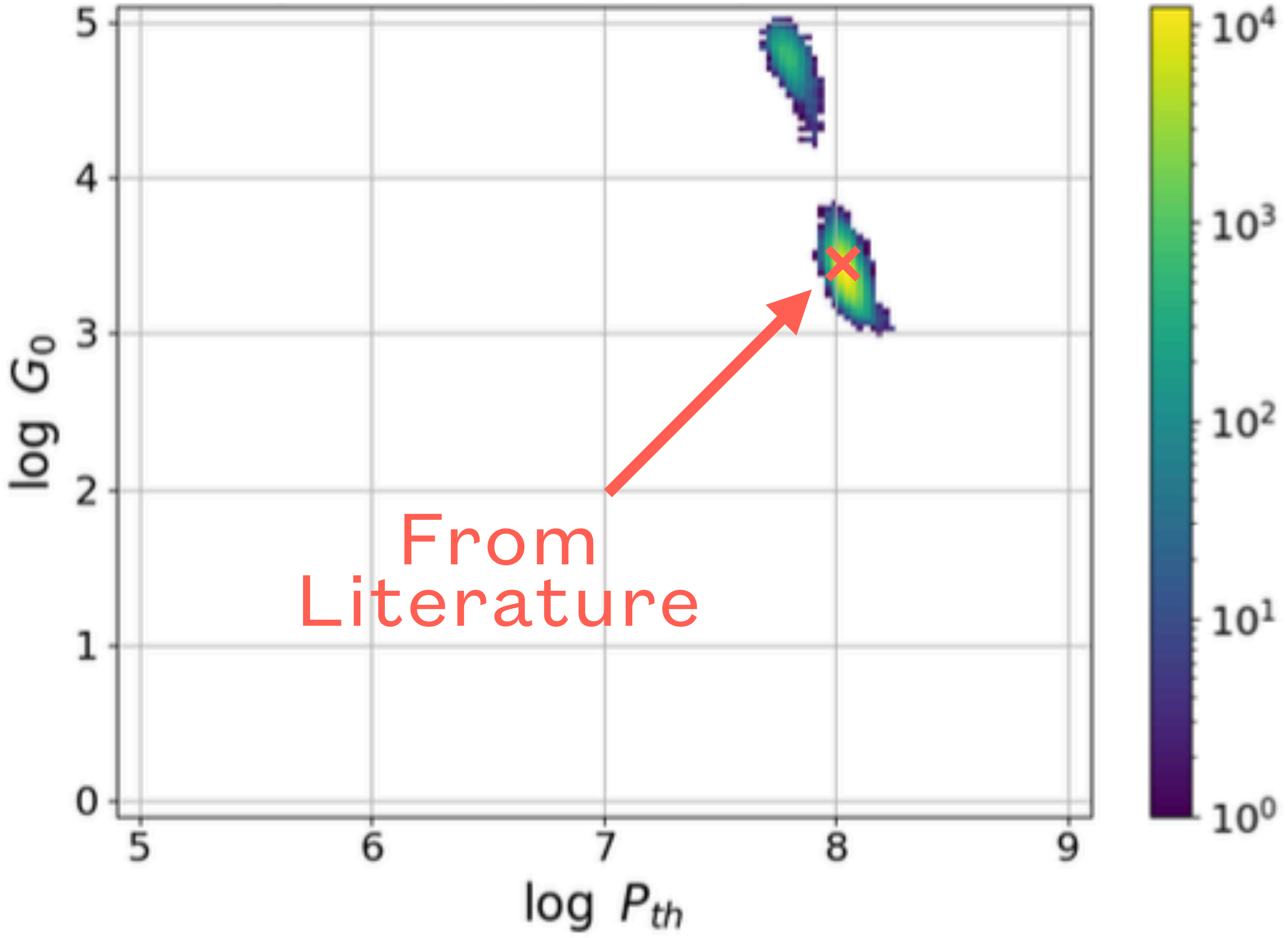
$G_0 \simeq 2600$ (Habing units) (Chokshi et al., 1988)

$P_{th} \simeq 10^8$ K cm^{-3} (Joblin et al., 2018)

$A_V^{tot} \simeq 10$ mag (Joblin et al., 2018)



