



Dust depletion in galaxies

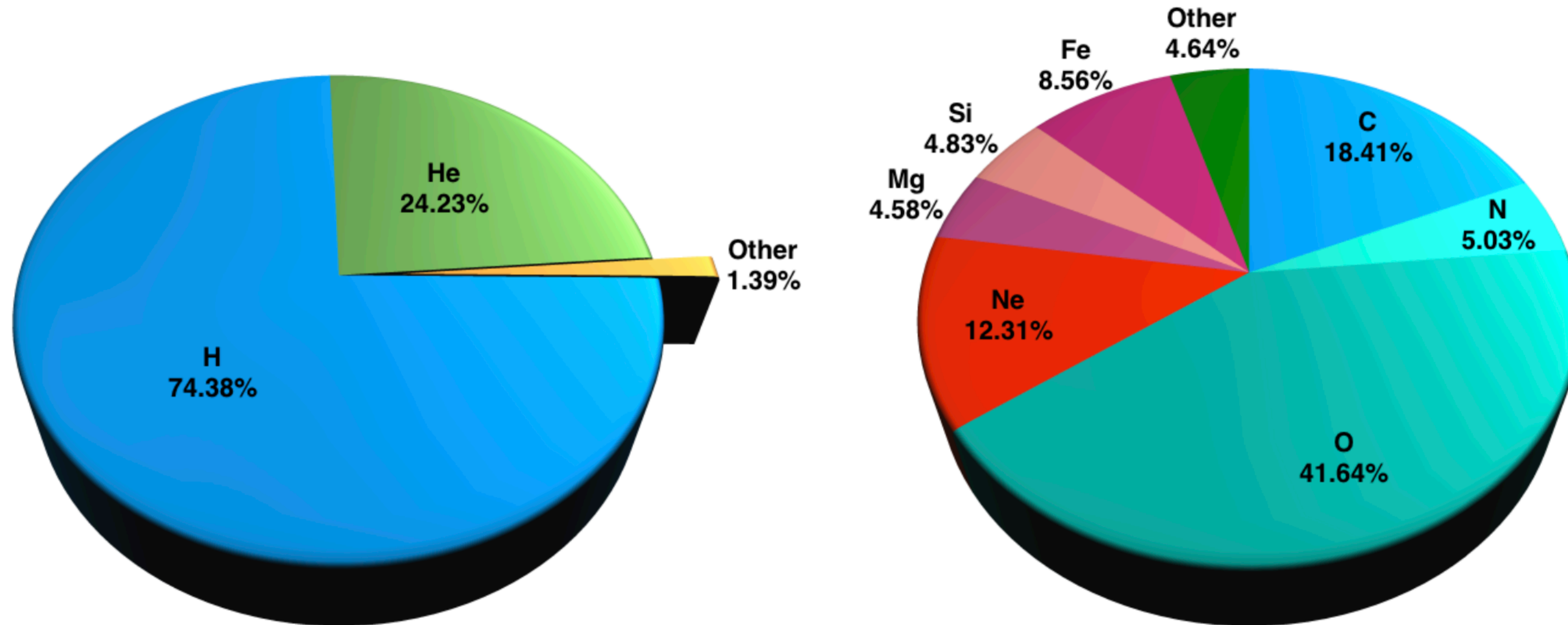
Annalisa De Cia

European Southern Observatory (ESO) Germany

The Dusty Universe 2025: The Fifth Pan Dust Conference, 9-14 Nov 2025, Tucson

1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og	
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

Metals in the interstellar medium (ISM)

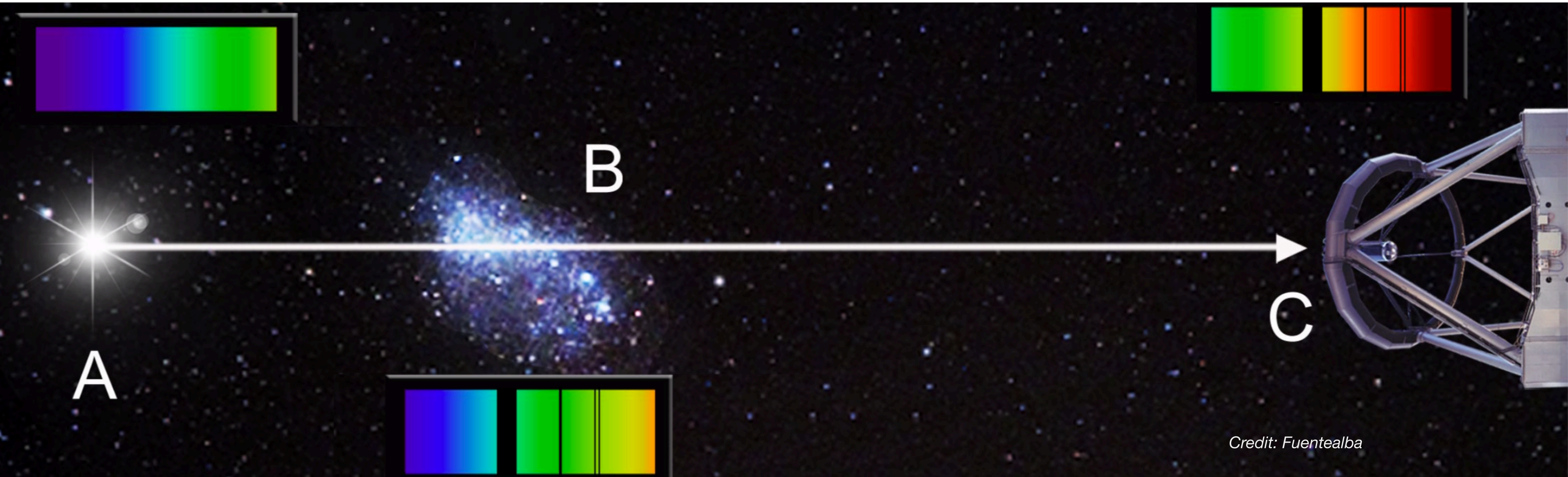


Solar abundances, Asplund et al. 2021

- Crucial for:
- galaxies
 - stars
 - planets
 - molecules
 - life
 - cosmic dust

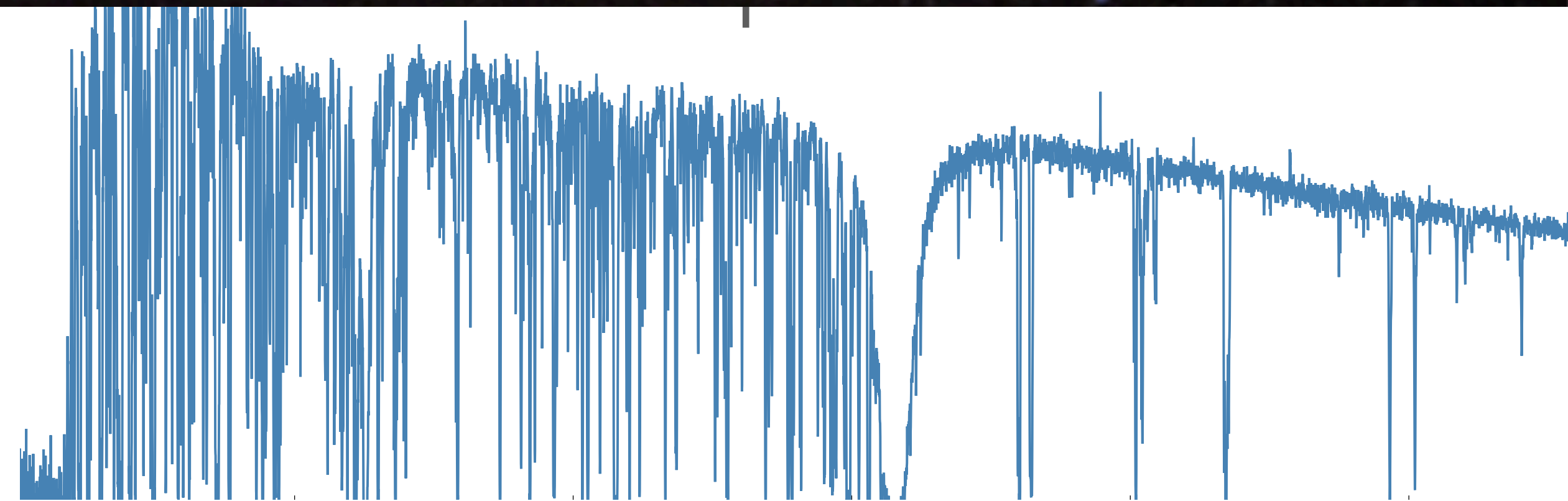
~50% of ISM metals are in cosmic dust

Probing metals in the ISM: absorption-line spectroscopy

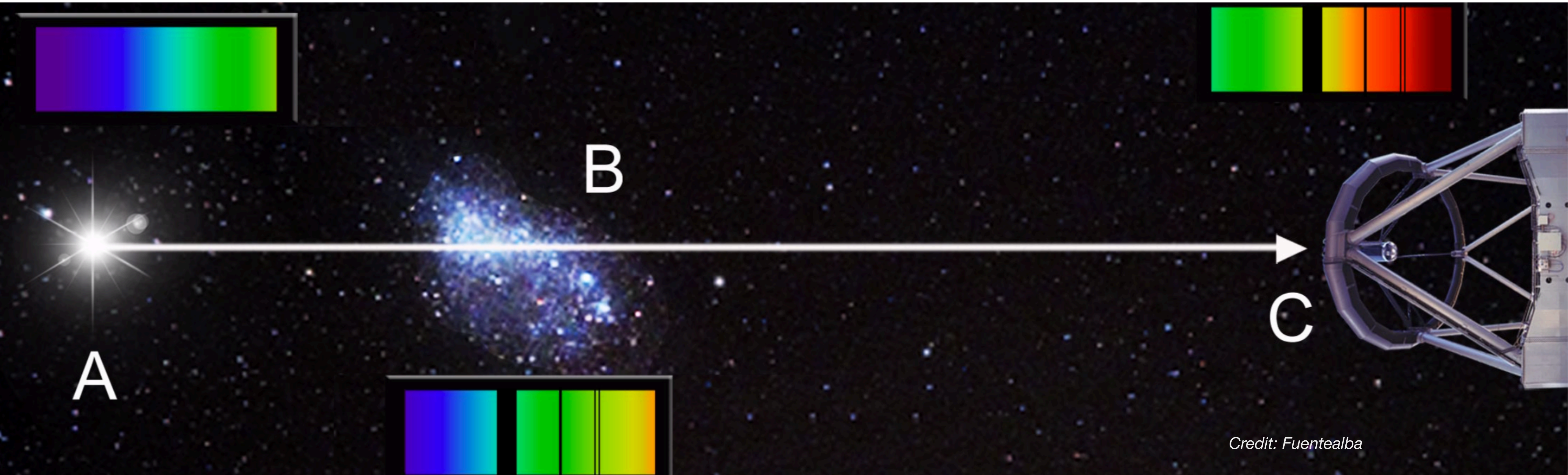


Credit: Fuentealba

- Stars
- Quasars
- Gamma-Ray Bursts



Probing metals in the ISM: absorption-line spectroscopy



➡ Including low-metallicity faint gas-rich galaxies (e.g. Damped Lyman- α absorbers, DLAs)

Observed metal abundances

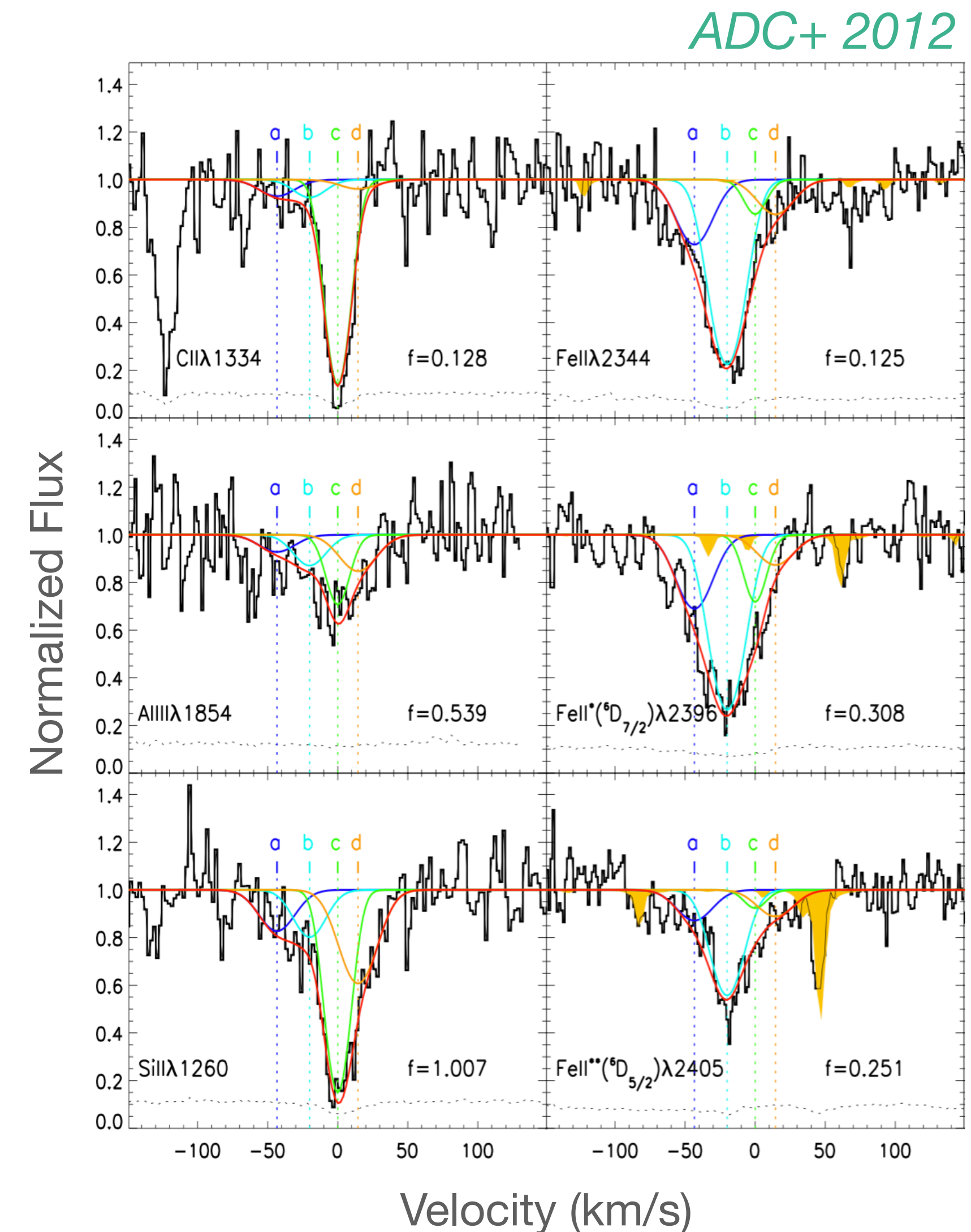
ABUNDANCES

$$[X/H] = \log \left(\frac{N(X)}{N(H)} / \frac{N(X)_{\odot}}{N(H)_{\odot}} \right)$$

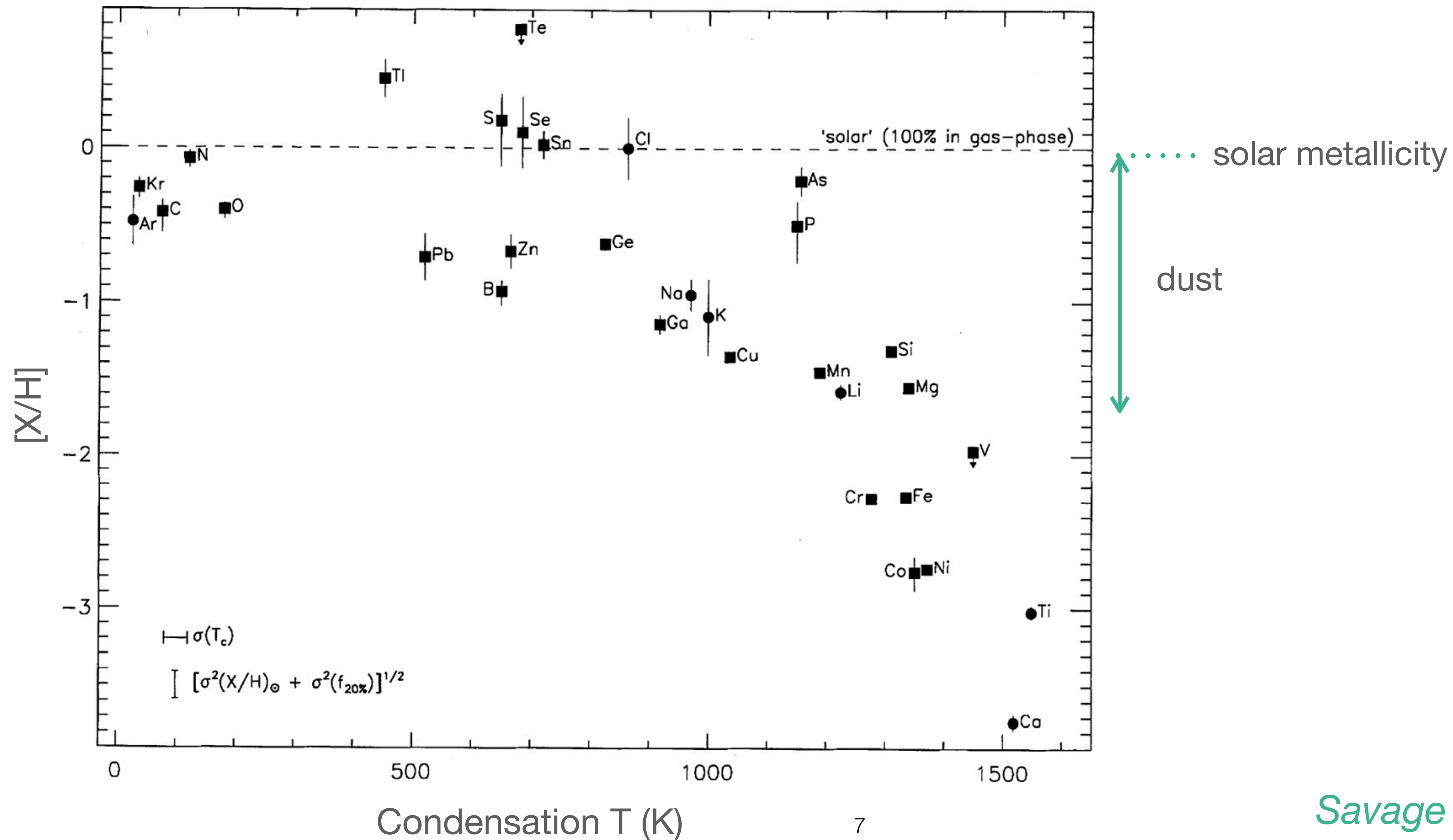
RELATIVE ABUNDANCES

$$[X/Y] = \log \left(\frac{N(X)}{N(Y)} / \frac{N(X)_{\odot}}{N(Y)_{\odot}} \right)$$

H, Fe, Ni, Mn, Zn, Cr, Ti, S, Si, Mg, O, Al, P, N, Kr,
Co, Cu, Ge, Cl, ...



