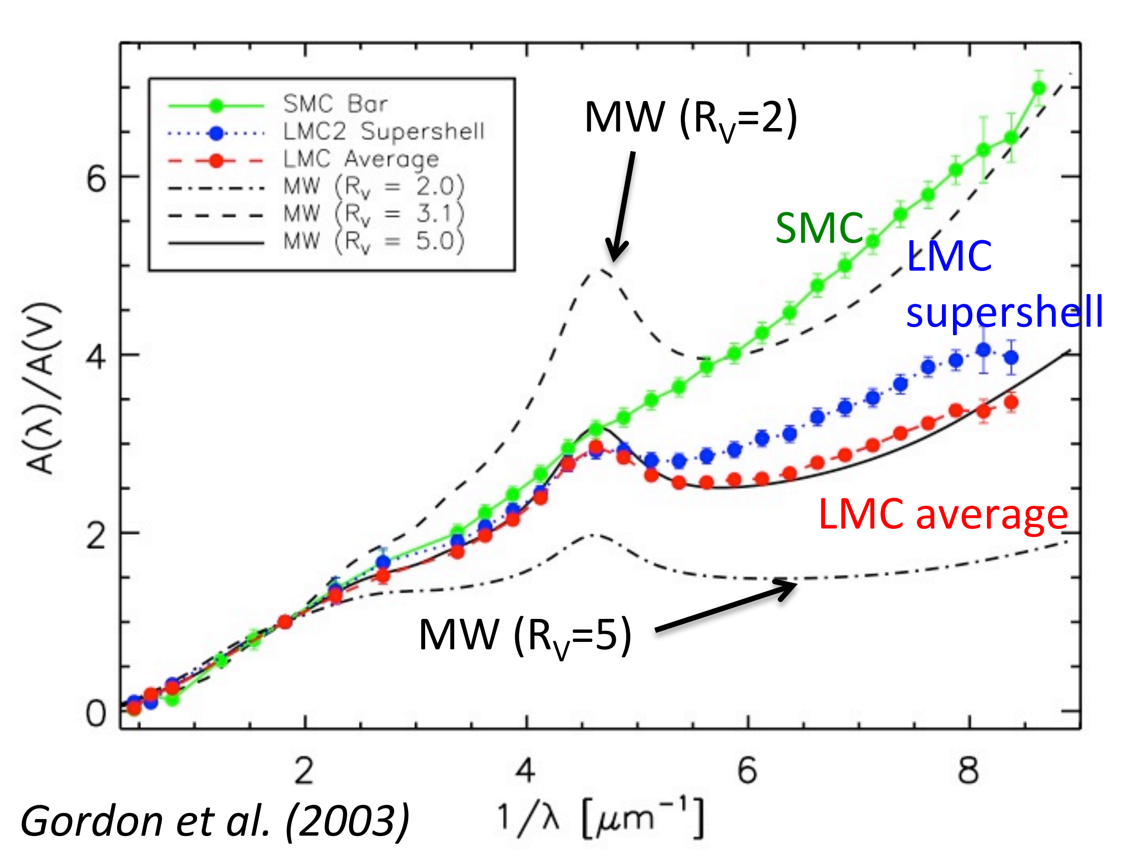
Relation between dust and gas in the LMC and SMC: Probing dust evolution between ISM phases

Julia Roman-Duval
Space Telescope Science Institute

GESF2014
September 9, 2014

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

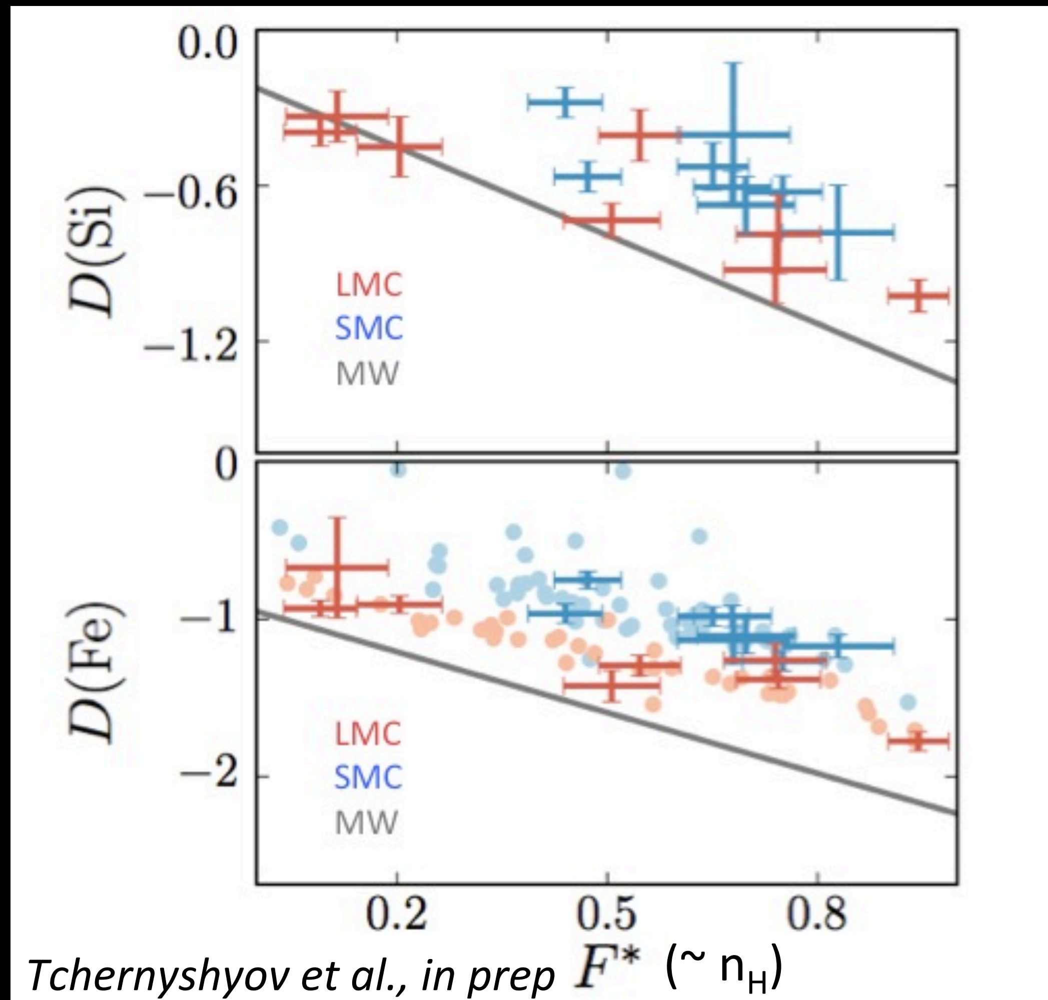
Evidence for dust evolution between ISM phases: UV Extinction Curves