Sampling results

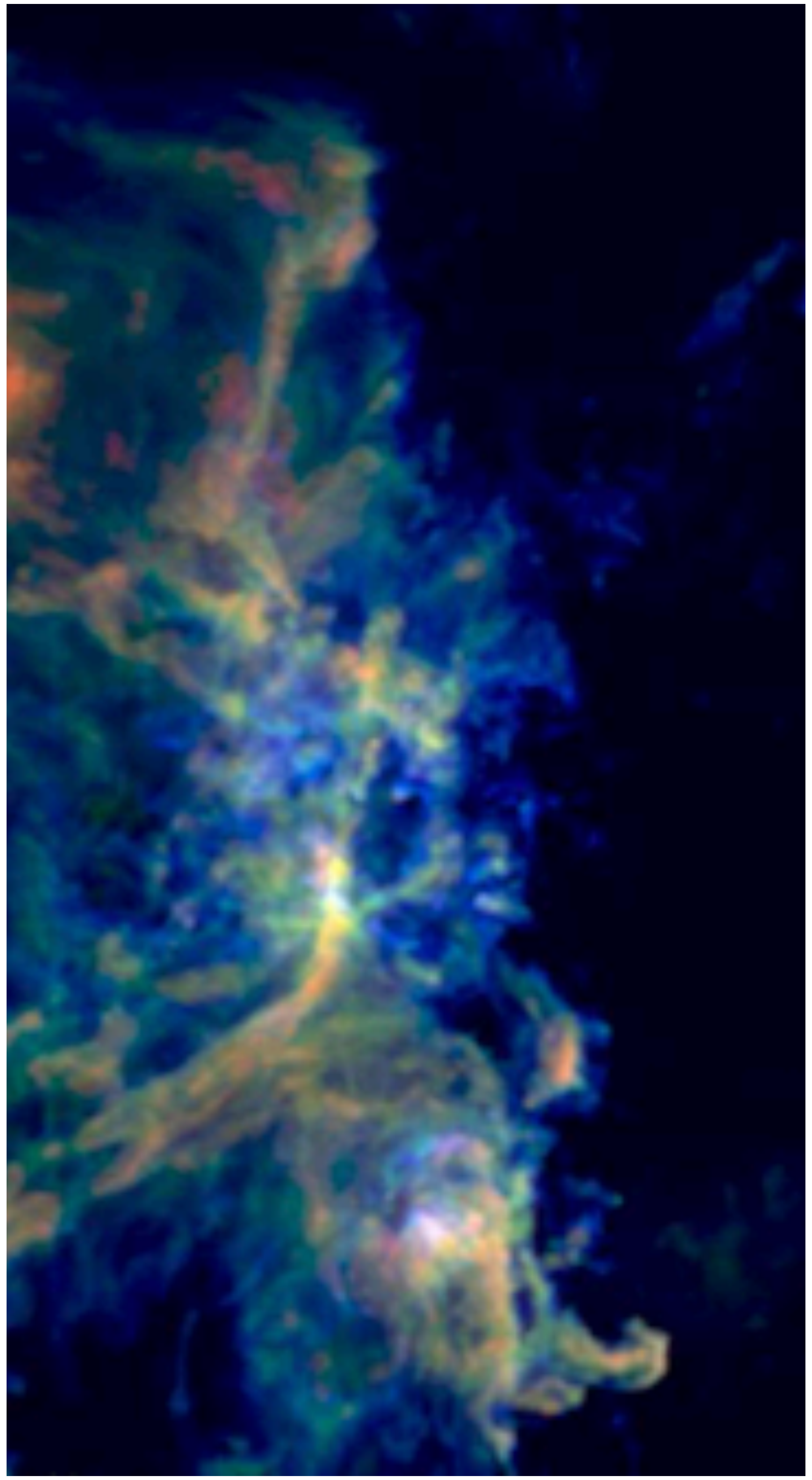


Reconstruction of observations

Conclusion

- New tool ready to be used! $\Longrightarrow$ will be available on ism.obspm.fr
  - **Spatial regularization** $\rightarrow$ enforces spatial smoothness
  - **Bayesian approach** $\rightarrow$ provides both estimates and credibility intervals

- Applications:
  - synthetic case with 4096 pixels ✓
  - NGC 7023 (1 pixel) ✓
  - Real data (Horse Head, $\simeq 10^3$ pixels / Orion B $\simeq 10^6$ pixels)
  - JWST observations



