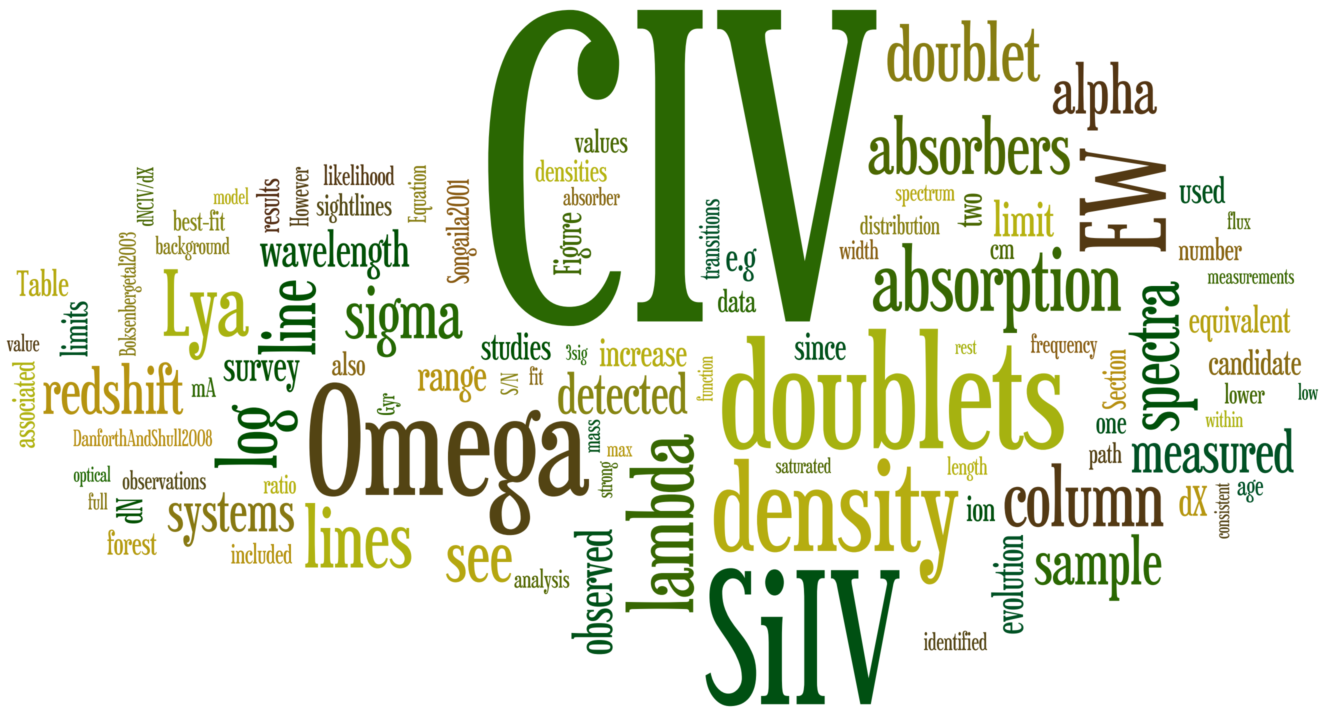

The Last Eight-Billion Years of Intergalactic CIV and SiIV Evolution

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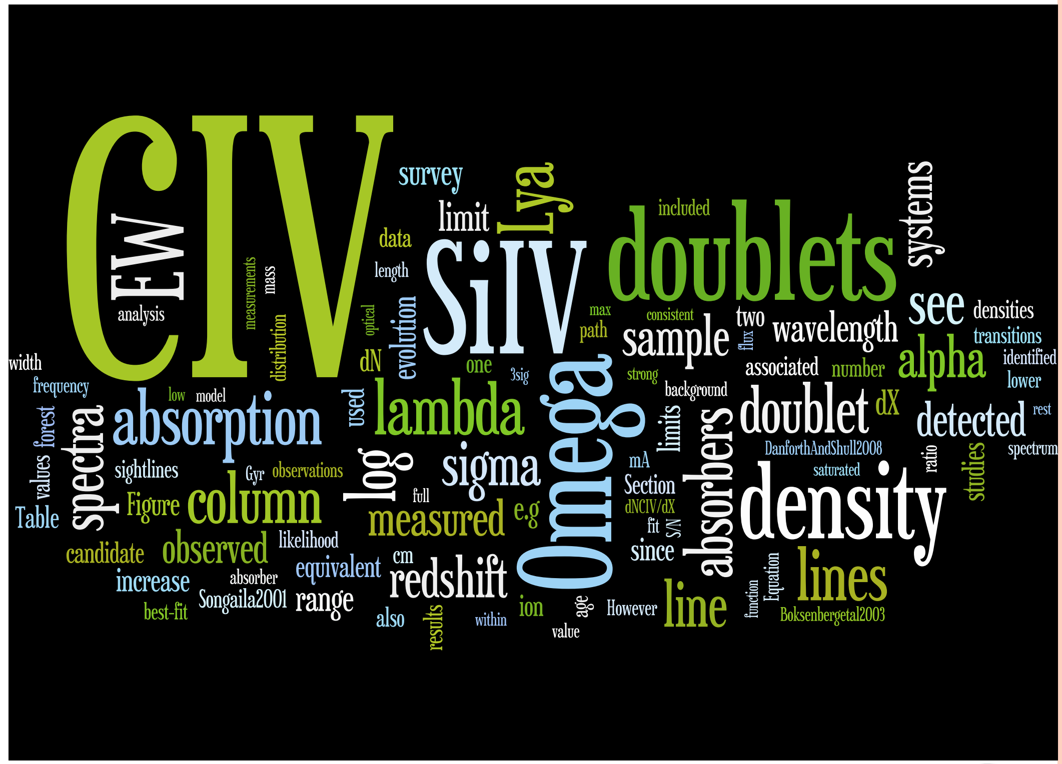
14 April 2011

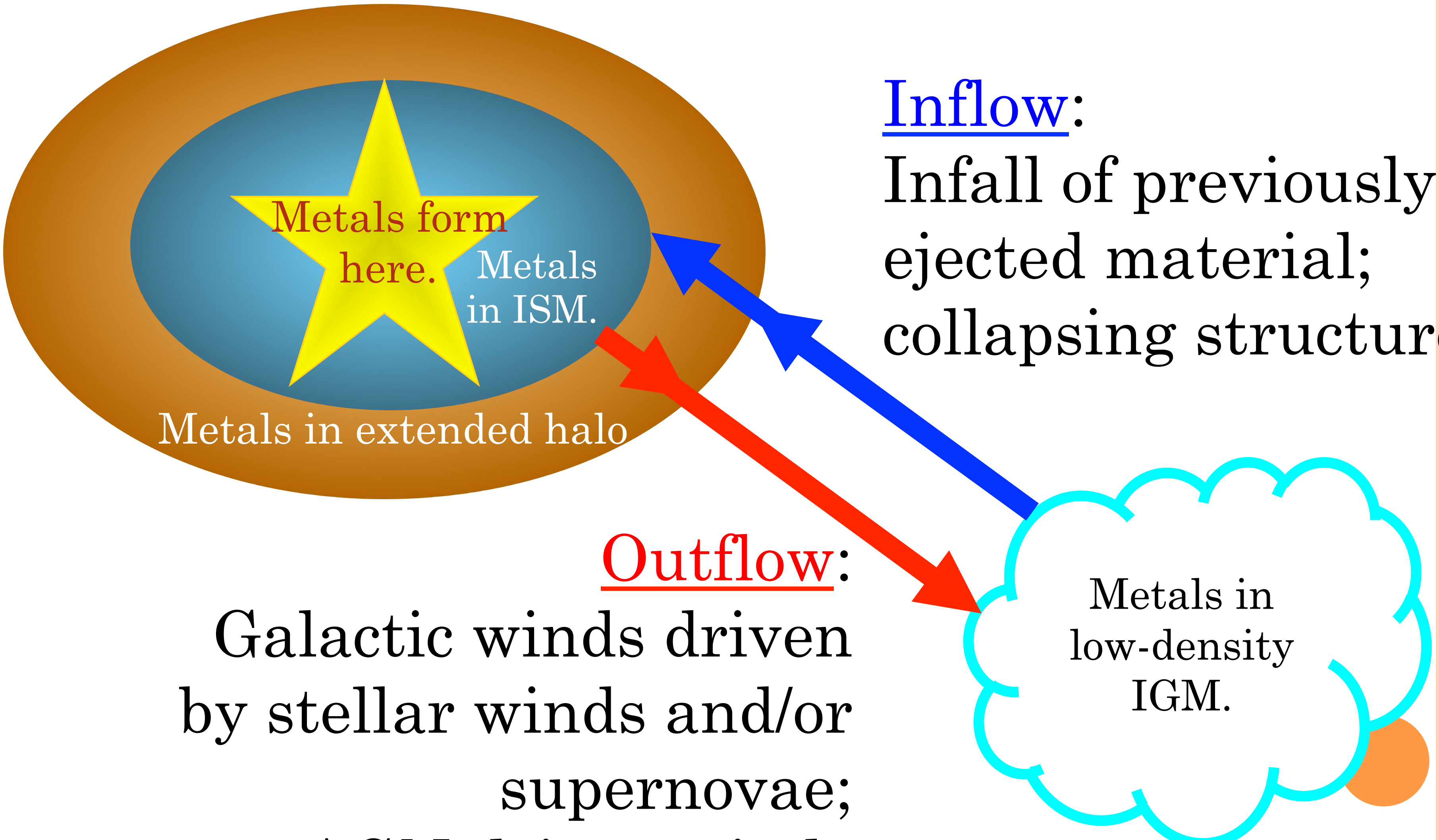
Collaborators: Rob Simcoe (MIT); Xavier Prochaska (UCSC); Chris Thom (STScI); Hsiao-Wen Chen (Chicago)

