Relation between dust and gas in the LMC and SMC: Probing dust evolution between ISM phases

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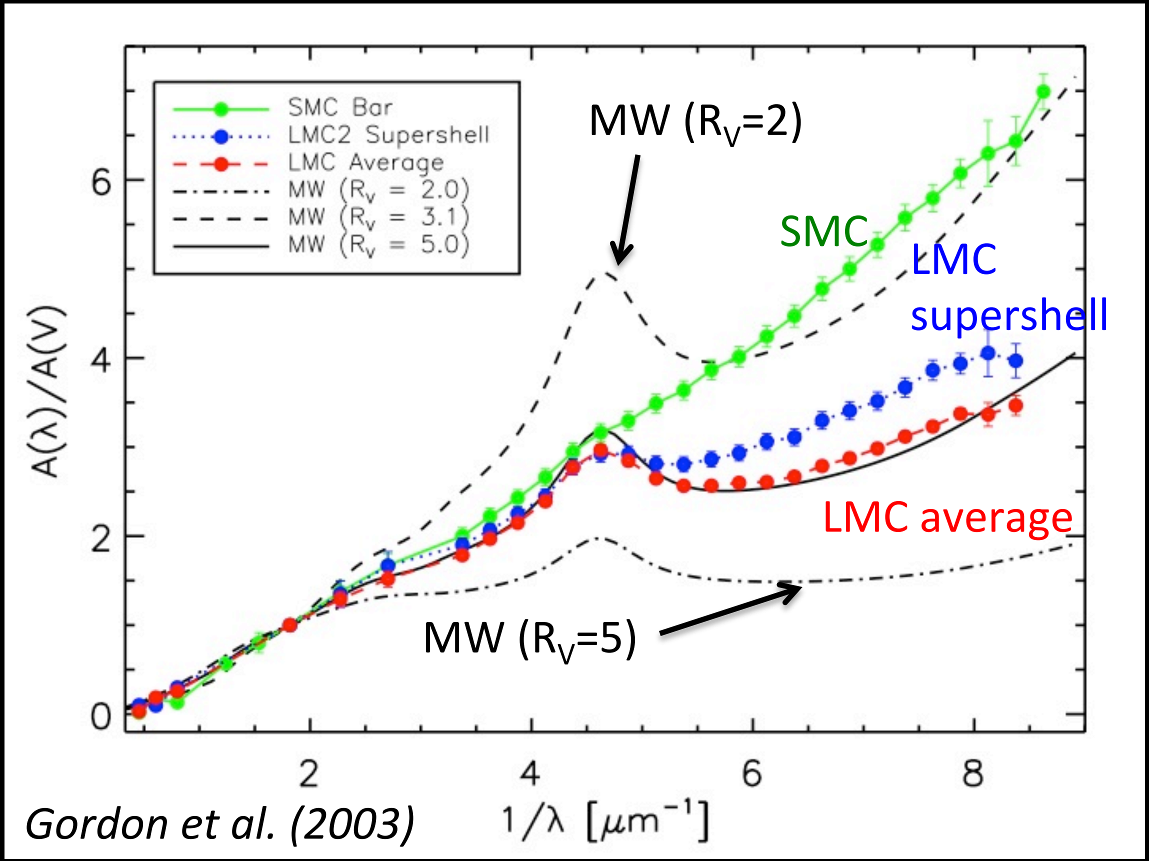
In collaboration with Karl Gordon, Margaret Meixner, and the HERITAGE Team

Evidence for dust evolution in the ISM: UV Extinction Curves



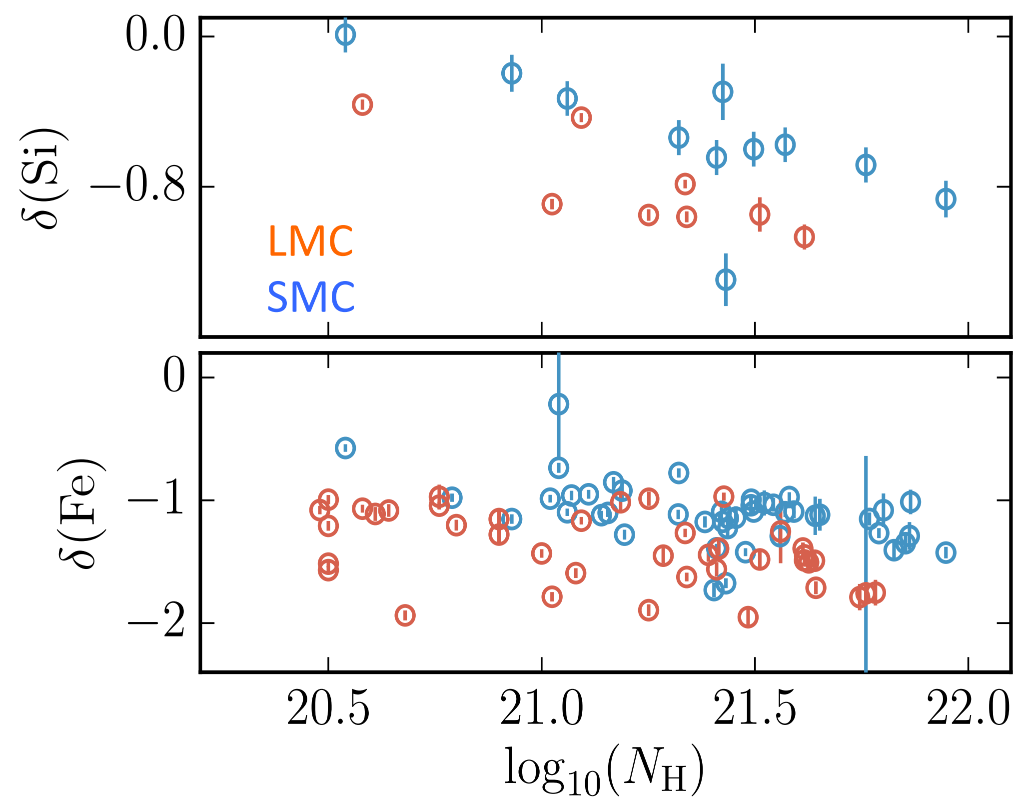
Gordon et al. (2003)

Size and composition of dust grains change with environment

Evidence for dust evolution in the ISM: Depletions

- Fraction of metals locked up in dust grains increases with increasing density

- This increases the abundance of dust and changes its composition in molecular clouds compared to the diffuse ISM