Size and composition of dust grains change with environment

Evidence for dust evolution between ISM phases: 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

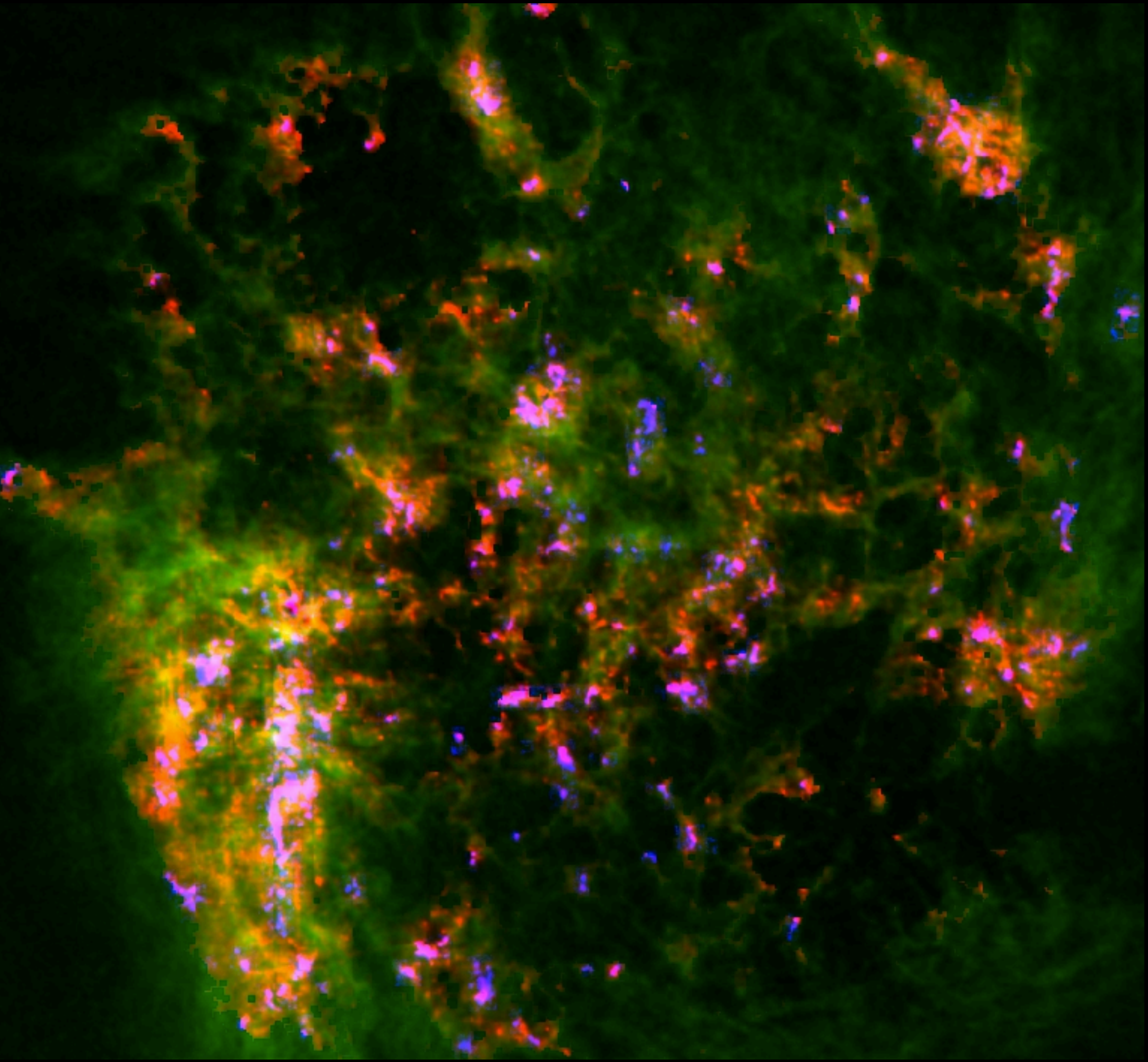


Tchernyshyov et al., in prep

Outline

- Data and Method
- Dust-Atomic gas relation
  - Location of the H I-H_2 transition
  - Gas-to-dust ratio in the diffuse atomic ISM
- Dust-total gas relation
  - Dust-gas slope in the dense ISM
  - Degeneracy with X_{CO}
- Interpretation of dense dust-gas slope
  - Effects of coagulation and accretion

LMC Dust and Gas Surface Densities



Σ_{dust} from *Herschel* HERITAGE maps at 100, 160, 250, 350, 500 μm at 40" resolution *(Gordon +2014)*

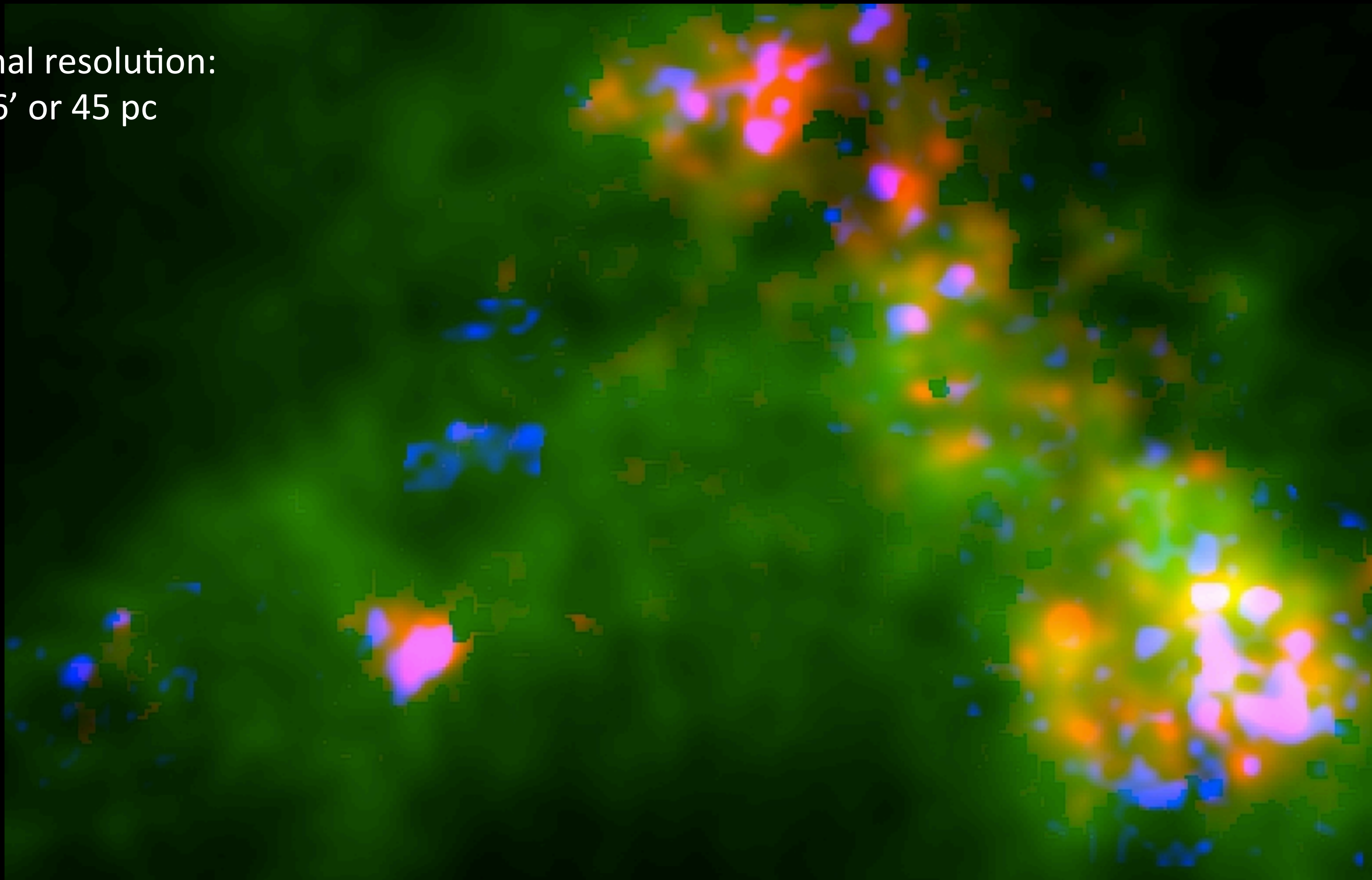
Σ(HI) from ATCA+Parkes at 1' resolution *(Kim +2003)*

