

$z=20.0$

C II

C IV

O VI

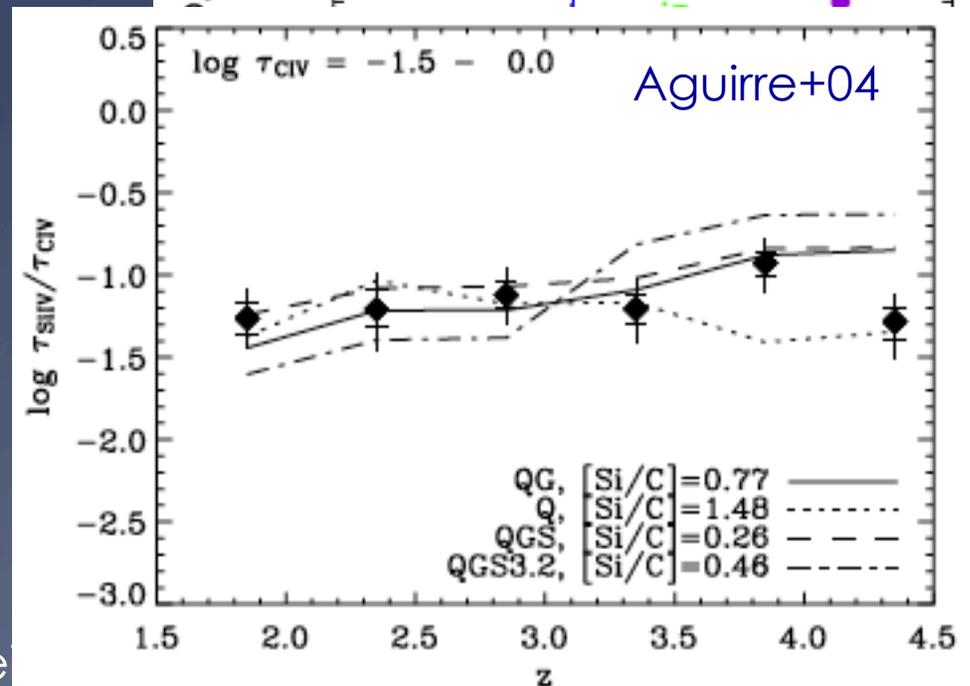
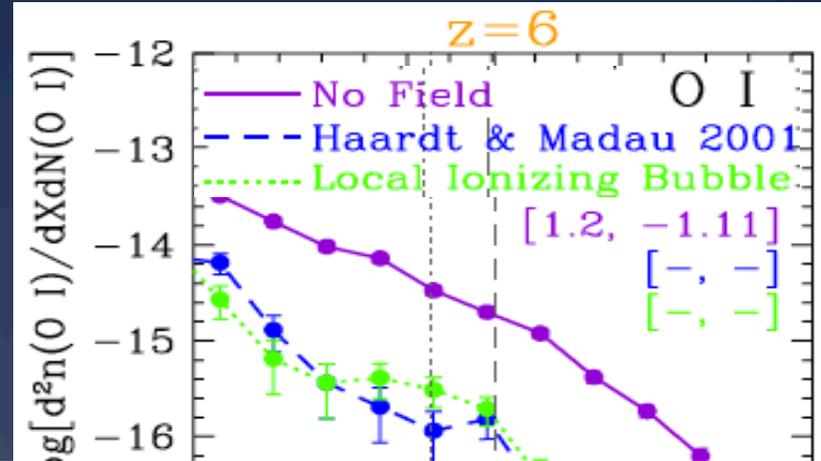
# The Enrichment of the Intergalactic Medium

Romeel Davé (Arizona)

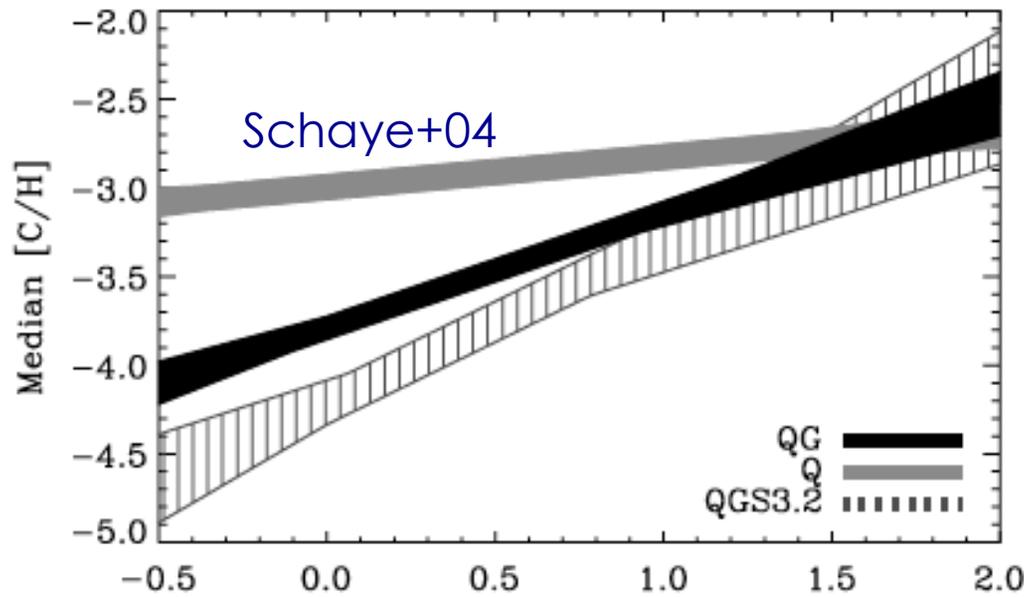
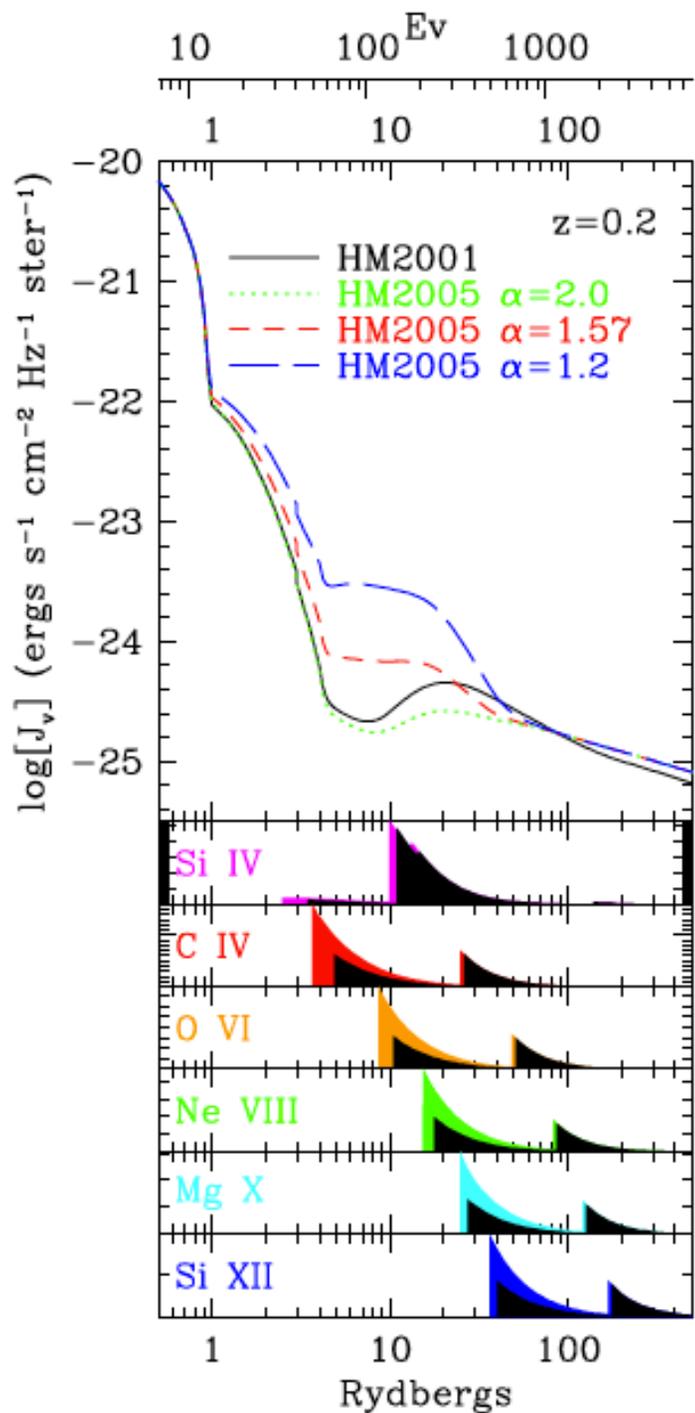
with Ben D. Oppenheimer,  
Neal Katz, David Weinberg,  
Amanda Ford, Molly Peeples