Appendix

Some formulae

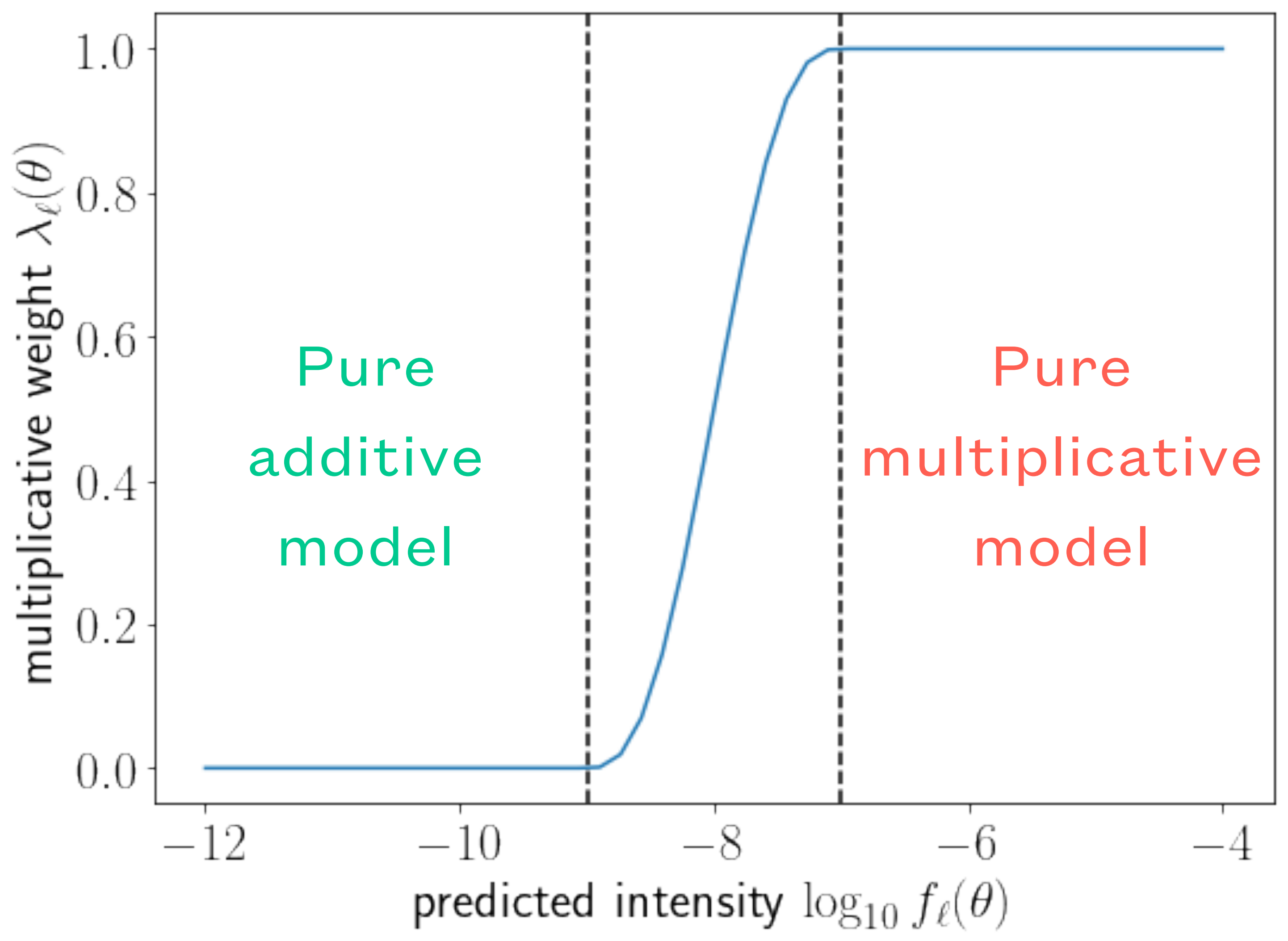
Spatial prior

$$\|\Delta\Theta_{\cdot d}\|_2^2 = \sum_{n=1}^{N} \sum_{i \in V_n} (\theta_{n,d} - \theta_{i,d})^2$$