WHAT'S TO COME…

- Science drivers
- Observations, analysis, results
- Comparisons with simulations
- Summary



Cosmic Chemical Enrichment Cycle

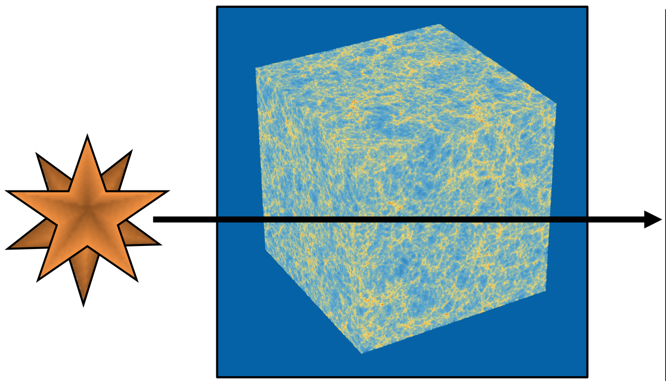


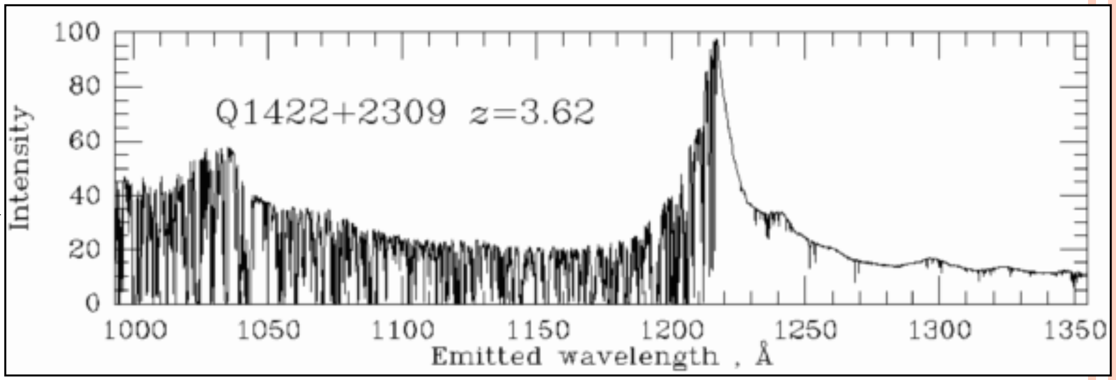
Inflow:
Infall of previously ejected material; collapsing structure

Outflow:
Galactic winds driven by stellar winds and/or supernovae; AGN-driven winds

Why CIV and SiIV Absorbers?

- Trace fairly common metals
  - And Si may trace O, which is most common
- Observable in optical pass bands for $1.5 \leq z \leq 5.5$
  - Well-studied with ground-based telescopes
- Resonant absorption-line doublets
  - Characteristic wavelength separation
  - Characteristic rest equivalent width ratio
    - 2:1 (unsaturated) to 1:1 (saturated) for 1548:1550 and 1393:1402
- Rest wavelengths red-ward of Lyα 1215
  - Outside Lyα forest



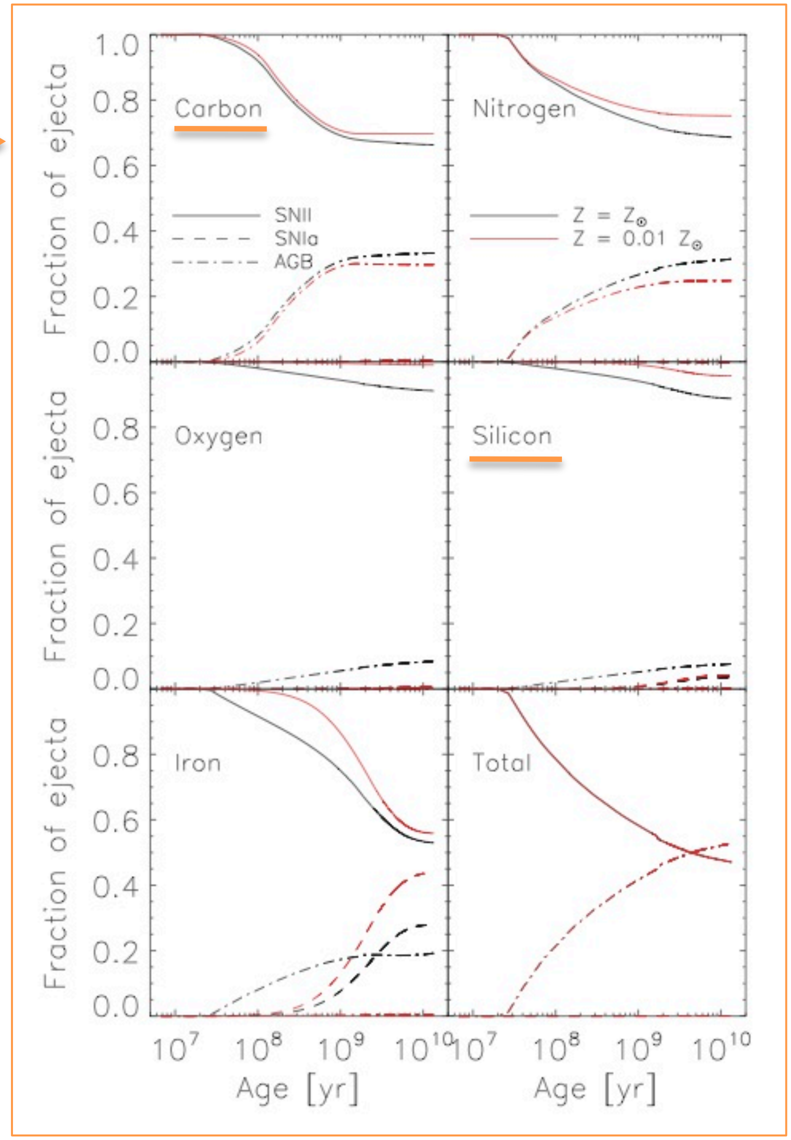


METAL ABSORPTION LINES AFFECTED BY…

- Metallicity and relative abundances

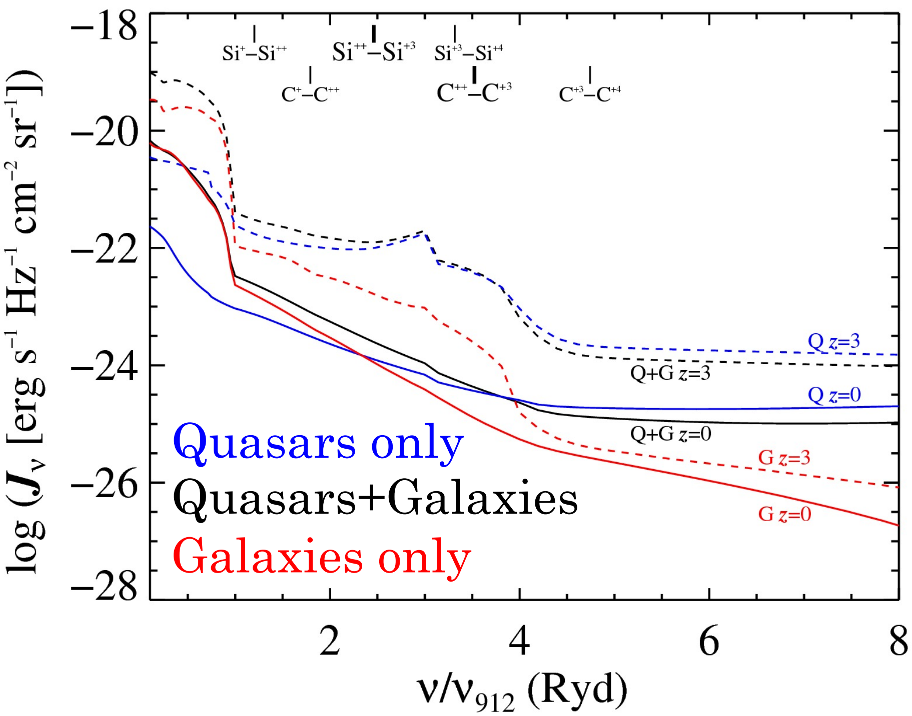
- Ionizing background
  - Changes ionization balance

- Physical distribution
  - Function of density and physical size



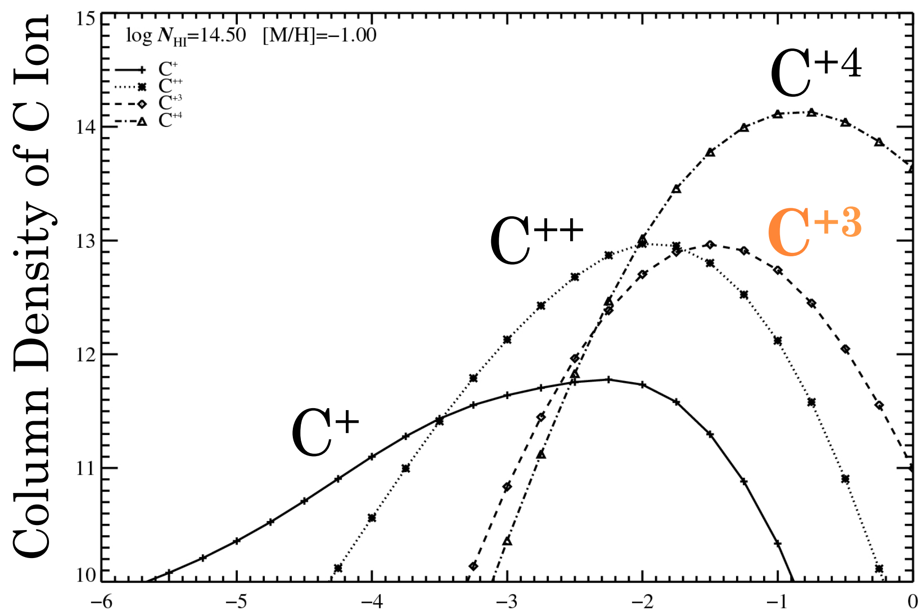
(Wiersma+ 2009)

METAL ABSORPTION LINES AFFECTED BY: IONIZING BACKGROUND AND IONIZATION BALANCE



(Haardt & Madau 1996, 2005)

C^{+3} not necessarily dominate C ion but best tracer observationally.

