Gas-To-Dust Ratio and X Factor in the Magellanic Clouds: New Insights from Herschel

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Goals

- Derive the global values of the gas-to-dust ratio (GDR) and X factor in the LMC and SMC
- Constrain dust models using the GDR
  - The GDR can tell us something about whether or not a dust model is realistic based on the metallicity of a galaxy !
- Look at spatial variations and variations with radiation field in the X factor

See Poster by P. Panuzzo

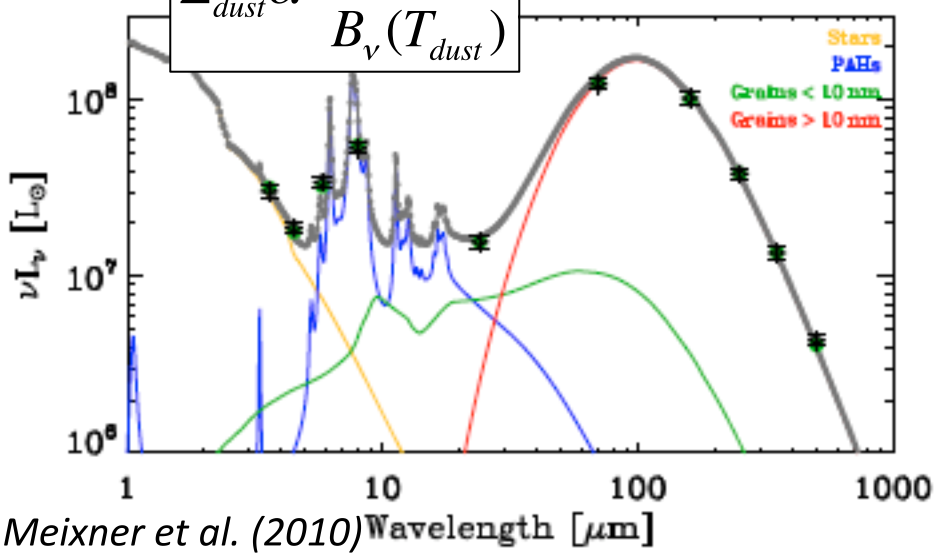
GDR From Abundances and Depletions

X	LMC N_X/N_H in ppm (M_X/M_H)	SMC N_X/N_H in ppm (M_X/M_H)	Solar N_X/N_H in ppm (M_X/M_H)	Depletion fraction (solar) (Draine 2007)
C	109.6 (1.32e-3)	53.7 (6.44e-4)	223.9 (2.69e-3)	0.43
N	13.80 (1.93e-4)	4.27 (5.97e-5)	57.5 (8e-4)	0.28
O	223.9 (3.58e-3)	107.2 (1.71e-3)	575.6 (9.21e-3)	0.27
Mg	29.5 (7.08e-4)	9.55 (2.29e-4)	36.31 (8.71e-4)	0.92
Si	64.6 (1.81e-3)	10.7 (3.e-4)	31.6 (8.85e-4)	0.95
Fe	16.98 (9.48e-4)	6.92 (3.86e-4)	27.54 (1.54e-3)	0.993
S	5.012 (1.69e-4)	3.891 (1.24e-4)	16.21 (5.19e-4)	
Total M_X/M_H	0.00873	0.003453	0.0165	
Z/Z_o	0.5	0.2	1	
$\mathrm{GDR} = \dfrac{1.36}{\sum_X \delta \times M_X / M_H}$	272 Assumption: The depletion fractions are the same in the LMC, SMC, and MW	816	170	
Min GDR ($\delta = 1$)	114	289	61	

Estimating the GDR

➔ Measure the dust and gas masses and take their ratio.

$$\Sigma_{dust} \alpha \frac{F_{160}}{B_{\nu}(T_{dust})}$$

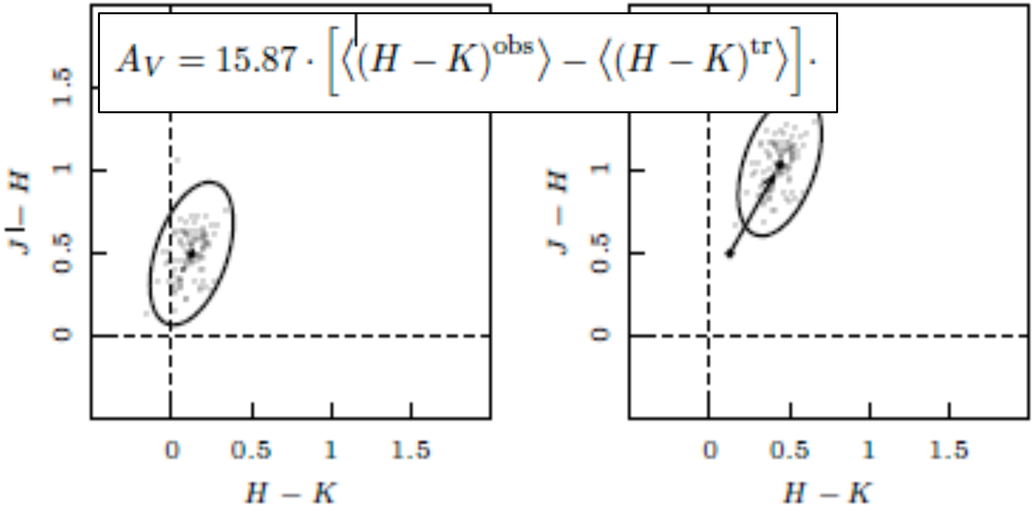


Meixner et al. (2010)

The dust mass can be derived from:

- FIR SED fitting, assuming a model for the grain properties, such as emissivity and composition.
- Extinction studies toward background stars the UV-NIR

The gas mass can be derived using H I 21 cm, CO rotational line emission observations to trace HI and H_2 (assume X factor, X_{CO})



$$A_V = 15.87 \cdot \left[\langle (H-K)^{obs} \rangle - \langle (H-K)^{tr} \rangle \right] \cdot$$

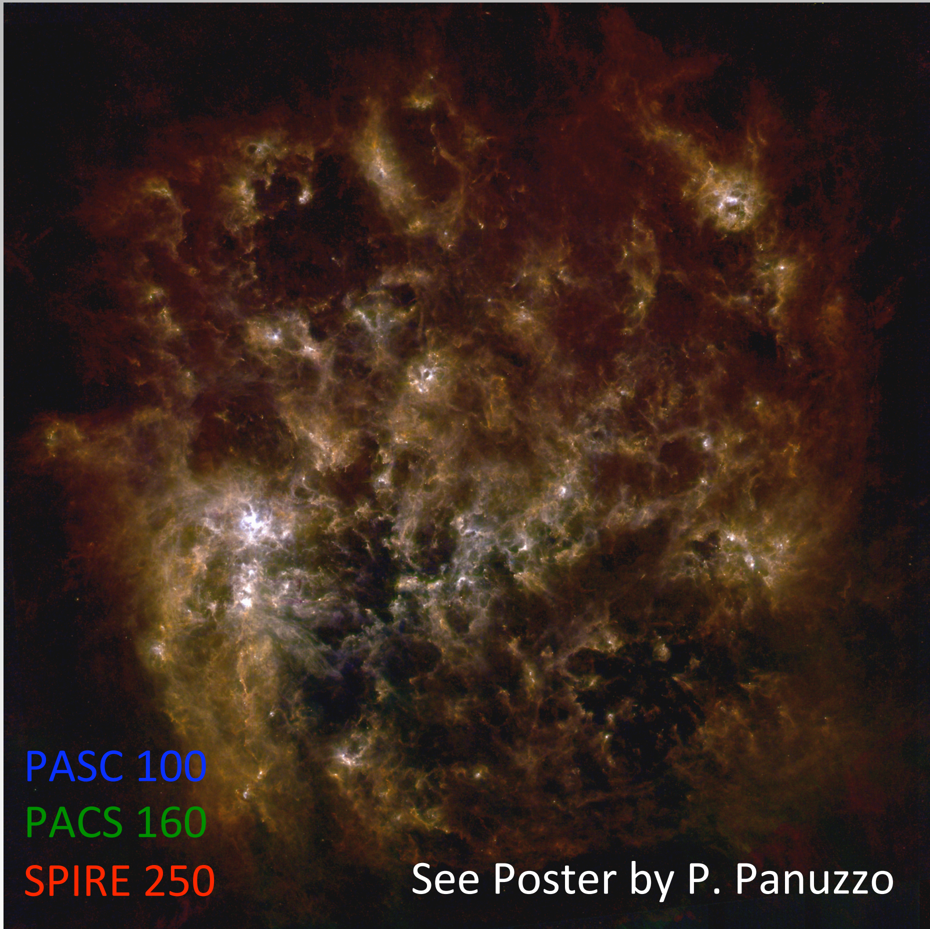
Observations

- ☐ FIR/dust: HERschel Inventory of The Agents of Galactic Evolution (**HERITAGE**, PI: Margaret Meixner, see Meixner et al. 2010)
  - ○ PACS 100, 160 μm, SPIRE 250, 350, 500 μm
  - ○ 40” resolution (SPIRE 500) convolved to 1’ resolution to match HI, CO
  - ○ Dust surface density maps derived in Gordon et al. (2010, 2011 in prep)

- ☐ Atomic Gas: HI 21 cm ATCA +Parkes survey (Kim et al. 2003) at 1’ resolution

- ☐ CO for the LMC: MAGellanic Mopra Assessment (**MAGMA**, PI: Tony Wong, see Wong et al. 2011, submitted). 1’ resolution

- ☐ CO for the SMC: **NANTEN** survey (Fukui et al. 2008). 2.6’ resolution



See Poster by P. Panuzzo

Derivation of GDR and X Factor

$$GDR = \frac{0.02\,\overset{\text{Observed}}{I_{HI}} + 2.16\times10^{-20}\,\overset{\text{Unknown}}{X_{CO}}\,\overset{\text{Observed}}{I_{CO}} + \overset{\text{Unknown}}{\Sigma(H_2^{CO-dark})}}{\Sigma_{dust}}$$

Derived from FIR SED fitting or extinction (MODEL DEPENDENT !)