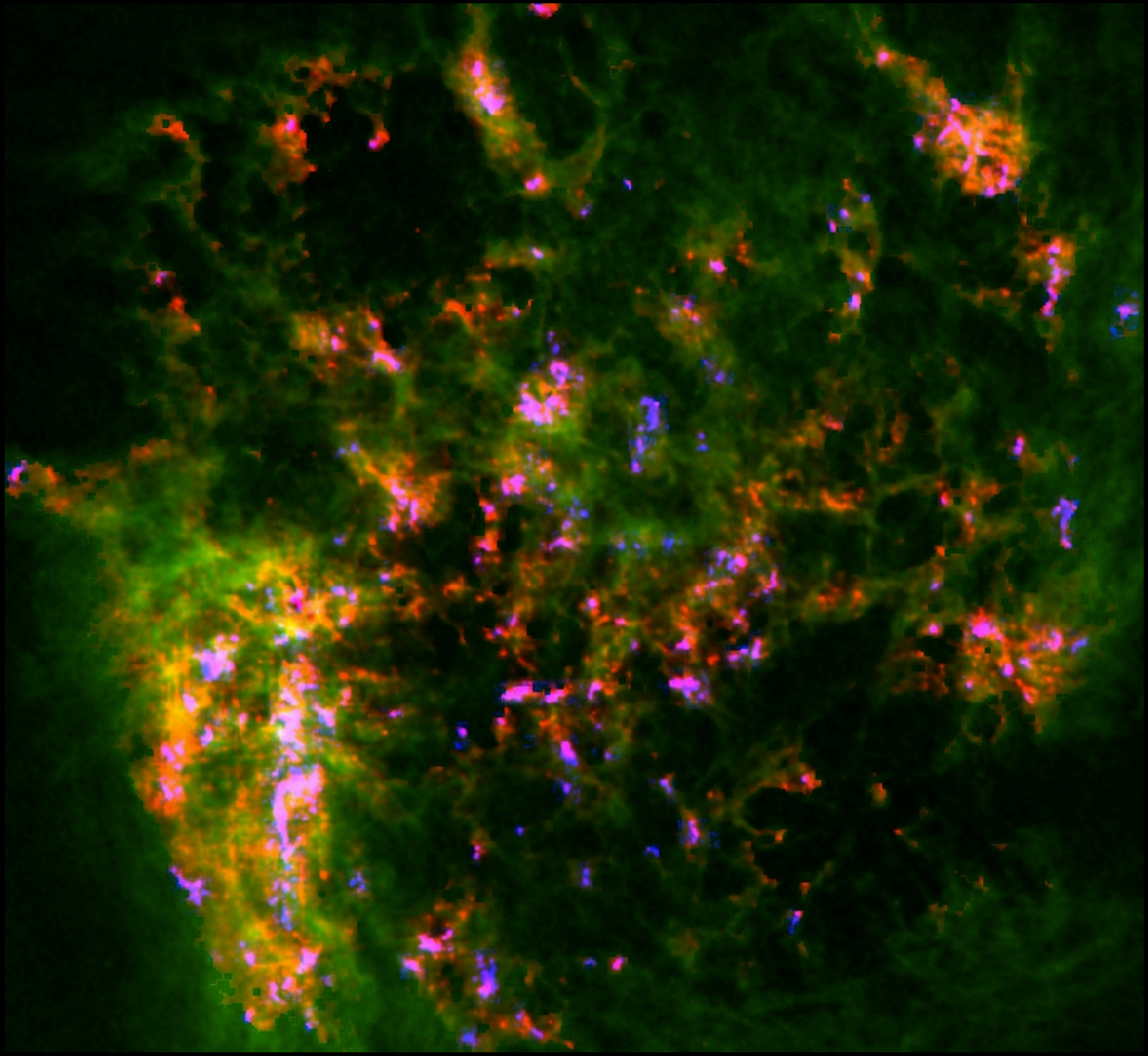
Tchernyshyov et al. 2015

Outline

- Dust-HI relation in the LMC and SMC
  - Location of the atomic-molecular transition
  - Gas-to-dust ratio of diffuse atomic ISM

- Dust-total gas relation in the LMC and SMC
  - Degeneracies between dust evolution and CO-dark H_2
  - Evidence for dust evolution in the LMC

LMC Dust and Gas Surface Densities



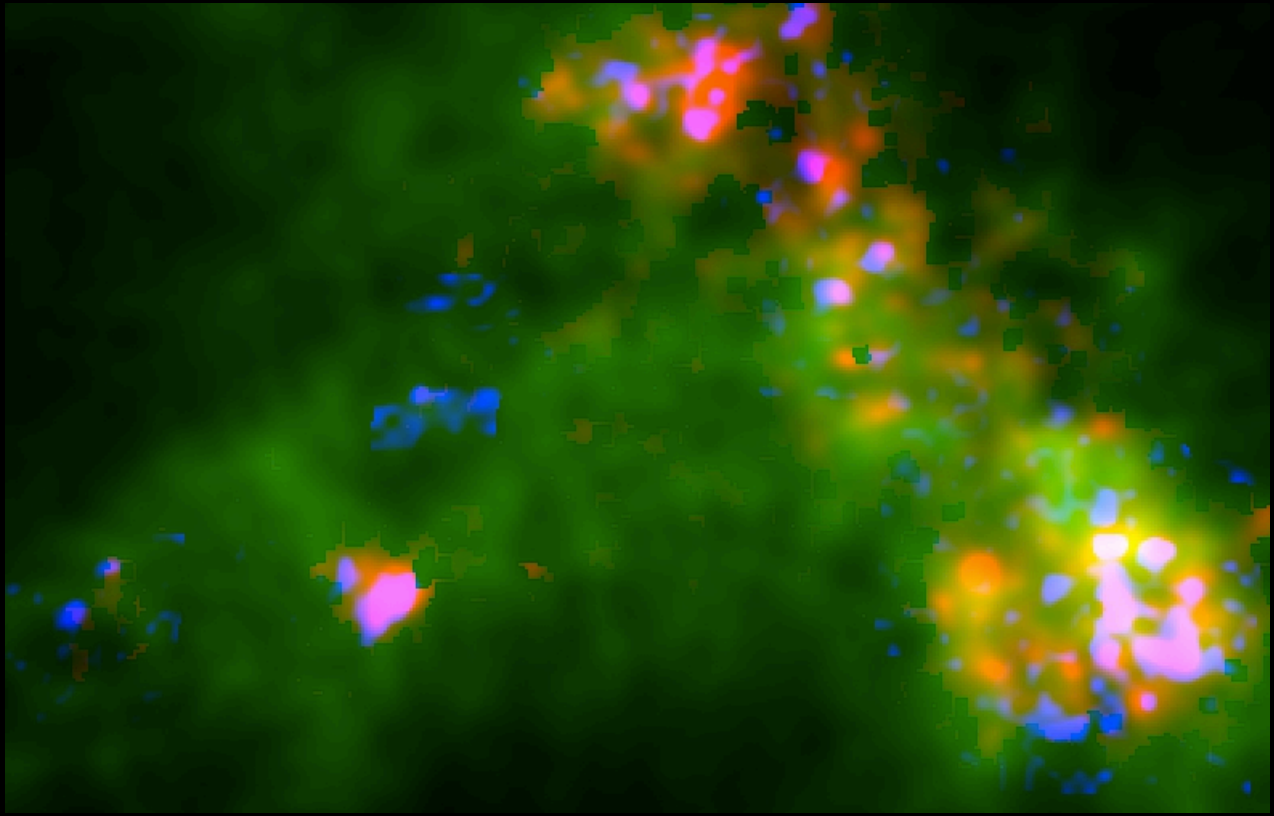
Σ_{dust} from *Herschel* HERITAGE
- SED fitting to 100, 160, 250, 350, 500 μm
- 40” resolution
- *Gordon+2014*

Σ(HI) from ATCA+Parkes
- 1’ resolution
- *Kim+2003*

I_{CO} from MAGMA (MOPRA)
- Targeted survey
- 45” resolution
- *Wong+2011*

Final resolution: 1’ or 15 pc

SMC Dust and Gas Surface Densities



Final resolution:
2.6’ or 45 pc

Σ_{dust} from *Herschel* HERITAGE
- SED fitting to 100, 160, 250, 350, 500 μm
- 40” resolution
- *Gordon+2014*

