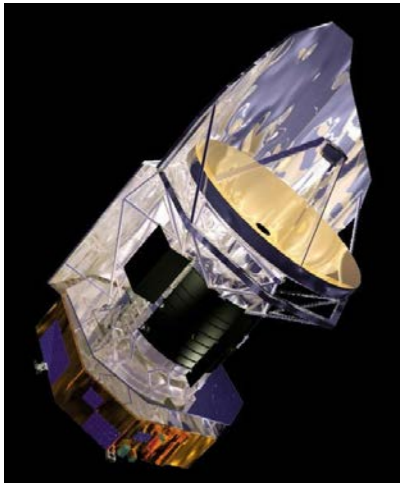
How Galaxies form Stars
Stockholm 2016

The transition from atomic to molecular gas in M33: a large scale investigation on the formation of star forming clouds in a low metallicity environment.

Gratier, P., Braine, J., Schuster, K.F., Rosolowsky, E., Boquien, M., Calzetti, D., Combes, F., Kramer, C., Henkel, C., Herpin, F., Israel, F., Koribalski, B. S., Mookerjea, B., Tabatabaei, F. S., Röllig, M., van der Tak, F. F. S., van der Werf. P., and Wiedner, M.

Gratier. P. et al, 2016 submitted to A&A

Druard C. et al 2014, A&A

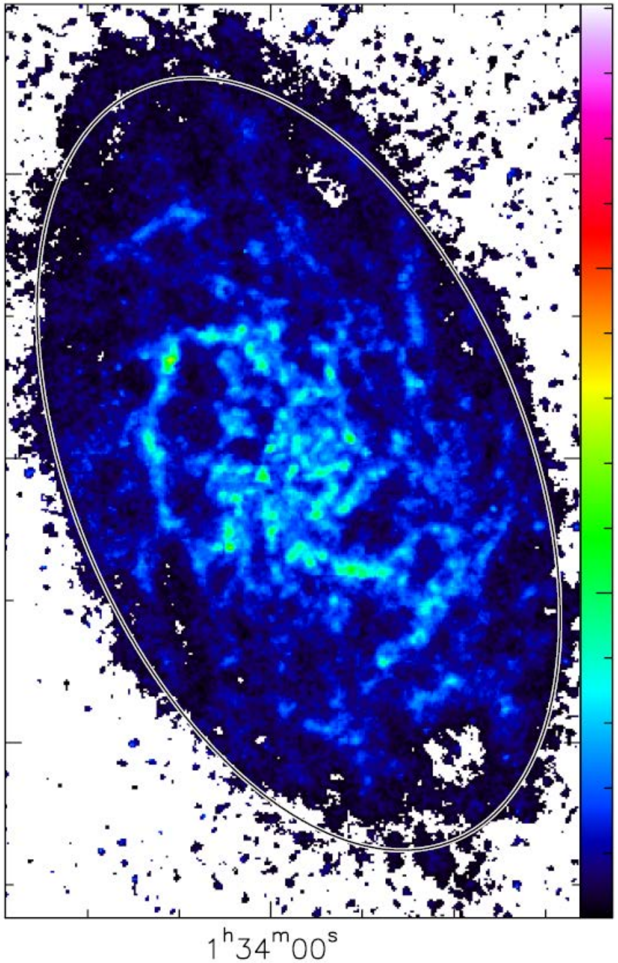


Astronomical Motivation

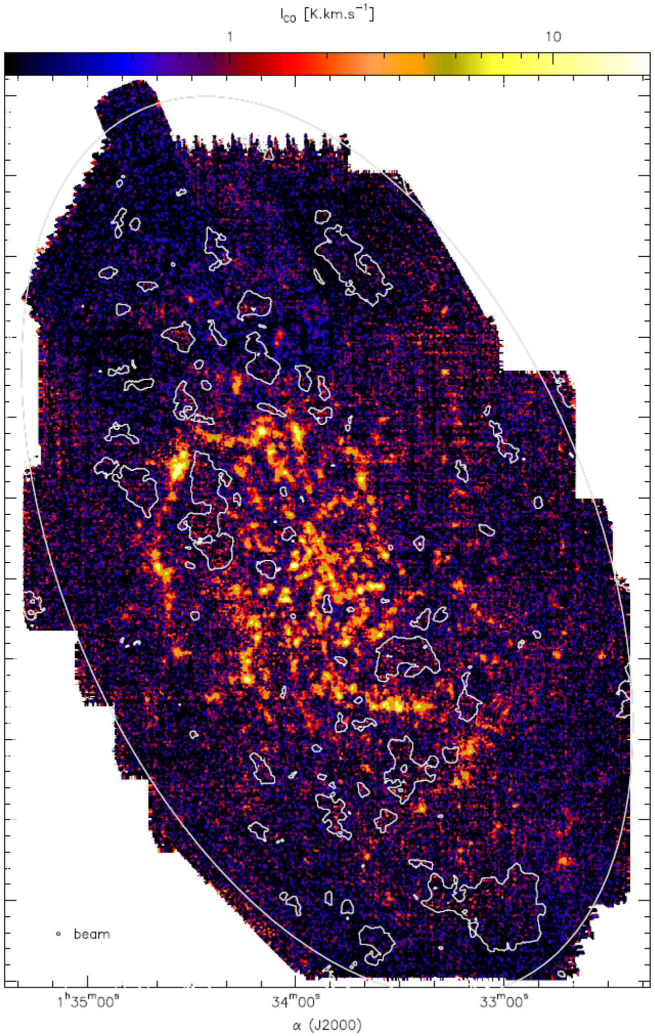
- Stars form from molecular gas. This statement has been the basic ingredient of the very general Kennicut-Schmidt relation. However scatter is large and not yet really understood.
- To understand SF on galactic and molecular cloud scales we need to be able to measure molecular gas to a high precision (ideally down to a 10% precision, until recently a factor of 2 was considered good).
- Strong, multiple evidence that CO measurement as a proxy for H_2 are missing part of the molecular gas (the so called "CO dark molecular gas").
- Methods are needed to assess this missing molecular gas.
- Here we describe the efforts to go a step further in the disk of M33 with methods which use FIR emission from dust, HI 21 cm, and mm CO(2-1) emission on scales down to 100 pc.
- Other methods are worked on (e.g. exploring CII emission, Accurso et al 2016 submitted) which allow to cross check in the near future.

Project is based on three high resolution, high sensitivity data sets.