- **PROBLEM: Presence of H_2 in low-Z GMC envelopes where there's no CO, making it invisible to CO emission observations !**

- **How to get around the issue of X_{CO} and CO-dark molecular gas ?**

Derivation of the “global” GDR and X Factor

➔ Compute GDR as the slope of the correlation between Σ_{gas} and Σ_{dust} in the **diffuse ISM (A_V<0.3)**, where no H_2 exists:

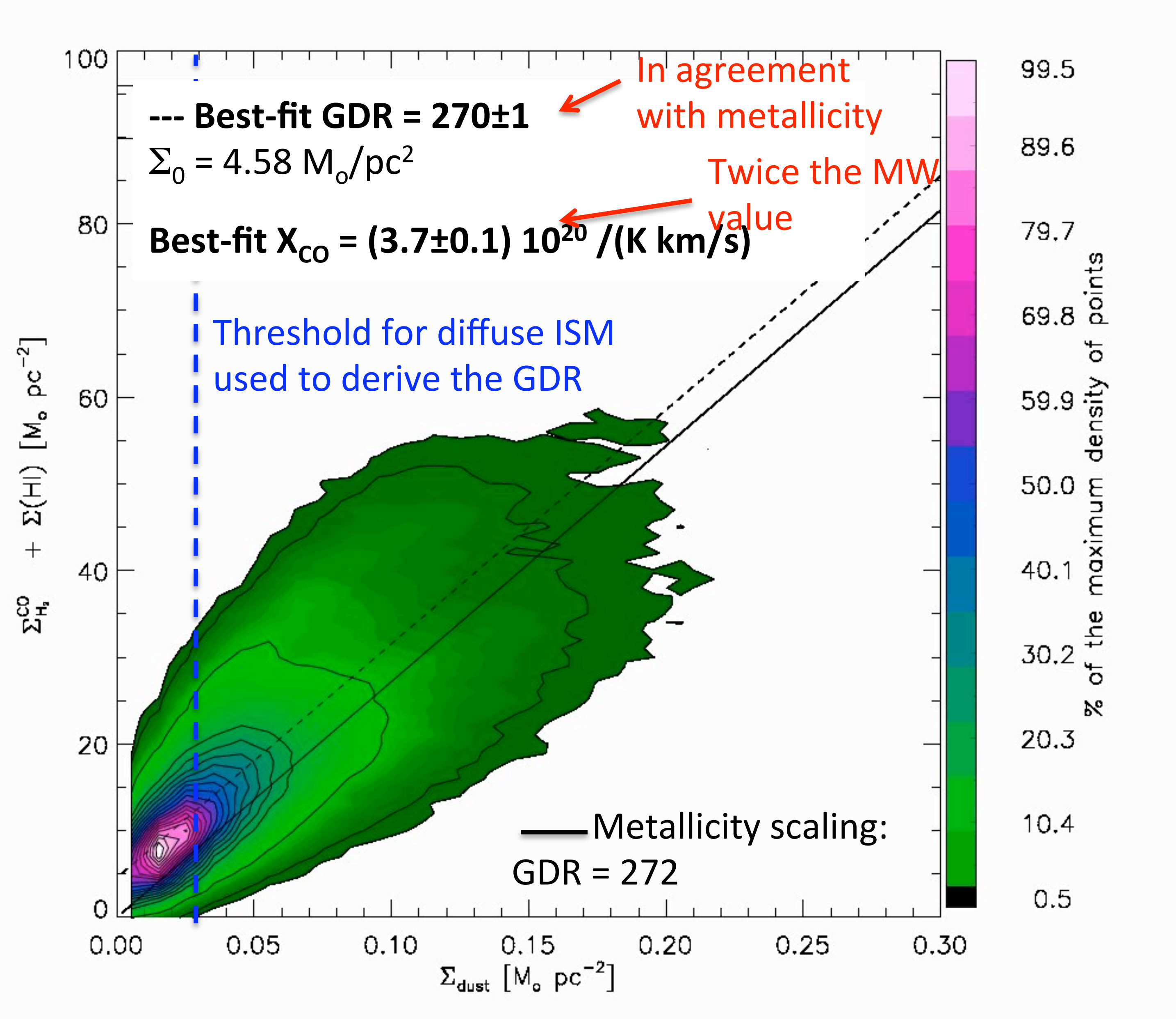
$$\underbrace{\Sigma(HI)_{diffuse}}_{\text{Observed}} = \underbrace{GDR_{diffuse}}_{\text{Slope of the correlation}} \underbrace{\Sigma_{dust}^{diffuse}}_{\text{Observed}} + \underbrace{\Sigma_0}_{\text{Intercept of the correlation}}$$

➔ Compute X_{CO} where CO is detected as best-fit to $\Sigma(H_2)=X_{CO}I_{CO}$

$$\underbrace{GDR_{diffuse}\Sigma_{dust}^{CO} - \Sigma^{CO}(HI) + \Sigma_0}_{\Sigma(H_2)} = \underbrace{X_{CO}}_{\text{Slope of the correlation}} \times \underbrace{2.16\times10^{-20} I_{CO}}_{\text{Observed}}$$

Assumption: The GDR is does not depend on density !

Case of the LMC $\beta = 1.5$ (amorphous Carbon)



--- Best-fit GDR = 270±1

$\Sigma_0 = 4.58\ M_o/pc^2$

Best-fit $X_{CO} = (3.7 \pm 0.1)\ 10^{20}$ /(K km/s)

In agreement with metallicity

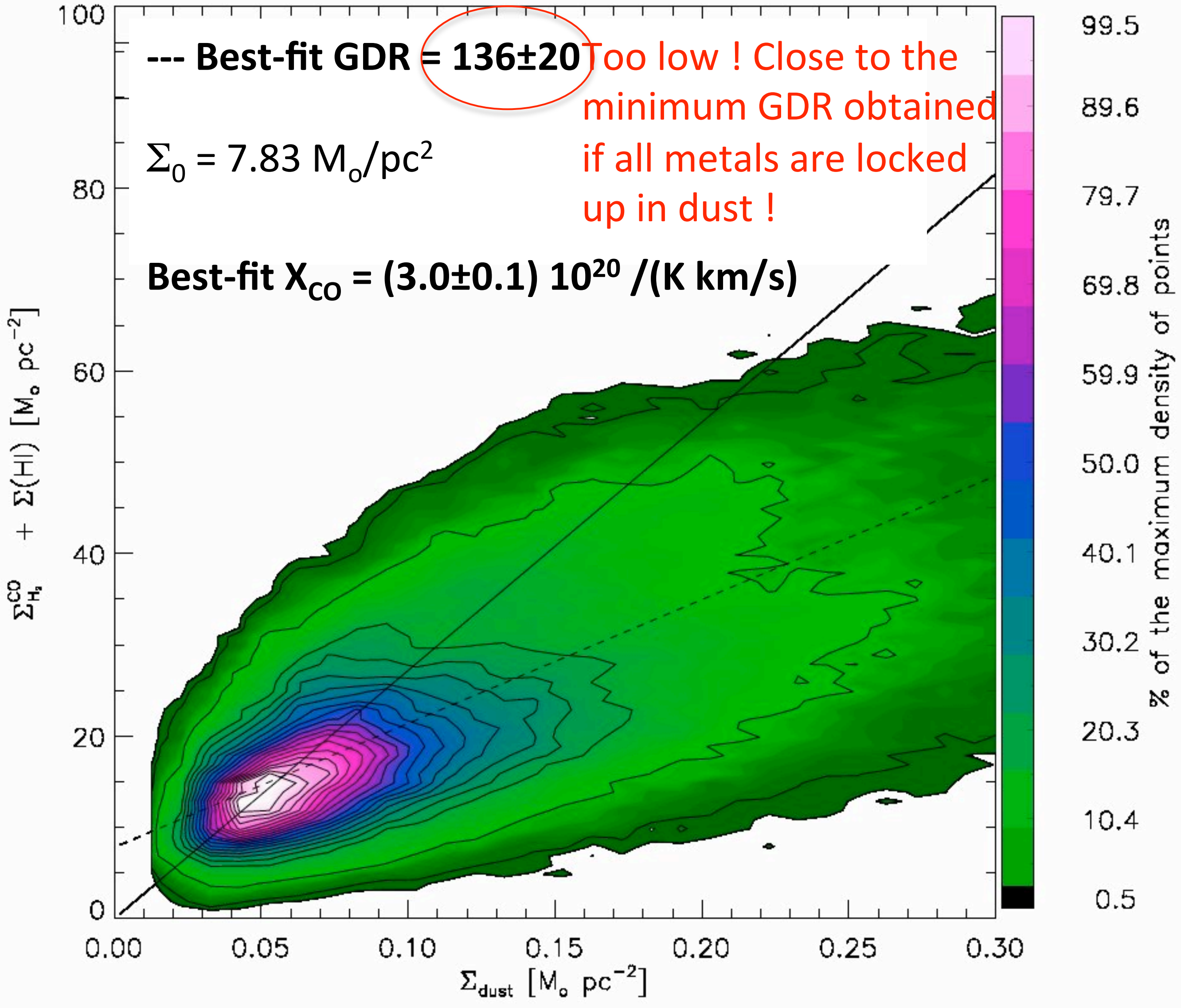
Twice the MW value

Threshold for diffuse ISM used to derive the GDR

—— Metallicity scaling: GDR = 272

Σ_{dust} obtained from SED fitting to **modified black body of emissivity index $\beta = 1.5$** with *Herschel* bands (PACS 100, 160 μm, SPIRE 250, 350, 500 μm)

Case of the LMC $\beta = 2$ (Carbon graphite)



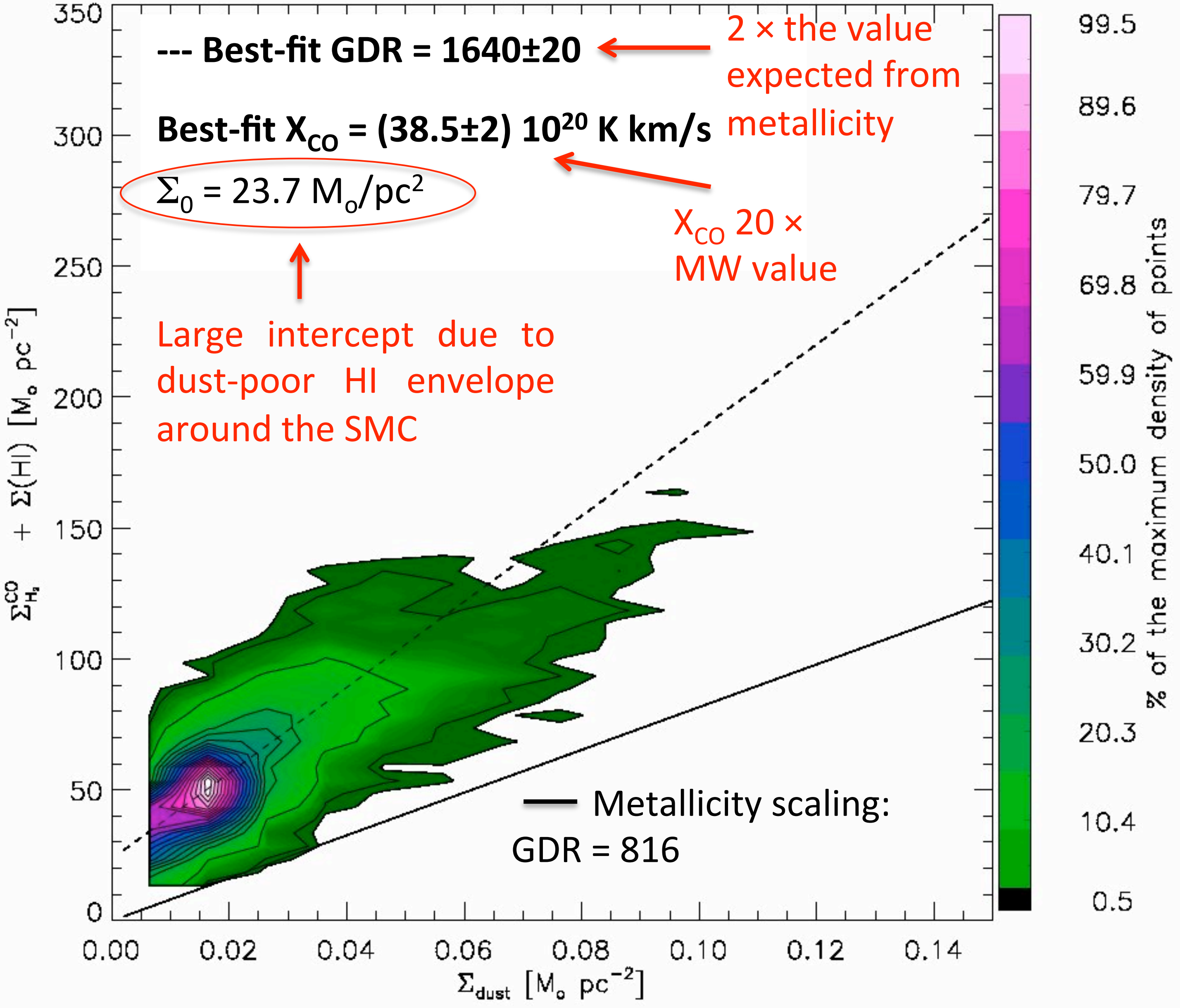
--- Best-fit GDR = 136±20 Too low ! Close to the minimum GDR obtained if all metals are locked up in dust !