# The IGM is enriched by winds

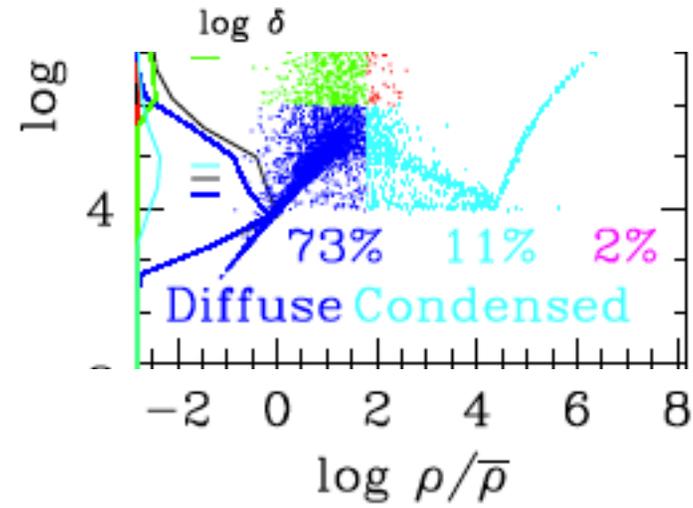
- \* Tidal/ram pressure stripping insignificant
- \* IGM enrichment...
  - \* constrains outflows
  - \* traces large-scale structure (even at  $z > 6$ !)
  - \* preserves fossil record of early SF (abund. ratios)