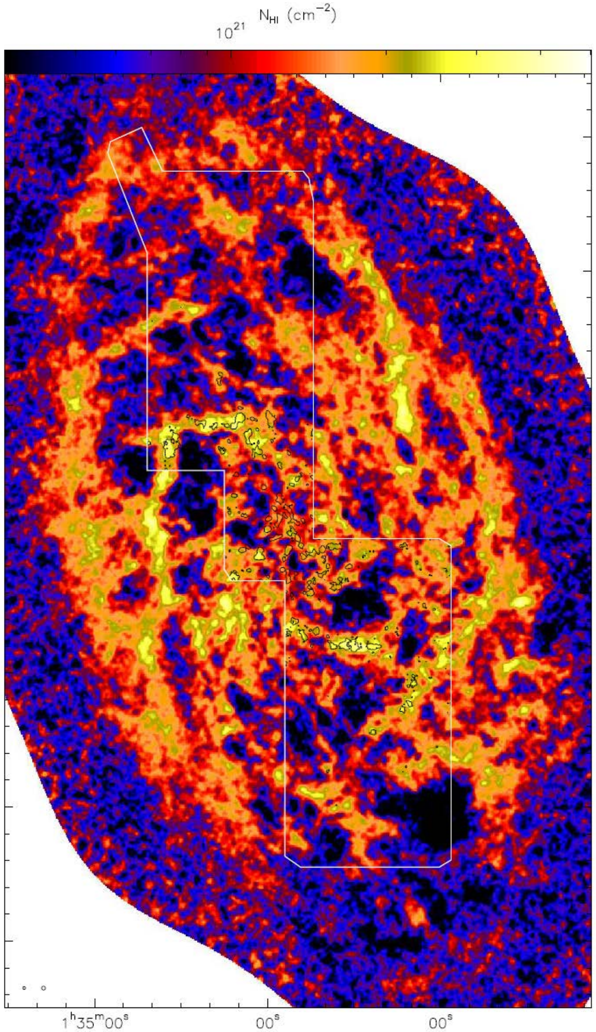
HERSCHEL SPIRE 250/350

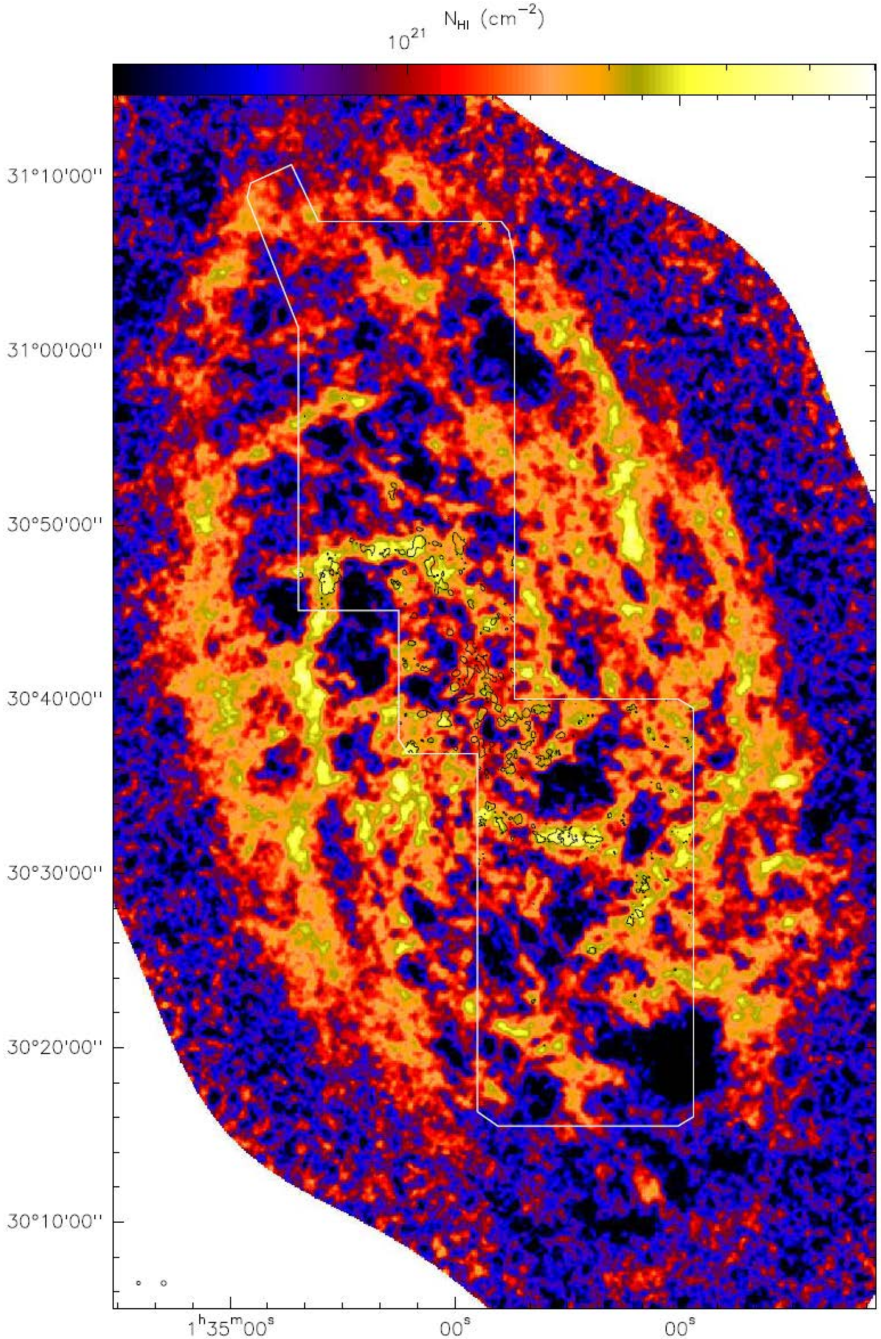


IRAM 30m HERA CO(2-1)