$\Sigma_0 = 7.83\ M_o/pc^2$

Best-fit $X_{CO} = (3.0 \pm 0.1)\ 10^{20}$ /(K km/s)

Σ_{dust} obtained from SED fitting to **modified black body of emissivity index $\beta = 2$** with *Herschel* bands (PACS 100, 160 μm, SPIRE 250, 350, 500 μm)

Case of the SMC β = 1.5



--- Best-fit GDR = 1640±20

2 × the value expected from metallicity

Best-fit X_{CO} = (38.5±2) 10^{20} K km/s

X_{CO} 20 × MW value

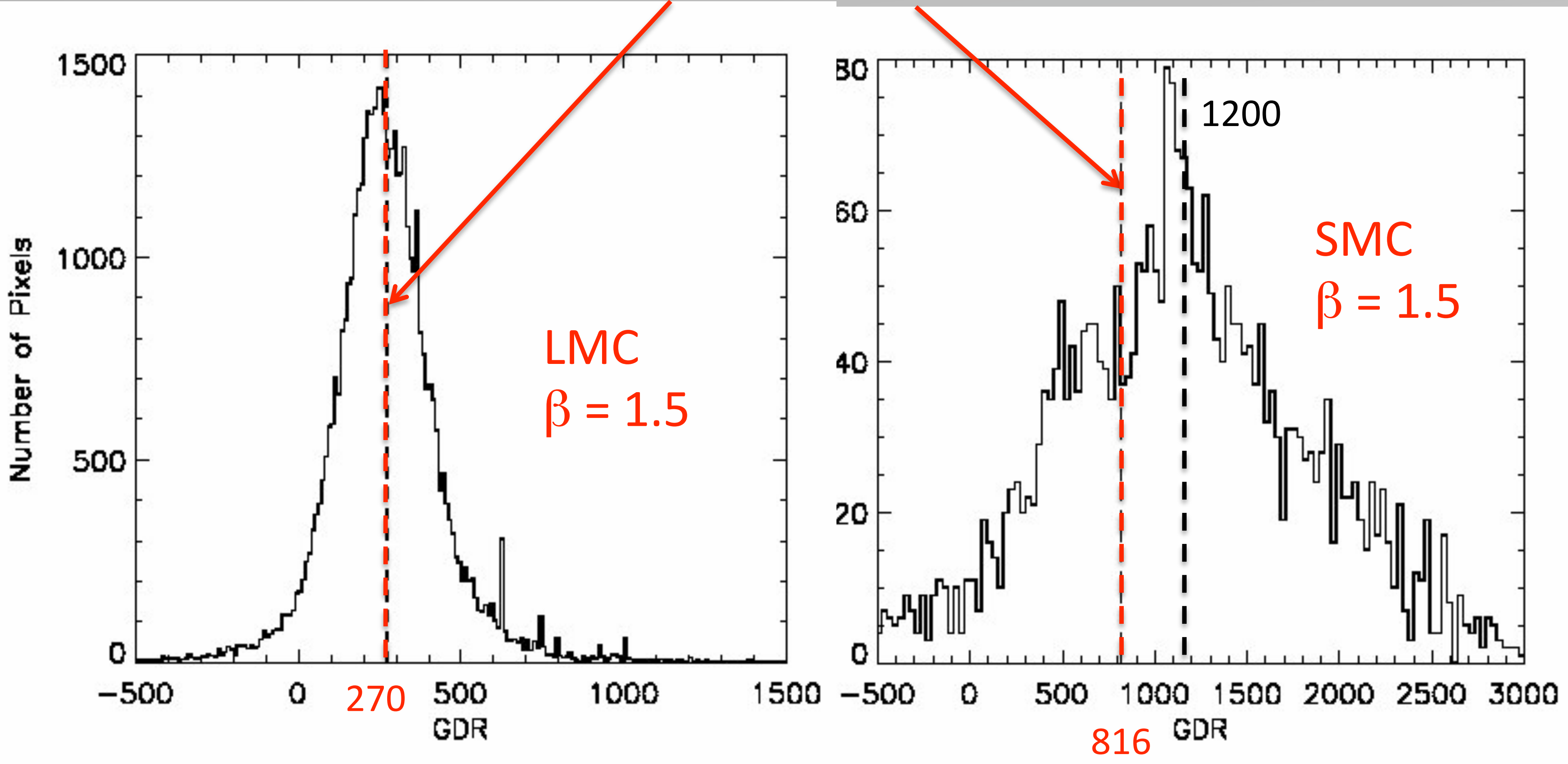
Σ_0 = 23.7 M_o/pc^2

Large intercept due to dust-poor HI envelope around the SMC

— Metallicity scaling: GDR = 816

GDR Map and Histogram

Coarse GDR map obtained from the same correlation method to pixels in aperture of diameter 100 pc (LMC) or 200 pc (SMC)



Prediction from metallicity, assuming GDR α 1/Z

LMC
$\beta = 1.5$

270

SMC
$\beta = 1.5$

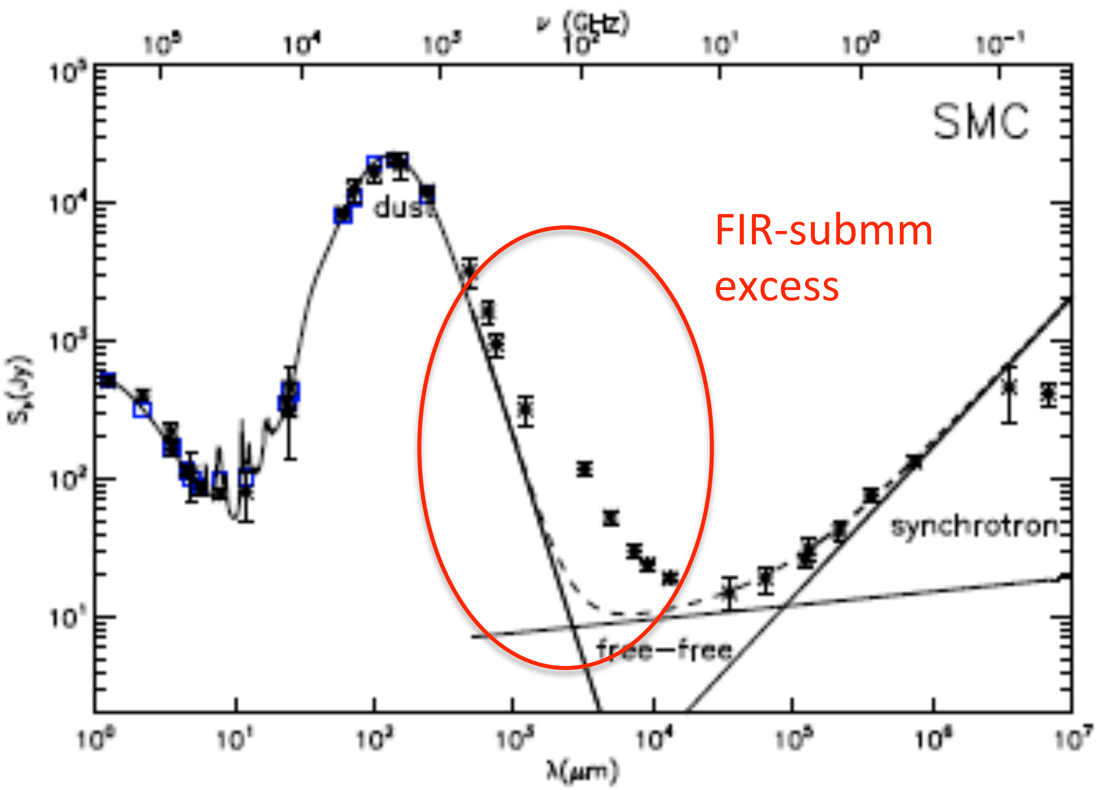
816

1200

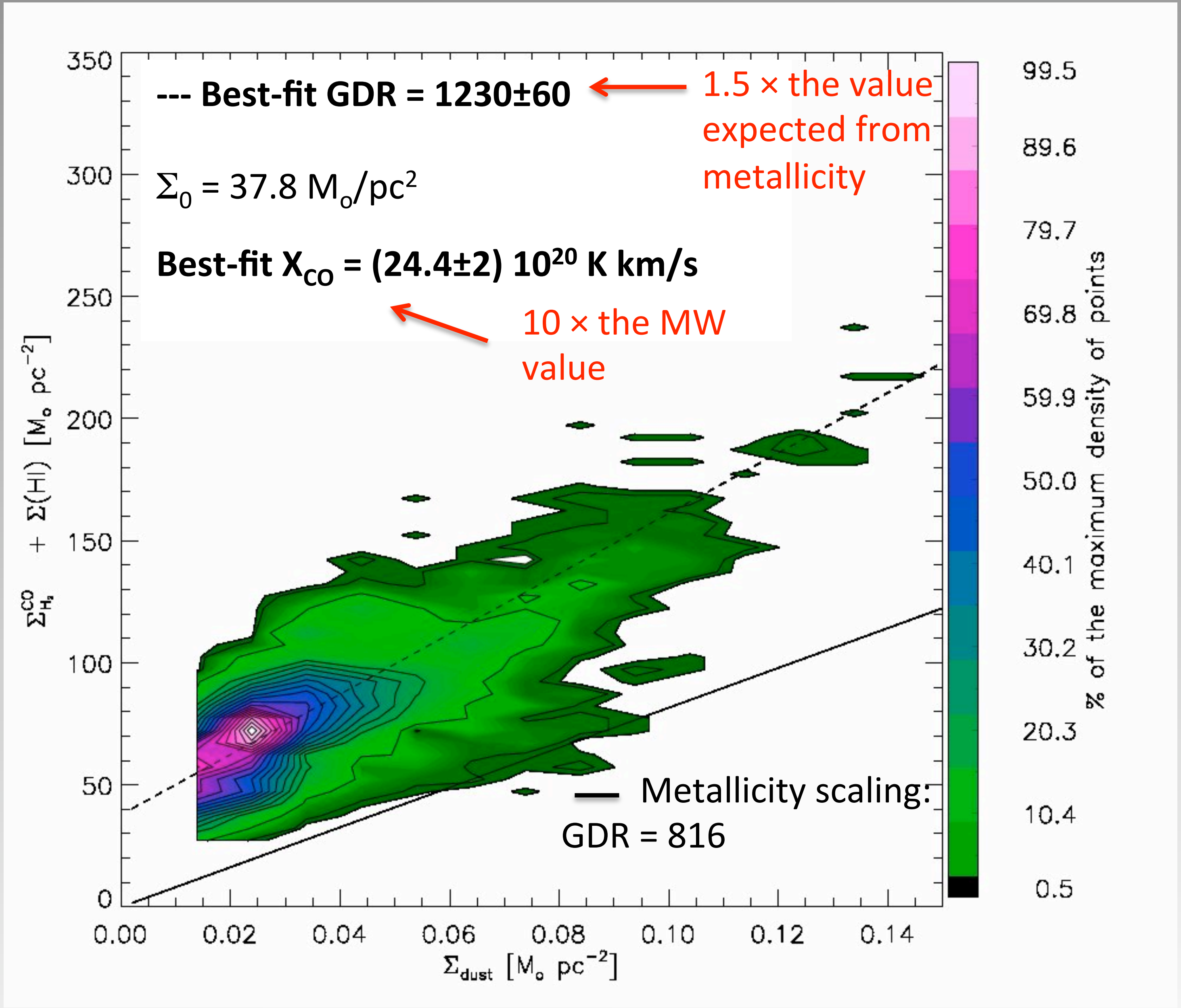
FIR and sub-mm Excess

- In the LMC and SMC, there is an observed excess emission at wavelengths > 200 μm compared to a modified black body with single emissivity index (Gordon et al. 2010, Bot et al. 2010, Israel et al. 2010)
- Possibilities to explain this excess include:
    - Modification of dust properties longward of 200 μm
    - Spinning dust
    - Cold dust component (T < 10 K)
- Residuals and quality of the fits itself can usually not discriminate between these possibilities.
- A large amount of cold dust would be required to explain FIR/submm excess, so GDR may eliminate this possibility

