The Abundance of Free Oxygen Atoms in the Local ISM from Absorption Lines

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Absorption Lines in the Ultraviolet Region

- Only forms of O that can be detected in absorption at wavelengths longward of the Lyman limit at 912 Å:
  - Neutral oxygen atoms in H I regions
  - Five-times ionized O ions that are created by collisional ionization in plasmas with temperatures $\approx 3 \quad 10^5$K

Objectives of Measuring the Abundance of Atomic Oxygen in the Neutral ISM and Relating it to that of Hydrogen

- Find out how much oxygen is tied up in the form of molecules and dust grains.
- Understand how the depletion of oxygen is related to other parameters, such as local gas density and the depletions of other elements.

The Spirit of this Conference

- “It is time to confront all these determinations and discuss thoroughly the **biases and uncertainties** to provide a firm ground for theories and models of chemical evolution of galaxies.”
- “This workshop would then not be principally one of `results’ but rather one of `confrontations and discussions’.”

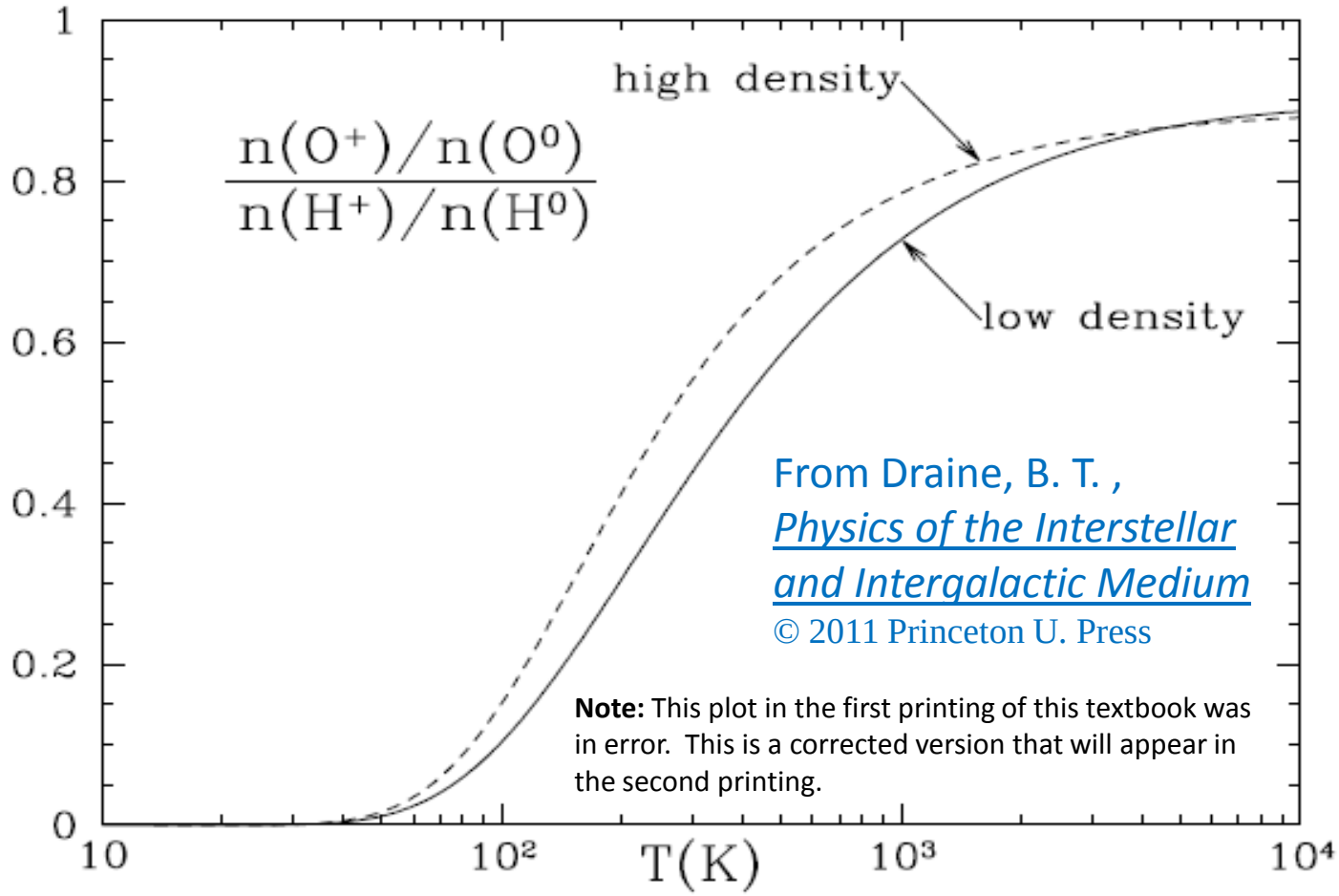
Biases and Uncertainties

- **Factors that can influence the outcomes of measurements of O/H in the atomic phase**
  1. Are all of the O and H atoms in a neutral form inside H I regions? (or must one apply ionization corrections?)
  2. Can we trust measurements of N(H I) in the ISM?
  3. Can we trust measurements of N(O I) in the ISM?
  4. Is the reference abundance of O relative to H well understood?

Ionization Balance of O and H

- Dominance of charge exchange in locking together the relative ionizations of O and H.
  - Ionization potentials differ by only 0.0197 eV
  - Resonant charge exchange $H^0 + O^+ \leftrightarrow H^+ + O^0$ has a large rate constant: $k \approx 10^{-9}$ cm^3 s^{-1} that ***usually*** results in a fractional ionization of O that is 8/9 times that of H.

Ionization Balance of O and H



From Draine, B. T. , *Physics of the Interstellar and Intergalactic Medium*

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Note: This plot in the first printing of this textbook was in error. This is a corrected version that will appear in the second printing.

Figure 14.5 Dependence of oxygen ionization fraction on hydrogen ionization fraction due to charge exchange. The low-density limit applies for $n_H \lesssim 10^4\ \mathrm{cm}^{-3}$. noted 2011.05.18 by E. B. Jenkins.

