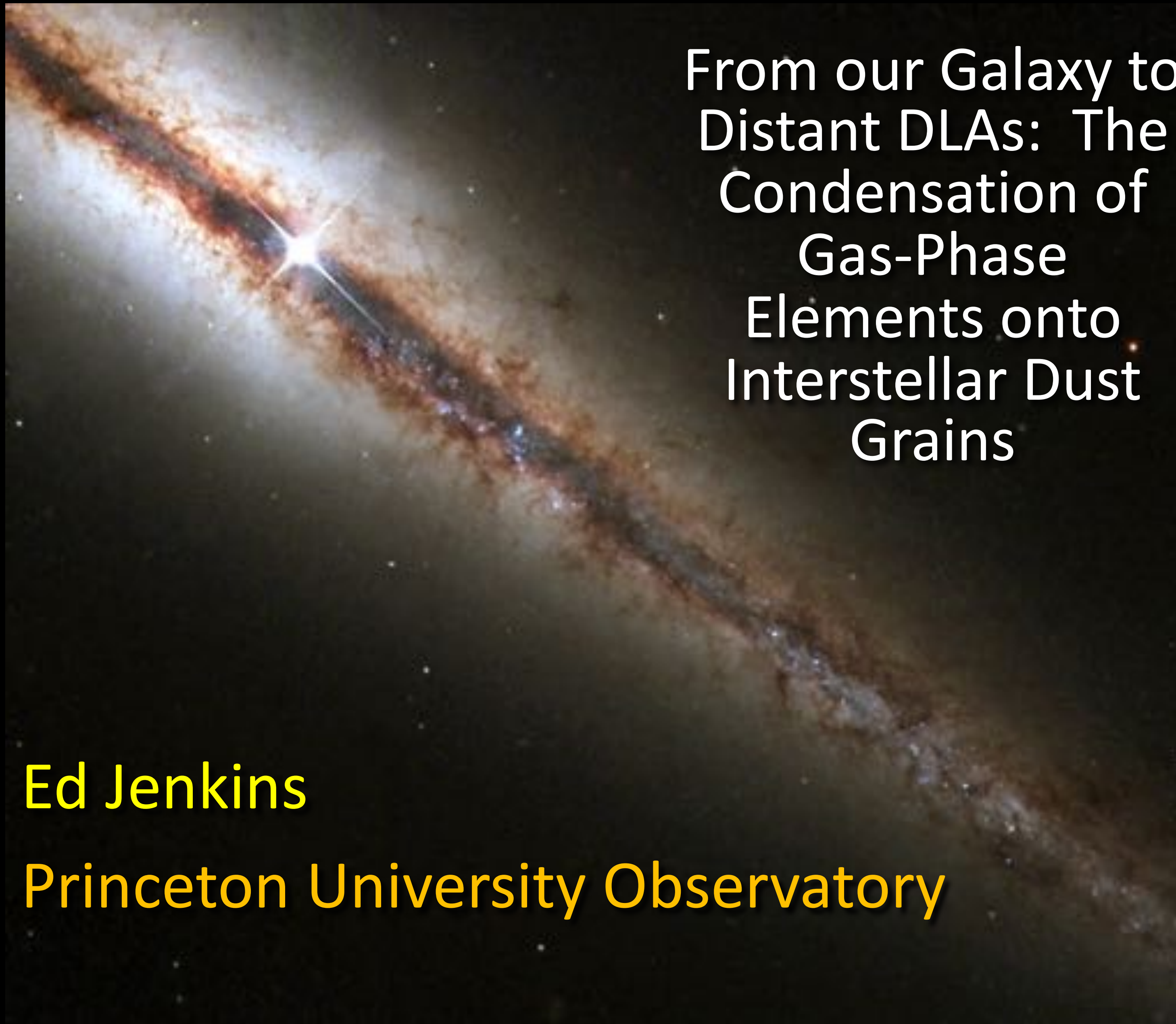

From our Galaxy to Distant DLAs: The Condensation of Gas-Phase Elements onto Interstellar Dust Grains

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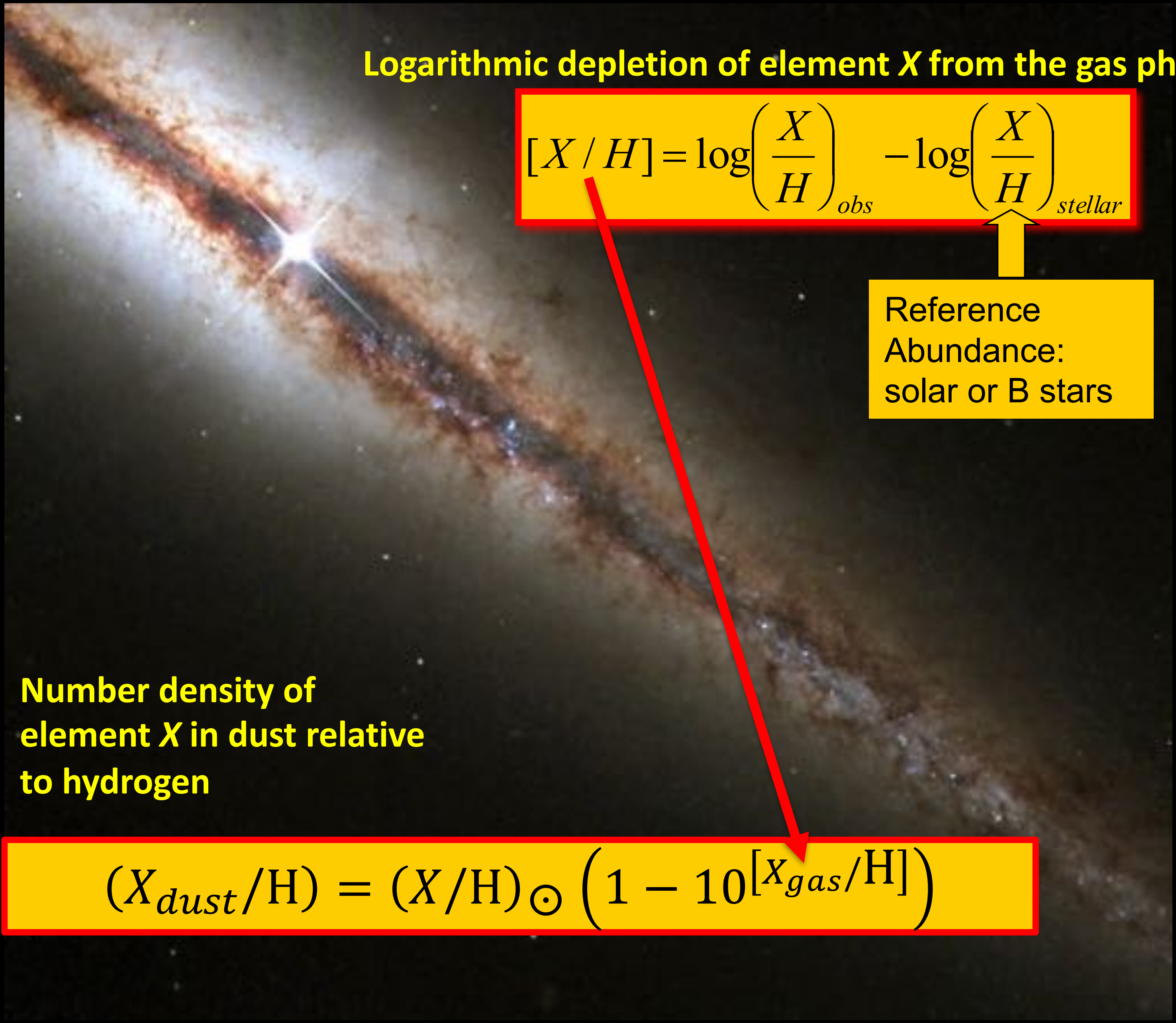


Logarithmic depletion of element *X* from the gas phase

$$[X/H] = \log\left(\frac{X}{H}\right)_{obs} - \log\left(\frac{X}{H}\right)_{stellar}$$

Reference Abundance: solar or B stars

Number density of element *X* in dust relative to hydrogen

$$(X_{dust}/\mathrm{H}) = (X/\mathrm{H})_{\odot}\left(1 - 10^{[X_{gas}/\mathrm{H}]}\right)$$

What has been Known for some Time

- Depletions vary from one location to the next
  - Sightlines with low average density N(H)/d have less depletion
  - Gas at high velocity displacements have less depletion: grains have been disrupted
- Depletions vary from one element to the next
  - Depletion strengths are greatest for elements that can form refractory compounds and are small for those that can only form volatile compounds

An Interpretation of Milky Way ISM Gas-Phase Abundances Reported in the Literature

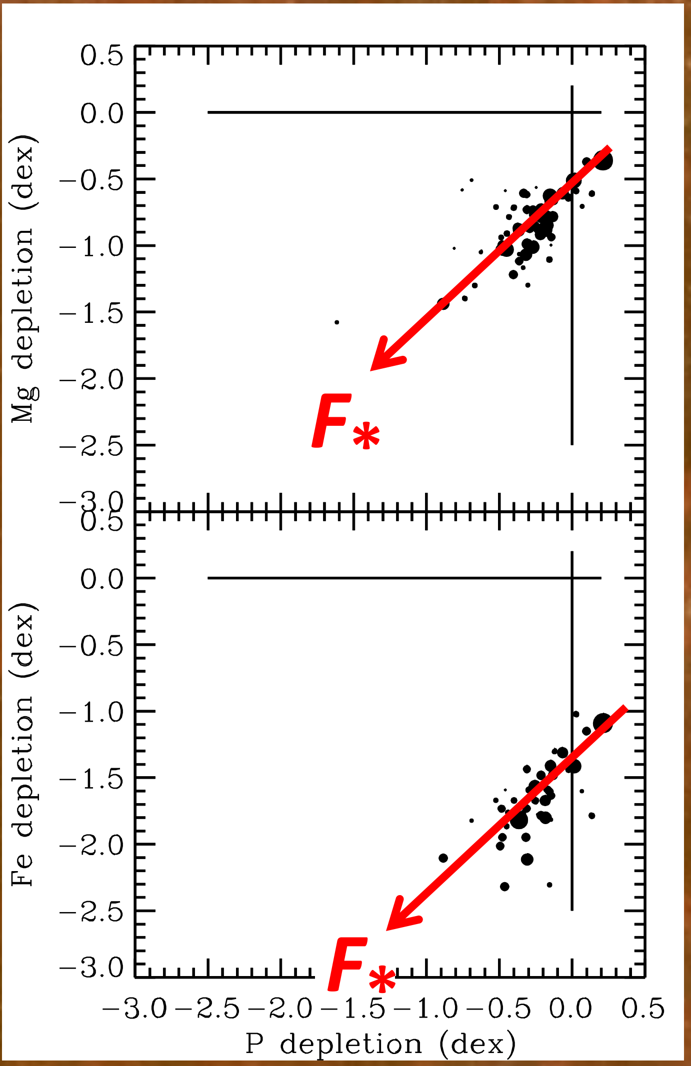
- Basic Tactic:
  - Adopt protosolar abundances as a reference standard
  - Ignore the sightline properties and characterize depletions of elements with respect to each other, recognizing that the severity of depletions differ from one element to the next and from one region of space to the next.

Published by Jenkins (2009: ApJ, 700, 1299)

Underlying Strategy

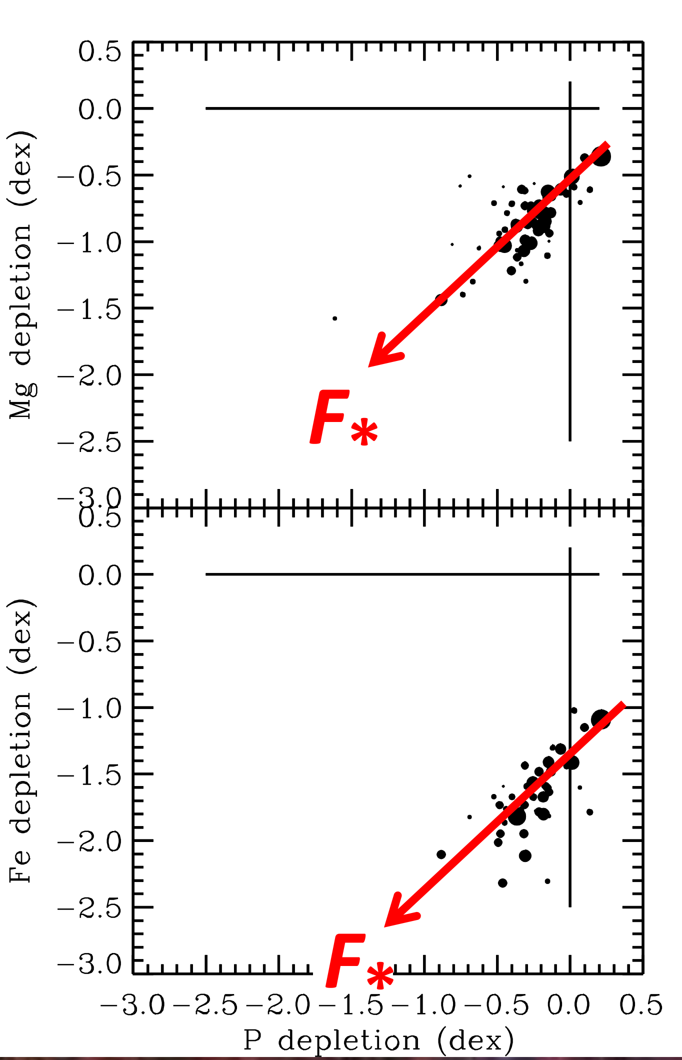
- Basic premise:
  - All elements deplete together in some systematic fashion, but by differing degrees that change from one region to another and from one element to the next.
  - Propose a single parameter, $\boxed{F_*}$, that expresses a general level of depletion along a sight line.

(F_* is much like <n(H)> that has been used in the past.)



Underlying Strategy

- Another basic premise:
  - Differences in how the elements respond to changes in F_* are represented by other parameters specific to each element.