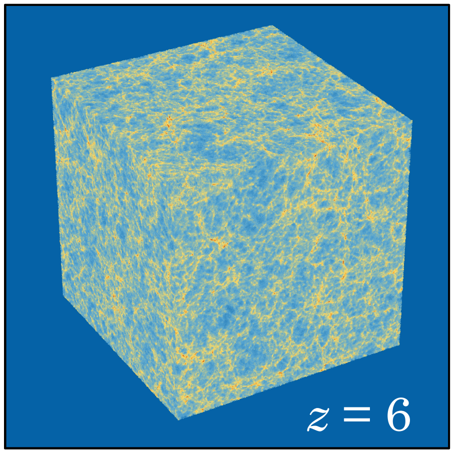


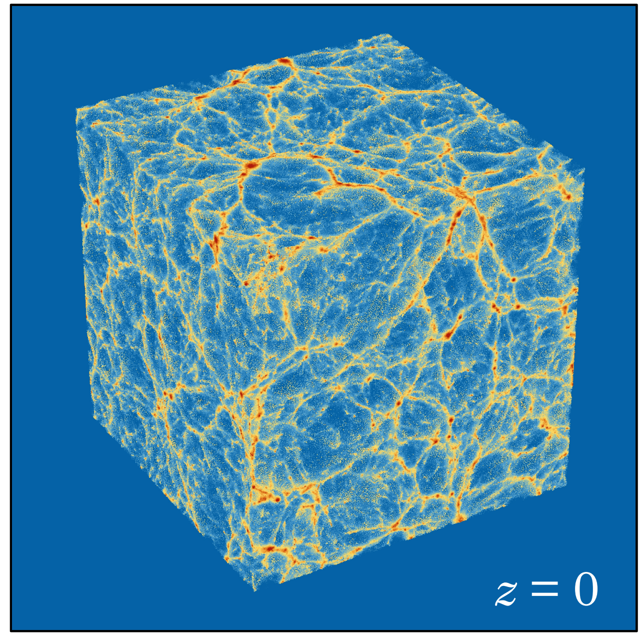
Local sources (e.g., stellar radiation field) softens background.

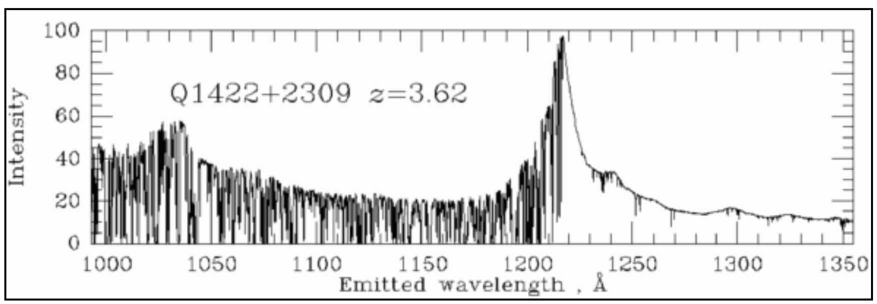
At $z \approx 3$, HeII reionization affects UVB around 4 Ryd.

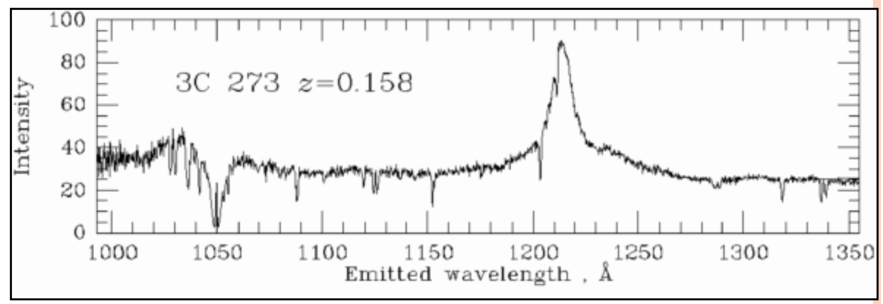
Metal Absorption Lines Affected by:

Physical Distribution





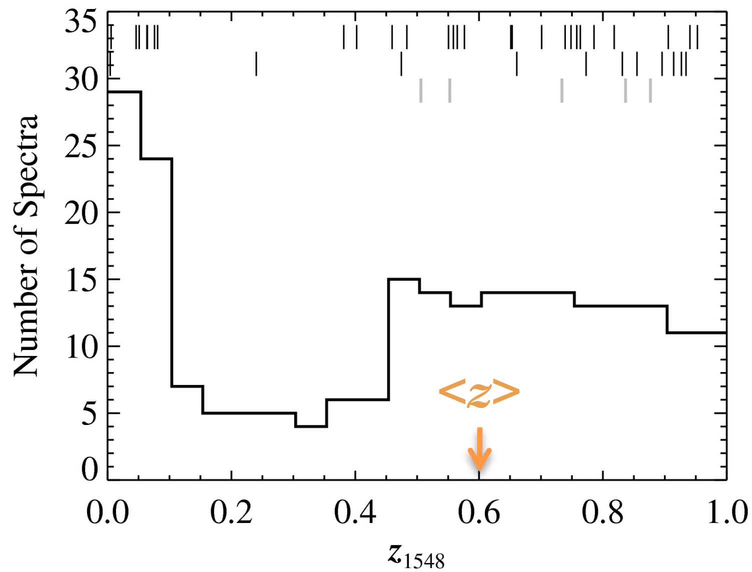


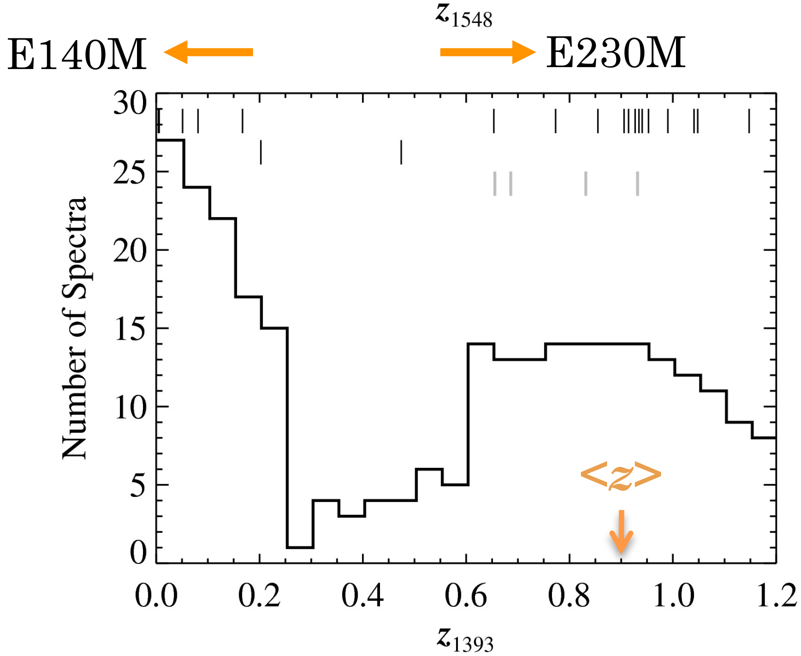


$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}X} = \frac{c}{H_0} n_{co\text{-}m} \sigma_{phys}$$

- Absorber line density ~ co-moving number density × physical cross section of absorber

CIV AND SiIV SURVEY AND FINAL SAMPLES





- 38 G = 1 CIV (43 G = 1+2)
  - log $N(C^{+3})$ = 13.2 to >15.3
- 20 G = 1 SiIV (24 G = 1+2)
  - log $N(Si^{+3})$ = 12.9 to >14.4
- 49 lines of sight (largest to date!)
  - *HST* STIS and GHRS
    - *FUSE* supplement
  - Pre-Servicing Mission 4

