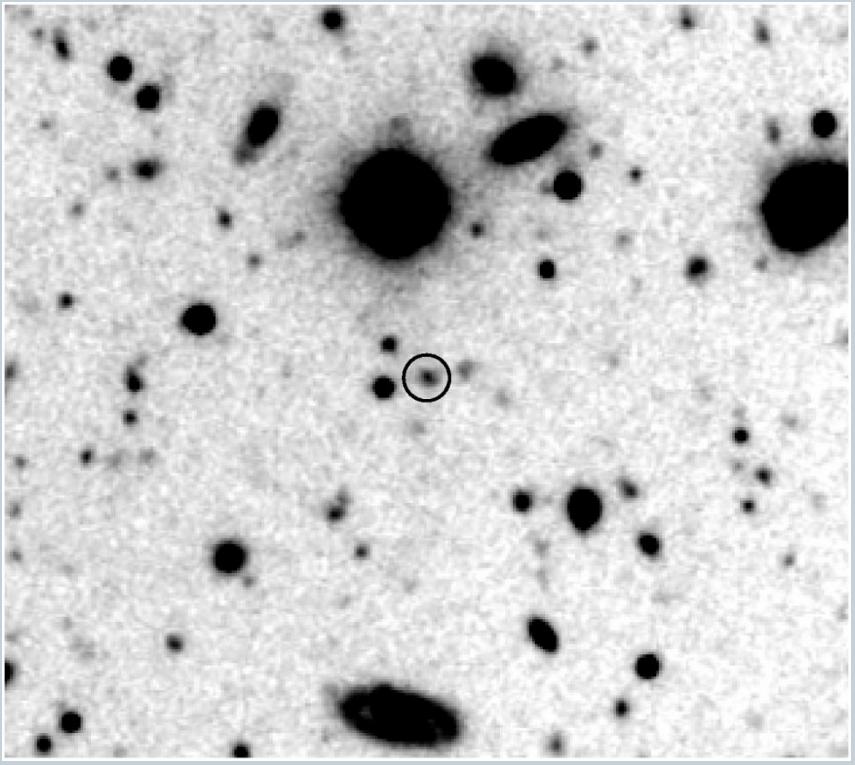
IGM chemical abundances at z > 4 and their evolution toward z ~ 2.5

ROB SIMCOE (MIT)

- Abundance evolution and feedback
- New measurements of intergalactic [C/H] at z ~ 4.3

IGM Chemistry is a direct indicator of galaxy formation feedback at high z

- Indirect indicators
  - M-Z
  - Metal-poor stars
  - Dwarf galaxy counts
  - ....
- IGM is metal-rich near z ~ 2-3 galaxies
  - [C/H] ~ -1.5 within 200 kpc
  - Galaxy outflows
- Boundary constraint



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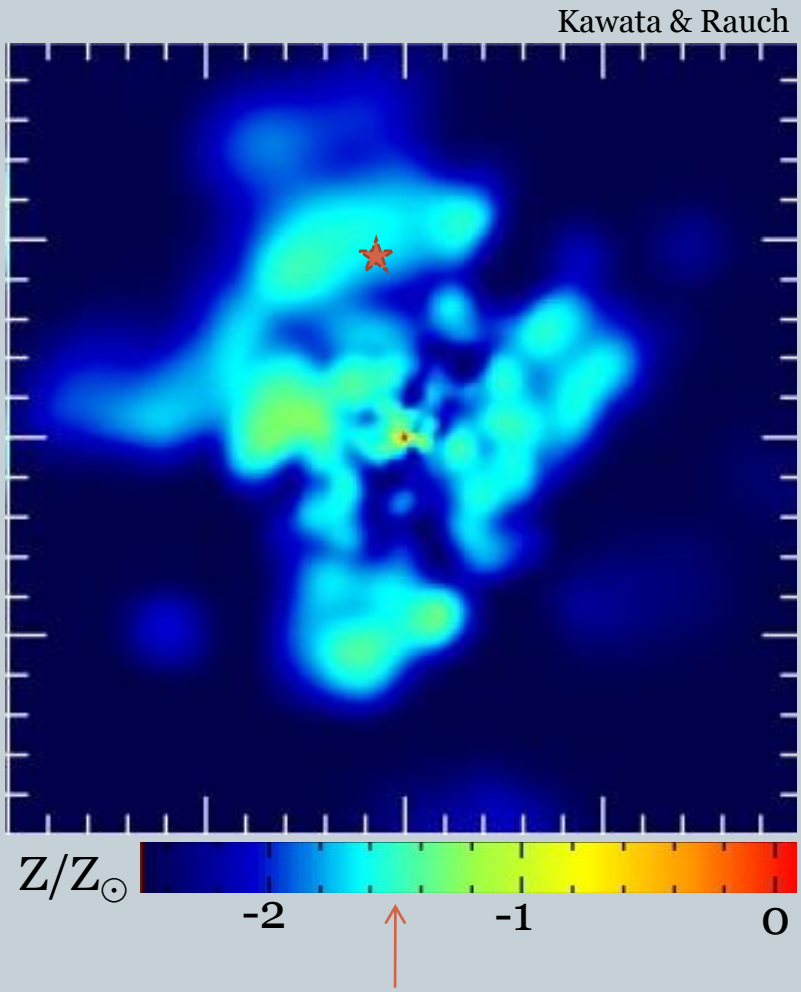
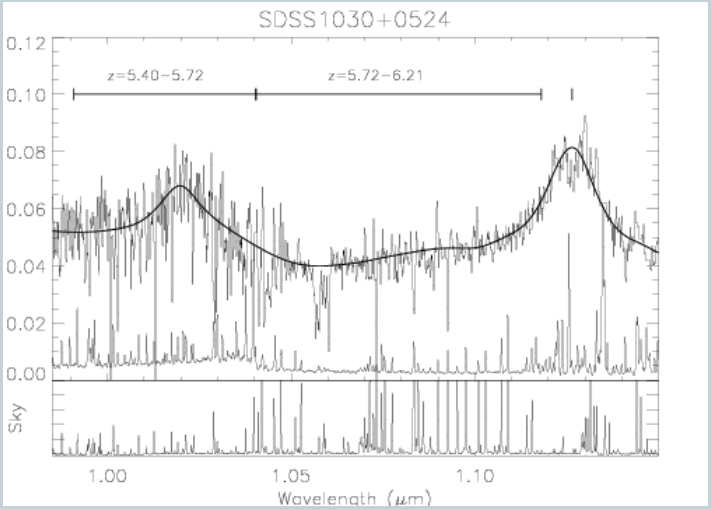
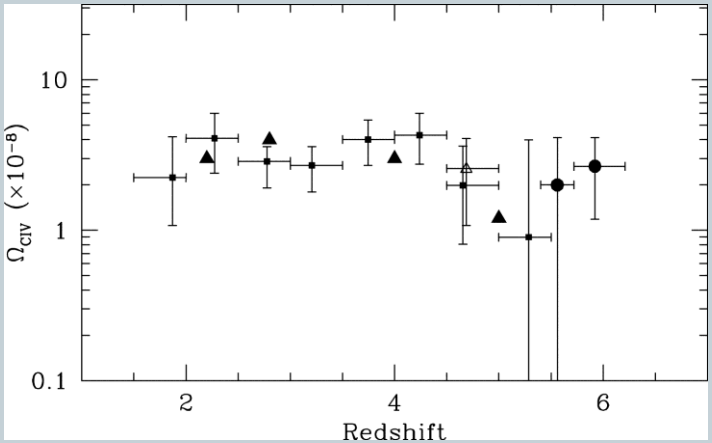


Why focus on abundance evolution?