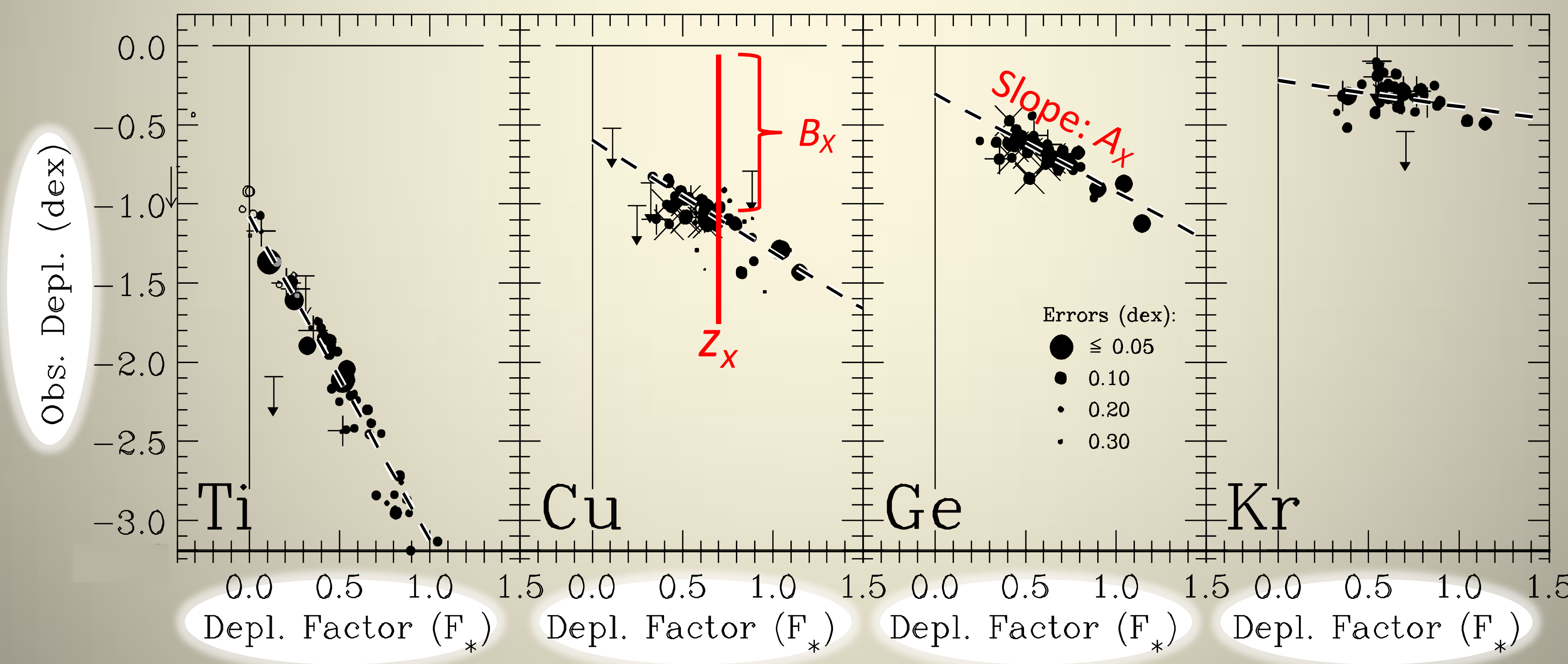


Basic Equation

For element *X*:

Logarithmic Depletion factor

$$\boxed{[X_{gas}/\mathrm{H}]} = B_X + A_X(F_* - z_X)$$

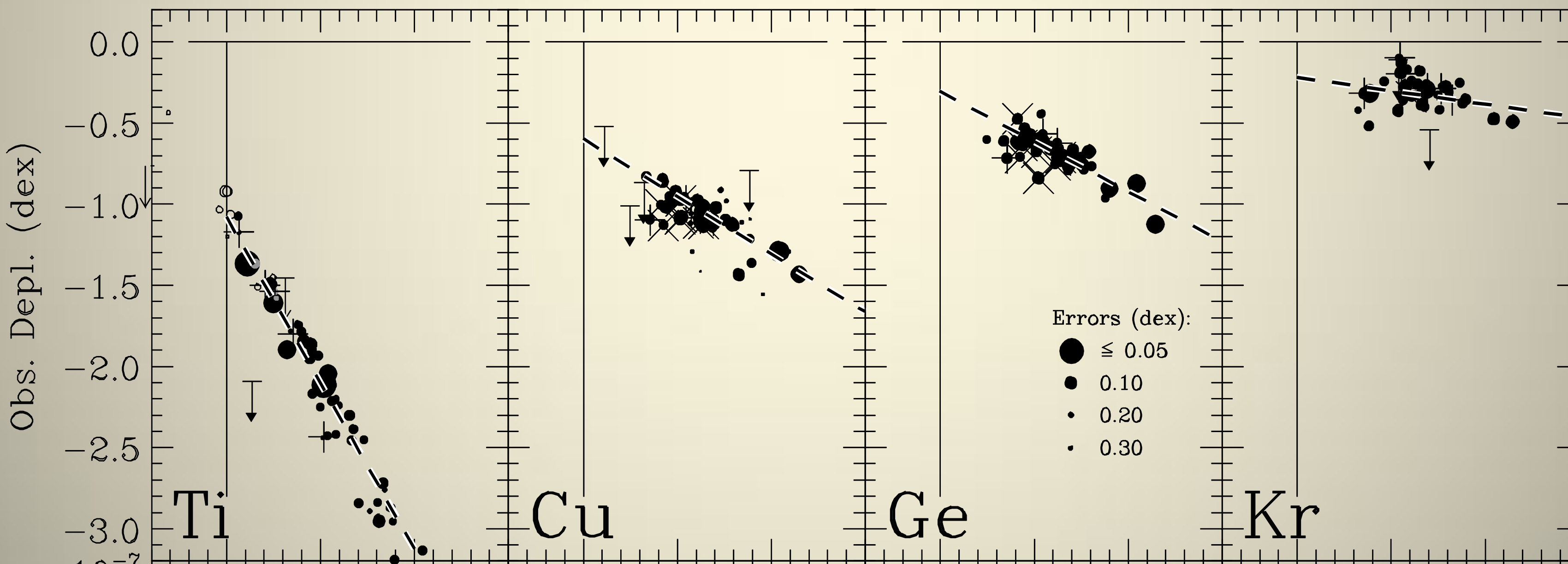


The Buildup of Dust Grains

Conventional Formula:

$$(X_{dust}/\mathrm{H}) = (\mathrm{X/H})_{\odot}(1-10^{[X_{gas}/\mathrm{H}]})$$

$|A_X|$ is a rate constant for element condensation

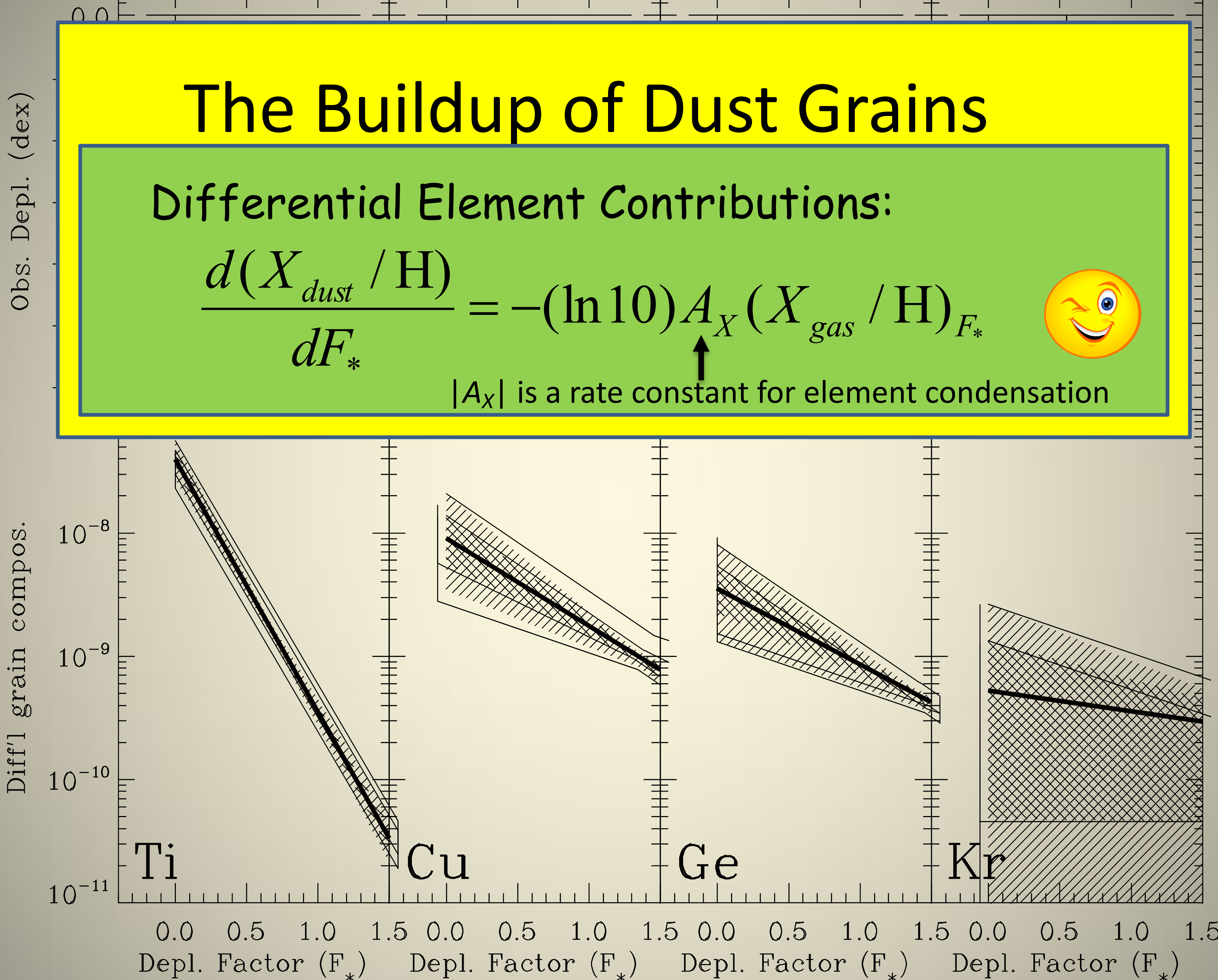


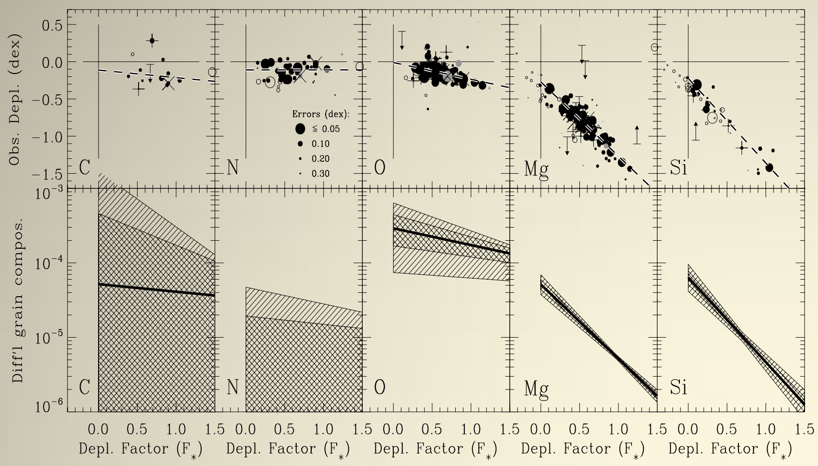
The Buildup of Dust Grains

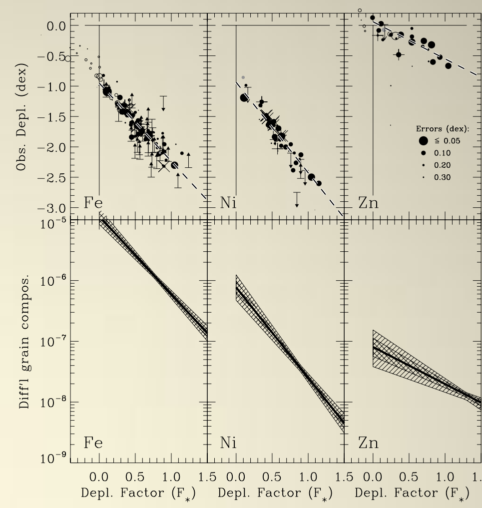
Differential Element Contributions:

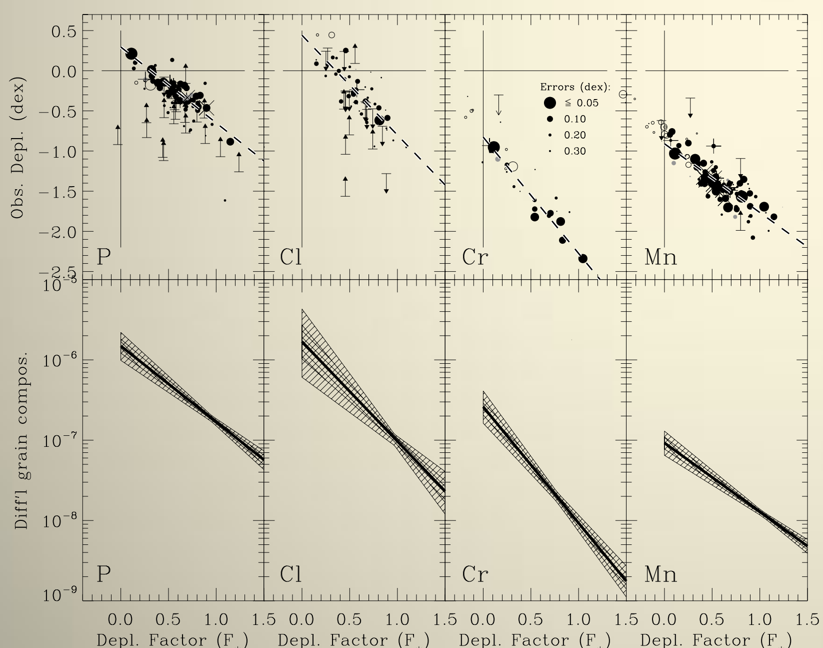
$$\frac{d(X_{dust}/\mathrm{H})}{dF_*} = -(\ln 10)\,A_X\,(X_{gas}/\mathrm{H})_{F_*}$$

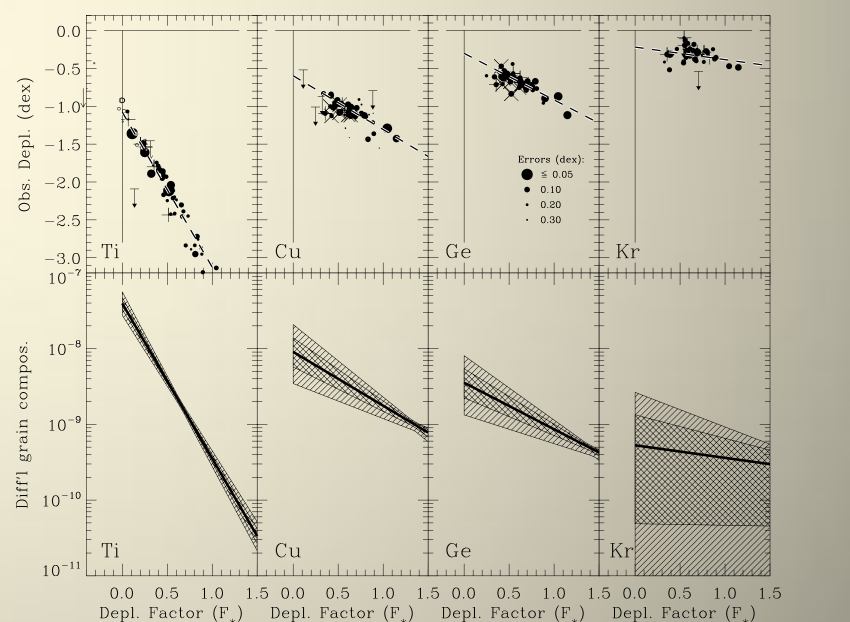
$|A_X|$ is a rate constant for element condensation



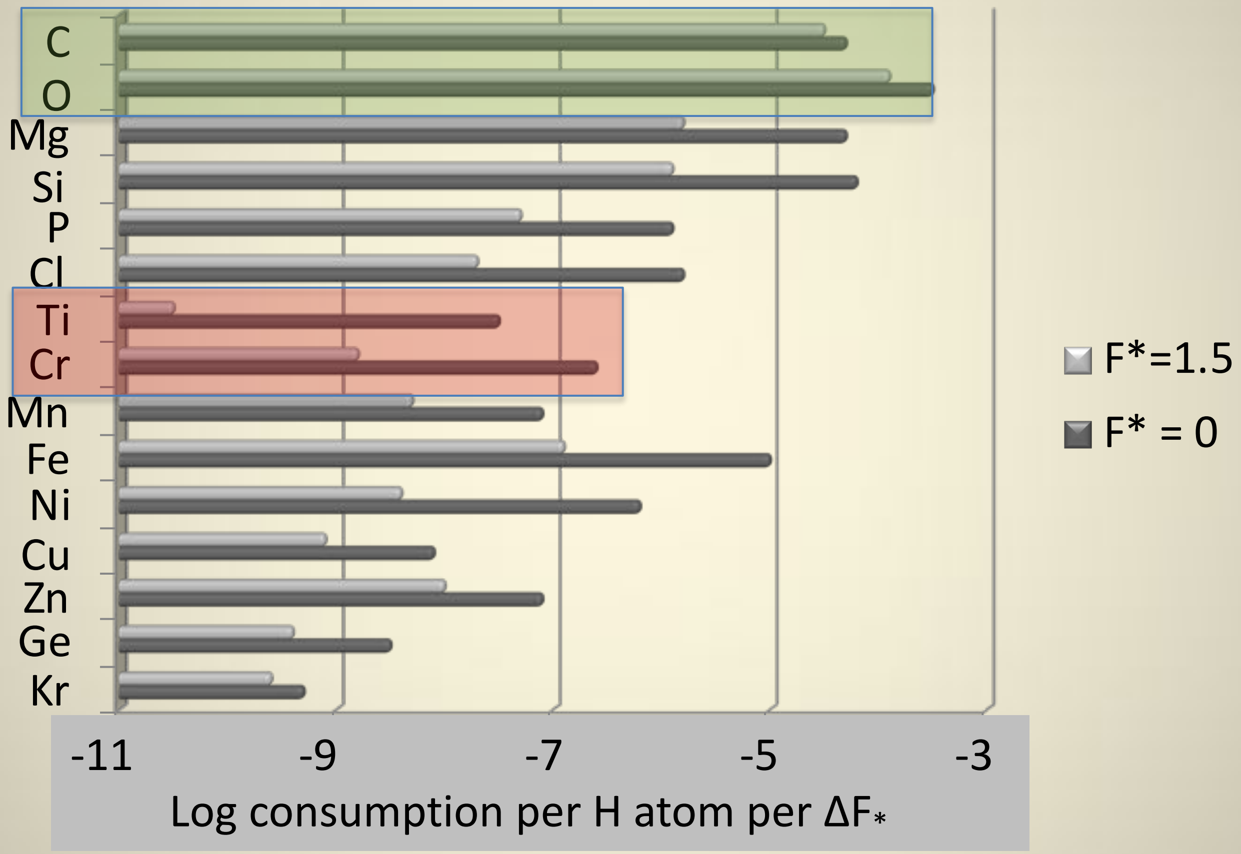

Obs. Depl. (dex)
Diff'l grain compos.
Depl. Factor (F*)
Errors (dex):
≤ 0.05
0.10
0.20
0.30
C
N
O
Mg
Si


Obs. Depl. (dex)
Diff'l grain compos.
Depl. Factor (F*)
Errors (dex):
≤ 0.05
0.10
0.20
0.30
Fe
Ni
Zn


Obs. Depl. (dex)
Diff'l grain compos.
Depl. Factor (F*)
Errors (dex):
≤ 0.05
0.10
0.20
0.30
P
Cl
Cr
Mn


Obs. Depl. (dex)
Diff'l grain compos.
Depl. Factor (F*)
Errors (dex):
≤ 0.05
0.10
0.20
0.30
Ti
Cu
Ge
Kr

Summary of Element Consumption Rates



(Mass of elements in dust)/(total element mass) = 0.20 ($F_* = 0$)

0.54 ($F_* = 1$)

Average Density of Dispersed Solids

Number of grains per unit area in a column of length *d*

Radius of each grain

Refractive index at low freq.