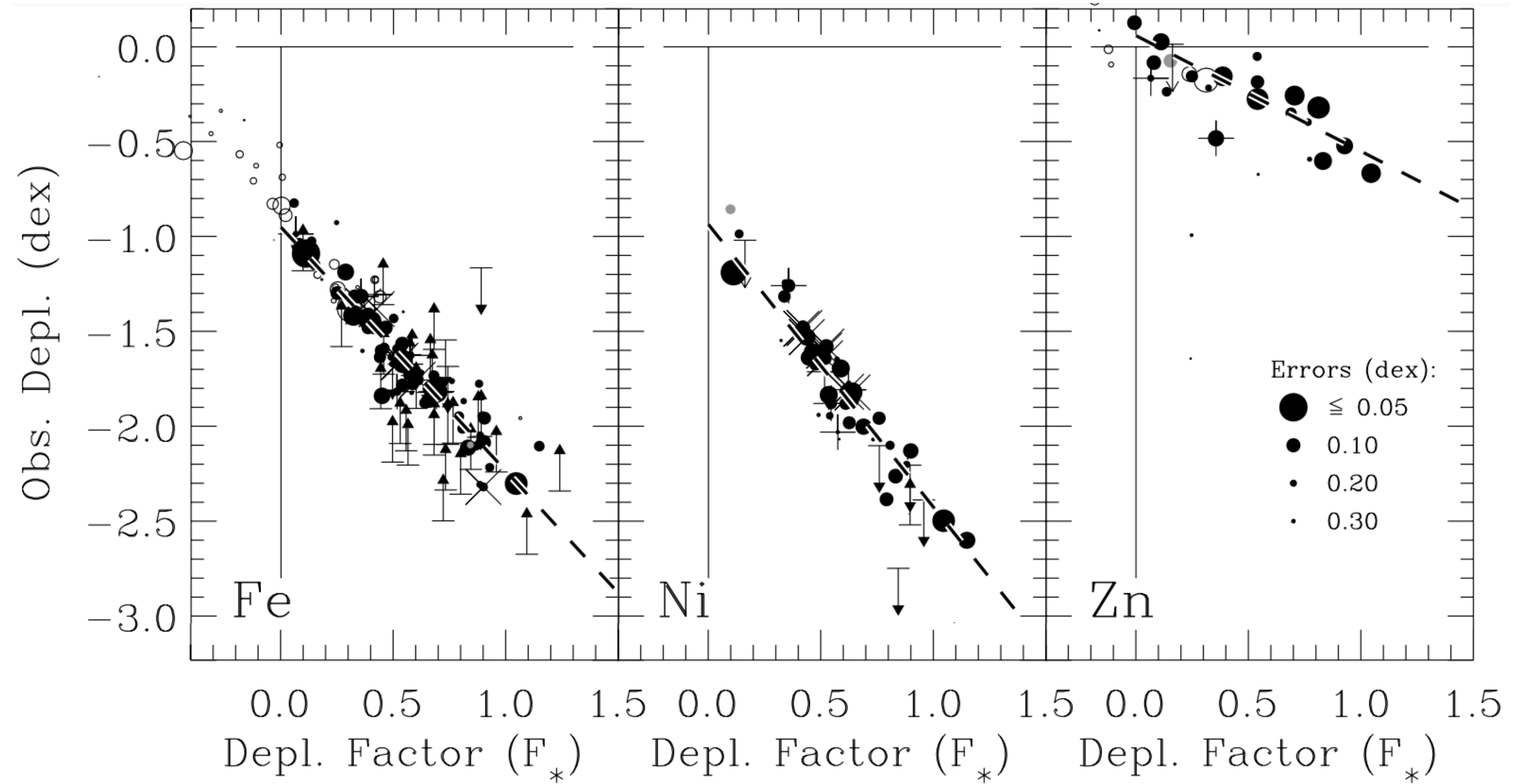
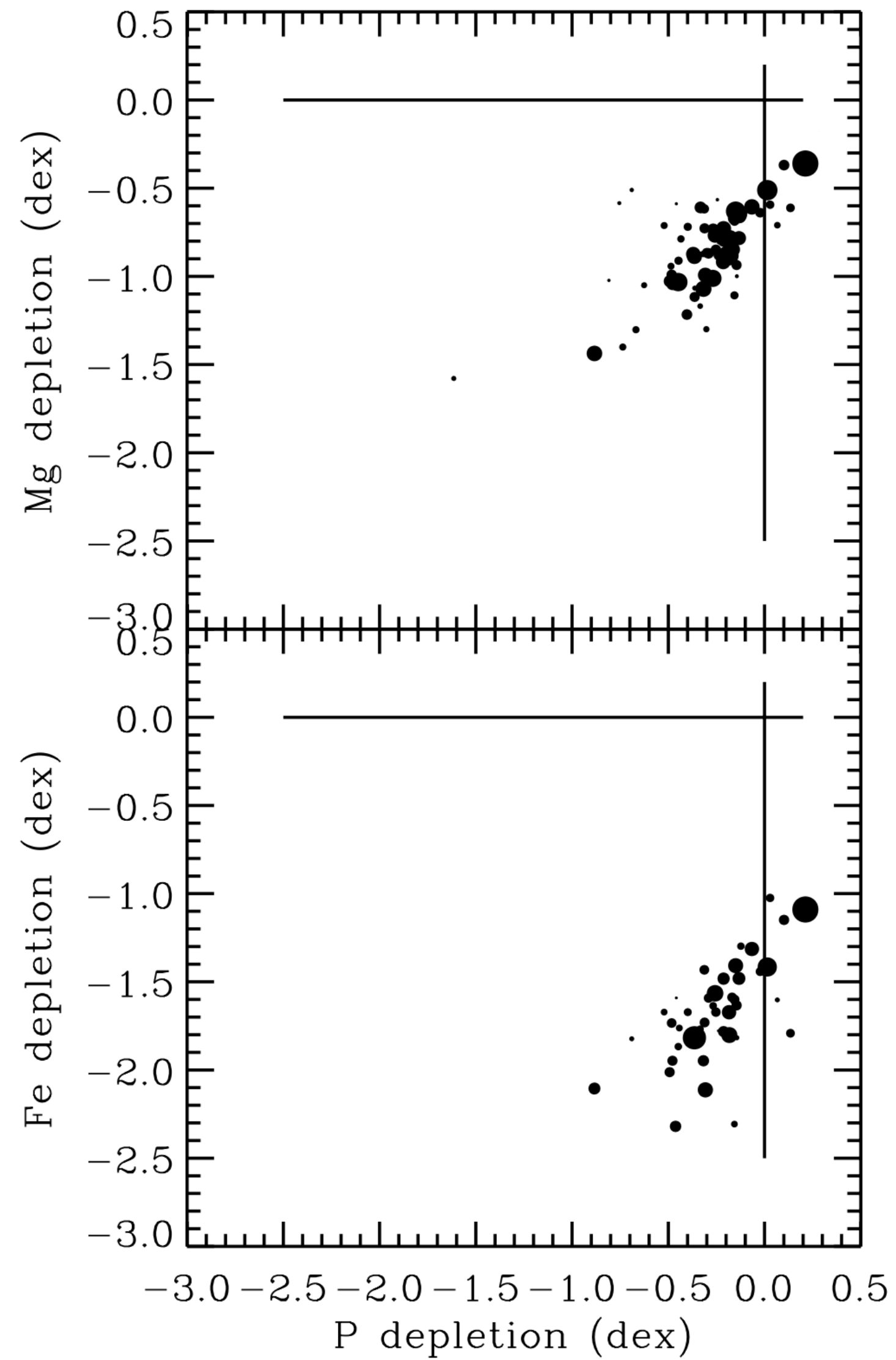
Dust depletion: metals missing from the gas phase, in dust grains



ζ -Oph
Field 1974

Savage and Sembach 1996

Dust depletion: from less to more dusty ISM





Missing metals: with respect to what?

Missing metals: with respect to what? I: $[X/H]$

$$\delta_X = [X/H]_{\text{obs}} - [X/H]_{\text{tot}}$$

Depletion **Observed abundance** **Reference abundance**

Assuming a fixed metallicity (Sun or young stars in Local Universe)

- Not sensitive to variations of gas metallicity
- Not sensitive to abundance variations (e.g. $[\alpha/\text{Fe}]$)
- Needs a measurement of H (i.e. not applicable in individual clouds)

➔ Not applicable at high- z

Missing metals: with respect to what? II: $[X/Y]$

$$\delta_X = f([X/Y])$$

Depletion

Dust tracer

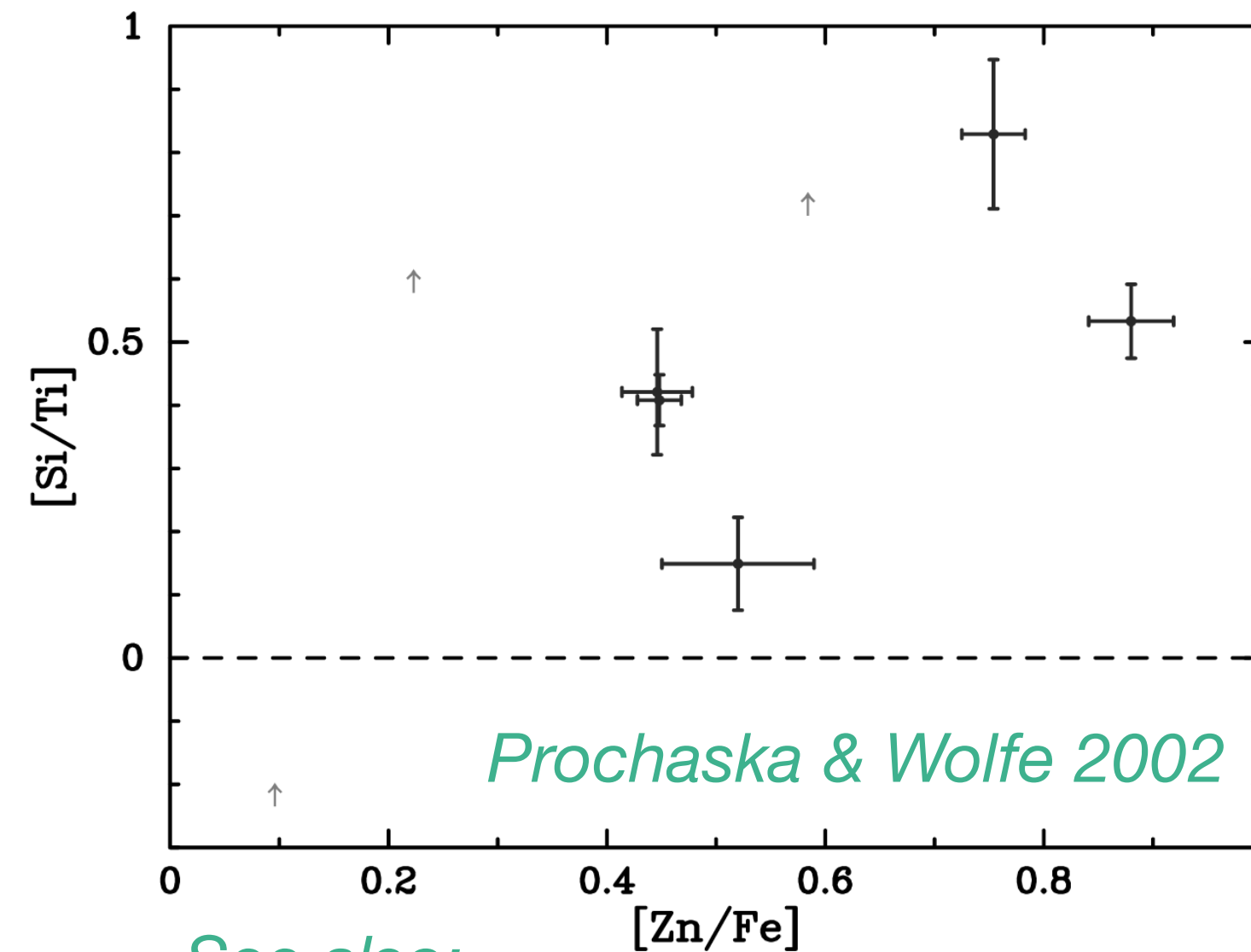
- Requires observations of multiple metals
- Sensitive to variations of gas metallicity
- Sensitive to abundance variations (e.g. $[\alpha/\text{Fe}]$)
- Applicable in individual clouds
- Applicable at any redshift

 Necessary at high- z

Dust depletion in Damped Lyman- α absorbers (DLAs): the early days

1

[Zn/Fe] and other [X/Y] trace dust

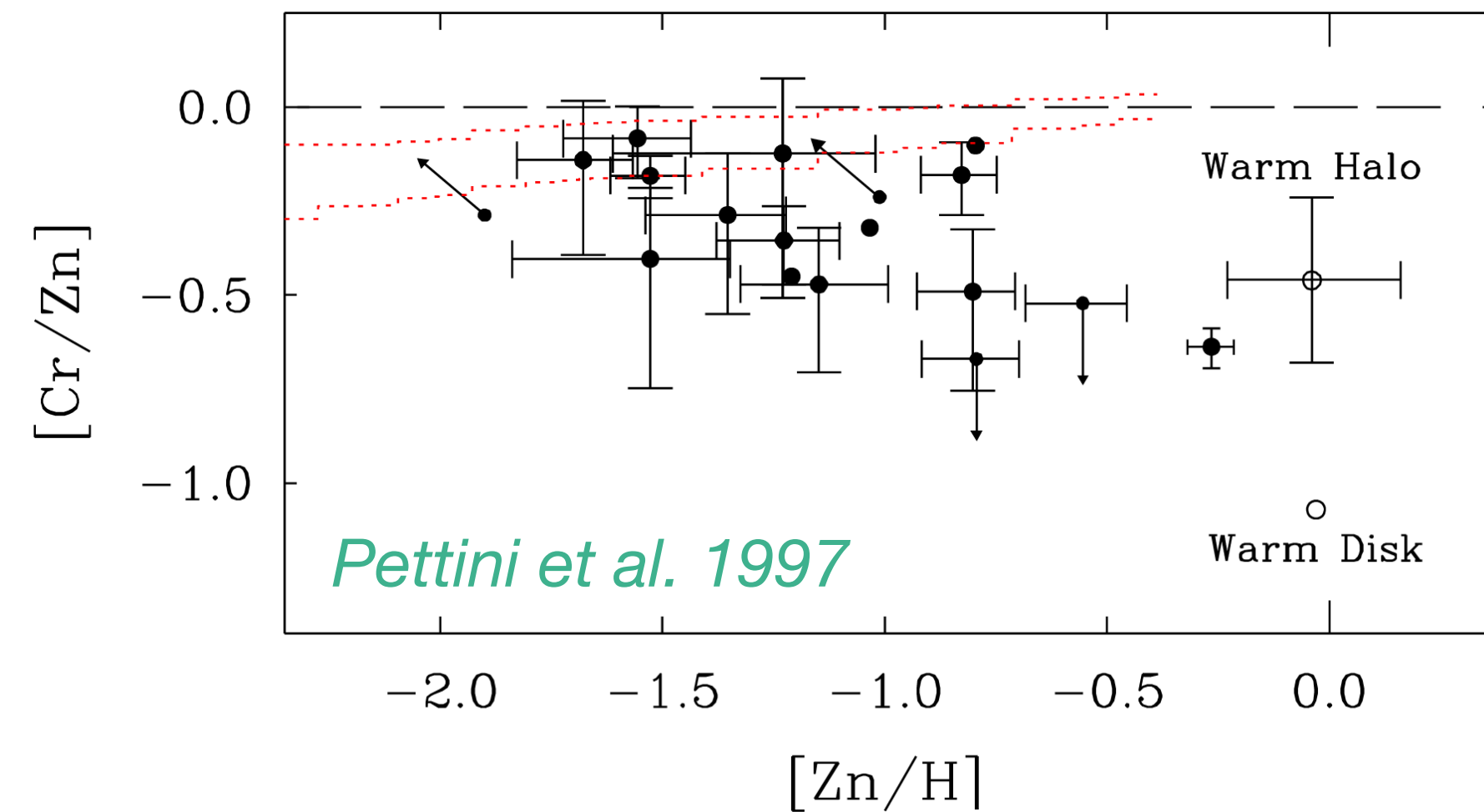


See also:

Ledoux et al. 2002, Vladilo et al. 2002

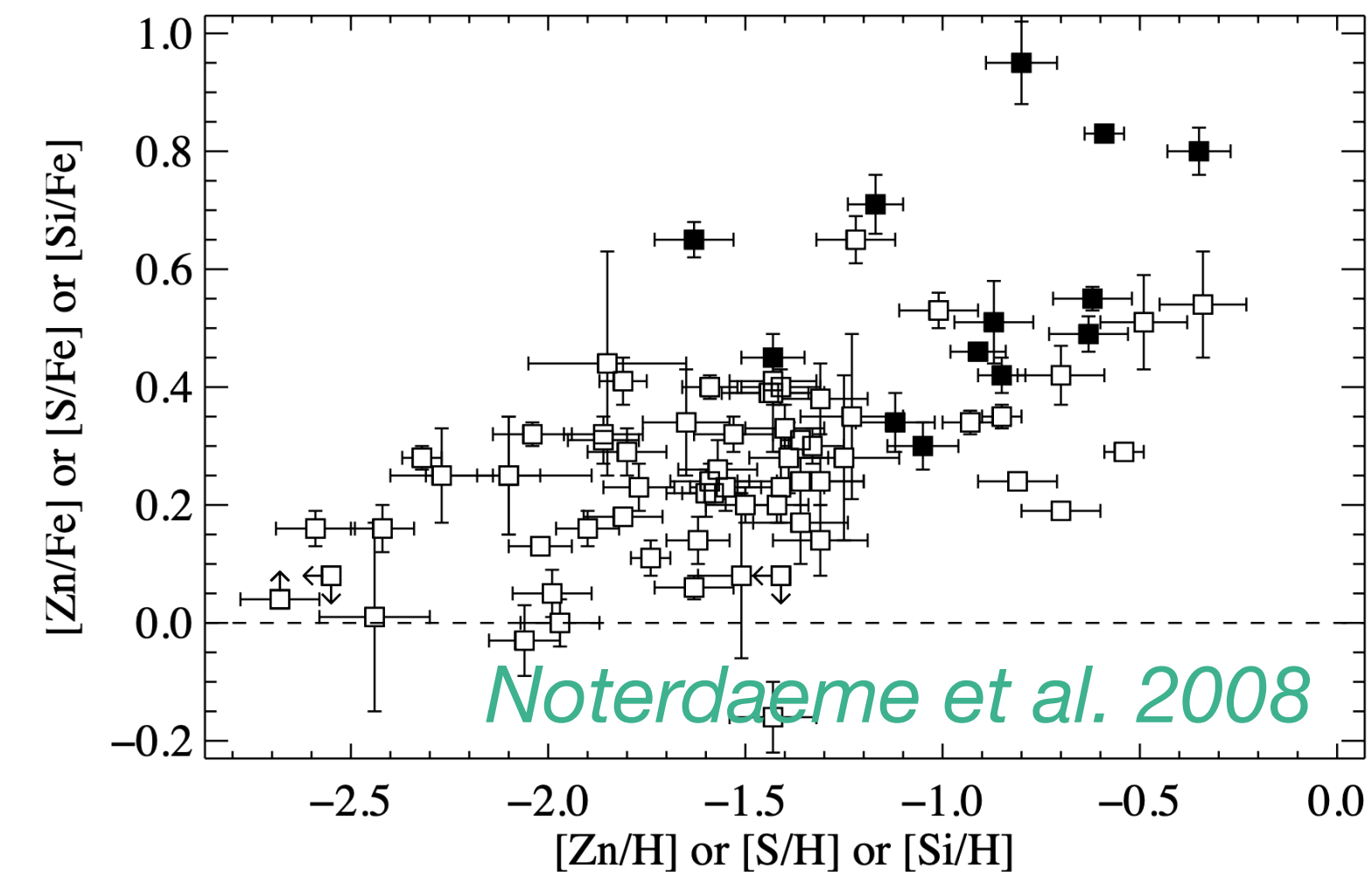
2

[Zn/Fe] and others trace metals



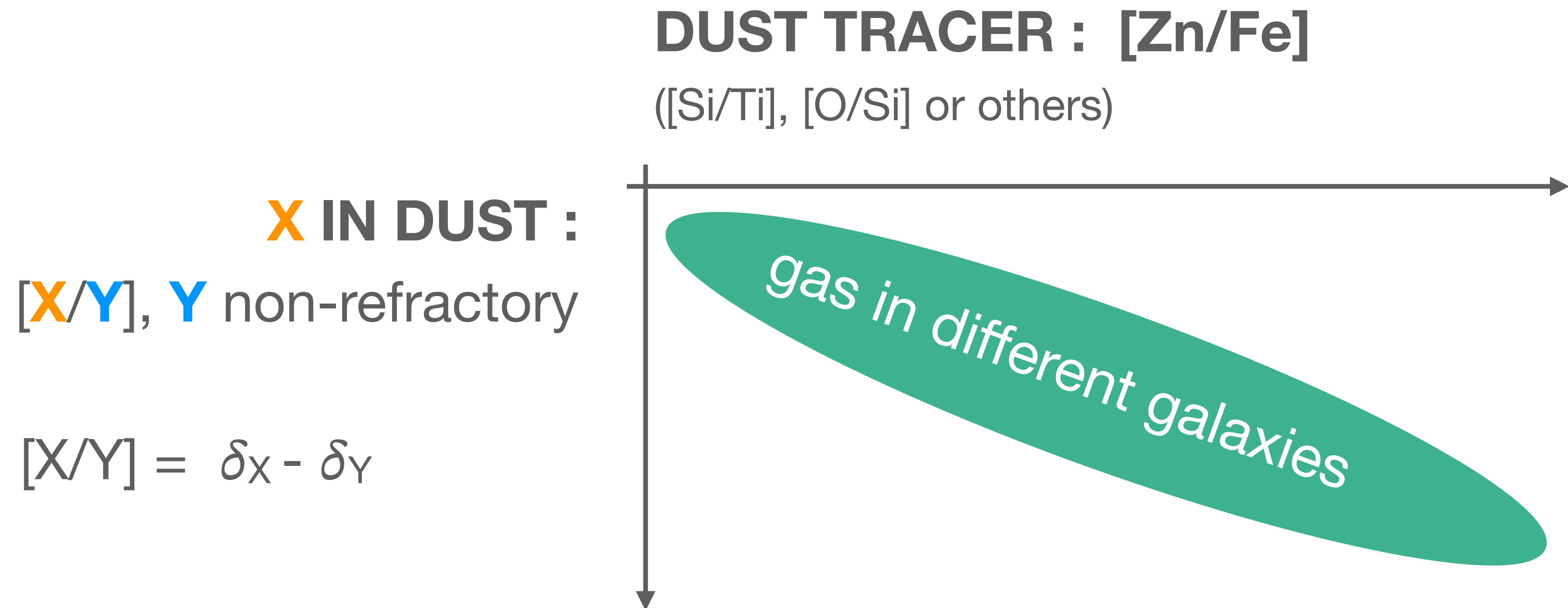
3

[Zn/Fe] and others trace molecules



Part I:
**Methodologies to characterise dust depletion
based on [X/Y]**

Characterise dust depletion based on $[X/Y]$: the “relative method”