- No significant trend detected over z ~ 2.5-3.5
- No gross evolution of C IV from z=2 to z=6
  - Includes first IR spectra
  - But see G. Becker's talk
- Yet evolution must occur at some level



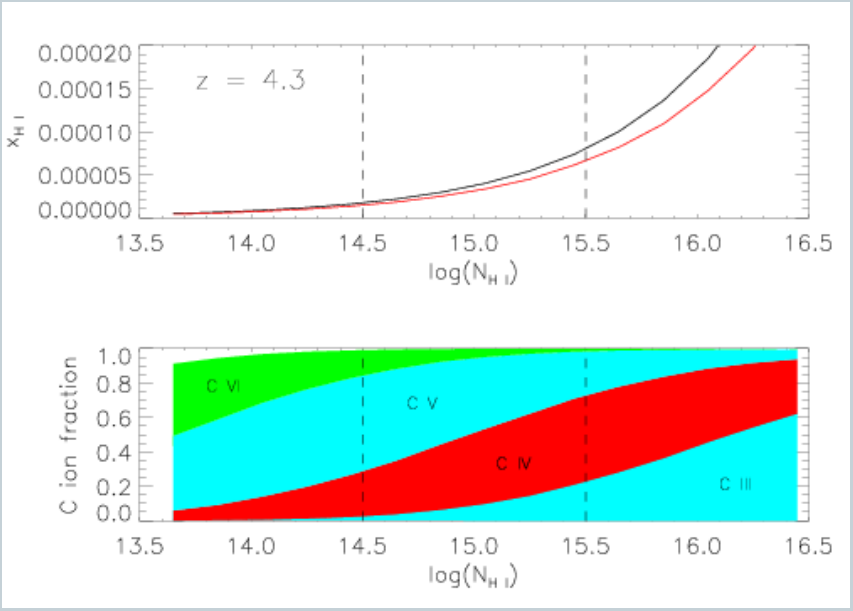


Simcoe 2006

z ~ 4 - 4.5 is a "sweet spot" for C IV abundance determinations

- Still dynamic range in H I
  - Use at least Lyα, β, γ
- Much of C is in C IV
  - Not so at lower z
- Can detect C IV at $\rho / \overline{\rho} \geq 1.5$

z = 4.3



Top: H I Fraction
Bottom: C ionization balance

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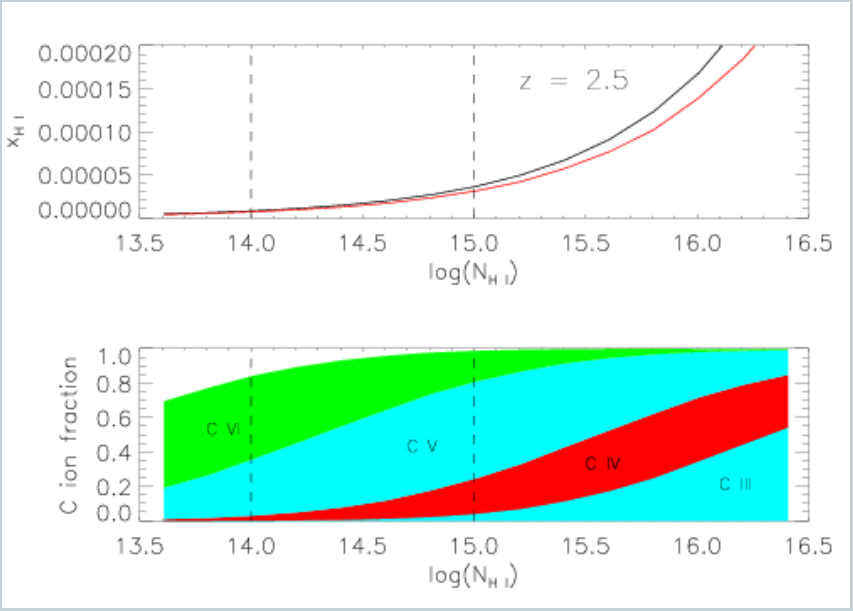
z = 2.5



