Overview of Dust Depletion Measurements in the Local Group

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PanDust2025

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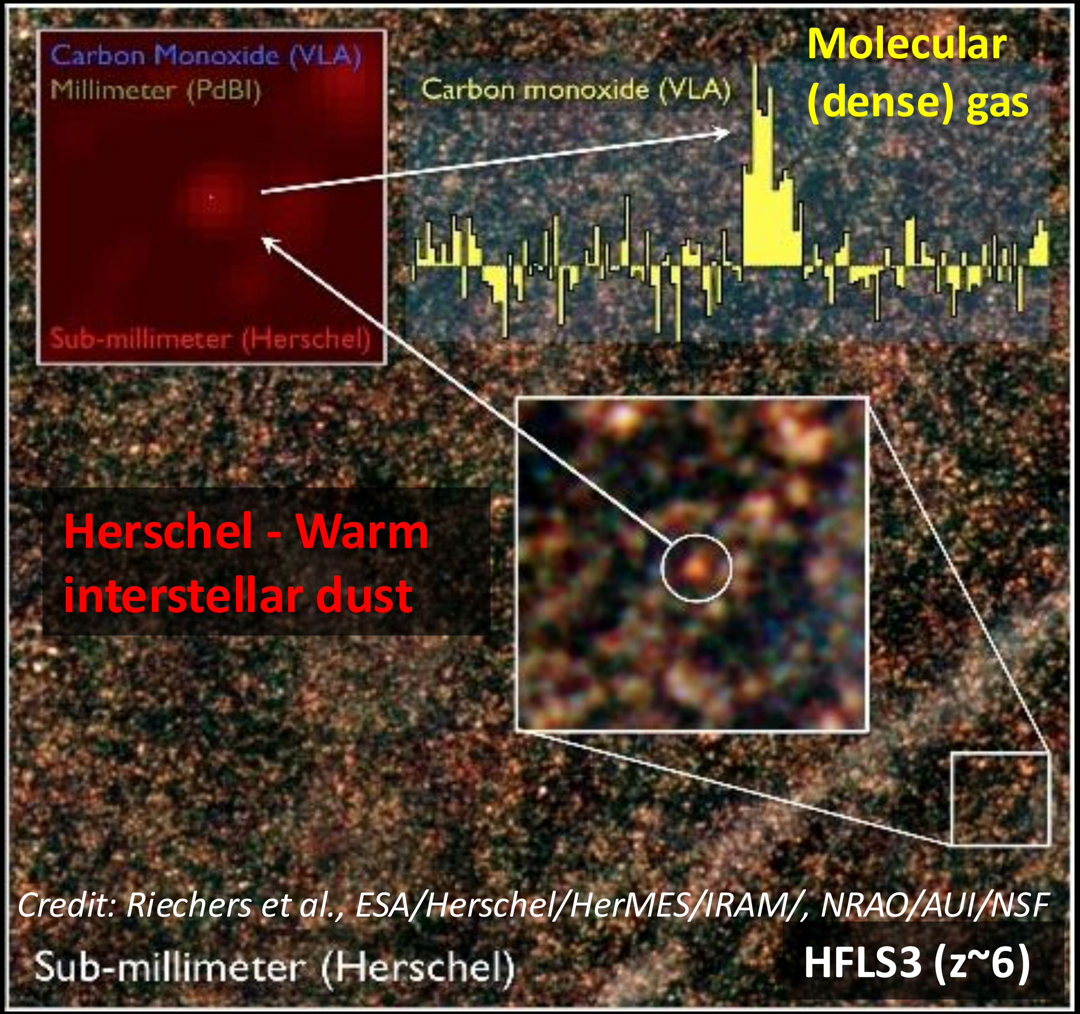
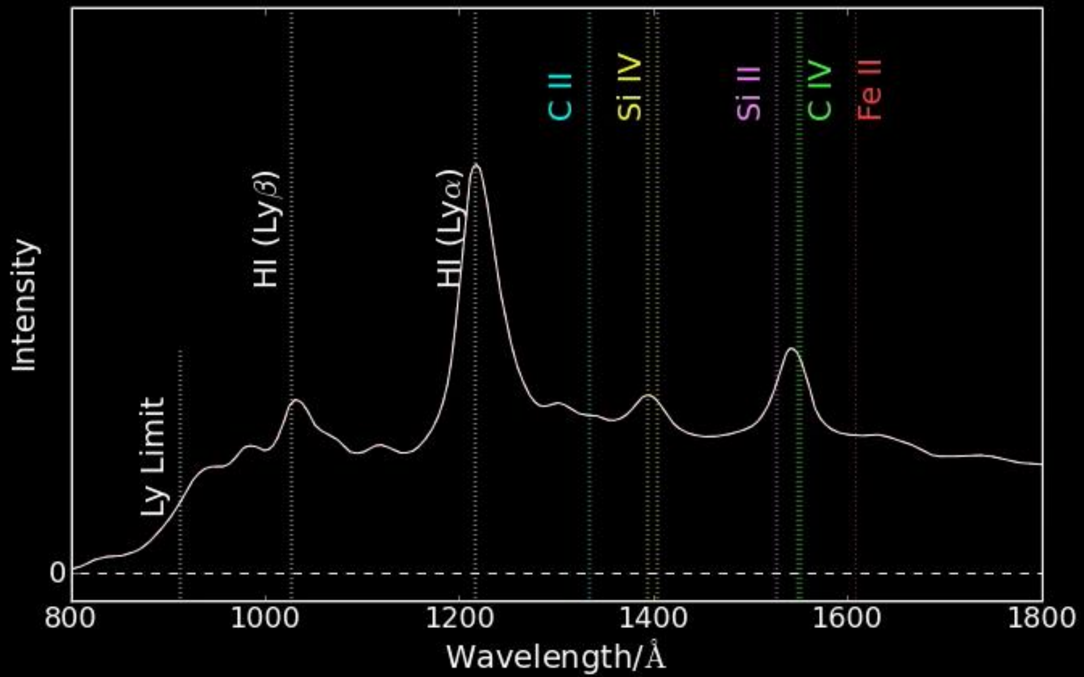
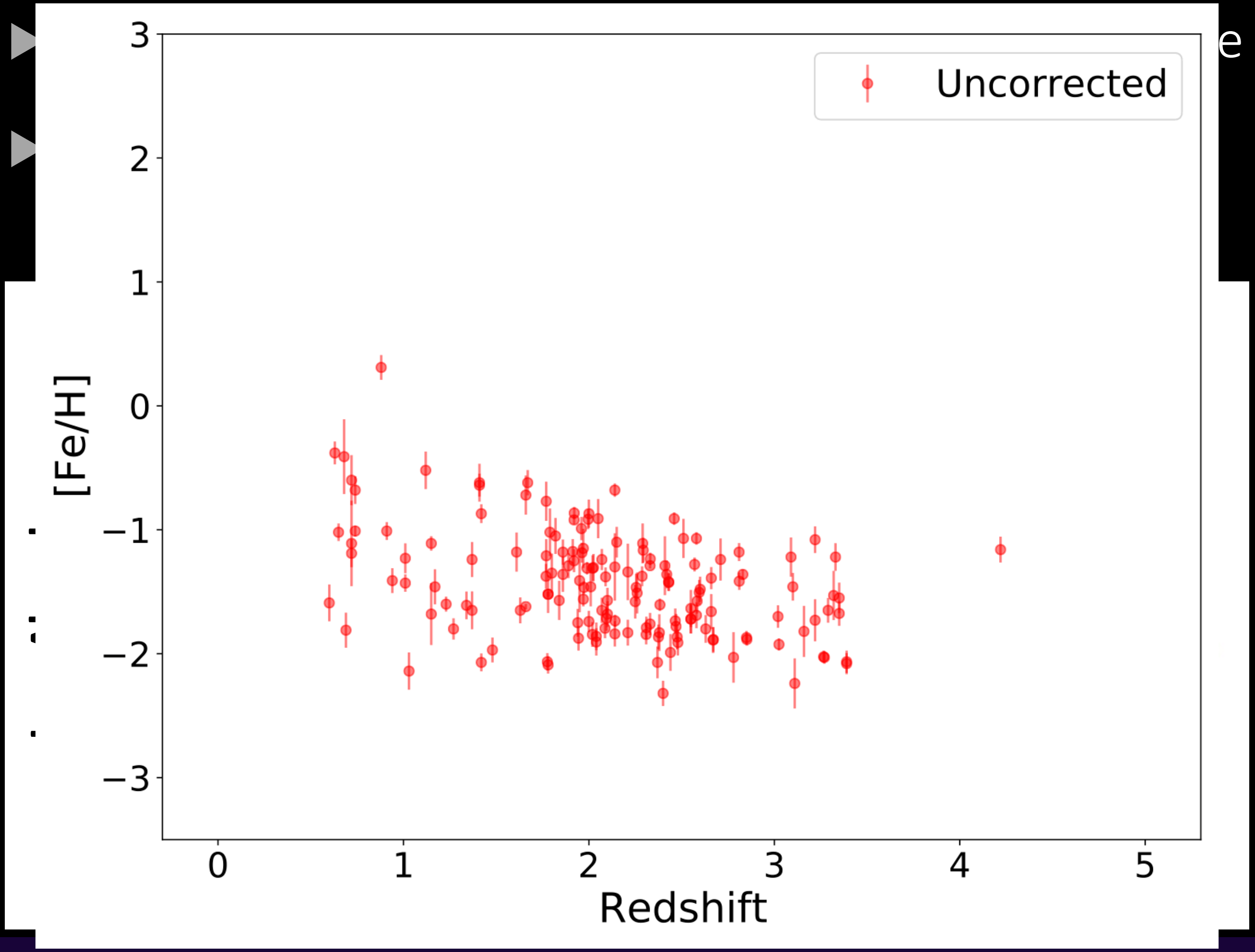
Why Must we Understand Dust in Galaxies?
Dust as an ISM Tracer

- Dust is a ubiquitous tracer of ISM gas
  - At high redshift ($z > 1.5$), dust is the ONLY tracer of the atomic ISM (molecular gas can be observed with CO emission)
- Need to understand how the ratio between dust and gas masses evolves with metallicity and density in order to infer gas masses from dust emission in the FIR
- This can be understood in the nearby universe

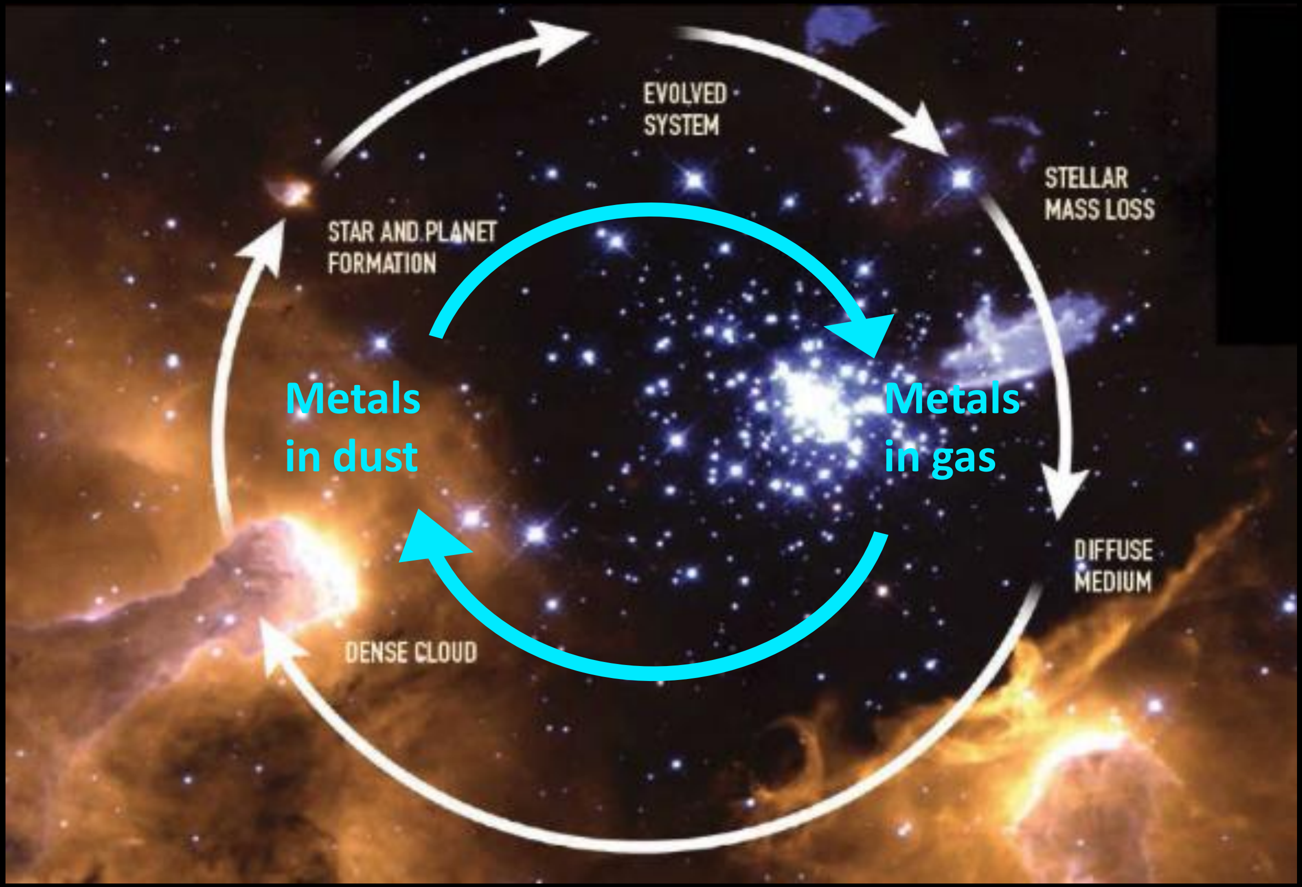


Why must we understand dust in galaxies? The chemical enrichment of the Universe through Damped Lyman-α Systems (DLAs)





Dust Growth in the ISM



- Timescale for accretion of gas-phase metals onto dust grains (Asano+2013)

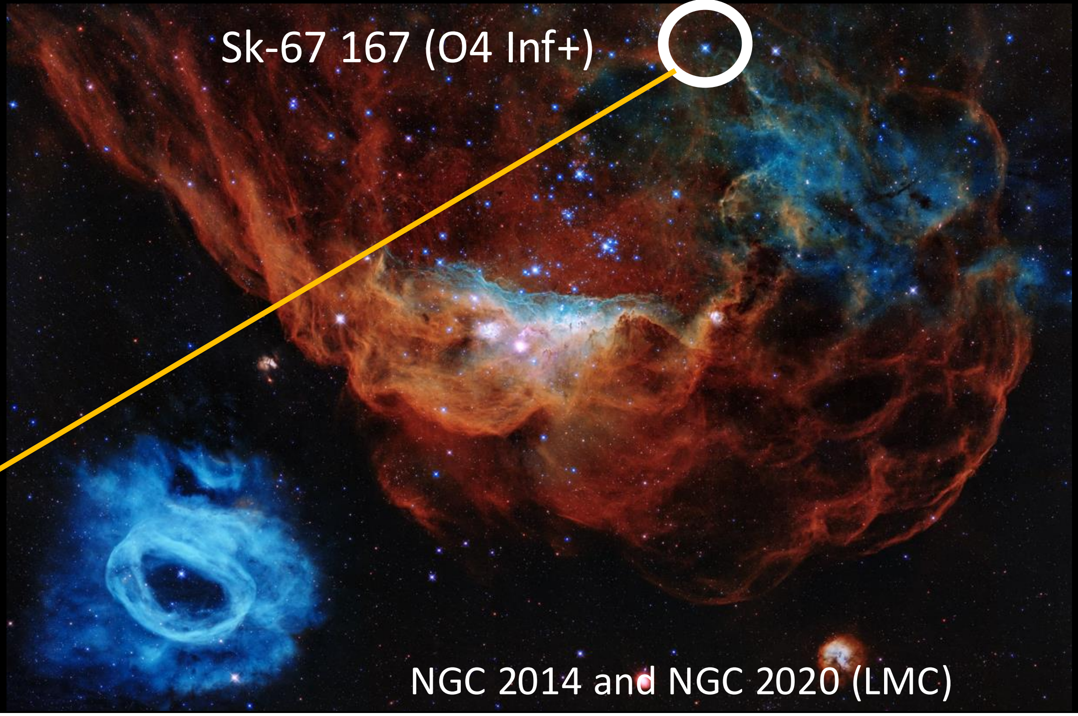
$$\tau \sim \frac{1}{n(H)} \frac{1}{Z}$$