# Ionization-Density Relation The shape of $J_{UV}$



$\Gamma) \rightarrow$   
 n  
 yon



# Constraints on Winds

wind speed ↑

Too few metals in IGM

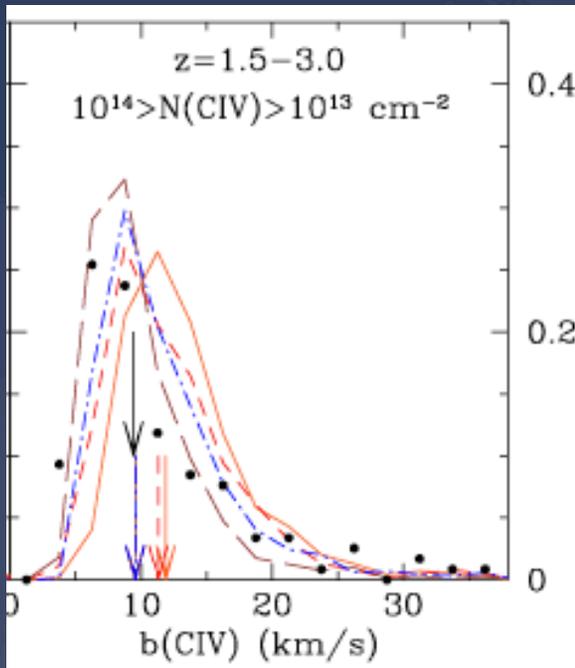
IGM too hot

**Just right!**

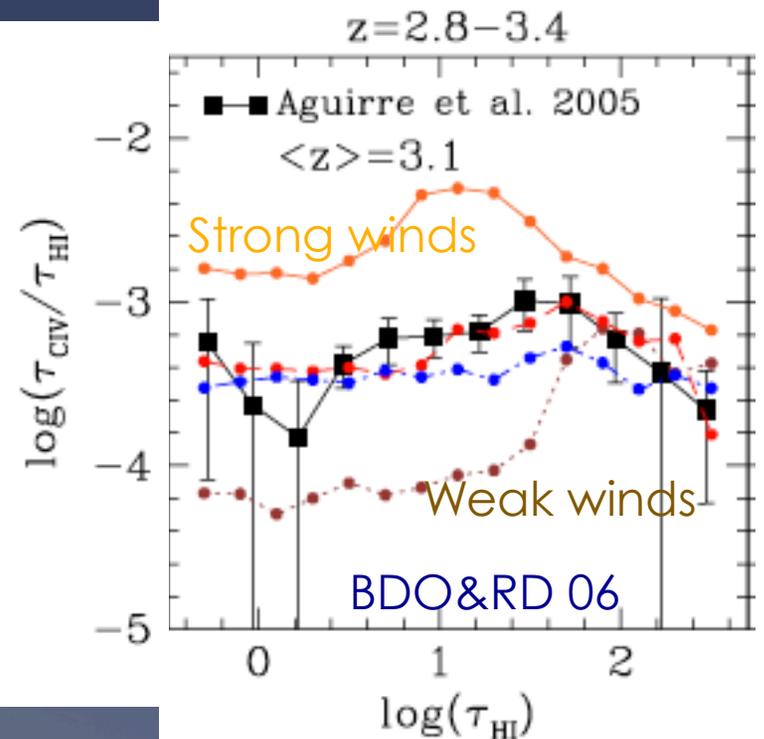
Diffuse IGM unenriched

Oppenheimer & RD 2006  
Oppenheimer & RD 2008  
Oppenheimer & RD 2009a,b

Too few metals produced



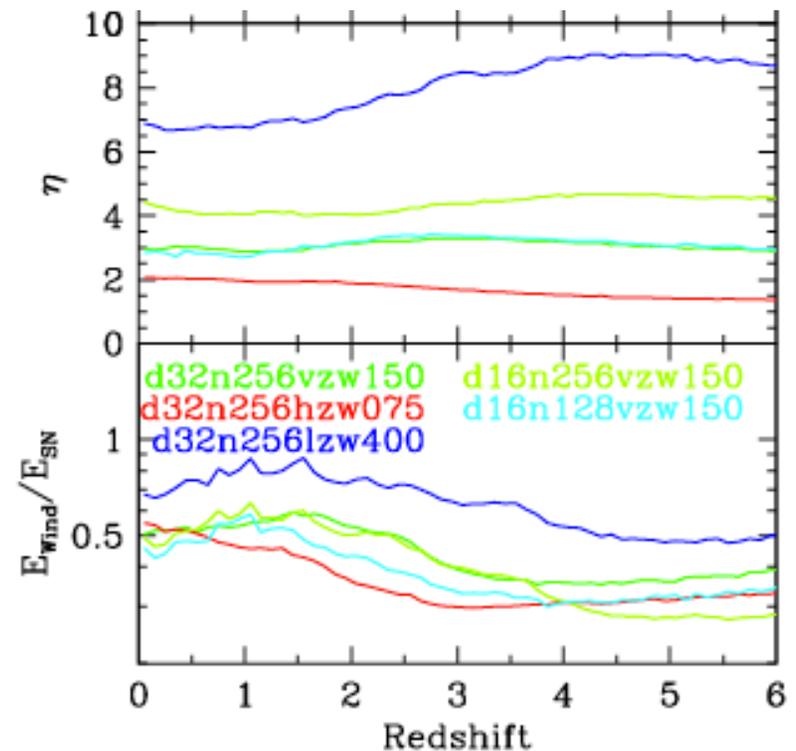
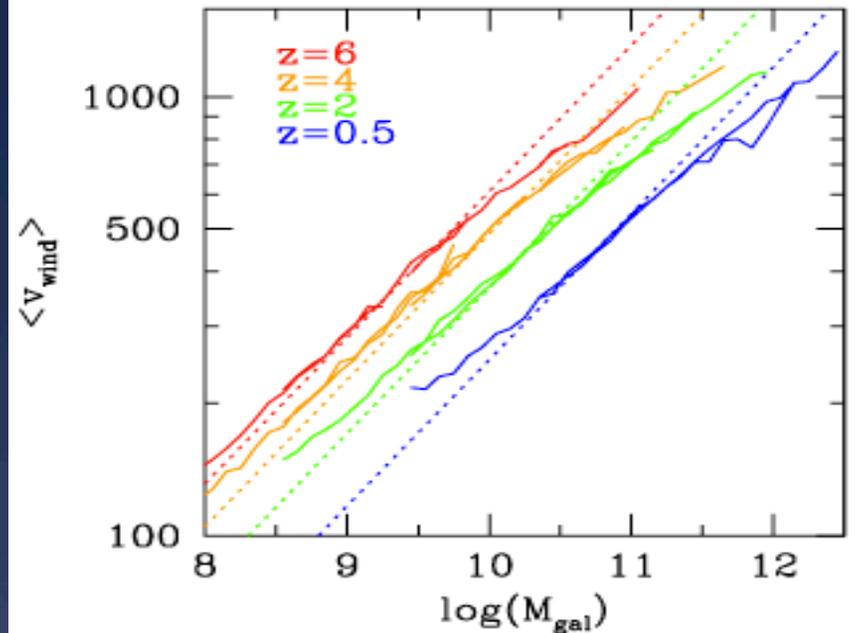
mass loading