Top: H I Fraction
Bottom: C ionization balance

Obtain high signal-to-noise ratio Magellan spectra of C IV at z ~ 4.3

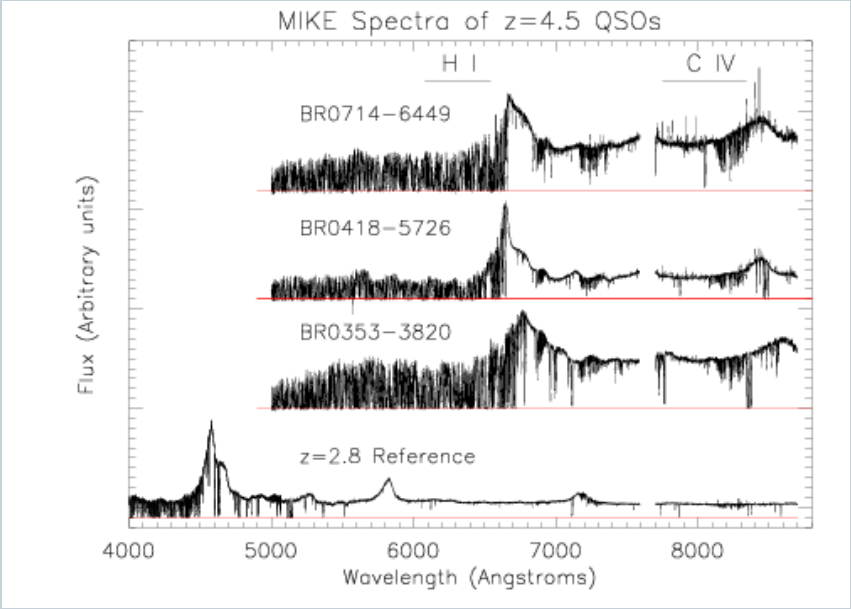
1) Select sample based on H I

2) Measure N_{CIV} or its upper limit

3) Apply ionization corrections

4) Apply survival statistics

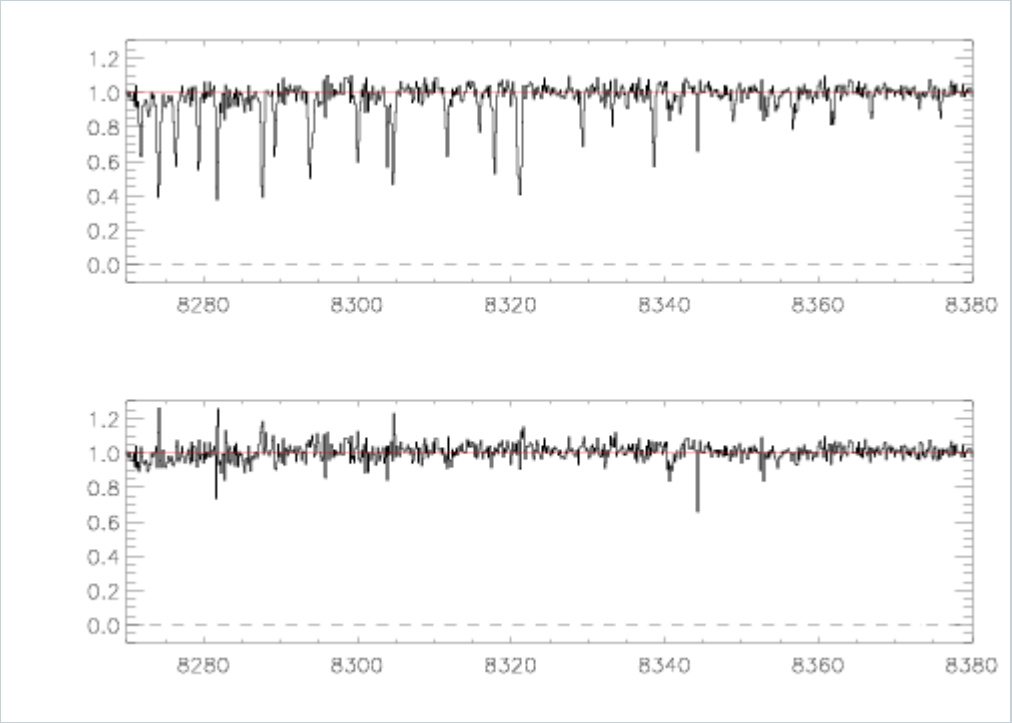
Yields cumulative distribution function of [C/H] at z ~ 4.3



Careful treatment of foregrounds essential at z > 4 (much harder than z ~ 2-3)

Uncorrected telluric features

Same spectrum, corrected



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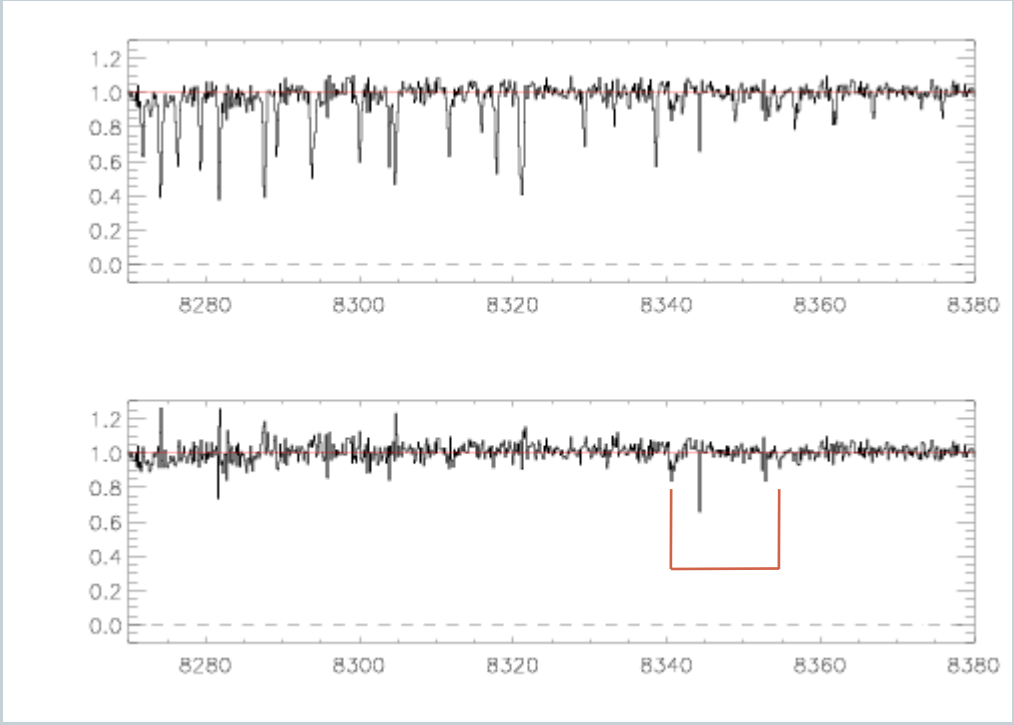
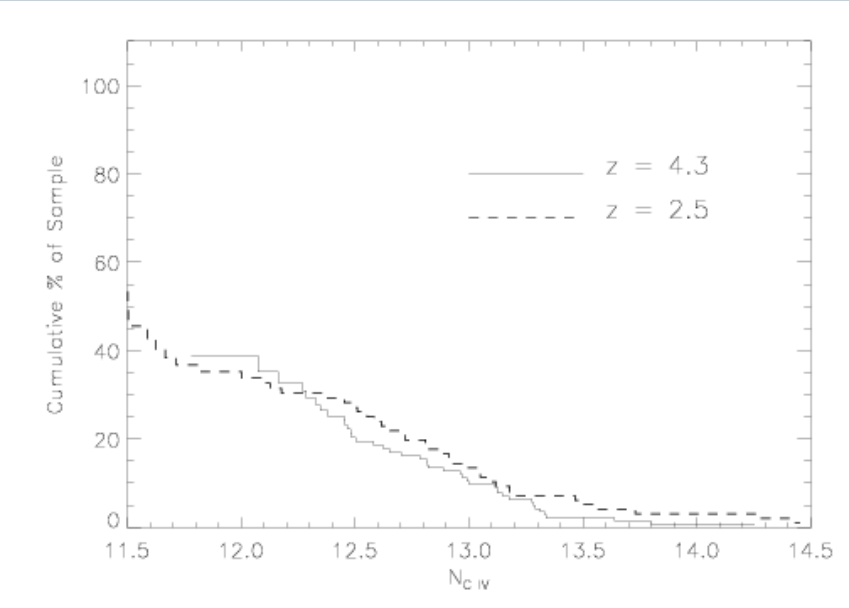
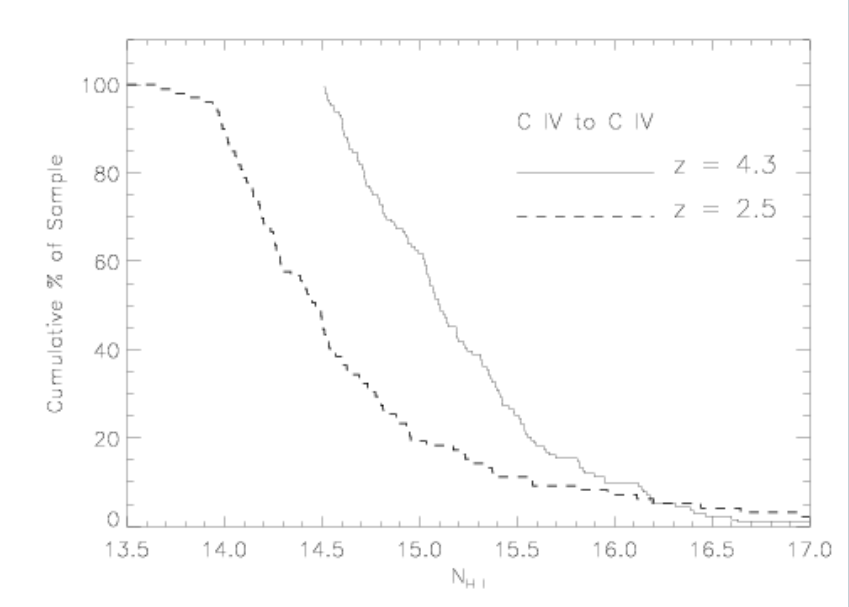