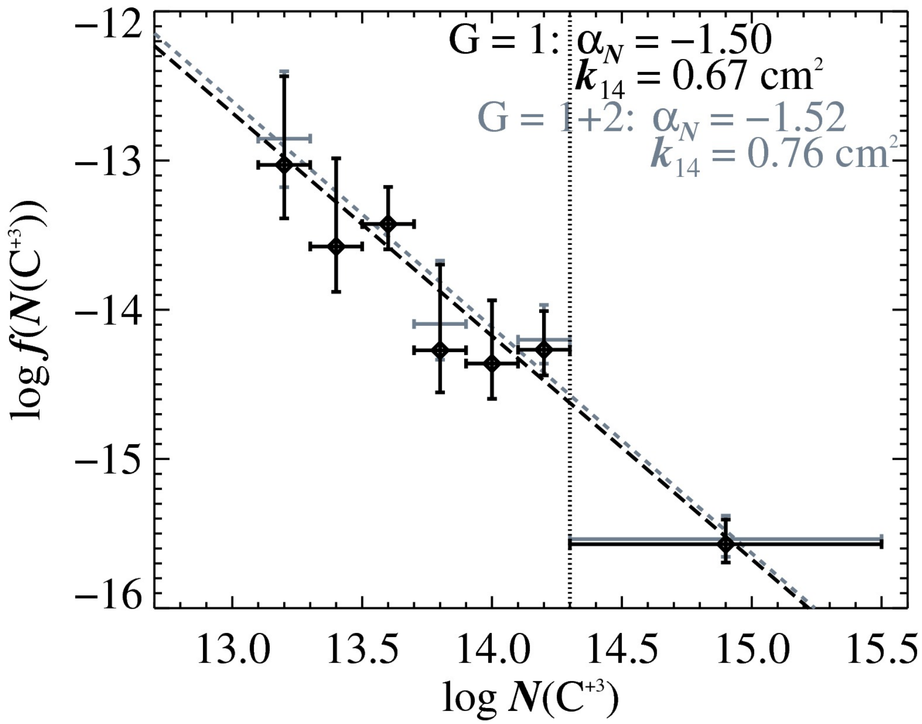
$N(C^{+3})$ and $N(Si^{+3})$ Frequency Distributions

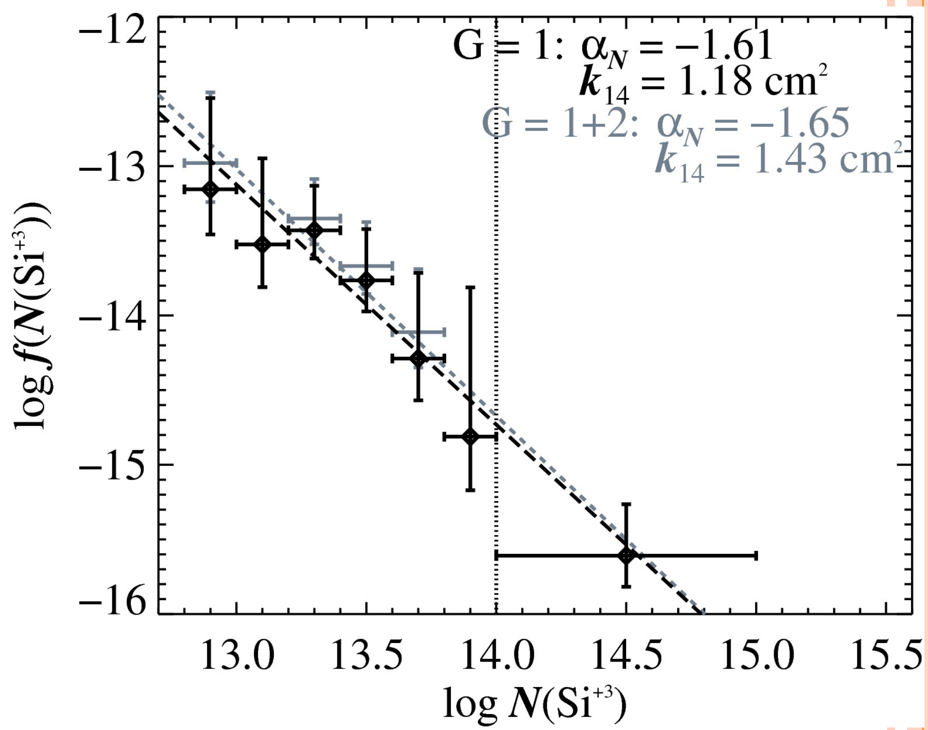
Definition:

$$f(N(C^{+3})) \equiv \frac{\Delta \mathcal{N}}{\Delta N(C^{+3})\ \Delta X(N(C^{+3}))}$$

Power-law model:

$$f(N(C^{+3})) = k\left(\frac{N(C^{+3})}{N_0}\right)^{\alpha}$$





No observed break in $f(N)$.

Defining and Measuring C^{+3} Mass Density

- Relative to critical density of Universe

$$\Omega_{C^{+3}} = \frac{H_0 m_C}{c\rho_{c,0}} \int_{N_{\min}}^{N_{\max}} f(N(C^{+3}))N(C^{+3})dN(C^{+3})$$

- Approximate by summing column densities

$$\Omega_{C^{+3}} = \frac{H_0 m_C}{c\rho_{c,0}} \sum_{\mathcal{N}} \frac{N(C^{+3})}{\Delta X(N(C^{+3}))}$$

- Assume power-law formulism and integrate $f(N(C^{+3})) = k\left(\frac{N(C^{+3})}{N_0}\right)^{\alpha}$

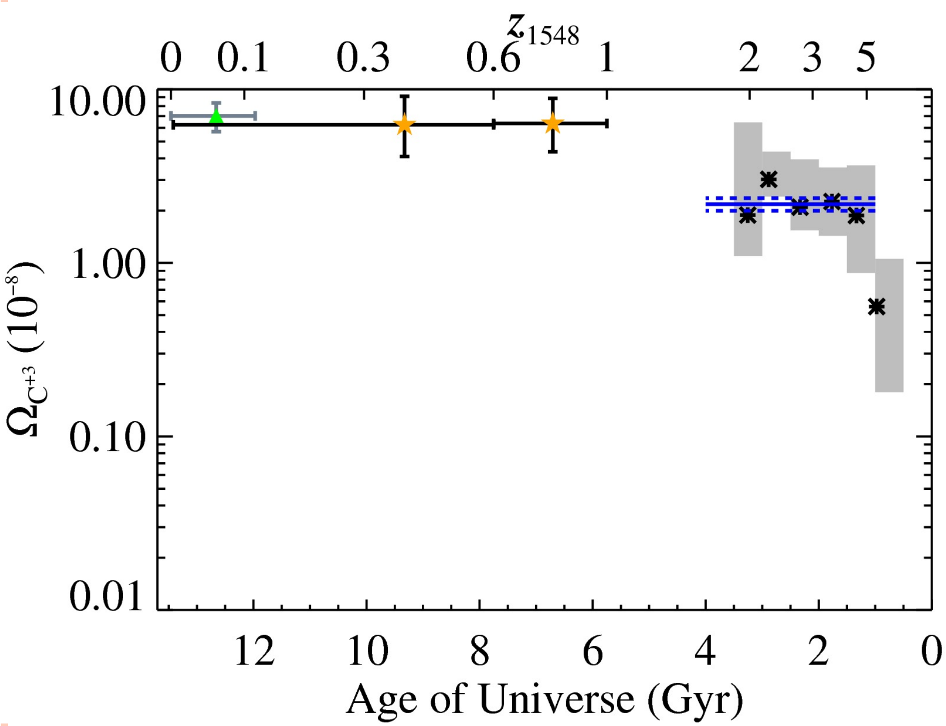
$$\Omega_{C^{+3}} = \frac{H_0 m_C}{c\rho_{c,0}} \frac{k}{2+\alpha}\left(\frac{N_{\max}^{2+\alpha} - N_{\min}^{2+\alpha}}{N_0^{\alpha}}\right)$$

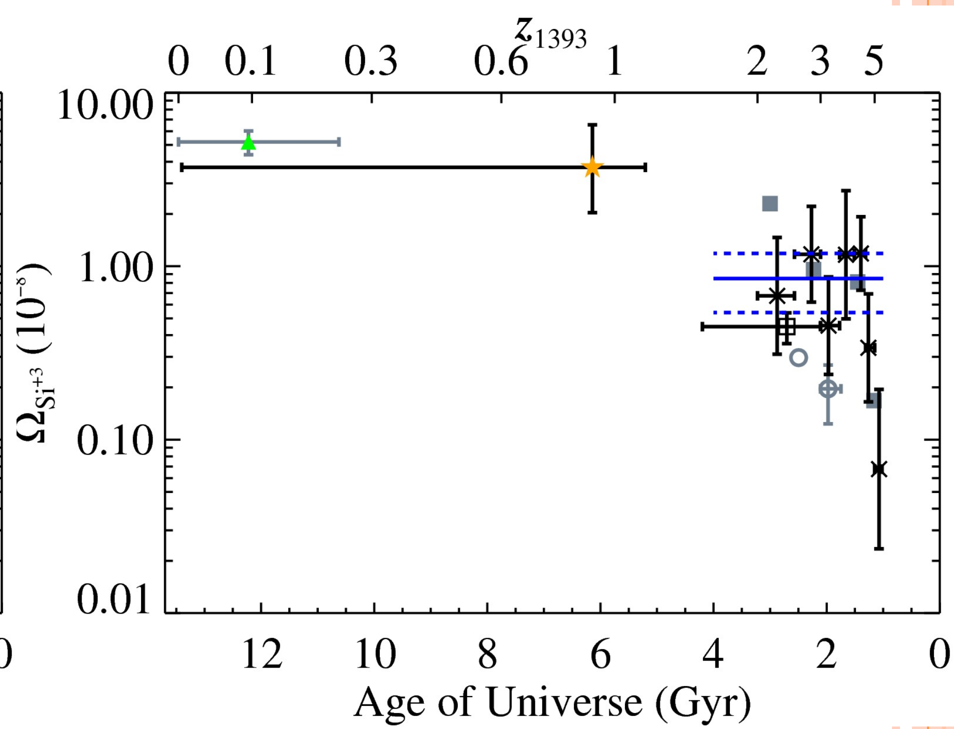
- Define finite bounds: $13 \leq \log N \leq 15$

Mass Densities Over Age of Universe

C^{+3}: Increases by 4±0.5 over high-*z* variance-weighted mean.
Rate: (0.51±0.16) × 10^-8 Gyr^-1