Optical depth over a distance *d*

$$\tau = N_g \pi a^2 Q_e$$

$$\int_0^\infty Q_e \, d\lambda = 4\pi^2 a \left(\frac{m^2 - 1}{m^2 + 2} \right)$$

Grain volume

Internal density

Extinction efficiency factor

An application of the Kramers-Kronig dispersion relation by Purcell (1969, ApJ, 158, 433)

$$<\rho_g> = \frac{N_g}{d} \times \frac{4\pi a^3}{3} \times \rho_s$$

$$\boxed{N_g = \left(\frac{\int_0^\infty \tau \, d\lambda}{4\pi^3 a^3} \right) \left(\frac{m^2 + 2}{m^2 - 1} \right)}$$

$$<\rho_g> = \frac{1}{3\pi^2} \times \frac{\int_0^\infty \tau \, d\lambda}{d} \times \left(\frac{m^2 + 2}{m^2 - 1} \right) \times \rho_s$$

Average Density of Dispersed Solids

Combine A_V = 1.8 mag kpc^{-1} with relative extinctions from 1000 Å to 20 μm

Compare with Z/X in the Sun

≈ 3

≈ 2 for most substances

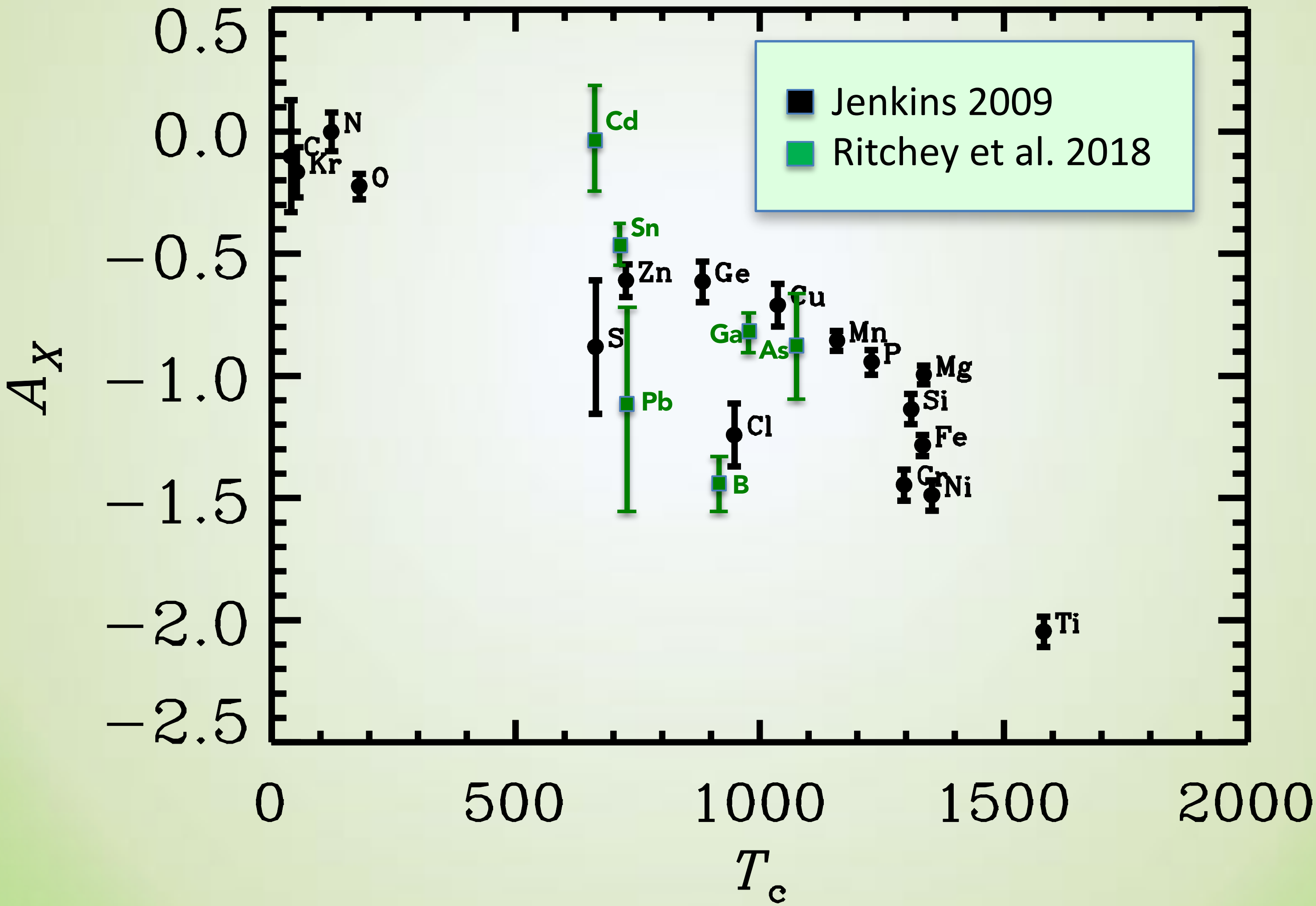
0.018

$$<\rho_g> = 1.8\times 10^{-26}\,\mathrm{g\,cm^{-3}} = 0.006 <\rho_{\mathrm{H}}>$$

$$<\rho_g> = \frac{1}{3\pi^2}\times\boxed{\frac{\int_0^\infty \tau d\lambda}{d}}\times\boxed{\left(\frac{m^2+2}{m^2-1}\right)}\times\rho_s$$

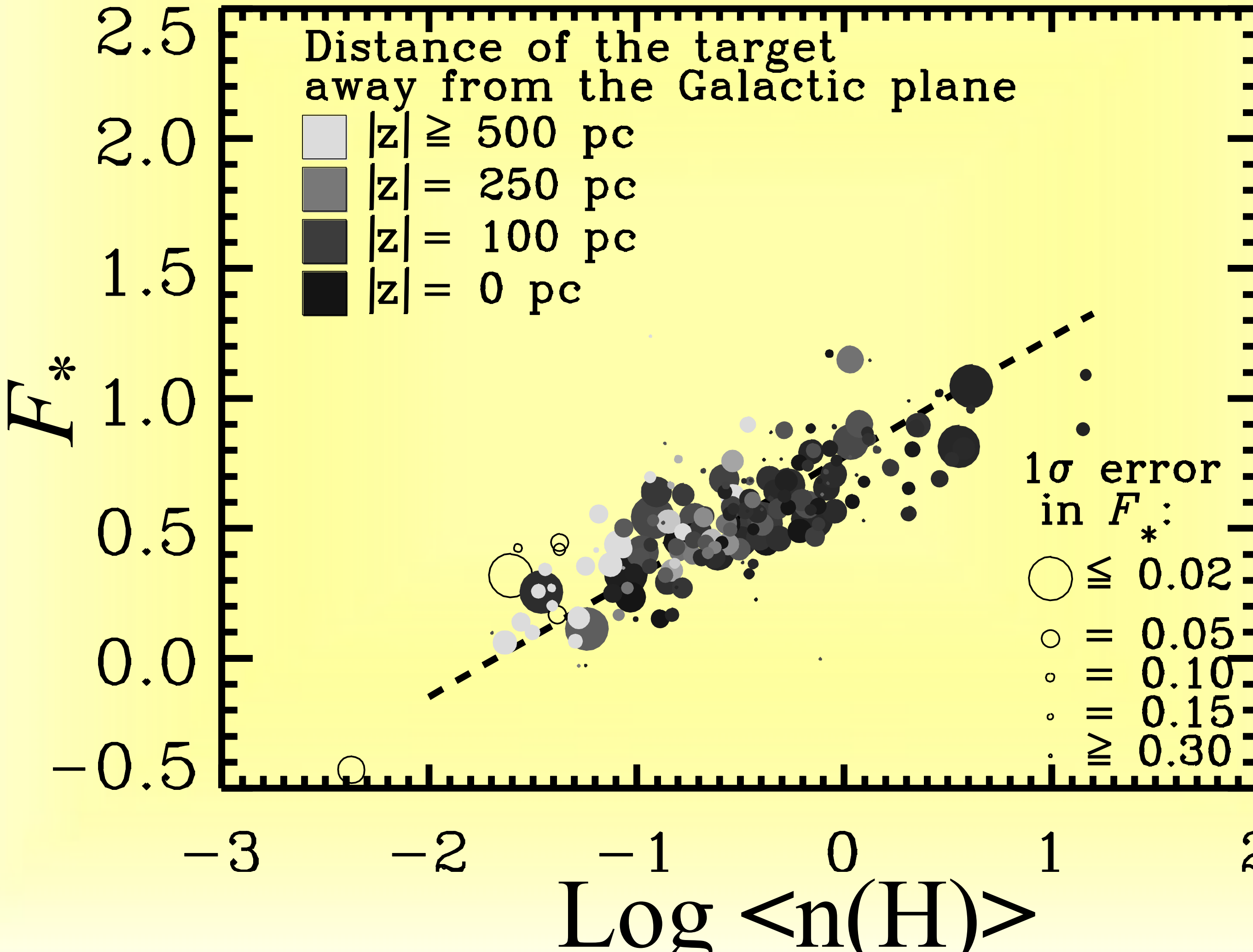
(Mass of elements in dust)/(total element mass) = 0.20 (F_* = 0)
0.54 (F_* = 1)

Depletion Trends against Condensation Temperatures

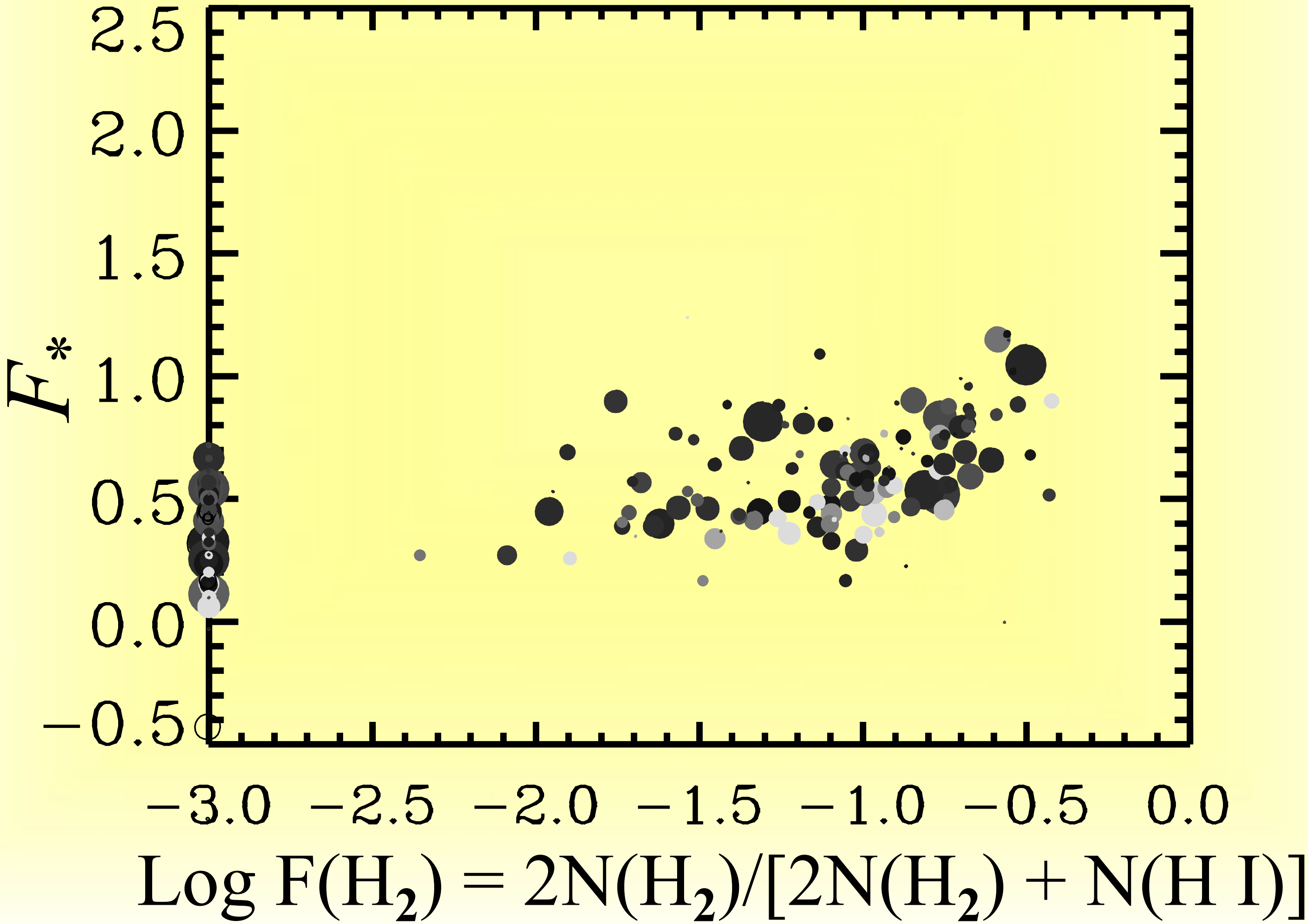


Sightlines

Trends of Overall Depletion Strengths



Trends of Overall Depletion Strengths



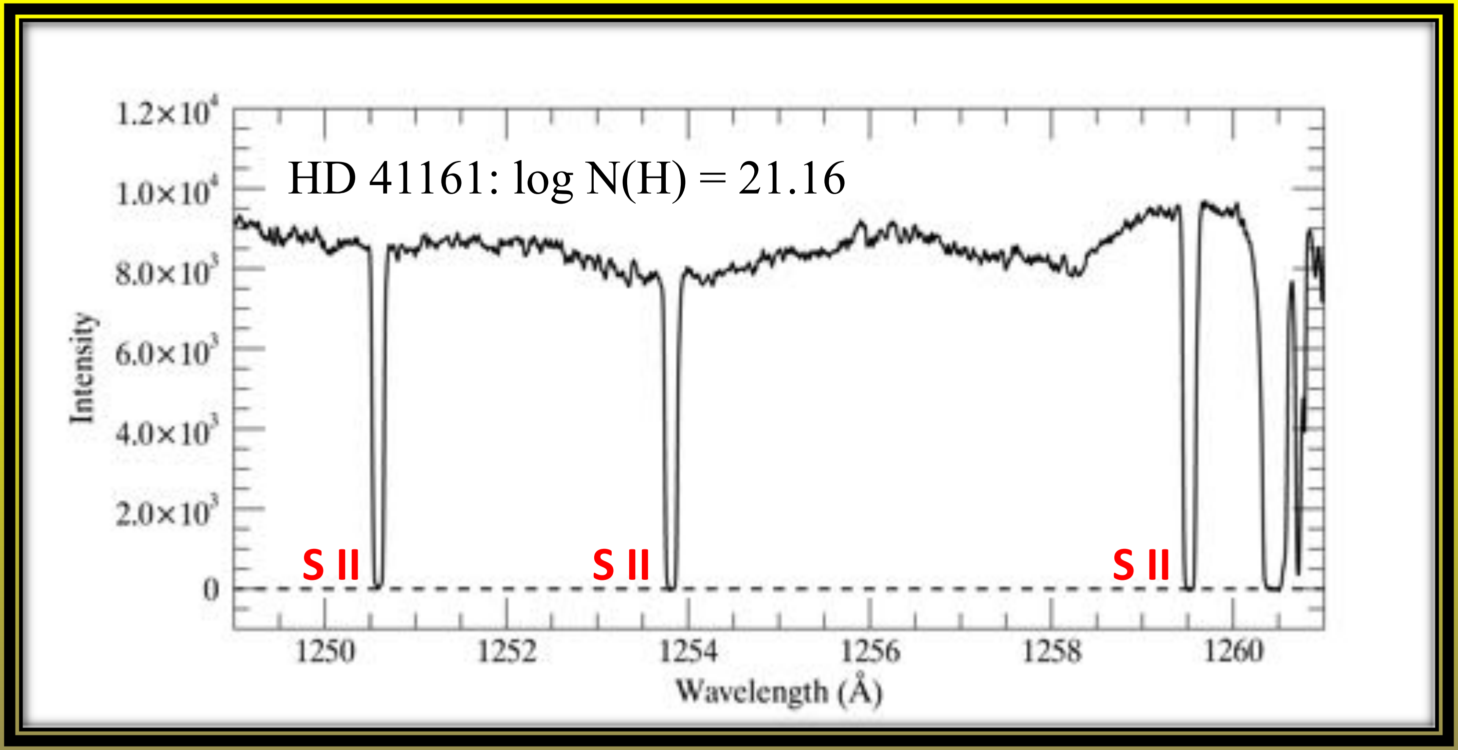
Some Notes about Specific Elements

Three noteworthy cases:

S, O, and Kr

Sulfur

- A problem element: many investigators have proposed that S is undepleted.
- Results may be misleading …



Sulfur

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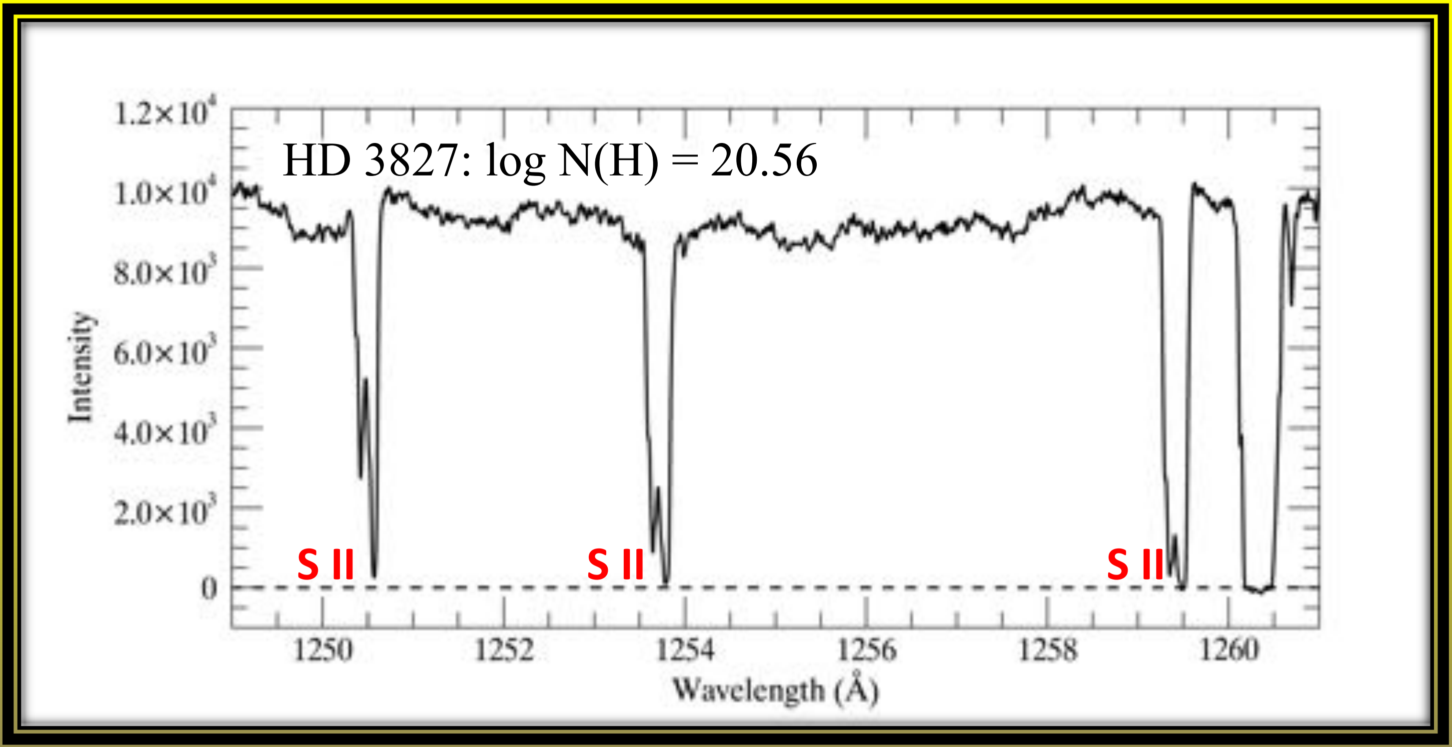
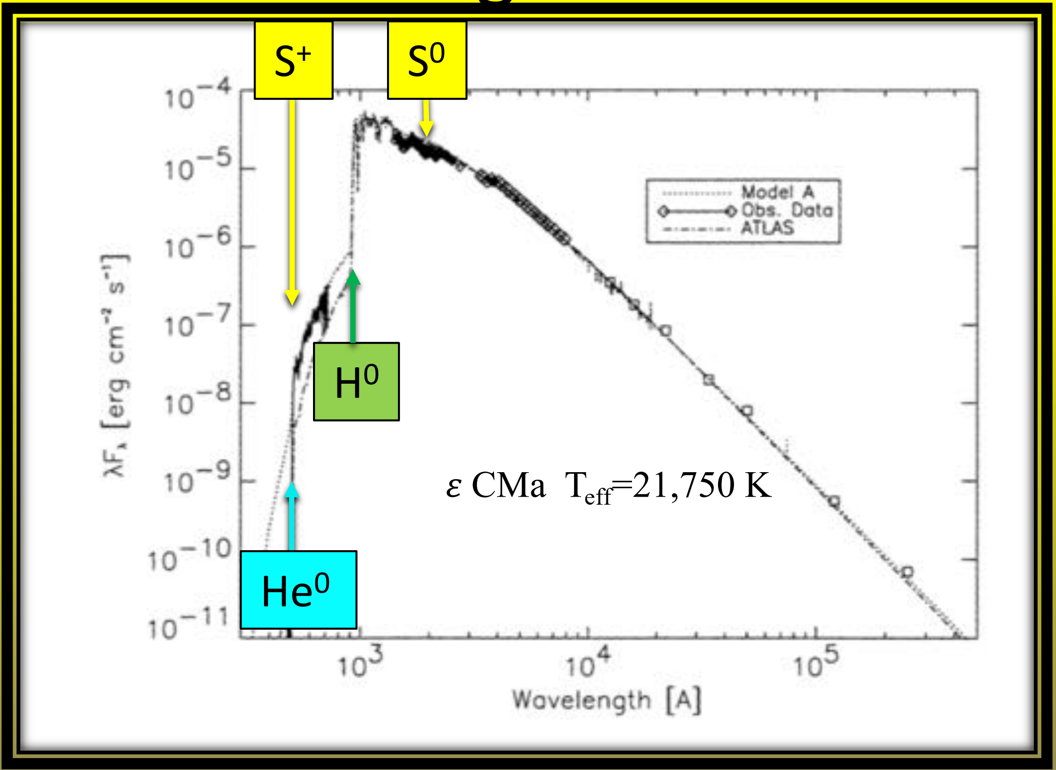


Sulfur

- A problem element: many investigators have proposed that S is undepleted.
- Results may be misleading …

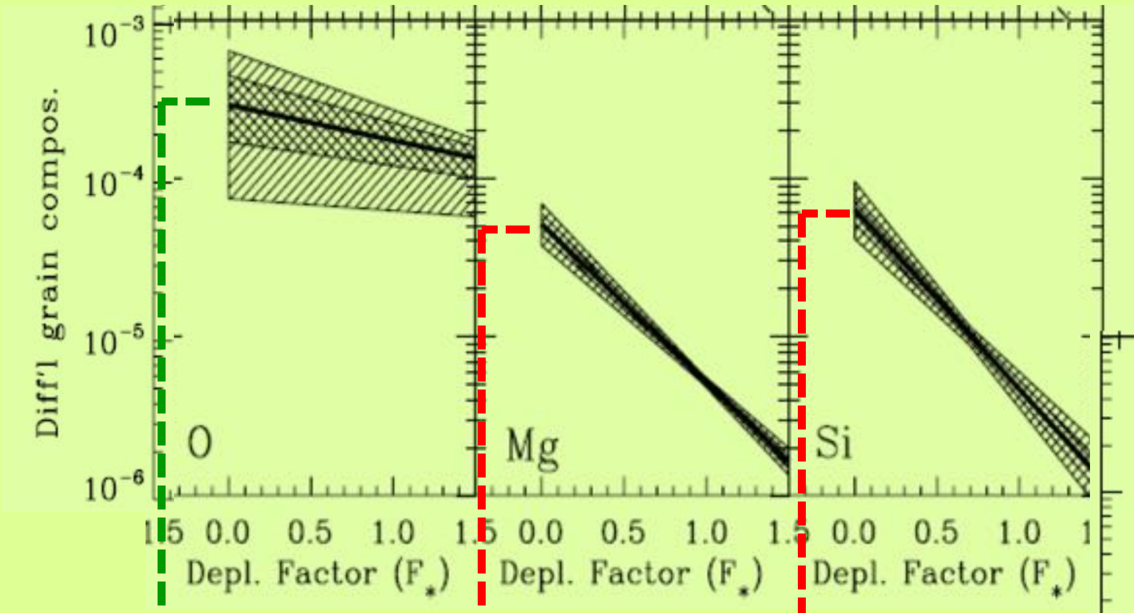
Inside the star's H II region, H is fully ionized, but S is only singly ionized. This can raise the amount of S II without increasing H I.

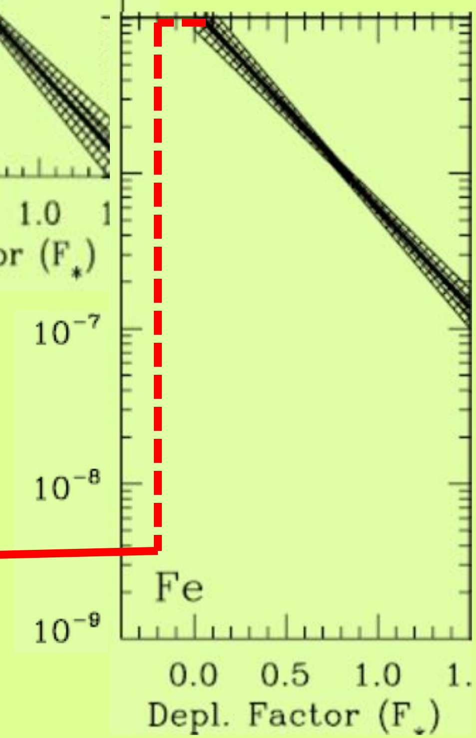


The Consumption of Oxygen Compared to other Elements

- Conventional view: oxygen is mostly incorporated into refractory compounds such as silicates and oxides.
- Let's examine whether or not this is consistent with our determinations of $d(X_{\rm dust}/{\rm H})/dF_*$