NRAO VLA 21cm HI

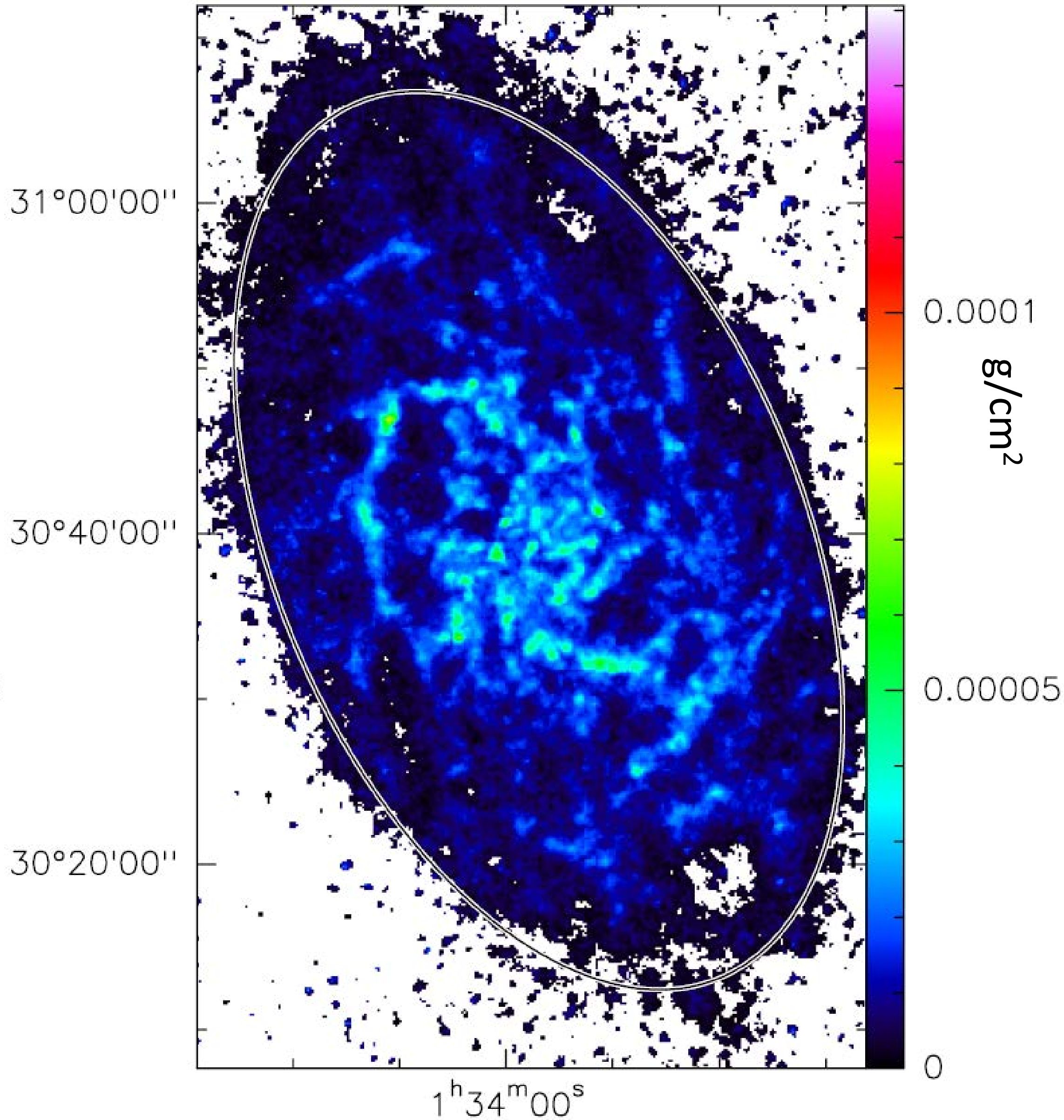




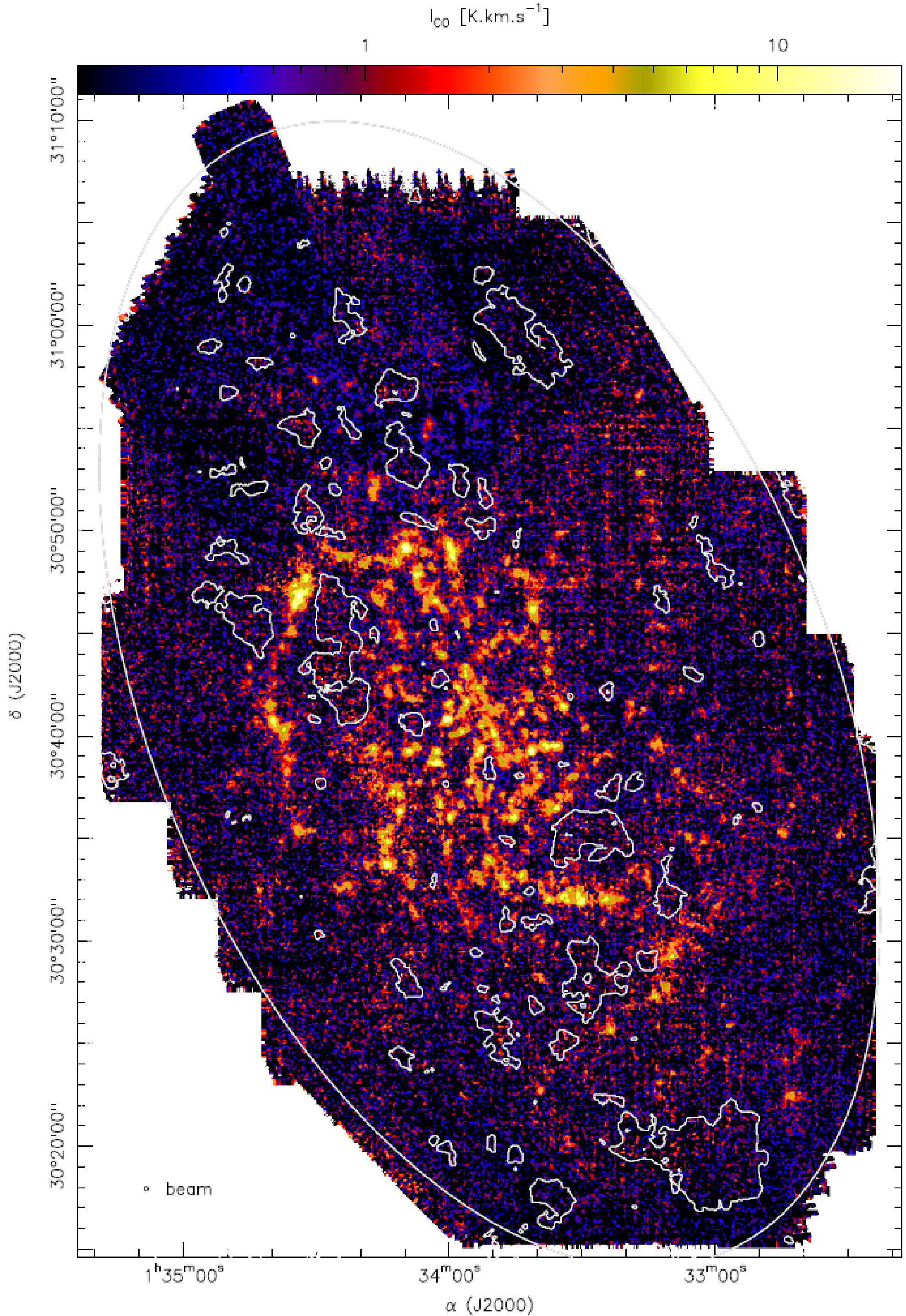
VLA HI 21 cm Mosaics

- VLA B, C and D config
- 12 " resolution
- Data published by Gratier et al 2010.
- We assume that HI is optically thin

Dust Surface Density from SPIRE 250/350 μm



- Data set from HERM33ES, (Kramer et al 2010)
- Radially varying β dust (Tabatabaei et al. 2014)
- Radially varying median dust cross section derived from HI only areas. (following Braine et al. 2010)
- Herschel 350 μm defines resolution of project with 25"



Complete high resolution Census of CO(2-1) emission in M33 with HERA at the IRAM 30m telescope.

- Continuous coverage out to 7 kpc
- Spatial resolution 12" = 50 kpc
- Baseline reduction done using HI velocity information.
- CO(2-1) int. noise 0.2 K km /s
- 400 h observing, 2 10^7 ind. spectra
- Data now public on IRAM archive

In 2011 Leroy et al and in 2012 Karin Sandstrom et al published two studies on nearby galaxies with the following approach.

a) Ansatz: $\Sigma_{gas} = GDR \times \Sigma_{dust}$

$= m_p \times [N(HI) + 2X_{CO} \times I_{CO}]$

$= \Sigma HI + \alpha_{CO} \times I_{CO}$

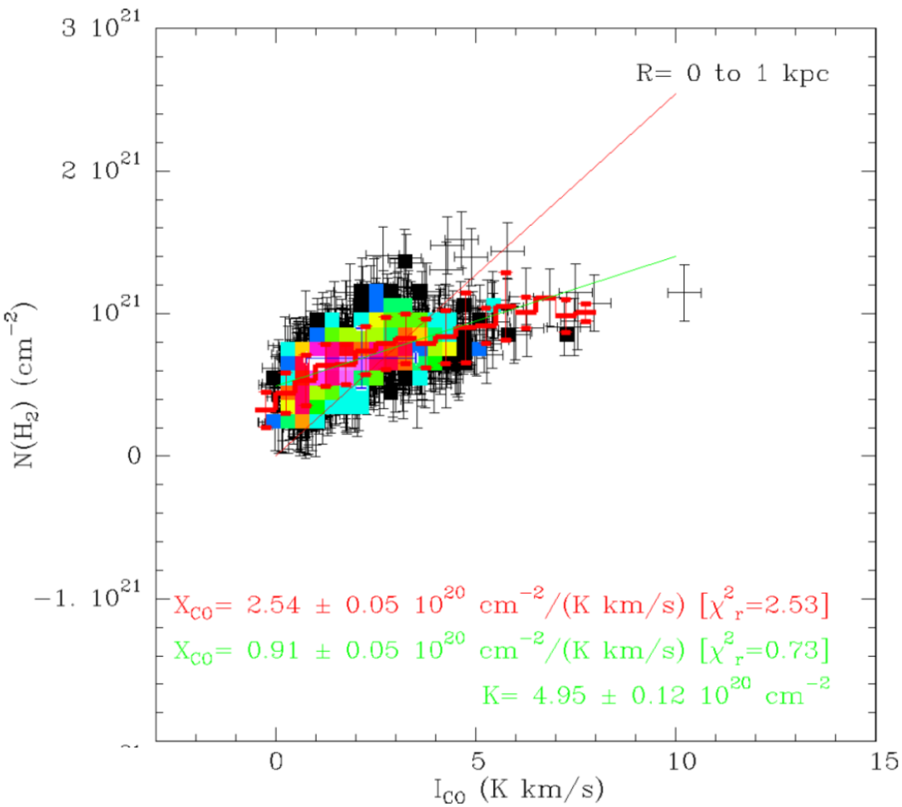
b) Measure $\Sigma_{dust,}$ ΣHI and I_{CO}

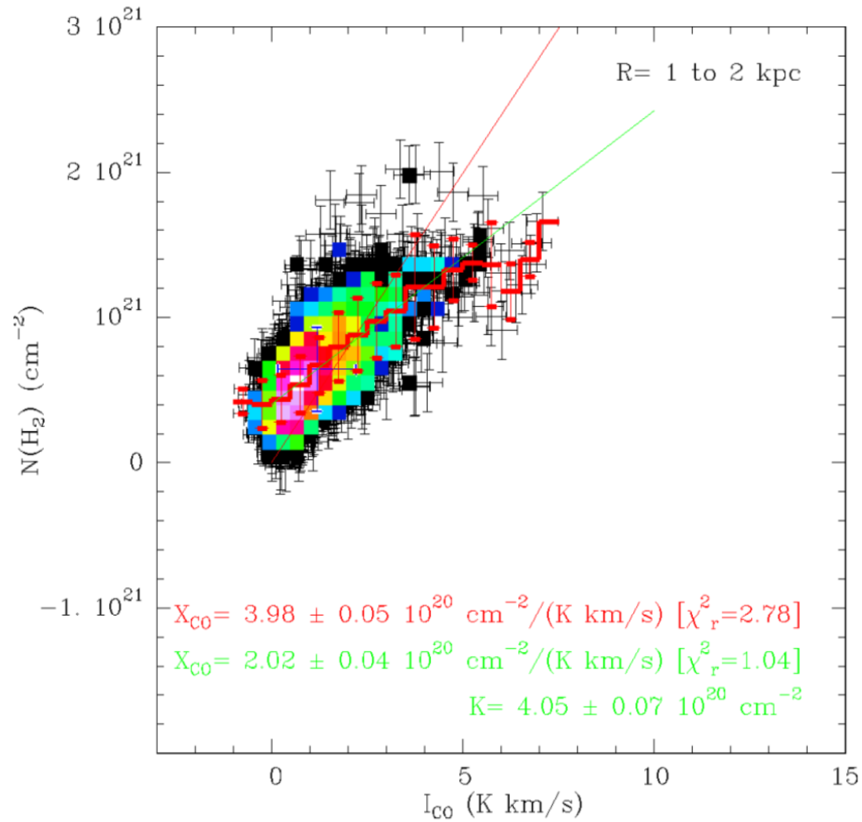
c) Tune GDR and α_{CO} to get minimum scatter on a suitable sample of adjanced pixels (“macro pixels”)