I_{CO} from MAGMA survey with MOPRA at 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 maps at 100, 160, 250, 350, 500 μm at 40” resolution *(Gordon+2014)*

Σ(HI) from ATCA+Parkes at 1.5’ resolution *(Stanimirovic+99)*

I_{CO} from NANTEN survey 2.6’ resolution *(Mizuno+01)*

Gas-to-dust ratio as a slope

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

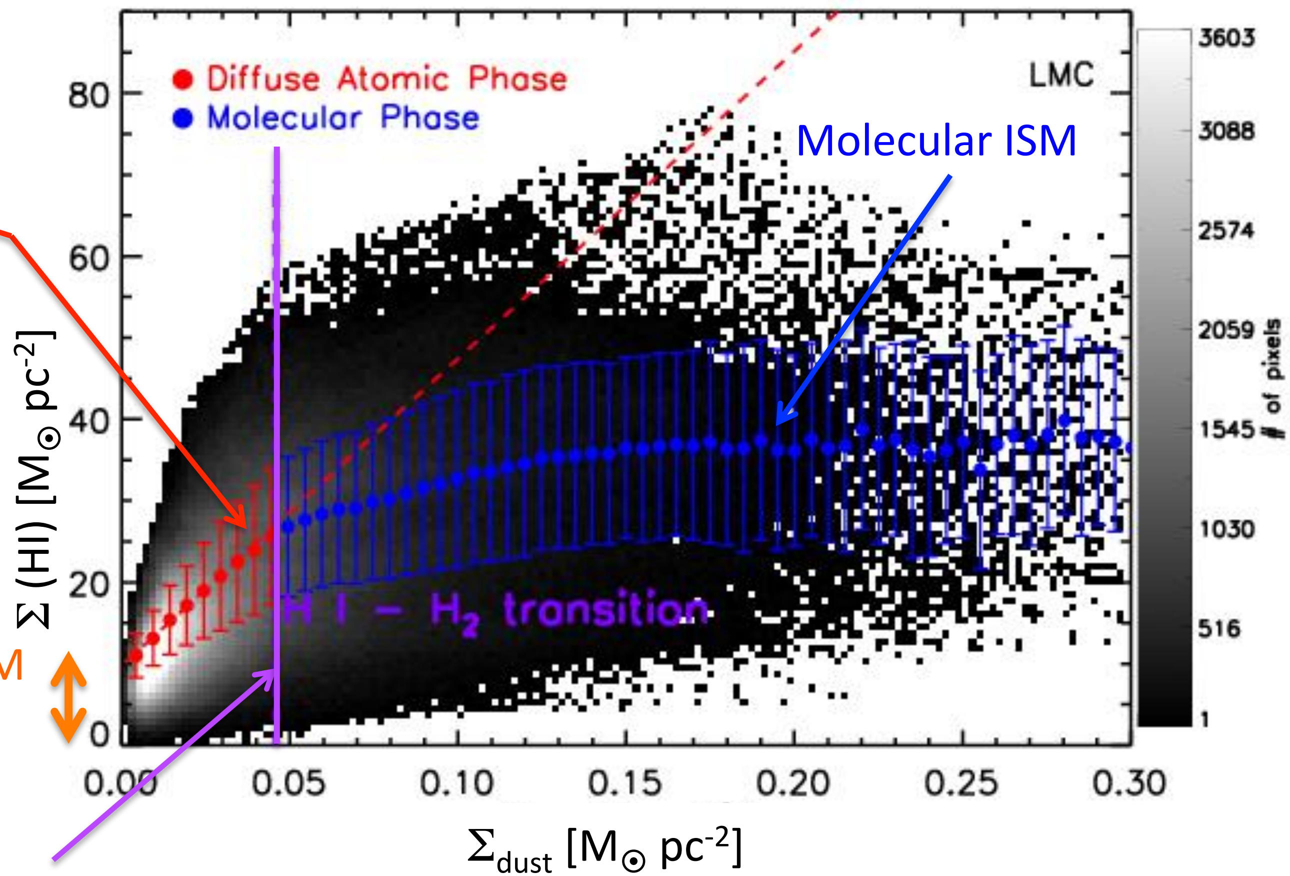
- The GDR is the derivative/slope of the relation between dust and gas surface densities
- Also allows one to separate different phases by deriving slope in different surface density regimes

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 5 times higher then FIR bright diffuse atomic ISM