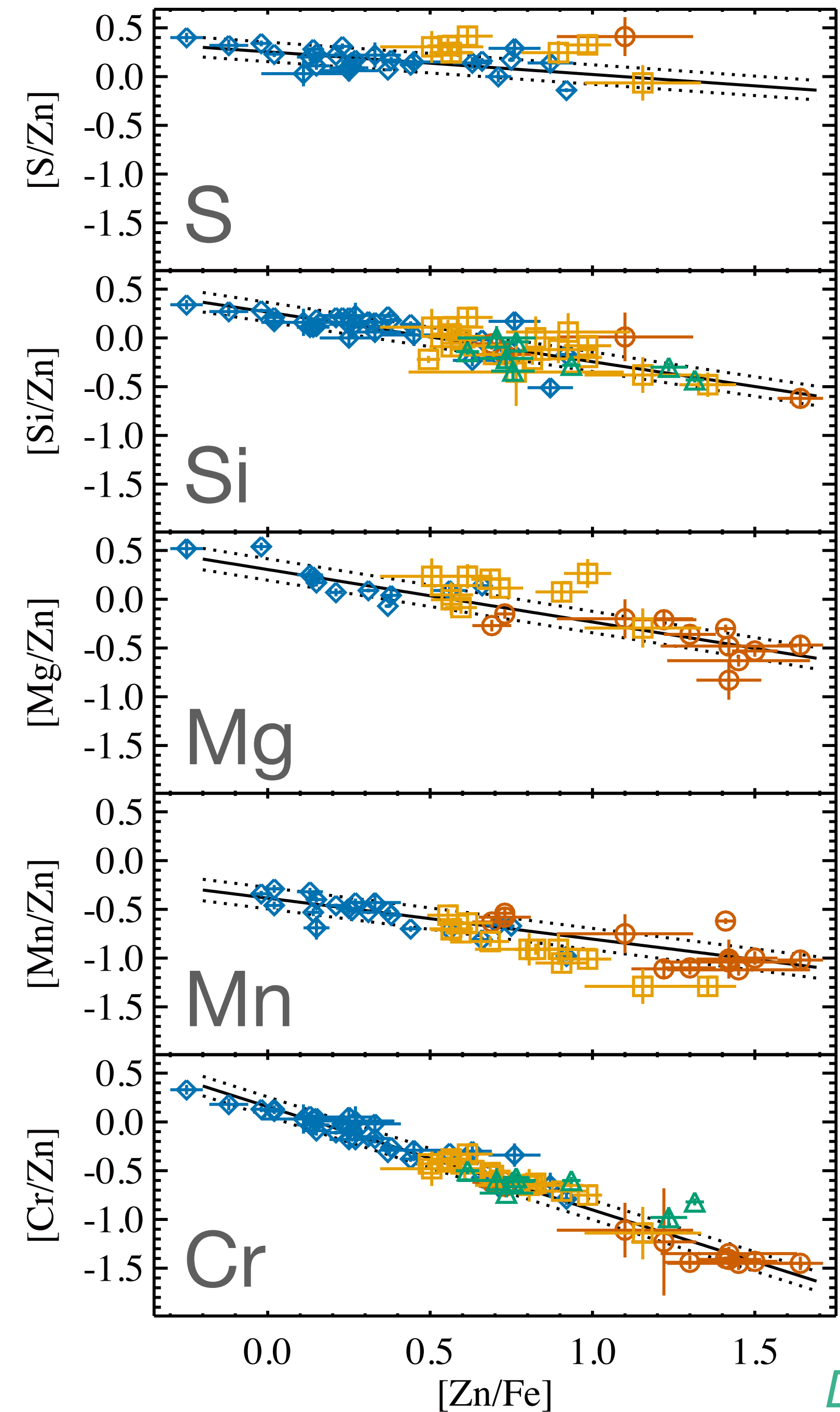


→ assuming δ_Y to retrieve δ_X

Dust depletion sequences

- ◇ DLAs (distant galaxies)
(*De Cia et al. 2016*)
- SMC (Small Magellanic Cloud)
(*Tchernyshyov et al. 2015*
Jenkins and Wallerstein 2017)
- △ LMC (Large Magellanic Cloud)
(*Tchernyshyov et al. 2015*)
- MW (Milky Way)
(*De Cia et al. 2016, Jenkins 2009*)

Dust growth in the ISM

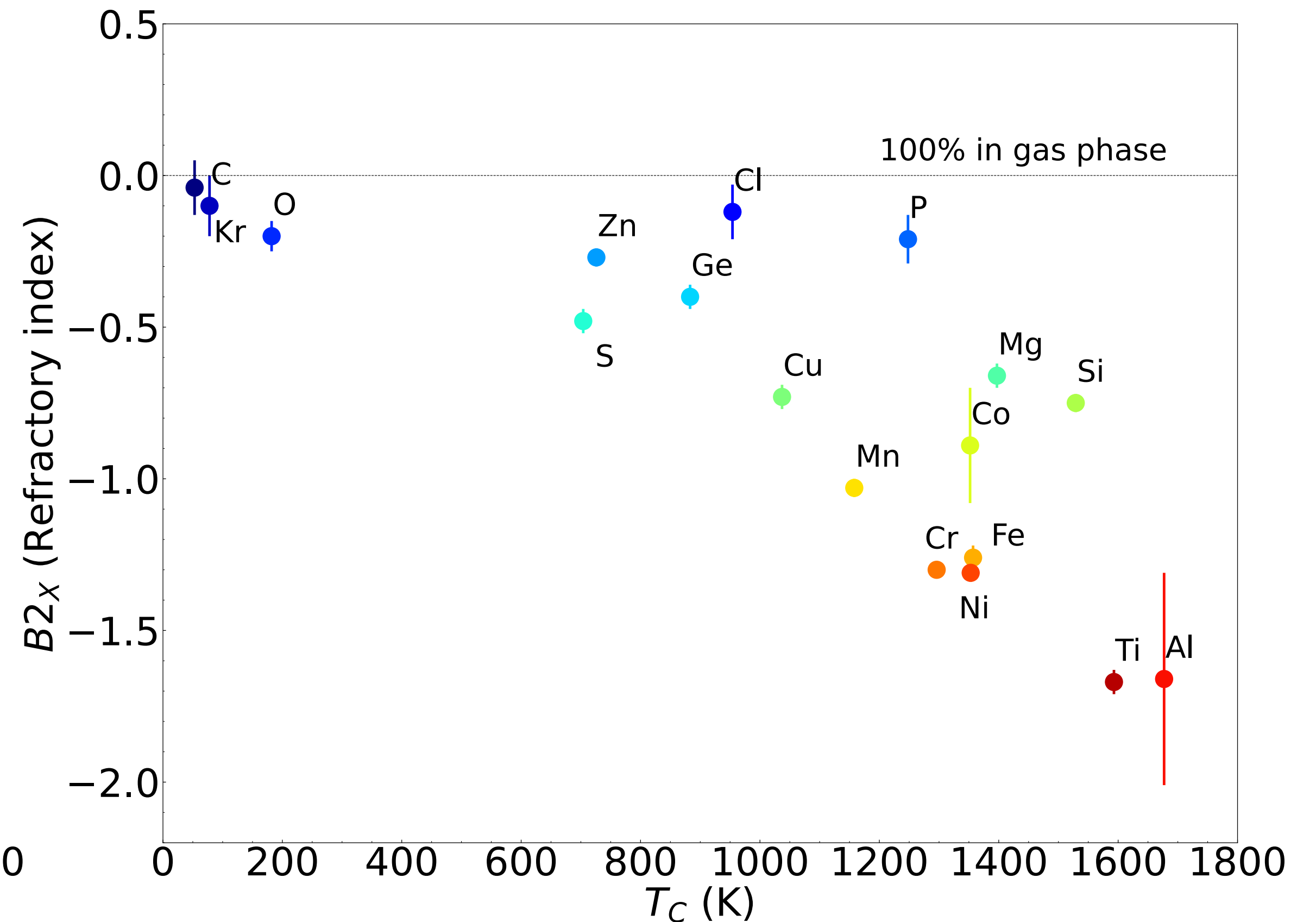
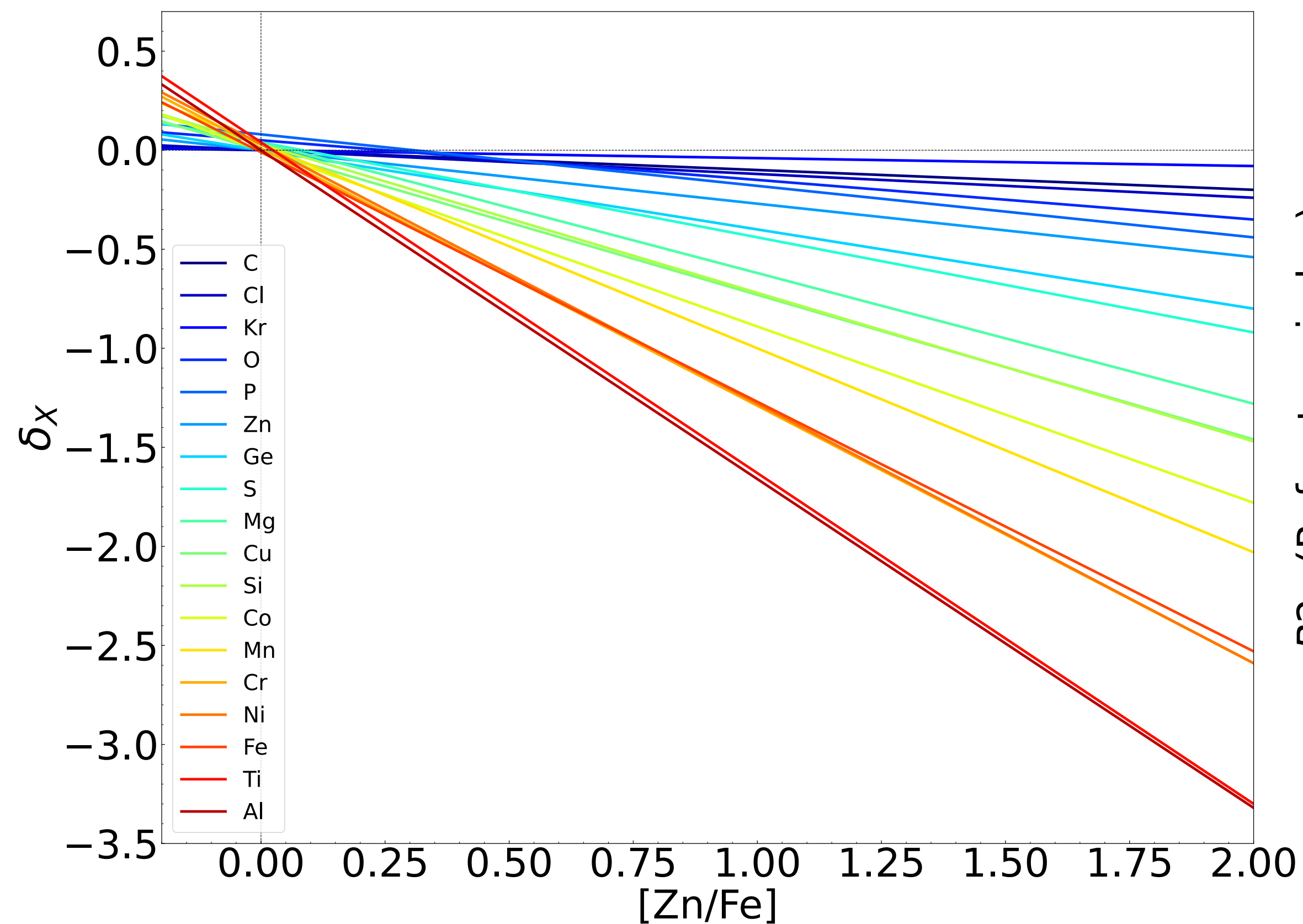


Dust depletion characterised for 18 metals



Data from: Milky Way, Magellanic Clouds, QSO-DLAs, GRB-DLAs

Christina Konstantopoulou



$$\delta_X = A2_X + B2_X \times [Zn/Fe]$$

Advantages



- Does not assume a fixed metallicity (e.g. MW ISM metallicity variations, *De Cia et al. 2021*)
- Partly sensitive to abundance variations (e.g. high $[\alpha/\text{Fe}]$ in LMC/SMC, *De Cia et al. 2024*)
- Applicable to individual clouds (e.g. MW cloud-to-cloud variations, *Ramburuth-Hurt, De Cia+ 2025*)
- Applicable at any redshift (e.g. GRB at $z=6.3$, *Saccardi, Vergani, De Cia et al. 2023*)

Limitations

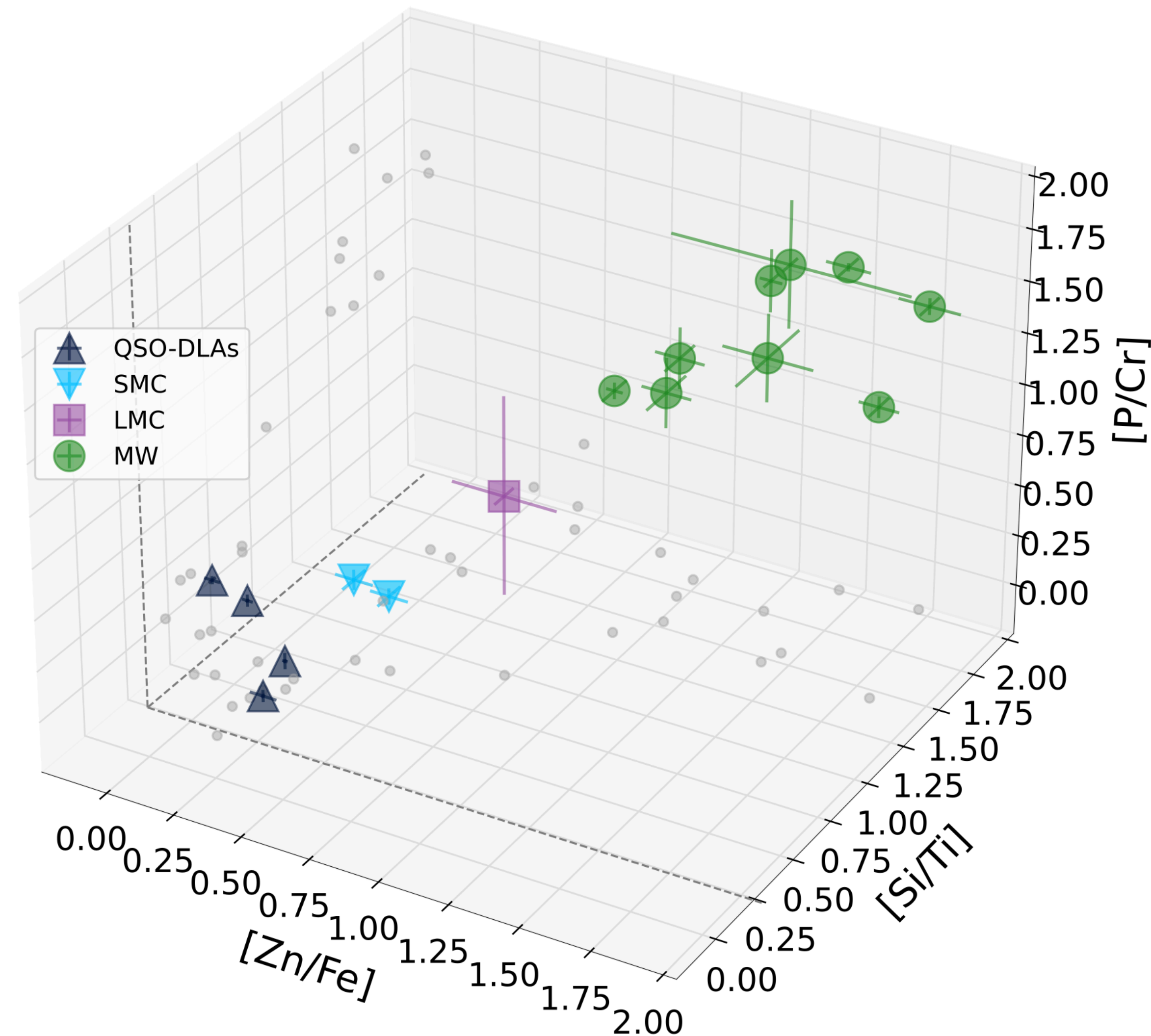


- Assumes a Zn depletion
- Assumes an α -element knee
- Needs several metals (≥ 2)
- Uses only $[\text{Zn}/\text{Fe}]$ as reference dust tracer

The revised relative method. DUNE: Dust depletion UNified method across cosmic time and Environments