From Bot et al. 2010



Case of the SMC



--- **Best-fit GDR = 1230±60** ← 1.5 × the value expected from metallicity

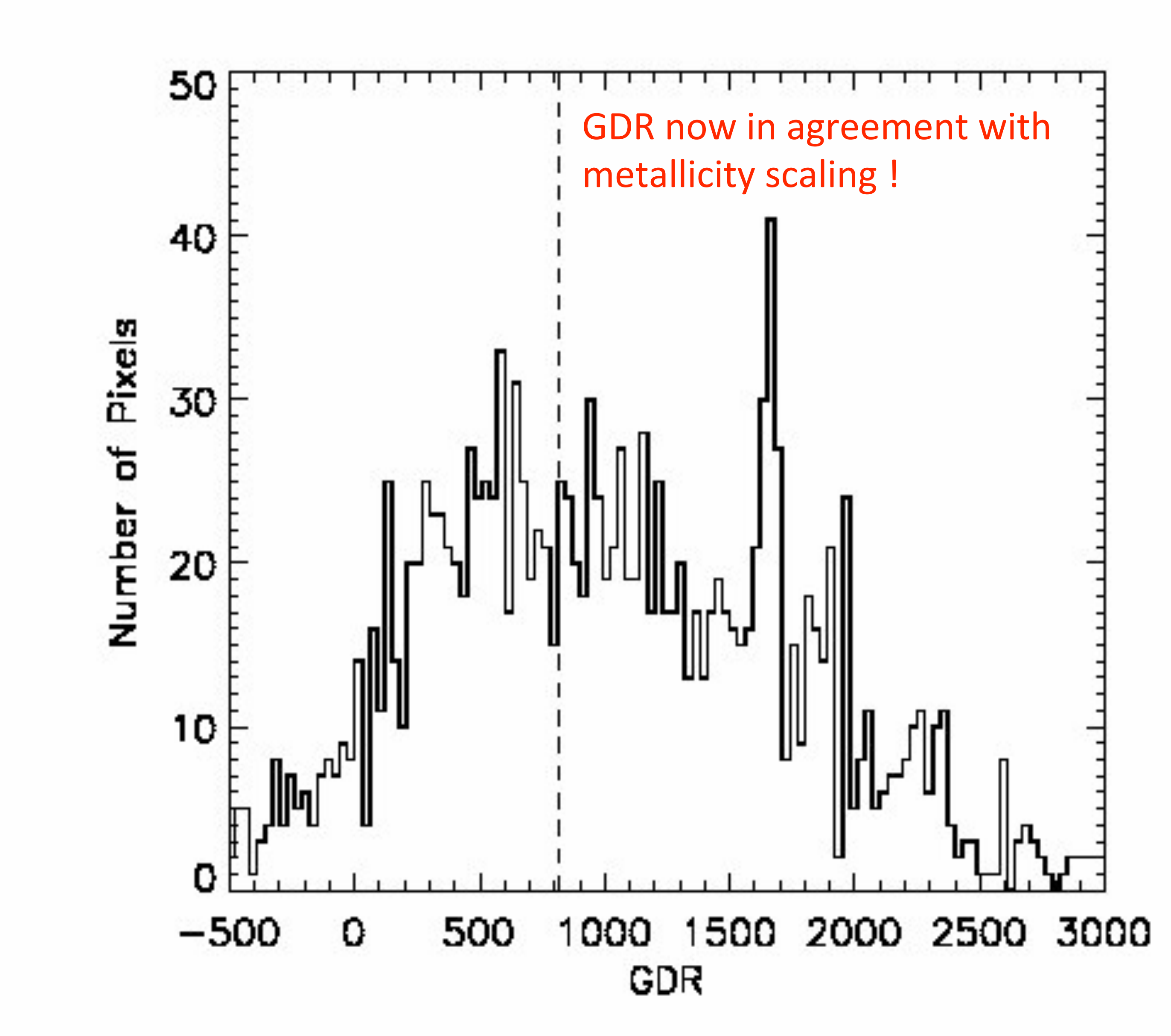
$\Sigma_0 = 37.8\ M_o/pc^2$

Best-fit X_{CO} = (24.4±2) 10^{20} K km/s ← 10 × the MW value

— Metallicity scaling: GDR = 816

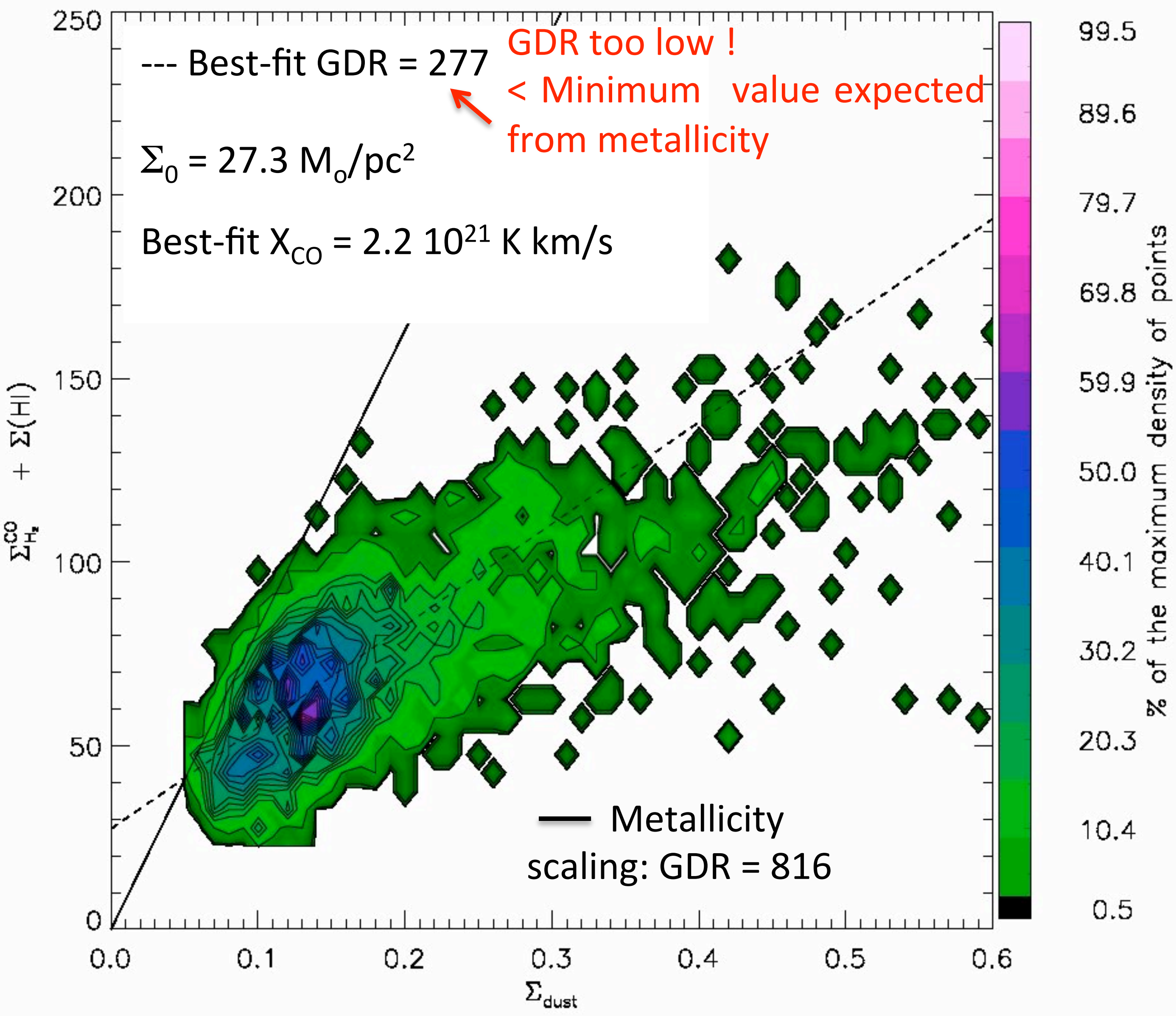
Σ_{dust} obtained from SED fitting to **modified black body of broken emissivity law with $\beta = 1.5$ for $\lambda < 300\ \mu m$, and set as free parameter for $\lambda > 300\ \mu m$**

Case of the SMC: Broken Emissivity Law



GDR now in agreement with metallicity scaling !

Case of the SMC: Very Cold Dust Component ?



--- Best-fit GDR = 277

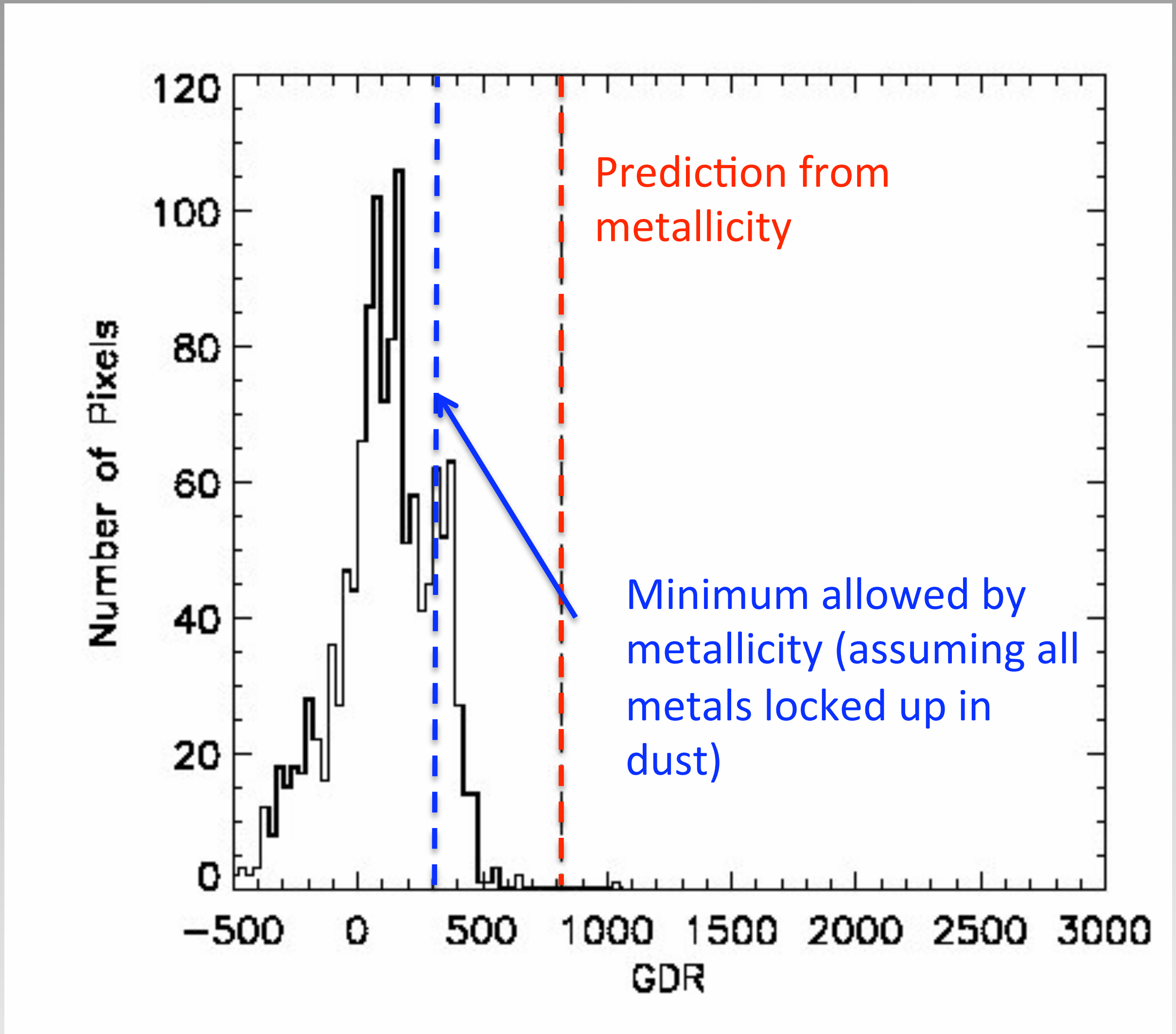
Σ_0 = 27.3 M_o/pc^2

Best-fit X_{CO} = 2.2 10^{21} K km/s

GDR too low !
< Minimum value expected from metallicity

SED fit to modified black body of emissivity index β = 1.5 + emission from T = 7.5 K dust

Case of the SMC: Very Cold Dust Component ?