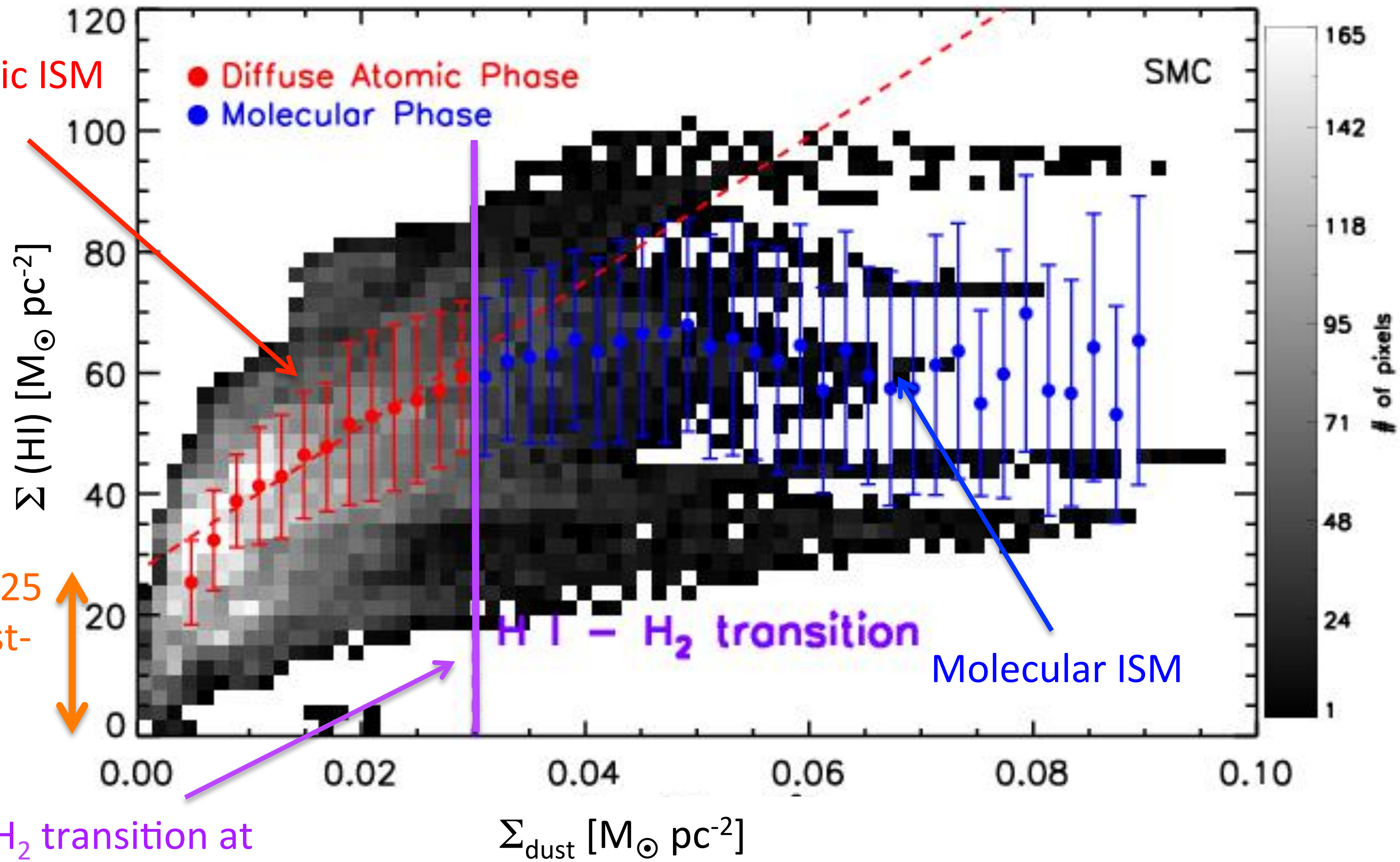


H I-H_2 transition at Σ_{dust} = 0.05 $M_\odot$ pc^{-2} (A_V ~ 0.4)

Dust – H I relation: SMC

Diffuse Atomic ISM

Slope GDR = 1200_{-500}^{+1500}



Intercept of 25 $M_\odot$ pc^{-2} (dust-poor gas component)

H I-H_2 transition at Σ_{dust} = 0.03 $M_\odot$ pc^{-2} (A_V ~ 0.2)

Dust-Total Gas Relation

Estimating H_2: X_{CO} factor

- X_{CO} factor is an empirical conversion factor between CO mean integrated intensity (I_{CO}) and mean 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:

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

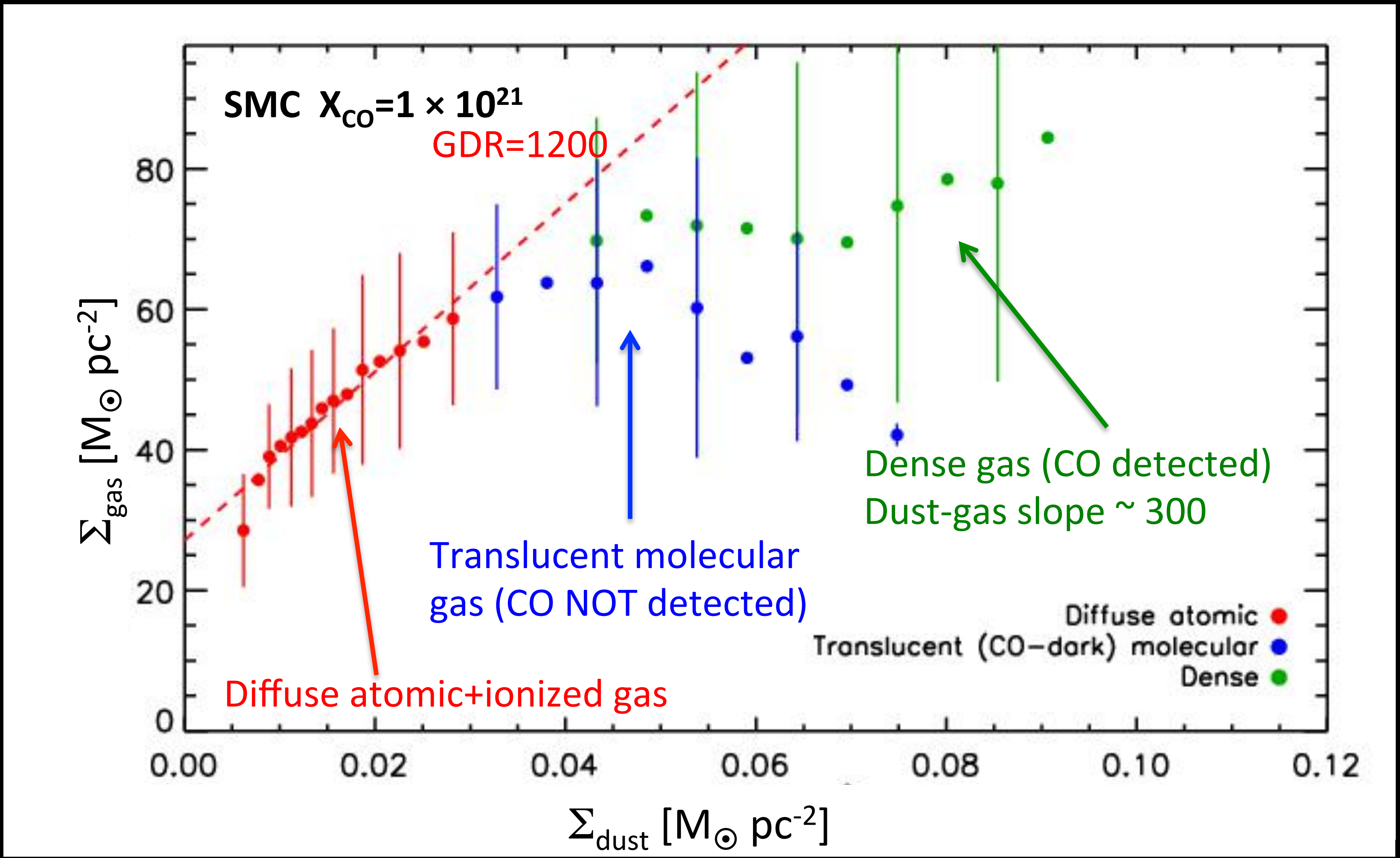
→ SMC: 5×MW (10^{21} cm^{-2} K^{-1} km^{-1} s)