# Wind Properties

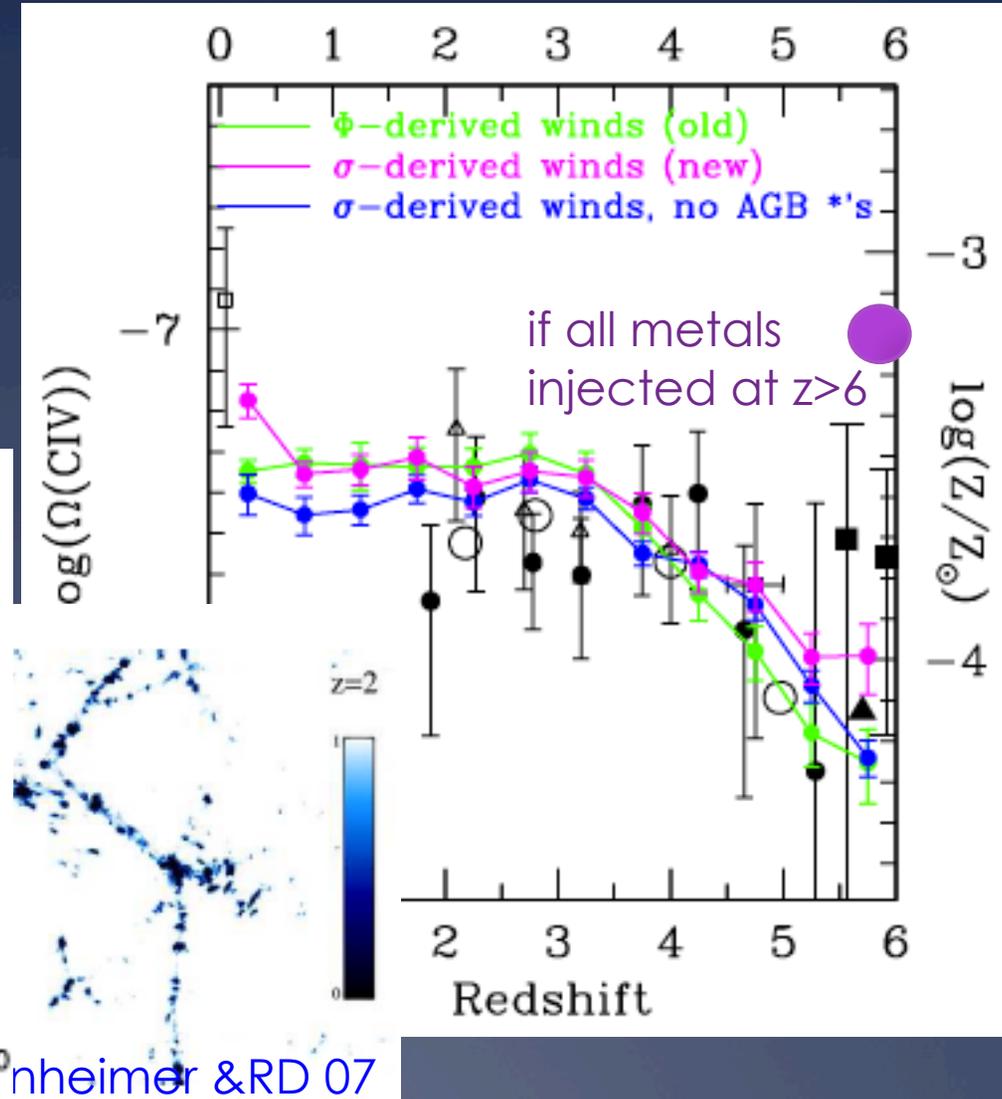
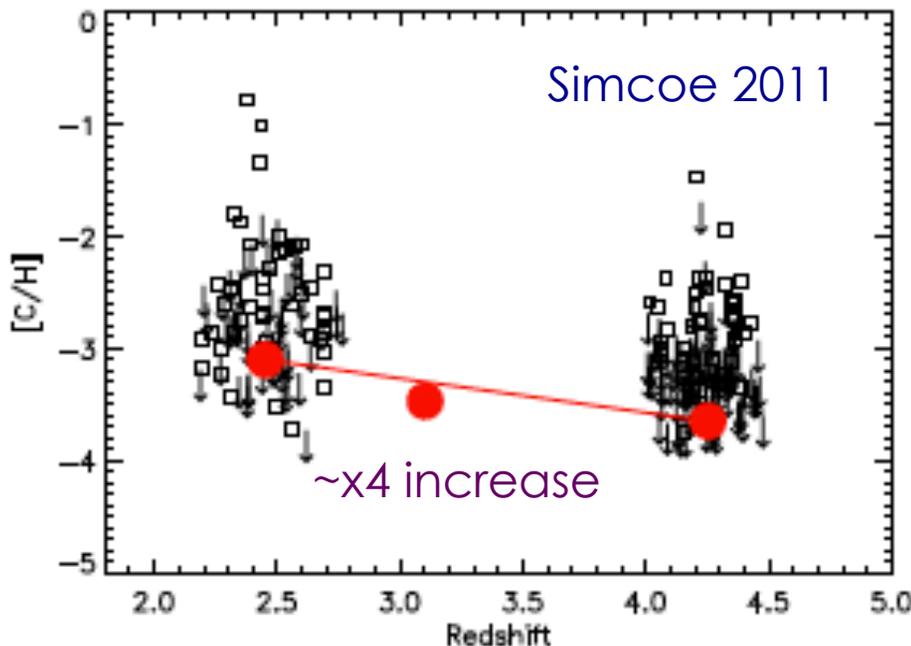
- \* Favored:  $v_{\text{wind}} \sim v_{\text{esc}}$ ,  $\eta \sim 1/v_c$ :  
Momentum driven?
- \* Mass loading factor  $> \sim 1 \rightarrow$   
 $M_{\text{winds}} > \sim M_*$
- \*  $v_{\text{wind}} \sim$  hundreds km/s
  - \*  $E_{\text{wind}} < \sim E_{\text{SN}}$ , but not by much!
- \* Similar to observed winds
  - \* *Observed galaxies can enrich the IGM!*