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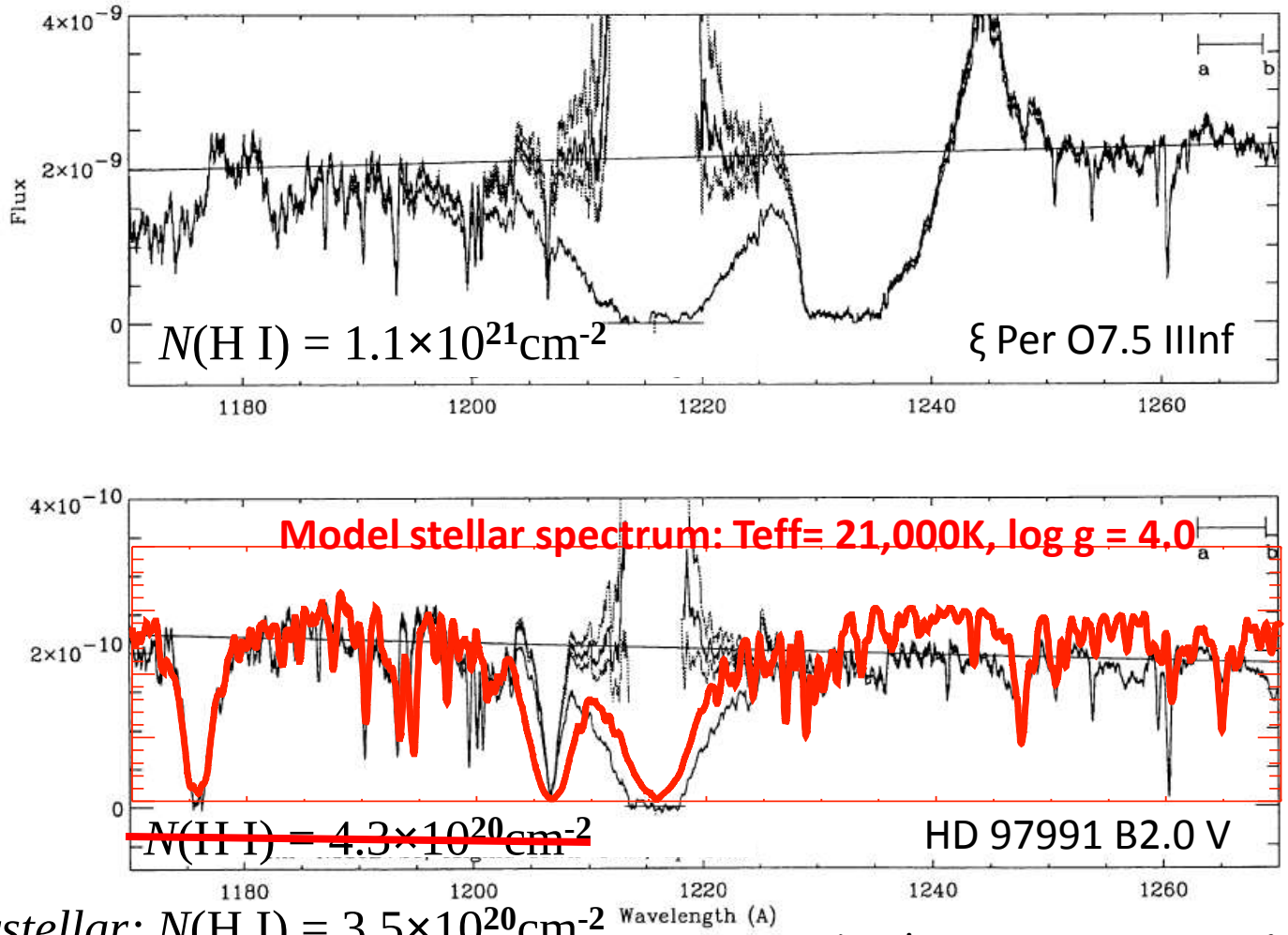
N(H I) Measured from the Lα Damping Wings



Interstellar: N(H I) = 3.5×10^{20}cm^{-2}

Effective stellar: N(H I) = 0.8×10^{20}cm^{-2}

Diplas & Savage 1994

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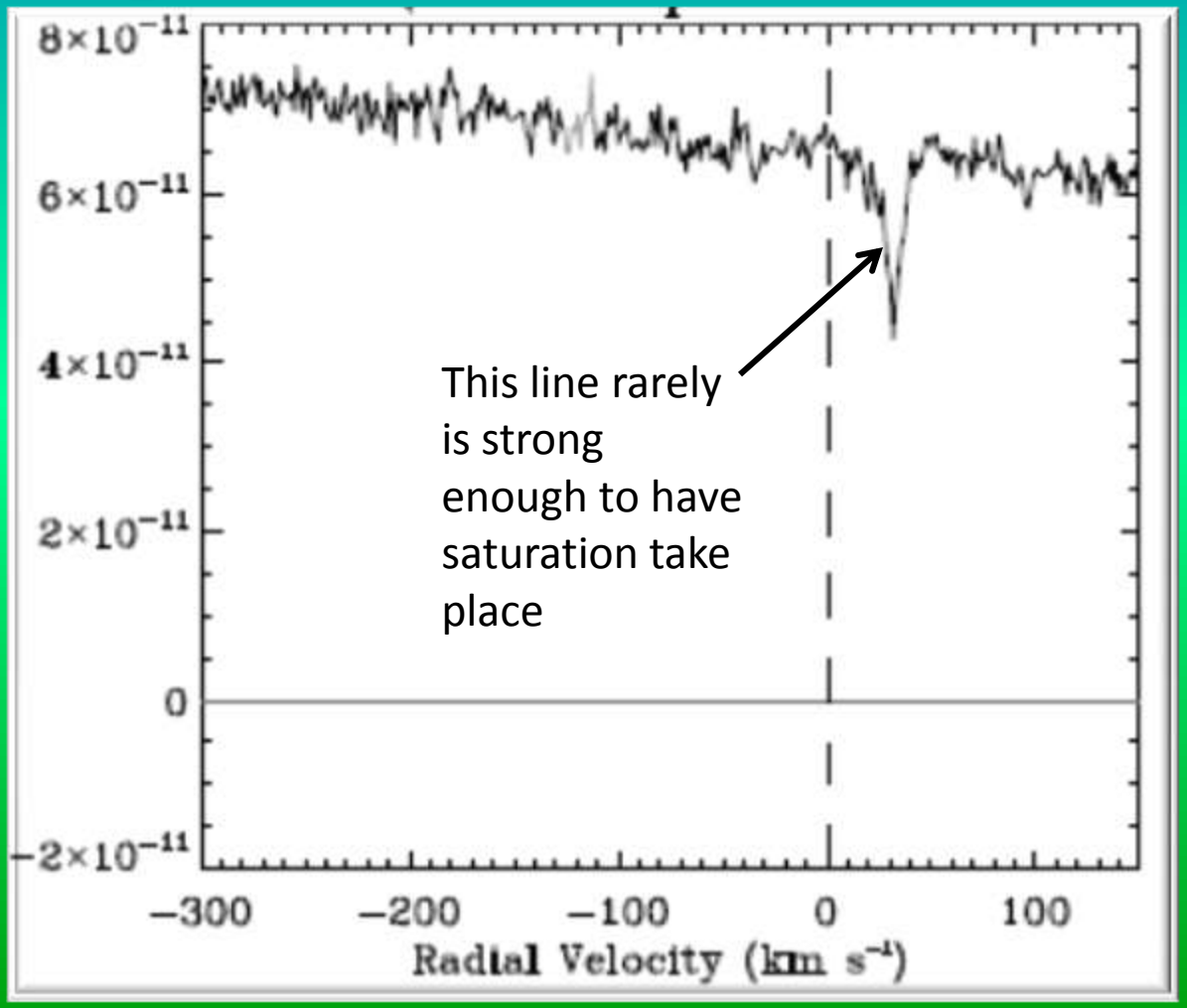
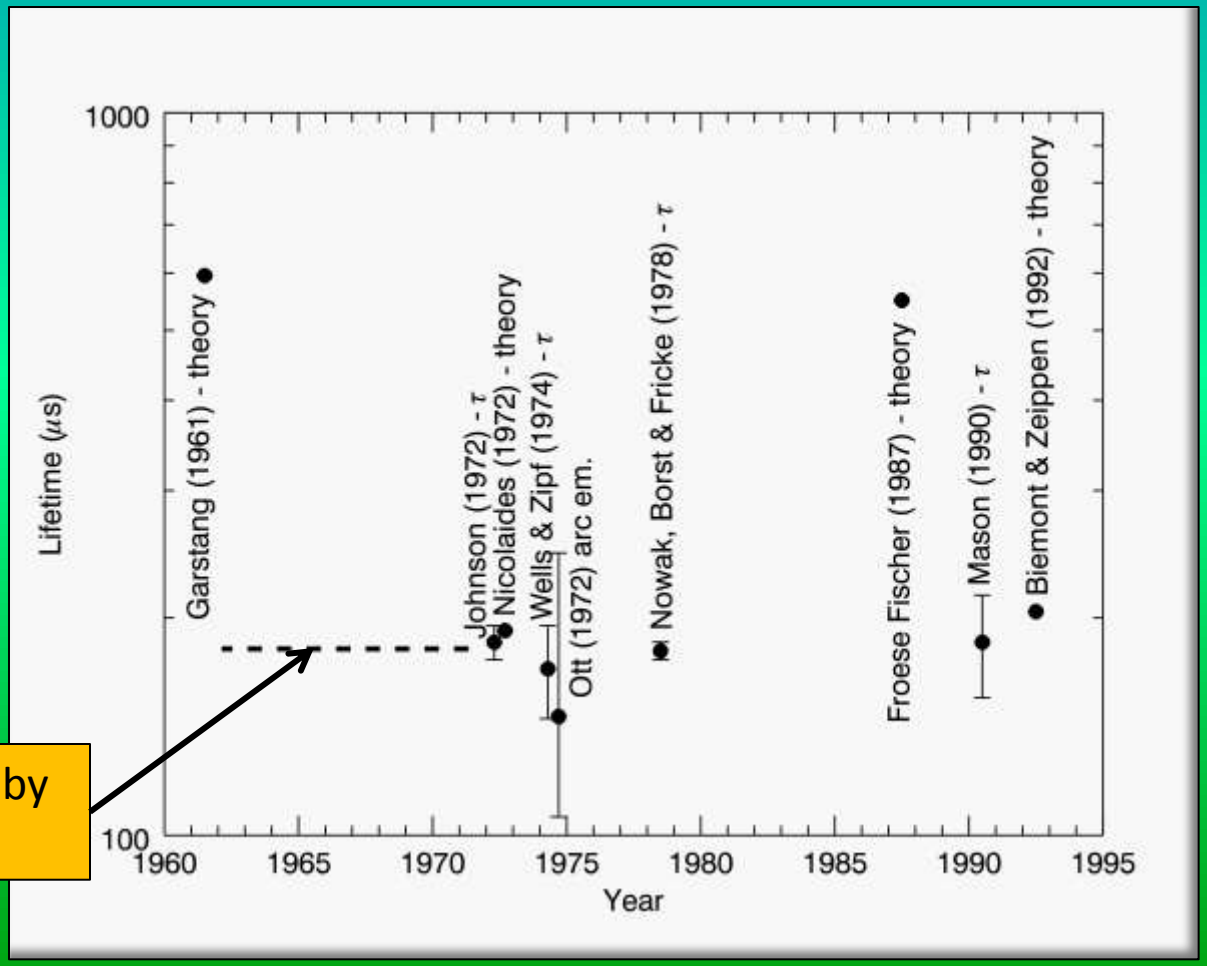
Most *N*(O I) Determinations Were Made Using the Weak Intersystem Absorption Line at 1355.598Å