Density

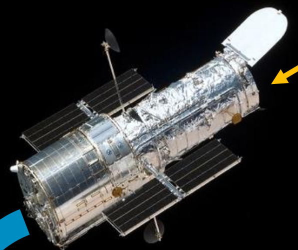
Metallicity

Timescale	Diffuse ($n \sim 1\ cm^{-3}$)	Translucent ($n \sim 50\ cm^{-3}$)	Dense ($n \sim 1000\ cm^{-3}$)
LMC ($0.5Z_o$)	4 Gyr	80 Myr	4 Myr
SMC ($0.2Z_o$)	10 Gyr	200 Myr	10 Myr
Sextans A ($0.08Z_o$)	25 Gyr	500 Myr	25 Myr

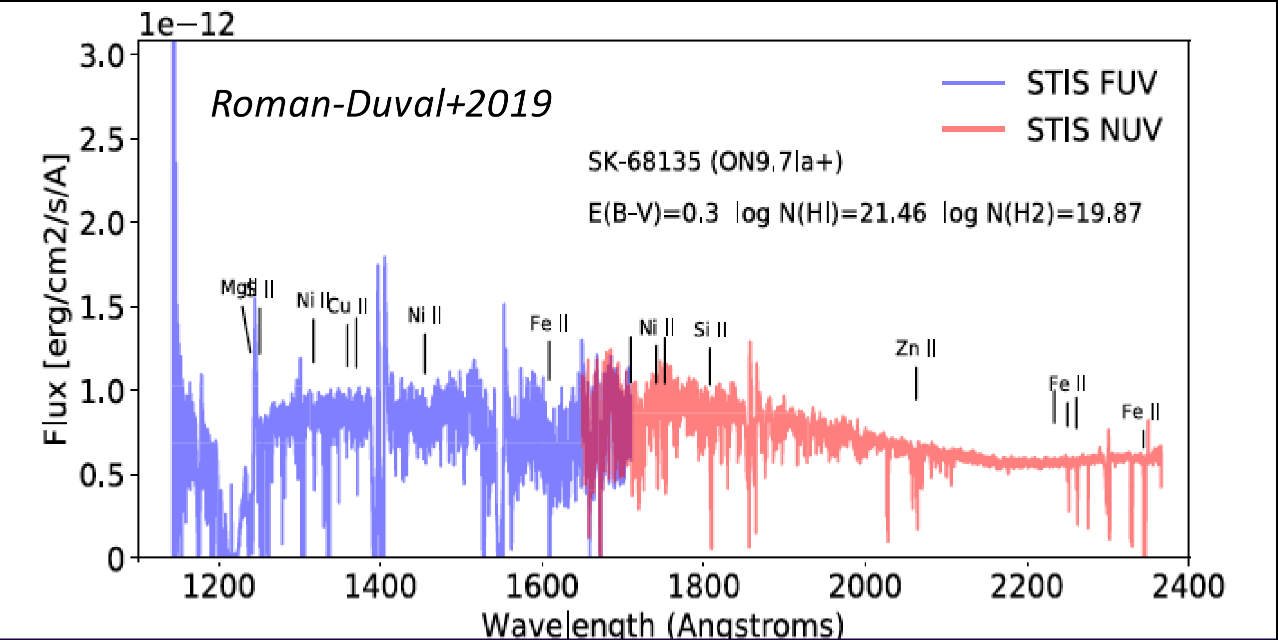
UV Spectroscopy of Interstellar Gas



- Samples of HST UV spectroscopy toward O and B stars to measure abundances in the intervening ISM

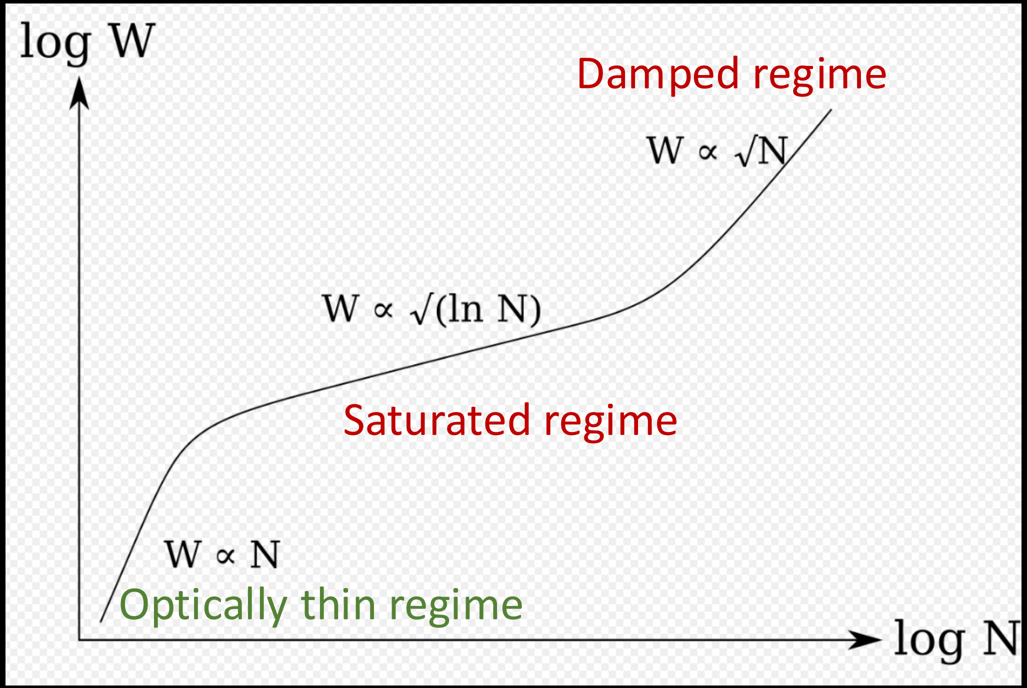


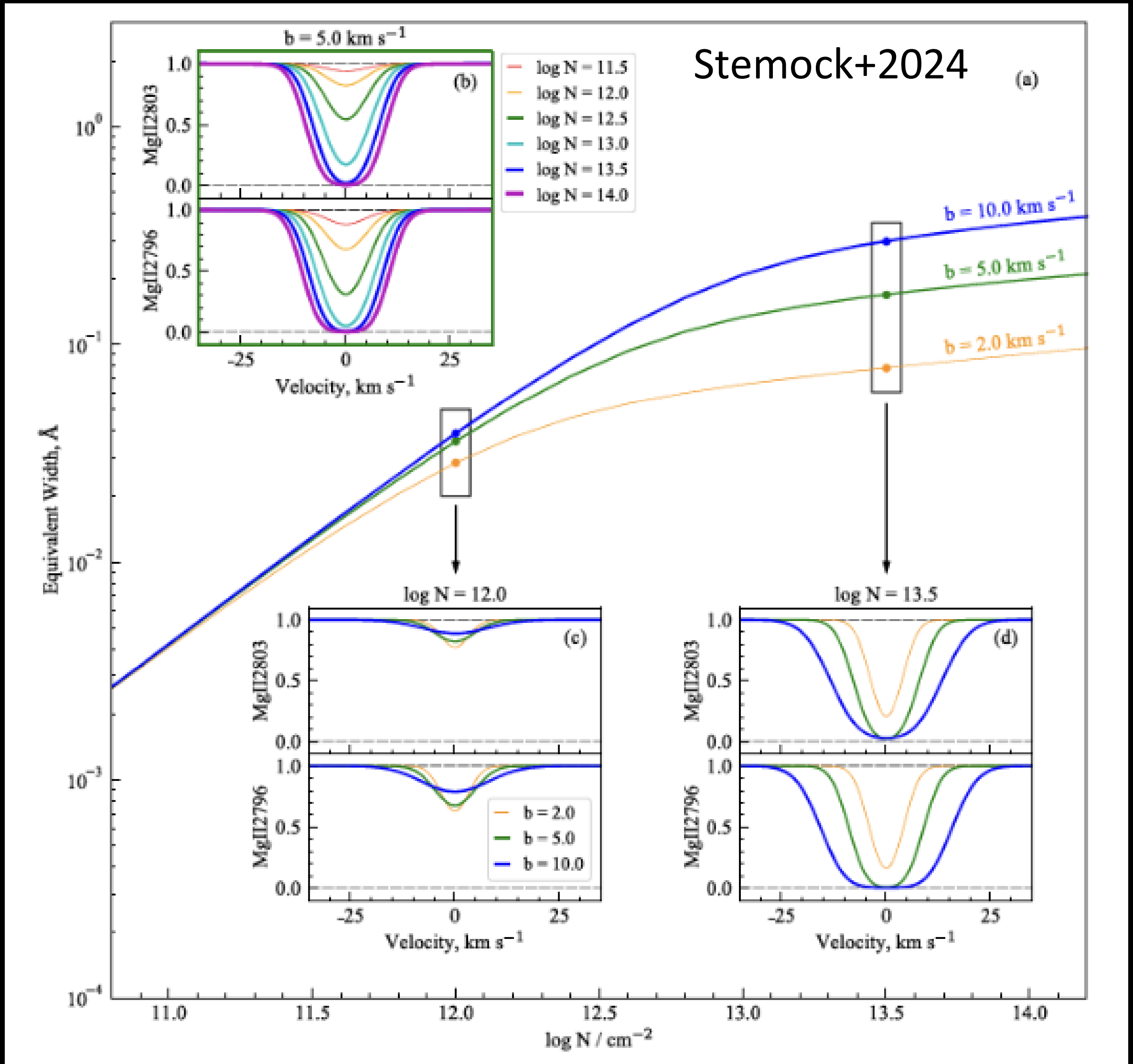
Galaxy	Z/Z_0	Reference
Milky Way	1	Jenkins+09
LMC	0.5	Roman-Duval+21 Tchernyshyov+2015
SMC	0.2	Jenkins+17 Tchernyshyov+2015
IC 1613	0.1-0.2	Hamanowicz+24
Sextans A	0.07	Hamanowicz+24



Measuring Column Densities from Absorption Line Profiles

- Profile fitting (see poster by Avery Kim)
- Apparent Optical Depth (Jenkins 1996)
- Curve of growth (e.g., Prochaska+2006)

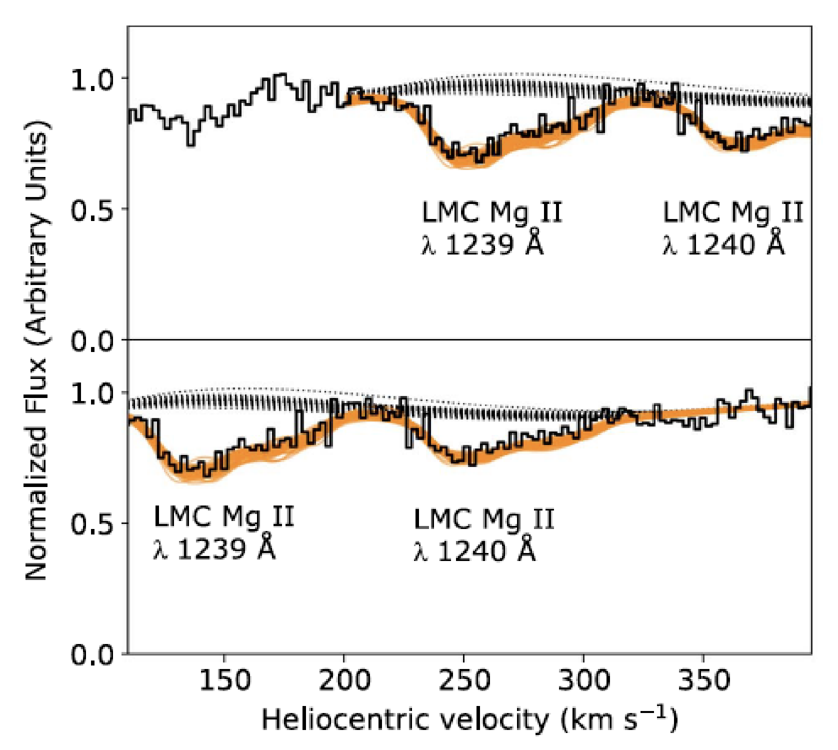




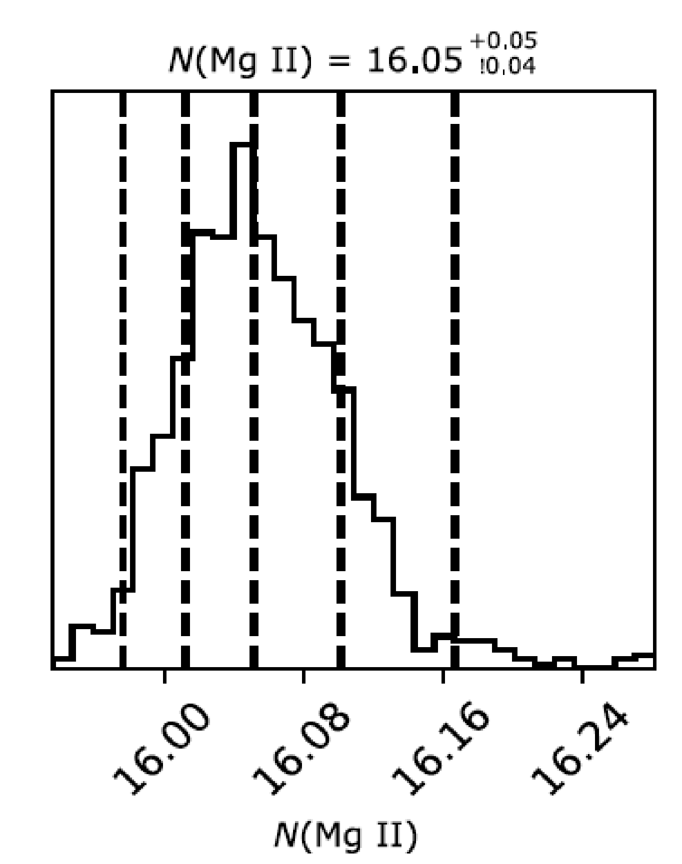
Absorption lines follow a Voigt profile, which is is the convolution of two broadening mechanisms, a Gaussian profile (thermal broadening), and a Lorentzian profile (damping, Waldemar Voigt 1912)

Measuring Column Densities from Absorption Line Profiles
Profile Fitting

- Profile fitting: fit absorption profiles by modeling over a range of column density (*N*) and Doppler parameter (*b*)
- Output is a two-dimensional probability density function for N and b



Roman-Duval+2021



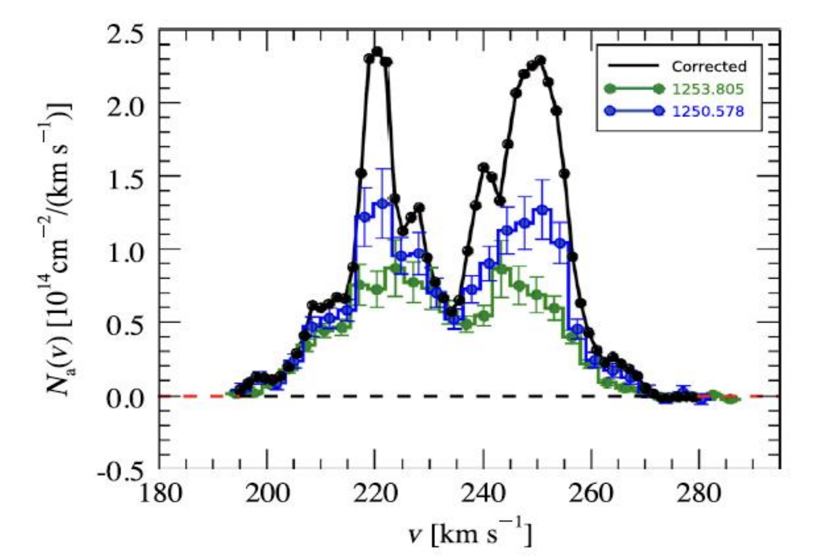
Measuring Column Densities from Absorption Line Profiles
Apparent Optical Depth