C IV at z ~ 4.3 very similar to z ~ 2.5; H I is much stronger

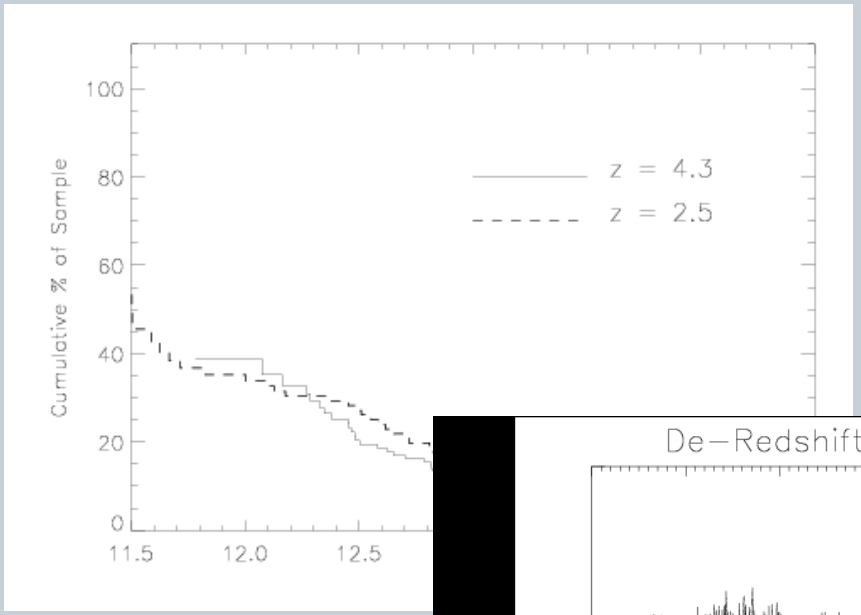


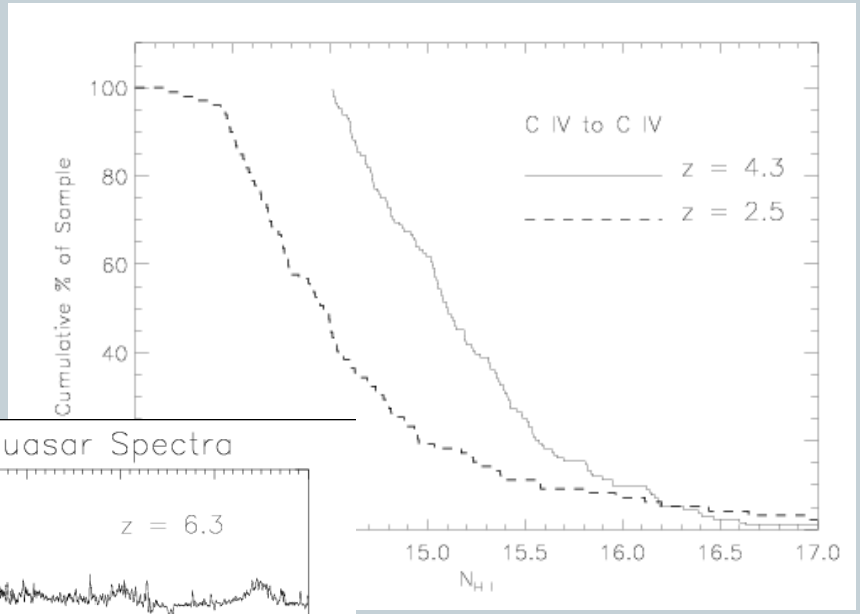
Distribution of N_{CIV}

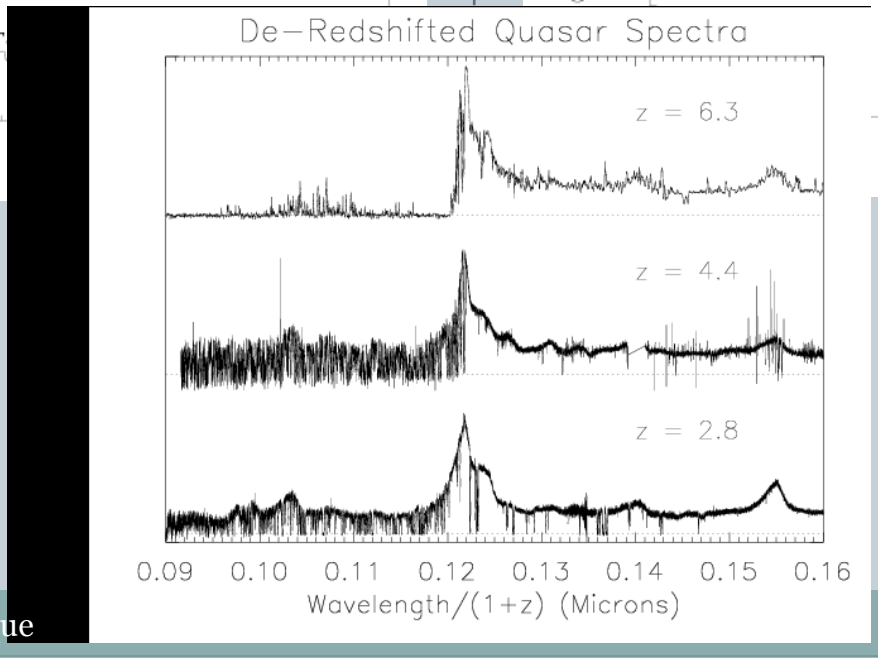


Distribution of N_{HI}

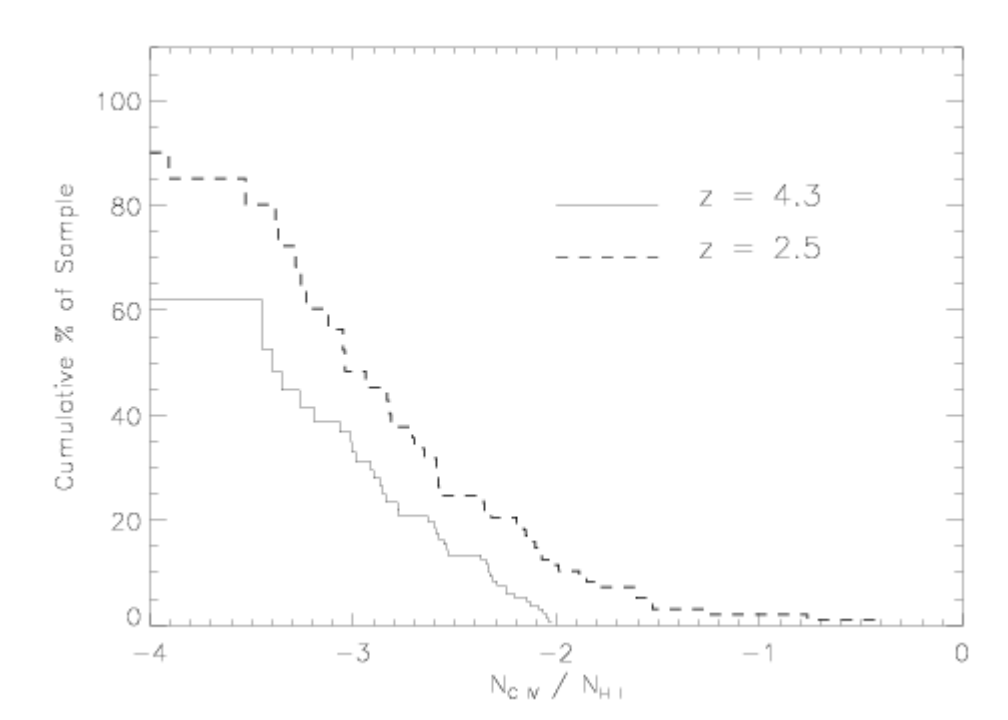