Underlying Assumptions:

- as much dust in atomic as in molecular gas.
- dust emissivity might be radius dependent but, for a given position, does not depend on whether dust is in molecular or atomic gas.
- no dust in fully ionized gas.
- no HI gas without dust.

An important observation in our data set if total H_2 is only determined via dust and HI in regions without CO emission:





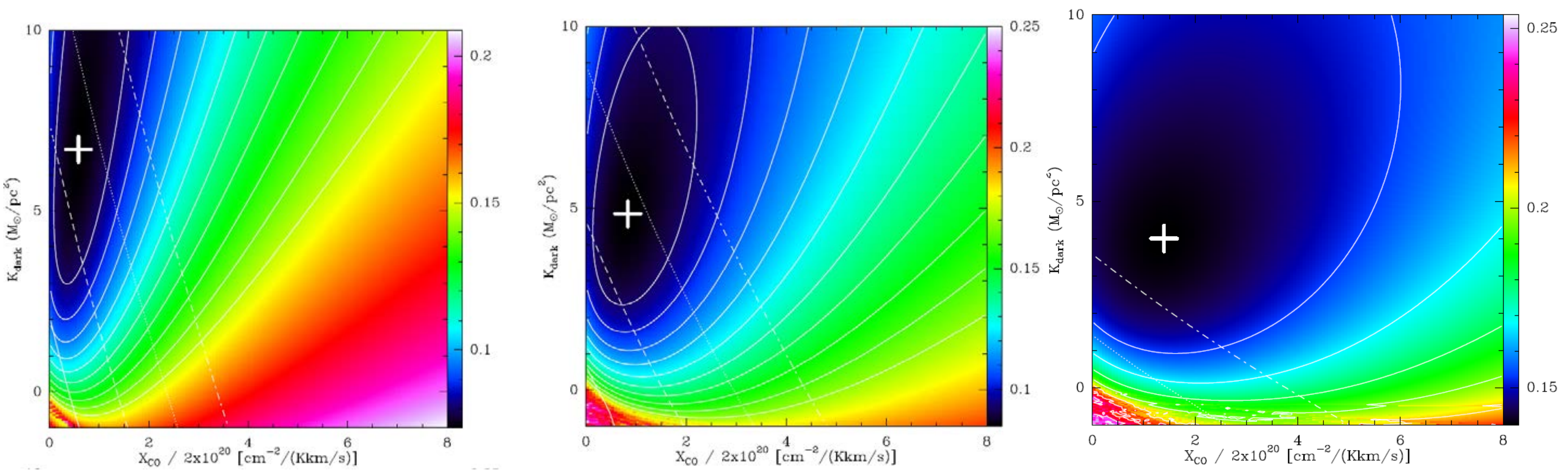
Fit is already largely improved
when introducing an offset ⇔ *"dark molecular gas"*

Extension of the Sandstrom Ansatz:

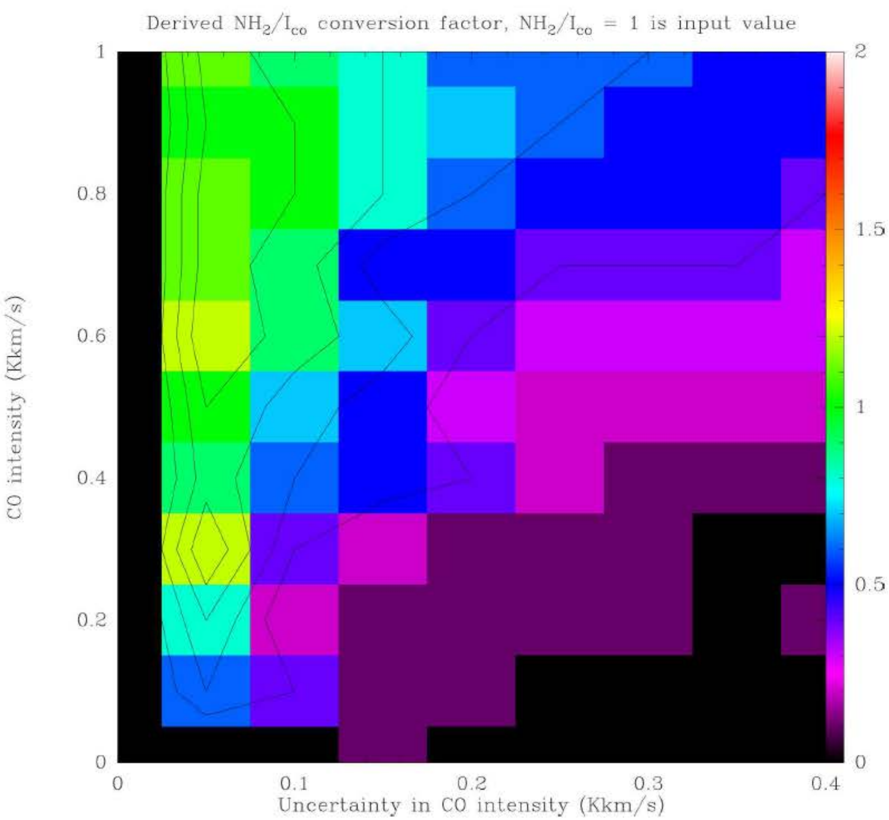
a) $$\Sigma_{gas} = GDR \times \Sigma_{dust}$$
$$= m_p \times [N(HI) + 2X_{CO} \times I_{CO} + K'_{dark}$$
$$= \Sigma HI + \alpha_{CO} \times I_{CO} + K_{dark}$$

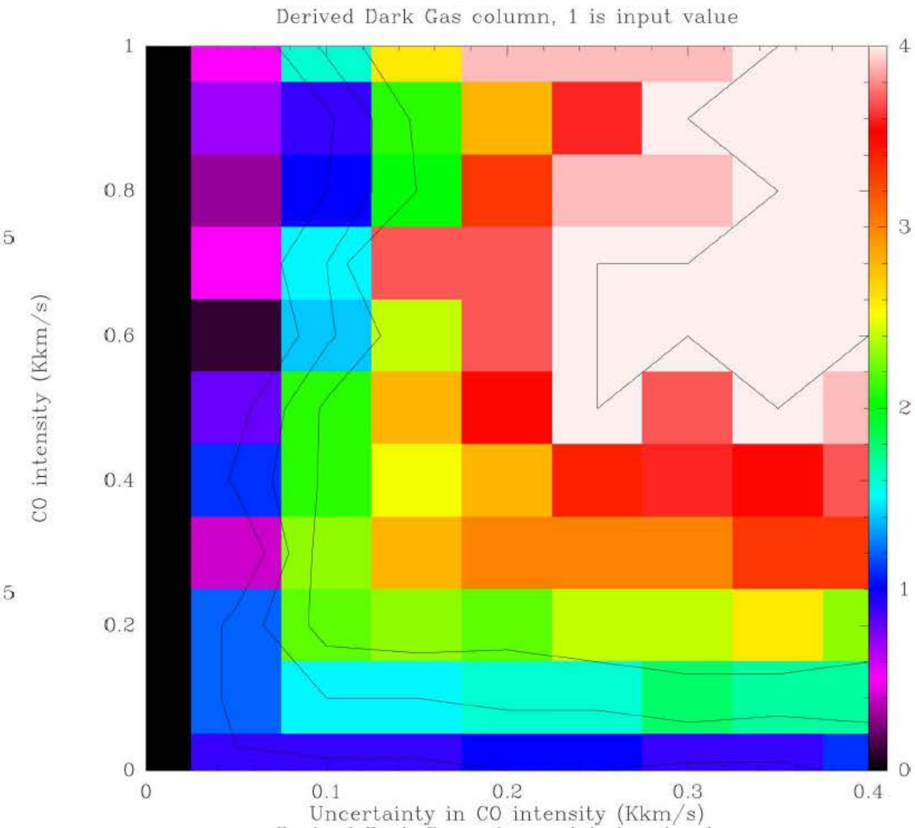
b) Measure $\Sigma_{dust,}$ ΣHI and I_{CO}

c) Tune GDR, α_{CO} **AND** K_{dark} to get minimum scatter on a suitable sample of adjanced pixels ("macro pixels") and assume that dust is similar as the one in CO bright gas.