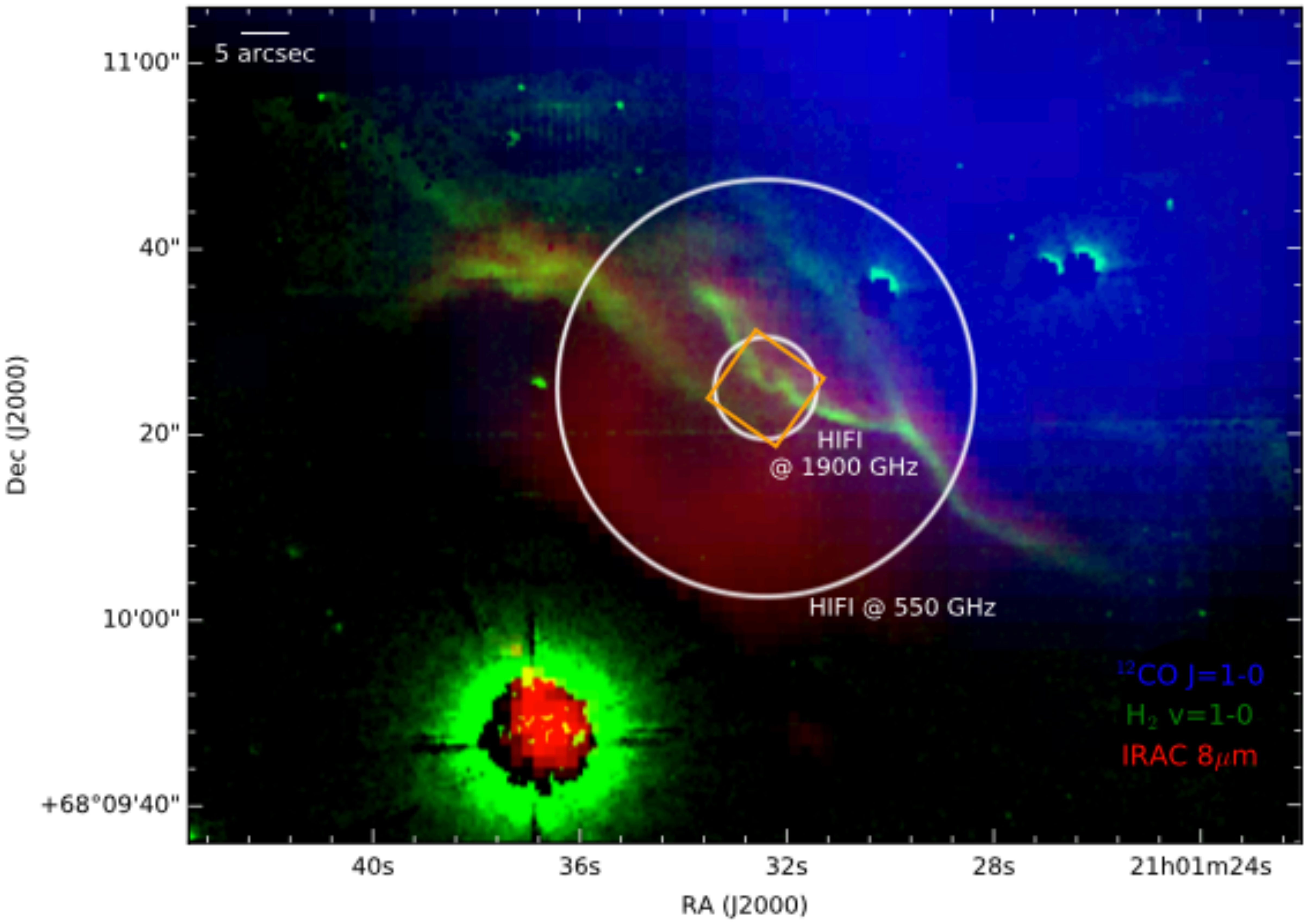
Likelihood approximation

$$\tilde{\pi}(y_{n,\ell} \,|\, \theta_n) \propto \left[\pi^{(a)}(y_{n,\ell} \,|\, \theta_n)^{1-\lambda(\theta_n)} \, \pi^{(m)}(y_{n,\ell} \,|\, \theta_n)^{\lambda(\theta_n)}\right]^{1-c_{n,\ell}}$$