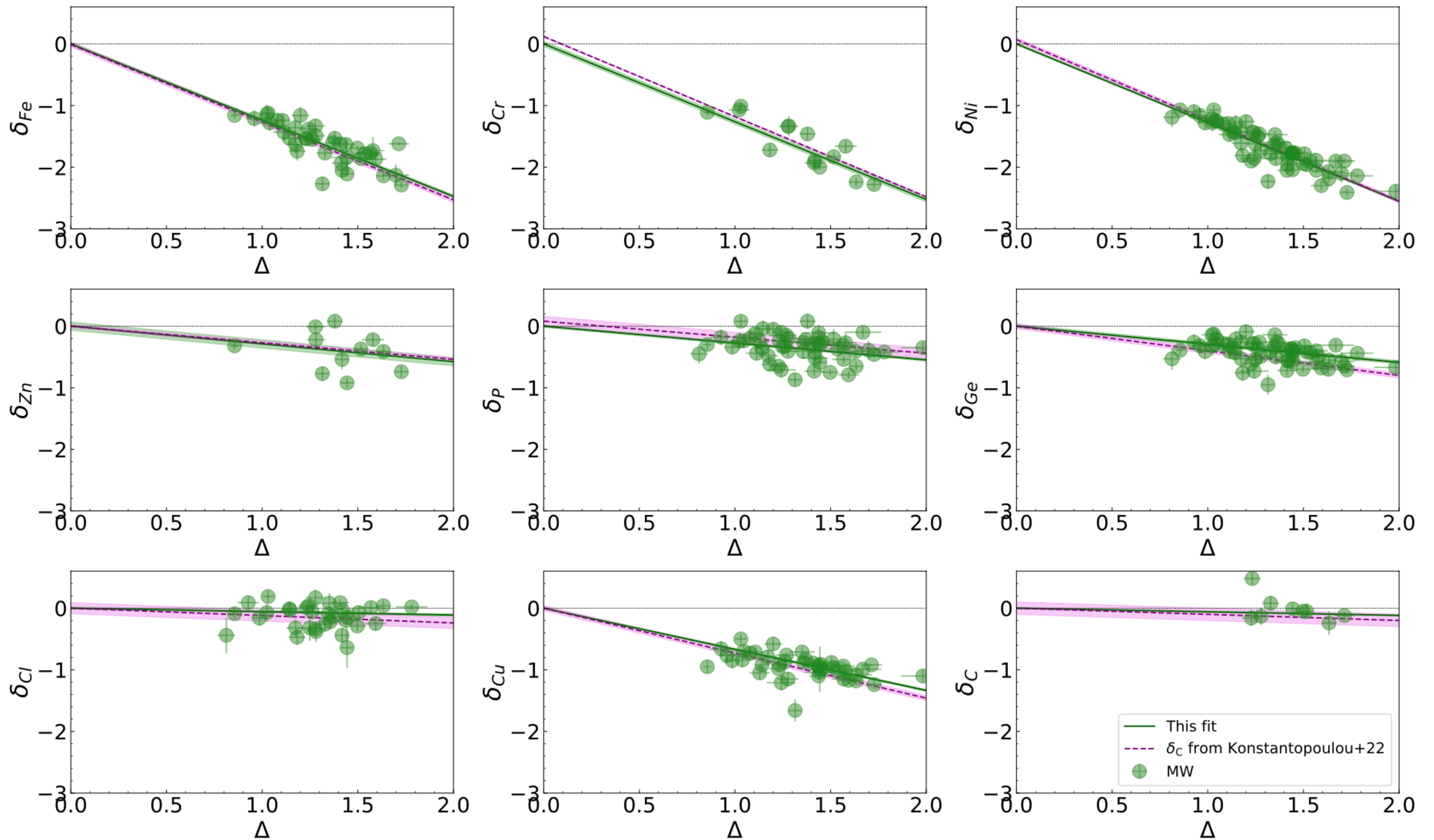
Christina Konstantopoulou



$$\Delta = \frac{\sum_i [X/Y]_i \times W_i \times \frac{1}{C_{XY_i}}}{\sum_i W_i}$$

Overall strength of depletion:

- **from all dust tracers**
- **with best correlations**
- **normalised by [Si/Ti]**



$$\delta_X - \delta_{Kr} = [X/Kr] = B_X \times \Delta \sim \delta_X$$

Advantages



- Uses all [X/Y] dust tracers
- Does not assume a fixed metallicity
- Fully sensitive to abundance variations (e.g. $[\alpha/\text{Fe}]$)
- Applicable to individual clouds
- Applicable at any redshift

Limitations



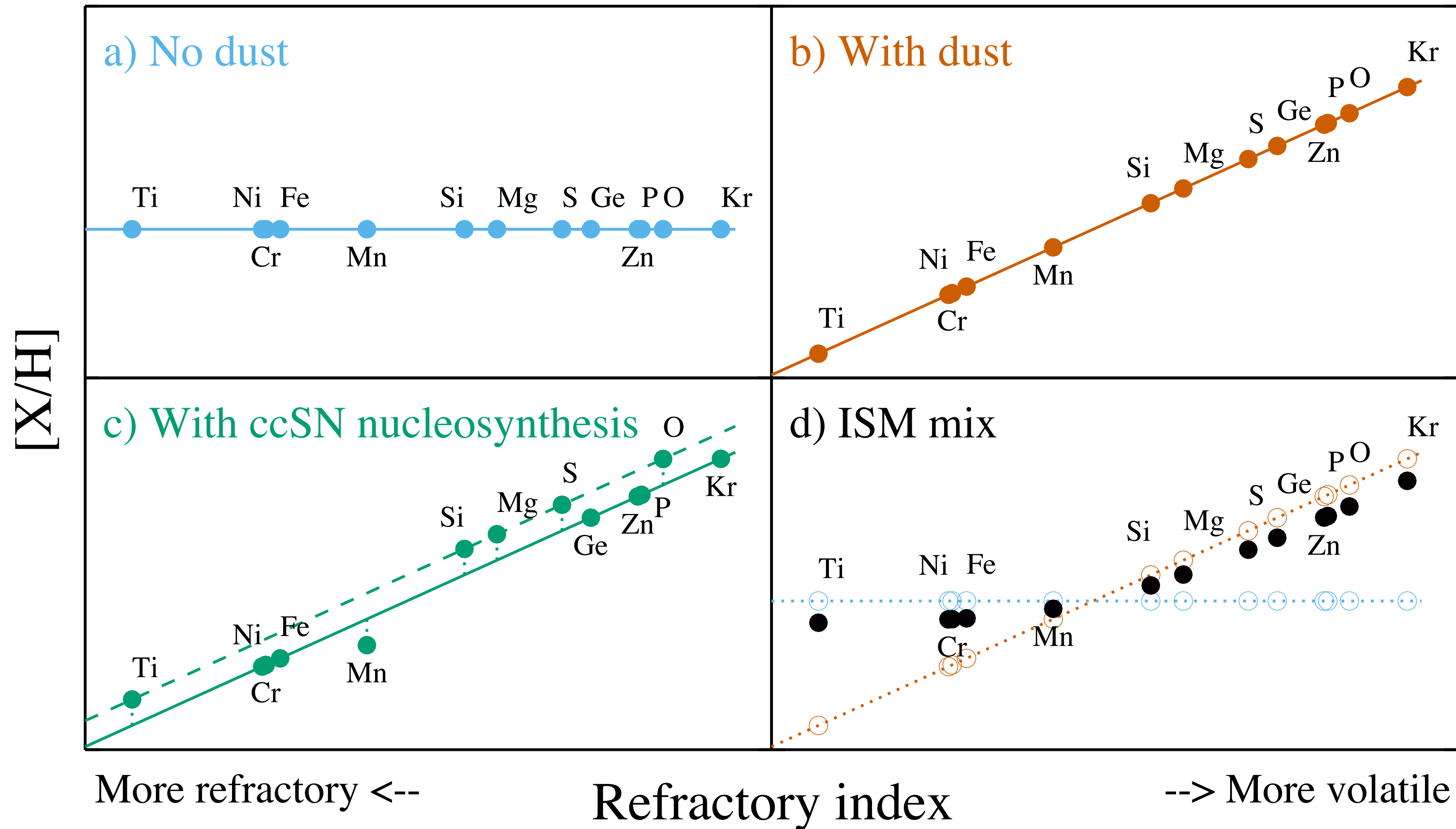
- Assumes Kr depletion
- Needs several metals (≥ 2)

Part II:

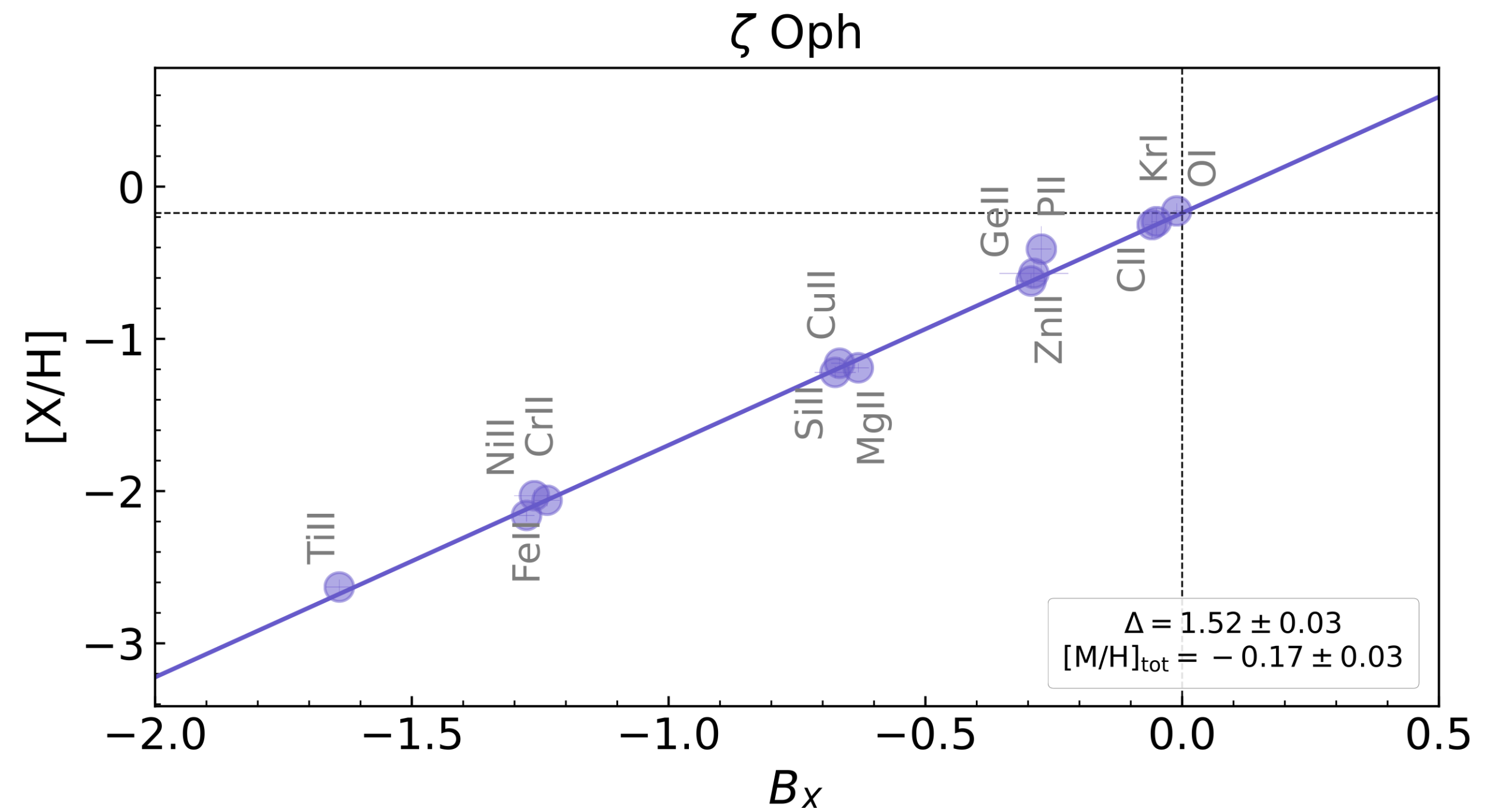
Dust properties from dust depletion

Applications of dust depletion methodology: abundance patterns

De Cia et al. 2024



Abundance patterns:



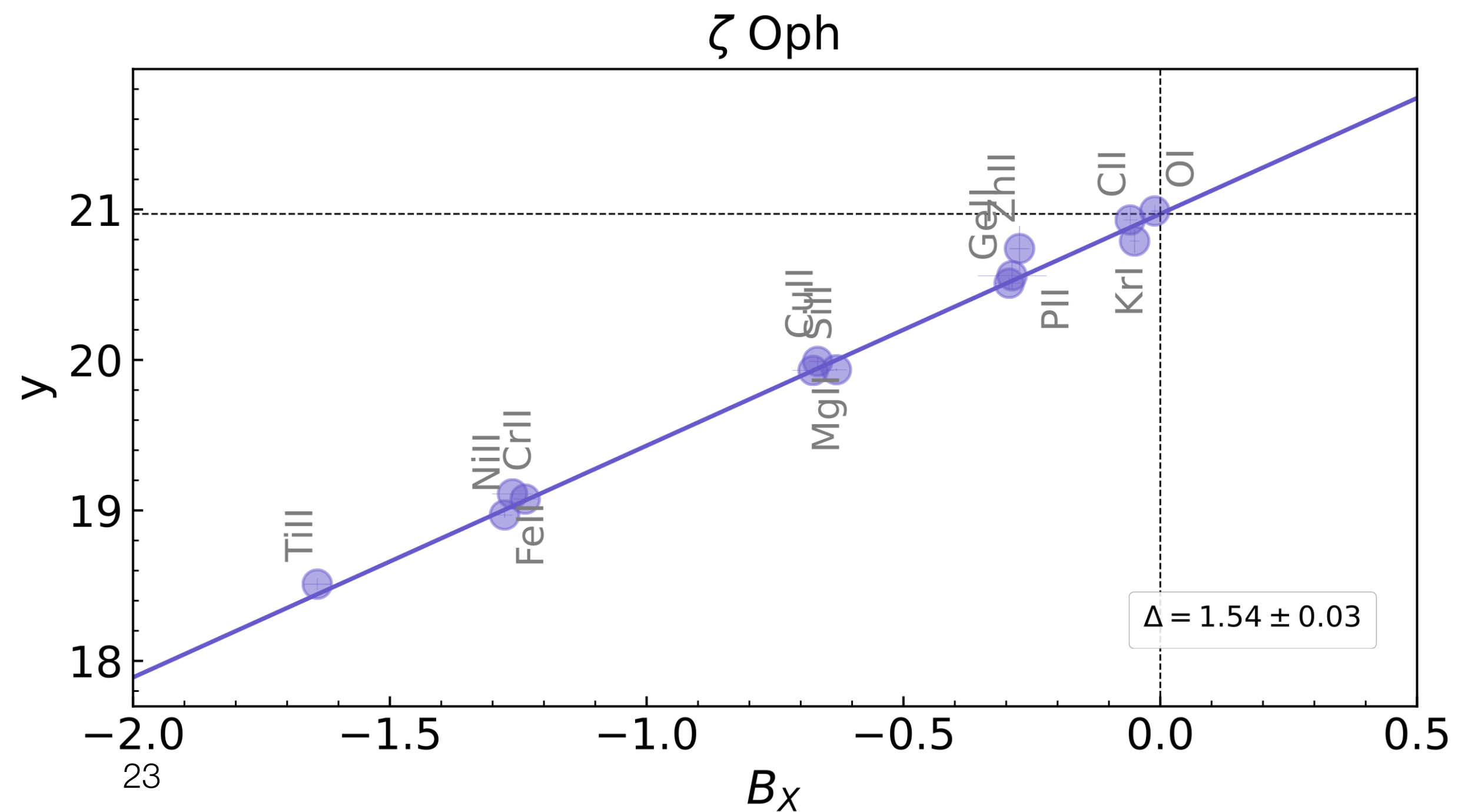
Metal patterns:

$$y_i = a_i + B2_X \times [Zn/Fe]_{\text{fit}}$$

$$y_i = \log N(X) - X_{\odot} + 12 - A2_X$$

$$a_i = [M/H]_{\text{tot}} + \log N(H)$$

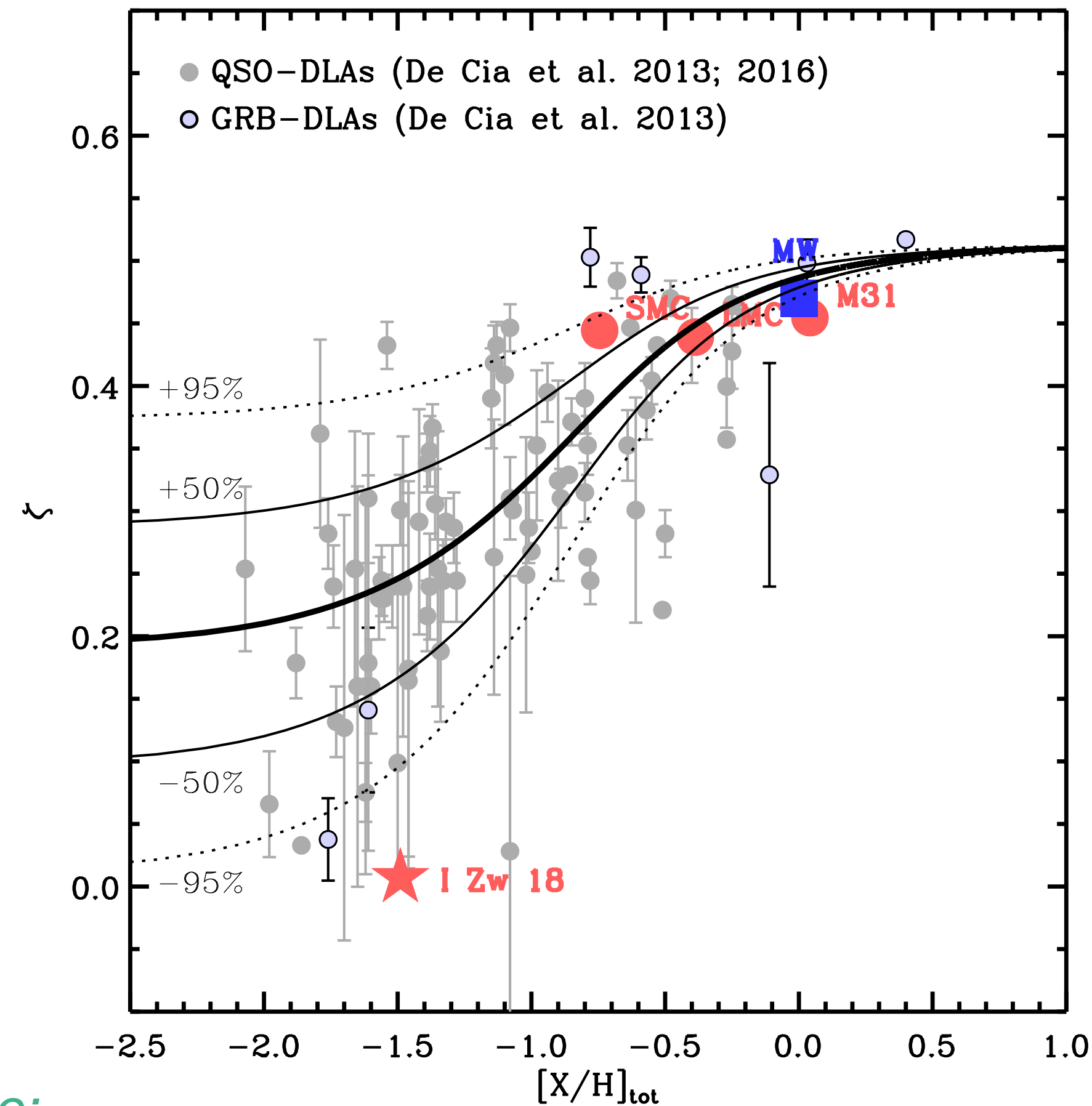
Ramburuth-Hurt, De Cia et al. 2023



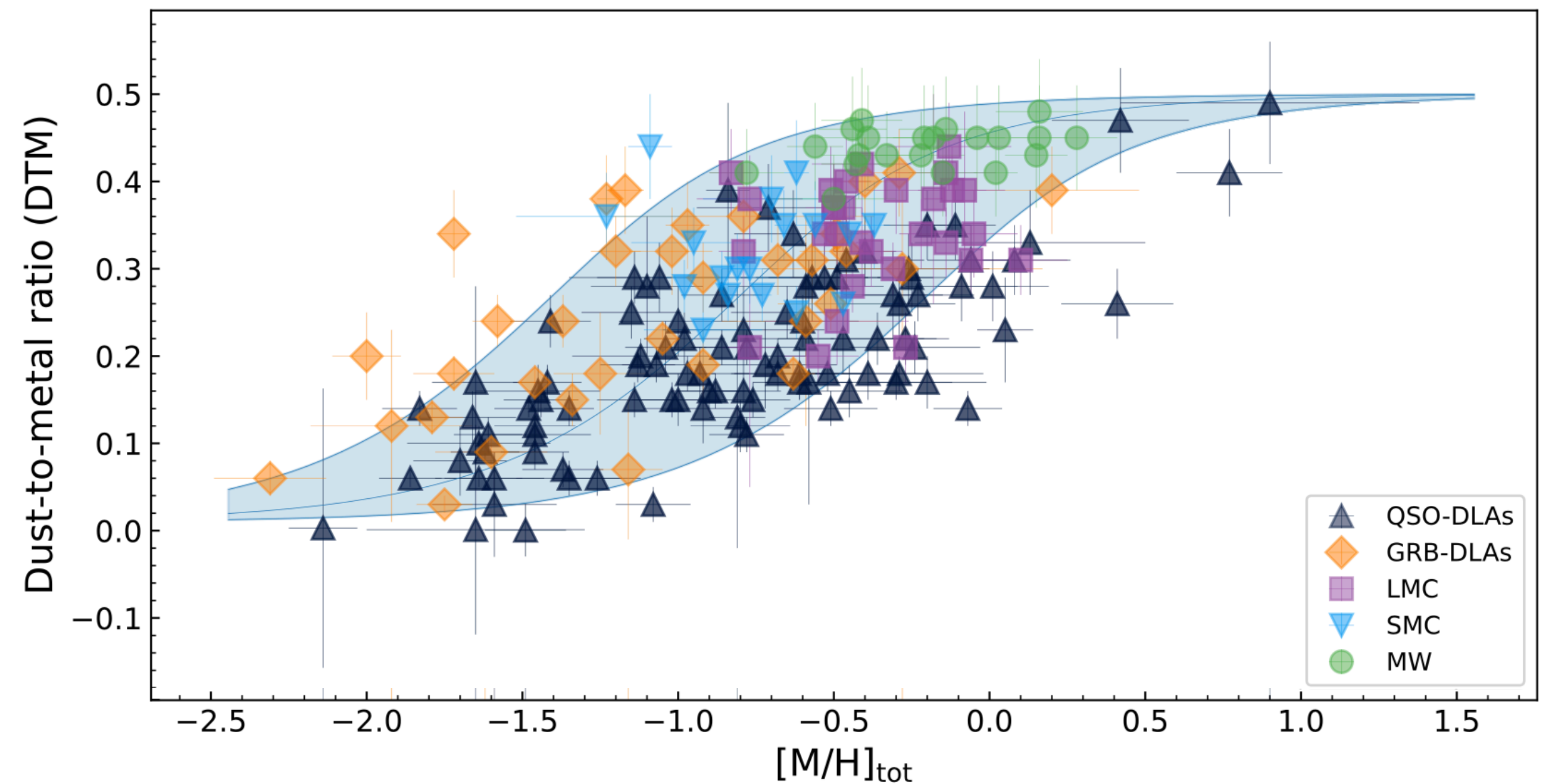
Dust-to-metal ratio

$$\text{DTM} = \frac{M_{\text{dust}}}{M_{\text{metals}}} = \frac{\sum_{X_i} (1 - 10^{\delta_{X_i}}) 10^{[X_i/H]_{\odot}} W_{X_i}}{\sum_{X_i} 10^{[X_i/H]_{\odot}} W_{X_i}}$$

Mattsson 2020



Konstantopoulou, De Cia, et al. 2024a



Grain growth in the ISM

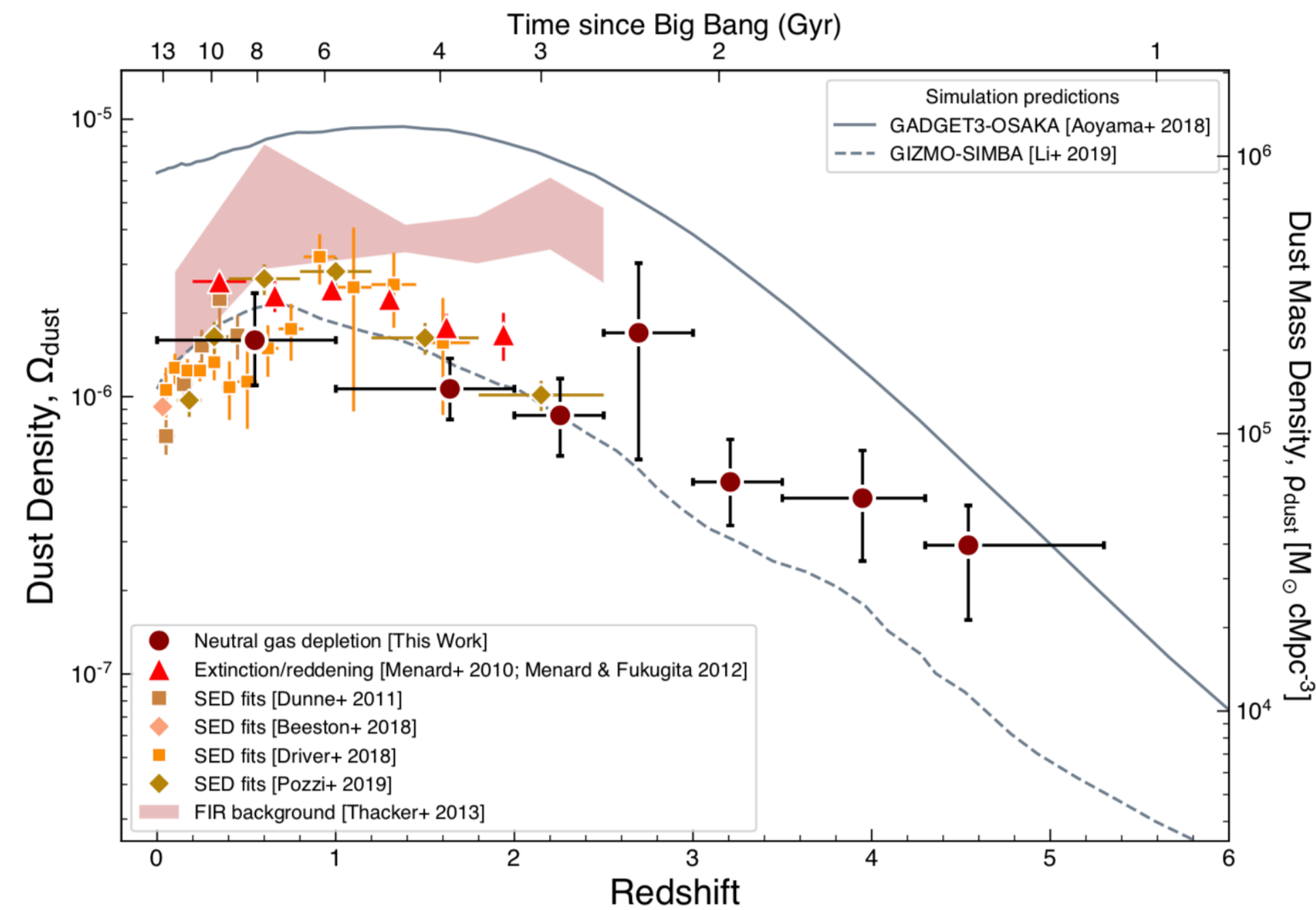
See also:

De Cia et al. 2013, 2016; Mattsson, De Cia, et al. 2013; Wiseman et al. 2017, Roman-Duval et al. 2022

Build-up of dust with cosmic time

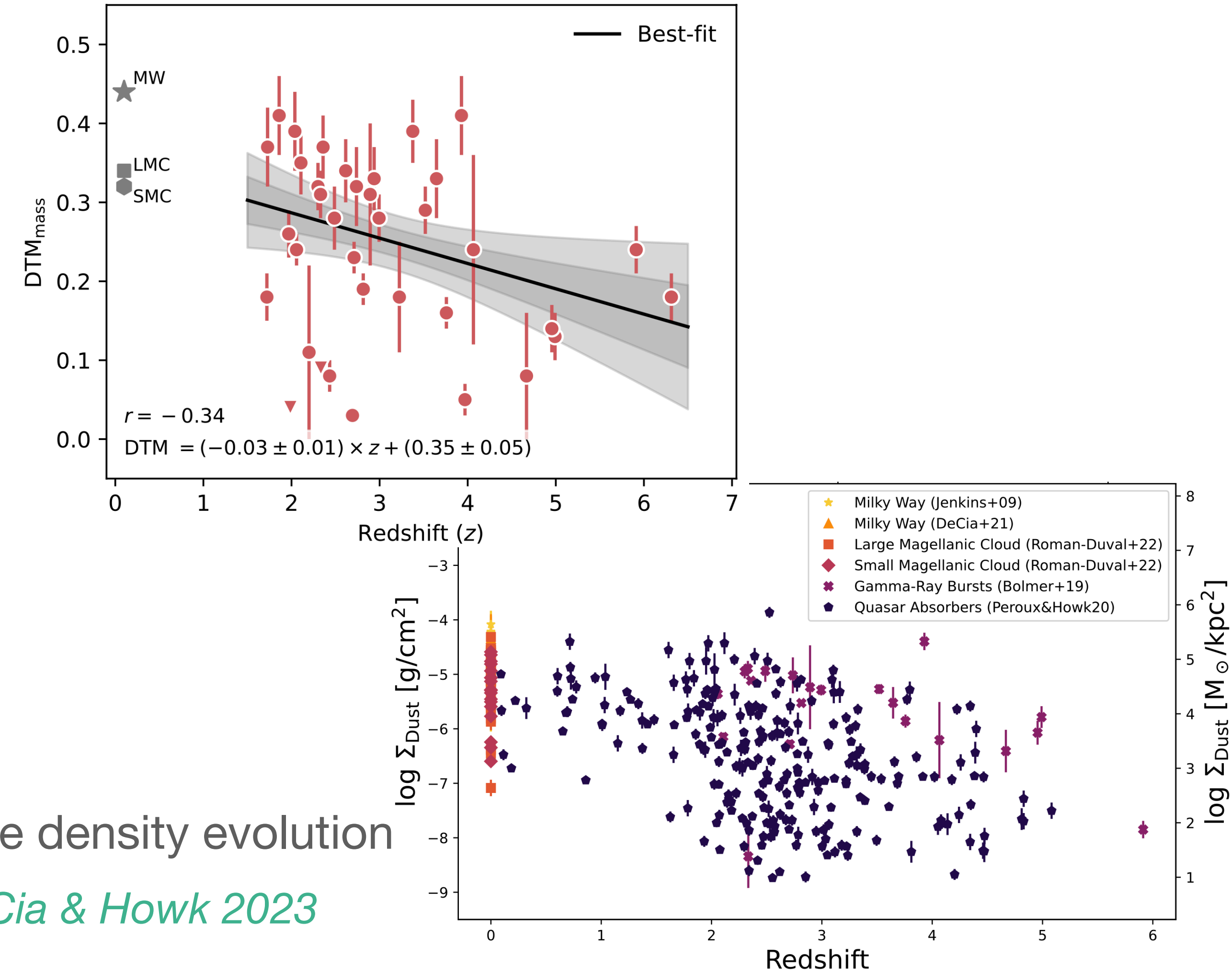


1 Dust density evolution



Peroux & Howk, ARAA 2020

2 DTM end DTG evolution *Heintz, De Cia et al. 2023*



3 Dust surface density evolution

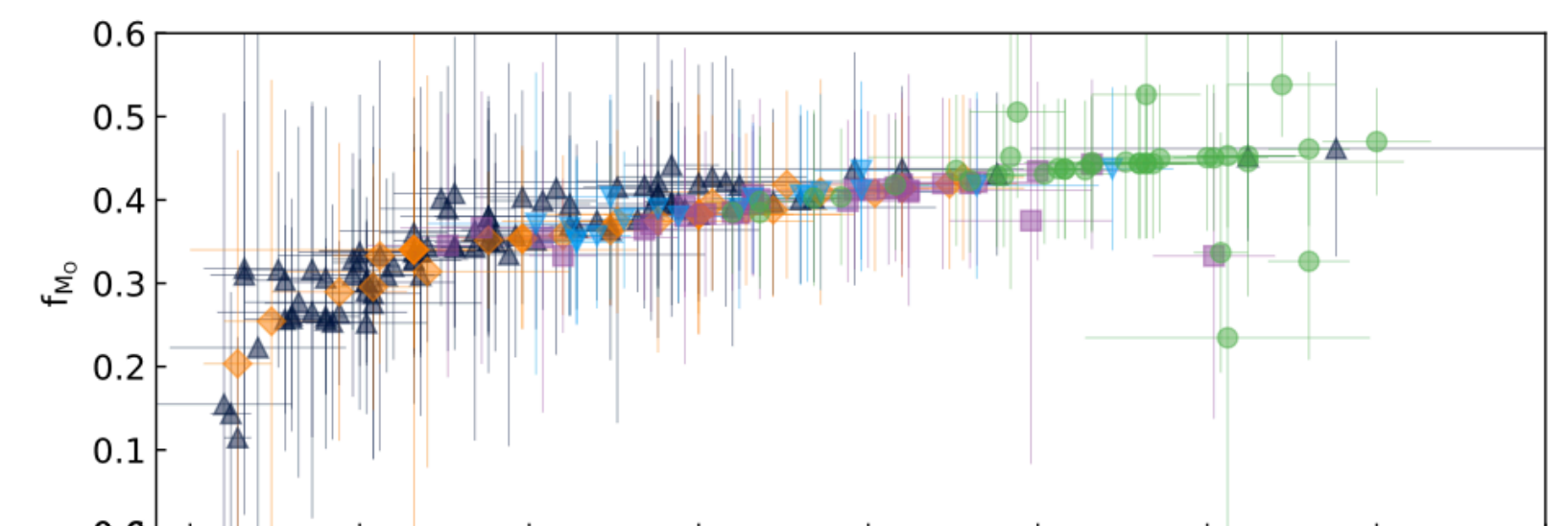
Peroux, De Cia & Howk 2023

Dust composition (in the WNM)

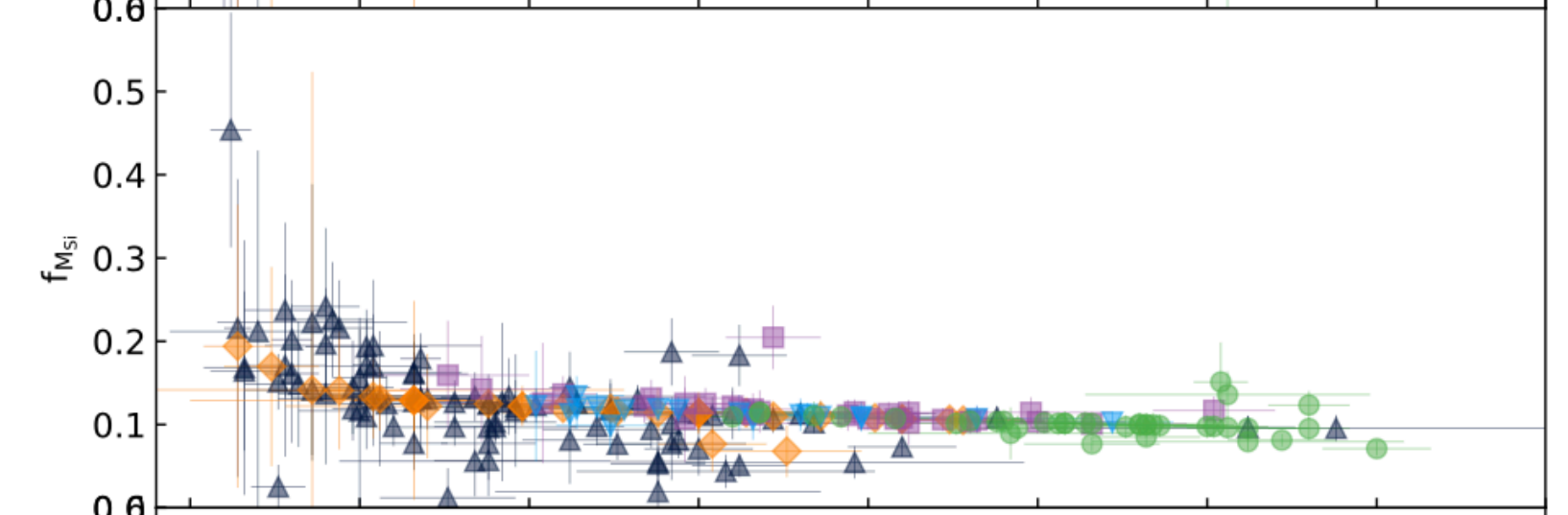
fraction of dust mass
contributed by element X:

$$f_{M_X} = \frac{(1 - 10^{\delta_X}) 10^{[X/H]_{\odot}} W_X}{\sum_{X_i} (1 - 10^{\delta_{X_i}}) 10^{[X_i/H]_{\odot}} W_{X_i}}$$