Prediction from metallicity

Minimum allowed by metallicity (assuming all metals locked up in dust)

Add emission from dust at T = 7.5 K to fit submm excess:

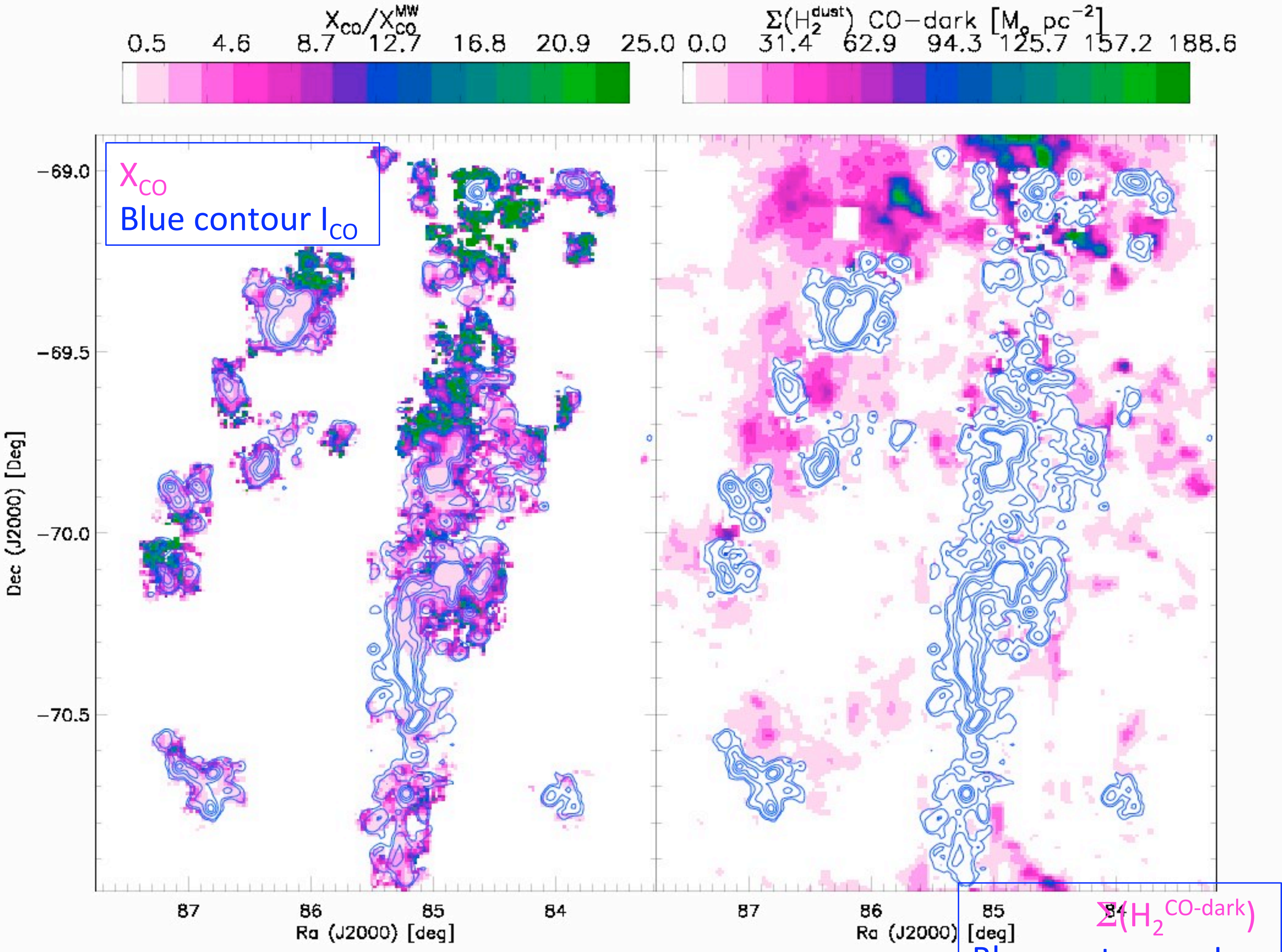
➔ GDR too low (lower than minimum allowed by metallicity (289)

X Factor Variations and CO-Dark H_2

- Coarse GDR map allows the derivation of a map of the X factor **where CO is detected**
- First calculate X_{CO} as a **ratio** to examine spatial variations

$$X_{CO} = \frac{\Sigma(H_2)}{2.16\times10^{-20} I_{CO}} = \frac{GDR\times\Sigma_{dust}+\Sigma_0-\Sigma(HI)}{2.16\times10^{-20} I_{CO}}$$

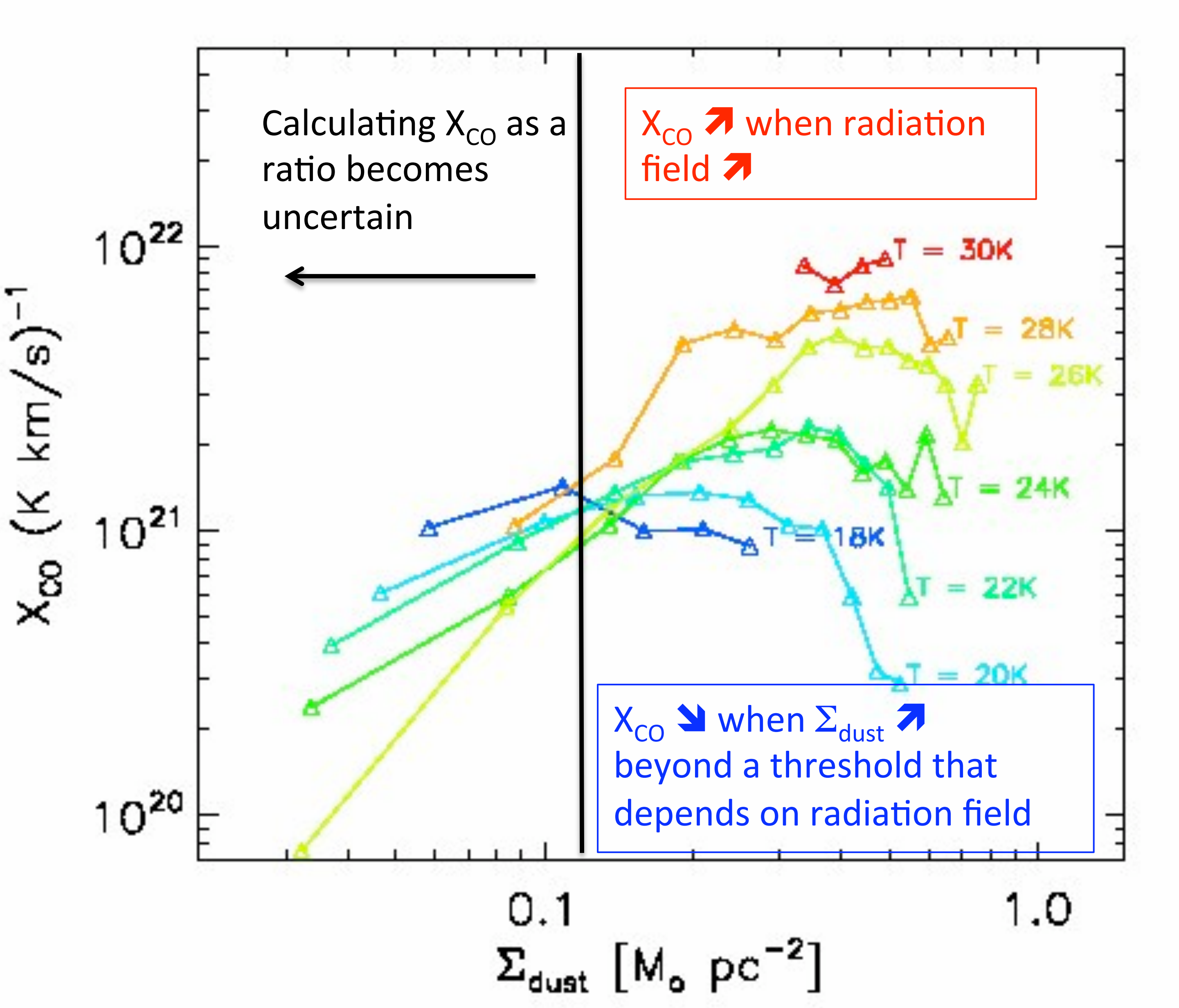
- Where no CO is detected, $\Sigma(H_2)$ is CO-Dark, but can be traced by dust !