Σ(HI) from ATCA+Parkes
- 1.5’ resolution
- *Stanimirovic+1999*

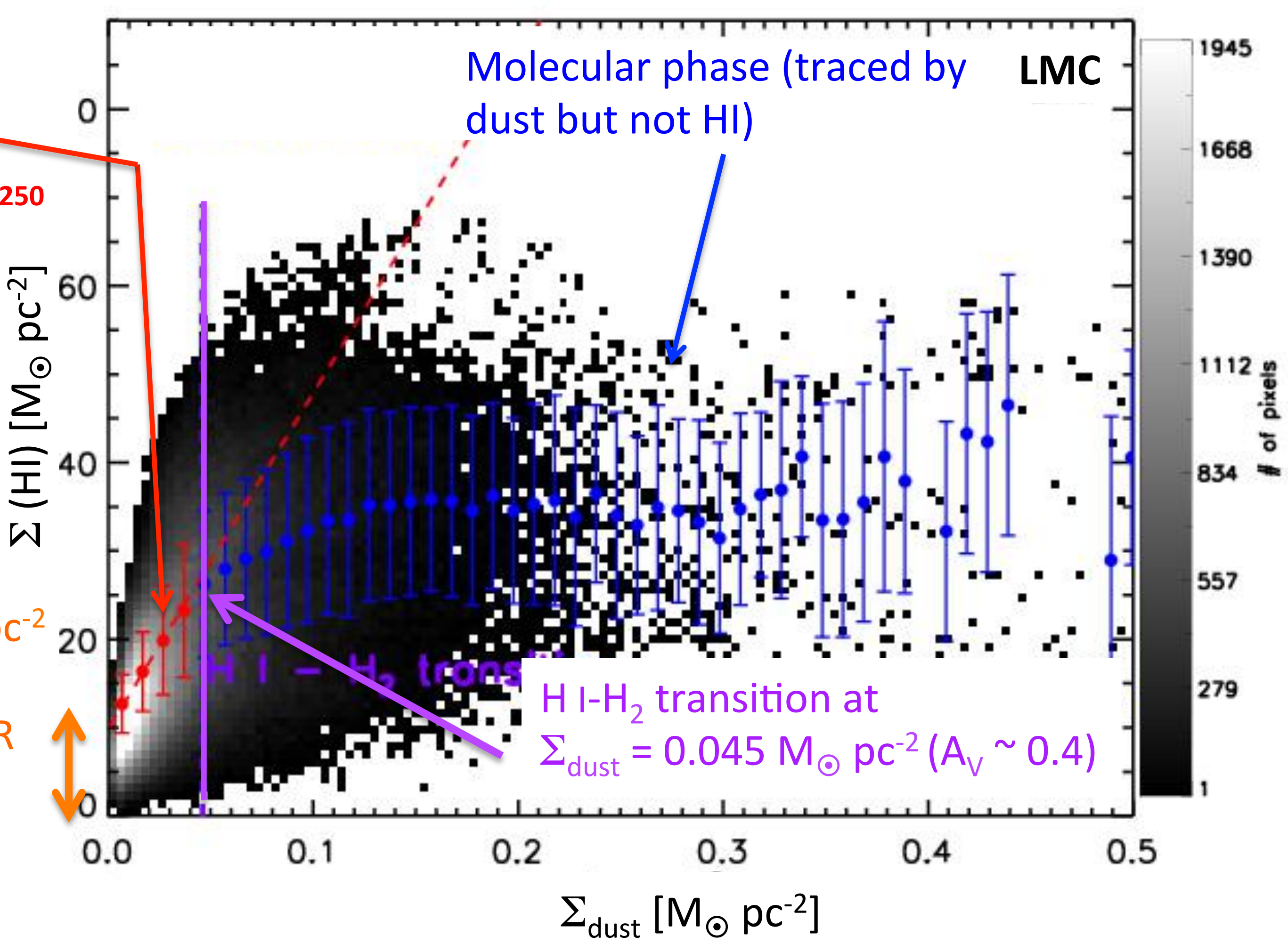
I_{CO} from NANTEN
- Full coverage
- 2.6’ resolution
- *Mizuno et al. 2001*

Measuring the dust abundance: Gas-to-dust ratio as a slope

$$GDR = n_{gas}/n_{dust} = d\Sigma_{gas}/d\Sigma_{dust}$$

- The GDR is the derivative/slope of the relation between dust and gas surface densities
- Also allows one to separate different phases by deriving slope in different surface density regimes

Dust – H I relation: LMC



FIR bright diffuse atomic ISM

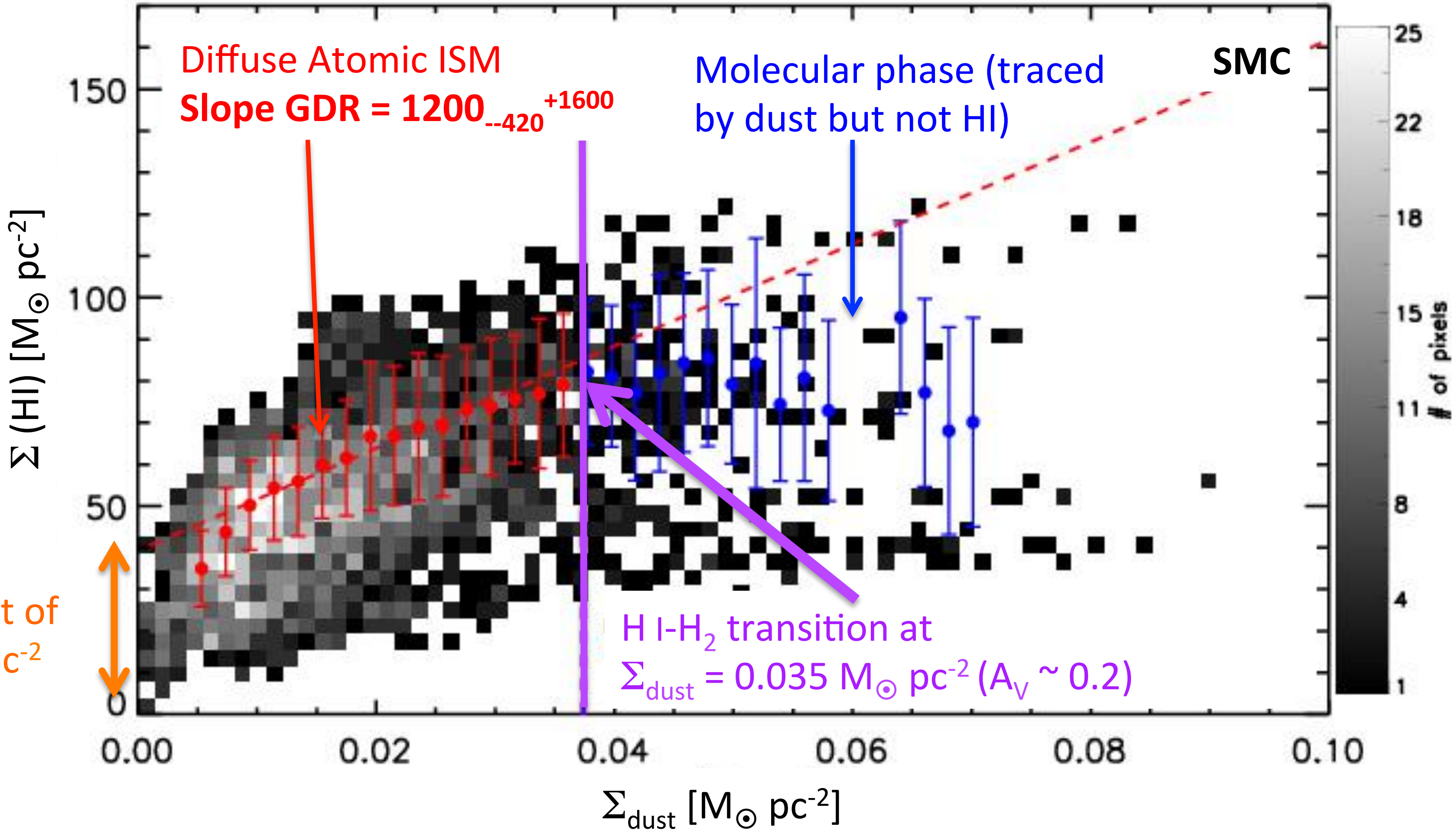
Slope GDR = 380_{-130}^{+250}

Intercept of 10 $M_\odot$ pc^{-2} due to dust-poor gas component with GDR 5x higher then FIR bright atomic ISM

Molecular phase (traced by dust but not HI)

H I-H_2 transition at Σ_{dust} = 0.045 $M_\odot$ pc^{-2} (A_V ~ 0.4)

Dust – H I relation: SMC



Dust-Total Gas Relation

Estimating H_2: X_{CO} factor

- X_{CO} : empirical conversion factor between CO integrated intensity (I_{CO}) and H_2 column density $N(H_2)$ in a given region

$$X_{CO} = \frac{\bar{N}(H_2)}{\bar{I}_{CO}}$$

- X_{CO} depends on spatial resolution, and many physical parameters: Z, G_0, τ, evolutionary and dynamical state of a GMC …
  - X_{CO} is not well theoretically or observationally constrained (H_2 is invisible!)
- We start with estimate from Bolatto+2013:

$$\frac{X_{CO}(Z)}{X_{CO}(MW)} = 0.67\ \exp\left(\frac{0.4}{Z\ \Sigma_{\overset{\sim 1}{GMC,100}}}\right)$$