C IV at z ~ 4.3 very similar to z ~ 2.5; H I is much stronger







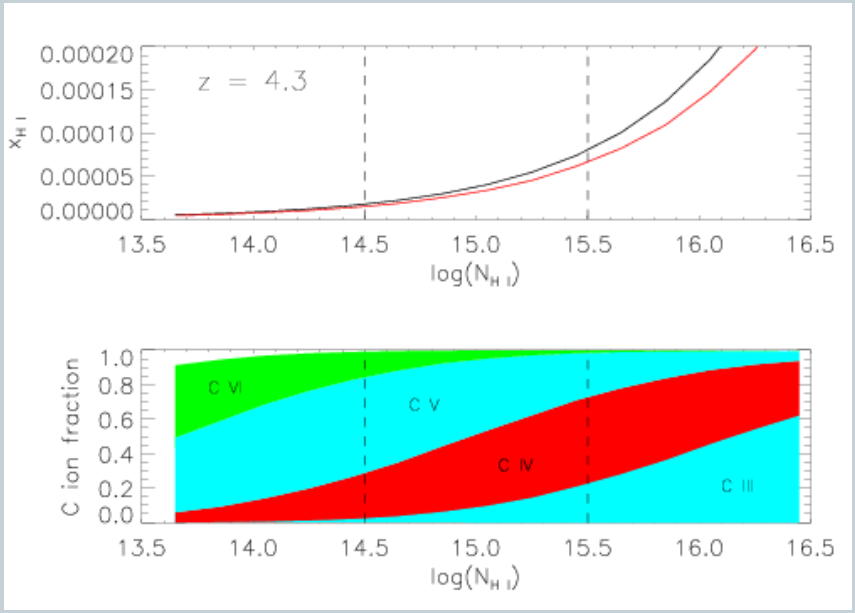
So, C IV / H I substantially smaller at z ~ 4.5



$N_{C\,IV}/N_{H\,I}$: Fundamental observable

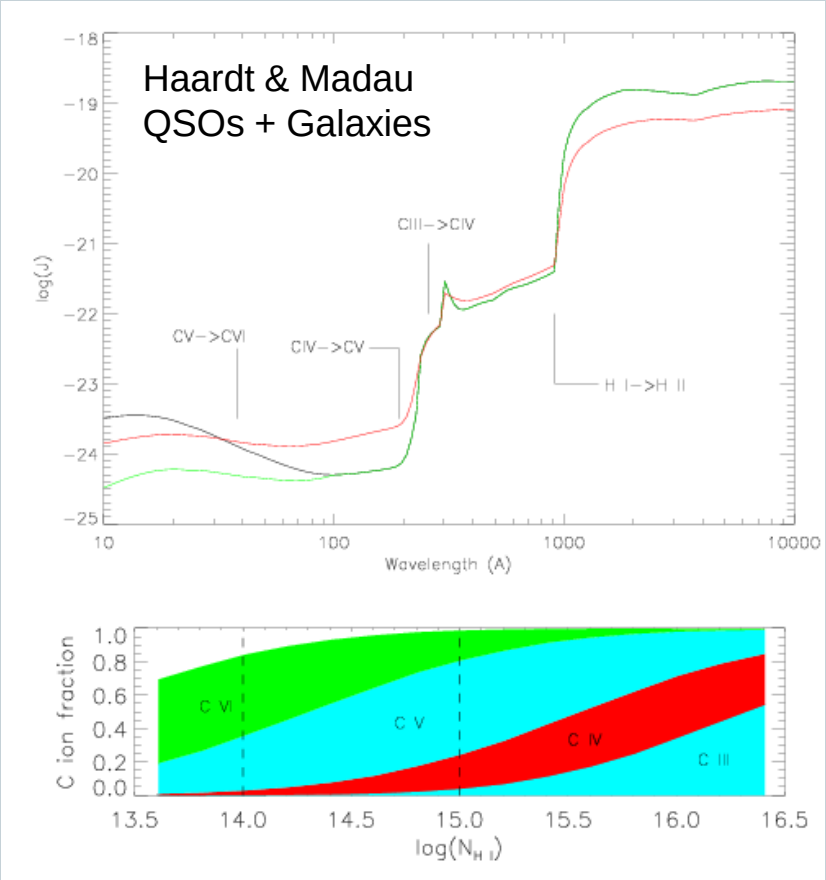
Convert N_{CIV} / N_{HI} to [C/H] Part I: H I / H