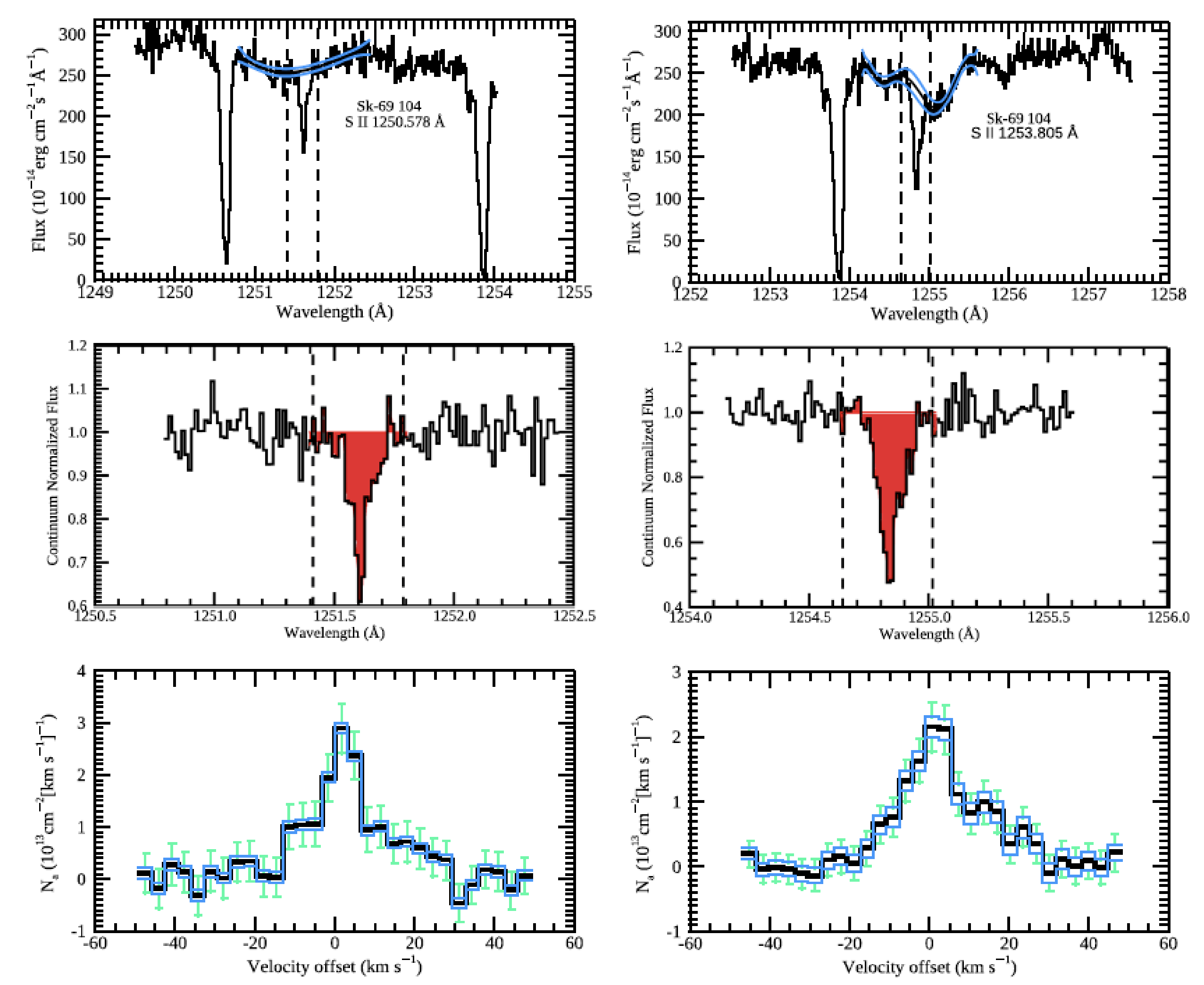
- Measure the apparent optical depth as $\tau_a = -ln(I/I_c)$ for transitions of the same element with different oscillator strengths
- Convert τ_a to apparent column density N_a

$$N = \frac{m_e c}{\pi e^2 f \lambda} \int C_R \, \tau_a(v) dv$$

Jenkins (1996)

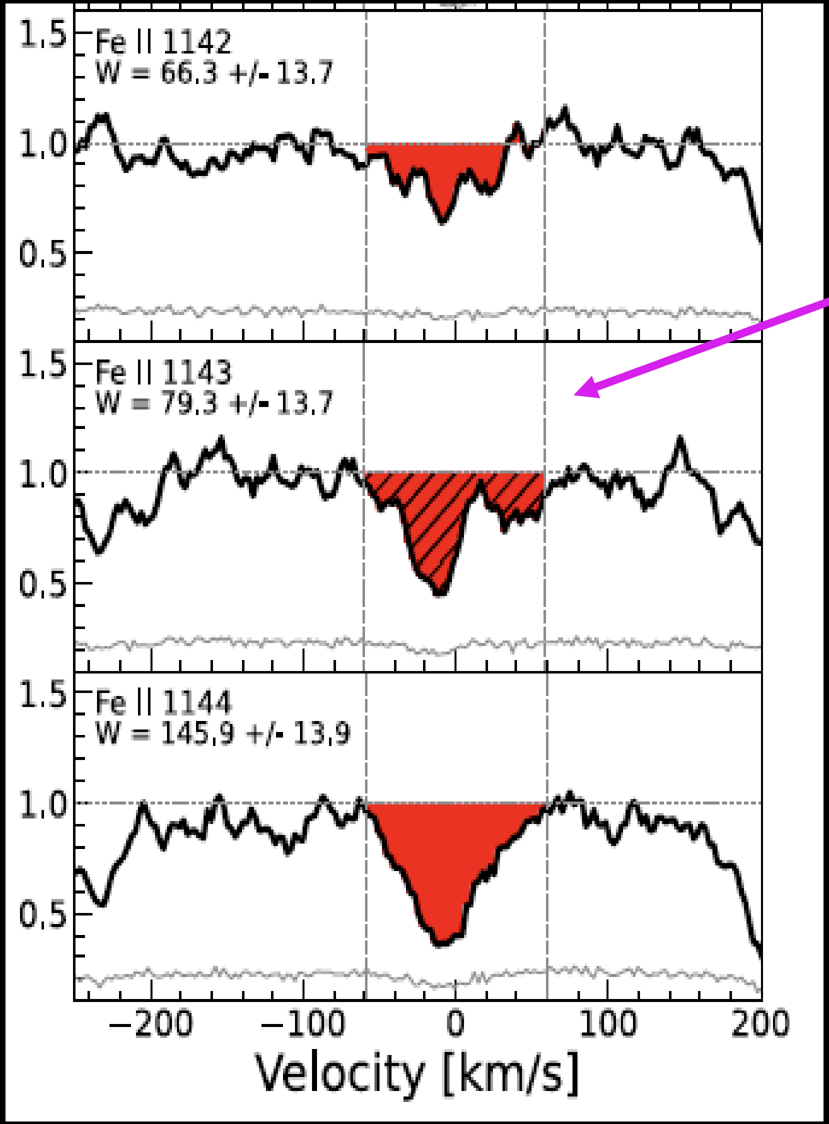
- Correct weaker line for unresolved saturation effect using method in Jenkins (1996)





Roman-Duval+2021

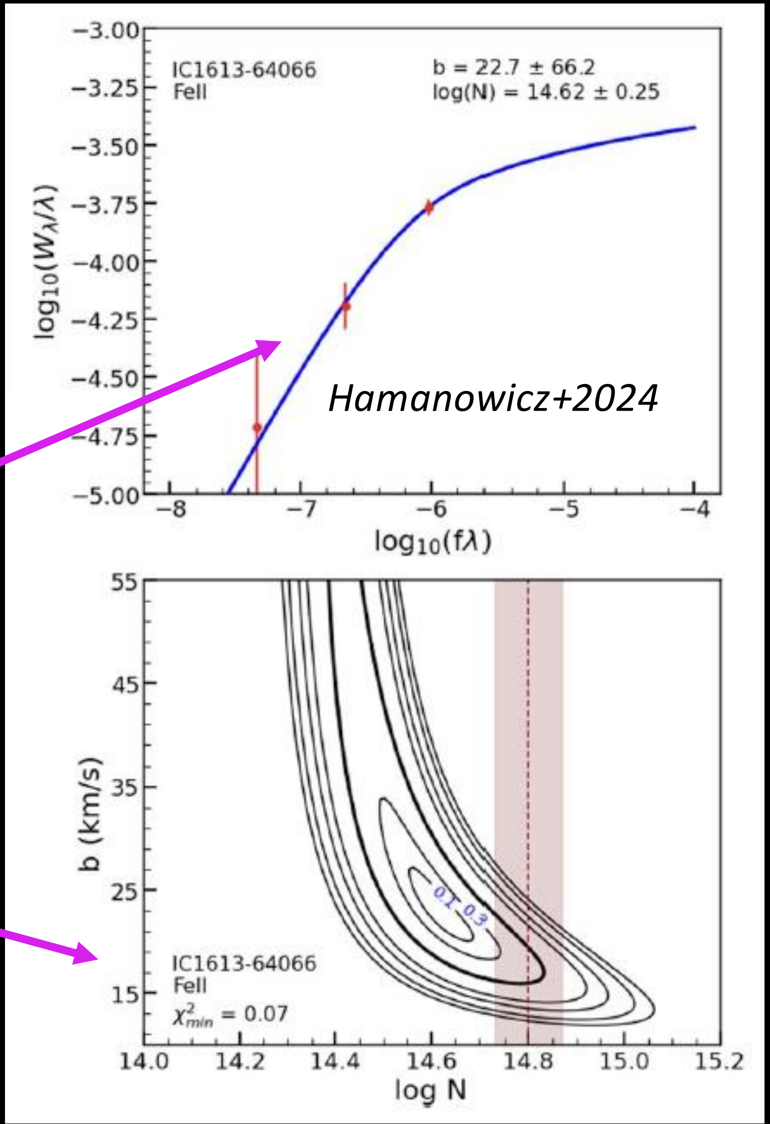
Measuring Column Densities from Absorption Line Profiles
Curve of Growth



- Measure equivalent widths (EWs) for transitions of the same element with different oscillator strengths
- Fit the curve of growth (see approach in Hamanowicz+2024)

$$W_\lambda/\lambda = F(N,b)$$

- Obtain a 2D PDF of N and b

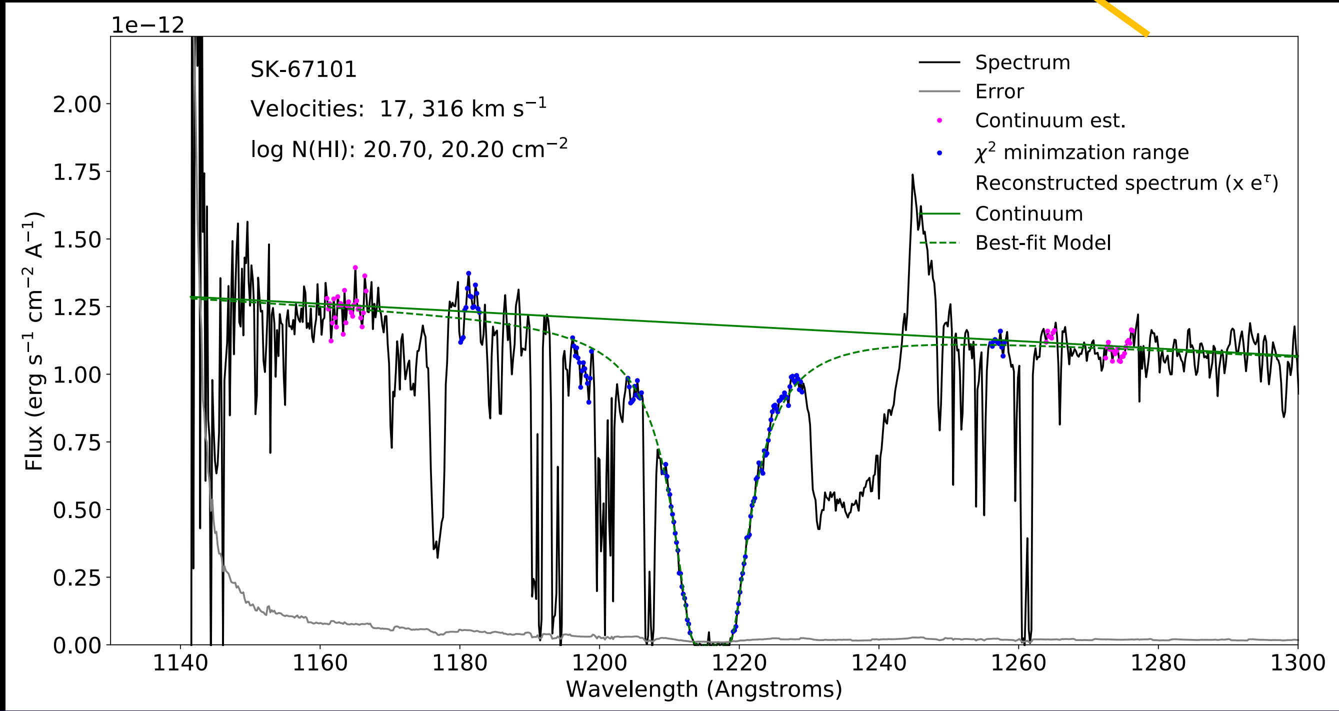


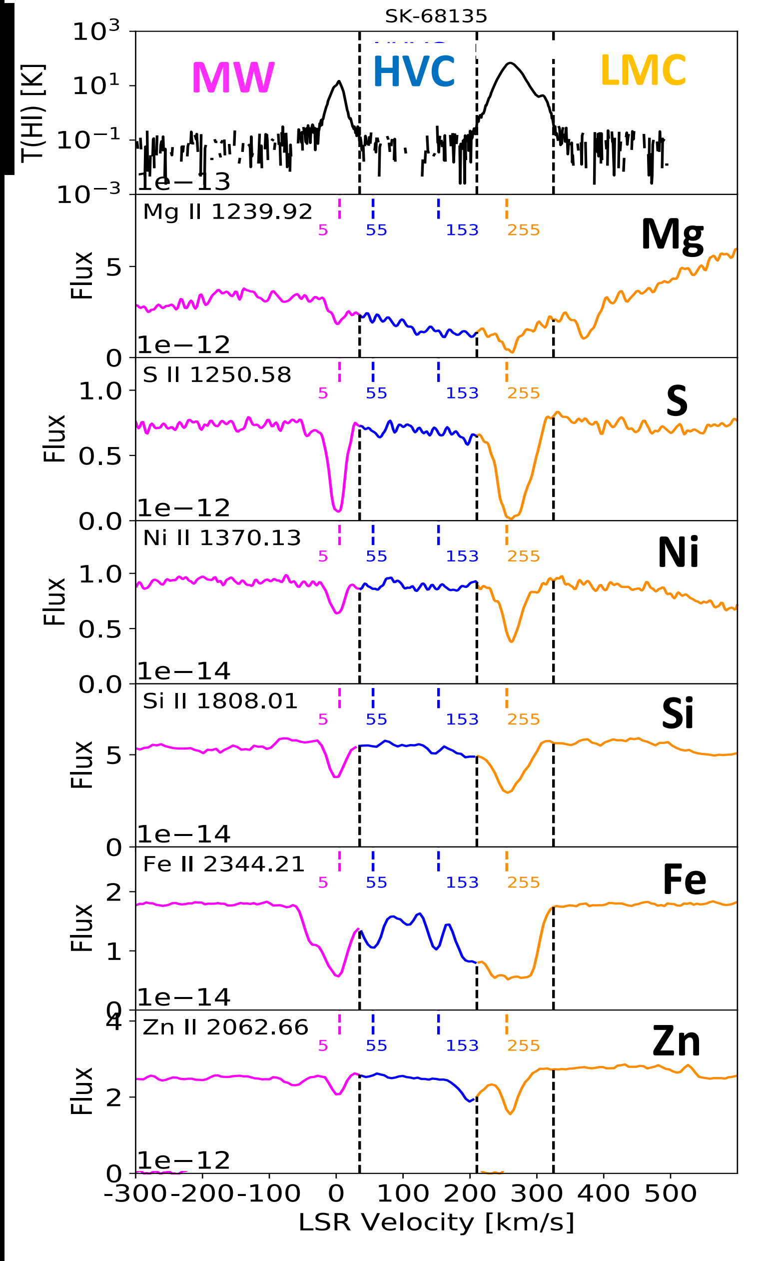
Counting metals in the gas: abundances

- ✓ **HI column densities**
- ✓ **Interstellar gas abundances and depletions for Si, Fe, Mg, O, Ni, Cu, S, Zn**