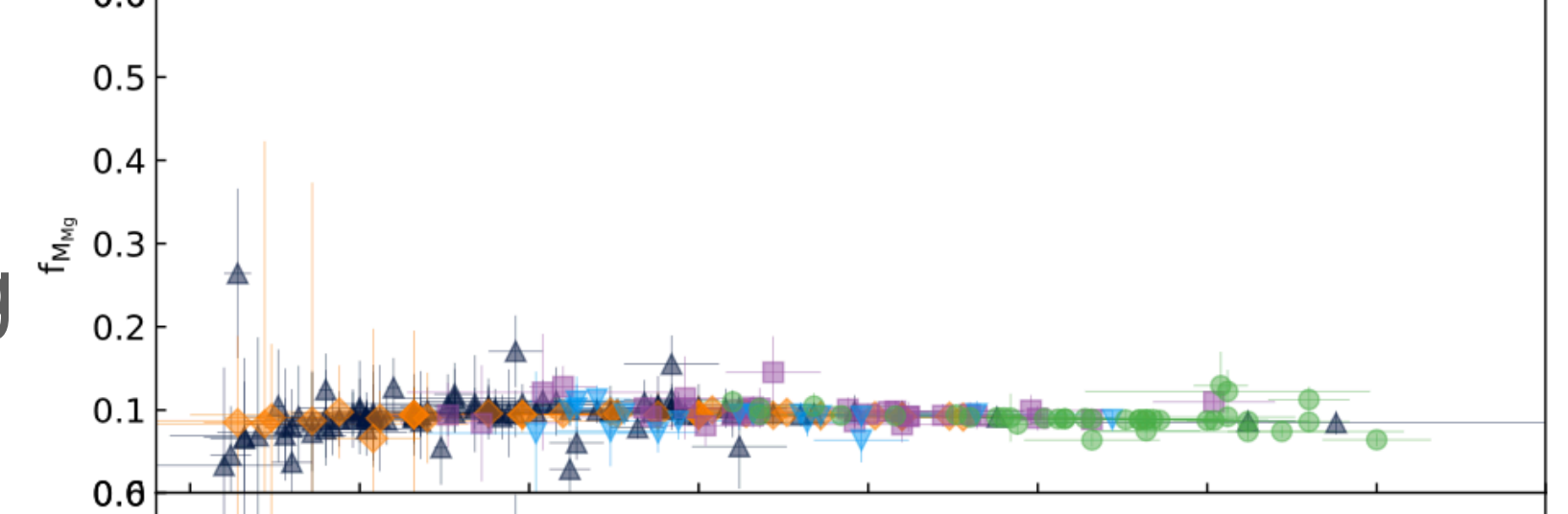
f_{MO}



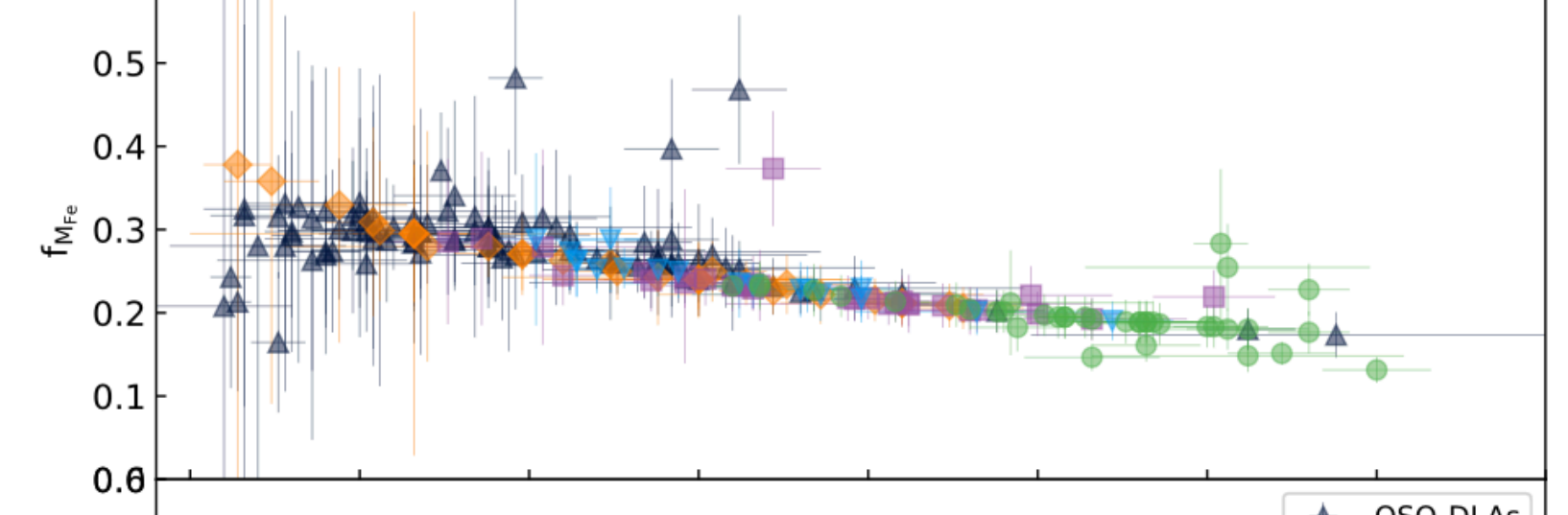
f_{MSi}



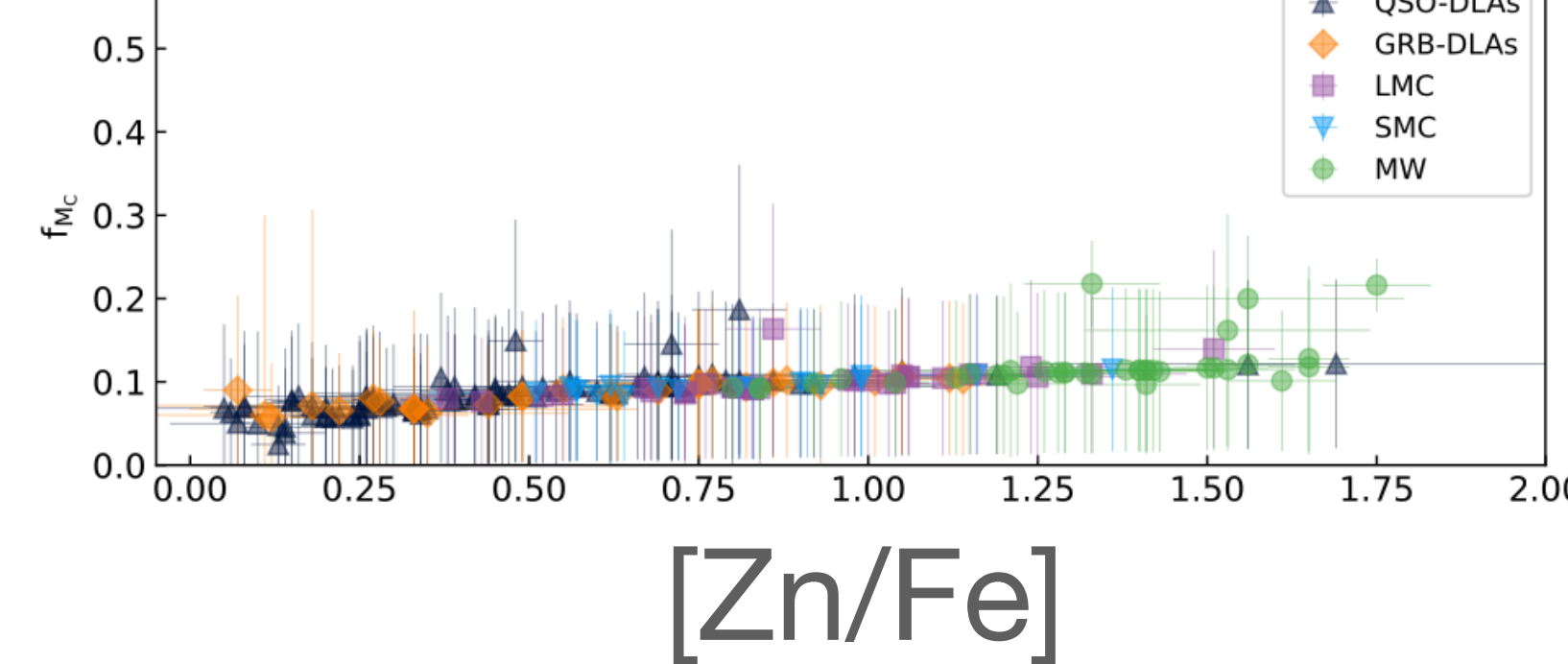
f_{MMg}



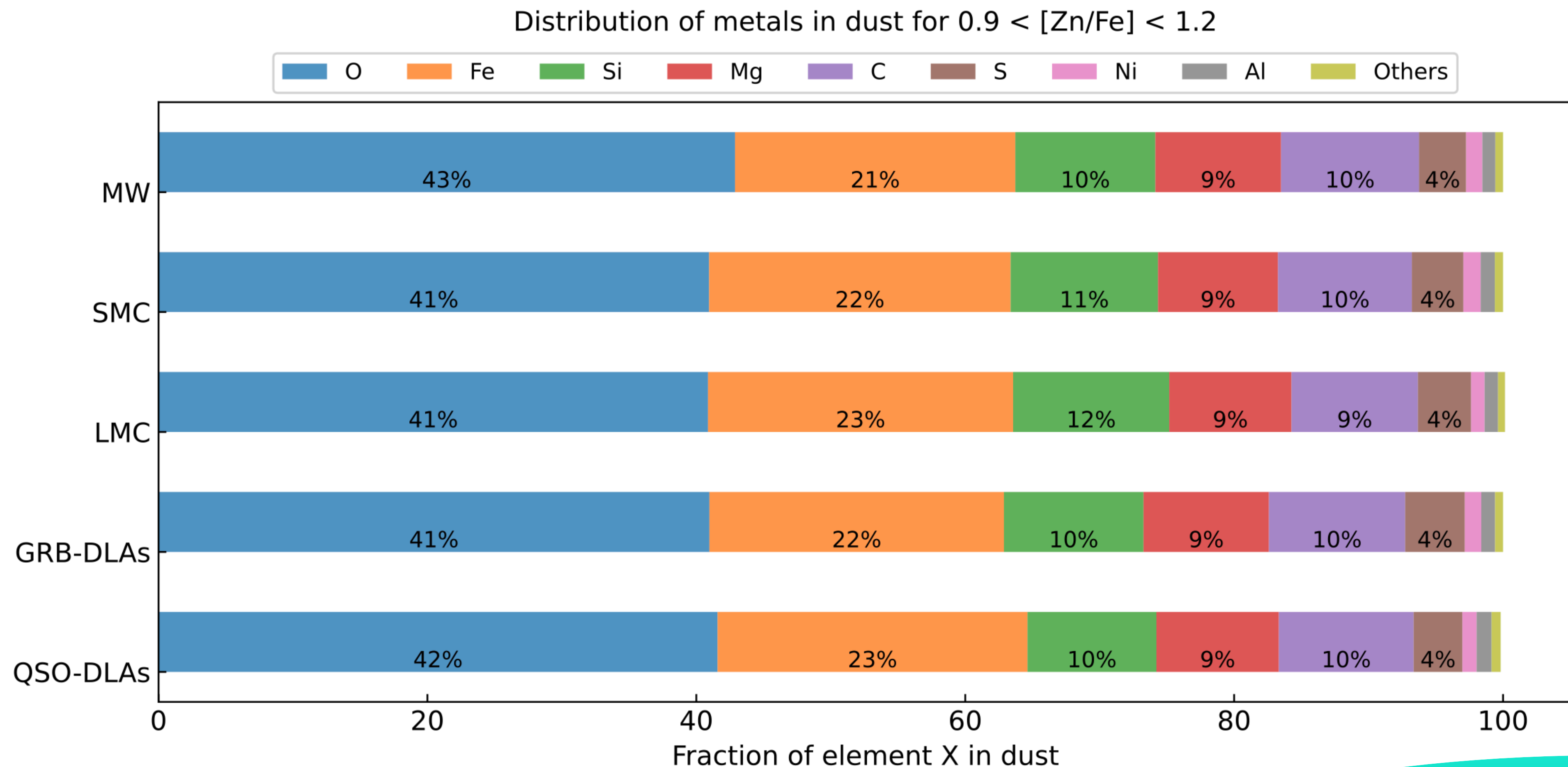
f_{MFe}



f_{MC}



Dust composition (in the WNM): the most dusty regime



Konstantopoulou, De Cia, et al. 2024a

$[\text{O}/\text{H}]_{\text{dust}} = 141 \pm 60 \text{ ppm}$; $[\text{Si}/\text{H}]_{\text{dust}} = 40 \pm 4 \text{ ppm}$

Konstantopoulou, De Cia, et al. 2024b, DUNE

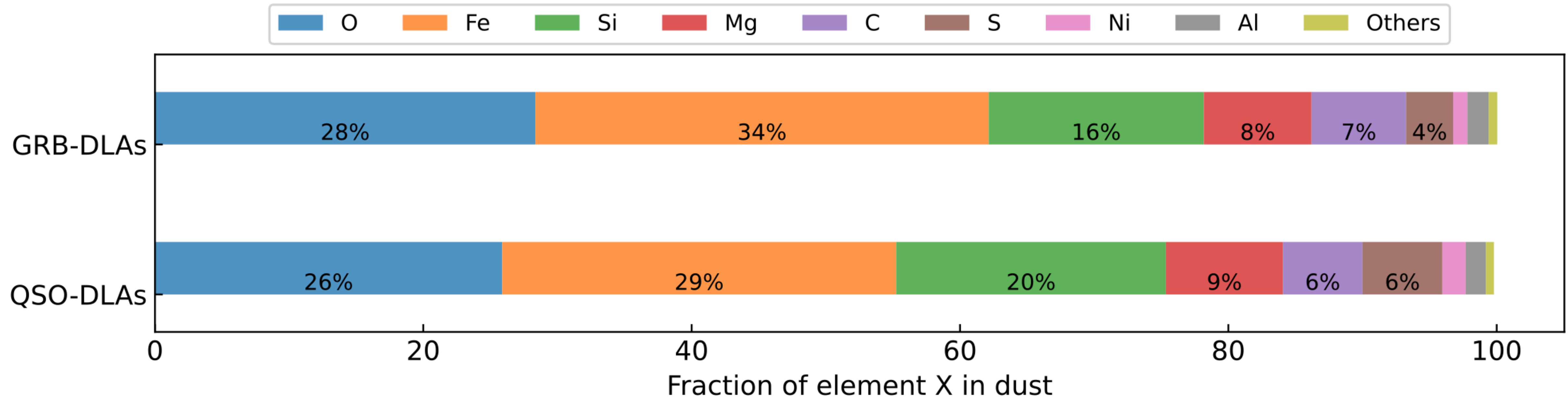
Olivine ($\text{Mg}_{2x}\text{Fe}_{2(1-x)}\text{SiO}_4$)

Pyroxene ($\text{Mg}_x\text{Fe}_{(1-x)}\text{SiO}_3$)

Fe-rich; C-rich

Dust composition (in the WNM): the least dusty regime

Distribution of metals in dust for $[Zn/Fe] < 0.3$



ppm: O 35; Si 13, Fe 10, Mg 7, C 10

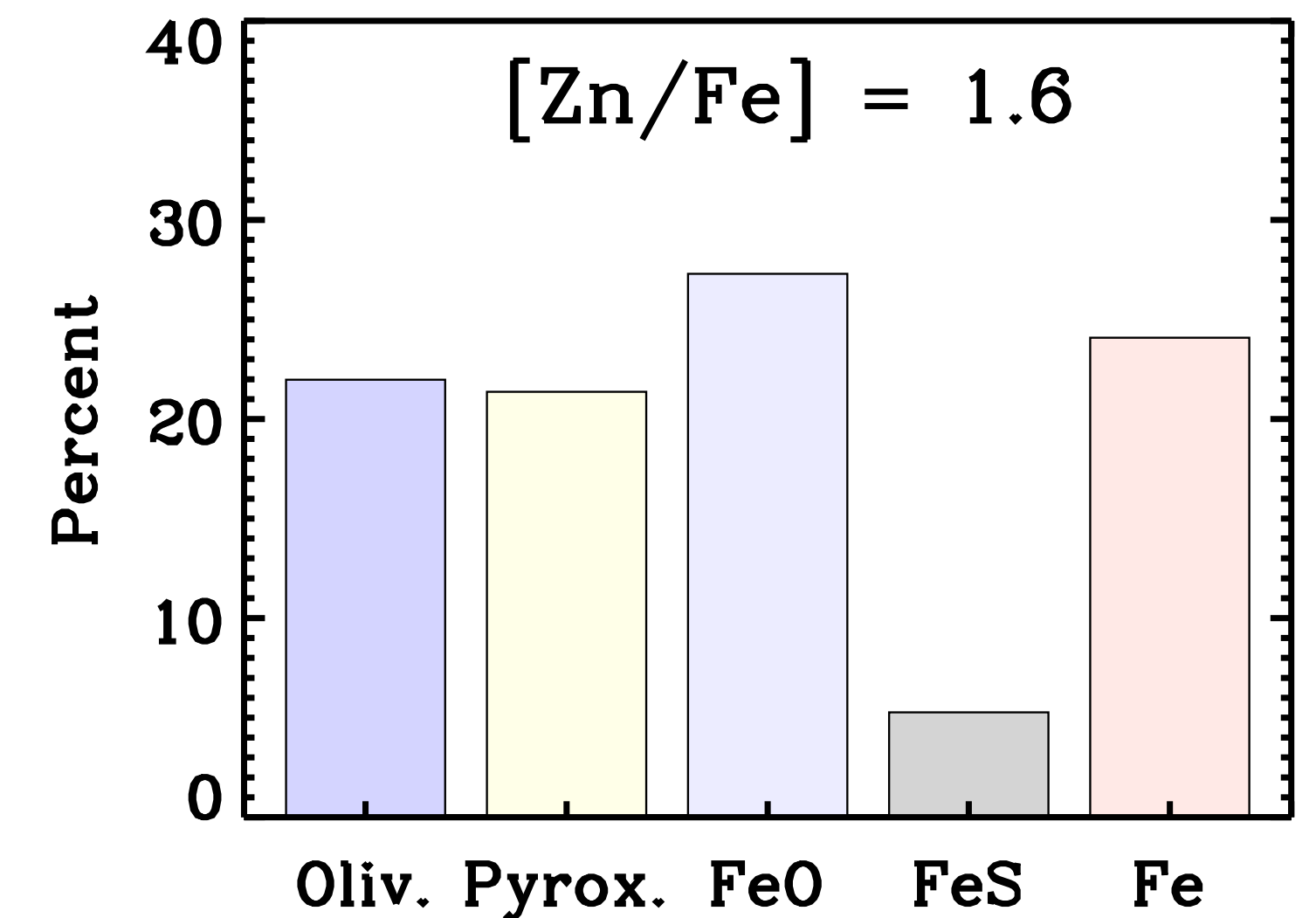
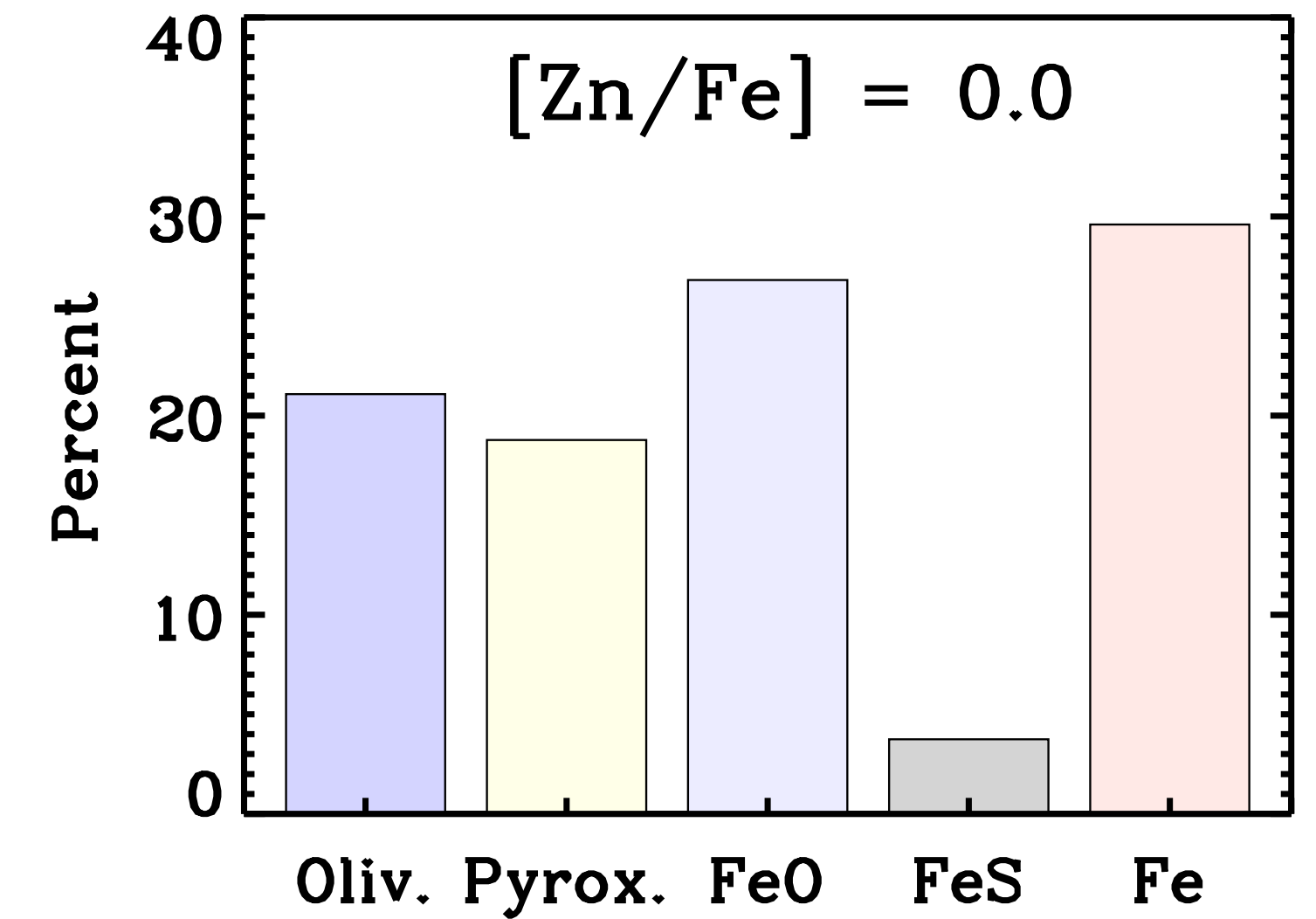
Pyroxene ($Mg_xFe_{(1-x)}SiO_3$)?