Measurements (or Calculations) of the Lifetime of the Upper State for the Intersystem Transition at 1355.598Å



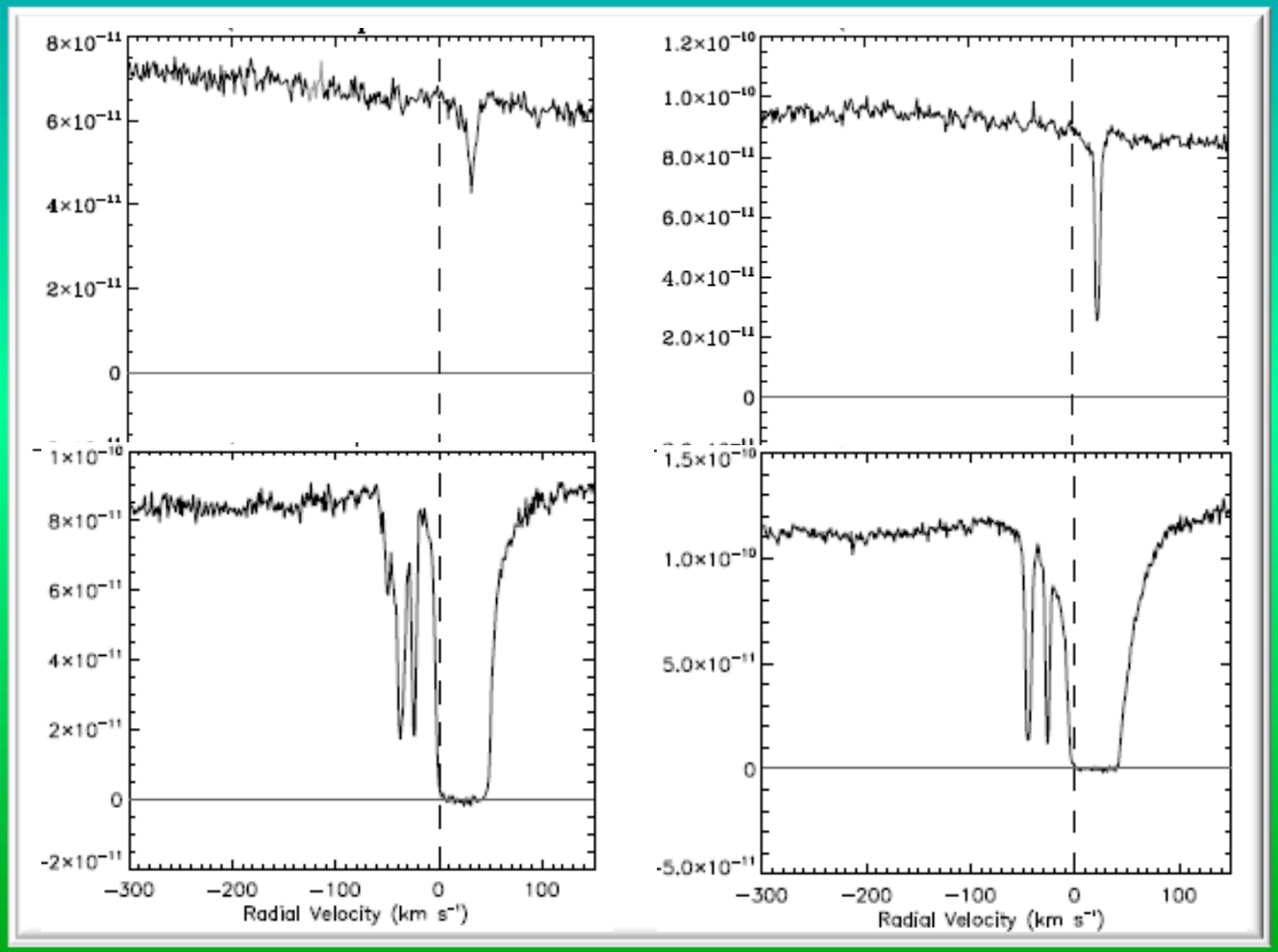
Value adopted by Morton (2003)