X_{CO}
Blue contour I_{CO}

$\Sigma(H_2^{CO\text{-}dark})$
Blue contours = I_{CO}

Variations with Radiation Field



Calculating X_{CO} as a ratio becomes uncertain ←

X_{CO} ↗ when radiation field ↗

X_{CO} ↘ when Σ_{dust} ↗ beyond a threshold that depends on radiation field

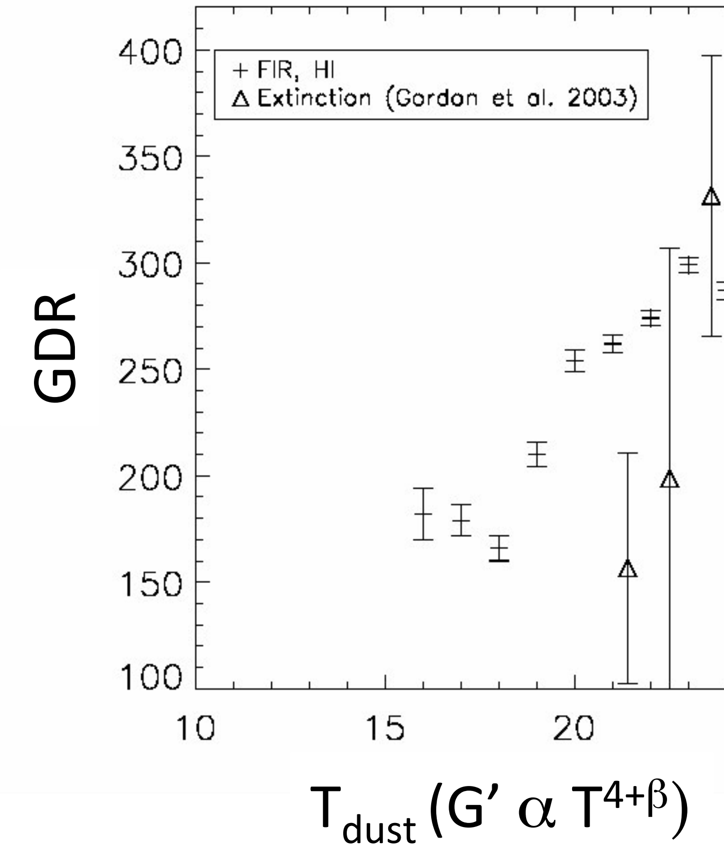
X_{CO} calculated as a slope for different radiation fields

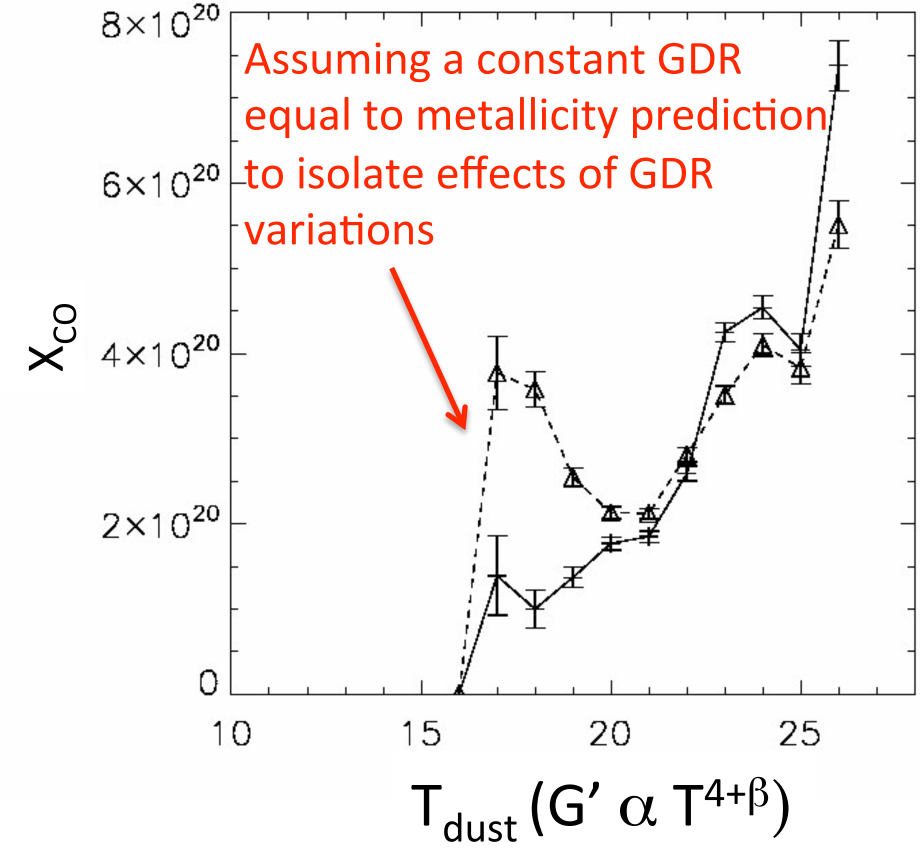
- Consider all the pixels where the dust temperature is within the interval [$T_i-\delta T$, $T_i+\delta T$], with T_i = temperature bin
- The same method used to derive the "global" GDR and X_{CO} can be applied to this subset of pixels
- Possibility to examine variations of GDR and X_{CO} with T_{dust}, radiation field

$$\Sigma(HI)^{T=T_i}_{diffuse} = \underbrace{GDR_{diffuse}(T_i)}_{\text{Slope of the correlation between } \Sigma_{dust} \text{ and } \Sigma \text{ (HI)}}\Sigma^{diffuse,T=T_i}_{dust} + \Sigma_0^{T=T_i}$$

$$\underbrace{GDR^{T=T_i}_{diffuse}\times\Sigma^{T=T_i}_{dust}+\Sigma_0^{T=T_i}-\Sigma(HI)^{T=T_i}}_{\Sigma(H_2,\ T\,=\,T_i)} = \underbrace{X_{CO}(T_i)}_{\text{Slope of the correlation}}\times\underbrace{2.16\times10^{-20}\, I_{CO}^{T=T_i}}_{\text{Observed CO}}$$

Variations with Radiation Field: X_{CO} calculated as a slope





Assuming a constant GDR equal to metallicity prediction to isolate effects of GDR variations

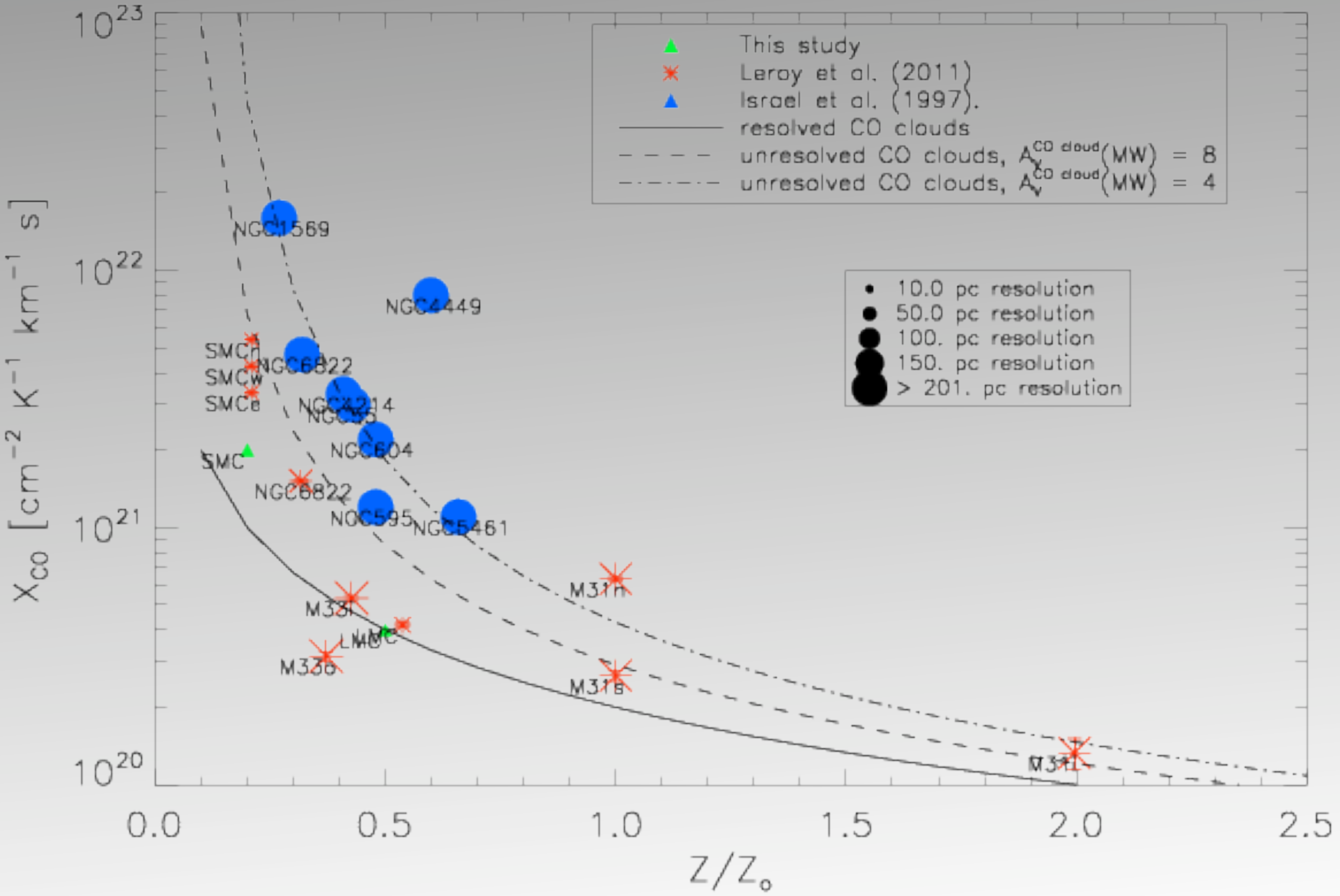
Systematics or real variation ?

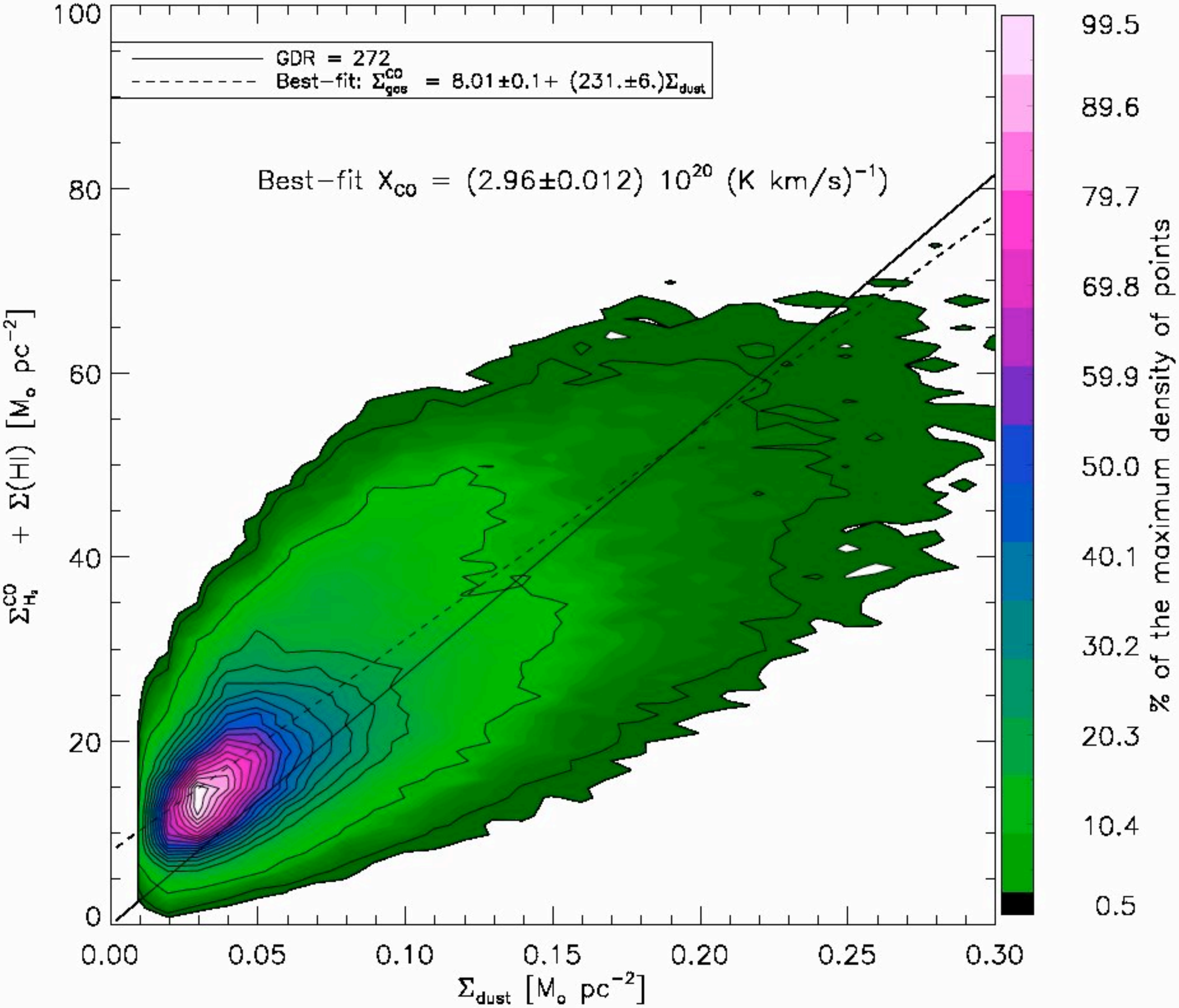
➔Factor of two in GDR consistent with dust destruction/grain growth