Oppenheimer&RD+08,09

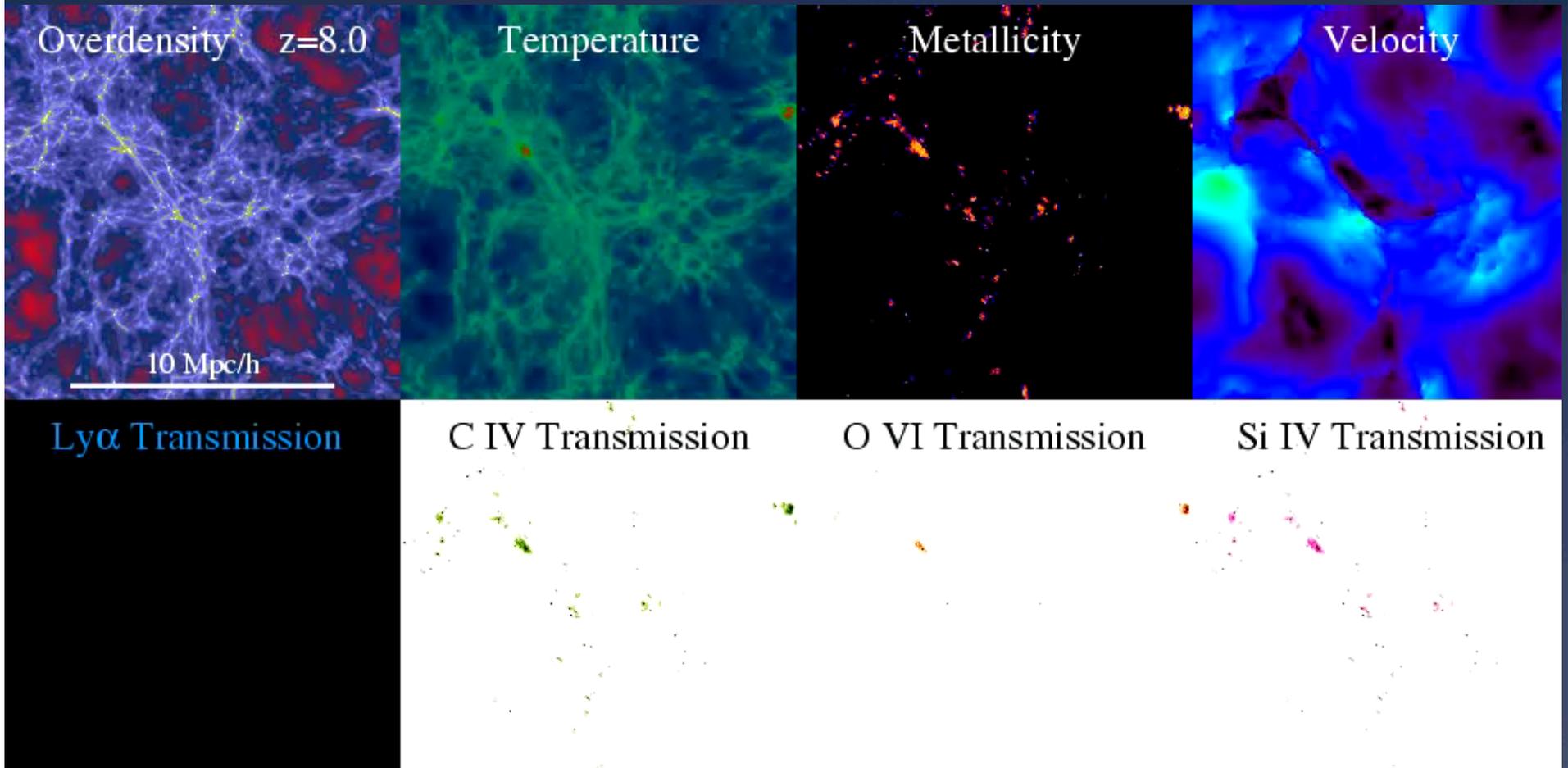


# Redshift Evolution: $z \sim 6-2$

- \* Flat  $\Omega_{\text{CIV}} \neq$  Flat  $Z_{\text{IGM}}$
- \* Filling factor  $< \sim 0.1$  @  $z > 2$
- \* Early enrichment ( $z > 6$ ) disfavored by  $\Omega_{\text{CIV}}$  drop.



# Physicals vs Observables

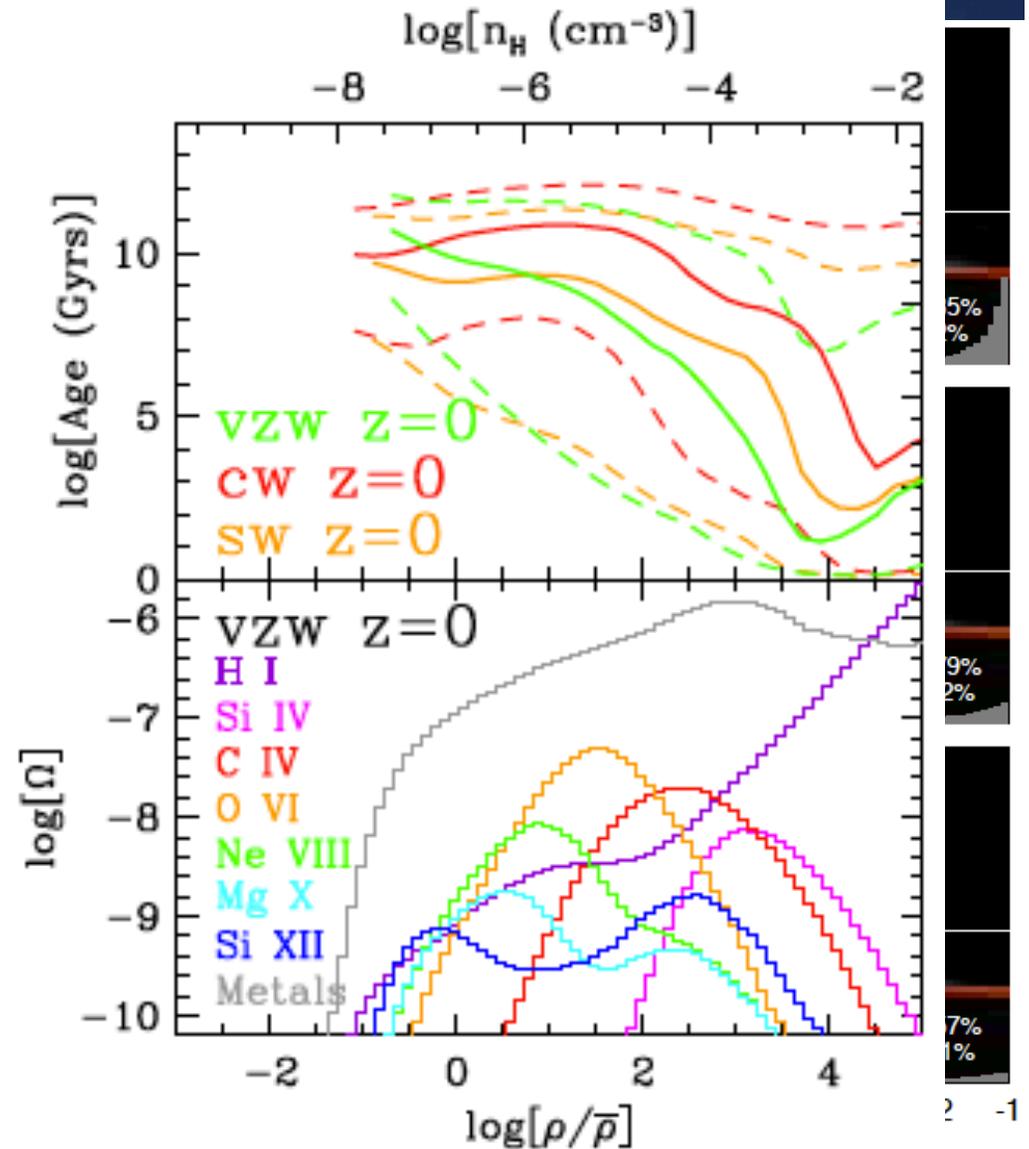
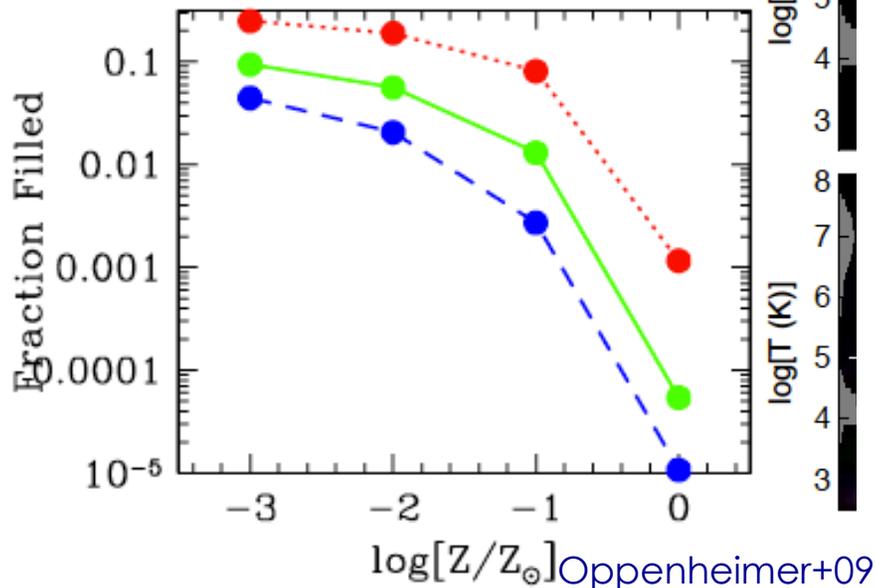