STIS Spectra of Two Stars

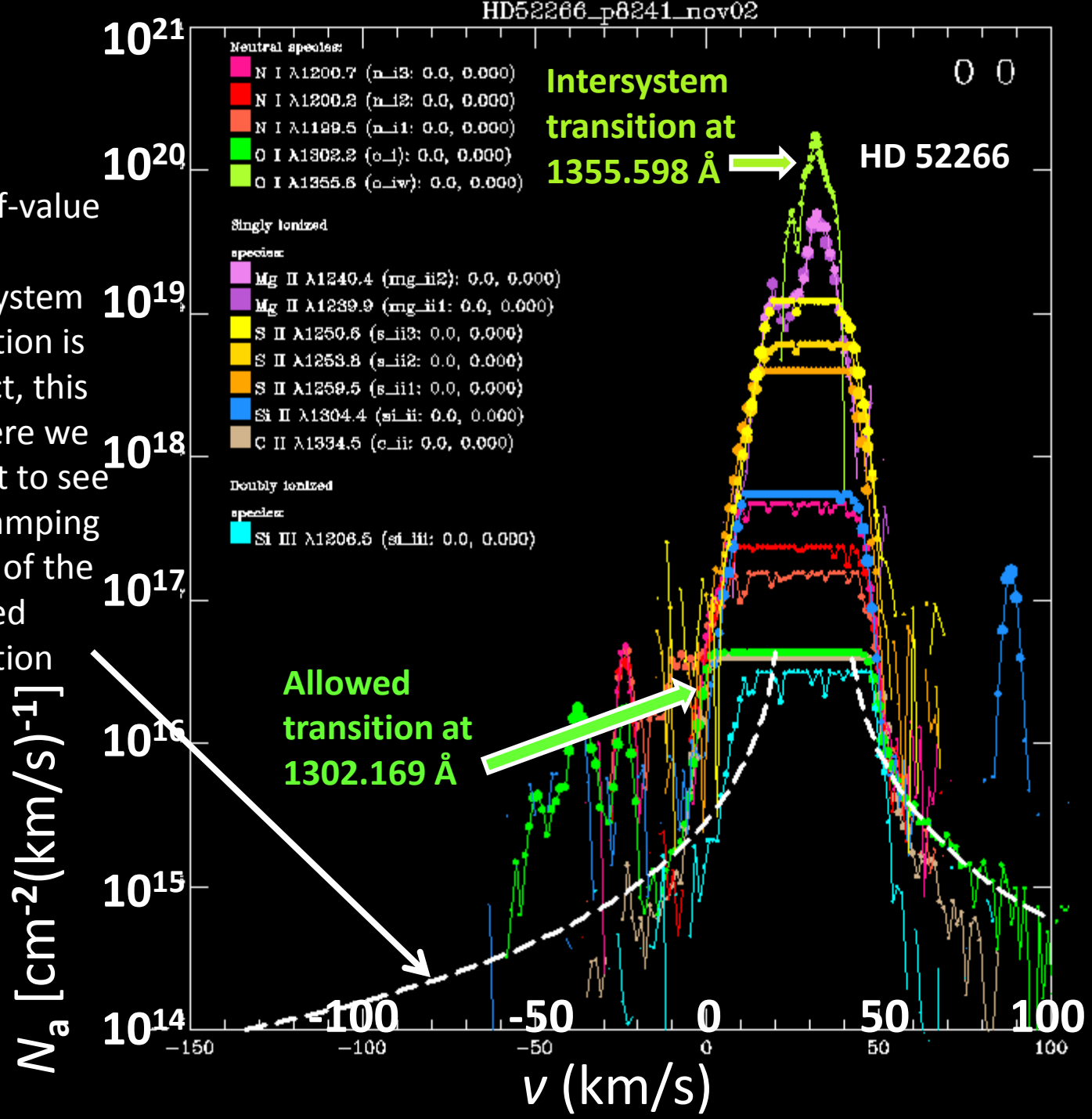
HD 52266 **HD 37061**

Intersystem transition at 1355.598 Å

Allowed transition at 1302.169 Å



If the f-value of the intersystem transition is correct, this is where we expect to see the damping wings of the allowed transition



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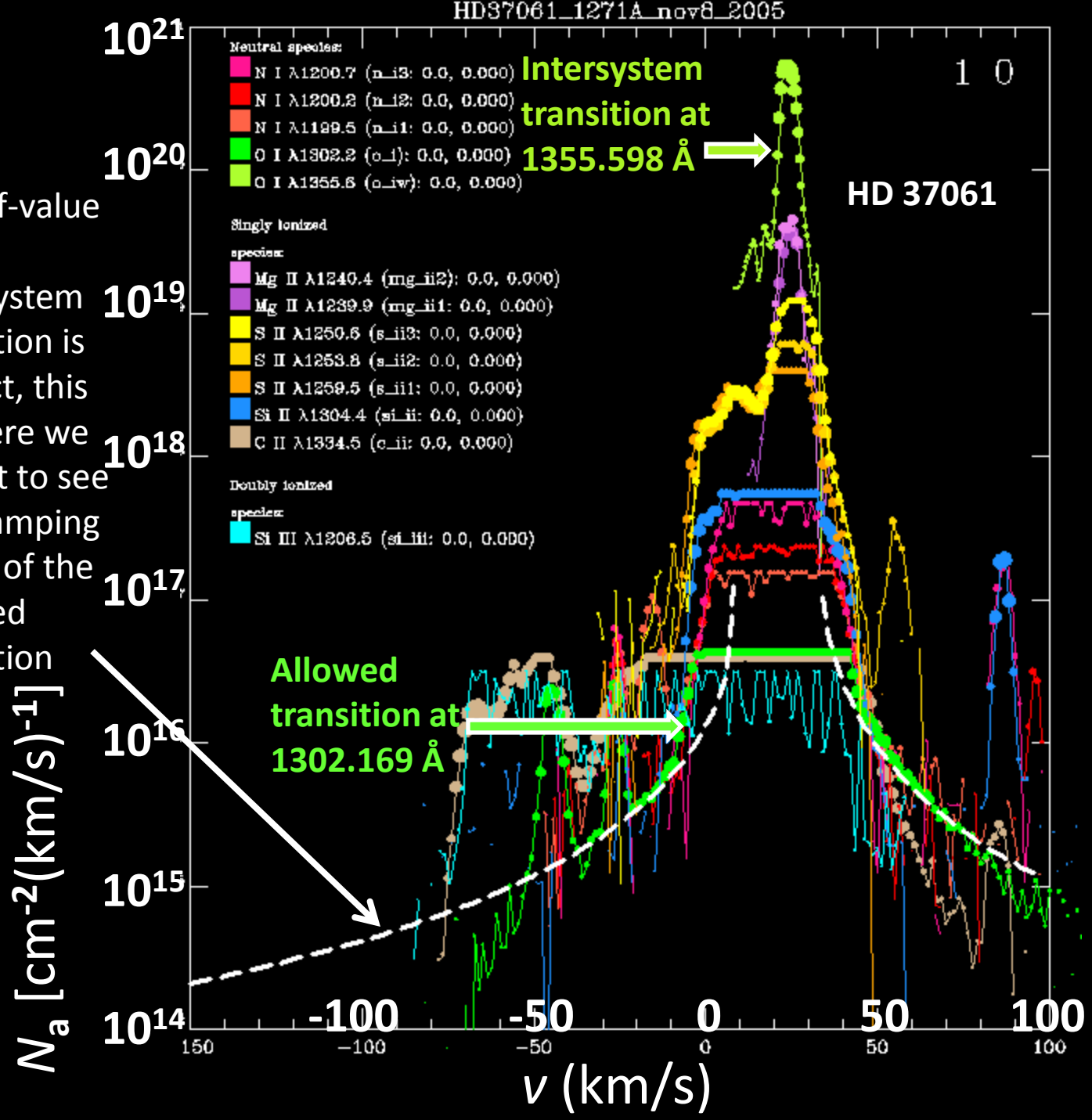

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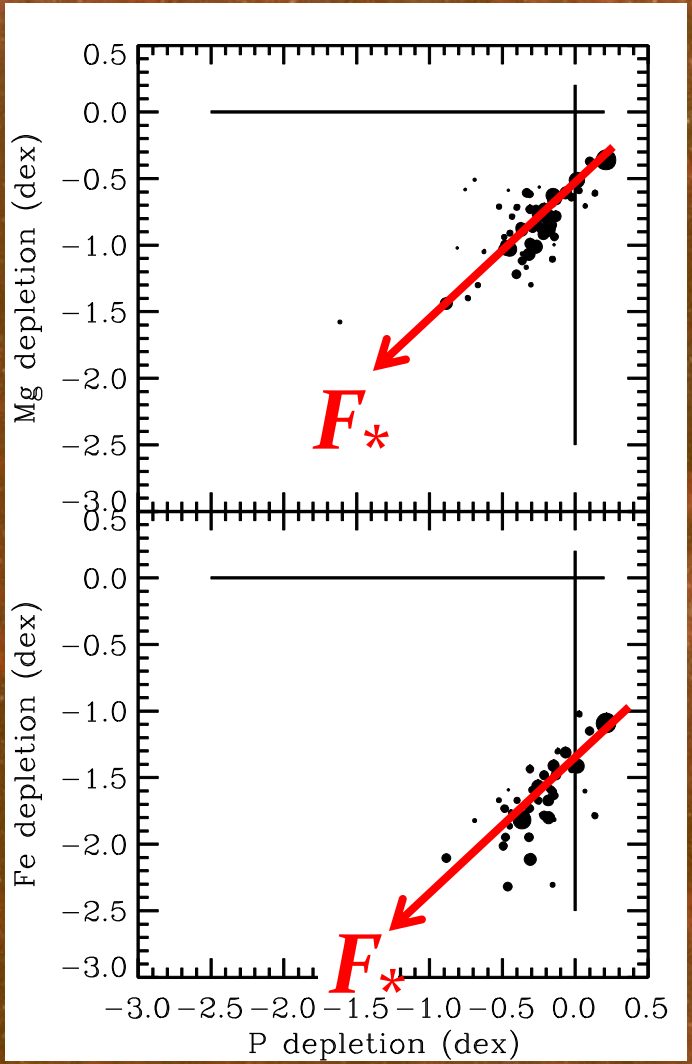
Underlying Strategy of the Unified Depletions Study (Jenkins 2009)