Si^{+3}: Increases by 4+3/-1.9 over high-*z* unweighted median.
Rate: (0.61±0.13) × 10^-8 Gyr^-1



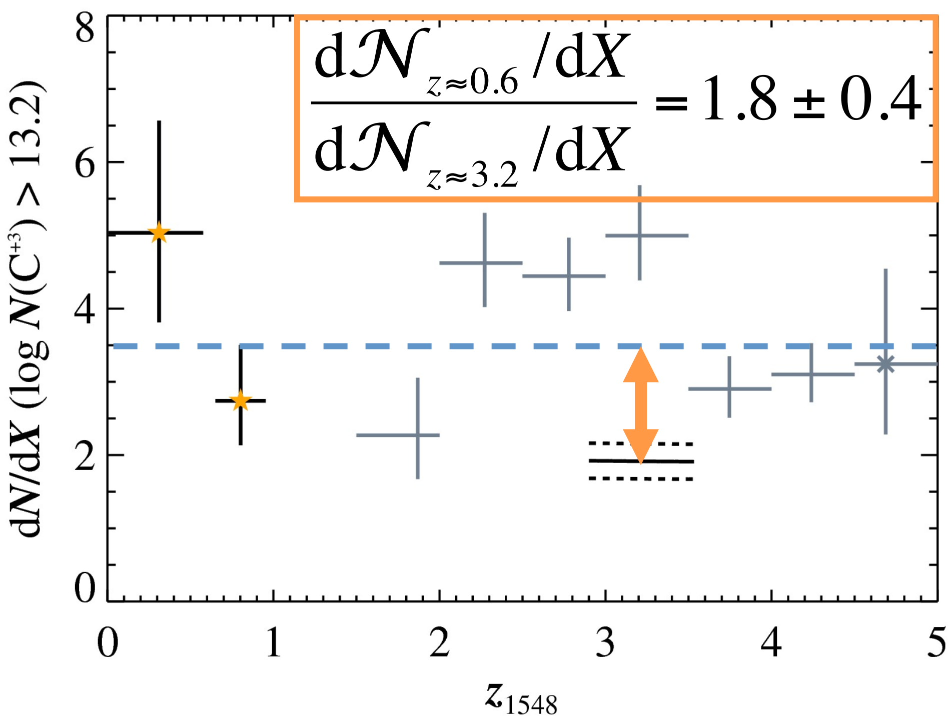


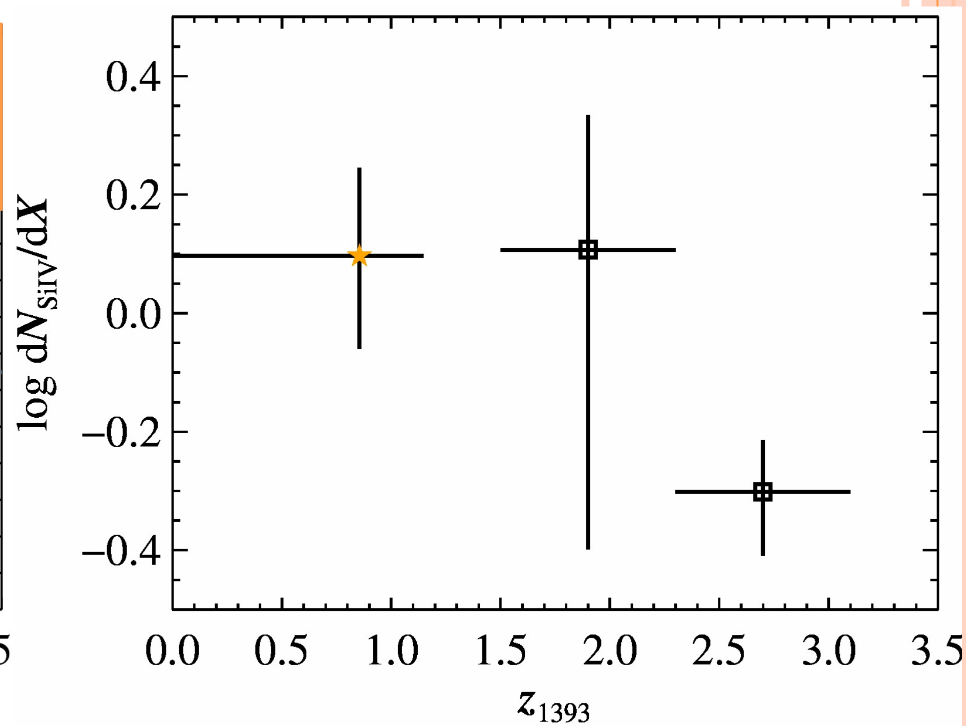
Songaila 1997, 2001, 2005; Pettini+ 2003; Boksenberg+ 2003; Scannapieco+ 2006; Danforth & Shull 2008; Becker+ 2008; Ryan-Weber+ 2009; Cooksey+ 2010, 2011

ABSORBER LINE DENSITY: EVOLUTION?

$d\mathcal{N}_{CIV}/dX$: Yes! But…
not significant, just statistically significant

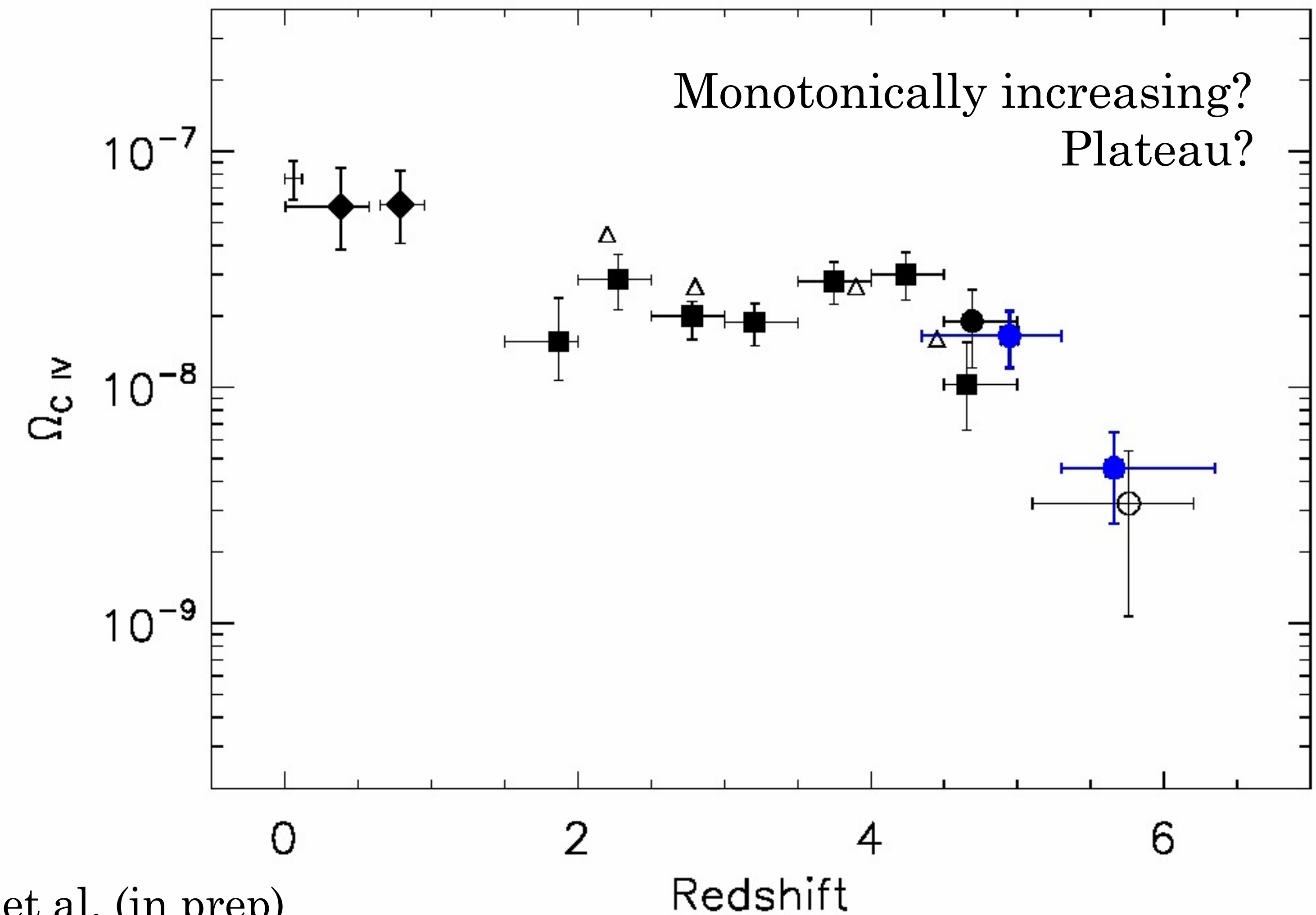
$d\mathcal{N}_{SiIV}/dX$: No! But…
high-redshift studies need to be improved…