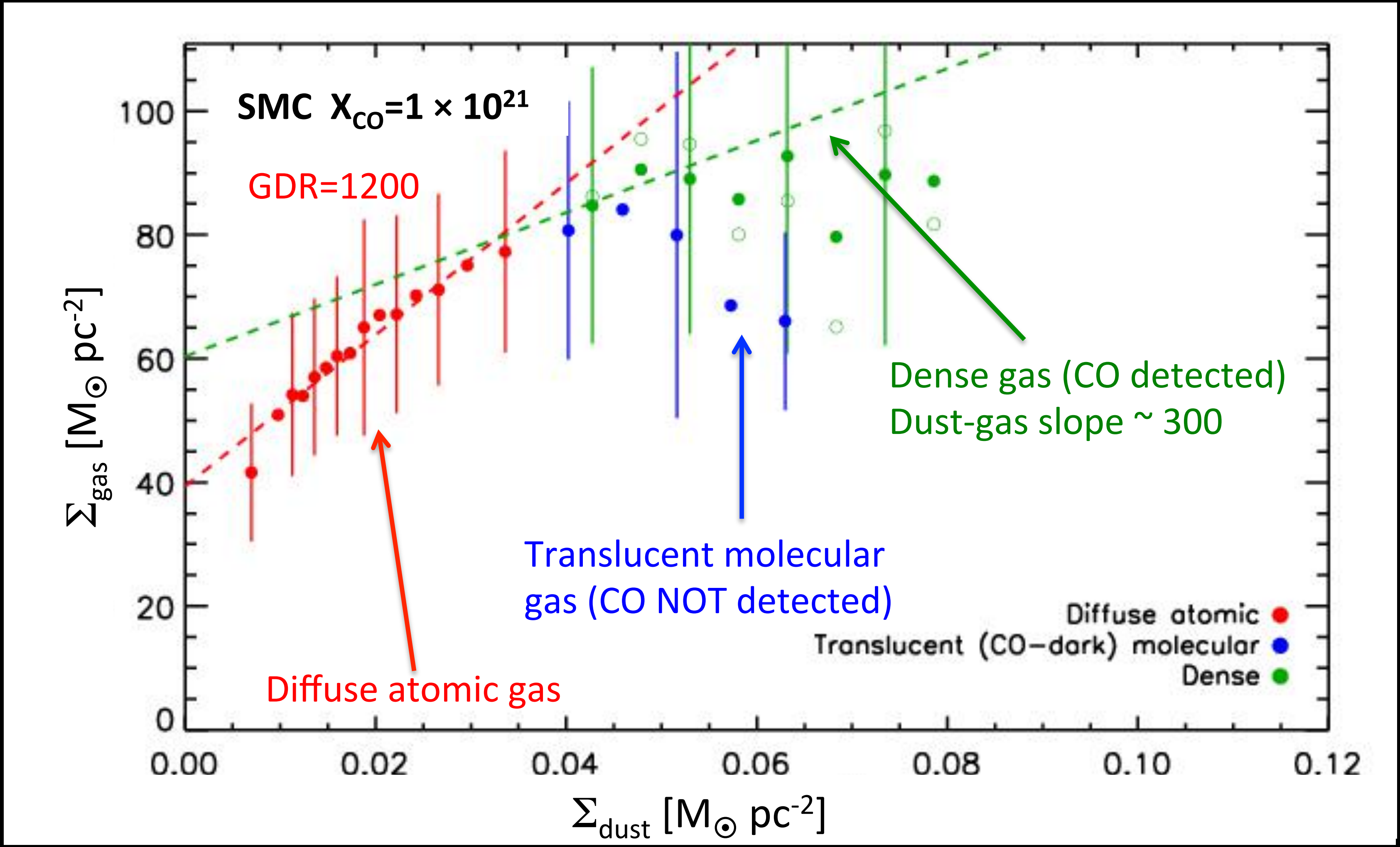
→ SMC: 5×MW (10^{21} cm^{-2} K^{-1} km^{-1} s)

→ LMC: 1×MW (2×10^{20} cm^{-2} K^{-1} km^{-1} s)

Dust-Total Gas Relation: SMC

$X_{CO} = 5 \times X_{CO}(MW)$

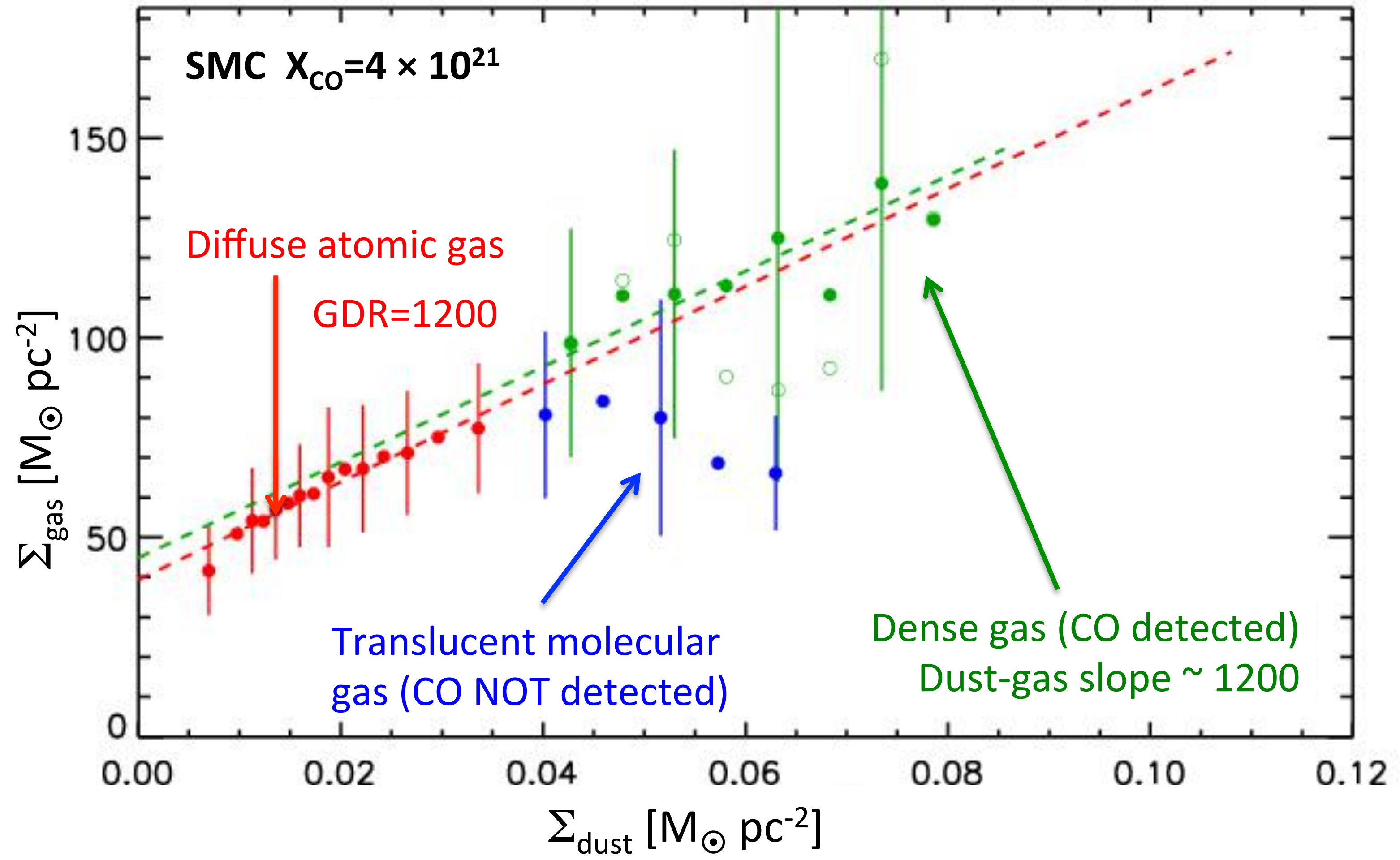
Dust-gas slope 4x shallower in dense ISM than diffuse ISM