However: “Simple fitting” for least scatter does not pass a “reproduction” test using a model distribution and with known parameters and added “noise” in data.

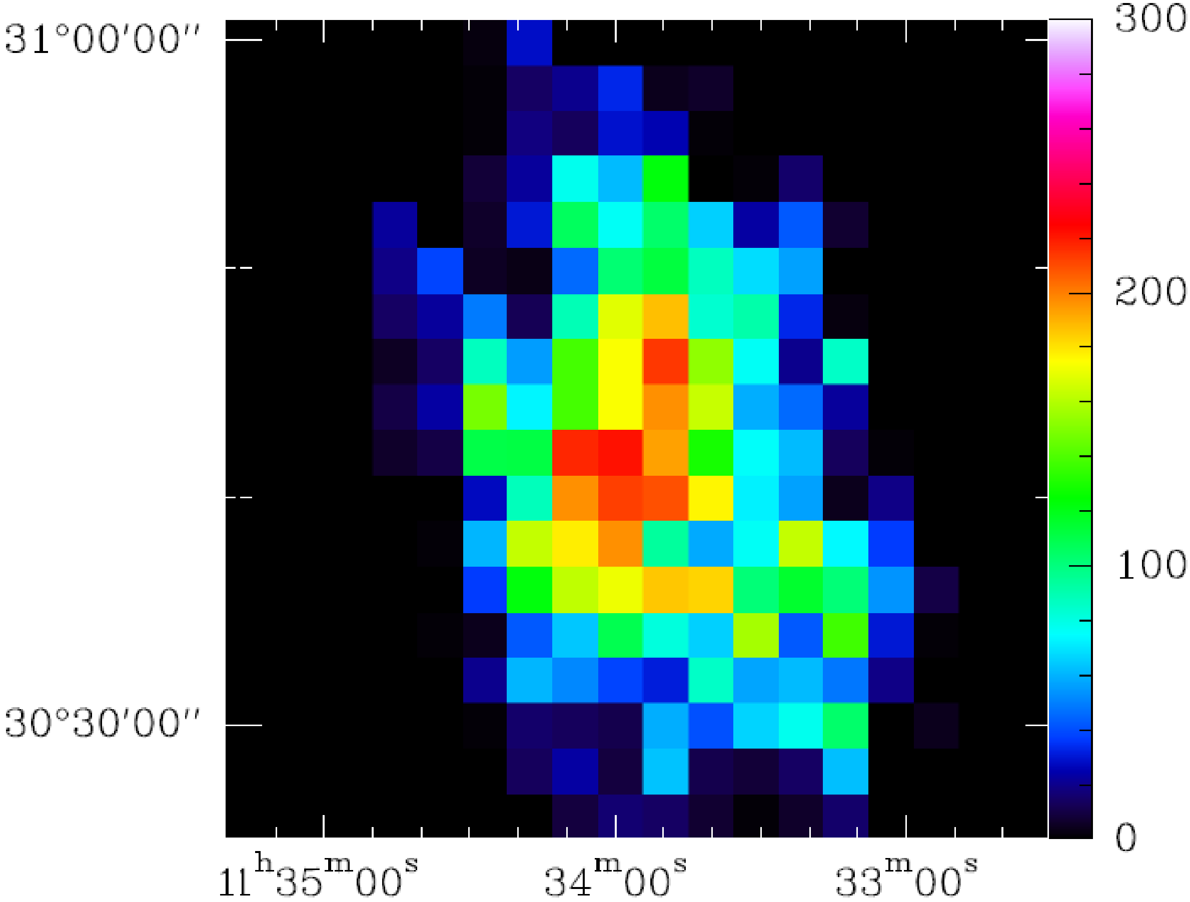


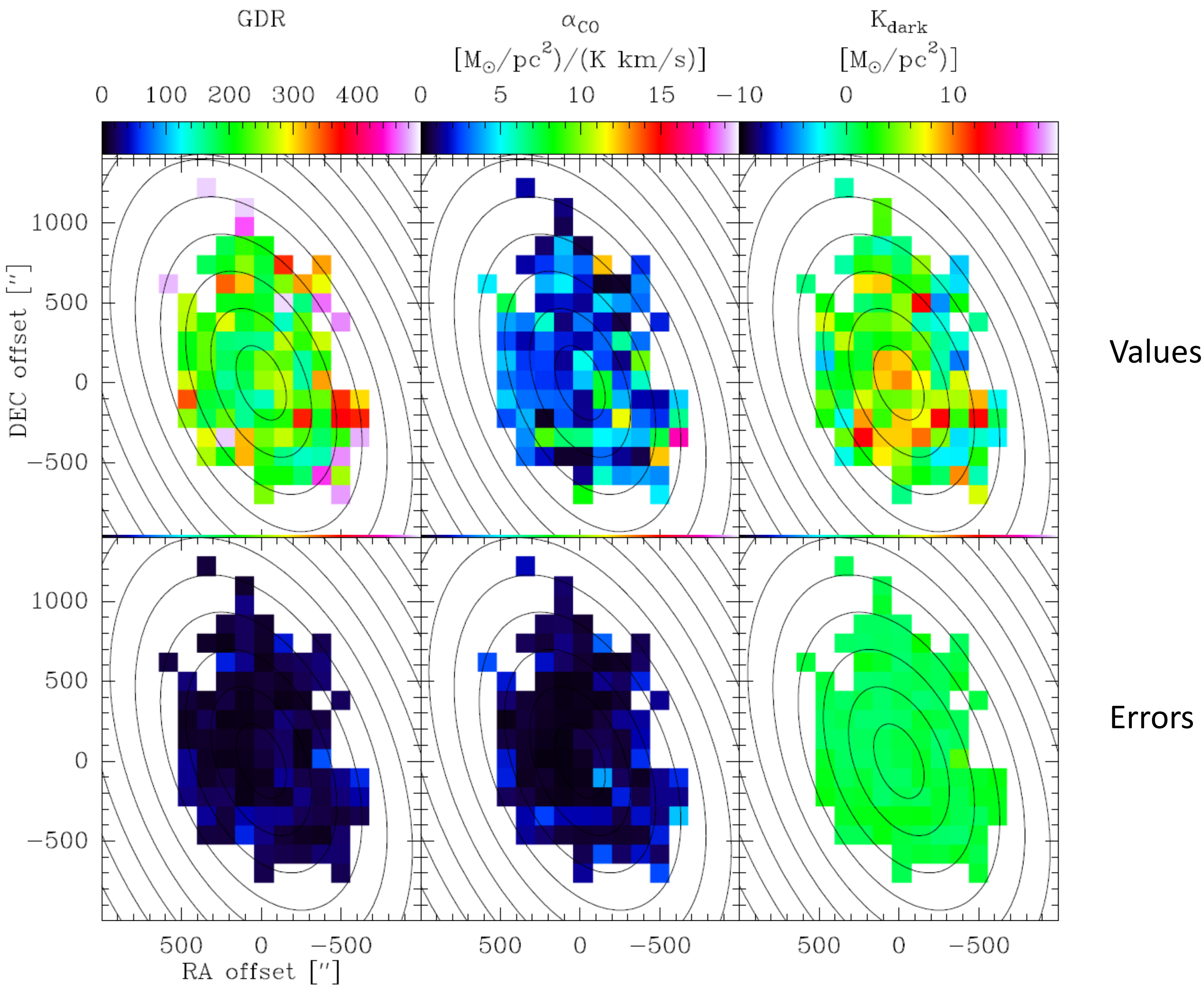


Bayesian Approach :