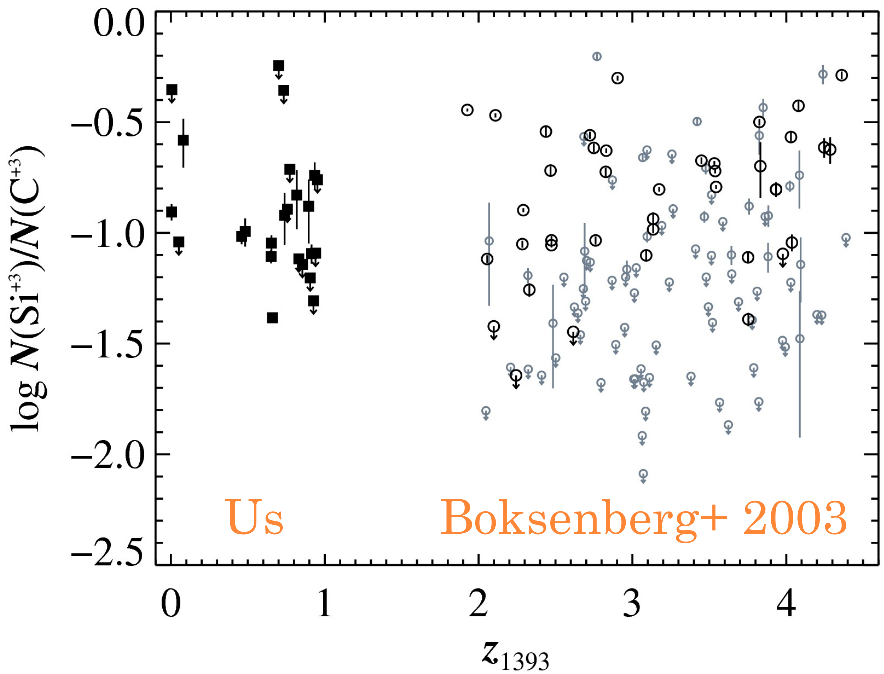
(Songaila 2001, Pettini+ 2003, Boksenberg+ 2003, Scannapieco+ 2006)

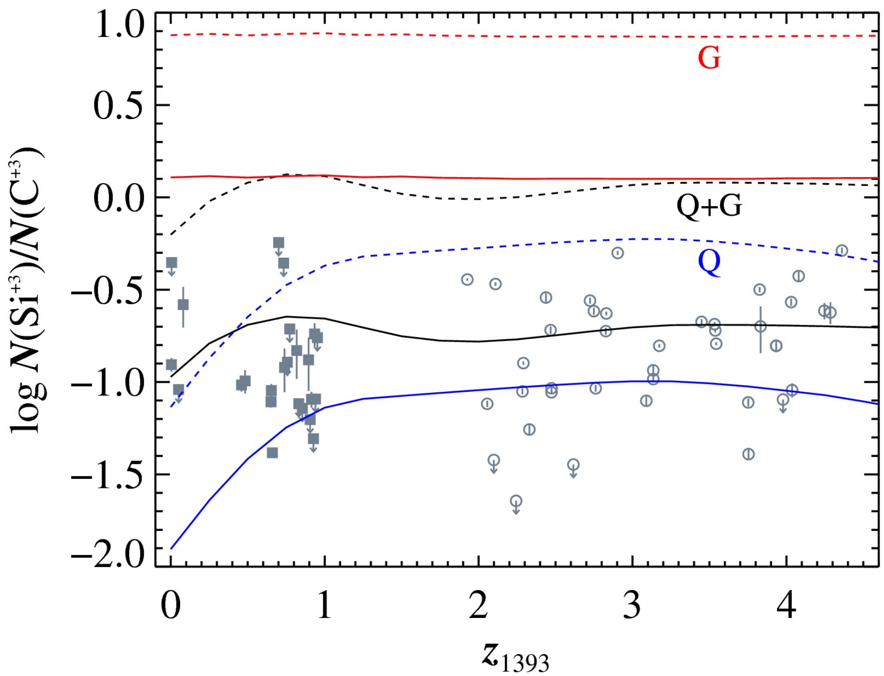
The C+3 Mass Density "Story"… Now Under FIRE



Simcoe et al. (in prep)

Ionic Ratio $N(Si^{+3})/N(C^{+3})$





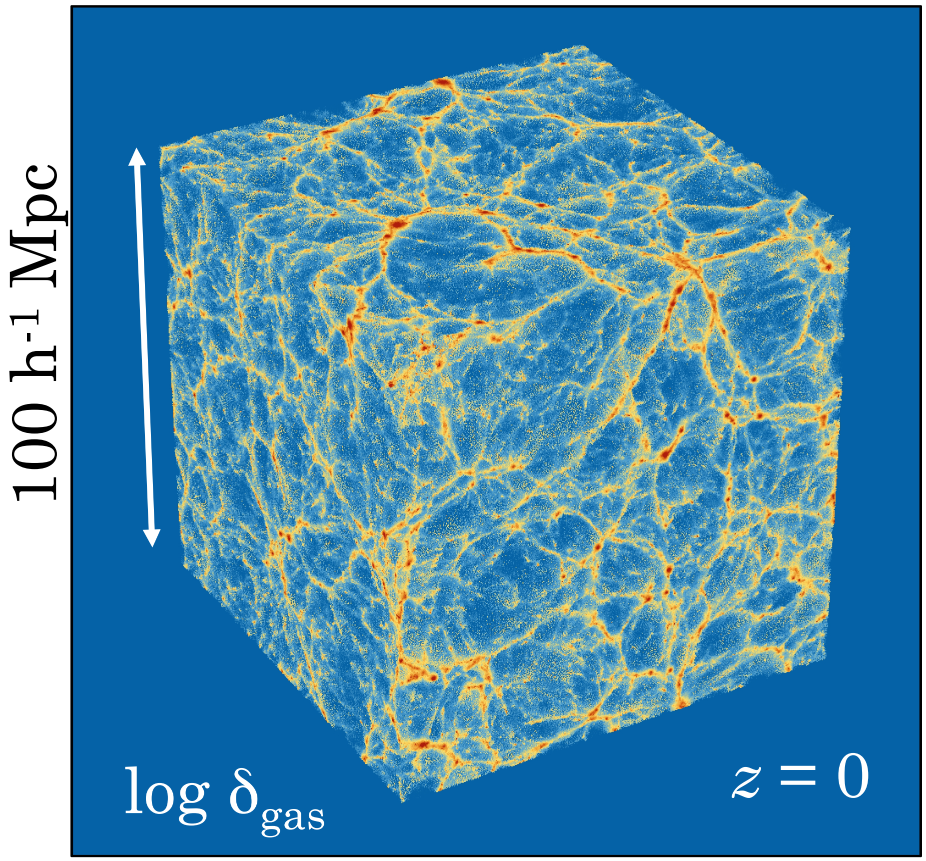
- No evolution with redshift
  - Both samples drawn from same parent population
- $N(Si^{+3})/N(C^{+3}) \approx 0.16$ for 12 Gyr!
  - No signature for HeII reionization at z ≈ 3
- Balanced interplay of three processes:

$$\frac{N(\mathrm{Si}^{+3})}{N(\mathrm{C}^{+3})} = \left(\frac{L_{\mathrm{Si}}}{L_{\mathrm{C}}}\right)\left(\frac{n_{\mathrm{Si}}}{n_{\mathrm{C}}}\right)\left(\frac{\chi_{\mathrm{Si}}^{\mathrm{Si}^{+3}}}{\chi_{\mathrm{C}}^{\mathrm{C}^{+3}}}\right)$$

- Must turn to simulations…

OverWhelmingly Large Simulations

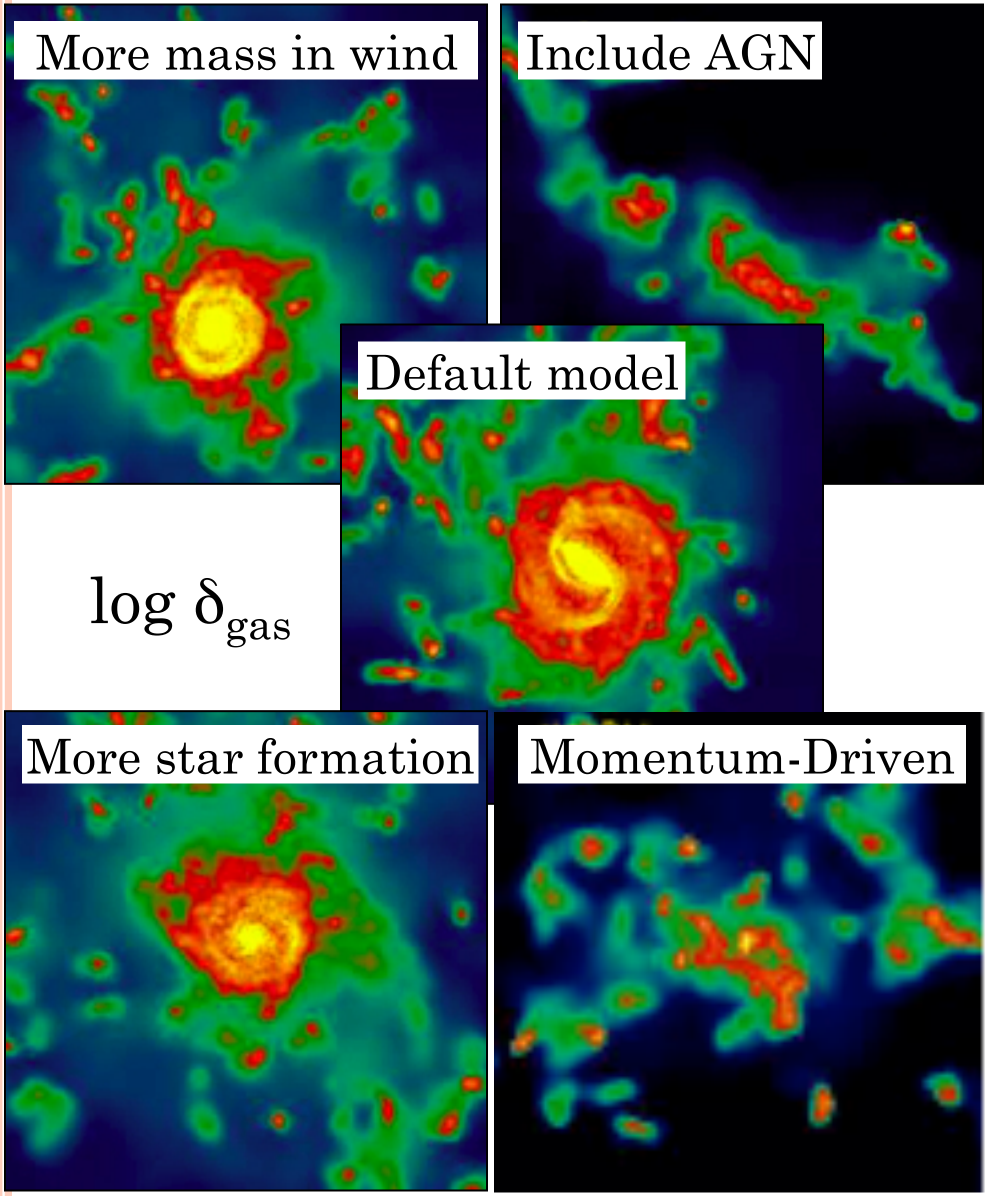
See Schaye et al. (2010)



(Schaye & Dalla Vecchia 2008; Dalla Vecchia & Schaye 2008; Wiersma et al 2009a, b; Booth & Schaye 2009; and more!)