Modeling of absorption features yields column densities of metals

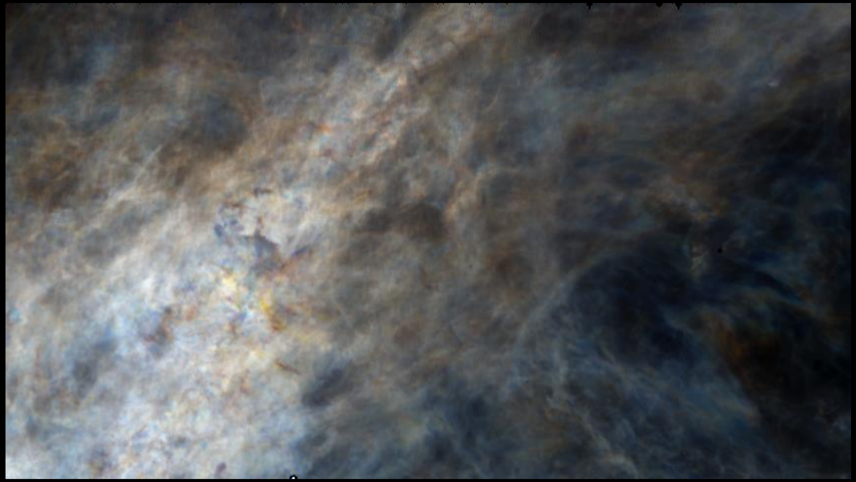
Modeling of Lyman-α 1216 A absorption line using Lorentzian profile fitting



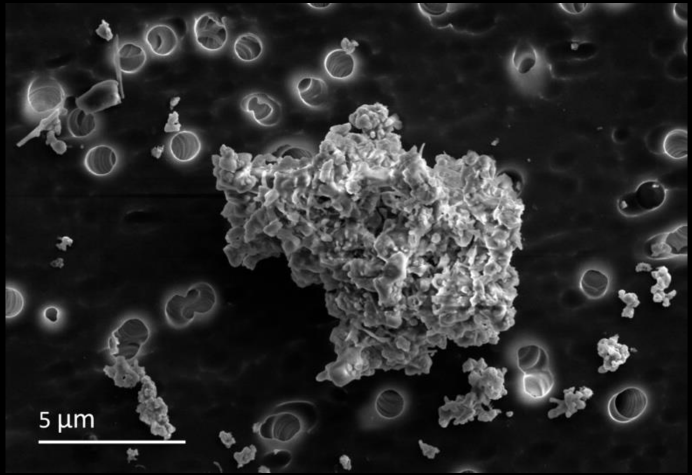


Counting Metals in the Gas and Dust: Depletions

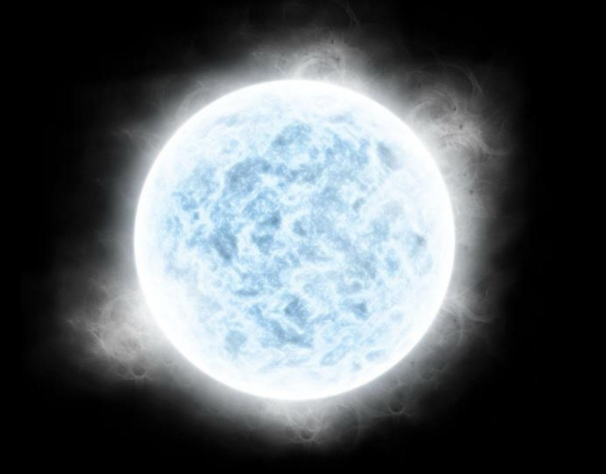
Metals in the gas (HST-METAL)



Metals in the dust (What we want)



Metals in young stars (VLT/optical spectra)



+ =

$$\delta(X) = \log \frac{X}{H}\Big]_{gas} - \log \frac{X}{H}\Big]_{star}$$

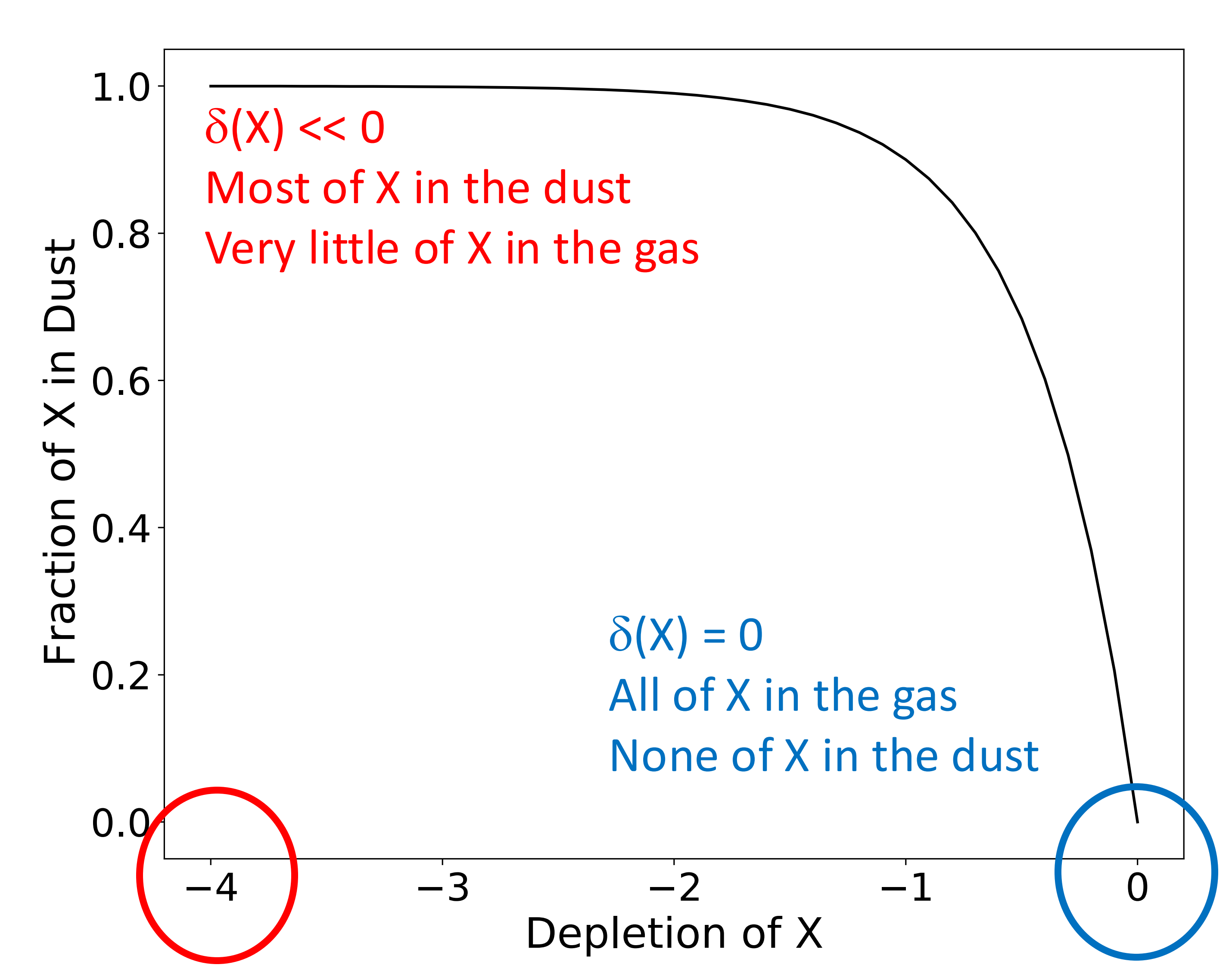
Depletion δ = log fraction in the gas

$$\frac{X}{H}\Big]_{dust} = (1\text{-}10^{\delta(X)})\,\frac{X}{H}\Big]_{star}$$

$$\frac{X}{H}\Big]_{gas} = 10^{\delta(X)}\,\frac{X}{H}\Big]_{star}$$

Definition of Depletions

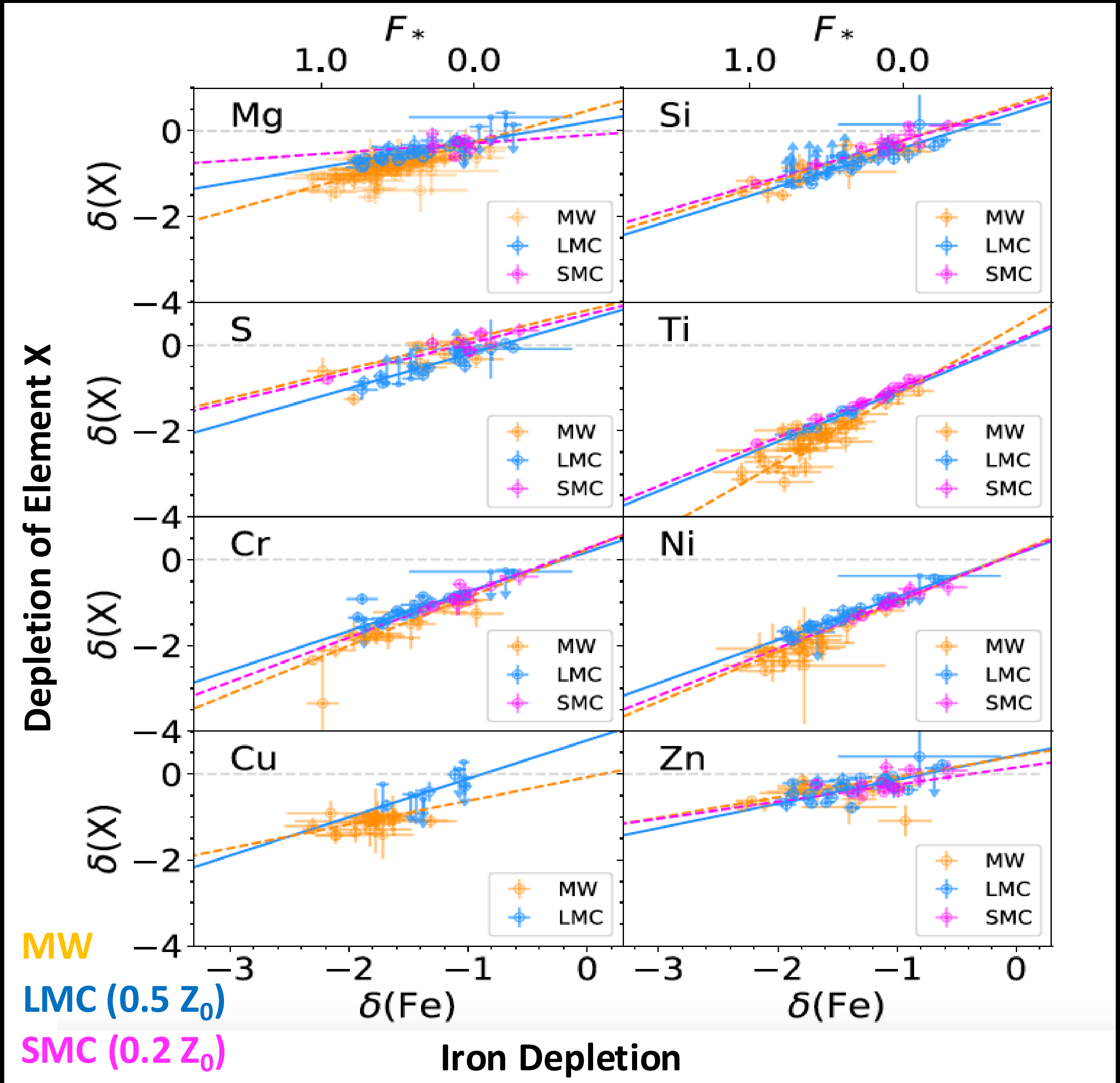
Depletion δ(X) =
log fraction of X in gas



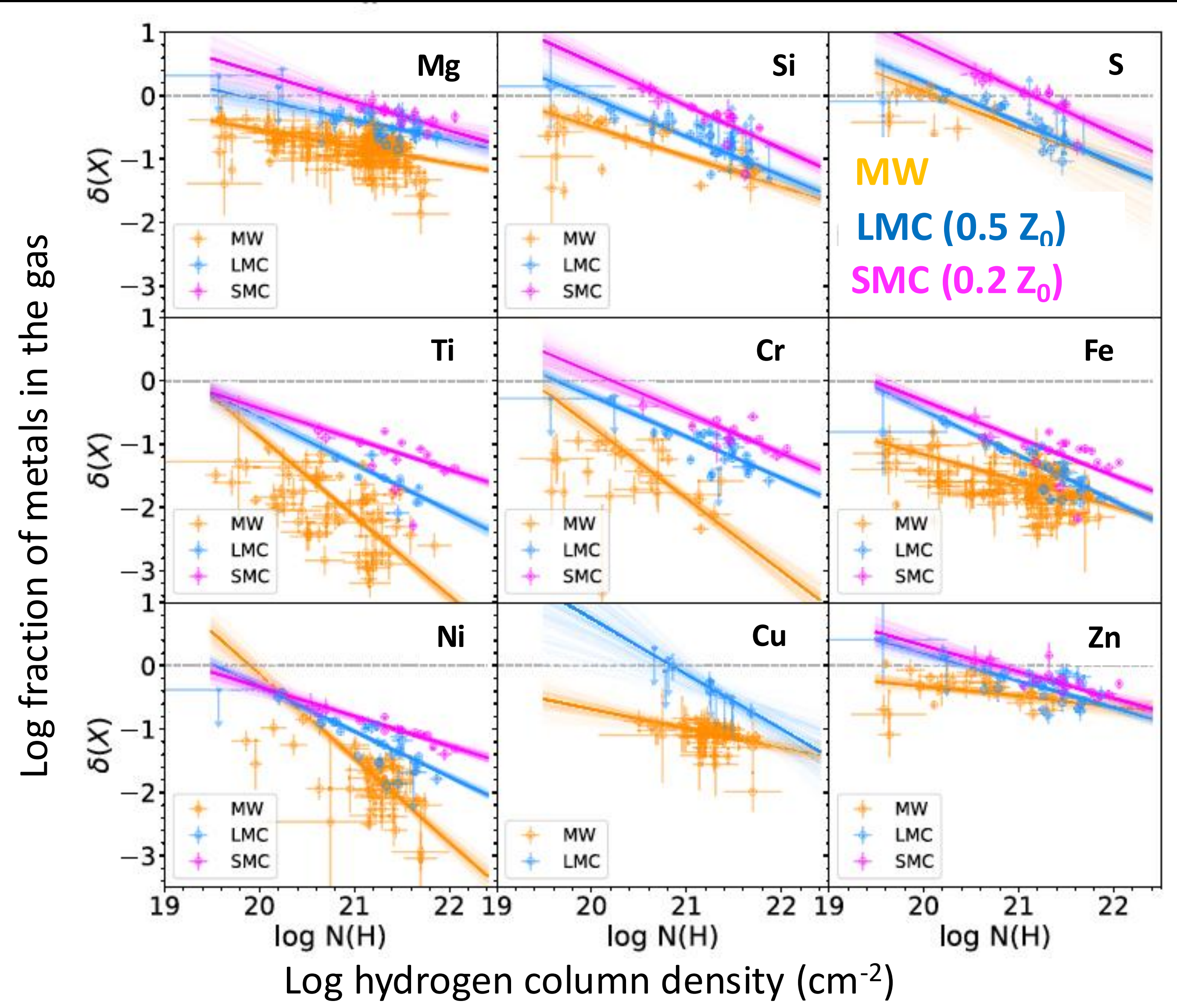
The Collective Behavior of Depletions

- Depletions exhibit collective behavior
- Correlation between depletions for different elements are very similar between Milky Way, LMC, SMC
- Respond to variations in same physical parameters