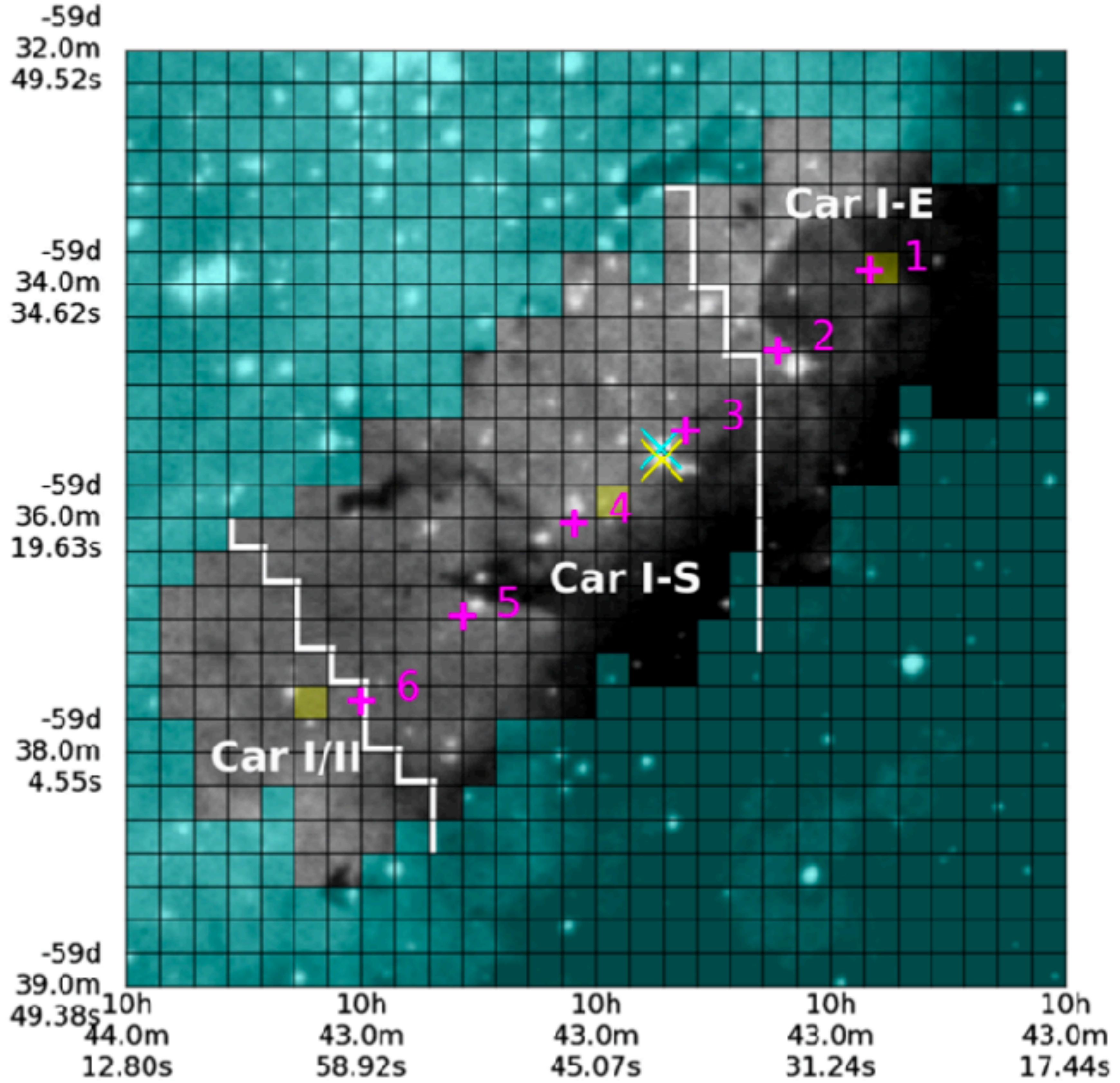
$$\times \left[F^{(a)}(\omega \,|\, \theta_n)^{1-\lambda(\theta_n)} \, F^{(m)}(\omega \,|\, \theta_n)^{\lambda(\theta_n)}\right]^{c_{n,\ell}}$$