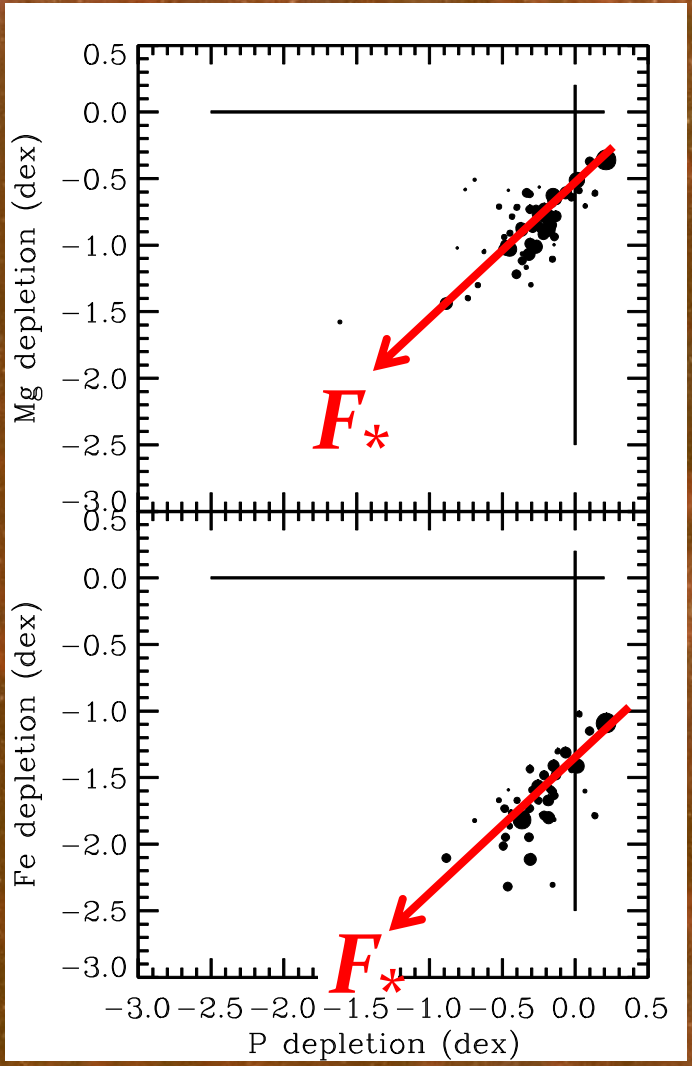
- Basic premise:
  - All elements deplete together in some systematic fashion, but by differing degrees that change from one region to another and from one element to the next.
  - Propose a single parameter, F_*, that expresses a general level of depletion along a sight line.

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



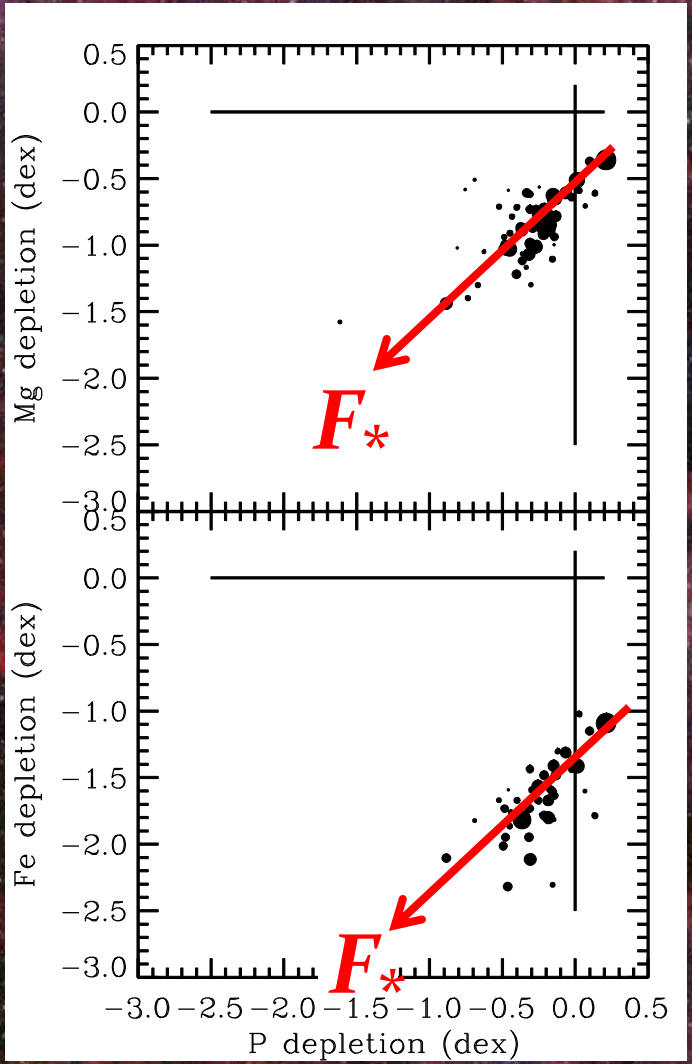
Underlying Strategy of the Unified Depletions Study (Jenkins 2009)

- Scale for F_* is arbitrary; I chose a calibration as follows:
  - $F_* = 0$ corresponds to lowest depletions seen (but subject to the restriction that N(H I) > $10^{19.5}$ cm^{-2}).
  - $F_* = 1$ corresponds to the depletion pattern observed toward ζ Oph



Underlying Strategy of the Unified Depletions Study (Jenkins 2009)

- Another basic premise:
  - The ways in which different elements respond to changes in F_* are represented by coefficients, which differ from one element to the next, in a linear equation for the logarithmic depletion with respect to F*.