Roman-Duval+2022a



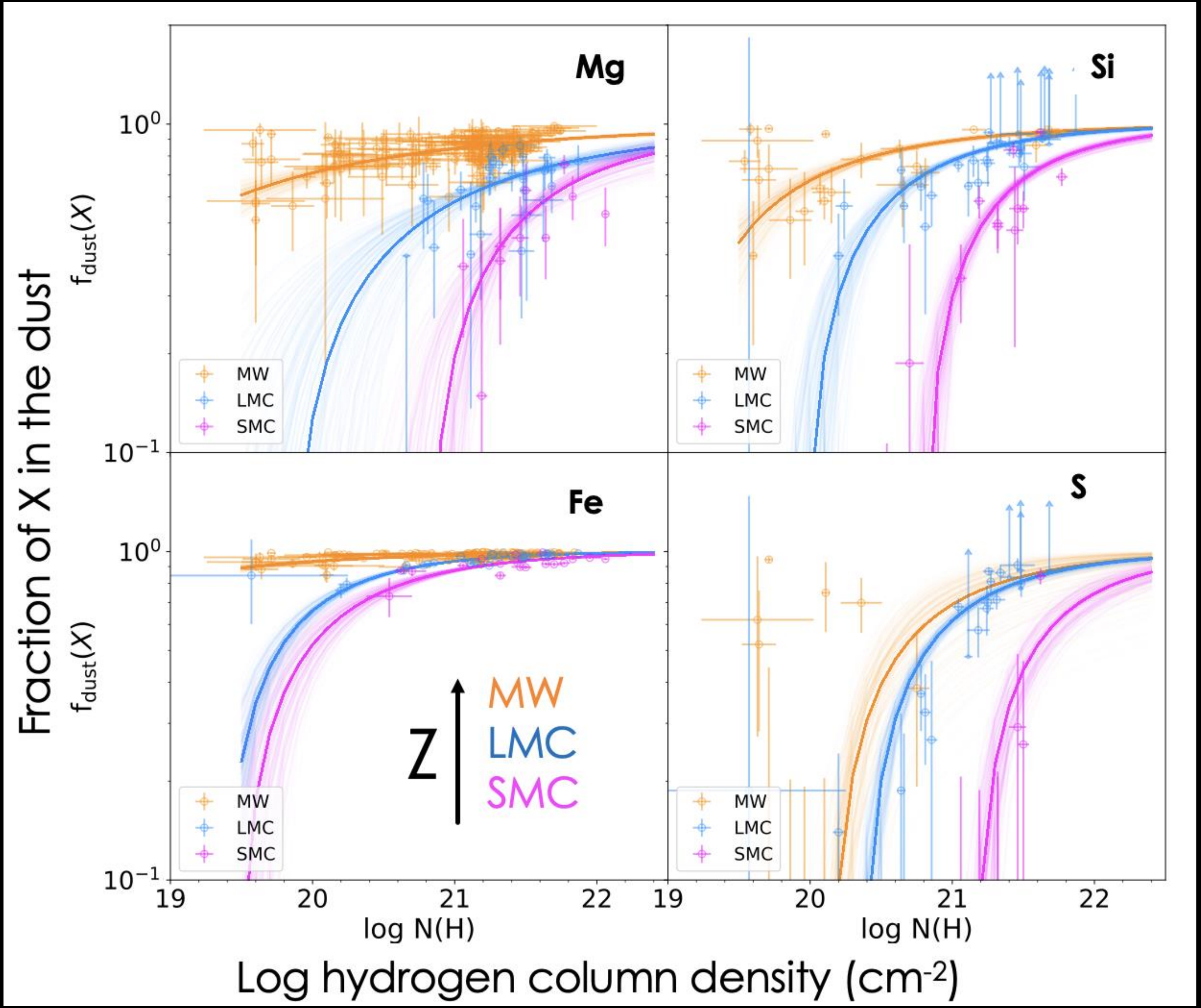
Depletions vs Density and Metallicity



- The fraction of metals in gas (depletion):
  - Decreases as the **density** of ISM increases
  - Increases as the **metallicity** decreases

Roman-Duval+2019, 2021, 2022a, b

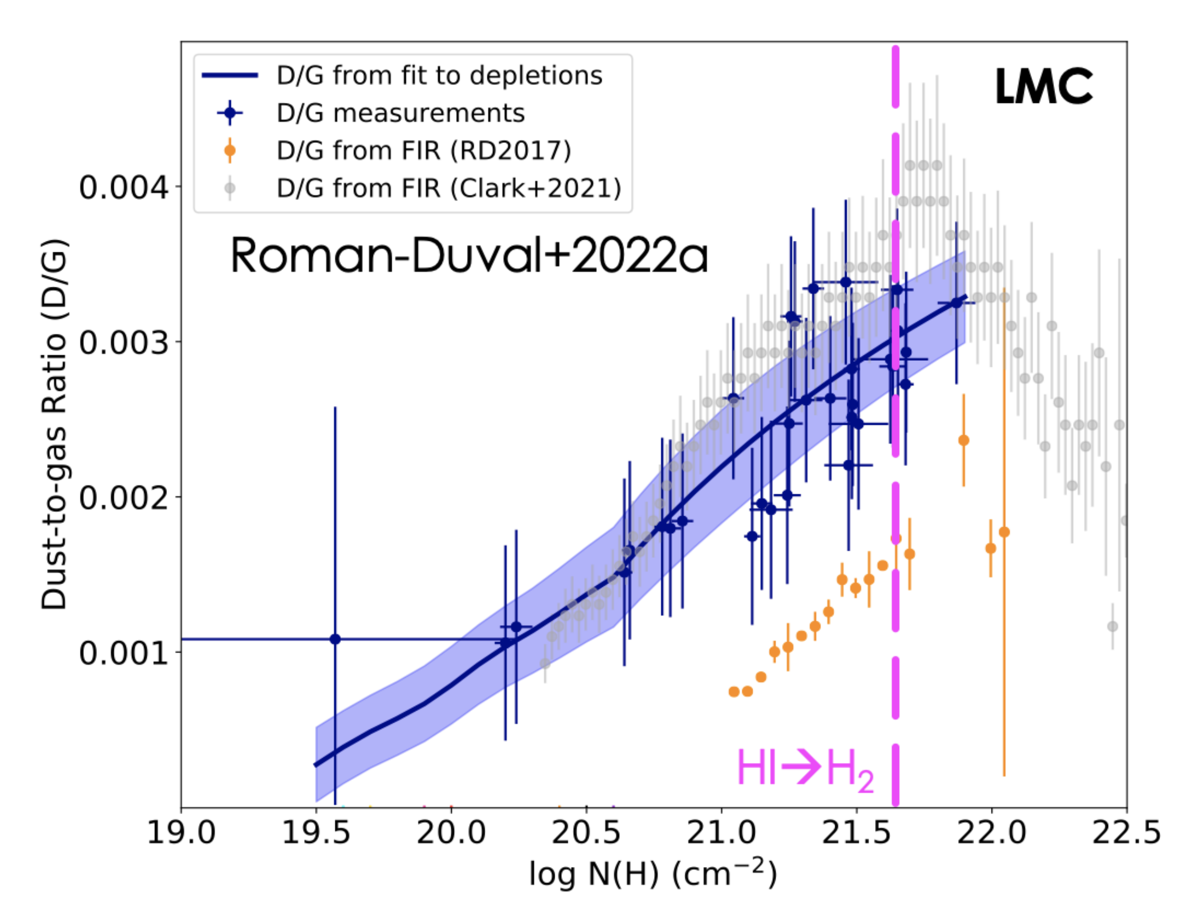
Depletions vs Density and Metallicity

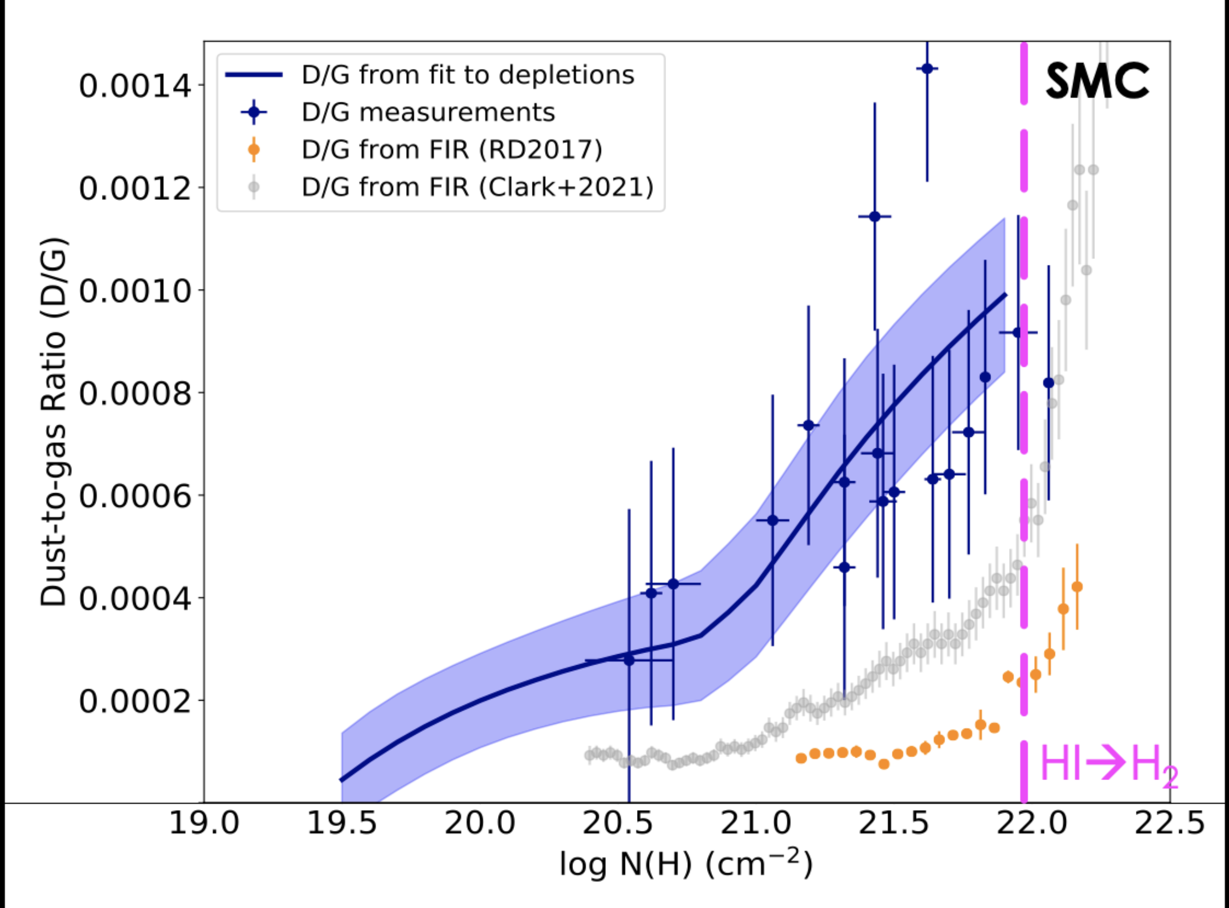


- The fraction of metals in dust (D/M):
  - Increases as the **density** of ISM increases
  - Decreases as the **metallicity** decreases
- Evidence of dust growth in the ISM through accretion

Dust-to-Gas Ratio Evolution with Density

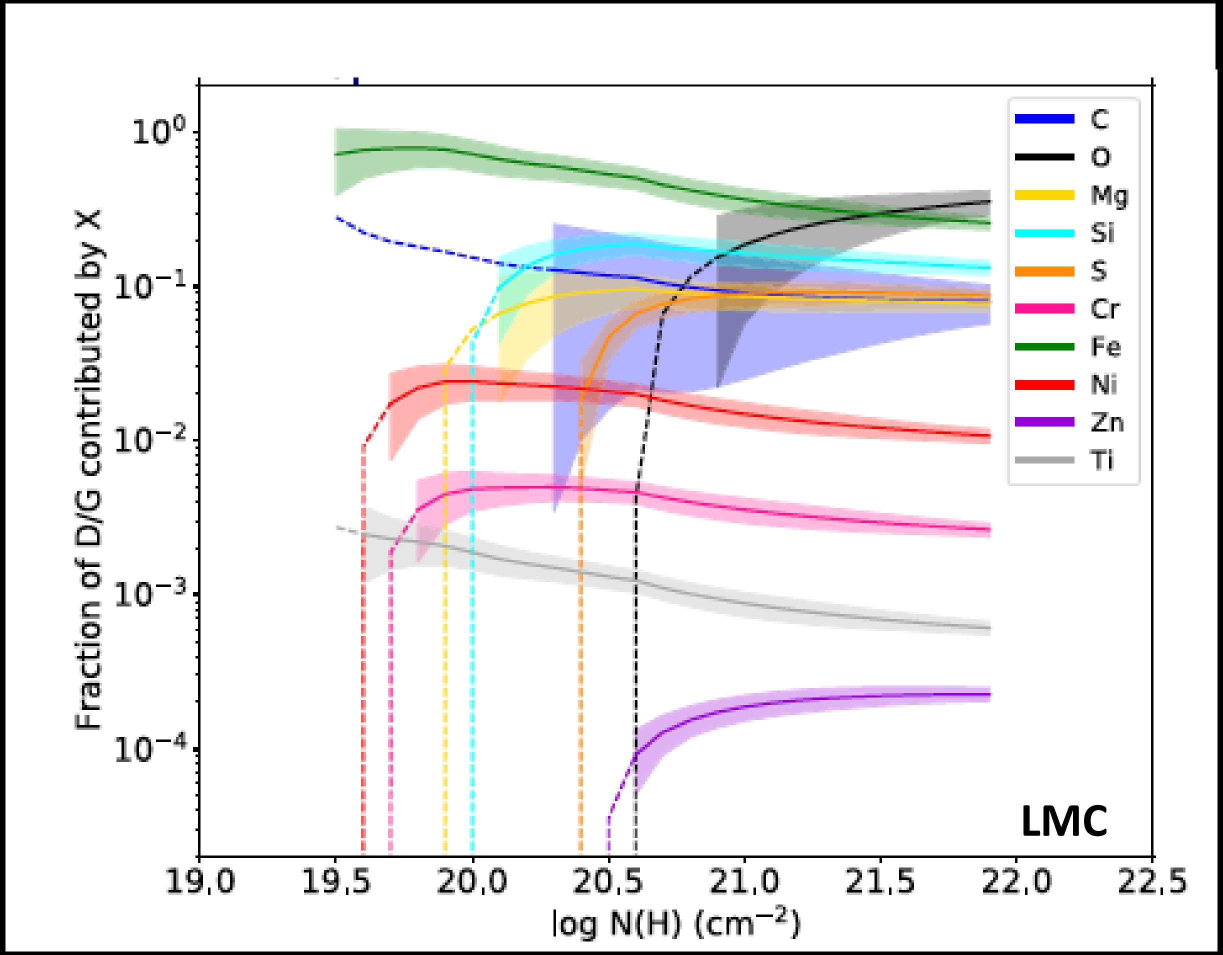
- The abundance of dust increases by factors 3-10 from the diffuse to the dense ISM
- Most metals are already in the dust when ISM turns molecular