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

Dust-Total Gas Relation: SMC

Dense ISM dust-gas slope is lower than in diffuse ISM

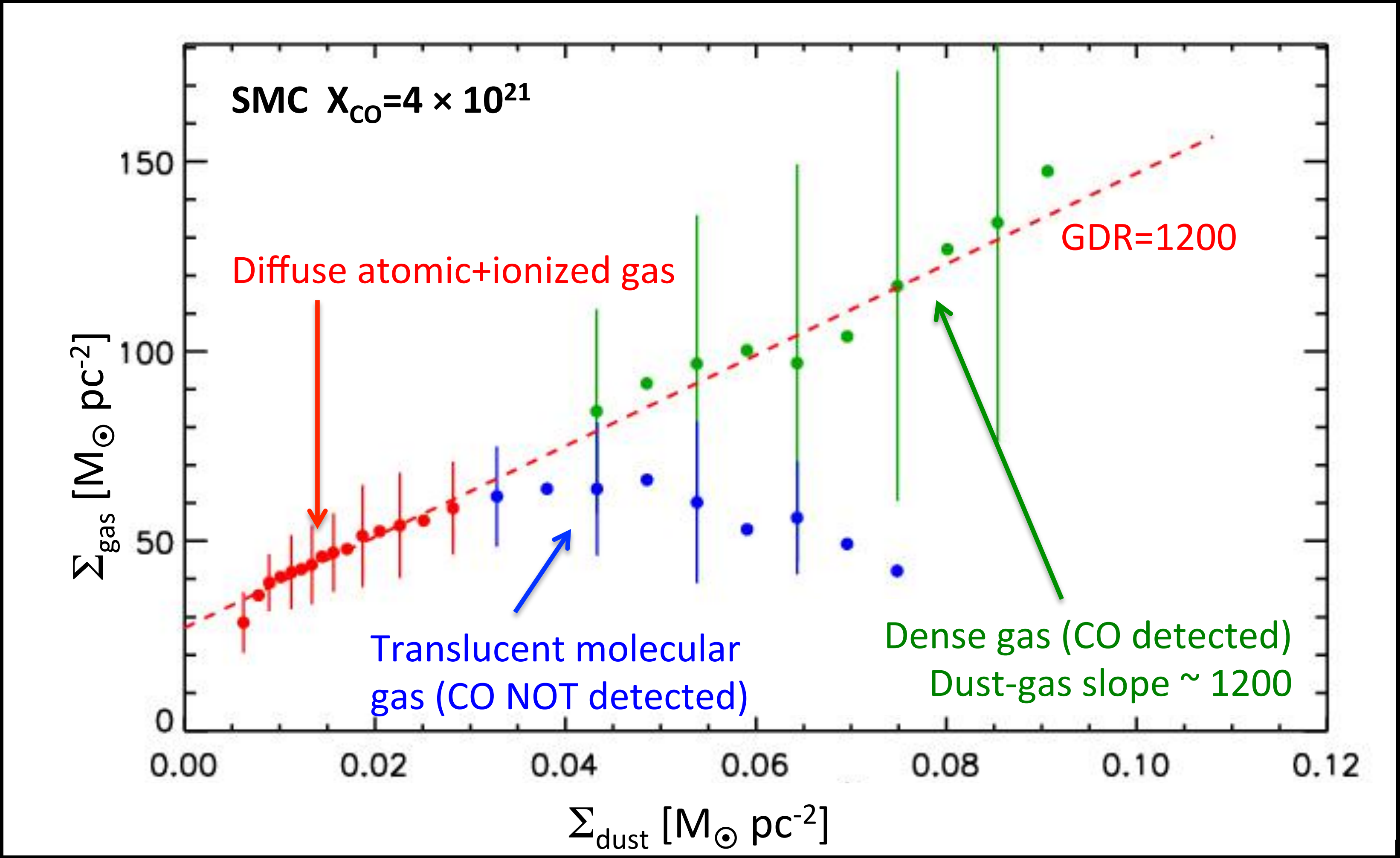
with $X_{CO} = 5 \times X_{CO}(MW)$



Dust-Total Gas Relation: SMC

Dense ISM dust-gas slope is lower than in diffuse ISM

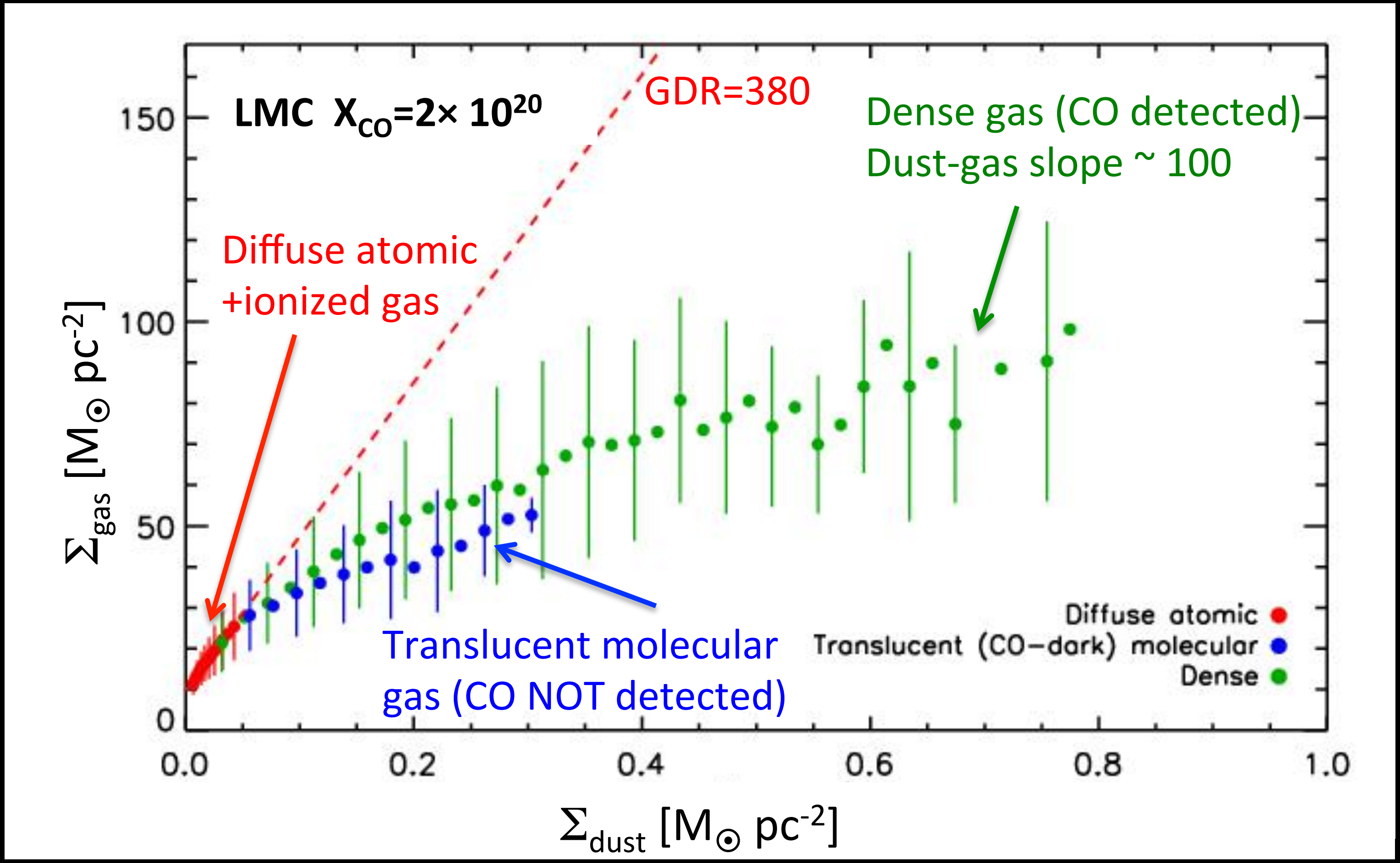
with $X_{CO} = 20 \times X_{CO}(MW)$ ($\Sigma_{GMC,100} = 0.6$)