Dust-Total Gas Relation: SMC

$X_{CO} = 20 \times X_{CO}(MW)$ $(\Sigma_{GMC,100} = 0.6)$

No dust-gas slope variation



Diffuse atomic gas

GDR=1200

Translucent molecular gas (CO NOT detected)

Dense gas (CO detected)
Dust-gas slope ~ 1200

Interpretation: SMC

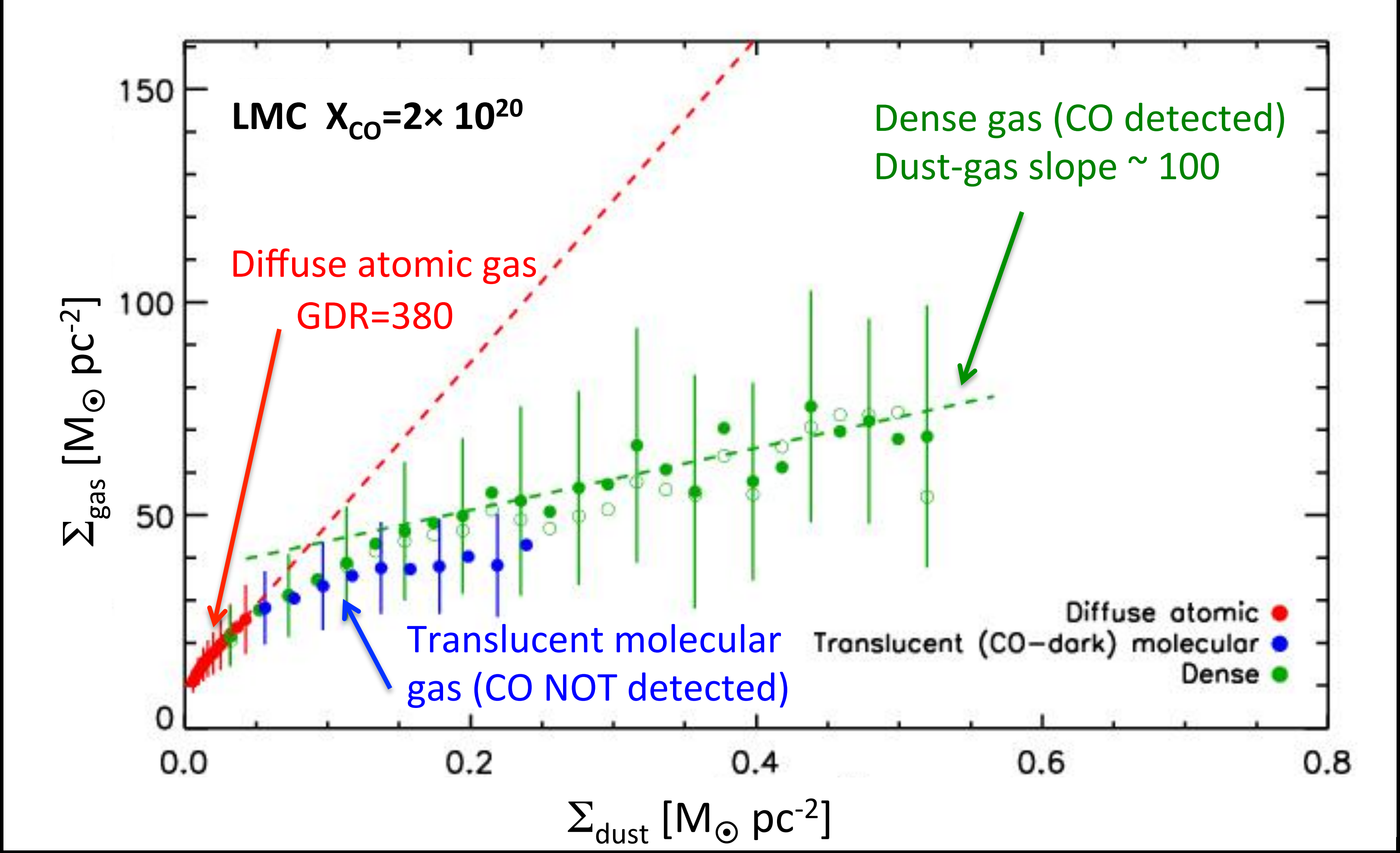
- Variations of the dust-gas slope can be due to:
  - Changes in the dust abundance (GDR)
  - Changes in the dust FIR opacity due to coagulation
  - Unaccounted for, CO-dark molecular gas

- **In the SMC, variations of the dust abundance and properties are degenerate with CO-dark H_2**

Dust-Total Gas Relation: LMC

$X_{CO} = X_{CO}(MW)$

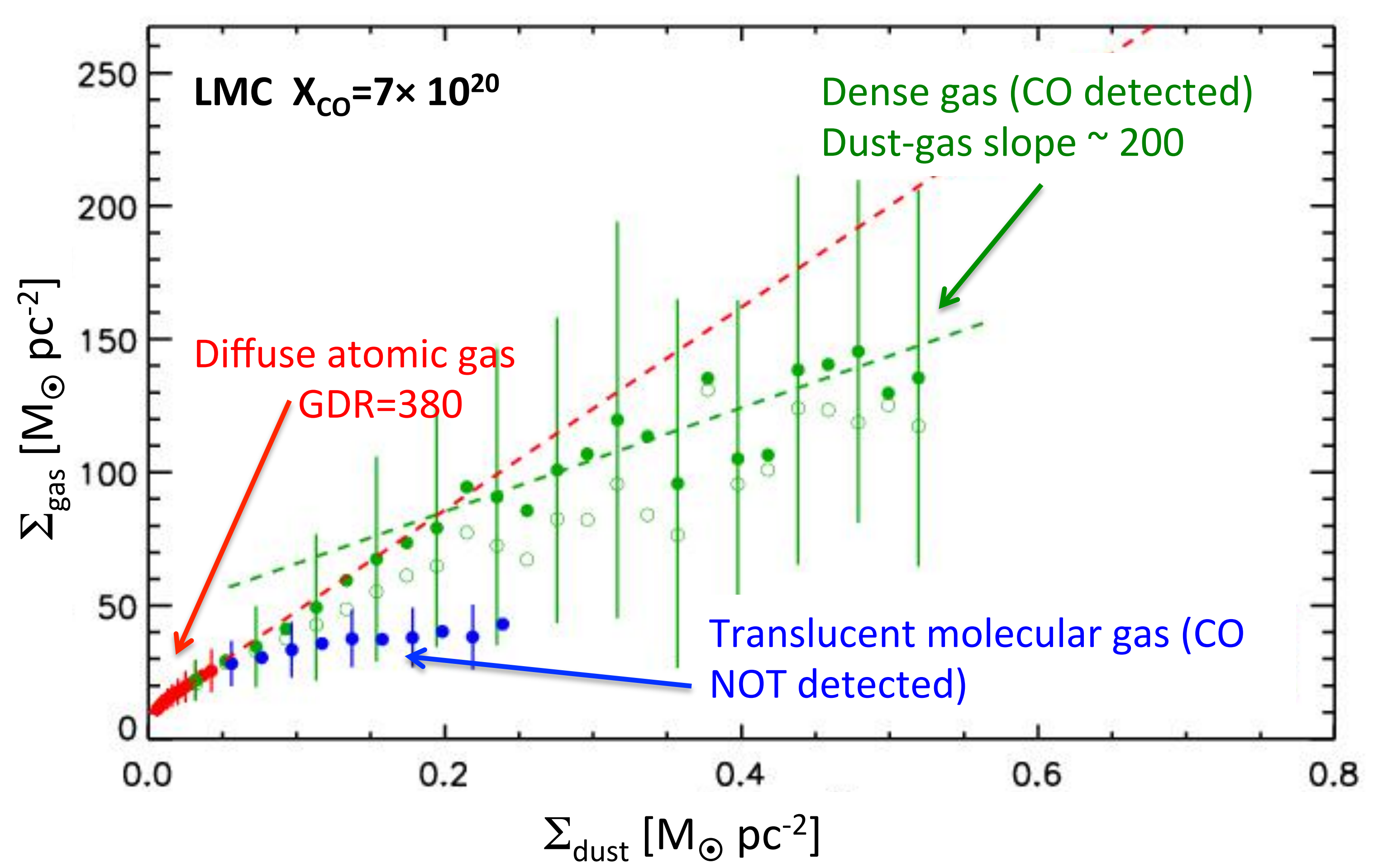
Dust-gas- slope 4x shallower in dense ISM than atomic ISM