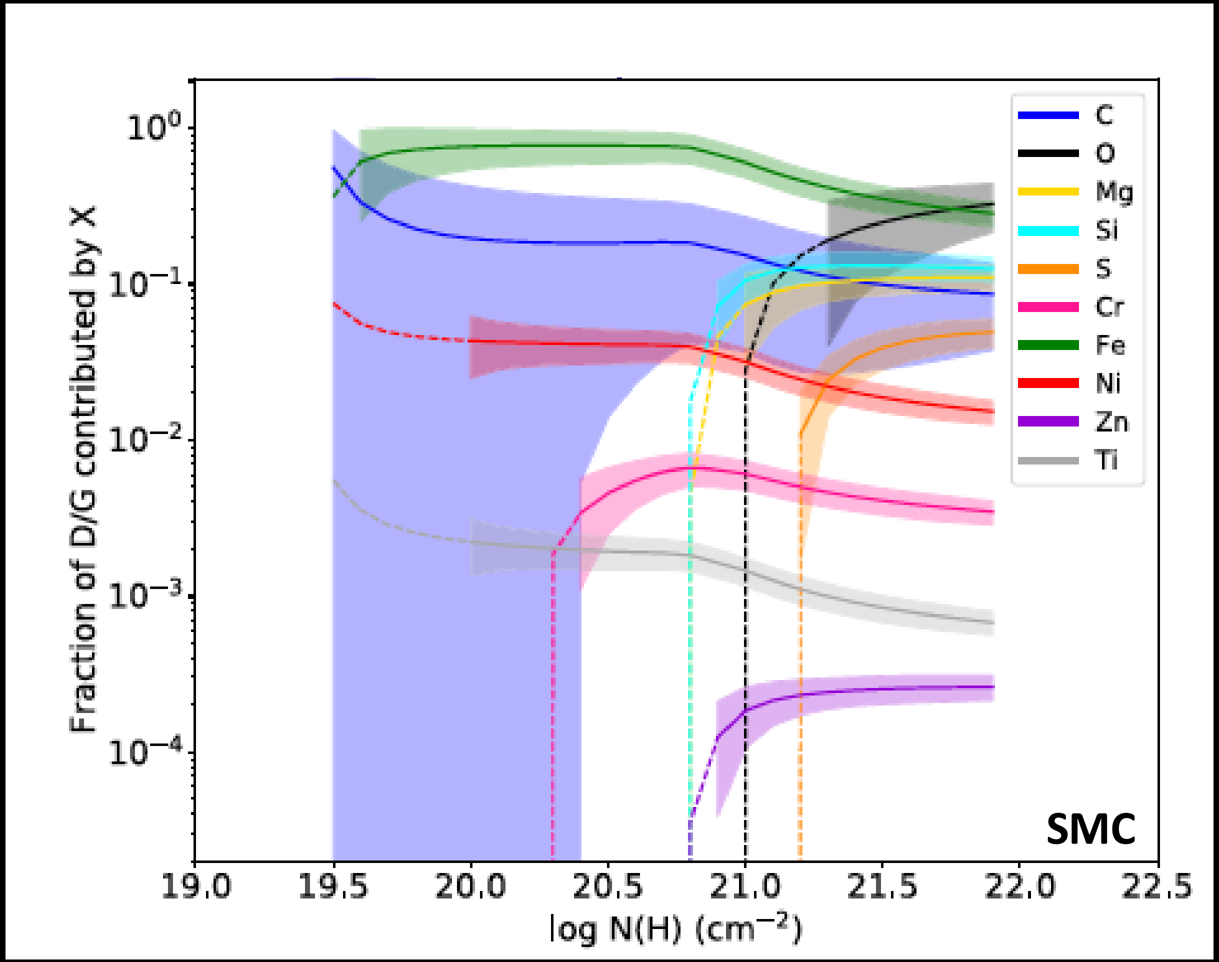




Dust Composition vs Density & Metallicity

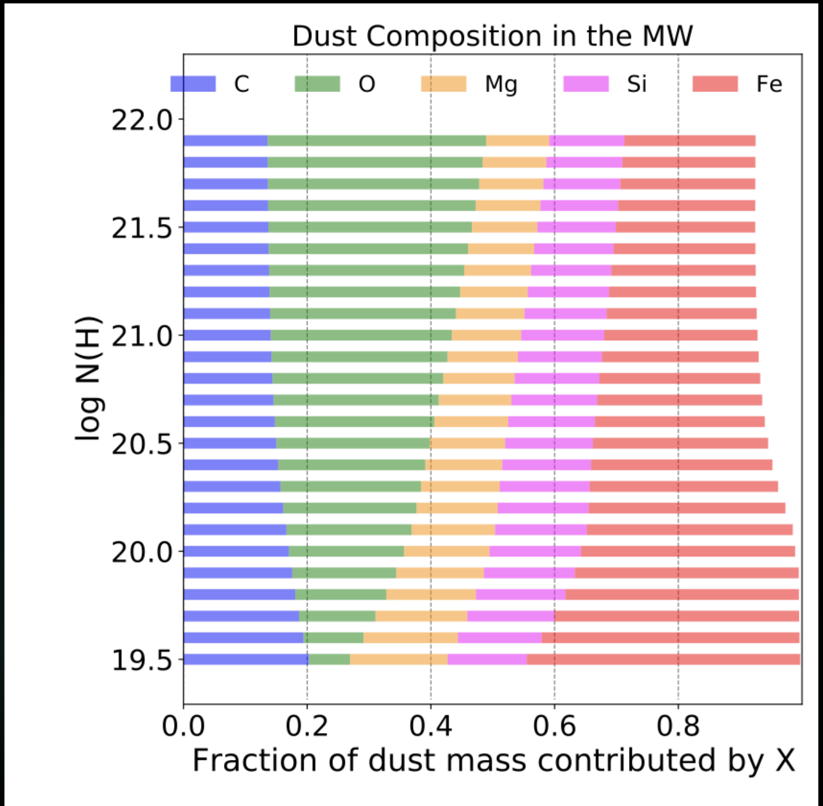
- Depletions probe the dust composition, albeit with large uncertainties on the fraction of C and O in dust outside the Milky Way



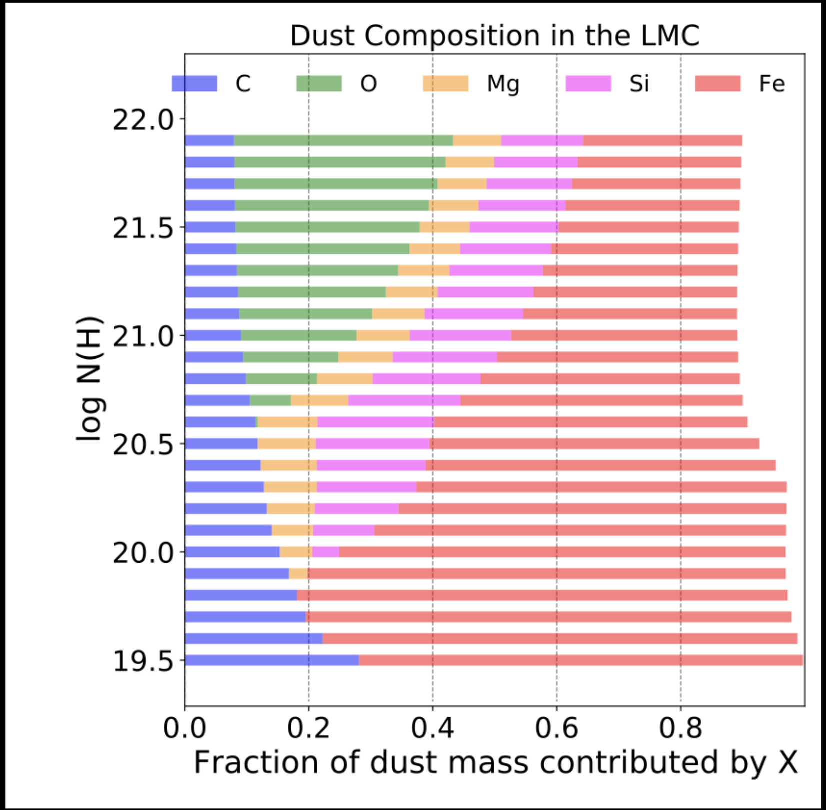


Dust Composition vs Density & Metallicity

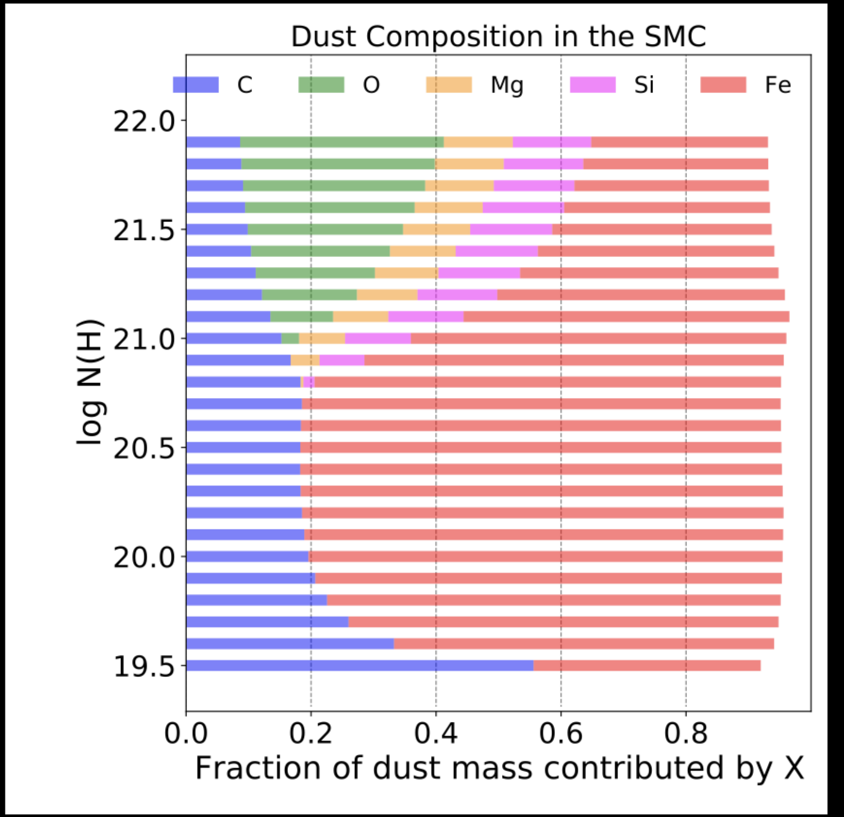
Milky Way

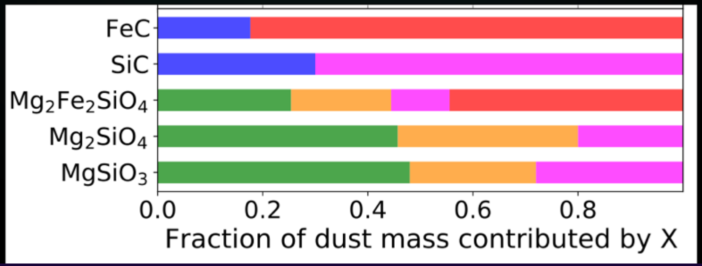


LMC (50% solar)



SMC (20% solar)





Iron Carbide
Silicon Carbide
Olivine
Forsterite
Enstatite

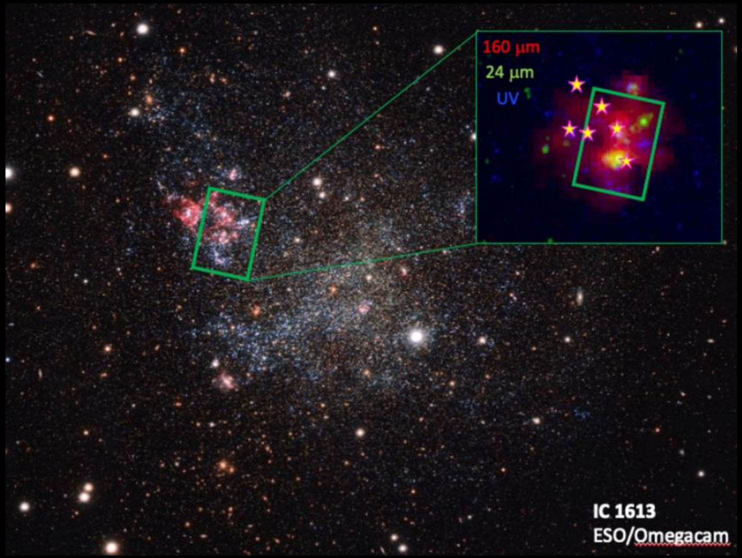
$\left.\begin{array}{l}\text{Olivine}\\ \text{Forsterite}\\ \text{Enstatite}\end{array}\right\}$ Silicates

Roman-Duval+2022a

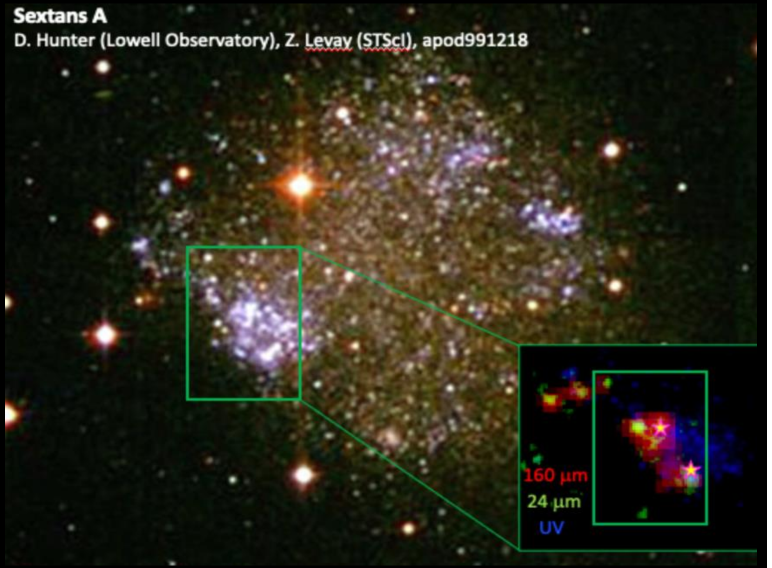
Depletions below 20% Solar Metallicity

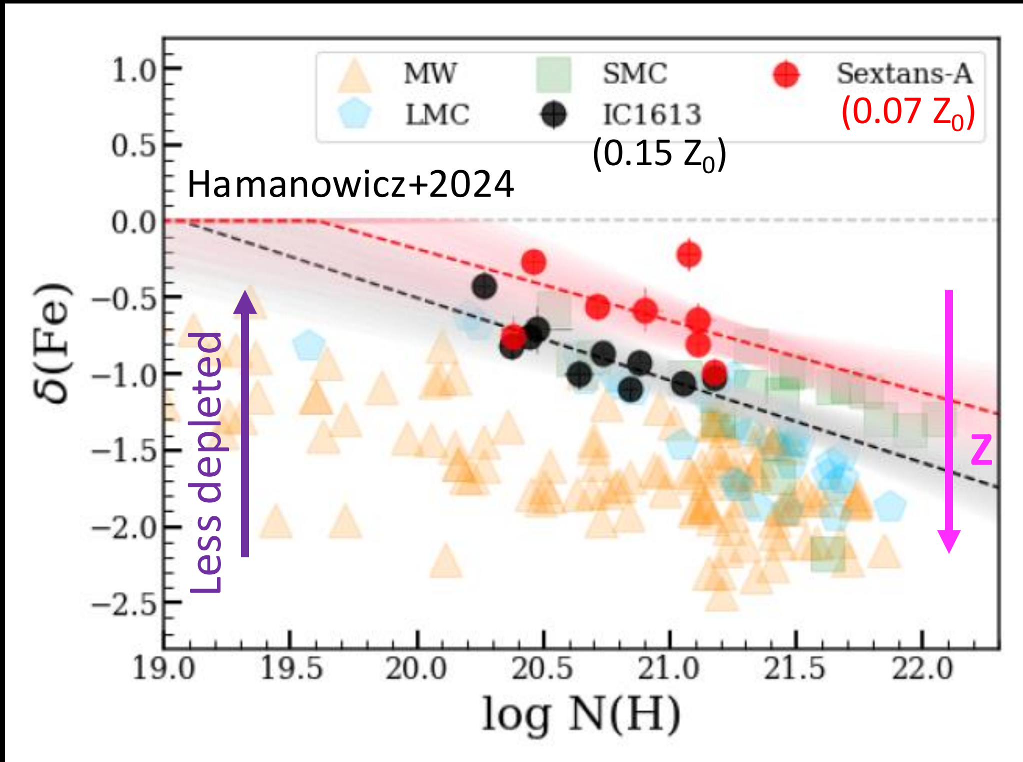
- Two trends continue at metallicities lower than the SMC:
  - Metals become more depleted from the gas as the density of the ISM increases (dust growth)
  - Metals become increasingly less depleted as the total metallicity decreases