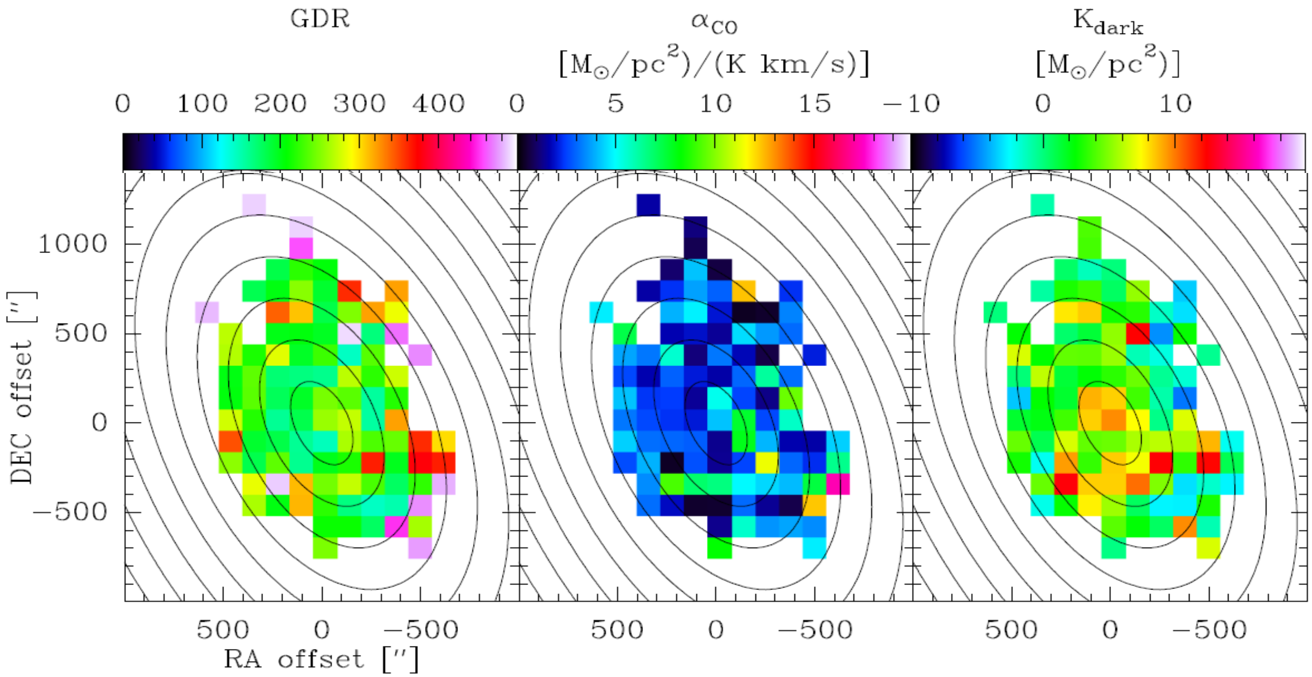
$$I_{\mathrm{H\,I},i}^{obs} \sim \mathcal{N}(I_{\mathrm{H\,I},i}^{true}, \sigma_{I_{\mathrm{H\,I}},i})$$
$$I_{\mathrm{CO},i}^{obs} \sim \mathcal{N}(I_{\mathrm{CO},i}^{true}, \sigma_{I_{\mathrm{CO}},i})$$
$$\Sigma_{dust,i}^{true} = \frac{1}{GDR}(\alpha_{\mathrm{H\,I}} I_{\mathrm{H\,I},i}^{true} + \alpha_{\mathrm{CO}} I_{\mathrm{CO},i}^{true} + K_{\mathrm{dark}})$$
$$\Sigma_{dust,i}^{obs} \sim \mathcal{N}(\Sigma_{dust,i}^{true}, \sigma_{\Sigma_{dust}})$$

~150 Macro-Pixels with 225 independent pixels each, only $I_{CO} > 3\,\sigma$

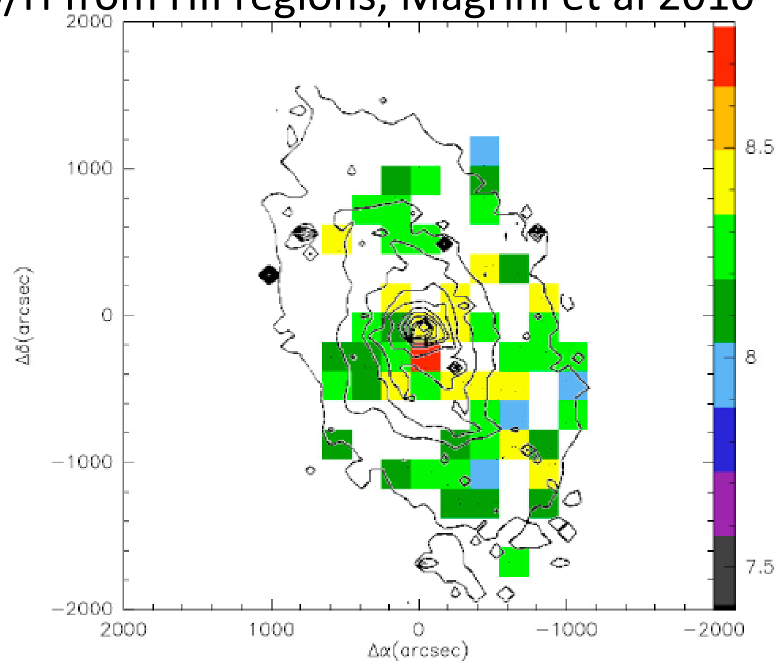




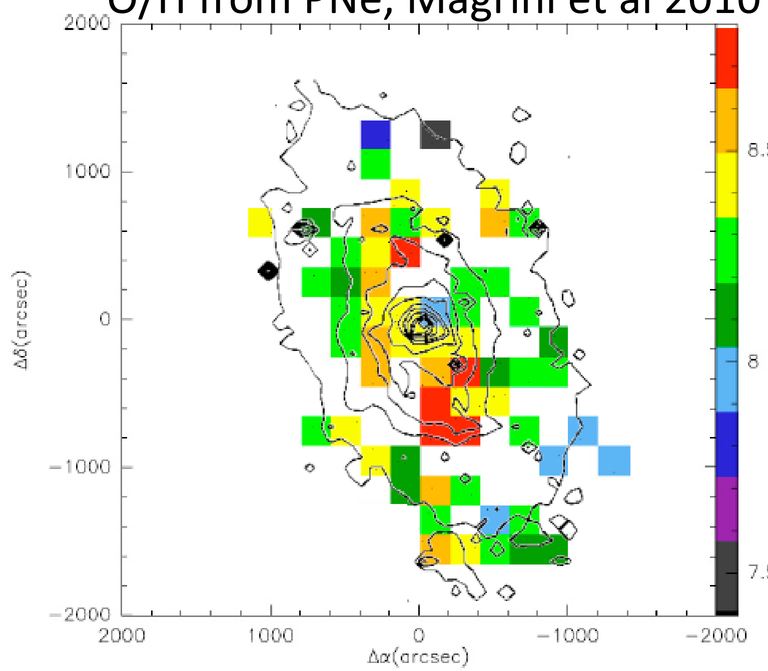
GDR
α_{CO}
$[M_\odot/pc^2)/(K\ km/s)]$
K_{dark}
$[M_\odot/pc^2)]$
0 100 200 300 400
0 5 10 15
−10 0 10
DEC offset ['']
1000
500
0
−500
RA offset ['']
500 0 −500
Values
Errors