Dust-Total Gas Relation: LMC

Dense ISM dust-gas slope is lower than in diffuse ISM

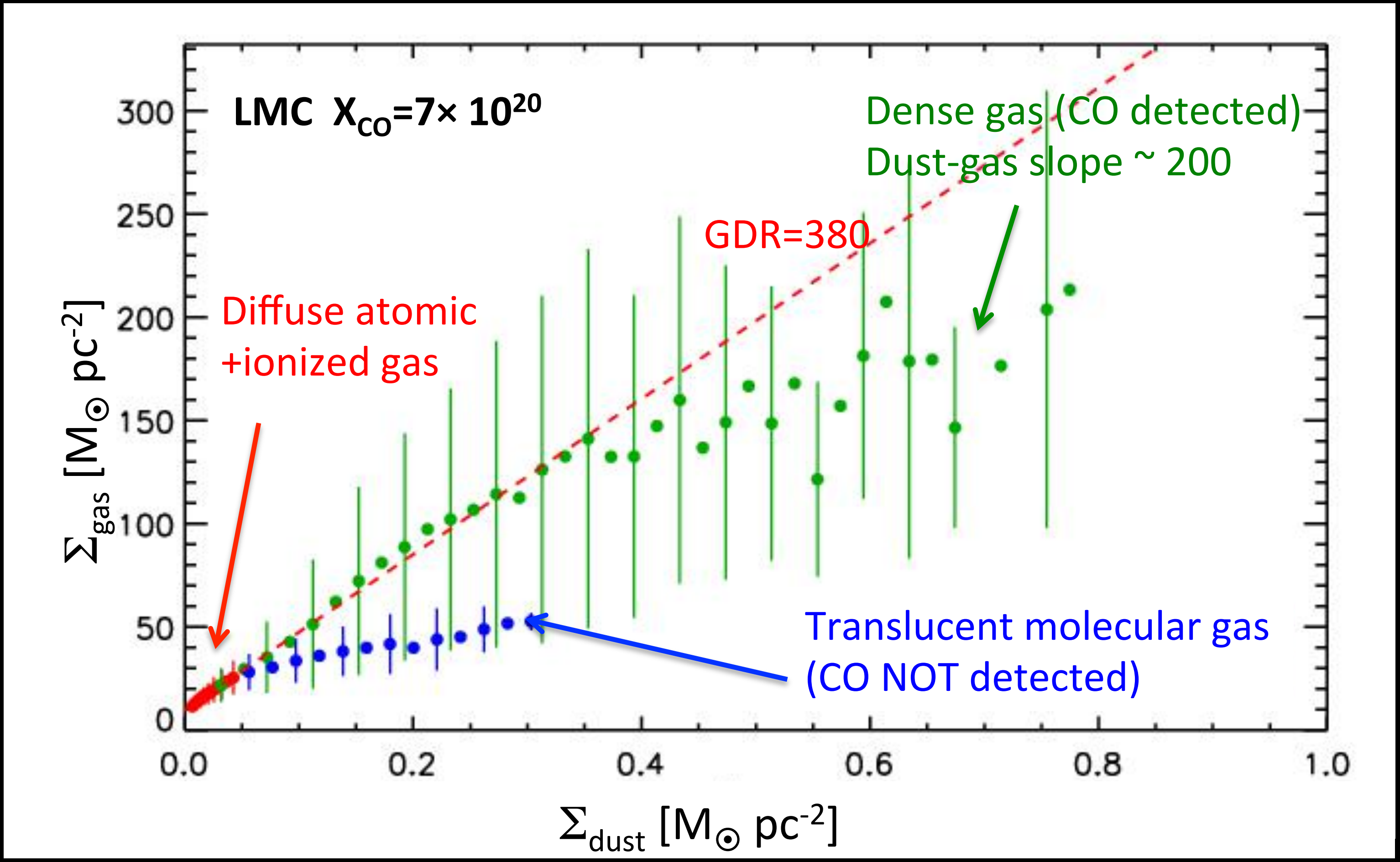
with $X_{CO} = X_{CO}(MW)$



Dust-Total Gas Relation: LMC

Dense ISM dust-gas slope is lower than in diffuse ISM

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



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 !!!!**

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 !!!!**

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 !!!!**