IC 1613
10% solar in O, 20% solar in Fe



Sextans A
7% solar metallicity

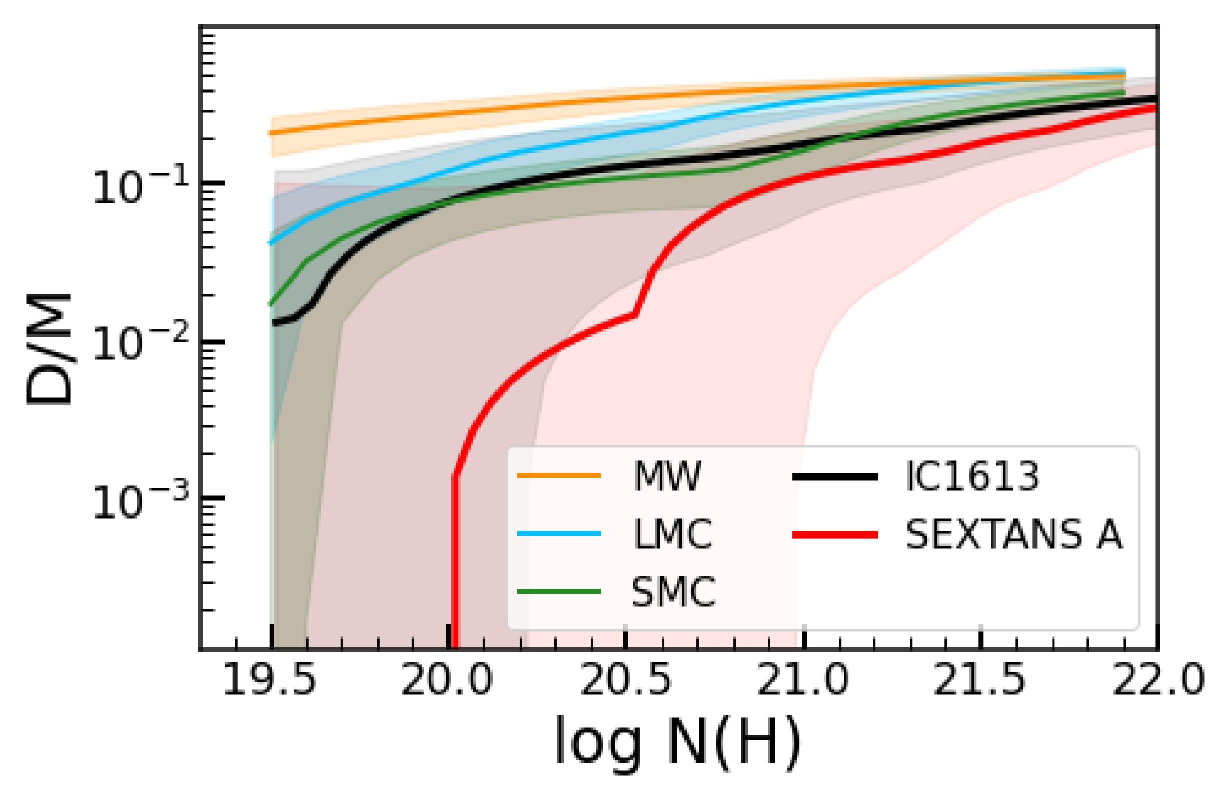


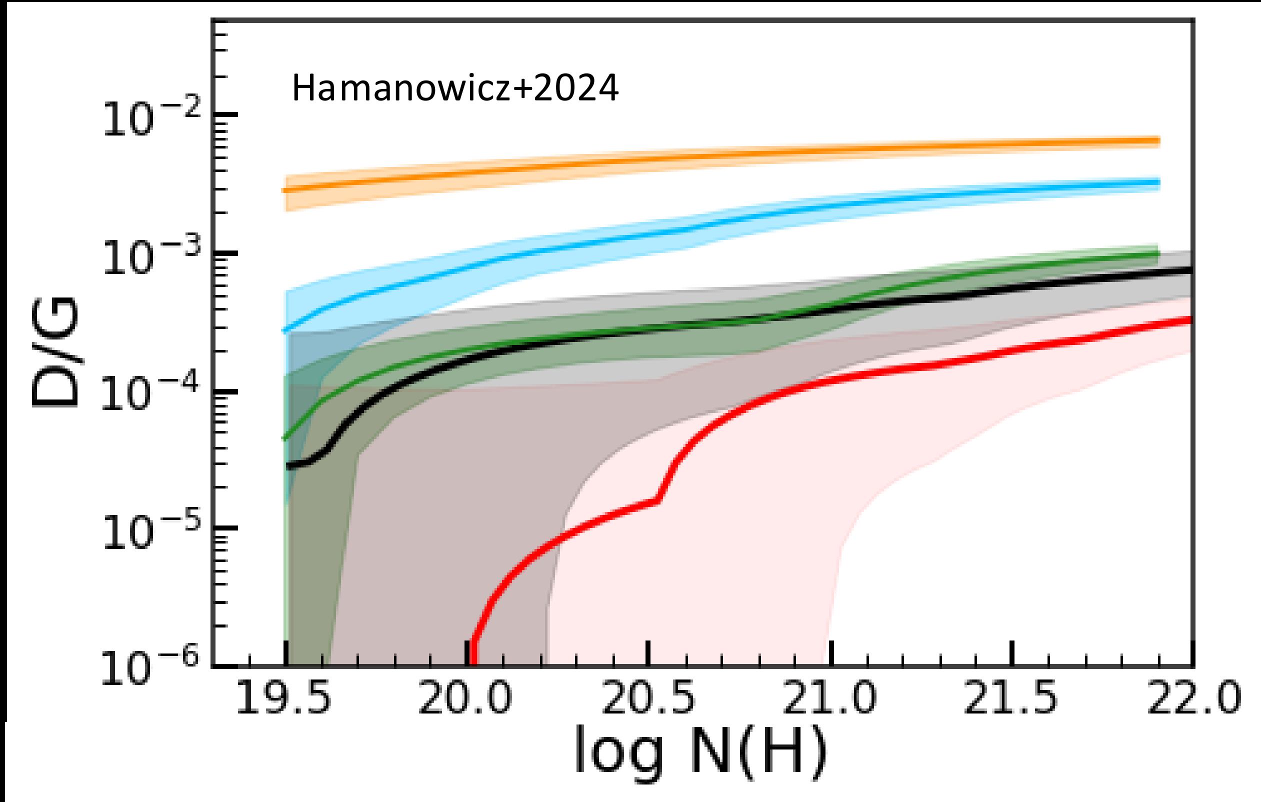


Dust-to-Gas Ratio Evolution with Density

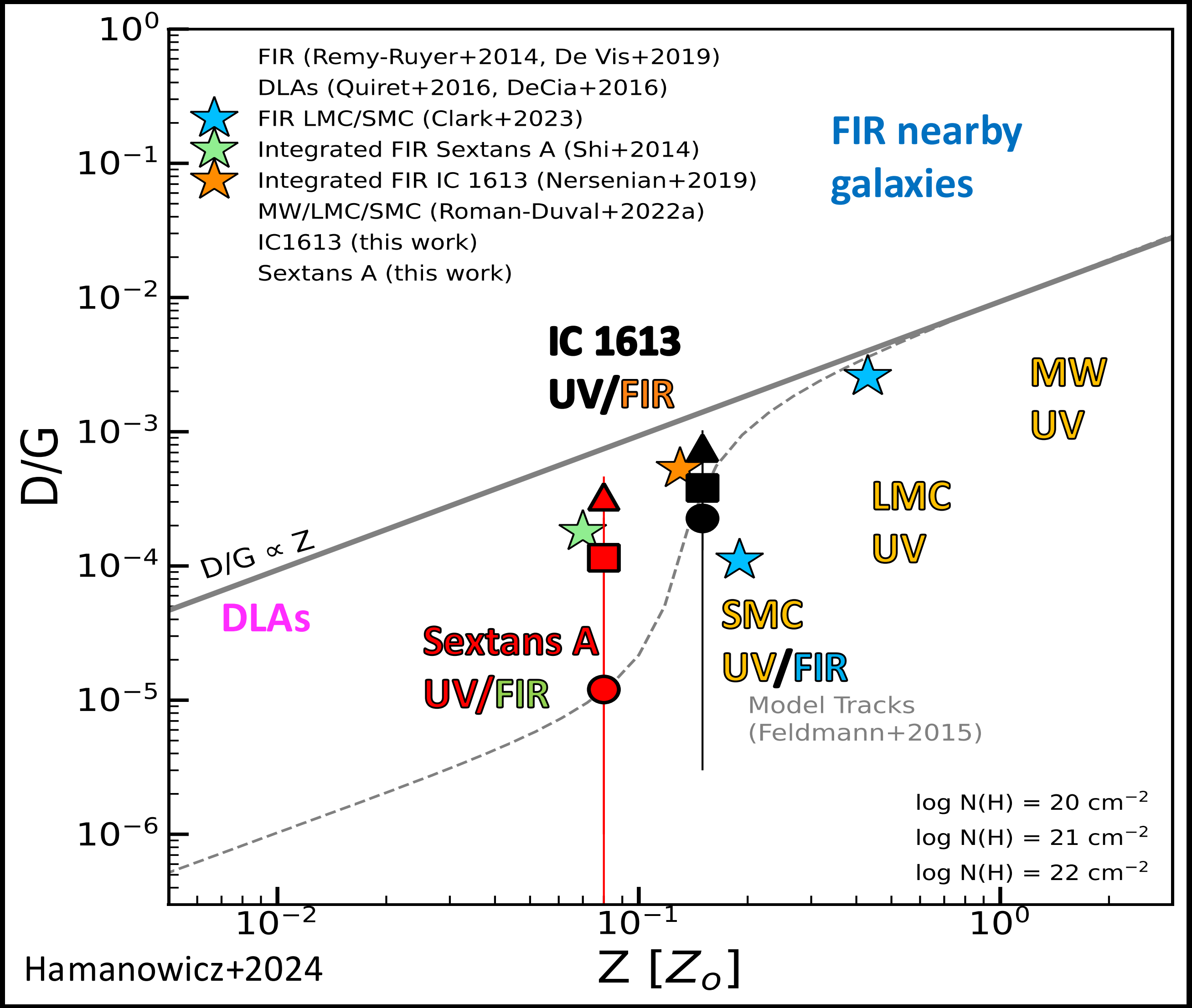
- D/G and D/M variations with gas density are even larger at very low metallicities

→ Two orders of magnitude in Sextans A





Dust-to-Gas Ratio below 20% Solar Metallicity

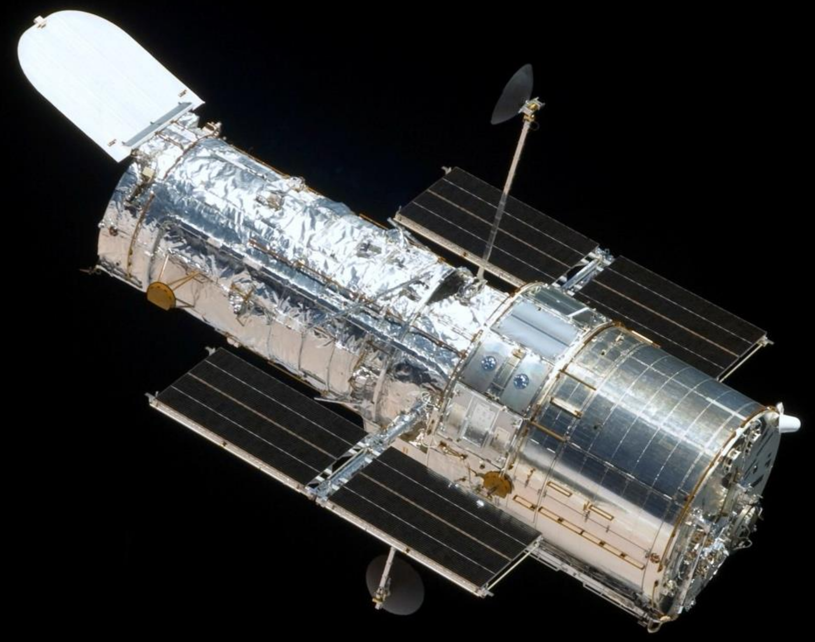


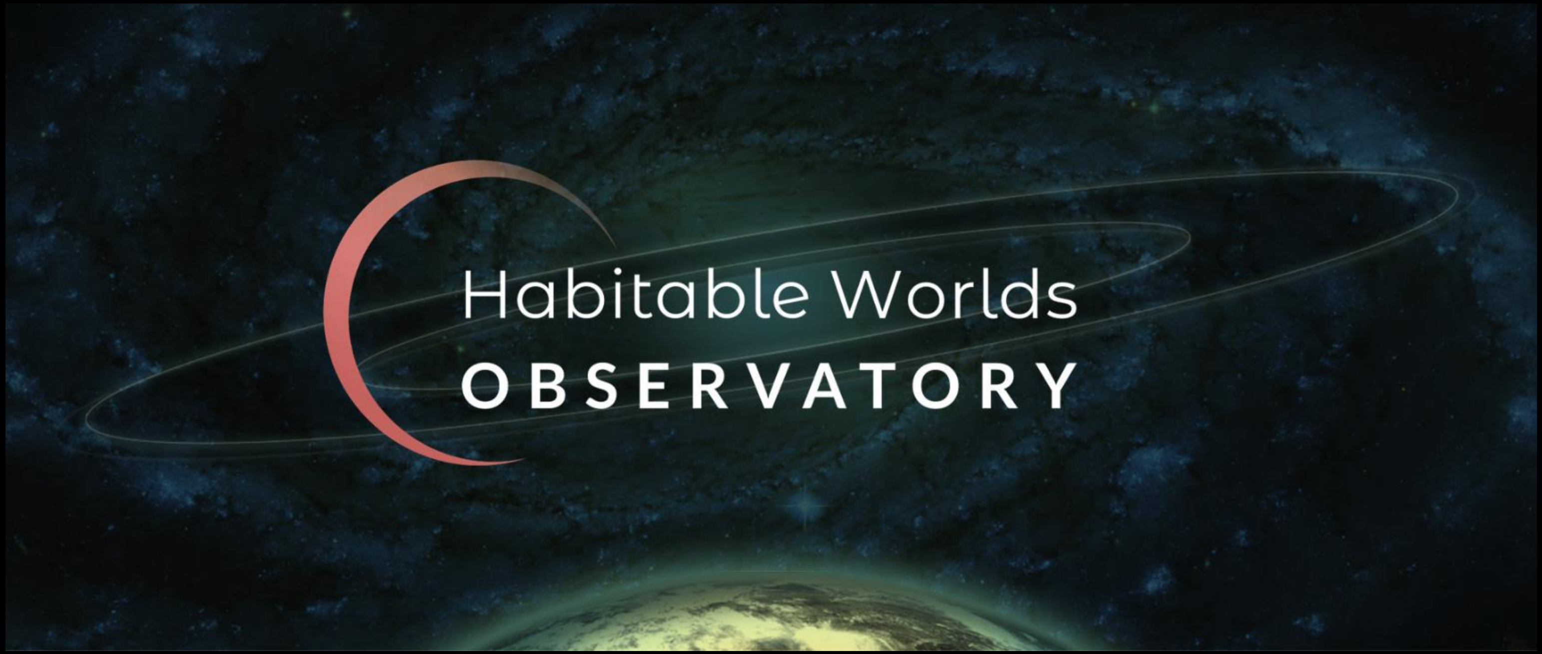
- D/G obtained from depletions follows the trend in DLAs for log N(H) >~ 21 cm^{-2}
- Tension in D/G versus Z between:
  - FIR-based estimates in nearby galaxies

    → D/G drops steeply below Z = 0.1 Z_0 indicating inefficient ISM dust growth ($\gamma = \tau_{H2,\ SF}/\tau_{d,\ ISM}$ ~ 3×10^4)
  - Estimates Rest-frame UV spectroscopy in nearby galaxies and high redshift DLAs

    → D/G drops steeply below Z = 0.01 Z_0 indicating fast ISM dust growth ($\gamma = \tau_{H2,\ SF}/\tau_{d,\ ISM}$ ~ 10^6)