The Consumption of Oxygen Compared to other Elements



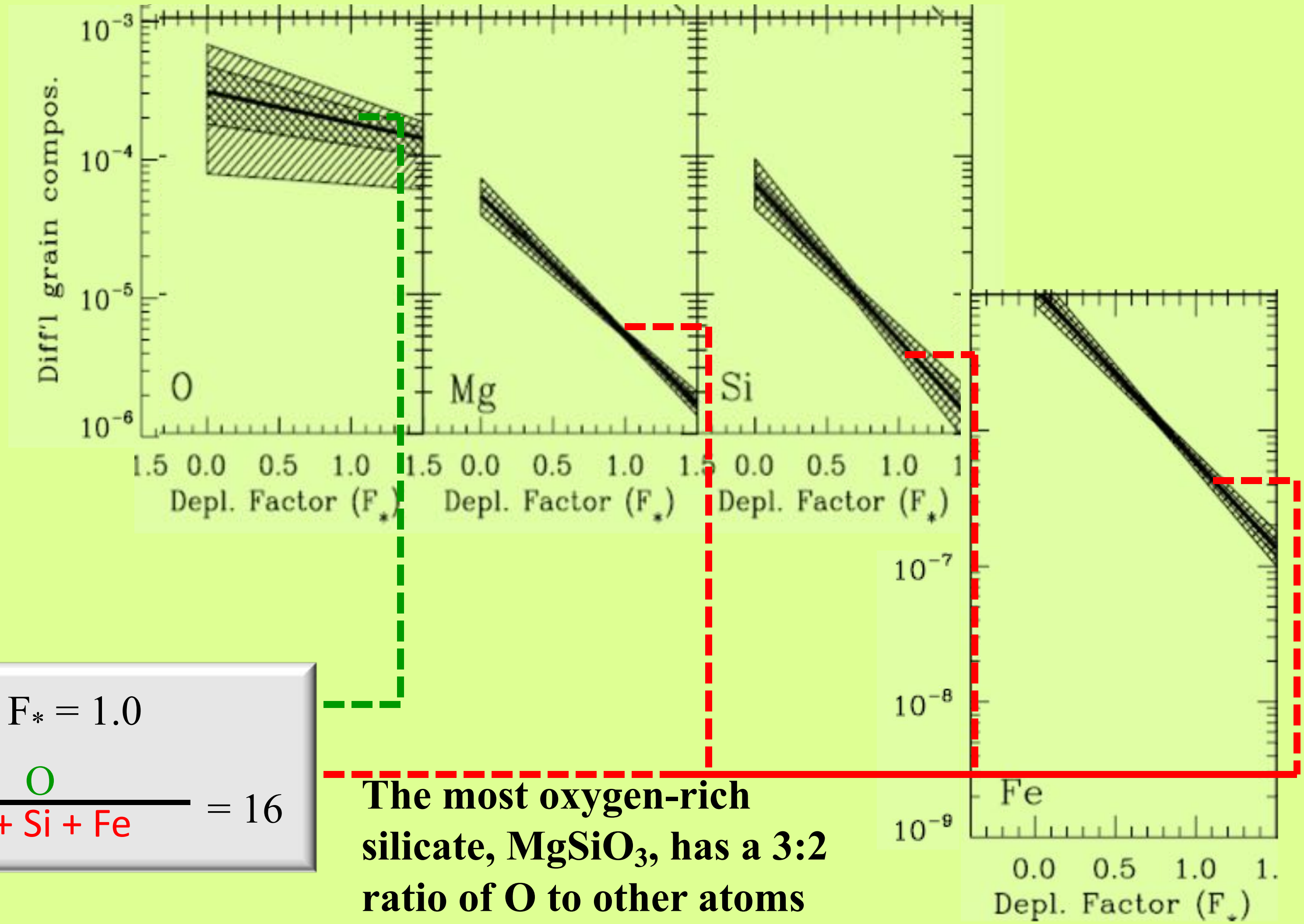


At $F_* = 0.0$

$$\frac{O}{Mg + Si + Fe} = 2.3$$

The most oxygen-rich silicate, $MgSiO_3$, has a 3:2 ratio of O to other atoms

The Consumption of Oxygen Compared to other Elements



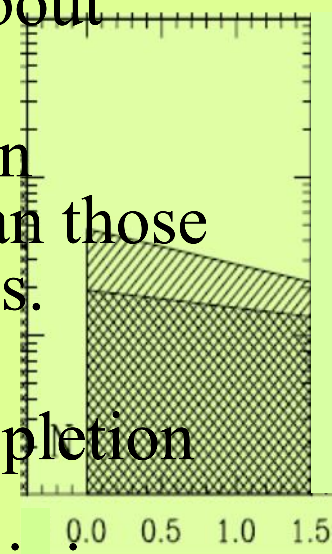
At $F_* = 1.0$

$$\frac{\text{O}}{\text{Mg + Si + Fe}} = 16$$

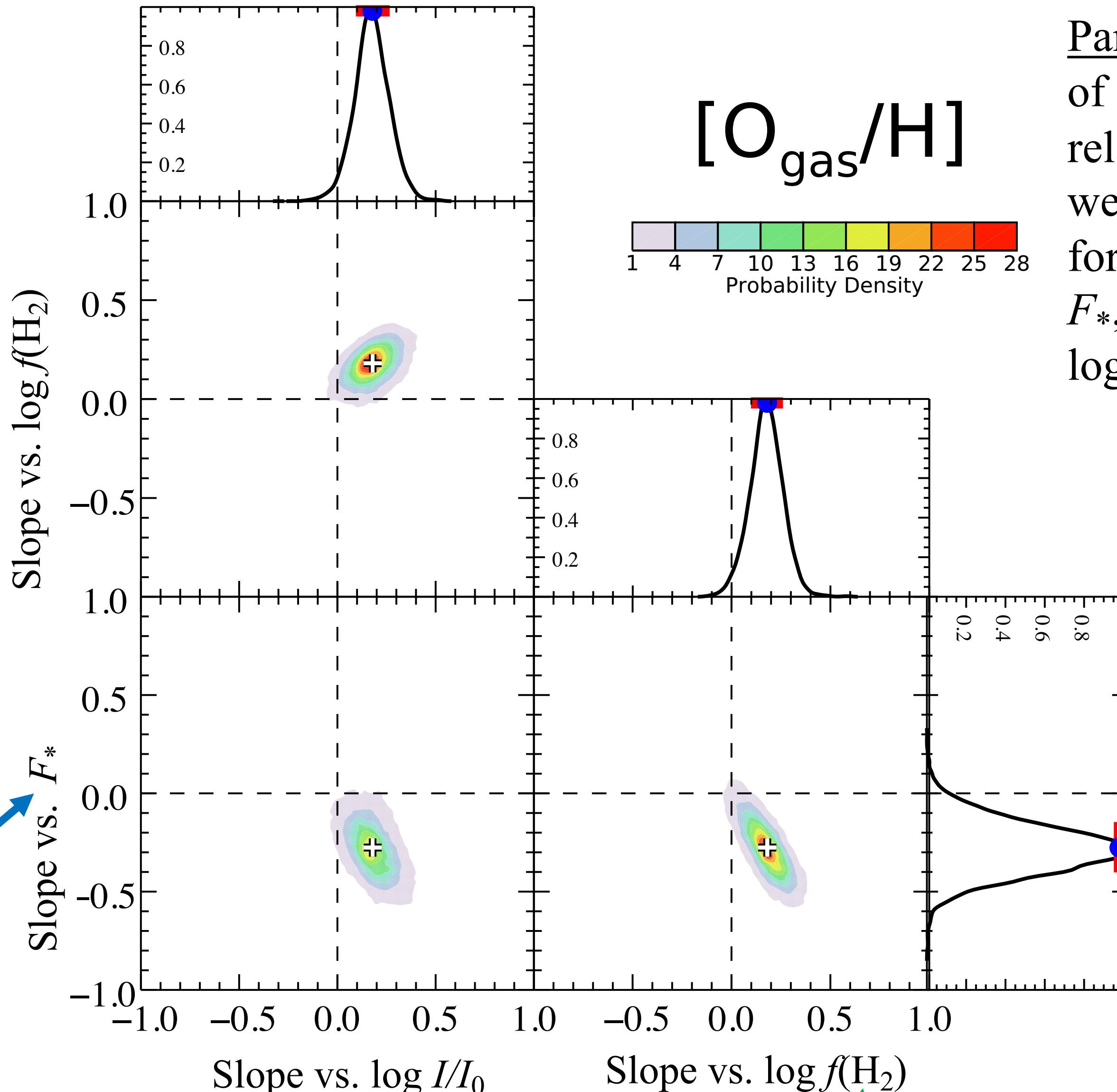
The most oxygen-rich silicate, $MgSiO_3$, has a 3:2 ratio of O to other atoms

The Consumption of Oxygen Compared to other Elements

- Conclusion: In addition to forming silicates, O must deplete by forming some other compound using another abundant element.
  - Various oxides of N? Unlikely, since N does not seem to deplete (at least not appreciably more than about 10^{-5} per H atom per unit change in F_*).
  - H_2O? Perhaps, but 3.05 μm ice feature only seen toward regions with extinctions much larger than those of the lines of sight in the UV absorption studies.
  - CO, CO_2 and O_2 are present in the ISM, but in amounts that are not sufficient to explain the depletion of O.



Perhaps very large grains (diam. >> 1μm) containing appreciable amounts of H_2O are present but not visible?



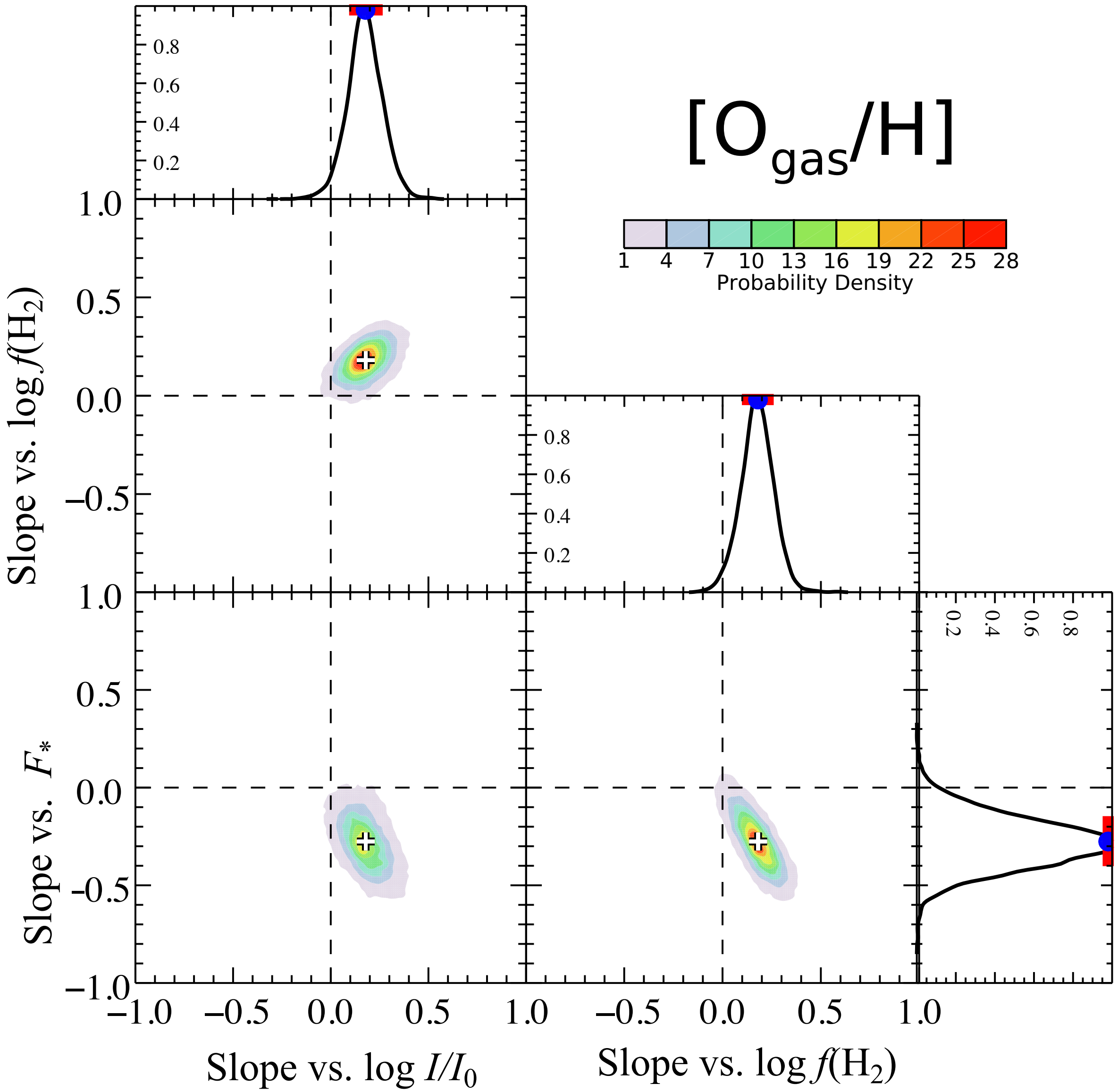
Partial correlations of O abundances relative to H$_{total}$ were investigated for the trends with F_*, log f(H$_2$) and log I/I_0.

O/H$_{total}$ shows positive correlations with log f(H$_2$) and log I/I_0, and a negative correlation with F_*.

Generalized depletion parameter

Relative starlight intensity

Fraction of hydrogen in molecular form



Interpretation:

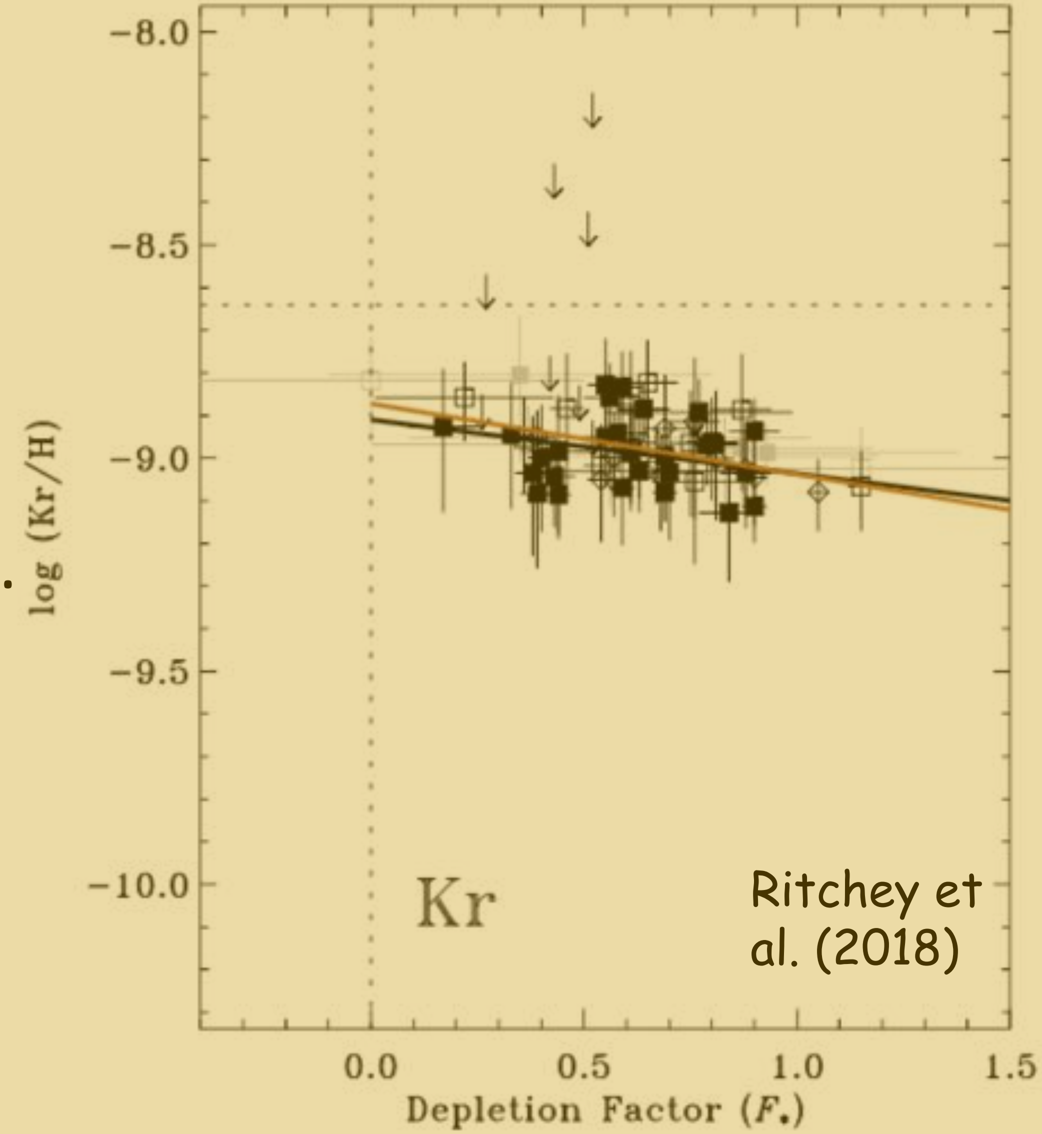
- Negative correlation with F_* no surprise, O follows other elements.
- Positive correlation with $f(H_2)$ seems counterintuitive: stronger molecular environment might favor reactions that create O-bearing molecules

A conjecture:

- $f(H_2) \propto n_H n_g / I = func(F_*)/I$
- If we could hold F_* and I constant, we'd expect f(H2) to also remain constant.
- A variation in [O_{gas}/H] with $f(H_2)$ indicates some factor(s) other than just F_* and I may influence $f(H_2)$ – perhaps grain size distribution, where surface to volume ratios could influence production efficiency.

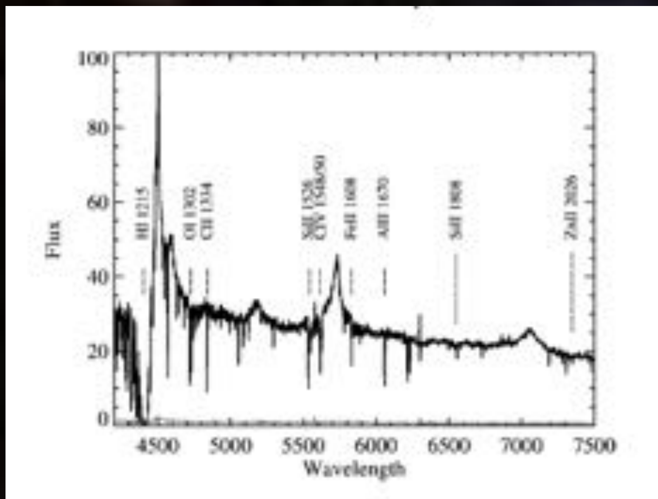
Krypton

- Chemically inert
- However, meteoritic studies and laboratory experiments indicate that heavy noble gases can bind to solids via enhanced physisorption.
- A negative correlation with I/I_0 may arise from the creation of active binding sites by UV radiation.



Ritchey et al. (2018)

Distant Absorption Line Systems



Basic Issues:

1. Absorption features in the spectrum of the quasar reveal column densities of the gas phases of various heavy elements and hydrogen.
2. Using the relationships of depletions seen in our Galaxy, can we interpret these outcomes in terms of a division between gas-phase and solid-phase abundances?