Movie by B. Oppenheimer

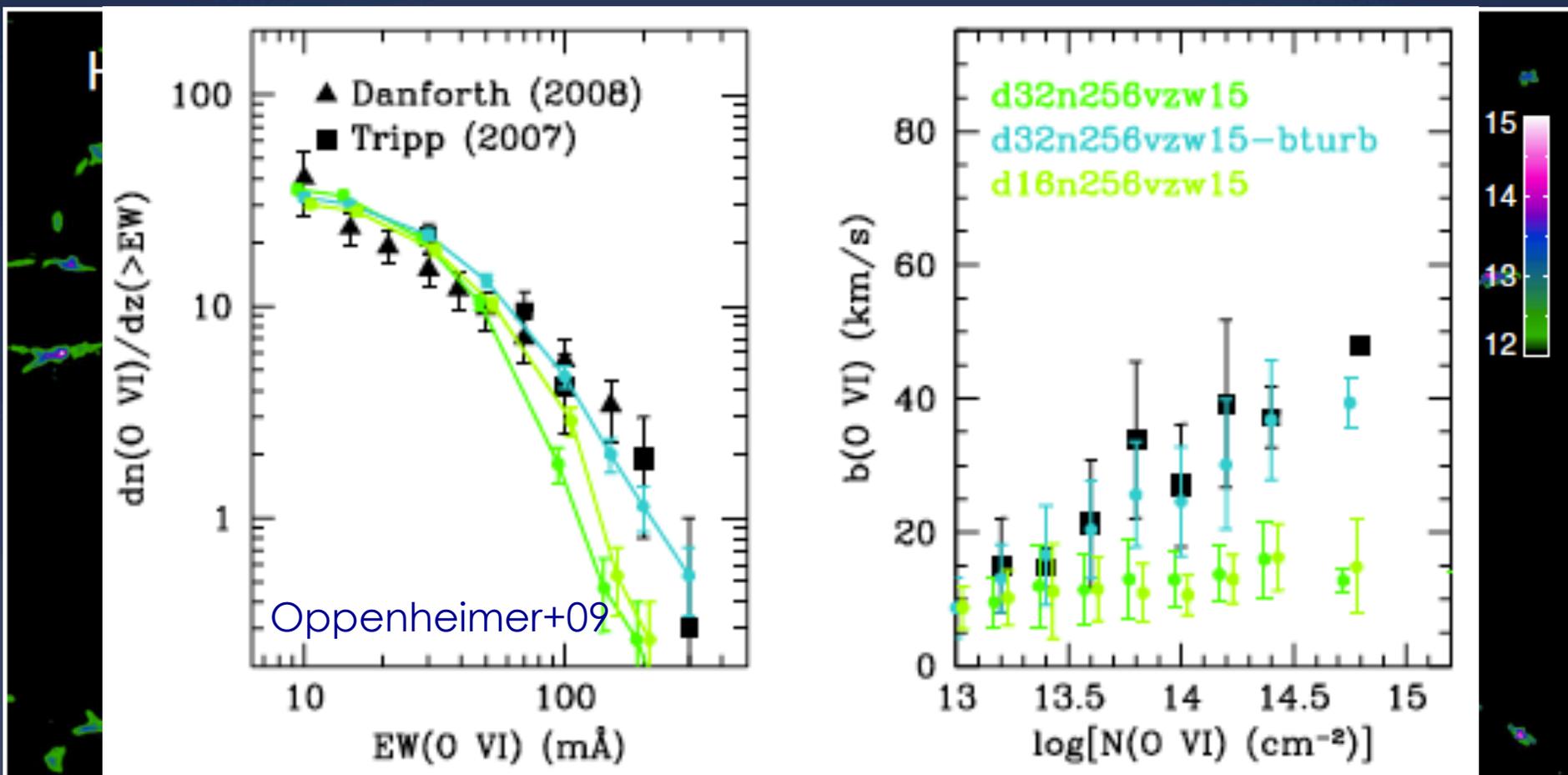
<http://luca.as.arizona.edu/~oppen/IGM/general.html>

# Redshift Evolution: $z \sim 2-0$

\* Metals migrate back towards galaxies. Oldest metals pushed into voids.