Dust composition

- [Carbon-rich]
- Pyroxine ($\text{Mg}_x\text{Fe}_{1-x}\text{SiO}_3$)
- Olivine ($\text{Mg}_{2x}\text{Fe}_{2(1-x)}\text{SiO}_4$)
- Fe-rich

See also Dwek 2016

Mattsson, De Cia et al., 2019



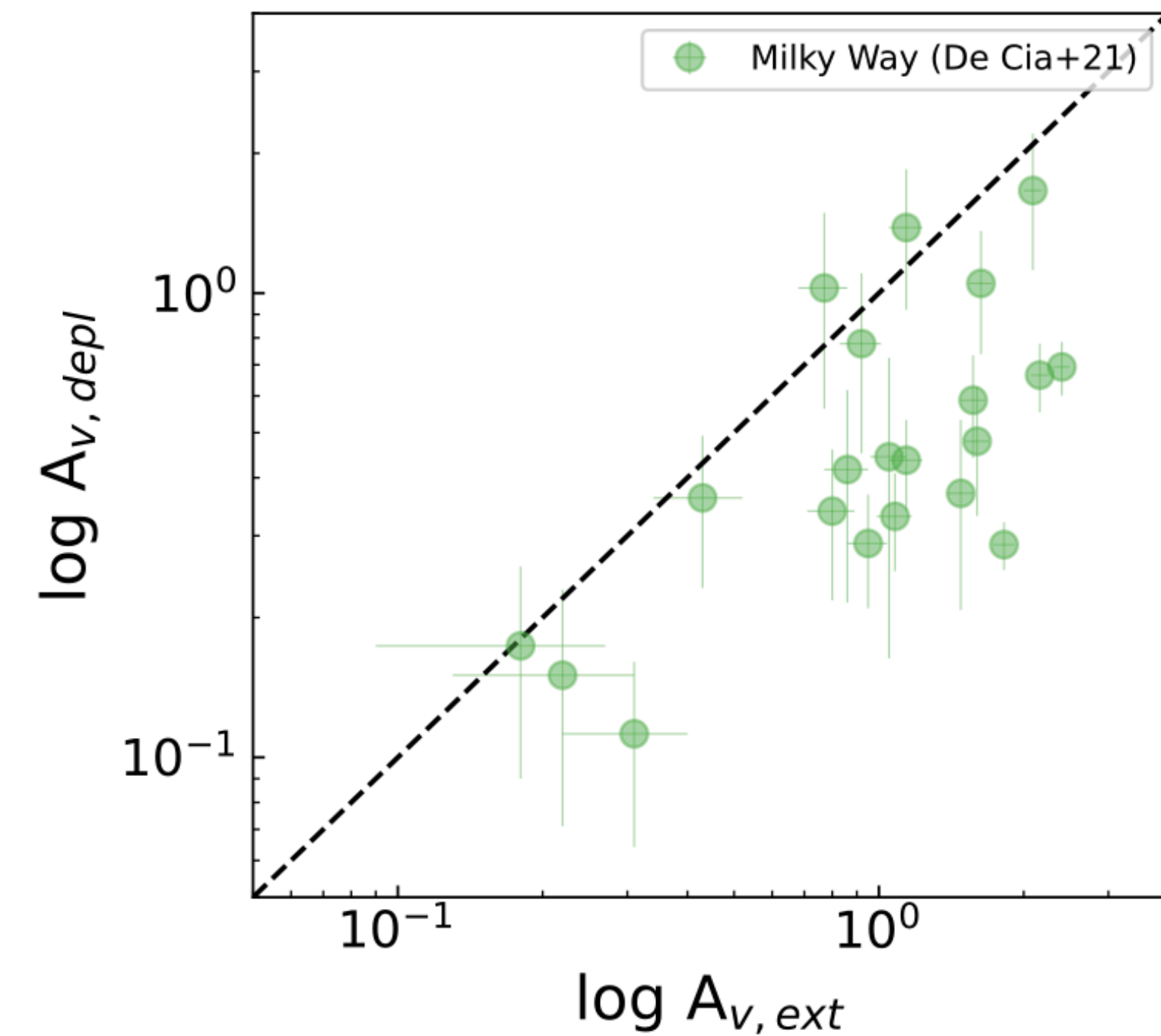
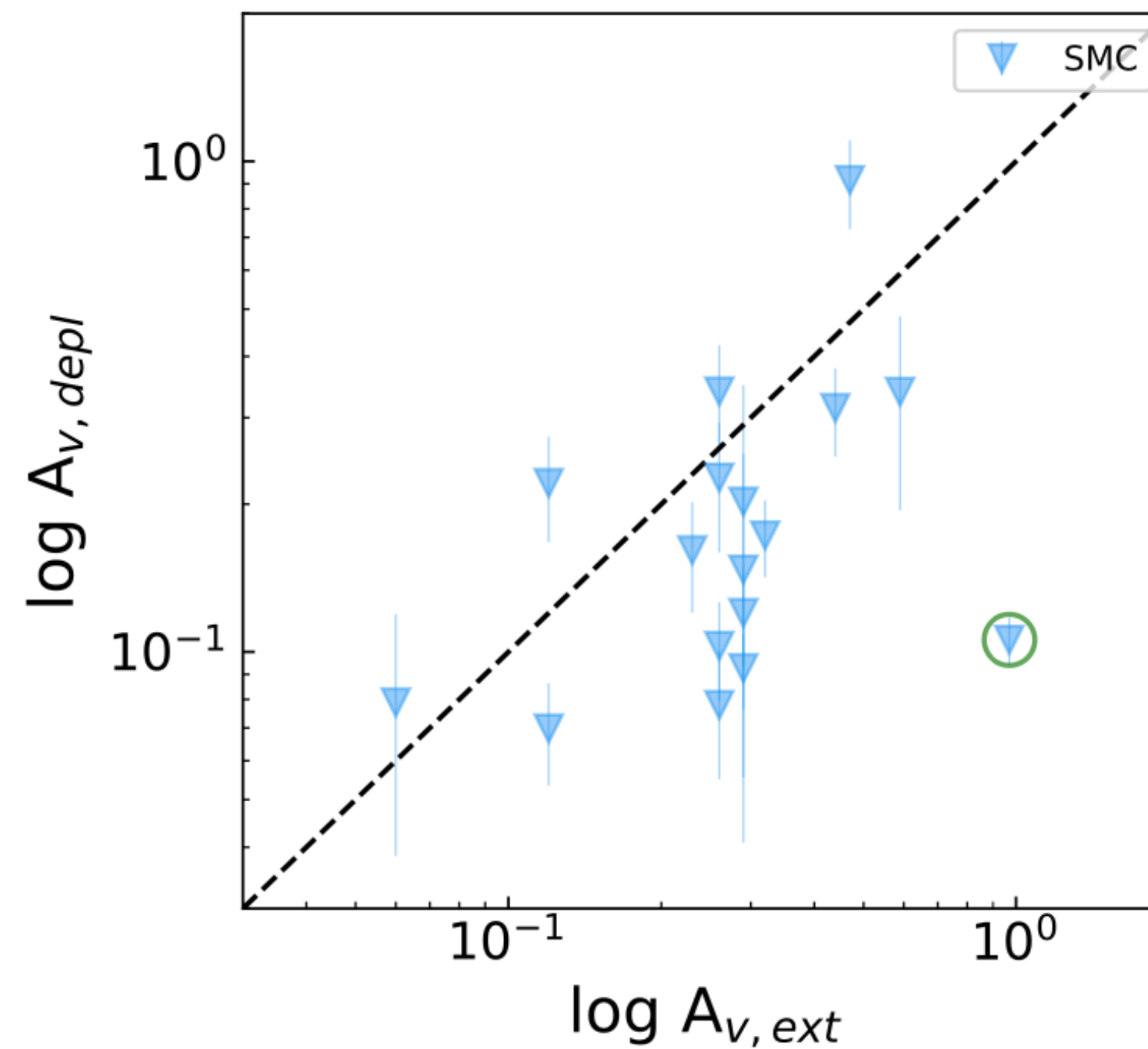
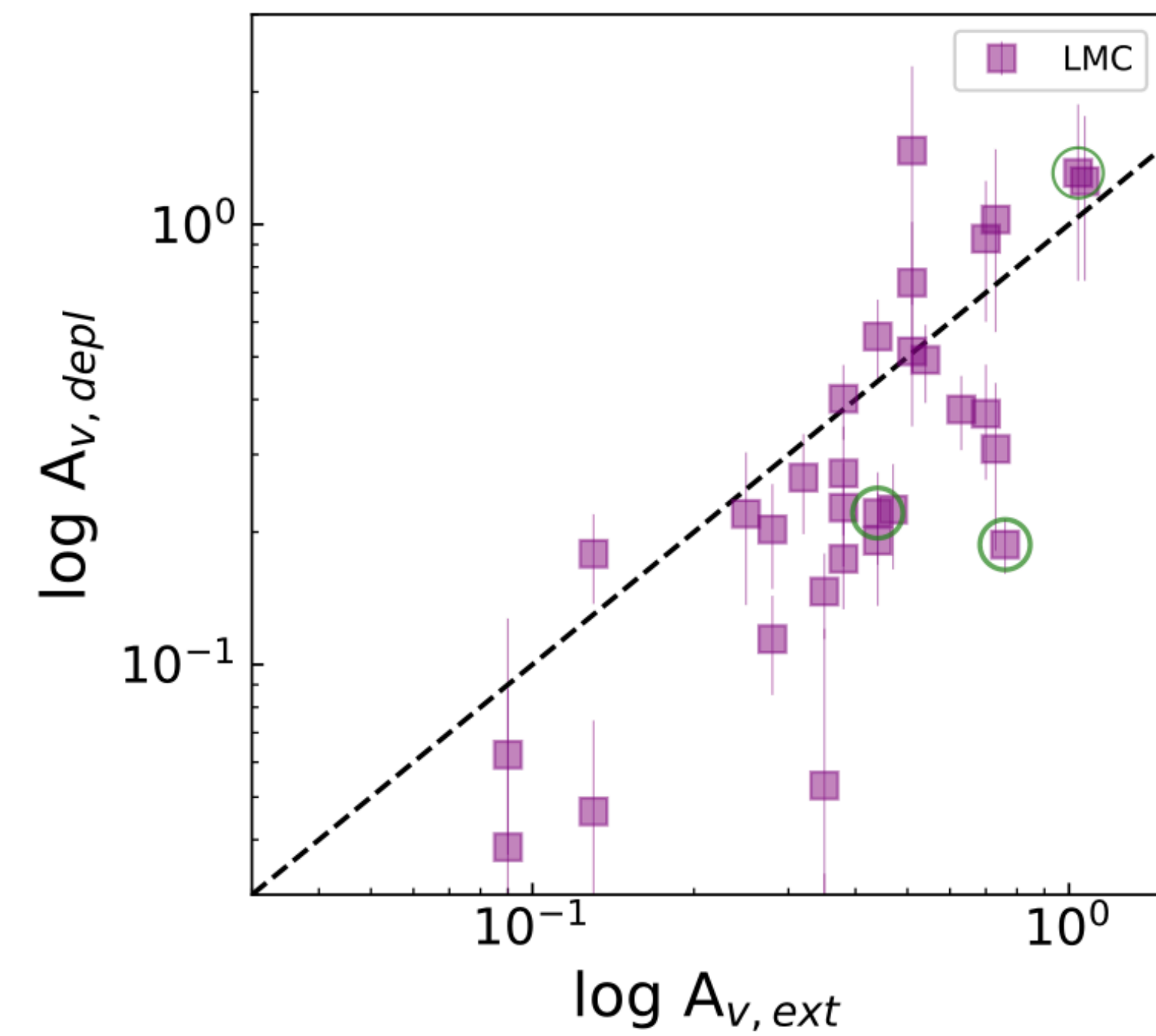
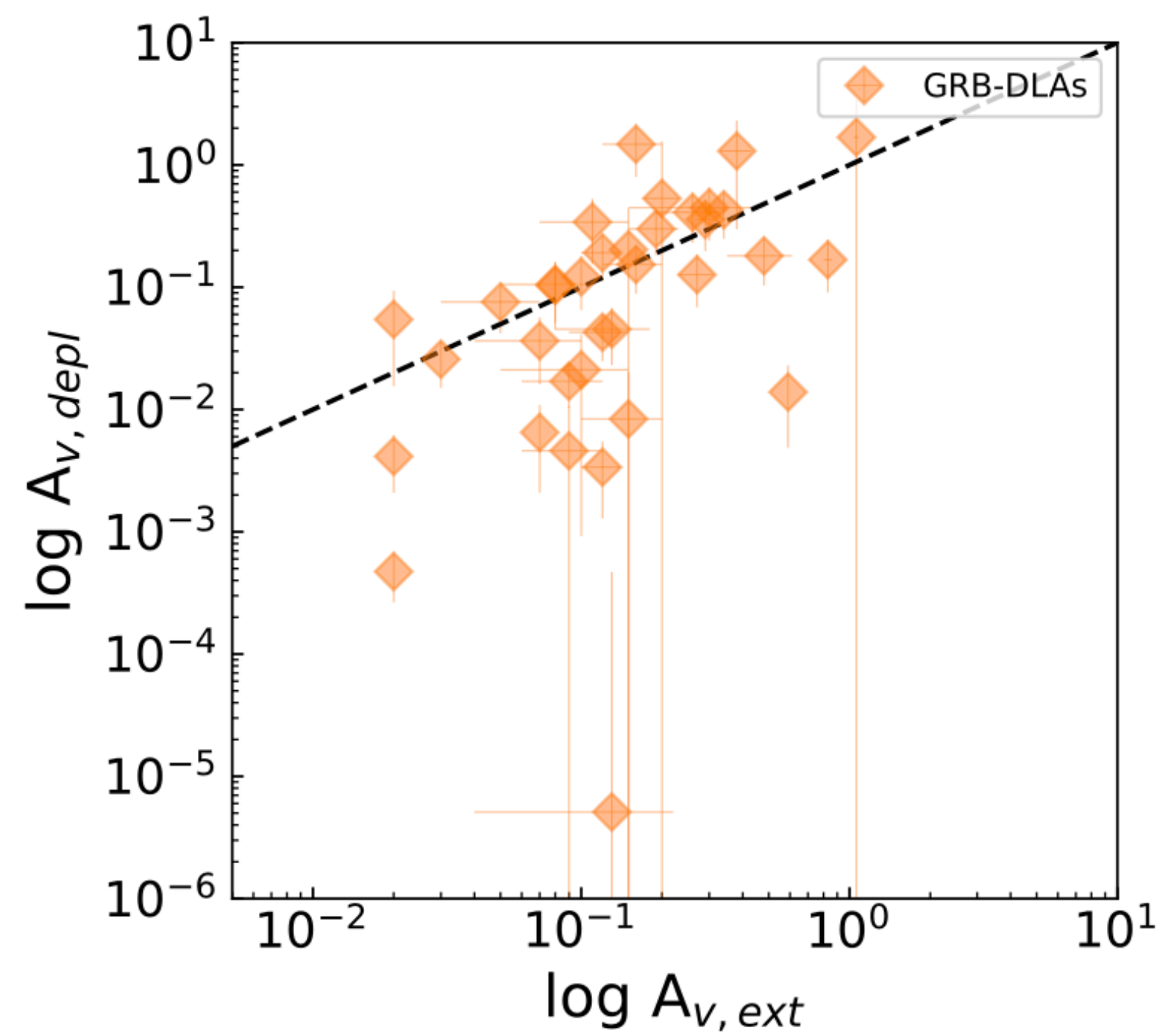
$A_{V,\text{extinction (total)}}$