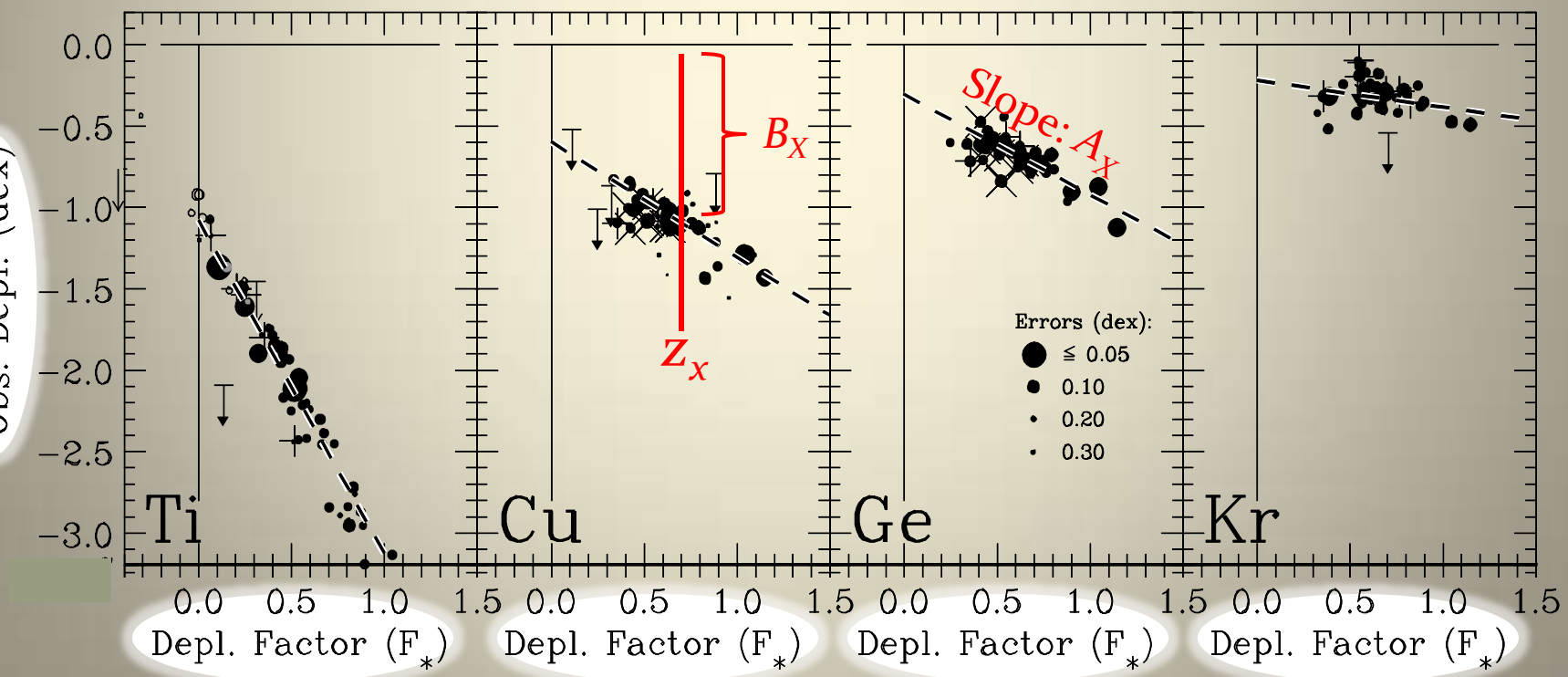


Basic Equation

For element X:

Depletion factor

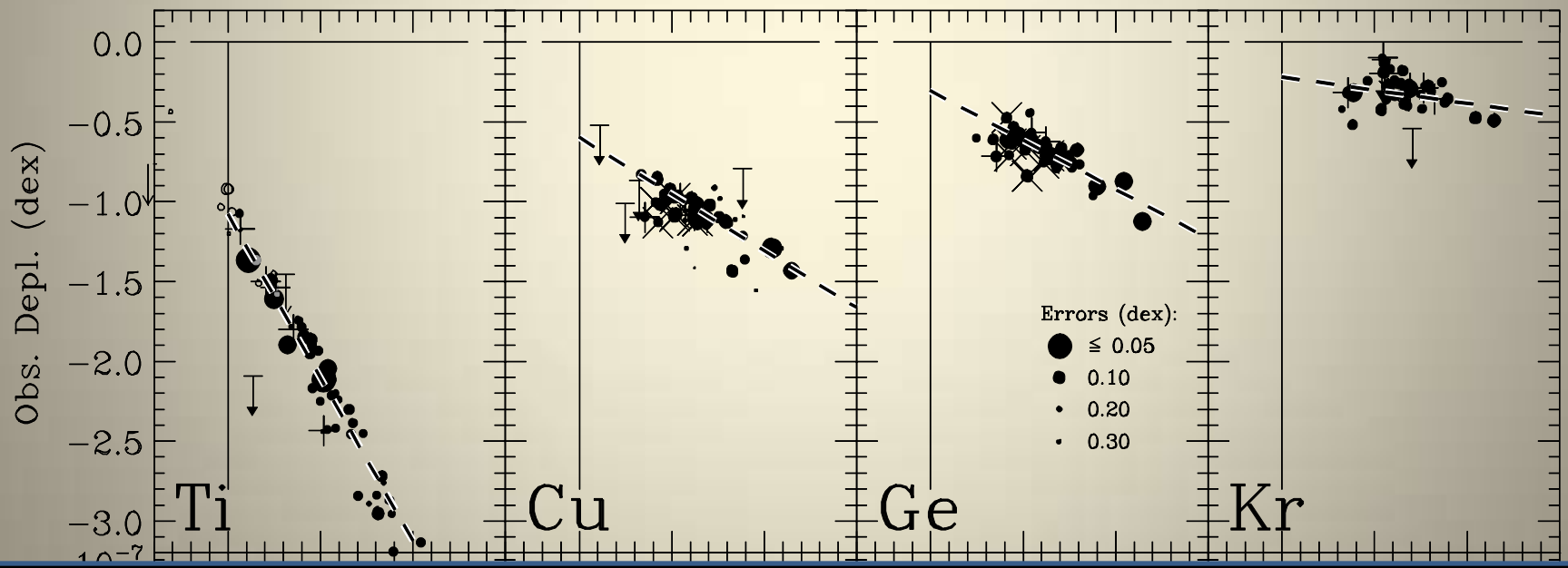
$$[X_{gas}/\mathrm{H}] = B_X + A_X(F_* - z_X)$$



The Buildup of Dust Grains

Conventional Formula:

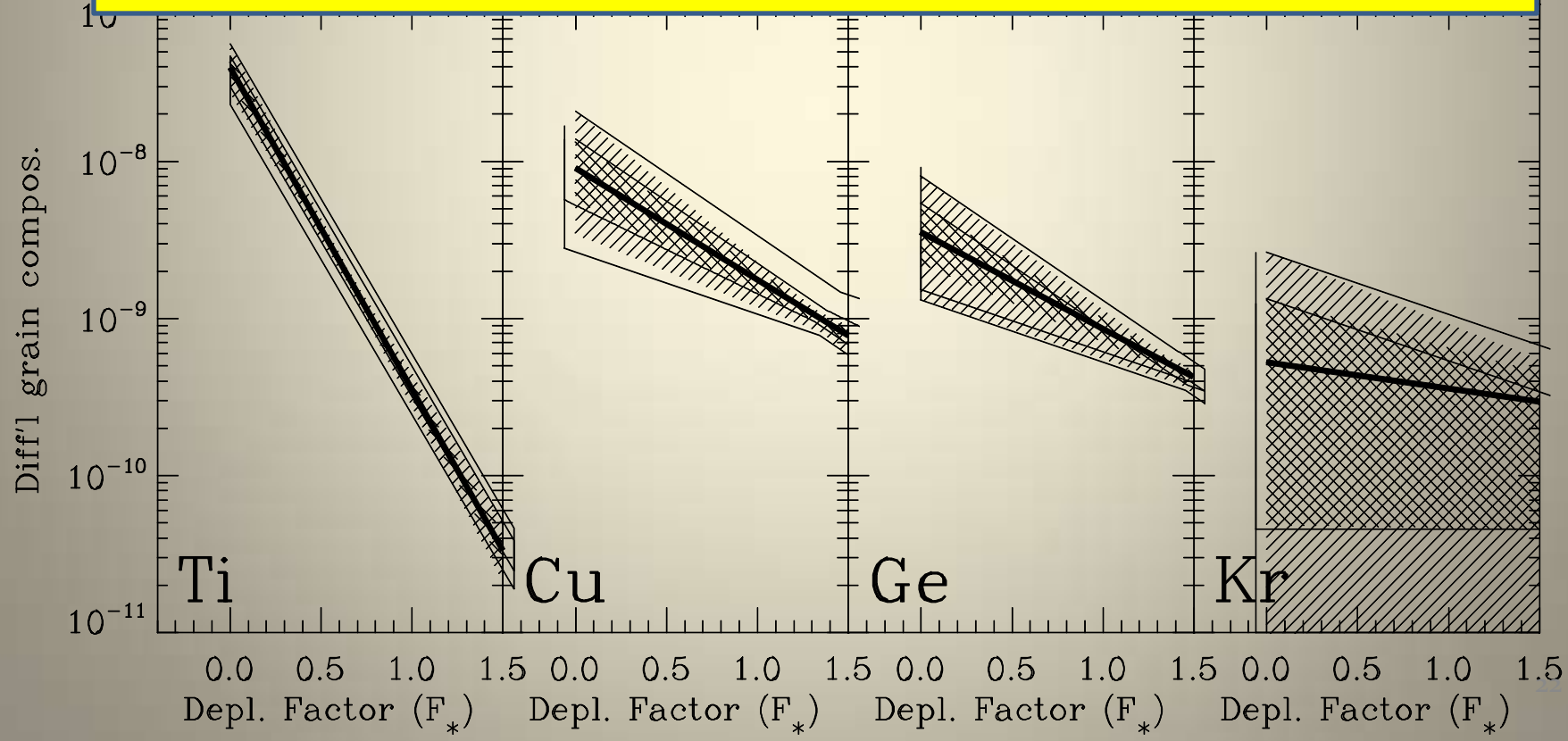
$$(X_{dust}/\mathrm{H}) = (\mathrm{X/H})_{\odot}(1-10^{[X_{gas}/\mathrm{H}]})$$