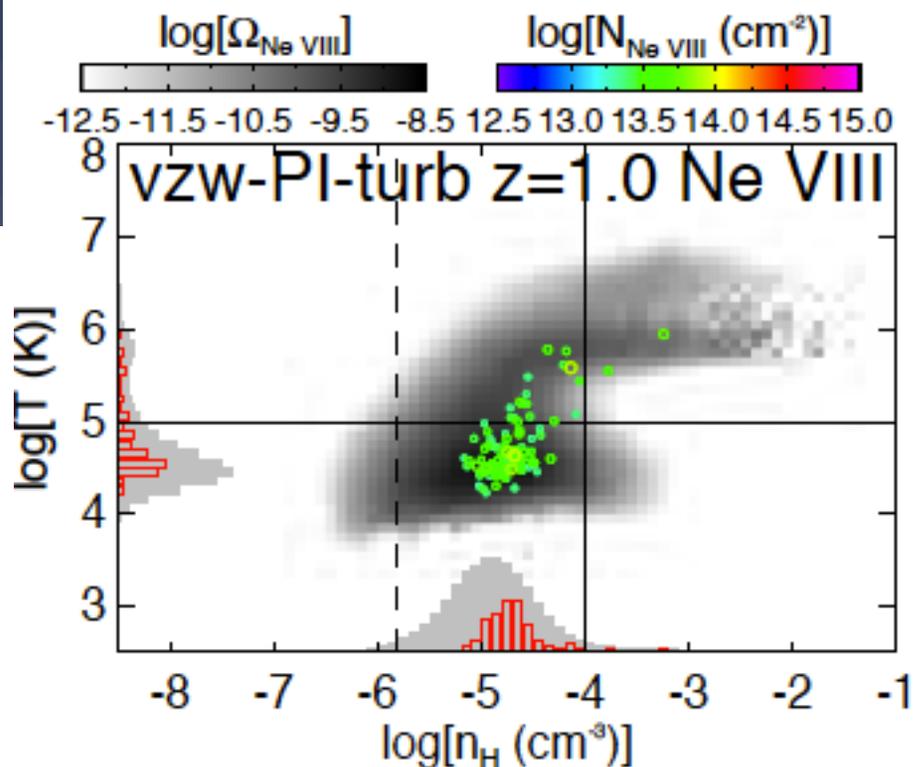
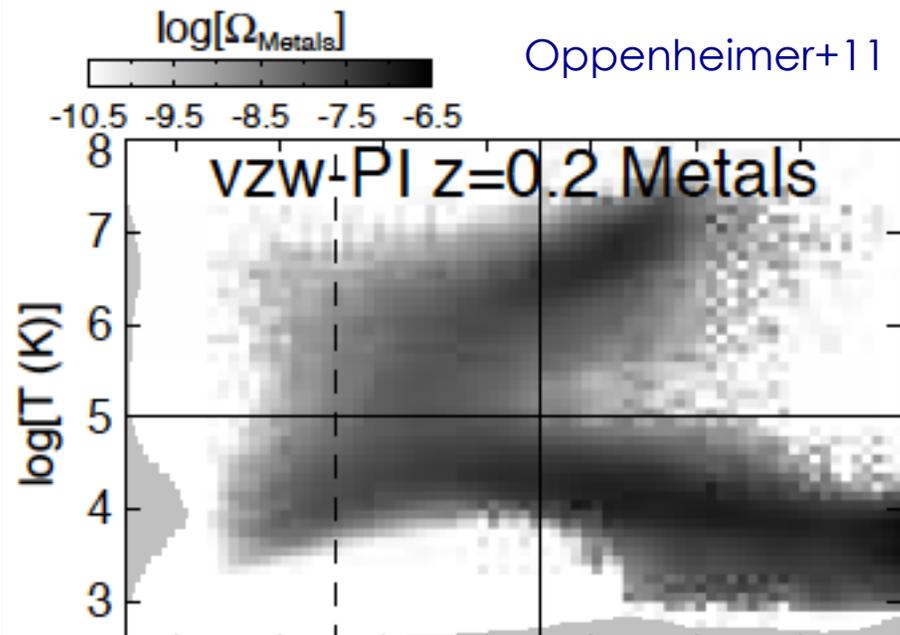
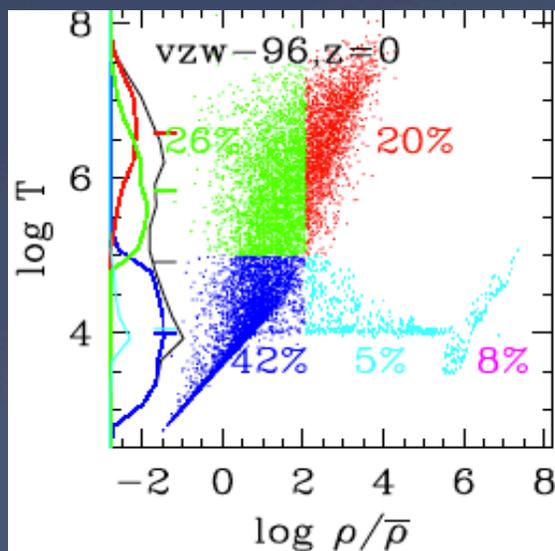


# Metals at low-z: OVI Turbulence in the IGM?



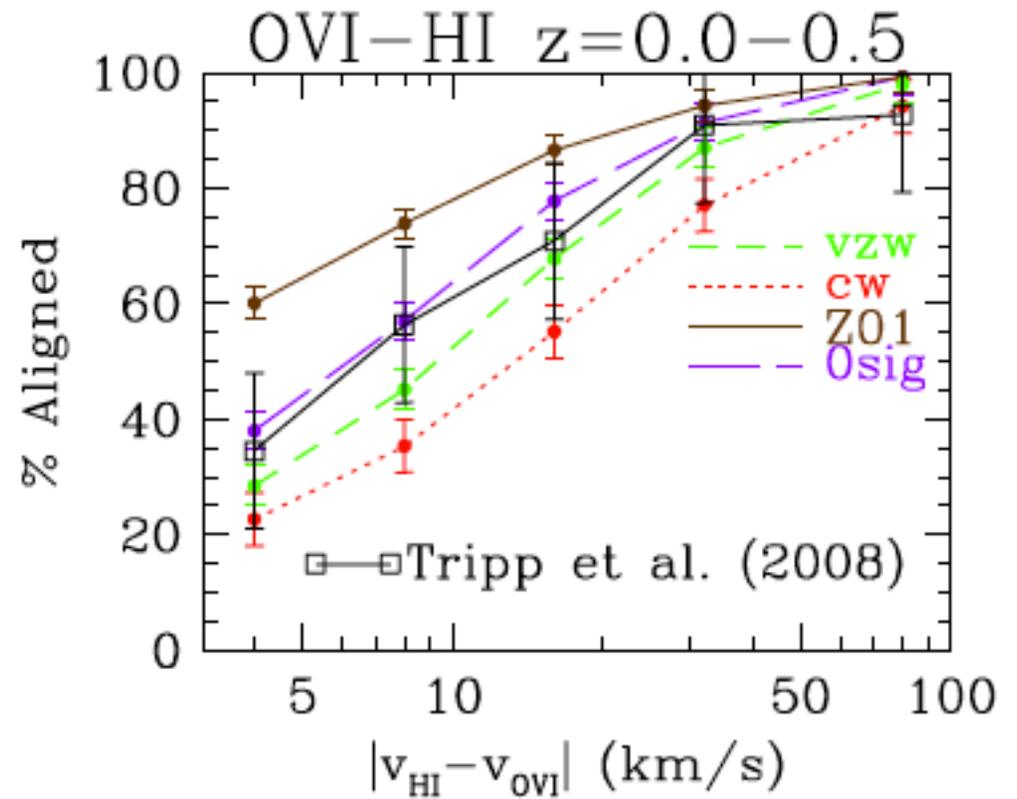
# Photo-ionised high ions: OVI, NeVIII(!)

- \* Even high ions can be photo-ionised.
  - \* UV background is *hard!*
- \* OVI poor tracer of WHIM
  - \* Need OVII, OVIII, CV... X-rays.