vs

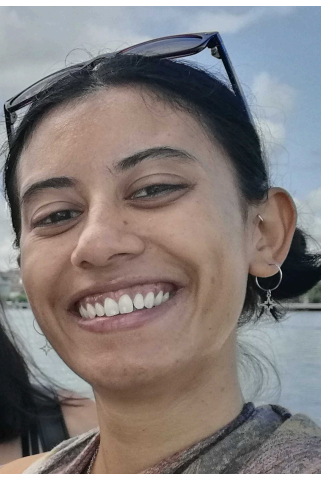
$A_{V,\text{depletion (WNM)}}$

○ 2175 Å bump

PAH in cold dense phase

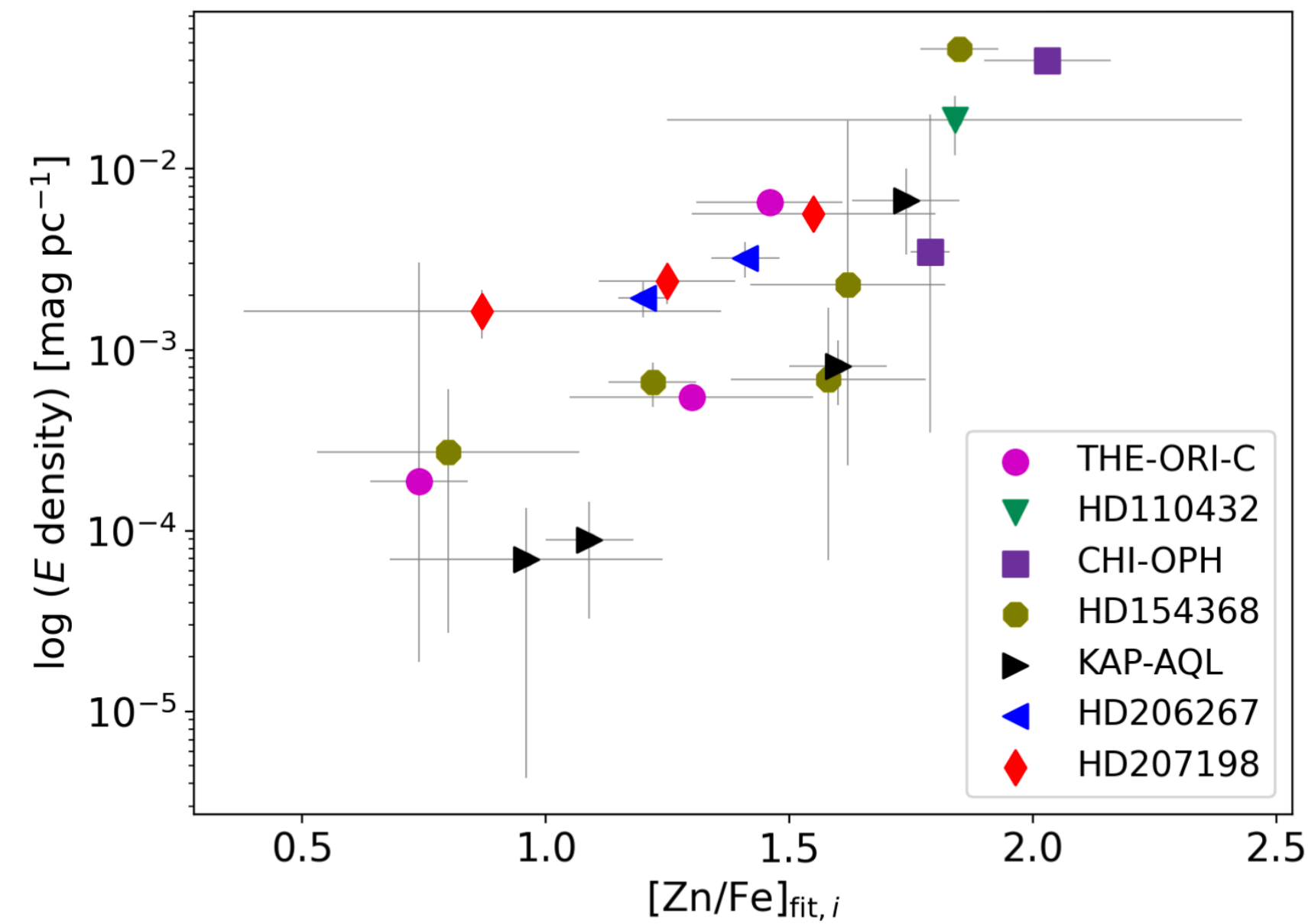
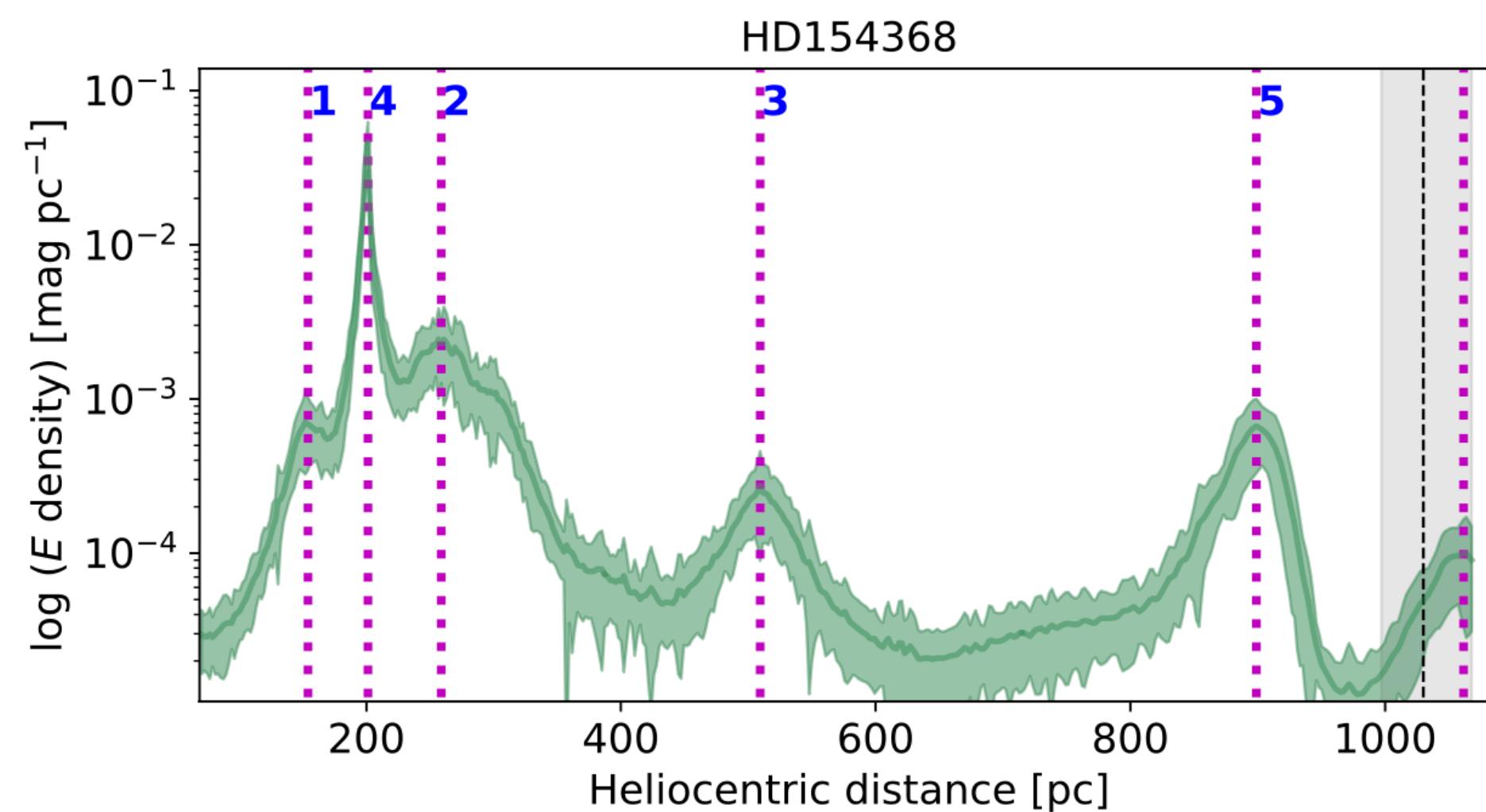
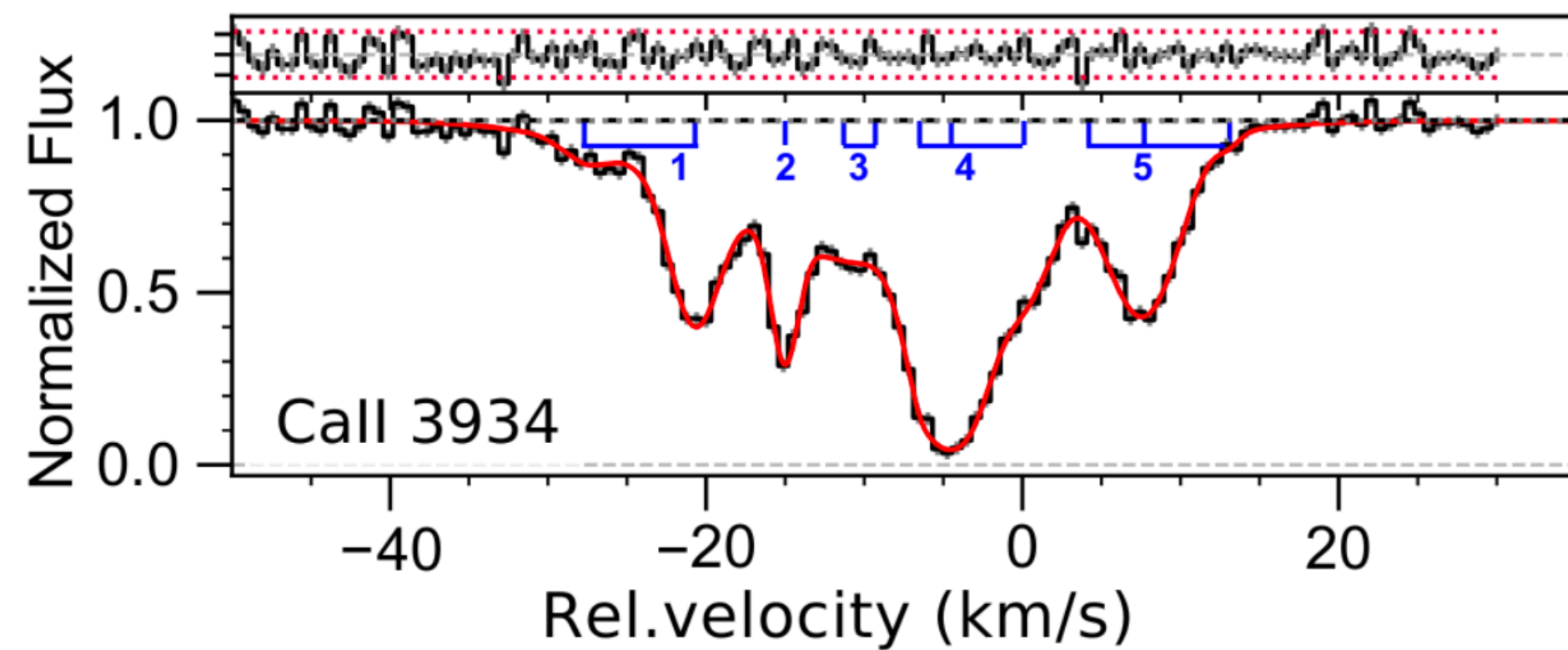


Connecting dust extinction and depletion in ISM clouds

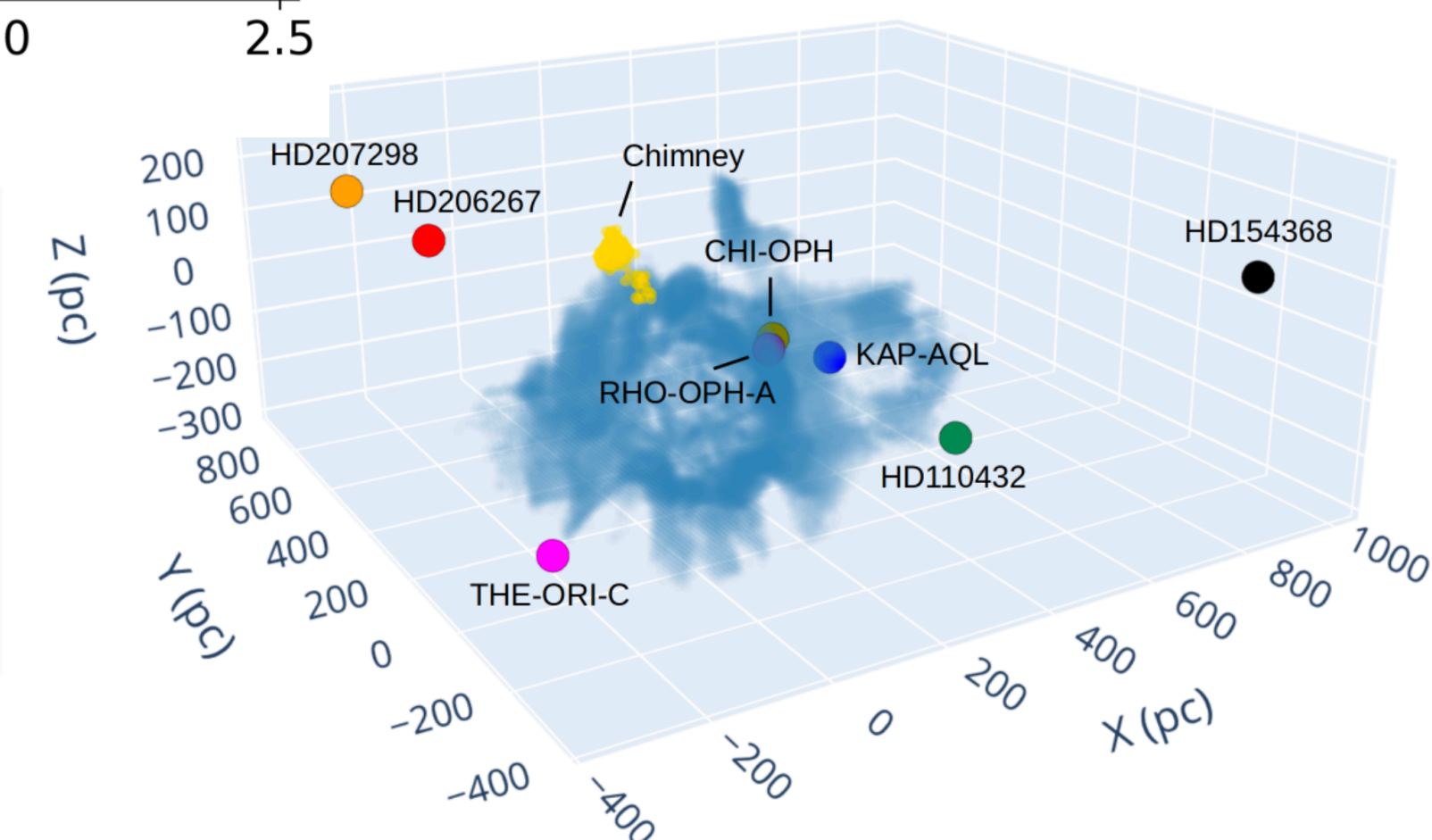


Tanita
Ramburuth-Hurt

Ramburuth-Hurt, De Cia et al. submitted

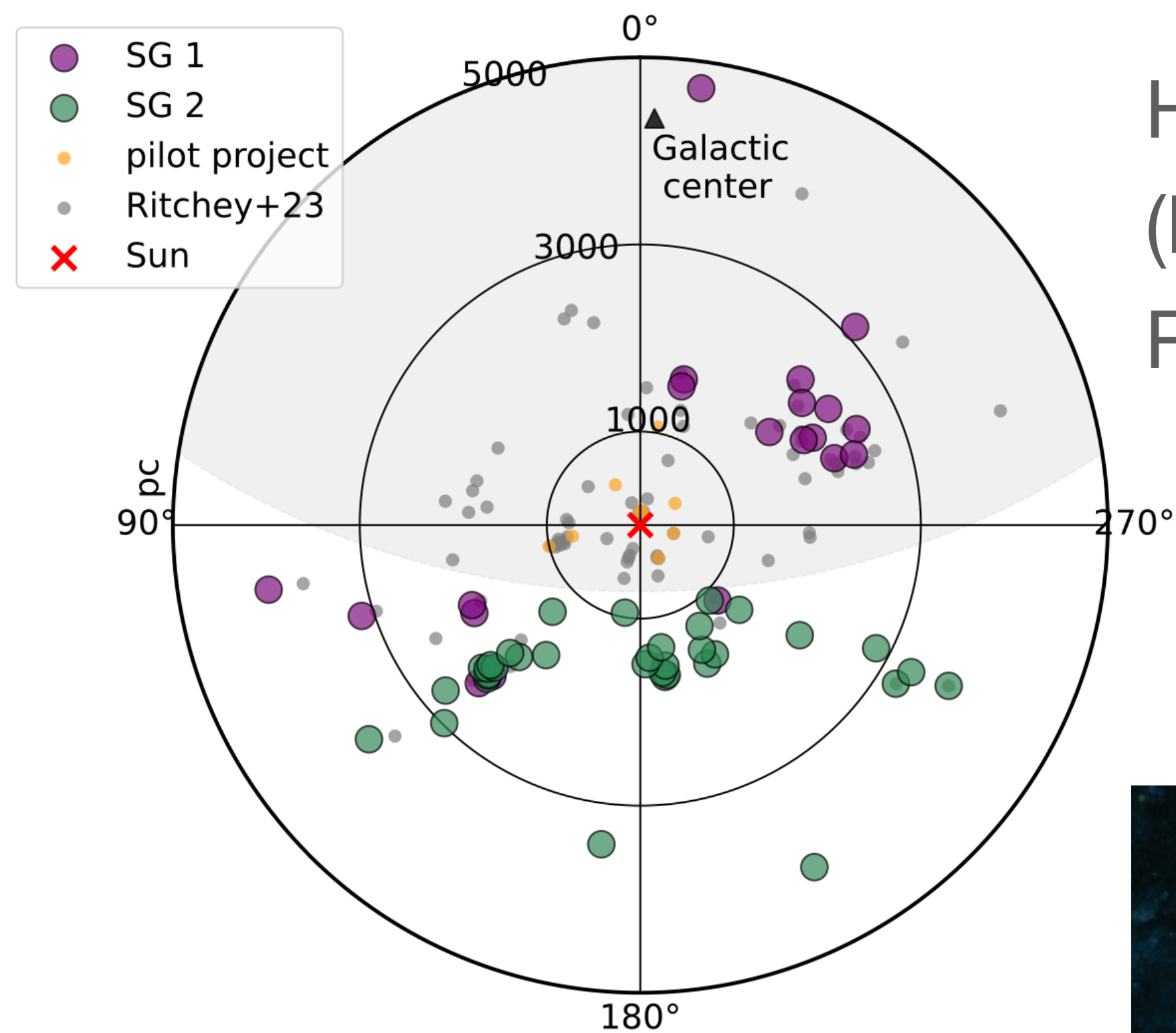


PRELIMINARY



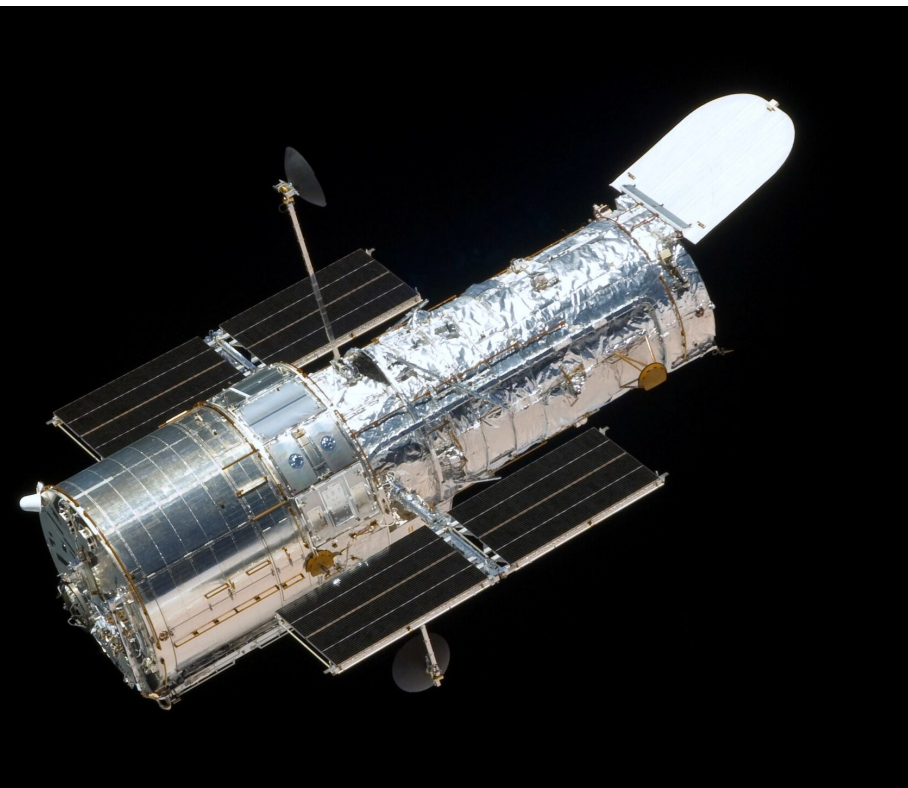
Using 3D extinction maps (Edenhofer et al. 2024)

HST “STIS-ISM:STIS ISM Survey in the Milky Way”



HST GO 17703
(PI De Cia)
 $R = 114000$

See Poster 115
by Doyeon Avery Kim



Conclusions

- ★ Dust depletion is key to the chemical properties of the ISM (metals and dust) in galaxies
- ★ $[X/Y]$ can trace dust depletion because different metals deplete differently
- ★ The relative method ($[X/Y]$) is necessary to study dust depletion in distant galaxies
- ★ DUNE combines the strengths and overcome the limitations of the F^* and $[Zn/Fe]$ methods

Dust depletion (in the WNM) gives important constrains on:

- ★ Dust origin: ISM growth dominant for the dust we measure in the WNM
- ★ Dust-to-metals and dust-to-gas ratios, the build-up of dust with cosmic time
- ★ Dust composition in the most dusty regime: Olivines, Pyroxenes, Fe and Fe oxides, C-rich
- ★ Dust composition in the least dusty regime: Pyroxenes, Fe, C-rich

Comparison of dust depletion (in the WNM) and extinction suggests that:

- ★ PAH form in the colder and denser phase (not in the WNM)
- ★ We start connecting depletion clouds to 3D maps

thank you!

Refractory index

Element X	A2 _x	B2 _x
C	0.00	−0.10±0.10
P	0.08±0.05	−0.26 ± 0.08
O	0.00	−0.20 ± 0.05
Cl	0.00	−0.12 ± 0.09
Kr	0.00	−0.04 ± 0.09
S	0.01 ± 0.02	−0.48 ± 0.04
Zn	0.00 ± 0.01	−0.27 ± 0.03
Ge	0.00	−0.40 ± 0.04
Mg	0.01 ± 0.03	−0.66 ± 0.04
Si	−0.04 ± 0.02	−0.75 ± 0.03
Cu	0.00	−0.73 ± 0.04
Co	0.00	−0.89 ± 0.19
Mn	0.07 ± 0.02	−1.03 ± 0.03
Cr	0.12 ± 0.01	−1.30 ± 0.01
Ni	0.07 ± 0.02	−1.31 ± 0.03
Fe	−0.01 ± 0.03	−1.26 ± 0.04
Al	0.00	−1.66 ± 0.35
Ti	−0.07 ± 0.03	−1.67 ± 0.04

Konstantopoulou, De Cia, et al. 2022

X	B _X	ν
Kr	−0.05 ± 0.01	33
Cl	−0.06 ± 0.02	30
C	−0.07 ± 0.02	5
P	−0.27 ± 0.02	51
Zn	−0.29 ± 0.07	9
Ge	−0.29 ± 0.03	61
Cu	−0.67 ± 0.02	40
Fe	−1.24 ± 0.02	37
Cr	−1.26 ± 0.04	12
Ni	−1.28 ± 0.02	59
α-elements ^(a)		
O	−0.06 ± 0.01	61
Mg	−0.63 ± 0.02	63
Si	−0.68 ± 0.04	8
Ti	−1.64 ± 0.03	39

Konstantopoulou, De Cia, et al. 2024b, DUNE