Classic observations: $10^0 - 10^2$ pixels

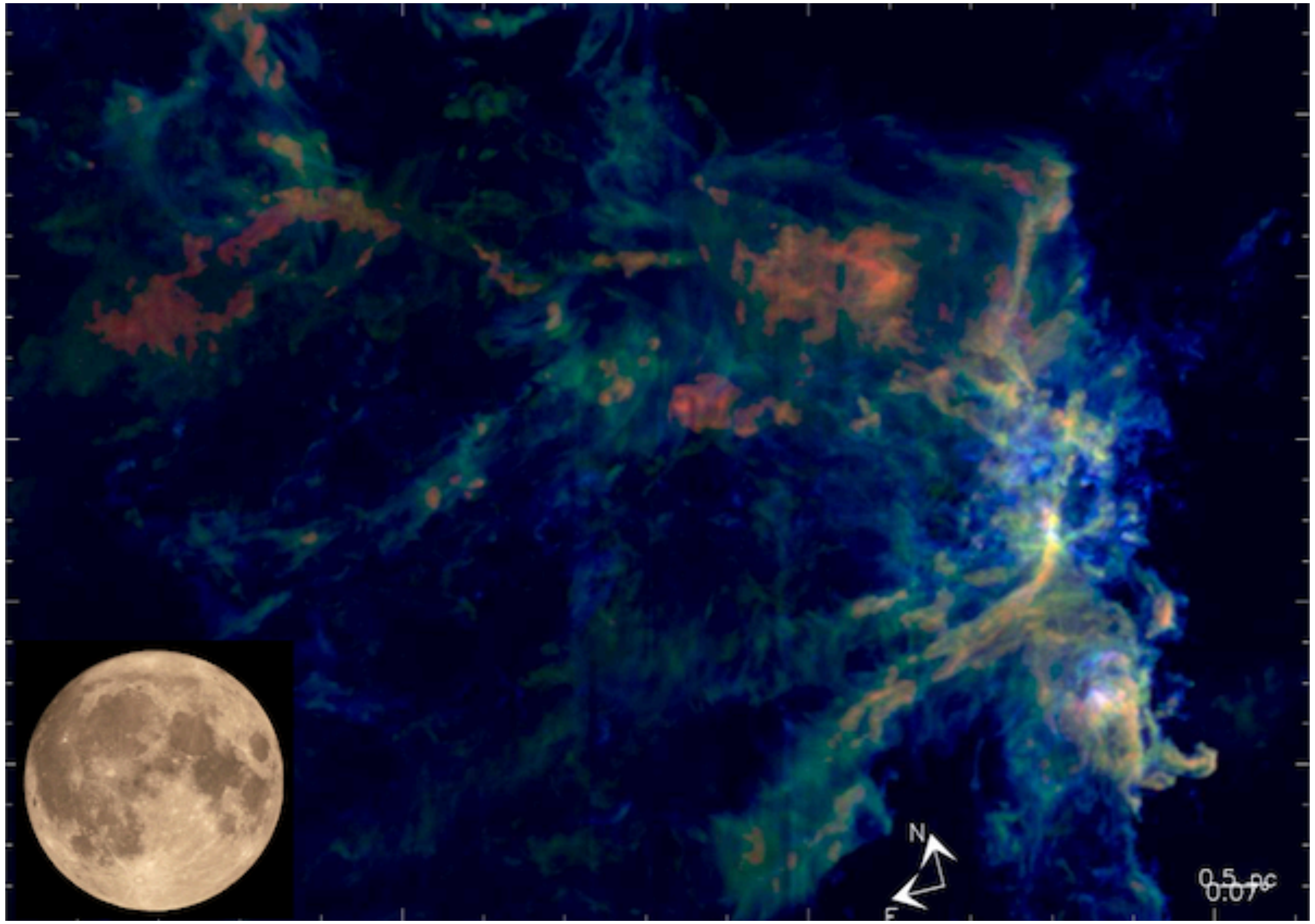


(Joblin et al., 2018)



(Wu et al., 2018)