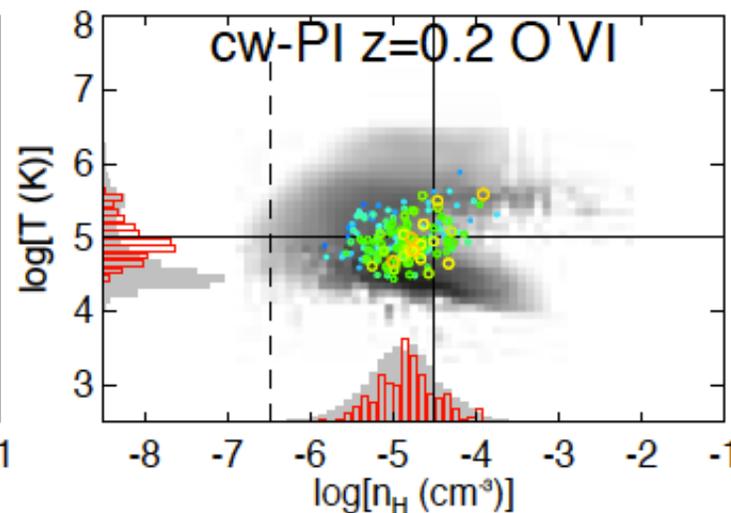
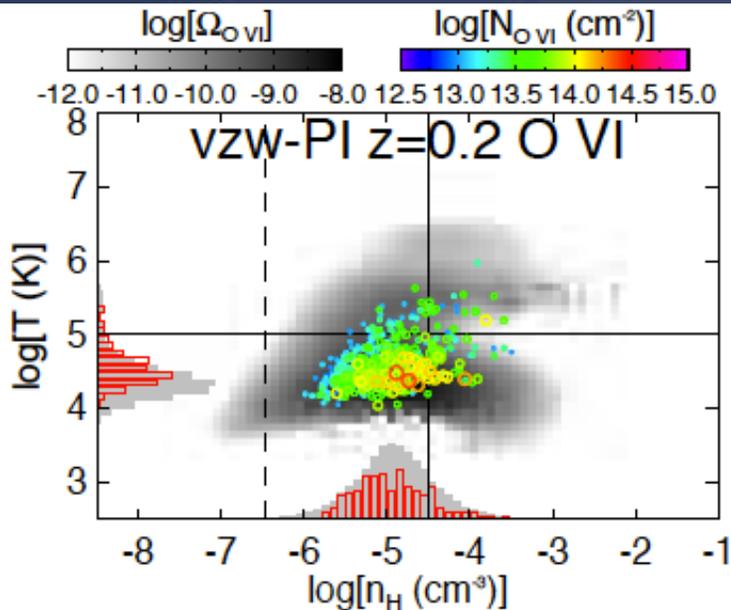


# Alignment Statistics

- \* Sensitive test of ionisation level.
- \* Data suggest lots of photo-ionised OVI



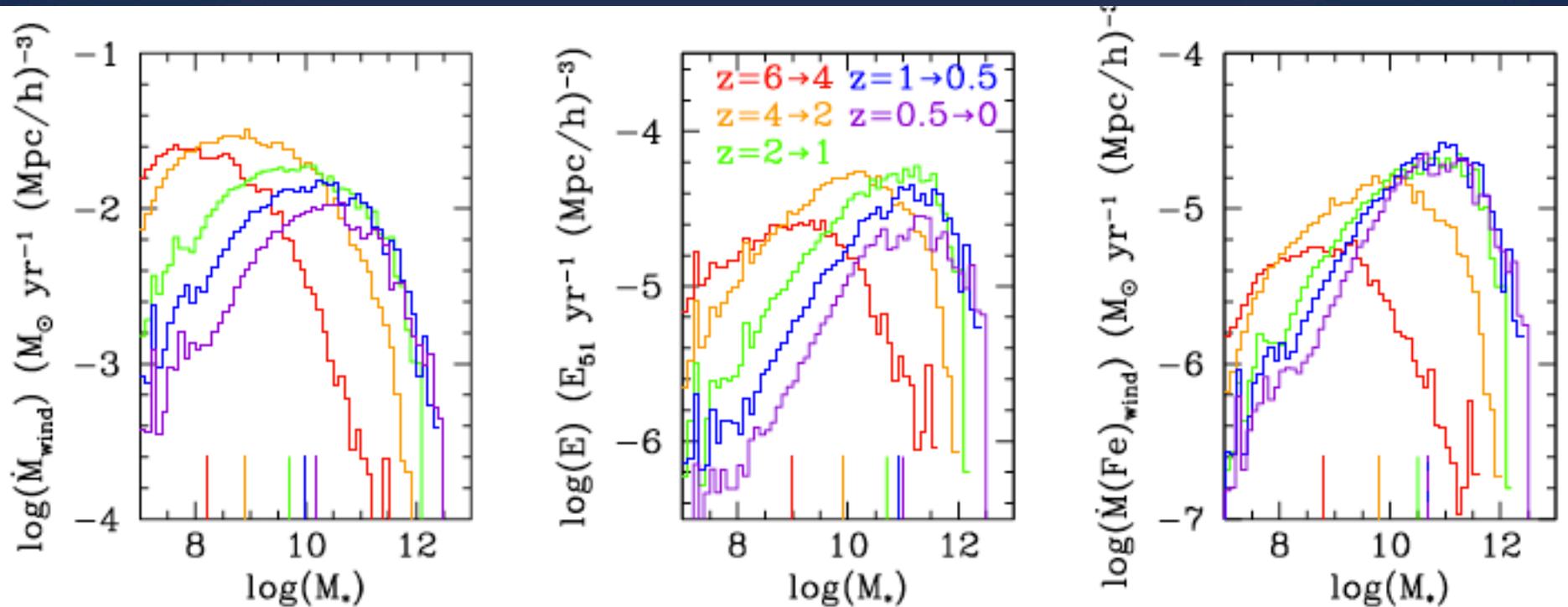
Oppenheimer+11



# Summary

- \* IGM metals are a sensitive tracer of galactic outflows.
  - \* More mass in outflows than in stars (globally)!
- \* IGM is enriched by normal galaxies, following cosmic SF. From  $z \sim 2-0$  metals migrate back towards galaxies.
- \* CIV, OVI, ... data are best matched by winds that
  - \* eject more material from small galaxies.
  - \* have modest speeds that do not overheat IGM.
- \* Weakest absorbers mostly photo-ionised, even OVI & NeVIII.
- \* Unresolved theoretical issues:
  - \* Large fraction of E and/or p needs to go into winds: How?
  - \* Metal mixing: How and how much?
  - \* How do winds interact with ambient/infalling gas?

# Which Galaxies Enrich IGM?



- \* Enriching mass evolves upwards with time
- \* At high-z, generally sub- $L^*$