- Correction for x_{HI} fairly robust
  - Can use CLOUDY
  - Compute for each line
  - Or use $n_{HI}\Gamma \approx n_H^2 R$
    - **Γ** (H I ionization rate) constrained from forest
    - **R** (recomb rate) depends on T
    - **Γ & T** ~constant for z=2.5 - 4.5

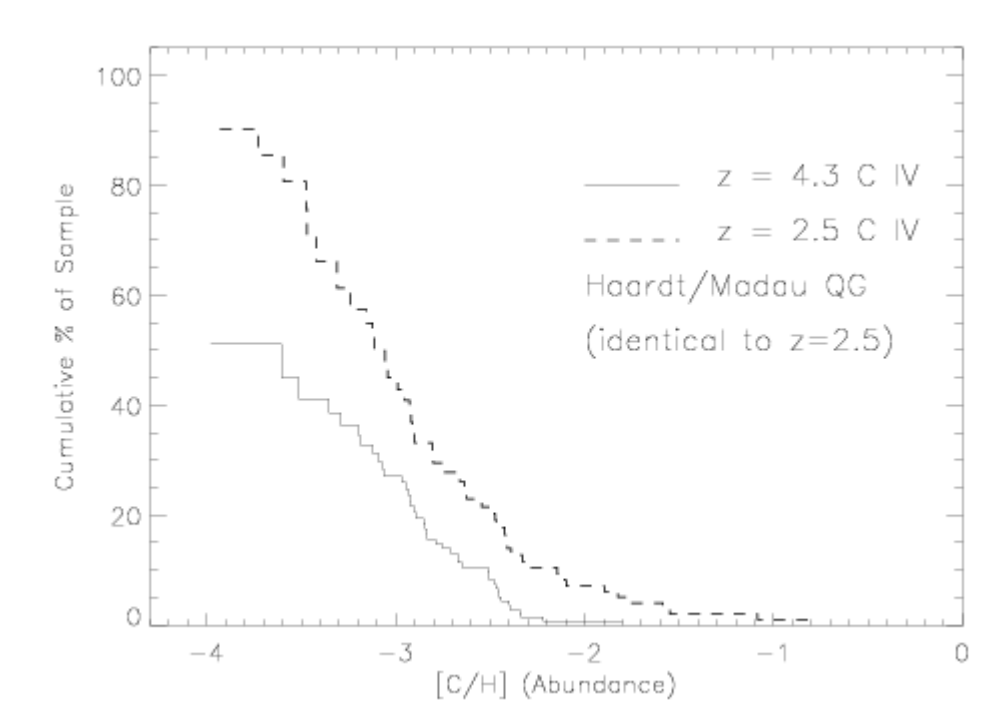


Convert N_{CIV} / N_{HI} to [C/H] Part II: C IV / C

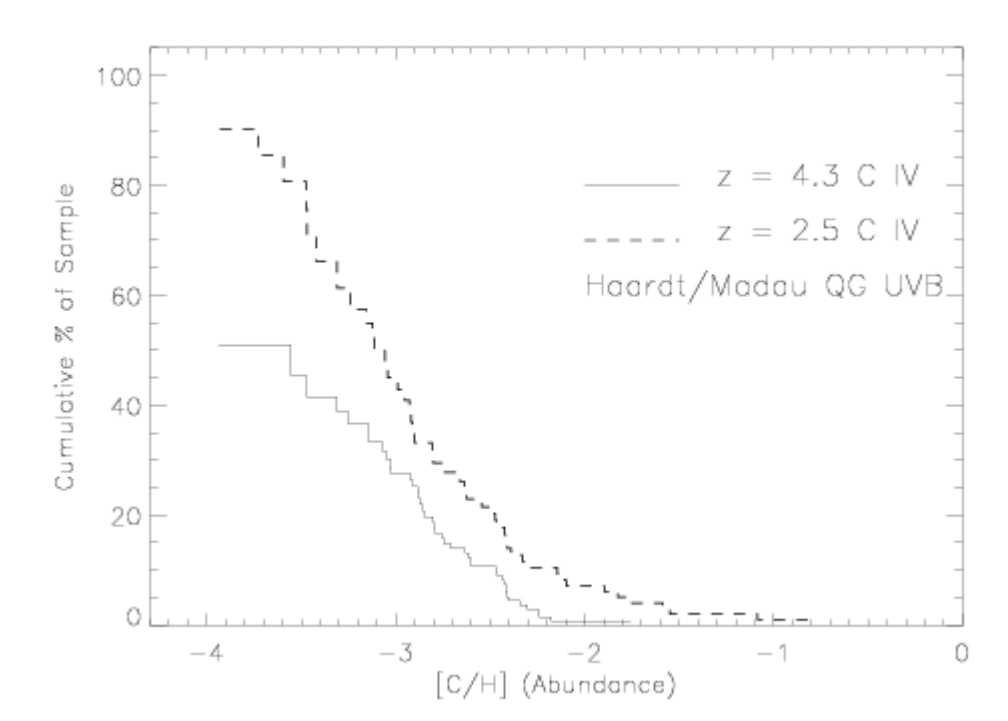
- Depends on UV/X-ray BG
  - Must use CLOUDY
  - What spectrum?
    - Softens by z ~ 4.3
  - Softer spectrum means
    - Higher C IV / C
    - Smaller correction
    - Smaller abundances