Next Steps in Constraining the Relation between Metallicity and Dust Content





The limits of HST

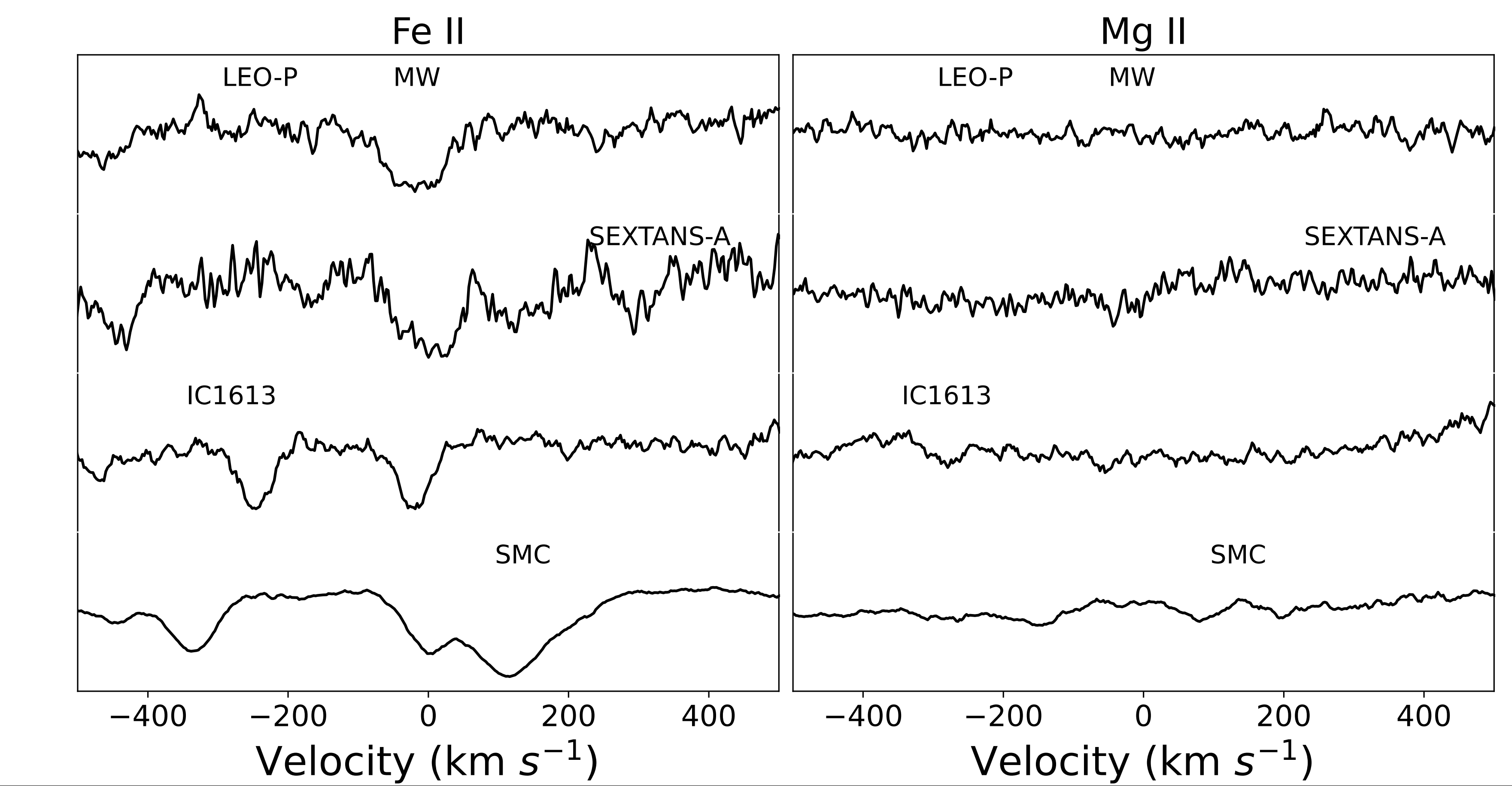
- Leo-P (3% solar, D = 1.6 Mpc) – only O star, S/N insufficient to detect even Fe II in 10 orbits

Leo-P — Z = 0.03 Z_o; d = 1.6 Mpc
COS/G130M 21.5 ks (~10 orbits)

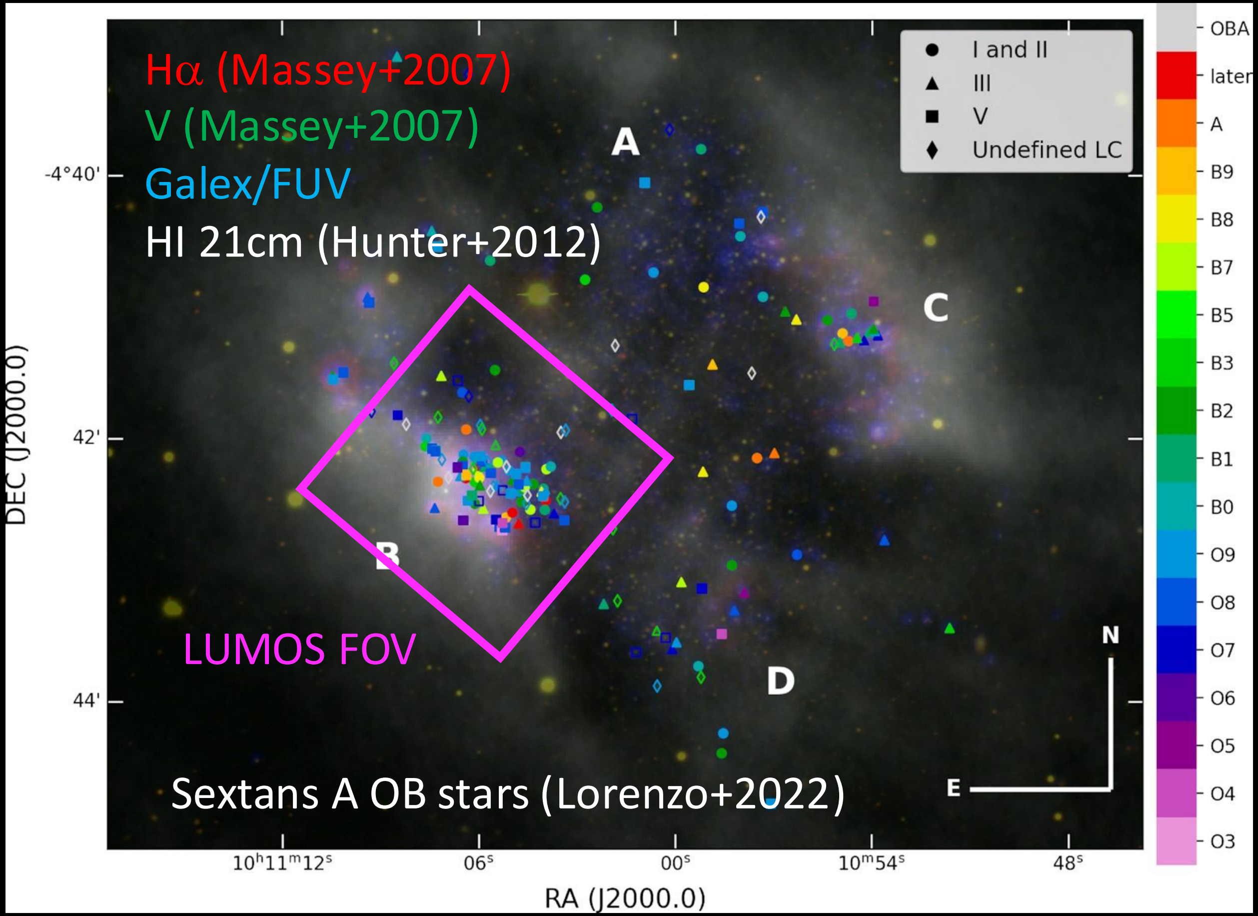
Sextans A (OB326) —
Z = 0.07 Z_o ; d = 1.3 Mpc
COS/G130M 32 ks (~14 orbits)

IC 1613 (BUG-B2) —
Z = 0.1-0.2 Z_o ; d = 0.73 Mpc
COS/G130M 19 ks (~9 orbits)

SMC (AzV 148) Z = 0.2 Z_o
D = 0.062 Mpc 1.1 ks (1 orbit)



Interstellar depletions in nearby galaxies with HWO



Mon Not R Astron Soc, Volume 516, Issue 3, November 2022, Pages 4164–4179, https://doi.org/10.1093/mnras/stac2050

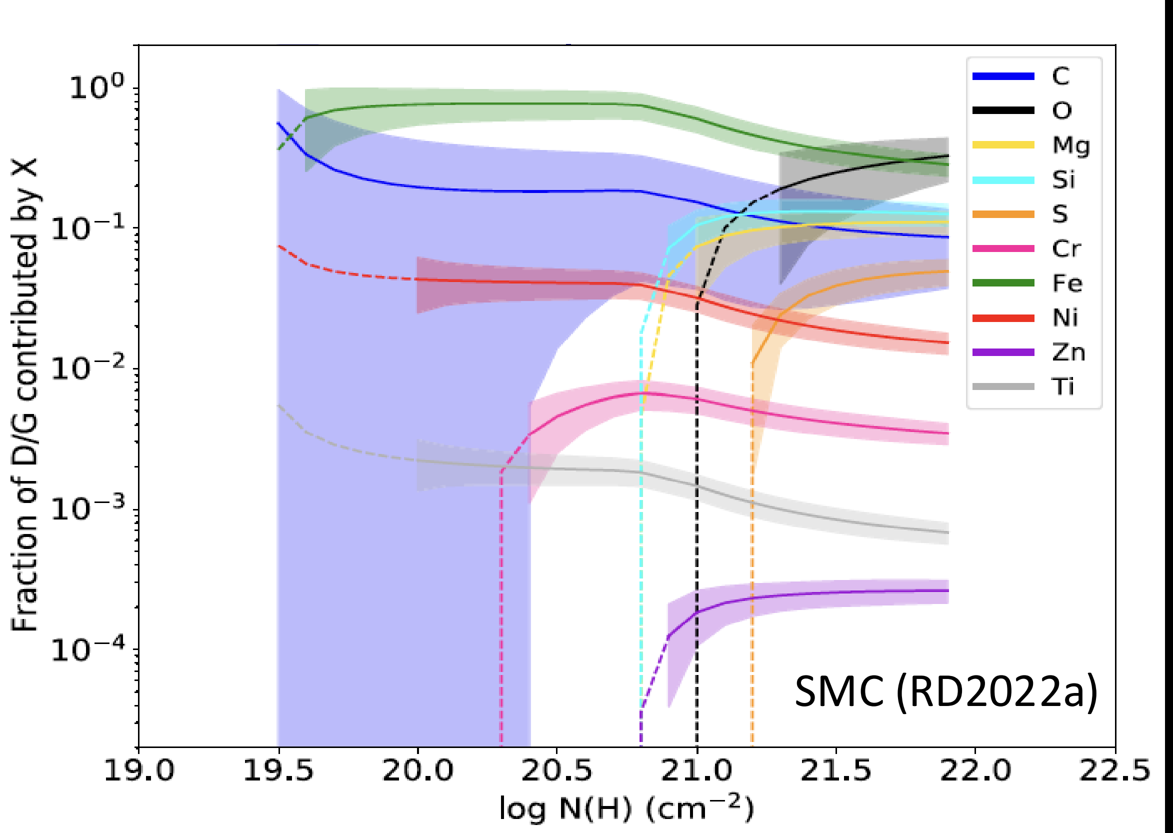
- Spectral types and abundances of OB stars measured from the ground (currently VLT, GTC)
  - ELTs will reach ~20 Mpc
- Abundances and depletions can be measured from atomic ISM absorption lines in the FUV + NUV with HWO (**950-2400 Å, R~50,000**)
  - HWO targets many stars at once
  - Need HI and H_2 column densities (Ly-α, Lyman-Werner band at 950-1100 Å)
  - HWO can reach stars within 10 Mpc, increasing the metallicity parameter space dramatically

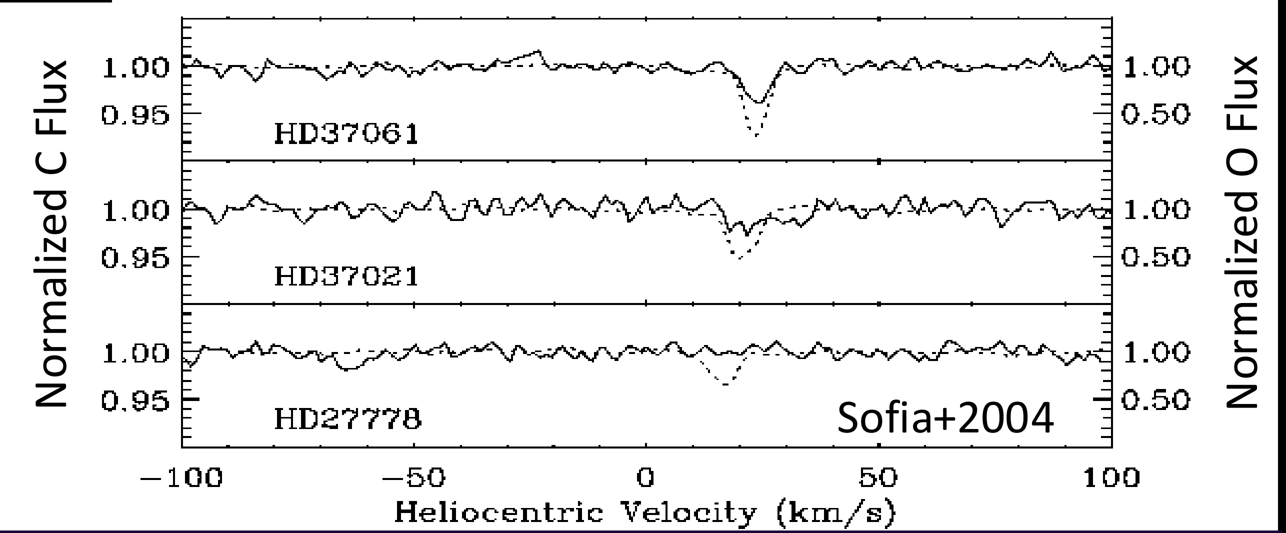
The C and O content of dust outside the Milky Way with HWO

- C (and to a lesser extent O) lines are either heavily saturated or too weak to be detected
- Only a few noisy C depletion measurements in the MW with STIS/H gratings (Sofia+2004)

→ Large uncertainty in the amount of carbon in dust

- Need R>100,000 and S/N > 100 in the FUV and NUV (i.e., high resolution gratings in the full UV range) to measure C and O depletions in the MW, LMC, SMC

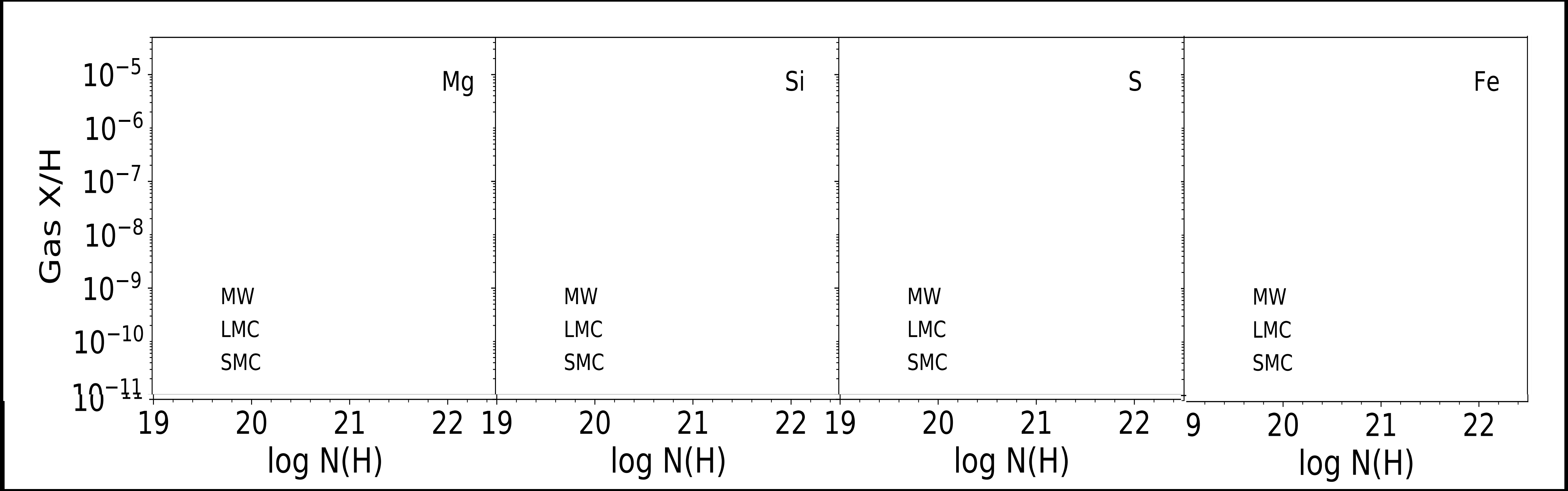




Take-away

- Abundance of dust increases with density by up to an order of magnitude between diffuse and dense ISM
- Fraction of metals in the dust decreases with decreasing metallicity
  - Dust abundance decreases faster than metallicity
- Relation between metallicity and dust abundance does not agree between:
  - FIR: steep decrease in D/G below 10% solar metallicity
  - Depletions and DLAs: D/G decreases only a bit faster than metallicity
- Composition of dust evolves with density and metallicity
  - Silicate dominate above a threshold column density that increases as metallicity decreases
  - Fe/C dominates at low column density and metallicity
- HWO needed to obtain large samples of depletions at metallicities 1-100% solar, constrain depletions of C and O, and accurately measure D/G vs metallicity

Gas-Phase Metallicities are the same in the SMC, LMC, and MW!



$$\left.\frac{X}{H}\right]_{gas} = 10^{\delta(X)} \left.\frac{X}{H}\right]_{star}$$

MW	x1	/1
LMC	x2	/2
SMC	x5	/5