Dust-Total Gas Relation: LMC

X_{CO} = 3.5 × X_{CO}(MW) ($\Sigma_{GMC,100}$ = 0.5)

Factor 2x variation in dust-gas slope between diffuse and dense ISM



Dense gas (CO detected)
Dust-gas slope ~ 200

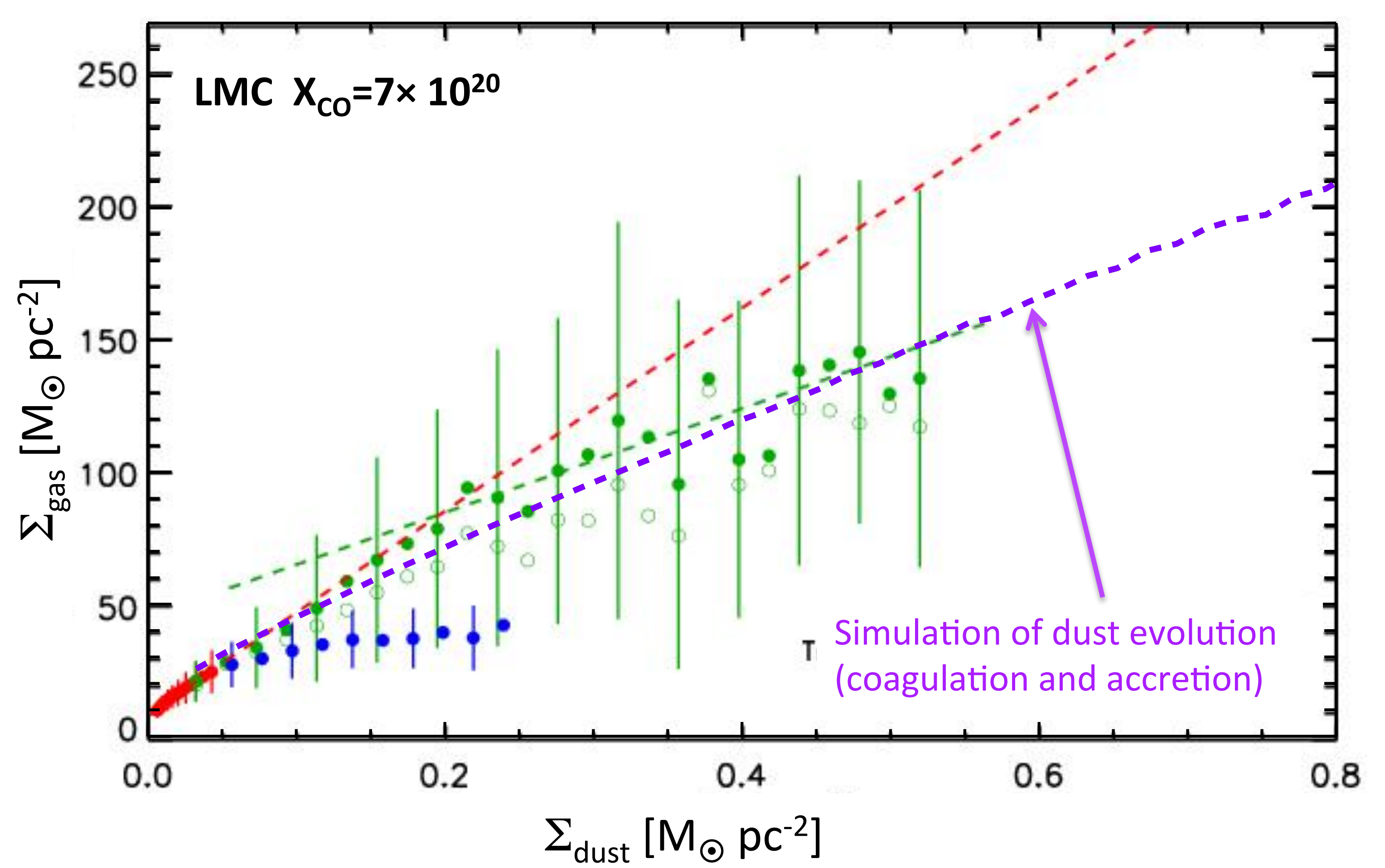
Diffuse atomic gas
GDR=380

Translucent molecular gas (CO NOT detected)

Effects of dust growth on dust-gas relation

With HD simulation of 10 pc ISM parcel ($\langle n_H \rangle = 200\ \mathrm{cm}^{-3}$) in which:

- Dust abundance is set by density following Zhukovska+08
- Dust FIR opacity determined by density following Ossenkopf & Henning 1994



Simulation of dust evolution (coagulation and accretion)

Interpretation: LMC

In the LMC, there is evidence for changes in the dust abundance (accretion) and/or opacity (coagulation)!

Conclusions

- In the LMC:
  - Diffuse atomic GDR = 380
  - Presence of a dust poor component (5x GDR of FIR bright regions) at very low surface densities ($\Sigma_{dust} < 0.007\ M_o\ pc^{-2}$)
  - HI-H_2 transition at $\Sigma_{dust} \sim 0.05$ ($A_V \sim 0.4$)
  - Evidence of a factor > 2 change in the dust-gas slope, indicative of dust evolution via:
    - Dust grain coagulation causing an increase in the dust FIR opacity, and/or
    - Accretion of gas-phase metals onto dust grains in dense ISM, increasing the abundance of dust and dust-to-gas ratio
- In the SMC:
  - Diffuse atomic GDR = 1200
  - Presence of a dust poor component (5x GDR of FIR bright regions) at very low surface densities ($\Sigma_{dust} < 0.007\ M_o\ pc^{-2}$)
  - HI-H_2 transition at $\Sigma_{dust} \sim 0.03$ ($A_V \sim 0.2$)
  - At 45 pc resolution, changes in the dust-gas slope are degenerate with CO-dark H_2 in the translucent envelopes of molecular clouds

Impact for star formation studies

- Estimating H_2 from dust to study star formation law: beware of GDR variations in GMCs!

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

Measured in diffuse ISM (no H_2), but not necessarily applicable in H_2 dominated regions.