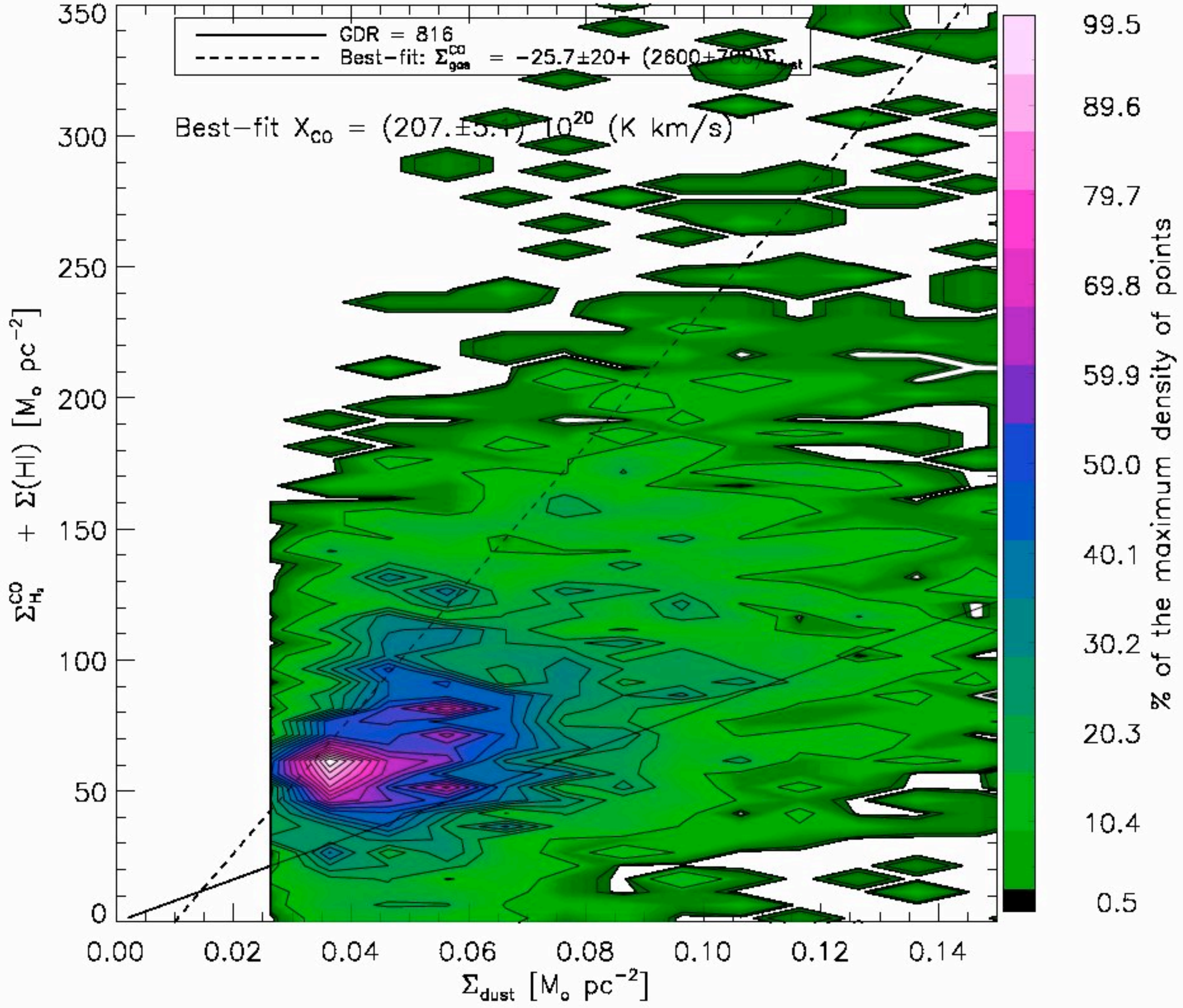
➔Need to estimate dust column independently (using extinction)

Summary/Conclusion

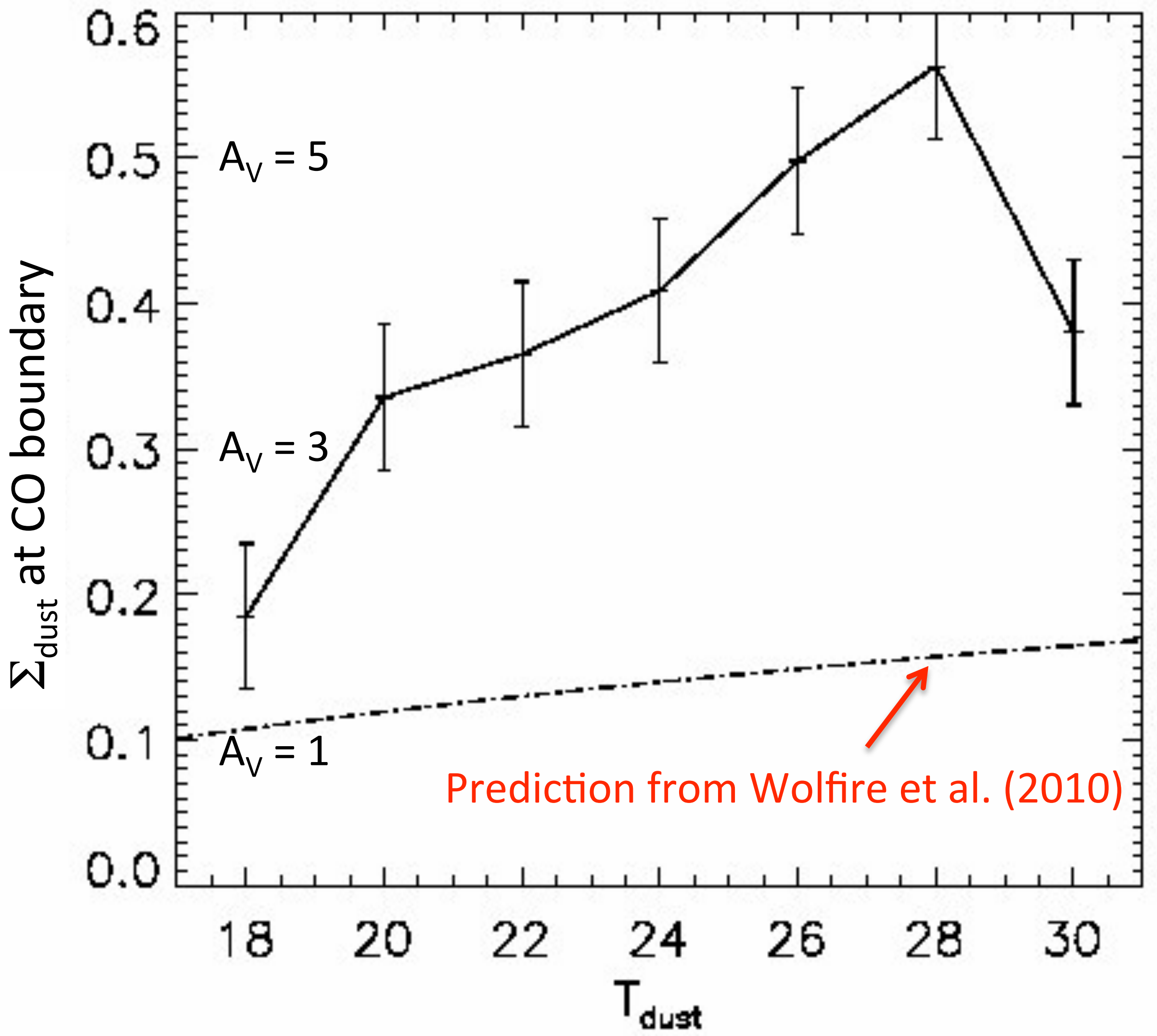
- GDR in the LMC and SMC based on the correlation between HI and dust surface densities in diffuse regions with no molecular gas
  - LMC: GDR = 270 (Modified black body with β = 1.5)
  - SMC: GDR = 1230 (Modified black body with broken emissivity law, β = 1.5 for λ < 300 mic)
  - Very cold dust component, carbon graphite (β = 2) not likely (GDR too low !)
- Global X factor in the LMC and SMC based on the H_2 surface density derived from FIR and HI, and the observed CO.
  - LMC: $X_{CO} \sim 4\times10^{20}$ K^{-1} km^{-1} s; SMC: $X_{CO} \sim 25\times10^{20}$ K^{-1} km^{-1} s
- CO-dark H_2 in GMC photo-dissociated envelopes can be traced by dust
- X_{CO} increases:
  - With radiation field (dust temperature), as CO becomes more and more photo-dissociated
  - Near the edges of GMCs, where CO starts to be photo-dissociated
- GDR increases with dust temperature/radiation field; Dust destruction in the diffuse ISM or in massive star formation regions such as 30 Dor?


This study
Leroy et al. (2011)
Israel et al. (1997).
resolved CO clouds
unresolved CO clouds, $A_V^{CO\ cloud}(MW) = 8$
unresolved CO clouds, $A_V^{CO\ cloud}(MW) = 4$
10.0 pc resolution
50.0 pc resolution
100. pc resolution
150. pc resolution
> 201. pc resolution
NGC1569
NGC4449
SMCn
SMCw
SMCe
NGC6822
NGC4214
NGC55
NGC604
SMC
NGC6822
NGC595
NGC5461
M31n
M33i
LMC
M33o
M31s
M31
X_{CO} [cm^{-2} K^{-1} km^{-1} s]
10^{23}
10^{22}
10^{21}
10^{20}
0.0
0.5
1.0
1.5
2.0
2.5
Z/Z_o


GDR = 272
Best−fit: Σ^{CO}_{gas} = 8.01±0.1+ (231.±6.)Σ_{dust}
Best−fit X_{CO} = (2.96±0.012) 10^{20} (K km/s)$^{-1}$)
$\Sigma^{CO}_{H_2}$ + Σ(HI) [$M_\odot$ pc^{-2}]
Σ_{dust} [$M_\odot$ pc^{-2}]
0
20
40
60
80
100
0.00
0.05
0.10
0.15
0.20
0.25
0.30
99.5
89.6
79.7
69.8
59.9
50.0
40.1
30.2
20.3
10.4
0.5
% of the maximum density of points