Wider maps: towards $10^3 - 10^6$ pixels

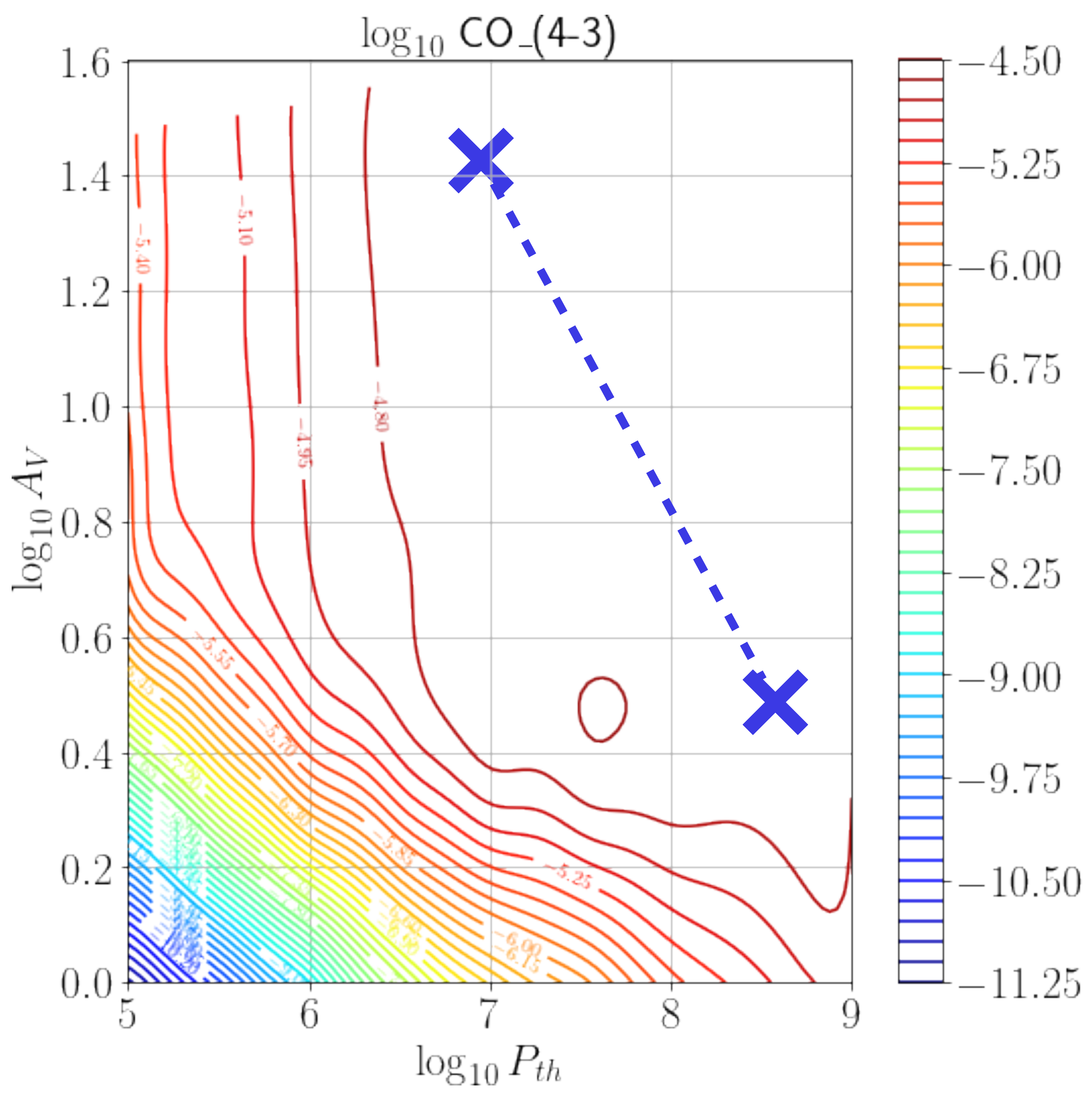


Source: https://www.esa.int/ESA_Multimedia/Sets/Webb_First_Images/(result_type)/images

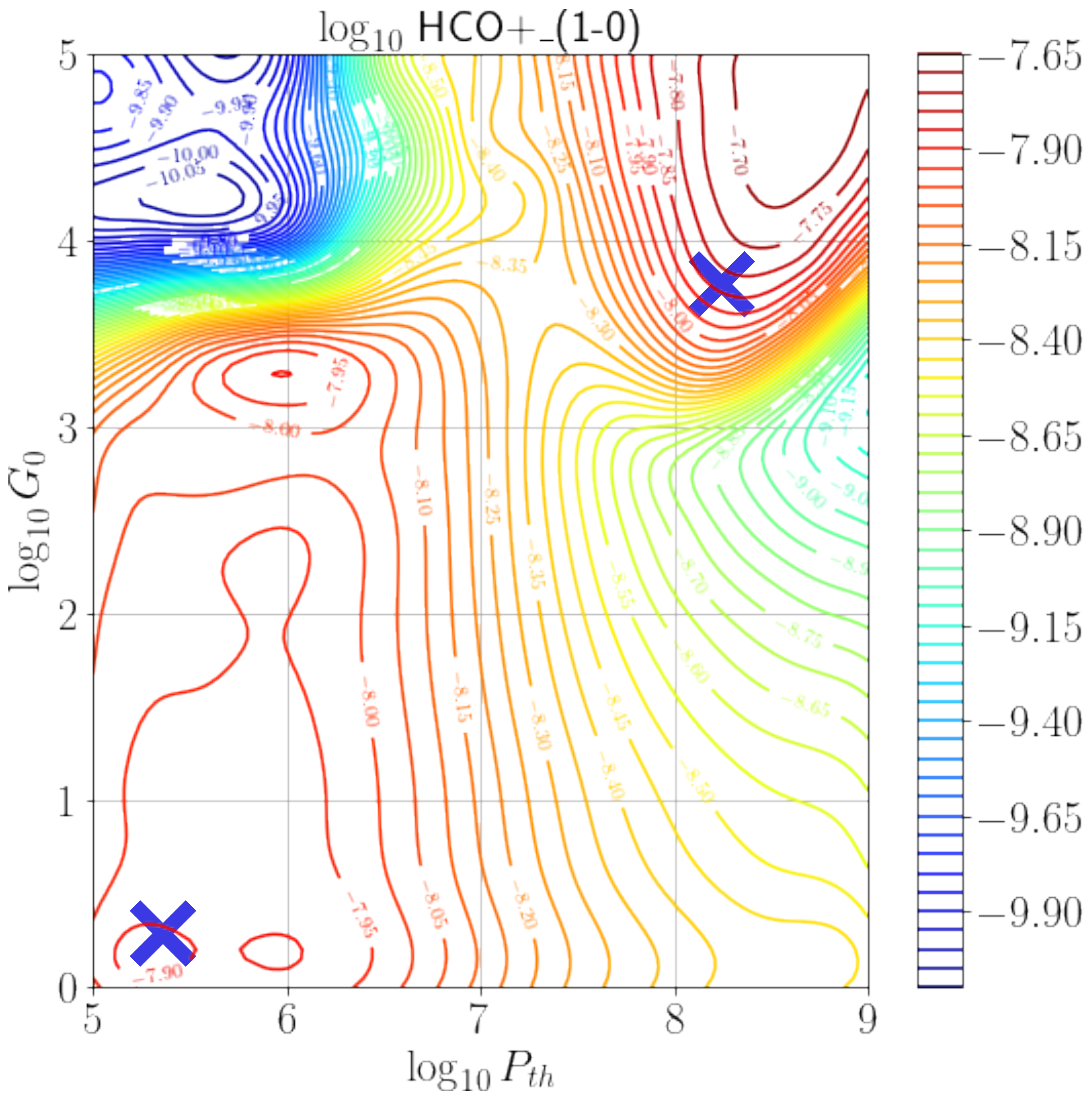
Source: https://www.esa.int/ESA_Multimedia/Sets/Webb_First_Images/(result_type)/images