May be overestimated by factor ~2 in GMCs due to coagulation

- Variations in dust abundance, size, and composition may affect the physical conditions in GMCs (radiative transfer, chemistry, thermal balance)
  - There may be more dust shielding in GMCs than assumed with constant GDR
  - H_2 formation rate on dust grains may be higher
  - Extinction curves vary in GMCs, in particular ratio of A_V to $A_{1000\ \text{Å}}$
  - These variations should be included in models

Back-up slides

Theoretical constraints on dust coagulation

- Coagulation timescale:

$$t_{coag} = \frac{573\ Myr}{n_{gas}} \frac{GDR}{150}$$

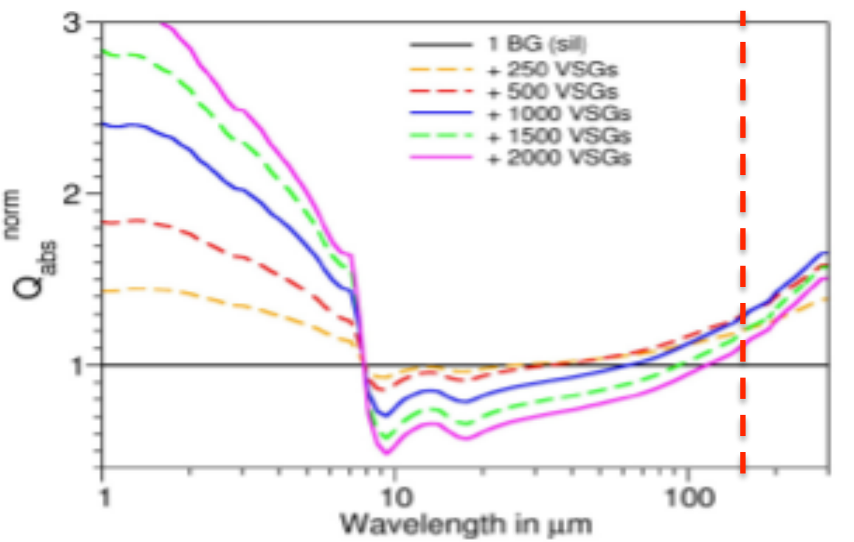
Kohler+2012

t_{coag}	Diffuse (n~1 cm^{-3})	Translucent (n~50 cm^{-3})	Dense (n~1000 cm^{-3})
LMC	1.5 Gyr	30 Myr	1.5 Myr
SMC	5 Gyr	100 Myr	5 Myr

- Unlikely coagulation occurs in SMC on GMC scales, except in very dense cores (n>5000 cm^{-3})
- Coagulation may well affect the dust surface density estimate on GMC scales in the LMC

Effects of dust coagulation

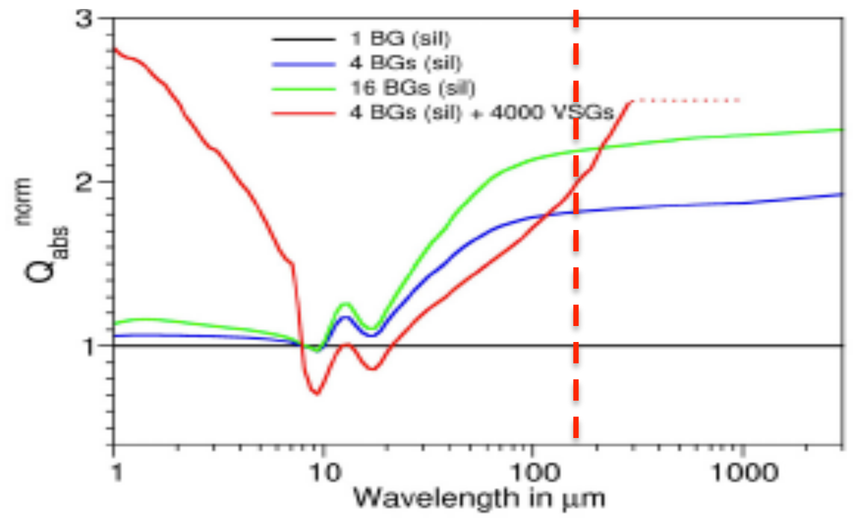
Silicate BG + VSG



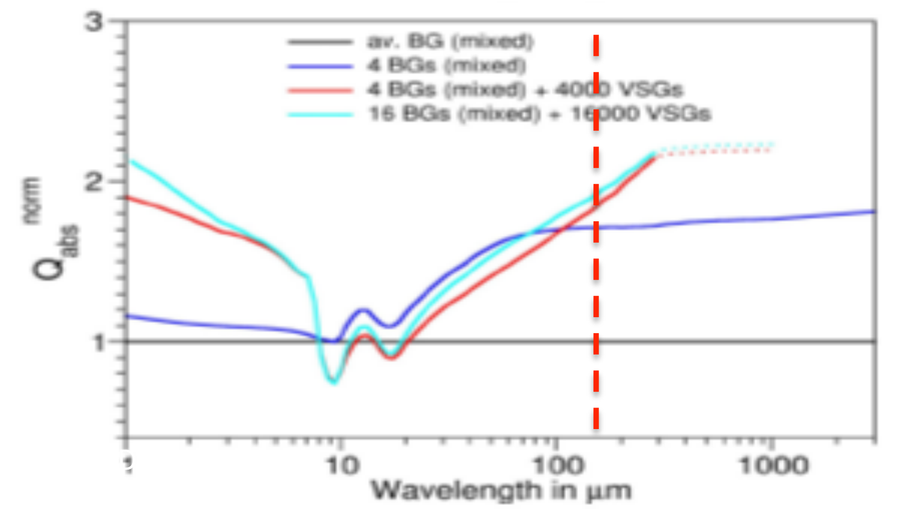
Coagulation can increase the FIR emissivity of dust grains by a factor ~ 2 or more