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 !!!!**

Theoretical constraints on dust coagulation

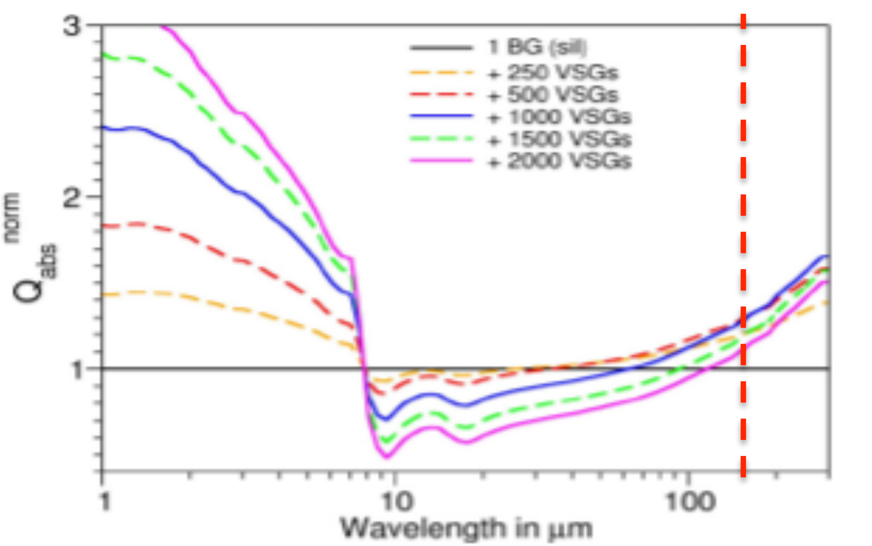
- Coagulation timescale: $$t_{coag} = \frac{573\ Myr}{n_{gas}} \frac{GDR}{150}$$ *Kohler+2012*

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

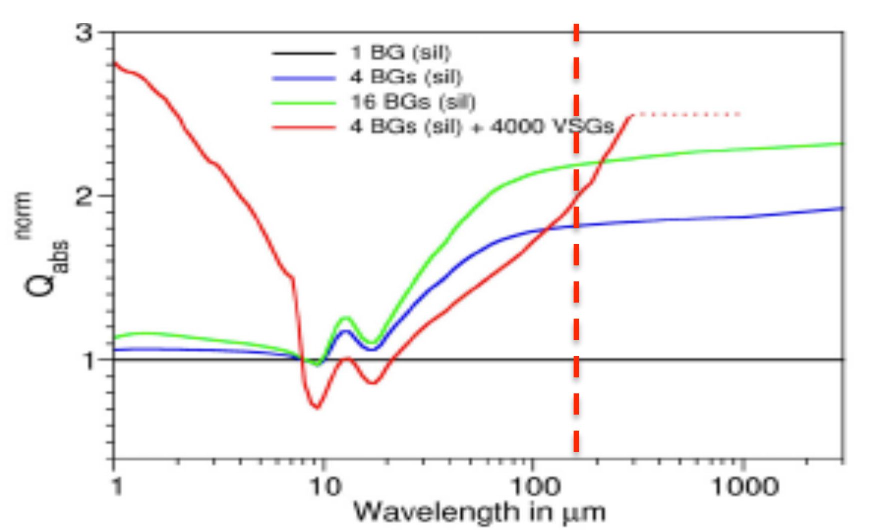
Silicate BG + VSG



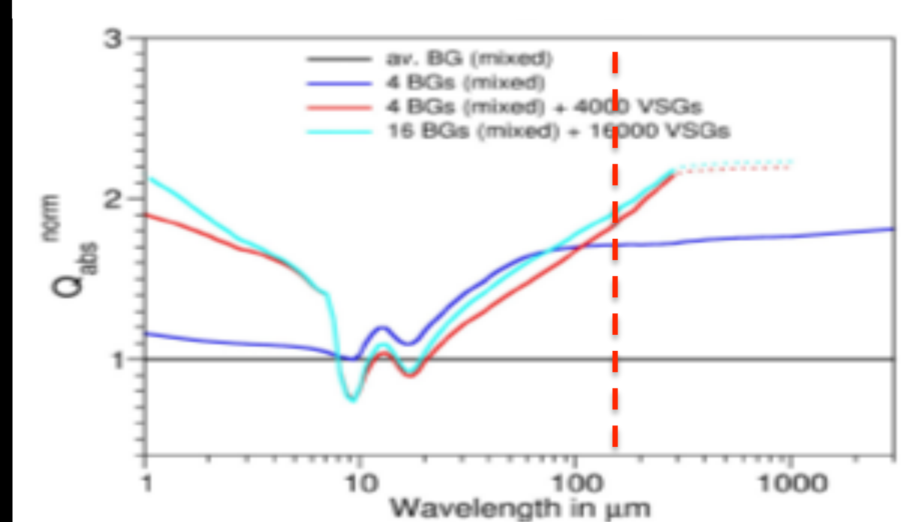
Coagulation can increase the FIR emissivity of dust grains by a factor ~ 2 or more