Galaxy that produces a Damped Lyman-α (DLA) absorption system in the quasar spectrum

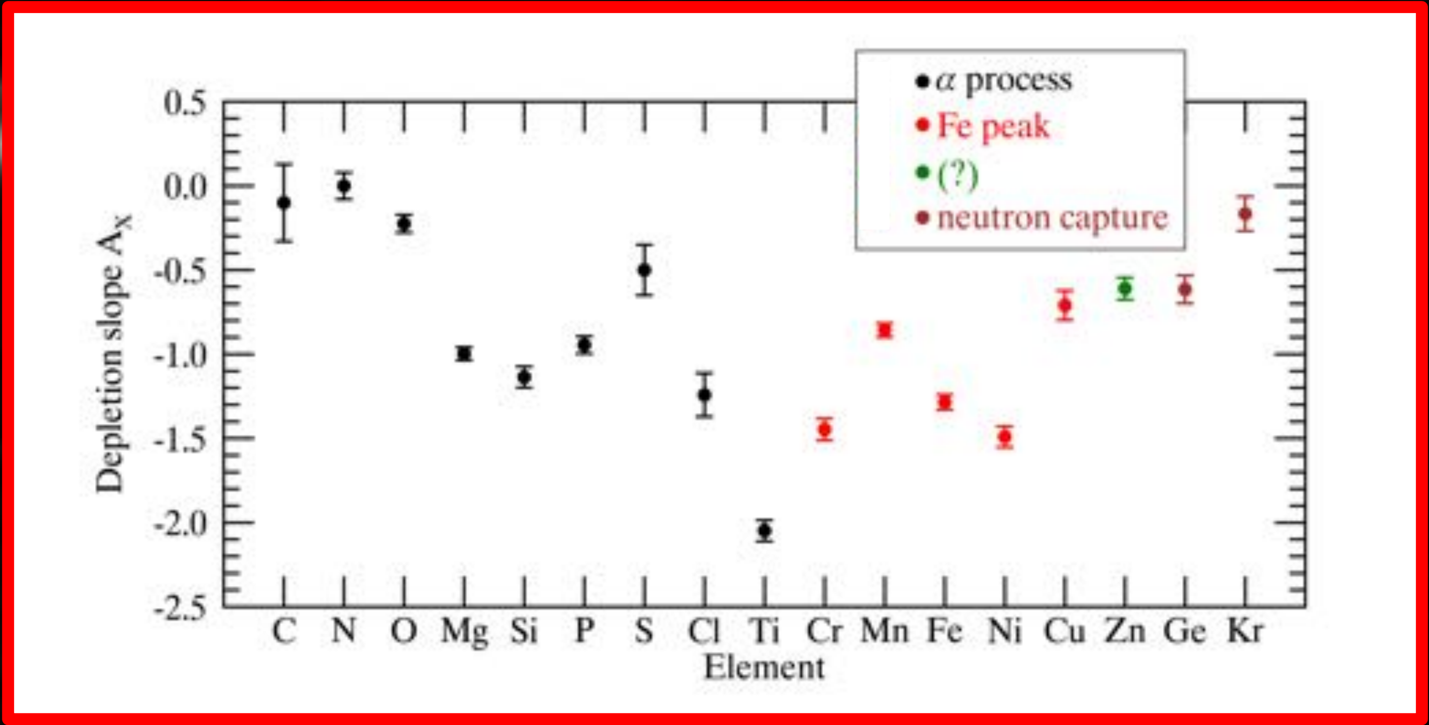
Background Quasar

Our Objectives

1. For each absorption system, what is the overall metallicity of the gas [M/H] compared to solar abundances?
2. What proportion of the matter in the gas has condensed onto dust grains?
3. What is the overall behavior of the above two properties in various systems as a function of z(abs)?

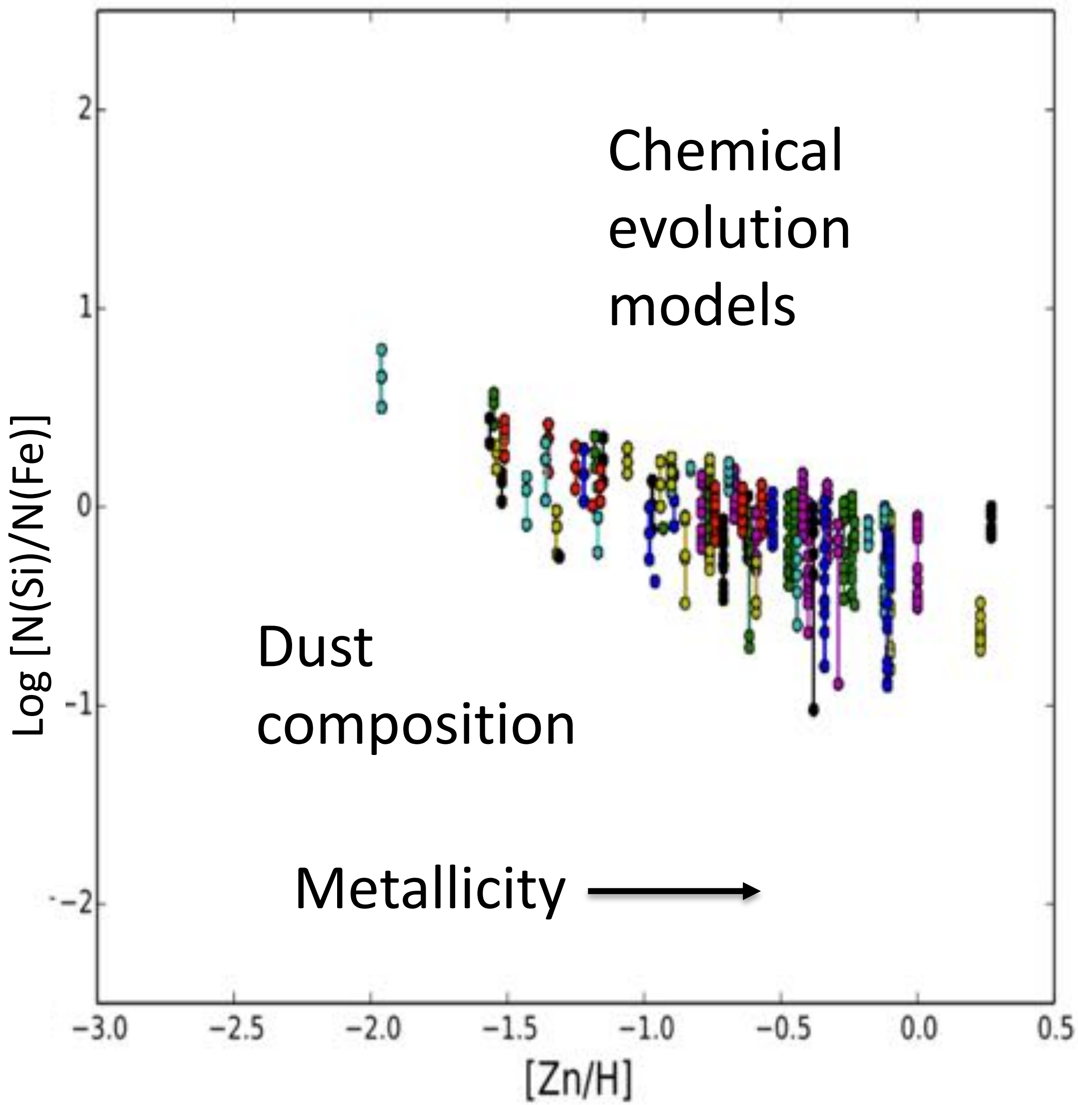
How this can be done

- Basic strategy: use differences in the rates of element depletions to differentiate between the effects of dust formation and low overall metallicities.
- A complication from chemical evolution: One must be aware of abundance differences between α-process and Fe-peak elements.



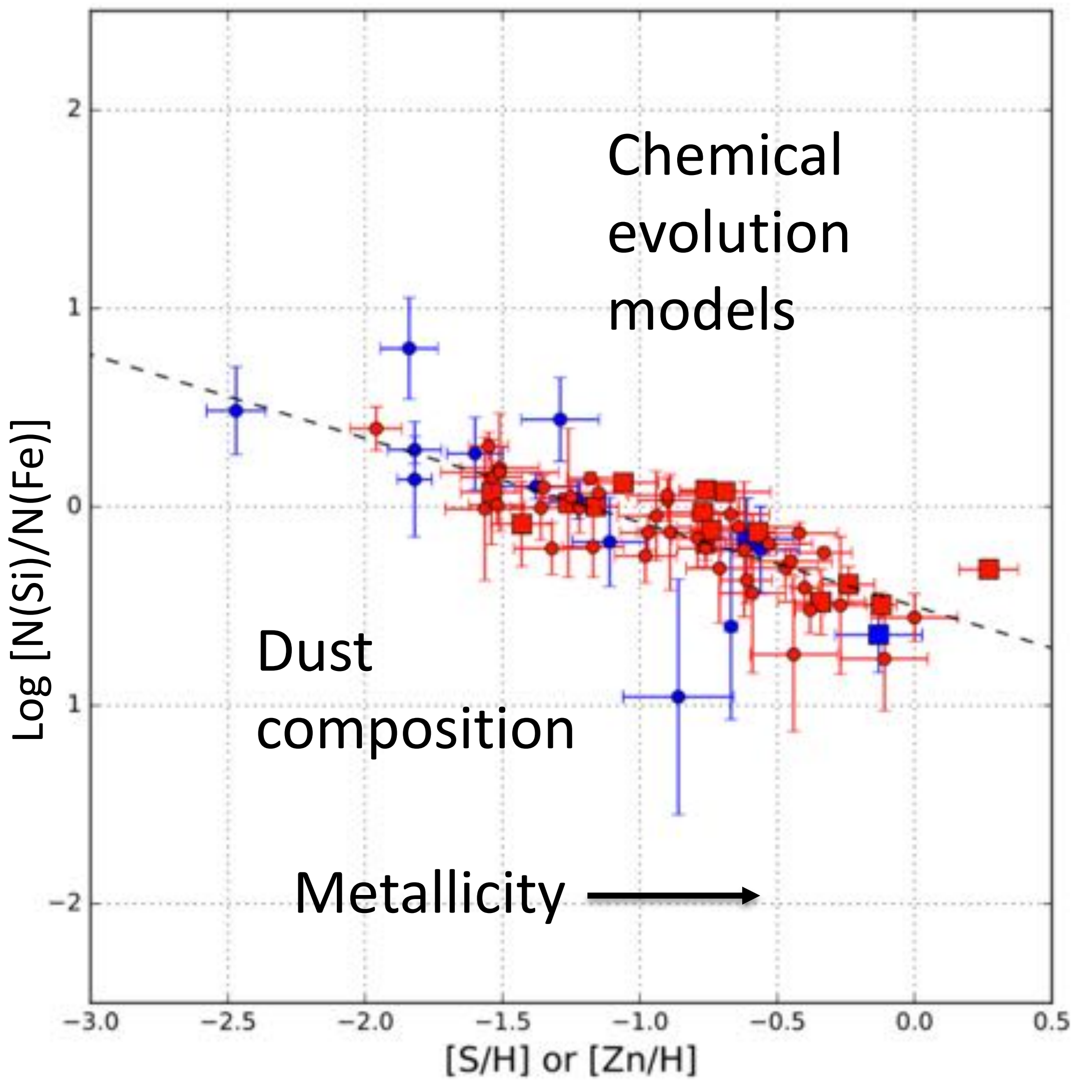
α process
Fe peak
(?)
neutron capture
Depletion slope A_X
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
C N O Mg Si P S Cl Ti Cr Mn Fe Ni Cu Zn Ge Kr
Element

Behavior of log(Si/Fe)$_{dust}$ vs metallicity



Vladilo et al. 2018, ApJ, 868, 127

Behavior of $\log(Si/Fe)_{dust}$ vs metallicity



Vladilo et al. 2018, ApJ, 868, 127

Recipe: Start with Depletion Coefficients

The basic equation:

$$[X_{gas}/\mathrm{H}] = B_X + A_X(F_* - z_X)$$

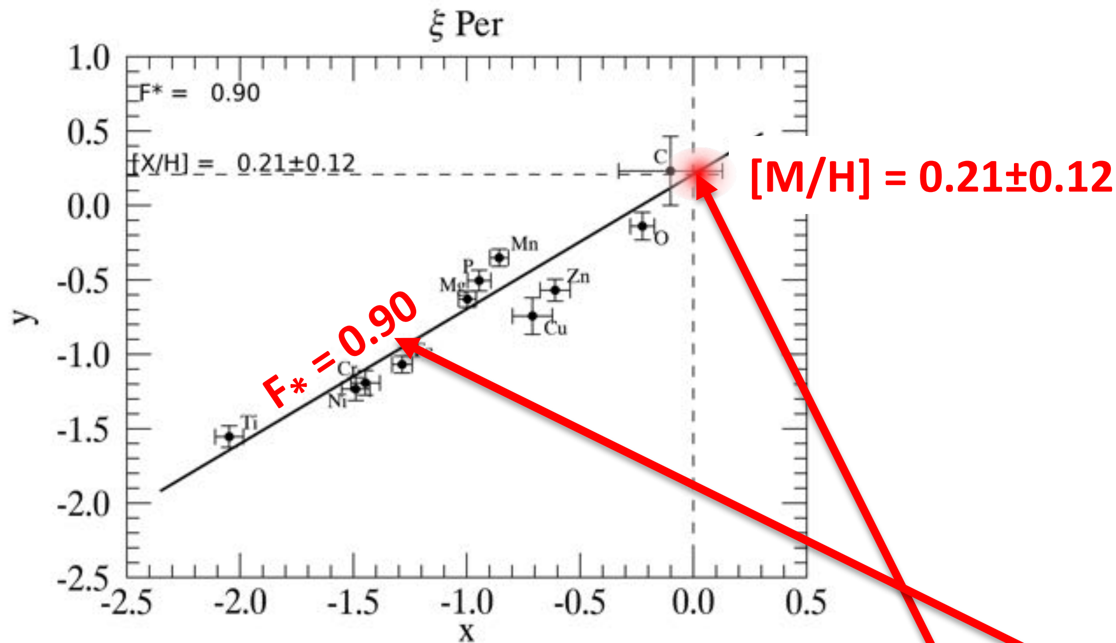
Elem. X Elem. X (1)	Log $(X/H)_\odot$ +12 Adopted $(X/\mathrm{H})_\odot$ [b] (2)	A_X A_X (3)	B_X B_X [c] (4)	z_X z_X (5)	$[X_{gas}/\mathrm{H}]_0$ [c] (6)	$[X_{gas}/\mathrm{H}]_1$ [c] (7)	χ^2 (8)	ν (9)	Prob. worse fit (10)
C	8.46 ± 0.04	−0.101 ± 0.229	−0.193 ± 0.060	0.803	−0.112 ± 0.194	−0.213 ± 0.075	3.7	8	0.881
N	7.90 ± 0.11	−0.000 ± 0.079	−0.109 ± 0.111	0.550	−0.109 ± 0.119	−0.109 ± 0.117	28.8	32	0.628
O	8.76 ± 0.05	−0.225 ± 0.053	−0.145 ± 0.051	0.598	−0.010 ± 0.060	−0.236 ± 0.055	75.0	64	0.164
Mg	7.62 ± 0.02	−0.997 ± 0.039	−0.800 ± 0.022	0.531	−0.270 ± 0.030	−1.267 ± 0.029	79.0	103	0.962
Si	7.61 ± 0.02	−1.136 ± 0.062	−0.570 ± 0.029	0.305	−0.223 ± 0.035	−1.359 ± 0.052	19.4	16	0.247
P	5.54 ± 0.04	−0.945 ± 0.051	−0.166 ± 0.042	0.488	0.296 ± 0.049	−0.649 ± 0.050	69.5	65	0.330
Cl	5.33 ± 0.06	−1.242 ± 0.129	−0.314 ± 0.065	0.609	0.442 ± 0.102	−0.800 ± 0.082	38.9	44	0.688
Ti	5.00 ± 0.03	−2.048 ± 0.062	−1.957 ± 0.033	0.430	−1.077 ± 0.043	−3.125 ± 0.049	50.7	43	0.195
Cr	5.72 ± 0.05	−1.447 ± 0.064	−1.508 ± 0.055	0.470	−0.827 ± 0.062	−2.274 ± 0.064	24.1	20	0.239
Mn	5.58 ± 0.03	−0.857 ± 0.041	−1.354 ± 0.032	0.520	−0.909 ± 0.038	−1.765 ± 0.038	106.3	83	0.043
Fe	7.54 ± 0.03	−1.285 ± 0.044	−1.513 ± 0.033	0.437	−0.951 ± 0.038	−2.236 ± 0.041	48.5	66	0.948
Ni	6.29 ± 0.03	−1.490 ± 0.062	−1.829 ± 0.035	0.599	−0.937 ± 0.051	−2.427 ± 0.043	30.7	34	0.630
Cu	4.34 ± 0.06	−0.710 ± 0.088	−1.102 ± 0.063	0.711	−0.597 ± 0.089	−1.307 ± 0.068	15.3	32	0.995
Zn	4.70 ± 0.04	−0.610 ± 0.066	−0.279 ± 0.045	0.555	0.059 ± 0.058	−0.551 ± 0.054	25.6	19	0.142
Ge	3.70 ± 0.05	−0.615 ± 0.083	−0.725 ± 0.054	0.690	−0.301 ± 0.078	−0.916 ± 0.059	12.4	24	0.975
Kr	3.36 ± 0.08	−0.166 ± 0.103	−0.332 ± 0.083	0.684	−0.218 ± 0.109	−0.384 ± 0.089	18.9	26	0.839