- Hydrodynamic cosmological simulations, $z = 127 \rightarrow 0$
  - Gadget III
  - Periodic boundary conditions
  - $2{\times}512^3$ (baryonic+dark matter) particles
  - 100 h^{-1} Mpc on a side
- Chemical evolution physics:
  - Radiative cooling by 11 elements
  - Photoionization by UV background in addition to collisional ionization equilibrium
  - Chemodynamics (production and dispersal of elements)

EFFECTS OF CHANGING "FEEDBACK"



- (i.e., movement of material and energy by stars and active galactic nuclei
  - Winds, jets, bubbles,…)
- Feedback affects…
  - **Star formation rate**
  - **Ionization balance**
  - **Physical distribution…**
- Effects felt near, far, and over time

Haas et al. (in prep.)

Probing CIV and SiIV in OWLS Universes: Simulations Description

Simulation	What does each really test?
DEFAULT	How well can reference (kinetic) model reproduce observations?
AGB0_SNIa0	Absence of delayed metal production and feedback.
AGN	Effect of AGN (thermal) feedback plus kinetic winds.
MILL	Effect of cosmology (higher σ_8) and more mass in winds.
NOFB	How much can dynamics do for enrichment?
THERMAL_FB	"Next generation": feedback model, cooling, ionizing, cosmology,…
WML4	Effect of more mass in winds and reference for *MILL* (σ_8) .
WMOM	Effect of scaling kinetic wind parameters with v_c (halo mass).
ZCOOL0	Absence of metal-line cooling.

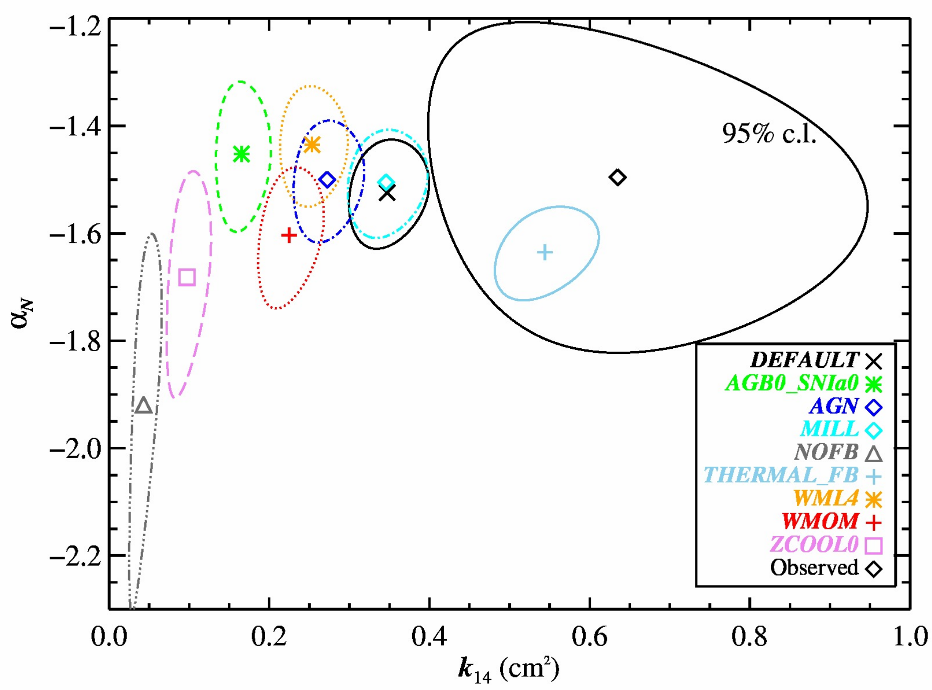
Also use variants of *DEFAULT* to test convergence, resolution, ionization balance (UV background), and abundances (yields).

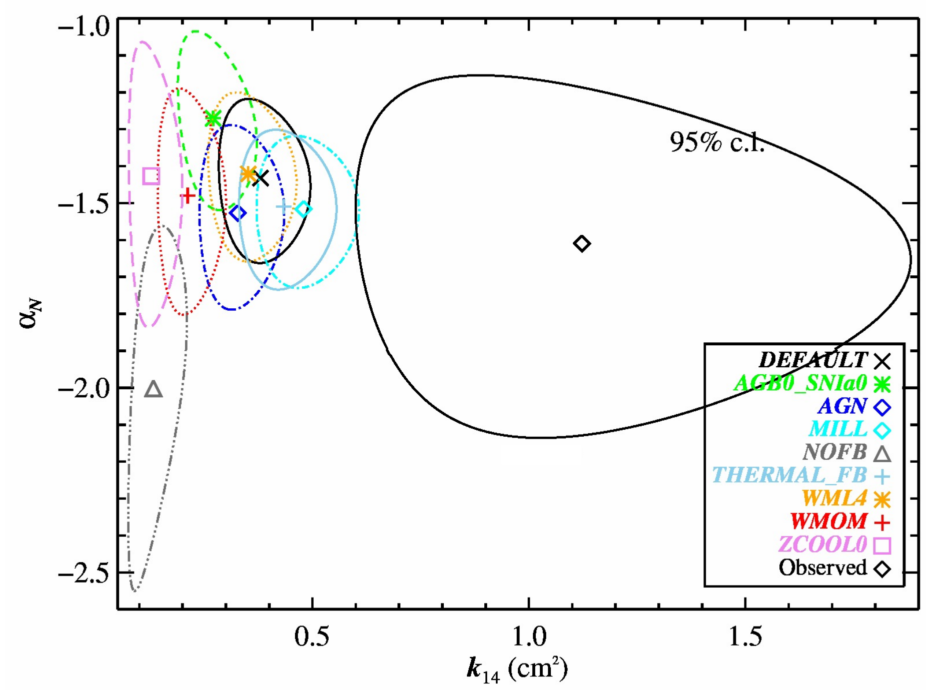
COMPARING SIMULATIONS TO OBSERVATIONS: $N(C^{+3})$ and $N(Si^{+3})$ Frequency Distributions

C^{+3}: Just need feedback and cooling to reproduce shape. Too few CIV absorbers! Except for THERMAL_FB…?

Si^{+3}: Just need feedback to reproduce shape but too few.

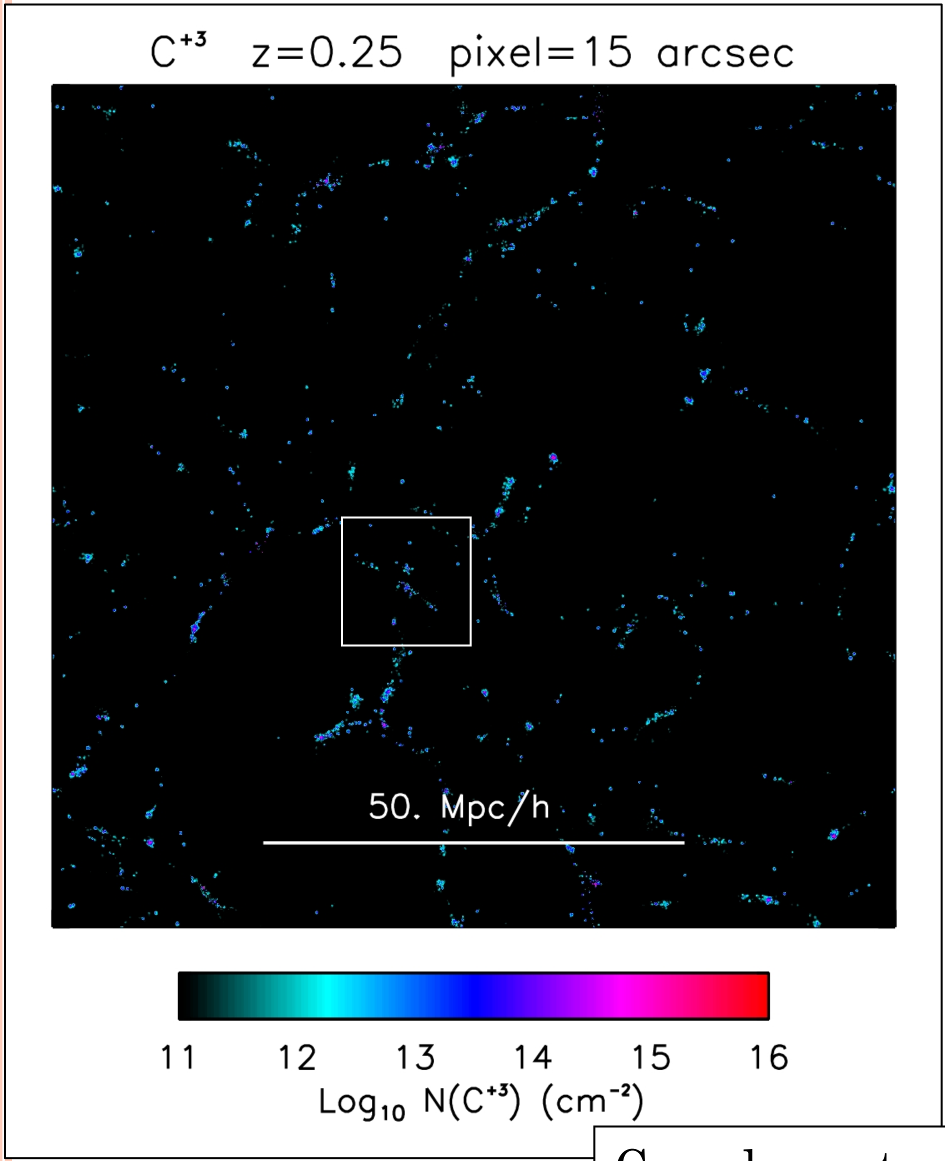
SiIV observations better reproduced with higher σ_8?