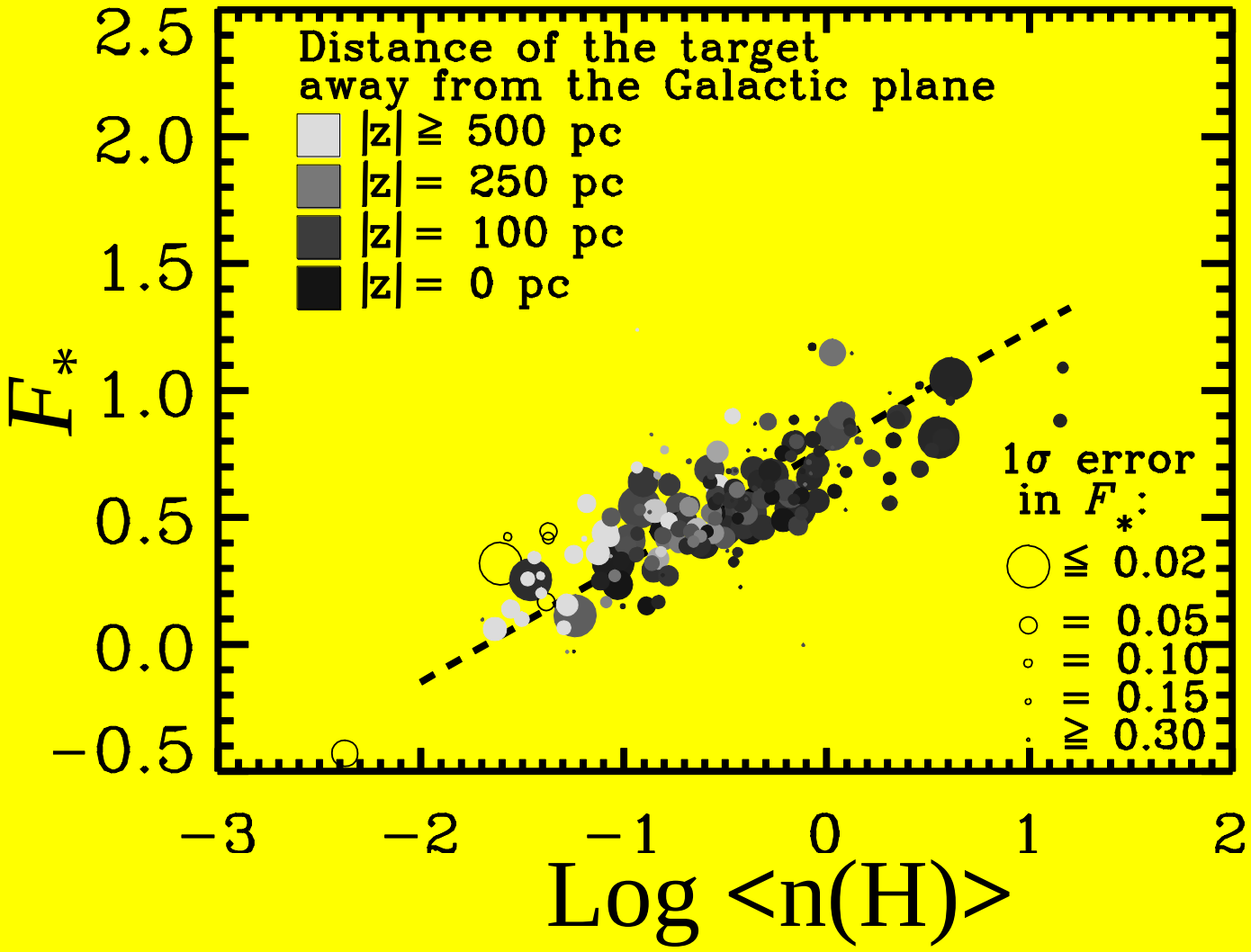
The Buildup of Dust Grains

Differential Element Contributions:

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



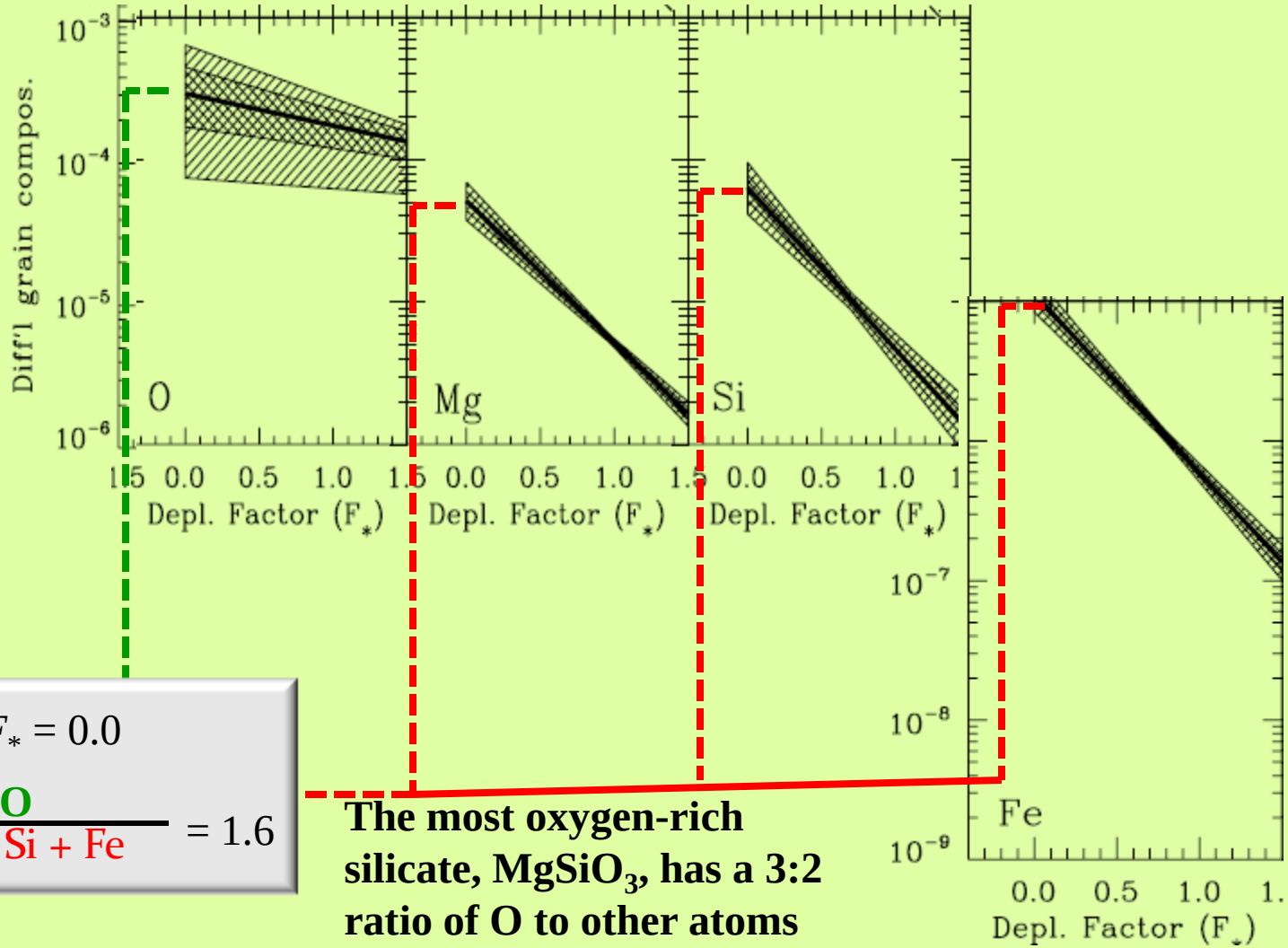
Trends of Overall Depletion Strengths



The Consumption of Oxygen Compared to other Elements

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

The Consumption of Oxygen Compared to other Elements

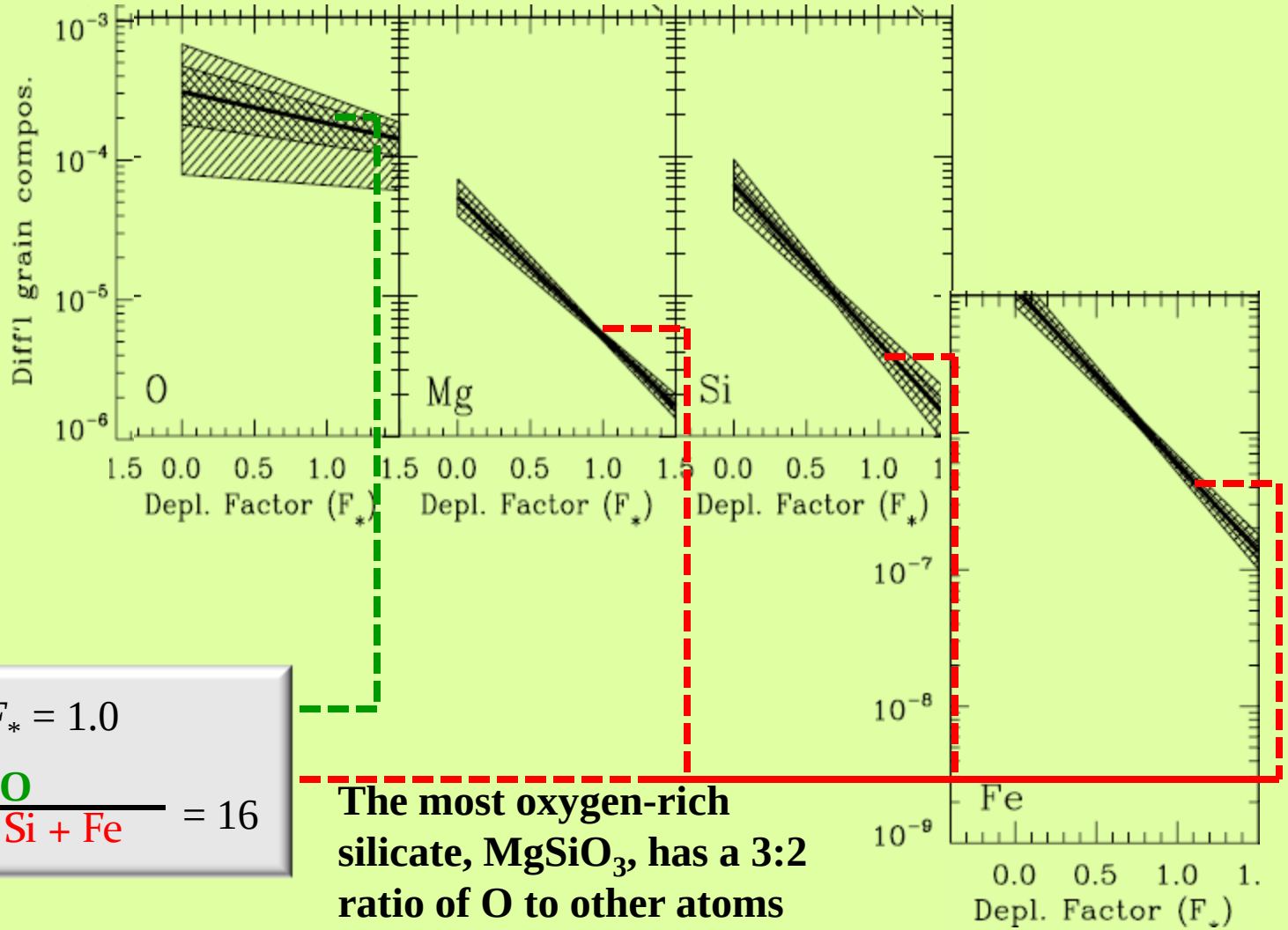


At $F_* = 0.0$

$$\frac{\mathbf{O}}{\mathrm{Mg + Si + Fe}} = 1.6$$

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 $F_* = 1.0$

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

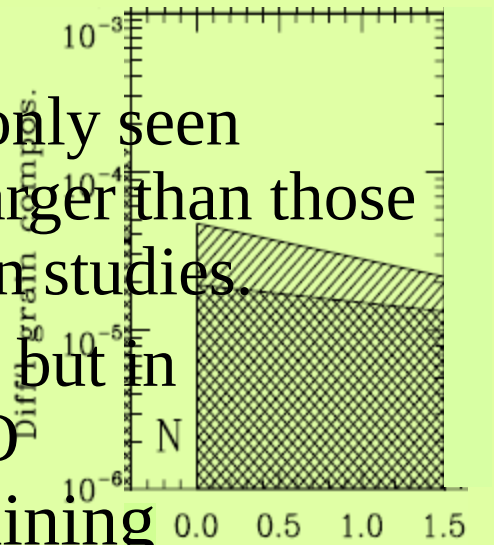
The most oxygen-rich silicate, $MgSiO_3$, has a 3:2 ratio of O to other atoms

The Consumption of Oxygen Compared to other Elements

- Another interpretation: Use **absolute abundances** of O in dust instead of differential ones, but this requires an assumed reference abundance for O/H. Assume that this is equal to 575 ppm (or log abund +12 = 8.76).
- Using the conventional formula for the dust fractional content of O, we find that at F_*=1, (O_{dust}/H) = 240±70 ppm. This value is much larger than a nominal expectation of about **135 ppm** (or even a maximum possible value of 180 ppm) that can be accommodated by the *total availability* of other elements that can be incorporated into silicates or metallic oxides or some combination of the two.

The Consumption of Oxygen Compared to other Elements

- Conclusion: In addition to forming silicates, O must deplete by forming some other compound using another ***<u>abundant</u>*** element.
  - Various oxides of N? Unlikely, since N does not seem to deplete (at least not appreciably by more than about 20-40 ppm 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 much smaller than H_2O



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

One Other Method of Measuring O Bound in Molecules and Grains

- Again, independent of adopted reference abundance:
- High resolution X-ray absorption spectroscopy at wavelengths in the vicinity of the K absorption edge, which can distinguish various stages of ionization of O atoms, as well as those which have chemical bonds.
- ***This topic should be covered by the next speaker***

Conclusions

- **Factors that can influence the outcomes of measurements of O/H in the atomic phase**
  1. Are all of the O and H atoms in a neutral form inside H I regions? (or must one apply ionization corrections?) **Yes, both atoms are primarily neutral in H I regions, but if not, ion fractions are about the same**
  2. Can we trust measurements of N(H I) in the ISM? **Yes, but stellar Lα contamination can be an issue for stars cooler than B1.5**
  3. Can we trust measurements of N(O I) in the ISM? **Yes, no problem** here
  4. Is the reference abundance of O relative to H well understood? **Most recent results reported here indicate the reference abundance is accurate. Moreover, the differential acquisitions of elements into solids give insights on the chemical compositions, *a result that is independent of the reference abundance of O.***

- **Major problem:** Oxygen consumption is greater than that which can be incorporated into silicates. Constituents such as CO, CO_2 and H_2O are not abundant enough in translucent clouds. So the large loss of free oxygen atoms is a mystery.