Degeneracies and multimodality

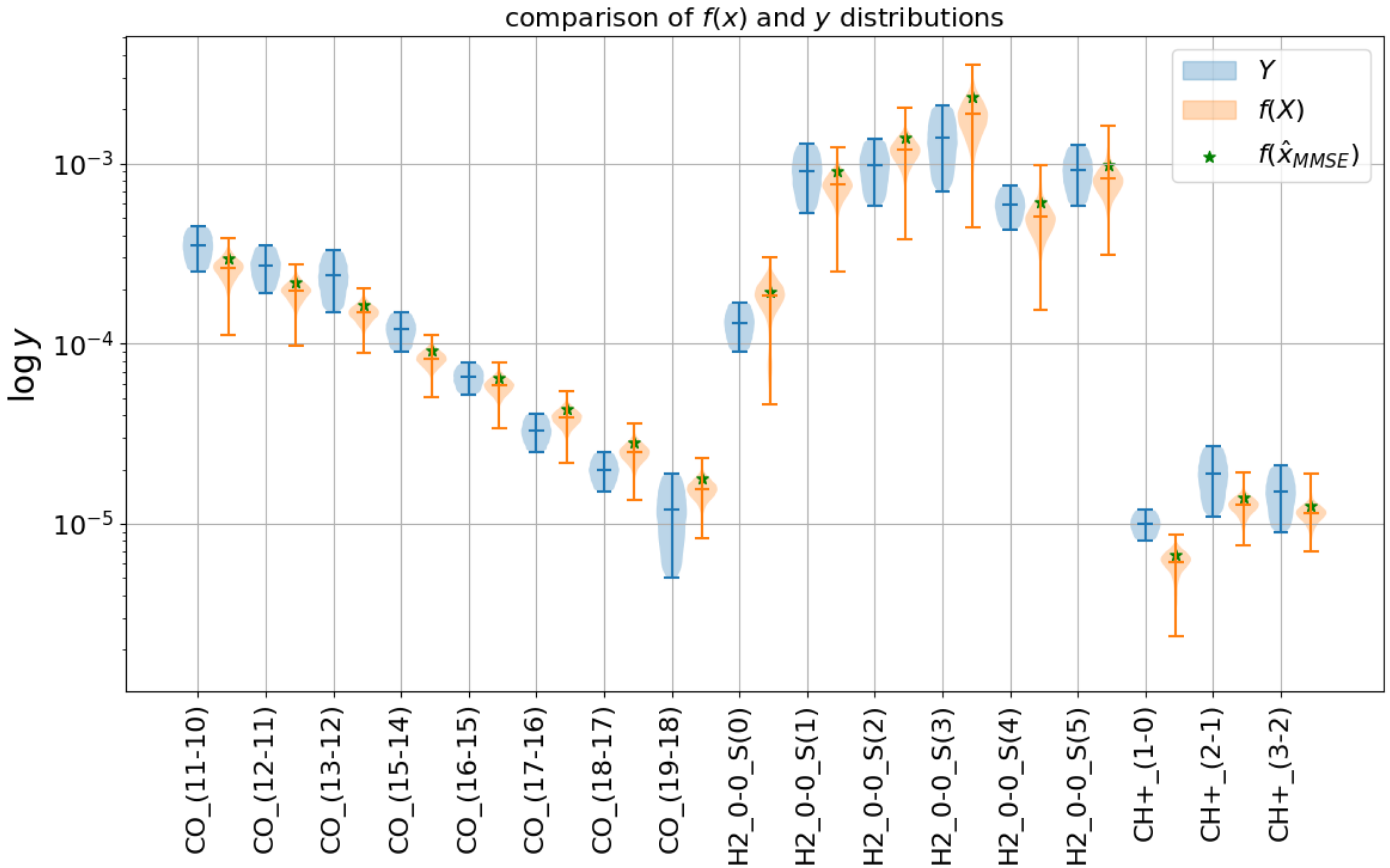
Saturation of CO lines with AV



Multimodality with HCO+



✕ Identical observations


comparison of f(x) and y distributions
log y
10^{-3}
10^{-4}
10^{-5}
Y
f(X)
$f(\hat{x}_{MMSE})$
CO_(11-10)
CO_(12-11)
CO_(13-12)
CO_(15-14)
CO_(16-15)
CO_(17-16)
CO_(18-17)
CO_(19-18)
H2_0-0_S(0)
H2_0-0_S(1)
H2_0-0_S(2)
H2_0-0_S(3)
H2_0-0_S(4)
H2_0-0_S(5)
CH+_(1-0)
CH+_(2-1)
CH+_(3-2)