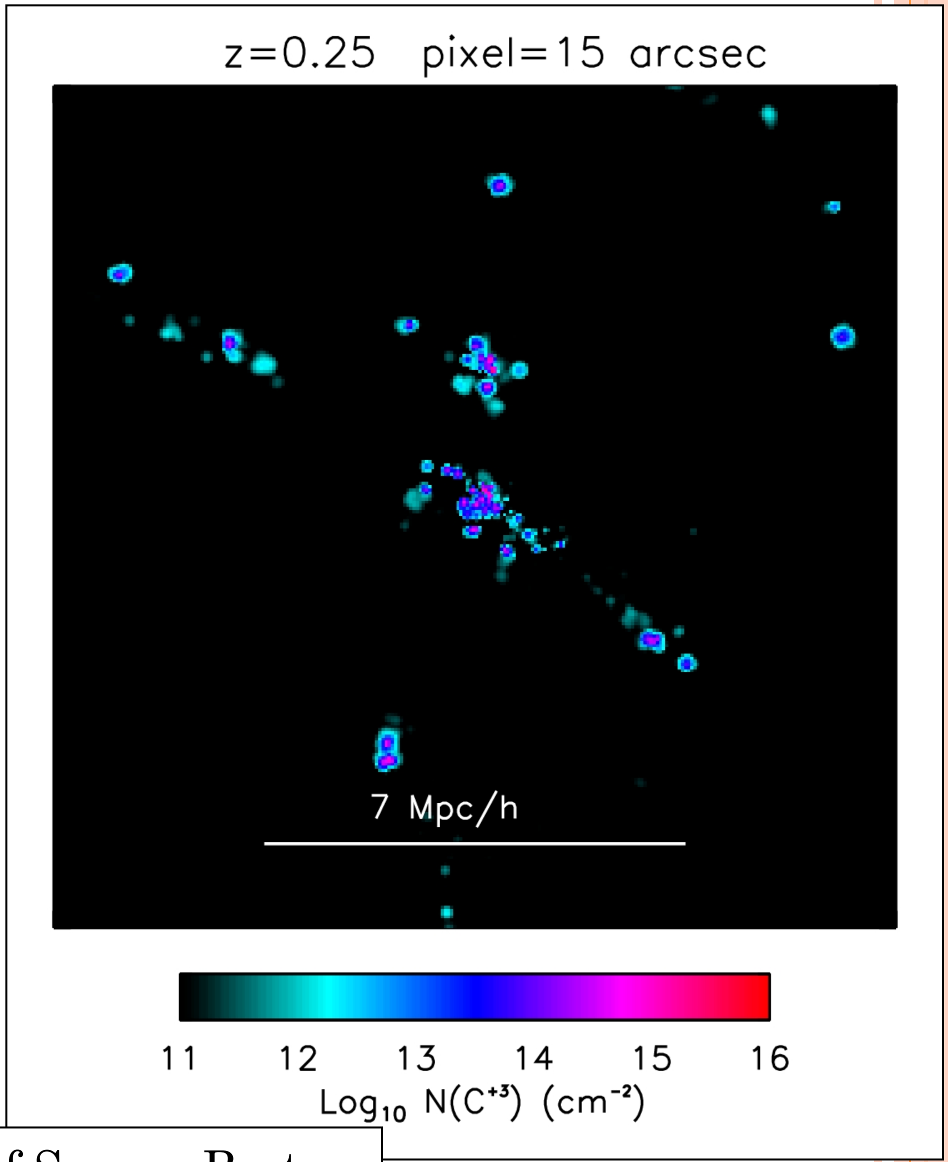




So much more to be explored…!

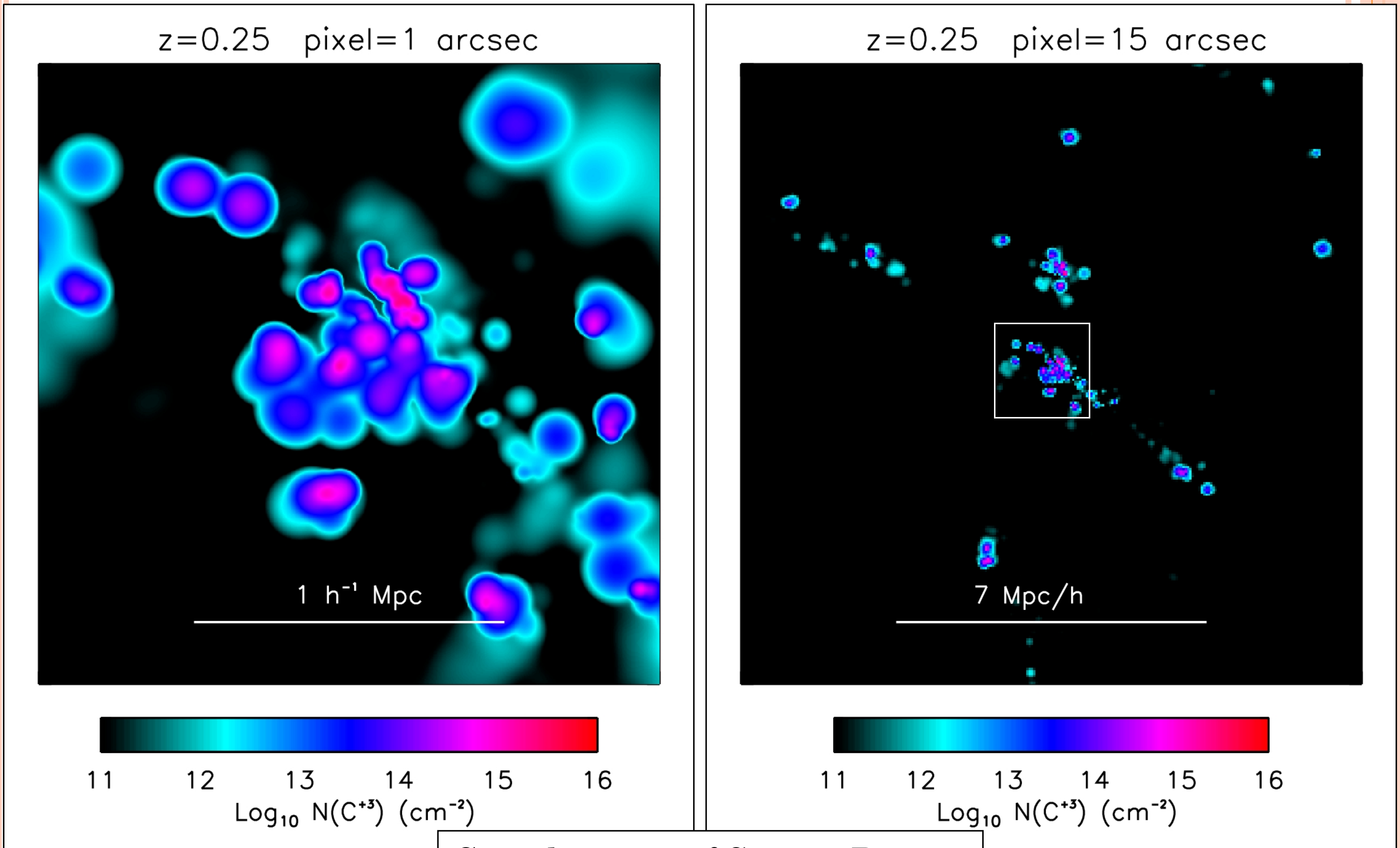
C^{+3} Column Density Maps: Galaxies?





Complements of Serena Bertone

C^{+3} Column Density Maps: Galaxies!



Complements of Serena Bertone

SUMMARY

- $z < 1$ C^{+3} and Si^{+3} mass densities increased compared to $1.5 < z < 5$ mean/median
- Physical distribution of absorbers "work" to keep d$\mathcal{N}$/dX within factor of two for 12 Gyr
  - Interplay of co-moving number density and cross section
  - CIV and SiIV absorbers likely trace circum-galactic medium more than IGM
    - At low redshift? At all redshifts?!
- Ionic ratio $N(Si^{+3})/N(C^{+3})$ constant for 12 Gyr
  - Processes balance to produce constant ratio…
  - … future work with OWLS to disentangle