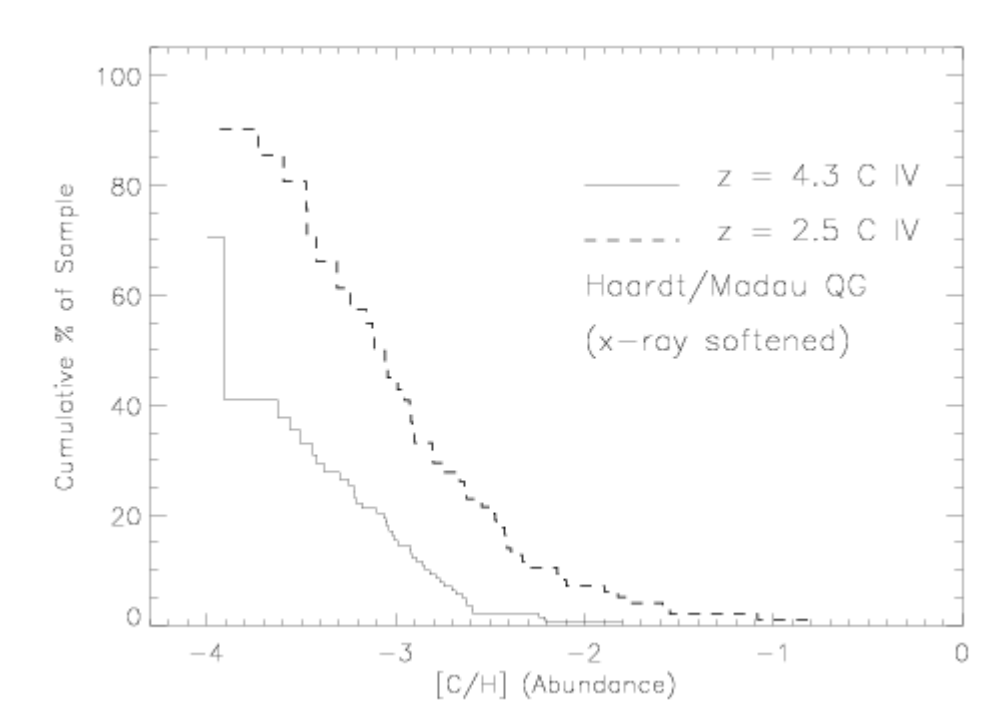
Most conservative (but unrealistic) estimate: Same spectral shape as z = 2.5



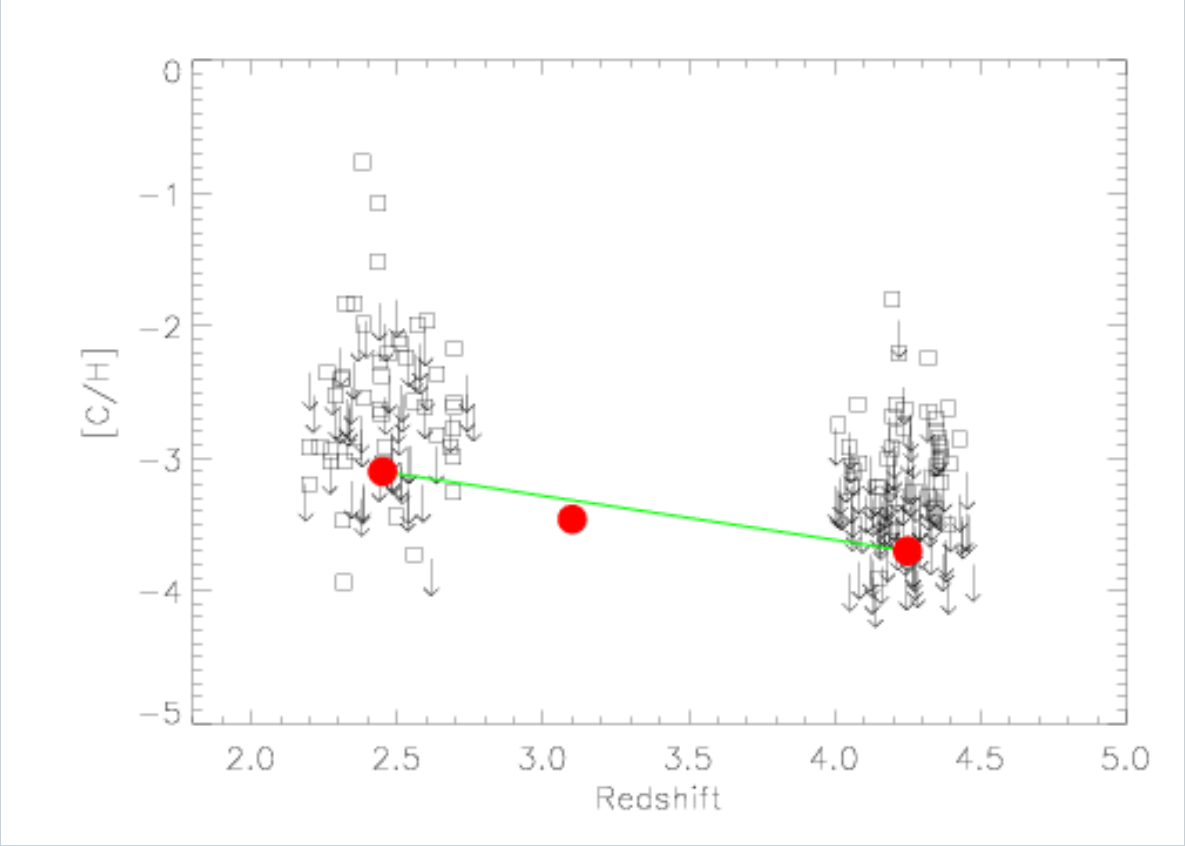
More realistic estimate: Use HM QSO/Galaxy for z = 2.5, z=4.3



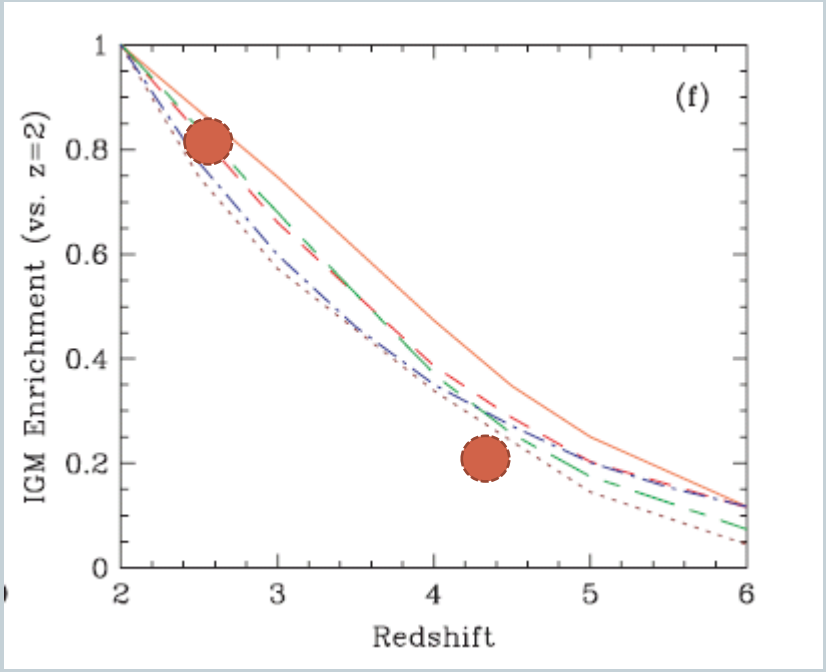
Most realistic estimate?
HM QSO+Galaxies, X-rays softened