Recall that for any element
X in the ISM of our Galaxy,
its depletion is given by

But if the metallicity [M/H] of some
other system differs from that of our
Galaxy, we must add a new term

$$[X_{\mathrm{gas}}/\mathrm{H}] = \mathrm{Log}\ \mathrm{N}(X) - \mathrm{Log}\ \mathrm{N}(\mathrm{H}) - \mathrm{Log}\ (X/\mathrm{H})_{\odot} - [\mathrm{M}/\mathrm{H}] = B_X + A_X(F_* - z_X)$$

Rearrange Terms in this Formula



$$\underbrace{\mathrm{Log}\ N(X) - \mathrm{Log}\ N(\mathrm{H}) - \mathrm{Log}\ (X/\mathrm{H})_{\odot} - B_X + A_X z_X}_{y} = \boxed{[\mathrm{M/H}]} + \boxed{F_*}\ A_X$$

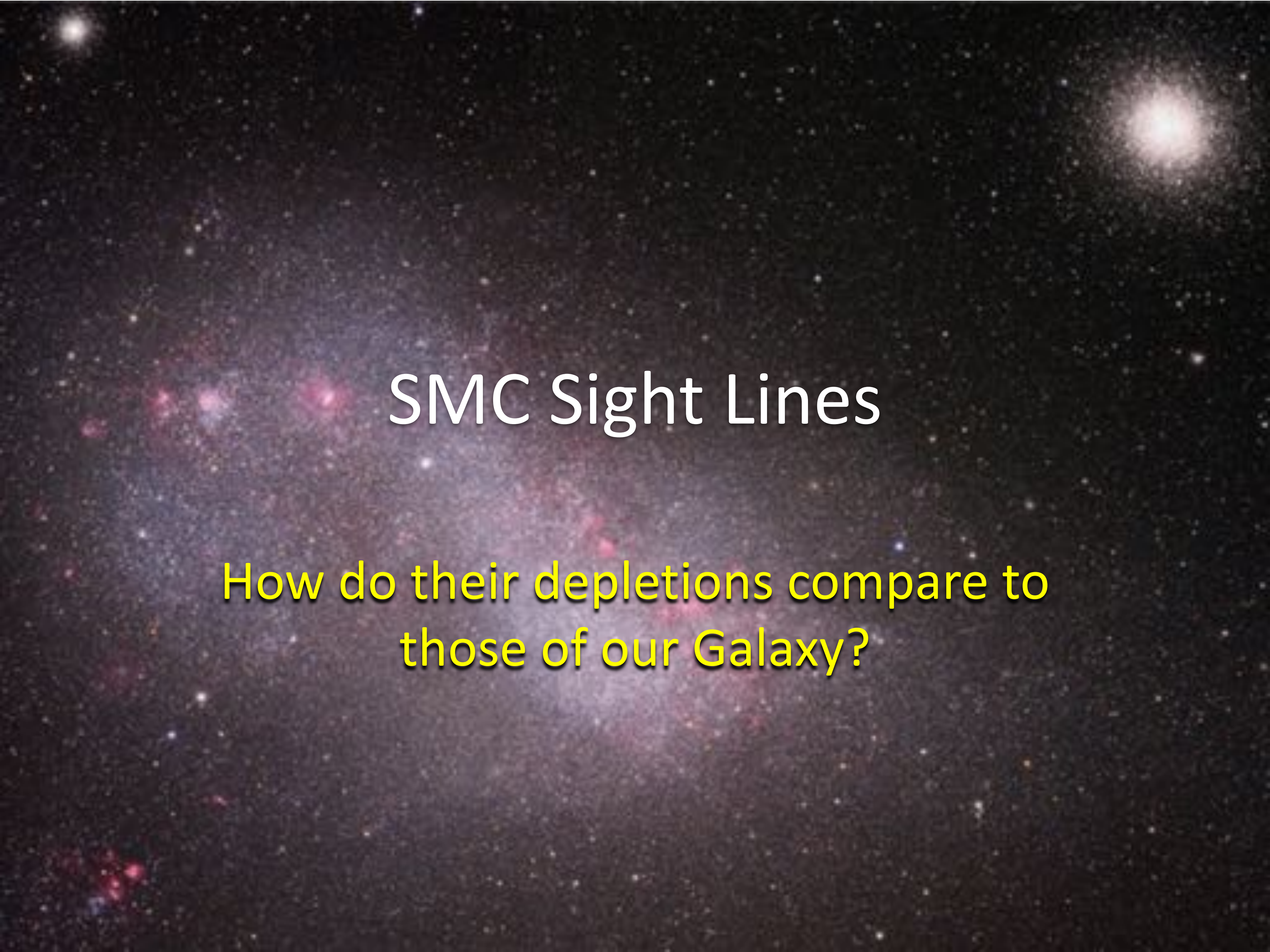
$$y = a + b\ x$$

These coefficients arise from a least squares best-fit equation for all *X* elements

SMC Sight Lines

Proof of concept:

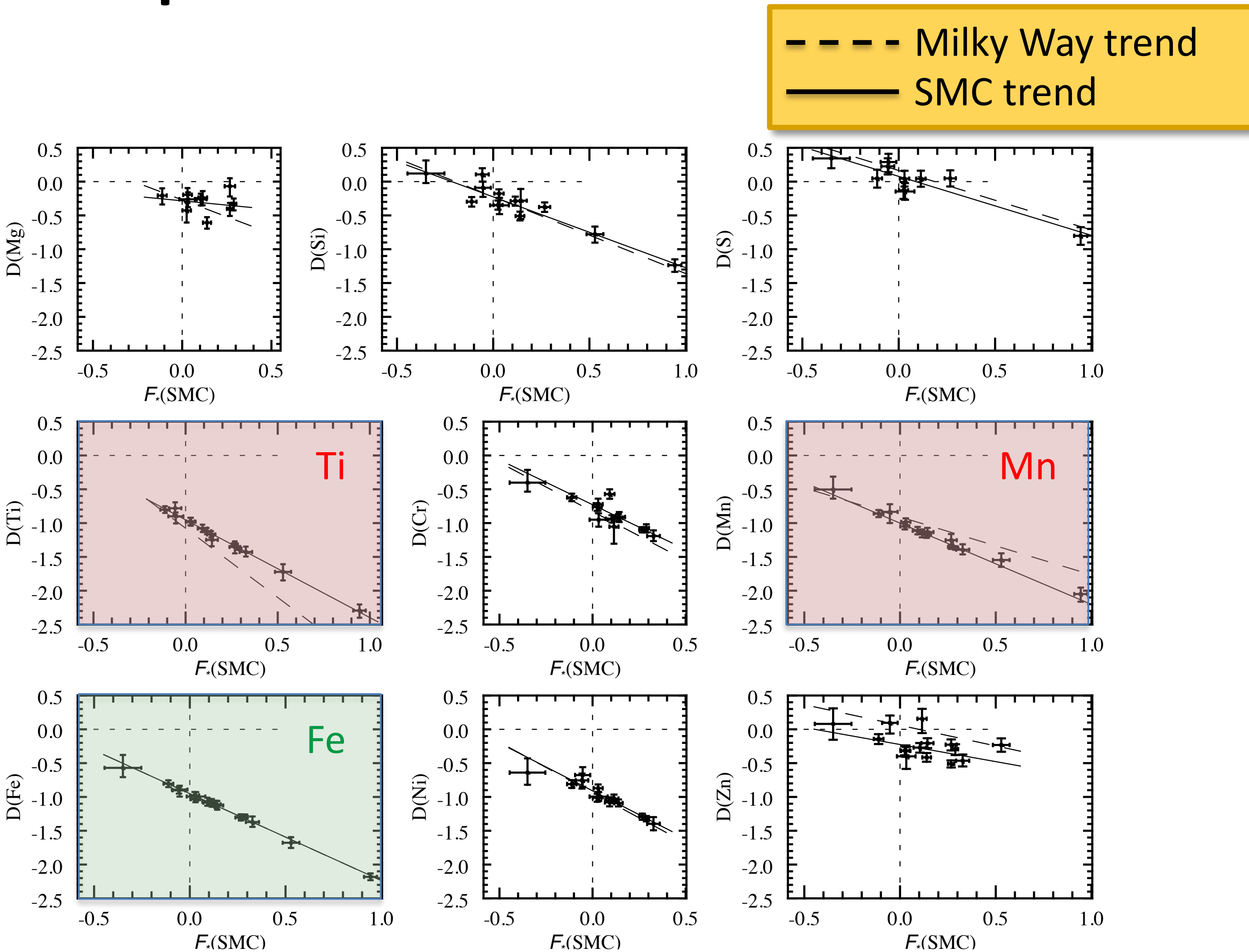
Can we use interstellar absorption features to determine [M/H] for the SMC, and if so, how does it compare with abundances in SMC stars?



SMC Sight Lines

How do their depletions compare to those of our Galaxy?

Depletion trends with F_*

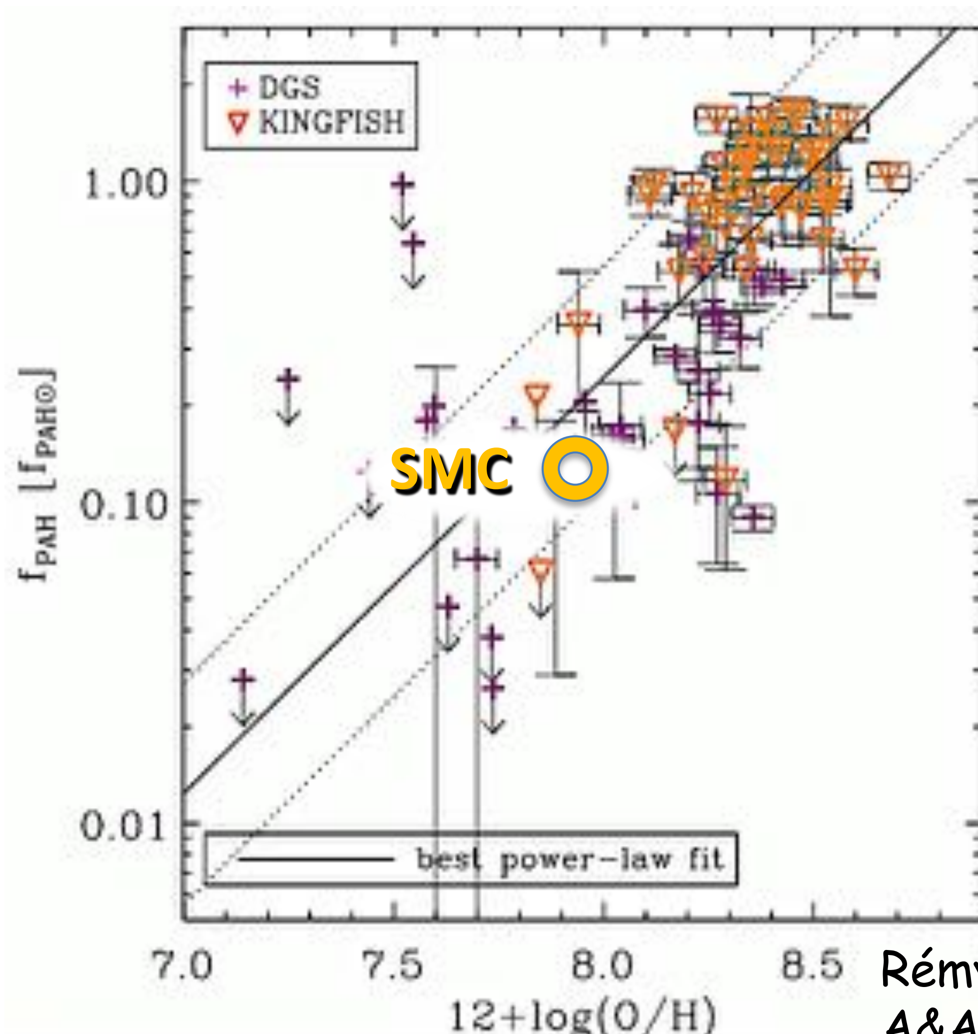


Jenkins & Wallerstein (2017, ApJ 838, 85)

Why do some of the SMC Depletions Differ from those of the Milky Way?

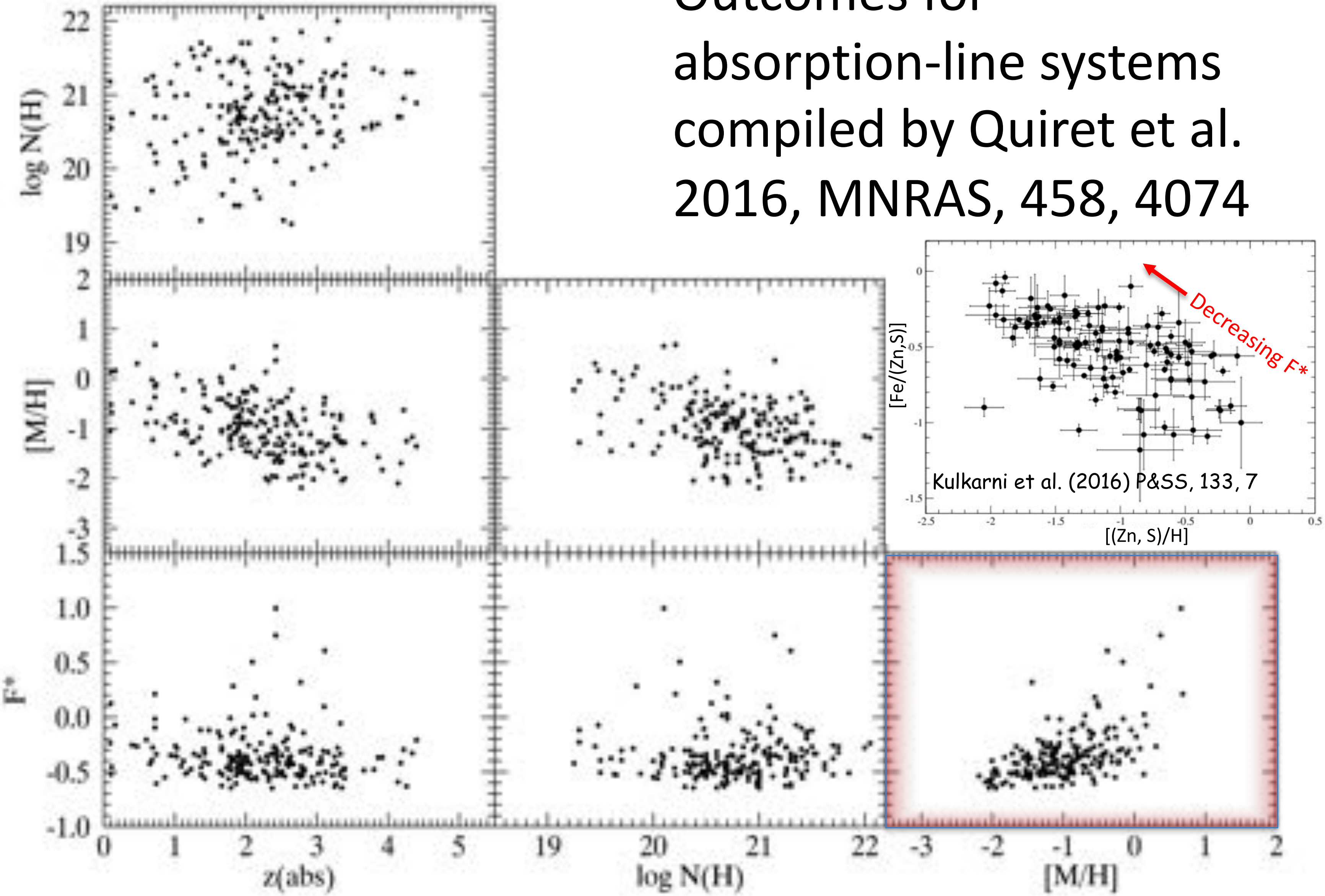
1. The stellar reference abundances of both α- and Fe-peak elements in the SMC are uniformly lower than those of the Milky Way by −0.65 dex.
2. So why does a gas with a dilute mixture of heavy elements exhibit a slightly different depletion behavior for Ti and Mn compared to that of Fe?
3. A possible answer: an exception to point 1 is the abundance of C in SMC stars is even lower by an additional −0.36 dex. This anomalously low C abundance is supported by a deficiency in PAHs, compared to the Milky Way PAH abundance.