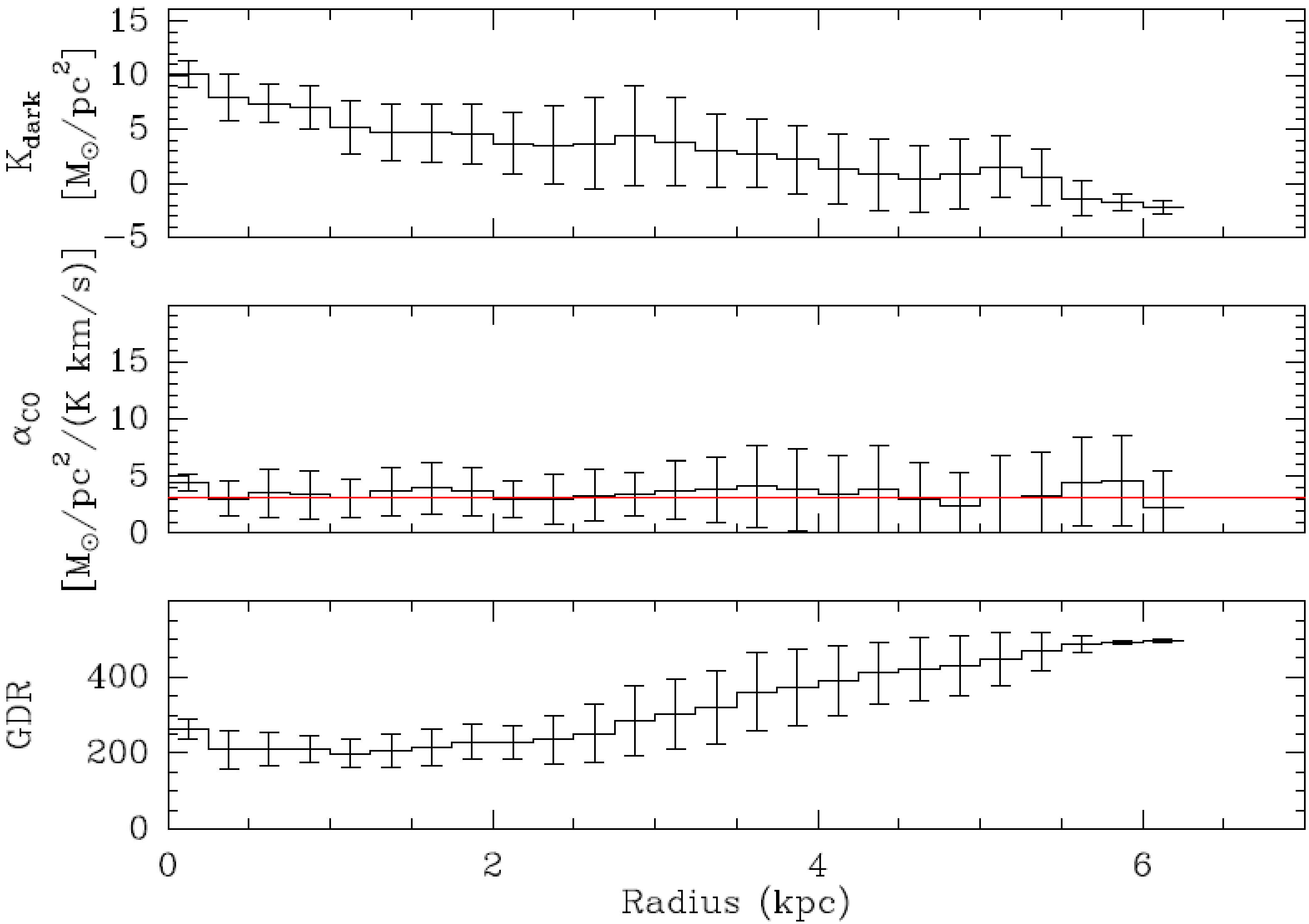


O/H from HII regions, Magrini et al 2010

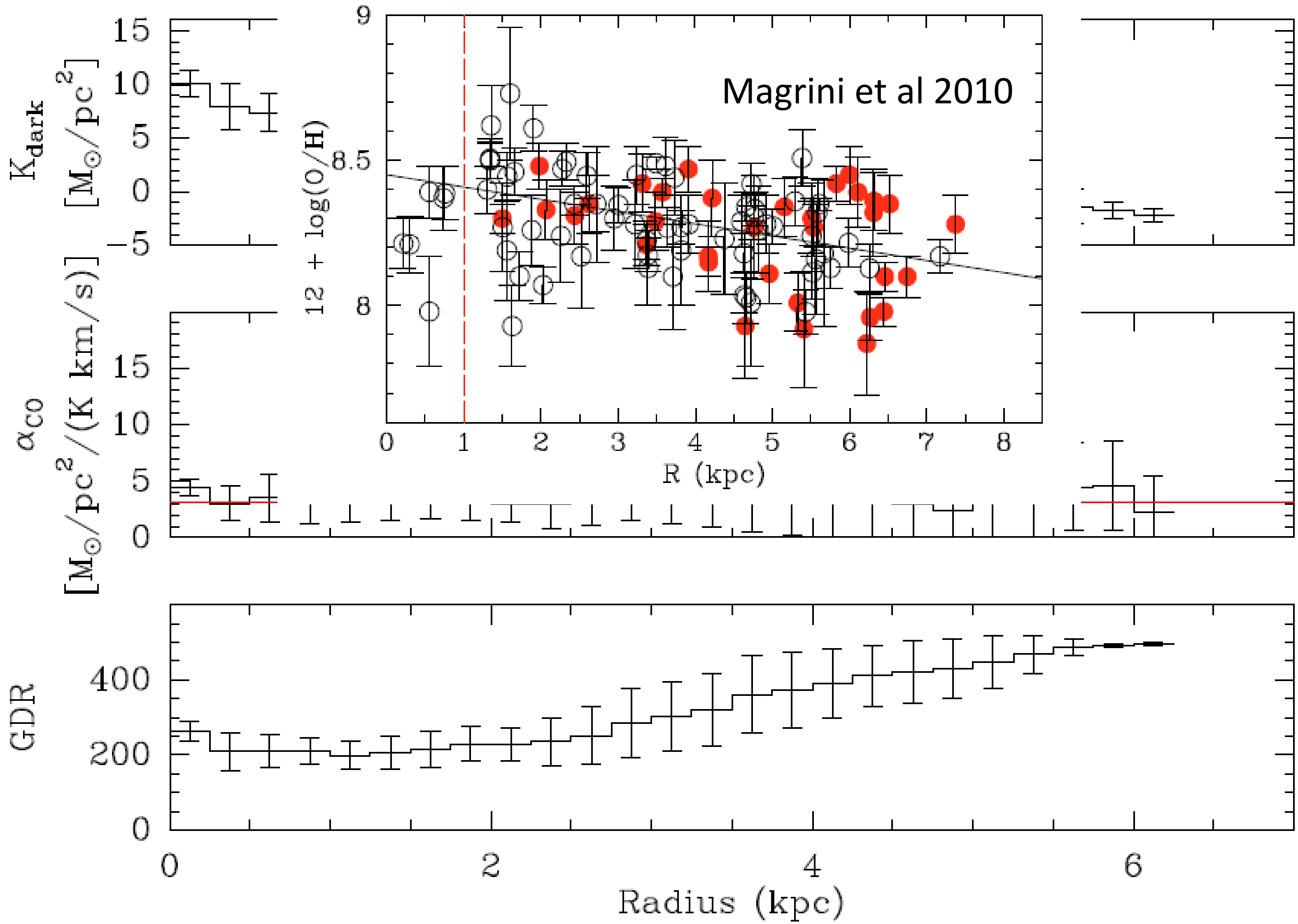


O/H from PNe, Magrini et al 2010





Several antagonist effects are at work – yet difficult which one is dominating



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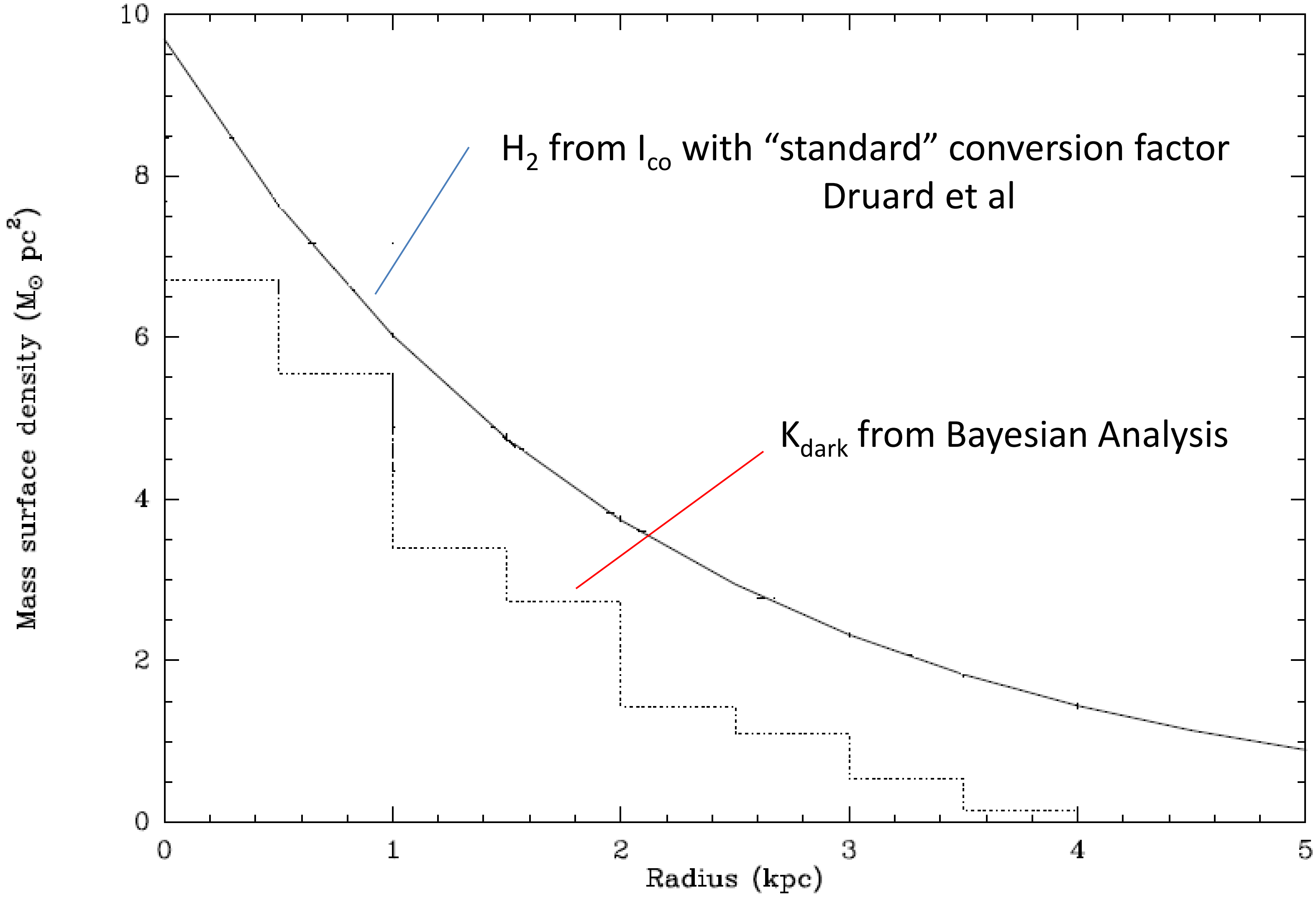
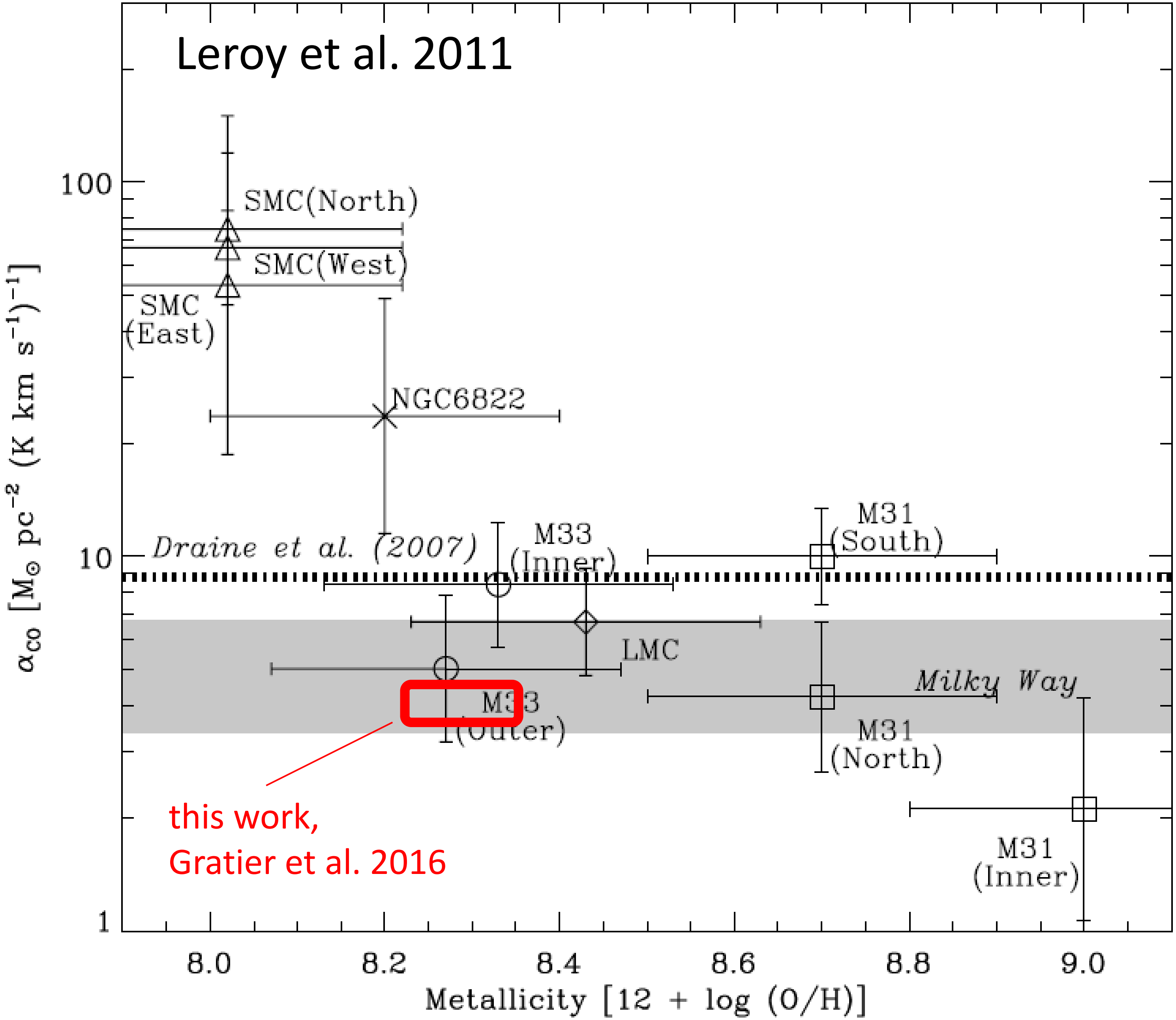


H_2 from I_{co} with "standard" conversion factor
Druard et al
K_{dark} from Bayesian Analysis
Mass surface density ($M_\odot$ pc^2)
Radius (kpc)
0
2
4
6
8
10
0
1
2
3
4
5



Leroy et al. 2011
SMC(North)
SMC(West)
SMC
(East)
NGC6822
Draine et al. (2007)
M33
(Inner)
M31
(South)
LMC
Milky Way
M33
(Outer)
M31
(North)
M31
(Inner)
this work,
Gratier et al. 2016
100
10
1
8.0
8.2
8.4
8.6
8.8
9.0
Metallicity [12 + log (O/H)]
α_{CO} [$M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$]

Summary and Outlook:

- High resolution molecular disk mapping can allow to extend statistical approach to more parameters including the “CO dark gas”.
- However degeneracies are a constant threat, Bayesian approach as described in Gratier et al 2016 is able to overcome most of them.
- Results for M33 roughly 50/50 CO vs CO dark, physical interpretation not yet at hand.
- Investigation on local specific SF efficiency using these results is currently underway for this collaboration.
- Validity of input hypotheses must be further investigated
- Comparison with physical models and CII observations will be crucial (eg Accurso, G. et al 2016 submitted).
- New higher resolution data for other galaxies OK for CO and HI. But we need to see what can be done to measure cold dust with ~ 1 arsec resolution.

Summary and Outlook:

- High resolution molecular disk mapping can allow to extend

IRAM NOEMA will help

- New higher resolution data for other galaxies OK for CO and HI. But we need to see what can be done to measure cold dust with ~ 1 arsec resolution.

Thank You for Your Attention