Kohler+2012

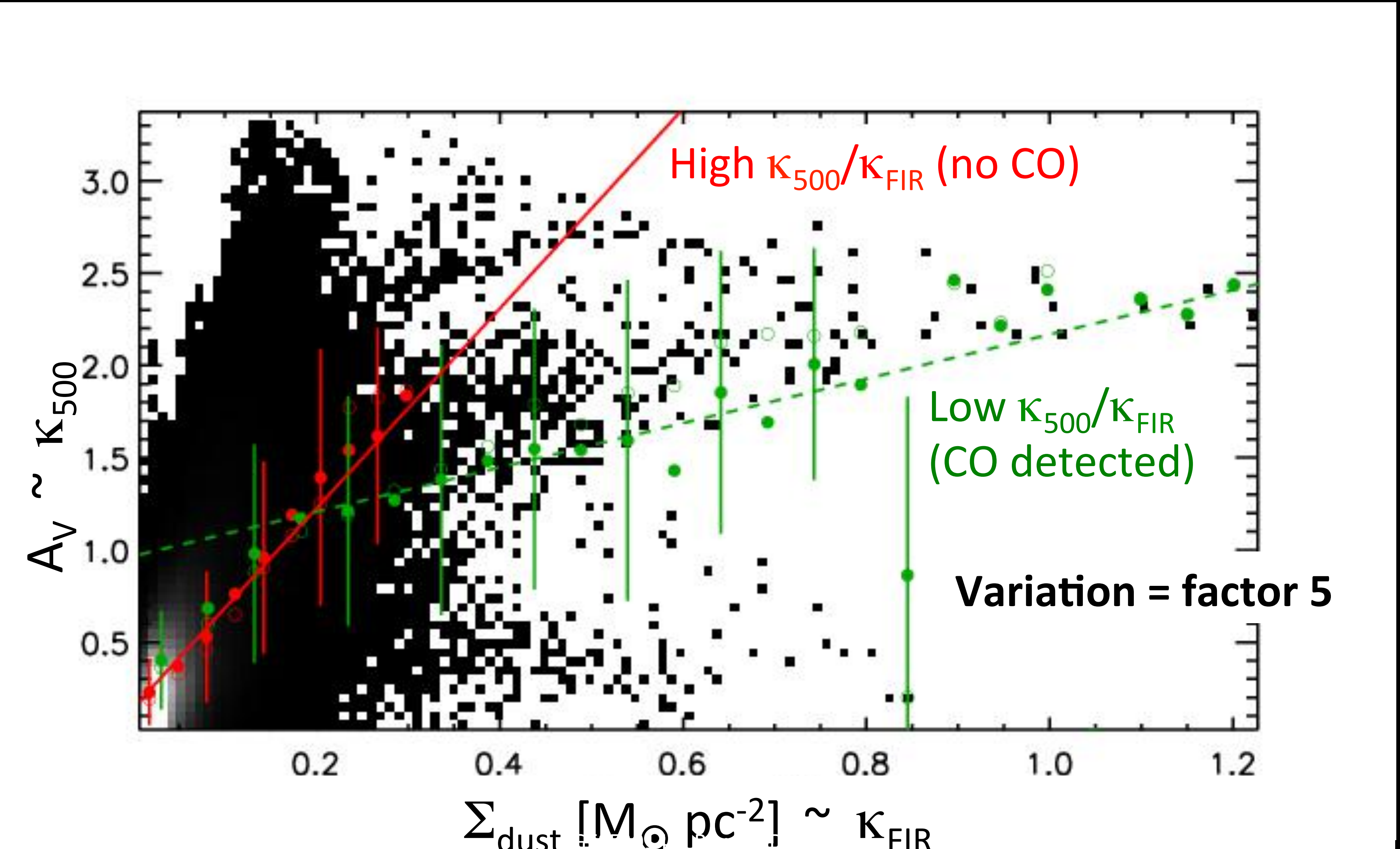
Silicate BG + BGs + VSG



Mixed BG + BG + VSG



Relation Σ_{dust}-A_V



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 ($n\sim1$ cm^{-3})	Translucent ($n\sim50$ cm^{-3})	Dense ($n\sim1000$ 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

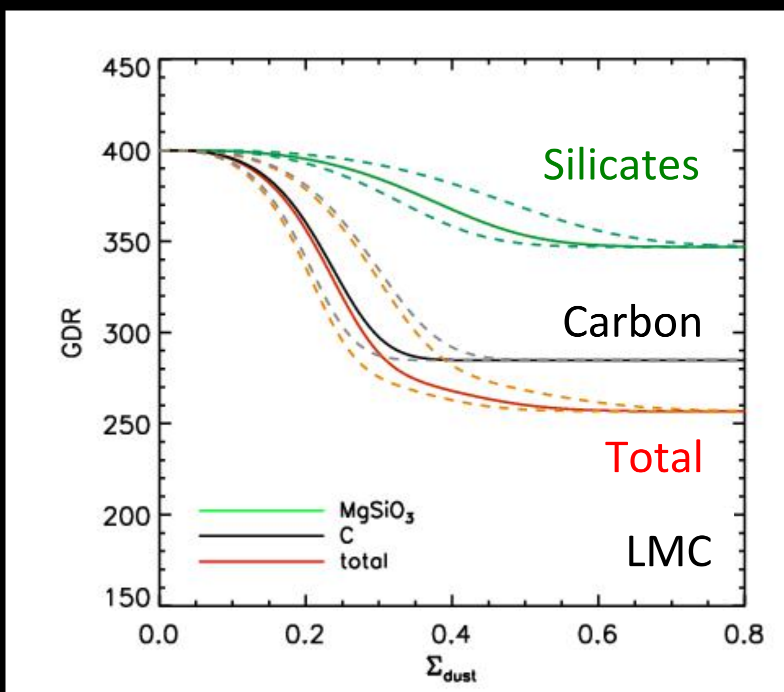
Gas-to-dust ratio variations via accretion

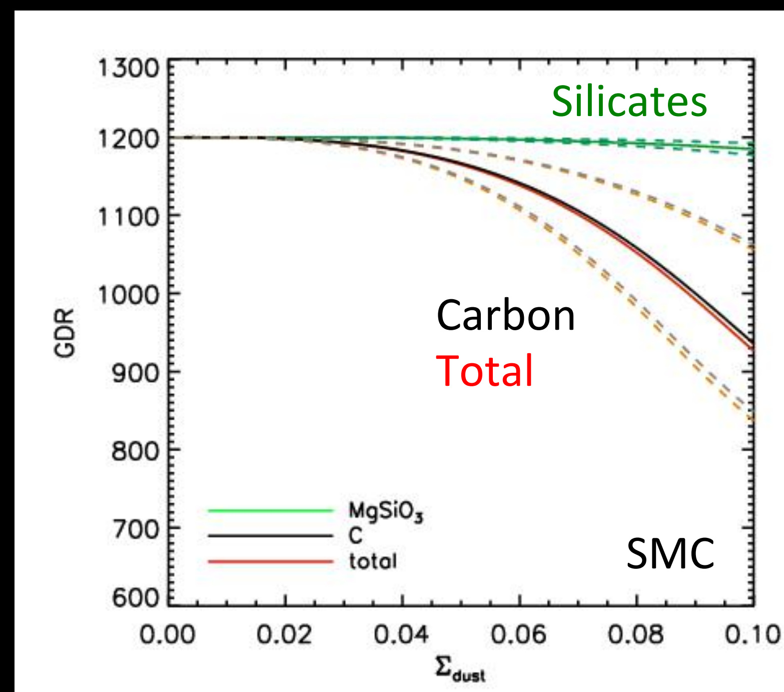
- Depletion fraction at t=5 Myr (~1/2 GMC lifetime)
  - For Mg, f_0=0.46

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

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 $M_\odot$ pc^{-2} (Snow+2006)





Impact for star formation studies

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

$$\Sigma(H_2) = \underbrace{\mathrm{GDR}}_{\text{Measured in diffuse ISM (no } H_2\text{), but not necessarily applicable in } H_2 \text{ dominated regions.}} \underbrace{\Sigma_{dust}}_{\text{May be overestimated by factor ~2 in GMCs due to coagulation}} - \Sigma(HI)$$

- 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 $A_{1000\ Å}$
  - These variations should be included in models