The Relative Lack of Carbon in low metallicity systems (distant DLAs)

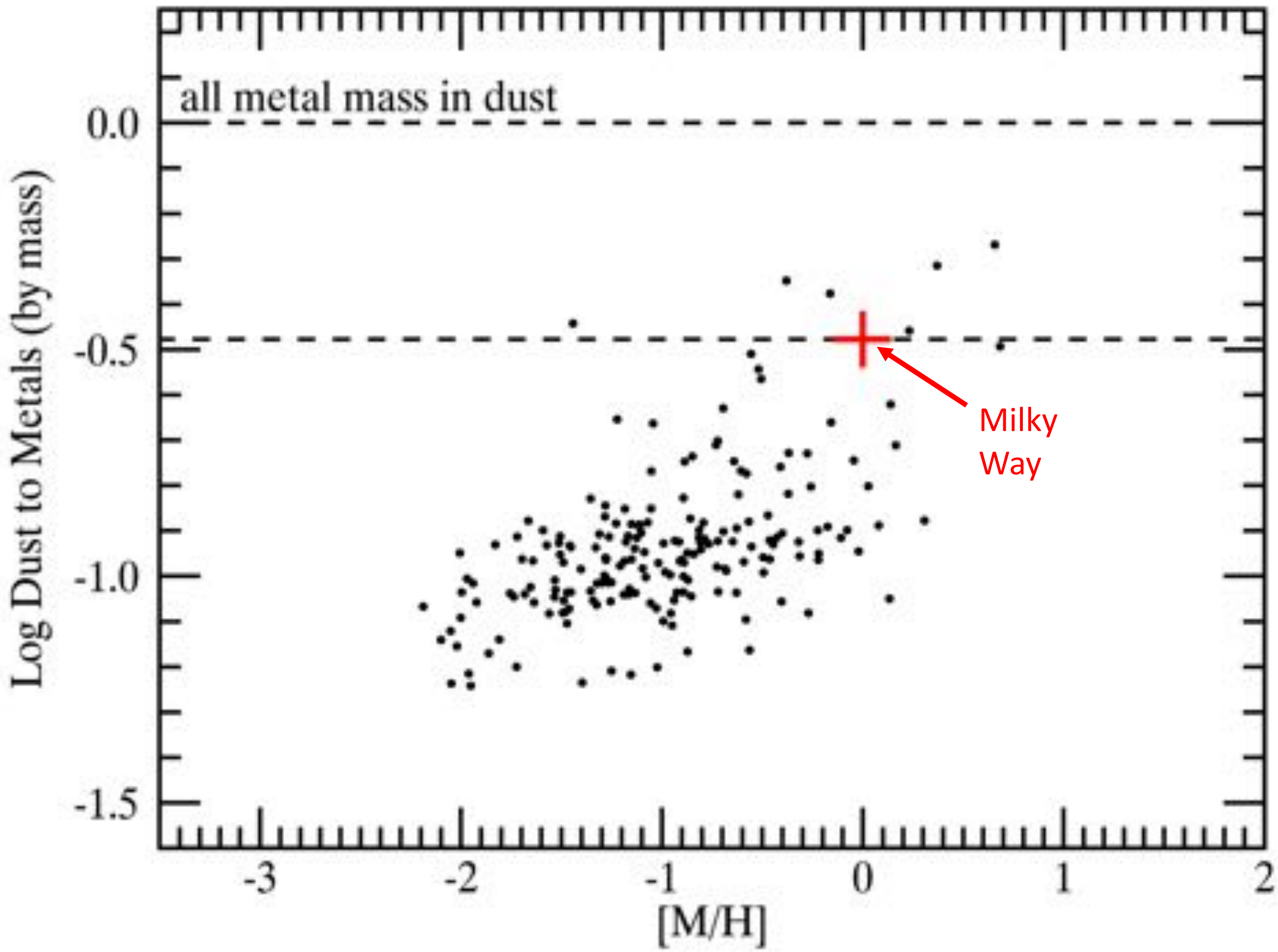


Rémy-Ruyer et al 2015, A&A, 582, A121

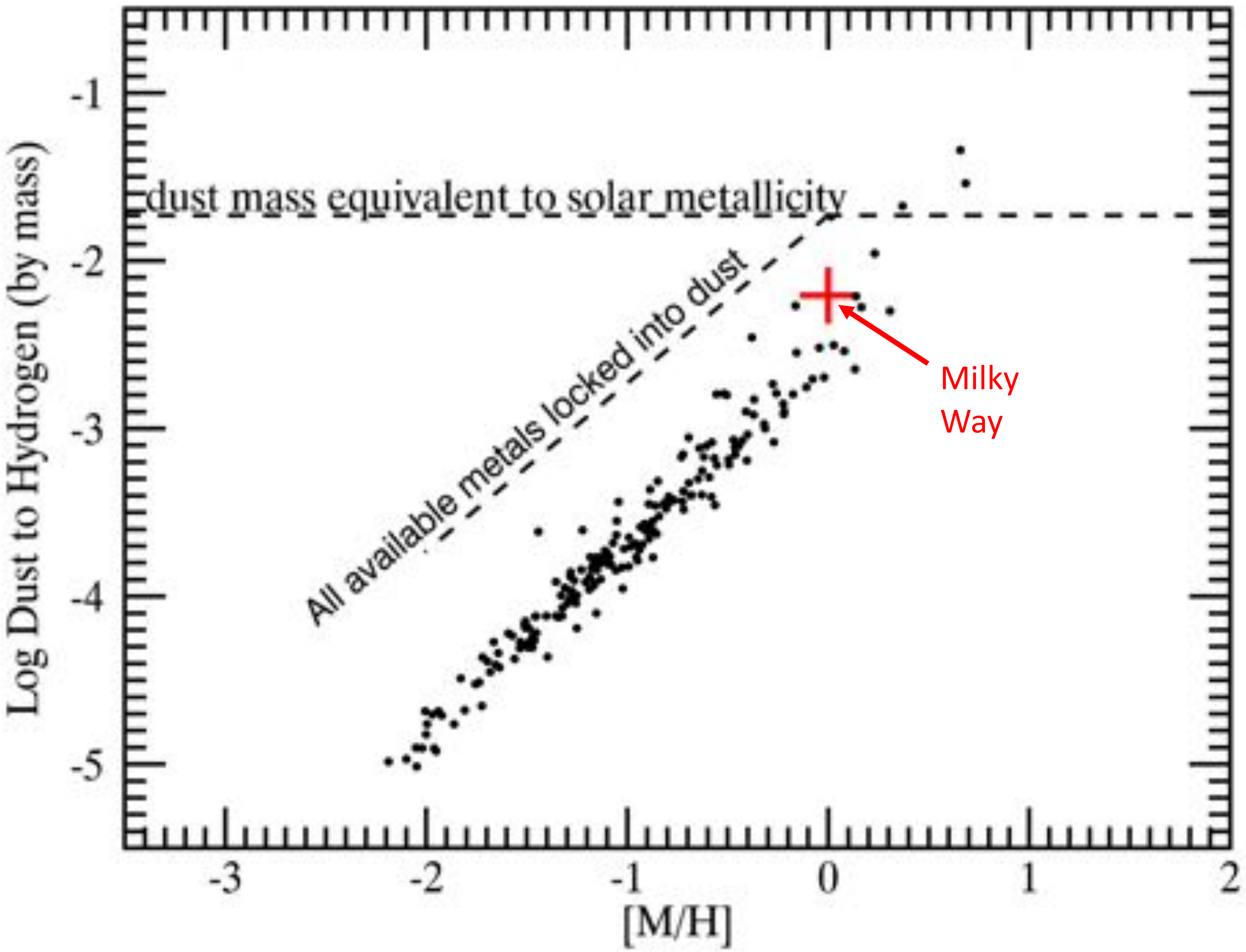
Outcomes for absorption-line systems compiled by Quiret et al. 2016, MNRAS, 458, 4074



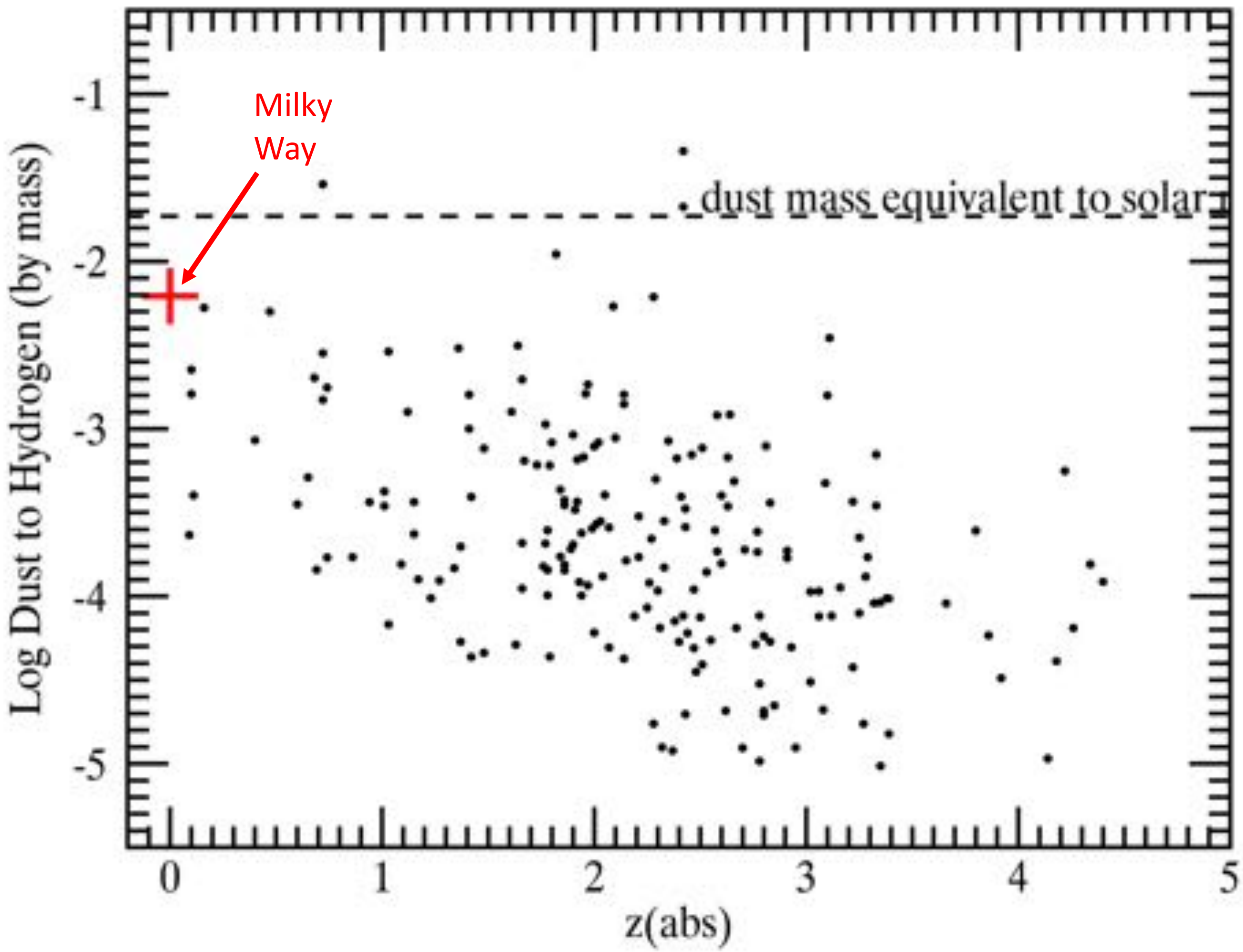
Mass Fractions of Heavy Elements in Dust



The Mass of Dust Relative to that of Hydrogen



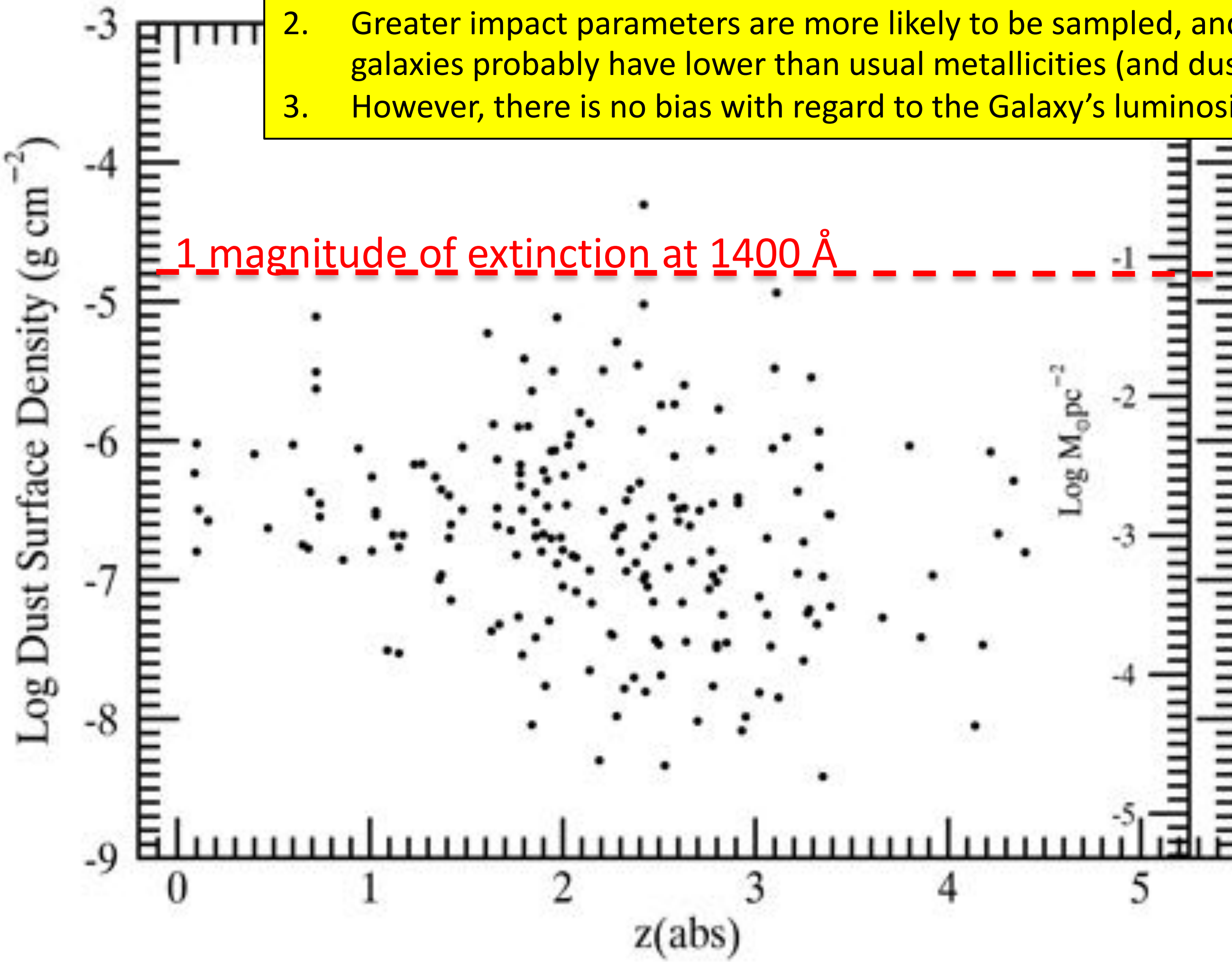
The Mass of Dust Relative to that of Hydrogen



Dust Surface Density and UV Opacity

Selection biases:

1. Not likely to record a spectrum of a quasar behind a galaxy with a large extinction.
2. Greater impact parameters are more likely to be sampled, and such locations in galaxies probably have lower than usual metallicities (and dust fractions).
3. However, there is no bias with regard to the Galaxy's luminosity.



Summary

- UV Spectroscopy offers insights on the systematics of interstellar gas-phase abundances, which in turn informs us about the element constituents in solids
- There is a challenge in understanding the behaviors of oxygen and krypton
- From an almost universal pattern of depletions, we can use measurements of two or more elements to make corrections for depletions that are needed to derive element abundances in distant galaxies
- Depletion strengths and element abundances together reveal the absolute abundances of dust