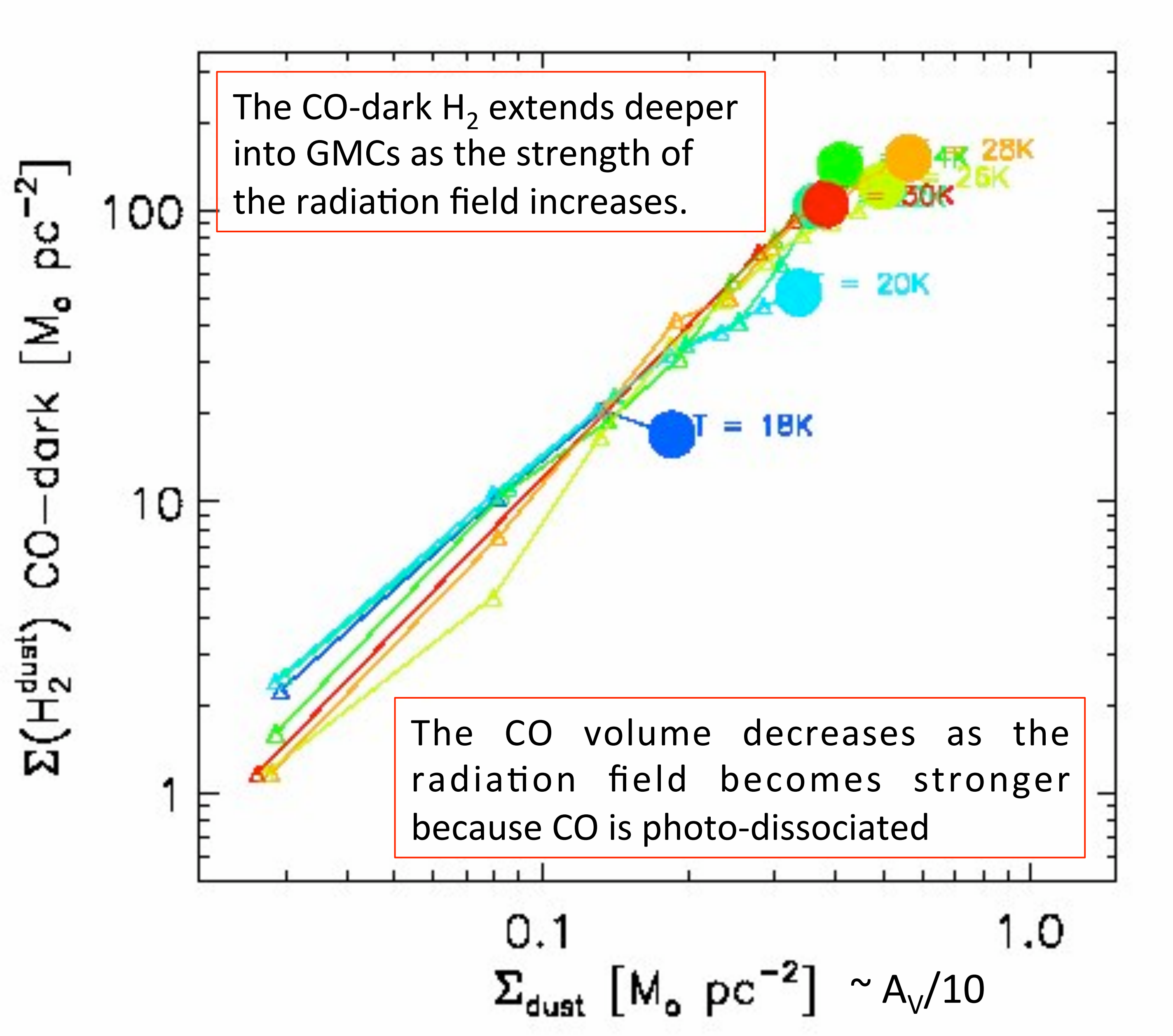

GDR = 816
Best-fit: Σ_{gas}^{CO} = −25.7±20+ (2600±700)Σ_{dust}
Best-fit X_{CO} = (207.±5.1) 10^{20} (K km/s)
350
300
250
200
150
100
50
0
$\Sigma_{H_2}^{CO}$ + Σ(HI) [$M_\odot$ pc^{-2}]
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Σ_{dust} [$M_\odot$ pc^{-2}]
99.5
89.6
79.7
69.8
59.9
50.0
40.1
30.2
20.3
10.4
0.5
% of the maximum density of points

Variations with Radiation Field



Prediction from Wolfire et al. (2010)

Variations with Radiation Field



The CO-dark H_2 extends deeper into GMCs as the strength of the radiation field increases.

The CO volume decreases as the radiation field becomes stronger because CO is photo-dissociated

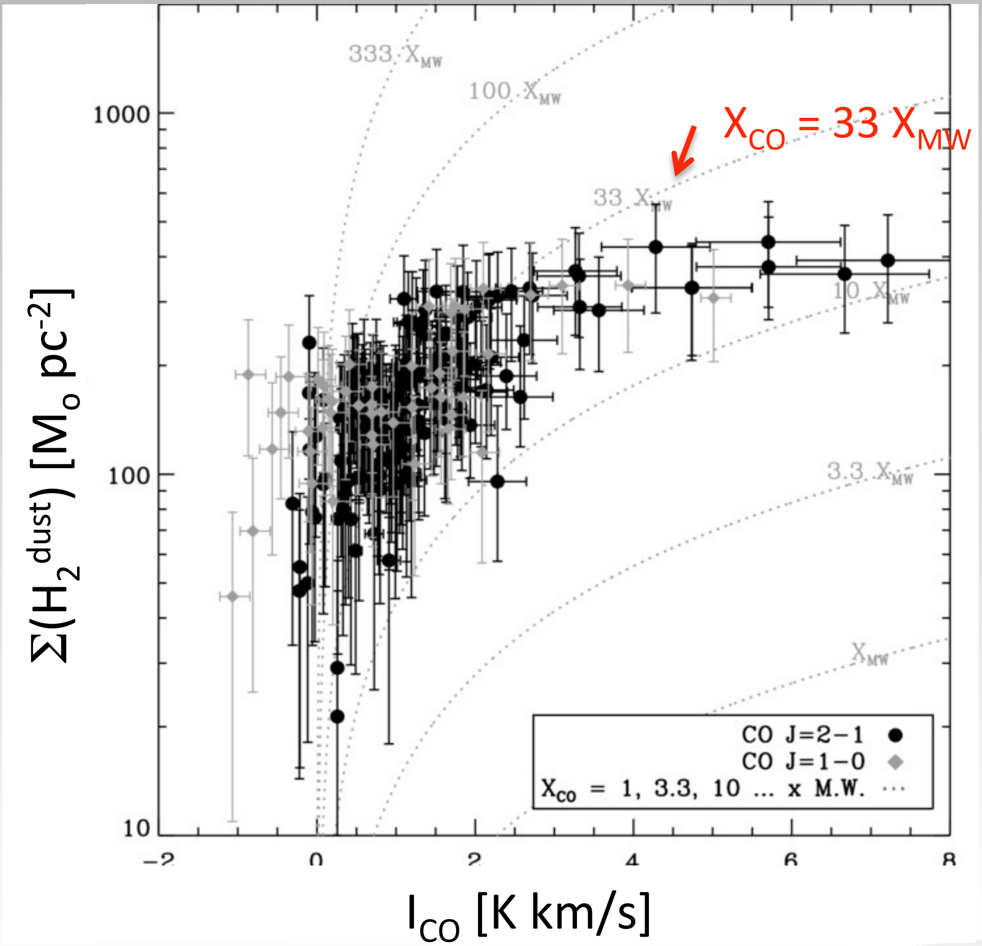
~ $A_V/10$

Why do we need the GDR ?

- ❑ In low-Z galaxies ($A_V \alpha Z$), CO is an ineffective tracer of molecular gas because it is photo-dissociated more easily than H_2
- ❑ A good estimate of the GDR is fundamental to estimate the X factor and mass of CO-dark molecular gas from FIR observations in low-Z galaxies.

$$\Sigma(H_2^{dust}) = GDR\ \Sigma_{dust} - \Sigma(HI)$$

$$X_{CO} = \frac{\Sigma(H_2^{CO})}{2.16\ 10^{-20}\ I_{CO}}$$

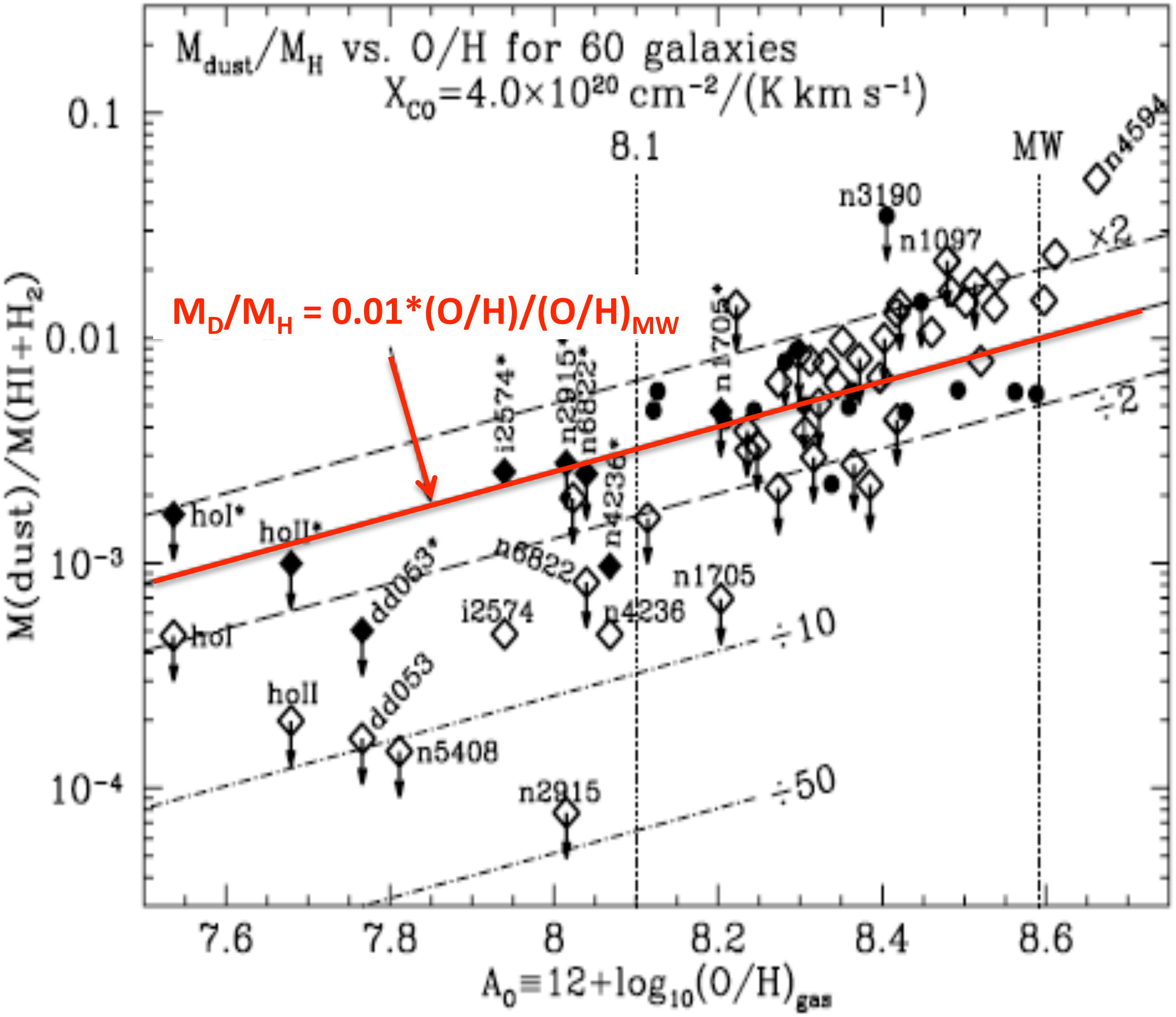


From Leroy et al. (2009):

Surface density of H_2, $\Sigma(H_2^{dust})$, derived from FIR and HI measurements as a function of CO integrated intensity (I_{CO}) in N83 (SMC)

Dependence on Metallicity

Theoretical prediction: GDR varies linearly with ISM metallicity, no matter what the star formation history is (e.g., Dwek 1998)



$M_D/M_H = 0.01*(O/H)/(O/H)_{MW}$

<u>From Draine et al. (2007):</u> Relation between metallicity and GDR in 65 SINGS galaxies. The filled points show results for the regions of the galaxies where IR emission is detected. The non-filled points include the HI envelopes