Kohler+2012

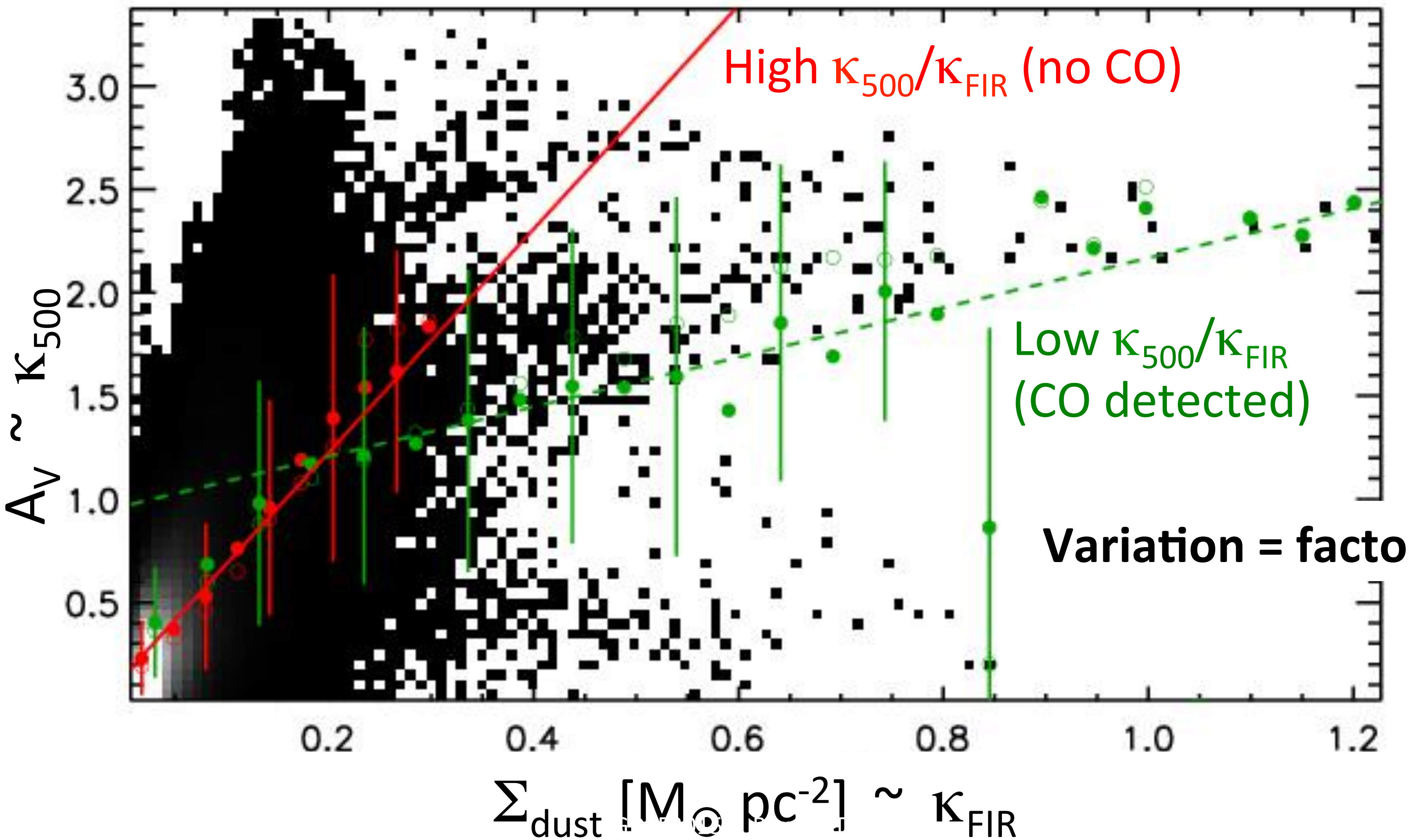
Silicate BG + BGs + VSG



Mixed BG + BG + VSG



Relation Σ_{dust}-A_V



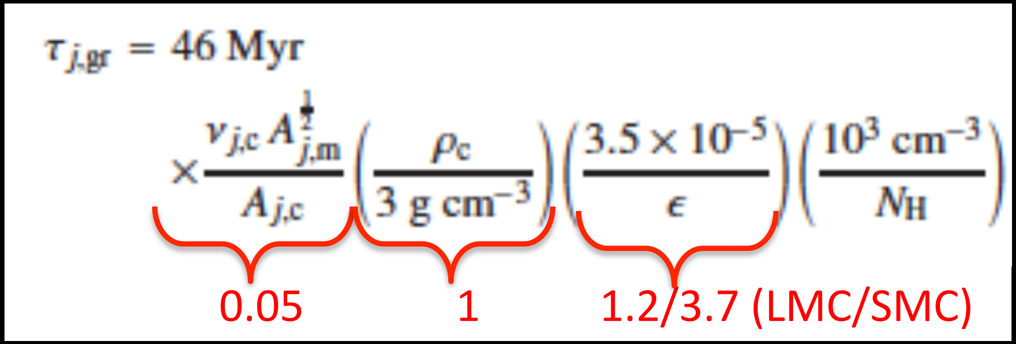
High $\kappa_{500}/\kappa_{FIR}$ (no CO)

Low $\kappa_{500}/\kappa_{FIR}$ (CO detected)

Variation = factor 5

Theoretical constraints on accretion

- Accretion timescale for $MgSiO_3$ (limiting element = Mg)



$$\tau_{j,\mathrm{gr}} = 46\ \mathrm{Myr} \times \underbrace{\frac{\nu_{j,\mathrm{c}} A_{j,\mathrm{m}}^{\frac{1}{2}}}{A_{j,\mathrm{c}}}}_{0.05} \underbrace{\left(\frac{\rho_\mathrm{c}}{3\ \mathrm{g\ cm^{-3}}}\right)}_{1} \underbrace{\left(\frac{3.5\times10^{-5}}{\epsilon}\right)}_{1.2/3.7\ \mathrm{(LMC/SMC)}} \left(\frac{10^3\ \mathrm{cm^{-3}}}{N_\mathrm{H}}\right)$$

Zhukovska+2008

t_{coag}	**Diffuse (n~1 cm^{-3})**	**Translucent (n~50 cm^{-3})**	**Dense (n~1000 cm^{-3})**
LMC	3 Gyr	60 Myr	3 Myr
SMC	10 Gyr	200 Myr	9 Myr

- Unlikely accretion occurs in SMC on GMC scales, except in very dense cores (n>5000 cm^{-3})
- Accretion may change the GMC scale gas-to-dust ratio in the LMC

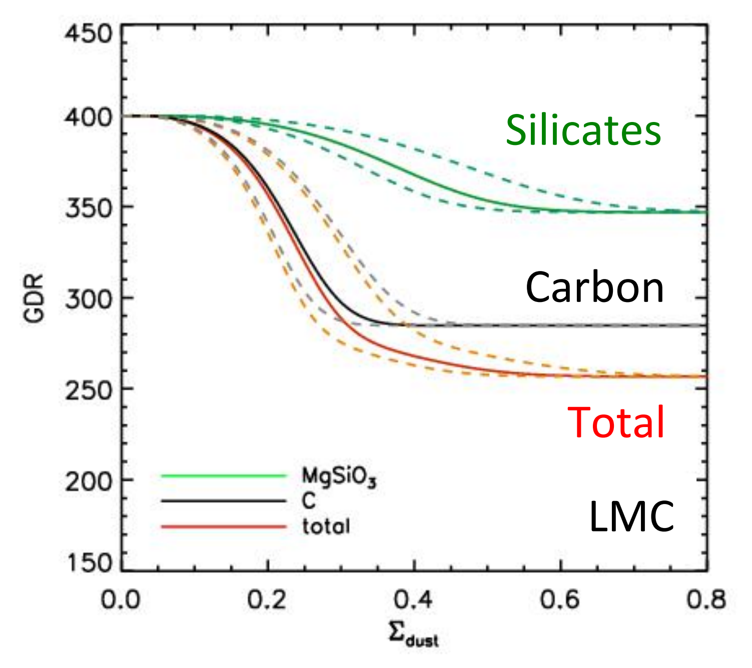
Gas-to-dust ratio variations via accretion

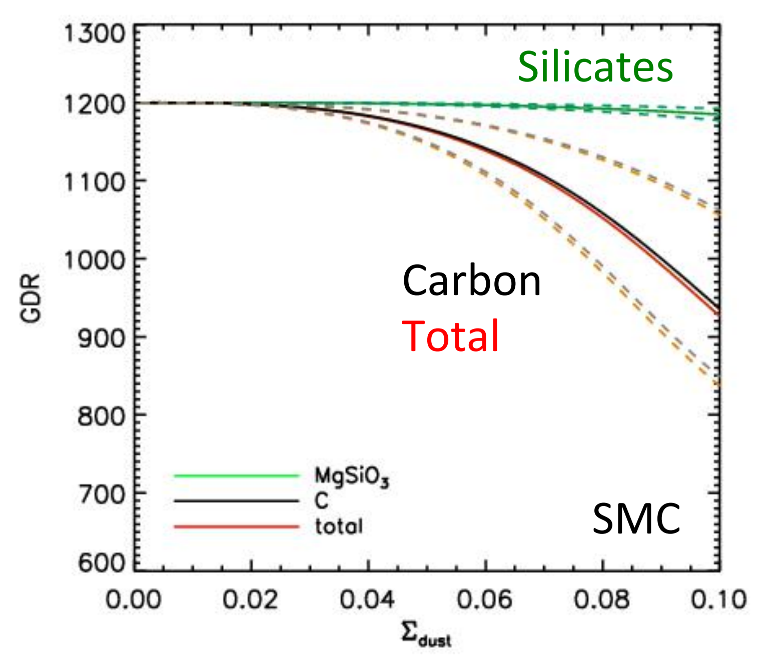
- Depletion fraction at t=5 Myr (~1/2 GMC lifetime)
  - For Mg, f_0=0.46

$$f(t) = \frac{f_0 e^{t/\tau_{gr}}}{1 - f_0 + f_0 e^{t/\tau_{gr}}}$$

Zhukovska+2008

- For τ_{gr}, assume density scales with surface density as $n \propto \Sigma^3$
  - n =1, 50, 1000 cm^{-3} for Σ = 20, 50, 200 $M_\odot\ \mathrm{pc}^{-2}$ (Snow+2006)





Interpretation of dust-gas slope variations

- Physical processes that can change the dust-gas slope:
  - **True dust abundance (gas-to-dust ratio) variations** by accretion of gas-phase metals onto dust grains or other processes (e.g., dust grain clustering by turbulence…)
  - Coagulation, by increasing emissivity of coagulated big grains in molecular clouds, leading to overestimate of dust surface density since constant emissivity is assumed
  - Dark (probably molecular) gas: CO-dark H_2 in beam should be accounted for by use of higher than Galactic X_{CO}
  - CO saturation: CO saturation could lead to a decrease of dust-gas slope at highest surface density if constant X_{CO} is assumed
    - Although not expected at metallicity of LMC, SMC (Shetty+2011)
- **PROBLEM: All of these effects are degenerate and lead to a decrease of observed dust-gas slope with increasing surface density !!!!**

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