Evolution of ionization-corrected [C/H] in the Lyman alpha forest



Implies that 60-80% of metals at z~2.5 left galaxies in the last ~Gyr



Model: Oppenheimer & Davé

- Robustness:
  - Confidence in N_{HI}?
    - Would strengthen evolution
  - Correct UV spectrum?
    - Even hard spectrum shows some trend
  - Range of densities?
    - Consistent with ([O/H]-0.5) at z = 2.5

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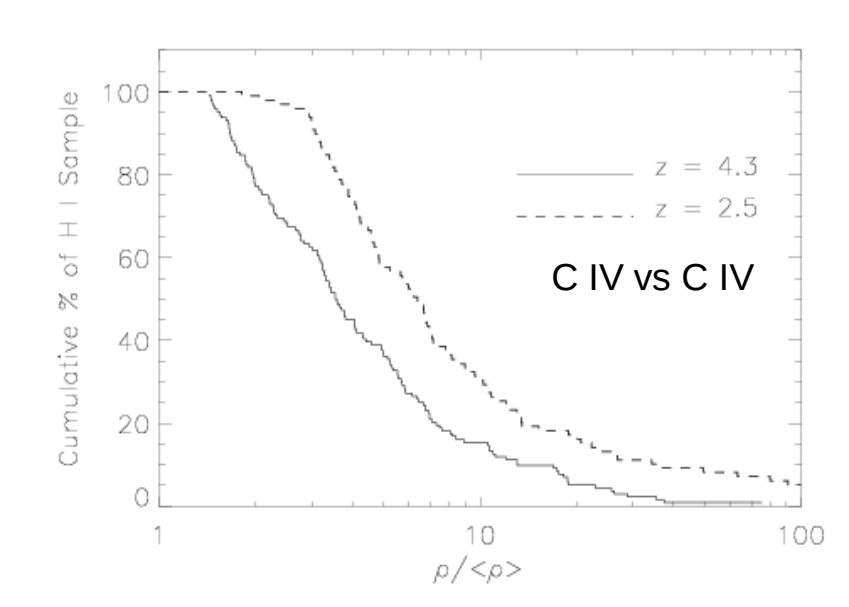

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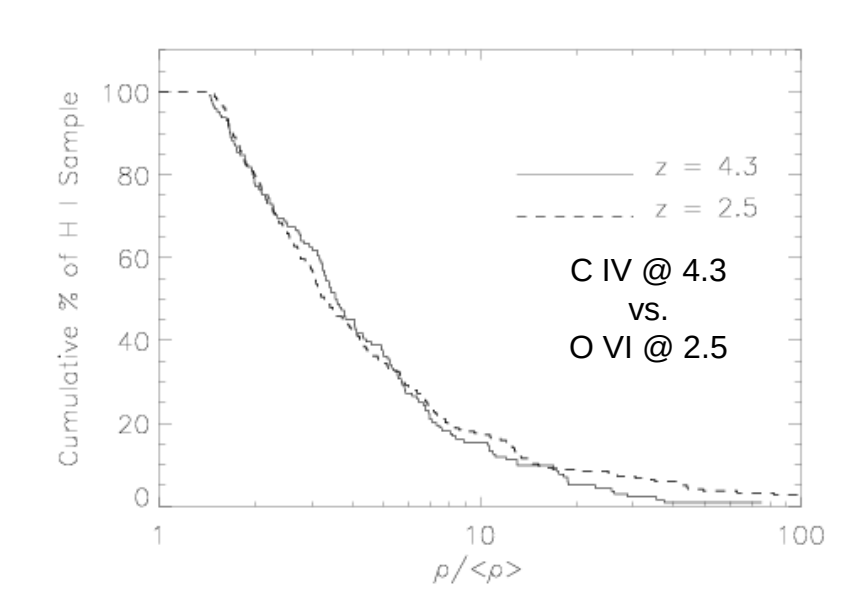

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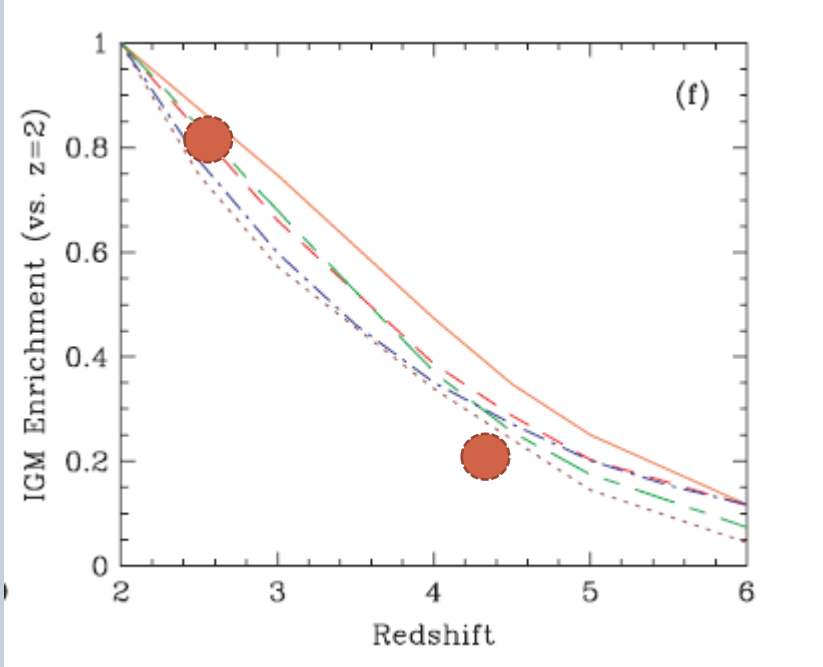

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IGM Abundances at z > 4

- Abundances are end state of feedback
- z ~ 4.3 is a good place to look
- Good evidence that [C/H] is lower at z ~ 4.3
  - Smaller by 0.5-0.75 dex
  - Linear factor of 3-5
- Heavy elements seen at z ~2 largely deposited "recently"